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Engineering Geology of British Rocks and Soils - Lambeth Group

Engineering Geology Directorate

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BRITISH GEOLOGICAL SURVEY

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Engineering Geology of British Rocks and Soils - Lambeth Group

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Report; Lambeth Group, geology, mineralogy, geotechnics, engineering geology, engineering properties.

Front cover

Top left - Near shore marine sand and gravel, Upnor Formation, Orsett Quarry, Kent. Top right – from bottom of section, slightly gravelly clay of Upnor Formation, Lignite and then shelly clay of the Lower Shelly Clay. Bottom left – Laminated Beds, Newhaven, Kent. Bottom right, mottled clay of the Reading Formation, Alum Bay, Isle of Wight.

Bibliographical reference

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Forward

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Other reports in the series:

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Summary

The report is the fourth of a series that examines the distribution, lithostratigraphy, lithology, engineering properties and regional variation of the geological units that are significant to engineering geology, civil engineering construction and land-use in Britain. In this volume the Lambeth Group is described by its lithological variation, mineral composition, geophysical characterisation methods, geotechnical properties and engineering behaviour.

The first section describes the geology including the deposits below and above, the named units, sequence stratigraphy and the lithological variation. The next chapter discusses the mineralogy, in particular the clay mineralogy and changes due to pedogenesis, which are illustrated with electron micrographs. Geophysical methods applicable to the Lambeth Group are described and discussed in the next section. This is followed by two sections on the geotechnical characteristics, the former describing the data acquisition, storage in the database, access and analysis and the latter the interpretation and presentation of the geotechnical data. The final chapter, on the engineering geology of the Lambeth Group, draws on the preceding chapters. A comprehensive cited reference list and bibliography are provided. The first three appendices provide extra information on the variability and distribution of the Lambeth Group and includes the type borehole, various cross-sections and an analysis of the described lithology type from borehole descriptions. The final appendix provided statistical summaries of the more commonly carried out geotechnical tests.

The lithology of different boreholes are presented as in cross-sections and as with all non-confidential boreholes held by the BGS are available, free to download (http://www.bgs.ac.uk/data/boreholescans/home.html). The individual items of data in the database are not attributed. The authors would like to thank all those who have contributed data to the BGS including clients, consultancies, contractors, authorities and individuals. It is hoped that this report will provide a useful sources of information to a wide range of engineers, planners, scientists and other interested parties concerned with the Lambeth Group.

It is stressed that whilst data are included in this report, these indicate the variability of the particular parameter of each unit and might be used to identify hazards or risk; they are not a substitute for an appropriate ground investigation for the project, including desk study and site investigation. This is the case for all the 'Engineering geology of UK rocks and soils' reports but is more important for the Lambeth Group, which is often lithologically variable.

1 INTRODUCTION

1.1 BACKGROUND TO REPORT

The Lambeth Group is a very variable sequence of near-shore marine, lagoonal, estuarine and alluvial deposits of the Palaeogene. It outcrops and underlies much of the London and Hampshire Basins. Although relatively thin, generally less than 50 m thick, its position within 50 m of the ground surface under much of London, in conjunction with its vertical and lateral lithological variation, has had a major influence on the capital's engineered infrastructure, particularly tunnel construction. The difficulty of predicting the lithology, especially where water lain sand occurs within stiff clay, presents significant engineering problems.

To understand where and why the different deposits are found it is important to understand the depositional conditions of the Lambeth Group including the formation of 'hard bands', which were generally formed by soil forming processes or pedogenesis under a sub-tropical climate. In general, the distribution of the lithostratigraphical units is well known and in some places it is possible to predict the lithologies. However, in many places predicting all the lithologies that are present is often not possible. This is particularly the case in London and impacts on the design of site investigations, particularly in relation to tunnels and deep shafts, and material for earthworks. Where near-surface construction is required, and in rural areas, boreholes and geophysical techniques may provide an almost complete ground model. Tunnelling in cities makes ground characterisation much more difficult. However, identifying what is likely to occur and the increasing availability of geological and geotechnical data as well as ground investigation will improve the ground model.

The Lambeth Group is split into three formations with other units within the formations. The units are based on the original depositional environment, which impacts on their content.

The Lambeth Group causes a number of investigation and construction problems due to lithological variation, namely sand filled channel, gravel beds, lignite, hard bands, closely fissured clay, the presence of sulphide and sulphate, swelling clay, and perched water. Where it is thin and on chalk the resulting dissolution of the chalk causes collapse of the lower Lambeth Group into the voids produced. The lower part of the Lambeth Group is known under certain circumstances to contain pressurised, de-oxygenated air, which is a hazard to tunnelling operations (Newman *et al*., 2013).

This report on the Lambeth Group is the fourth of a series on the rocks and soils of Britain, which aims to satisfy a need of geologists and engineers for reference works describing the engineering behaviour of important geological formations. It complements, to some extent, the CIRIA report on the Lambeth Group (Hight *et al*., 2004).

1.2 Methodology

The properties and behaviour of Lambeth Group materials are controlled by their texture, structure, mineral composition and alteration. These factors are a reflection of their depositional environment including the climate, penecontemporaneous pedogenic alteration, diagenesis and subsequent tectonic history that also have a major influence on the engineering behaviour of the strata as a whole. Also, the near-surface zone has been influenced by more recent earth surface processes such as 'modern' (Holocene) weathering. The Lambeth Group study comprised several interdependent parts. An extensive literature search was carried out at the start of the study to collect and review previous work thus guiding the activities of the present study. At the same time an extensive geotechnical database was assembled from data extracted from high quality site investigation reports, which was then analysed to establish the typical range and values of the most commonly determined geotechnical parameters, and to look for lithostratigraphical and regional variation in geotechnical properties. When the scope of the database was clear, a sampling and testing programme was carried out to investigate in more detail some of the geotechnical properties and behaviour not satisfactorily covered in the database.

As lithological variation is of such importance, cross-sections based on boreholes from selected major civil engineering projects are presented to illustrate the geological units and described lithological types. Summary diagrams showing lithological and lithostratigraphical variations based on borehole descriptions were also produced for areas where there was sufficient data.

2 GEOLOGY

This chapter provides information on the lithologies and lithostratigraphy of the Lambeth Group and those deposits below and above that may be confused with the Lambeth Group, that is, the Thanet Formation beneath and the Harwich Formation above.

The term *Lambeth Group* has been in the public domain only since 1995 (see Ellison *et al*., 1994) and replaces the formerly used *Woolwich and Reading Beds*. The term was introduced in order to clarify the stratigraphy shown on British Geological Survey maps, initially in the London area. The change in name was necessary for two reasons. Firstly, the strata within the group exhibit considerable lateral and vertical lithological variation, and the new classification helps to constrain some of the variation within the formations. Secondly, the Lambeth Group is within 50 m of the surface beneath large tracts of London and, therefore, has been, and continues to be, an important issue in many engineering projects. Much of the drive for the improved understanding of the complexity of the Lambeth Group has been from major infrastructure projects in London and the information derived from high quality ground investigations, including the development of London Docklands, new underground services including the London Underground and the Channel Tunnel Rail Link.

In the following account the principal constituent lithological units of the Lambeth Group are defined. Their correlation and three-dimensional relationships are demonstrated in a series of cross sections and maps. For each unit, aspects of the geology that may pose problems for engineering are identified. Accounts are also given of the underlying Thanet Formation and the overlying Harwich Formation.

2.1 REGIONAL SETTING

After the deposition of the Chalk across much of Europe, increased tectonic activity relating to the opening of the Atlantic Ocean and building of the Alps in southern Europe in the late Cretaceous and early Tertiary resulted in a period of uplift and tilting and a global fall in sea level. This produced newly emergent landmasses in the north and west of Britain and the Amorican Massif (Skipper, 1999) and the erosion of the youngest part of the Chalk from southern England. The depositional hiatus between the Chalk and the sediments of the Palaeocene in southeast England lasted about 10 to 15 Ma. During this hiatus, many major plate tectonic changes occurred worldwide. In the west was the widening proto-Atlantic Ocean, the development of which was associated with rifting and volcanic activity that culminated in early Eocene times about 55 million years ago (Knox, 1994). This led to much smaller depositional areas and a change from carbonate sedimentation to increased clastic sedimentation (Chadwick, 1986), followed by the intermittent deposition of Tertiary sediments about 58 Ma when a shallow sea extended from the North Sea across the south east of England. The Lambeth Group forms part of this sedimentary sequence deposited around 55 to 56 Ma. About 20 Myr later, during the Miocene, the outcrops of the London and Hampshire Basins were separated by gentle folding.

During the Palaeocene the climate warmed, with short-term rapid increases in temperature of 4 to 6°C (Beck *et al*., 1995). Evidence of broad-leaved evergreen vegetation suggests a mean annual land temperature of 10 – 20°C with abundant precipitation. However, the rainfall was probably seasonal particularly during the deposition of the upper Lambeth Group.

Volcanic activity to the north west of Britain provided ash, which can be seen in layers in the Ormesby Clay Formation (Cox *et al*., 1985) below the Lambeth Group and in the Harwich Formation and London Clay above. The reworked and weathered (argillized) ash was subsequently deposited as smectite throughout most of the Palaeocene. However, ash bands have not been reported in the Lambeth Group and are very rare in equivalent deposits in the North Sea Basin, currently thought to be Sele Formation (King, 2006).

At the beginning of Palaeogene time the south east of England lay on the edge of a sedimentary basin that included much of the present North Sea, and extended eastwards at least as far as Poland. The Palaeogene deposits were laid down during alternating transgressions and regressions driven by global sea level changes and this broad pattern was overprinted locally by changes in ground level from tectonic activity. The general succession (Figure 2.1) is divided into major depositional sequences (Knox, 1996a).

Deposition of the Thanet Formation, Lambeth Group and Harwich Formation occurred in embayments on the western margin of a deep-water marine basin of the North Sea. These marginal deposits were very sensitive to relatively minor changes in sea level. This resulted in alternating incursions and recession of the sea and migration of depositional environments, followed by erosion, changes in groundwater levels, soil formation and down-cutting by rivers that contributed to the development of complex lithologies. Rising sea level led to rapid inundation and a new phase of sedimentation.

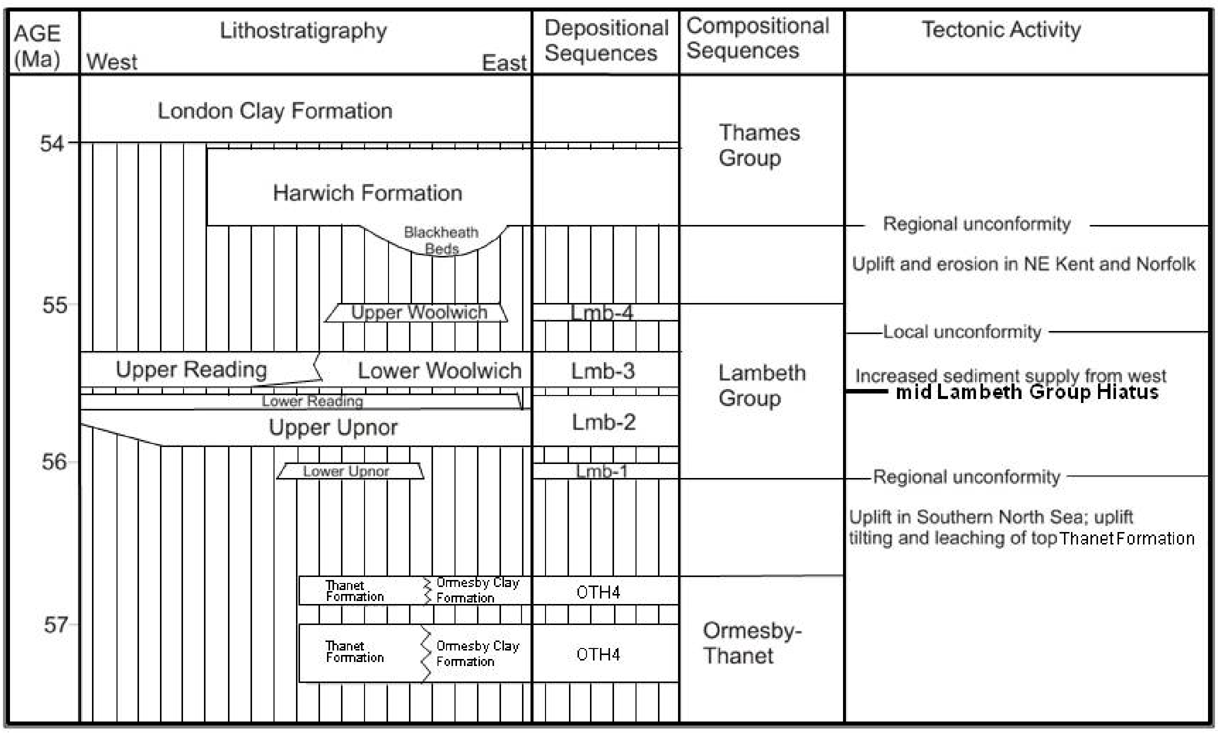

Figure 2.1 The sequence stratigraphy of the middle part of the Palaeogene, with the depositional sequence and tectonic activity (after Knox 1996a). (Vertical stripes indicate no deposition).

2.2 DEPOSITS BENEATH THE LAMBETH GROUP

The main deposits immediately beneath the Lambeth Group are listed below and their distribution is shown in Figure 2.2.

- White Chalk Subgroup in the Hampshire Basin and the west of the London Basin.
- Thanet Formation in the middle and east of the London Basin.
- Ormesby Clay Formation to the north east of the London Basin.

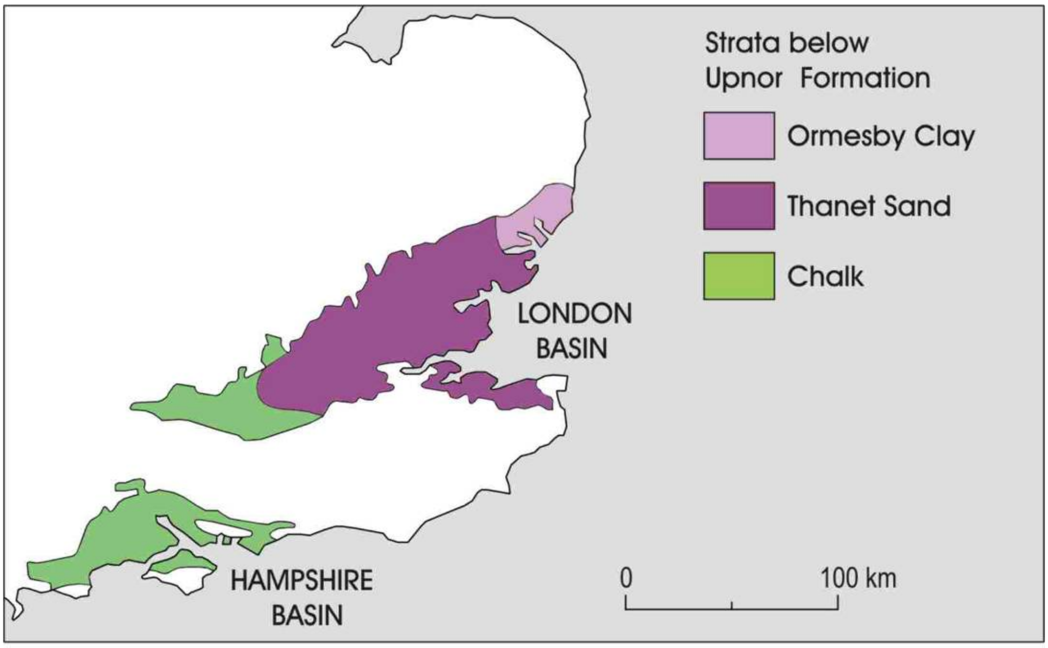

Figure 2.2. The strata underlying the Lambeth Group.

The surface of the chalk can be karstic and undulating. However, it is very easy to differentiate between the Chalk and the lowest part of the Lambeth Group comprising the sandy facies of the Upnor Formation.

The boundary of the Upnor with the underlying Ormesby Clay Formation is relatively simple to identify as the latter is predominantly clay as opposed to sand, but there is little available information. Restricted to eastern East Anglia, the Ormesby Clay Formation is not found at surface and is only known in a limited number of boreholes. It consists generally of very stiff glauconitic clay or very weak mudstone with sporadic, thin ash bands occurring in the lower part of the formation. The clay mineral assemblage is dominated by smectite, derived from weathered and redeposited volcanic ash that results in extremely high clay/mudstone plasticity (liquid limits ranging from 98 to 172% and plastic limits from 36 to 78%, Cox *et al.*, 1985). The unit is over 25 m thick in east Norfolk thinning to about 10 m in Suffolk and less than 10 m in Essex.

Differentiating between the Upnor Formation and the underlying Thanet Formation can be more difficult. It is usually possible in boreholes as the sand at the top of the latter is generally denser and finer grained than the coarser clayey sand of the Upnor Formation. However, when field mapping, this boundary can be extremely difficult to identify particularly where the two formations are weathered and the base of the Upnor Formation does not contain flint gravel. The distribution, lithological characteristics and boundary of the Thanet Formation with the overlying Lambeth Group Upnor Formation is described in more detail below.

2.2.1 Thanet Formation

2.2.1.1 INTRODUCTION

The Thanet Formation (Aldiss, 2012) deposits are interpreted as inner shelf to coastal in origin. In general, they are well sorted, indicating considerable winnowing and reworking prior to deposition. Grain shape suggests a rather juvenile origin with only minor recycling from older sedimentary formations.

The base of the Thanet Formation is unconformable on the eroded surface of the Chalk Group. The unconformity is not caused by a single event but is attributed to erosion and reworking during two or more depositional sequences (Knox, 1996a, 1996b). The base of the Thanet Formation is marked by the unconformable contact between the bouldery, cobbly gravelly sand of the Bullhead Bed and the Chalk, and the top by the unconformable boundary marked by an upward change from the fine-grained grey sands of the Thanet Formation to grey to greenish grey, commonly gravelly, clayey, fine to medium sand of the base of the Upnor Formation of the Lambeth Group. At outcrop and, where weathered, the Upnor Formation sands are speckled with dark green grains of glauconite.

2.2.1.2 DISTRIBUTION

The Thanet Formation occurs in the east and middle part of the London Basin but is absent from the Hampshire Basin. The principal outcrops are in south-east London and north Kent including outliers around Dartford [TQ 520 730], Swanley [TQ 510 690], Southfleet [TQ 614 711] and Cobham [TQ 671 685]. The Thanet Formation is also preserved locally in dissolution pipes and hollows in the Chalk peripheral to these outliers, in some cases beneath a cover of Head or Clay-with-flints. In central London it is typically 10 to 15 m thick and in west London and Surrey it thins westwards where it is below the Lambeth Group. In the eastern parts of the London Basin it is generally thicker being thickest in north Kent, where it generally 20 to 30 m but as much as 37 m in the Canterbury district. Pockets of Thanet Formation occur in dissolution cavities within the surface of the chalk, but the majority of them do not form features. At surface, the formation forms positive, well-drained features with convex slopes. The basal contact with the chalk often forms a pronounced concave break of slope. The top of the formation is generally located by augering or placed on the evidence of borehole data. In the north east of the London Basin the Thanet Formation has not been mapped separately from the Lambeth Group as, in the field, it is not possible to distinguish consistently between the top of the Thanet Formation and the base of the Upnor Formation. Here, they are mapped as the Lower London Tertiaries on the current England and Wales 1:50k geological maps of Sudbury (206) (Pattison *et al*., 1993), Braintree (223) (Ellison and Lake, 1986), Ipswich (207) (Boswell, 1927), Great Dunmow (222) (Lake and Wilson, 1990), Epping (240) (Millward *et al*., 1987) and Woodbridge and Felixstowe (204) (Boswell, 1928). However, with good quality borehole data it is possible to differentiate between the Thanet Formation and Lambeth Group in this area.

2.2.1.3 DESCRIPTION

Most of the Thanet Formation is composed of very dense, grey or greenish grey, slightly clayey or slightly silty fine sand. In the London area, it is generally coarsens upwards with larger proportions of silt and clay in the lower part. Figure 2.3 shows the particle size envelopes based on over 700 analyses of the Thanet Formation, not including the Bull Head Beds, and the more restricted slightly silty fine sand within 2 m of the base of the Lambeth Group. The sand grains consist almost exclusively of quartz, and are mainly angular and subangular, with only a small proportion of subrounded grains and flint chips (Figure 2.4). Smectite is generally the dominant clay mineral, a weathering product of penecontemporaneous volcanic ash falls (Knox, 1994). Although predominantly sand, this is not always the case and in Kent a number of named units are described (Aldiss, 2012). These are the Base Bed Member, which includes the Bullhead Bed, the Stourmouth Silt Member, the Kentish Sands Member, the Pegwell Silt Member and Reculver Sand Member.

The basal unit of the Thanet Formation is commonly represented by the Bullhead Bed. This distinctive unit generally comprises very dense, greenish grey, glauconitic, slightly gravelly, silty fine to medium SAND with low cobble and boulder content. The gravel is of fine well-rounded flint, whilst the larger gravel, cobbles and occasional fine boulders (up to 0.3 m in diameter) are unworn nodular flint, which can have large protuberances similar to a bull's head, hence the name. This unit is generally up to 0.5 m thick but in parts of north London it is sometimes up to 1.5 m thick.

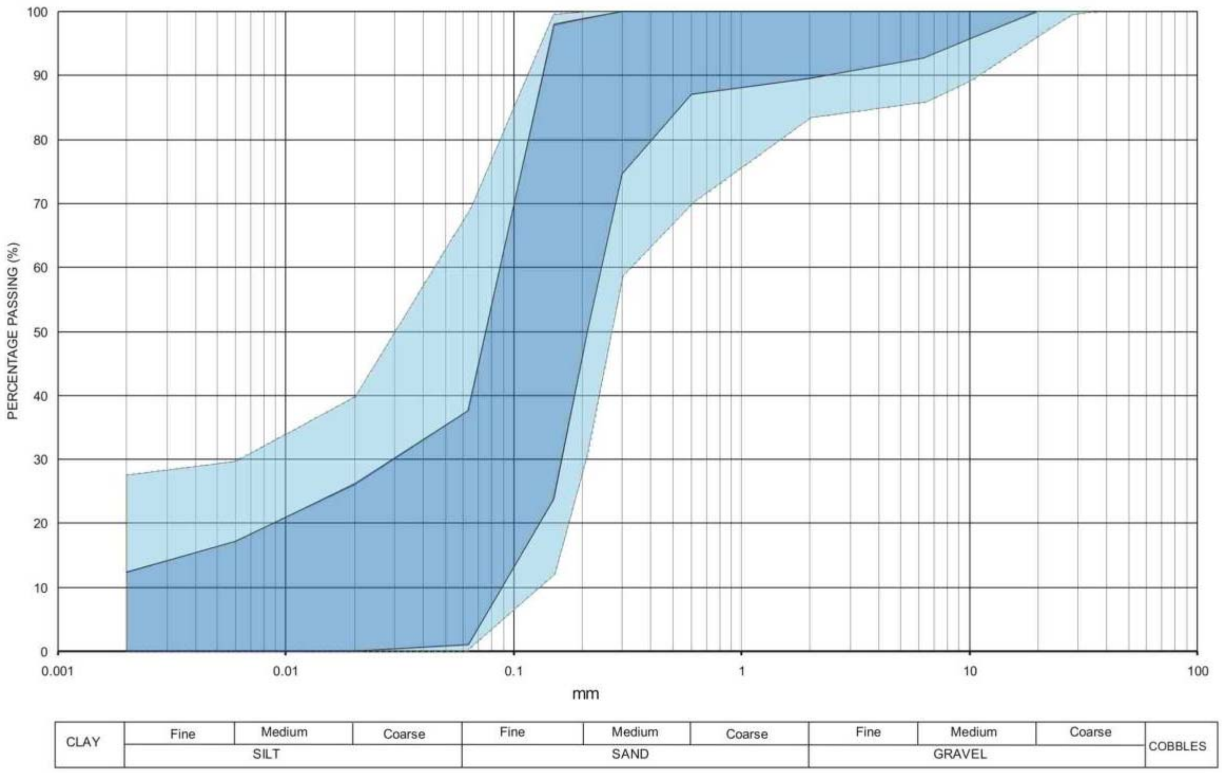

Figure 2.3. The particle size distribution of the Thanet Formation. Dark blue represents the Thanet Formation within 2 m of the base of the Upnor Formation (over 100 samples) and pale blue all the Thanet Formation not including the Bullhead Beds (over 700 samples).

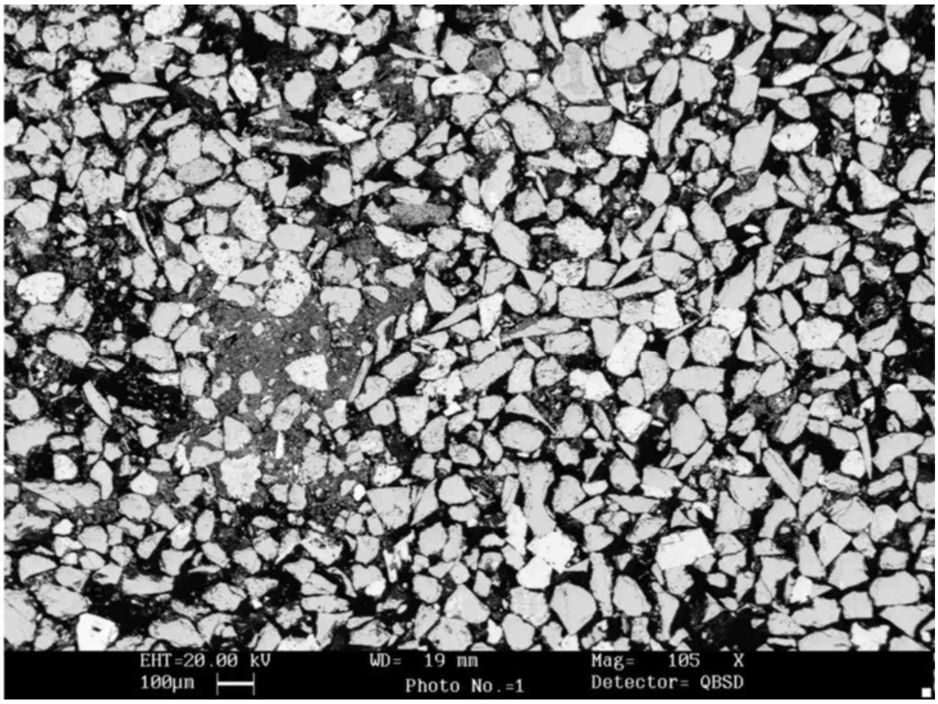

Figure 2.4. Typical example of Thanet Formation lithology, comprising well sorted fine-grained sand, locally weakly cemented by detrital clay. The large secondary voids are due to feldspar dissolution. Jubilee Line Extension borehole 404T (BGS borehole TQ37NW/2118 [TQ 33638 79604]), 52.80 m (BGS Photomicrograph No. D789P101).

The unweathered sediments are pale to medium grey to brownish grey but weather at surface to pale yellowish grey. Figure 2.5 is an example of borehole core from the Thanet Formation in south central London. Contemporary weathering and pedogenic processes locally give rise to a typical podsol profile, with purplish brown weak ferruginous cement developed within 0.8 m of the surface.

Figure 2.5. Typical Thanet Formation core sample, showing grey, slightly silty fine SAND; top to left. (CTRL (Union Rail), borehole 1112B.

The sediments are intensely bioturbated so that primary sedimentary structures such as lamination are generally missing. Bioturbation structures are identified as wisps of relatively dark grey clay in hand specimen and in exposures. Dark grey to black manganese-rich silt may occur in the linings of sinuous burrows up to 8 mm in diameter. Scattered oblique and near-vertical burrows also occur in the top 1 to 1.5 m. These are usually filled with glauconitic sand derived from the overlying Upnor Formation (CTRL borehole 1131, Figure 2.6a). This mixing contrasts with the sharp contact between the Thanet Formation and the base of the Upnor Formation comprising clayey rounded flint gravel, as shown in CTRL borehole 2112 (Figure 2.6b).

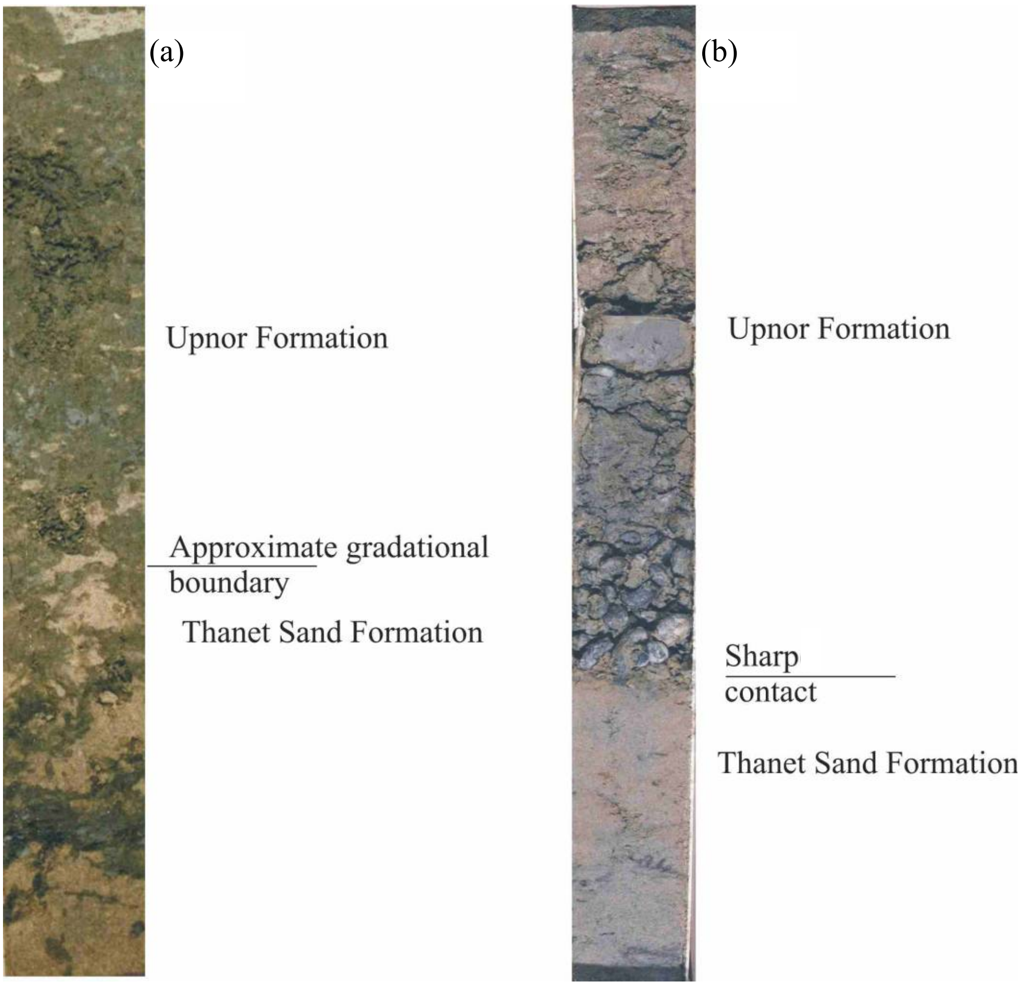

Figure 2.6. Two different forms of the interface between the Thanet and Upnor formations.
(a) The pale yellow brown of the Thanet Formation has been mixed (bioturbated) with the dark green of the overlying Upnor Formation. (CTRL (Union Rail) Borhole 1131).
(b) the very dense, pale green fine sand of the Thanet Formation has a sharp contact with the slightly clayey, black, sub rounded to rounded, fine to coarse flint gravel of the overlying Upnor Formation (CTRL (Union Rail) Borehole 2112).

In places, faint bedding is seen in weathered exposures, and some fine lamination is recorded near the top of the Thanet Formation in the Crystal Palace Borehole at 152.2 m to 145.8 m depth (BGS borehole TQ37SW/671 [TQ 3379 7082]). Glauconite grains and flakes of white mica are sparsely disseminated throughout. Beds weakly indurated by iron oxide have been described in north Kent. Irregular to oblate masses of siliceous sandstone (colloquially known as ‘doggers’) have been recorded in the vicinity of Thurrock and Grays. Irregular nodules of pyrite less than 5 mm across occur rarely, and Prestwich (1852) described gypsum at Blackheath, presumably derived from the oxidation of pyrite by weathering and the reaction of the products with calcium carbonate.

Thin sections indicate the presence of corroded feldspar, minor randomly orientated white mica, chlorite and ilmenite. Authigenic pyrite and glauconite clasts are rare. Some larger voids may be caused by dissolution of framework grains. Apatite occurs as fine sand grade detrital grains in samples from central London, but is absent in the Crystal Palace (BGS borehole TQ37SW/671 [TQ 3379 7082]) and Stanford–le-Hope (BGS borehole TQ68SE/35 [TQ 6965 8241]) boreholes, presumably due to dissolution by acidic groundwater (Hallsworth, 1993).

2.2.1.4 Representative sections

There are few natural exposures. The basal few metres of the Thanet Formation can be seen in the top part of exposures in former Chalk quarries at Grays [TQ 609 792] and Swanscombe Western Quarry [TQ 606 728]. The top part of the formation is exposed in sand pits near Orsett [TQ 673 806]. There are a number of coastal sections including Pegwell Bay ([TR 355 644] and [TR 350 642]), Herne Bay ([TR 193 685] to [TR 224 693]) (Daley and Balson, 1999).

Almost complete sequences through the entire formation are held by the BGS from Borehole CTRL A2 (BGS borehole TQ38SW/2201 [TQ 32096 80510]) in southeast London and Jubilee Line Extension Borehole 404T (BGS borehole TQ37NW/2119 [TQ 3376 7956]).

2.3 LAMBETH GROUP

Exposures of deposits that constitute the Lambeth Group were first described in pioneering work by Prestwich (1854) and systematically mapped by the Geological Survey in the late 19th century. The findings of these surveys were published in Geological Survey Memoirs covering the London Basin (Whitaker, 1872) and much of the Hampshire Basin (Reid, 1897, 1898, 1899, 1902, 1903a and 1903b). Subsequently, memoirs covering the whole of the London and Hampshire Basins have been published. The most recent of these, in which there are accounts of the Lambeth Group, cover Southampton (Edwards and Freshney, 1987) and Bournemouth (Bristow *et al*., 1991) in the Hampshire Basin, and Chelmsford (Bristow, 1985), Braintree (Ellison and Lake, 1986), Sudbury (Pattison, 1993), Great Dunmow (Lake and Wilson, 1990), Epping (Millward *et al*., 1987) and London (Ellison *et al*., 2004) in the London Basin. The distribution and relationships of the Lambeth Group in the London and Hampshire Basins are illustrated in Figure 2.7 and Figure 2.8. A full list of memoirs and map explanations covering the Lambeth Group is given as a supplement to the Reference list.

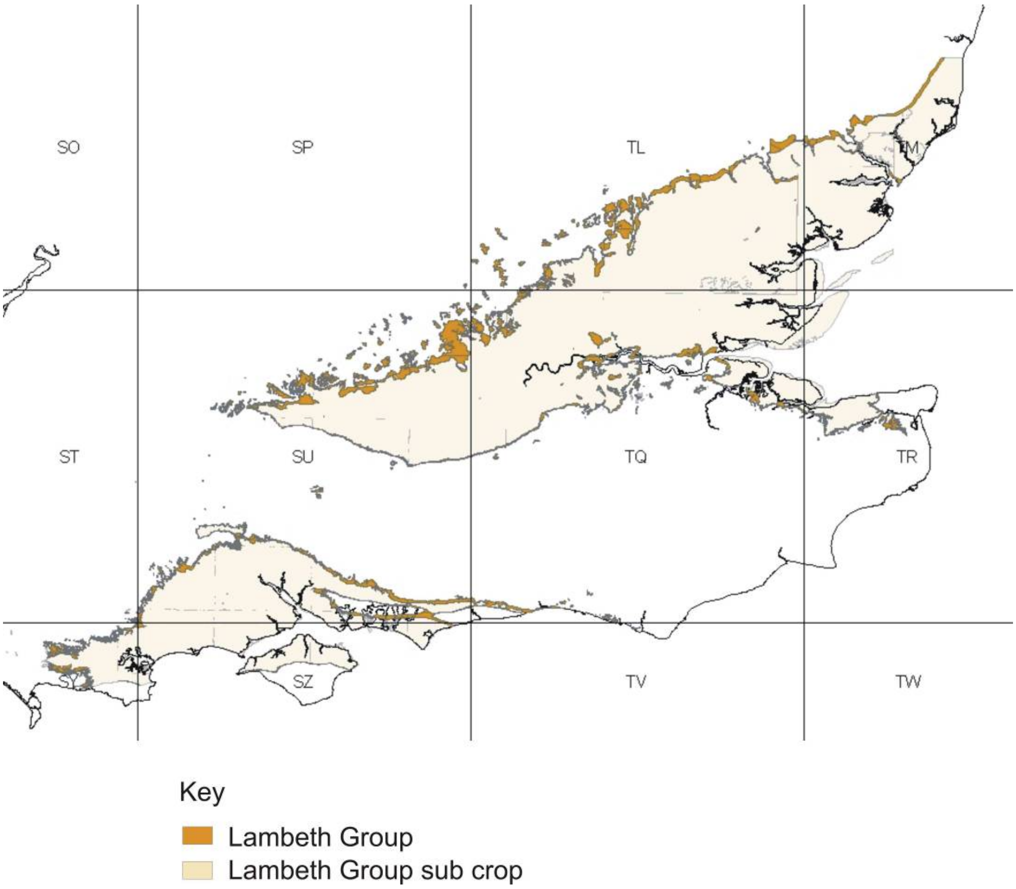

Figure 2.7. The surface and subsurface distribution of the Lambeth Group (Quaternary deposits are not shown).

The formal term Lambeth Group has been adopted in recent years (Ellison *et al*., 1994) to replace the Woolwich and Reading Beds of earlier authors (see for example Whitaker, 1899; Hester, 1965). The group is divided into three formations and several informal lithological units (Table 2.1). The relationship between these informal units is most complex in the central part of the district, coincident with central and south-east London.

Table 2.1. Lambeth Group nomenclature used in this report

Formation	Previous nomenclature	Informal units used in this account
Woolwich Formation	Woolwich Beds	Upper Shelly Clay† 'striped loam'* Laminated Beds† Lower Shelly Clay†
Reading Formation	Reading Beds	Upper Mottled Clay‡ Lower Mottled Clay‡
Upnor Formation	Bottom or Basement Bed	

†Ellison *et al*., 1994
* Dewey *et al*., 1924
‡ This report.

The base of the Lambeth Group is represented by the **Upnor Formation**, formerly known as the 'Bottom' or 'Basement Bed' of the Reading or Woolwich Beds. Above it, the **Reading Formation** (formerly the Reading Beds) is predominant in the Hampshire Basin and in the north and west of the London Basin. In the extreme east of the Hampshire Basin and the south and east of the London Basin, deposits above the basal Upnor Formation are those of the **Woolwich Formation** (Formerly the Woolwich Beds). The distribution of formations is shown in Figure 2.8. Distribution of the Lambeth Group: (a) Woolwich Formation, (b) Reading Formation, (c) Upnor Formation.

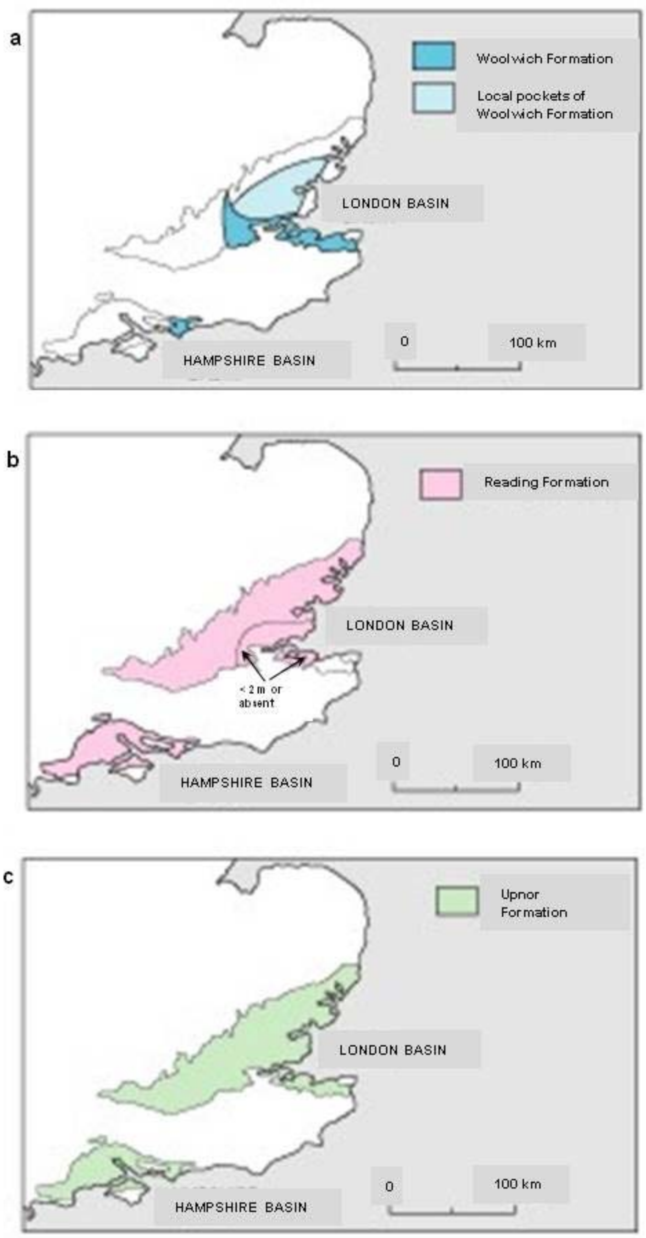

Figure 2.8. Distribution of the Lambeth Group: (a) Woolwich Formation, (b) Reading Formation, (c) Upnor Formation.

In an area coincident more or less with central and south London, Hester (1965) identified a transition zone between what he termed the 'Reading type' and 'Woolwich type' strata where both types occur and in some places interdigitate. It is principally in this zone where a new classification of the Lambeth Group was devised (Figure 2.9). Initially, the interpretation of borehole records, the results of drilling by BGS of cored boreholes and detailed examination of exposures in Essex and Suffolk led Ellison (1983) to recognise a relationship between several units of the Lambeth Group.

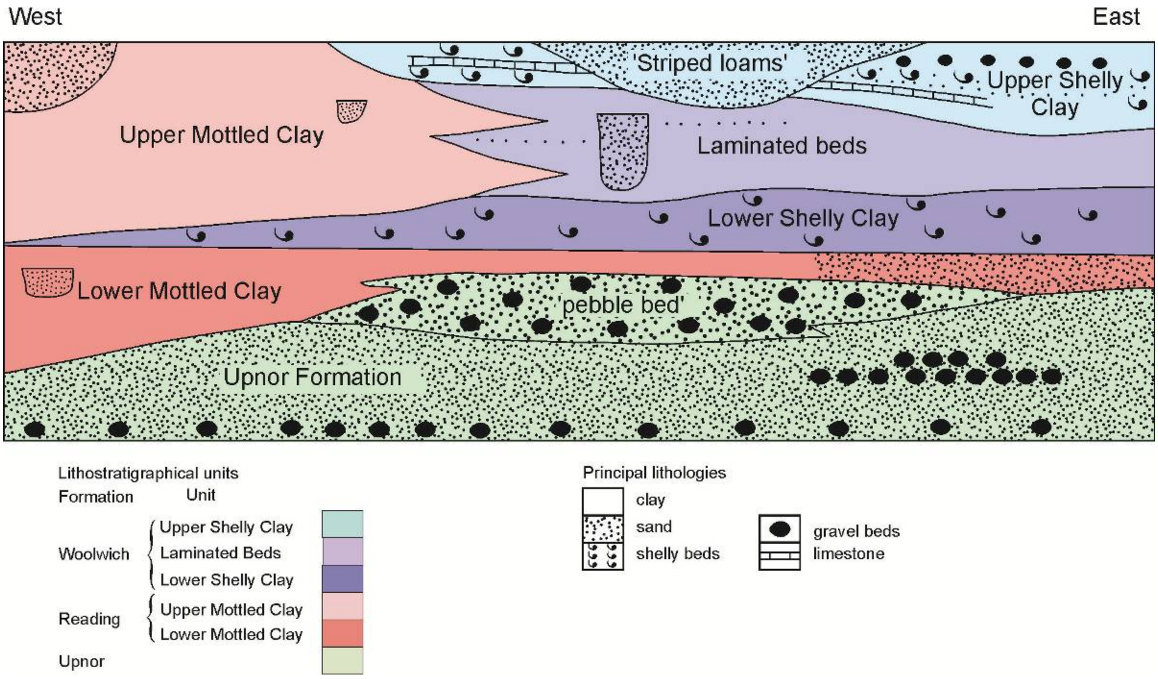

Figure 2.9. Schematic diagram showing the relationship of the informal lithological units in the Lambeth Group in central London (after Ellison, 2004).

The Reading Formation comprises the Upper and Lower Mottled Clay (Ellison *et al*., 1994; Ellison *et al*., 2004). Industry practice in the London area is based on the work by Skipper (Page and Skipper, 2000), and uses a slightly different classification. Pedogenically altered deposits are included within the Reading Formation either as the Lower or Upper Mottled *Beds*. The Lower Mottled Beds, therefore, includes the pedogenically altered, Upnor Formation as defined by Ellison *et al*. (1994) and Aldiss (2012) and may be called mottled Upnor Formation.

The thickness of the Lambeth Group in the London Basin ranges from less than 10 m in the southeast where much of it is eroded away beneath the Harwich Formation (Oldhaven and Blackheath Beds) to about 30 m in the central part of the basin, around Chertsey. In the Hampshire Basin it is generally around 25 m thick; on the Isle of Wight the sequence is up to 50 m thick, and it is thinnest in the far west. Figure 2.10 shows the thickness below London.

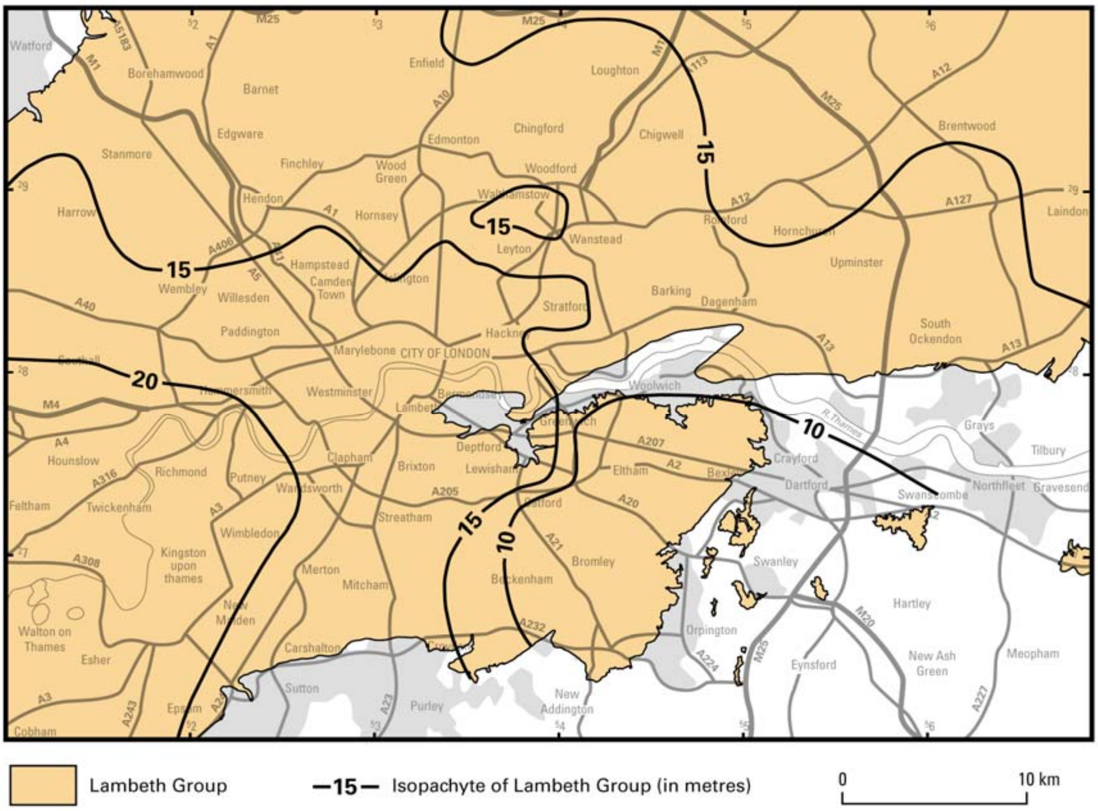

Figure 2.10. Distribution and thickness of the Lambeth Group in London (from Ellison, 2004).

The Lambeth Group is overlain by sands and gravel beds of the Harwich Formation (Ellison, 1994), which in turn is overlain by the London Clay Formation.

2.3.1 The Lambeth Group Sequence

To understand the distribution and complex lithologies of the Lambeth Group it is necessary to understand the sequence of the deposition of the formations, the conditions in which they were deposited, and their alteration due to contemporaneous soil formation or pedogenesis.

2.3.1.1 SEQUENCE STRATIGRAPHY

The Lambeth Group is made up of four depositional units, that is Lambeth sequences 1 to 4, Lmbe1-4, (after Knox, 1996a), with depositional hiatus, erosion, weathering and soil formation between. Other local disruptions to deposition, indicated by erosional surfaces, with or without soil formation, are found in many sections. The sequences and the formations deposited are summarized in Figure 2.1 with the upper part of the Ormesby-Thanet sequence and the Thames Group (Harwich and London Clay Formation). The complete sequences are as follows:

Lambeth sequence Lmbe-1 comprises the lower Upnor Formation.

Lambeth sequence Lmbe-2 comprises the upper Upnor Formation and the Lower Mottled Clay (lower Reading Formation).

Lambeth sequence Lmbe-3 comprises the Upper Mottled Clay (upper Reading Formation) and the lignite, lower Shelly Clay and Laminated Beds (lower Woolwich Formation).

Lambeth sequence Lmbe-4 comprises the Upper Shelly Clay (upper Woolwich Formation).

The lower Upnor Formation of sequence Lmbe-1 is a glauconitic, calcareous, gravelly, clayey SAND with a rich and diverse marine flora and fauna. It represents a temporary transgressive phase, re-establishing open marine conditions. A relative sea level fall and a period of regression, emergence and erosion subsequently reduced its original development to its present thickness and extent. The lower Upnor Formation was first identified in central London (Ellison *et al*., 1994; Knox, 1996a) but recent work suggests that it is more widespread (Skipper, 1999).

Sequence Lmbe-2 comprises the transgressive upper Upnor Formation and the lower leaf of the Reading Formation, the Lower Mottled Clay. The upper Upnor Formation generally consists of non-calcareous, glauconitic, sometimes clayey, SANDS and GRAVELS with a relatively restricted microfauna and palynoflora. The basal beds of the Lambeth Group in the west Hampshire Basin have characteristics of fluvial deposits and contain reworked glauconite derived from material similar to the lower Upnor Formation (Skipper, 1999). In eastern parts of the Greater London area and in parts of Essex and Kent the upper Upnor Formation contains relatively thick accumulations of gravel, deposited from fast flowing marine or estuarine channels. High concentrations of glauconite indicate periods of maximum flood. In Central London and further east, a progressive change from shallow marine to estuarine Upnor Formation deposits becomes shallower and is replaced in some areas by water logged soils and then drier soils of the Reading Formation. Further east in north Kent shallow marine Upnor Formation deposits became emergent and pedogenically altered. The upper part of the sequence tends to be more pedogenically altered than other parts of the Lambeth Group.

The transgression of the Lower Mottled Clay terrestrial facies eastwards indicates a relative sea level fall due to further uplift in the west. The continuing fall in relative sea level resulted in a period of erosion and weathering that produced a subdued topography and resulted in widespread pedogenesis. Skipper (1999) and Page and Skipper (2000), have referred to the sharp boundary marking the end of this sequence as the mid-Lambeth Hiatus, which is now known as the mid-Lambeth Group Hiatus. The top of the deposits are typically pale, often bleached and contain many burrow traces, which may be filled with material from the bed above. These deposits are generally clay overbank deposits with sand filled river channels, but in the east of the London Basin they are mainly sand.

Most of the hard beds are from the upper part of this sequence and include silicate cemented beds to the north of London and south of the South Downs, calcium carbonate cemented beds in central and east London and near Arundel in the Hampshire Basin and iron oxide cemented beds in the east, most notably in north Kent.

The transition from sequence Lmbe-2 to Lmbe-3 is marked by the relative uplift of sediment sources in the west leading to an influx of sediment.

This sequence Lmbe-3 comprises the Lower Woolwich Formation (lignite, Lower Shelly Clay and Laminated Beds) and the Upper Reading Formation (Upper Mottled Clay). At the base of the sequence hydromorphic, lignitic, reduced black or dark grey soils are widespread. They are markedly different in colour and appearance to the bioturbated bleached or oxidised palaeosols at the top of sequence Lmbe-2. The lower Woolwich Formation marks a westwards extension of lagoon environments. Although these deposits are well documented in central London and the east of the Hampshire Basin they are often represented by thin lignitic or near black clay deposits above a bleached horizon of Lmbe-2 seen in borehole log descriptions as far west as Newbury in Berkshire and Alum Bay on the Isle of Wight. This represents a short high stand when lagoonal conditions prevailed on a wide, nearly flat plain. The upper Reading Formation, to the west, represents a re-establishing of mainly continental conditions with pedogenically altered, multicoloured overbank clay and river infill sands. The Upper Mottled Clay of the upper Reading Formation generally overlies the lower Woolwich in central London where the top of lower Woolwich Formation is pedogenically altered beneath the upper Reading Formation. On occasion, the two might be interleaved, because of local deposition conditions or apparently interleaved due to faulting. There followed sequences of initial water-logging, followed by upwards drying and oxidising of the Upper Mottled Clay (Skipper, 1999). Isolated deposits similar to the Woolwich Formation have been found within the Lower Mottled Clay near Kings Cross, London (J. Skipper, personal communication, 2005) and in the Upper Mottled Clay.

The upper Woolwich Formation or Upper Shelly Clay of Lambeth sequence Lmbe-4 is deposited on an irregular and eroded surface. It is much more limited and patchy in extent than the other sequences and is only known in central, eastern and north eastern parts of the London Basin (Knox, 1996a).

2.3.2 Description of the Lambeth Group Formations

2.3.2.1 Upnor Formation

The Upnor Formation was formerly known as the Bottom Bed (of the Woolwich and Reading Beds) in the London Basin, and the Basement Bed (of the Reading Beds) in the Hampshire Basin.

Distribution

The Upnor Formation is present nearly everywhere at the base of the Lambeth Group (Figure 2.8c).

Basal Boundary

Chalk

The Upnor Formation rests on the Chalk in the Hampshire Basin and in the west of the London Basin (Figure 2.2) northwest of a line from Northolt [TQ 130 840] to Borehamwood [TQ 200 950]. In the central and southern part of the London Basin the Upnor Formation lies on the Thanet Formation and in parts of Essex and Suffolk on the Ormesby Clay Formation, though this contact is at depth. A basal bed containing flint gravel is usually present.

The contact with the Chalk is unconformable and sharp and in the west Thames Basin either frequently burrowed by the ichnofossil *glyphichus* (Bromley and Goldring, 1992), or often undulating because of dissolution features in the Chalk. The dissolution features often have steep sides and undulating bases, and may be a few metres deep and tens of metres across (Figure 2.11). They are generally lined with clay derived from the insoluble remains of the Chalk (Figure 2.12). In some areas this process is still active. The lowest Upnor Formation bed contains nodular unworn green-coated flint gravel.

Figure 2.11. Fine-grained brown sands of the Upnor Formation filling dissolution pipes in the Upper Chalk. A27 road-cutting at Falmer, East Sussex [TQ 3541 0890]. Field of view is about 6 m wide. (BGS photograph A13398).

Figure 2.12. Upnor Formation basal gravel bed above Newhaven Chalk Formation. The contact is undulating due to solution features and bioturbation. (Newhaven, East Sussex, [TV 4459, 9990]. Field of view is about 1.5 m wide.

Thanet Formation

The junction with the Thanet Formation may be gradational because of relatively intense bioturbation, and burrows may extend 2 m below the contact (Figure 2.6). The contrasting lithological characteristics between the lowest bed of the Upnor Formation and the upper part of the Thanet Formation are:

- Upnor Formation sands are generally slightly coarser, and more clay-rich, which can be identified when reworked, than the silty fine sands of the Thanet Formation,
- The lowest bed of the Upnor Formation may contain some flint gravel (Figure 2.6b),
- The Upnor Formation, when fresh, is generally green or dark green, whereas the upper part of the Thanet Formation is grey,
- Whilst both are generally very dense the Thanet Formation is generally denser than the lowest part of the Upnor Formation,
- The Upnor Formation may contain fossil molluscs, which are very rare in the Thanet Formation,
- The Upnor Formation commonly contains more clay than the top of the Thanet Formation,
- In the field there may be weak seeps at the contact due to the greater fine material in the Thanet Formation and its greater density.

Thickness

The thickness of the Upnor Formation is well documented in cored boreholes and exposed sections in the London area (Figure 2.13). Over much of the London and Hampshire Basins the formation is generally less than 3 m thick. However, in parts of central London, north Kent and Essex it may be 6 to 7 m thick. At Orsett in south Essex it is up to 9 m thick. Thicknesses may also be greater where the Upnor Formation has filled solution features in the Chalk.

Lithology

The dominant lithology of the Upnor Formation is fine to medium SAND and clayey sand with variable amounts of fine to medium sand grade glauconite grains and sporadic beds or stringers of well-rounded flint gravel and laminations of clay. At outcrop and when weathered the sediments are pale grey-brown to orange-brown and yellow-brown. The glauconite grains are dark green and impart a speckled ‘pepper and salt’ appearance. At depth, the sediments are mainly dark grey or dark greenish grey. In the central and eastern parts of the London Basin some of the sandy beds contain up to 25% glauconite. Shelly clay occurs in unweathered sections and, in places, oyster and pychnodontid shells occur near the base. In the west of the Hampshire Basin the glauconite content declines and the flints are decomposed and associated with irregularly developed ironstone.

The sands may be completely bioturbated with no primary bedding, and with vertical and subhorizontal burrows filled with sand of contrasting colour to the bioturbated matrix. Rare fragments of carbonaceous material also occur. A few impersistent seams of grey clay and angular clasts derived from such seams have been recorded within dominantly bioturbated beds. Other parts of the succession are well bedded and with horizontal planar lamination, ripple lamination, hummocky and planar cross bedding, and clay drapes. Stringers of well-rounded flint gravels occur on a few bedding surfaces and there are beds of gravelly sand, mostly less than 0.3 m thick. Thin seams of grey clay, angular clay clasts and rounded balls of clay are also present. Ophiomorpha and Macaronichnus burrows are typical in these beds (Figure 2.14) and can be seen in the quarries at Upnor and Orsett. Clay-dominated units, up to 0.3 m thick, contain relatively small amounts of sand, arranged in flaser lamination and with lenticular cross-lamination. These strata are well exposed at Lower Upnor Pit, north of Chatham, north Kent [TQ 759 711], Orsett Cock Pit, [TQ 656 811], and Orsett Tarmac Pit near Walton's Hall Orsett, Essex [TQ 673 803].

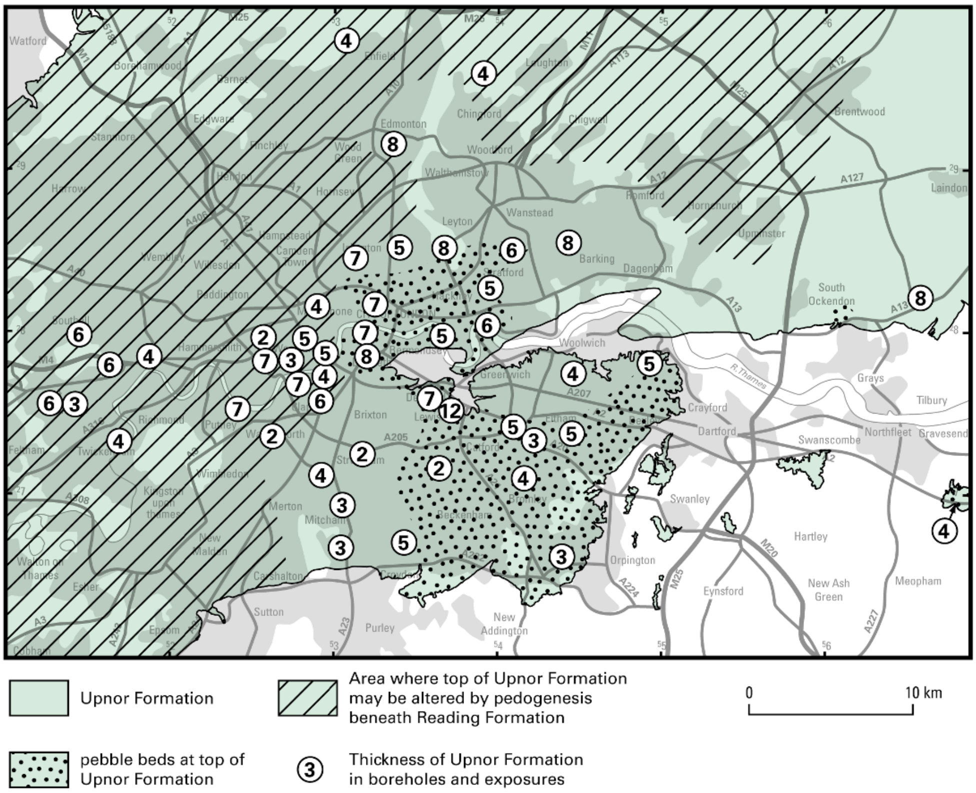

Figure 2.13. Distribution of the Upnor Formation in London (Ellison *et al*., 2004).

Figure 2.14. Detail of Upnor Formation. Cross-stratified fine-grained sand overlain by finely-interbedded fine and medium-grained sand and clay. Burrows and clay laminae are seen to stand out on the weathered face. Orsett Depot Quarry, West Pit. Looking south, [TQ 656 810], (BGS photograph A12266).

The flint gravels that occur in the London Basin are generally less than 30 mm in diameter, but cobbles up to 200 mm occasionally occur, for example around Gravesend. In central and south-east London there is a persistent gravel bed (Ellison, 1991) up to 5 m thick at the top of the formation consisting of well-rounded flint gravel. At Orsett, south Essex, a wedge of gravel up to 9 m thick occurs at the base of the formation.

Four main facies have been identified in the Upnor Formation (Skipper, 1999):

1. Transgressive gravel and sands,
2. Laminated silts, clays and fine sand,
3. Upper gravelly sands,
4. Sand beds.

These facies may be pedogenically altered beneath thin Lower Mottled Clay of the Reading Formation in north and west London leading to major lithological and other character changes.

1. Transgressive gravel and sands

The contact of the basal Upnor Formation with the underlying Thanet Formation and White Chalk Subgroup often contains a few courses of well- rounded, spheroidal black flint gravel in a matrix of very glauconitic clayey sand, up to 1 m thick. This bed sometimes fines upwards. Shells are rare but often well preserved, although frequently abraded and chaotically oriented in the gravel. The gravel may also have a green coating of glauconite and percussion marks. The basal gravel may be missing, for instance in the north east of the London Basin. Figure 2.12 shows cemented slightly clayey sandy gravel above the Newhaven Chalk Formation, west of Newhaven, East Sussex [TV 4459 9990].

2. Laminated silts, clays and fine sand

The basal transgressive gravel and sand is often succeeded by thinly laminated clay, silt or fine sand. It may contain lignite but in places is extensively bioturbated sometimes destroying the laminations. In the London area, e.g. around Islington, this bed may be up to 7 m thick.

3. Upper gravelly sands

To the east of London the upper part of the Upnor Formation comprises up to 5 m of well rounded fine to coarse flint gravel in a clayey sand matrix. This is known as the 'pebble bed' (Ellison *et al*., 1994 and 2004) and is distinct from the basal gravels. Pedogenesis and calcrete formation have altered the matrix removing any sedimentary structure. These deposits are best seen at Orsett Cock Quarry, [TQ 657 811] in Essex (Figure 2.15) where gravel beds, up to 50 cm thick, are interbedded and interdigitated with glauconitic fine to medium sand with clay laminations.

Figure 2.15. View looking east showing the Upnor Formation at Orsett Cock Quarry [TQ 657 811] with inclined sets of well rounded flint gravel 'pebble' beds. (BGS photograph A12263).

Where the Upnor Formation is overlain by thin Lower Mottled Clay pedogenesis has altered the highest beds, which are mottled brown and purple-brown. In the gravel bed at the top of the Upnor Formation, a clay matrix is developed and the pebbles are brittle and red stained. Irregular-shaped carbonate concretions, up to 0.5 m in diameter, are sometimes present and are often described as 'limestone' in borehole logs. Pedogenic processes have also given rise to the development of silcretes (silica cementing), small ironstone nodules, and clay coatings on sand grains and. These secondary alterations may locally occur throughout the entire formation in the western part of the London Basin and Hampshire Basin.

4. Sand Beds

In the east, the sand may change from horizontal bedding to trough cross-bedding. In the west Hampshire Basin the lowermost 'Upnor' Formation comprises fluvial deposits of angular to well-rounded, sometimes clayey, usually fine to coarse sand, as at Studland [SZ 0416 234] and Alum Bay [SZ 3054 0852]. In places irregular hollows up to 2 m deep in the Chalk are infilled with a thin bed of red-stained, angular flints up to 100 mm. This is succeeded by lignitic, glauconitic, fine to medium sand.

2.3.2.2 Reading Formation

The Reading Formation is now considered to comprise those deposits once referred to as the Reading Beds minus the Basement or Bottom Bed, which is now attributed to the Upnor Formation.

Distribution

The Reading Formation occurs throughout the London and Hampshire Basins, reaching a maximum thickness the south-west of the district, up to 49 m thick at Whitecliff Bay [SZ 639 581] on the Isle of Wight; thinning progressively eastwards, where it passes laterally into, and interdigitates with, the Woolwich Formation.

The Reading Formation consists of two leaves, the Lower Mottled Clay and the Upper Mottled Clay. The Lower Mottled Clay was deposited on the Upnor Formation before the mid-Lambeth Group Hiatus, afterwards followed by deposition of the Upper Mottled Clay. The Lower Mottled Clay persists across the entire area of the Reading Formation, but the Upper Mottled Clay is absent from most of the eastern part of the London Basin (Figure 2.16).

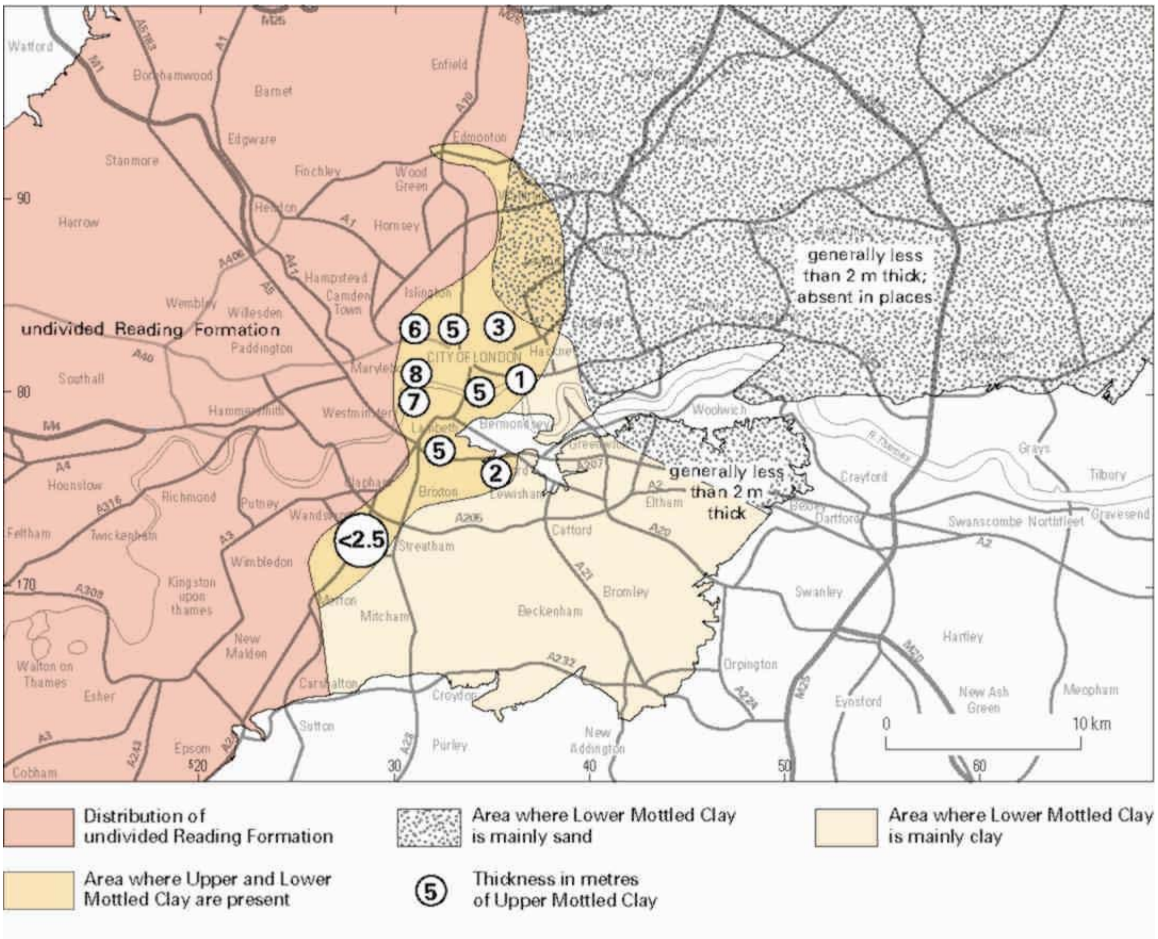

Figure 2.16. Reading Formation distribution and main lithologies in London (Ellison *et al.*, 2004).

Basal Boundary

The boundary of the Lower Mottled Clay with the underlying Upnor Formation is usually diffuse and difficult to place precisely because of pedogenic alteration that may include either migration of clay particles into the Upnor Formation and/or colour mottling. The degree of alteration may be such that it is impossible to identify the boundary accurately. Examples of some of the contact variations identified in rotary borehole cores are in shown in Figure 2.17.

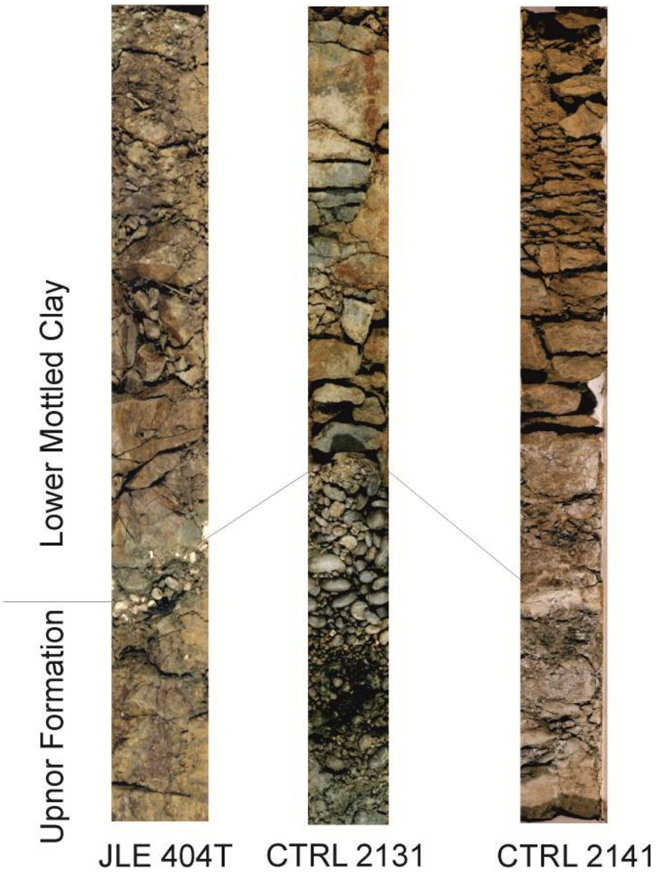

Figure 2.17. Examples of the variable contact between the Upnor Formation and the Lower Mottled Clay of the Reading Formation. JLE404T - top of Upnor Formation is marked by 0.06 m of oyster fragments and red, white and black sub angular to well rounded flint gravel in a clay matrix. CTRL2131 the 'pebble bed' tops the Upnor Formation. CTRL2141 the change from Upnor Formation to Lower Mottled Clay is taken at the sharp contact of very finely laminated pale greenish grey fine sand (Upnor Formation) and the mottled clayey fine to coarse sand (Lower Mottled Clay of the Reading Formation).

The base of the Upper Mottled Clay gives rise to a similarly diffuse contact with the Laminated Beds of the Woolwich Formation, except around Stratford where the two units sometimes interdigitate. Where both the Lower and Upper Mottled Clay are present, differentiating between the two is relatively easy in central London as they are separated by the Woolwich Formation (Figure 2.9). Elsewhere, where the Woolwich Formation is absent, it is difficult to identify the boundary, although the top of the Lower Mottled Clay is often pale or bleached and the base of the Upper Mottled Clay usually consists of a thin carbonaceous grey, blue or black clay layer. Many of the site investigation boreholes used in this study identify this darker layer or lignite that is likely to be the base of the Upper Mottled Clay. This can be seen in coastal section at Alum Bay in the Isle of Wight, and was documented during the excavations for the Newbury Bypass in Berkshire. . This is best identified in section, as at Alum Bay, or in good quality core, this boundary has also been described in core retrieved from standard ground investigations using cable percussion techniques.

Thickness

The Reading Formation is over 30 m thick in the Isle of Wight where, due to folding, it is almost vertically bedded, but is generally about 15 m thick around Newbury, up to 20m in the south-west of London and thins progressively eastwards. In the east of London, where the upper leaf is missing, it is generally less than 2 m thick and locally may be missing altogether.

Lithology

The bulk of the Reading Formation consists of indistinctly or poorly bedded, colour mottled or multicoloured, silty clay and clay. This characteristic lithology was formerly called the 'Reading Beds' or 'plastic clay'. Colours include pale brown, pale grey-blue, dark brown, pale green, red-brown and crimson, depending on the oxidation and hydration state of the iron in the sediments. The clays contain numerous fissures, many of them listric, which give rise to a blocky texture. Thin, black, carbonaceous clays are recorded locally in the west of the district in the middle of the sequence and this marks the approximate boundary of the upper and lower leaves of the Reading Formation (Upper Mottled Clay and Lower Mottled Clay). Beds of colour-mottled silt and sand constitute up to 50 per cent of the unit, particularly in the east, in the west around Newbury and the north Hampshire Basin. The colour is dominantly of brown hues, red hues being less prevalent than in the clays (Figure 2.18). These beds are thinly laminated in places with small burrows and root traces, and minor brecciation caused by soft sediment deformation. The clays are generally stiff to very stiff and occasionally extremely weak, closely or very closely sometimes extremely closely fissured, the fissures may be sub vertical or randomly oriented, striated or polished, undulating to planar and clean.

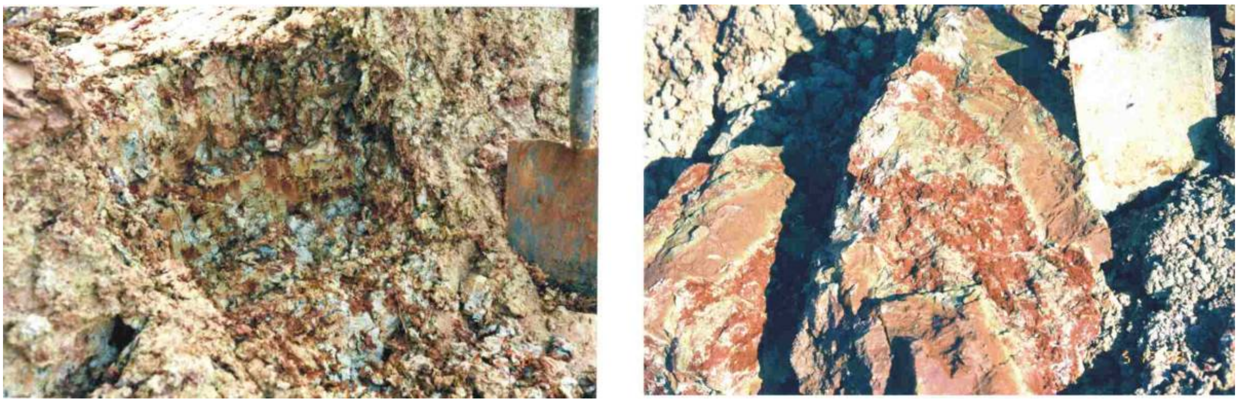

Figure 2.18. Reading Formation examples of mottled clays from Alum Bay, Isle of Wight (left), Knowl Hill Quarry, near Maidenhead (right), Berkshire [SU 8160 9770].

Beds of well-sorted sand, mainly in the west of the region, represent sand in-filled river channels (Figure 2.19).

Figure 2.19. Channel sand (below) and mottled clay (above). Newbury Bypass, Berkshire.

The Lower Mottled Clay may be purple-red. The top part of the unit contains irregular-shaped, soft and 'powdery' to strong 'limestone' nodules up to 0.5 m in diameter. Sands become increasingly dominant in an easterly direction east of central London and are sometimes referred to as lower mottled sand. In Essex and Kent, the sediments pass into pale grey-brown, turquoise to dark green and brown mottled, structureless slightly clayey sand with minor amounts of irregularly iron-cemented calcareous clayey sands. In places in north Kent these iron-cemented sands are known locally as Winterbourne Ironstone.

The Upper Mottled Clay is not distinguished lithologically either from the Lower Mottled Clay or the main bulk of the undivided Reading Formation. It is identified by its position, above the Lower Shelly Clay or dark beds associated with the Woolwich Formation. It consists largely of mottled clay, silty clay and silt with channel sand infill. The colours are similar to those of the Lower Mottled Clay, but the purple hues are absent. However, in some parts of London the colours are more limited and are mostly mottled grey and brown (Figure 2.20).

Figure 2.20. Reading Formation, Upper Mottled Clay comprising very stiff, grey mottled brown, extremely to very closely fissured, slightly sandy CLAY. CTRL borehole 2112, (top to the left).

Very occasionally, deposits similar to the Woolwich Formation occur in both the Upper and Lower Mottled Clay. For example dark grey sulphide-rich clay could be deposited in permanent vegetated ponds or small lakes, possibly ox-bow lakes, in the alluvial tract. If these deposits are thick enough they might be preserved within the mottled clays.

Origin of mottled appearance in Reading Formation

The Reading Formation sediments were deposited at a time when SE England had a sub-tropical climate, similar to that which exists currently in parts of Africa, the Far East and Central America. Although these sediments would have originally been deposited in a variety of environments from rivers to marshes, shortly afterwards they were subjected to sub-tropical weathering or *pedogenesis*, at or just above base water/sea level.

Tropical pedogenesis rapidly alters the mineralogy changing the colour and textures of the original material. The main processes involved in this change are hydrolysis, downward transport of fines (illuviation), chemical breakdown and dissolution, and redeposition of minerals from solution (e.g. iron, calcium, silica). Seasonal changes in the height of the water table, cause radical changes in the dominant weathering process from reducing to oxidising, and this affects the final colour of the sediments.

Other, mechanical, affects also have a huge influence during tropical pedogenesis. These include expansion and contraction during daily temperature change and shrinkage and swelling caused by drying and wetting probably caused by seasonal rains. These two processes resulted in multiple fissuring, the fissures often with polished surfaces. Finally, animals, such as burrowing crustaceans and worms, and plants all radically change the texture of the soil.

Two examples of Reading Formation sediments from a cored borehole in north London are shown in Figure 2.21. The top core run is firm to stiff, multicoloured, sandy clay, which is light blue green with large (up to 25% of the sediment) bright red and occasional smaller, orange yellow mottles, which are seen to be even more abundant in the lower core. The red is the oxidised iron mineral haematite, which is commonly formed during drier periods. The yellow coloured mottles are goethite, a hydrated iron oxide that forms in damper conditions. The lower core material is superimposed with a fine network of blue-grey to brown formed by plant roots and rootlets. The activity of bacteria during the decaying of the roots produces reduced iron minerals, which are grey.

Figure 2.21. Borehole core from St Pancras area of north London. See text for description. (Copyright Jackie Skipper).

2.3.2.3 WOOLWICH FORMATION

The Woolwich Formation rests on the Lower Mottled Clay of the Reading Formation (Figure 2.9) and is present in the east of the London Basin and the easterly part of the Hampshire Basin (Figure 2.8). There are several distinctive units within the Woolwich Formation, namely:

1. Lower Shelly Clay (including the basal lignite),
2. Laminated Beds,
3. Upper Shelly Clay,
4. ‘Striped Loam’.

1 Lower Shelly Clay

Distribution

The Lower Shelly Clay occurs principally in east and southeast London (Figure 2.22), north Kent and the eastern edge of the Hampshire Basin. It has been identified recently in boreholes near Wandsworth Bridge [TQ 260 755] but not at Putney Bridge [TQ 242 757] (Jackie Skipper personal communication June 2013). In general, the unit thickens from central London towards the southeast, reaching a maximum of about 6 m.

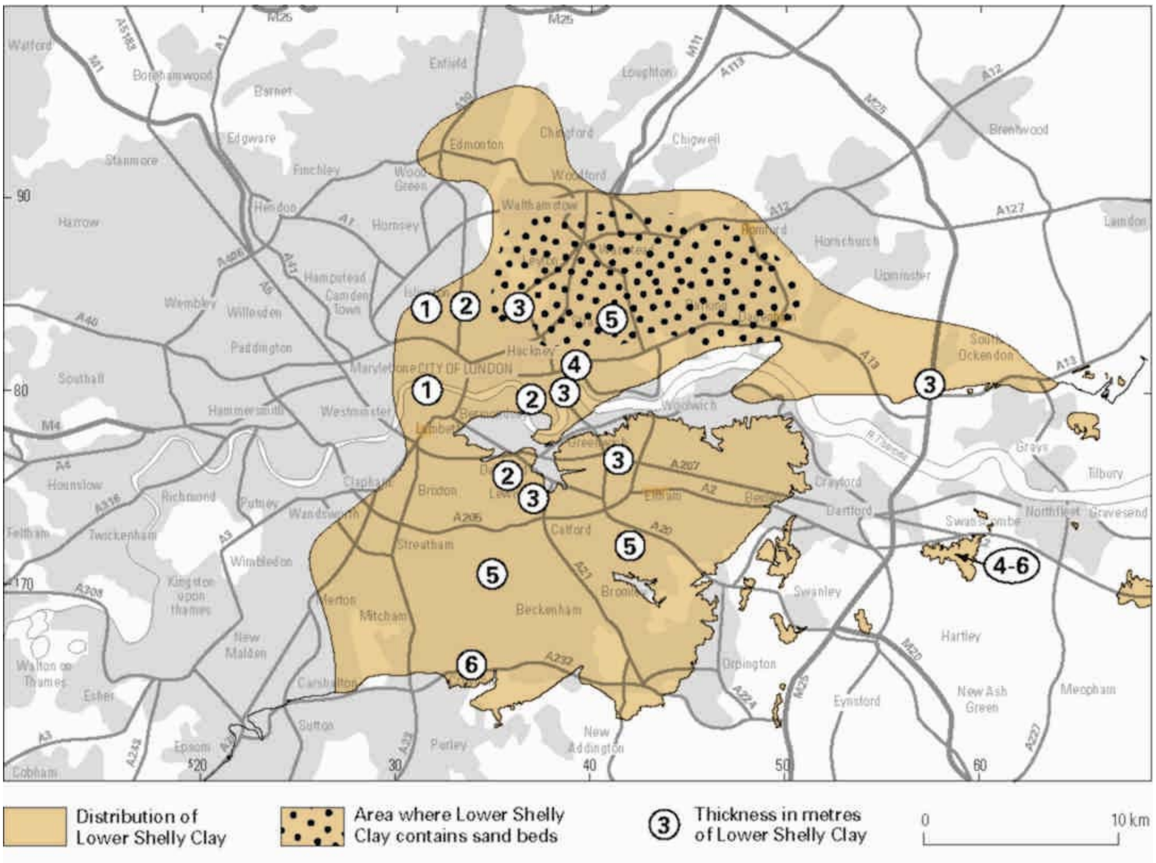

Figure 2.22. Distribution and thickness of the Lower Shelly Clay in London (Ellison *et al*., 2004).

Basal Boundary

The basal boundary of the Lower Shelly Clay is sharp, well defined and disconformable on the often pale and bleached, pedogenically altered Lower Mottled Clay. Burrows containing dark clay, lignite or shells may occur in burrows extending up to 1.5 m into the Lower Mottled Clay. In some parts of central London the contrast is between multicoloured clay with calcium carbonate concretions or pale, bleached Lower Mottled Clay and overlying dark grey shelly clay (Figure 2.23).

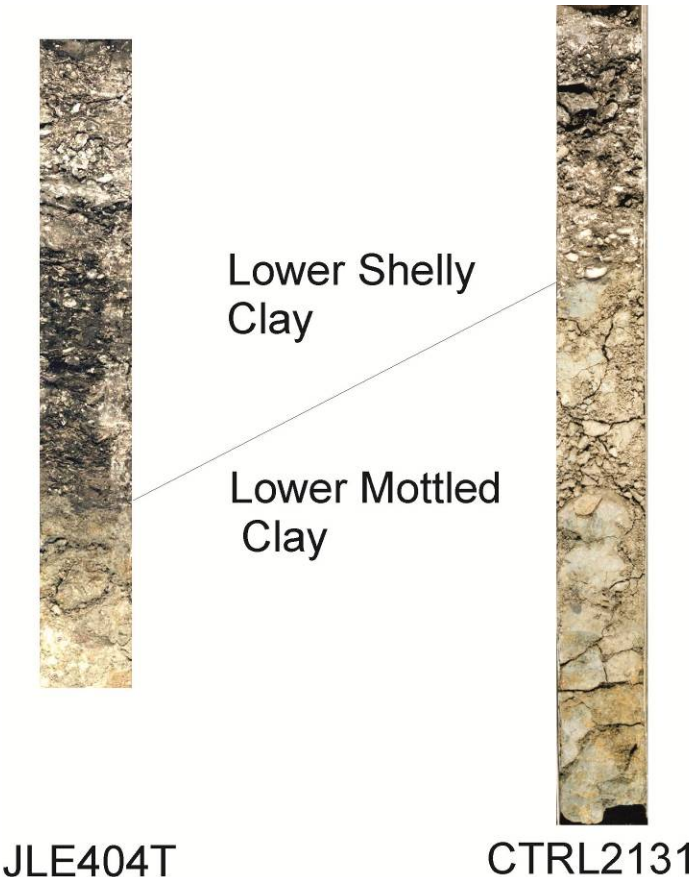

Figure 2.23. The contact between the Lower Mottled Clay and Lower Shelly Clay. JLE404T, 33.00 to 33.90 m. Very stiff multicoloured grey CLAY with 'powdery' and nodular calcium carbonate (Lower Mottled Clay, 33.77 to 33.90 m.b.g.l.) below stiff highly fossiliferous grey clay with sand at the base (Lower Shelly Clay, 33.19 to 33.70 m.b.g.l.). CTRL 2131. Very stiff, multicoloured sandy clay (Lower Mottled Clay) (below) very stiff, thickly laminated, fissured gravelly clay. Gravel is of shell fragments (Lower Shelly Clay). Base irregular sharp and inclined.

Lithology

The dominant lithology of this unit is dark grey to black clay that contains abundant shells. In east London, there is a general increase of medium sand in the matrix and, in places (e.g. near Stratford) beds up to 1 m thick occur consisting almost entirely of shells forming weakly cemented limestone. The basal few centimetres of the unit also tend to be relatively sandy and commonly contain oyster shells. About 1 to 2 m above the base of the Lower Shelly Clay a bed dominated by oysters encrusted with bryozoa and cemented in places, occurs locally (Dewey and Bromehead, 1921; Tracey, 1986). These shell-dominated beds indicate that sediment input was low, thus allowing the development of shell banks, and they may represent a maximum flooding surface. A few beds of brownish grey clay, slightly cemented with siderite, occur sporadically throughout, particularly in the higher parts of the unit and, in places, fine carbonaceous debris occurs, some of it is pyritised.

Lignite is commonly seen at the base of the Lower Shelly Clay in southeast London. It consists of very weak to weak, extremely to very closely fractured, sometimes thinly laminated, dark brown and black, lignite with soft black and brown very organic clay. The lignite may be recovered as dark brown and black clay, angular and sub-angular fine to coarse lignite gravel or extremely to very closely fractured lignite. It is generally less than 0.3 m thick but at Shorne [TQ 678 697], in north Kent, it is up to 2 m thick and displays a cleat (closely spaced joints) similar to a sub-bituminous coal (Figure 2.24) (Collinson *et al*., 2003). It is interbedded with pale grey, leached, medium-grained sand and pale grey clay with lignitic wood fragments and small listric fractures, similar to seatearth.

Figure 2.24. A succession of partly bleached Lower Mottled Clay sand facies overlain by a 1.5 m thick lignite bed, displaying cleat, and 1 m of shelly clay, of the Lower Shelly Clay unit. HS1 railway cut at Shorne, Kent [TQ 678 697].

Dewey and Bromehead (1921, p.20) recorded a ‘freshwater bed’ of limited distribution, within the middle of the ‘shell beds’ in an area around Leytonstone, Dulwich, Pechham and Brockley. The Upper Shelly Clay may rest directly on the Lower Shelly Clay in south-east London in the vicinity of Petts Wood and St Mary Cray [TQ 45 68] (Whitaker, 1872, p.116, Figure 14).

2. Laminated Beds

This unit is the equivalent to the “laminated sands and silts” of Ellison (1991).

Distribution

The Laminated Beds occur in the south-east of the London as far as Swanscombe (Figure 2.25) and in the east of the Hampshire Basin most notably at Newhaven, and reaches a maximum thickness of up to about 5 m south of Stratford.

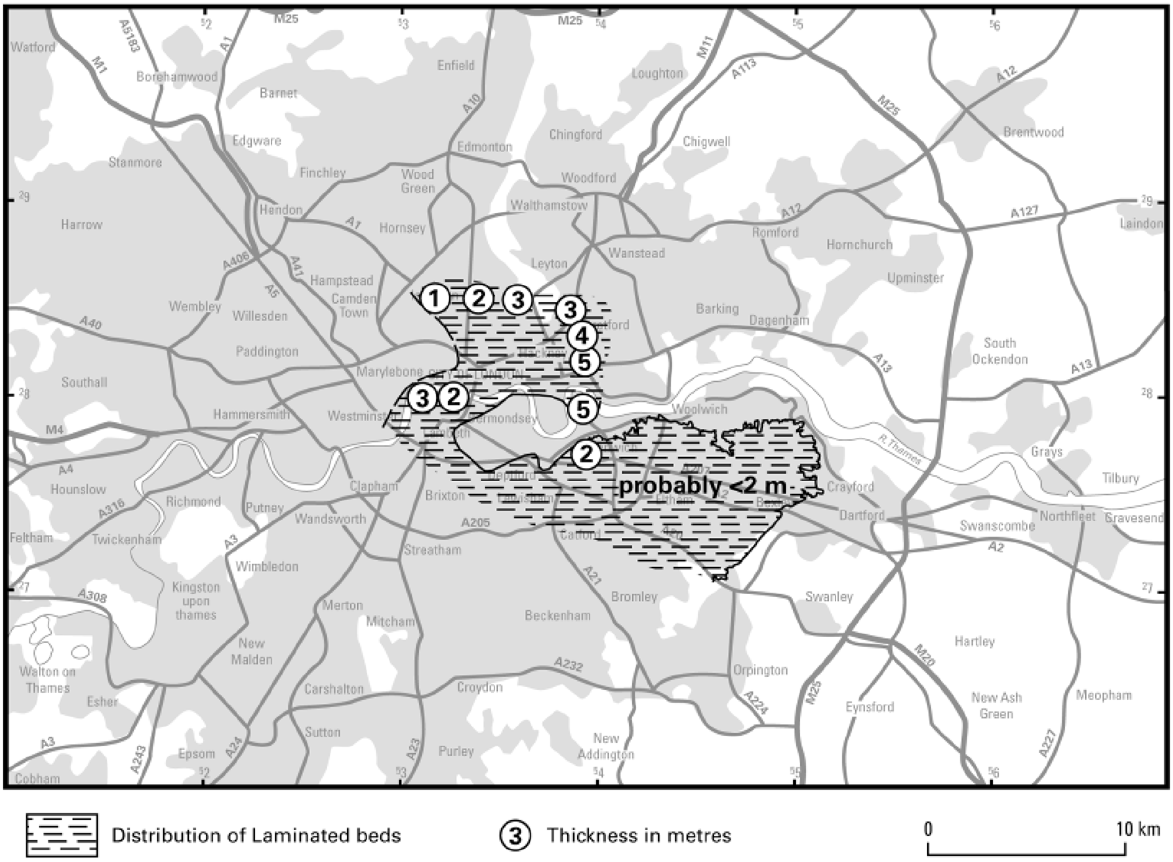

Figure 2.25. Distribution and thickness of the Laminated Beds in London (Ellison *et al.*, 2004).

A second unit of laminated beds occurs higher in the succession and are part of the Upper Shelly Clay around Lewisham where it was formerly known as 'Striped loams' (Dewey *et al.*, 1924). The stratigraphical relationships of these laminated beds are uncertain but they probably have an erosive base, cutting down through the Upper Shelly Clay.

Basal Boundary

The base of the Laminated Beds is sharply defined with the underlying Lower Shelly Clay (Figure 2.26) or, locally, on the Lower Mottled Clay.

Figure 2.26. The contact between the dark grey very shelly clay of the Lower Shelly Clay below, and the thinly laminated clay and silt of the Laminated Beds above. (Borehole JLE404T, (TQ (5) 3363 (1)7960, 33.00 to 33.60 m).

Lithology

The Laminated Beds consist of thinly to thickly laminated silt and clay and laminated to thinly bedded clay or silt and sand with scattered, occasionally thin beds of packed, intact bivalve shells. Beds are generally less than 50 mm (Figure 2.27). These deposits are typically pale grey to dark grey when un-oxidised and pale greenish brown, yellow to orange when oxidised. Sedimentary features include lenticular bedding; ripple lamination, burrows and some bioturbated, structureless beds. Bodies of sand are commonly present and vary in thickness from 5 mm to 1.4 m thick , but locally up to 5 m (for example Jubilee Line extension [JLE] borehole 404T [BGS borehole TQ37NW/2118 {TQ 33638 79604}]). They occur throughout London as channel fills or more extensive sheets and are best known around Lambeth and Bermondsey. Typically the sand is medium grained and cross-laminated, with some clay drapes and rare bivalves. Thin beds of colour mottled clay and silt occur within the Laminated Beds between Docklands and Stratford.

Figure 2.27. The lithologies of the Laminated Beds from Borehole JLE404T, west of Bermondsey Station (a) finely laminated clay and silt, laminae with some ripple lamination (32.20 to 33.00 m). (b) Laminated fine to medium sand with cross lamination (30.70 to 31.50 m).

At Abbey Wood [TQ 484 787], shelly medium-grained sands underlie the Harwich Formation. The strata are included in the Laminated Beds, although their age and precise stratigraphical relationship is uncertain (Hooker, 1991).

3. Upper Shelly Clay

Distribution

The main occurrence of the Upper Shelly Clay is in south London (Figure 2.28). To the southeast and northwest there are isolated occurrences, proved sporadically in boreholes, preserved in shallow depressions below an erosion surface at the base of the Harwich Formation. The unit is up to about 3 m thick. It is likely that beds equivalent to the Upper Shelly Clay are present farther southeast than is shown in (Figure 2.28) but, in the absence of the intervening Upper Mottled Clay unit, they cannot be distinguished from the Lower Shelly Clay in sections or borehole cores. One exception to this is in the Crystal Palace Borehole [TQ 3379 7082] where the base of the Upper Shelly Clay is taken at a thin lignite bed. In some borehole records, the Upper Shelly Clay was formerly interpreted as the Harwich Formation.

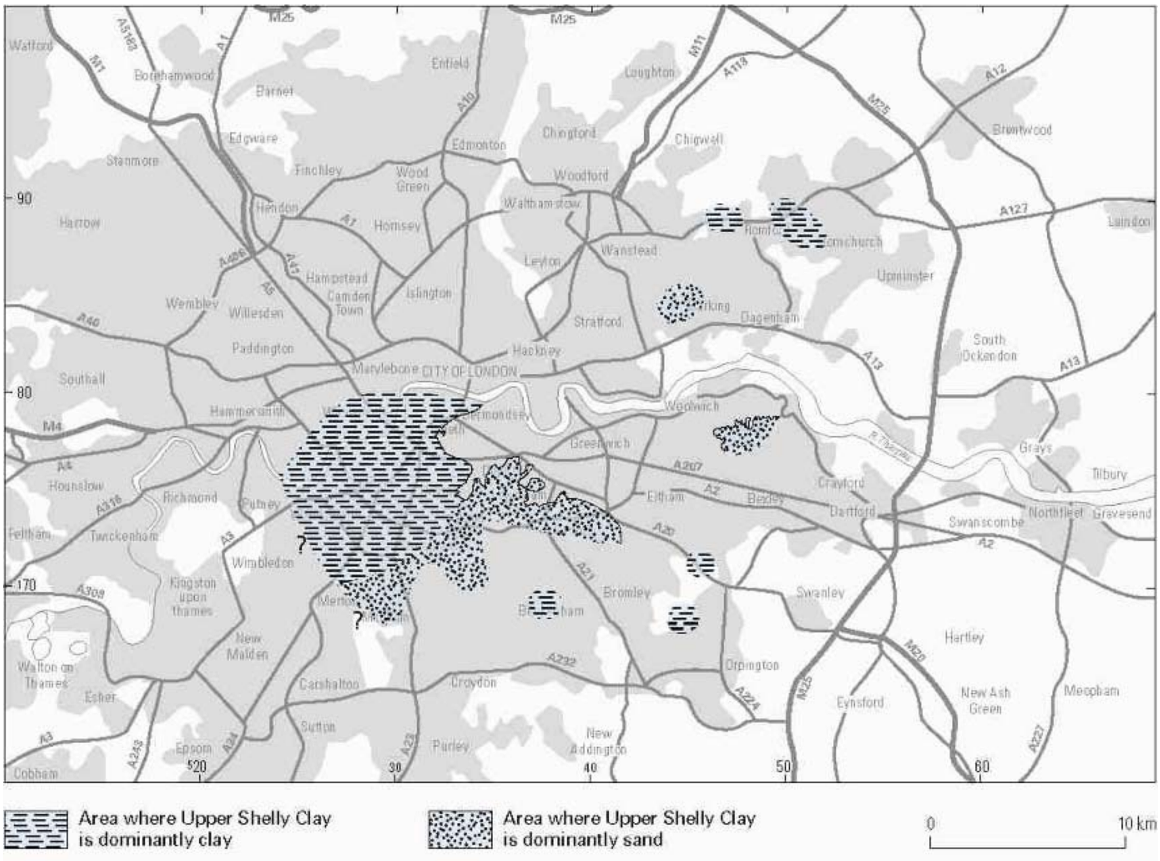

Figure 2.28. The distribution and thickness of the Upper Shelly Clay in the London area (Ellison *et al*., 2004).

Basal boundary

The base of the unit is sharp and it rests disconformably on the Upper Mottled Clay; where it rests on Laminated Beds the contact may be a rapid gradation.

Lithology

The Upper Shelly Clay consists mainly of stiff, brown and dark grey to black shelly clay, sandy clay and very weak to strong argillaceous limestone with fossil oysters. Thinly interbedded grey-brown silt and very fine-grained sand with scattered glauconite grains also occur and it becomes mainly sand to the south east. However, the sands may be partly incised channel-fills that post date the deposition of the Upper Shelley Clay (King, in press). Bioturbated beds, sand-filled burrows and clay rip-up clasts (less than 5 mm in diameter) are characteristic, and locally there is a weakly to strongly cemented shell bed (up to 0.43 m thick) containing *Ostrea*. Between Bermondsey and Lewisham is a more or less continuous bed of grey argillaceous shelly limestone known as the Paludina Limestone. The bed is generally 0.1 to 0.3 m thick, up to a maximum of 1.89 m, and contains unbroken and broken gastropods *Hydrobia*, *Planorbis* and *Viviparus*, which indicate deposition in a freshwater lake. A thin bed of lignite occurs locally at the base of the unit at Crystal Palace.

Most of the Upper Shelly Clay contains disarticulated bivalves of more marine-tolerant species and a generally greater diversity of fauna than in the Lower Shelly Clay.

4 'Striped Loam'

Distribution

South East London up to about 9 m thick.

Basal boundary

Sharply-defined contact between the shelly clay, sandy clay and muddy limestone of the underlying part of the Upper Shelly Clay to laminated and thinly-bedded fine sand, silt and clay of the Striped Loam.

Lithology

Laminated and thinly bedded fine sands, silts, clay and sandy clay. Seen in the Charlton Pit [TQ 418 786] where it comprises laminations and thin bedded fine sand and clay with lignite.

2.3.3 Depositional Environment and Processes

The regional distribution of deposits of the Lambeth Group was recognised as cyclic in nature by Stamp (1921), an idea developed further by Hester (1965) and Ellison (1983). Four depositional sequences separated by unconformities are now recognised (Knox, 1996a; Table 6). The sediments as a whole were laid down in a coastal or possibly estuarine setting (Figure 2.29) in which small fluctuations in sea level led to marked changes in depositional environment.

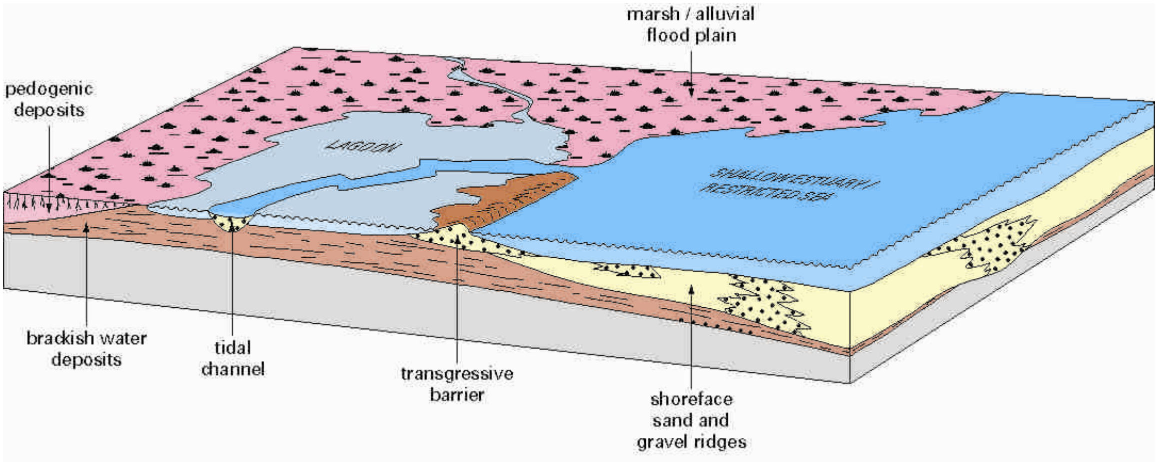

Figure 2.29. Schematic block diagram to illustrate the environment of deposition of the Lambeth Group (Ellison *et al*., 2004).

Following a period of regression and weathering of the top of the Thanet Formation, the lowest beds of the Upnor Formation were laid down in transgressive littoral to sub-littoral marine, tidal conditions.

The abundance of glauconite indicates periods of sediment starvation. The Upnor Formation as a whole is interpreted as highstand deposits in which marine flooding events are marked by pulses of glauconite deposition, winnowing and low sediment input (Ellison *et al*., 1996).

Deposition of the upper part of the Upnor Formation followed a lowering of sea level that may have led to the removal of some of the earlier deposits. A reduction in sea level, possibly combined with uplift, led to emergence and establishment of a terrestrial environment in which the Reading Formation was laid down on marshy mudflats that formed an alluvial floodplain crossed by river channels. This period of emergence marked the beginning of deposition of the

Lower Mottled Clay of the Reading Formation on an alluvial floodplain that was liable to intermittent floods and water table fluctuation. Periodic emergence led to oxidation, pedogenesis and the development of the characteristic red coloration, but the instability of this environment precluded the development of extensive colonisation by vegetation. The prevailing sub-tropical climate of high temperatures and pronounced wet and dry seasons led to subaerial weathering and soil-forming processes (pedogenesis) that affected both the Lower Mottled Clay and the Upnor Formation where they were close to the ground surface. This led to the formation of local silcretes (Kerr, 1955) and clasts of silica-cemented conglomerate in gravel beds at the top of the Upnor Formation. These clasts are typical of the 'Hertfordshire Puddingstone' that, in association with silica cemented sandstones (sarsens) were widespread to the north and west of the district (see Section 3.6.1.2 and Potter, 1998) and in the eastern South Downs. Estuarine and fresh water palynomorphs in the sandier parts of the Lower Mottled Clay in the east are evidence for intermittent encroachment by the sea onto the alluvial floodplain. This period of emergence represented the mid-Lambeth Group Hiatus and not only resulted in pedogenesis, but also erosion and low relief. A temporary rise in sea level led to the establishment of lagoonal and estuarine conditions and the deposition of the Lower Shelly Clay and Laminated Beds of the Woolwich Formation in the central and eastern parts of the district. Sand bodies in these units contain a brackish water palynomorph assemblage consistent with deposition in estuarine tidal channels. This sequence culminated with a return to continental conditions and deposition of the Upper Mottled Clay. Following a further depositional hiatus a rise in sea level and renewed flooding resulted in the deposition of brackish lagoonal and estuarine sediments (Upper Shelly Clay and 'striped loams'). This period of deposition was terminated by uplift and erosion that removed much of the Lambeth Group sediments in the north and east of the district.

The variation of the lithology and lithostratigraphy of the London Basin and Hampshire Basin are shown in (Figure 2.30).

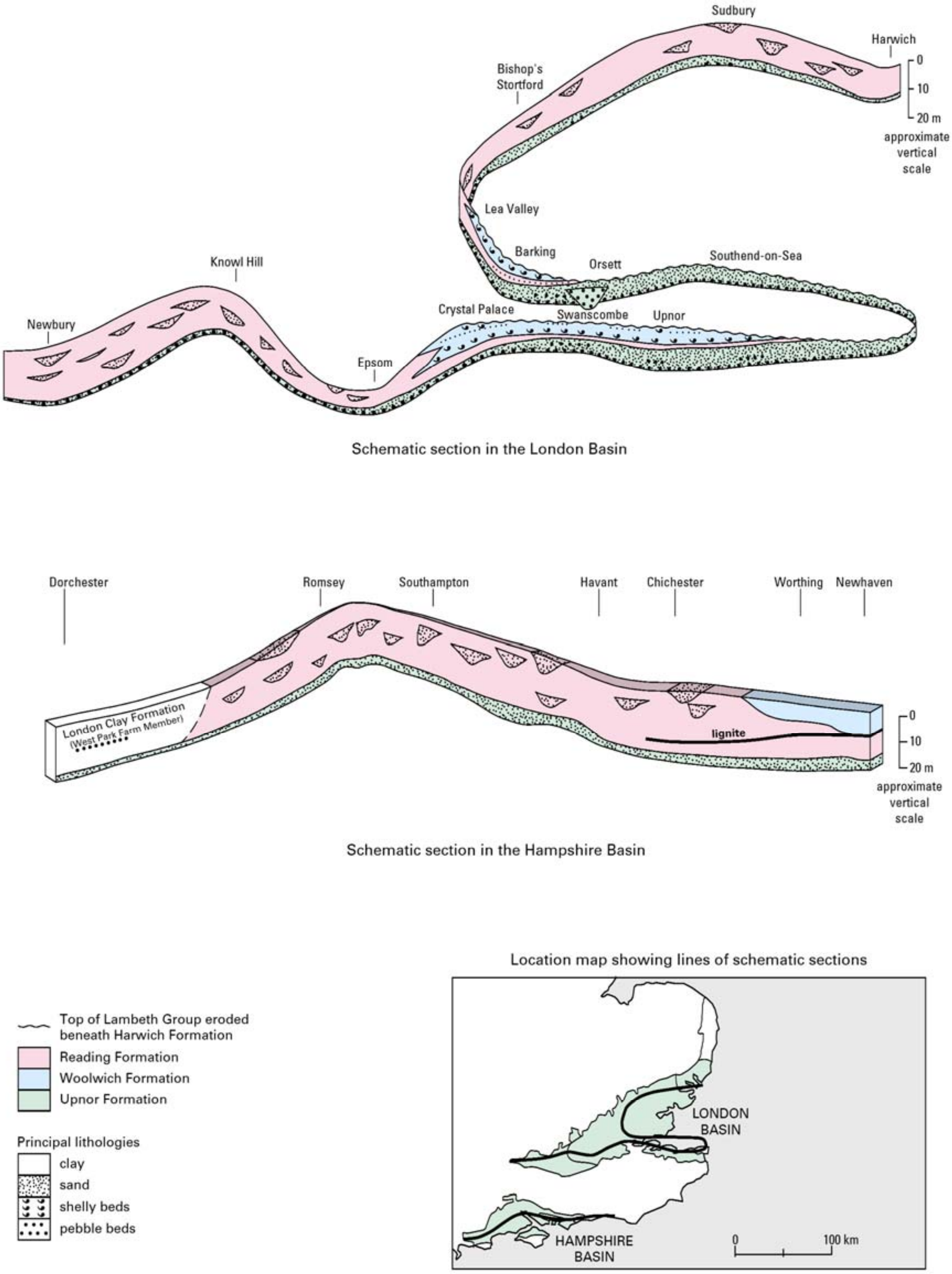

Figure 2.30. Schematic sections showing the lithostratigraphic variation in the Lambeth Group in the London Basin (top) and Hampshire Basin (bottom) (after Ellison *et al.*, 2004).

2.3.4 Post depositional features

The principal post depositional influences on the Lambeth Group are tectonic forces, glacial and periglacial processes and changing groundwater level. In areas of outcrop surface weathering effects also may have modified the deposits.

2.3.4.1 Structural features

The Lambeth Group has been gently folded on a regional scale and the beds in the majority of the London and Hampshire Basins generally dip less than 1º. Steep dips, greater than 45º, occur principally along the Hog's Back and in the Isle of Wight. In these areas the Lambeth Group, mainly Reading Formation, may contain shear planes and minor faults. Steep dips have also been recorded close to the Greenwich Fault in south-east London (Bromehead, 1922). Major fault systems with large throws are fairly well delineated and, in London, include the Greenwich Fault, Wimbledon Fault and the Streatham Fault. However, in the London area the Tertiary deposits and chalk are faulted by generally minor normal faults, generally with throws of less than 10 m. They often trend between N-S to NW-SE and ENE-WSW to E-W. In boreholes both normal and reverse faulting have been observed. Complex faulting systems have been identified during the site investigation of the Lee Valley Tunnel (Newman, 2008), Thames Water Ring Main (Newman, 2009), Thames Tunnel (Newman and Hadlow, 2011) and in the 3D geological model for the Farringdon Station area of the Crossrail project (Aldiss *et al.*, 2012) in which seven faults of about 2 to 10 m throw were identified within a study area of about 900 m east to west and about 500 m north to south. High quality borehole description, the lithological variation and recent understanding of the units within the Lambeth Group has meant that detailed modelling of these small faults can be undertaken. These fault, although most are minor, may have implications for engineering design and construction particularly in tunnelling projects due to rapid localised changes in lithology and hydrogeology conditions.

2.3.4.2 Features related to glaciation

Only the north-western areas of the Lambeth Group, from north London to Essex and Suffolk, have been covered by glacial deposits. There is no specific information about glacial disturbance but it is possible that release of high hydrostatic pressure beneath an ice margin may have caused disruption of bedding in sands within the Lambeth Group when near surface.

2.3.4.3 Features related to periglaciation

Periglacial conditions existed in southern England during at least two glacial episodes in the past 500, 000 years. The thinly bedded nature of the Lambeth Group, in particular the presence of water-bearing sands, resulted in a relatively high susceptibility to disturbance caused by ground ice and cryoturbation.

Pingos, large dome-shaped bodies of ground ice developed below the ground surface, grow by the progressive addition of water, probably under artesian pressure. Melting of pingos is thought to be at least partly responsible for more than 25 anomalously deep subsurface depressions in the rockhead beneath London (Hutchinson, 1980). Associated with some of these hollows are masses of Lambeth Group sediments that have been injected, under high hydrostatic pressure, through the London Clay into the base of the hollow. Artesian groundwater conditions occurred in much of the central part of the London Basin, and, therefore, there is a possibility that undiscovered areas of similarly disturbed Lambeth Group exist.

Modification of the Lambeth Group at outcrop by active-layer processes such as cryoturbation is largely unstudied. It is likely to have resulted in the development of small-scale structures such as involutions and the diapiric injection of sands. These features may be particularly well developed in interbedded sand and clay because of the potential contrast in the freezing point of groundwater in coarser compared to fine grained sediments, dependent on the relative pore pressures. Slopes formed of the clay-dominated Reading Formation owe their present form to periglacial slope processes and are likely to be mantled by 1 to 3 m of Head deposits containing shear surfaces aligned roughly parallel to the ground surface. Immediately beneath the Head, periglacially weathered clay is generally brecciated and softer than the unweathered clay beneath (see for example Spink, 1991). Periglacial shearing of the Reading Formation is likely to be exacerbated by the presence of pre-existing shears in the mottled clays.

Valley bulging involves broad anticlinal deformation of strata underlying valley floors, under periglacial conditions. It is commonly associated with clay-dominated strata and is likely to affect all valleys that have been rapidly incised. This releases large horizontal stresses, which under favourable conditions may be sufficient to initiate lateral deformation of the deposits towards the valley axis.

2.3.4.4 Features due to chalk dissolution

The Chalk dissolves to give a karstic surface with pipes and swallow holes up to several metres deep. The most significant dissolution has occurred at the margin of overlying impermeable deposits where surface drainage is concentrated, for example close to the junction with the Lambeth Group. Although many of the dissolution features are filled with superficial deposits, the Lambeth Group and the underlying Thanet Formation, particularly close to the edge of the outcrops, may also be let down into Chalk dissolution features.

2.3.4.5 The effect of rising groundwater

Major abstraction of water from the London aquifer, starting in the early part of the 19th century, led to a fall in groundwater levels in the central region of the basin (Water Resources Board, 1972). Consequently the top of the Chalk was probably dewatered over an area of several square kilometres in the centre of the basin (Lucas and Robinson, 1995).

The current rise in groundwater levels in London, caused by a reduction in water abstraction, is well documented (see for example Environment Agency, 2001). It has an influence on the Lambeth Group because the sandy Upnor Formation is regarded as being in hydrogeological continuity with the underlying Thanet Formation and Chalk. Historically, these sandy Tertiary beds together have been known as the ‘Basal Sands aquifer’.

The abstraction of water from the aquifer, starting in the early part of the 19th century, led to a fall in groundwater levels in the central region of the basin (Water Resources Board, 1972). Consequently the Upnor and Thanet formations and the top of the Chalk were probably dewatered over an area of several square kilometres in the centre of the basin (Lucas and Robinson, 1995). However, some sand beds not in contact with the main aquifer, particularly within the upper part of the Lambeth Group, still contain water and ground water lowering of these units required dewatering.

The recovery of groundwater levels in London has several implications that were considered in a report by CIRIA (Simpson *et al*., 1989). Basements or tunnels excavated above the water table and not sealed against the ingress of water would be subject to flooding. Sealed structures submerged by rising water would become buoyant and liable to uplift pressures detrimental to stability. Structures originally below the water table might not be sufficiently watertight to contend with increased hydrostatic head and remedial sealing or continuous pumping would be required. In response, the GARDIT (general Aquifer Research Development and Investigation Team) strategy was launched to control the rising groundwater level in the lower aquifer, which are now broadly stable throughout central London (Jones, 2007).

Tunnels are already suffering from increased seepage, and chemical attack. One example is on the London Underground Northern Line, where very acidic waters caused deterioration of the tunnel linings south of Old Street station. Investigations there suggested that the source of the acid was oxidised pyrite in sands in the Lambeth Group, probably in the Laminated Beds. These beds had originally been saturated, but dewatered as the water table was lowered. The pyrite was subsequently oxidised by air from the railway tunnels, in particular by the piston effect of passing trains and by changes in barometric pressure. Water seeping from the overlying London Clay, has resulted in the production of highly acidic, aggressive groundwater (Robins *et al*., 1997). As the water table rises, increasing amounts of oxidised pyrite will give rise to potentially corrosive acidic groundwater (Rainey and Rosenbaum, 1989).

During conditions of falling water table, the resultant under drainage and consolidation of strata resulted in the lowering of the ground surface in Central London by several hundred millimetres (Water Resources Board, 1972). It also increased the strength of the London Clay and clays in the Lambeth Group. As a result of rising groundwater, increase in pore water pressure and the swelling of clay may result in a loss of shear strength.

2.3.4.6 Features due to burial

After deposition the Lambeth Group was buried beneath the London Clay and later Tertiary sediments that together were possibly up to 250m thick in London. The Lambeth Group sediments have become denser, stronger and stiffer by consolidation. However, within the Lower Mottled and Upper Mottled Clay and the alter Upnor Formation pedogenic processes including desiccation and cementing will have increased these characteristic before the deposition of the London Clay Formation. This has been overprinted by relaxation because of erosion of the overburden after uplift over the last 20 million years. Both the initial burial and the subsequent swelling associated with stress relief due to erosion may have weakened cementation; particularly in the clays with higher plasticity. Additional fissuring may also have developed during unloading, although this will have been resisted by the presence of cementing and is likely to occur only near surface.

2.3.5 Current geological mapping

The Lambeth Group is represented on the current BGS DIGMapGB50 in a number of ways, as indicated below and in (Figure 2.31).

- Lower London Tertiaries (Lambeth Group and Thanet Formation) in northeast London Basin,
- Lambeth Group in the rest of the London Basin and east Hampshire Basin,
- Reading Formation in the west central Hampshire Basin,
- West Park Member of the London Clay Formation in the west Hampshire Basin.

The lithostratigraphical classification is further separated by lithology as below:

- Lambeth Group, undifferentiated clay, silt and sand or clay, sand and gravel,
- Lambeth Group or Reading Formation, sand and gravel,
- Lambeth Group or Reading Formation, sand,

- Reading Formation, clay, silt and sand,
- Reading Formation, sand and gravel,
- Reading Formation, sand,
- Lower London Tertiaries, clay, silt and sand,
- West Park Farm Member, clay,
- West Park Farm Member, clay and silt,
- West Park Farm Member, sand.

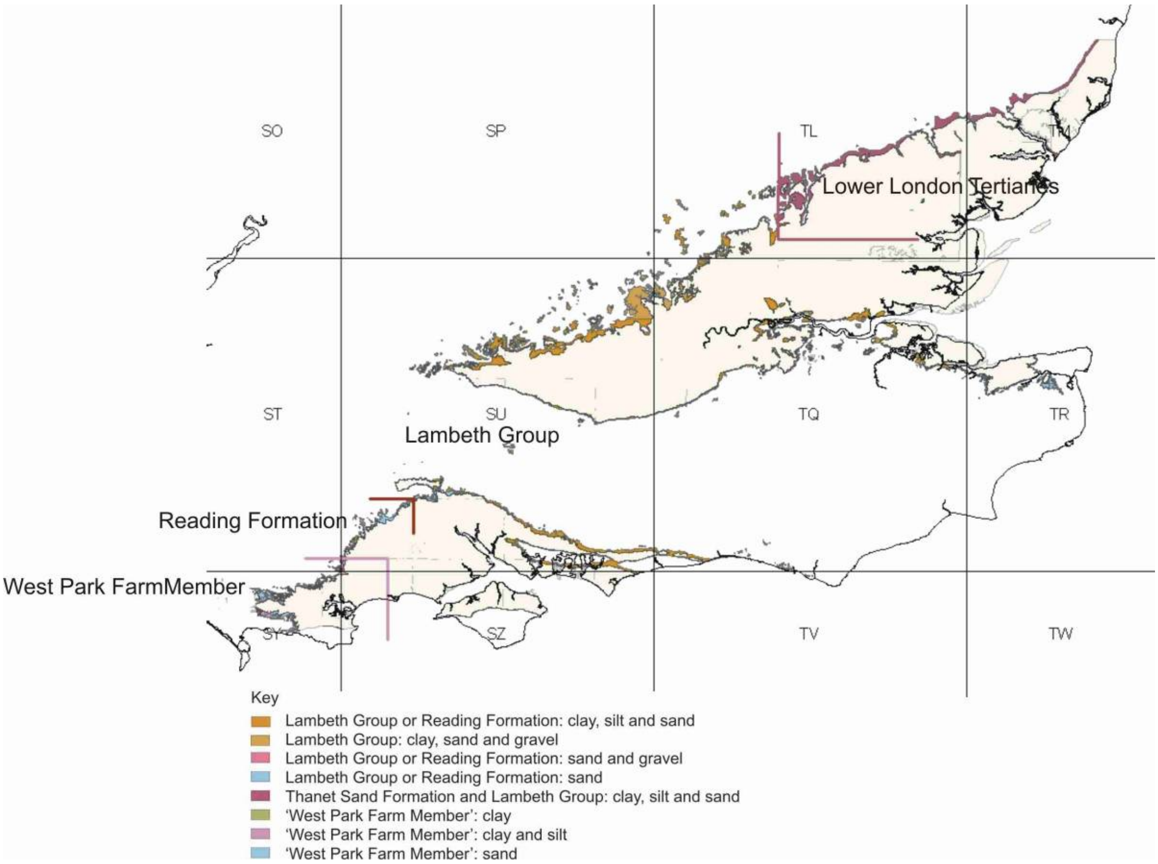

Figure 2.31. The distribution and differentiation of the Lambeth Group as recorded in the BGS DIGMapGB50.

Much of the Lambeth Group is described as clay, silt and sand on the maps. However, there are some exceptions. In east Kent, where the Upnor Formation predominates, it is mapped as sand. Three lithological units are mapped in the north and west Hampshire Basin, that is, clay, silt and sand, sand only and gravel only. In this area more of the deposits are thought to have of fluvial origin and hence the greater importance of coarse material. In the west Hampshire Basin what was mapped as the Lambeth Group is now mapped as clay and silt or sand of the West Park Farm Member of the London Clay Formation.

2.3.6 Locations of exposures and borehole core material from the Lambeth Group

Man-made and natural exposures are useful aids to understand the lithologies and possible variation of a deposit. The complexity of the Lambeth Group does mean that there are no 'typical' exposures; however, they can be used as a guide. Borehole core is available for inspection on request at the British Geological Survey in Keyworth.

2.3.6.1 NATURAL EXPOSURES

Daley and Balson (1999), Ellison *et al*. (2004) and Skipper (1999) have reviewed the accessible exposures of the Tertiary deposits (Table 2.2). Permission may be required to access the sites.

Table 2.2. Location of Lambeth Group exposures

Basin	Site	Site type	Grid reference	Formations
London	Hearne and Reculver Bay	Cliff section	TR 218 690	Upnor Formation
London	Lower Upnor Sand Pit	Quarry	TQ 759 711	**Upnor Formation**, Lower Mottled Clay(?) – sand Woolwich Formation
London	Orsett Cock	Quarry	TQ 657 811	Upnor Formation
London	Orsett Tarmac Quarry	Quarry	TQ 671 805	Upnor Formation
London	Swanscombe Eastern Quarry	Quarry	TQ 605 730	Upnor Formation Lower Mottled Clay Woolwich Formation
London	Charlton Sand Pit (Gilbert's Pit)	Old quarry (SSSI)	TQ 419 786	Upnor Formation Lower Mottled Clay **Woolwich Formation**
London	Harefield Great Pit	Old quarry	TQ 050 898	Upnor Formation Reading Formation
London	Pincent's Kiln, Theale	Old quarry	SU 651 721	Upnor Formation Reading Formation
London	Bolter End, Bucks.	Old quarry	SU 651 721	Upnor Formation Reading Formation
London	Knowl Hill	Quarry	SU 825 795	Upnor Formation **Reading Formation**
Hampshire	Newhaven	Cliff section	TQ 446 002	Upnor Formation Woolwich Formation
Hampshire	Whitecliff Bay	Cliff section	SZ 639 858	Upnor Formation Reading Formation
Hampshire	Alum Bay	Cliff section	SZ 305 858	Upnor Formation Reading Formation
Hampshire	Studland Bay	Cliff section	SZ 043 823	Upnor Formation (?) Reading Formation (?)

Bold = type section

2.3.6.2 REFERENCE CORE MATERIAL

Some borehole core has been retained by the British Geological Survey as reference material that can be inspected on request (Table 2.3). (Contact: The National Geoscience Data Centre, British Geological Survey, Keyworth, Nottingham). Photographs and description of JLE404T (BGS borehole TQ37NW/2118) cores are in Appendix 1.

Table 2.3. Reference borehole core

Basin	Borehole	BGS Borehole Reference.	Nation Grid Reference	Formations
London	JLE404T	TQ37NW/2118	TQ 3363 7960	Upnor Formation Reading Formation Woolwich Formation

2.3.7 Detailed distribution and lithological cross-sections

Sediments of the Lambeth Group are lithostratigraphical and lithologically complex, being extremely variable both laterally and vertically. To illustrate this, a number of sections with schematic borehole logs are presented.

2.3.7.1 Lithostratigraphical sections

Detailed lithostratigraphical borehole logs of the Lambeth Group by Skipper (1999) and Ellison *et al*. (2004) are shown in Figure 2.32 to Figure 2.37 using the mid-Lambeth Group Hiatus as a common lithostratigraphic horizon.

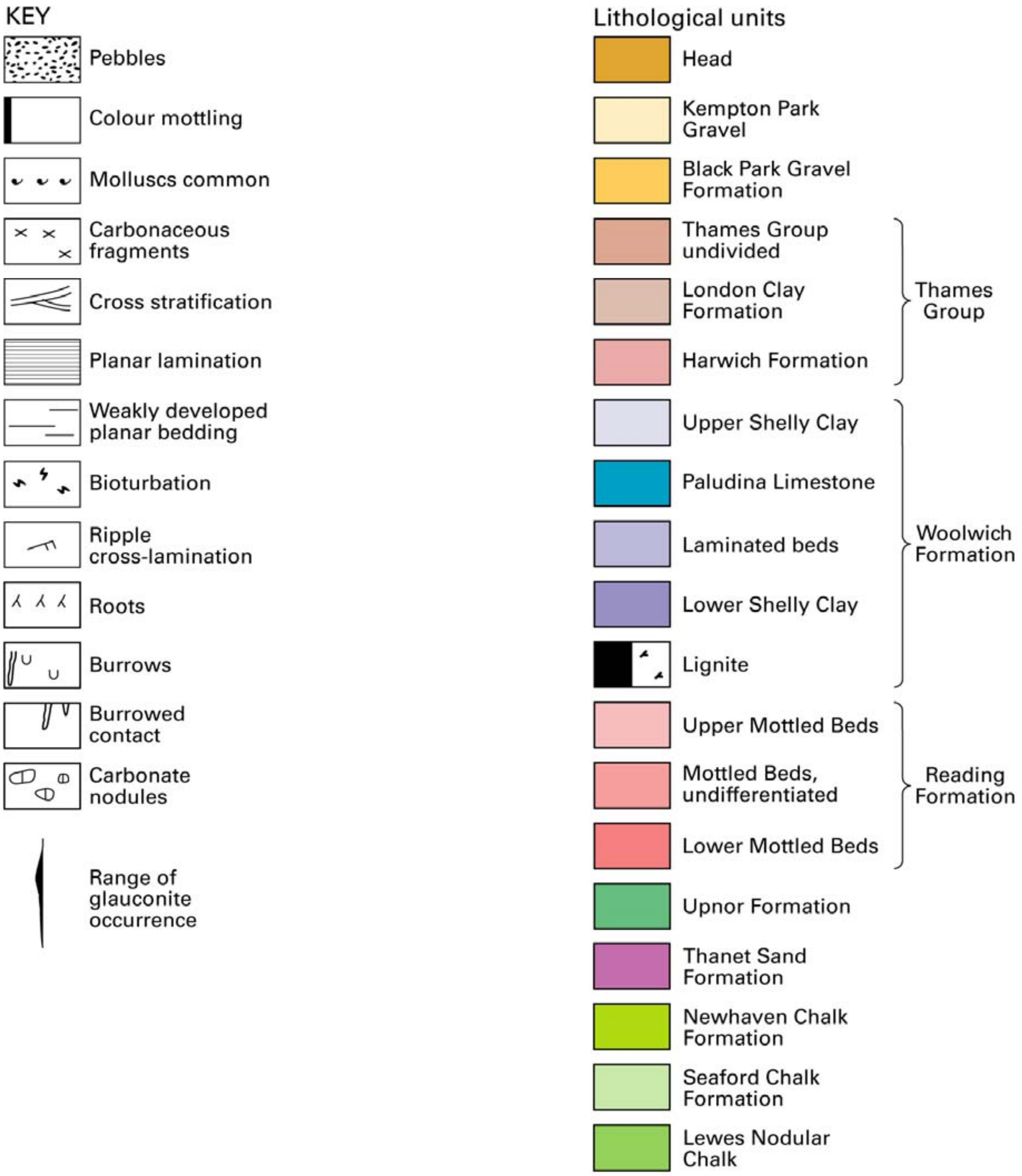

Figure 2.32. Key to the lithostratigraphical boreholes shown in Figure 2.33 to Figure 2.37.

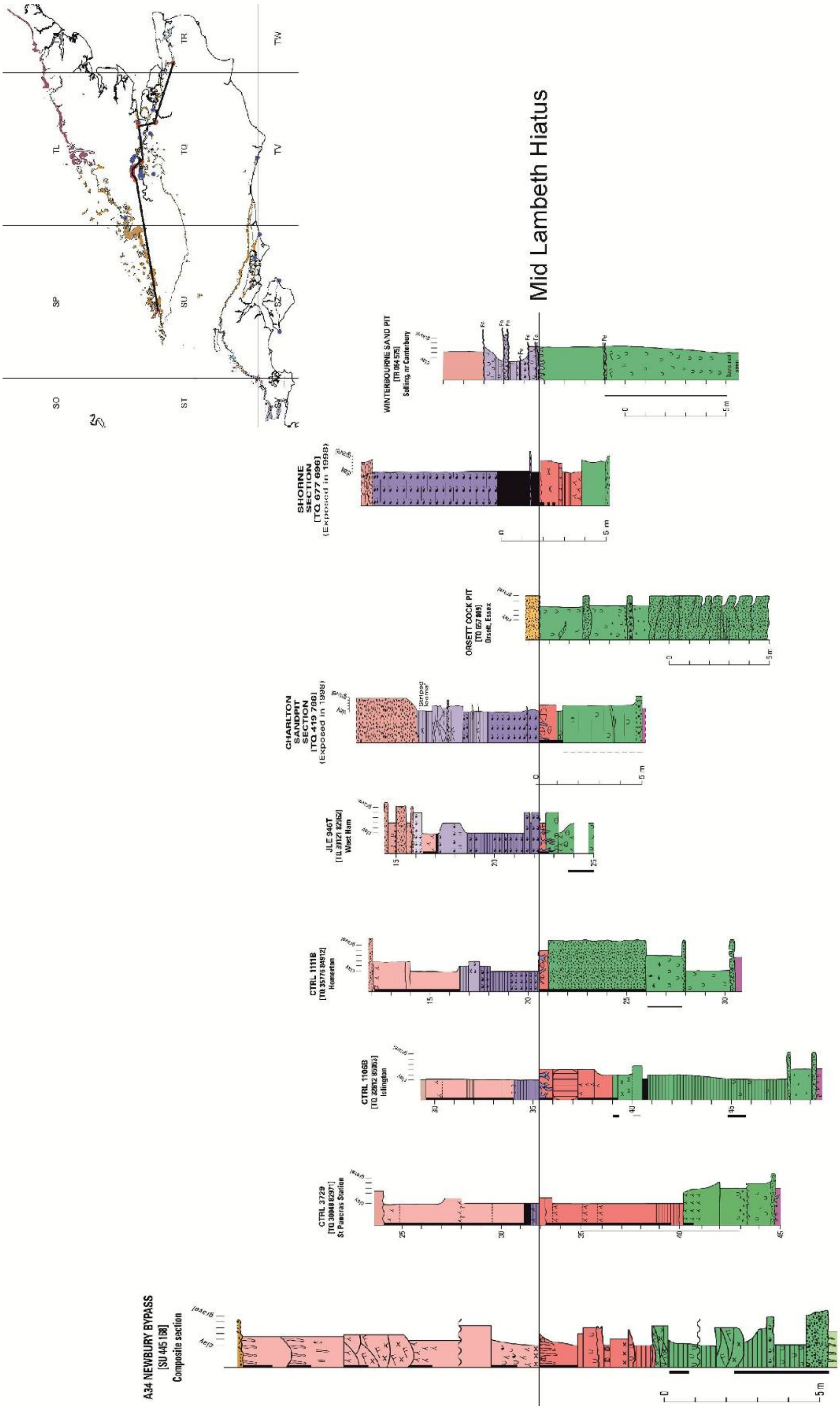

Figure 2.33. Lithostratigraphical boreholes in the London Basin, west to east, from the Newbury Bypass to Winterbourne Sand Pit. For key see Figure 2.32.

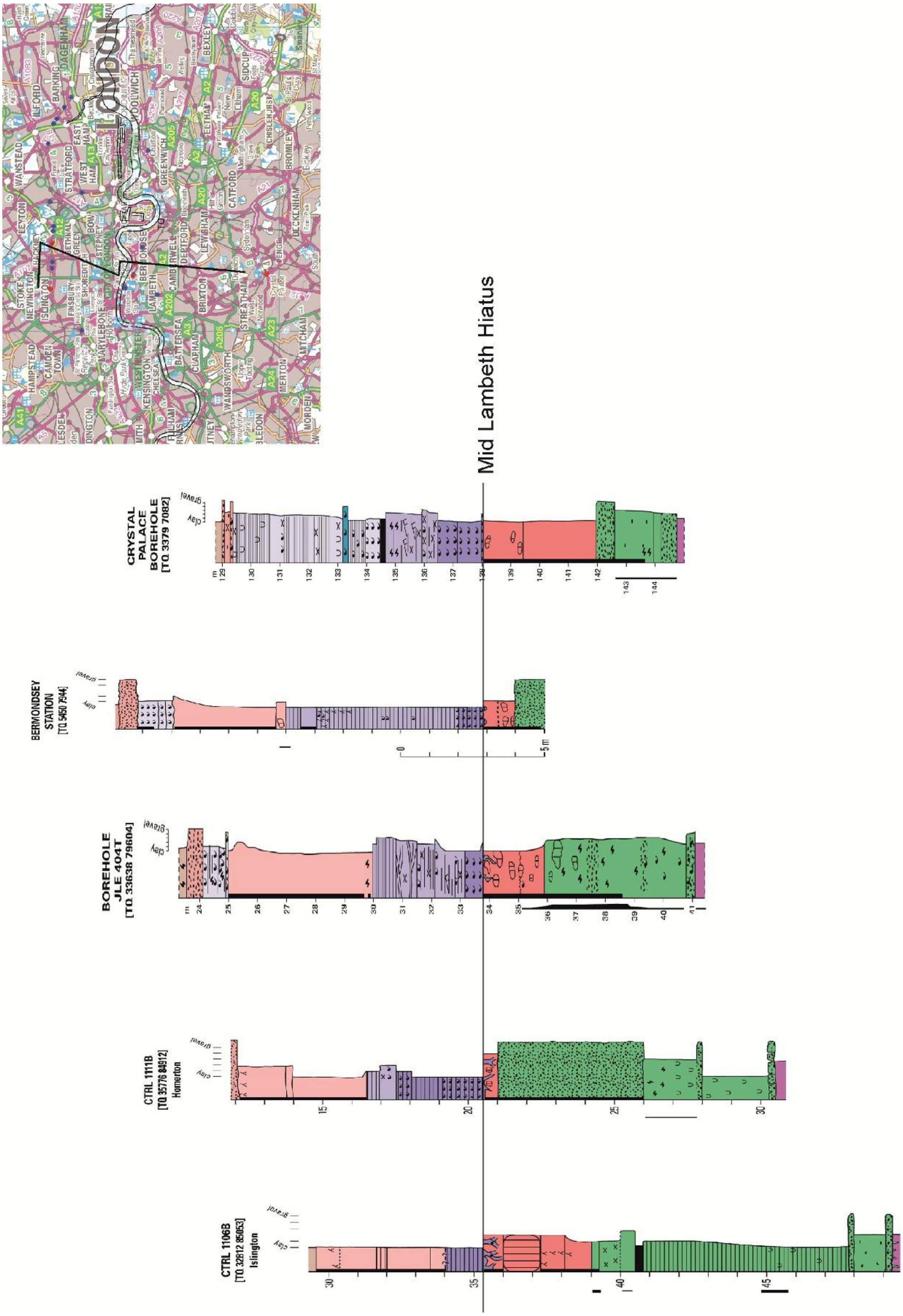

Figure 2.34. Lithostratigraphical boreholes in the London Basin, north to south from Islington to Crystal Palace. For key see Figure 2.32.

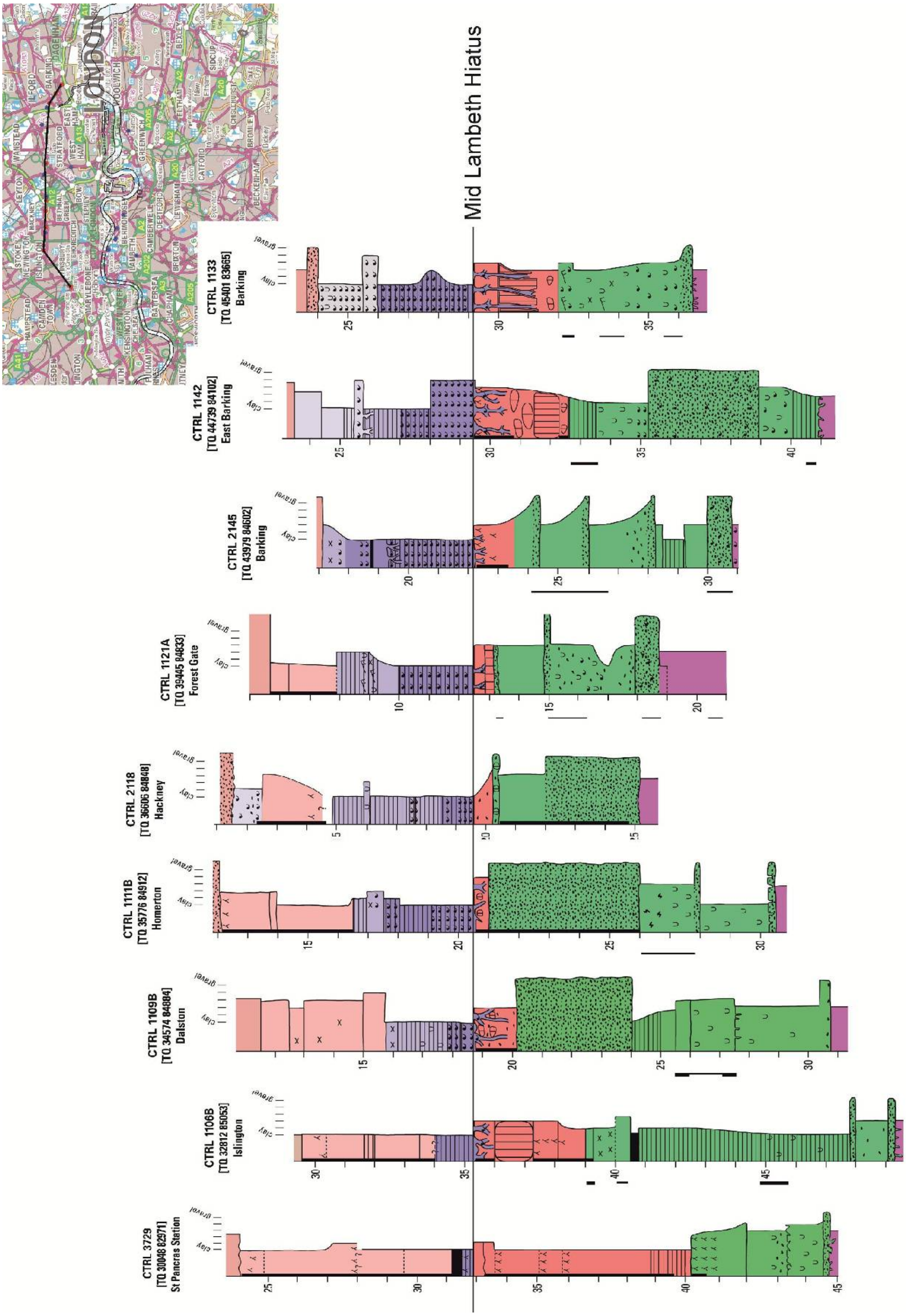

Figure 2.35. Lithostratigraphical boreholes in the London Basin, west to east, St. Pancras to Barking. For key see Figure 2.32.

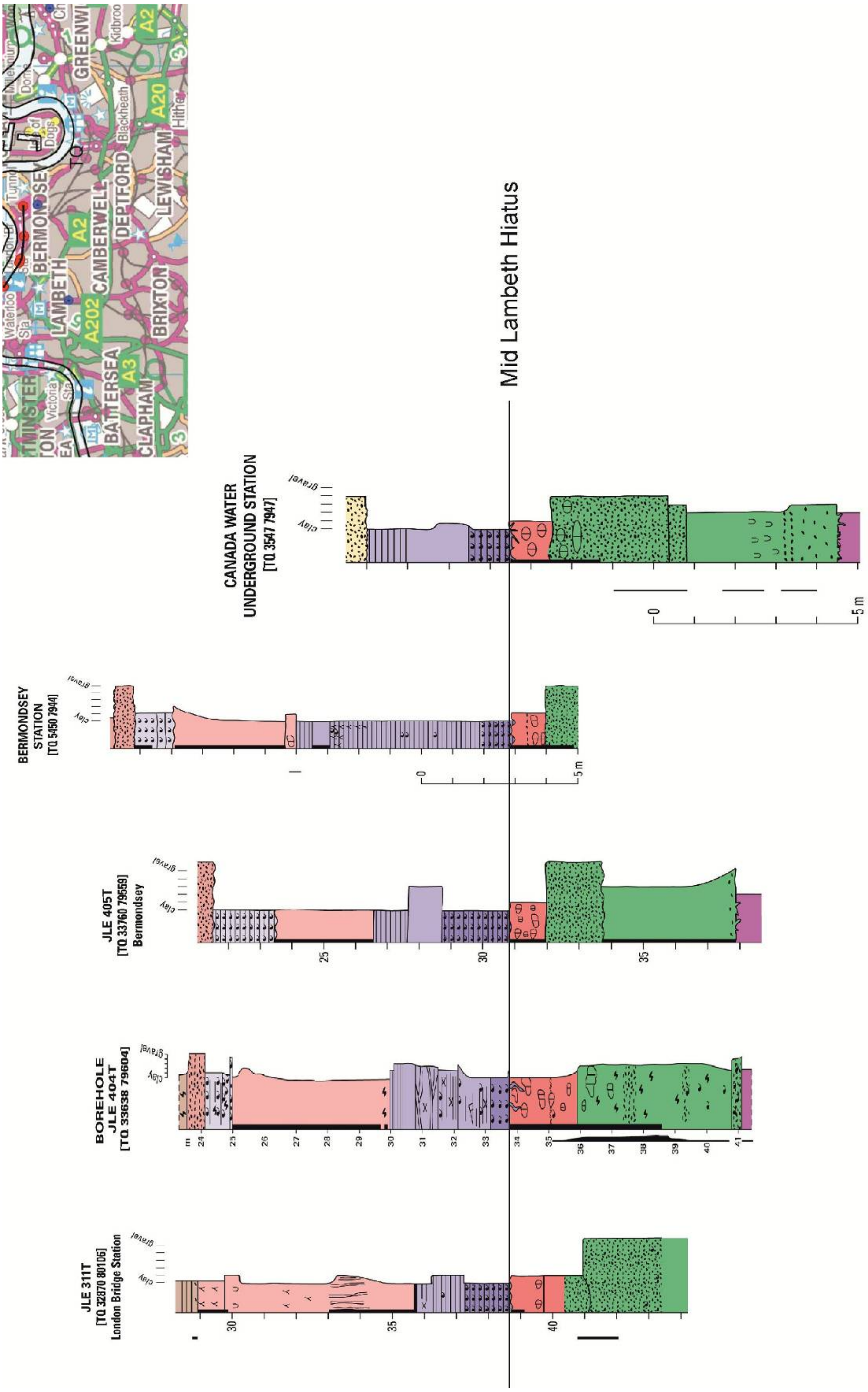

Figure 2.36. Lithostratigraphical boreholes in the London Basin, west to east, London Bridge Station to Canada Water Station. For key see Figure 2.32.

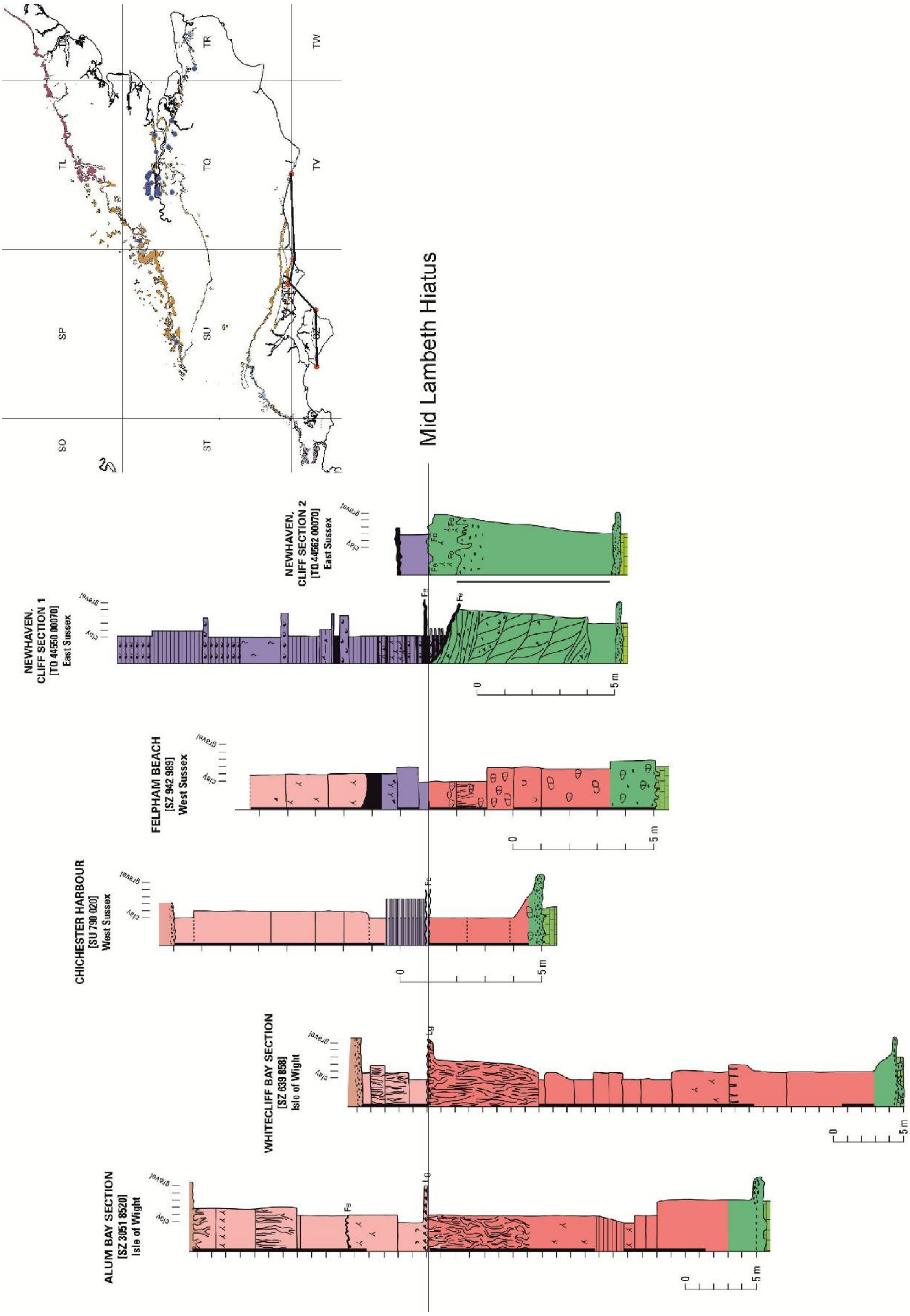

Figure 2.37. Lithostratigraphical boreholes in the Hampshire Basin, west to east, Alum Bay to Newhaven. For key see Figure 2.32.

2.3.7.2 LITHOSTRATIGRAPHICAL AND LITHOLOGICAL CROSS SECTION

Twenty selected cross-sections based on boreholes drilled for major site investigations (including motorways, other major roads and road and railway tunnels) are listed in Table 2.4 and presented in Appendix 2. The sections presented show both lithostratigraphy and lithology (indicated by annotated 'borehole sticks') and highlight the lithological variations within the lithostratigraphic divisions. The sections provide an impression of continuous lithostratigraphy and are based on more closely spaced boreholes than those shown in Figure 2.33 to Figure 2.37.

Lithostratigraphic and lithological data for the boreholes used to construct the cross sections shown in Appendix 2 were extracted from records held in the BGS National Geotechnical Database and displayed graphically, in their correct geographic position, using a 3D modelling package (GSI3D).

Table 2.4. Cross-sections in Appendix 2

Number	Figure	Project name	Area
1	4	A34 Newbury Bypass	Curridge to Bunkers Hill
2	5	M4 J8(9)–12 Widening	South Reading, Berkshire
3	6	M40 J1A-3 Widening	Beaconsfield to M40/M25 junction
4	7	M25: M4 to Maple Cross	
5	8	Crossrail	Paddington to Bishop's Gate
6	9 + 10	Jubilee Line Extension	Green Park to Millennium Stadium
7	11 + 12	Channel Tunnel Rail Link	St Pancras to A406 Barking
8	13	M11 Link – A104/A114 to A12	Hackney
9	14	Channel Tunnel Rail Link	Stratford to Leyton
10	15 + 16	Channel Tunnel Rail Link	A406 Barking to Rainham
11	17	A406 South Woodford to Barking Relief Road	South Woodford to Barking
12	18	Docklands Light Railway: Lewisham extension	Greenwich to Island Gardens, Isle of Dogs
13	19	A102 Blackwall Tunnel Third Bore	Blackwall Tunnel
14	20	Jubilee Line Extension	North Greenwich to Canning Town
15	21	A13 Orsett Cock to Stanford Interchange	A13 Orsett Cock to Stanford Interchange
16	22	Stanford Le Hope Low Level Sewerage Scheme	Stanford-Le-Hope
17	23	M2 widening	Shorne Cut, Kent

2.3.8 Summary of lithostratigraphical and lithological data

Lithological variation has been identified as the main engineering problem of the Lambeth Group. To further highlight this, summaries of the lithostratigraphic units and their dominant lithologies as described in boreholes, for selected areas, are presented graphically in Appendix 3. The graphs show percentage core lengths of the lithostratigraphic units encountered in each area and the dominant lithologies (clay, silt, sand, gravel, limestone and lignite) described for each unit and the Lambeth Group as a whole. Where 'limestone' lithologies are indicated, these may be either calcrete, found in the Lower Mottled Clay and the Upnor Formation, or shell limestone in the Lower or Upper Shelly Clay. The graphs also show the total number of metres of Lambeth Group core described in each area in order to give an indication of the significance of the data.

2.4 DEPOSITS ABOVE THE LAMBETH GROUP

2.4.1 Harwich Formation

This term was introduced by Ellison *et al*. (1994) to include all sediments between the Lambeth Group and the London Clay Formation. They were formerly differentiated by Prestwich (1854) as the ‘Basement-bed of the London Clay’, and subsequently divided by Whitaker (1866) into the Basement-bed, the Oldhaven Beds and the Blackheath Beds. Currently, the Harwich Formation is divided into the Blackheath, Oldhaven, Swanscombe, Orwell, and Wrabness members (Aldiss, 2012).

2.4.1.1 DISTRIBUTION

The Harwich Formation occurs in the London and Hampshire Basins but is best known and described for the latter region (Figure 2.38), where it reaches a maximum thickness of 10 to 12 m around Orpington and Chiselhurst, Kent. South and east of London, where the deposits were formerly mapped as Blackheath Beds, there are numerous descriptions of former exposures recording very variable thicknesses over quite short distances; this probably indicates an irregular base. Elsewhere in the region, most of the information on the Harwich Formation is from borehole records (for strata formerly referred to the Basement Bed of the London Clay), and recent excavations for Crossrail, which indicate that the Harwich Formation is up to 4 m thick. In the northeast, an incomplete thickness of 6.88 m was proved in the Stock Borehole [TQ 7054 0045], and in the south-east the Stanford-le-Hope Borehole [TQ 6965 8241] proved 4 m.

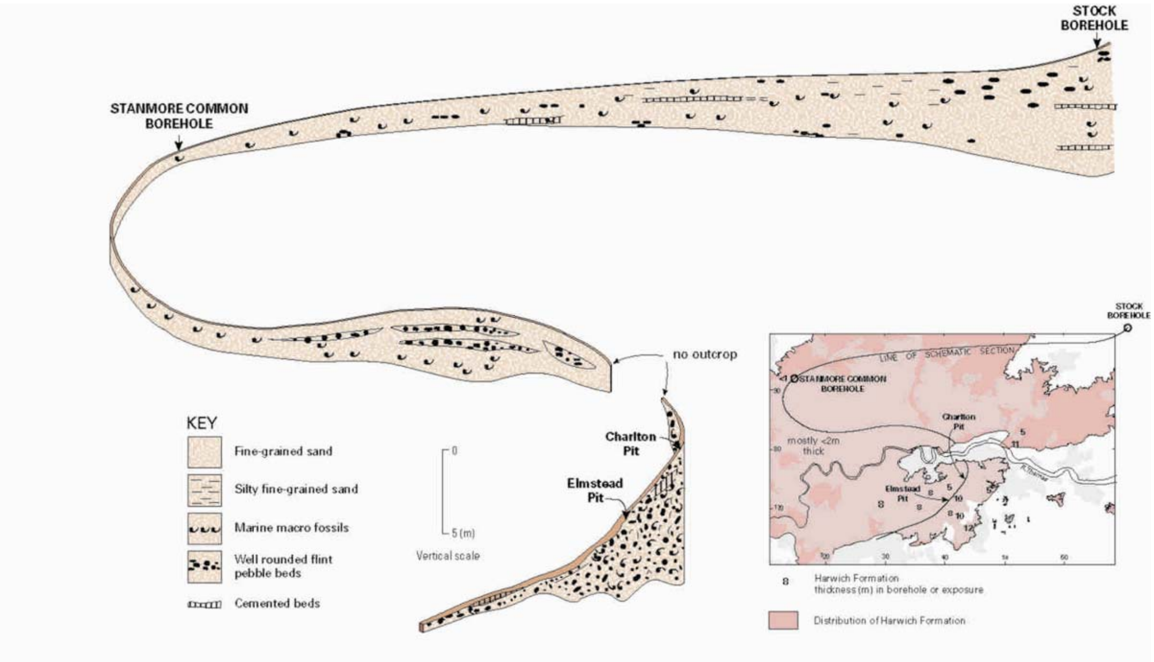

Figure 2.38. Ribbon diagram of the Harwich Formation showing the lithological variation and general thickness in London (Ellison *et al*., 2004).

2.4.1.2 BASAL BOUNDARY

The base is sharply defined, and forms an erosive contact on the Lambeth Group. Locally, in outliers at Kelvingtown [TQ 485 675] and Swanley [TQ 515 686], the Harwich Formation oversteps onto the Thanet Formation.

2.4.1.3 LITHOLOGY

Glauconitic fine-grained sand and gravel beds of rounded black flints are the principal lithologies with, in places, common disarticulated and broken shells of marine to brackish fauna (see Dewey *et al*., 1924). The proportion of gravels varies considerably. Calcareous, ferruginous and siliceous cements occur locally in beds and masses up to several metres thick (for details see Dewey and Bromehead, 1921; Dewey *et al*., 1924), particularly at outcrop in the southeast of the district. Recent excavations for Crossrail and Thames Water projects have found multiple, discontinuous layers of calcite cemented sand and gravel beds in the Blackheath and Oldhaven members up to 750 mm thick in the West Ham and Isle of Dogs areas of east London. Also in these areas, weak calcareous mudstone and strong calcareous siltstone concretions up to 250 mm thick and 450 mm wide occur in the Swanscombe Member.

In the northeast the Harwich Formation is dominated by relatively fine-grained sand and is generally less pebbly. The succession is known in detail only in Stock Borehole [TQ 7054 0045] where grey-green silty fine-grained sand with scattered broken shell fragments and stringers of black flint gravels are recorded. At outcrop in south Essex, the Harwich Formation consists of green-grey, weathering to pale yellow-brown, highly glauconitic fine to medium-grained sand and gravelly sand. Calcareous mollusc fossils and scattered sharks' teeth are typical although the shells are decalcified in places.

In areas where gravel beds dominate the sequence they consist of a series of superimposed channels as is seen, for example, in the cutting for the A2 at Shorne (Figure 2.39), with large foresets composed almost entirely of flint gravels, imbricated in places, and rare gravels of siliceous sandstone (similar to sarsenstone). The gravel beds include clasts up to 150 mm in diameter but generally less than 20 mm.

Figure 2.39. Harwich Formation sand and gravels in a cutting for the HS1 railway at Shorne, Kent.

Harwich Formation gravel beds are best exposed in former quarries, now Sites of Special Scientific Interest (SSSI), at Charlton [TQ 419 786] and Elmstead Rock Pit, Chiselhurst [TQ 423 706], and in a small pit at the Inn on the Lake [TQ 675 699] near Gravesend.

3 MINERALOGY

3.1 INTRODUCTION

Knowledge of the Lambeth Group mineralogy and the processes that alter them allows for a more informed appreciation of the sediments at a desk study level, resulting in better designed site investigations. This section gives an account of the mineralogy of the Lambeth Group sediments and its effect on engineering behaviour, based on mineralogical data from a number of sites in the London and Hampshire Basins.

Heterogeneity within the Lambeth Group is not only due to the changes in primary sediment lithology but also, in certain parts, by hard bands such as ferricretes, calcretes and silcretes formed during penecontemporaneous pedogenesis. Pedogenesis alters and transports minerals by washing them through the soil profile (eluviation) and enriching zones where they collect (illuviation). Pedogenic processes also produce the mottled colouring characteristic of some of the Reading Formation clays and the upper part of the Upnor Formation beneath thin Lower Mottled Clay, and may lead to localised changes in clay mineralogy. The clay minerals present will affect behaviour, most notably smectite, which results in higher plasticity clays, generally prone to shrink/swell hazards.

Deoxygenation of the Upnor Formation, which has caused deaths during tunnelling and deep shaft excavation operations in London (Lewis and Harris, 1998,) is due to 'green rust'. There is little information on the mineral as it oxidises very rapidly and may be seen, very briefly when inspecting fresh core (Newman *et al*., 2013) (see Section 7.6.3).

In stiff clay beds, pedogenesis may give rise to the partial infilling and cementing of fissures (possibly originating from post depositional drying and wetting cycles) by iron oxides. Sampling methods may destroy or damage these cemented bonds, resulting in laboratory strength tests underestimating the strength *in situ,* possibly leading to unnecessarily increased construction costs due to over-design (Hight *et al*., 2004).

Where both pyrite and calcium carbonate in the form of shell debris or calcrete are present, near surface oxidation of pyrite (e.g. during excavations) may produce sulphuric acid that reacts with calcium carbonate to form gypsum. High sulphate contents derived from subsequent dissolution of gypsum may require the use of sulphate resistant cements.

3.2 DATA SOURCES

There is limited published literature on the mineralogy of the Lambeth Group and the stratigraphical control of some of the available information is poor. Most of the work carried out on clay mineralogy in the 1960's is summarised in Perrin (1971). Buurman (1980) investigated intra-formational soil horizons. However, recent interest in the Lambeth Group, particularly in London, has resulted in new data, particularly that acquired by Skipper (1999, and personal communication), and Knox (personal communication, 1997). Other information has come from work produced for this project (Pearce *et al*., 1998) and various BGS reports and memoirs and the paper by Huggett and Knox (2006).

As part of the BGS Lambeth Group study, samples were collected from a number of sites for mineralogical, petrographic and geotechnical determinations to supplement existing published data and information held in archived site investigation reports in the BGS National Geoscience Data Centre (NGDC). Most of the samples were collected from the Newbury

Bypass construction site in Berkshire, Orsett Quarry in Essex, Upnor Quarry in Kent and cliff sections at Alum Bay, Isle of Wight. Data acquired from these sampling sites was supplemented by similar test data determined on samples from the Jubilee Line Extension Borehole 404T (BGS borehole TQ37NE/2118, [TQ 33638 79604]) selected from the same depths as used by Knox in his study of the clay mineralogy.

3.3 NON-CLAY MINERALS

3.3.1 Quartz

Quartz is usually the dominant non-clay mineral of the Lambeth Formation and is generally present as sand-size particles but may also occur as clay grade material (Gilkes, 1966, 1968). Much of the fine to medium sand particles are angular or subangular but coarser grains are usually rounded. Some beds are of almost pure quartz sand. Grains or layers maybe cemented with silica, in some cases forming silcretes such as sarsen stones.

3.3.2 Silica - flint or chert

Most flint or chert gravels, and occasional cobbles, are found in the Upnor Formation where it is often present at the formation base. These gravels also make up approximately 75% of the pebble beds in the upper part of the Upnor Formation in the central part of the London Basin (Ellison, 1983) and occur sporadically throughout. Elsewhere, flint gravel is very rare, but is found in the upper part of the Upper Mottled Clay sequence beneath the Shepperton Formation (‘Thames Basal Gravel’) and as thin beds in the Woolwich Formation.

Where present, flint gravels are usually rounded, often black, dark grey or green but when affected by contemporaneous pedogenic processes may be brown or white coated and may have a red core; these are porous and weaker than unaltered flints. Some altered flints can be mistaken for chalk. They are usually less than 2 cm across although they may be of cobble size and up to 200 mm across in some places. In the Upnor Formation the gravels show percussion cracks (or “chatter” marks) indicating a high-energy shallow marine or tidal depositional environment. Flint gravels are also present in the form of ‘puddingstones’ and as fragments in some more breccia-like sarsens, with silica being the primary cementing agent and chert usually a minor constituent (see Hard Bands below). Irregular silica may form in voids, such as old root holes, as shown in Figure 3.1.

3.3.3 Feldspar

Feldspar is usually a minor constituent of the Lambeth Group sediments and may be altered or corroded (Figure 3.2).

3.3.4 Mica

Mica generally occurs as a minor component. Colourless flakes of muscovite and biotite are often present (Ellison and Lake, 1986) and the clay-grade mica, illite, is a common and important component of the clay mineral assemblage (see Section 3.4).

3.3.5 Calcite and calcium carbonate

Calcite is present as shells in parts of the Upnor and Woolwich formations and may be the dominant material in parts of the Lower Shelly and Upper Shelly Beds where it may form limestone. Due largely to soil forming processes (pedogenesis), calcium carbonate is redeposited to form concretions that are present as scattered small white calcareous nodules (Bloodworth *et al*., 1987, Edwards and Freshney, 1987). These concretions coalesce and develop into hard bands in the upper parts of the Upnor Formation especially where the overlying Lower Mottled Clay Bed is thin; in the upper part of the Lower Mottled Clay in much of the London area; and in localised pockets, most commonly in sand lenses in the undifferentiated Reading Formation.

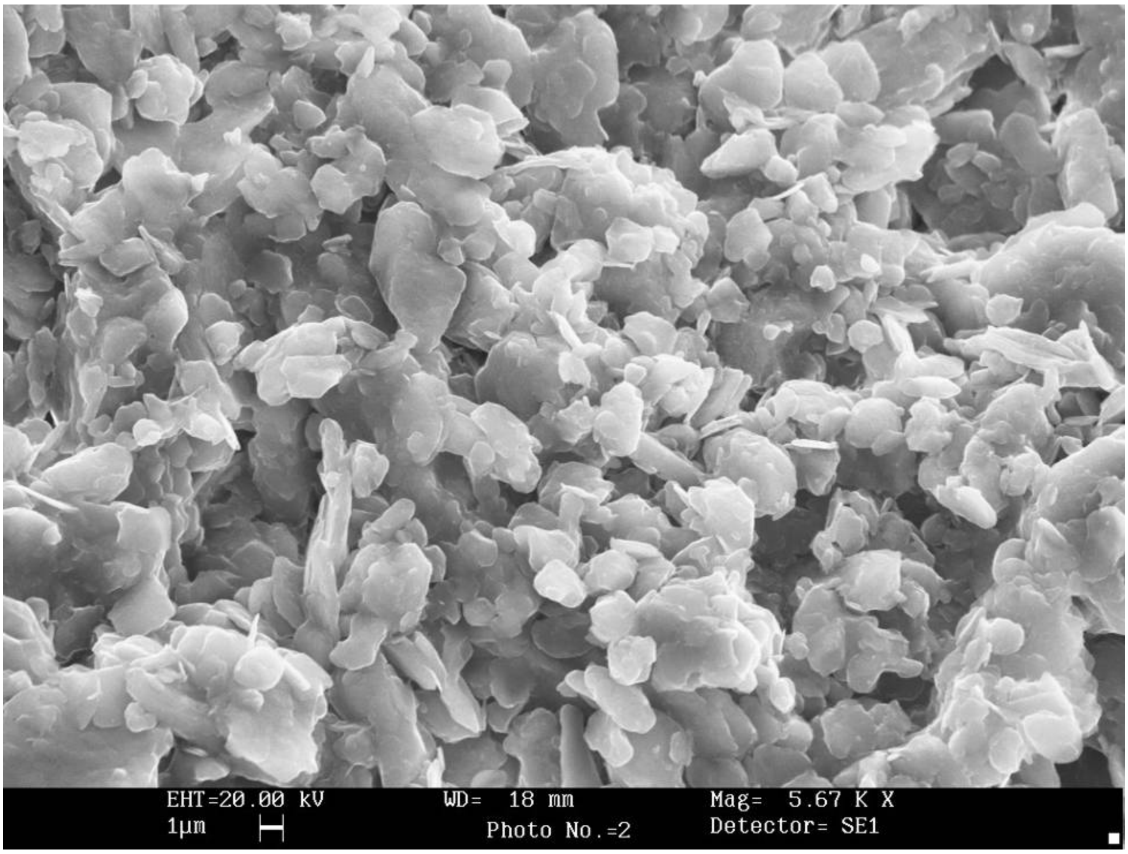

Figure 3.1. Irregular, micron-scale silica crystals forming a void lining in the Upper Mottled Clay, Newbury Bypass, 19.70 m above Chalk [SU 4500 6810]. (BGS electron micrograph No. E442S1/02).

Shrinkage cracks may be filled with calcite crystals in parts of the succession, such as at Alum Bay on the Isle of Wight (Buurman, 1980). In these areas the calcite has been removed from the matrix and fossils and re-deposited by percolating calcium carbonate-rich waters. Aragonite, derived from shell debris, is present in the upper part of the Upnor Formation in the Bradwell area (Bloodworth *et al*., 1987) and in the Chilterns (Bateman and Moffat, 1987).

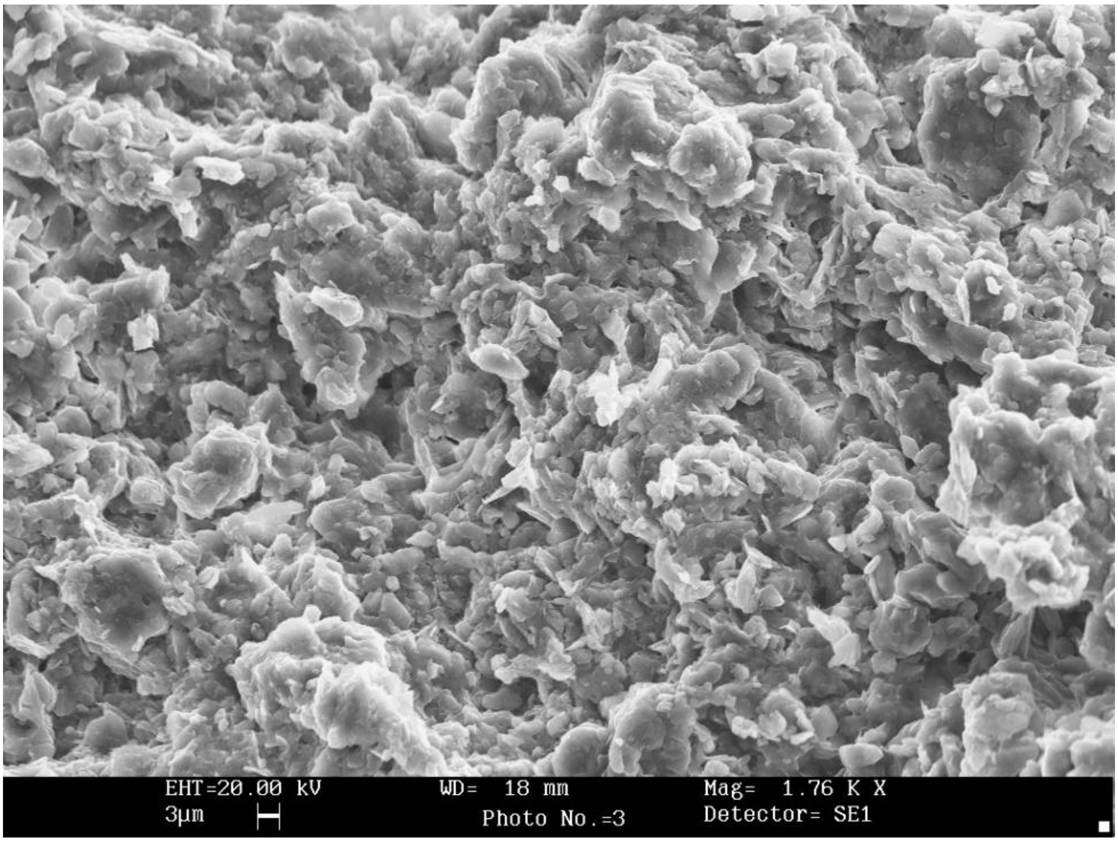

Figure 3.2. Corroded K-feldspar in the Upper Mottled Clay from Newbury Bypass, 19.7 m, above Chalk [SU 4500 6810]. (BGS electron micrograph No. E442S1/01).

3.3.6 Iron-bearing minerals

There are a wide range of iron-bearing mineral present in most of the Lambeth Group including pyrite, limonite, haematite, magnetite/ilmenite, goethite, jarosite, lepidocrocite and leucocene. These minerals provide most of the colour variation, most notably within the mottled beds of the Reading Formation and some upper parts of the Upnor Formation. Pyrite, FeS_2, was probably the dominant iron bearing mineral present at deposition, the oxidation of which, particularly in the Reading Formation and parts of the Upnor Formation, would have occurred during or shortly after deposition by sub-tropical weathering, soils pedogenesis and biological activity. During dry periods, the oxidation process would be enhanced by lowering of the ground water table to allow the introduction of air. In clay-rich deposits dry conditions could cause shrinkage and induce cracks, thus increasing the depth of oxidation. For example, fissures in the Reading Formation may be coated in a different coloured mineral to the material surrounding it. Air, and material from above, can also be introduced too much greater depths by burrowing animals such as crustaceans, and the rotting and removal of roots. Some of the most vivid examples of colour contrasts have been formed in this way (Figure 3.3). Iron minerals are also redeposited in ferricrete (see Section 3.6.1) such as the Winterbourne Ironstone of north Kent and in shrinkage cracks and other voids such as root holes (Figure 3.4).

Figure 3.3. Examples of mottling in the Reading Formation from the Newbury bypass construction site [SU 4500 6810] (right) and from Alum Bay, Isle of Wight [SZ 3054 8520] (left).

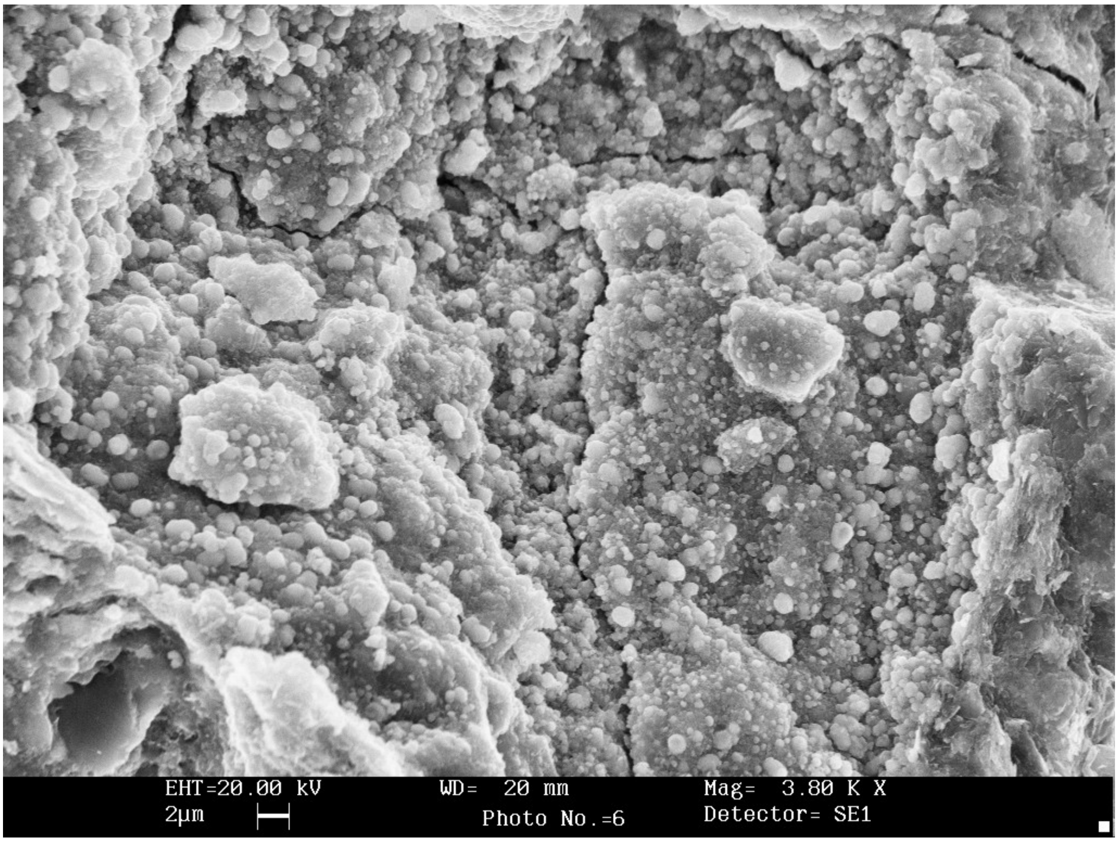

Figure 3.4. Anhedral to occasionally micro-botryoidal goethite lining voids in the Lower Reading Formation, 17.6 m above the Chalk, Alum Bay, Isle of Wight [SZ 3052 8522]. (BGS electron micrograph No. D821S1/06).

The oxidised iron minerals may be reduced by the activity of bacteria consuming organic material such as roots or by water logging, as illustrated in Figure 3.5.

Figure 3.5. Variation in colour of the Reading Formation, showing blocks with a red interior and grey reduction exterior. Star Brickworks, Knowl Hill [SU 8160 7970].

In the Reading Formation at Alum Bay, Buurman (1980) found that the mottling is due to local sharp boundaries between iron-rich and iron-poor spots. He found that the iron was transported and accumulated in favourable conditions (pyrite where organic material was present and other iron minerals in oxidised zones).

Contemporary oxidation occurs where reduced deposits are exposed. This can be seen in the sands of the Upnor Formation, which are generally green due to the presence of glauconite but change to the typical 'pepper and salt' appearance on exposure. The grey deposits of the Woolwich Formation oxidise to grey brown or brown, and if calcium carbonate is present may form gypsum.

Pyrite is the main iron mineral in grey and black deposits such as those found in the Woolwich Formation and some parts of the Upnor Formation. It is often associated with deposits containing fossil remains such as shells, lignite, wood or roots.

A yellow mineral, jarosite, colours a sandy clay at, or near the base of, the lignitic beds of the lower Woolwich Formation at Newhaven. Jarosite, $KFe_2(SO4)_2(OH)_6$, is an alteration mineral that is usually associated with oxidation of pyrite.

Red or dark red colouring or mottling is usually due to hematite, Fe_2O_3, (see Figure 3.3 and Figure 3.5) which is the oxidised and dehydrated form of iron. It is likely to be present where a bed was subjected to longer periods of surface or near surface exposure resulting in drying and dehydration. It is commonly seen in the upper parts of the Lower and Upper Mottled Clay, in burrow deposits and root holes. The strong red colour requires only small quantities of hematite and in some cases this may be below the detection limit of x-ray diffraction apparatus. Earthy hematite rosettes also form linings in voids in the Reading Formation (Figure 3.6).

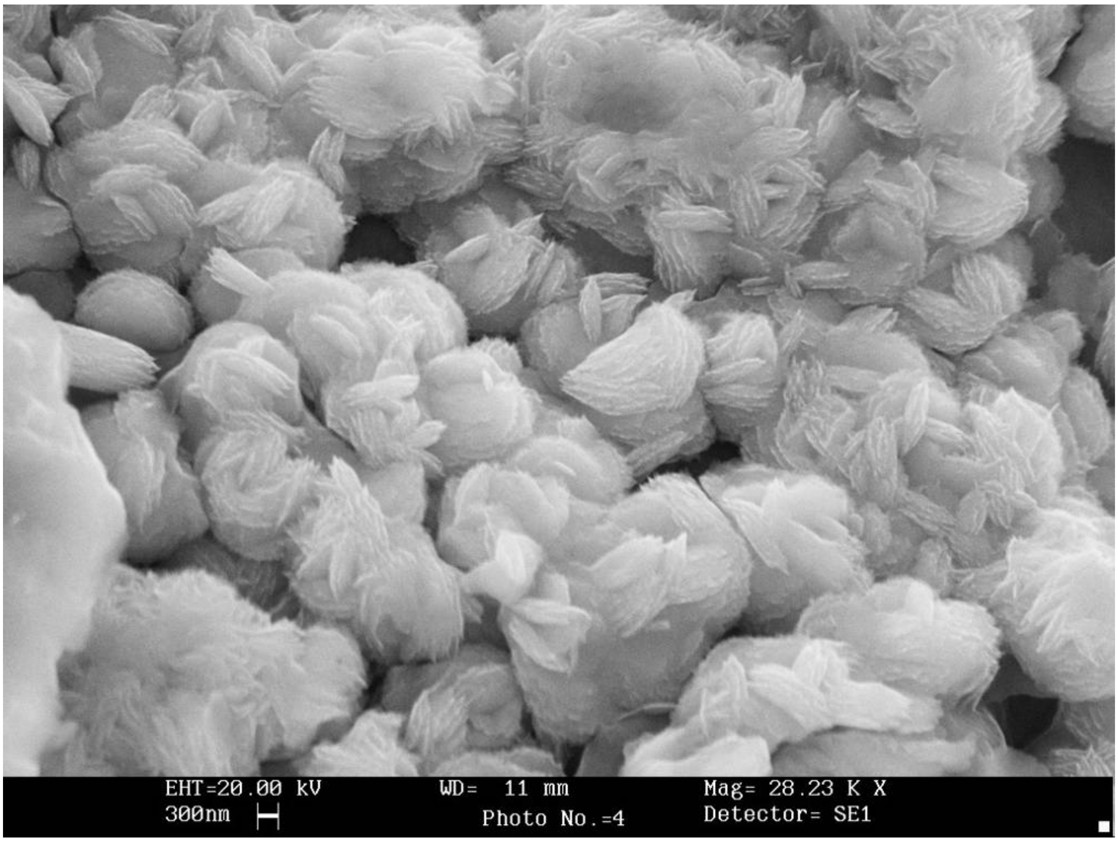

Figure 3.6. Earthy hematite rosettes forming thin linings in voids in the Lower Mottled Clay, 18.6 m above Chalk, Alum Bay, Isle of Wight [SZ 3055 8523]. (BGS electron micrograph No. D822S1/04).

Most of the common yellow-brown and brown ferric oxides, often known as limonite, belong to the goethite species, FeO(OH). It is probably the most common form of oxidised iron in the Reading Formation and is also found in the Upnor Formation. It may be present as a minor or trace mineral and can be found with siderite in the Bradwell Borehole [TM 0530 8507], or with hematite or lepidocrocite at Newbury. Goethite is usually formed as the result of weathering of iron or iron-containing minerals such as pyrite, siderite and glauconite, under oxidising conditions. It may be found in bioturbated material in the clays of the Reading Formation and Upnor Formation, in drying cracks and in root holes. In sands it may be ubiquitous, as in the upper part of the Upnor Formation and the lower and middle part of the Upper Mottled Clay in the Bradwell Borehole BH 202 (BGS borehole TM00NW/27) [TM 0530 8507].

Lepidocrocite, FeO(OH) has the same chemical formula as goethite but a different (γ) structure. It usually dark brown with an 'earthy' texture and is rather uncommon. In the Lambeth Group, lepidocrocite has been found as a minor or trace clay-size mineral in a 2 to 3 m section in the middle part of the Lower Mottled Clay at Newbury and in a sample of Lower Shelly Clay from the Lower Upnor Quarry. It is rarely found in gleyed calcareous soils and infrequently in groundwater gley soils, but is common in surface-water gley soils (Karim and Newman, 1986).

3.3.7 Glauconite

Glauconite is a green potassium iron silicate mineral that imparts the greenish colour typical of the Upnor Formation. It also occurs occasionally in some of the coarser parts of the Reading and Woolwich formations. Glauconite forms as an alteration product of detrital biotite mica or other parent materials, by marine diagenesis in shallow water under reducing conditions; it is characteristic of some sands, sandstones (such as greensand), and impure limestones such as the Zig Zag Chalk and West Melbury Marly Chalk formations of the Grey Chalk Subgroup of Southern England. It forms up to 30% of parts of the Upnor Formation where glauconite grains are of similar size or slightly larger than the quartz grains, between 0.1 to 0.3 mm, and are rounded or subrounded (Figure 3.7). On weathering and oxidation glauconite breaks down to form brown-red limonite or yellow-brown goethite. When fully weathered these sediments are light greyish brown to orange brown, speckled with dark green grains of glauconite, as seen at outcrop.

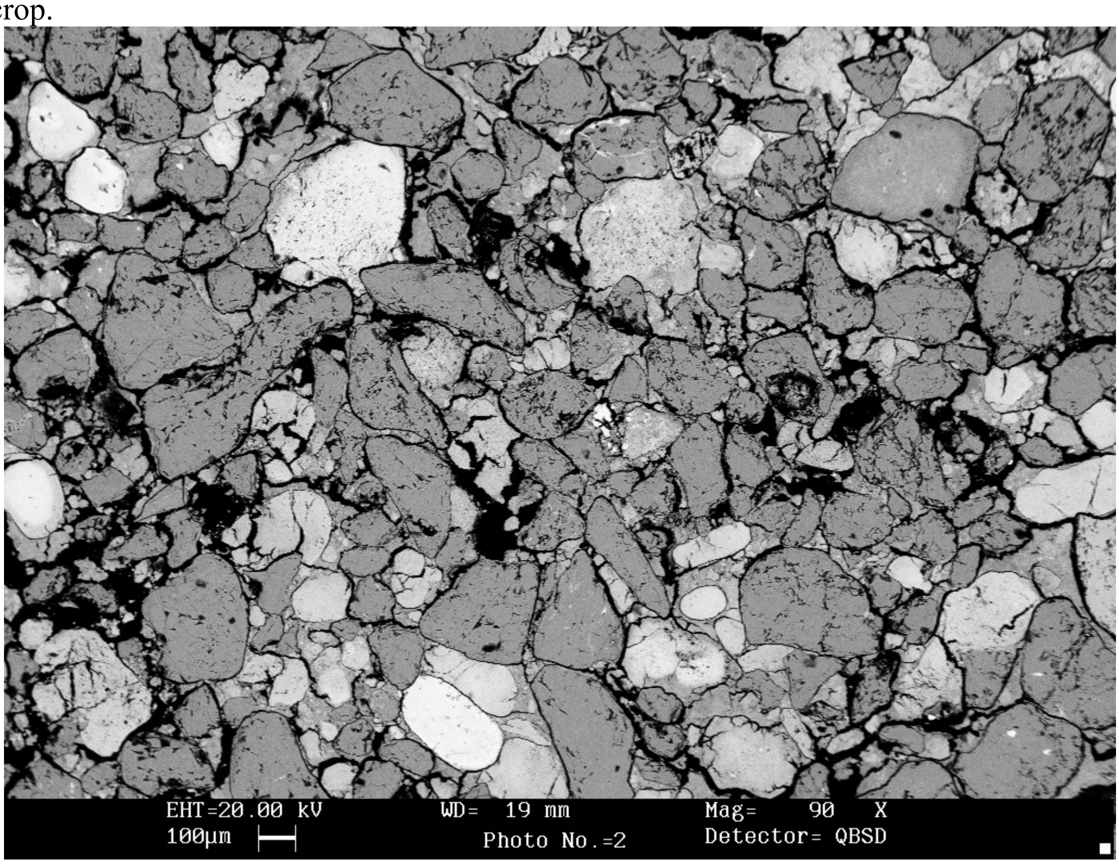

Figure 3.7. Example of the clay-rich glauconitic sands from the Upnor Formation. The glauconite grains, dark grey, are rounded and some have oxidised (pale grey) (BGS borehole TQ37NW/2118, [TQ 33638 79604], 38.01 m). (BGS electron micrograph No. D783P1/02).

3.3.8 Gypsum

Gypsum is not a primary mineral in the Lambeth Group but is formed during modern weathering where pyrite and calcium carbonate are found together, and is most likely to occur in the Upnor and Woolwich formations. Pyrite is typically found in association with sediments deposited in anoxic conditions and often with organic matter that restrict its oxidation (see Section 3.3.6). However, during modern weathering pyrite oxidises to produce sulphuric acid that reacts with calcium carbonate, often derived from shell fragment, producing gypsum. It is likely that all the gypsum in the Lambeth Group is formed in this way:

Pyrite + oxygen + water → Iron II sulphate + sulphuric acid

$$FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4 \quad (1)$$

Sulphuric acid + Calcium carbonate→ Gypsum + water + carbon dioxide

$$H_2SO_4 + CaCO_3 + 2H_2O \rightarrow CaSO_4.2H_2O + H_2O + CO_2 \quad (2)$$

Gypsum may have formed as a part of the sub-tropical weathering process shortly after deposition but, because it is soluble, would have been removed from the near surface by water movement. It is rarely described in the Lambeth Group and there are only a few references to gypsum in the BGS National Geotechnical Properties Database, all associated with the Lower Shelly Clay. In cliffs at Newhaven, Skipper (1999) describes gypsum in a thick lignitic clay bed about 0.80 m above yellow (jarositic) very sandy clay (Figure 3.8). In a section exposed in the Upnor Brick and Stone Quarry at Lower Upnor in Kent [TQ 7590 7110], a lignitic bed at the base of the Woolwich Formation Lower Shelly Clay contains occasional shell moulds and abundant gypsum as selenite crystals. It is likely that these parts of the bed were originally shelly and have now been replaced by the gypsum.

Figure 3.8. Pseudomorphs after gypsum in the Lower Shelly Beds at Newhaven [TQ 7590 7110].

Although gypsum is most likely to form in parts of the Woolwich and Upnor formations it has been seen where reworked calcareous nodules mix with lignite, for instance at the mid-Lambeth Group Hiatus at Alum Bay (Skipper 1999).

3.4 CLAY MINERALOGY

3.4.1 General clay mineral trends and distribution

The clay mineralogy of the Lambeth Group usually comprises smectite, illite, kaolinite and chlorite; mixed layer clays and very rare halloysite have also been identified. A summary of the clay mineral assemblages typically found in the Lambeth Group formations is given in Table 3.1 and outlined below for the London and Hampshire Basins.

Table 3.1. Summary of typical Lambeth Group clay mineralogy

Lambeth Group	London Basin, North and East Hampshire Basin	South and west Hampshire Basin
Upper Woolwich Formation (Upper Shelly Clay)	Mixed clay assemblage with increasing smectite and decreasing kaolinite upwards	Not present
Upper Mottled Clay and lower Woolwich Formation (Laminated Beds and Lower Shelly Clay)	Mixed clay assemblage, smectite, illite and kaolinite	Illite major Kaolinite major Smectite minor increasing at top
Lower Mottled Clay	Smectite dominant or major, Illite major or minor, Kaolinite minor to absent but sometimes locally dominant particularly at top.	Illite major, Kaolinite major, Smectite minor but locally dominant at top, Rare exotic and mixed layer clays
Upnor Formation	Smectite dominant Illite minor Kaolinite minor to absent.	Illite major, Kaolinite major, Smectite minor sometimes major.

3.4.1.1 London Basin

A summary diagram of the relative abundance of clay minerals for samples from Jubilee Line Extension borehole 404T (BGS borehole TQ37NW/2118, [TQ 33638 79604]) is shown in Figure 3.9 and other sites in Figure 3.10 provide a general guide to the clay mineralogy of the London Basin.

The clay mineralogy of the Upnor Formation and Lower Mottled Clay typically contains dominant or major smectite with minor illite, although illite content is usually higher in the north and west in the upper part of the Lower Mottled Clay. Kaolinite is usually a trace or minor component and is often absent in the east Essex area.

Above the major mid-Lambeth Group Hiatus, in the Woolwich Formation and Upper Mottled Clay (see Section 2.3.1), the clay assemblage becomes more mixed. Kaolinite and illite content tend to increase and smectite decreases upwards through Lambeth sequence 3 (lower Woolwich and Upper Reading sequences). In central London illite and smectite tend to have similar contents, whilst chlorite becomes more important.

There is limited data for the Upper Shelly Clay of the Upper Woolwich Formation sequence 4. In central London smectite content increases upwards as illite and chlorite reduce. At the top of the Upper Shelly Clay sequence smectite is the major to dominant clay mineral.

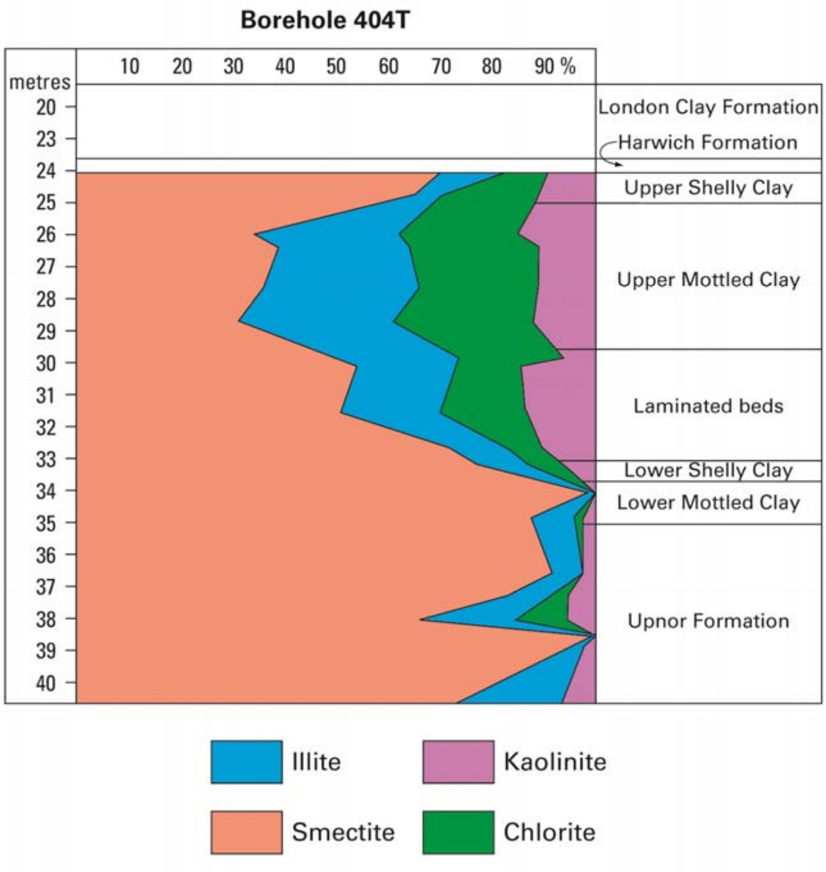

Figure 3.9. Relative percentages of clay mineral for samples from Jubilee Line Extension borehole 404T (BGS borehole TQ37NW/2118 [TQ 33638 79604)].

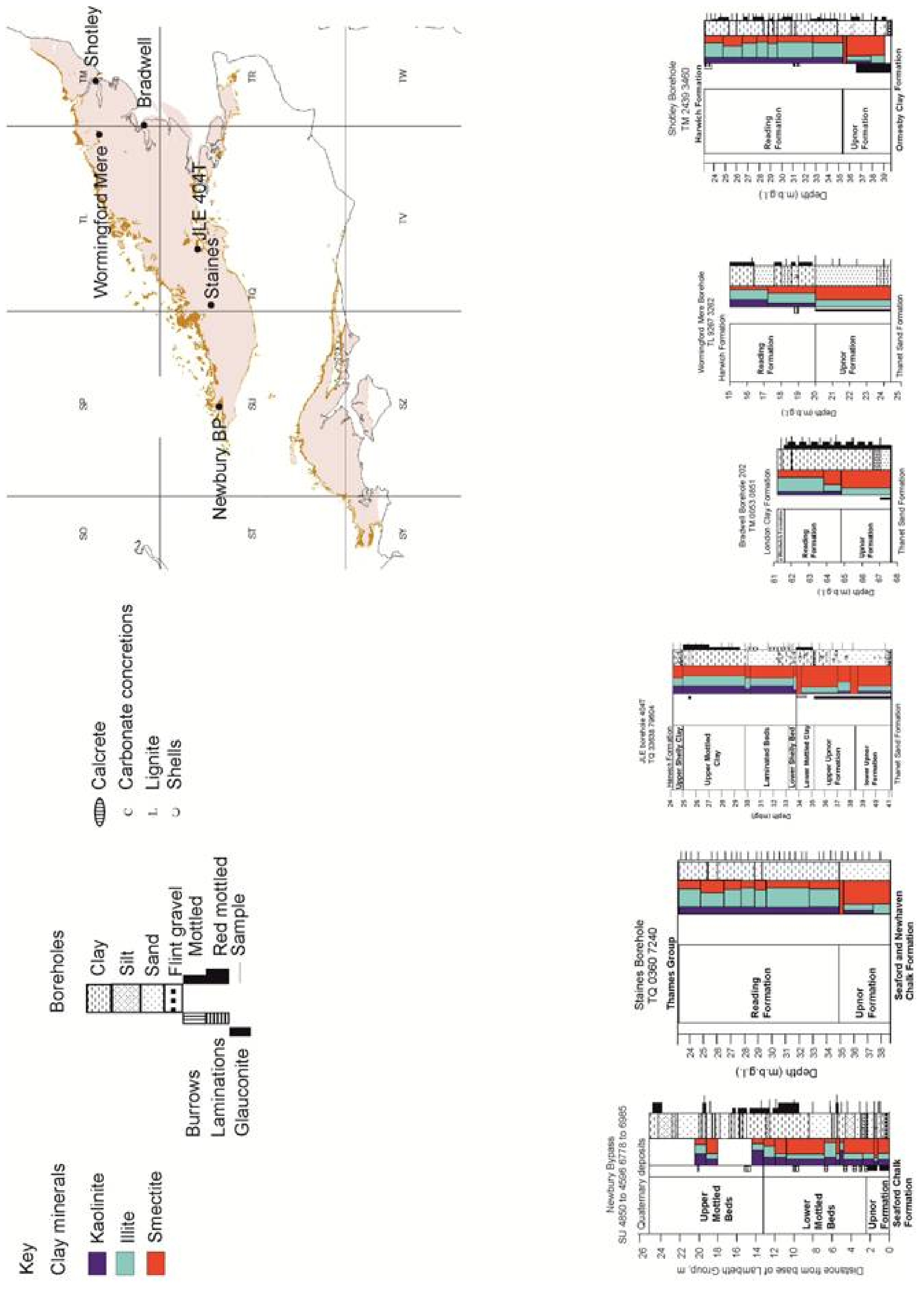

Figure 3.10. Clay mineralogy of borehole core in the London Basin.

The clay minerals of the Hampshire Basin show a general trend of decreasing smectite content to the south west, with the north of the basin being similar to the western part of the London Basin. The Upnor Formation is smectite-dominated with illite and minor kaolinite (Edwards and Freshney, 1987b). The rest of the succession contains major illite with smectite and kaolinite in approximately equal quantities, minor amount of chlorite may also be present. To the south, at Studland and Alum Bay, the Basement Beds contain a mixed assemblage of approximately equal quantities of smectite, illite and kaolinite, or major illite with minor smectite and kaolinite. Above these beds a majority of the succession usually contains major kaolinite with minor illite and smectite. However, in the upper part of the Lower Mottled Clay smectite is the dominant clay mineral with minor or trace kaolinite and illite (Buurman, 1980; Pearce *et al*., 1998). Chlorite is absent or in trace quantities.

In the east of the basin at Felpham, the clay assemblage is more typical of that in the London Basin having high smectite content in the lower part and smectite with illite and kaolinite in the upper part (Skipper, personal communication 1999). This is not surprising as at the time of deposition the north and east of the Hampshire Basin and the London Basin were part of a continuous marginal depositional area.

The simple models of clay mineral distribution described above are general trends. Due to the complex nature of the deposition, pedogenic alteration and the tectonic and volcanic activity during the late Palaeocene detailed studies have shown rapid local and possible regional changes. A good example is Alum Bay, described by Gilkes (1966, 1968), Buurman (1980) and Pearce (1998). Investigating the clay mineralogy of the early Tertiary of the Hampshire Basin, Gilkes (1966, 1968), and analysed nine samples from the cliff section and found them to contain mainly illite and kaolinite with minor or trace smectite. Buurman (1980), studying pedogenesis, analysed forty-five samples including at least one sample from each identifiable bed, apart from the basal unit which was obscured at the time. Most of the results showed a clay mineral assemblage of illite and kaolinite. However, a marked contrast in clay mineralogy occurs within a few metres of the top of the lower Reading Formation. Here, a two to three metre thick mottled clay bed contains increasing quantities of smectite that becomes the dominant clay mineral at the top of the bed. At the top of the Lower Mottled Clay kaolinite is the dominant clay mineral. More recent analysis of samples from this section for this project (Pearce *et al*., 1998) showed a similar smectite peak. A smectite peak also occurs near the top of the Lower Mottled Clay in Central London (Knox, personal communication, 1997).

Rapid changes in the clay mineral assemblage occur elsewhere. At the Lower Upnor Quarry [TQ 757 712] and Orsett Pit [TQ 673 808] the typically smectite-rich Upnor Formation contains a kaolinite-rich zone associated with a palaeosol horizon. In the lower Reading Formation at the Newbury Bypass section the clay minerals change from smectite-rich to kaolinite-rich or illite-rich and smectite-poor within a few metres (Skipper, 1999; Pearce *et al*., 1998).

In the Hampshire Basin, the Bunker's Hill Borehole [SU 3038 1498] contained a very unusual clay mineral assemblage about 3 m above the Upnor Formation, consisting of halloysite with random mixed-layer chlorite-vermiculite and chlorite-smectite.

3.4.2 Detailed clay mineralogy

3.4.2.1 LONDON BASIN

The major London Basin sites are summarised in Figure 3.10.

Essex

Shotley Borehole, Shotley, Suffolk (BGS borehole TM23SW/19, [TM 24390 34600]) (Huggett and Knox, 2006)

The Shotley Borehole (Figure 3.10) contains about 3.3 m of Upnor Formation and the five analyses is dominated by smectite with minor illite and kaolin, which is not present in the lower part of the formation. Smectite content peaks near the top of the Upnor Formation where is comprises nearly all the clay minerals. The Reading Formation is 11.7 m thick and the 26 analyses show that illite is the major clay minerals with minor smectite and lesser quantities of kaolin.

Bradwell Borehole BH202, Bradwell, Essex (BGS borehole TM00NW/27, [TM 0053 0851]) (Bloodworth *et al*., 1987)

The Bradwell Borehole BH202 (Figure 3.10) records about 2.8 m of Upnor Formation comprising a lower 0.7 m of sand and 2.1 m of clay, and 3.2 m of clay from the Upper Mottled Clay (Knox, personal communication, 1997). The lowest part (Upnor Formation) is glauconitic and the clay mineralogy is dominated by smectite with a little illite. Smectite is also the major clay mineral in the lower part of the overlying Reading Formation but illite becomes a more important constituent and kaolinite occurs as a trace clay mineral. In the upper part of the succession, smectite content reduces and illite is the dominant clay mineral with minor quantities of smectite and kaolinite.

Wormingford Mere Borehole, BGS Borehole TL93SW/1 [TL 9267 3262] and Bures Borehole, BGS borehole TQ05SE/2 [TL 9120 3399] (Ellison *et al*., 1986).

The Wormingford Borehole and Bures Borehole (Figure 3.10) record a lower bed (4.4 and 4.5 m thick respectively) comprising green and red mottled glauconitic clayey fine to medium sand of the Upnor Formation. Above is about 5 m predominantly of stiff to very stiff, red to purple, with vertical veining and mottles of orange and pale greyish blue clay with silt beds and sandy silt beds of the Reading Formation. The clay assemblage of the Upnor Formation is dominated by smectite, which becomes significantly less abundant in the overlying Reading Formation where illite is the dominant clay mineral. Kaolinite, rarely present in the Upnor Formation, becomes more common further up the Reading Formation succession, in conjunction with decreasing smectite.

BGS Dowsetts Farm Borehole, BGS Borehole TL32SE/38 [TL 3806 2079] (Moorlock and Highley, 1991)

During an appraisal of fuller's earth resources in England and Wales, Lambeth Group samples from the BGS Dowsetts Farm Borehole at Colliers End, Essex were initially tested for whole rock specific surface area using the 2-ethoxyethane method (Carter, 1965). As a part of this assessment those samples with specific surface area values of greater than 240 m^2/g, inferring a smectite content of >30%, were examined by X-ray diffraction analysis. Only clays were analysed. The highest specific surface areas were present in the lower part of the Lambeth Group, that is in the clay facies of the Upnor Formation and the lower part of the Reading Formation, indicating dominant or major smectite. X-ray diffraction analyses confirmed major smectite and low or trace quantities of illite and kaolinite.

Chiltern Hills (Bateman and Moffat, 1987)

Bateman and Moffat (1987) carried out a study of the petrography of the Lambeth Group of the Chiltern Hills to the north and north west of London, including a number of outliers. They describe the clay mineralogy of thirteen samples from ten sites. Most of the exposures sampled were small, shallow (<3 m) and degraded, although some were from brick or sand pits. The samples were classified as '*Bottom Beds'*, '*Sand*' or '*Clay*'; the former are from the Upnor Formation and the other two are from the Reading Formation but it is not possible to identify which part of the where in the Reading Formation they come from. Of the four samples identified as from the 'Bottom Beds', most contained major illite with minor "expansibles". Kaolinite was a minor or trace mineral. The "expansibles" were vermiculite, mixed layer illite-smectite or vermiculite/smectite. Only one sample contained the more typical smectite>illite>kaolinite clay assemblage. The 'clays' from the Reading Formation contained major smectite and sometimes with mixed layer smectite-vermiculite or other mixed layer clay. Illite was present as a minor or trace mineral and kaolinite as a trace component.

The six 'sand' samples were more varied with major illite, kaolinite or smectite and little or no vermiculite. A sample from Hedgemoor [SU 977 944] contained no smectite.

Central London

Channel Tunnel Rail Link (CTRL) Borehole A2, BGS borehole TQ38SW/2201, [TQ 3296 8051] and Jubilee Line Borehole 404T, BGS borehole TQ37NW/2118 [TQ 3363 7960], (Knox, personal communication, 1997)

The clay mineralogy of the <4 μm fraction of the two Lambeth Group reference sections in London, the Channel Tunnel Rail Link (CTRL) Borehole A2 and Jubilee Line Borehole 404T, show similar trends. Borehole 404T is more complete (Figure 3.9 and Appendix 1) and records an approximately 17 m thick sequence comprising all the main units of the Lambeth Group, ranging from the lower and upper Upnor formations through to the Upper Shelly Clay of the Woolwich Formation. The clay mineral assemblage of the lower and upper Upnor Formation and the Lower Mottled Clay (Lambeth sequences 1 and 2) are dominated by smectite, usually with minor quantities of illite and smaller amount of kaolinite. Chlorite is sometimes present. Above, in the Upper Mottled Clay and Lower Shelly Clay and Laminated Beds (Lambeth sequence 3), there is a reduction in smectite content and an increase in illite and kaolinite. Smectite content again increases in the Upper Shelly Beds (Lambeth sequence 4).

Staines borehole, Staines, Surrey, (BGS borehole TQ07SW/156, [TQ 0360 7240] (Huggett and Knox, 2006)

The Staines borehole was considered to contain less than 1 m of Upnor Formation and 21 m of Reading Formation Figure 3.10. The single sample tested form the Upnor Formation contain major illite with minor quantities of smectite and kaolin. The 45 analyses on 21 m of Reading Formation shows that the lower and middle part is dominated by illite with minor smectite, kaolin and chlorite. However, 3 m horizon within the upper part contains only smectite only Above, smectite and illite are major clay minerals with minor kaolin.

Newbury Bypass (Pearce *et al*., 1998; Huggett and Knox, 2006)

A lithological and mineralogical correlation of a composite section of a cutting through the Lambeth Group at the Newbury Bypass site is presented in Figure 3.10. The lower part of the section was sampled in detail whereas there were few samples taken in the upper part.

The Lambeth Group in the Newbury Bypass section is approximately 25.5 m thick and comprises about 2.5 m of Upnor Formation sands and clays overlain by about 11 m of Lower Mottled Clay and 12 m of Upper Mottled Clay of the Reading Formation. The major clay mineral is usually smectite with minor or trace illite and kaolinite. However, there are parts of the sequence that contain major illite or kaolinite and these occur more commonly within the Upper Mottled Clay. The exceptions are below.

Starting about 3.5 m above the top of the chalk, is the base of a 0.8 m coarsening up sequence. The silty clay contains major smectite, whereas the flaser-bedded sand, silt and clay at the top of the sequence contains major kaolinite with minor illite and trace smectite. About 4.9 m above the top of the chalk is 2 m thick pale grey sand channel infill. About 0.5 m above the base the infill the sample contained major illite with minor kaolinite and trace smectite, but at the top of the sand body smectite was the major clay mineral. Smectite content tends to decrease towards the top of the Lower Mottled Clay. Only three samples were collected above the mid-Lambeth Group Hiatus, in the Upper Mottled Clay, only three samples were collected. Just above the hiatus a sample of mottled grey and light yellowish brown clay contained major kaolinite with minor smectite and illite. A sample of brownish orange sandy clay nearly six metres above the previous sample contained major smectite with minor kaolinite and illite and 0.8 m above, brown sandy clay contained major illite and kaolinite with minor smectite.

3.4.2.2 HAMPSHIRE BASIN

The major Hampshire Basin sites are summarised in Figure 3.11.

Coastal sites

Studland Bay, Dorset [SZ 044 824] (Gilkes, 1966, 1968)

The lower part of the Lambeth Group at Studland Bay was studied by (Gilkes, 1966, 1968). This part of the sequence equates to the basal fluvial glauconitic sands (possibly reworked Upnor Formation) and iron cemented sands, pedogenically altered sands and silts and fluvial channel sands, Lower Mottled Clay (Skipper, 1998). The lower fluvial sands contain approximately equal quantities of smectite, illite and kaolinite. Smectite is the main clay mineral at the base of the pedogenically altered sands and silts with minor illite and kaolinite. However, in the upper part of these silts the clay mineralogy is similar to the basal beds. In the lower part of the fluvial channel sands the only reported clay mineral is mixed layer illite-smectite. The rest of these sands comprise illite and kaolinite with trace or no detectable smectite.

Whitecliff Bay, Isle of Wight [SZ 4639 8580 to 4639 8585] (Gilkes, 1966, 1968; Huggett and Knox, 2006).

Eight samples tested by Gilkes (1966, 1968) from Whitecliffe Bay from the Reading Formation were all dominantly illite and kaolinite with minor amounts of smectite and occasional trace chlorite. Smectite content increases in the uppermost beds. The fourteen samples from the 34.5 m exposure reported in Hugget and Knox (2006) (Figure 3.11) was generally dominated by illite with moderate amounts of smectite and kaolin with rare chlorite. Within the upper part of the succession smectite was absent with increased illite content.

Alum Bay, Isle of Wight (Gilkes, 1966, 1968; Huggett and Knox, 2006; Buurman, 1980; Pearce *et al*., 1998; Skipper, personal communication, 2003)

Alum Bay provides probably the best cliff exposure of Reading Formation deposits and because of this has been studied by a number of workers. The cliff exposes a c. 41 m sequence of Upnor Formation sands (up to 2 m thickness at the cliff base) overlain by c. 19 m of Reading Formation Lower Mottled Clay and c. 20 m of Upper Mottled Clay. Gilkes (1966, 1968) tested nine samples and found that the clay mineral assemblage consisted mainly of illite and kaolinite with minor amounts of smectite and occasional traces of chlorite. Buurman (1980) took forty-five samples at Alum Bay to investigate the palaeosols of the Reading "Beds" but did not sample the pedogenically altered sands at the base. X-ray analyses, carried out on less than 1 μm fractions, showed results similar to those of Gilkes, that is most of the sequence is dominated by illite and kaolinite with smectite a minor or trace mineral and often absent from the lower 10 m; chlorite is also occasionally present as a trace mineral. However, almost half way up the sequence, in a zone containing a ferricrete, kaolinite is the dominant clay mineral and illite and smectite are absent or present as only minor constituents. This coincides with the top of the Lower Reading Formation and the lowest part of the Upper Reading Formation (Skipper, 1998). The smectite content appears to be cyclic (Figure 3.11). In the lower 10 m there is a low amplitude increase and decrease in smectite, that is, from absent to trace to absent. Above is an approximately 5 m cycle where smectite becomes a minor to a trace constituent. In the next 3 to 4 m smectite increases to become the dominant clay mineral corresponding to a marked decrease in illite content. In the ferricrete zone, smectite and illite contents reduce to either trace or absent constituents in contrast to a marked dominance of kaolinite. For 17 m in the Upper Mottled Clay above the kaolinite-dominated ferricrete zone, smectite again forms a minor component with illite. In the upper 3 m of this sequence smectite content increases until it becomes the major clay mineral.

Pearce *et al*. (1998) report on twenty-two samples tested from the Alum Bay coastal section Skipper (personal communication, 2003) on twelve samples and Huggett and Knox (2006) eight analyses. These three sets of analyses found similar trends to Buurman (1980), although Pearce found greater proportions of kaolinite and Skipper found more smectite throughout.

<u>Felpham, Sussex</u> [SZ 942 989] (Skipper, Personal communication, 2003)

At Felpham the clay mineralogy of the Upnor Formation is dominated by smectite with illite and kaolinite as trace or minor clay minerals in the upper part of the formation. Within the Lower Mottled Clay smectite is the dominant or major clay mineral with minor illite and kaolinite. However, near the top of this unit smectite again becomes dominant. The lower Woolwich Formation, represented by the 'Felpham lignite bed' (Bone, 1986) contains a lower clay with sphaerosiderite and upper lignitic clay has major smectite, and minor illite and kaolinite. The Upper Mottled clay has major illite with minor smectite and kaolinite. Chlorite is occasionally present in the upper half as a minor or trace mineral.

<u>Newhaven</u> [TQ 444 000] (Pearce *et al*., 1998).

Two samples from the cliff at Newhaven were analysed as part of the present study, one from the sandy clay above the ferricrete zone and the other from a gypsiferous, dark brown silty clay with rootlets (Lower Shelly Beds). The lower sample contained major illite with minor smectite and trace kaolinite whereas the upper sample contained major smectite with minor kaolinite and illite.

Inland sites

<u>Bunker's Hill Borehole, BGS borehole SU31SW27</u> [SU 3038 1498] (Edwards and Freshney, 1987b)

The sequence recorded for the Bunker's Hill Borehole (Figure 3.11) consists of a basal c. 2 m thickness of Upnor Formation sands overlain by c. 22 m of Reading Formation deposits. The basal Upnor sequence is smectite-dominated with minor illite. Two metres above the Upnor Formation boundary the lower Reading Formation sequence comprises a 3 to 4 m thick layer of atypical clay minerals dominated by halloysite with minor or trace quantities of mixed layer chlorite-vermiculite and chlorite-smectite. Halloysite is commonly found in the tropical residual red clays of East Africa. This unusual clay mineral assemblage may represent the product of subtropical weathering of volcanic ash. Above this assemblage illite is the main clay mineral with minor smectite and kaolinite, and trace chlorite. However, over a 2 m zone at the top of the borehole kaolinite reduces to a trace or minor component with trace chlorite accompanied by a corresponding increase in smectite content within the still illite-dominant assemblage.

Shamblehurst Lane Borehole, BGS borehole SU41SE336, [SU 4927 1456] (Edwards and Freshney, 1987b)

The clay mineralogy of the Reading Formation, Lower and Upper Mottled Clay from the Shamblehurst Borehole (Figure 3.11) is a consistent assemblage comprising major illite with minor smectite and kaolinite and occasional minor amounts of chlorite and/or vermiculite.

Knowl Manor brick pit [SY 973 975]

The precise stratigraphic positioning of Reading Formation samples from the sand and brick pit sites at Knowl and Michelmersh is unclear. However, the clay mineralogy of two samples tested from the Knowl Manor pit contained major kaolinite with minor illite and minor or trace smectite.

Michelmersh Brick Pit [SU 345 259]

The only sample acquired from the Michelmersh pit contained major smectitic with minor illite and kaolinite.

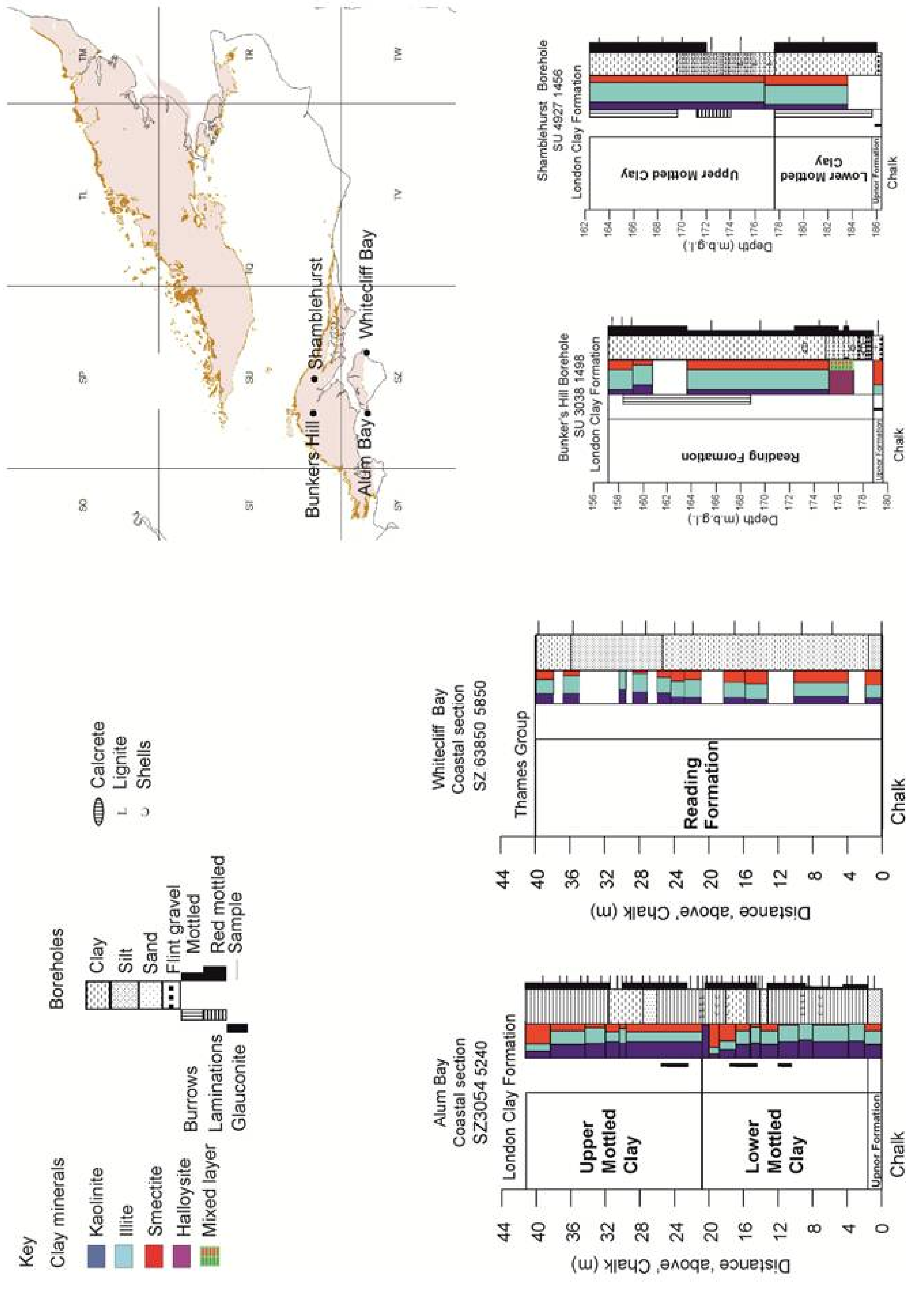

Figure 3.11. Clay mineralogy of boreholes and natural sections in the Hampshire Basin.

3.5 ORIGIN OF THE CLAY MINERALS.

The major clay minerals of the Lambeth Group are probably mainly detrital in origin. Illite and chlorite were mostly derived from the erosion of rocks and subsequent redeposition, although chlorite may also be derived from the alteration of fine-grained volcanic material (Knox, 1996a). The other two major clay minerals, smectite and kaolinite, are also detrital but were formed by the contemporaneous weathering and alteration of other minerals.

Gilkes (1969) considered the origin of the two clay mineral assemblages he encountered: the illite-kaolinite suite with little or no smectite or chlorite, and the smectite-illite suite with lesser quantities of kaolin and minor amounts of chlorite. The former could be considered as typically non-marine, and the latter as marine. However, the presence of smectite in non-marine samples indicates that this is not always the case. He concluded that the distribution of the clay minerals showed a clear geographical influence, with illite-kaolinite sediments in the west and illite-smectite in the east. He further suggested that this reflected two different sediment sources - . the kaolinite-rich material being derived from granitic rocks of the Cornish Massif (with variation in kaolinite content thought to be due to the degree of tropical weathering and erosion), and the smectite-rich sediments being derived from the Chalk (from the insoluble fraction produced after erosion and dissolution in a wet sub-tropical climate). Smectite formed from altered ash was considered to be of minor importance.

Volcanic ash deposits are now well documented within the North Sea and in the Thanet Formation and Ormesby Clay Formation below the Lambeth Group, and in the Thames Group above. Knox and Harland (1979), Knox and Morton (1983, 1988) and Jolley and Morton (1992) identified two major phases of explosive volcanism within this area. Phase 1 (mid Palaeocene) occurred during the deposition of the Thanet and Ormesby Clay formations. The smectite-rich clay facies of the Ormesby Clay Formation comprises clays of very high to extremely high plasticity with liquid limits up to 172% and plasticity indices up to 116% (Cox *et al*., 1985). Phase 2 occurred during the latest Palaeocene to earliest Eocene. Phase 2.1, the least active phase, probably correlates to the lower half of the Lambeth Group but may also include the Lmb-3 sequence (upper Reading and lower Woolwich formations) (Knox, 1996a). After a period of limited pyroclastic activity volcanism resumed in phase 2.2 and is recorded in volcanic ash bands of the Harwich Formation and lower part of the London Clay Formation. Ash layers have not been observed in the Lambeth Group. However, smectite is usually the dominant or main clay mineral in the lower part of the Lambeth Group below the mid-Lambeth Group Hiatus within the London Basin and parts of the Hampshire Basin. The smectite is probably derived from the reworking of volcanic ashes that were deposited, eroded and altered, and subsequently redeposited. Other evidence for a pyroclastic origin for the smectite comes from the presence of the halloysite clay assemblage in the Bunker's Hill Borehole, which is thought to have formed by *in situ* subaerial weathering of underlying volcanic material, probably ash (Edwards and Freshney, 1987b). However, no evidence for a direct volcanic origin has been found during mineralogical or scanning electron microscope investigations.

Two smectite peaks are present in the sample test data from borehole JLE404T, one in the Upnor Formation and the other in the Reading Formation, Lower Mottled Clay. The latter may correlate with those from the CTRL A2 borehole and Alum Bay. This peak may be due to a short-term increase in pyroclastic activity. However, this correlation must be considered as circumstantial because regional and local erosion events and deposition rates were probably different. The likely source of the pyroclastic material is the Greenland-Faeroes Province (Knox, 1996b).

Kaolinite in the Lambeth Group was formed as a result of rock weathering during moderate to high climatic temperatures (10 – 20 °C) with abundant or seasonal precipitation as indicated by palaeobotany data (Wolfe, 1980). Leaching of the host rock in this climate produces residual soils rich in clay minerals of the kaolin group along with iron and aluminium sesquioxides. Quartz is usually unaffected and remains, in general, as sand grains. In favourable conditions these residual soils may be 40 to 50 m or more thick. Kaolin may have formed *in situ* or transported from the weathered rock of the hinterland. Contemporaneous deep-sea sediments from the central North Sea show trends of higher kaolinite content in deposits of similar age to the Lambeth Group above the mid-Lambeth Group Hiatus. Equivalent deposits to the Upnor Formation contain no or little kaolinite (Knox, 1996a). Evidence from scanning electron microscopy shows that the majority of the kaolinite is very fine grained and intimately mixed with the other clay minerals, lending support to a purely detrital origin. The higher quantities of kaolinite in the south and west of the Hampshire Basin are probably derived from sub-tropical weathering and erosion products of granites in southwest England (Cornubia) and northwest France (Amorica).

However, there are some anomalous, discrete layers of kaolinite-rich materials that occur in otherwise smectite-rich deposits, for example in the Upnor Formation at Upnor, Kent. A sample from the Upnor Formation in the Upnor pit (UQ3, pale grey clayey sand) contained predominantly kaolinite with trace smectite and no illite. This sample was from just beneath a soil horizon and it is, therefore, likely that kaolinite formed *in situ* by pedogenesis during a period of near surface sub-tropical weathering in a relatively freely draining soil. There is also some evidence for the *in situ* formation of kaolinite for example in the upper part of the Lower Mottled Clay in the Alum Bay succession and at a site near the M40. Samples from these sites show rare delicate 'booklets' of kaolinite (Figure 3.12 and Figure 3.13). These delicate forms are unlikely to survive erosion and deposition and are considered to have formed *in situ*. Note that in both cases the kaolinite 'books' are silt-size and well developed and are likely to have developed by alteration of detrital micas (Psyrillos *et al*., 1999) during pedogenesis.

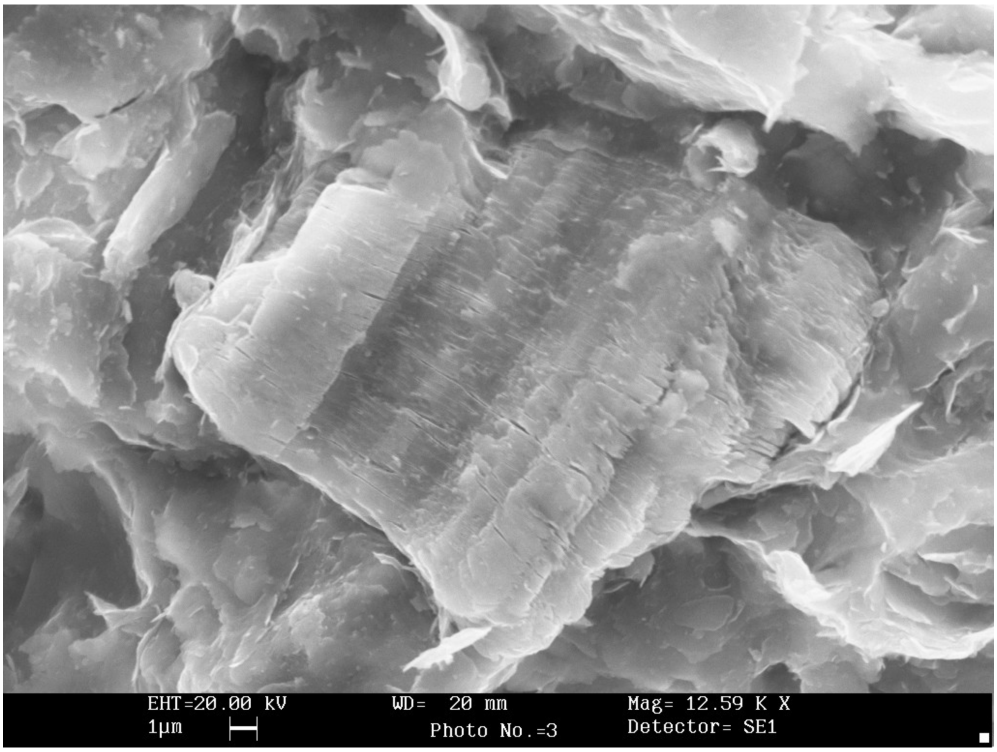

Figure 3.12. A rare, well developed silt-size kaolinite 'book' within the clay matrix of major kaolinite and minor smectite and illite of the Reading Formation from a site on the M40 [SU 947 895]. (BGS photomicrograph No. E444S1/03).

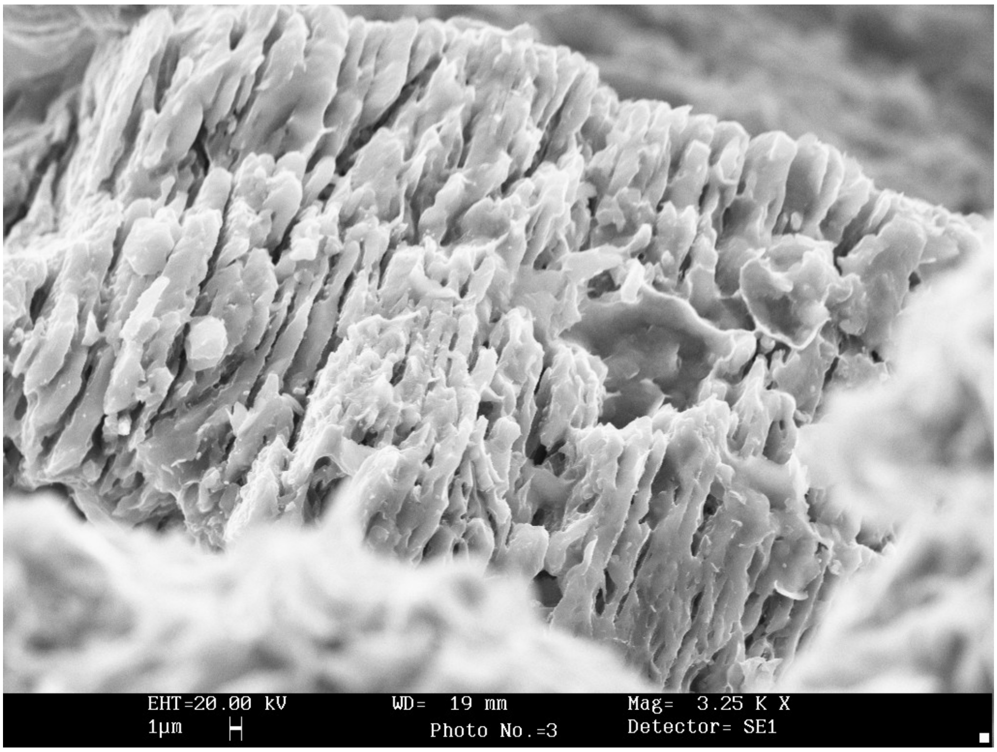

Figure 3.13. Rare, silt-sized corroded silt-size kaolinite 'book' from the Lower Mottled Clay, Alum Bay, Isle of Wight, 17.6 m above the Chalk. (BGS photomicrograph No. D821S1/03).

The contrast in smectite distribution between most of the Lambeth Group and the south and west of the Hampshire Basin is probably due to the distance from the pyroclastic source, the pathway of deposition and the rate of deposition. In the London Basin the source of the Upnor Formation sediments was mainly the Mesozoic rocks of the Midlands or the equivalent rocks of Mainland Europe with some reworking of the Lambeth Group (Hallsworth, 1994). The lower Woolwich and upper Reading Formation deposits have some different mineral characteristics, including a restricted garnet suite, in comparison with the lower Lambeth Group that indicates other sources of sediments, such as the Armorican or Cornubian massifs plus material from the Midlands. The rocks in the south and west of the Hampshire Basin are probably derived from the Amorican and Cornubian Massifs, whereas those to the north and east are similar to those in the London Basin.

Dramatic changes in the clay mineralogy may occur during the mid-Lambeth Group Hiatus or after erosional events, particularly if the new material source is from a different area or a different type such as continental or marine, or weathered differently. Also, biogenic activity mixes sediments from different origins and may also result in different clay mineral assemblages.

3.6 PEDOGENIC ALTERATION

The Lambeth Group, in particular the Upnor Formation and the Reading Formation, have undergone alteration. As described above, mottling indicates penecontemporaneous tropical weathering. Buurman (1980) identified such soils as pseudogleys. The iron of these soils is mobilised in the ferrous state during periods of high water table and after moving a short distance, it precipitates and re-oxidises when the water table falls (Duchaufour, 1982). This forms rusty patches or concretions and grey or yellowish bleached patches, which give a mottled appearance. The transition between the two colours can be sharp or gradual. The iron compounds and the resulting colour depend on the degree of hydration. Periodic wetting and drying may lead to the alteration or the decomposition of clay minerals; however, the *in situ* alteration of the clay minerals appears to be limited, partly because the low permeability of the clay facies restricts the movement of ions. Alteration of minerals in the clays is generally restricted to near contemporaneous bioturbated parts, such as in or near burrows or old root holes, and shrinkage cracks and may go down a metre or more below surface. Examples of root holes from the Upnor Formation include open holes (Figure 3.14) with clay particles aligned or infilled with well-sorted clean sand (Figure 3.15). The former is an open root hole with clay particles aligned around the root channel in the Upnor Formation at the Newbury Bypass site. The latter is a section through a root channel filled by well-sorted clean sand grains in the Upnor Formation at Orsett Quarry. Pseudogley soils are usually restricted to landscapes of low relief.

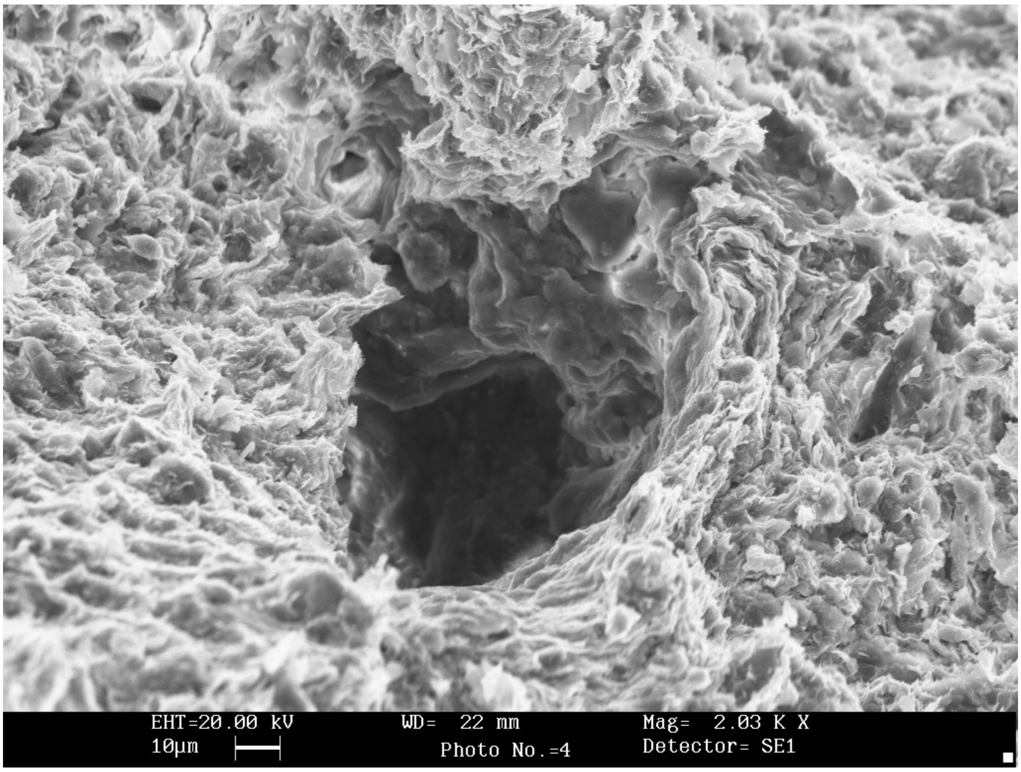

Figure 3.14. Open root channel with clay particles oriented around channel wall. Upnor Formation, Newbury Bypass, 1.5 m above Chalk. (BGS photomicrograph No. E431S1/04).

The following sequences of processes were identified by Buurman (1980):

1) Sedimentation, sometimes with reworking of the top of the underlying sediments;

2) Emergence, drying, consolidation, burrowing cracking and structural formation, with the segregation of iron along root holes. In better drained soils the clays are mobilised, forming oriented bodies, resulting in horizons of dense clay accumulations;

3) Segregation of iron when the soil is saturated;

4) Submergence producing accumulations of pyrite in former root holes, voids and sites containing organic material. This may have occurred during periods of rising groundwater and a new sedimentation phase;

5) Oxidation of pyrite.

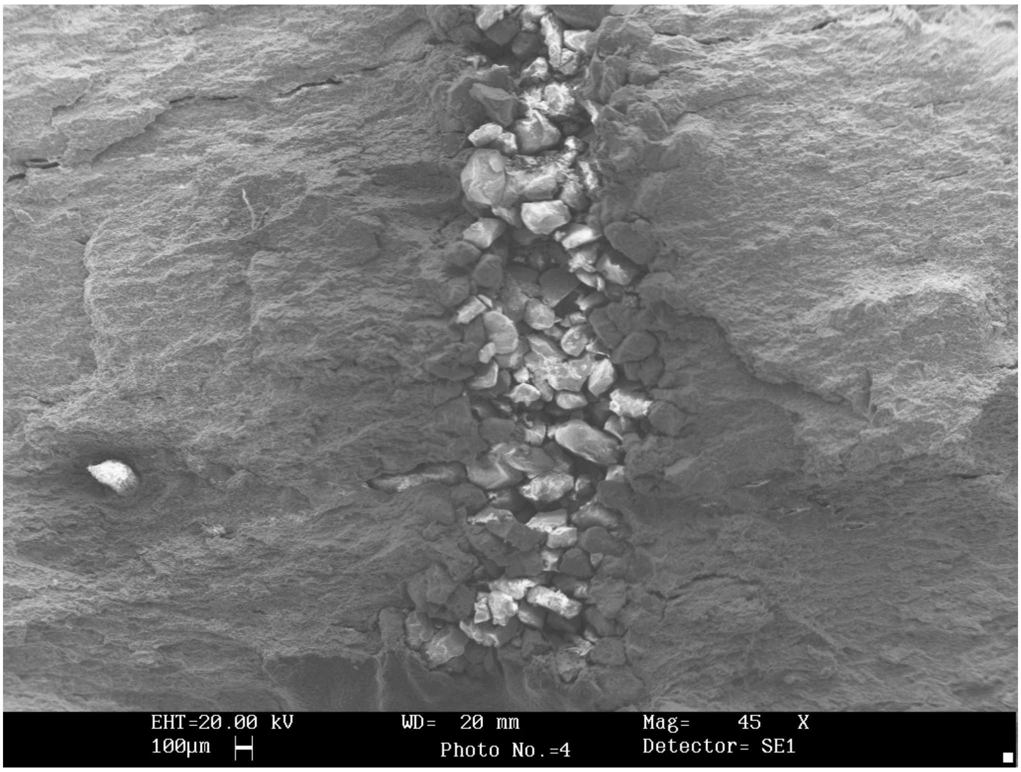

Figure 3.15. Root channel infilled with sand with clay particles oriented around channel wall. Upnor Formation, Newbury Bypass, 1.5 m above Chalk. (BGS photomicrograph No. E431S1/04).

This sequence is repeated many times. The oxidation of pyrite may occur during any subsequent phase of emergence. Different minerals are produced by different rates of oxidation. Hydroxides are produced by slow oxidation and jarosite during rapid oxidation. The dominance of pseudogley features indicates terrestrial conditions. This sequence probably originated in an environment of intermittent sedimentation and soil formation. Most of the beds of the Reading Formation at Alum Bay show alteration due to pedogenesis, indicating that for most of the time the soil formation kept pace with sedimentation and that sedimentation was slow. The soils also show a pattern of increasing degrees of soil development that occurred during periods of falling base level/water table. These soils were probably deposited as overbank fines in a floodplain environment. They were seasonally waterlogged but as the water table or base level fell, leading to increasing emergence, a degree of soil development occurred (Skipper, 1999).

3.6.1 Hard Bands

The Lambeth Group is a Tertiary deposit and has not been buried to any great depth after deposition nor has it been greatly altered by tectonic activity; it is considered that most of the hard bands were formed during periods of subaerial exposure and changes in the height of the phreatic surface (water table or perched water table). Different hard beds normally tend to be limited by both stratigraphy and area.

Three types of hard bands are encountered, iron oxide-cemented (ferricrete), calcium carbonate-cemented (calcrete), and silica-cemented (silcrete). However, not all the hard bands were formed by significant post depositional mineral dissolution, movement and precipitation. Shelly bands, notably in the Lower and Upper Shelly Clay, may form local limestone bands; for example. The fresh water “Paludina Limestone” of the Upper Shelly Clay is one of the more persistent biogenic limestones. Cemented shell layers can be seen in the cliff section at Newhaven. These limestones may have undergone some recrystallisation producing a stronger, more coherent rock.

The hard bands formed by pedogenesis are generally found in the upper part of the Upnor Formation, particularly where it was at or near the surface during the mid-Lambeth Group Hiatus, and the upper metre or so of Lower Mottled Clay. Iron, carbonate and silica cements occur in many other parts of the Lambeth Group and occasionally form coherent hard beds. Although most of the hard bands are of a specific type a combination of cemented material can sometimes occur. For example Figure 3.16 shows alteration of clays of the Lower Mottled Clay to form silica along with the formation of calcite concretions and pervasive iron oxide staining.

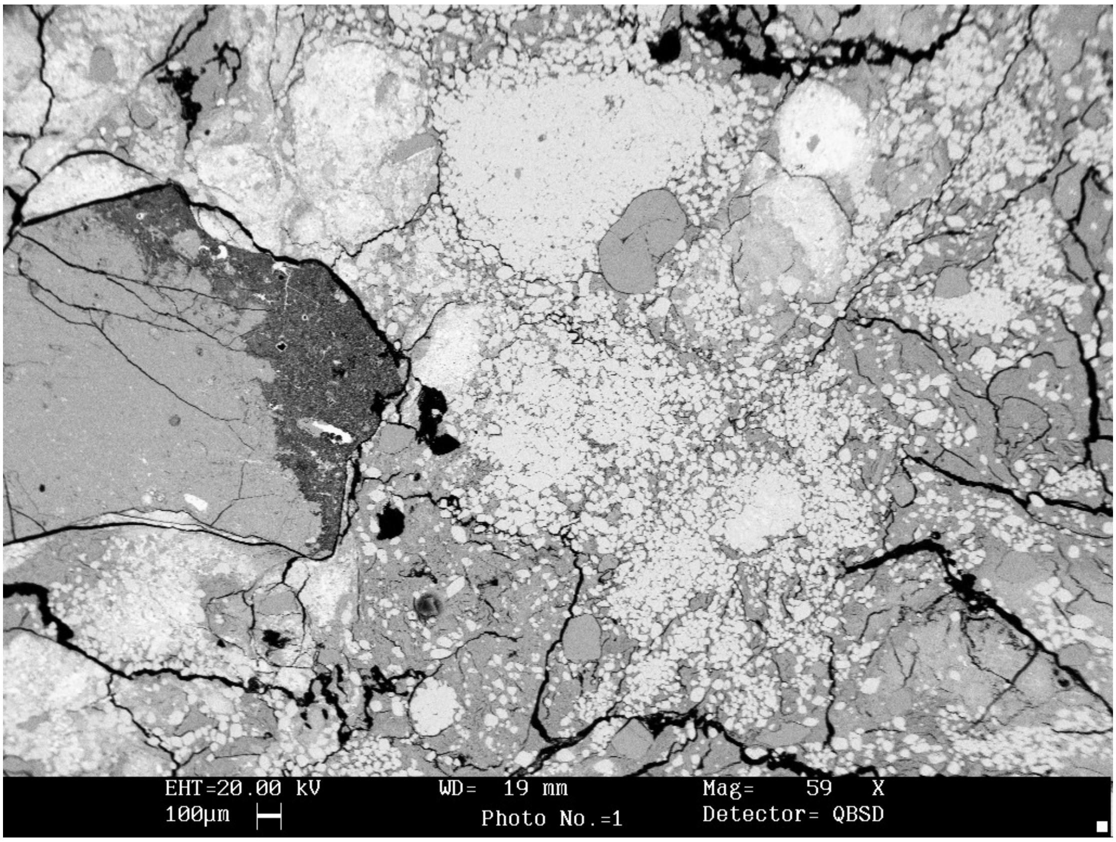

Figure 3.16. Heavily altered clay from the Lower Mottled Clay. The original clay has been patchily altered to leave a siliceous matrix (dark grey) and is pervasively stained by iron oxide (light grey). Calcite rhombs (mid grey) form concentrations. Sample JLE 404T, 34.20 m.b.g.l. (BGS photomicrograph No. D777P1/01).

3.6.1.1 CALCIUM CARBONATE AND CALCRETE

Calcium carbonate nodules are present in parts of the Upnor and Reading formations. They coalesce into more coherent cemented beds (calcrete) up to 1.6 m thick in the Upnor Formation, where the overlying Lower Mottled Clay is thin, and in the Lower Mottled Clay in central and east London. Calcareous nodules are also seen near Arundel in the Hampshire Basin. In east London calcite veins are present in the clays of the Lower Mottled Clay and described in ground investigation reports as very weak to weak mottled green-grey, purple grey and brown mudstone. The calcretes and calcareous nodules vary between very weak to moderately strong, brown, light grey brown, bluish-grey, grey or white, sometimes crystalline limestone. Calcretes may have been more widespread and a possible precursor to silcretes such as the Hertfordshire puddingstones, which were then altered to silcretes as conditions changed (Skipper, 1999).

Core from the Jubilee Line Extension (BH JLE 404T) contained two zones of calcrete, one near the top of the Upnor Formation and the other in the Lower Mottled Clay, which is about 1.30 m thick. The calcrete in the Upnor Formation is about 0.30 m thick as shown in Figure 3.17.

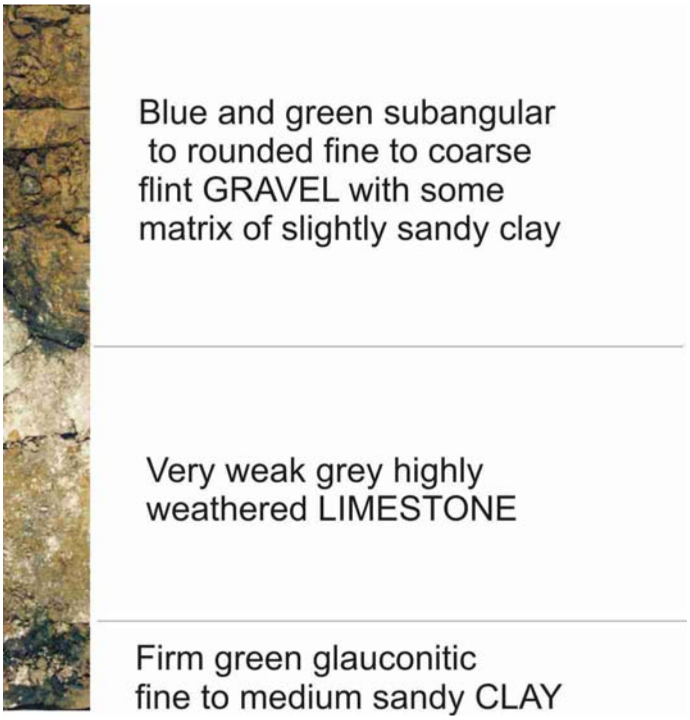

Figure 3.17. Core from the Upnor Formation with the description showing a calcrete, described as highly weathered limestone. Borehole JLE 404T (TQ 3363 7960), 35.30 to 36.00 m.b.g.l.

Accumulations of calcium carbonate usually exhibit a dense, continuous micritic groundmass. Different areas of the nodules contain different densities or size of calcite crystal creating a mottled fabric and the growth is dispersive (Wright, 1990). Figure 3.18 shows pyrite and calcite concretions from the upper part of the Upnor Formation that may have replaced the original clay matrix. The presence of calcite, pyrite and fractured quartz crystals indicates that the calcrete must have formed in anoxic conditions of high alkalinity. A mechanism for grain breakage associated with calcareous concretions indicates rapid crystallisation from calcium carbonate saturated water (Skipper,1999). The structure of an Upnor Formation calcrete nodule from Limehouse, London (TQ 362 809), shows equant calcite crystals (Figure 3.19), which is consistent with a freshwater environment. Occasional quartz crystals in a calcite matrix indicates an expanded detrital grain framework where the quartz has been pushed apart by the formation of the calcite (Figure 3.20), indicating that the formation of the calcite was near surface.

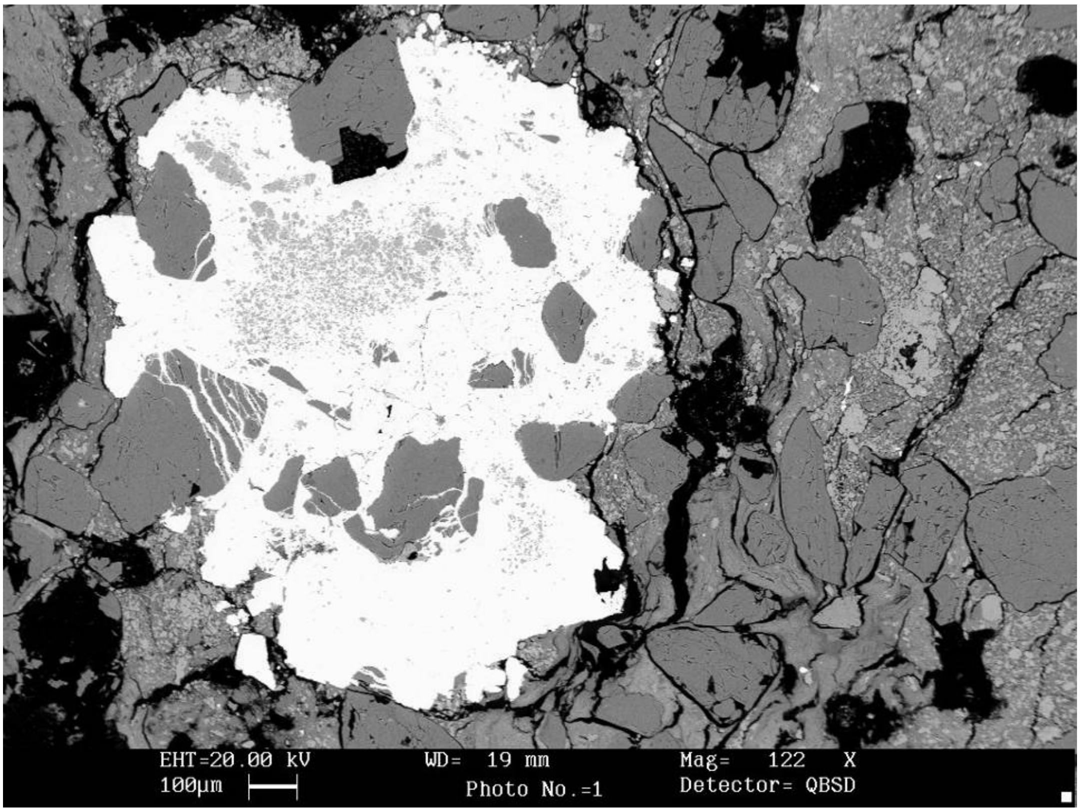

Figure 3.18. Core from the Upnor Formation with the description showing a calcrete, described as highly weathered limestone. Borehole JLE 404T (TQ 3363 7960), 35.30 to 36.00 m.b.g.l.

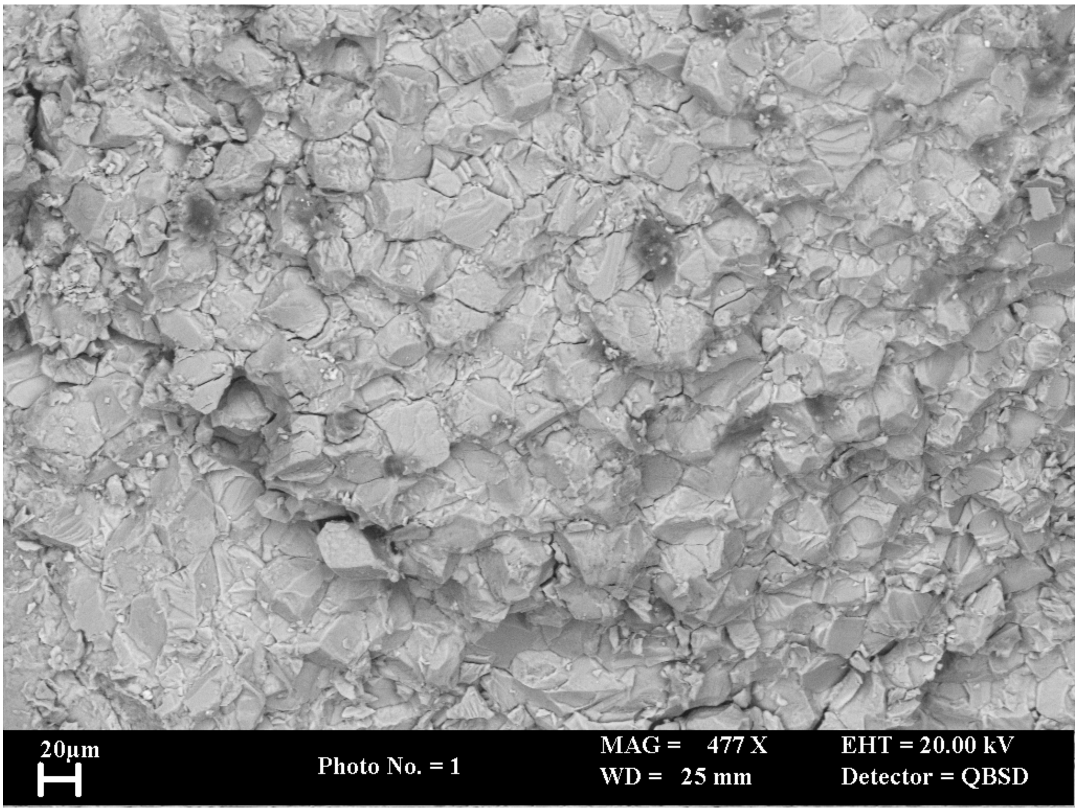

Figure 3.19. Equant calcite crystals in the Upnor Formation calcrete, which is consistent with pedogenesis in a freshwater environment, Limehouse, London (TQ 362 809).

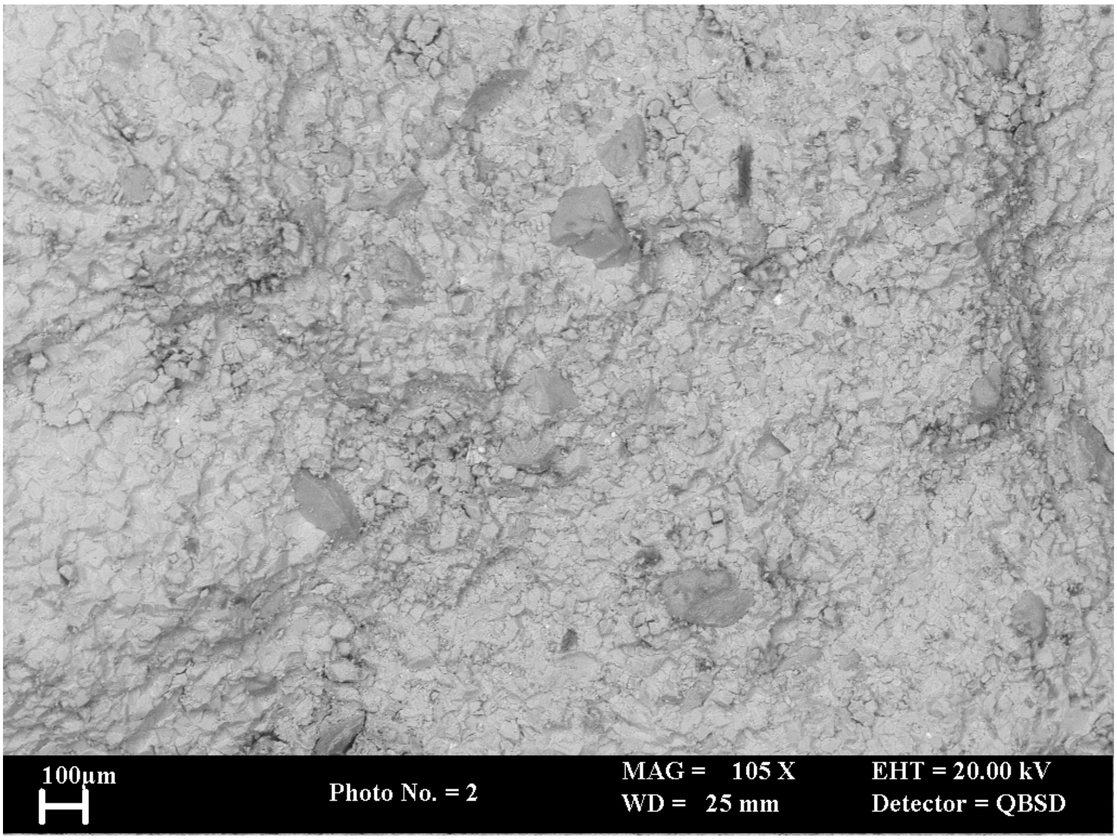

Figure 3.20. A few quartz crystals in a calcite matrix in an Upnor Formation calcrete. This represents an expanded detrital grain framework where the quartz has been pushed (blown) apart by the formation of the calcite, suggesting that the formation of the calcite was near surface. Limehouse, London (TQ 362 809).

3.6.1.2 SILICA CEMENTING AND SILCRETE

The hardest and strongest of the hard bands are the silcretes. The sarsen stones and puddingstones (conglomerates) of southern England are probably mostly derived from the Lambeth Group, although some may be from Eocene deposits such as the Harwich, Bagshot and Barton formations (Summerfield, 1983; Summerfield and Goudie, 1980). Most are found to the south of a line from Lowestoft to the Severn Estuary. The distribution of most of the silcretes relate to the original outcrop of the Lambeth Group. Many are post erosion relicts found as isolated block or in groups on the Chalk or in Clay-with-Flints on the chalk away from the current outcrop of the Lambeth Group (Figure 3.21). The conglomerates are commonest to the north and west of London; for instance in Hertfordshire (Hertfordshire Puddingstone), and further west towards High Wycombe (Bradenham Puddingstone). In Hampshire and Sussex the conglomerates often contain angular flints (flint breccia). All the puddingstones are derived from the gravel beds of the Upnor Formation. Whereas other sandstone silcretes are also likely to be from the Upnor Formation sand beds but some may originate from the sand facies of Lower Mottled Clay. Other examples may not be *in situ*, as they may have been utilised in walls, buildings or rockeries as this stone may be one of the few strong rocks available in the area. The sarsens in the Ipswich area have similar heavy detrital minerals to the Reading Formation (Boswell, 1927).

Figure 3.21. Sarsens in Clay-with-Flint. The stones are surrounded by red clay derived from the Lambeth Group with clay and flint around. Lee Gate, near Wendover, Buckinghamshire [SP 895 055]. (BGS photograph P201387, 1911).

Silica-cemented rocks are well known in parts of the Lambeth Group as localised zones of silicification, such as in the ferruginous sands in the London Basin and sandstones of the Hampshire Basin. More significant silcretes have been found in the Lambeth Group as partially and fully silicified breccia or sandstone in the Rotherhithe tunnel (Barrow, 1919), at Bushey Station (Hopkinson and Kidner, 1907), in a well section at Neasden (Whitaker et al., 1872), near the base of the Lambeth Group (Upnor Formation) east of Siblets Wood (Sherlock *et al*., 1922), the Great Western and Great Central Joint Railway cuttings at Gerrard's Cross (Sherlock and Pocock, 1924) and in gravel pits near Bernards Heath, St Albans (Kerr, 1955). Puddingstones were found in chalk swallow-holes with sands of the Upnor Formation (Sherlock and Pocock, 1924).

A list of localities where silcrete has been attributed to the Lambeth Group is shown in (after Potter 1998).

The formation of the puddingstones and possibly some of the sarsens probably occurred after formation of calcrete that was subsequently removed and replaced by silica (Skipper, 1999). The red, pink and brown colours of some of the flints probably occurred under alkaline conditions present during carbonate deposition. The mixture of colours and textures of flint gravels indicate that varying degrees of calcrete formation affected the flints prior to silicification.

The silcretes are generally found on the edges of the basin areas that have better drainage and extended periods of subaerial exposure. However, silicification occurs elsewhere very locally at mm or cm scale, often associated with biogenic disturbance such as root holes and other voids, usually in the Lower and Upper Mottled Clay of the Reading Formation. This is illustrated in Figure 3.22 which shows a back-scatter electron micrograph of clay that has been altered to siliceous matrix from borehole JLE404T (34.20 m). The void, probably a root hole, is lined by colloform silica that has subsequently been lined by iron oxide. The same material contains heavily altered clay (Figure 3.22) that has been patchily altered to leave a siliceous matrix that has been previously stained by iron oxide (light grey). There are also concentrations of calcite rhombs (mid grey).

Table 3.2. Silcretes attributed to the Lambeth Group (mostly Upnor Formation) (After Potter, 1998).

Approximate location	Reference	Notes
West of London	Prestwich, 1854	Conglomerate
West of London	Sumbler *et al*., 1996	
London	Woodward, 1891	
East London	Barrow, 1919	
North and east London	Barrow and Wills, 1913	*In situ*
North London	Bromehead *et al*., 1925	
Cuffley, Herts	Pocock and Fortescue Wells, 1914	Conglomerate *in situ*
Hertford, Herts.	Sherlock and Pocock, 1924	Conglomerate
Radlett, Herts	Whitaker, 1864	
Radlett, Herts	Whitaker, 1875	Conglomerate
Radlett, Herts	Hopkinson, 1884	Conglomerate *In situ*
Radlett, Herts	Woodward, 1909	
Radlett, Herts	Barrow *et al*., 1914	Conglomerate *In situ*
Rickmansworth, Hertfordshire	Hopkinson, 1909	
Ruislip and Radlett, Herts.	Whitaker, 1899	
St Albans, Herts	Hopkinson, 1892	
St Albans, Herts	Catt and Moffat, 1980	Conglomerate *In situ*
Watford, Herts	Kidner, 1907	Conglomerate *In situ*
Herts.	Whitaker, 1899	Conglomerate *In situ*
Newbury, Berks.	Adams, 1973	*In situ*
High Wycombe, Bucks	Sherlock *et al*. 1922	
Luton, Beds	Sherlock, 1922	Conglomerate *In situ*
Pinner, Middlesex	Gallois, 1993	Conglomerate *In situ*
Greys, Essex	Holmes, 1904	
Ipswich, Suffolk	Boswell, 1927	
Sudbury, Suffolk	Boswell, 1929	
Sudbury, Suffolk	Pattison *et al*., 1993	
Woodbridge, Suffolk	Boswell, 1928	
Suffolk	Boswell, 1915	
Basingstoke, Hants.	White, 1909	

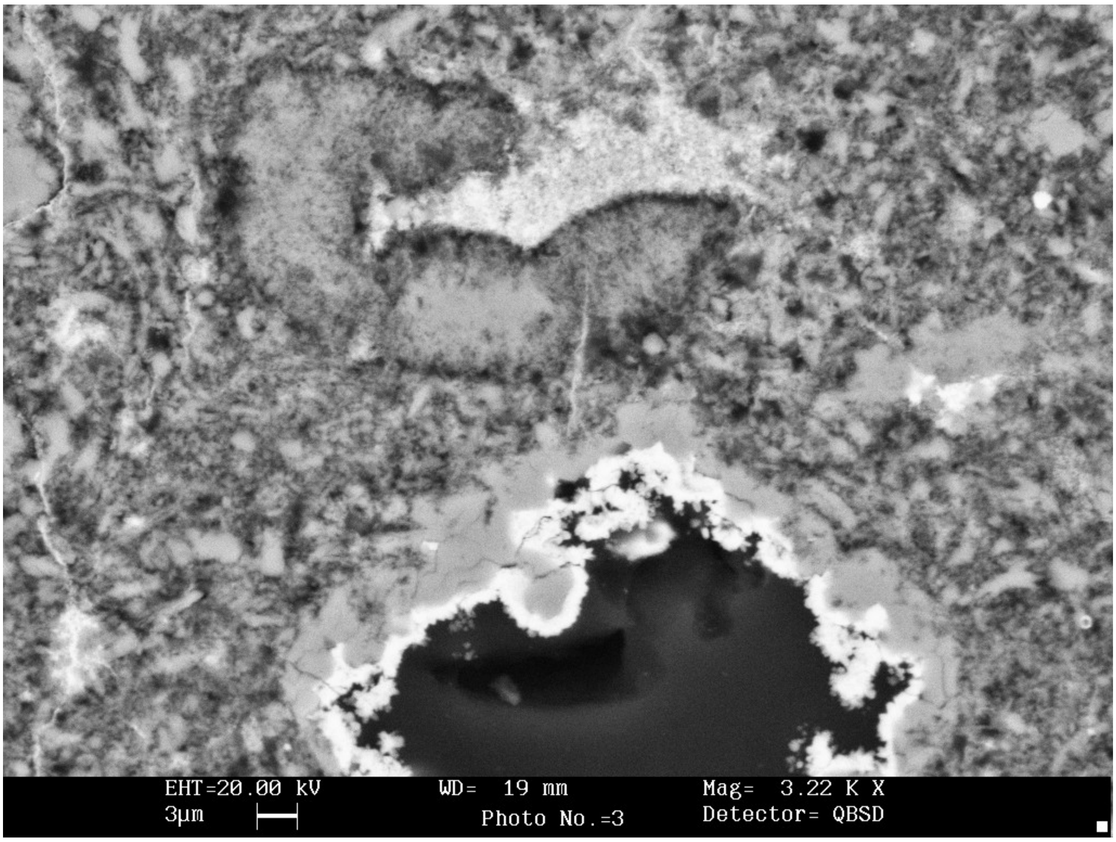

Figure 3.22. Detail of a clay from the Lower Mottled Clay showing alteration to a siliceous matrix. The void is lined by colloform silica and subsequently by iron oxide. Sample JLE 404T [TQ 3444 7941], 34.20 m. (BGS photomicrograph D777P1/03).

3.6.1.3 IRON CEMENTING

The movement of iron is very common in the Lower and Upper Mottled Clay and results in most of the colour variations in these beds. The major iron cemented beds are generally found in east London and north Kent. The best example is the "Winterbourne Ironstone" which is attributed to the Lower Mottled Clay (Ellison *et al*., 1994) or the Upnor Formation (Gamble, 1985). In the Lower Upnor Pit [TQ 785 711] a series of iron cemented beds are found below the Lower Shelly Clay and are detailed in Table 3.3 (Kennedy and Sellwood, 1970).

The Winterbourne Sand Pit [TR 065 570], south of Winterbourne, and Iron Hill Sand Pit [TR 064 582], north of Winterbourne, northwest of Canterbury, Kent also contain well developed iron cemented beds. As at the Lower Upnor Pit, the main ironstone is from the Upnor or Lower Mottled Clay and is generally about 0.50-0.60 m thick and described as very dark brown, orange or red, ferruginous, coarse to medium-grained sands, sometimes silty with irregular hard-pans and lenticular masses of well-cemented ferruginous sandstone or carstone. Here too, the Lower Woolwich beds contain limonite-cemented nodules. Thin bands of iron-rich angular to sub angular gravel are found also near the mid-Lambeth Group Hiatus at Alum Bay [SZ 305 824], and were observed along erosional surfaces within the Lambeth Group during the construction of the Newbury Bypass.

Table 3.3. Description of iron-cementing from the Lower Upnor Pit (TQ 757 711).

Stratigraphy	Thickness, m	Description
Lower Shelly Clay	0.60	Laminated black and brown sandy clay with gypsum, underlying a 'line' of ironstone nodules.
Upnor Formation	0.27	Iron-cemented sandstone.
Upnor Formation	0.55	White sand with low-angle cross-bedding. Occasional baryte rosettes. Large *Ophiomorpha* penetrates this bed, arising from the base of the sandy clay.
Upnor Formation	0.18	Sandy ironstone.
Upnor Formation	1.90	Hard, massive, purple sandstone with scattered small flint pebbles. Burrowed, and passing down into purple and yellow cross- and ripple-drift bedded sands.
Upnor Formation	Below	'Typical Upnor Formation'.

3.6.1.4 RECENT WEATHERING

The oxidation of minerals containing reduced iron such as glauconite and pyrite is seen where these minerals are exposed or near surface where oxygen is available due to reduced saturation and ingress of air or where oxygenated water flows through the deposit. In the Upnor Formation there is a change from pale to dark green to yellow-brown and an often speckled "pepper and salt" appearance due to the weathering of glauconite, often to goethite and or limonite. Oxidation of pyrite, found in the Upnor and Woolwich formations, produces sulphuric acid, which reacts with calcium carbonate commonly occurring as in shells, to form gypsum (see Section 3.3.8).

4 GEOPHYSICS

The use of surface geophysics to investigate and characterize the Lambeth Group is problematical for two reasons. Firstly, in urban areas, where most of the engineering development and investigations are carried out, it is difficult to apply traditional geophysical techniques; secondly, the Lambeth Group is lithologically complex, exhibiting both vertical and lateral variation (Hight *et al*., 2004). Page and Skipper (2000) demonstrated this variability when they identified at least 20 different recognizable sediment types from their work on exposure sections and high-resolution cored borehole logs throughout south-east England. This lithological variation may result in an overlap of physical properties and hence a reduction in the overall geophysical contrast.

The urban environment, in particular, poses a major challenge for many of the geophysical techniques due to a combination of anthropogenic effects. For instance, magnetic and electromagnetic surveys (including ground-penetrating radar) may be seriously affected by anthropogenic noise such as buried pipes, concrete reinforcing bars and electrical cables both above and below ground. Standard seismic methods and ground contacting resistivity profiling or 2D imaging/tomography techniques are restricted by the presence of buildings and large paved or bituminous surfaced areas. In addition, the seismic reflection technique suffers from significant signal degradation due to the high levels of vibration noise associated with urban areas. In contrast the microtremor survey method (Okada, 2003) is the one technique that is ideally suited to the urban environment as it uses background microseismic and anthropogenic noise in its measurements.

4.1 GEOPHYSICAL METHODS APPLICABLE TO THE LAMBETH GROUP

The generally applied geophysical methods and their suitability with respect to the Lambeth Group are shown in Table 4.1.

The detailed heterogeneity of the Lambeth Group is best observed in borehole logs as exemplified by Jubilee Line Extension borehole 404T (see Appendix 1). The gamma ray logs reflect the presence of gamma ray emitters due to the radioactive decay, primarily, of potassium, thorium and uranium. In the Lambeth Group it generally reflects the varying sand/silt/clay and in someplace calcium carbonate content. Peaks often correspond to increased clay content either because the clay mineral contains potassium, as in the case of illite or they absorb uranium and thorium. Very low values may be associated with calcium carbonate-rich deposits such as chalk, limestone or calcrete as in parts of the Lower Mottled Clay and the pedogenically altered Upnor Formation. Examples from London (Ellison *et al*., 2004) show that the higher values are found in Lower Shelly Clay and Upnor Formation, whilst the intervening Lower Mottled Clay has a generally low gamma count. These variations have proved useful for correlation over relatively short distances; but may not be successful on a regional scale due to the rapid lateral and vertical variation in lithology.

Table 4.1. Generally applied geophysical methods and their suitability with respect to the Lambeth Group

Method	Advantages	Disadvantages	Comments
High-Resolution Seismic Reflection	Generates high-resolution seismic images; maximum resolution of a few metres.	Expensive, good results require water-saturated consolidated deposits. Needs low-noise.	Good delineation of hard bands, shelly limestone and gravel beds.
Seismic Refraction	Relatively cheap method for determining thickness of weak sediments overlying bedrock.	Low resolution; assumes increasing velocity with depth.	Possibly useful in determining the depth to base of Lambeth Group.
Surface wave methods	Best seismic technique for measuring the moduli of sediments. Can discriminate useful signal against all other types of noise, especially useful in urban environments, whilst also being able to map velocity reversals. Field data is easily collected using standard seismic equipment as surface waves comprise the strongest energy. Derives shear wave velocities and hence shear moduli from ~1 to100m below surface. Large area can be covered in relatively short time period, hence it is highly cost effective and time efficient.	Can be limited resolution and may miss thin layers of anomalous velocity. Only average shear wave velocities derived. Passive methods work best when noise is coherent and directed parallel to array set-up.	Can map velocity reversals and may be able to map out limestone, hard bands and gravel beds in relation to lower velocity sand/clayey beds.
Ground Penetrating Radar	High-resolution image (sub-metre resolution) of near-surface; much cheaper than seismic reflection.	Strong signal attenuation in conductive ground (clays); Penetration of 12-20m possible in resistive ground.	Possibly useful if the Lambeth Group is at or near surface.
Resistivity Tomography	High resolution 2D image of the sub-surface enhanced by inversion processing. 3D imaging and volumetric analysis possible.	Technique requires a relatively large amount of space; very difficult to operate in urban areas. Also quite slow data collection, which is restricted to the top 35m.	Good for showing lateral lithological variations and for delineating sand/gravel bodies within clay.
Resistivity Sounding	Quick method for mapping horizontal layers with appropriate resistivity contrasts.	Relatively slow data collection, Interpretation is 1D and more than one model may match data.	Could be useful for assessing overall thickness of Lambeth Group.
Ground conductivity (EM)	Maps variation in conductivity, usually related to clay content; useful for conductive horizons; 50m exploration depth.	Difficult to operate in culturally noisy environments. Limited vertical discrimination.	Good for detecting near-surface (i.e. < 20m depth) sand channels within clay bodies.
Transient Electromagnetism (TEM)	150m depth from small loop set-up to map depth conductivity variations; smaller ground volume involved than resistivity sounding.	Difficult to operate in noisy environments. Low resolution in top 10m; most interpretation is 1D and assumes horizontal layers.	Useful on constrained sites, but susceptible to urban noise.

Downhole 'wire line' logging	High resolution, good for stratigraphic correlation and bulk physical properties. Logs can be run in cased boreholes.	Point source data that can be difficult to interpret and correlate in laterally variable environments.	Electrical logs show clear delineation of divisions in monotonous strata like the Thanet Formation, but natural gamma logs appear best suited for Lambeth Group.
Microgravity	Apart from borehole logging this is the only technique that can be used over relatively small grids in noisy urban environments.	Relatively expensive and slow data capture and processing. Requires accurate height of each data point.	Can be used to detect near-surface collapse zones due to dissolution, or map, relatively large bodies of lower density sands that cut into clay (e.g. channels and buried valleys).

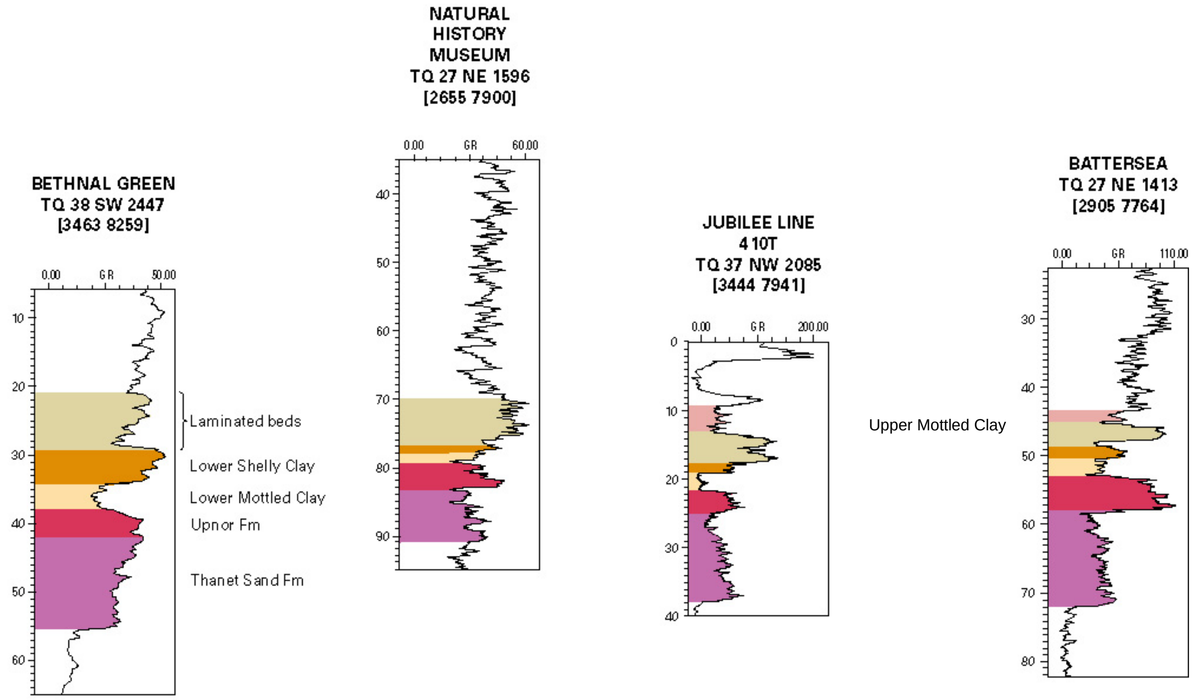

Figure 4.1. Correlation of gamma-ray signatures in the Lambeth Group and Thanet Formation (Ellison *et al*., 2004).

4.1.1 Ground Probing Radar (GPR)

Ground Penetrating Radar uses radio waves in the range of 1-1000 MHz to map the internal structure of the ground. It is an efficient and cost effective technique that works best in dry resistive lithologies (Davis and Annan, 1990), but has a limited depth of investigation in the UK (generally less than about 15 m) due to signal attenuation from a predominance of conductive clay in superficial deposits and bedrock. However, it may be useful in delineating and characterizing channel sands and/or laminated beds (where they are mainly sand). An example of this type of radar section is shown in Figure 4.2a where a 50 MHz antenna was used to examine the relatively dry, clean sands and gravels of the Blakeney Esker in East Anglia (Busby and Raines, 1999). Data is observed down to about 14 m, whilst the sub-horizontal reflectors show an indication of the Esker's depositional history. Similarly, detailed reflections are observed over resistive ground near Sellafield, Cumbria, UK (Busby and Merritt, 1999), which was interpreted as a kettle hole infilled with later horizontally bedded silty sand and gravels (Figure 4.2b). A comparison between signal resolution and depth of penetration can be observed in slumped (mine induced) Carboniferous strata near Ebbw Vale. In Figure 4.3a the 100 MHz antenna section shows good stratigraphic resolution and limited depth profile, whilst a greater depth of signal penetration is noted in the lower frequency 50 MHz antenna section (Figure 4.3b), but offset by a lower bed resolution. This method may be suitable where site conditions are favourable and where the Lambeth Group is near or at surface.

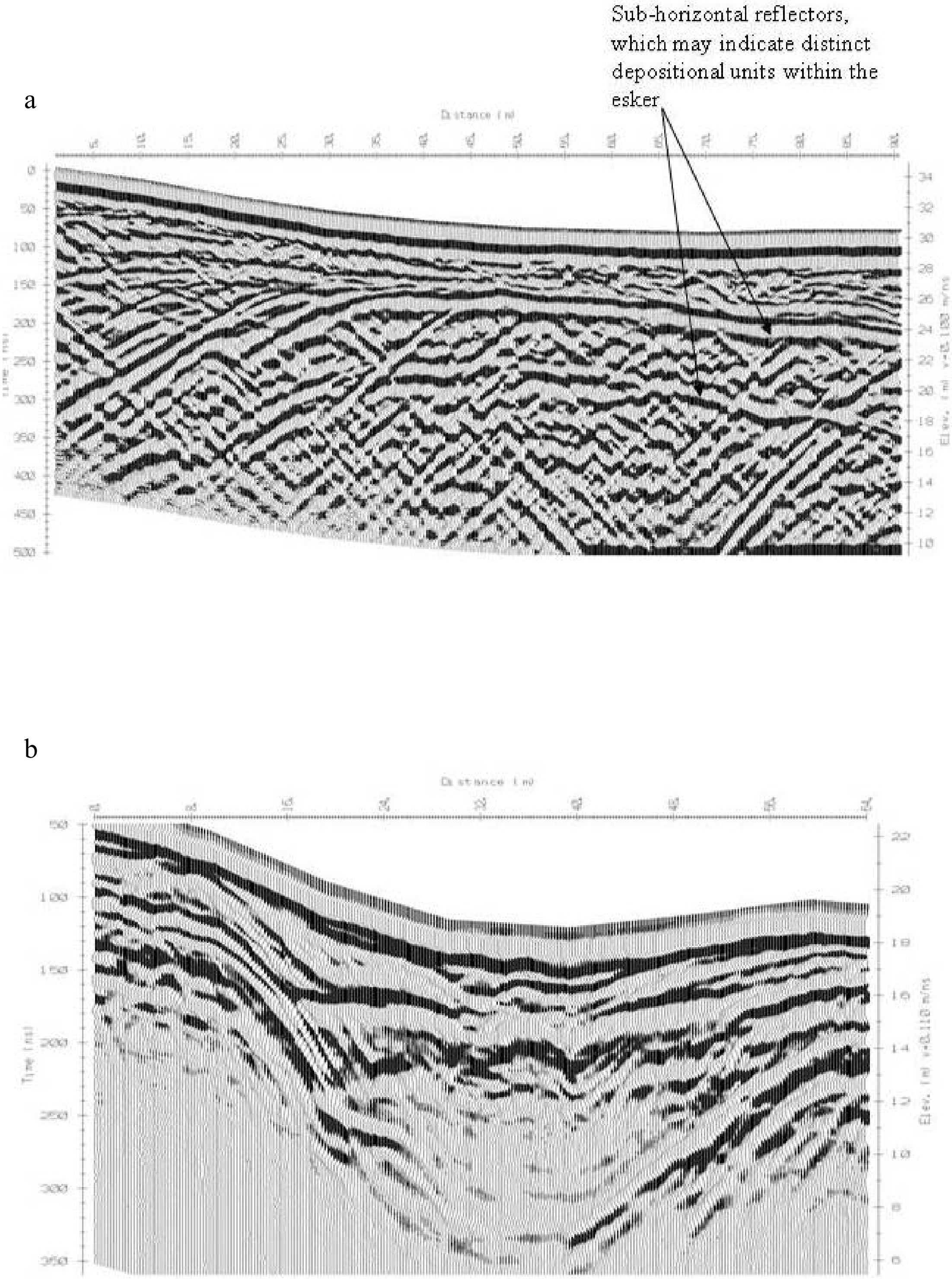

Figure 4.2. GPR reflection sections a) orientated along the Blakeney, Esker, Norfolk (after Busby and Raines, 1999) and b) GPR reflections interpreted as a kettle hole infilled with horizontally bedded, on lapping sediments (after Busby and Merritt, 1999).

a) b)

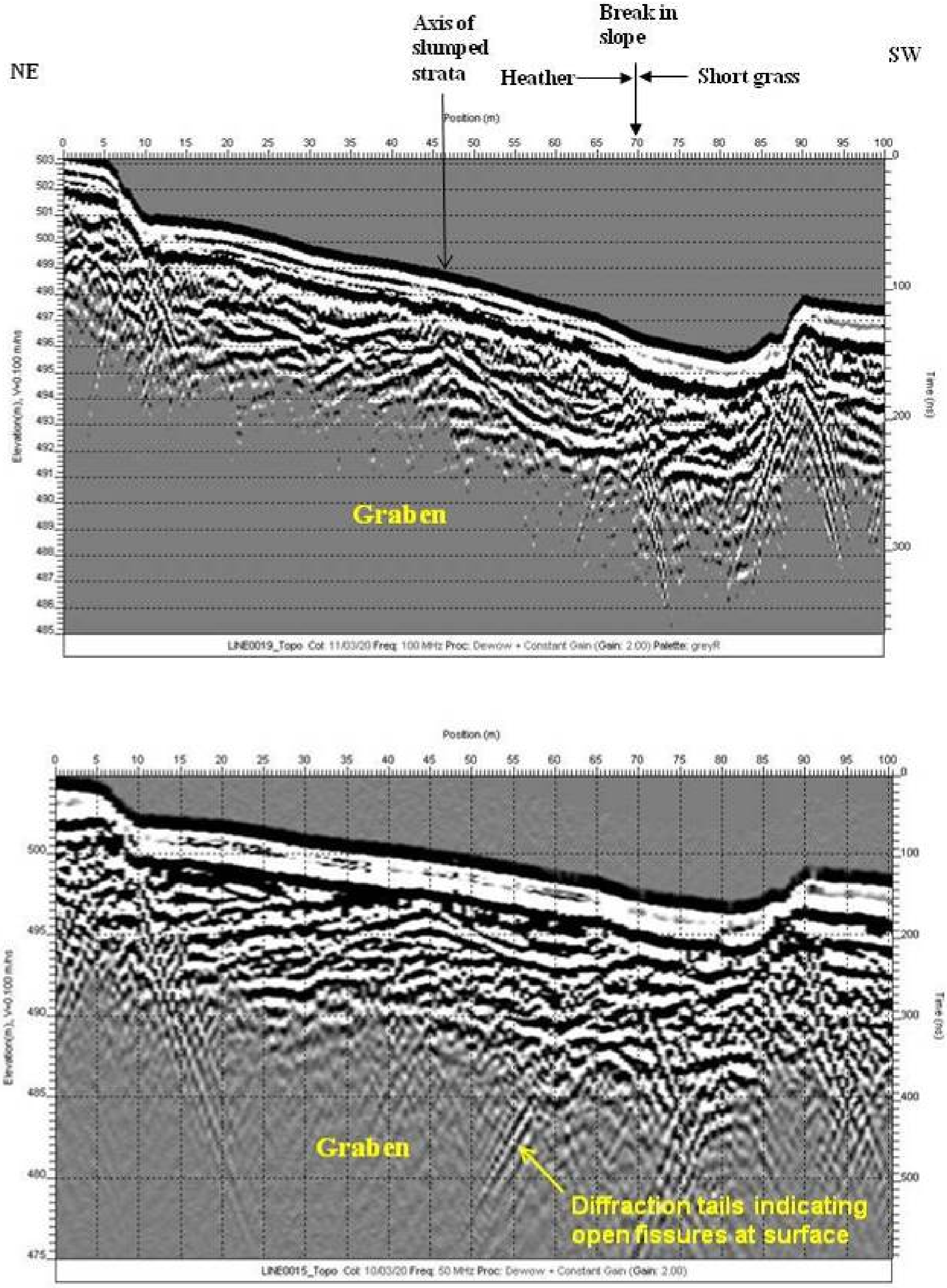

Figure 4.3. a) GPR measured with 100 MHz antenna, b) GPR measured with a 50 MHz antenna.

6.2.2 Electrical resistivity tomography (ERT)

Electrical resistivity tomography techniques generate 2D slices and 3D models of even complex geological environments and should be used in conjunction with seismic or GPR surveys as they provide complementary information about the subsurface. This is a powerful geological mapping tool, for use in engineering and environmental applications, including hydrogeological mapping. Reliable models of the subsurface can be created where ERT is used in combination with a 'ground truthing' boreholes at locations informed by the resistivity results (Loke, 1997, 1999).

One of the limitations of the technique is that increasing the depth of investigation requires longer electrode arrays and, therefore, larger available areas of ground. The site must permit an electrode array length of about 10 times the depth of investigation (e.g. an array length of 300 m would provide a depth of investigation of approximately of 30 m). This was observed in the Three Valleys Tunnel project (Baker and James, 1990), where a resistivity survey was deemed inconclusive due to the limited array length.

Nevertheless, given the space and relatively low levels of electrical noise, it is the one technique that should identify the vertical and lateral variation present in the Lambeth Group across a site. For example, the Harwich Formation (a good marker horizon dominated by glauconitic sands); occasional beds of Paludina Limestone; sand-filled channels generally; and the gravel beds at the top of the Upnor Formation, would all be expected to have relatively high resistivity. In contrast, intermediate resistivity might be expected from the laminated beds and shelly clays, whilst the clays of the Reading Formation (not in the east of the London Basin) would have relatively low resistivity. This assumes little overlap in the physical properties of the lithologies, which may not always be the case.

Space notwithstanding, the technique has some other limitations that might need to be considered when characterising the Lambeth Group. Realistically, resistivity data can be acquired to between 35 and 50 m below ground level as may be required in some areas of London, but the resolution tends to decrease with depth. An obvious resistivity target within the Lambeth Group is where sand-filled channels cut into the clay of the Reading Formation. A similar example of this scenario can be observed in Figure 4.4 where ERT was used over a landslide (Chambers *et al*., 2011; Wilkinson *et al*., 2011). Here, an approximately 35 m thick, relatively resistive sandstone (Staithes Sandstone Formation, SSF) is sandwiched between two relatively conductive mudstone formations (Whitby Mudstone Formation, WHM and Redcar Mudstone Formation, RMU). However, identifying resistive bodies, particularly if relatively small, beneath 20 m of superficial deposits and London Clay Formation would be difficult, as the current would tend to flow mainly in the conductive clay, hence decreasing the depth of investigation. The technique is ideal for mapping rapid lateral changes in resistivity as indicated by Figure 4.5, where a 2D resistivity section of a cambered slope in the Cotswolds (Raines *et al*., 1999) show small sediment infilled graben/half graben structures, lying between limestone blocks.

4.1.2 Shallow seismic reflection

Shallow seismic reflection (when and where site conditions permit) may also indicate some of the affects of variable lithology. For example, in The Three Valleys Tunnel survey (Baker and James, 1990) marked reflections were recorded at the top and base of the Lambeth Group and horizons of major contrast in the acoustic impedance (i.e. density x seismic velocity), possibly denoting limestone or gravel beds.

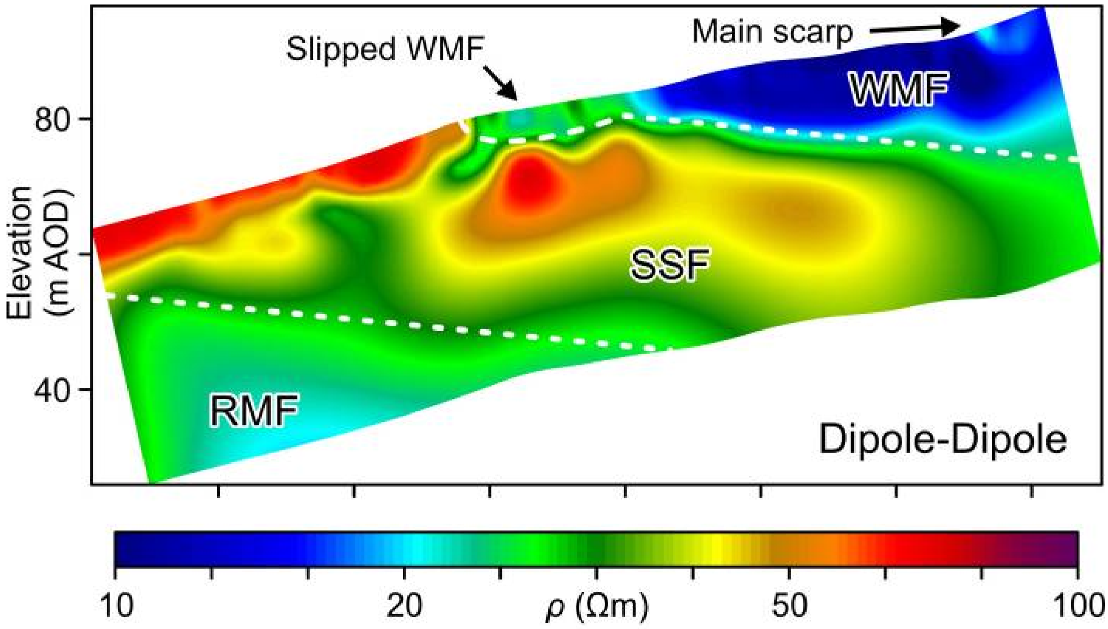

Figure 4.4. Inverted dipole-dipole ERT images. Inferred boundaries between the WMF, SSF and RMF are shown by dashed white lines.

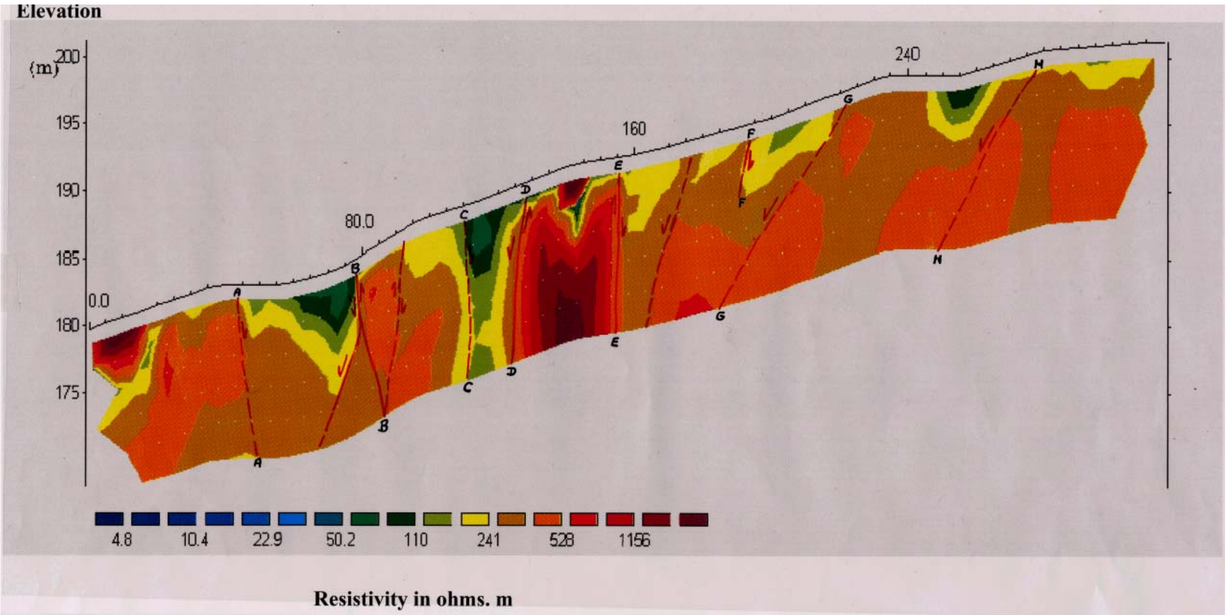

Figure 4.5. 2D pole-dipole resistivity section of a cambered slope at Aston Farm, North Cotswolds.

4.1.3 Surface wave methods

The growth in the use of seismic surface waves in earthquake and foundation engineering over the past decade has been remarkable. Their main attraction is the ability to derive values of shear wave velocities and hence shear moduli, at depths ranging from less than a metre to 100 metres below the surface, as a practical alternative to drilling expensive boreholes (Milsom and Eriksen, 2011).

Surface waves (Rayleigh and Love waves) are seismic waves propagating parallel to the earth's surface without spreading energy through the earth's interior: their amplitude decreases exponentially with the depth, and most of the energy propagates in a shallow zone, roughly equal to one wavelength. Surface waves are dispersive, resulting in a different wavelength of propagation for each frequency that propagates over different depth intervals within the ground (Reynolds, 2011). Thus, field survey methods that can propagate and record multi-frequency surface waves can be applied to characterise the shear wave velocity and stiffness properties of the near surface. Passive surveys utilise so-called background 'noise', whereas active surveys use a vertically impacting point source to produce Rayleigh waves. Different field set-ups range from use of dual geophones to 2D multi-geophone arrays. This enables characterisation of 1D profiles, 2D sections or pseudo 3D volumes, which can be applied to map engineering interfaces and disturbed ground via disruption to the subsurface stiffness (Park *et al*., 1999, 2007).

In engineering geophysics Rayleigh waves are considered the most important as their velocities are related to those of shear waves in the same elastic media. The exact relationship depends on the Poisson's ratio, but generally they are within 10% across a range of materials (Milsom and Eriksen, 2011). The recent popularity of surface wave surveys are due to the fact that they are non-invasive and can be quickly mobilised to provide shear wave velocity, and thus, small strain stiffness (shear modulus) information, from which heterogeneity can be assessed, (Foti, 2000; Menzies, 2001).

In the Multi-channel Analysis of Surface Wave (MASW) method, data is gathered using the same receiver array configuration adopted in shallow seismic refraction and reflection surveying (Gunn *et al*., 2012, 2013). The method utilises the dispersion property of surface waves for the purpose of shear wave profiling in 1D (depth) or 2D (depth and surface location) format (Park *et al*., 1999, 2007) and illustrated in Figure 4.6. The active method generally permits the determination of apparent phase velocity (or dispersion curve) within the frequency range 5 – 70 Hz. Hence, the active method can provide information concerning the top 30 – 35 m, depending on the stiffness of the site. The passive method, in contrast, has a much lower frequency range (5 – 15 Hz) and consequently provides information on deeper layers, below 50 m, again depending on site stiffness (Roma, 2010).

'Microtremor' is the name given to the background low-amplitude seismic waves that are present everywhere at the earth's surface. Microtremors with frequencies above one Hertz are generally associated with man-made sources (such as road traffic, trains, machinery, etc.), while those below one Hertz are generally associated with natural phenomena such as wind action and variations in atmospheric pressure.

The microtremor survey method has been adapted and applied as the Refraction Microtremor (ReMi) method by Louie (2001) and is equivalent to the passive MASW method. It uses standard seismic refraction equipment and a linear geophone array to measure the ambient noise or 'microtremors' to derive a shear-wave velocity profile down to about 100 m with 15% accuracy. In the inversion procedure, the Rayleigh wave dispersion curve is picked from a wavefield transformation, and iteratively modelled to derive the S-wave velocity structure.

A ReMi survey conducted over a buried mineshaft at Brighouse in Yorkshire, (Raines, *et al*. 2011), showed the technique's potential. In Figure 4.7a plots of shear wave velocity versus depth are shown for the various geophone groups. An advantage of this method over seismic refraction is observed in Figure 4.7a, where small velocity reversals are noted between 5 – 6 m below ground on Geophone groupings G9-G-16 through to G17-G24 respectively. The profiles at this site could be associated with weathered sandstone (600 m/s) overlying weathered mudstone or siltstone (400 m/s) as proved in various nearby boreholes.

The contoured shear wave velocity data shown in the 2D velocity section of Figure 4.7b suggests that the method has successfully mapped relatively low velocity structures beneath the made ground or colliery waste (5 – 6 m thick) that are associated with the backfilled mineshaft and edge of the former sandstone quarry. As this method can be used to measure velocity reversals it may be possible to delineate the relatively low velocity Upper and Lower Mottled clays, where they interdigitate with and/or underlie some of the limestone bands and gravel beds.

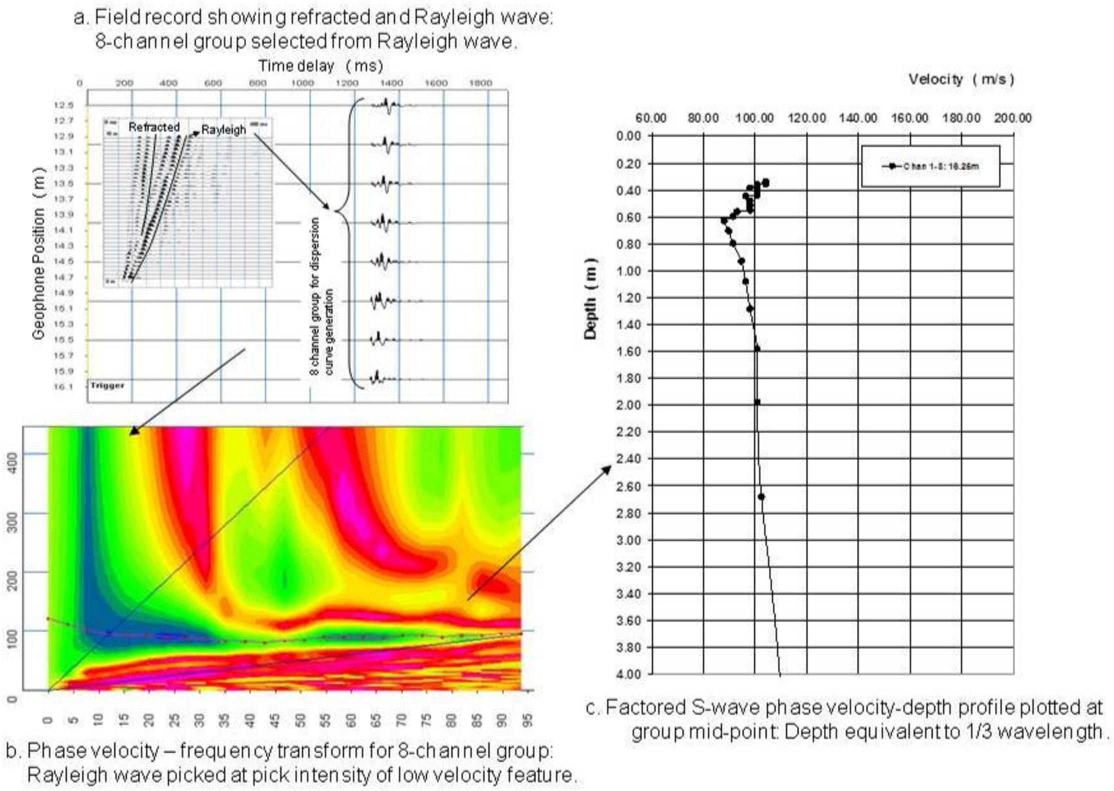

Figure 4.6. A 3-step processing scheme for Multichannel Analysis of Surface Waves data; a) Typical 8-channel field record; b) Dispersion curve constructed from phase velocity – frequency transform; c) Dispersion curve inverted to produce shear wave phase velocity with depth.

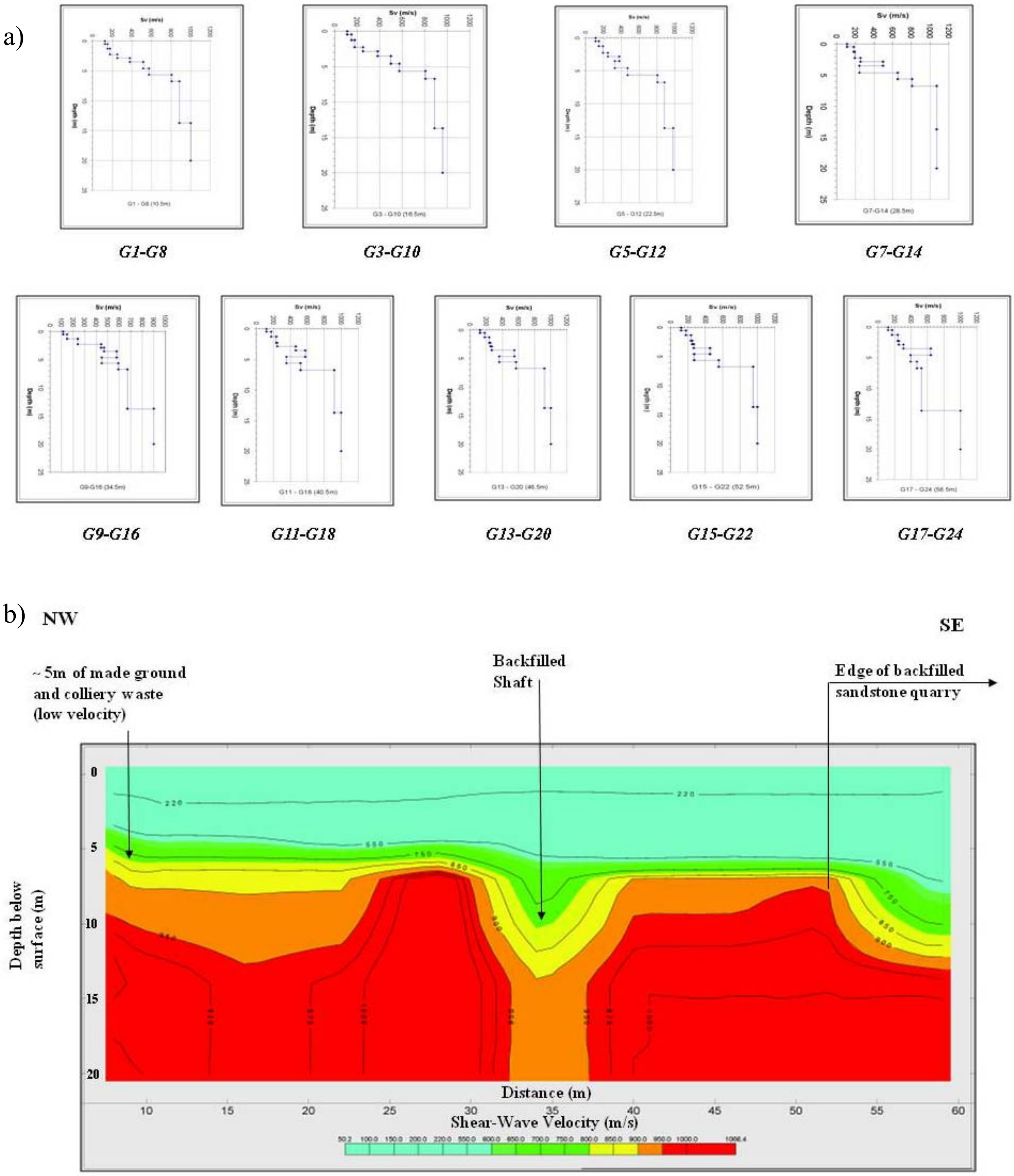

Figure 4.7. a) Plots of shear wave velocity (m/s) versus depth for geophones groups, G1-G8, G3-G10, G5-G12 and G7-G14 (top); G9-G16, G11-G18, G13-G20, G15-G22 and G17-G24 (bottom), b) 2D Pseudo-section of contoured shear wave velocity data from geophone groupings shown in above.

5 DATA ACQUISITION, QUALITY AND PRESENTATION

The data presented show that the geotechnical properties of the Lambeth Group and its units are extremely variable, even within an area and within a unit. The data presented here shows the changes with depth and primarily the median values for comparison between different units. They should not be used for design purposes. The box and whisker plots in Appendix 5 represents the variation in values of some parameters. It is, therefore, important to carry out site and lithology specific investigations for use in design.

5.1 DATA SOURCES AND COVERAGE

The majority of the data presented and assessed in this report were extracted from site investigation records for the motorway and trunk road network, underground railway lines and large water pipelines. In addition, a small number of tests have been carried out at BGS's laboratories and are referred to. The site investigation records used were those held at the British Geological Survey National Geoscience Data Centre (NGDC), with additional data requested from a number of sources in Association of Geotechnical and Geoenvironmental Specialists (AGS) digital data transfer format. These site investigation records provided good quality data. Most of the selected reports were for investigations produced after 1985, although data from earlier site investigations were added where it was considered of high quality or in areas where there was little or no recent data. AGS digital data transfer format data were chosen wherever possible.

The data records selected were either from near surface site investigations along the outcrop or, in the case of central London, from investigations for tunnels. Data for the Lambeth Group have been split into four areas as shown in Figure 5.1, reflecting the lithostratigraphic variation, present outcrop, the extent of current and potential development, and the availability of data sources.

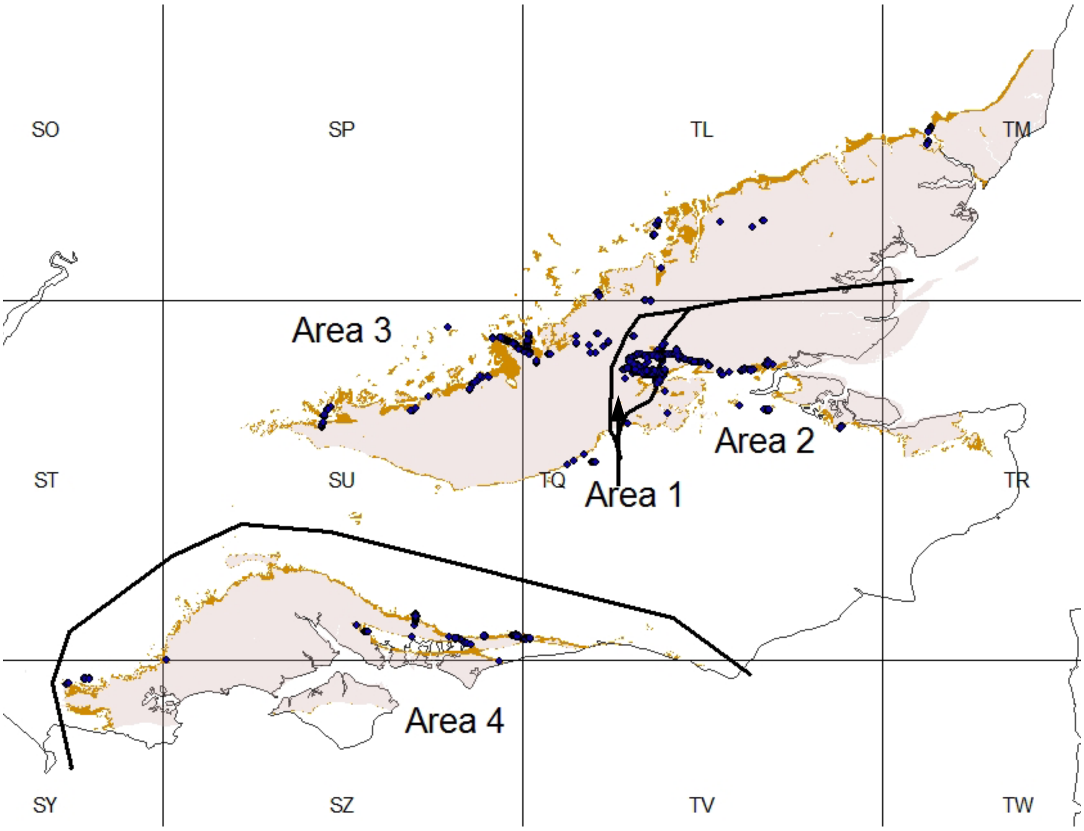

Figure 5.1. Areas 1 to 4 used in the analysis of the geotechnical data, with the outcrop of the Lambeth Group and borehole sites shown.

Most of the data are from Areas 1 and 2 with fewer boreholes and data points occurring in Areas 3 and 4. The depth of investigation of the Lambeth Group varies between the areas. Many of the site investigations in Area 1 and 2 are for tunnels whereas those for Areas 3 and 4 are mostly for roads. This is reflected in the data profile plots presented in Section 6. However, there are a few deep investigations in Area 3 and 4, most notably for bridge construction along motorway or main road routes. The total data set for the Lambeth Group comprised values for approximately 4,900 test samples and 4,000 *in situ* Standard Penetration Tests (SPT) from almost 1,500 boreholes and test pits, abstracted from 104 site investigations.

5.2 DATA QUALITY

The data sources primarily comprised recent contracts carried out by ground investigation contractors for the Highways Agency or its predecessors, and investigations for major railway lines such as the Jubilee Line Extension (JLE), Crossrail and the Channel Tunnel Rail Link (CTRL). The extreme values in each data field were examined, and those that appeared to be gross errors were deleted. Nevertheless, it has to be recognised that much of this original data, as in other geoscience fields, was potentially 'dirty' in the statistical sense. The values in the database often reflect the final result of a succession of field, laboratory and transcription procedures, during which one must expect errors to occur, however small or infrequent. Some data, such as stratigraphy, are interpretative and hence subjective. The information that could be extracted from borehole descriptions varied to some degree with the age of the site investigation but also the drilling method. In some areas a full assessment of the variability of the Lambeth Group would require closely-spaced boreholes with, preferably, continuous, undisturbed sampling. In such instances, lithostratigraphic details are likely to be missed when using standard cable percussion drilling with selected undisturbed sampling intervals often used in site investigation practise, or as required by BS5930 (BSI, 1981, 1999a, 1999b, 1999c). In some site investigations rotary drilling was employed to retrieve continuous core in plastic liners. This method provided generally good quality core, and the related borehole records were particularly useful for providing good lithological descriptions and lithostratigraphical interpretation.

5.3 CLASSIFICATION OF LITHOSTRATIGRAPHY

Wherever possible the lithostratigraphic classification in this report follows Ellison (1994). The various lithostratigraphic divisions are listed in Table.5.1. In many instances detailed, or correct, geology (stratigraphy) was not indicated in the site investigation reports or borehole logs. This necessitated revised lithostratigraphical classifications being assigned to the borehole logs (and associated measured data for particular borehole intervals) based on known lithostratigraphy of particular areas and from borehole descriptions. This proved difficult to do in some cases and required very good lithological logs such as those available from more recent site investigations for tunnels under London.

With regards recognition of the Lower and Upper Mottled Clays of the Reading Formation, their separation is relatively straightforward in those areas where the lower part of the Woolwich Formation is present between them, but elsewhere this is more difficult. However, based on the observations of Skipper (1999), this has been attempted where the borehole descriptions are of high quality. Skipper (1999) observed a dark organic horizon above a bleached bioturbated horizon within the Mottled Clay and designated this as representing the boundary between the upper and lower Mottled Clays of the Reading Formation. The boundary indicates a depositional hiatus followed by faunal activity, weathering and then inundation by organic-rich waters in a low energy environment. However, this organic horizon may be thin and difficult to observe during normal cable percussion drilling and sampling operations.

In parts of the Hampshire Basin, the Lambeth Group is often coarse-grained giving rise to difficulty in distinguishing between the Upnor and Reading formations. Where this distinction was not possible to determine from borehole logs, the coarse-grained deposits were simply classified as ‘Lambeth Group’(LMBE). It should be noted that the ‘basement beds’ of the Reading Formation shown on some geological maps of the Hampshire Basin are here interpreted as the Upnor Formation. Note: “Woolwich and Reading Beds” in the western Hampshire Basin are thought to have been mapped as part of the West Park Farm Member (Bristow *et al*., 1990), the basal member of the London Clay, but is considered here to be part of the Lambeth Group

Table.5.1. Stratigraphical subdivisions of the Lambeth Group used in the geotechnical database, after Ellison (1986).

Formation	**Stratigraphical position**	**Units in the database**
Woolwich Formation	Upper Woolwich	Upper Shelly Clay (striped loam)*
	Lower Woolwich	Laminated Beds Lower Shelly Clay
Reading Formation	Upper Reading	Upper Mottled Clays
	Reading Formation	Mottled Clays
	Lower Reading	Lower Mottled Clays
Upnor Formation	Upnor Formation	Upnor Formation

[Note: * indicates no geotechnical data available]

5.4 DATA SUB-DIVISION AND PRESENTATION

Statistical tables and plots used to illustrate the range and distribution of data values according lithostratigraphy (Figure 5.1) and location (Areas 1 to 4; Table 5.2) are presented in Section 6 and in Appendix 4. The Areas were selected by stratigraphy and geography and do not have any significance outside the database, and are *not* represented by uniformly distributed data. In addition, the samples from any general location should not necessarily be considered as representative of that area as a whole.

A variety of plots including 'line' and 'scatter' plots are used to display correlations of various key geotechnical parameters (Section 6). For example, selected geotechnical parameters are plotted against depth or other parameters, in order to determine variations caused by depth, and other related factors. Weathering may be related in a general sense to depth below ground level, but this is **not** a simple relationship of decreasing weathering with increasing depth in the case of the Lambeth Group. It should be noted that the plots of parameters with depth should be treated with some caution as they may contain random errors, and are meant only to give an indication of general trends. **As such, depth relationships shown here should not be used in design calculations**. Median values, 50^{th} percentile value, are used in Section 6 to illustrate differences between the different units.

In addition, summary statistical analyses of the data are given in the form of tables accompanied by 'extended box' plots that give a graphical representation of the range and distribution of the geotechnical data with respect to area and lithostratigraphy. These are presented in Appendix 4.

The extended box plot (Hallam, 1990) is a method of summarising a frequency distribution based on the robust *median* and *quartiles*. Unlike mean and standard deviation, it portrays all the data. It shows the percentiles as a central box icon the ends of which are the 25th and 75th percentiles (or quartiles), and the centre-line of which is the 50th percentile (or median), and the latter as values with the median shown in bold. Values lying above or below the box are shown as subsidiary boxes, representing percentiles above the 75th and below the 25th. The height of the box is proportional to the square root of the number of data. The median is the most commonly occurring value, and in a normal distribution has the same value as the mean. Several extended box plots may be compared by placing them on the same scale. This is more compact than comparing the equivalent histograms.

Table 5.2. Areas used in geotechnical data analysis and the associated geological units and codes used in the geotechnical database

Area	Location	Lambeth Group Formation	Units
1	Central London	Woolwich Formation (WL)	Upper Shelly Clay (UPSCL) Laminated Beds (LBED) Lower Shelly Clay (LSCL)
		Reading Formation (RB)	Upper Mottled Clay (UMCL) Lower Mottled Clay (LMCL)
		Upnor Formation (UPR)	Upnor Formation (UPR)
2	East London, Kent and South West Essex	Woolwich Formation (WL)	Laminated Beds (LBED) Lower Shelly Clay (+ lignite beds) (LSCL)
		Reading Formation (B	Lower Mottled Clay (LMCL)
		Upnor Formation (UPR)	Upnor Formation (UPR)
3	North Essex, Suffolk, Hertfordshire. Buckinghamshire, North east Hampshire, Berkshire, West London, Surrey	Reading Formation (RB)	Mottled Clay (Upper and Lower Mottled Clays undifferentiated) (LCM)
		Upnor Formation (UPR)	Upnor Formation (UPR)
4	Hampshire Basin	Woolwich Formation (east only)* (WL)	
		Reading Formation (RB)	Mottled Clays (Upper and Lower Mottled Clays undifferentiated) (MCL)
		Upnor Formation (UPR)	Upnor Formation (UPR)

[.Note: ***** indicates no geotechnical data available]

6 GEOTECHNICAL PROPERTIES

6.1 GENERAL

The geotechnical data reported in this section are derived in the main from routine laboratory testing (BSI, 1990; Head, 1980, 1982 and 1986 and subsequent editions, Brown, 1981). Geotechnical tests on soils and rocks may be broadly sub-divided into '*index*' and '*mechanical*' property and engineering chemical tests. The term 'index' implies a simple rapid and repeatable test, the equipment and procedure for which are recognised worldwide (e.g. liquid limit); or a test, which measures a fundamental physical property of the material (e.g. particle density). Mechanical property tests measure a particular behaviour of the material under the imposed conditions (e.g. a triaxial strength test). If conditions are changed the result of the test will be different. Equipment and methods for these tests tend to vary worldwide, and note should be taken of the test methodology, particularly where no standard exists. Mechanical property tests tend to require carefully prepared specimens. Index tests tend to be used to characterise a formation and to plan further testing, whereas mechanical property tests may be used for design calculations. For mechanical properties where little or no data are available, such as swell-shrink, permeability and durability, index tests are often used as a guide if correlations have been established elsewhere. In some cases, however, such correlations may not be appropriate. The parameters are in the glossary.

6.1.1 Water content and density

The database contains 4,165 natural water content values (w %) for Lambeth Group samples. The values range between 1% and 74%, however, most values fall between 13% and 28%. The median values for the Reading, Woolwich, and Upnor formations are 19%, 24% and 19% respectively. The distribution of water content values for the Upnor and Reading formations are similar and generally lower than those of the Woolwich Formation. However, the reasons for this may be different. For the Upnor Formation, the lower water contents probably reflect the greater proportion of coarse material present, whilst for the Reading Formation; past subtropical weathering has probably resulted in desiccation and alteration leading to reduced water content values. The Woolwich Formation is the least altered formation and may be slightly or very organic, most notably in Area 2.

Water content data are presented in a series of depth profiles (water content vs. depth) differentiated by formation and by area (Figure 6.1). The wide variation reflects the varied lithologies and degree of alteration (e.g. by subtropical weathering), but some of the higher and lower values are may be due to sampling disturbance and sample storage. This is indicated, for example, by water content values a little below or above the liquid limit for samples described as stiff or very stiff.

The natural water content of the Lambeth Group of the different areas by lithostratigraphical unit are in Figure 6.2 to Figure 6.5.

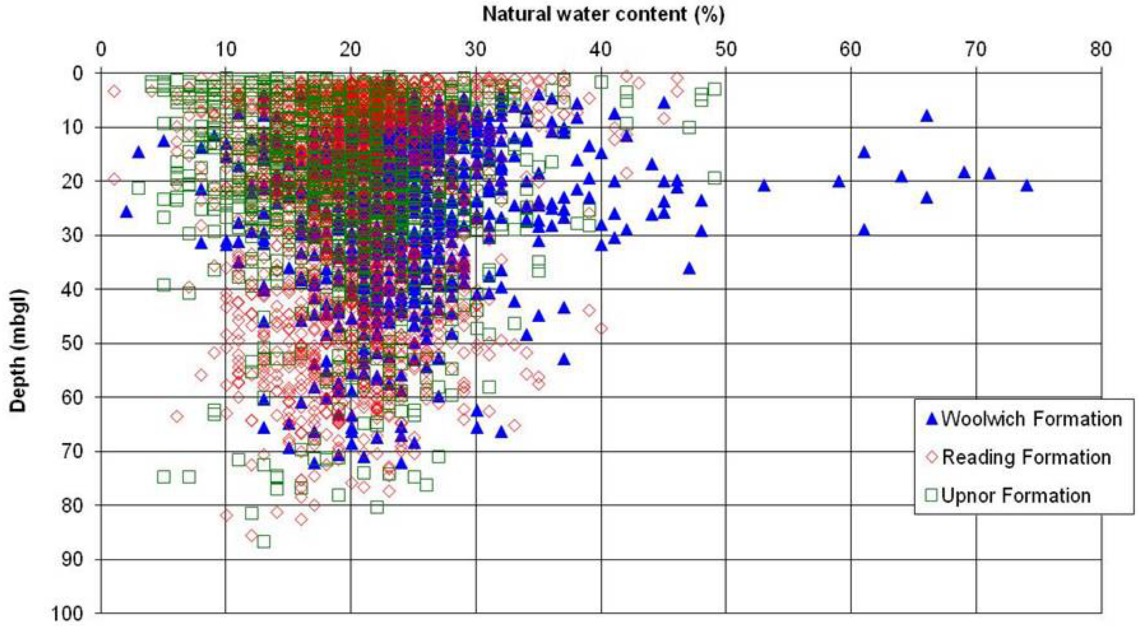

Figure 6.1. Natural water content profile differentiated by formation.

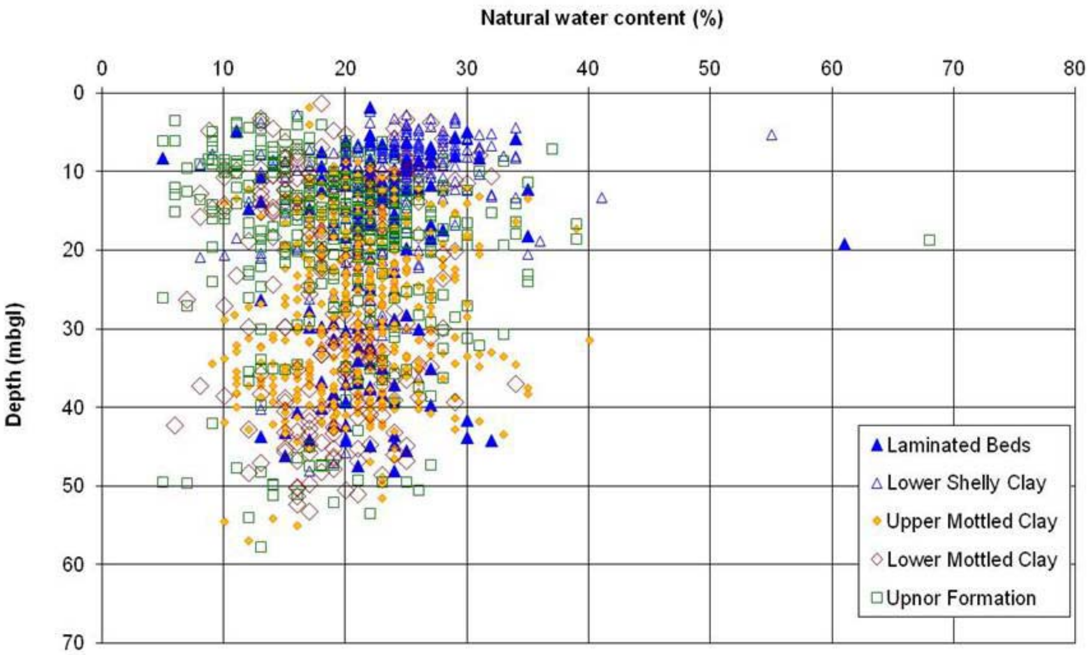

Figure 6.2. Natural water content profile of Area 1, differentiated by lithostratigraphical units.

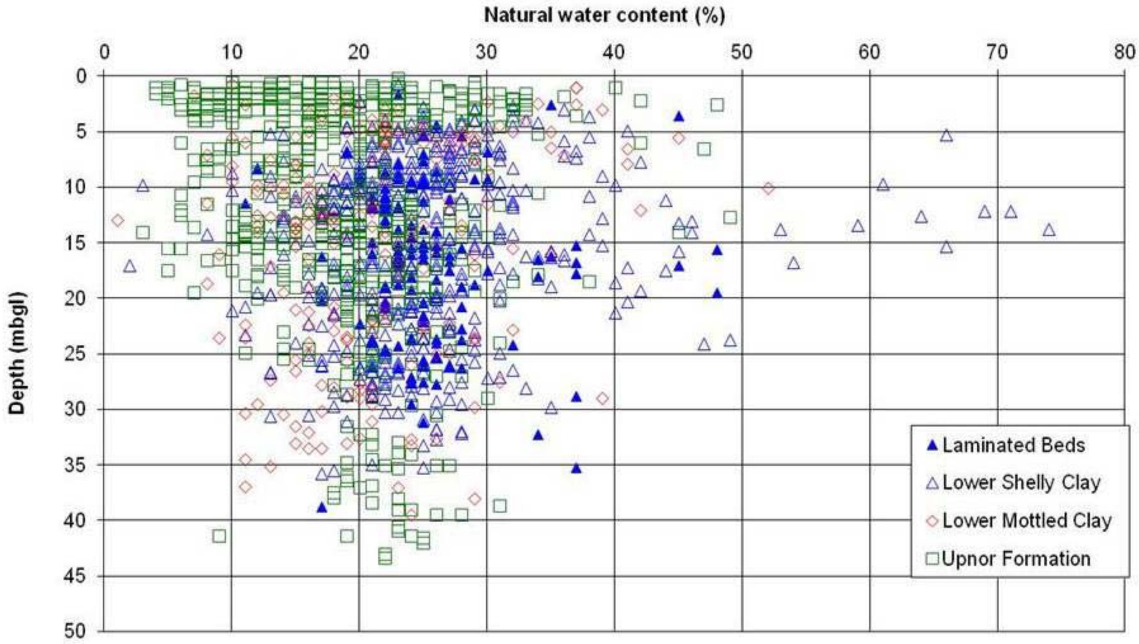

Figure 6.3. Natural water content profile of Area 2, differentiated by lithostratigraphical units.

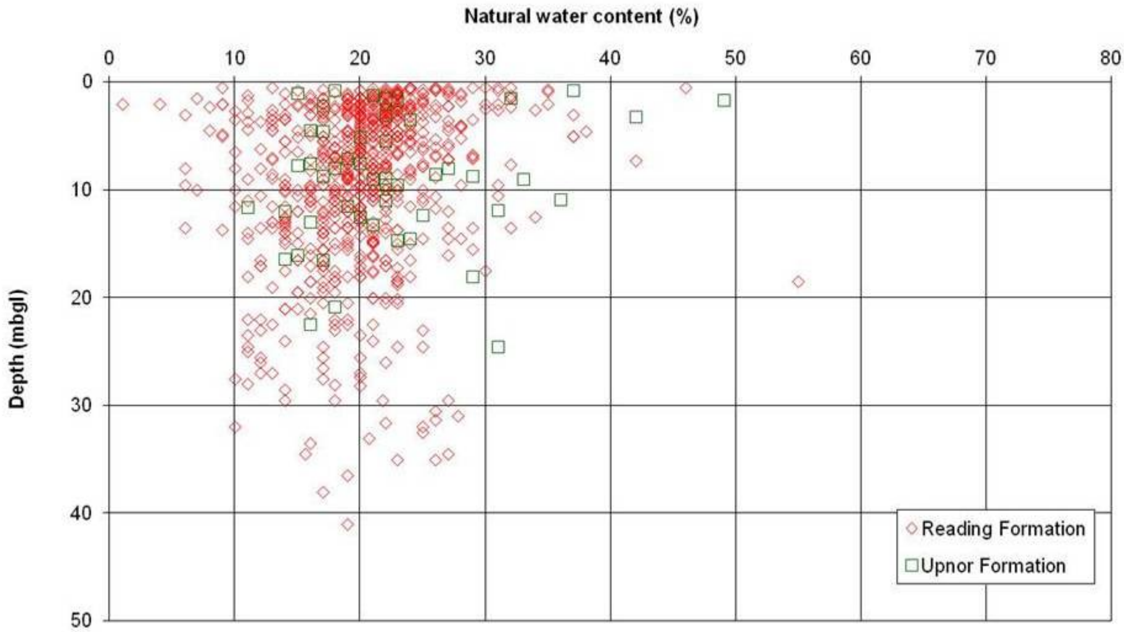

Figure 6.4. Natural water content profile of Area 3, differentiated by formation.

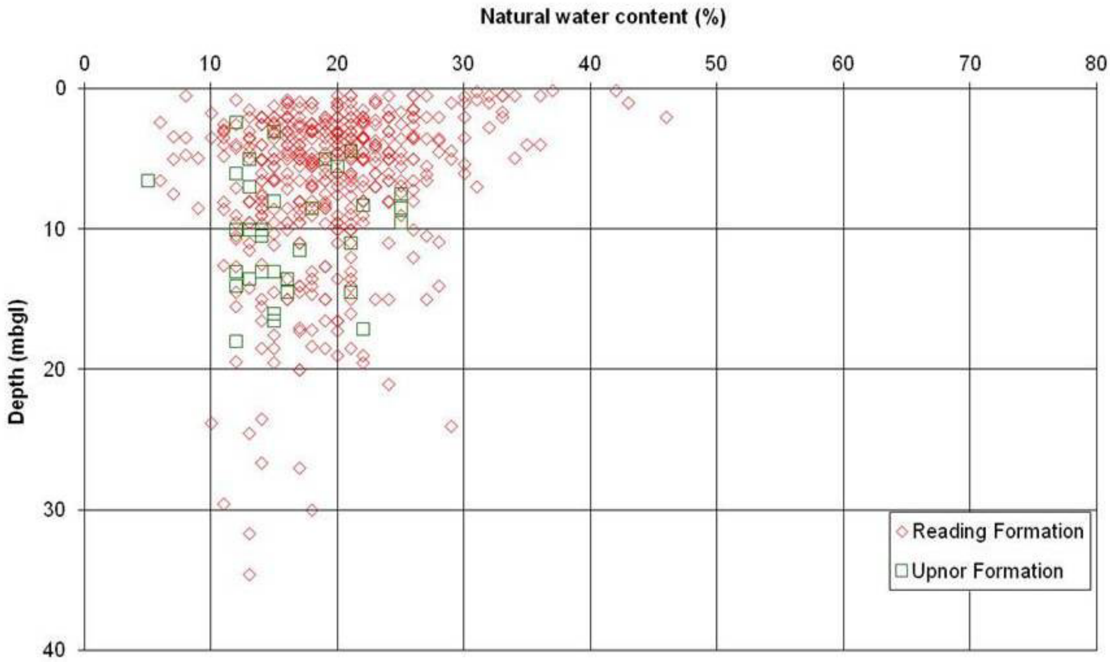

Figure 6.5. Natural water content profile of Area 4, differentiated by formation.

Very low water content determinations on samples occur for a number of reasons, for example:

- *Near surface*. Many low water content values are from the near surface and probably reflect sampling during an extended period of dry weather. This is most noticeable in sand samples of all the formations and in the gravel deposits of the Upnor Formation;
- *At depth*. Shell beds and some very shelly deposits from the Upnor and Woolwich formations and gravel beds of the Upnor Formation often have low water contents, as do some very dense sands. This may be due, at least in part, to sampling disturbance. Pedogenic alteration and formation of calcium carbonate, iron oxide or silica concretions in parts of the Upnor Formation and the Reading Formation (mostly the Lower Mottled Clay).

High water content values, above 40%, near surface may be due to sampling after extended rainfall. However, a majority of those below 3 m are mostly from the Lower Shelly Clay in Areas 1 and 2. Theses samples are mostly described as lignite, which is found at the base of the Lower Shelly Clay most notably in the Shorne inlier, north of Cobham [TQ675 695], Kent.

Some very high water content values (water content > liquid limit) are suspect. These may have been obtained from poorly executed or flooded cable percussion boreholes. The natural water content depth profile is plotted with points differentiated for sampling method in presented in Figure 6.6. The terms used for sampling are those in generally use. “Undisturbed” is taken with cable percussion sampler (U100) and “core” is from rotary coring. The plot shows that nearly all the high values, greater the 40%, are from ‘bulk’, disturbed or ‘undisturbed’ cable percussion samples. However, there are many fewer rotary core samples tested and they do not include such potentially high water content materials such as lignite. Natural water content of clean sand and gravel are not generally useful as they are prone to sample disturbance. The data for the site investigations presented are from before the sampling requirements as stated in Eurocode 7 (BSI, 2007) had come into use, hence the variety of different sampling methods and material types tested.

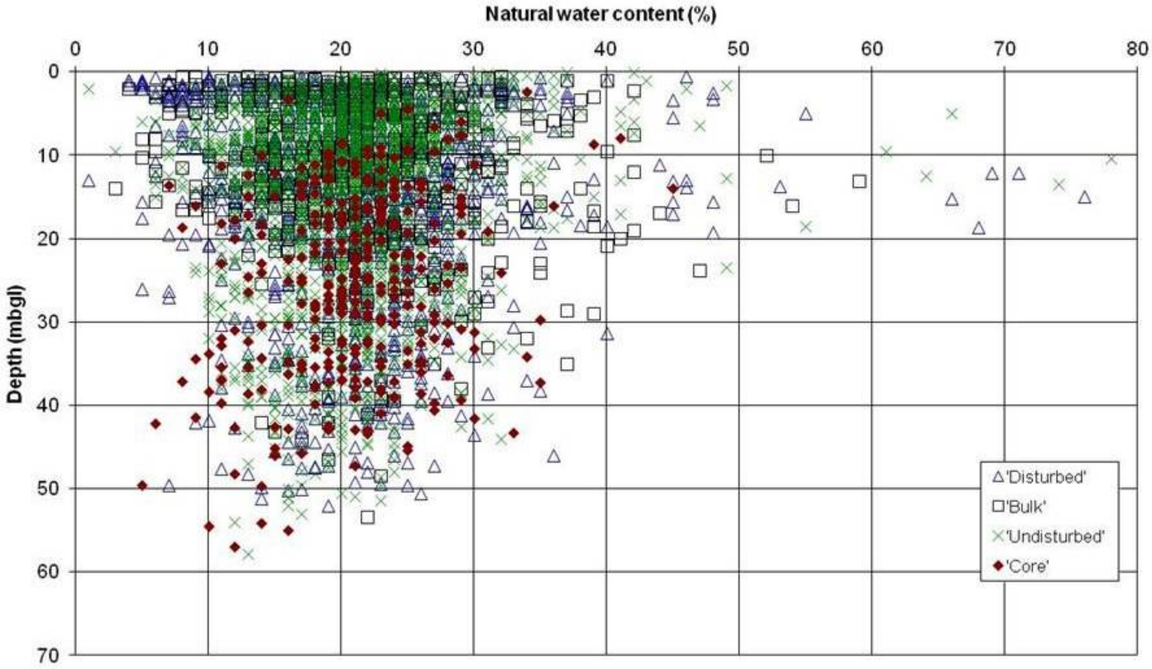

Figure 6.6. Natural water content profile differentiated by sample type, all data.

The database contains 1,565 values for bulk density, ρ, (Mg/m^3). This parameter may also be expressed as the total unit weight, γ kN/m^2, where γ is equivalent to the bulk density multiplied by the acceleration due to gravity (9.807 m/s^2). The values of bulk density vary between 1.43 Mg/m^3 and 2.375 Mg/m^3, although most fall between 1.64 and 2.36 Mg/m^3. The median values for the various formations are similar, lying in the range 2.04 to 2.08 Mg/m^3, however, overall values may vary considerably locally, both vertically and laterally. The bulk density depth profile for all data differentiated by formation (Figure 6.7) shows a broad spread of values with a generally reduction in variation with depth as there is a reduction in lower bulk density with increasing depth. The London Clay Formation (Figure 6.8) shows a more consistent increase of density with depth. The Lambeth Group has many values between 2.0 Mg/m^3 and 2.2 Mg/m^3 at all depths particularly within the Reading Formation and the Upnor Formation. The scatter of the Lambeth Group data probably reflects changes due to depth but also lithology, pedogenic effects (including cementation) and other structural features. Whereas, scatter of data for the London Clay Formation is probably associated with depth, the different units within the formation and structural features. The comparison is crude being as the depth is from ground level without any information of units above but it does show the gross differences of the bulk density and depth relationship between the two units. Some low values may be the result of sample disturbance resulting in de-saturation due to stress relief (Hight *et al*., 2004). Values of bulk density for the Upnor Formation, Lower Shelly Beds, and Laminated Beds may be unreliable due to sample disturbance (Hight *et al*., 2004), for example where samples are taken by driven tube sampling that can readily disrupt the soil fabric leading to reduced density measurements that are not representative of the *in situ* state. The CIRIA report (Hight *et al*., 2004) states that values of less than 1.95 Mg/m^3 beneath central London should be treated with caution. The bulk density vs. depth profiles for each of the area locations recognised in this study are presented in Figure 6.7 to 6.12 .

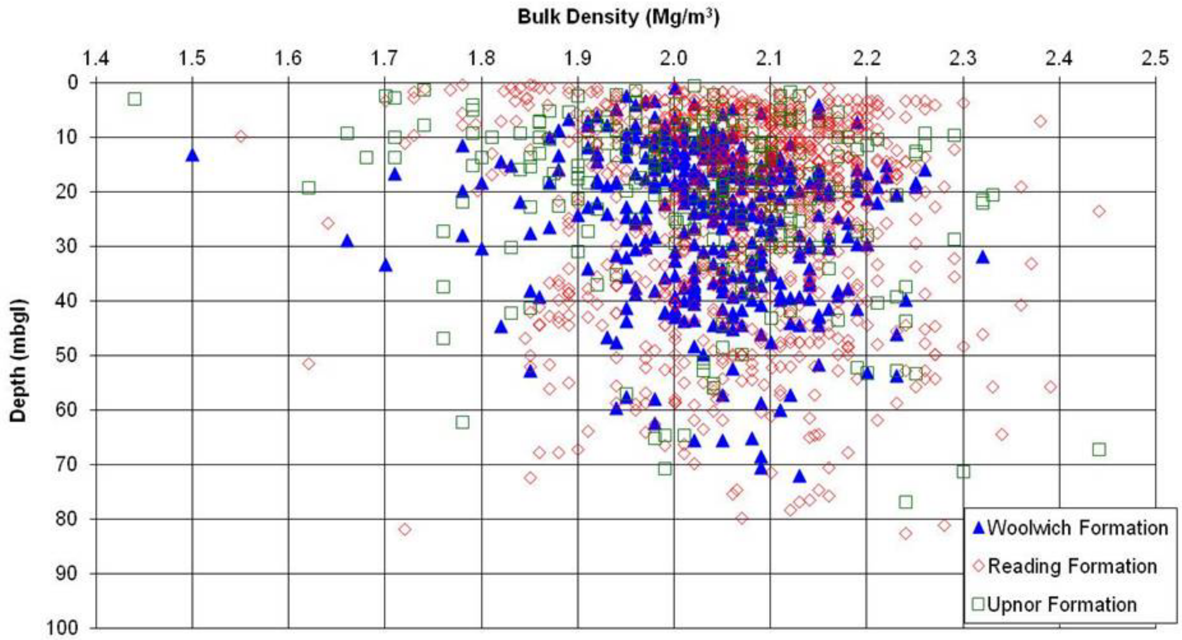

Figure 6.7. Bulk density profile for the Lambeth Group data differentiated by Formation.

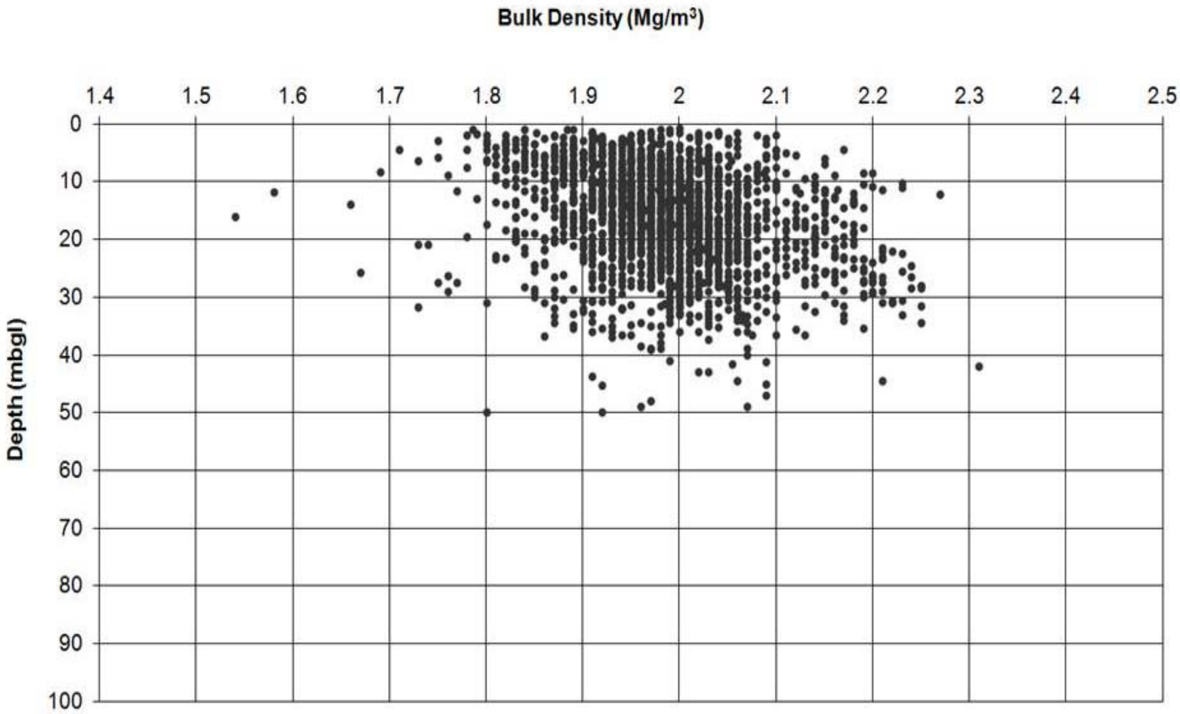

Figure 6.8. Bulk density profile of the London Clay Formation in Area 1.

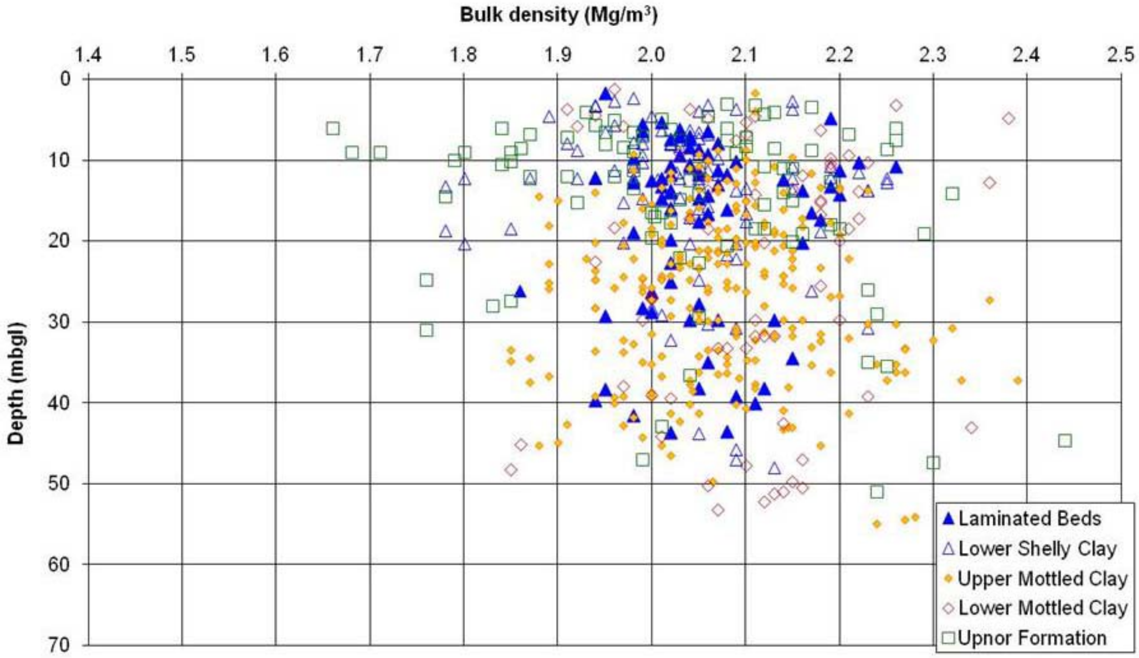

Figure 6.9. Bulk density profile of the Lambeth Group in Area 1 differentiated by lithostratigraphic unit.

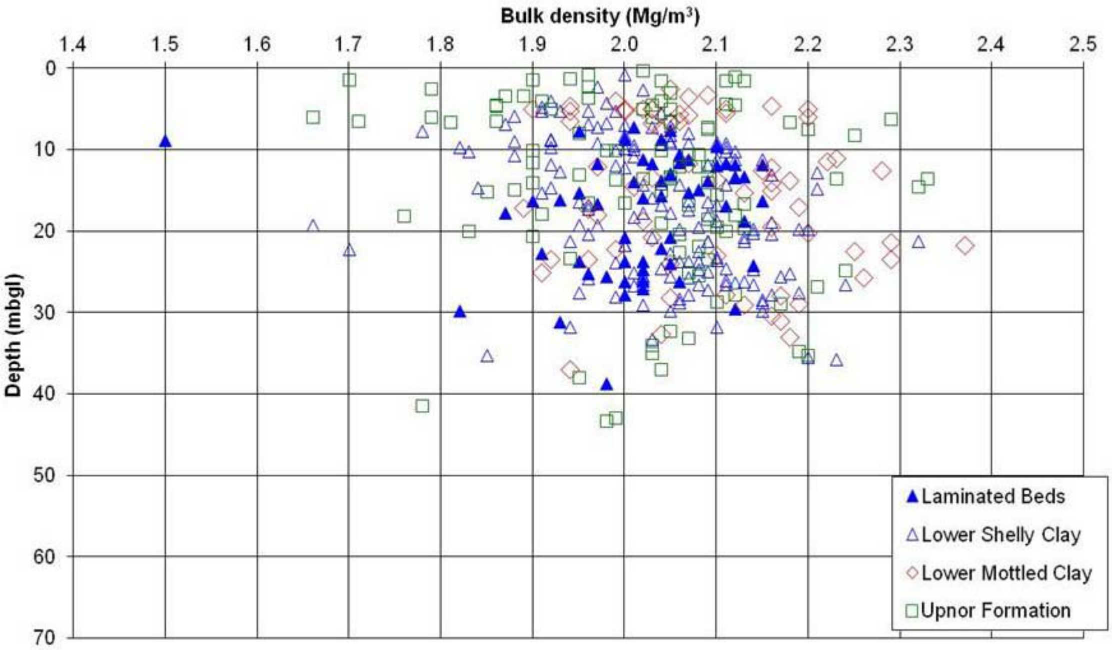

Figure 6.10. Bulk density profile of the Lambeth Group in Area 2 differentiated by lithostratigraphic unit.

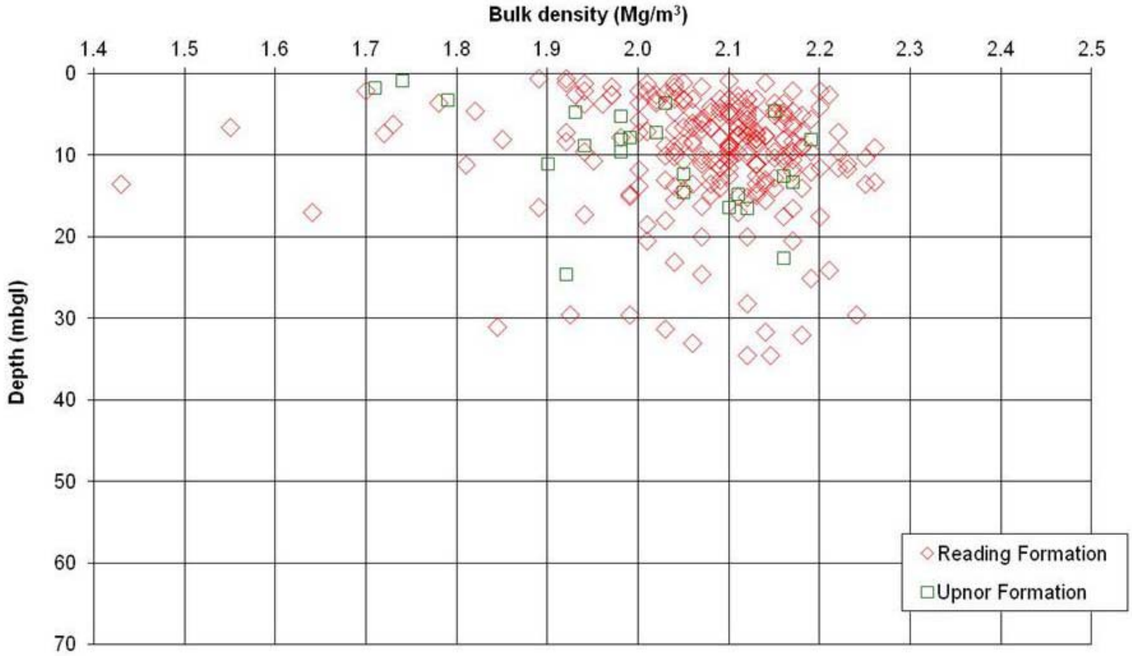

Figure 6.11. Bulk density profile of the Lambeth Group in Area 3 differentiated by lithostratigraphical unit.

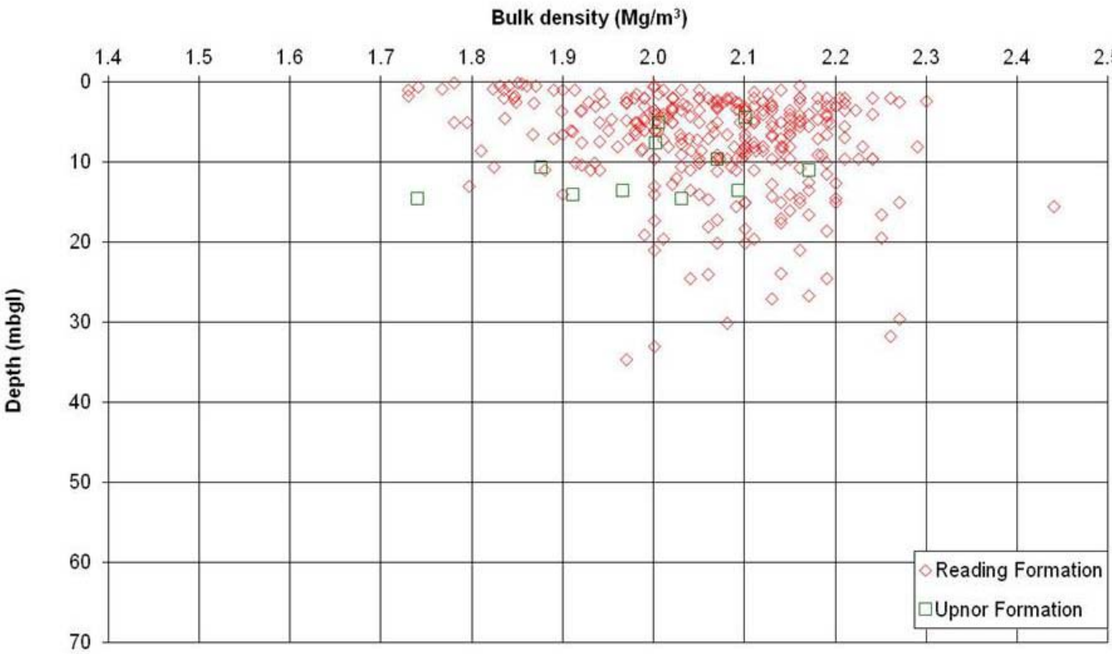

Figure 6.12. Bulk density profile of the Lambeth Group in Area 4 differentiated by lithostratigraphical unit.

The dry density, ρ_d, is the density (or dry unit weight, γ_d)„ of the oven-dried soil, i.e. with no 'free' water contained in the voids. Measured dry densities are poorly represented in the database, but can be calculated from the bulk density, ρ Mg/m^3, and water content, w %, by the following relationship:

$$\rho_d = (100 / 100 + w\%) \times \rho$$

The overall median value of dry density from 1,569 values is 1.71 Mg/m^3,with values for the Upnor, Reading and Woolwich formations of 1.71 Mg/m^3, 1.736 Mg/m^3 and 1.669 Mg/m^3, respectively. Median values for Areas 1, 2, 3 are close to the overall dry density median for all data.

Particle density (or specific gravity) is poorly represented in the database (109 values), the majority of these being from the Reading Formation. Of these the overall median value is 2.65 Mg/m^3. There are insufficient particle density data values for Woolwich or Upnor formations to draw any meaningful conclusions concerning their statistical distributions.

6.1.2 Plasticity

The results of all Atterberg, or liquid and plastic limit, test data are shown as Casagrande A-line plasticity plots (liquid limit, w_L vs. plasticity index, I_P), differentiated by formation in Figure 6.13, and by area in Figure 6.14. Plasticity plots of data for each area (Areas 1 to 4) are shown in Figure 6.15 to Figure 6.18 differentiated by formation or unit.

A total of 2,883 liquid limit (w_L %) results are contained in the database. Values for liquid limit range from 16 to 123% with an overall median of 53%. Median values for each of the formations range from 40 to 56%. Where distinguished, the Upper Mottled Clay of the Reading Formation, and the Lower Shelly Clay of the Woolwich Formation, have the highest median liquid limits. The data for the undifferentiated Reading Formation, Mottled Clay, is intermediate between the Upper and Lower Mottled Clays in Area 1. The lowest liquid limit values occur in the Upnor and Reading formations of Area 2, reflecting their higher sand content. A few samples in all the formations have extremely high liquid limit values, although this makes up only about 1% of all data.

A total of 2,769 plastic limits (w_P %) and plasticity indices ($I_P = w_L - w_P$) are in the database. The plasticity indices range from 2 to 92%, the overall median being 31%. Median values for the Upnor, Reading, and Woolwich formations are 23%, 36%, and 31%, respectively.

There is a wide range of plasticity values within the Lambeth Group, and within its formations. Overall, the data fall within the 'low' to the 'extremely high' range, although the great majority fall within the 'low' to 'very high' range. The clays of the Upper Mottled Clay tend to be of higher plasticity than those of the Lower Mottled Clay. The clay mineralogy of the Lower Mottled Clay and the Upnor Formation is sometimes dominated by the active clay mineral smectite, which suggests that they should have the higher plasticity. However, the Lower Mottled Clay and Upnor Formation contain significant silt and sand that tends to ‘dilute’, or reduce, the plasticity. In the Upnor Formation clays are often present in thin bands and retrieved samples are often mixed with coarser sandy material that results in lower plasticity determinations during laboratory testing. The Laminated Beds in Area 1 are generally more plastic than those in Area 2, probably because they contain more clay. The liquid limit of the Lower Shelly Clay in Area 2 is more variable than in Area 1 as Area 2 contains samples of lignite or highly organic clay, which have higher liquid limit values. Plasticity of the Upper and Lower Mottled Clays and Laminated Beds may increase towards the base. This is may be due to changes in clay mineralogy, and it has been considered that it may also be due to deposits coarsen upwards (Hight *et al*., 2004), however, the Upper and Lower Mottled Clays generally fine upwards.

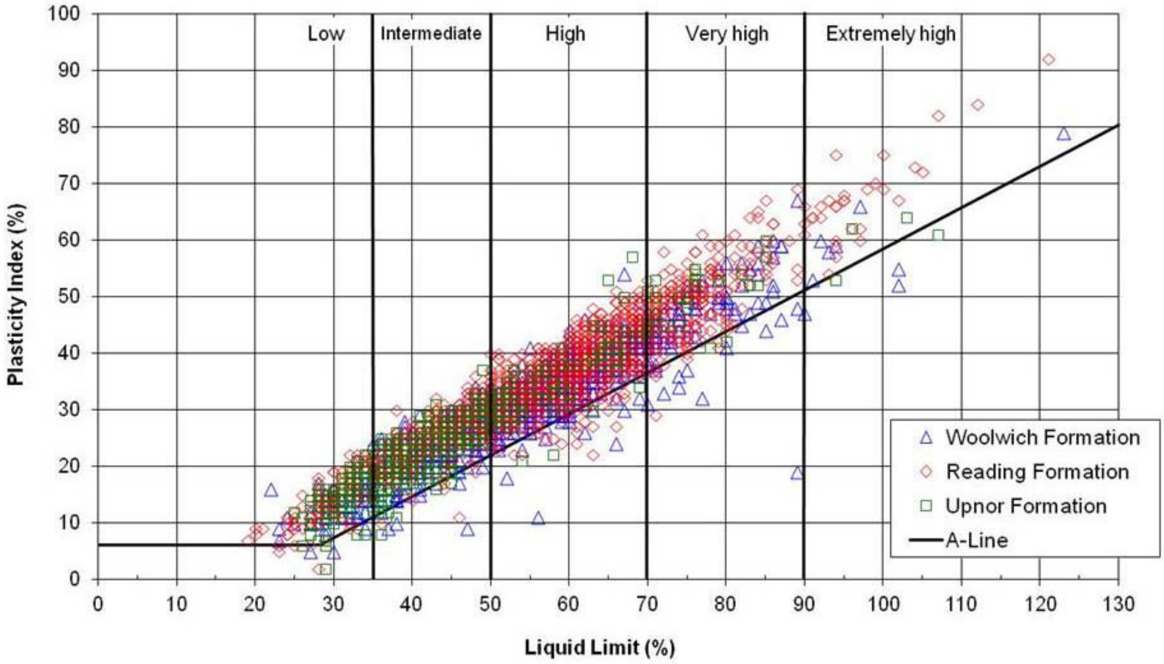

Figure 6.13. Plasticity chart for the Lambeth Group data differentiated by formation.

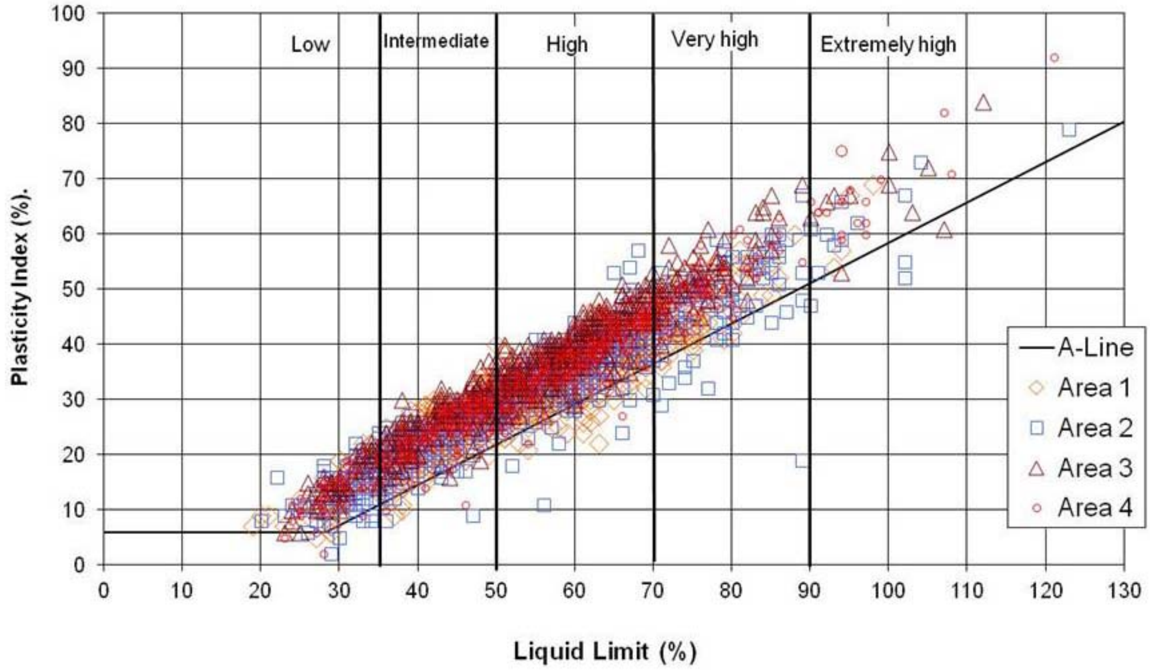

Figure 6.14. Plasticity chart for the Lambeth Group data differentiated by Area.

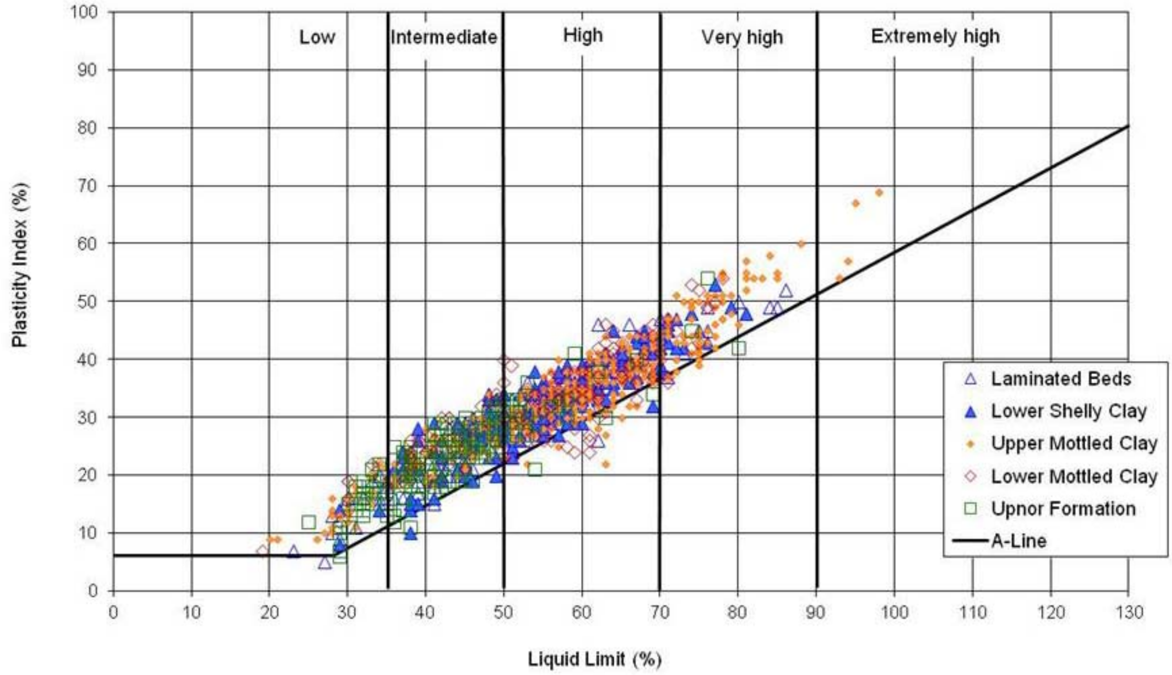

Figure 6.15. Plasticity chart for the Lambeth Group data in Area 1, differentiated by lithostratigraphic unit.

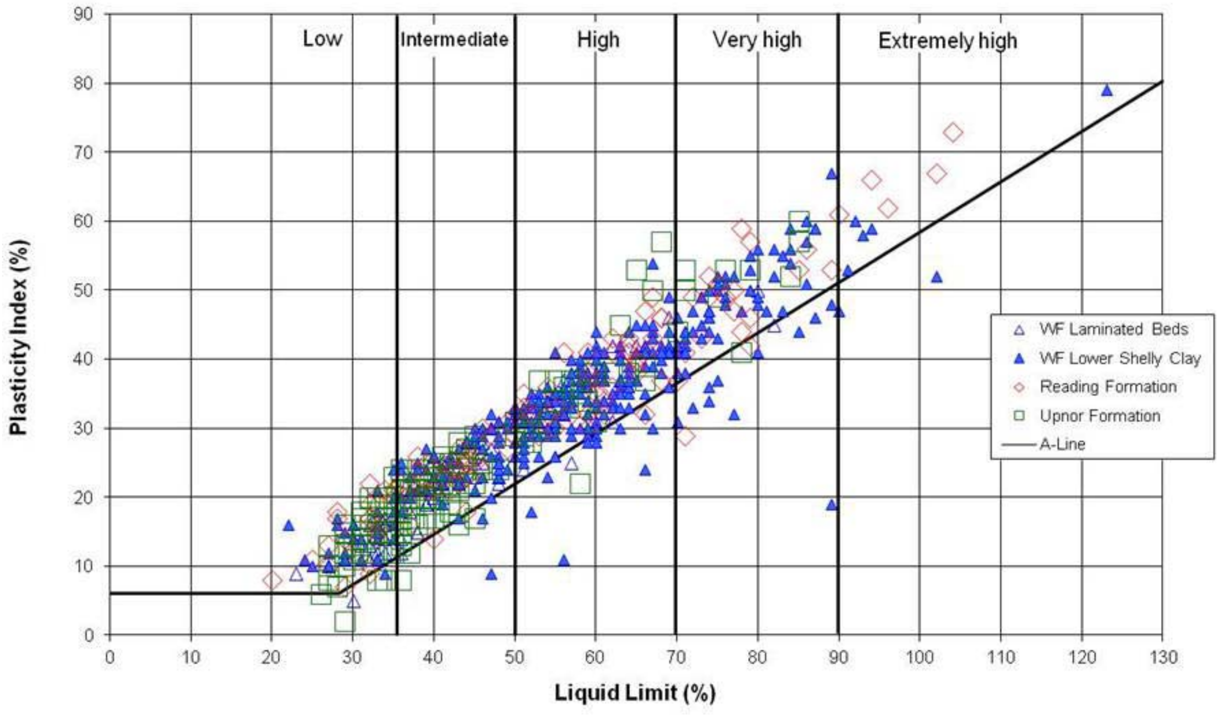

Figure 6.16. Plasticity chart for the Lambeth Group data in Area 2, differentiated by lithostratigraphic unit.

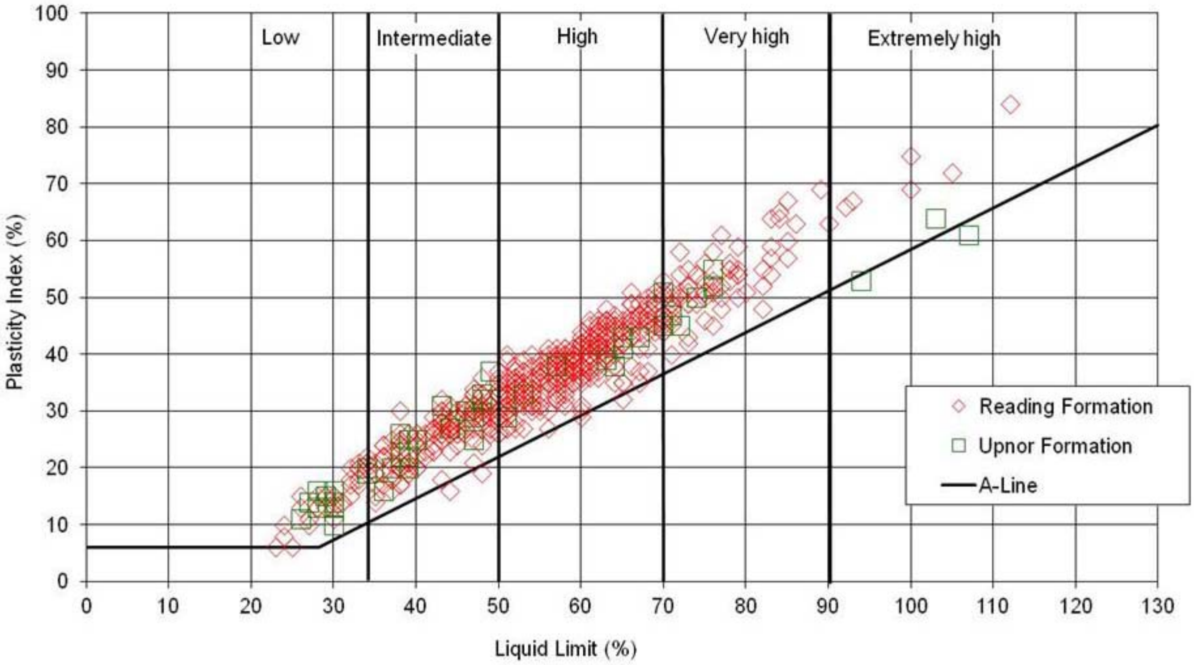

Figure 6.17. Plasticity chart for the Lambeth Group data in Area 3, differentiated by formation.

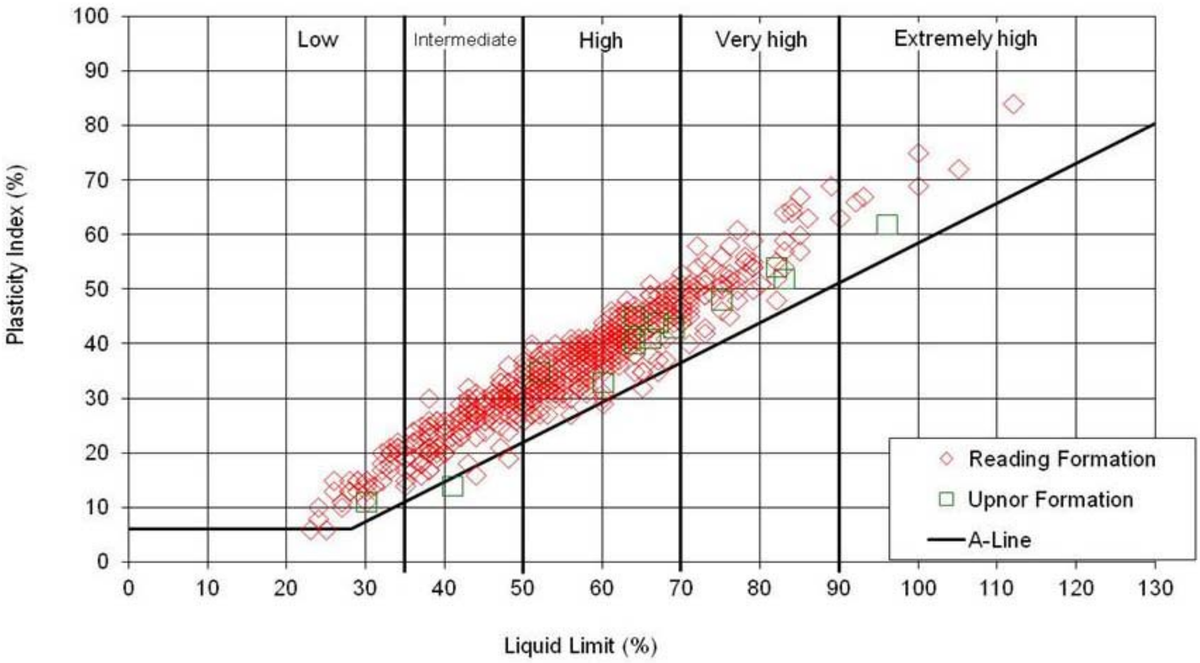

Figure 6.18. Plasticity chart for the Lambeth Group data in Area 4, differentiated by formation.

Liquidity index, I_L, is a ratio which gives an assessment of the 'position' of the *in situ* condition of a soil in its consistency range related to the Atterberg limits.

$$I_L = (w - w_P)/I_P$$

Values of liquidity index may be used as a guide to desiccation or, where equilibrium water content is established, the degree of over-consolidation of a soil. A value of 0 indicates that the natural water content (w) equals the plastic limit (w_P). A value of +1.00 indicates that the natural water content equals the liquid limit (w_L). There are 2,591 liquidity indices for the

Lambeth Group in the database. Values range from –0.6 to +0.86, with overall median and mean values of zero (that is, water contents are predominantly equal to the plastic limits). The median values of all the formations lie very close to zero. The liquidity index is variable near-surface depths because of seasonal changes in water content. The liquidity index profile for all the data, differentiated by formation and shown in Figure 6.19, tends to show a general trend of decreasing liquidity index with increasing depth. However, there are occasionally relatively high values at depth in samples from all formations, but particularly the Woolwich and Upnor formations. Low values occur near-surface but also at depth in all formations.

Liquidity indices for all data differentiated by area are shown in Figure 6.20, and for each area differentiated by lithostratigraphy (Figures 6.21 to 6.24). Area 1 (Figure 6.21) shows a general trend of reducing liquidity index with depth for the majority of the data but with a significant number of random higher or lower data points. Area 2 (Figure 6.22) shows little change in liquidity index with increasing depth. In this area the Reading Formation consists of the Lower Mottled Clay, which tends to be sandy, as does the Upnor Formation; the Lower Shelly Clay contains lignite, which tends to have a higher liquidity index. Areas 3 and 4 (Figure 6.23 and Figure 6.24) comprise the Upnor and Reading formations and show a weak trend of decreasing liquidity index with increasing depth. However, in both areas there are a number of low values in the Reading Formation and, in Area 3, high values in the Upnor Formation below 10 m. It has been suggested (Hight *et al*., 2004) that unusually high and low values may be spurious as a result of sample disturbance resulting in mixing of sands and clays (which may be the case for some parts of the Laminated Beds and the Upnor Formation), or redistribution of water during sampling. High liquidity index values are generally measured on cable percussion samples rather than on rotary core samples (Hight *et al*., 2004). However, some of the unusual values may be due to the variation in particle size where the sample has a large >0.425 mm component, the water content being measured on the whole sample and the plasticity being measured on part of the sample. This effect could be partly removed by correcting the plasticity values but the percentage of <0.425 mm particles has not been recorded in many cases. Also, the Reading Formation may have lower liquidity values due to its desiccation by pedological soil formation processes shortly after deposition.

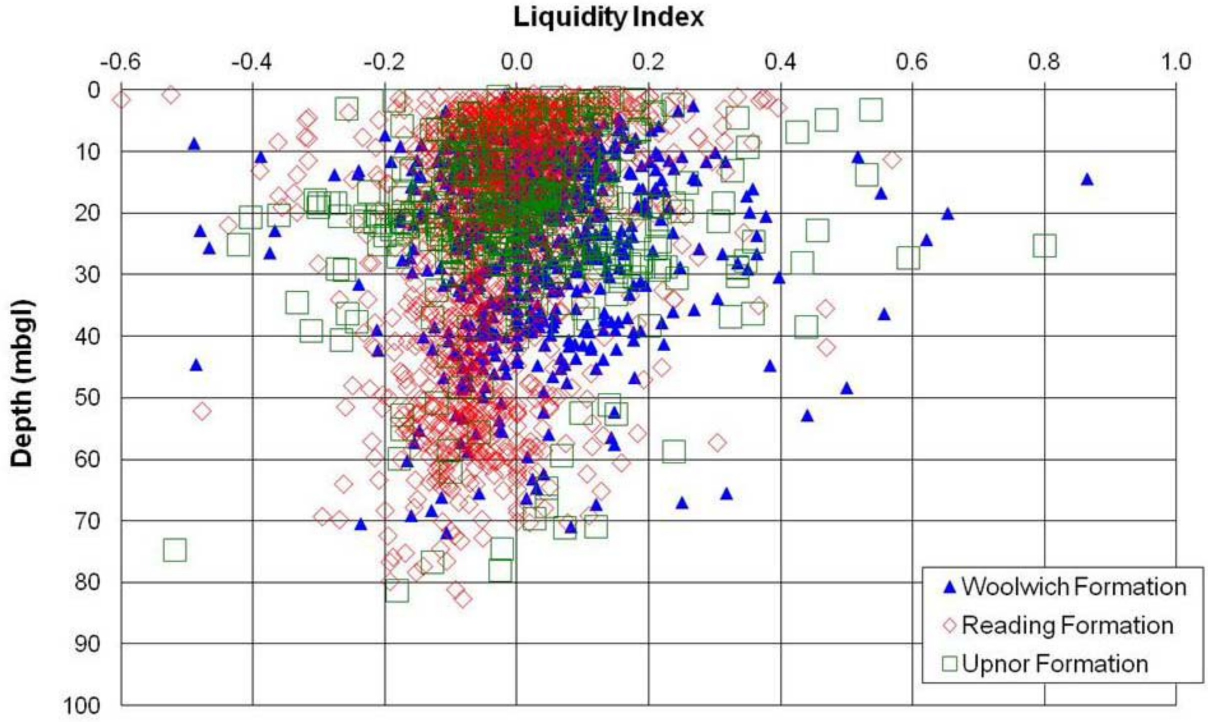

Figure 6.19. Liquidity index profile for the Lambeth Group data, differentiated by Formation.

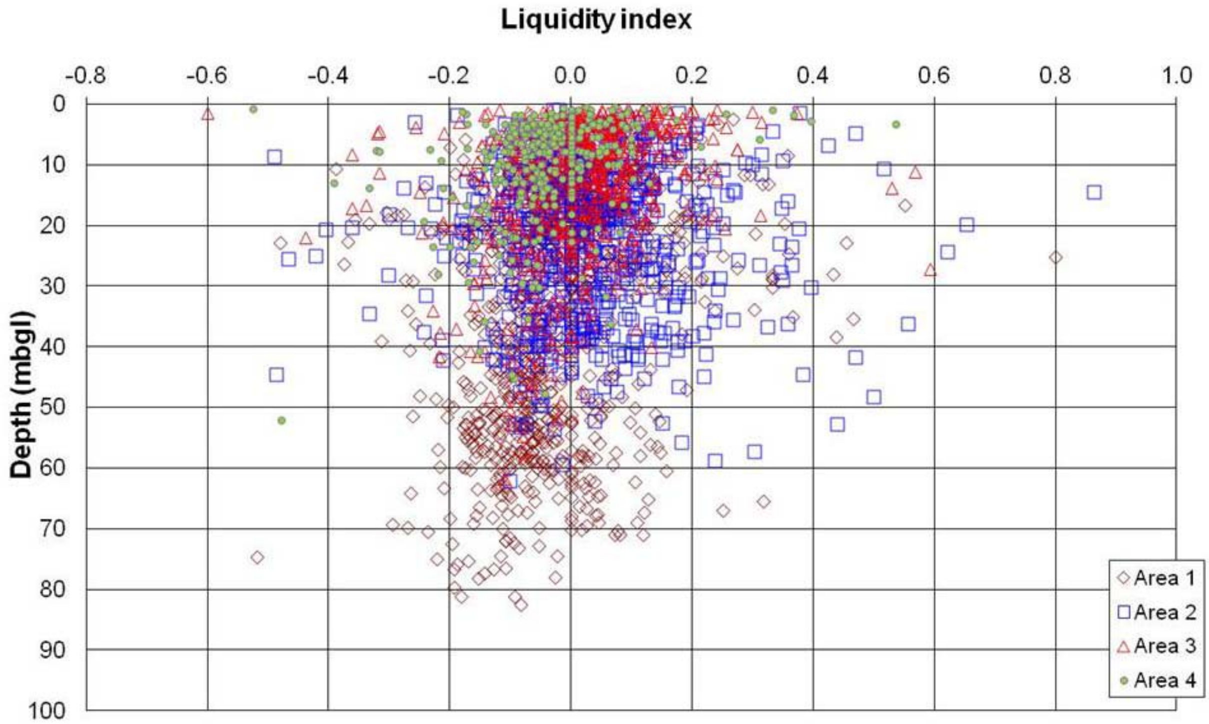

Figure 6.20. Liquidity index profile for the Lambeth Group data, differentiated by Area.

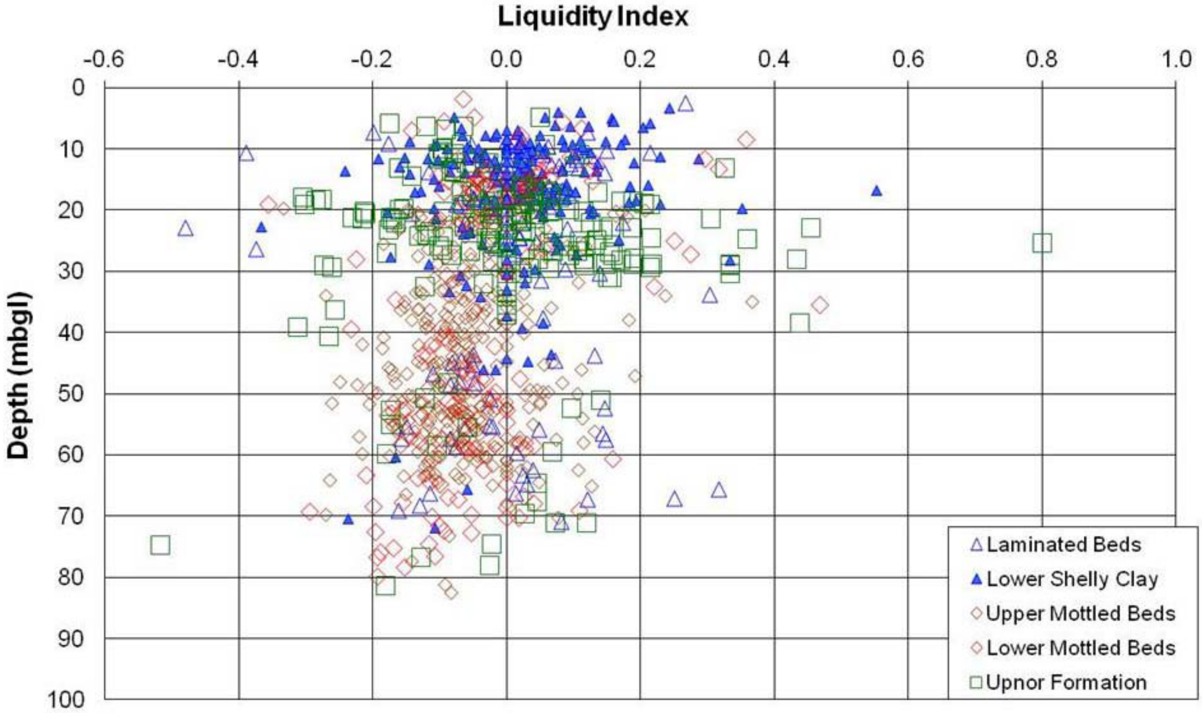

Figure 6.21. Liquidity index profile for the Lambeth Group data in Area 1, differentiated by lithological unit.

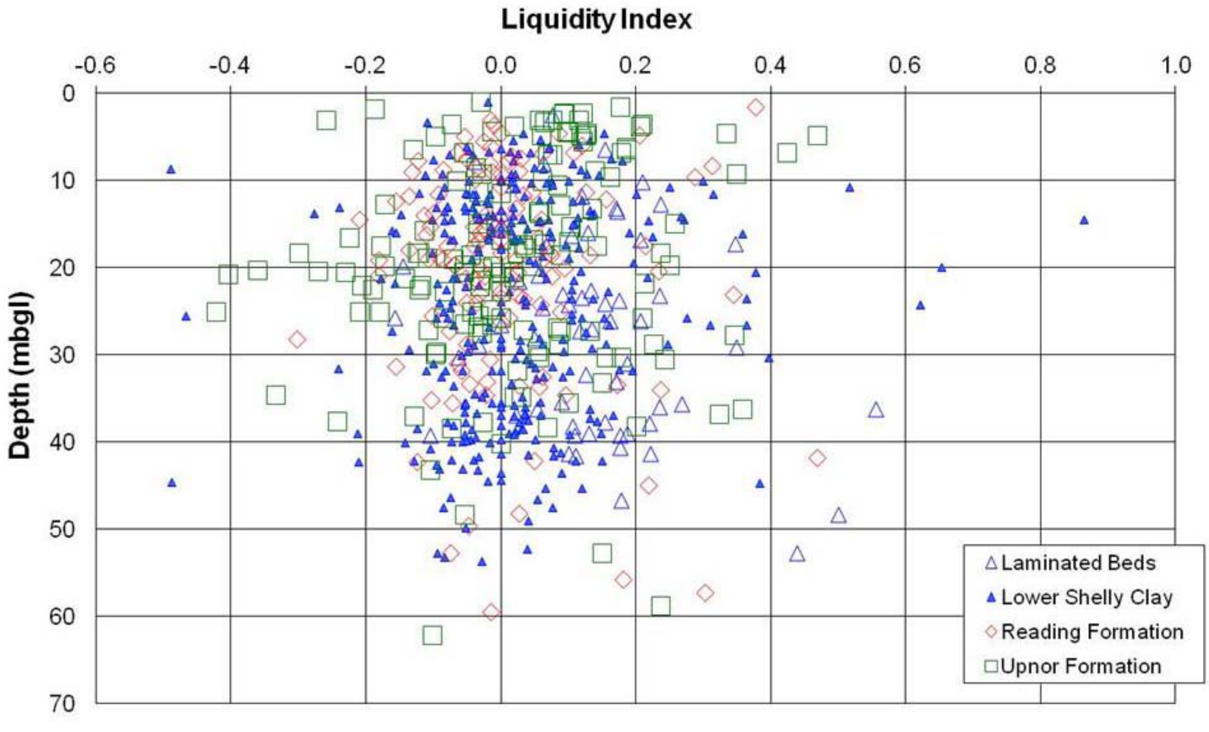

Figure 6.22. Liquidity index profile for the Lambeth Group data in Area 2, differentiated by lithological unit.

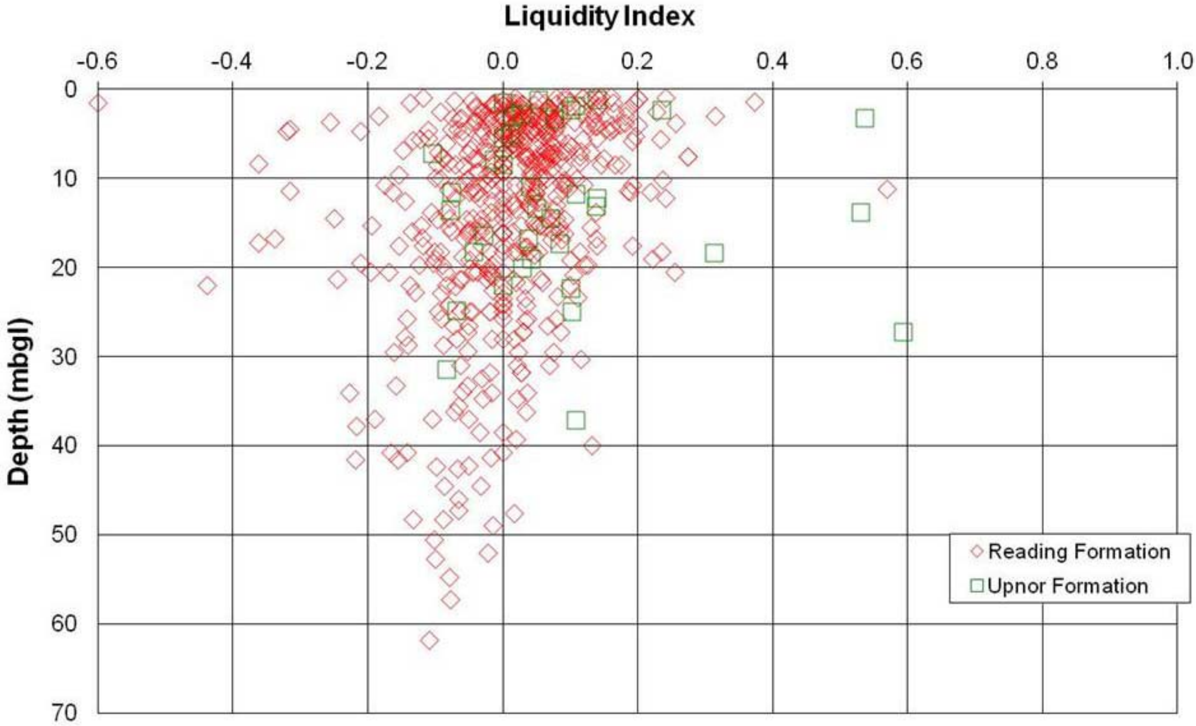

Figure 6.23. Liquidity index profile for the Lambeth Group data in Area 3, differentiated by lithological unit.

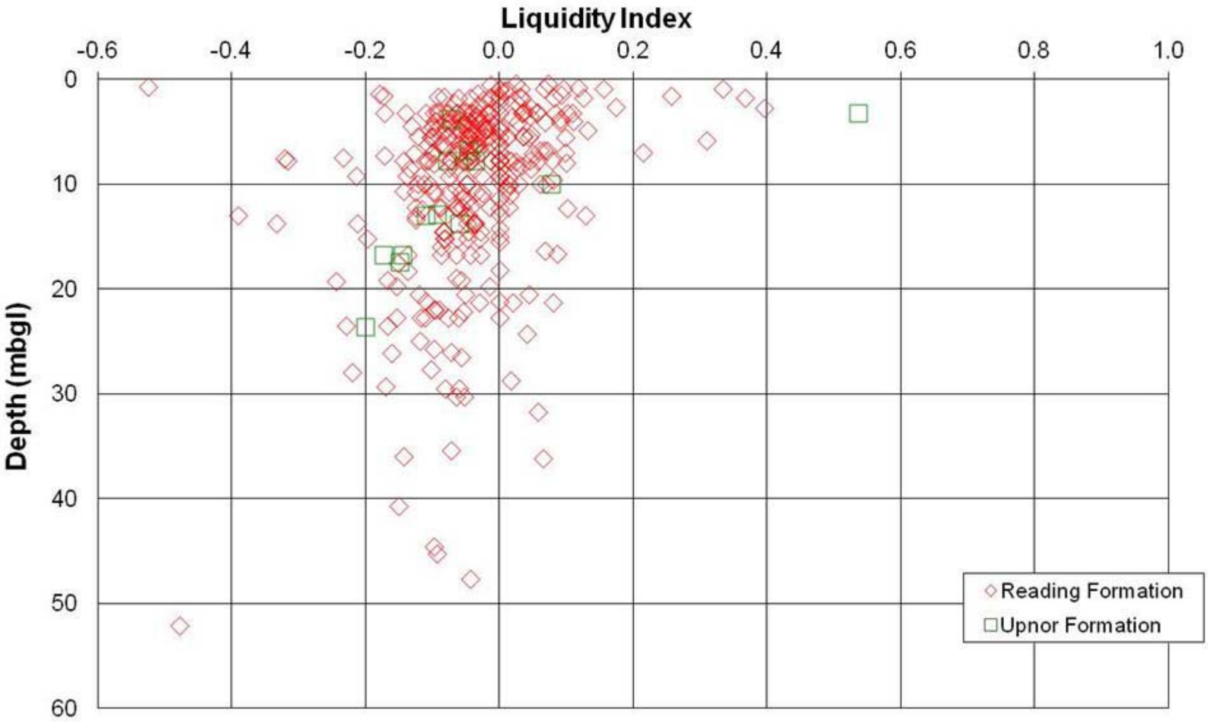

Figure 6.24. Liquidity index profile for the Lambeth Group data in Area 4, differentiated by lithological unit.

6.1.3 Particle size

A total of 1,858 particle-size grading curves are contained in the database. The particle size distribution data are presented as percentile plots including the minimum (coarsest sample) and maximum (finest sample). The different percentiles shown depend on the number of data for each different category, as shown in Table 6.1. Figure 6.25, illustrates the different percentile boundary lines and colours to depict percentile ranges. Whilst the percentile plots do not represent individual grading curves they conveniently summarise large amounts of data and show the distribution of different proportions of the data.

Table 6.1. Number of samples for the percentiles shown in the particle size graphs

Number of samples	Percentile values shown
25 to 99	10th and 90th
100 to 499	2.5th and 97.5th
500 or more	0.5th and 99.5th

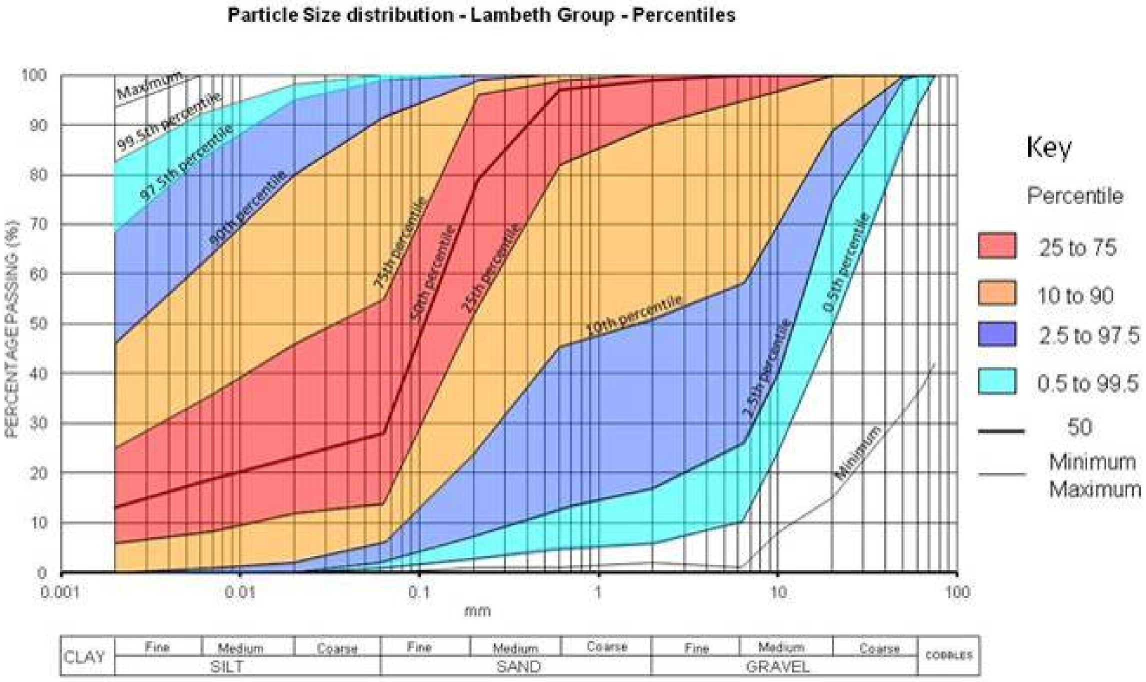

Figure 6.25. Key for the particle size distribution graphs.

The particle size distribution of the Lambeth Group for all data and by formation are shown in Figure 6.26. The Lambeth Group as a whole is very varied ranging from clay to slightly sandy, gravelly cobbles. However, most of the Lambeth Group ranges between slightly sandy clays and silty sands and gravels. The Upnor Formation is the most variable but a majority of samples are coarse grained with over 10% gravel. The Woolwich Formation is more often finer grained than the other formations with fewer samples containing gravel. The Reading Formation also contains a wide spread of lithologies with a higher proportion of clay samples, and less than 10% gravel samples.

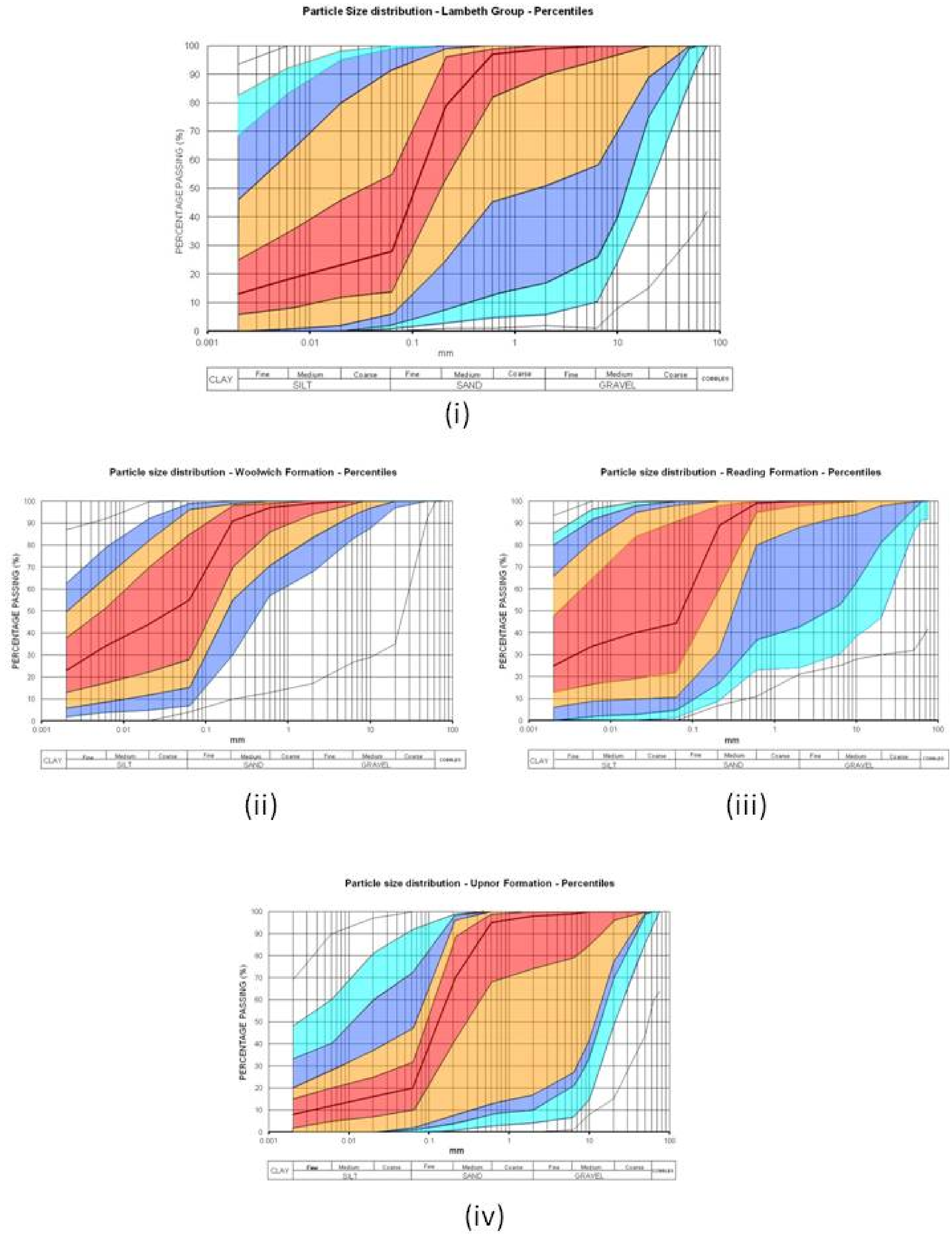

Figure 6.26. Particle Size distribution of the (i) Lambeth Group, (ii) Woolwich Formation, (iii) Reading Formation and (iv) Upnor Formation.

6.1.3.1 Upnor Formation

Fifty percent of the Upnor Formation (Figure 6.27) varies between a clayey or silty fine to medium sand and a slightly silty slightly gravelly fine to medium sandy clay with a little coarse sand. Nearly 90 percent of all samples are predominantly coarse-grained varying from clayey or silty fine sand to gravel and cobbles. Between 5 and 10% of samples are fine-grained.

Grading by area of the Upnor Formation shows that for the finer sand to clay fractions the median values and interquartile ranges (i.e. the area shown between the 25 and 75 percentiles, representative of the central half the data distribution) are similar in Areas 1, 2 and 3 and indicative of clayey fine to medium sands with a little fine to medium gravel. However, gravel content is variable, with Area 1 having a greater proportion of gravel samples followed by Area 2. Flint gravel is often present in the basal part of the Upnor Formation in all the areas, but in Areas 1 and 2 additional gravel occurs in the ‘pebble beds’ in the upper part of the formation and as gravel-sized particles of hard bands, most commonly calcrete. The sandy gravels ’pebble beds’ might not be recovered or be only partially recovered by either rotary or cable percussion drilling methods, and this may reduce the representation of these materials within the dataset.

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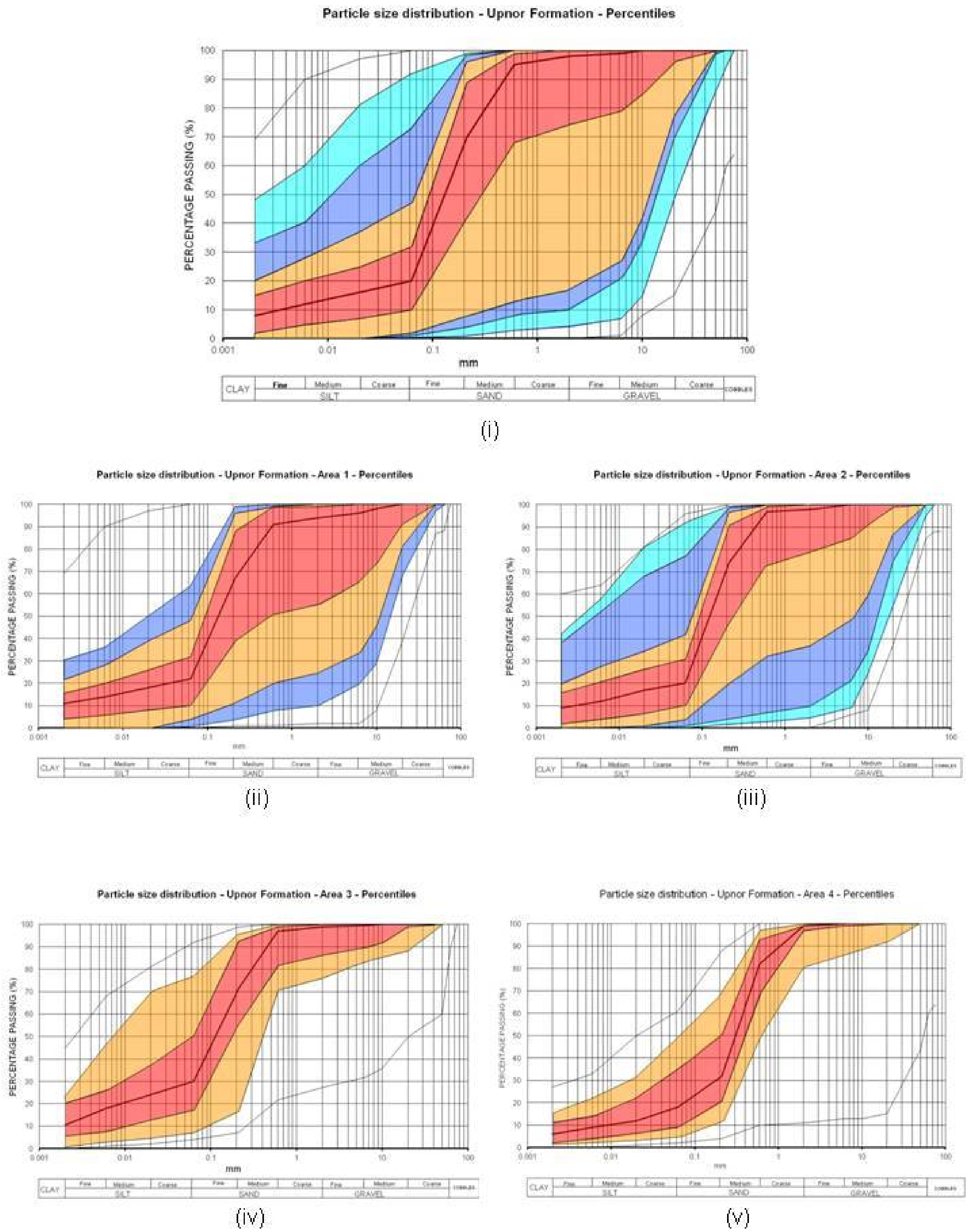


Figure 6.27. Particle size distribution of (i) Upnor Formation, (ii) Area 1, (iii) Area 2, (iv) Area 3 and (v) Area 4.

6.1.3.2 Reading Formation

The grading of the Reading Formation (Figure 6.28) is almost as variable as the Upnor Formation, however, it is generally finer-grained, the majority being clay, sandy clay or clayey/silty fine to medium sand. Gravel is a major component of less than about 5% of samples.

The particle size distributions of the Reading Formation differentiated by stratigraphical unit for different areas shows some differences between the Upper and Lower Mottled Clay in Area 1 and 2. No such distinction can be made in Areas 3 and 4 and the grading data are presented for undifferentiated Mottled Clay. In Area 1 the Lower Mottled Clay are coarser than the Upper Mottled Clay. The Upper Mottled Clay is predominantly clay with sand layers that are almost always fine-grained, and it is essentially gravel free. Less than half the samples contained more than 10% sand. In contrast the Lower Mottled Clay generally contains a greater proportion of sand, particularly in Area 2, where these beds generally grade into a sand to the east. A majority of the Lower Mottled Clay samples contain over 10% sand; most samples comprising sandy clay or clay/silty fine to medium sand, with some samples containing significant proportions of gravel, which is generally composed of calcium carbonate or iron concretions.

In Area 3, the undifferentiated Reading Formation generally varies between clay and fine to medium sand, and contain much less gravel in comparison to the Lower Mottled Clay. The grading distribution appears to reflect a ‘mix’ or amalgamation of the Lower and Upper Mottled Clay of the Reading Formation in Area 1, but with much less gravel. The gravel particles, where described, comprise calcium carbonate concretions (calcrete), which are less common in Area 3.

In Area 4, the undifferentiated Reading Formation is generally more variable, as shown by the wider interquartile range. These deposits tend to be more gravelly than both the Reading Formation of Area 3 and the Upper Mottled Clay of Area 1. Here the gravel may consist of flint or calcium carbonate concretions.

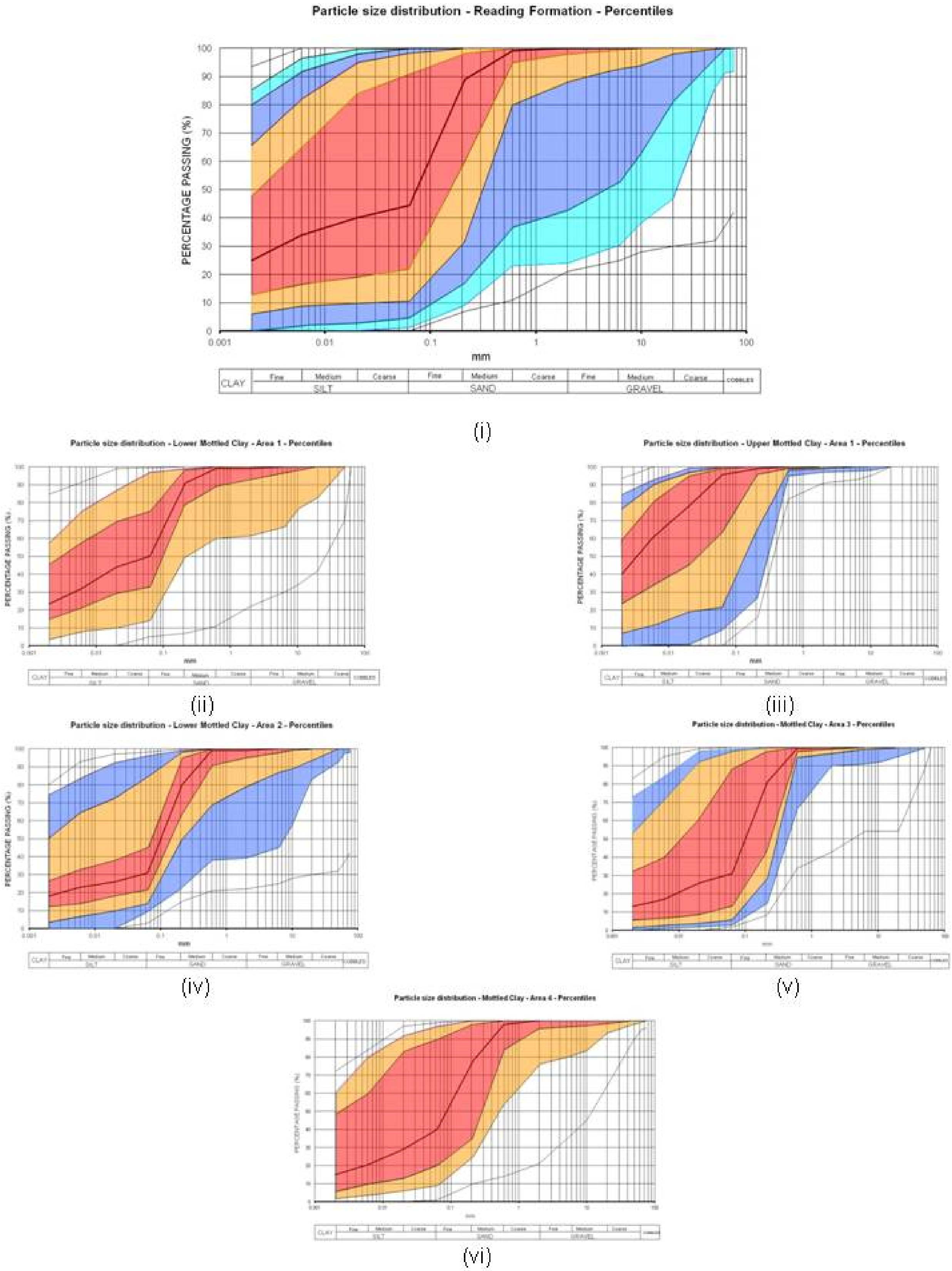


Figure 6.28. Particle size distribution of the (i) Reading Formation, (ii) Upper Mottled Clay in Area 1, (iii) Lower Mottled Clay in Area 1 and (iv) Area 2, and (v) Mottled Clay in (vi) Area 3 and (vi) Area 4.

6.1.3.3 Woolwich Formation

The Woolwich Formation as a whole appears to be, generally, more well-graded than the Upnor and Reading formations (Figure 6.29) and the Laminated Beds are more well-graded than the Lower Shelly Clay. This may be a true reflection of the particle size or could be due to the mixing of laminations of different lithology before testing to provide suitable sample size, or during drilling and sampling, for instance in disturbed samples. If the particle size distribution of the Laminated Beds is affected by mixing then the resulting particle size will depend on the lithologies and thickness of the laminations.

Gradings for the Laminated Beds in Areas 1 and 2 show some differences, Area 2 is generally coarser, containing a greater proportion of fine sand and more gravel. The gravel is predominantly shelly but may also comprise iron-rich concretions such as siderite.

The Lower Shelly Clay in Area 1 is predominantly a slightly sandy clay or, less frequently, clayey sand often with some shell gravel; whereas, in Area 2 it tends to contain coarser material as it is sandier further east. The increase in gravel in this area is predominantly shell but also lignite particles in the southeast.

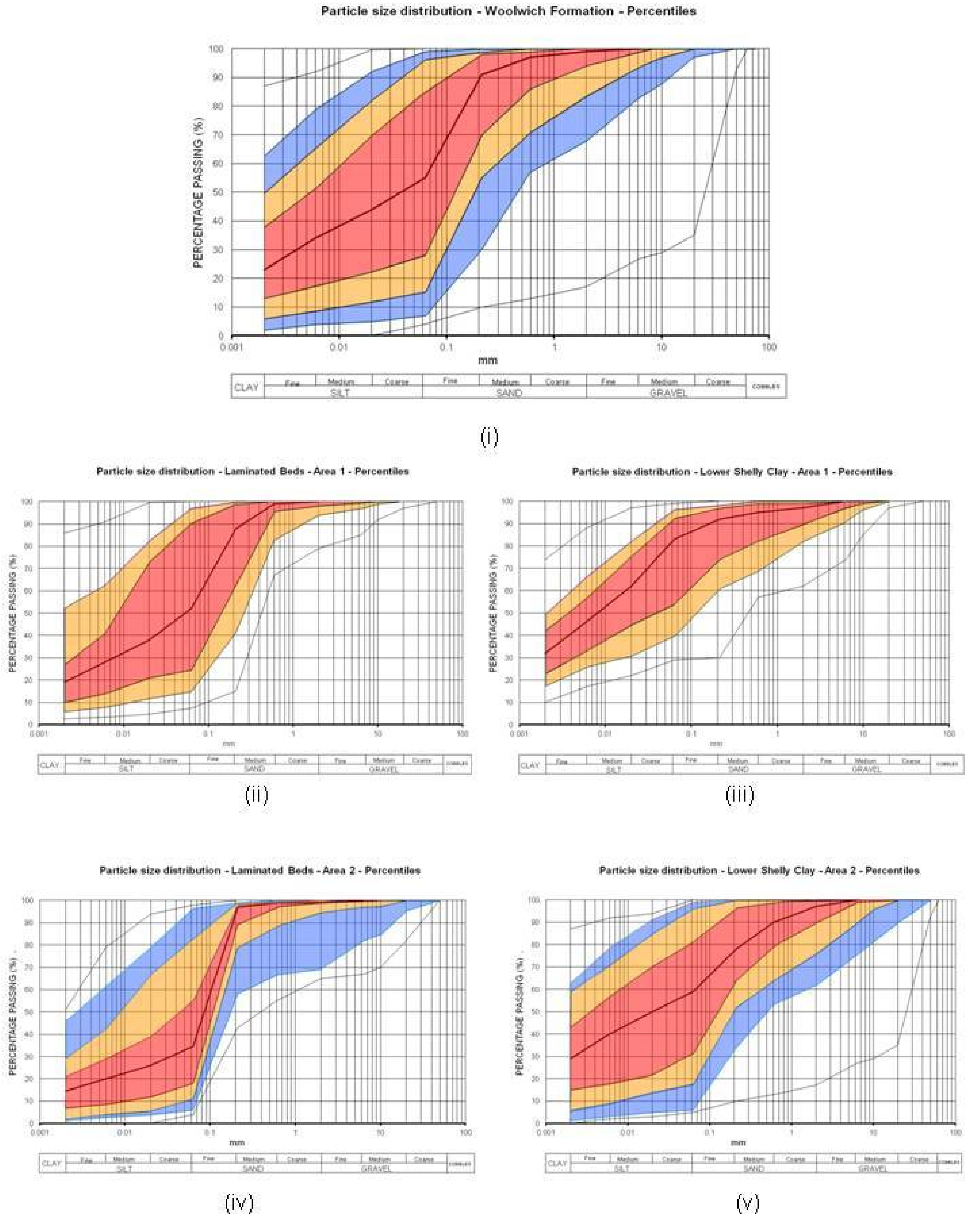


Figure 6.29. Particle size distribution of the Woolwich Formation. (i) All the Woolwich Formation data, (ii) Laminated Beds in Area 1, (iii) Lower Shelly Clay in Area 1, (iv) Laminated Beds in Area 2 and (v) Lower Shelly Clay in Area 2.

6.1.3.4 SUMMARY OF PARTICLE SIZE

The Lambeth Group contains a wide variety of deposits varying from clay to gravel and cobbles. The different formations and units do, however, show certain characteristics that may limit the variability. The Upnor and Reading Formation are the most variable.

Upnor Formation

- Highly variable,
- Generally coarser than the other formations, more than 75% of samples contained more than 50% coarse fraction,
- A majority of samples contain some gravel and over 25% of samples contained more than 20% gravel,
- The gravel is generally flint but may also be shell or calcium carbonate or iron concretions,
- Gravel in the upper part of the formation is an important component in Areas 1 and 2 (‘pebbles beds’), however, they may be under represented in the dataset as they might not be recovered during drilling and sampling.

Reading Formation

- Highly variable,
- The Lower Mottled Clay is generally coarser than the Upper Mottled Clay, containing more fine to medium sands and gravels, and becoming sandier to the east in Area 2,
- The Reading Formation in Areas 3 and 4 have similarities with both the Upper and Lower Mottled Clay of Area 1 but contain more sand,
- Gravels in the Reading Formation generally consist of calcareous or iron oxide concretions, and are predominantly found in the Lower Mottled Clay. Flint gravel may occur in Area 4,
- The particle size distribution of the Reading Formation is consistent with fine-grained overbank deposits with mostly fine and sometimes medium sand representing channel infill. In some places, generally in the lower part, gravel has formed as calcium carbonate and iron oxide cemented concretions as a result of subtropical soil formation processes.

Woolwich Formation

- Highly variable,
- Generally more well graded than the other formations,
- Acquired Laminated Beds test samples may often comprise a mix of different coarse and fine laminae,
- Generally the east (Area 2) is coarser than the west (Area 1),
- Most of the gravel is shell but may also comprise iron concretions such as siderite, and, in the Lower Shelly Clay in Area 2, lignite.

6.1.4 Sulphate, pH, and other chemical tests

A small group of relatively simple chemical tests for soils is usually included in geotechnical testing. These are: pH, water soluble sulphate (2:1 water/soil extract), acid soluble sulphate, water soluble chloride (2:1 water/soil extract), and organic content (BS1377 [BSI, 1990a]; Head, [2006]; BRE Special Digest 1,[2005]). In addition, there are tests for the sulphate content of ground water used in modern chemistry laboratories. Other chemical tests that relate to environmental assessments, including total sulphur, water soluble magnesium (2:1 water/soil extract), ammonium ion, water soluble nitrate (2:1 water/soil extract), are not considered here as they are usually a result of site-specific contamination studies and are normally of very local occurrence.

Organic matter is derived from a wide variety of animal and plant remains so there may be a wide range of compounds. The organic compounds present depend on the origin and maturation, which is usually a result of burial and heat. Organic matter, particularly peat or recent organic-rich deposits have reduced bearing capacity, higher and more long term compressibility, lower acidity, and may produce and contain gas.

Excessive acidity or alkalinity of groundwater can have detrimental effects on concrete below ground level. Even moderate acidity can corrode metals. Some soil stabilisation agents may be unsuited to alkaline conditions. The pH also affects the solubility of many metal ions. The measurement is usually carried out on groundwater samples whenever the sulphate content is measured.

Groundwater and pore-water containing sulphate can attack concrete and other materials containing cement. A reaction takes place between the sulphate and aluminium compounds in the cement, causing crystallisation of complex compounds resulting in expansion and build up of internal stresses in the concrete and softening of the concrete. The values obtained from the sulphate tests are used primarily for concrete specification during construction design.

Classification and testing recommendations for sulphate content in soil and groundwater have developed and changed in recent years. A former classification for sulphate in soils given by the Building Research Establishment (BRE Digest 250, [BRE 1981, 1986]) is shown in Table 6.2. This would have informed many of the test regimes carried out prior to 1991 and hence a significant proportion of the sulphate data in the Lambeth Group database.

Table 6.2. Classification of sulphate content in soil and groundwater, for near-neutral groundwater conditions (after BRE, 1981; 1986)

Class	Concentration of sulphate as SO_3		
	Solid		Groundwater
	Total by acid extraction %	2:1 water:soil extract g/l	g/l
1	<0.2	<1.0	0.3
2	0.2 to 0.5	1.0 to 1.9	0.3 to 1.2
3	0.5 to 1.0	1.9 to 3.1	1.2 to 2.5
4	1.0 to 2.0	3.1 to 5.6	2.5 to 5.0
5	>2	>5.6	>5.0

In 1991 the classification changed to BRE Digest 363 (BRE 1991; 1995). This BRE classification (Table 6.3) requires assessment of total sulphate, then if above the threshold for Class 1, the aqueous sulphate test is carried out to decide on the appropriate cement type. The classification concentrations for the water extraction and groundwater sulphate are the same as the previous classification but multiplied by 1.2 as the values are now expressed as SO_4 and not SO_3.

Table 6.3. Classification of sulphate content for soils and groundwater, for near-neutral groundwater conditions (after BRE 1991; 1995)

Class	Concentration of sulphate as SO_4		
	Soil		Groundwater
	Total by acid extraction %	2:1 water:soil extract g/l	g/l
1	<0.24	<1.2	0.4
2	If >0.24 classify on the basis of 2:1 extract	1.2 to 2.3	0.4 to 1.4
3		2.3 to 3.7	1.4 to 3.0
4		3.7 to 6.7	3.0 to 6.0
5		>6.7	>6.0

The current classification system in use is BRE Special Digest 1: 2005 (BRE, 2005). This BRE classification uses different classification schemes depending on the category of the site. The classification system used for natural ground locations is presented in

Table 6.4. The four site categories are:

- Natural ground locations except those containing pyrite
- Natural ground locations that contain pyrite
- Brownfield locations except those containing pyrite
- Brownfield locations that contain pyrite

In addition to specifying a Design Sulphate (DS) Class (based on water soluble sulphate and total potential sulphate), the scheme also specifies an Aggressive Chemical Environment for Concrete (ACEC) Class (based on groundwater mobility and pH). For natural ground locations water soluble sulphate and pH of soil and water are assessed against criteria in Table 6.4. If pyrite is present in significant amounts and concrete will be exposed to disturbed ground then assessment is also made against total potential sulphate (conservatively estimated as three times the total sulphur). For brownfield locations water soluble sulphate, pH and total potential sulphate of soil and water are assessed. Where concentration of sulphate are high and pH low, additional criteria for magnesium, chloride and nitrate are also assessed. See BRE Special Digest 1: 2005 (BRE, 2005) for full assessment methodology.

Table 6.4. Classification of sulphate content for soils and groundwater for natural ground locations (after BRE SD1 (BRE, 2005)

Design Sulphate Class	Concentration of sulphate as SO_4			pH		ACEC Class
	Soil		Groundwater	Static water	Mobile Water	
	Total potential sulphate (SO_4%)	2:1 water:soil extract (SO_4 g/l)	(SO_4 g/l)			
DS-1	<0.24	<0.5	<0.4	≥2.5		AC-1s
					>5.5	AC-1
					2.5 – 5.5	AC-2z
DS-2	0.24 – 0.6	0.5 – 1.5	0.4 to 1.4	>3.5		AC-1s
					>5.5	AC-2
				2.5 – 3.5		AC-2s
					2.5 – 5.5	AC-3z
DS-3	0.7 – 1.2	1.6 – 3.0	1.5 to 3.0	>3.5		AC-2s
					>5.5	AC-3
				2.5 – 3.5		AC-3s
					2.5 – 5.5	AC-4
DS-4	1.3 – 2.4	3.1 – 6.0	3.1 to 6.0	>3.5		AC-3s
					>5.5	AC-4
				2.5 – 3.5		AC-4s
					2.5 – 5.5	AC-5
DS-5	>2.4	>6.0	>6.0	>3.5		AC-4s
				2.5 – 3.5	≥2.5	AC-5

Results from eight 'chemical' laboratory test parameters are contained in the database: total (solid) sulphate, aqueous extract (solid) sulphate, sulphate in groundwater, pH, organic content, total chloride (solid), aqueous extract (solid) chloride and chloride in groundwater. Total sulphate or total chloride are the acid-soluble sulphate content, whilst aqueous 2:1 water/soil extract sulphate or chloride is the water-soluble sulphate content. Both are obtained from liquid extracts but give the content of the soil itself rather than of the ground water, and are expressed as a percentage by weight and as grams per litre, respectively. Sulphate and chloride content data may be quoted as below detection level. This greatly complicates statistical assessment of the raw data as these data cannot be included. If they are not included, then the dataset is not wholly representative and may be slightly biased. However, the use of classes for cement type for sulphate content does not have this problem as the 'below detection level' data will all be DS Class 1. The number of values used in statistically analysing the chemical data and those below detection level, for each test type, are presented in Table 6.5. Assessment has only been made for natural ground using only pH, total sulphate by acid extraction, water soluble sulphate and groundwater sulphate. There is little data for chloride and no data were available for total potential sulphate, magnesium, or nitrate.

The percentage of samples in the different 'Design Sulphate Classes' for each Formation using the accepted classification schemes (Table 6.4) are given in Table 6.6. Aqueous extract sulphates are represented by 140 data values that range from below detection level to 9.21 g/l. About 10% of the Woolich Group and 6% of the Lambeth Group are classified as DS Class 3 or more. The Reading Formation has the lowest DS Class, nearly always DS Class 1.

Groundwater sulphate tests show similar trends to the total sulphate and aqueous sulphate results. Less than 20% of all the samples are classified as DS Class 2 or more, the great majority being from the Woolwich Formation.

Table 6.5. The number of data values for chemical tests

Test type	Lithostratigraphy	Number of values used in statistical analysis	Below detection level
Sulphate, Acid extraction or Total Sulphate	Lambeth Group	488	40
	Woolwich Formation	178	8
	Reading Formation	171	28
	Upnor Formation	138	4
Sulphate, 2:1 Aqueous extraction	Lambeth Group	136	4
	Woolwich Formation	53	0
	Reading Formation	55	4
	Upnor Formation	28	0
Sulphate, Groundwater	Lambeth Group	92	5
	Woolwich Formation	22	0
	Reading Formation	33	4
	Upnor Formation	37	1
pH	Lambeth Group	664	-
	Woolwich Formation	213	-
	Reading Formation	264	-
	Upnor Formation	187	-
Organic content	Lambeth Group	58	-
	Woolwich Formation	33	-
	Reading Formation	17	-
	Upnor Formation	8	-
Chloride, Aqueous extraction	Lambeth Group	30	3
	Woolwich Formation	10	1
	Reading Formation	3	1
	Upnor Formation	13	1
Chloride, Groundwater	Lambeth Group	124	-
	Woolwich Formation	40	-
	Reading Formation	14	-
	Upnor Formation	68	-

Table 6.6. Percentage of total sulphate class, aqueous extract sulphate and groundwater sulphate (BRE, 1995) of the Lambeth Group and its formations

Test type and formation	Percentage of samples in each sulphate class				
	DS-1	DS-2	DS-3	DS-4	DS-5
Aqueous soluble sulphate					
Lambeth Group	55	38	6	0	<1
Woolwich Formation	40	56	10	0	0
Reading Formation	87	13	0	0	0
Upnor Formation	67	30	0	0	2
Groundwater sulphate					
Lambeth Group	81	19	<1	0	
Woolwich Formation	66	34	0	0	
Reading Formation	93	7	0	0	
Upnor Formation	90	9	1	0	

The total sulphate, aqueous soluble sulphate and ground water sulphate versus depth profiles (Figure 6.30 to Figure 6.32) do not show a discernible trend with depth; unlike the London Clay Formation (Figure 6.33 and Figure 6.34), which shows a general decrease in maximum sulphate contents (total and aqueous) with increasing depth. Typically, sulphate in clay deposits is associated with subaerial weathering, hence the reduction of sulphate with depth in the London Clay Formation. Low sulphate values in the Reading Formation are most likely the result of sub-tropical weathering shortly after its deposition, when oxidation of sulphide to sulphate would have happened and the sulphate removed by dissolution as a part of the weathering process. In contrast, the Woolwich Formation and much of the Upnor Formation were not subject to similar weathering to any great extent and usually retain iron sulphide and calcium carbonate until the iron sulphide is oxidised by contemporary weathering. This may occur at depth due to air ingress when the water table is depressed. This is much less likely in the thick clay sequence of the London Clay Formation.

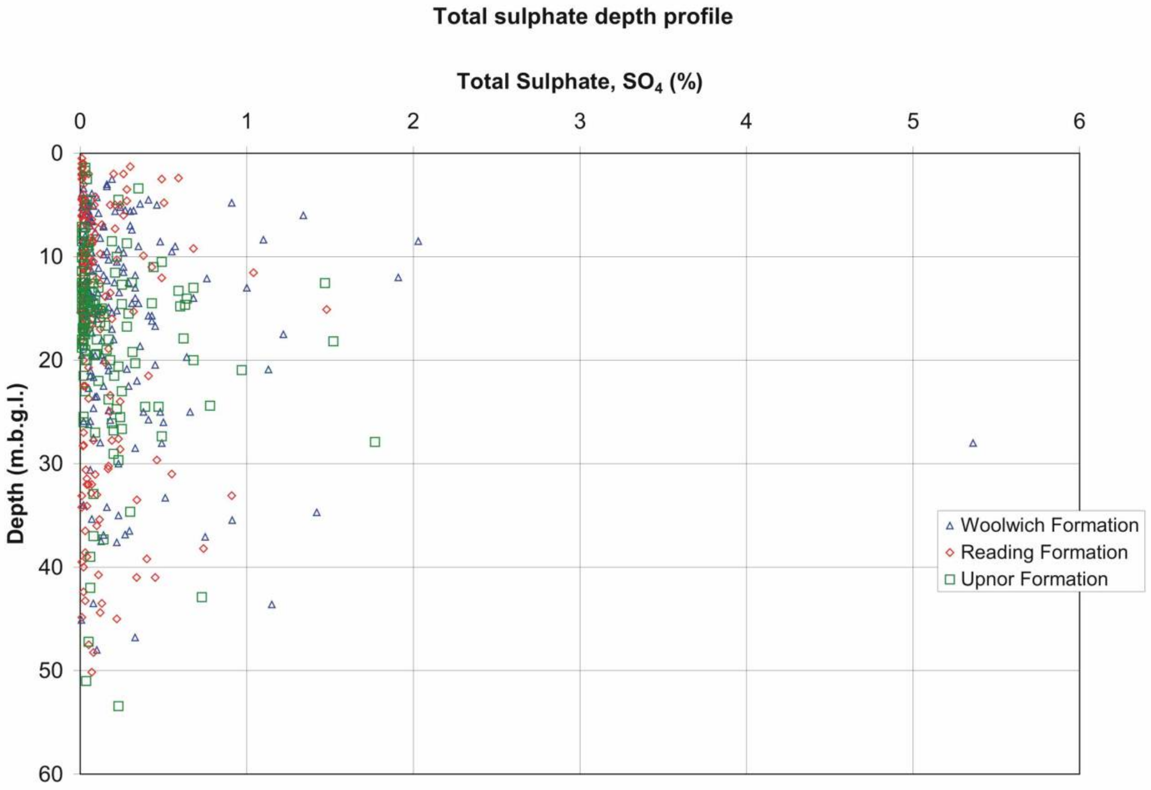


Figure 6.30. Lambeth Group total sulphate profile differentiated by formation.

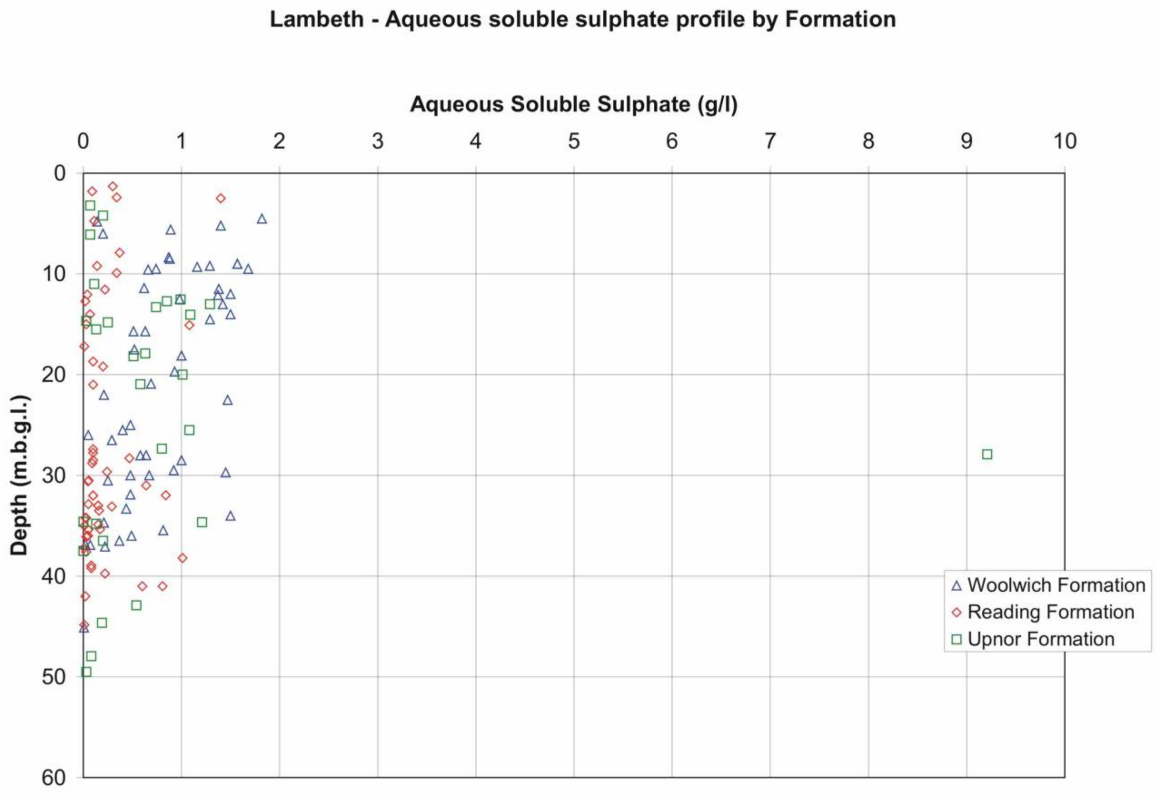


Figure 6.31. Lambeth Group aqueous soluble sulphate profile differentiated by formation.

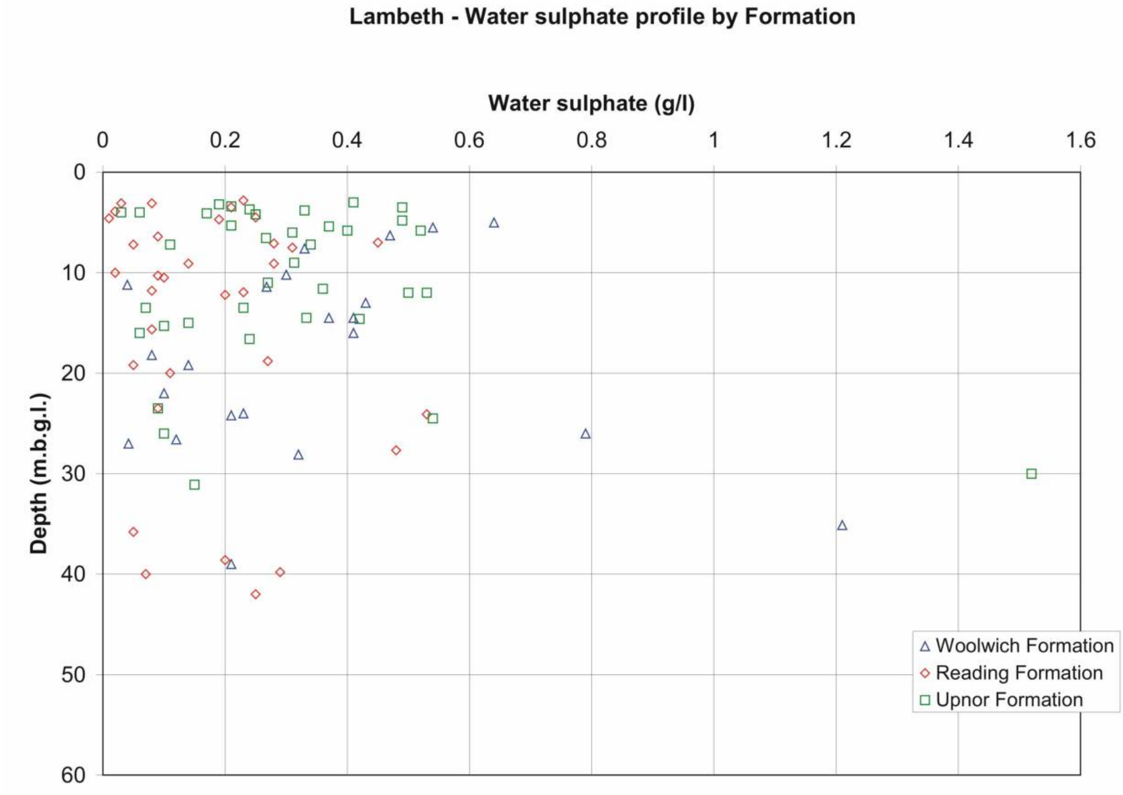


Figure 6.32. Lambeth Group groundwater sulphate differentiated by formation.

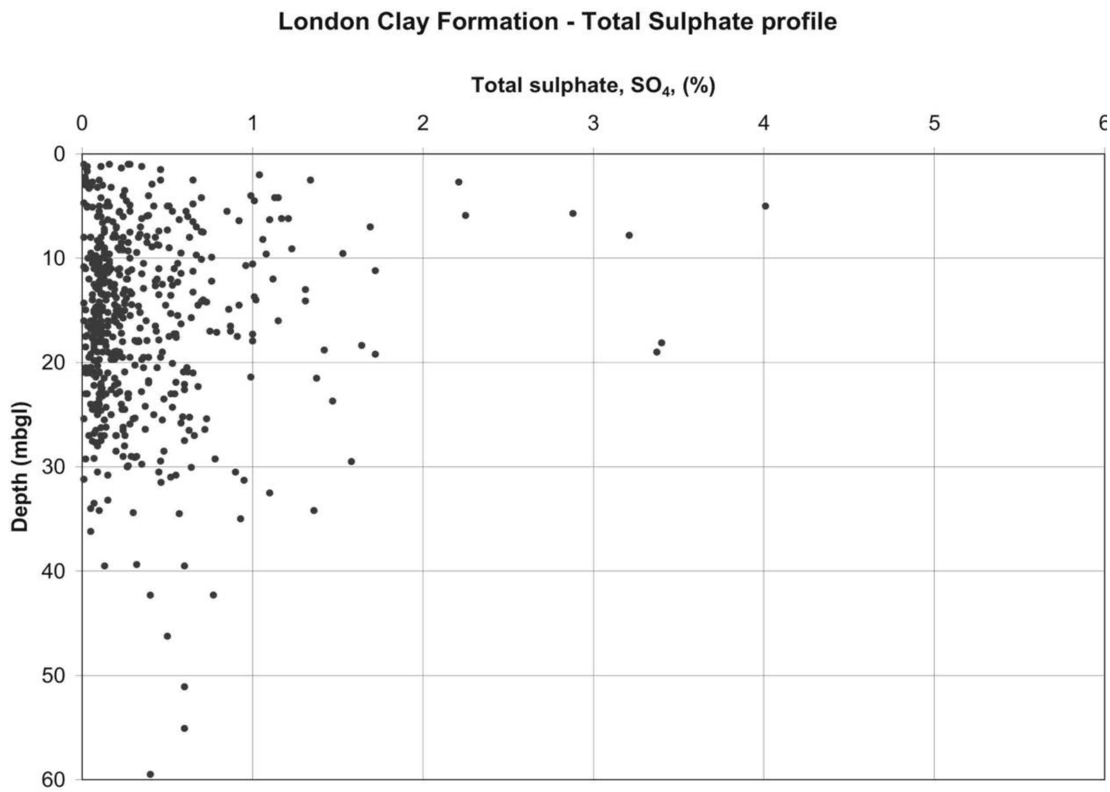


Figure 6.33. London Clay Formation total sulphate profile.

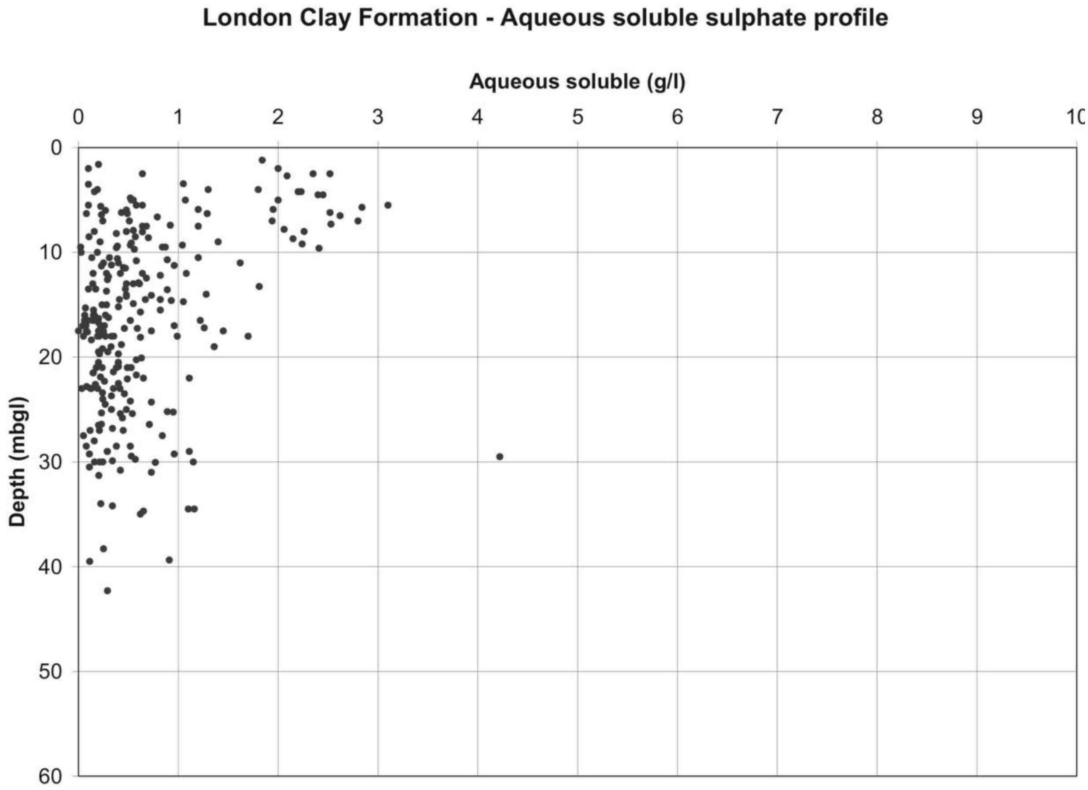


Figure 6.34. London Clay Formation aqueous soluble sulphate profile.

6.1.4.1 pH

The analysis of pH is based on 664 data values ranging between 3.7 and 9.9. The median values of all the formations and units vary between 7.3 and 8.1, that is, slightly alkaline. About 70% of all values indicate that the samples have pH of 7 to 8. Most of the more acidic samples (pH <6) are from the Upnor and Woolwich formations, particularly from Area 2. This is probably related to organic content and/or the oxidation of pyrite. All the samples with pH of less than 6 are from the top 10 m, those with values in excess of pH 9 may be from any depth (Figure 6.35).

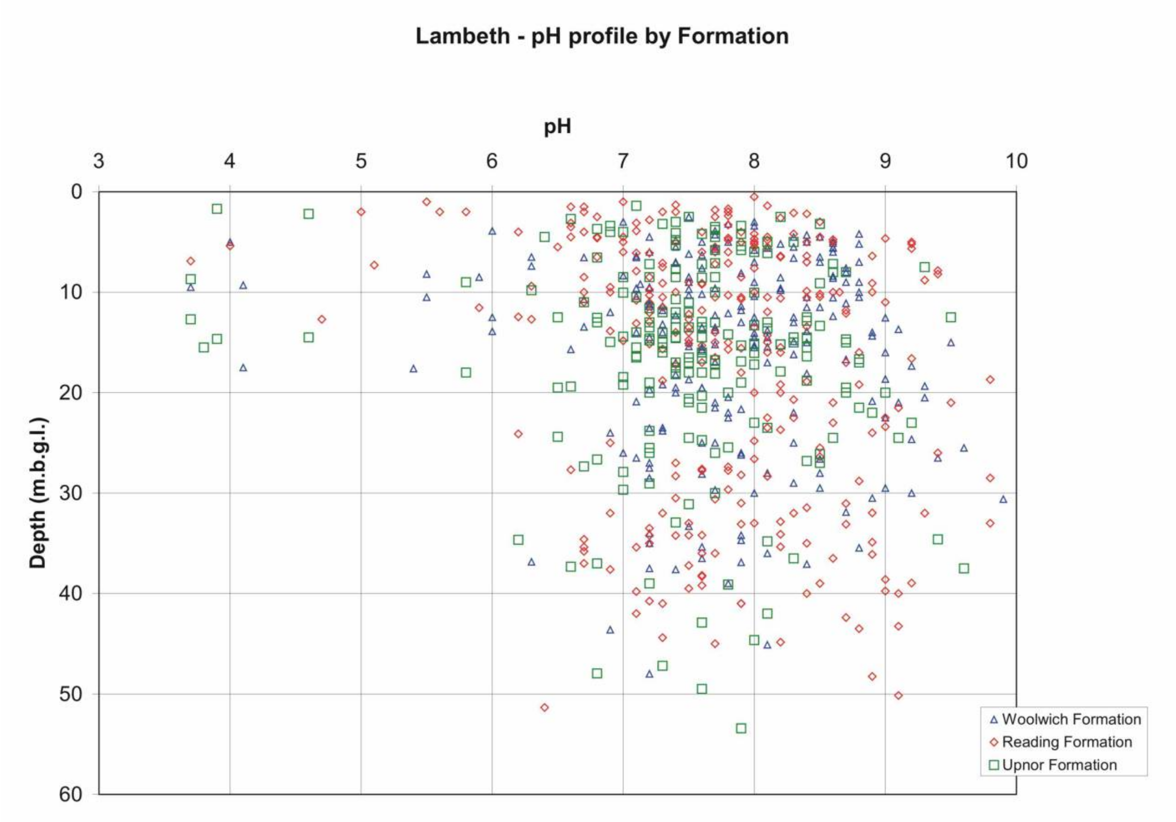


Figure 6.35. Lambeth Group pH profile.

6.1.4.2 Chloride Content

The water-soluble chloride is generally less than 0.2 g/kg with two values from the Upnor Formation of 0.4 and 0.6 g/kg, which were from over 15 m below ground level in the Canary Wharf area of London. Groundwater chloride content is generally less than 0.5 g/l, with 6 values greater than 1.0 g/l. Four of the the higher values, from the Woolwich and Upnor formations, are from boreholes drilled in the Thames River or in the docks on the Isle of Dogs. The other two higher values, both greater than 2 g/l were from the Reading Formation from a site in Brey, north west of Windsor, Berkshire.

6.1.4.3 Organic content

Acquired site investigation data indicates that organic content is not regularly carried out on material from the Lambeth Group, even where the organic content is likely to be high. The Reading Formation will tend to have very little or no organic content, although there may be some at or above the mid-Lambeth Group Hiatus in the west. Organic material is described in the Laminated Beds and in some of the sand channels in the Upper Mottled Clay in Area 1 and occasionally in the Upnor Formation. The Woolwich Formation may contain significant organic content, most notably in the Lower Shelly Clay, the highest values being for lignite in Area 2.

6.1.4.4 Summary

Most of the higher sulphate values occur within the Woolwich Formation, therefore, appropriate tests to assess the need for sulphate resistant cement are particularly required in this formation. The Woolwich Formation has the greatest potential to form sulphates due to its high pyrite content, often associated with organic material, and calcium carbonate (shell) content, which has been preserved by anoxic conditions of deposition. Sulphate contents appear to show little change with depth, unlike marine clays such as the London Clay Formation.

The few low values of pH (below 6) are all found in the upper 10 m, whereas, high values (greater than 9) are found at any depth.

Organic content is highest in the lagoonal and estuarine Woolwich Formation, most notably at the base of the Lower Shelly Clay in the southeast of the London Basin and the eastern part of the Hampshire Basin, where significant thickness of lignite are present. It is also present in the Laminated Beds and sometimes in the sand channels in the Upper Motteld Clay and occasionally in the Upnor Formation.

6.1.5 Strength

The strength of a soil or rock is a measure of its capability to withstand a stress (or stresses) in a particular direction or configuration. Strength is not a fundamental property of a soil or rock, but is dependent on the condition of the soil/rock and the type of stresses applied to it. The measured strength of soils is particularly sensitive to the drainage conditions and duration of the test, in addition to specimen characteristics such as density and fissuring. If drainage is allowed the test is capable of measuring *effective* strength parameters, which are usually required for the assessment of 'long-term' strength. These are usually determined from tests that include consolidated drained triaxial (CD) tests, consolidated undrained (CU) triaxial tests with pore pressure measurements, and drained shear box tests. If the conditions are undrained the test is assumed to measure *total* strength parameters, unless pore-water pressures are measured, in which case the effective stress parameters may be calculated. Total strength parameters are generally determined using unconsolidated undrained (UU) triaxial tests, shear vane and penetrometer tests. All effective and total strength tests reported here have been acquired from intact 'undisturbed' laboratory specimens.

Total shear strength (τ) is usually defined by the Mohr-Coulomb failure criteria, the equation of which is as follows:

$$\tau = c + \sigma \tan \phi$$

Where: c = cohesion, σ = normal (perpendicular to shearing) stress, and ϕ = angle of internal friction.

For a fully saturated, intact specimen, prevented from draining at all stages of the test, the value of the internal friction angle, ϕ, is zero. The undrained shear strength, s_u, thus equals the undrained cohesion, c_u. However, if triaxial test specimens are consolidated at each stress level by allowing drainage, as in the consolidated-undrained (CU) or consolidated-drained (CD) tests, effective shear strength may be measured if pore-water pressure is measured and subtracted from the total stresses. This is reported in terms of the 'effective' cohesive and frictional strength parameters c' and ϕ'. The effective shear strength, s', is then calculated from the Coulomb equation as follows:

$$s' = c' + (\sigma - u)\tan \phi'$$

The *residual* strength is the minimum strength of rocks and fine-grained soils after initial shear failure has occurred and may be determined on intact or remoulded samples in a shear box or a ring shear apparatus. The residual strength is usually determined to assess the strength along a pre-existing shear plane (e.g. on samples from a landslide slip surface), or in certain highly fissured clays.

It is difficult to give typical or average values of strength for the Lambeth Group or individual formations and members within it, because of the variability of lithology, fabric, structure, and cementation and the post-depositional processes of weathering and consolidation it has undergone. This results in variable depth profiles for intact strength on a scale of metres or centimetres, whether these are determined *in situ* or in the laboratory.

6.1.5.1 UNDRAINED SHEAR STRENGTH

Undrained (total) triaxial strength data are reported in site investigations either with the assumption that the friction angle,ϕ, is zero, or that it has a positive value, despite this being contrary to the principles of the test (Head, 1992; Head, 1998). Undrained strength data containing a positive friction angle have been omitted from the database.

The 1,338 undrained cohesion (c_u) values analysed show variable undrained strengths within the Lambeth Group. Median strength values range between 112 kPa and 164 kPa, with overall values ranging between c. 10 kPa to over 800 kPa ,with the Reading Formation tending to have the highest and the Woolwich Formation the lowest values. The data show undrained strengths to be particularly variable in central London and Hight *et al*. (2004) comment that the project-wide variability in undrained strength is similar to that found at a single location. This is the case for all formations and units.

The profile of Lambeth Group undrained strength values with depth (Figure 6.36) shows a great deal of scatter with an indistinct, trend of increasing strength with depth. Samples of extremely high strength and stronger (>300 kPa) occur near surface and increase in number with depth. There are also low strength samples at depth. In comparison to the Lambeth Group data, the undrained strength profile based on 2,100 data values for the London Clay Formation, from all areas, shows a clear overall trend of increasing strength with depth, but with generally less scatter of the data at all depths (Figure 6.37). The contrast between the Lambeth Group and the London Clay Formation results reflect the differences in their depositional environments and the post-depositional processes in particular pedogenic processes (cementing and fissuring) that affected some of the Lambeth Group deposits (Hight *et al*., 2004).

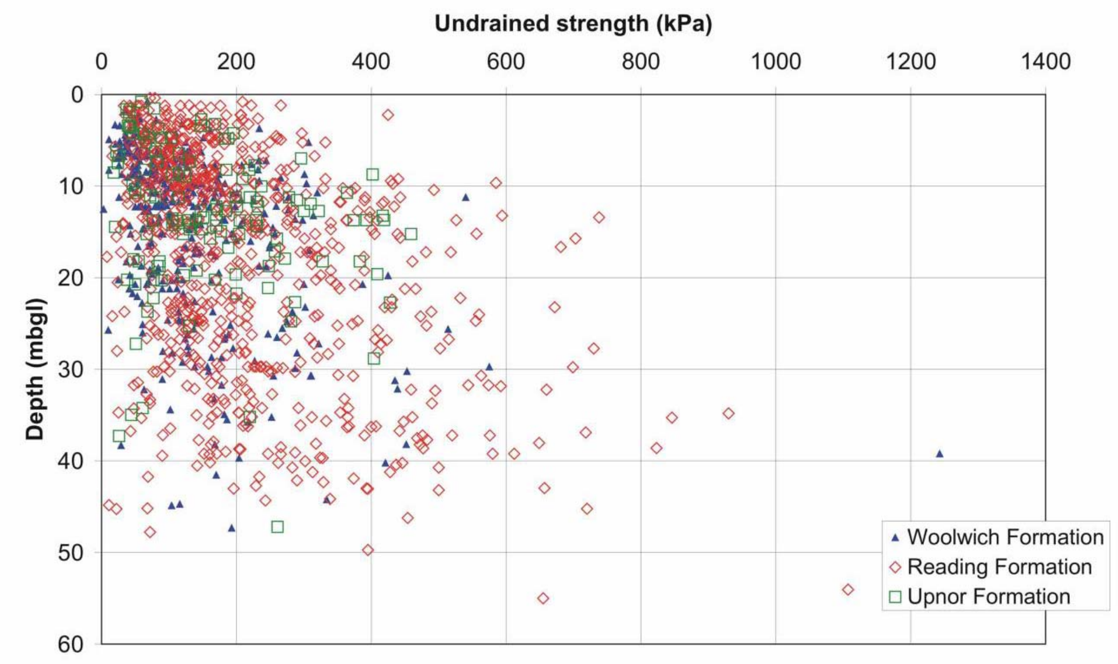


Figure 6.36. Undrained shear strength profile for all Lambeth Group data, differentiated by formation.

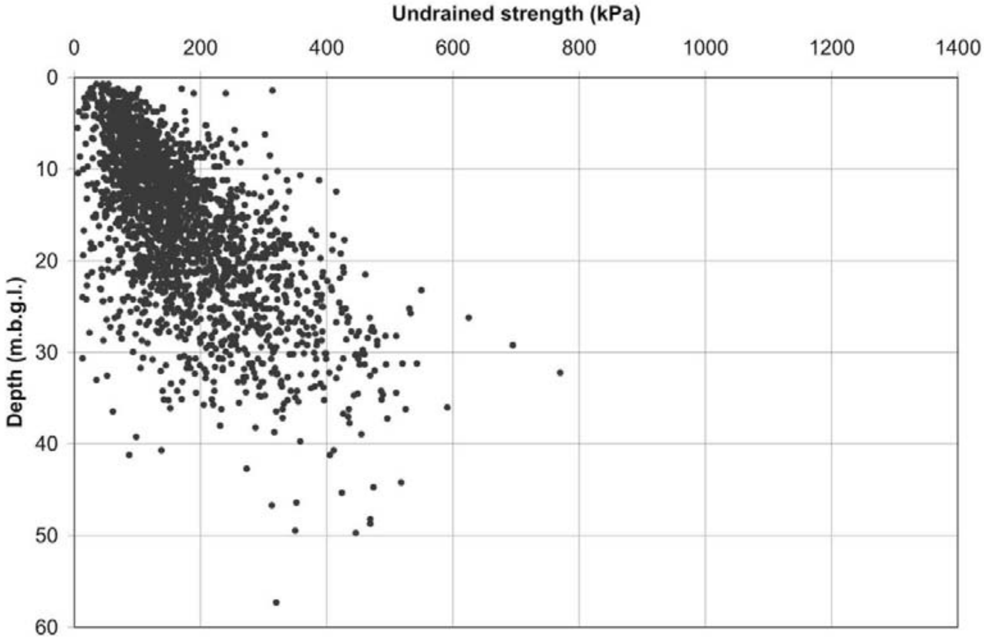


Figure 6.37. Undrained strength profile of the London Clay Formation.

Depth profiles of undrained strength values for each area are given in Figure 6.38 to Figure 6.41. Again, a high scatter of results is evident but an overall trend of increasing strength with depth can be seen.

- In Area 1 (Figure 6.38) the undrained strength vs. depth plot indicates a general increase in undrained strength with depth for all units in the top 10 m, but with increasing variability for all units at depths greater than 10 m. The Upper Mottled Clay has the greatest increase in strength with depth but also the greatest variability. Below 10 m, the Upnor Formation shows no clear trend of increasing strength with depth;
- Area 2 (Figure 6.39) shows a similar general trend of increasing undrained strength with depth for all formations/units to about 30 m, with the exception of the of the Lower Shelly Clay where no such trend is discernible;
- Area 3 (Figure 6.40) a trend of increasing strength with depth for the Reading and Upnor formations is seen to about 10 m below ground level. Below this depth the variability of the strength data for the Reading Formation increases markedly with no clearly discernible trend to 40 m;
- Area 4 (Figure 6.41), based on a more limited dataset, shows a similar general trend of increasing undrained strength with depth for both the Reading Formation and undifferentiated Lambeth Group samples to 35 m.

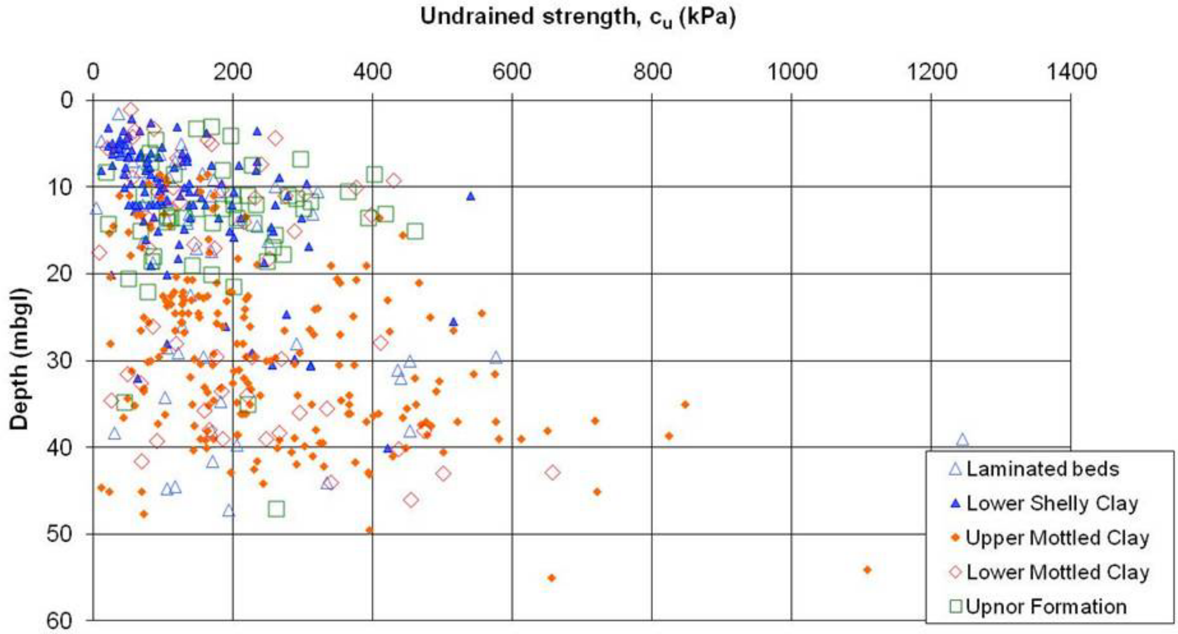


Figure 6.38. Undrained shear strength profile of the Lambeth Group in Area 1 differentiated by lithostratigraphical unit.

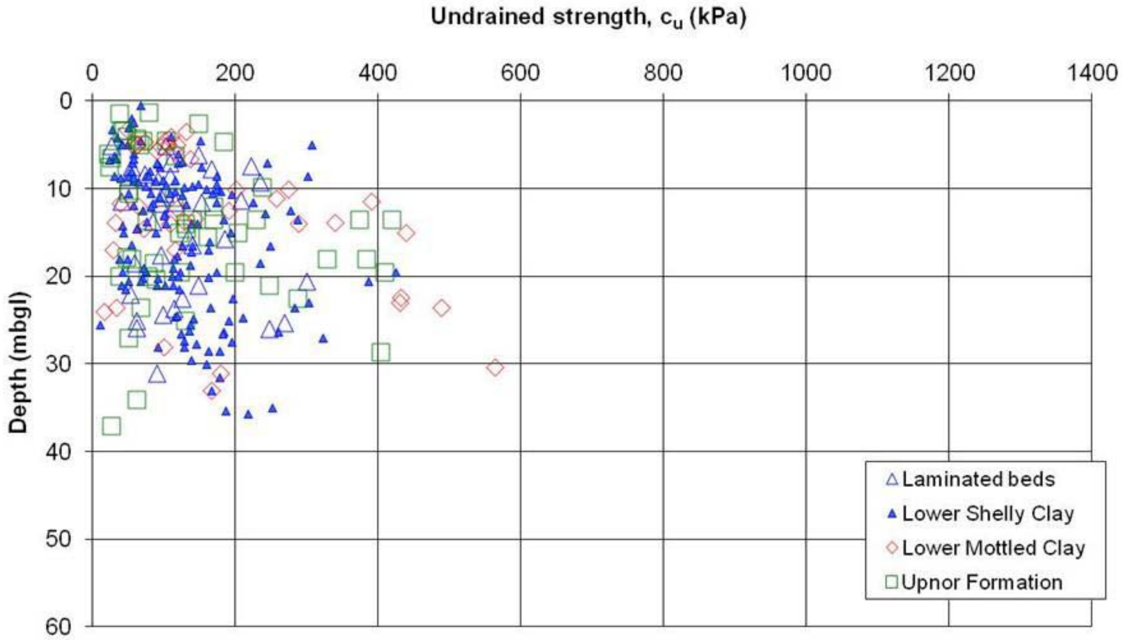


Figure 6.39. Undrained shear strength of the Lambeth Group in Area 2 differentiated by lithostratigraphical unit.

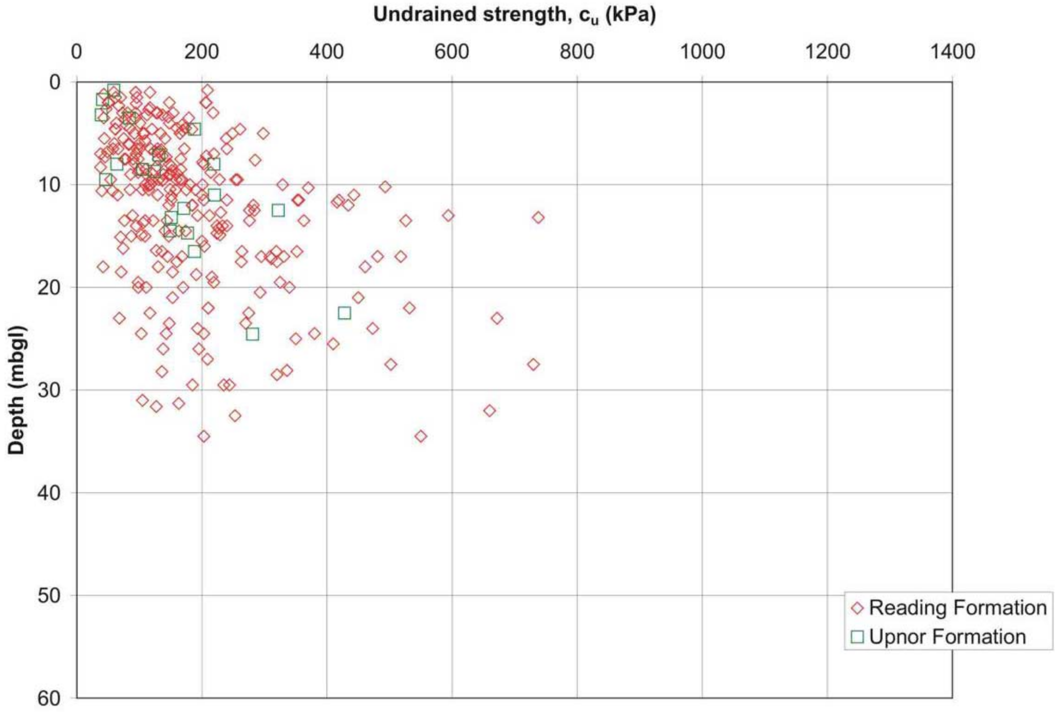


Figure 6.40. Undrained shear strength of the Lambeth Group in Area 3 differentiated by lithostratigraphical unit.

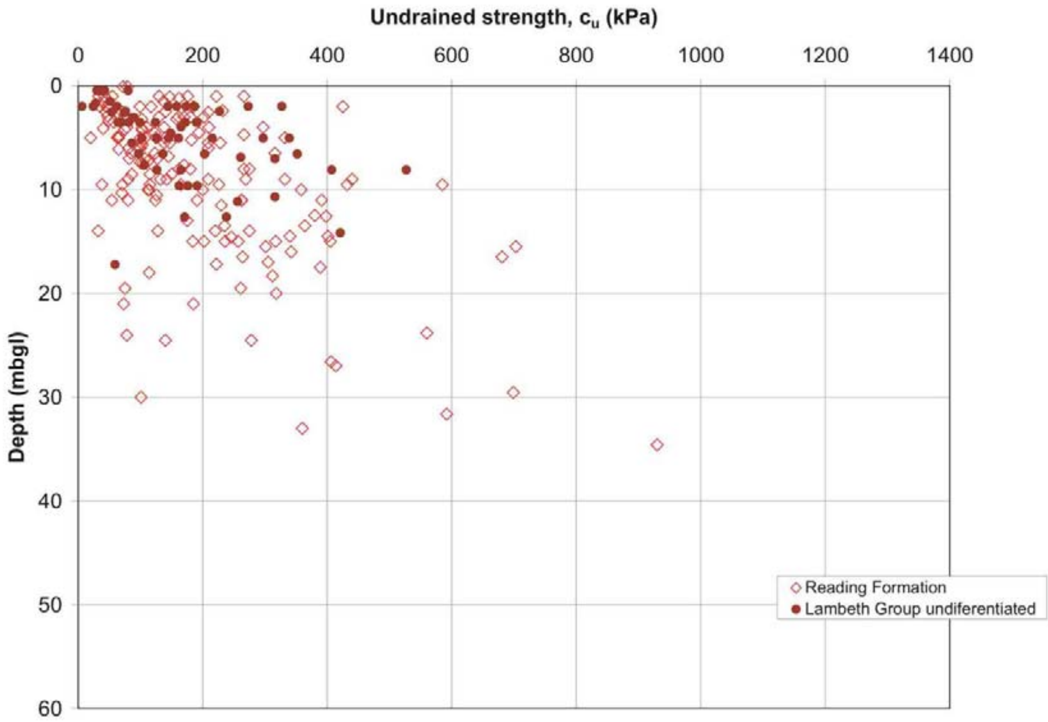


Figure 6.41. Undrained shear strength of the Lambeth Group in Area 4 differentiated by lithostratigraphical unit.

6.1.5.2 EFFECTIVE STRENGTH

Median effective strength data, (c´ and ϕ´ values) for the Lambeth Group formations are shown in Table 6.7.

Table 6.7. Median values effective cohesion and angle of shear resistance.

Group/Formation	Number of samples	Dominant lithology	Test type	c´ (kPa)	ϕ´ (°)
Lambeth Group	74	Clay	Triaxial	9.5	25
	14	Sand	Triaxial	14	32
	38	Clay	Shear Box	28	23
	8	Sand	Shear Box	6.5	33
Upnor Formation	4	Clay	Triaxial	26	27.5
	10	Sand	Triaxial	20	30.5
	4	Clay	Shear Box	20.5	32
	6	Sand	Shear Box	8	33
Reading Formation	43	Clay	Triaxial	12	22
	22	Clay	Shear Box	29.5	22
Woolwich Formation	28	Clay	Triaxial	4	25
	3	Sand	Triaxial	0	37
	11	Clay	Shear Box	34	19
	2	Lignite	Shear Box	8	37

As would be expected, the data show that the effective cohesion, c´, values are greater for clay samples, with sand samples having higher median angles of internal friction. However, a number of data values for Upnor Formation sand are similar to Upnor Formation clay, which may reflect the presence of clay laminae in the tested ‘sand’ samples or differences in lithology between the field description and test sample.

A plot of effective shear strength (*s’*) vs. depth (Figure 6.42), calculated using effective triaxial test data combined with estimated overburden stresses obtained from median densities, shows an overall well-defined trend of strength increase with depth for the Upnor and Reading formations, but with the latter showing some scatter of high data values within 10 m of the ground surface.

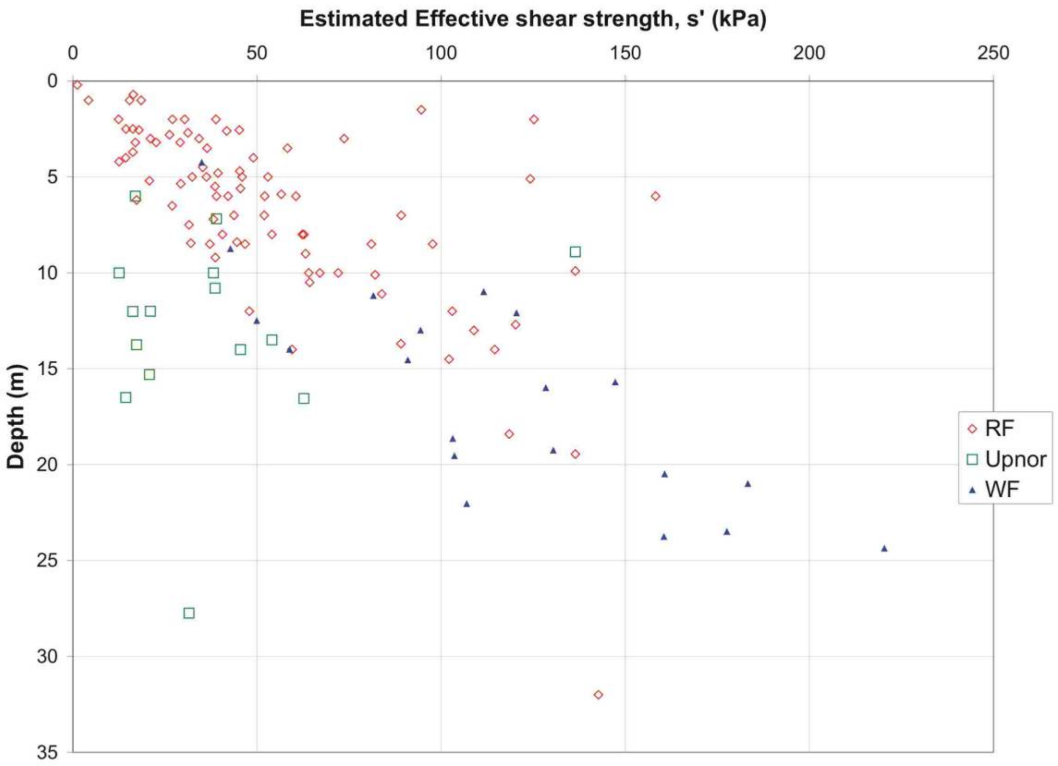


Figure 6.42. Plot of estimated effective strength vs. sample depth.Effective strength envelopes for the Upnor, Reading and Woolwich Formation data are presented in Figure 6.43 to

Figure 6.45. Effective strength envelopes for the Woolwich Formation.

. The dominantly sandy Upnor Formation data is distinguished by test type (shear box and triaxial tests) and by major lithology (clay or sand). The Reading and Woolwich Formation envelopes are distinguished by test type and also by different plasticity classes as suggested by Hight *et al*. (2004).

The effective strength envelopes for the Upnor Formation (Figure 6.43) show that, in general, there is little difference between most of the clay and sand envelopes, which probably reflects the mixed lithology of this formation (most of the samples tested being described as sandy clays or clayey sands). The triaxial and shear box test results are similar, as factors that may provide a difference in results between the two test types (e.g. fissuring) are rare in the Upnor Formation. However, two sand samples have high cohesion values due to cementing.

The effective stress envelopes of the Reading Formation (Figure 6.44) from both triaxial and shear box tests show a reduction in angles of internal friction in samples with higher plasticity index (>35%). Effective cohesion values are more variable and there are major differences between values from shear box tests and triaxial tests. In general, effective cohesion values determined from shear box tests vary little between the different plasticity index classes, whereas for the triaxial tests samples in the higher plasticity classes generally have lower effective cohesion, with over 50% of values recording 0 kPa.

Effective stress envelopes for the Woolwich Formation (

Figure 6.45. Effective strength envelopes for the Woolwich Formation.

) indicate that samples in the lower plasticity classes tend to have higher effective cohesion values.

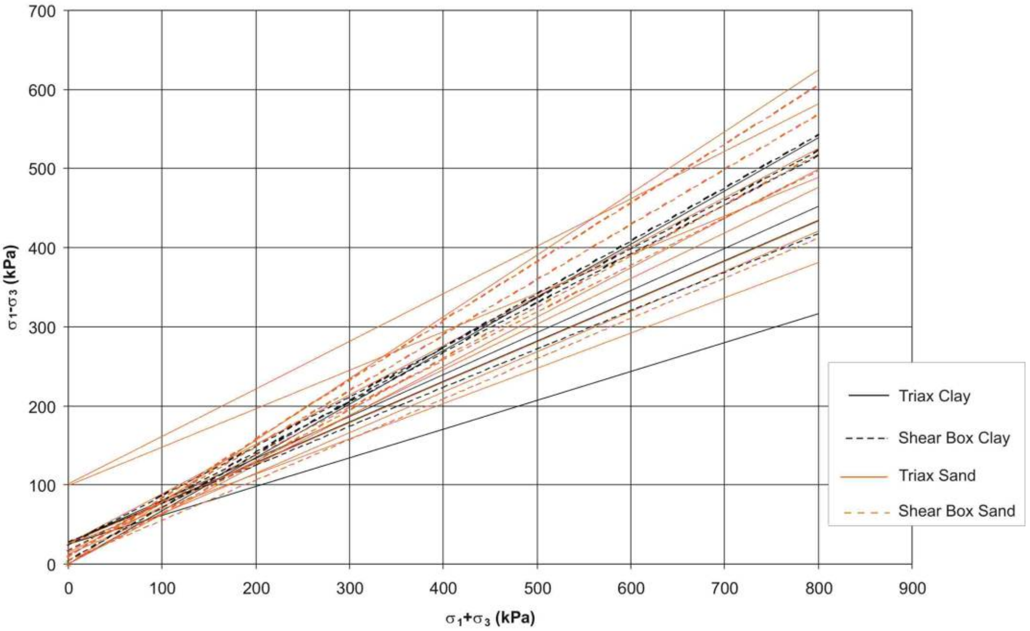


Figure 6.43. Effective strength envelopes for the Upnor Formation.

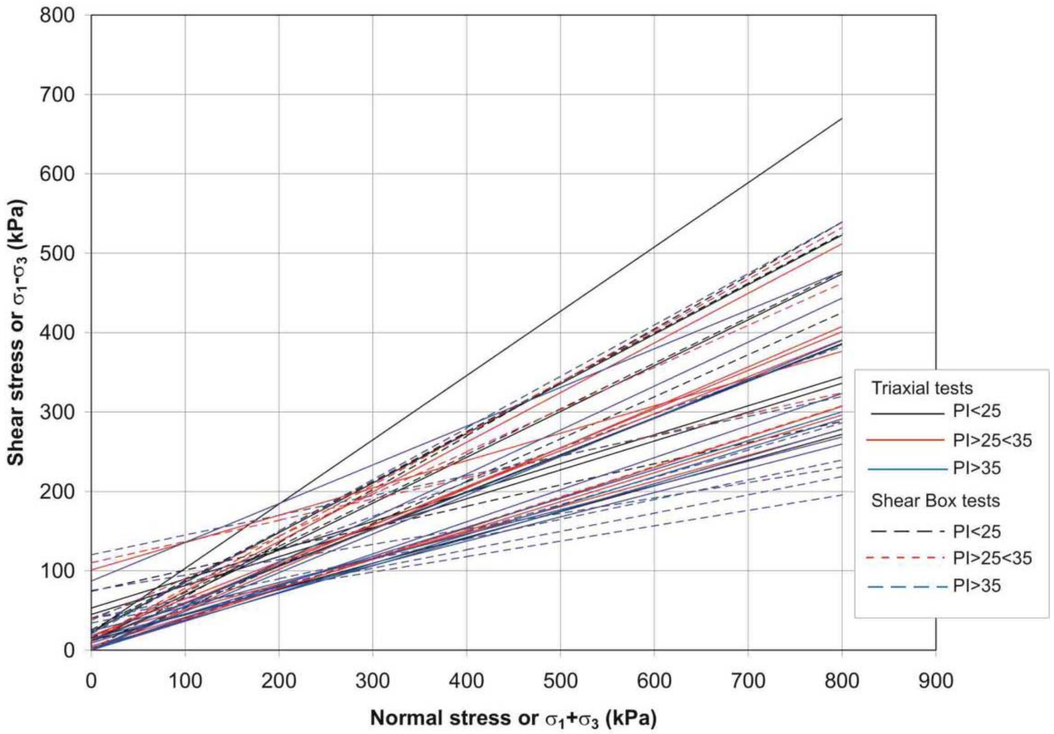


Figure 6.44. Effective strength envelopes for the Reading Formation.

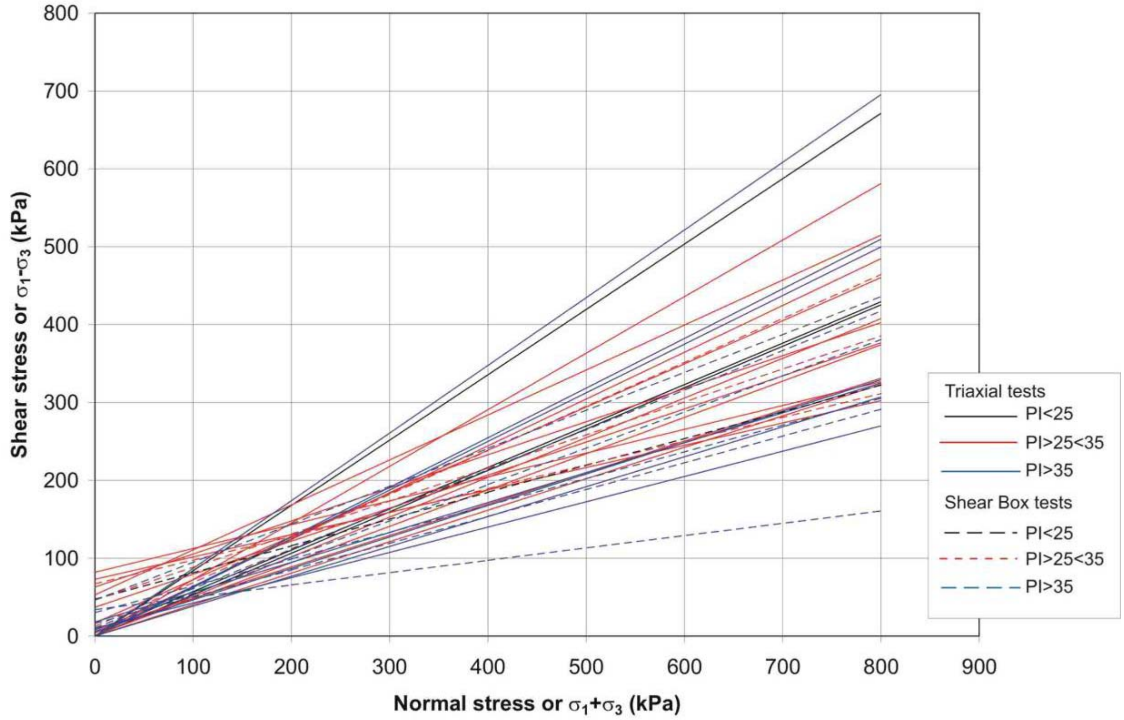


Figure 6.45. Effective strength envelopes for the Woolwich Formation.

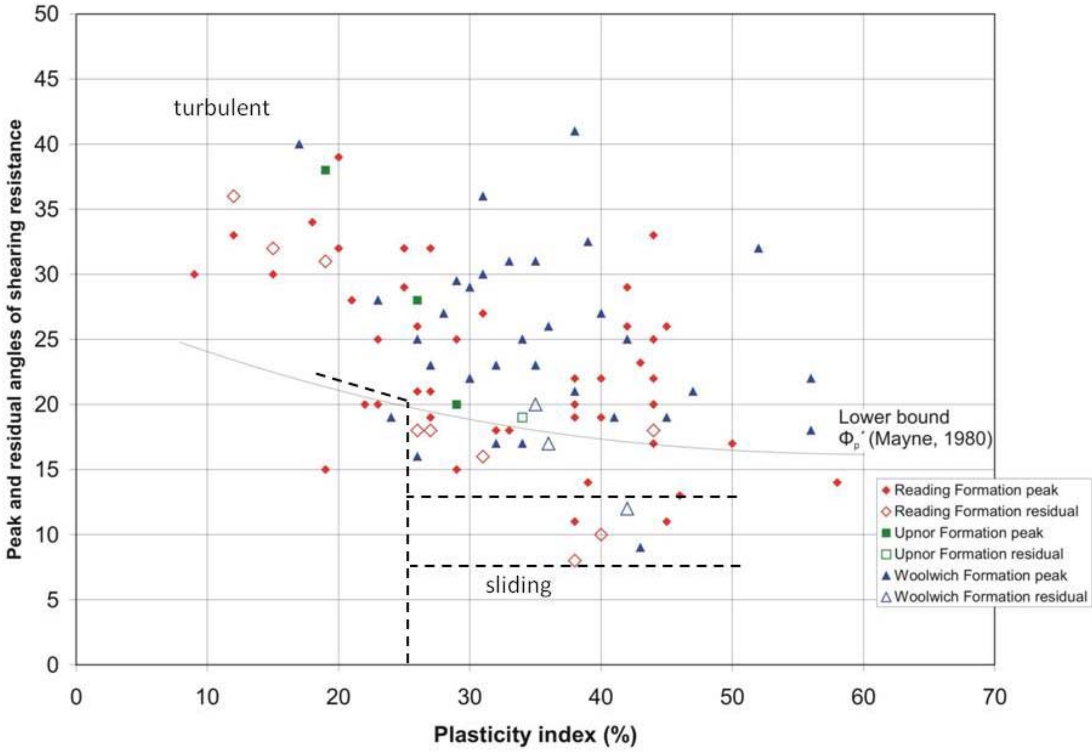


Figure 6.46. Peak, ϕ´, and residual angle of shear resistance, ϕ_r´, in relation to plasticity index for the different formations in the Lambeth Group. The lower bound of peak strength is from Mayne (1980) and the changes in failure mode of the residual strength (turbulent to sliding failure) is based on Vaughan *et al*. (1978).

6.1.5.3 Residual strength

Residual shear strength is the minimum strength of a soil reached after continuous shearing along a pre-determined shear plane, and can be tested on intact or remoulded samples in the laboratory. The results are expressed in terms of the residual angle of internal friction, ϕ_r', and residual undrained cohesion, c_r', from a plot of effective normal stress vs. shear stress, which is generally considered to be a straight line. The values of c_r' should be very low or zero but this can only ascertained if tests are carried out at a series of low normal stresses.

Only a few residual shear strength values were available for the Lambeth Group mostly from shear box tests. Residual angles of internal friction, ϕ_r', ranged from 8 ^{o} to 36^o with an overall median value of 27^o, and a median value for clays of the Reading Formation of 18^o. Residual shear strength (angle of internal friction) has been plotted against plasticity index in Figure 6.46. This shows an inverse correlation between residual shear strength and plasticity index as demonstrated for Lambeth Group data by Lehane *et al.* (1995), Lupini *et al.* (1981), and Voight (1973). It also suggests a change in residual strength behaviour from turbulent to sliding (Lupini *et al.*, 1981) at a plasticity index, I_p, between 20 and 25%. Lehane suggested that for clays with plasticity indices of greater than 30% the residual angle of internal friction, ϕ_r', was approximately 11±3°. The plot of ϕ_r' and plasticity index indicates that a majority of values with plasticity index values of greater 25% where the sliding mode is expected to occur had ϕ_r' values are above the bounds based on Vaughan *et al.* (1978). This may be due to insufficient shearing strain during the shear box tests.

6.1.5.4 Factors affecting the strength of the Lambeth Group clays

Hight *et al.* (2004) considered the factors affecting strength, such as the effects of plasticity, fissuring and sample disturbance, in some detail. Much of the findings from the work presented here corroborate those described by these authors.

The undrained shear strength of the Lambeth Group is very variable and despite overall trends, increase in strength is not necessarily related to depth below ground level. Hight *et al.* (2004) considered that Lambeth Group samples with undrained strengths greater than 500 kPa were probably cemented. However, the high strength may also be due to desiccation during the sub tropical climatic conditions of the Palaeocene. Low undrained strength values occur in samples described as stiff or very stiff. This may be due to failure along fissures, which are commonly described in the clays of the Lambeth Group, most commonly in the Reading Formation, and/or sample disturbance.

For the Reading Formation clays samples of higher plasticity tend to be weaker than low and intermediate plasticity materials (<50%) of similar liquidity index (Figure 6.47). This is may be due to a greater concentration of fissures in the high plasticity soils or more cementing in low plasticity soils; cementing agents such as iron oxides and hydroxides and calcium carbonate are inactive minerals and are likely to reduce plasticity. In some cases the peak and residual angles of internal friction are similar (Figure 6.46), indicating that the samples are, to some extent, shearing along preformed fissures.

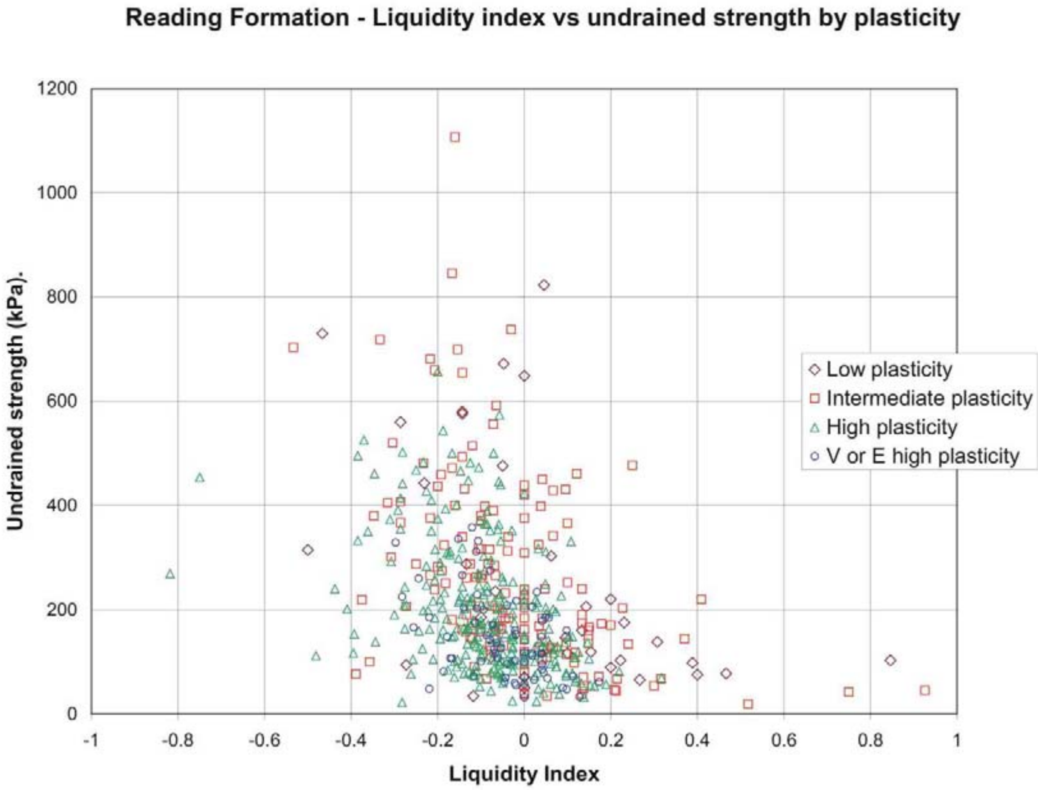


Figure 6.47. Undrained strength vs. liquidity index for the Reading Formation, in relation to plasticity.

Under a subtropical climate with pronounced seasonal rainfall, as prevailed during the deposition of the Lambeth Group, higher plasticity clays are most prone to shrink and swell. They are, therefore, more likely to fissure during the dry season. In contrast, low plasticity clays are less likely to shrink and swell to the same extent, will tend to form fewer fissures to a more limited depth, and develop fissure surfaces likely to be less smooth than those formed in high plasticity clays. Also, pedogenic cements, in particular calcium carbonate, will tend to reduce plasticity and increase strength.

6.2 CONSOLIDATION

Consolidation is the process whereby pore water is expelled from a soil as the result of applied, static, external stresses, resulting in structural densification of the soil. For most purposes, the external stress is considered to be unidirectional, and usually vertical. Swelling strain data may also be obtained from the oedometer test. The oedometer is a simple laboratory apparatus, which applies a vertical load to a small disc-shaped soil specimen, laterally confined in a ring. The consolidation test is normally carried out on undisturbed specimens by doubling the load at 24-hour intervals, and measuring the resulting consolidation deformation (BS1377: BSI, 1990; Head, 1998). This test is only suitable for fine-grained samples.

The *rate* at which the consolidation process takes place is characterised by the coefficient of consolidation, c_v, and the *amount* of consolidation by the coefficient of volume compressibility, m_v. Consolidation data derived from the oedometer test on undisturbed specimens are used in the calculation of likely foundation settlement, and may also provide information on the stress history, geological history, state of disturbance, permeability, and elastic moduli of clay soils.

The consolidation data considered here is from laboratory oedometer tests. Only those tests where the load has doubled at each stage are included in the National Geotechnical Properties Database.

This section includes information on the following:

- Initial voids ratio,
- Change of volume (coefficient of volume compressibility, m_v) with consolidation stress,
- Change of the rate of consolidation (coefficient of consolidation, c_v) with consolidation stress.

There are results from 370 oedometer tests in the database. A majority, 244, are on Reading Formation clays, 91 on Woolwich Formation clays and silts, 33 on the Upnor Formation and 2 on undifferentiated Lambeth Group.

The initial voids ratio, e_0, of the Lambeth Group samples are plotted against depth in Figure 6.48. Maximum voids ratio reduced slightly with depth, whereas there is little increase in the minimum values.

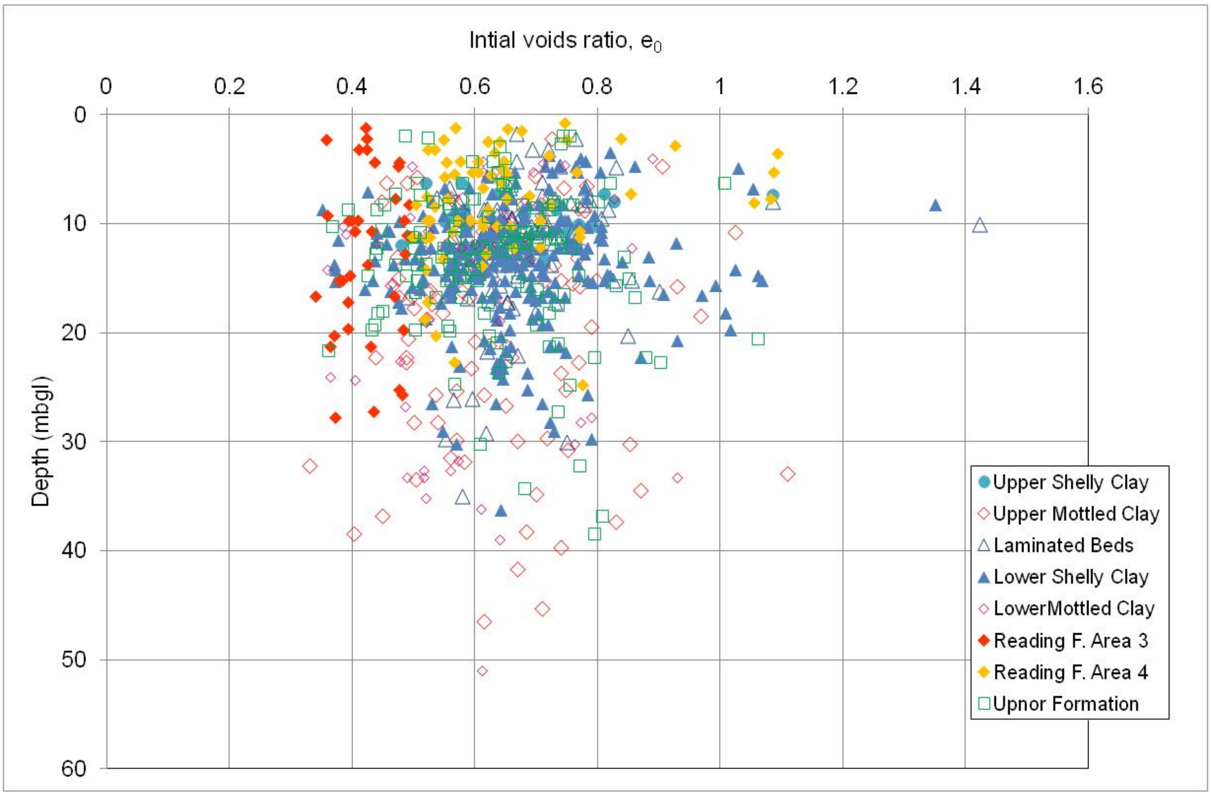


Figure 6.48. Lambeth Group - voids ratio depth profile by main lithostratigraphical units.

Coefficients of volume compressibility and consolidation data for estimated *in situ* stress +100 kPa, similar to the data given in Hight *et al*. (2004), are summarised as minimum maximum and percentile values in Table 6.8, and presented as graphs with respect to consolidation stress in Figure 6.49 and Figure 6.50.

Table 6.8. Summary of consolidation values of coefficient of volume compressibility and coefficient of consolidation.

Unit	n	Estimated *in situ* stress +100 kPa													
		Coefficient of volume compressibility, m_v,(m^2/MN)							Coefficient of consolidation, c_v, (m^2/year)						
		Min	Percentiles					Max	Min	Percentiles					Max
			0.1	0.25	0.5	0.75	0.9			0.1	0.25	0.5	0.75	0.9	
LMBE	244	0.01	0.04	0.06	0.10	0.14	0.20	0.56	0.015	0.38	1	2.4	7.5	17.5	54
LB	19	0.04		0.08	0.12	0.15		0.34	0.79		1.7	4.9	10.7		13.7
LSCL	42	0.02	0.05	0.08	0.11	0.18	0.22	0.35	0.38	0.6	1	3.8	6.9	22.2	54
UMCL	37	0.02	0.03	0.04	0.06	0.11	0.15	0.2	0.03	0.06	1.1	3.0	5.9	14.9	40.4
MCL	96	0.01	0.03	0.06	0.09	0.12	0.18	0.34	0.05	0.38	0.92	1.8	7.4	17.7	39
LMCL	26	0.02	0.03	0.05	0.09	0.12	0.19	0.29	0.02	0.46	0.79	1.5	4.3	7.1	17
UPR	14	0.04		0.08	0.11	0.20	0.27	0.34	0.79		1.7	4.7	10.7		13.7

The data show that the clays and silts of the Lambeth Group have very low to medium compressibility, with the Reading Formation tending to have lower values than the Upnor and Woolwich formations. This may be due to the effects of subtropical weathering, typical of the Reading Formation decreasing water content, and voids ratio and increasing stiffness. The coefficient of consolidation values are variable for all the units but the Lower Mottled Clay generally have slightly lower values and the Upnor Formation and Laminated Beds slightly higher values. The variation probably reflects differences in the initial voids ratio, particle size and plasticity and perhaps the changes in particle size within the sample, i.e. the samples of Laminated Beds and Upnor Formation may contain laminated clay and silt reducing the time to consolidate as water drains more rapidly within the silt laminae.

Summaries of the coefficient of volume change (m_v) and coefficient of consolidation (c_v) with stress (Figure 6.49 and Figure 6.50, respectively) show that, in general, coefficient of volume change of all materials tends to reduce with increasing stress. The coefficients of consolidation of the Reading Formation and the Lower Shelly Clay samples from Area 1 reduce with increasing stress, but there is little reduction with stress for the Upnor Formation, Lower Shelly Clay from Area 2 and Laminated Beds. This may be due to the greater clay content of those that do show this reduction with stress.

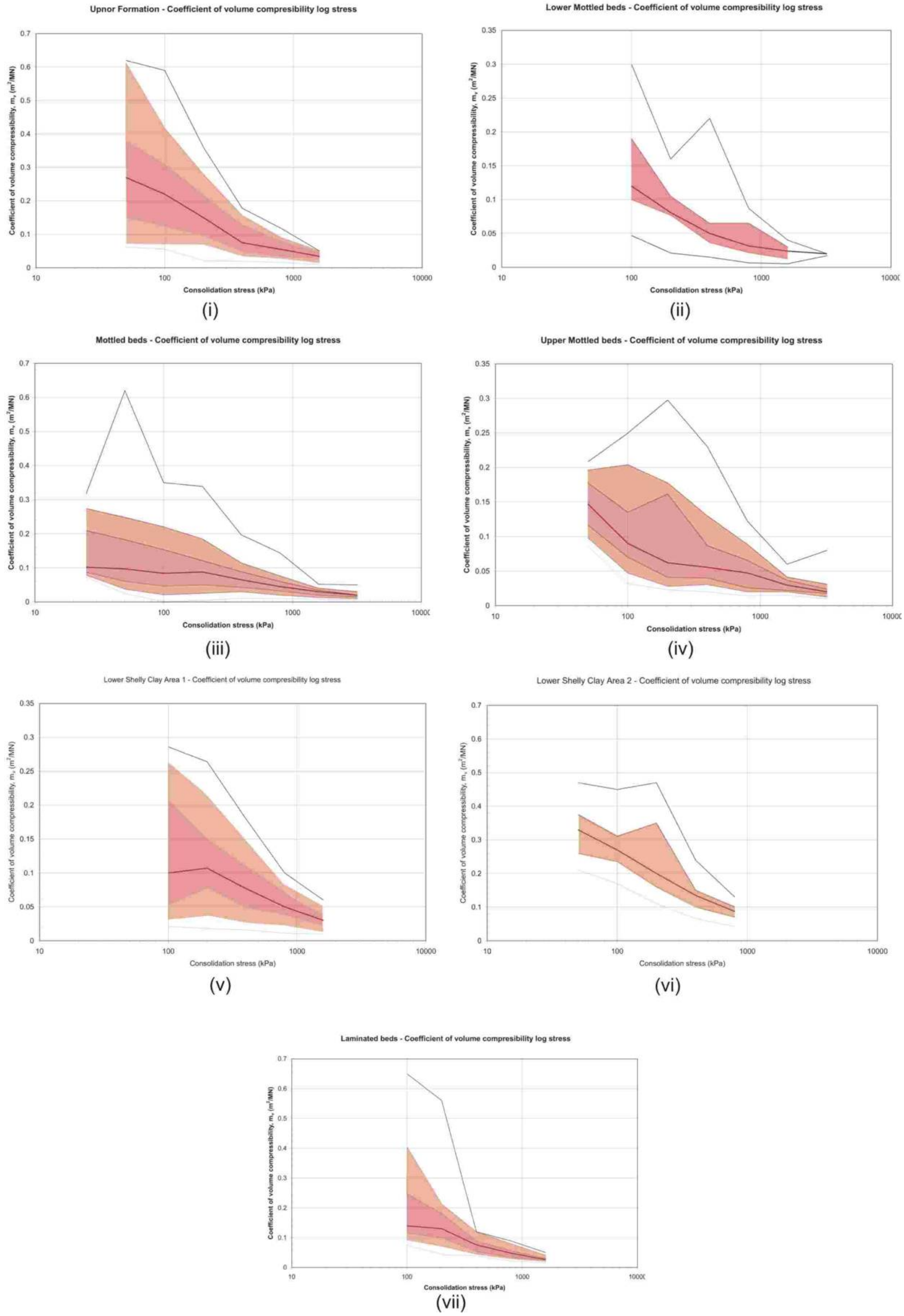


Figure 6.49. Summary plots of the coefficient of volume compressibility against consolidation stress for i) Upnor Formation, ii) Lower Mottled Clay, iii) Mottled Clay, iv) Upper Mottled Clay, v) Lower Shelly Clay in Area 1, vi) Lower Mottled Clay in area 2 and vii) Laminated Beds.

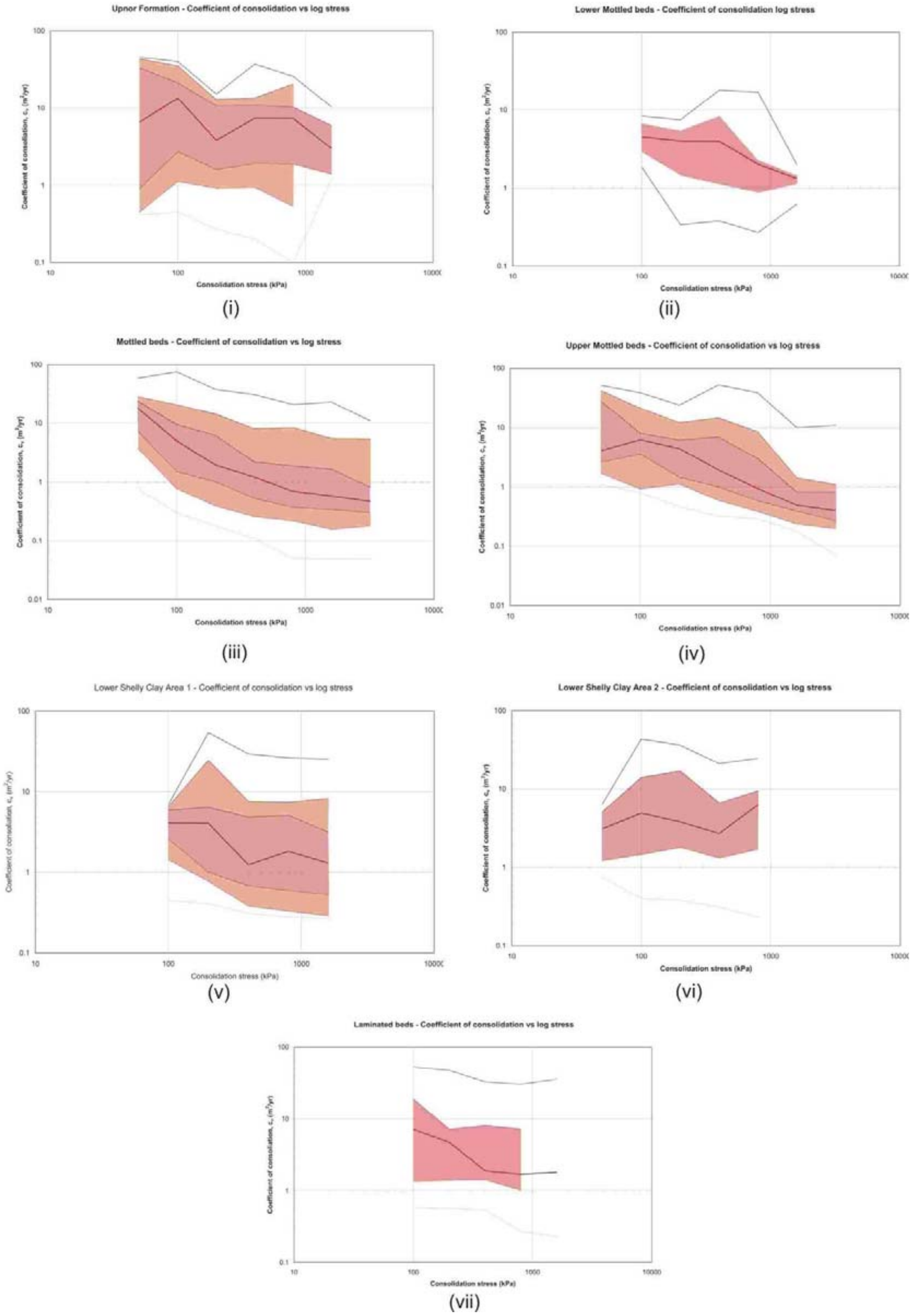


Figure 6.50. Summary plots of the coefficient of consolidation against consolidation stress for i) Upnor Formation, ii) Lower Mottled Clay, iii) Mottled Clay, iv) Upper Mottled Clay, v) Lower Shelly Clay in Area 1, vi) Lower Mottled Clay in area 2 and vii) Laminated Beds.

6.3 DEFORMABILITY

Deformability (the terms compressibility and stiffness may also be used) is a measure of the strain undergone by a soil or rock subjected to a particular level and direction of stress. This strain may be unidirectional or volumetric. Deformability may be measured in both laboratory (intact) and field (rock or soil mass). Usually, test data are interpreted from stress-strain plots, with several parametric variants of deformability available. The elastic properties of a material are defined by the fundamental properties: bulk modulus, K, and shear modulus, G. Bulk modulus represents the change in all-round stress per unit change in volume, whereas shear modulus represents the change in shear stress per unit change in shear strain. The simplest form of deformability measurement is that of Young's modulus, E, which is derived from a uniaxial compression test and is defined as follows:

$$E = \frac{\sigma_1}{\varepsilon_1}$$

where: σ_1 = major principal stress

ε_1 = strain in direction of major principal stress

The relationship between strain in the direction of stress and strain at right angles to it is defined by the Poisson's ratio, ν, as follows:

$$\nu = \frac{\varepsilon_{2,3}}{\varepsilon_1} \qquad = \frac{E\,\varepsilon_{2,3}}{\sigma_1}$$

where: σ_1 = major principal stress

ε_1 = strain in direction of major principal stress

$\varepsilon_{2,3}$ = strain at right angles to major principal stress

E = Young's modulus

Shear modulus, G, is defined as:

$$G = \frac{E}{2(1+\nu)}$$

where: E = Young's modulus

ν = Poisson's ratio

Also: $$E' = 2G(1+\nu)$$

where: G= shear modulus

E' = drained Young's modulus

ν' = drained Poisson's ratio

Shear modulus may be measured in a variety of ways from the stress vs. strain plots. The most commonly quoted are the initial shear modulus, G_i, and the unload/reload modulus, G_{ur}.

No deformability data are contained in the database. However, Hight *et al*. (2004) gave an account of case studies where small-strain stiffness determinations were made in the laboratory using triaxial tests. Undrained Young's moduli at 0.1% strain, normalised for effective overburden, were quoted as 820 and 1265 for Upper Mottled Clay samples obtained from tunnels at the Angel, Islington (London). These values were considerably higher than those for the London Clay. The low plasticity clays of the Upper Mottled Clays were found to be stiffer than the higher plasticity clays of the Upper Mottled Clay (Hight *et al*., 2004). Also stiffness reduces almost by an order of magnitude with increasing strain form 0.001% to 1% strain from consolidated anisotropic undrained triaxial compression and extension tests.

6.4 PERMEABILITY

Permeability, in the geotechnical context, is a measure of the ability of soil or rock to allow the passage of water subject to a pressure gradient. The permeability measured on intact specimens in the laboratory is usually distinct from that measured in the field, as a result of the huge scale difference, and the influence, in the field tests, of discontinuities and lithological variations. The database contains 241 permeability determinations covering the major lithostratigraphic units. The medians for the Reading Formation members range from 3.5×10^{-8} to 2.5×10^{-7} m/s. The Upnor Formation gave medians of 8.3×10^{-7} m/s (Glauconitic Sand) and 5×10^{-7} m/s (Pebble Beds). The Woolwich Formation medians were 3.5×10^{-7} m/s (Laminated Beds) and 6.0×10^{-7} m/s (Lower Shelly Clay). The overall minimum and maximum for the Lambeth Group were 1.8×10^{-10} m/s and 2.0×10^{-4} m/s. The permeability medians, maxima, and minima for each Formation were unexpectedly similar.

Hight *et al*. (2004) gave ranges of *in situ* permeability for the Lambeth Group from the Crossrail and Channel Tunnel Rail Link (CTRL) projects as shown in Table 6.9.

Table 6.9. Typical field permeability from Crossrail and CTRL projects (Hight *et al*., 2004)

Formation	Permeability, k (m/s)	Permeability, k_H (m/s)
RBUMC	5×10^{-7} to 5×10^{-9}	
RBLMC	1×10^{-8}	
WLLB	2×10^{-7} to 3×10^{-8}	
UPRGS	1×10^{-8} to 4×10^{-8}	
UPR		1×10^{-4} to 1×10^{-8}

where: k_H is horizontal permeability

The permeability figures quoted for the Reading Formation Mottled Clays are probably influenced by the presence of sandy layers and possibly, fissure flow clays. The permeability of the mottled clays material is probably lower than the figures quoted. Sand layers within the Reading Formation Mottled Clay members impart a distinctly anisotropic element to the permeability. The contrast in permeability between these two component lithologies is considerable.

The general ranges shown in Table 6.10 may be used for comparison:

Table 6.10. Typical permeability values of main soil types

Lithology	Permeability (m/s)
Gravels	1 - 10^{-2}
Clean sands	10^{-2} - 10^{-5}
Very fine or silty sands	10^{-5} - 10^{-8}
Silt	10^{-5} -10^{-9}
Fissured and weathered clays	10^{-4} - 10^{-8}
Intact clays	10^{-8} - 10^{-13}

6.5 COMPACTION, CALIFORNIA BEARING RATIO AND MOISTURE CONDITION VALUE

6.5.1 Compaction

Compaction is the process whereby soil is densified, usually by reworking in layers, in order to produce an engineering fill of known properties. This is achieved by applying dynamic forces, using special plant, such as rollers, vibratory rollers, rammers, or by special ground improvement processes. The densification is achieved by the soil particles packing closer together to:

- increase shear strength and, therefore, bearing capacity,
- increase stiffness and, therefore, reduce future settlement,
- decrease voids ratio and permeability, thus reducing the potential for frost heave.

The water content of the placed fill and the amount of energy input are critical to the density that can be produced. The process is not the same as consolidation.

The Lambeth Group is variable source of fill material for earthworks due to the scale of its lateral and vertical lithological variation and water content changes. The acceptance criteria of the different materials encountered and the potential for blending will be needed as part of the planning and designing of earthworks. Also, some of the material, such as lignite, is unsuitable. For these reasons the Lambeth Group is often considered to be a difficult material to use as an engineered fill. However, the increasing financial and environmental costs of importing and removing material to and from site have increased the use of such materials. Engineering fill requires identification of suitable material from the site investigation, appropriate specification and control of the material and its emplacement. If this is done then it is possible to keep importation and waste to a minimum. In some areas, for instance near Orsett of south Essex and Upnor in north Kent, the sand and gravels of the Upnor Formation dominate the Lambeth Group providing suitable material for some earthworks.

Most of the compaction data are from road schemes in Areas 3 and 4. In Areas 1 and 2 the data are from investigations for roads and railway construction projects (e.g. the Channel Tunnel Rail Link, CTRL). Of the 139 optimum water content and maximum dry density data test values available 20 were for California bearing ratio (CBR). Most of the data are for light or heavy compactive effort, and a few vibro-compaction tests. Compaction data are generally presented as plots of optimum water content vs. maximum dry density as shown for different lithologies and compactive efforts (Figure 6.51). The data show fairly typical behaviour;

- The clays have higher optimum water contents than the sands.
- Light compactive effort tests have lower dry density and higher optimum water contents.

Unusually, the vibro-compaction values are similar to light or heavy compactive effort results.

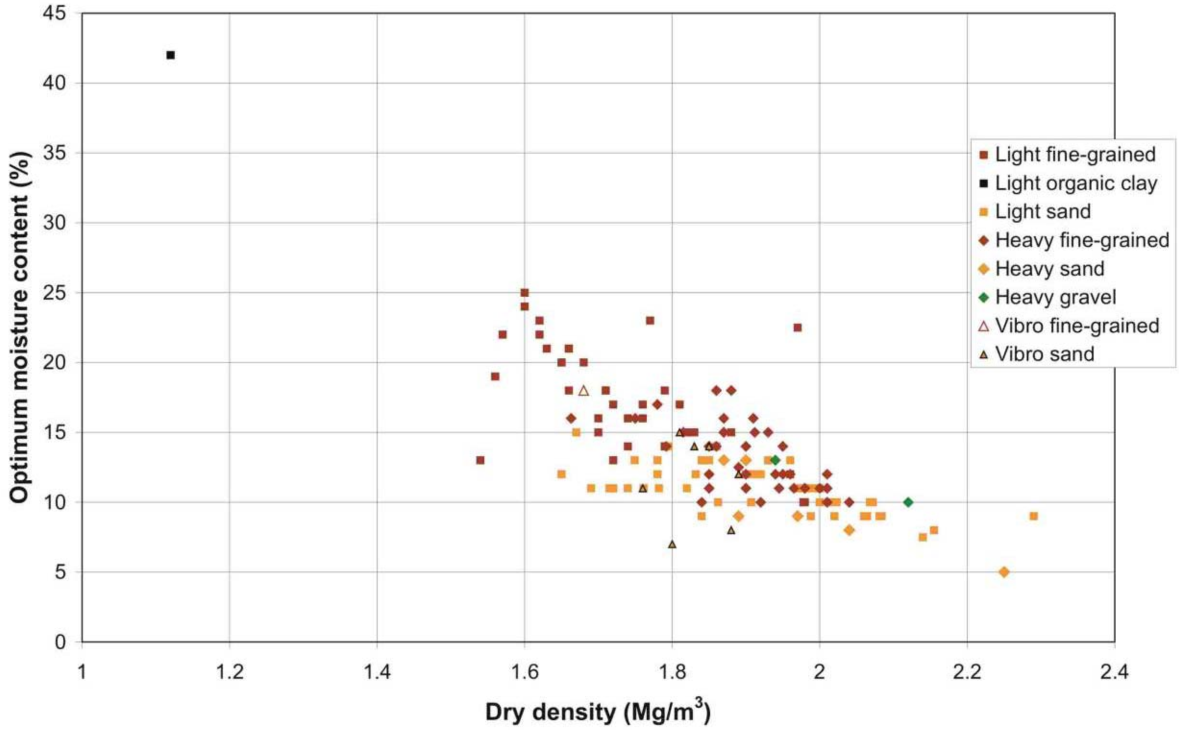


Figure 6.51. Optimum water content vs. maximum dry density showing different compactive efforts and lithologies.

6.5.2 California bearing ratio

California bearing ratio is plotted against optimum water content and maximum dry density (Figure 6.52 and Figure 6.53 respectively). The two plots show a tendency of increase in CBR with decreasing optimum water content and increasing optimum dry density for each lithology.

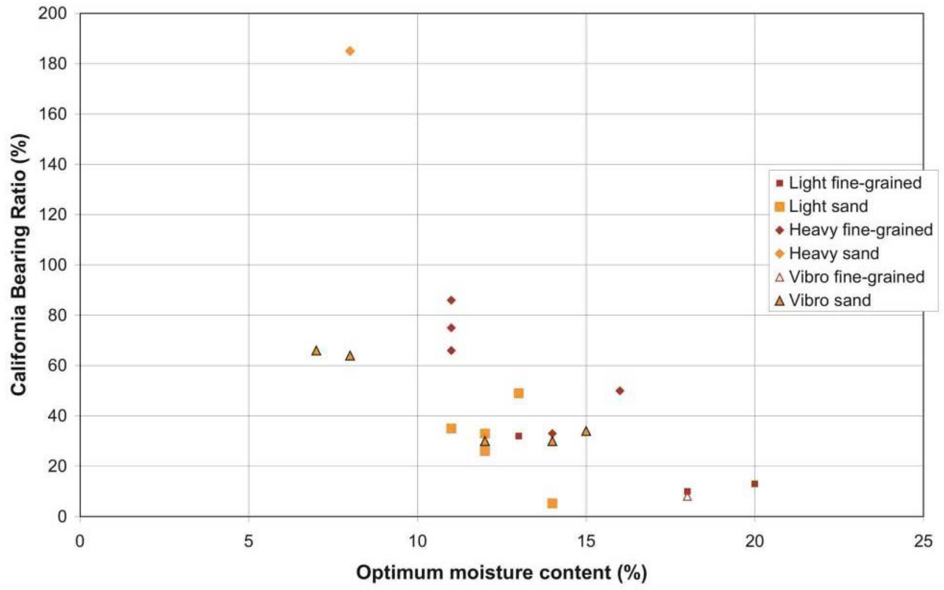


Figure 6.52. Optimum water content vs. California bearing ratio for different compactive effort and lithology type.

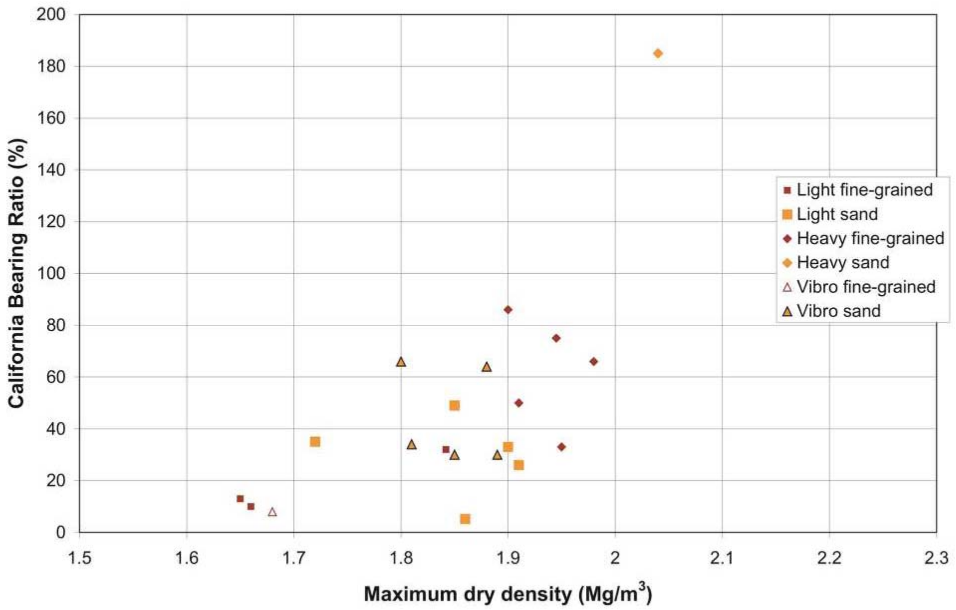


Figure 6.53. California bearing ratio vs. maximum dry density for different compactive effort and lithology type.

6.5.3 Moisture condition value

The moisture condition value (MCV) is a laboratory or field test, and is a means of selection, classification, and specification of fill material (BSI, 1990; Highways Agency, 1991; Caprez and Honold, 1995). The test aims to determine the minimum compactive effort required to produce near-full compaction of a 1.5 kg sample of soils passing a 20 mm sieve. The test differs from the traditional Proctor compaction test in that the compaction energy is applied across the entire sample surface, and compaction energy can be assessed as an independent variable. A total of 38 MCV data for Reading Formation Mottled Clays are contained in the database. The MCV values range from 0 to 18%, with a median of 9.3%. MCV values less than 7% tend to indicate very poor trafficability.

6.6 SWELLING AND SHRINKAGE

Swelling and shrinkage are two mechanical properties of a soil, which though driven by related physio-chemical mechanisms, are usually treated separately in the laboratory. Swelling is mainly a function of the clay minerals present in the soil or rock. The engineering phenomenon of *heave* may be caused by factors other than swelling of clay; for example, by stress relief. The geological processes affecting swelling and shrinkage were described by Gostelow (1996). Assessment of swelling and shrinkage usually does not involve direct measurement, but rather indirect estimation of volume change *potential* from index tests on reworked samples. Swell/shrink tests are not well catered for in British Standards.

The wide variety of test methods applicable to swelling/shrinkage is described by Hobbs and Jones (1995). Laboratory tests may be carried out on *undisturbed* or *disturbed* samples. Undisturbed samples are as near to their *in situ* condition as possible, whereas disturbed samples may be reworked, reconstituted, or compacted depending on the engineering application. Swelling tests usually measure either the *strain* due to swelling, resulting from access of a sample to water, or the *pressure* produced when the sample is restrained from swelling (zero strain test). Swelling strain samples may be disc-shaped oedometer type samples for one-dimensional (1-D) testing of soils and slaking rocks, or cubes for three-dimensional (3-D) testing of non-slaking rocks. The 1-D samples are laterally restrained. Swelling pressure samples are usually oedometer discs and may be mounted in a normal oedometer or a special swelling pressure apparatus. Two shrinkage tests are specified by British Standards (BSI, 1990). These are the shrinkage limit test, carried out on undisturbed or disturbed samples, and the linear shrinkage test, carried out on reworked soil paste (prepared as for Atterberg limits). *It should be noted that the shrinkage limit is a specific water content below which little or no volumetric shrinkage occurs, whereas the linear shrinkage is a percentage reduction in length (strain) on oven drying.*

The Lambeth Group is generally considered to be of 'low' to 'medium' swell/shrink potential depending on lithology and mineralogy. Whilst no directly determined swelling or shrinkage data are held in the database, a small number of tests were carried out at the BGS on undisturbed samples of Reading Formation, Mottled Clays from various locations. The results found a good positive correlation between 1-D swelling strain, $\varepsilon_{1\text{-}D}$, and swelling pressure, P_{sw}, as follows:

$$\varepsilon_{1-D} = 0.09.P_{sw} + 2.2 \qquad (r^2 = 0.92)$$

The tests have also shown that the laterally confined vertical swelling strains (1-D swelling strain test) are typically between 1 and 2 times unconfined maximum vertical swelling strains (3-D cube test). Volumetric swell strain ranged from 0.4 to 14.0%. Vertical swell (i.e. perpendicular to bedding) was found to always exceed horizontal swell in the 3-D cube test, by up to 4 times. This swell anisotropy was greatest for the Knoll Manor 2 and Whitecliff Bay 1 samples. Maximum swell was typically achieved between 10 and 100 hours. Free swell test data had a range of 18 to 80%. No correlations were obtained between free swell, volumetric swell strain, and the index parameters (liquid limit, plasticity index, liquidity index) and activity.

The BRE Digest 240 (BRE, 1993) gives a scale of susceptibility to volume change (i.e. swelling or shrinkage) for over-consolidated clays in terms of a modified plasticity index, I_p' (Table 6.11).

Table 6.11. Volume change susceptibility.

I_p'	Volume change potential
>60	Very High
40 - 60	High
20 - 40	Medium
<20	Low

where: I_p' is a modified plasticity index:

$$I_p' = I_p\left(\frac{\% < 0.425mm}{100\%}\right)$$

The purpose of the modified plasticity index is to take account of the proportion of fines in relation to the total sample and to reduce the measured plasticity index in proportion. Many Atterberg limit data in the database do not include <0.425 mm results. This may be because the sample did not require sieving, or that a small number of coarse particles were removed by hand, without sieving. The modified plasticity index and volume change susceptibility data are shown in Table 6.12.

Table 6.12. Volume change potential for Lambeth Group units

Formation	Number of samples	Median I_p´ (%)	Median volume change potential	Samples with high or higher volume change susceptibility (%)
LB	74	24.5	medium	12
LSC	371	28	medium	17
UMCL	213	33	medium	22
MCL	463	34	medium	32
LMCL	166	32	medium	19
UPR	254	19	low	8

The BRE Digests 240 and 241 (BRE, 1993 and 1990, respectively) classifications do not indicate the actual volumetric shrinkage to be expected for each of the volume change potential categories. Net volume changes depend on the initial saturation condition of the test sample. In the case of the shrinkage limit test this is usually natural water content, whereas in the case of the linear shrinkage test it is close to the liquid limit. All the Mottled Clay samples tested at BGS for swell/shrink gave a 'medium' volumetric susceptibility according to the BRE classification.

6.7 STANDARD PENETRATION TEST (SPT) RESULTS

The Standard Penetrometer Test (SPT) is a long-established method of *in situ* geotechnical testing, which was initially designed to measure the density of coarse-grained deposits but is now commonly used on most materials encountered during cable percussion drilling. This dynamic method employs a falling weight to drive a split-sampler and cutting shoe (or solid 60^o cone in the case of coarse soils or soft rock) 300 mm into the ground from a position 150 mm below the base of a borehole; the initial 150 mm being the 'seating' drive. The use of the test is described in British Standard 5930 (BSI, 1999; BSI, 2010) and the methodology in British Standard 1377: Part 9: Clause 3.3 (BSI, 1990), which has been superseded by BS EN ISO 22476-3 (BSI, 2005). There has been much discussion concerning the test method, test apparatus, and test interpretation (Stroud and Butler, 1975; Stroud, 1989).

It was recommended (Clayton, 1995; BSI, 1990) that test results be reported in the form of six 75 mm penetration increments; the first two representing the 'seating' drive and the final four the 'test' drive, the sum of the latter providing the SPT 'N' value. This is often not the case in site investigation reports, though it does form part of the Association of Geotechnical Specialists (AGS) digital data transfer format.

The Standard Penetration Test (SPT) may be regarded as crude, but it is inexpensive and effective. In most cases, site investigation reports included a record of the incremental blows and penetrations. These have been entered into the geotechnical database for analysis. The summaries presented for the SPT are derived from over 3,000 tests.

For a small proportion of tests the incremental data were not available. In these cases, tests giving a full N value were accepted, together with those in which a partial main test drive could be distinguished from a seating drive.

A total of 3,010 completed SPT N-values were assessed statistically and another 1,511 incomplete tests were considered. Incomplete tests were stopped before the full depth of 0.45 m had been completed (0.15 m seating blows and 0.30 m test). Historically, tests were often aborted if the N value was >50 blows, indicating very dense sand or gravel or material that could not be driven into. However, higher values have been reported where the information has geotechnical importance but cut off values are, generally, still used; such as, for example, 140 blows for the investigations at Farringdon Station, 150 for the Jubilee Line Extension and 200 for the Crossrail, Channel Tunnel Rail link (CTRL) and the Newbury Bypass (Hight *et al*., 2004). Table 6.13 shows the SPT completion data and percentage of tests over 50 blows for the Lambeth Group, its formations as well as the London Clay and Thanet formations for comparison.

The Woolwich and Reading formations have similar percentages of incomplete tests and tests of over 50 blows (54% and 53%, respectively), whereas the 70% of tests on the Upnor Formation were greater than 50 blows. Although this is significantly more than the rest than of the Lambeth Group, it is markedly less than the Thanet Formation, which is usually a very dense sand (Table 6.13). The London Clay Formation has only 13% of test values greater than 50 blows and most tests are completed.

Table 6.13. Number of SPT tests attempted, successfully completed and the percentage of tests >50 blows for the Lambeth Group, its formation and the London Clay and Thanet formations.

Lithological unit	**Number tests (including incomplete tests)**	**Completed tests**	**Completed tests %**	**% of tests >50 blows (including incomplete tests)**
London Clay Formation	2941	2866	97.4	13
Woolwich Formation	855	600	70.2	54
Reading Formation	1784	1351	75.7	53
Upnor Formation	1810	990	54.7	70
Lambeth Group	4521	3010	66.6	59
Thanet Formation	1773	545	30.7	91

The medians and ranges of SPT N-values for the Lambeth Group formations are similar, with the Upnor Formation tending to have slightly higher values (median 47 blows) and the Woolwich Formation slightly lower values (median 40 blows). The *range* of values for each unit, each area and for each unit in an area, is very large, usually greater than 100 blows. The highest values tend to occur in the Upnor and Reading formations of Area 1 and the lowest in Area 4, which may be due to the greater depth of test in Area 1. The depth vs. SPT N-value plots for the Lambeth Group by formation and for each area by unit are given in Figure 6.54 to Figure 6.58. In all cases there is a trend of increased N-value with depth, which is most marked in the upper 20 to 25 m. Higher values (N-values >100) may occur at any depth. Increases in the minimum and maximum values with depth are more obvious in Areas 3 and 4. These variations were considered by Hight *et al*. (2004) to be due to:

- Cementing due to pedogenic processes,
- Shelly limestone,
- Desiccation,
- Plasticity and fissure texture.

Figure 6.59 shows the SPT N value vs. depth profile for data from the 1:10k map sheet TQ38SE in east London, which area includes Hackney and Poplar, for Thanet Formation, Lambeth Group and London Clay Formation. The graph shows an increase in N-values with depth for the London Clay Formation, typically high values for the Thanet Formation and a large scatter of the Lambeth Group tests.

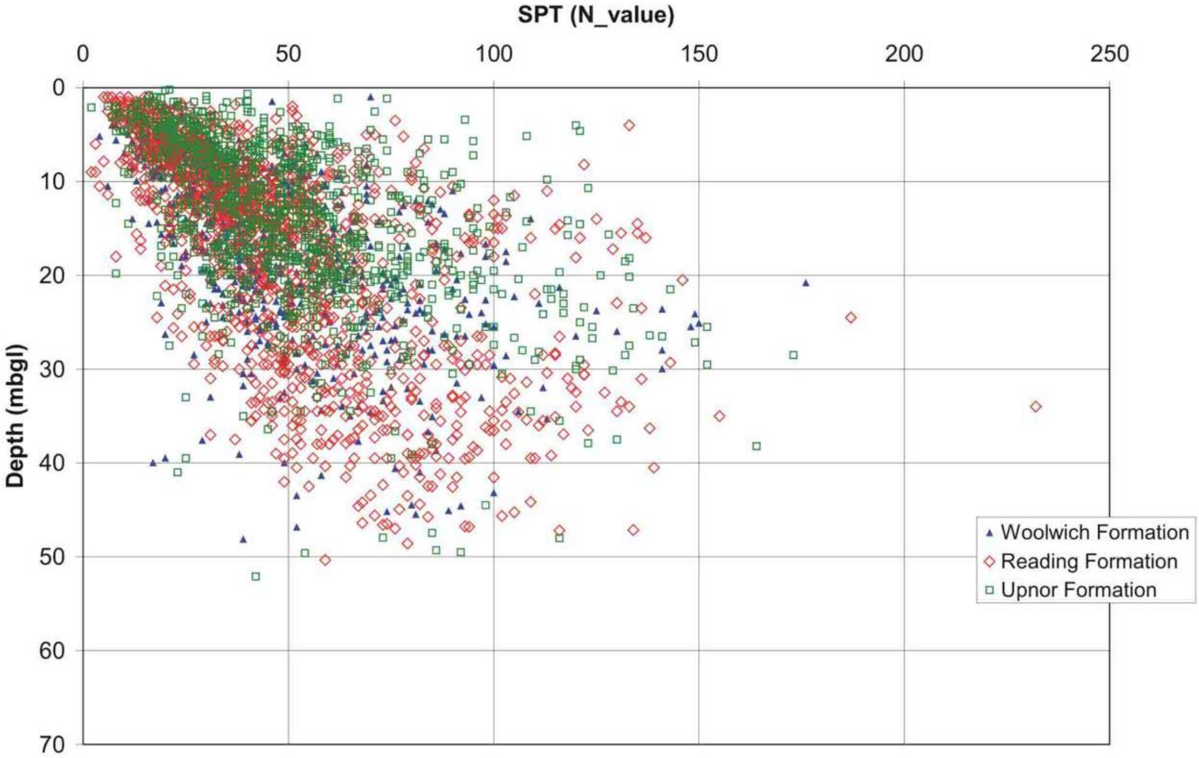


Figure 6.54. Variation of SPT N-values with depth for the Lambeth Group by formation.

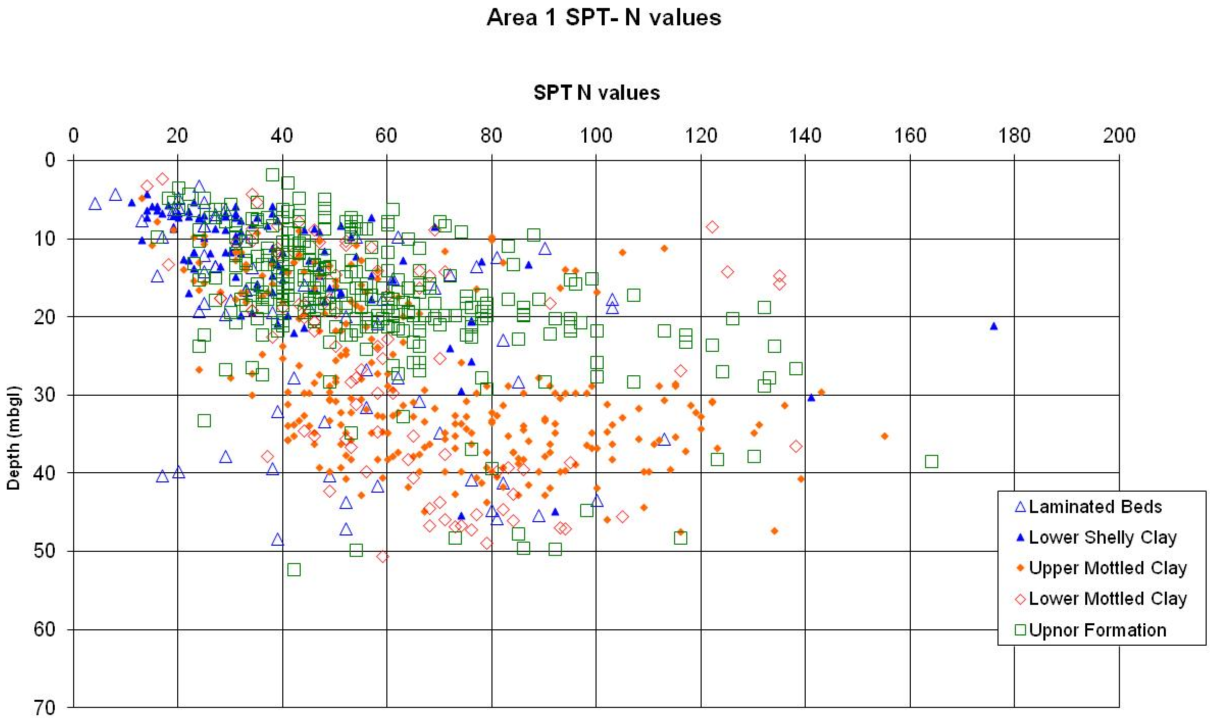


Figure 6.55. Variation of SPT N-values with depth for the Lambeth Group in Area 1 by unit.

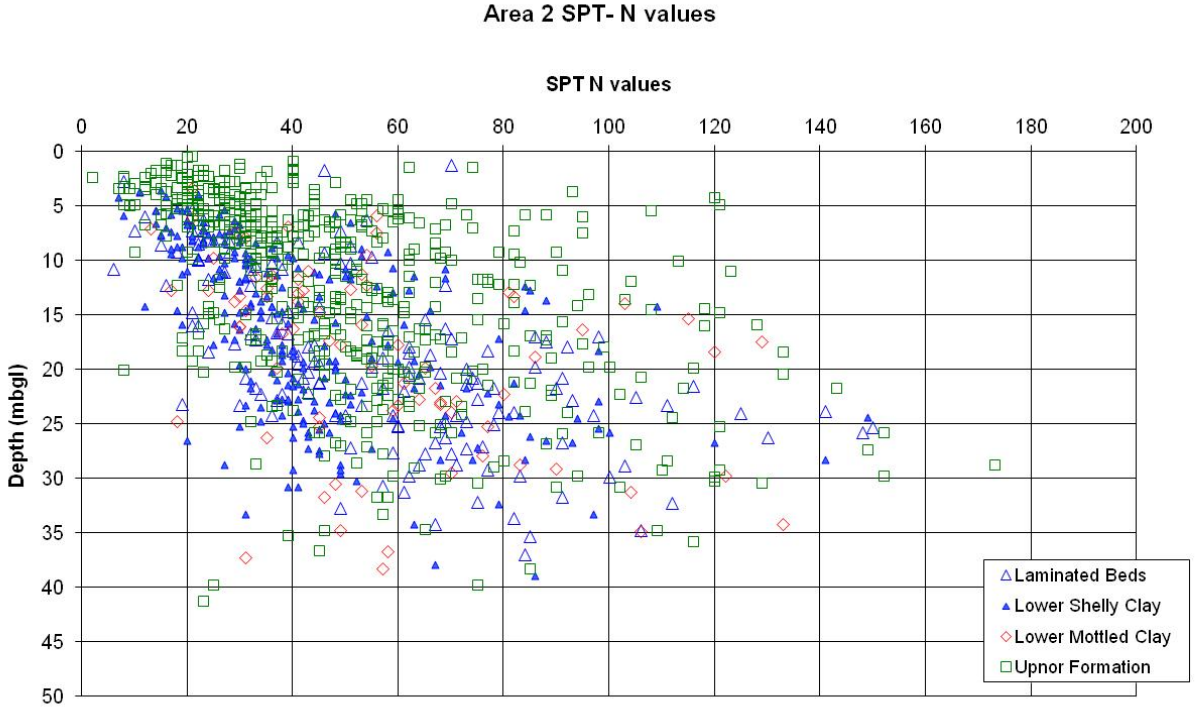


Figure 6.56. Variation of SPT N-values with depth for the Lambeth Group in Area 2 by unit.

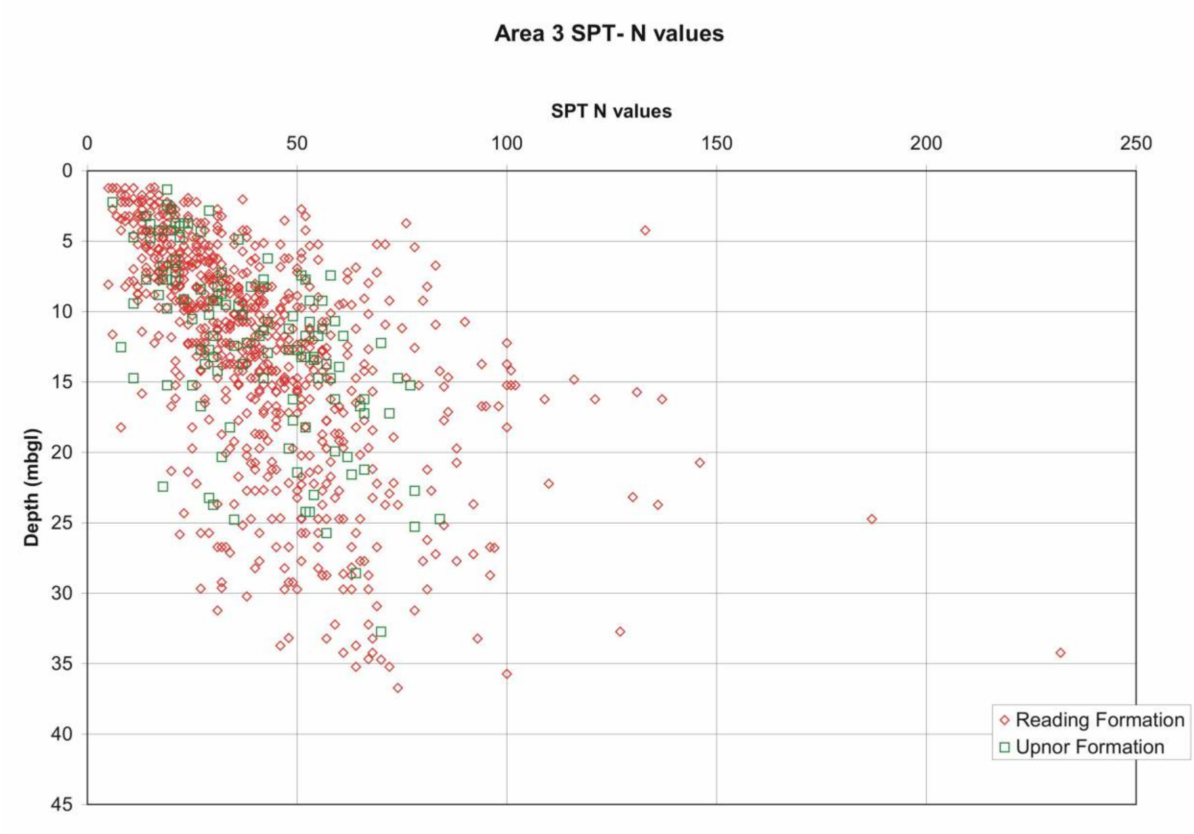


Figure 6.57. Variation of SPT N-values with depth for the Lambeth Group in Area 3 by formation.

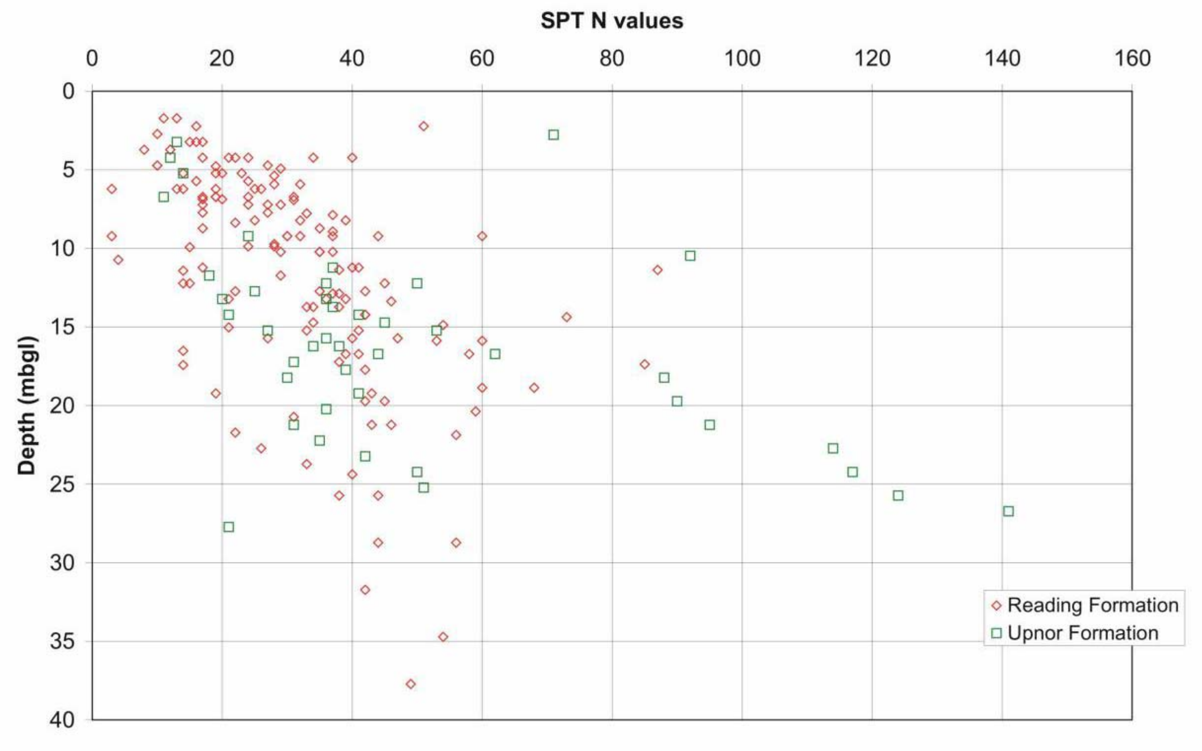


Figure 6.58. Variation of SPT N-values with depth for the Lambeth Group in Area 4 by formation.

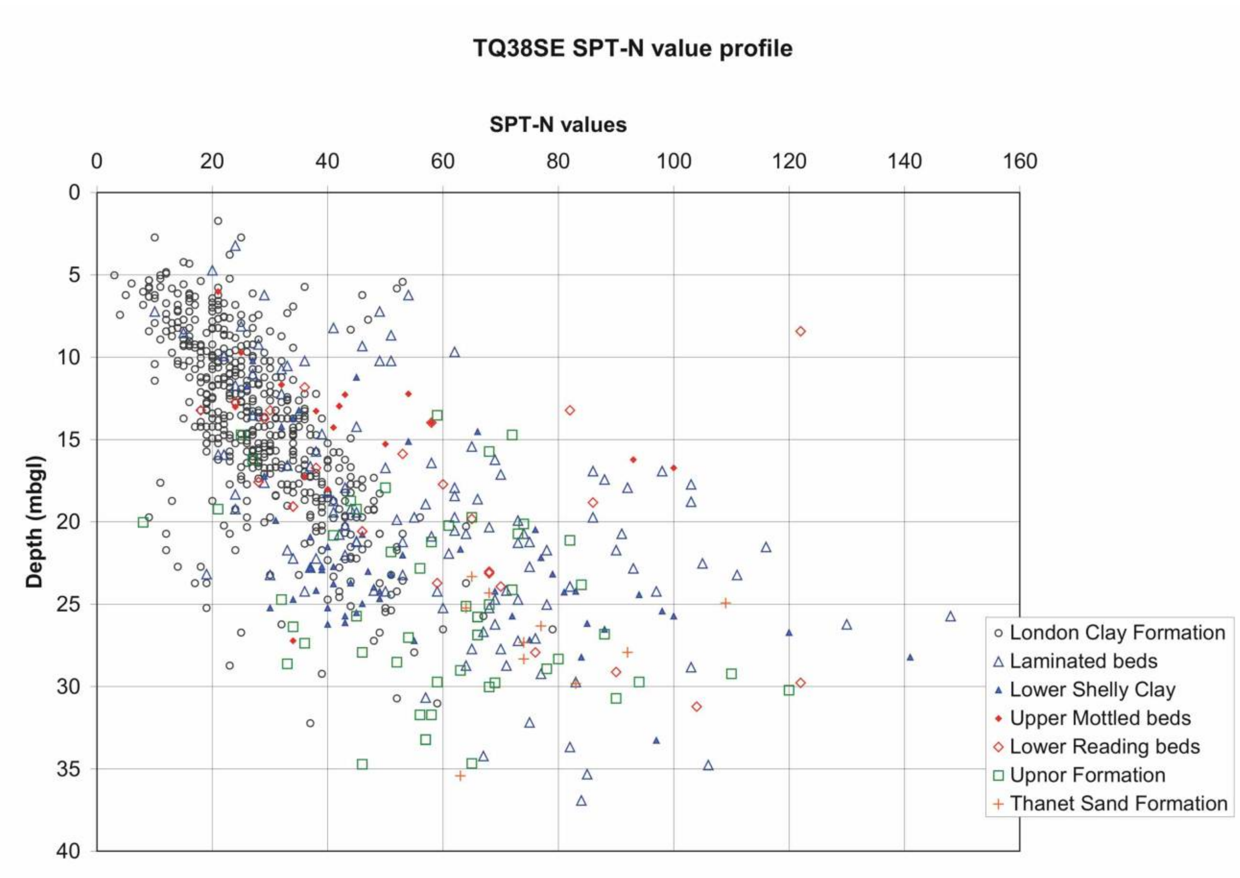


Figure 6.59. Variation of SPT N-values with depth for the Thanet Formation, Lambeth Group by unit and the London Clay Formation for data from TQ38SE.

6.8 BRIEF SUMMARY OF GEOTECHNICAL PROPERTIES

Despite a generally wide variation in geotechnical properties, analysis of parameters held in the geotechnical database has revealed some recognisable trends in the properties and engineering behaviour of the principal formations within the Lambeth Group. Data have been analysed by stratigraphical formation and unit (where available) and according to arbitrarily defined geographical areas. Some areas give contrasting parameter values compared with others. However, the data are by no means equally distributed across the areas, and in many cases variation within a single area is similar to that across multiple areas.

The densities of the Reading Formation Mottled Clays are consistently high (bulk density median = 2.1 Mg/m^3).

The particle size distribution of the Lambeth Group varies from coarse, cobbly gravel or sandy gravel in the Upnor Formation to nearly pure clays within the Reading and Woolwich formations. All the formations were variable. The Upnor Formation generally varied between a sandy gravel to a slightly sandy clay but is primarily coarse-grained. The gravel within the Upnor Formation is primarily flint but, in some areas is calcrete and occasionally silcrete of ferricrete. The Reading Formation is a sandy gravel to a clay but a majority is a clay, sandy clay or clayey/silty fine to medium sand. The gravel comprising mostly of calcrete. Of the units within the Reading Formation the Upper Mottled Clay tends to be finer than the Lower Mottled Clay partly due to the presence of calcrete gravel in the latter unit. The Woolwich Formation is generally more well graded than the other formations and the Laminated Beds is more well graded than the Lower Shelly Clay. Both the Lower Shelly Clay and Laminated Beds tend to be coarser in Area 2; either because of more sand of gravel composed of shell in the case of the Lower Shelly Clay or iron-rich concretions in the Laminated Beds. The Laminated Beds and Lower Shelly Clay, Woolwich Formation, gave the highest total sulphates. This is because of oxidation of pyrite due to near surface weathering and it reaction of the sulphate ions with calcium ions primarily from shell.. They range from zero to 1.5 g/l with a median of 0.08 g/l overall. The Reading Formation medians range from 0.05 to 0.30 g/l, whereas the Woolwich Formation median is 0.57 g/l. Organic contents ranged from 0 to 60% with an overall median of 0.34%. The highest values are from the Woolwich Formation, most notably the lignite of the Lower Shelly Clay Member which has a median of 16%.

The undrained strength, c_u, for the Lambeth Group is relatively high, ranging from 82 to 223 kPa. The Reading Formation Upper Mottled Clays show the highest median (223 kPa), and the Upnor Pebble Beds the lowest (82 kPa). The remaining units represented lie within a relatively narrow band between 122 and 151 kPa with the exception of the Reading Formation Lower Mottled Clay at 178 kPa. Undifferentiated Reading Beds Mottled Clays gave a median c_u of 151 kPa. The profile of c_u with depth is highly scattered although a general trend of increasing strength with depth can be discerned. A negative correlation is found between residual shear strength and plasticity index. The median residual friction angle for Reading Formation Mottled Clays was 18^o.

The results of oedometer consolidation tests place the Lambeth Group in the 'low' to ‘medium' rate of consolidation c_v class, typical of medium and high plasticity soils. The overall median values for coefficient of volume compressibility, m_v, reduce consistently with increasing stress from 0.09 to 0.004 m^2/MN The m_v results place the Lambeth Group in the 'low' to 'very low' category.

The permeability medians, maxima, and minima for each formation were unexpectedly similar. The medians for the Reading Formation members range from 3.5×10^{-8} to 2.5×10^{-7} m/s. The Upnor Formation gave medians of 8.3×10^{-7} m/s (Glauconitic Sand) and 5×10^{-7} m/s (Pebble

Beds). The Woolwich Formation medians were 3.5 x 10^{-7} m/s (Laminated Beds) and 6 x 10^{-7} m/s (Lower Shelly Clay). Overall, values ranged from 1.8 x 10^{-10} to 2.0 x 10^{-4} m/s.

Compaction data gave maximum dry density and optimum water content formation medians in the range 1.80 to 1.99 Mg/m^3 and 10 to 13%, respectively. A total of 38 MCV data for are contained in the database. The range of MCV results for the Reading Formation Mottled Clays was 0 to 18, with a median of 9.3%.

Swell/shrink test data obtained from Reading Formation Mottled Clay samples at BGS showed a good relationship between 1-D swelling strain and 1-D swelling pressure. Vertical swell (i.e. perpendicular to bedding) was found to always exceed horizontal swell in the 3-D cube test, by up to four times. Maximum swell was typically achieved between 10 and 100 hours. Overall (volumetric) swell in the 3-D cube test ranged from 0.4 to 14%, but was typically around 7%. Linear shrinkage ranged from 12 to 16%.

The majority of Standard Penetration Test (SPT) data represent the Reading Formation Mottled Clays and Upnor Formation Glauconitic Sands. The median N value for the undifferentiated Reading Formation Mottled Clays is 35 blows / mm with a range of 3 to 232 blows / mm.

7 ENGINEERING GEOLOGY

7.1 INTRODUCTION

The complex and variable lithologies of the Lambeth Group give rise to variable ground conditions. This has been determined largely by the variation of depositional environments and by post-depositional processes such as erosion, weathering, leaching, pedogenic processes, soil formation processes, tectonics, and dissolution of chalk beneath the Lambeth Group. Thus the engineering geological considerations of the Lambeth Group are determined directly by this variability and complexity, and also the location and nature of engineering applications and groundwater conditions. The history of engineering within the Lambeth Group dates back to the beginnings of the industrial revolution in Britain when the pioneering engineers of the modern era, such as Brunel, Beamish, Trevithick, and Page, developed the now familiar techniques of tunnelling, excavation, shaft-sinking, drilling, and piling, much of it in east London, included within the Lambeth Group deposits. Simultaneously, these engineers shed new light on London's geological formations. The expansion of a wide variety of large-scale engineering activity focused on central and east London during the last twenty years of the 20th century and beginning of the 21st century coincided with the distribution of deposits of the Lambeth Group, and greatly increased the knowledge of these deposits. Developments included the Jubilee Line Extension (JLE), the Limehouse Link (LL) Road, Union Rail and the Channel Tunnel Rail Link (CTRL) 2. Many such projects have evolved from London's need to extend its transport links to the southeast.

Many of the early 19th century. projects represented firsts for engineering worldwide; for example, the Thames Tunnel (1843) was the first sub-aqueous public tunnel and the first use of a tunnelling shield (Skempton and Chrimes, 1994). These early projects proved extremely difficult because of the variable properties of the Lambeth Group and gave rise to novel technologies. Whilst the London Clay Formation has long been known as a consistent and reliable tunnelling and excavation medium, at least within the bounds of traditional techniques, this could not be said of the Lambeth Group.

Perhaps of greatest note have been the tunnels beneath the Thames, and elsewhere in London, starting with the unsuccessful Thames Driftway begun in 1806 and ending with phase 2 of the CTRL (begun 2000). Also included are the Thames, Rotherhithe, Blackwall (1 and 2), Dartford (road and rail), Victoria Underground Line, Jubilee Line Underground Extension Limehouse Link (cut and cover), Docklands, Thames-Lee Water Main (TLWM), and Thames Water Ring-Main (TWRM) tunnels. Many of the early tunnels beneath the Thames were, in places, just a few metres below the riverbed. Consequently, natural undulations or channels within the clay would result in funnelling-down of the soft or loose sediments into the face and catastrophic flooding of the works. Techniques used to combat soft ground and groundwater ingress have included compressed air (first proposed in 1826), riverbed sealing, grouting (cement and chemical), and ground freezing (Skempton and Chrimes, 1994; Clarke and Mackenzie, 1994).

The limited outcrop of the Lambeth Group and variable lithologies has meant that surface problems, such as shrink/swell, have been less prevalent and less well documented than the extensive London Clay Formation outcrop. This applies equally to coastal exposures and to landslides, the occurrence of which are low due to the limited exposure and subdued landscape. However, cuttings for railways (e.g. Park Hill railway cutting, Croydon in 1883 [Klassen, 1883]) and roads (Southwark landslide on A259 at Shoreham, W. Sussex in 1957) have resulted in engineering- induced slope failures within the Lambeth Group. Recently, wastewater schemes on the south coast have encountered the Lambeth Group (Hight *et al*., 2004).

7.2 GROUND INVESTIGATION

Best practice for undertaking ground investigations in the Lambeth Group has been addressed by Hight *et al*. (2004). In particular, the report recommendations attempt to address the problems of inappropriate and incomplete sampling that has, using past conventional site investigation practice, resulted in missing key layers (such as hard bands and water-bearing sands) and in the poor quality of "undisturbed" tube-samples that has resulted in almost certain underestimation of both strength and stiffness.

7.2.1 General considerations for ground investigation

Major projects, including tunnels, major excavation and underground structures, in which a good understanding of the Lambeth Group and its lithological variation is essential, clearly need more detailed information than routine piled foundation. For some major projects involving sensitive structures it may be necessary to have high quality, well-logged, rotary core at up to 50 m spacing. However, few projects will plan for this type of investment at the ground investigation stage and 100 m spacing are more common even in well-funded projects. If 100% rotary boreholes are considered too expensive, a mixture of rotary and cable percussion boreholes can enhance information since SPT and water strike data can be used to aid boundary definition and identifying water-bearing units. Cable percussion boreholes can also recover more accurate thicknesses of Upnor Formation gravel beds, which are rarely 100% recovered in rotary-cored boreholes. For less sensitive projects, such as housing development, site investigation may not support the expense of rotary drilling so cable percussion and pits may be used. If this is the case then 0.5 m spacing jar samples and 1 m spacing split U100's may be adequate. Also, SPT drives should be carried on to 100 or 200 blows in the more resistive materials. As with rotary drilling, the quality of the logging is very important.

Site supervision of the ground investigation should be costed into the specification. Expensive rotary core will be of limited use if best care is not taken when drilling. Drilling may be rapidly carried out but may not recover the sand units or gravel beds precisely the layers that need to be characterised (see Section 7.2.2). Runs of less than 1.5 m drilled more slowly should improve recovery.

After the quality of the driller, a most important factor is the experience and knowledge of the logger who should preferably have undertaken specific training on the Lambeth Group lithologies and lithostratigraphy. Logging needs to take place under conditions of good lighting, strictly adhering to BS EN ISO 14688-1 (BSI, 2002 et seq.) and BS 5930 (BSI, 1999 et seq.). Although core needs to be kept undisturbed and intact for laboratory testing purposes, the testing will not fully characterise the ground unless the stratigraphy of the sample is known. Most cores can be split open with palette knives or spatulas or similar tool. Alternately, scrape the surface off before logging, since the outside of the core will be contaminated with drilling fluid and disturbed sediment. Colour differences are very important and the use of colour codes such as the Munsell© colour charts (Munsell, 2009) or similar should be used. Colour photographs in suitable light with colour, monochrome and measurement scales of rotary core material are essential.

7.2.2 Lithology and Stratigraphy

The Lambeth Group is highly variable and may therefore still surprise during ground investigations. Training in, or experience of, this stratigraphy; high quality ground investigations; and sound interpretation skills are essential to best construction practice and, hence, cost-effective decision making.

7.2.2.1 IDENTIFICATION OF STRATIGRAPHICAL BOUNDARIES

Thanet Formation and Upnor Formation Boundary

Identification of the boundary between the Thanet and Upnor formations is often a problem in the London Basin area as far west as central London where the Upnor Formation directly overlies the Thanet Formation.

The boundary between the two may be clear in some boreholes as the colours or textures are different. The Upnor Formation is often darker, greener, of coarser (medium) sand and clayey, making it 'stickier' when reworked with water; the Thanet Formation often feels clean and the grain contacts can be easily heard when rubbed between the fingers because of the angular grains and lower fines content.

However, the boundary can be problematic for three main reasons:

- Both formations were deposited in similar sedimentary environments, occasionally leading to similar lithologies. This is particularly so in the north and west of London where only the basal part of the Thanet Formation (which is darker, contains more fines and is most similar to the Upnor Formation) is present.
- Much of the basal Upnor Formation is derived from reworked Thanet Formation materials.
- The contact between the two formations is frequently intensely burrowed, with an irregular contact (Figure 7.1) and in some cases, an indistinct, diffuse contact.

Generally, if gravel, has an appreciable clay content, with distinct clay laminae, abundant medium sand size glauconite or fossil shells are present, the sediment is Upnor Formation (Figure 7.2).

Standard Penetration Test (SPT) N-values from cable percussion boreholes can be useful in determining the boundary. N-values frequently rise sharply and stay consistently higher within the Thanet Formation, reflecting their greater density and (generally) lower clay content. In the Upnor Formation N-values are extremely variable.

Logging these sediments is best done both when freshly excavated and also, if in doubt, after a couple of hours exposure to air as the differences between the two often become more distinct during drying.

Figure 7.1 Sharp contact between the Upnor Formation (darker, above) and Thanet Formation (lighter, below), showing irregular topography of the boundary. From the Channel Tunnel Rail Link, Stratford box excavation after dewatering. (Copyright Jackie Skipper).

Figure 7.2. Borehole core from north London showing Upnor Formation dominantly comprising black shiny flint gravel, overlying fine to medium sand of the Thanet Formation. (Copyright Jackie Skipper).

UpnorFormation and lower Reading Formation Boundary

The boundary between the Upnor Formation and lower Reading Formation is probably the most problematic of the Lambeth Group boundaries to distinguish. The strict definition of Reading Formation is of 'continental facies' dominantly 'clay', which is 'mottled due to pedogenic processes in a humid environment' (Ellison, 1983; Buurman, 1980). However, where the Lower Mottled Clay is thin the Upnor Formation is also pedogenically altered, which, in those areas affected, makes separating these two units extremely difficult. This is not only due to changes in colour but also the translocation of clay downwards into coarser material. A pragmatic method of classification was proposed in Page and Skipper (2000) (and is commented on in Section 2) in which the pedogenically altered Upnor Formation and the Lower Mottled Clay are combined into the Lower Mottled Beds. Core loggers from this part of the sequence still need to make decisions about labelling units. This system used the following guidance:

- If the sediment is primarily glauconitic, shelly and with black rounded flint gravel, or a laminated sand and clay/silt (frequently with fine but abundant glauconite), it should be labelled '<u>Upnor Formation'</u>. On the other hand if colour mottling, and fractured and coloured flint pebbles (they go brown, then white or red, then fall apart when they are weathered – see Figure 7.3 and Figure 7.4) are the primary features seen, then '<u>Lower Mottled Beds'</u> (Lower Mottled Clay and mottled Upnor Formation) is the best assignation. If there is still an indeterminate boundary in between, then be honest and say so: 'gradational boundary over 200 mm consisting of…'

This method allows comparison with older borehole records - if the words 'mottling', 'multicoloured', or 'angular gravel' are recorded, it strongly suggests the presence of the 'Mottled Beds'.

This does not agree with the geological methods, which separate by the original depositional environment, but provides a pragmatic method that is generally easier to use than the standard geological requirement.

The Lower Mottled Beds (Page and Skipper, 2000) includes the Lower Mottled Clay and the pedogenically altered or mottled Upnor Formation (Aldiss, 2013). This classification should be used if possible. As such gravel beds are from the Upnor Formation, but where pedogenically altered, may be described as mottled Upnor Formation. However, separating the Upnor Formation from the Lower Mottled Clay can still be very difficult in some areas.

Figure 7.3. Borehole core from London Wall, City of London, showing gradational change from dark green marine Upnor (right end of core), passing upwards to mottled blues and red browns of the Reading Formation, Lower Mottled Clay (middle and left). (Copyright Jackie Skipper).

Figure 7.4. Borehole core from Whitechapel, east London, showing multicoloured, fractured and contemporaneously weathered flint gravel of the altered mottled Upnor Formation. Compare with more 'normal' Upnor flint gravel in Figure 7.3. (Copyright Jackie Skipper).

7.2.2.2 DIFFERENTIATING BETWEEN UPPER AND LOWER MOTTLED CLAY

One of the most useful ways of to differentiating between the Upper and Lower Mottled Clay when logging core is the identification of the mid-Lambeth Group Hiatus (MLH – see page 15 and Skipper, 2000), which separates the Upnor Formation and lower Reading Formation beneath from the Woolwich Formation and upper Reading Formation (which are above it). The mid-Lambeth Group Hiatus is the most useful horizon (and only true planar horizon) in the Lambeth Group, and represents the period when sedimentation ceased - between the Upnor Formation/Lower Mottled Clay deposition, and the transgression by the next depositional phase, the Woolwich Formation. Because there is such a sharp contrast in the depositional conditions between the two periods (from low sea level with much weathering to a sea level rise and drowning of former land surface), it can be recognised in core by the following:

- A sharp change down core/section from reduced (grey/black/blue) sediments to oxidised (pale, often mottled or multicoloured yellow, red or reddish brown), sediments (Figure 7.5). This is also the case in the Hampshire Basin where the Upper Mottled Clay directly overlies Lower Mottled Clay (Figure 7.5).
- In the London area, a sharp change from the Woolwich Formation shelly clays, to the first appearance of calcrete layers and Lower Mottled Clay or mottled Upnor Formation.
- In some cores from the London area, a confusing mixture of both mottled sediments AND shelly grey clay may be present just below the MLH. This is caused by crustaceans, (such as crabs), which lived in the Lower Shelly Clay sediments and dug large burrows (up to 30 mm in diameter and 2 m deep) into the underlying Lower Mottled Clay or Upnor Formation. As sea level rose, the burrows were abandoned and in filled with Lower Shelly Clay (Figure 7.7).

NB. If all else fails, the Lower Mottled Clay is generally sandier than the Upper Mottled Clay, and has a greater range of colours.

Figure 7.5. The mid-Lambeth Group Hiatus. Borehole core from east London showing Woolwich Formation Lower Shelly Beds (top left) overlying a sharp contact (mid-Lambeth Group Hiatus – here demarcated at 30.2 m depth) with Lower Mottled Clay below (right and lower core). In this case the Lower Mottled Clay is cemented with calcrete. (Copyright Jackie Skipper).

Figure 7.6. The mid-Lambeth Group Hiatus in the Hampshire Basin. Here, in a section of 40 m of Upper and Lower Mottled Clay in Alum Bay (Isle of Wight), the MLH is discernible as reduced, grey clay overlying an oxidised, reddened clay. Field of view is 900 mm wide. (Copyright Jackie Skipper).

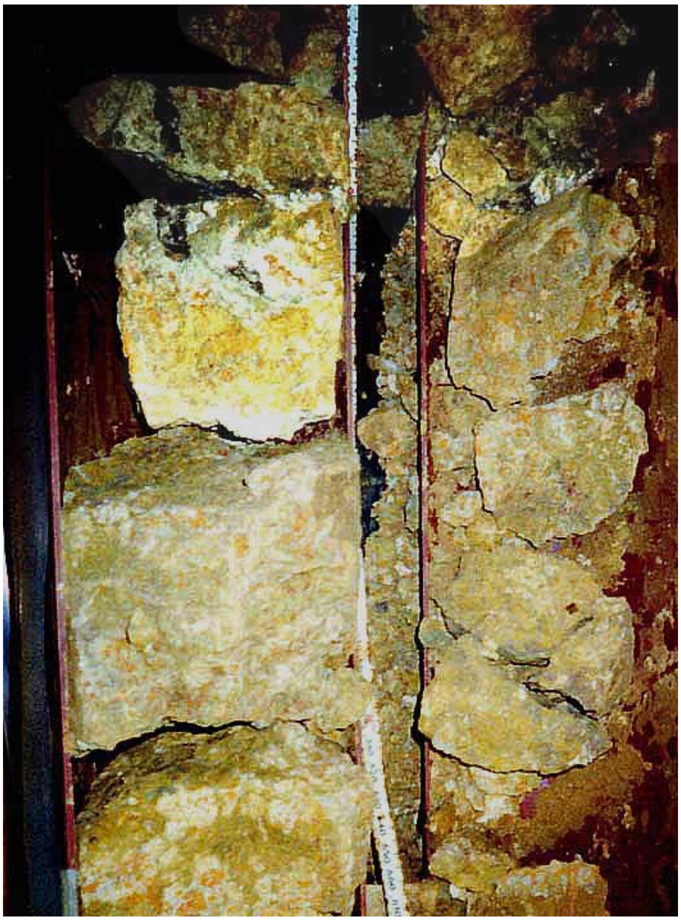


Figure 7.7. Cored borehole from east London, showing crustacean burrows (dark grey in colour, top left of picture). The burrows contain Woolwich Formation shelly grey clay. (Copyright Jackie Skipper).

7.2.2.3 Occurrence of Hard Bands/Layers

Hard bands or layers present a significant problem for drilling (see Section.3.6.1). They are most common approximately a metre below the mid-Lambeth Group Hiatus (see Section 7.2.2.2) in the Lower Mottled Clay or the upper part of the Upnor Formation when the Lower Mottled Clay is thin or absent. This is because the MLH represents the period when little or no sedimentation took place over a wide area of SE England, and the prevailing sub-tropical climate led to the formation of a variety of duricrusts at or near to the ground surface. Over most of the Greater London area, the most commonly encountered duricrust is calcrete (calcium carbonate concretion), which can vary from just a few white nodular lumps, to a layer up 1.5m thick. In areas of central to east London where the thickest calcrete is sometimes found, it can halt drilling progress and may damage drilling equipment (Figure 7.8).

In some areas of outer northeast London to areas of Hertfordshire, Bedfordshire and Buckinghamshire, a very strong, siliceous, gravelly duricrust or silcrete, called Hertfordshire Puddingstone, (Figure 7.9) may occur. It may up to 750 mm thick and has again been known to cause damage to cable percussion drills.

In the east Kent area and around Newhaven in Sussex, a third type of duricrust – ferricrete (iron-cemented concretion) may be found (Figure 7.10) and includes the Winterbourne Ironstone. Although ferricretes are not as strong as the other two types of duricrust, they can be up to 750 mm thick and have been used locally in Kent as a building stone and mined as an iron ore.

Less commonly, hard layers occur in the Woolwich Formation. In the upper part of the Laminated Beds, a hard, grey-brown, siderite-cemented layer up to 100 mm thick may be present, especially from east London into the Essex. Drillers have reported difficulty penetrating this layer. In addition, the layer can cause confusion in the logging of cable percussion boreholes, where they have been miss-interpreted as being concretions in the London Clay Formation.

In the Upper Shelly Clay of the Woolwich Formation there are shelly limestones beds. The most well-known is the Paludina Bed, which is present between Dulwich [TQ 340 726], New Cross [TQ 363 764] and Honor Oak [TQ 355 744] in south London (Figure 7.11). This unit, is up to 300 mm thick, consists of extremely weak, thinly laminated mid to dark grey mudstone often contains fossil freshwater gastropods (the *Paludina* in question). It is a lacustrine deposit deposited during a freshwater incursion. Other cemented shellbeds are also found throughout the Upper Shelly Beds, but are rarely greater than 200 mm thick, and are not consistently cemented over distances more than a few tens of metres.

Figure 7.8. Cored borehole from south London showing hard calcrete layers. (Copyright Jackie Skipper).

Figure 7.9. Excavated boulder of Hertfordshire Puddingstone (silica cemented pebble beds) from the Cheshunt area of Hertfordshire. Field of view is 1 m wide. (Copyright Jackie Skipper).

Figure 7.10. Ferricrete from the Swanscombe area, near Gravesend, Kent. This particular ferricrete also contains calcrete (white). Field of view is 1.5 m wide. (Copyright Jackie Skipper).

Figure 7.11. Cored Paludina Bed from the Honor Oak area of south London, showing round white *Paludina* gastropods. Left specimen is 100 mm wide. (Copyright Jackie Skipper).

7.2.2.4 PRESENCE OF WATER-BEARING BEDS AND LENSES

All the units in the Lambeth Group may contain high permeability units, but the likelihood will vary depending on the unit and location of the project.

A simplified summary is given below:

Upnor Formation

Sandy gravel beds up to five metres thick may be present in the upper part of the Upnor Formation (see Figure 7.12 for where they are most commonly encountered) where they have been deposited in large relatively steep-sided channels. They are generally water-bearing unless drained or unconfined (see Figure 7.13).

Reading Formation – Lower Mottled Clay

Permeable lenses appear to be relatively rare in central London but may be more common elsewhere. In east London and further east the Lower Mottled Clay tends to be sandy.

Woolwich Formation – Lower Shelly Clay

Occasional sandy beds (generally up to 150 mm thick but rarely, thickening to channels up to 2 m deep) (see Figure 7.14).

Woolwich Formation – Laminated Beds

Permeable units are common within the Laminated Beds, occurring as beds and channel infills of fine grey sand from 50 mm to 2 m thick, and locally thicker. The sands often contain disseminated pyrite, organic matter (lignite) and may also contain minor glauconite. The channels are steep-sided, up to 5 m wide, have very good connectivity with water/air, and widespread but can be difficult to find in site investigation boreholes, especially if sampling is not continuous (see Figure 7.15 and Figure 7.16).

Reading Formation - Upper Mottled Clay

Sand-filled channels in the Upper Mottled Clay are relatively rare in the London area, but occur within the main body of the unit or cutting down into the top of the unit. Although they have not yet been observed in open excavations in the London area they are present in excavations to the west of London, for example in the Newbury area. Here, they are commonly 2 to 3 m wide and 1 to 2 m thick within the mottled lithologies. In the Hampshire Basin they are laterally extensive, up to 100's of metres, fluvial sand beds generally 1 to 2 m thick.

Sand-filled channels in the Upper Mottled Clay can be up to 9 m deep in London, for instance in Bermondsey excavated during the construction of the Jubilee Line Extension (Figure 7.17). The channel was in direct hydraulic continuity with local aquifers and required extensive dewatering measures. In central London a sand-filled channel measured up to 12.5 m deep and up to 200 m wide has been identified.

Note that, because of the likelihood of highly permeable lenses within the Lambeth Group, piezometer results should be interpreted in conjunction with a good understanding of the lithologies and lithostratigraphy.

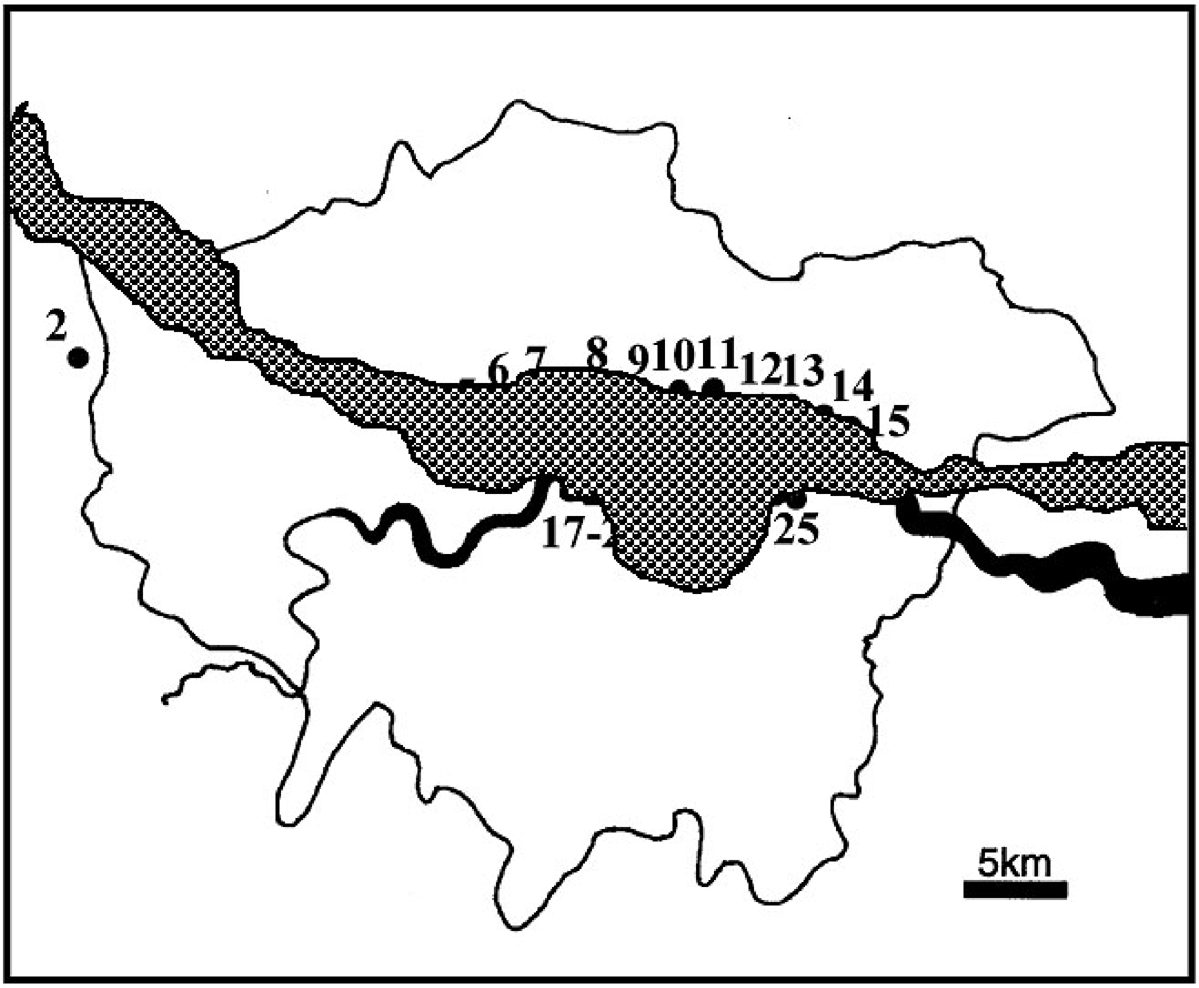


Figure 7.12. Map showing approximate distribution of gravel beds in the upper part of the Upnor Formation in the London area. (Copyright Jackie Skipper).

Figure 7.13. Upper Upnor gravel beds showing alternating layers of gravel and pale grey sand. This bed has very high permeability. Field of view is 4m wide. (Copyright Jackie Skipper).

Figure 7.14. Sand unit within the Woolwich Formation (Lower Shelly Beds), showing spring line at the base of the sand. Excavation for A2 at Shorne, near Gravesend, Kent. (Copyright Jackie Skipper).

Figure 7.15. Excavation in Stratford area of east London showing sand channel within the Laminated Beds of the Woolwich Formation. (Copyright Jackie Skipper).

Figure 7.16. Excavation for the M4/A34 interchange at Chieveley, Berkshire revealing sand-filled channels in the Woolwich Formation, Laminated Beds (upper part of the view), and infilling karstic features in the underlying Chalk. (Copyright Jackie Skipper).

Figure 7.17. Excavation for the Jubilee Line Extension in Bermondsey, south London, showing grey sands infilling a channel that cut down into the Upper Mottled Clay Reading Formation. (Copyright Jackie Skipper).

7.2.3 Sampling

7.2.3.1 Effect of sampling methods on sample quality

An important part of site investigation is the provision of suitable samples for geotechnical testing to provide relevant data for design. Sampling methods can significantly affect the quality of acquired samples and, therefore subsequent test results. Where ‘undisturbed’ samples are required then the use of sampling techniques that damage the sample may result in non-representative values, which in most cases result in data that provide conservative design parameters.

Sampling techniques are discussed in Hight *et al*. (2004) and are summarized in Table 7.1. However, note should be taken of the requirements of Eurocode 7 part 2 (BSI, 2007) and British Standard sampling methods (BSI, 2006).

Table 7.1. A summary of the advantages and disadvantages of different sampling techniques for the Lambeth Group (after Hight et al. 2004).

Sampling technique	Advantages	Disadvantages
Block sampling	Good samples where carefully taken in appropriate situations.	Time consuming if done correctly. Limited to surface, pits and shafts.
Cable percussion U100 thick-wall samples	Relatively cheap, well-known technique. Standard penetration tests provide some physical data.	Likely to result in sample disturbance, particularly in stiff and 'cemented' material; laboratory strength and stiffness results unlikely to be representative of *in situ* conditions. Use for laboratory tests requiring 'undisturbed' samples will need to be justified.
Pushed thin-wall tube sampler	Provides good quality samples.	Only suitable for sampling a limited range of material, i.e. those with undrained shear strength < ~250 kPa.
Rotary, double-tube core barrel	Generally provides good samples with some provisos.	Fairly expensive. Some disturbance of samples is likely. Drilling fluids may contaminate and/or soften the sample. Sample may be disturbed when removed from the core barrel.
Rotary, triple-tube core barrel	Good quality samples, Successfully used with biodegradable mud flush on a number of projects.	Expensive; not all ground investigation companies can provide this service.
Wireline drilling with triple tube core barrel	Good quality samples. Successfully used on a number of projects.	Expensive; only a limited number of companies provide this service. Drill bit cannot be inspected until the drill string has been withdrawn.

Sample disturbance and core loss may occur even with careful drilling; the latter is most common in the gravels of the Upnor Formation, and sand throughout, whereas core loss in the Reading and Woolwich formations outwith coarse grained beds is generally rare, but is encountered in faulted strata.

Hight *et al*. (2004) note that sample disturbance is particularly likely to occur in laminated or closely interbedded units as negative pore pressures (or suctions) are likely to develop in acquired samples when taken from the ground and relieved of their *in situ* boundary stresses. Inevitably there will be a redistribution of water contents from more permeable silt/sand layers to less permeable clays, which will swell and increase in water content. More permeable layers will also increase the swelling process and take-up of water from drilling flush or seepage into the borehole during rotary coring or boring. Where this occurs, water content measurements in laminated units will not be representative of *in situ* conditions.

Other drilling-related recommendations described in Hight *et al*. (2004) are:

- Polymer flushes have been used successfully for rotary drilling.
- Drilling-induced sample disturbance may be reduced by the use of face discharge drill bits, and tungsten or diamond impregnated bits on 'hard' bands.

- Recommendations for drill bits to be used in the Lambeth Group (Beckwith *et al*., 1996) are:

  In the Reading and Woolwich formations:
  - use of diamond saw-tooth bits,
  - switching to tungsten carbide bits when problems of core loss encountered and changing from biodegradable polymer mud flush.

  In the Upnor Formation:
  - use of diamond-set, face discharge bits.

7.3 TUNNELS AND SHAFTS

Tunnelling has been the engineering activity most associated with the Lambeth Group strata, particularly beneath the Thames during the early 19th C, and then throughout the 20th C, notably with the development of the London Underground system. An extensive review of tunnelling in the Lambeth Group is given in Hight *et al*. (2004). Much pioneering work was carried out in overcoming the difficulties posed by these strata. Preventing unacceptable entry of water ahead of, and around, a tunnel face has been a key factor in creating a workable and safe tunnelling environment within Lambeth Group strata. Hence, the absolute and relative permeability, and permeability anisotropies of the Lambeth strata, as well as water from the Thanet Formation and Chalk beneath, have been crucial factors in the design and execution of engineering remediation such as de-watering, ground-freezing, and compressed-air. Groundwater inflow, and in some cases direct river inflow, have become infamous in the Lambeth Group strata from the early days of the Thames Tunnel onward. These events have not only flooded workings, but have created voids above the face and behind tunnel linings due to the displacement of sand, silt, and occasionally clay blocks. Prior to the development of modern closed-face tunnelling techniques, the high permeability of formations within the Lambeth Group discouraged the development of the Underground system into southeast London and the Lambeth Group subcrop (Hight *et al*., 2004).

7.3.1 Early Thames tunnels

The first attempt to build a tunnel under the Thames, from Rotherhithe to Limehouse, was made by Ralph Todd between Gravesend and Tilbury in 1798. This failed due to lack of money and inflow of sand. The second attempt was the so-called Thames Driftway by Robert Vazie and Richard Trevithick. The work began in 1805, within the Upnor Formation, by hand tunnelling from Rotherhithe, but was halted in 1808 due to running sands from the Laminated Beds (Skempton and Chrimes, 1994; Hight *et al*., 2004).

The Thames tunnel from Rotherhithe to Wapping in East London, was begun in March 1825 with a shaft at Rotherhithe on the south side of the river, and eventually opened to the public in March, 1845 (Muir-Wood, 1994). The world's first articulated tunnelling 'shield', designed by Marc Brunel, was launched in December 1825. A segmented rectangular shaped structure, made of cast iron, was settled on following rejection of a circular shape. The 366 m long tunnel was driven throughout in Lambeth Group strata, which dip slightly from south to north, in the direction of the tunnel drive.

The cross-section of the tunnel was large and unusual in that it was essentially a twin tunnel with an interconnecting arched gallery. Site investigations were begun in 1824, revealing a stratum of 'blue alluvial earth inclining to clay of sufficient depth', which was at the time 'found to resist infiltration'. This is thought to refer to the Upper Mottled Clay (Muir-Wood, 1994). Tunnelling revealed this not to be the case, but more a case of 'insufficient' depth of clay and much of the underlying sands (Ferruginous Sand and Lower Mottled Sand). From an early stage, many inundations from the riverbed damaged the shield, made conditions extremely difficult, and culminated in the development of a swallow-hole and cessation of work between 1828 and 1835. It is believed that some of the inundations were due to the presence of natural scour hollows, up to several metres in depth, in the Lambeth Group strata, and hence critical thinning of the clay overburden (Skempton and Chrimes, 1994). In the most difficult stages of tunnelling the clay overburden (as little as 2 m thick) often cracked and subsided by as much as two or three metres due to loss of the underlying sand. However, in the later stages this clay was thick enough (> 3 m) to remain stable despite sand loss due to ground water, rather than river, inflow. It is not clear to what extent these fissures were natural or induced by the water pressure. The inundations were tackled by laying clay-filled bags on the riverbed, sometimes using a primitive diving bell. The silt layers at depth within the Lambeth Group, which had been included with the clay on drill logs as 'uniform tenacious clay', did give engineering problems in the tunnel, but only where the sand content was high and runs occurred (Skempton and Chrimes, 1994). A major hazard, particularly in the later stages was inflow of sewage and methane from the riverbed, the latter igniting on many occasions (Muir-Wood, 1994). Currently the tunnel forms part of the East London Underground branch, and has recently been relined.

7.3.2 Blackwall Tunnels

The 1st Blackwall tunnel connecting Poplar (north) with Greenwich peninsula (south), close to the present Millennium Dome, was built in 1897 and now carries northbound traffic only. The tunnel was constructed using compressed air as the strata consisted mainly of sands (Upnor and Thanet formations). As the overburden between tunnel roof and riverbed was sometimes as little as 1.7 m, the compressed air frequently blew holes in the riverbed, resulting in spectacular waterspouts. Clay blankets up to 3 m thick were routinely employed on the riverbed to counter compressed air loss and inundation of the tunnel. This was a development of the clay bags used on the Thames Tunnel, but the more generous navigation clearances downstream at Blackwall allowed a rigorous solution to a now familiar problem (Skempton and Chrimes, 1994). The eastern tunnel was opened in 1967 and carries southbound traffic. The western tunnel, narrower than the eastern, had been built by Sir Alex Binnie using James Greathead's shield (as for Tower Subway) and opened in 1897.

7.3.3 Jubilee Line Extension (JLE)

The Jubilee Line Extension (JLE) extends from Charing Cross to Stratford, crossing the Thames four times. The tunnels lie mostly within Lambeth Group strata between London Bridge and Canada Water stations, and also at Canary Wharf and North Greenwich Stations (Ellison *et al*., 2004). The cross-section is of the line between Green Park and the given in Appendix 2 Figure A.2.9.

Within the Lambeth Group strata the tunnels were driven using a pressurized closed-face tunnel boring machine (TBM). Bermondsey Station was excavated using a combination of tunnels and deep-box. Specialised rotary trench cutting diaphragm wall tools were used in the Lambeth Group to penetrate limestone layers. Compressed air working methods (to reduce water ingress) were also used on the Central Line west of Stratford in the 1890's, and on other tunnelling projects since. The log of Jubilee Line Extension borehole 404T contains all the units of the Lambeth Group sequence (Ellison, 1991). The information on the borehole including a generalised section, lithostratigraphy, core photographs, geologist's and site investigation description is in Appendix 1.

7.3.4 Channel Tunnel Rail Link (CTRL)

The Channel Tunnel Rail Link (CTRL), which became High Speed 1 (HS1), between Folkestone and London was fully opened in November 2007. Phase 1 of the CTRL was constructed during the 1990's to provide a high-speed rail route from the Channel Tunnel at Folkestone, via Ashford, to London. It was opened in 2003 with Eurostar services terminating at Waterloo, but with the route west of Fawkham Junction on normal (low-speed) track. Phase 2 takes the route from Dartford to St Pancras, crossing the Thames between Swanscombe and West Thurrock, and completing most of the route west of Dagenham, via Stratford, in 19 km of tunnel. With the exception of the two ends, the tunnels forming the Barking to St Pancras section of Phase 2 are driven through Lambeth Group strata. The geological cross-section along the route between Stratford and Rainham is shown in Appendix 2 Figures A.2.15 to A.2.16.

7.3.5 Limehouse Link

The Limehouse Link is a 1.8 km dual-carriageway section adjacent to the A13 trunk road, constructed in the early 1990's for the Docklands Development Corporation, linking Canary Wharf with the City of London. Most of the route was excavated to form a deep cut-and-cover tunnel. This necessitated massive reinforced concrete diaphragm walls up to 33 m deep and 42 m wide, constructed using a top-down method. In order to cross the Limehouse Basin a section of bottom-up construction within a cofferdam was required (Glass and Powderham, 1994). The Woolwich and Reading formations are at a depth of about 14 m and are overlain by a thin London Clay Formation, Thames Gravel, and Fill. Underdrainage to the chalk was observed both within the Thanet Formation and the Upnor Formation. Elevated pore pressures within the Laminated Beds were relieved by a series of wells, which connected it hydraulically with the under-drained Thanet Formation (Hight *et al*., 2004). Horizontal stresses were determined by self-boring pressuremeter tests to give values of K_0 of 2.5 for the Lambeth Group clays compared with 1.5 for the London Clay Formation.

7.3.6 Docklands Light Railway

The Docklands Light Railway, Lewisham Extension (DLRLE) runs between Mudchute Station on the Isle of Dogs to Lewisham Station, crossing the Thames in twin tunnels from Island Garden Station on the north bank of the Thames 4.2 km to Greenwich Station on the south bank (Sugiyama *et al*., 1999). The tunnels were driven using a slurry shield method. More than half of the tunnel was constructed within Lambeth Group strata overlain by Terrace Gravels (Appendix 2 Figure A.2.18). A large proportion of this was within the clay formations.

7.3.7 Greenwich pedestrian tunnel

The Greenwich pedestrian tunnel, built in 1902, connects Greenwich Pier with the Isle of Dogs, running close to the JLE. The tunnel is 2.7 m in diameter and 366 m long. It was built to allow workers to travel from Greenwich to the docks on the north bank. The tunnel is accessed via shafts containing lifts and stairs. The north shaft is close to the Island Gardens station on the DLR, and the southern shaft close to the Cutty Sark.

7.3.8 Thames Water Ring Main (TWRM)

The Thames Water Ring Main (TWRM) was constructed to provide 80 km of 2.5 m diameter tunnel, several shafts, and three large underground installations linking London's water treatment works along two principal NE–SW routes: one north and the other south of the Thames. Serious inundation took place at Tooting Bec (between Streatham and Brixton) due to high pressures within the Thanet Formation. Whilst most of the tunnels (including all of the

North London section) were driven in London Clay, the 9.5 km of tunnel within the Lambeth Group were found to have only moderate water pressures (Farrow and Claye, 1994). Different tunnel lining methods were used in the London Clay and the Lambeth Group, that in the former being cheaper and quicker. Ground freezing and grouting were used to control ground water ingress (Clarke and Mackenzie, 1994).

7.3.9 Difficulties experienced during tunnelling

1) Lithological variability

   a. Variable strength/density (sometimes associated with hard bands) leading to:

      - Difficulties in controlling the alignment of the tunnelling machine,
      - Variable jack pressures.

   b. Variable, inconsistent and difficult to predict distribution of water-bearing sediments.

   c. Faulting, introducing unexpected strata, such as clay suddenly changing to water bearing sand,

   d. Variable and inconsistent slurry material due to changes in lithology and material behaviour:

      - May lead to clogging of slurry shield,
      - Problems associated with controlling slurry conditioning,
      - Problems with slurry/muck handling.

2) Other reasons

   a. Face instability issues in the Laminated Beds, gravels in Upnor Formation and sands in all units.

   b. Sensitivity to compressed air (170 kPa) of fine sand and silt of the Laminated Beds.

   c. Swelling clays.

   d. Possible hydraulic continuity with water-bearing strata beneath the Lambeth Group (Thanet Formation and Chalk).

   e. Removal of oxygen from the atmosphere in dewatered sand of the Upnor Formation and potentially the Laminated Beds (Newman et al., 2013).

7.3.10 Difficulties experienced during shaft construction

1. De-watering may need to be designed specifically for local ground conditions (may need to de-water below construction depth into Thanet Formation and Chalk),
2. Hard bands or gravels may obstruct sheet steel or bored piles, or cause unbalanced caisson sinking,
3. Base heave,
4. Flooding of shafts in Laminated Beds and sand layers in the Lambeth Group.

Table 7.2 Tunnelling and deep excavation projects and references

Project name	Reference	Subject
Thames Tunnel	Skempton and Chrimes, 1994	Engineering and geology
Rotherhithe Tunnel	Tabor, 1909	Engineering
Blackwall Tunnel	O'Reilly, 1997	Construction, 'scour hollows'
Limehouse Link – (A13), Canary Wharf to City of London	Stevenson and DeMoor, 1994	Design and performance
Victoria Line	Follenfant *et al*., 1969	
Jubilee Line Extension (JLE)	Linney and Page, 1996 Burland *et al*., 2001, Batten *et al*., 1996	Engineering geology Construction
Docklands Light Railway (DLR) Lewisham Extension	Sugiyama *et al*., 1999	Tunnelling
Channel Tunnel Rail Link (CTRL)	Beckwith *et al*., 1996 Whittaker, 2004	Ground investigation Groundwater control
Crossrail	Lehane *et al*., 1995	Lithological variability

7.4 FOUNDATIONS

7.4.1 Deep foundations

Within the Lambeth Group deposits the choice of whether to found on, or to penetrate, hard layers within a weaker medium is made more difficult by the impersistence, variability in thickness and strength, and unpredictability, of such layers. These layers may be in the form of shelly limestones (Lower and Upper Shelly Clays of the Woolwich Formation), calcretes (Upnor Formation and Lower Mottled Clays) or silica-cemented gravels and sands (e.g. Upnor Formation). A 1 m thick layer of limestone nodules (calcrete) within the Lambeth Group was successfully used as a founding medium for some 2000 kN capacity 600 mm x 16 m continuous flight auger piles on the South Quay Plaza (Phase 2), Isle of Dogs (Solera, 1998). Other piles were founded in underlying Lambeth Group sands. In central London, under-reamed piles have been successfully foundered in the Upper Mottled Clay, Reading Formation.

The de-stressing of the Lambeth Group clays following excavation can result in de-structuring, swelling, and softening. Thus the relationship between strength, bearing capacity, and depth is important in the design of foundations as is timely construction after pile boring, and control of surface water. Although in central London where the water table has been lowered, the Lambeth Group is generally considered to be under-drained by the Thanet Formation and Chalk. Water bearing sand units such as sand channels in the Laminated Beds and Upnor Formation gravel should be carefully monitored during the site investigation phase of projects involving deep pile foundations. If high water pressures are encountered then actions such as bentonite support introduced towards the base of the London Clay Formation, should be considered to prevent collapse of bored piles.

Canary Wharf was one of the largest developments in Europe. Started in the late 1980's it has expanded across many of London's 19th and early 20th century docks. Notable infrastructure developments have included the Docklands Light Railway (DLR) and a network of roads, whilst preserving much of the waterway system. Fill, Alluvium, Terrace Gravel and Lambeth Group strata underlie the centrally situated Canary Wharf site in the West India Docks area of the Isle of Dogs. Here, the Lambeth Group is approximately 12 m thick, with typically twothirds of this consisting of Reading Formation deposits. The Lambeth Group strata are of uniform thickness across most of the site, but limestone and gravel layers are intermittent. As a result of the heterogeneity of the strata, it was found that SPT data best characterised the engineering properties (Troughton, 1992).. Considerable seepage from the gravel bed in the upper beds of the Upnor Formation, and the Thanet Formation beneath was managed by using bentonite and casing (Troughton, 1992). Major buildings were founded in the Thanet Formation, while smaller structures and roads, usually by driven piles, and cofferdams were founded within the Lambeth Group. Some driven piles reached refusal in the limestone/marl layers.

Large diameter bored piles were successfully used under dry conditions at the British Library site in Euston, London, where shaft adhesions of over 200 kPa were achieved in Lambeth Group clays and sands at between 9 and 13 m depth (O'Riordan, 1982). Design compressibility and permeability parameters for the clays and sandy clays of the Lambeth Group for the Royal Albert Dock Spine Road (RADSR) are given as m_v = 0.15 m^2/MN, c_v = 10 m^2/yr, and k = 1 x 10^{-8} m/s (Card and Carter, 1995). Other examples of pile design and tests are given in Hight *et al*. (2004).

7.4.2 Shallow Foundations

The lack of publications on problems associated with shallow foundations on the Lambeth Group indicates that their construction generally presents no major difficulties. Those settlements that have been documented indicate that they are about half those generally found for the London Clay Formation (Morton and Au, 1974). Nevertheless, shrinkage and swelling of high plasticity Reading Formation clays, and possible instability in the Upnor Formation gravel or loose sand beds in any unit, should be considered during the site investigation and design stages.

Mobilisation of pyritic material within the lignite layers of the Lambeth Group can give rise to sulphate-rich groundwater and consequent local damage to foundation concrete, after oxidation. Deposits with a large proportion of plant remains may provide poor and variable foundation conditions.

7.4.3 Summary of key issues for foundation design in the Lambeth Group

Deep foundations:

- Control of groundwater (for example by site specific designed de-watering),
- Founding-on, or penetrating, strong layers or lenses (i.e. shelly limestone within the Lower and Upper Shelly Clays of the Woolwich Formation and calcrete in the Upnor Formation and Lower Mottled Clay),
- Sulphate attack of concrete foundation in the Woolwich Formation,
- De-stressing, heave and softening of clays in excavation.

Shallow foundations:

- Shrink/swell in clays:

  Related to

  - Seasonal moisture content changes,
  - Desiccation due to trees,
  - Heave due to removal of trees,
  - Swell due to leaking drains.

- Softening of clays in the presence of water bearing sand beds.

7.5 EMBANKMENTS AND USE AS FILL MATERIALS

Due to the highly variable lateral and vertical nature and extent of the Lambeth Group lithologies and their relatively thin development, fill materials derived from these deposits are likely to be composed of more than one unit and lithology. Therefore, use of the Lambeth Group as an engineered fill will require a good knowledge of the lithologies present and available at a potential source area and their strength/compaction characteristics. During the construction of the Newbury bypass (A34) the Lambeth Group provided a good source of fill for embankments and landscaping when emplaced in the correct condition, but low plasticity clays and silty sands typically proved to be highly sensitive to changes in moisture content. Acceptable criteria for use as engineered fill should be ascertained during the planning, investigation and construction phases (Hight *et al*., 2004).

Data on embankments constructed from the Lambeth Group is sparse partly because it has a relatively small outcrop. A survey of the motorway networks by TRL (Perry, 1989) found failure of 7.6% of embankments constructed from Lambeth Group deposits (undertaken prior to revision of the stratigraphy, the survey reported ‘Reading Beds’ as ‘Eocene’, rather than Palaeocene in age). This was second only to the Gault Formation. Typically failure occurred on 1 in 2 slopes within 22 years of construction. Failure modes include not only slope failures but also tension and shrinkage cracks, excessive settlement, water seepage and erosion of the toe. The survey noted that drainage ditches on the slope itself contributed significantly to reducing the number of failures. The maximum allowable embankment slopes assessed during this survey are presented in Table 7.3.

Table 7.3. Maximum slope (vertical to horizontal) allowable for embankments constructed from the Reading Formation to reduce failure to below 1% within 22 years of construction (Perry, 1989).

	Maximum slope		
Slope height (m)	0 - 2.5	2.5 - 5.0	>5.0
Fine grained	1:3	1:4	1:4
Coarse grained	1:1.75	1:1.75	1:1.75

7.5.1 Subgrade

Lithological variability of the Lambeth Group may make designing subgrade on, or from, the Lambeth Group difficult. CBR values vary greatly, as do maximum dry density, and are dependent on lithology. Design of the pavement on the Newbury Bypass (A34) was based on a subgrade CBR of < 2% and included all the lithologies encountered, i.e. very stiff clay and silty sand.

7.5.2 Cut slopes

Cut slope failures are not very common on the Lambeth Group, partly because of its limited area of outcrop. The first well-documented case was the Park Hill cutting, Croydon, (approx. NGR 5328 1654). This was a cut and tunnel scheme a total of 1,095 m long, of which 382 m was tunnel. It was constructed by the Woodside and South Croydon Railway from the Upper Addiscombe Road (A232) to near the Combe Road (A212) between 1880 and 1885 as a route to the South Coast. The cut was up to 26 m deep and the slopes graded to 45°. The geology, described by Klaasen (1883), is shown in Table 7.4 and Figure 7.18.

Table 7.4. Geological description of the Park Hill cutting.

Lithostratigraphy	Thickness, m	Description
Harwich Formation	Up to 7.3	Grey SAND occasionally calcareous with clay partings and thin layers of carbonaceous matter
	0 to ?	Brown shelly sandy GRAVEL with occasional carbonaceous fragments.
	0 to 3	Calcareous rounded black shelly sandy flint GRAVEL generally cemented with occasional more strongly cemented concretions of flint gravel and shells.
Woolwich Formation Lower Woolwich Formation	0.0 to 3	White shell bed with some carbonaceous fragments. Sometimes forming tabular limestone 0.4 m long and 0.15 m thick.
	0.9	Soft brownish grey shelly CLAY
	2.2	Interbedded hard and soft shelly pale blue CLAY with some pyrite. Hard bands cemented by calcium carbonate from shells. Lignitic in the north of the cutting.
Reading Formation Lower Mottled Clay	2.3	Mottled red with some purple CLAY with calcium carbonate near the base in wavy bands and concretions and beds up to 5.5 m wide. Lens shaped lignite layer reported within the clay in the south of the section with associated gypsum.
	1.2	Multicoloured red with greenish blue and purple patches. Calcium Carbonate streaks and nodules in the upper 0.6 m.
	1.5	Vertical smooth or polished jointed or fissured greenish blue with purple and orange red CLAY
	1.4	Purple, greenish-blue and orange red patches CLAY. At the base is a 2.5 cm thick lignite layer.
Upnor Formation	0.45	Purple sandy GRAVEL. Gravel is fine to coarse and black. At the top is a thin, hard orange and carbonaceous layer – an iron pan
	0.92	Green slightly gravelly SAND. Gravel is yellow or olive green and rounded.
	2.0	Greenish-brown slightly gravelly SAND with orange red veins. Gravel is greenish grey, rounded to subrounded flint.
	0.6	Grey SAND with calcareous cemented sand
	0.6	Brown, slightly gravelly fossiliferous sandy CLAY. Gravel is black, rounded, fine flint
Thanet Formation		Quartz-rich SAND

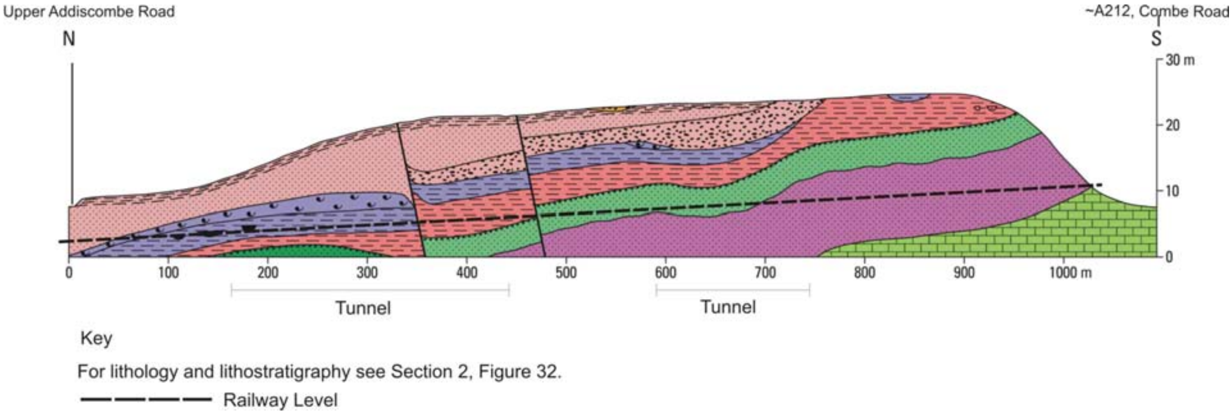


Figure 7.18. Park Hill cutting on the Woodside and South Croydon Railway (after Klassen, 1883). For key see Figure 2.31.

During construction of the railway a section of the central cut failed on 27th August 1882 and subsequent movement in the central cutting was described as "inconveniently frequent'. This was followed on 6th October 1882 by slipping of a 61 m long a 10 m wide section in the north cutting after heavy rainfall. The failure occurred initially in the 'blue clay' of the lower Woolwich Formation. The steep slope, depth of cut and high rainfall in addition to the character of the Lambeth Group contributed to the failure of the slope.

At the time of the construction of the Park Hill cut, the Lambeth Group had a reputation for being unstable. This was also the finding of an extensive survey of the motorway networks in the UK by TRL (Perry, 1989), which reported that 2.95% of cuts in the Lambeth Group had failed or showed signs of failure. Typically the failure occurred within 22 years of construction with the most common failures being in 1 in 3 slopes.

The slopes of the cut and cut and fill section of the A259 coast road about 1.5 km north-east of Castle Hill, Newhaven, West Sussex also suffered regular slope failures. Most of the movement was in the Woolwich Formation and resulted in cracking and deformation of the road. Much of the remedial work was piecemeal patching of the road but more permanent corrective action has been carried out, including the installation of sheet pile and a bored pile wall, rock fill on the toe, road realignment, shallow and deep drainage and decreasing the slope to 1 in 4.

7.6 GEOHAZARDS

7.6.1 Landslides

Landslides are rare in the Lambeth Group because of the small outcrop area and subdued landscape; although some slope failures are due to subsidence from the dissolution of the Chalk. Slope instabilities in the Lambeth Group are, however, common at coastal outcrops which, although relatively limited in extent, may be subject to continuous erosion of the toe, and hence repeated landsliding. The coastal outcrops of the Lambeth Group mainly occur at Reculver (North Kent), Newhaven (East Sussex), Shoreham, Worthing, and Felpham (W. Sussex), Portsmouth (Hampshire), Whitecliffe Bay and Alum Bay (Isle of Wight) and Studland Bay although he geological map (EW 343, Swanage published 1993) indicates that these are of the London Clay Formation.

The best examples of coastal landslides occur at sites near Newhaven, Sussex and Alum Bay and Whitecliff Bay in the Isle of Wight (Bromhead, 1979). The near vertically bedded Lambeth

Group (mostly Reading Formation) form the complete slopes at Alum Bay (Figure 7.19) and Whitecliff Bay. They fail regularly, mainly as mudslides, particularly during the winter when the slopes become saturated. The mudslides slump and flow onto the beach, and are then eroded away by the sea, maintaining the steep coastal cliffs and further enhancing instability. At Newhaven, the Lambeth Group, comprising the Upnor and Woolwich Formation, is nearly horizontally bedded above the Chalk. The steep slopes in the area are associated with gulleys of weaker material. Failures in the Woolwich Formation are common and in wet winters develop large rotational slides despite attempts to re-profile the slope and to improve drainage. The underlying Upnor Formation is also commonly heavily gullied along this part of the coast.

Figure 7.19. View from the top of Alum Bay cliff with the White Chalk Subgroup to the left and the landslide in the Lambeth Group centre.

Inland, small-scale landsliding involving the Lambeth Group and London Clay Formation was noted along the River Arun, to the south-east of Arundel, Sussex at [TQ 025 065] (Aldiss, 2002; Shephard-Thorn *et al*., 1982) and to the north of Angmering [TQ 5080 1060].

Whilst some clay-rich formations of the Lambeth Group are fissured, highly plastic, and of low strength, overall slope stability is frequently found to have been improved by the under-drainage effect of high permeability sand layers within the dominantly clay formations (e.g. the Lower Mottled Clays), and/or underlying sand-rich formations (e.g. the Upnor Formation beneath the Woolwich Formation). Conversely, the alternation of high and low permeability strata may result in perched water tables, resulting in small-scale, local slope failure, for example by sand runs and subsequent camber or slump.

7.6.2 Subsidence

Subsidence in the Lambeth Group is usually due to the dissolution or mining of the Chalk. Karst features, formed by dissolution of the Chalk, are likely to be concentrated at the feather-edge of the Lambeth Group where surface run off is concentrated by clay beds (Edmonds, 1995). The result is an irregular undulating junction between the Chalk and Lambeth Group commonly with dissolution pits (dolines) or pipes. The Lambeth Group subsides into the karstic features.

Subsidence is more likely to occur in sand and silt deposits, and catastrophic subsidence may occur as a result of very heavy rainfall or water main failures. Soakaways should not be sited where large quantities of water may cause dissolution of the Chalk or where sands or fine-grained materials may be washed into karstic features. Fossil irregularities in the Chalk subcrop resulting from these karstic processes are up to 10 m deep in West Sussex and elsewhere in southern England.

Large-scale subsidence features involving the Lambeth Group, indicated as 'Foundered strata' on geological maps, are shown on the BGS Brighton-Worthing 1:50,000 sheet (318/333), particularly at West Blatchington, Brighton, and probably also in the Hove and Worthing areas (Young and Lake, 1988). These are thin relic outliers of Lambeth Group overlying the Chalk, where preferential saturation and dissolution of the Chalk, at the feather-edge of present and former Lambeth Group outcrops, has led to subsidence. Much of the outcrop is mantled by thin superficial deposits, which are often rich in Lambeth Group materials resulting from various periglacial processes, including solifluction. One possible mechanism is that sulphate-rich acidic groundwater formed by oxidation of pyrite from lignite beds within the Woolwich Formation overlying the Chalk have partially converted chalk to gypsum; this being more prone to dissolution and hence subsidence (Young and Lake, 1988). Similar conditions occur in the Chichester area (Aldiss, 2002).

Where founding on Lambeth Group strata underlain by the Chalk in southern England, consideration should be given to the likelihood of solution features and other karst/periglacial features affecting the Chalk/Lambeth Group junction, particularly at the feather-edge of the Lambeth Group outcrop. These will have serious implications for foundation design, in particular the risks associated with re-mobilising Lambeth Group material infilling solution features, for example as a result of water pipe fracture.

Karst features may be identified beneath the Lambeth Group using a number of methods including probing and geophysics (Bell *et al.,* 2004). If it is essential to find the dissolution features then removal of the Lambeth Group cover may be required. For example, the karstic feature may be infilled with Lambeth Group materials as seen during the construction of the A34 at Chieveley (Rhodes and Marychurch, 1998). The difference in behaviour between chalk and the infill meant that standard road construction was not suitable. Alternatives included digging out the Lambeth Group and replacing with a suitable material or constructing a reinforced road. The size of the dissolution features meant that the reinforced road was the best option.

Man-induced subsidence occurs where chalk was mined below the Lambeth Group. Chalk, usually taken from surface, is added to clay to reduce shrinkage and as a flux in brick making and flint mining. The presence of former shallow chalk mines adjacent to and beneath the Lambeth Group outcrop represent a potential foundation collapse hazard (for example in the Coley district of Reading, where former shallow chalk mines resulted in the need for remedial foundation work to houses [Edmonds, 2008]). Small vertical Chalk mines, dene holes, occur in Kent and Essex, and sand mines in the Thanet Formation are known in the Blackheath area, south east London.

7.6.3 Deoxygenated air in tunnels and deep excavations

Deoxygenated, pressurised air primarily in the Upnor Formation has caused health and safety risks during tunnelling or deep shaft excavation operations in London and has caused deaths (Lewis and Harris, 1998; Newman *et al*., 2013). The hazardous conditions occur where the deoxygenated, pressurised air is intercepted by tunnels or deep shafts as follows:

- Groundwater lowering by pumping of the Chalk during the 19th century and the first part of the 20th century for potable and industrial water,
- Ingress of air into mostly coarse-grained deposits such as the Upnor Formation now above the water table,
- Rising groundwater during the late 20th century and early 21st century as the industrial need for borehole water is reduced,
- Trapped of pressurised air due to rising ground water within parts of the Upnor Formation beneath clay beds including the Lower Mottled Clay,
- Deoxygenation of the trapped air in the Upnor Formation probably by 'green rust', a mixed Fe(II) and Fe(III) layered double hydroxide (Newman *et al*., 2013),
- Interception of the deoxygenated, pressurised air in the Upnor Formation by tunnelling or construction of deep shafts.

7.7 INDUSTRIAL USES

When carrying out a desk study for construction concerning the Lambeth Group it is important to consider whether any old extractive industry workings may be present. These workings may be poorly documented and include deep, steep-sided pits, which may be infilled. The fill may have markedly different geotechnical characteristics to the undisturbed materials. Buildings overlapping the fill and *in situ* material may be liable to differential settlement unless foundations are designed accordingly.

Materials extracted from the Lambeth Group include sand, ochre and lignite, and clays for the manufacture of brick, pipes and tiles and as a fuller's earth for absorbing lanolin, oils and other greasy impurities as part of the finishing process for cloth. Although extraction is becoming more limited, during the 19th century and early part of the 20th century numerous small pits may have been opened for local purposes. The extent and depth of many of these pits is generally unknown or poorly documented although relevant information can often be found in:

- memoirs of the Geological Survey, especially those published during the 19th century and first half of the 20th century, when most of this activity occurred,
- the British Geological Survey quarries database, which includes historical data,
- historical O.S. maps,
- County mineral records.

During the 19th century and first half of the 20th century, quarries and pits provided much of the geological information on the geology on the Lambeth Group and are often well described in British Geological Survey memoirs, reports and published scientific papers.

7.7.1 Brick and tile manufacture

The Reading Formation clays have been used for brick and tile manufacture throughout much of the outcrop and are described in the Memoirs of the British Geological Survey as the borrow pits often provide the best exposures for geological descriptions. In recent times, activity has been restricted to small-scale operations near Chesham [SP 984 018], Buckinghamshire; Knowl Hill [SU 819 797], near Maidenhead, Berkshire (Sumbler *et al*., 1996); and Michelmersh [SU 343 260], near Romsey, Hampshire. Similar workings have been carried out elsewhere within the outcrop, for example at Arundel [TQ 000 073] and Westhampnett [SU 881 065], Sussex (Aldiss, 2002). Modern robotic brick making methods, however, do not favour heterogeneous or smectitic clays, and use of Reading Formation clays is now very limited (Bloodworth *et al*., 2001).

7.7.2 Sand and gravel

Sand and gravel has been taken from the Lambeth Group for local use, often with clays for brick and tile manufacture. Few of the pits were very large but two areas, at Orsett [e.g. TQ 565 810] in south Essex and Upnor [e.g. TQ 765 695] in north Kent, have a number of large sand and gravel pits. These pits provide the best examples of the Upnor Formation sequence. The pit at Shelford [TR 166 614], to the north of Canterbury, ceased extraction of sand gravel from the Upnor Formation in 2007 – 2008 and is now a landfill site for non-hazardous waste.

7.7.3 Fuller's earth

Fuller's earth is a clay-rich material containing high proportion of smectite (usually calcium smectite) which imparts extremely high plasticity and shrink-swell potential, and low residual strength. An investigation into the fuller's earth resources in England and Wales (Moorlock and Highley, 1992) found that some parts of the Lambeth Group, notably the Lower Mottled Clay, contained high proportions of smectite The Lambeth Group is not currently considered to be a viable economic source of fuller's earth but a 1 m thick clay bed beneath clean white sand was extracted during the 19th century by "clothiers" (Blake and Munckton, 1903).

7.7.4 Lignite

Lignite was extracted from a seam up to 4 m thick along a drift mine near Cobham, Surrey. It was quarried for domestic purposes at Cobham Hall by Lord Darnley. A drift mine was started in 1947 and produced 80 tons (81.2 Mg) per week and expansion planned were formulated to increase output to 150 tons (152.4 Mg) a week. Difficulties were encountered including flooding, which was controlled by pumping. The proposed expansion did not happen due to the water problems, methane encountered in a gallery driven deeper into the hillside and difficulty in selling the product. In 1953 the mine was closed and the entrances blown up. Deep depressions in the woods nearby are probably due to the collapse of the workings (Kent Underground Research Group, 1991). . The site was rediscovered during site investigation for the Channel Tunnel Rail Link, where collapsed adits were also found. Excavations in the lignite were recorded during embankment construction (Collinson et al., 2003).

7.8 ENGINEERING GEOLOGICAL SUMMARY

The engineering geological descriptions and characteristics of the Reading, Woolwich and Upnor formations are summarised in Table 7.5, Table 7.6 and Table 7.7, respectively. Note that in all cases where the Lambeth Group overlies Chalk strata, the potential problem of subsidence or collapse of Lambeth Group materials into voids created by dissolution of the underlying Chalk should be considered and assessed.

Table 7.5. Engineering geological descriptions and characteristics of the Reading Formation.

<table>
<tr><th>Formation</th><th>Unit</th><th>Lithology</th><th>Engineering Description</th><th>Foundations</th><th>Excavation</th><th>Engineered Fill</th><th>Site Investigation</th></tr>
<tr><td rowspan="5">Reading Formation</td><td rowspan="3">Upper and Lower Mottled Clays</td><td>Clay</td><td>Stiff to very stiff often closely or very closely fissured, brown, grey, red or purple (Lower Mottled Clay only) mottled or multicoloured CLAY. Numerous fissures are often listric and polished (grey) giving rise to a ‘blocky’ texture. Upper Mottled Clays of high to extremely high plasticity. Lower Mottled Clays of intermediate to very high plasticity.</td><td rowspan="5">Shallow Foundations: Clay lithologies may be prone to shrink/swell movements that can be exacerbated by presence of trees, leaking drains and high water tables.

Presence of water-bearing sand bodies, beds or laminae may make foundation construction difficult. Water ingress may lead to reduced bearing capacity of clays.

Piled Foundations: Lithological heterogeneity and presence of water-bearing strata will dictate type, length and construction methods adopted.

Continuity of strata across site may influence pile design where part of resistance is end-bearing.

Presence of hard bands may prove an obstruction or very occasionally offer a foundation solution for different pile designs.</td><td>Diggable. Fissuring likely to give rise to instability in excavations and provide potential pathways for water ingress.</td><td rowspan="5">Variability and relatively thin nature of each unit mean fill materials are likely to be composed of more than one unit and lithology. Acceptance criteria should be taken into account at planning, investigation and construction stages.

May prove to be a good source of fill, material for embankments and landscaping if in an acceptable condition.

Moderately low plasticity clays and silty sands likely to be highly sensitive to changes in water content.</td><td>Important to determine groundwater conditions, thickness of clay sequence and lithological variability (e.g. sand-filled channels). Samples required to ascertain strengths and shrink-swell potential.</td></tr>
<tr><td>Sand</td><td>Dense to very dense, orange, brown or grey sometimes red or mottled, sometimes slightly clayey or silty fine to medium coarse SAND. Sometimes weakly cemented. Generally occurs as impersistent layers or lenses but may be more extensive in some places.</td><td>Diggable. Likely to be water-bearing and unstable in excavations, requiring immediate support. Their presence within mostly clay will affect tunnelling methods and operations.</td><td>Important to determine position, extent and thickness of sand and associated groundwater conditions.</td></tr>
<tr><td>Variable, clay with channel sands</td><td>See description of clays and sands above. Contact between sand and infilled clay channel is usually sharp.</td><td>As above.</td><td>Important to determine position, extent and thickness of sand-filled channels and associated groundwater conditions.</td></tr>
<tr><td rowspan="2">Lower Mottled Clay</td><td>Cemented sands</td><td>Very weak to occasionally strong orange, brown or grey sometimes red or mottled, generally iron-cemented sand (SANDSTONE). Generally thin (<1 m thickness) and often impersistent.</td><td>May require hard digging locally; variable strength leads to variable stability in excavations, particularly below the water table.</td><td>Important to determine elevation, thickness, extent and strength of cemented sand layers prior to construction.</td></tr>
<tr><td>Calcrete/ Limestone</td><td>Very weak/powdery to strong carbonate concretions (CALCRETE) ranging from gravel-size up to 0.5 m diameter. Exceptionally, in east London, concretions coalesce to form a strong to very strong bluish-grey or grey, sometimes nodular, fine-grained crystalline LIMESTONE, up to 1.6 m thick. Inconsistent in lateral and vertical extent and strength.</td><td>Digging, ripping or pneumatic tools may be required due to variable strengths. May enhance stability in excavation but dependant on hard-band thickness, strength of surrounding strata and potential water ingress.</td><td>Important to determine elevation, thickness, extent and strength of hard bands prior to construction.</td></tr>
</table>

Table 7.6. Engineering geological descriptions and characteristics of the Woolwich Formation.

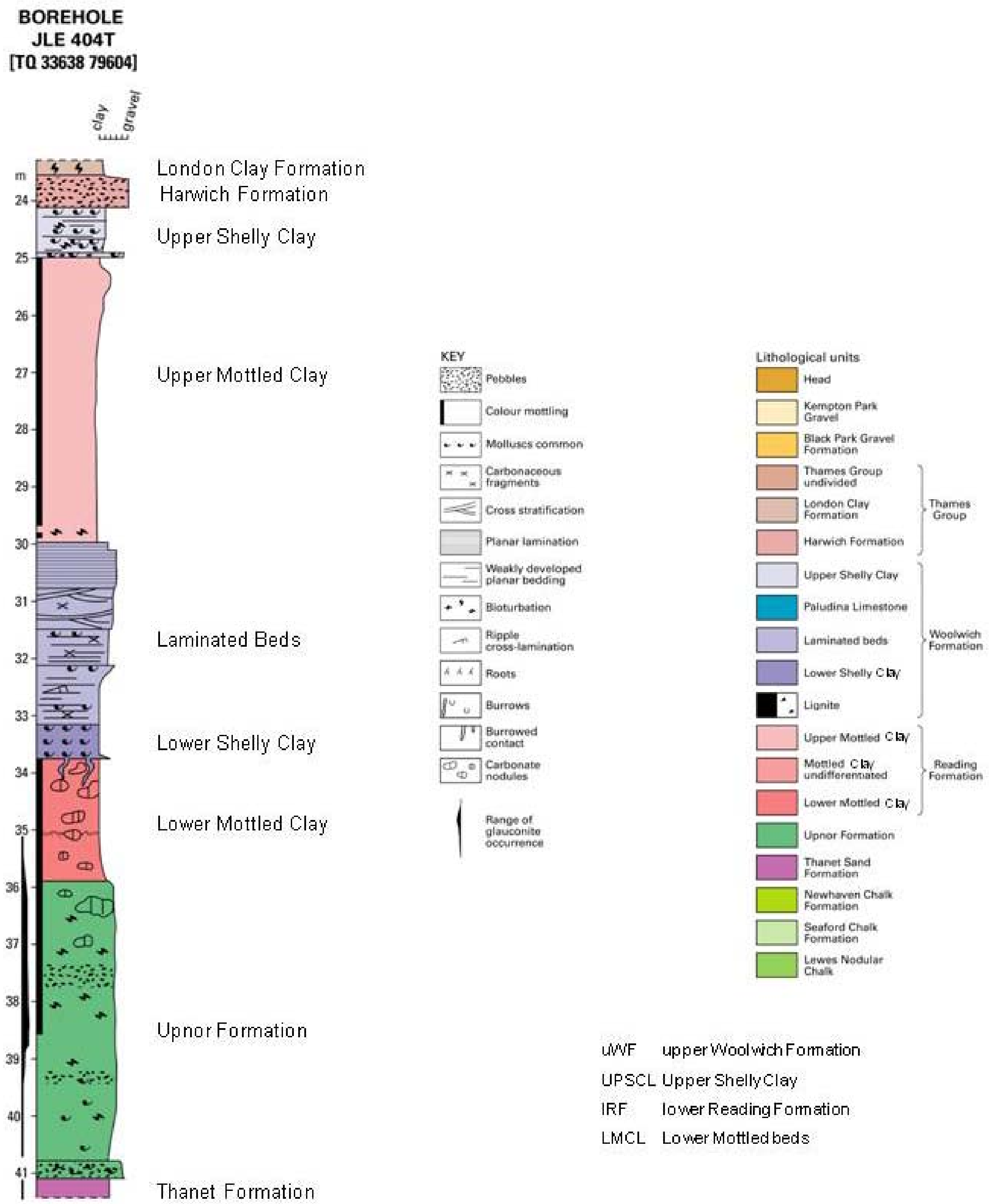
Formation	Unit	Lithology	Engineering Description	Foundations	Excavation	Engineered Fill	Site Investigation
Woolwich Formation	Upper Shelly Clay/Lower Shelly Clay	Shelly clay	Firm to very stiff, often closely to extremely closely fissured, sometimes thinly to thickly bedded, generally dark grey sometimes mottled brownish grey shelly CLAY. Some beds, up to 1 m thick, are almost entirely shells, locally weakly cemented (see limestone below).	*Shallow Foundations*: Clay lithologies may be prone to shrink/swell movements that can be exacerbated by presence of trees, leaking drains and high water tables. Presence of water-bearing sand bodies, beds or laminae may make foundation construction difficult. Water ingress may lead to reduced bearing capacity of clays. *Piled Foundations*: Lithological heterogeneity and presence of water-bearing strata will dictate type, length and construction methods adopted. Continuity of strata across site may influence pile design where part of resistance is end-bearing. Presence of hard bands may prove an obstruction or offer a foundation solution for different pile designs.	Diggable. Strength contrasts between clay-dominant and shell-dominant lithologies may lead to instability in excavations.	Variability and relatively thin nature of each unit mean fill materials are likely to be composed of more than one unit and lithology. Acceptance criteria should be taken into account at planning, investigation and construction stages.	Important to determine groundwater conditions and lithological variability, particularly thickness and extent of shell bands. Sulphate/sulphide content.
	Laminated Beds	Clay, silts and sands	Variable, thinly interbedded succession of CLAY, SILT and SAND. Beds usually < 50 mm thick and typically laminated on a millimetre scale. Localised sand bodies (probable channels) up to about 4 m thick occur, particularly in SE London.		Diggable. Usually water-bearing, giving rise to perched water tables and instability in excavations.		Important to determine presence of water-bearing Laminated Beds of sand and silt and associated perched water tables; also presence and extent of possible water-bearing sand-filled channels.
	Upper Shelly Clay	Shelly sand (Generally in the east of London)	Medium dense to very dense, sometimes laminated, grey sometimes brown, occasionally with organic remains, silty, fine to medium, occasionally coarse SAND (representing infilled channels). Generally high sulphate and organic contents.		Diggable. Impersistent and often water-bearing, leading to unexpected water strikes and instability in excavations. Immediate support required.		Important to determine position, extent and thickness of sand-filled channels and associated groundwater conditions.
	Upper Shelly Clay/Lower Shelly Clay	Shelly Mudstone and LIMESTONE (Limited to south and east London)	Weak generally thin but up to 300 mm thick beds of shelly MUDSTONE and strong dark grey LIMESTONE (Paludina limestone, Upper Shelly Clay)..		Digging, ripping or pneumatic tools may be required due to variable strengths. May be stable in excavation but dependant on hard-band thickness, strength of surrounding strata and potential water ingress.		Important to determine elevation, thickness, extent and strength of hard bands prior to construction.
	Lower Shelly Clay	Lignite (Mainly to south and east of London)	Firm to weak, sometimes thickly to thinly laminated, sometimes with extremely closely spaced fissures/fractures, dark brown or black, sometimes clayey or sandy LIGNITE. Sometimes with interbeds or thick laminations of black coal.		Diggable, but trees and large roots preserved *in situ* may cause difficulties locally. Variable thickness, strength and close fracturing/jointing may result in instability in excavations. May be stable in short-term.	Unsuitable	Important to determine presence and extent of lignite bands associated with variable thicknesses and strengths.

Table 7.7. Engineering geological descriptions and characteristics of the Upnor Formation.

Formation	Lithology	Engineering Description	Foundations	Excavation	Engineered Fill	Site Investigation
Upnor Formation	Glauconitic sand	Medium dense to very dense greenish grey or green becoming orange or brown, occasionally gravely, sometimes shelly, clayey or silty fine to medium, sometimes coarse SAND. Gravel often rounded fine to coarse. Thin seams of grey clay are also present. Clay-dominated units of firm to stiff CLAY up to 0.3 m thick with minor sand laminae may also occur. Clays have high smectite content.	*Shallow Foundations*: Clay lithologies within dominantly sand units may be prone to shrink/swell movements that can be exacerbated by presence of trees, leaking drains and high water tables. Presence of water-bearing sand bodies, beds or laminae may make foundation construction difficult. *Piled Foundations*: Lithological heterogeneity and presence of water-bearing strata will dictate type, length and construction methods adopted. Continuity of strata across site may influence pile design where part of resistance is end-bearing. Presence of hard bands may prove an obstruction or very occasionally offer a foundation solution for different pile designs.	Diggable. Generally water-bearing with possible artesian conditions if in hydraulic continuity with underlying Thanet Formation. Interbedded clay bands may give rise to perched water tables. Generally unstable in excavation with immediate support required.	Variability and relatively thin nature of each unit mean fill materials are likely to be composed of more than one unit and lithology. Acceptance criteria should be taken into account at planning, investigation and construction stages.	Important to determine presence depth and thickness of sands and associated clay bands (often highly plastic smectite-rich) and associated groundwater conditions, particularly potential artesian pressures.
	Gravel	Dense to very dense, usually well-rounded flint GRAVEL. Gravel generally less than 30 mm diameter with occasional cobbles (up to 200 mm).		Diggable. Highly permeable and possibly water-bearing. Immediate support required in excavations. Flint gravel will increase wear on cutting and excavation machinery.		Important to determine presence and extent of potentially abrasive gravel beds, and associated groundwater conditions. May pose drilling/sampling difficulties
	Hard bands	Weak to moderately strong, irregular-shaped carbonate concretions (CALCRETE) which locally may be 0.5 m diameter. Strong to extremely strong silcrete nodules which may be up to 3 m long and 1 m thick		Generally diggable but may require ripping or pneumatic tools locally. Variable size, strength and extent of concretions may cause problems in excavation. Depending on thickness, may enhance stability of excavations.		Important to determine elevation, thickness, extent and strength of hard bands prior to construction.

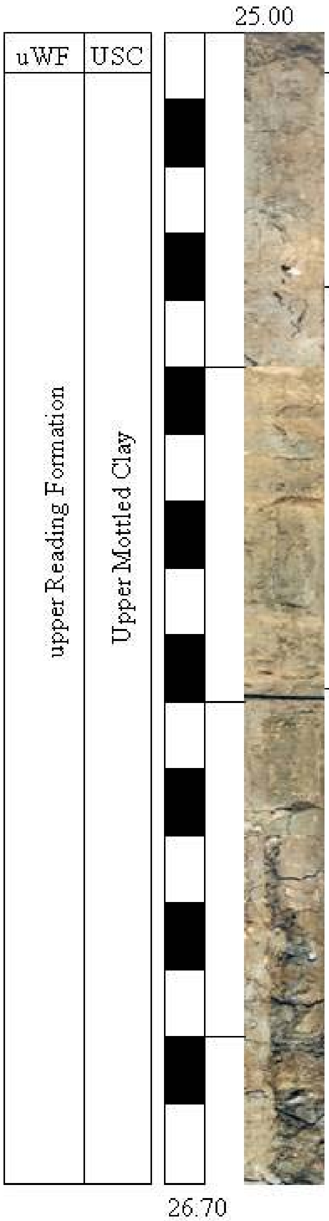
Appendix 1 Jubilee Line Extension 404T:- Graphical log, core photographs and description

(BGS borehole TQ37NW2118, [TQ 33638 79604])



Graphical log of Borehole JLE 404T.

Formation	Beds	Depth mbgl	Geologists description	Ground investigation description
London Clay Formation		23.40	Clay, with some fine sand, brownish olive (5Y 3/1), pyrite nodule at 22.63. Becoming more sandy in lowest 0.07 m, with a few medium sand grains and black ?glauconite grains of medium sand grade and worn sub angular black flint chips.	Very stiff thinly laminated, closely fissured grey-brown slightly sandy (fine) CLAY. Fissures vertical, rough, planar with black mottling
Harwich Formation	Blackheath Beds	24.00	Fine to coarse GRAVEL; black-coated flints, well rounded, white and brown interiors,	Very stiff grey very silty CLAY with occasional black rounded firm to medium flint gravel. Below 23.67m, clay absent and gravel mainly medium to coarse.
		No recovery 24.11		
upper Woolwich Formation	Upper Shelly Clay		Silt, clayey, olive grey, 5Y 5/1, scattered shells, bioturbated to 24.31 very fine lamination from 24.31 to 24.34 m; bioturbated from 24.34 to base but with some lamination, a few dark grey wisps and lignite fragments, vague base.	Very stiff thinly laminated closely fissured black very silty CLAY with rare shell fragments. Fissures subvertical, clean, planar.
			Clay as above but with abundant disarticulated shells including *Ostrea*.	
		25.00	Shelly limestone with coarse sand and flint fragments	Strong, grey slightly weathered shelly LIMESTONE



Geologists description

CLAY, medium to coarse sandy, grey 5Y 5/1 as above, finely comminuted shell fragments including Ostrea. Sharp inclined base over 0.02 m.

Silt to very fine SAND grading to clean to clean fine sand at about 25.24 to 25.50 m, one pellet of grey fine to medium sandy clay, 3 mm diameter, of similar lithology to bed above, at 25.08 m, faint horizontal lamination at 25.05 m, mottled blue grey 5B 7/1 and pale brown 5Y 6/2. Becoming generally more silty and clay wisps, ?bioturbated.

Clay, mottled blue grey 5B 7/1 and pale brown 5Y 6/2, to very fine sandy, from 26.03 – 26.06 m. Generally 50% blue grey including patches and veins, 50% yellowish brown 5YR 6/4, 100% blue grey 26.60 to 26.72 m, nearly all chocolate brown 5YR 3\4 with blue veins 26.72 to 27.42 m. Closely fissured throughout.

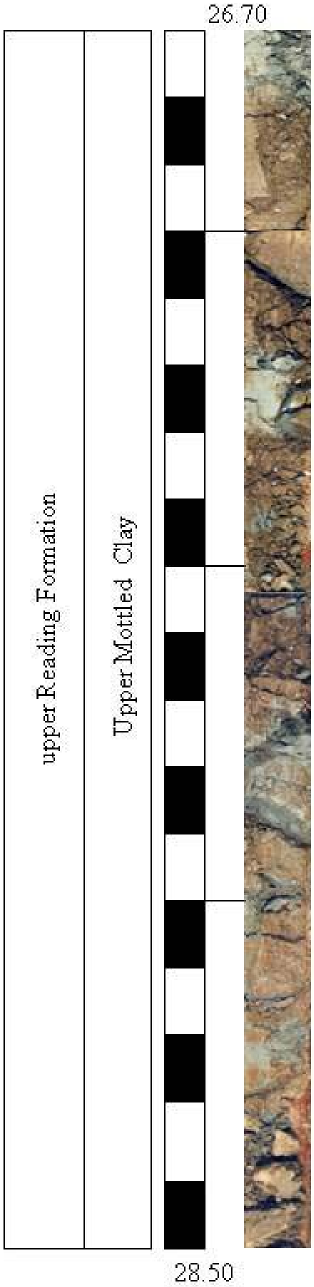
Clay, mottled brown and blue grey with blue veins to 27.20 m. Red patches(10Y 5/6) up to 40% from 28.01 to 28.29 m, mainly brown 28.29 to 28.85 m, mostly blue grey 28.85 to 29.07 m, yellowish-brown up to 50% and blue grey up to 50% 29.53 to 29.63 m. Gradational base.

Ground investigation description

As above

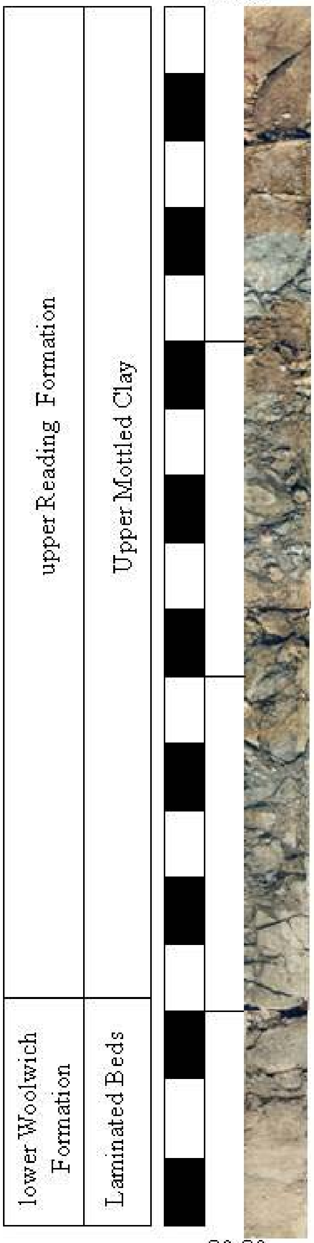
Grey very clayey fine to medium SAND

Very stiff extremely closely fissured mottled brown and grey CLAY. Fissures randomly oriented planar, smooth and locally striated. Grey below 29.77 m

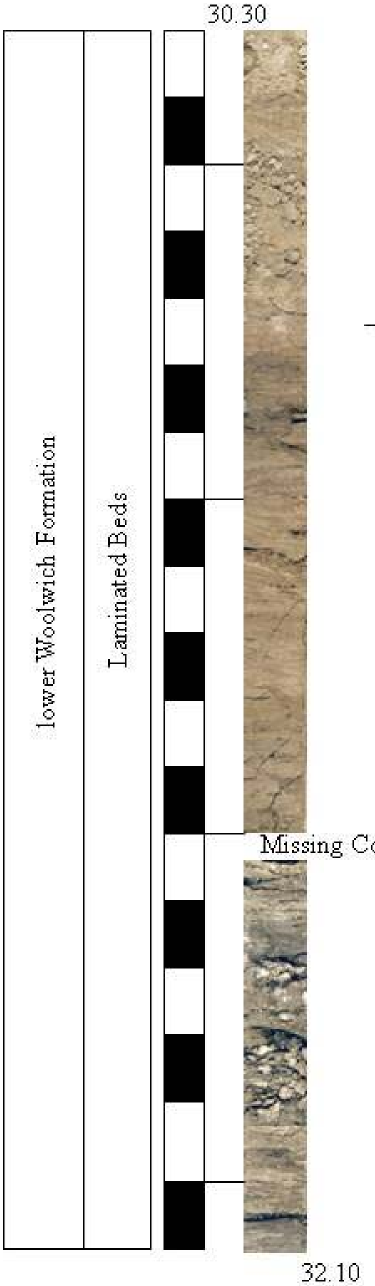


Geologists description	Ground investigation description
Mottled brown and blue grey with blue veins to 27.20 m. Red patches (10Y 5/6) up to 40% from 28.01 to 28.29 m, mainly brown 28.29 to 28.85 m, mostly blue grey 28.85 to 29.07 m, yellowish-brown up to 50% and blue grey up to 50% 29.53 to 29.63 m. Gradational base.	Very stiff extremely closely fissured mottled brown and grey CLAY. Fissures randomly oriented planar. Smooth and locally striated. Grey below 29.77 m.

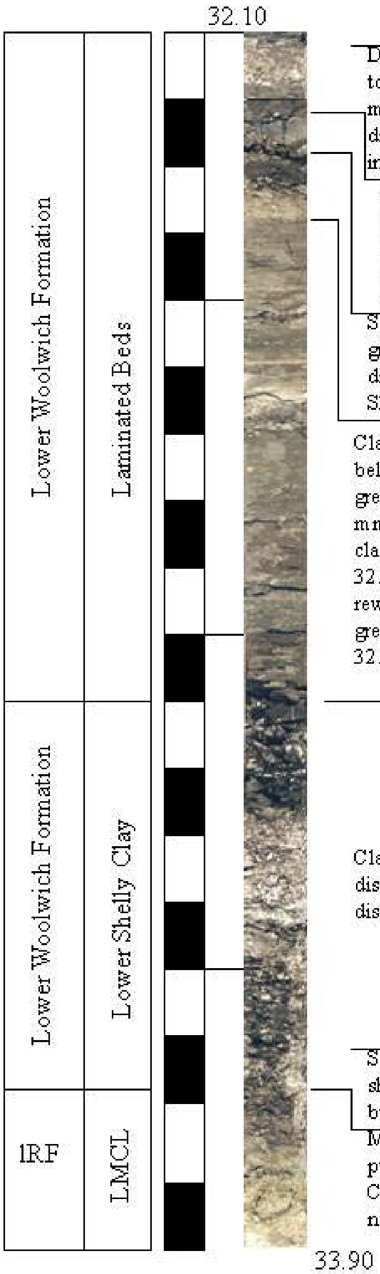
Geologists description	Ground investigation description



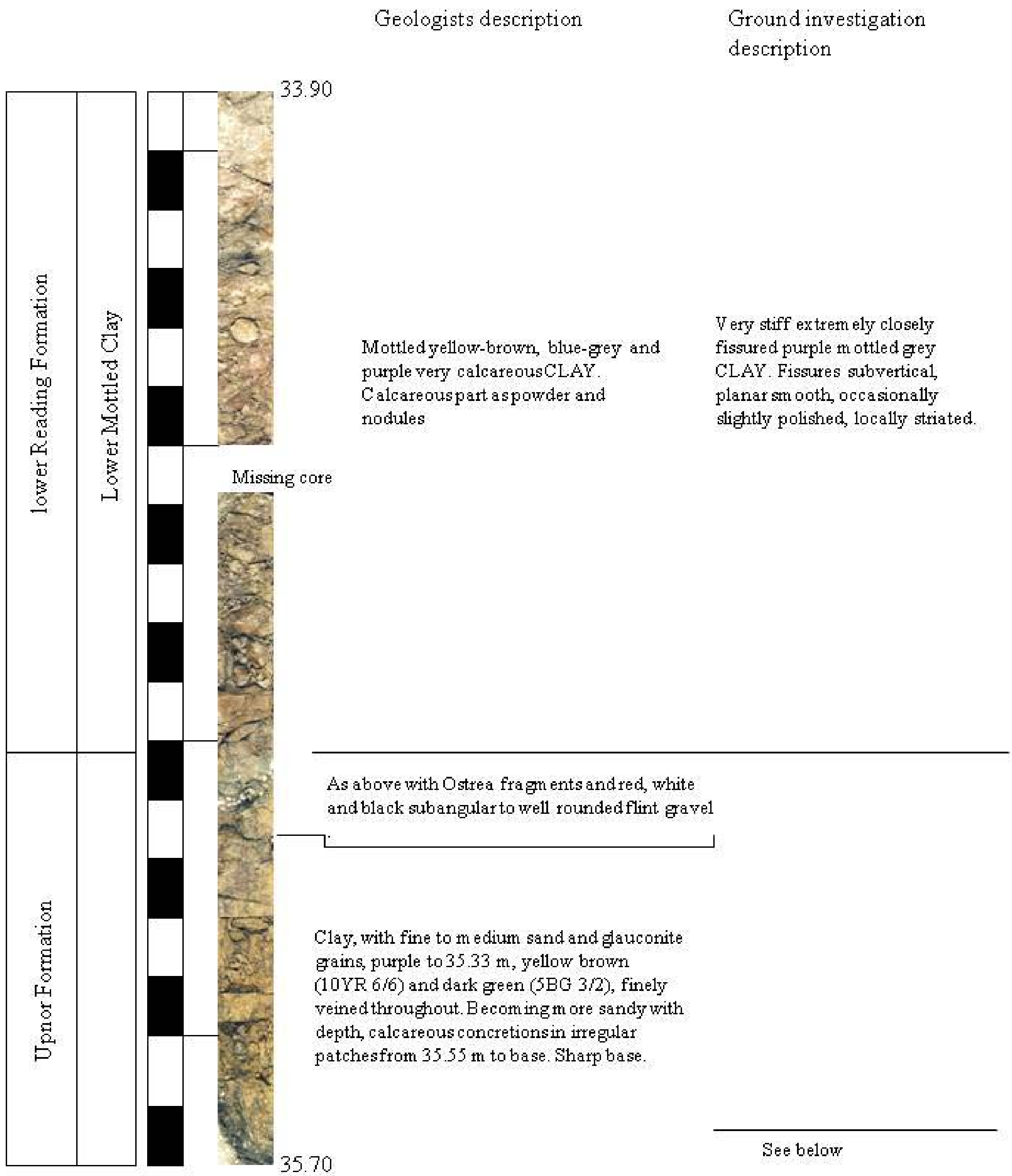
Geologists description	Ground investigation description
Mottled brown and blue grey with blue veins to 27.20 m. Red patches (10Y 5/6) up to 40% from 28.01 to 28.29 m, mainly brown 28.29 to 28.85 m, mostly blue grey 28.85 to 29.07 m, yellowish-brown up to 50% and blue grey up to 50% 29.53 to 29.63 m. Gradational base.	Very stiff extremely closely fissured mottled brown and grey CLAY. Fissures randomly oriented planar, smooth and locally striated. Grey below 29.77 m.
Clay, medium grey N5 to N6, silt crips (bioturbated) increase downwards, sharp base	
Silt to very fine sand, clayey, grey brown, carbonaceous wisps < 1 mm diameter and 20 mm long, pale brown fine sand bed at 30.07 to 30.08 m with gradational top and sharp base, vaguely laminated, clay 30.08 to 30.10 m. Sharp base	Grey fine to medium SAND. Below 31.23 m brown and occasionally coarse
See below	

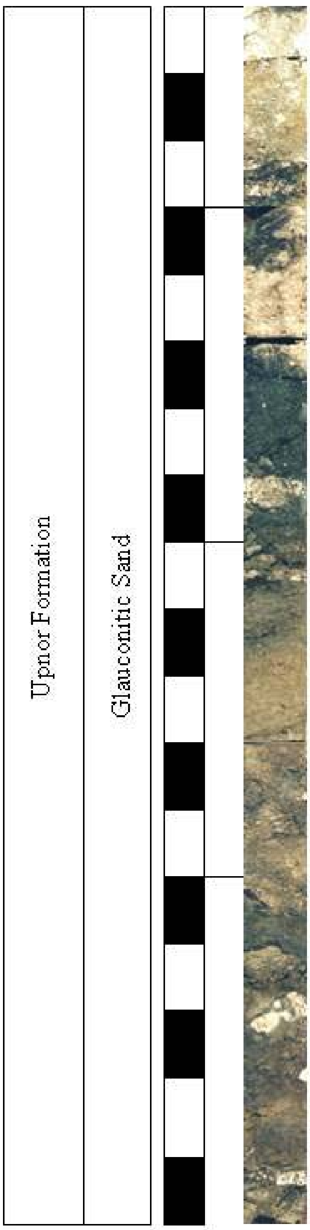


Geologists description	Ground investigation description
SAND, medium grained, quartzose, greyish-brown (10YR 6/2 to 5Y 7/2), well sorted, subrounded grains, vague lamination, subhorizontal to horizontal. Sharp base.	
SAND, fine to medium, greyish-brown(10YR 6/2 to 5Y 7/2) more clayey cross sets grey, cross laminated in units about 50 mm thick, clay drapes common every 2-3 mm, some dark grey finely disseminated ?carbon on laminated planes at 30.86, 31.12 and 31.38 m and sporadic throughout, shell fragment at 31.44 m.	Grey fine to medium SAND. Below 31.23 m brown and occasionally coarse
Silt and fine sand and clay, very finely interlaminated to 1 mm, some very finely disseminated, grey (N3) clay to olive grey (5Y 5/1) silt and fine sand, some 1-2 mm cut and fill troughs, some bioturbated units to 10 mm, coquina of disarticulated Corbicula at 31.67 – 31.69 m. Mostly pale grey clay interlaminated silt below 31.69 m. Sharp base	Very stiff thinly interlaminated grey CLAY and brown fine SAND with occasional shell fragments(30 –40 mm).
	Very stiff grey CLAY thinly laminated with partings (<6 mm) of brown silt.



Geologists description	Ground investigation description
As above	
Dark slightly greenish grey (5Y 3/1 to 5GY 3/1) very shelly fine to medium sand. Shells are disarticulated, at 32.18 m grades into fine sand. Bioturbated contact.	Very stiff thinly interlaminated grey CLAY and brown fine SAND with occasional shell fragment (30 – 40 mm)
Clay, grey, N3 to N4 with pale brown silt very thin interlaminae and sand-filled burrows to 5 mm diameter. One greenish grey lamination at 32.27 m. Gradational base.	
Sand, fine and clay, biotubated, dark grey (N3), basal 20 mm is coquina of disarticulated and broken *Corbicula*. Sharp base.	
Clay, pale olive grey (5Y 6/1), becoming clay below 32.59 m, thinly laminated with silt, paler grey, 1 – 2 mm, finely disseminated carbon to 1 mm scattered throughout, lenses of grey-brown clay to 10 mm 32.59 – 32.60 m. Fine sand bed 32.61 to 32.64 m, cross laminated, sharp base reworked top, shelly 32.66 to 32.69 m, browner grey 32.85 – 32.89, (5YR 5/1) scattered shells 32.95 – 33.16 m. Gradational base.	Very stiff grey CLAY thinly laminated with partings (<6 mm) of brown silt
Clay, dark grey (N3), organic, disarticulated bivalves, coquina with disarticulated *Corbicula* at base	Grey SHELLS generally oysters with an occasional stiff grey clay matrix, locally cemented
Sand, fine grained with many disarticulated shells, dark grey. Sharp irregular base with burrows extending 0.30 m into bed below	
Mottled yellow-brown, blue-grey and purple very calcareous CLAY. Calcareous part as powder and nodules	Very stiff extremely closely fissured purple mottled grey CLAY. Fissures subvertical, planar smooth, occasionally slightly polished, locally striated


Geologists description
Ground investigation description
33.90
lower Reading Formation
Lower Mottled Clay
Mottled yellow-brown, blue-grey and purple very calcareous CLAY. Calcareous part as powder and nodules
Very stiff extremely closely fissured purple mottled grey CLAY. Fissures subvertical, planar smooth, occasionally slightly polished, locally striated.
Missing core
Upnor Formation
As above with Ostrea fragments and red, white and black subangular to well rounded flint gravel
Clay, with fine to medium sand and glauconite grains, purple to 35.33 m, yellow brown (10YR 6/6) and dark green (5BG 3/2), finely veined throughout. Becoming more sandy with depth, calcareous concretions in irregular patches from 35.55 m to base. Sharp base.
See below
35.70



Geologists description

See above

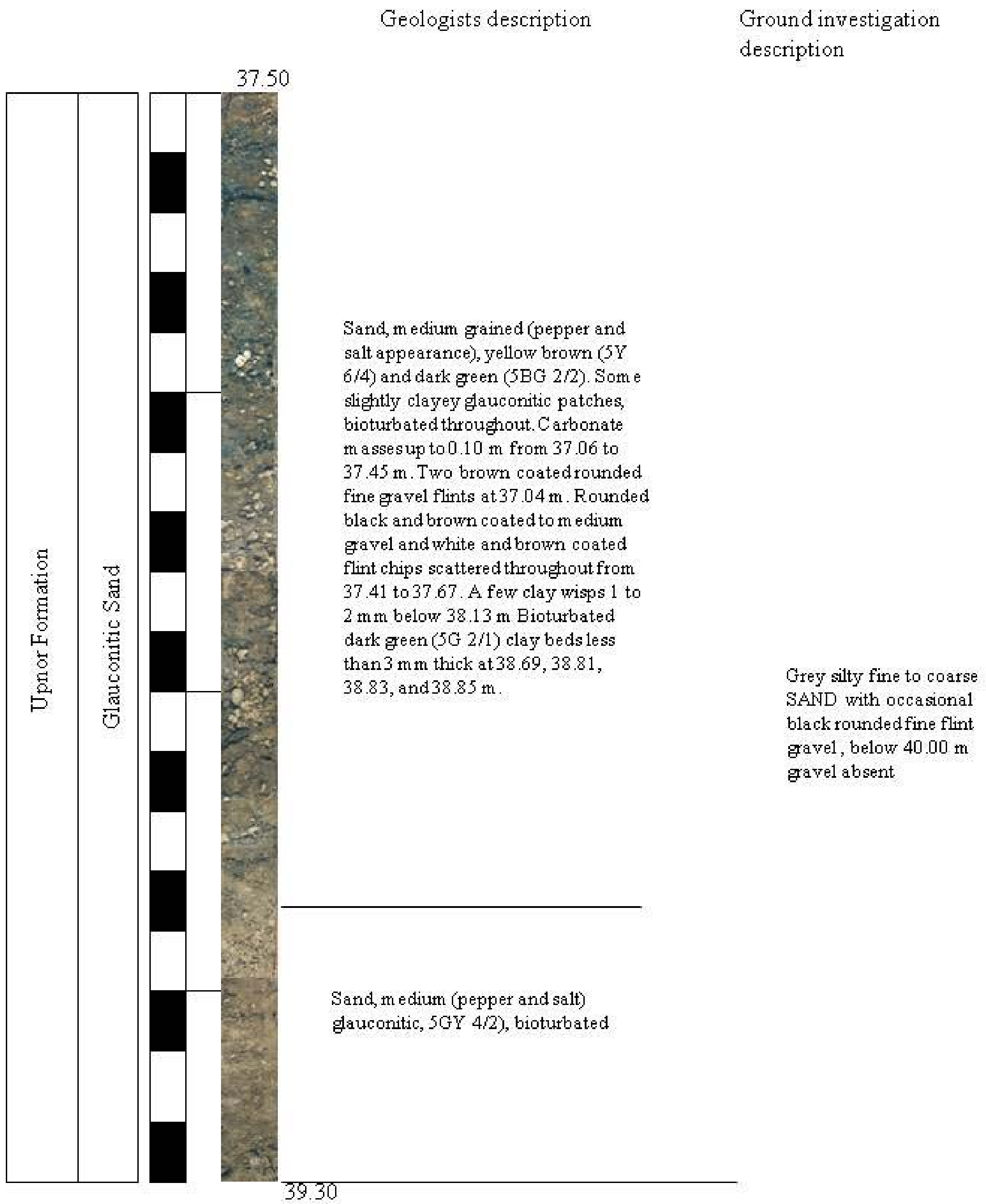
Sand, fine to medium grained, very clayey, glauconitic, dark green (5BG 2/2). Calcareous patches up to 0.22 m across are bioturbated with burrow infills of glauconitic sand. Sharp, bioturbated base

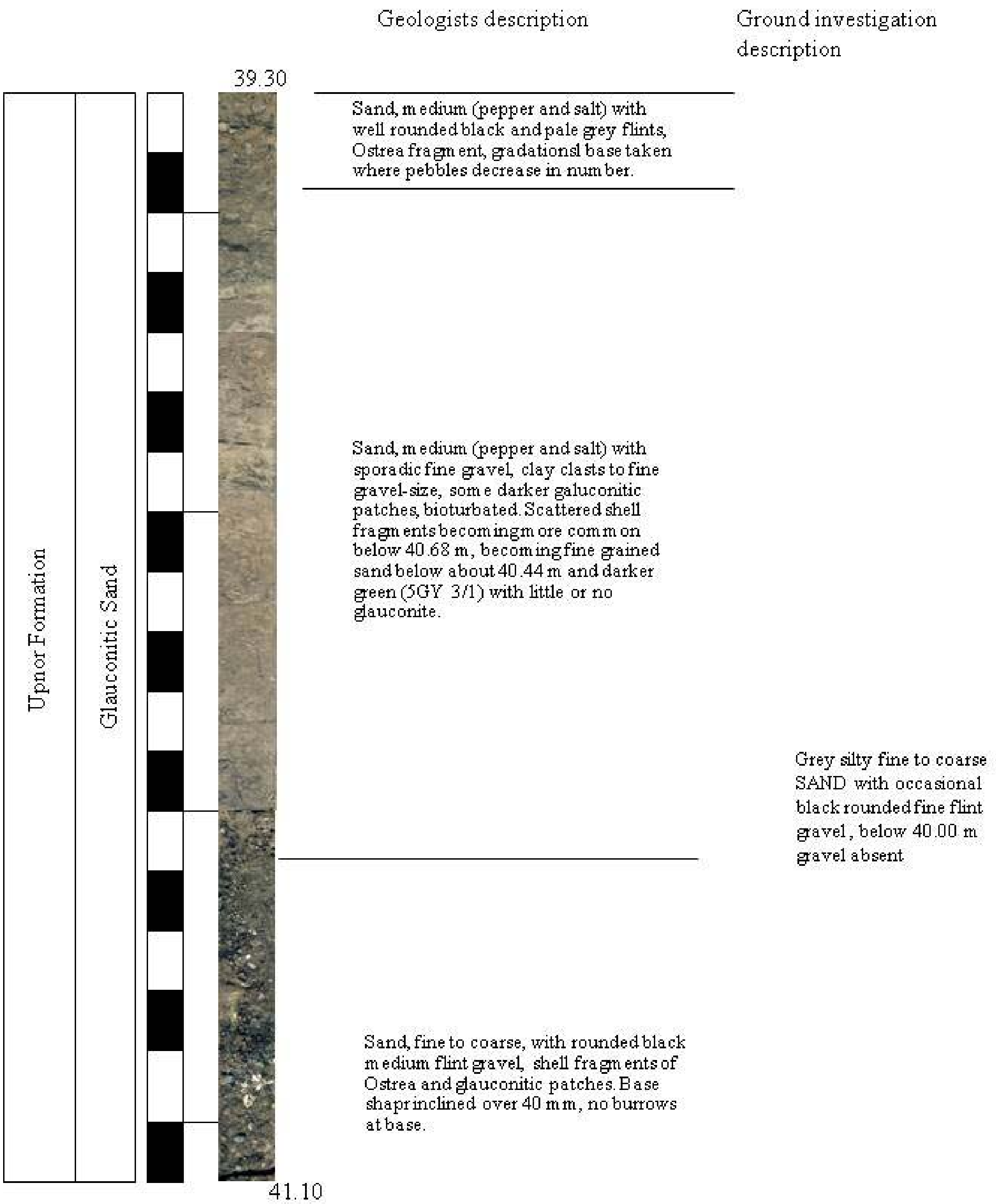
Sand, medium grained (pepper and salt appearance), yellow brown (5Y 6/4) and dark green (5BG 2/2). Some slightly clayey glauconitic patches, bioturbated throughout. Carbonate masses up to 0.10 m from 37.06 to 37.45 m. Two brown coated rounded fine gravel flints at 37.04 m. Rounded black and brown coated to medium gravel and white and brown coated flint chips scattered throughout from 37.41 to 37.67. A few clay wisps 1 to 2 mm below 38.13 m Bioturbated dark green (5G 2/1) clay beds less than 3 mm thick at 38.69, 38.81, 38.83, and 38.85 m.

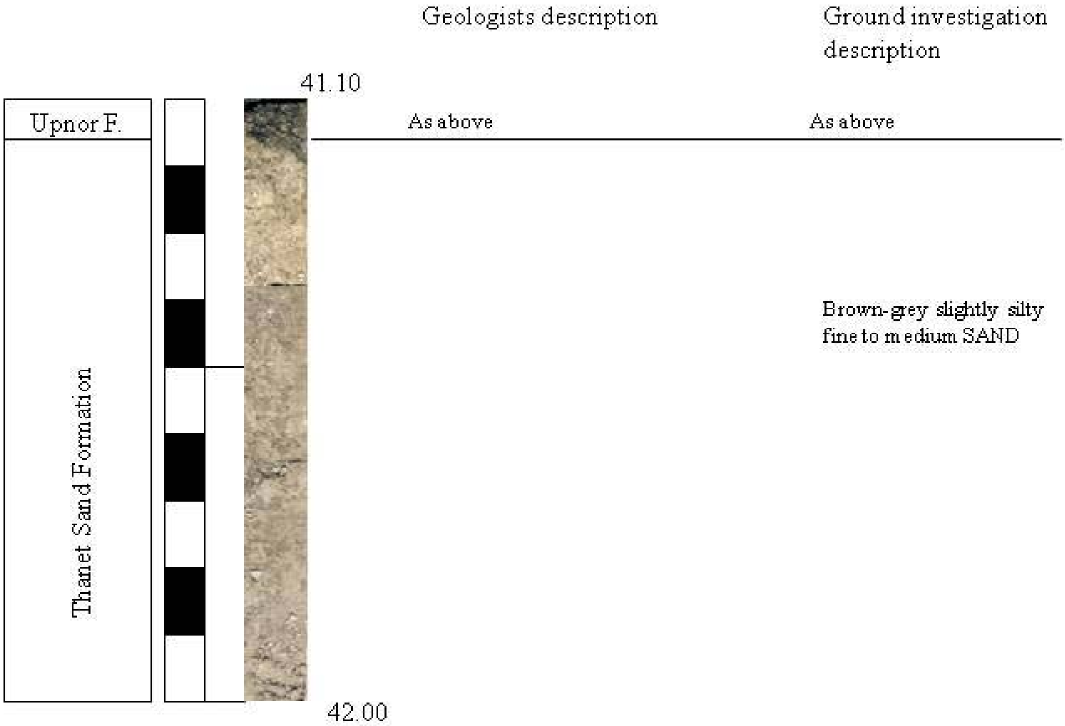
Ground investigation description

Very weak grey highly weathered LIMESTONE

Firm green glauconitic sandy (fine and medium) CLAY


Geologists description
Ground investigation description
37.50
Upnor Formation
Glauconitic Sand
Sand, medium grained (pepper and salt appearance), yellow brown (5Y 6/4) and dark green (5BG 2/2). Some slightly clayey glauconitic patches, bioturbated throughout. Carbonate masses up to 0.10 m from 37.06 to 37.45 m. Two brown coated rounded fine gravel flints at 37.04 m. Rounded black and brown coated to medium gravel and white and brown coated flint chips scattered throughout from 37.41 to 37.67. A few clay wisps 1 to 2 mm below 38.13 m Bioturbated dark green (5G 2/1) clay beds less than 3 mm thick at 38.69, 38.81, 38.83, and 38.85 m.
Sand, medium (pepper and salt) glauconitic, 5GY 4/2), bioturbated
Grey silty fine to coarse SAND with occasional black rounded fine flint gravel, below 40.00 m gravel absent
39.30


Geologists description
Ground investigation description
39.30
Sand, medium (pepper and salt) with well rounded black and pale grey flints, Ostrea fragment, gradationsl base taken where pebbles decrease in number.
Sand, medium (pepper and salt) with sporadic fine gravel, clay clasts to fine gravel-size, some darker galuconitic patches, bioturbated. Scattered shell fragments becoming more common below 40.68 m, becoming fine grained sand below about 40.44 m and darker green (5GY 3/1) with little or no glauconite.
Grey silty fine to coarse SAND with occasional black rounded fine flint gravel, below 40.00 m gravel absent
Upnor Formation
Glauconitic Sand
Sand, fine to coarse, with rounded black medium flint gravel, shell fragments of Ostrea and glauconitic patches. Base shaprinclined over 40 mm, no burrows at base.
41.10


Geologists description
Ground investigation description
41.10
Upnor F.
As above
As above
Thanet Sand Formation
Brown-grey slightly silty fine to medium SAND
42.00

Appendix 2 Cross sections

This Appendix has a series of cross-sections of the lithostratigraphy and lithologies using data from a number of ground investigations. The distribution of the cross-sections are shown in Figure App2.1 and listed in Table App2.1. A more detailed map of London is in App 2-1. Each set of sections contains a map with the boreholes, a lithostratigraphical cross-section and one or more detailed cross-sections with the lithostratigraphy and boreholes with lithologies. Most of the cross-sections do not include faults.

Table App2.1. Cross-section name and area

Figure No.	Project name	Area
1		
2		
3		
4	A34 Newbury Bypass	Curridge to Bunkers Hill
5	M4 J8(9)–12 Widening	South Reading, Berkshire
6	M40 J1A-3 Widening	Beaconsfield to M40/M25 junction
7	M25: M4 to Maple Cross	
8	Crossrail	Paddington to Bishop's Gate
9 + 10	Jubilee Line Extension	Green Park to Millennium Stadium
11 + 12	Channel Tunnel Rail Link	St Pancras to A406 Barking
13	M11 Link – A104/A114 to A12	Hackney
14	Channel Tunnel Rail Link	Stratford to Leyton
15 + 16	Channel Tunnel Rail Link	A406 Barking to Rainham
17	A406 South Woodford to Barking Relief Road	South Woodford to Barking
18	Docklands Light Railway: Lewisham extension	Greenwich to Island Gardens, Isle of Dogs
19	A102 Blackwall Tunnel Third Bore	Blackwall Tunnel
20	Jubilee Line Extension	North Greenwich to Canning Town
21	A13 Orsett Cock to Stanford Interchange	A13 Orsett Cock to Stanford Interchange
22	Stanford Le Hope Low Level Sewerage Scheme	Stanford-Le-Hope
23	M2 widening	Shorne Cut, Kent

FIGURES

Figure A.2.1. Map of the cross sections.

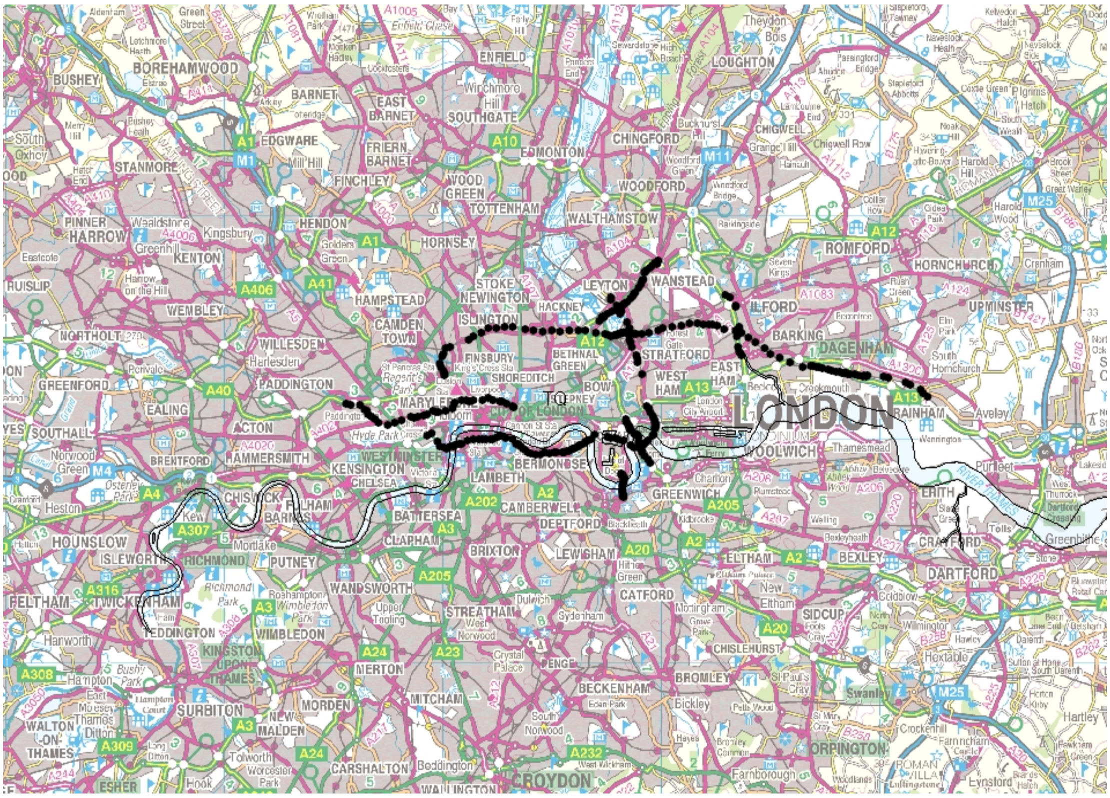


Figure A.2.2. Detailed map of the cross sections in central London.

Figure A.2.3. Key to Appendix 2 figures.

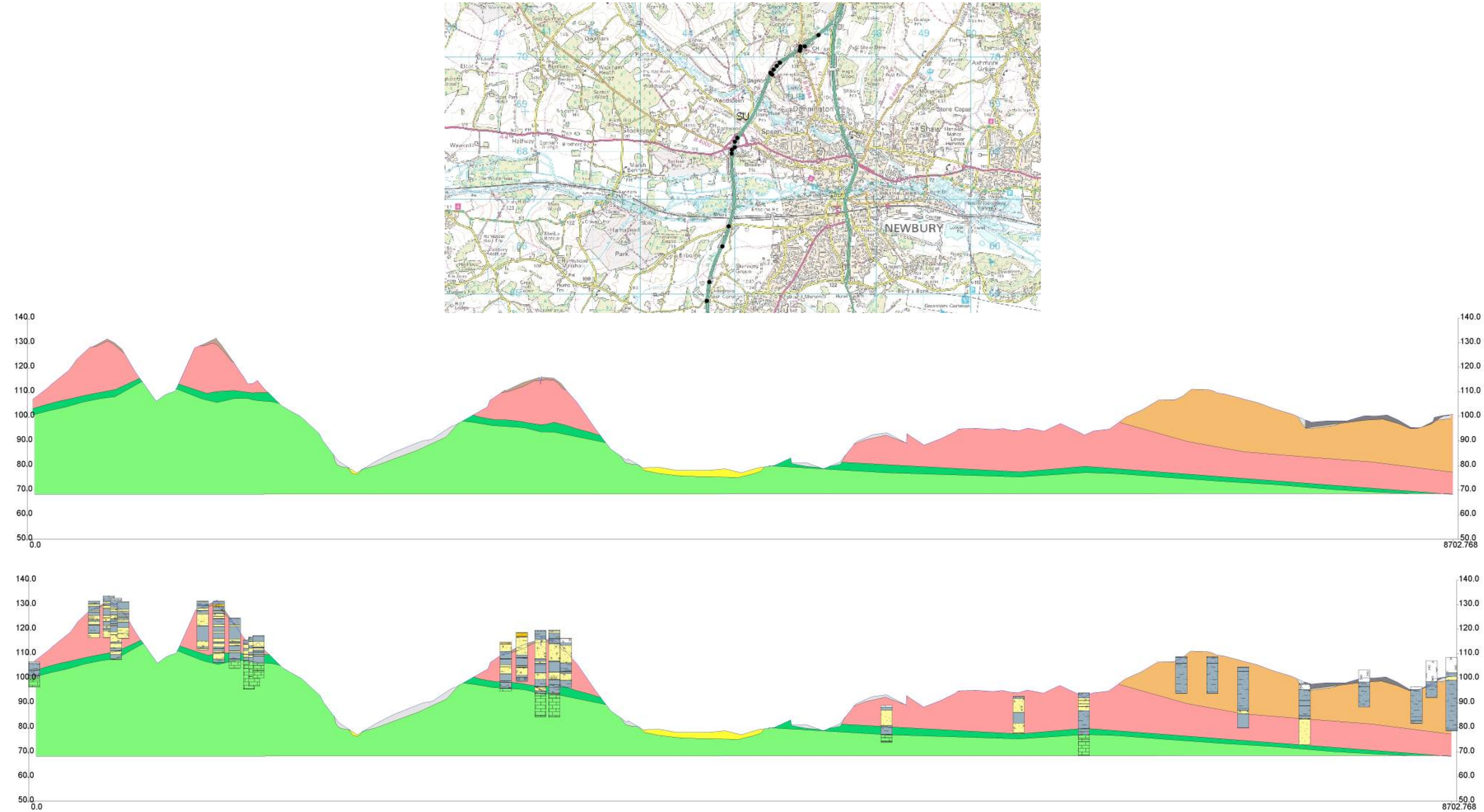


Figure A.2.4. A 34 Newbury Bypass, Curridge [SU 4677 7047] to Bunkers Hill [SU 4485 6284], north to south; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

Figure A.2.5. M4 J8(9)-12 Widening, South Reading, Berkshire [SU 8374 7382] to [SU 9062 7900]; west to east; line of route (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom) .

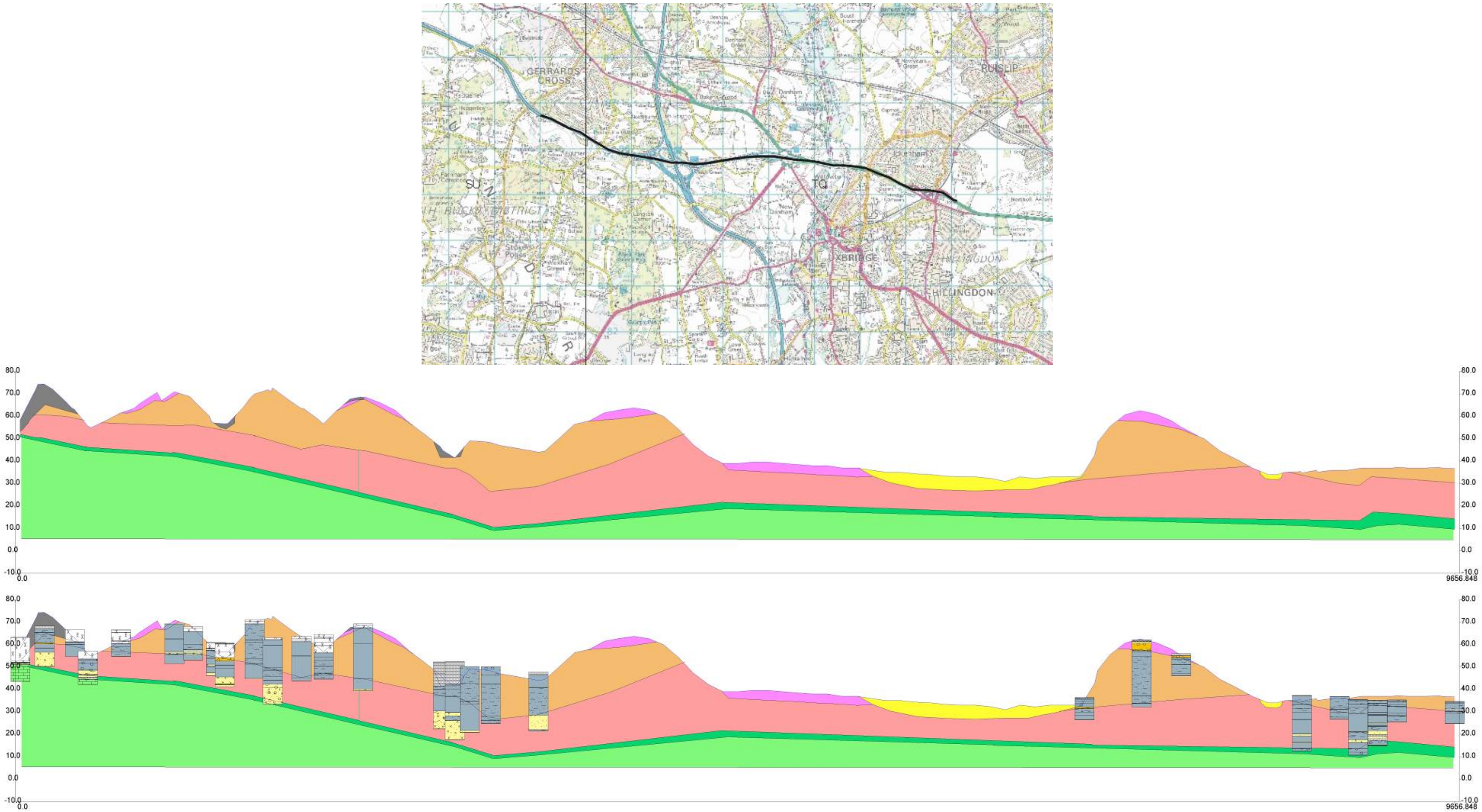


Figure A.2.6. M40 J1A to 3 Widening, Beaconsfield [SU 92020 89610] to Ickerham [TQ 0817 8485]; line of route (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

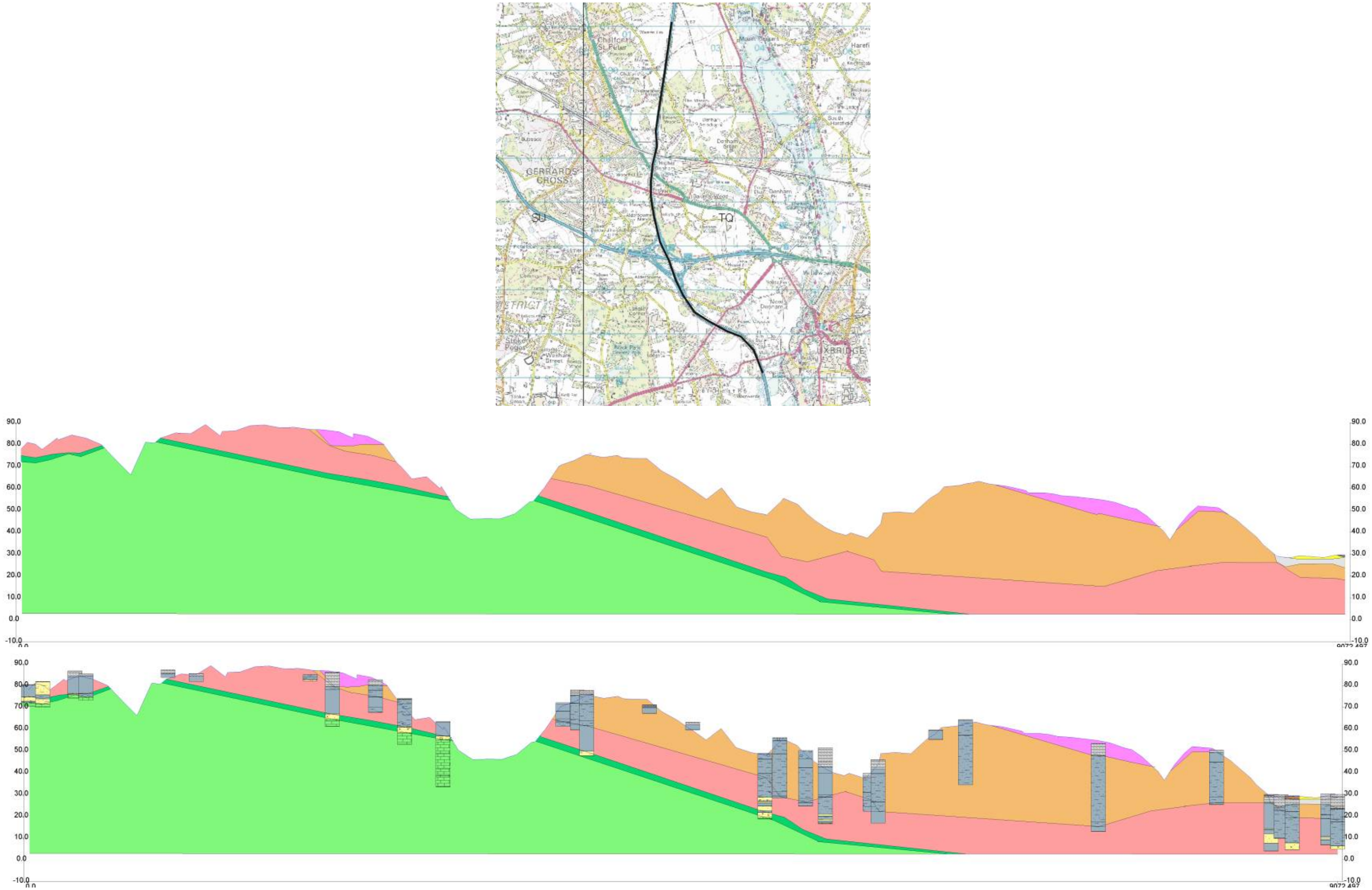


Figure A.2.7. M25 - M4 interchange, Chalfont St. Peter [TQ 0204 9104] to A4007 [TQ 0428 7940], north to south; line of route (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

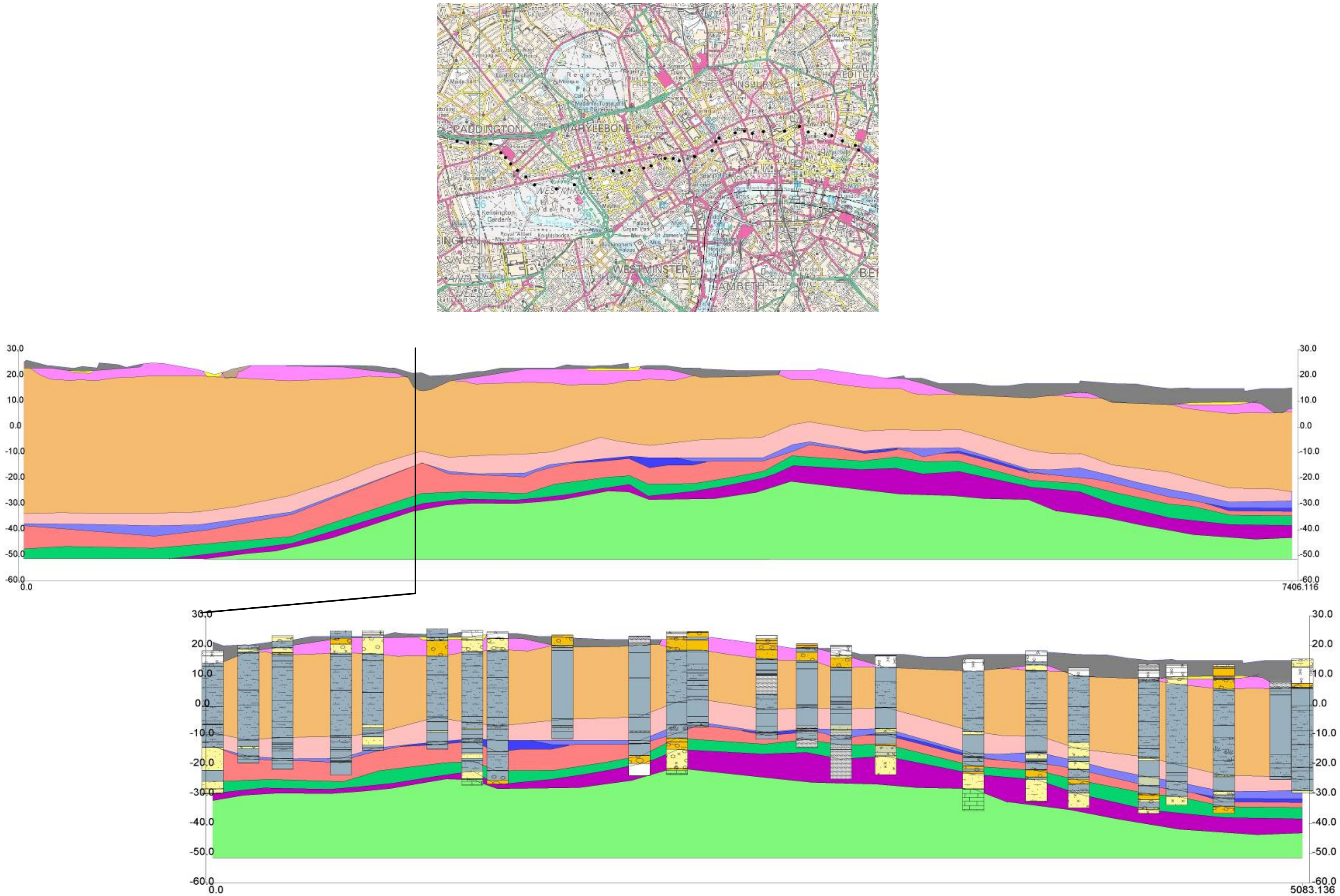
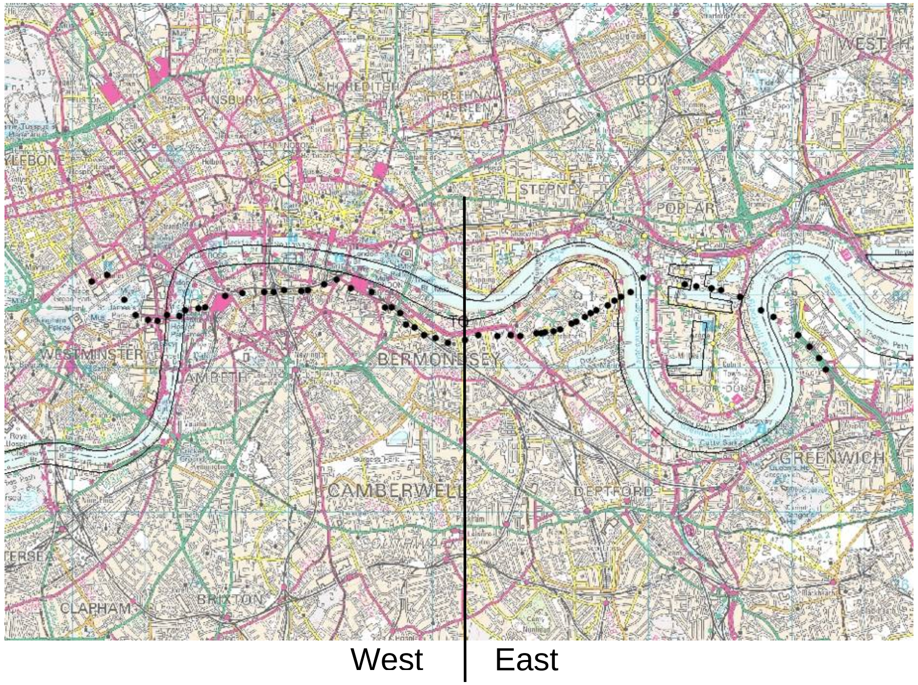


Figure A.2.8. Crossrail, Paddington [TQ 25580 81620] to Liverpool Street Station [TQ 33230 81460]; borehole distribution (top), lithostratigraphy (middle) and lithostratigraphy and lithology in borehole sticks from Hyde Park [TQ 27820 80800] to Liverpool Street Station (bottom).



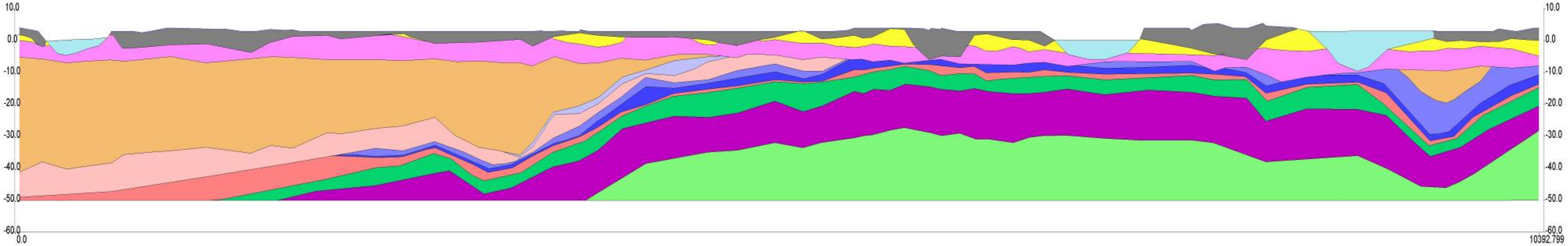


Figure A.2.9. Jubilee Line Extension, Green Park [TQ 2927 8019] to North Greenwich [TQ 3947 7897] borehole map (top) and lithostratigraphical cross section (bottom).

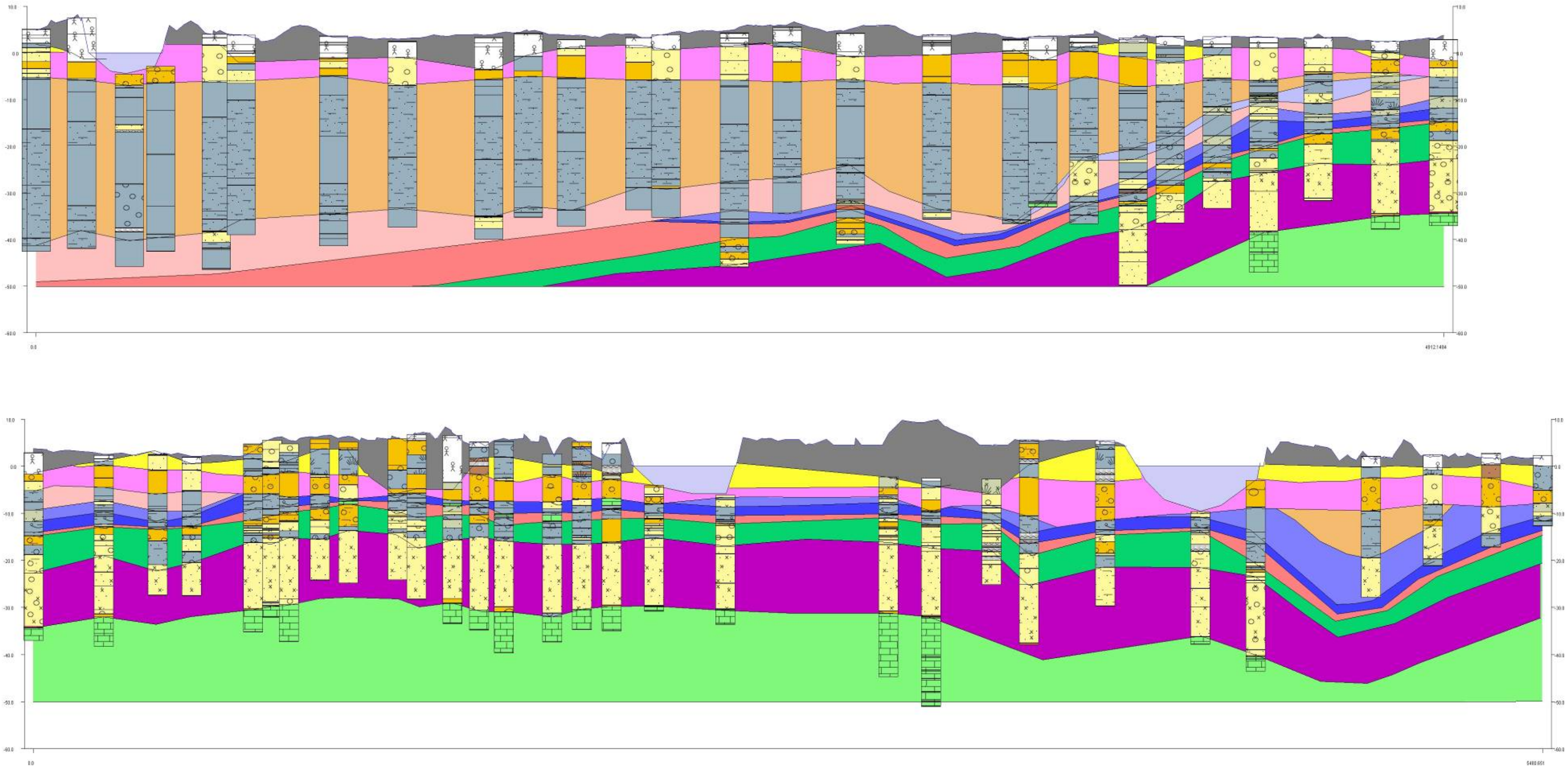


Figure A.2.10. Jubilee Line Extension, lithostratigraphy and lithology, in borehole sticks (top) west [TQ 2927 8019] to [TQ 3439 7938] (bottom) east [TQ 3439 7938] to [TQ 3947 7897].

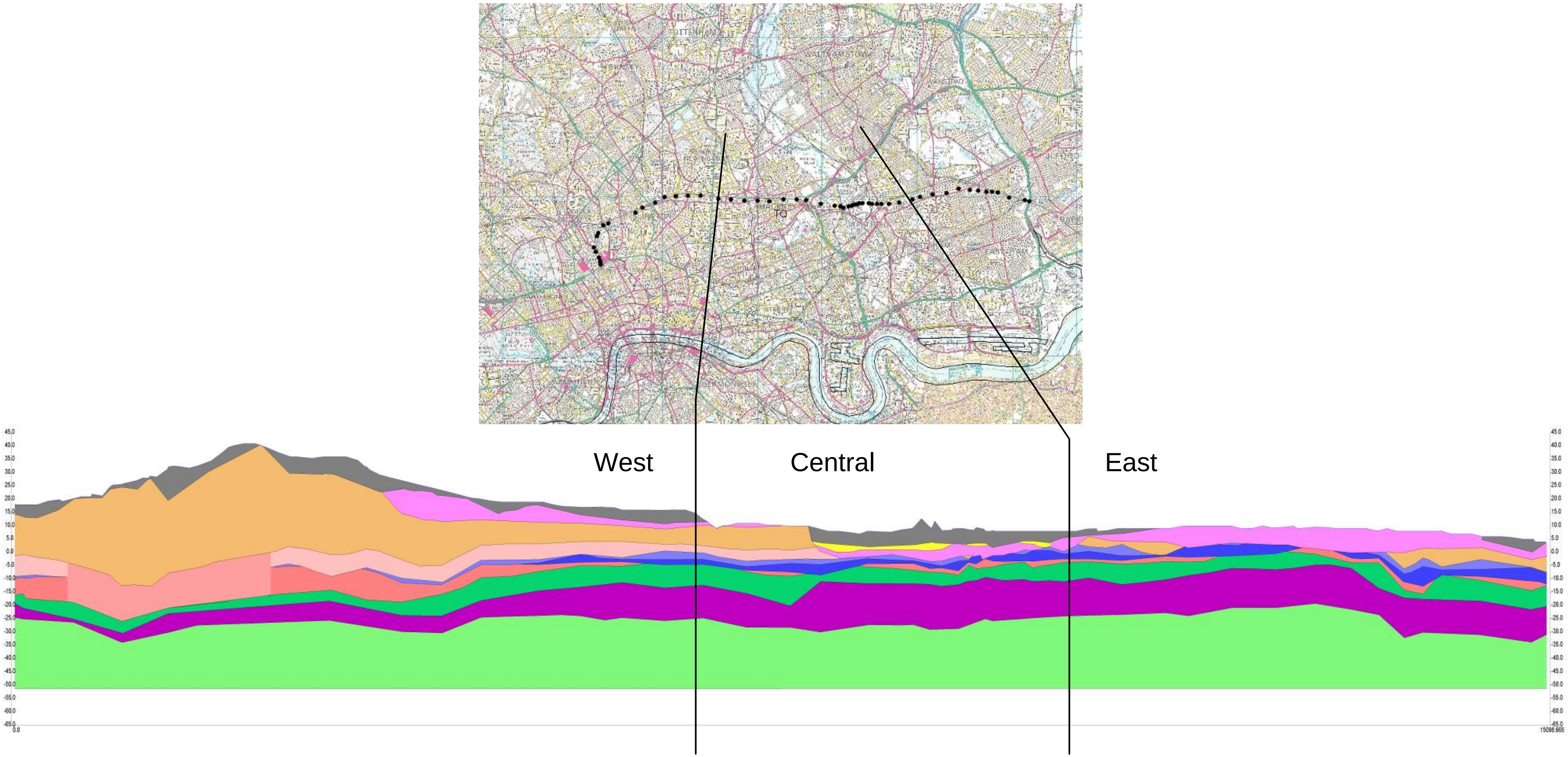


Figure A.2.11. Channel Tunnel Rail Link from St. Pancras [TQ 3008 8289] to A406 Barking [TQ 4352 8492], west to east; borehole map (top) and lithostratigraphical cross section (bottom).

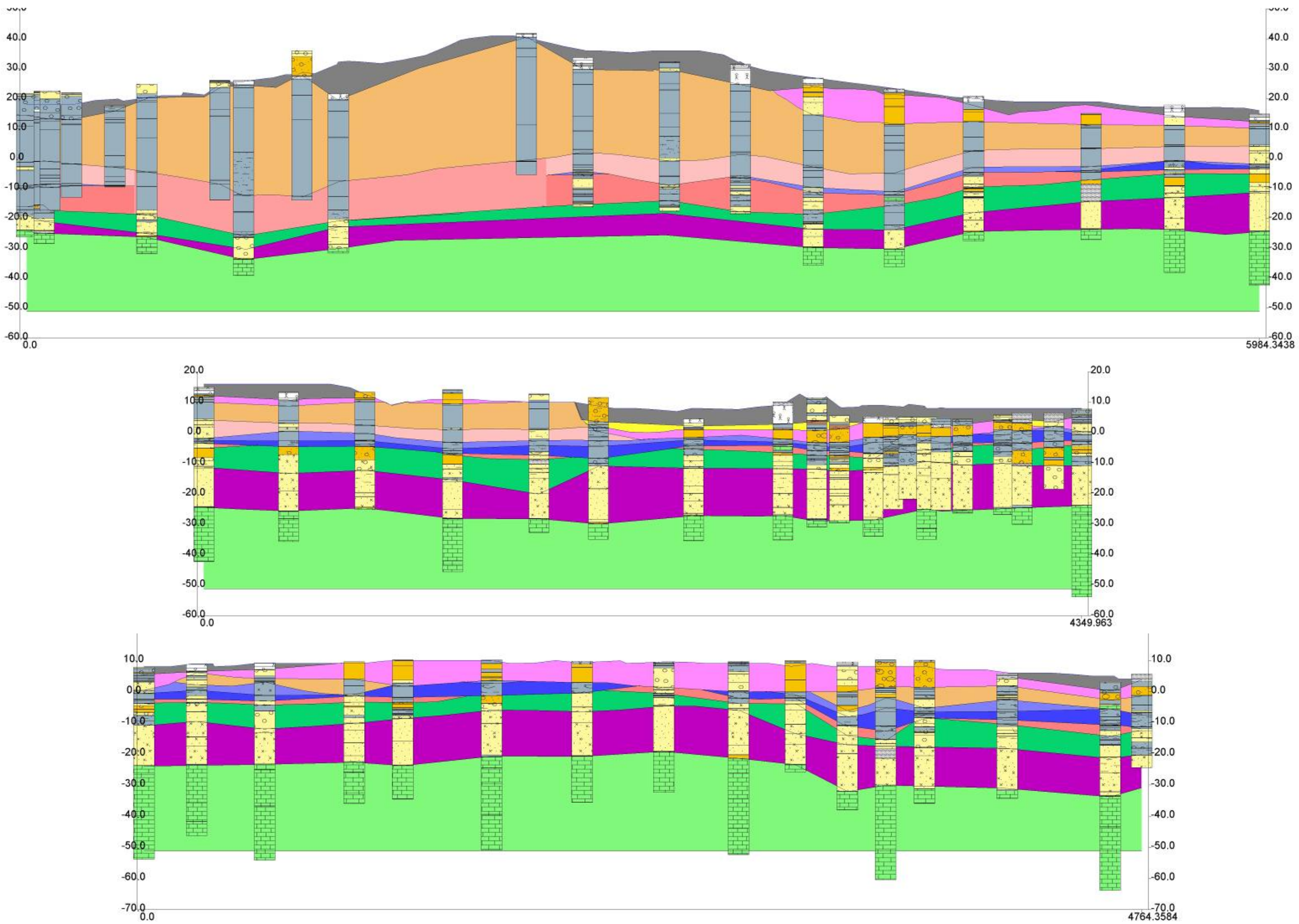


Figure A.2.12. Channel Tunnel Rail Link from St. Pancras to Barking, lithostratigraphy and lithology, in borehole sticks: west [TQ 3008 8289] to [TQ 3376 8496] (top), centre [TQ 3376 8496] to [TQ 3986 8494] (middle), east [TQ 3986 8494] to [TQ 4352 8492] (bottom).

Figure A.2.13. M11 Link – A104/A114 to A12, Leyton; [TQ 3716 8535] to [TQ 3986 8805], west to east, borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

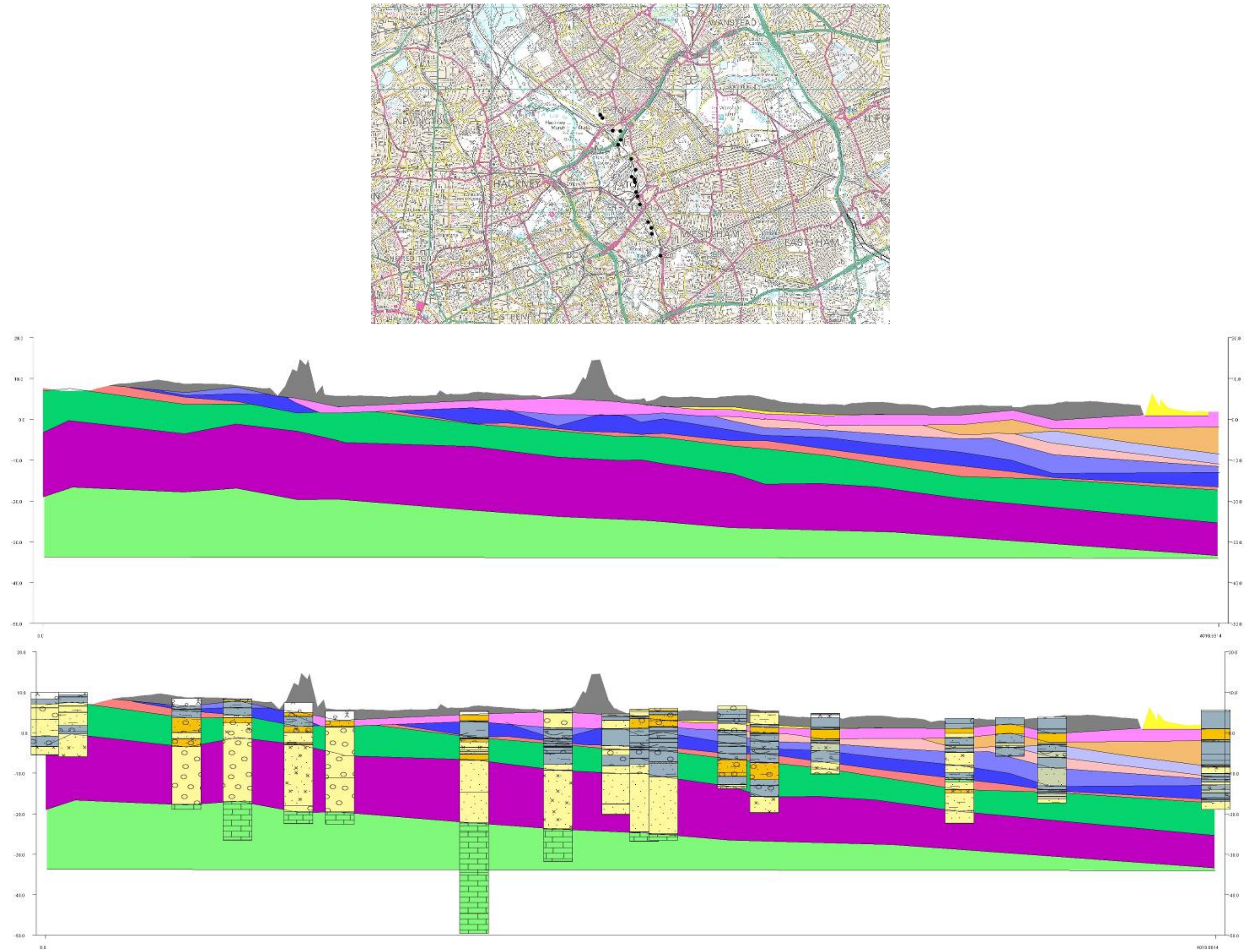


Figure A.2.14. Jubilee Line Extension, Stratford [TQ 4293 8653] to Leyton [TQ 4367 8381], north to south; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

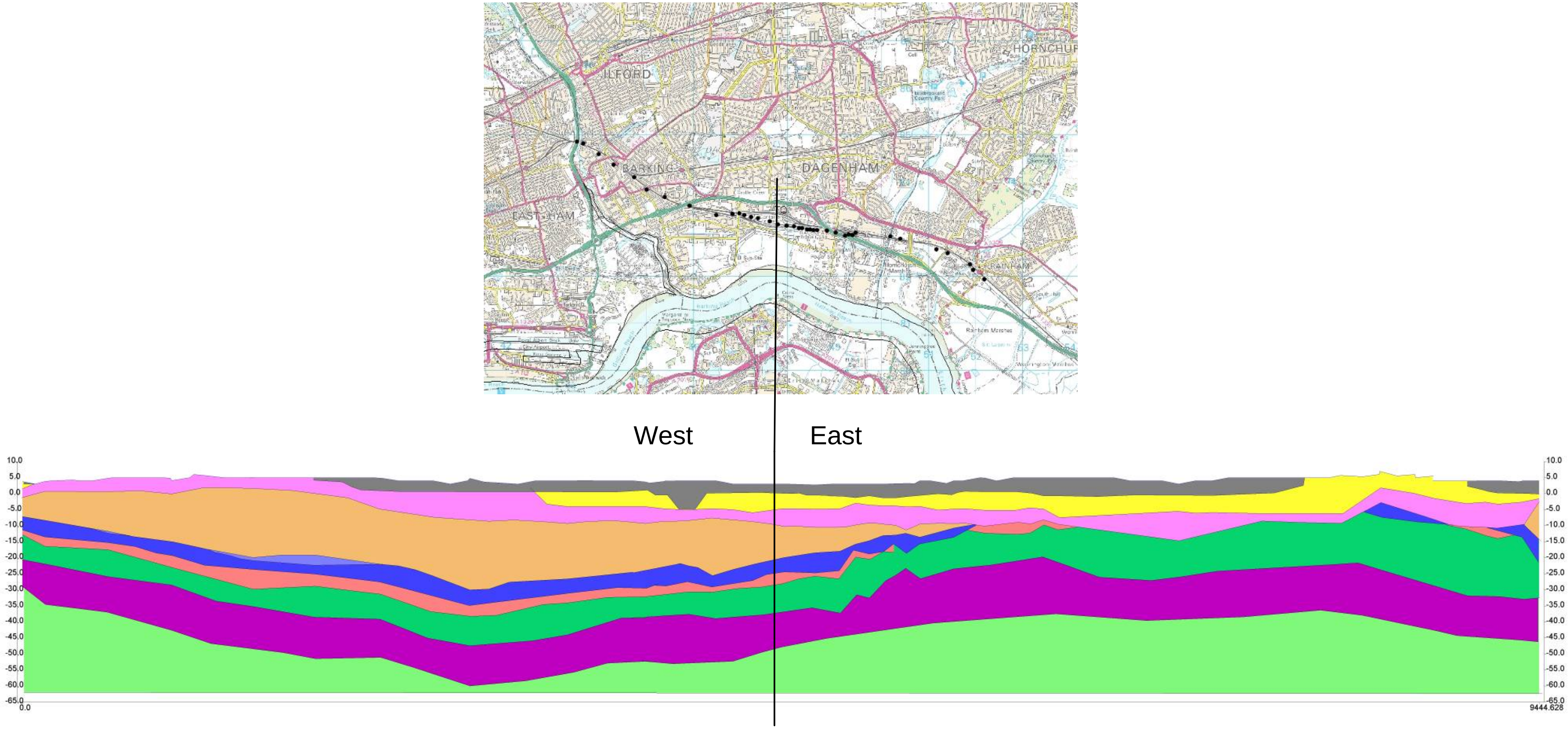


Figure A.2.15. Channel Tunnel Rail Link from A406 Barking to Rainham, west to east; borehole distribution (top) and lithostratigraphical cross-section.

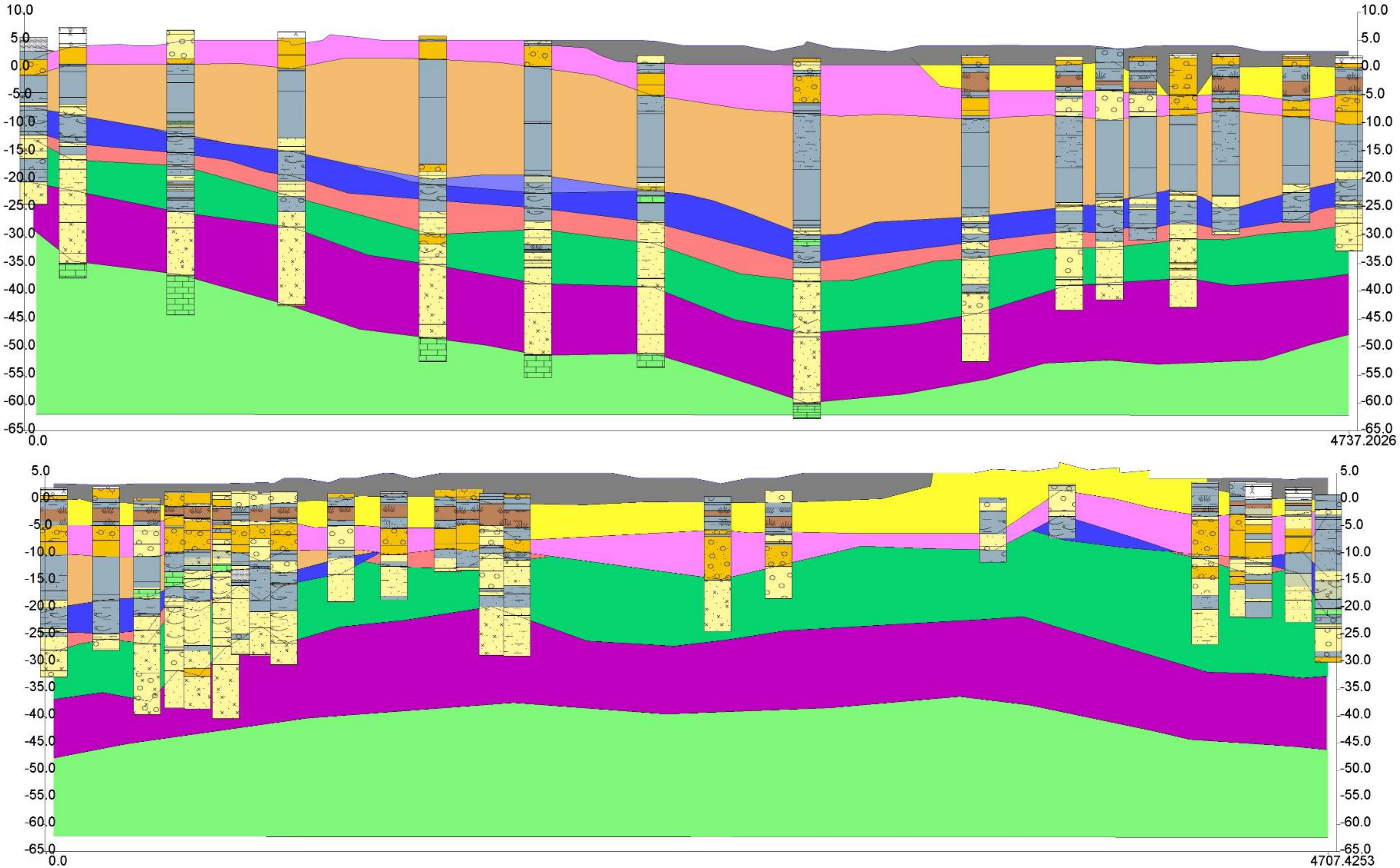


Figure A.2.16. Channel Tunnel Rail Link, A406 Barking to Rainham, lithostratigraphy and lithology, in borehole sticks west to (top) and east (bottom).

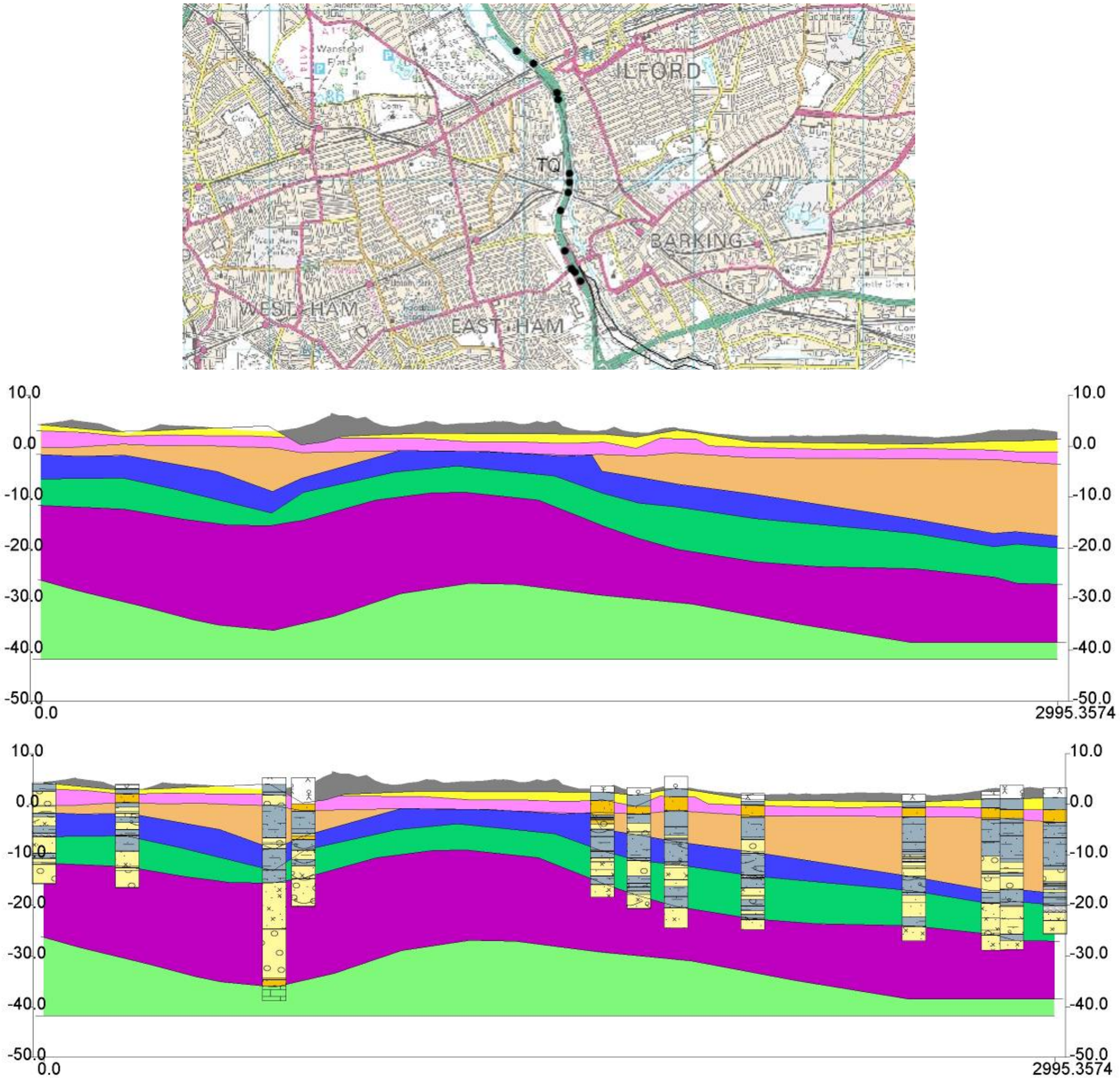


Figure A.2.17. A406 South Woodford [TQ 4293 8653] to Barking Relief Road [TQ 4366 8387], north to south; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

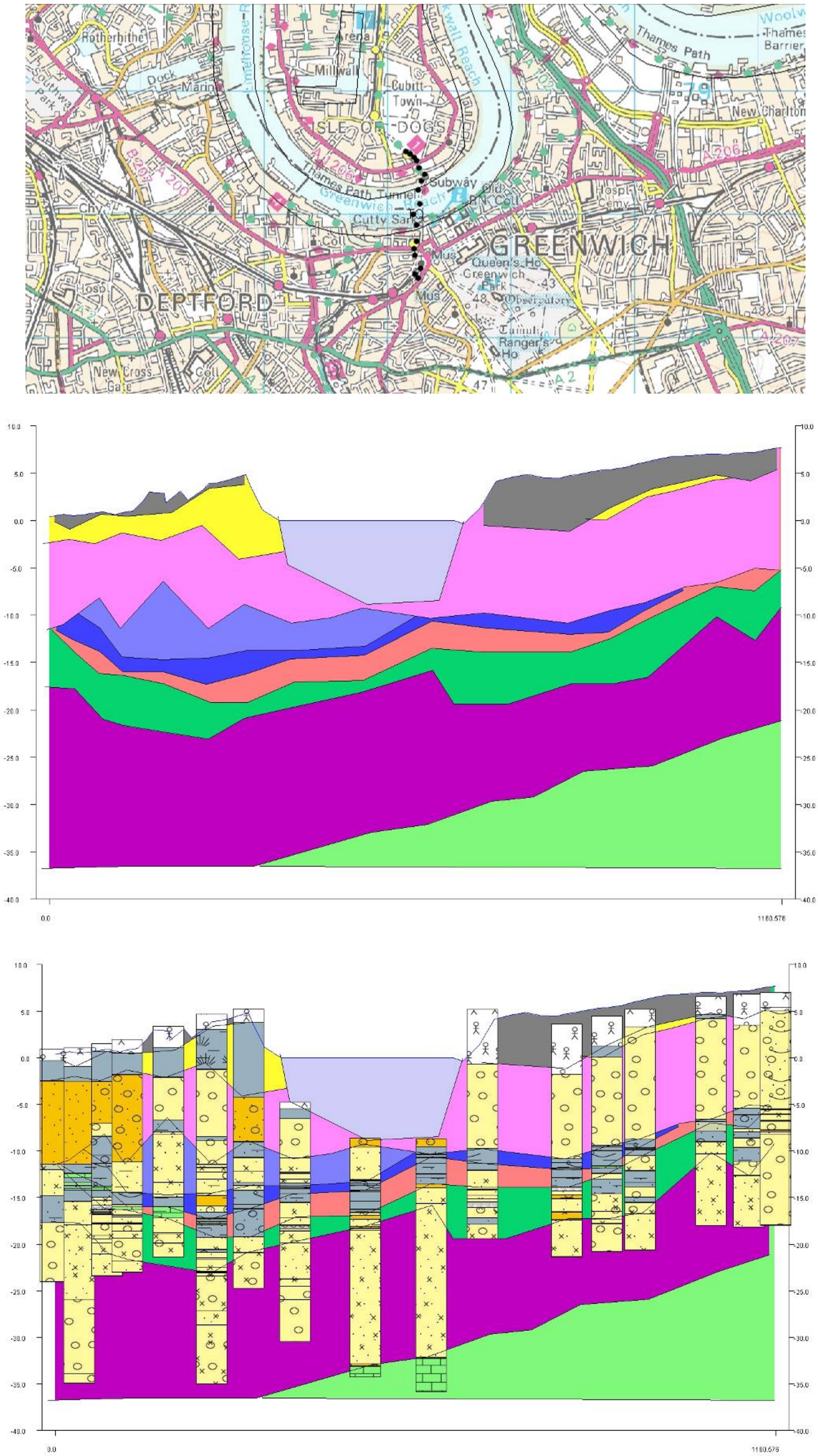


Figure A.2.18. Dockland Light Railway, Lewisham Extension, Greenwich [TQ 3815 7851] to Island Gardens, Isle of Dogs [TQ 3842 7748]; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

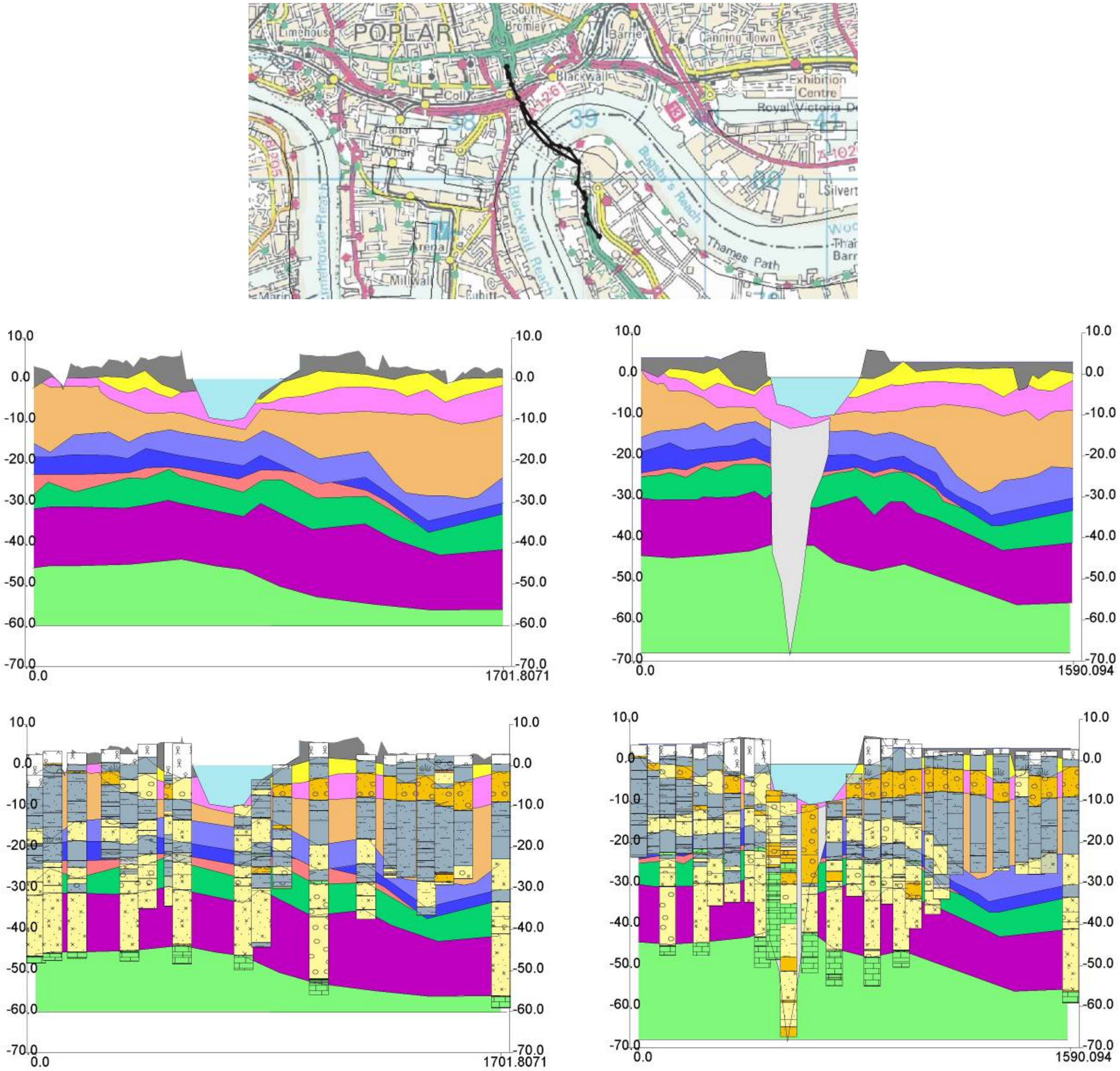


Figure A.2.19. A102 Blackwall Tunnel, Third Bore [TQ 3838 8087] to [3913 7953], north to south; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

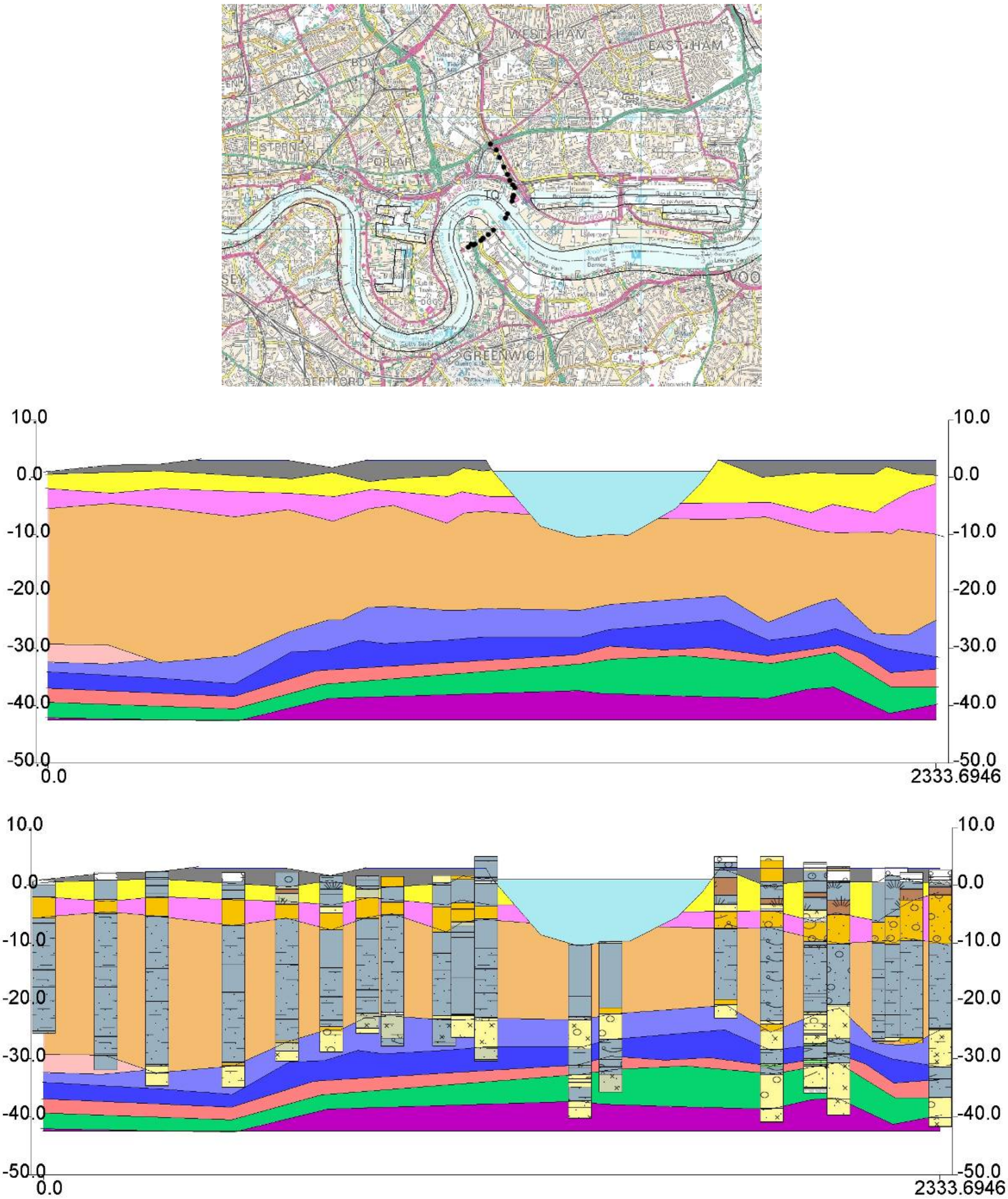


Figure A.2.20. Jubilee Line Extension, Canning Town to North Greenwich [TQ 3932 8153] to [TQ 38930 7968], north to south; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

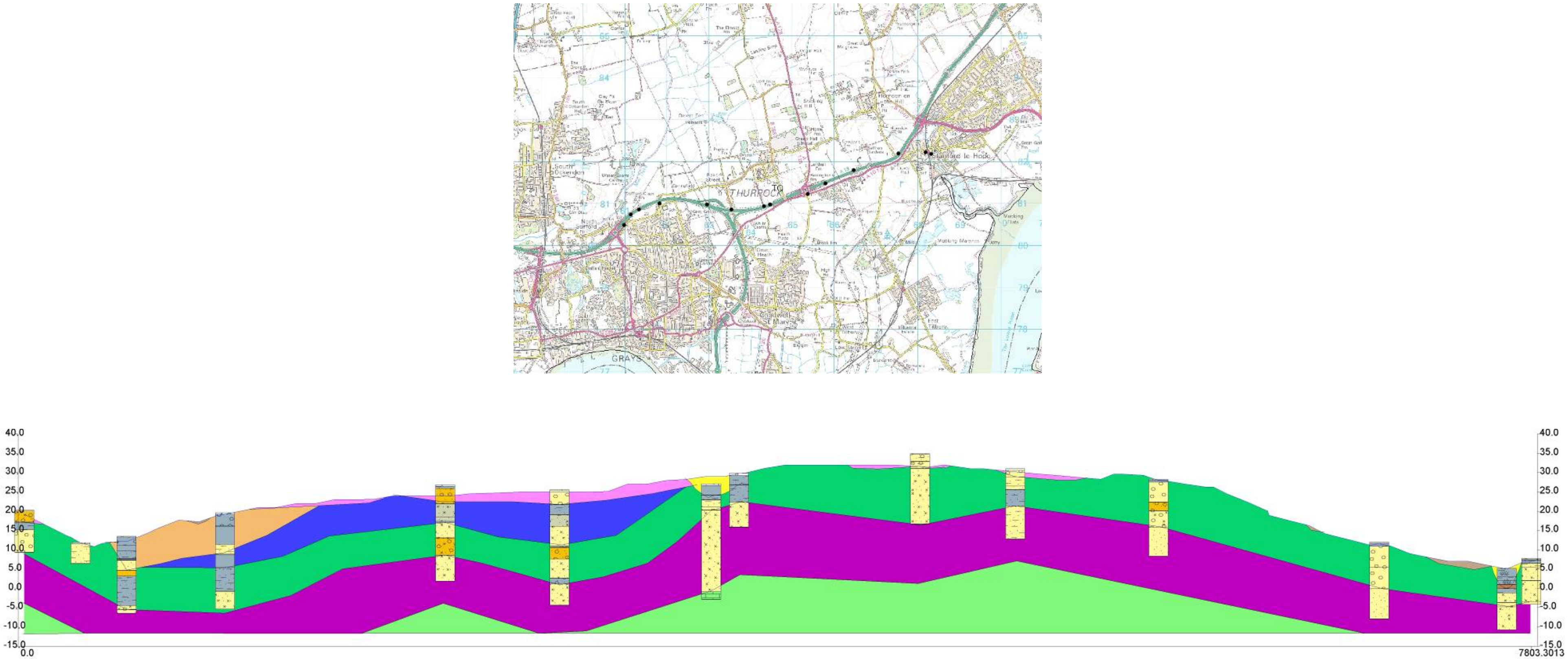


Figure A.2.21. A13 Orsett Cock [TQ 6099 8049] to Stanford-le-Hope [TQ 6832 8219], west to east, interchange in Essex; borehole distribution (top) and lithostratigraphical and lithological cross-section (bottom).

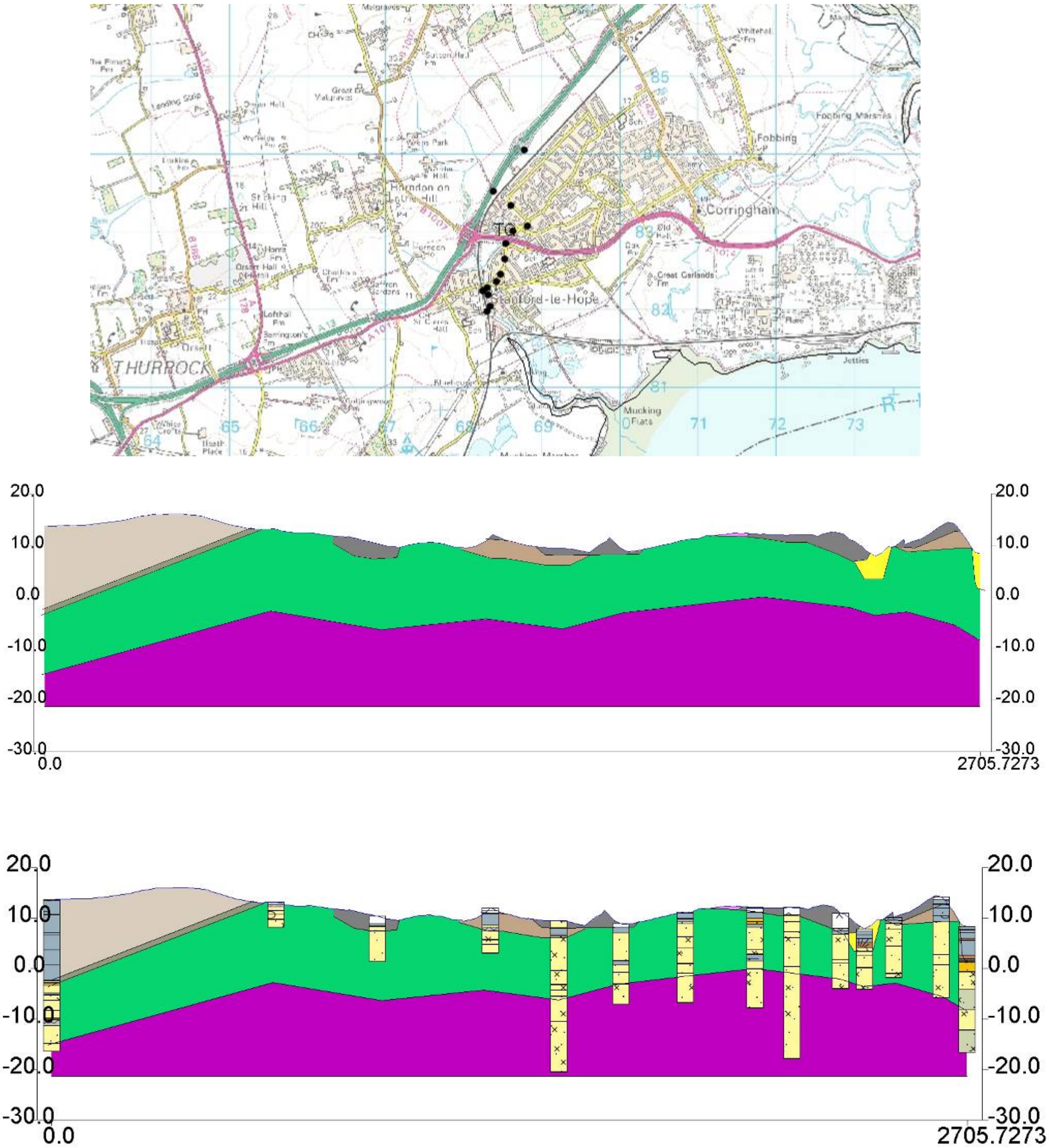


Figure A.2.22. Stanford-le-Hope, Low Level Sewerage Scheme [TQ 6878 8406] to [TQ 6831 8198], north to south; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

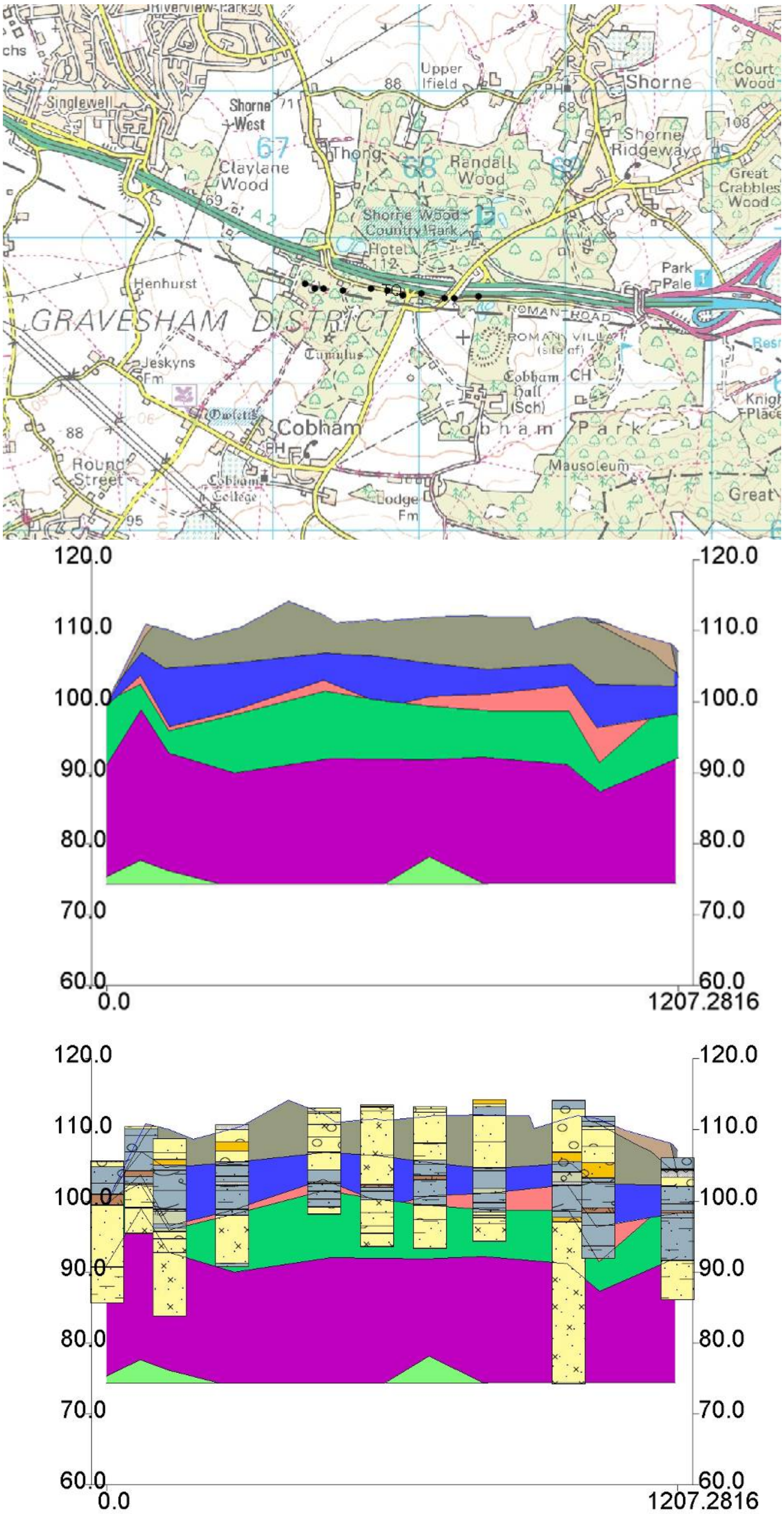


Figure A.2.23. M2 widening, Shorne Cut, SE of Gravesend [TQ 6722 6969] to [TQ 6841 6960], west to east; borehole distribution (top), lithostratigraphical cross-section (middle) and lithostratigraphical and lithology in borehole sticks cross-section (bottom).

Appendix 3 Summary diagrams of lithostratigraphical and lithological variation from boreholes

This Appendix contains graphs that summaries the percentage of each lithostratigraphy and main lithology descriptor for the Lambeth Group and main lithology descriptor for each formation or unit from ground investigation borehole descriptions. The data has been split into areas or 1:10000 sheets. Main lithology includes clay, silt, sand, gravel, limestone (calcrete or shell limestone), and lignite as used in Appendix and the areas covered and order are in Table App. 3.1.

An annotated example is given in App. 3 Figure 1.

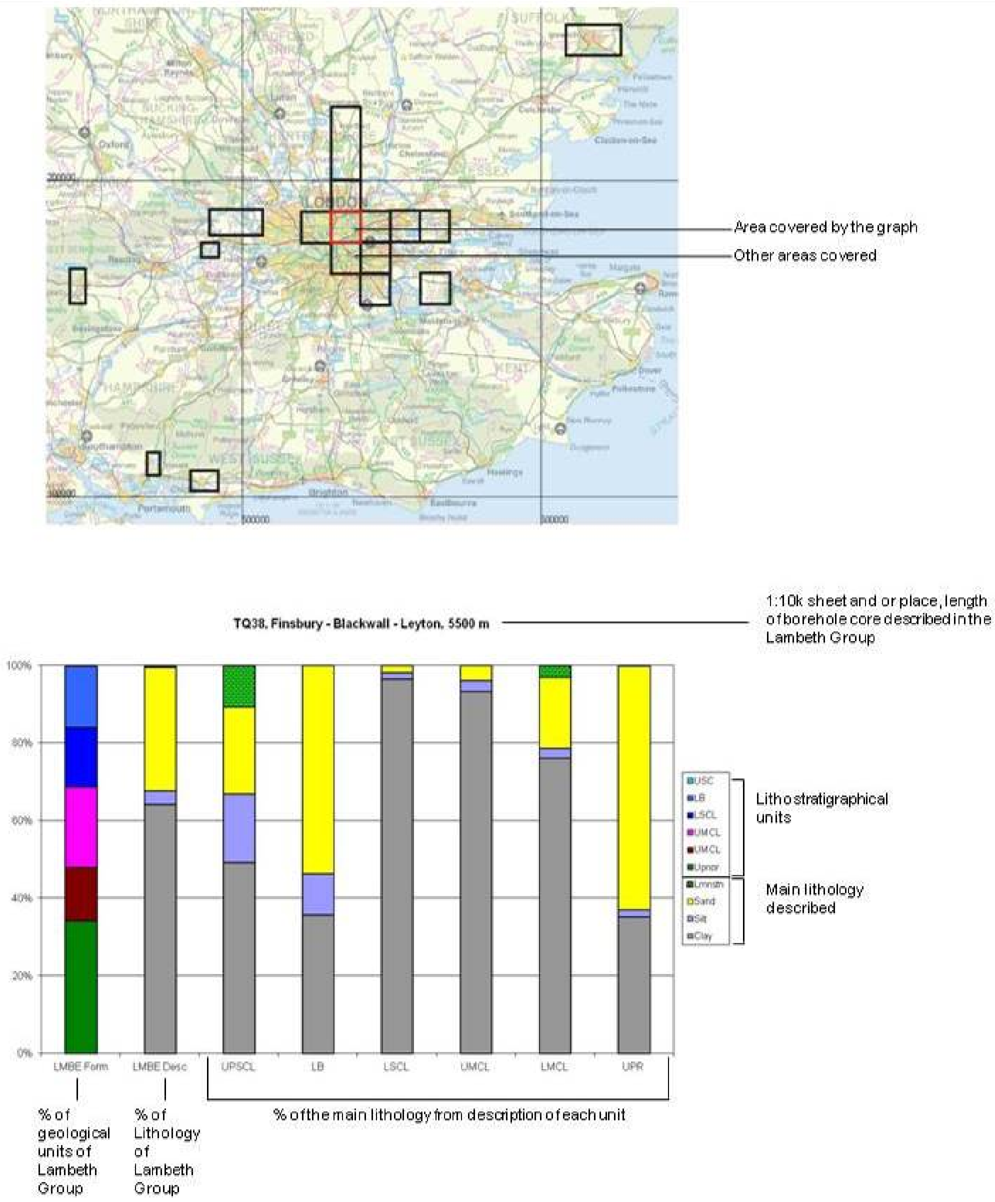
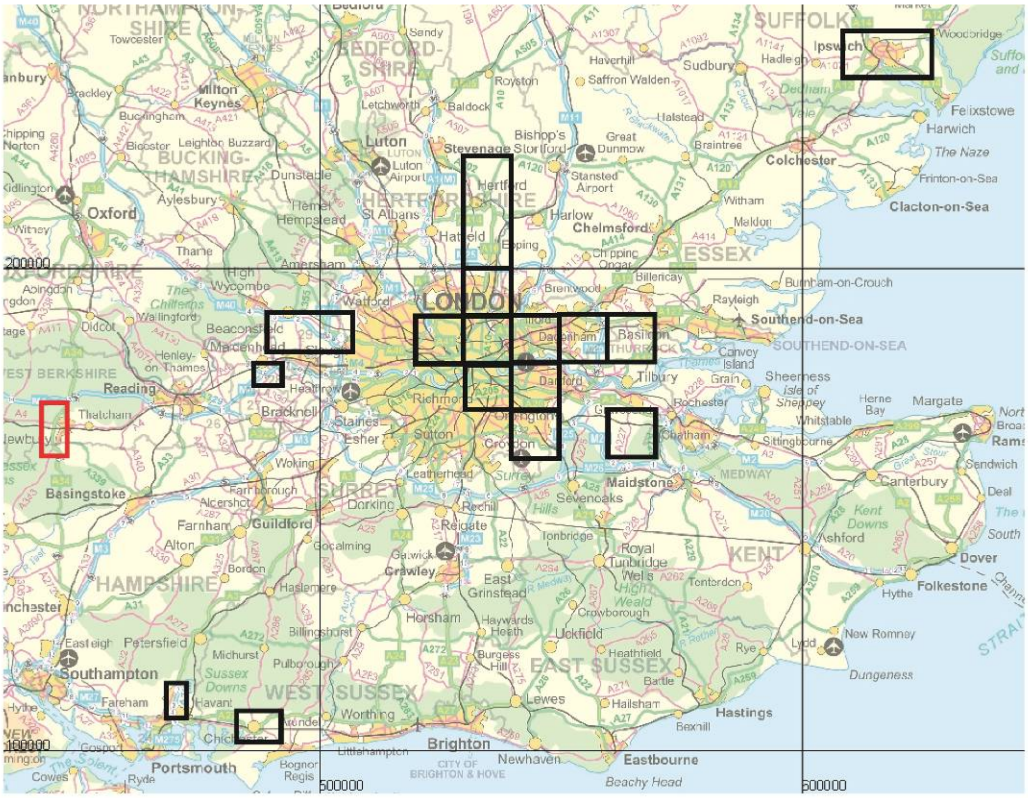


Figure A.3. 1. Key for Appendix 3.

Table A.3. 1. Appendix 3 figure numbers with areas covered.

Appendix 3 Figure	1:10k map sheet number(s)	Area
Figure 2	SU45-47	Newbury
Figure 3	SU87	South of Maidenhead
Figure 4		West London, M25 – M40
Figure 5	TL30-32	Cheshunt – Bishops Stortford
Figure 6	TM04-14	Ipswich
Figure 7	SU60 - 71	Horndean to Bedhampton
Figure 8	SU80	Chichester
Figure 9	TQ28	Hendon – Paddington – St. Pancras
Figure 10	TQ37	Lambeth – Bermondsey - Lewisham
Figure 11	TQ38	Finsbury – Blackwall - Leyton
Figure 12	TQ39	Enfield – Wood Green - Woodford
Figure 13	TQ46	Bromley
Figure 14	TQ47	Woolwich - Sidcup
Figure 15	TQ48	West Ham - Dagenham
Figure 16	TQ58	Rainham - Aveley
Figure 17	TQ66	South Shorne, North Kent
Figure 18	TQ68	Orsett – Stanford - le – Hope, Essex



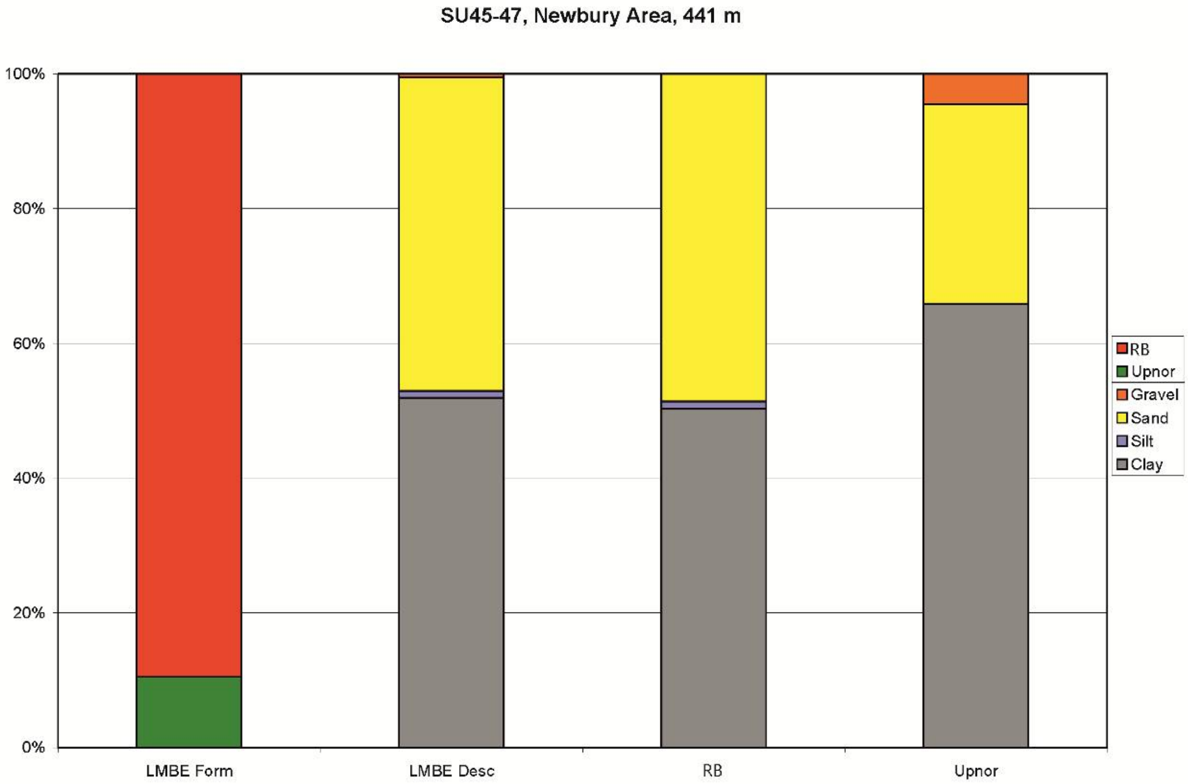


Figure A.3. 2. Newbury Area.

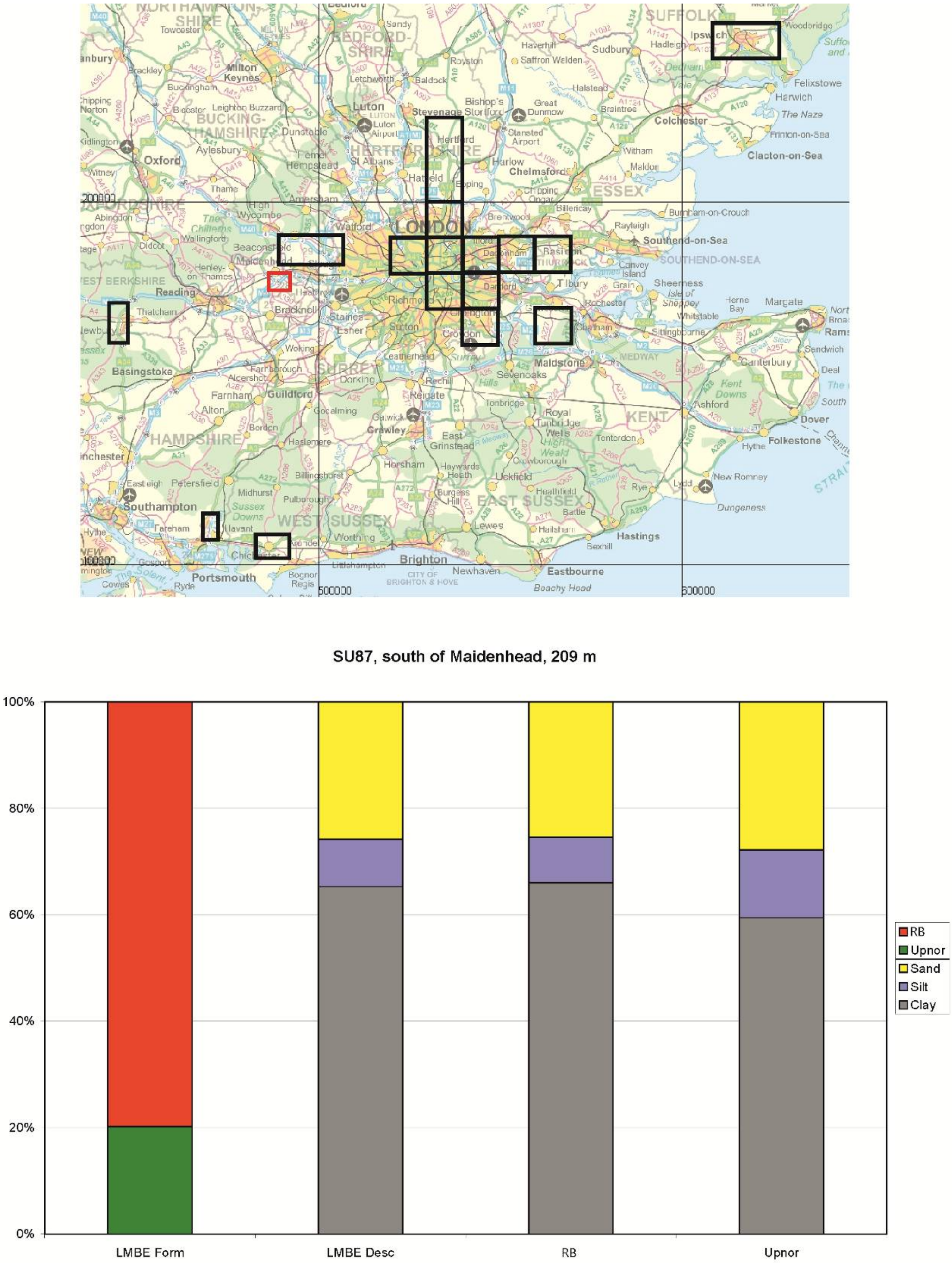
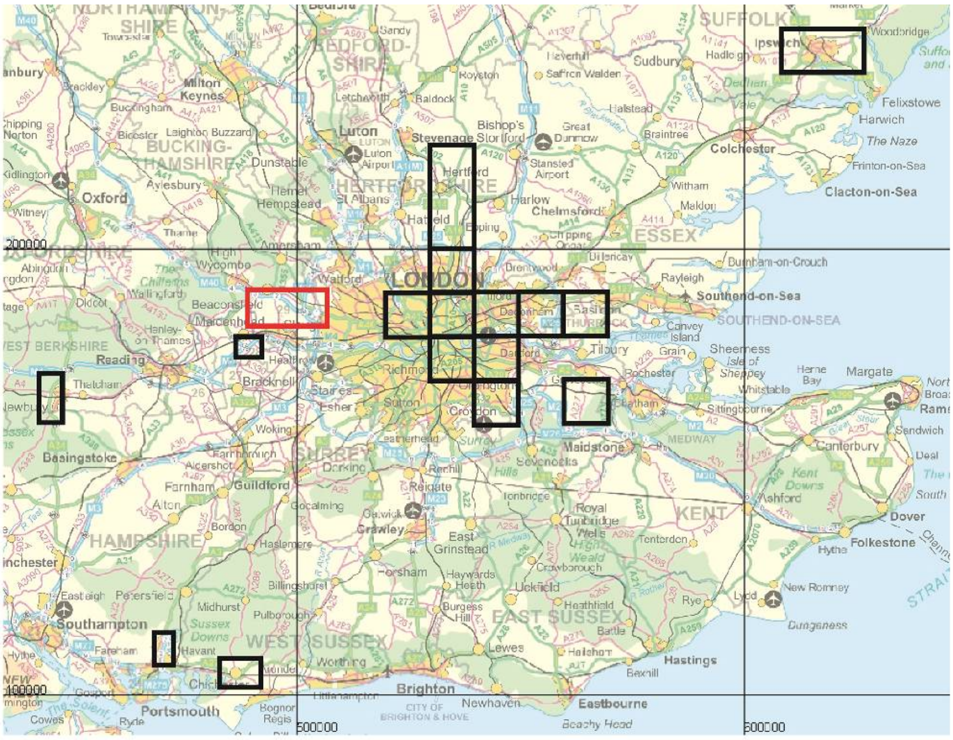


Figure A.3. 3. SU87, south of Maidenhead.



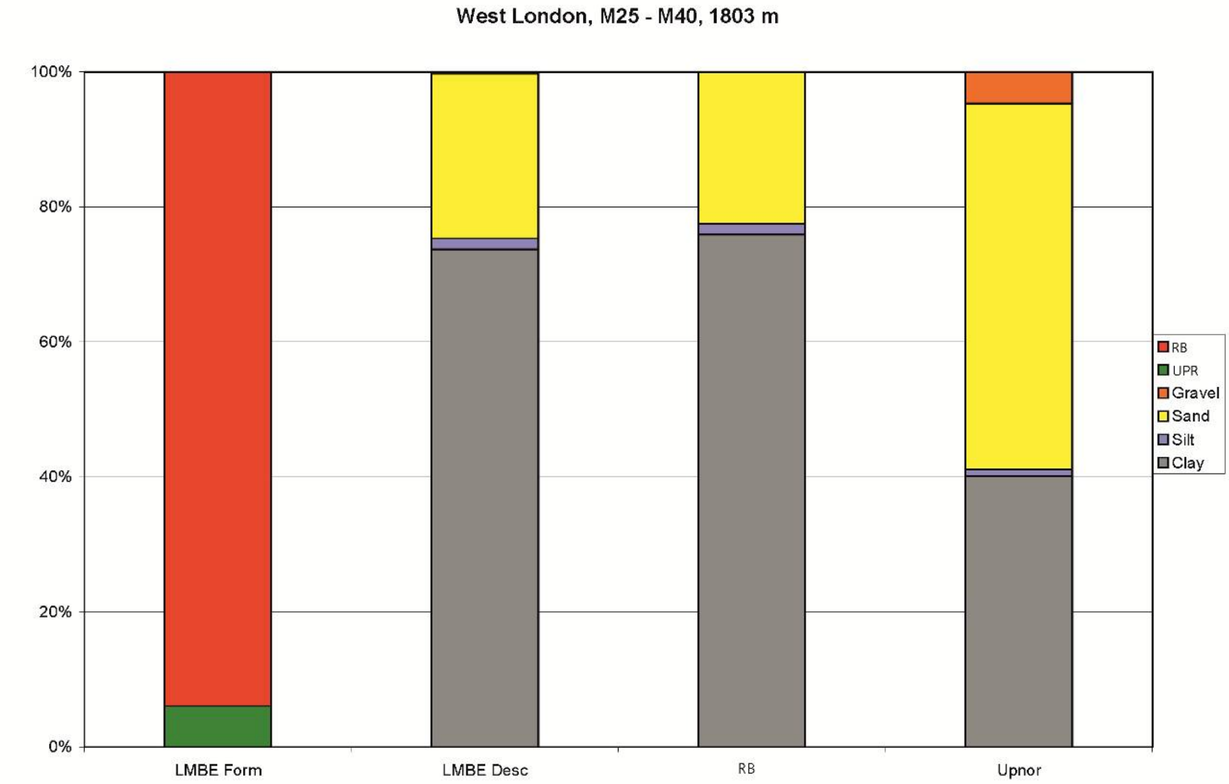
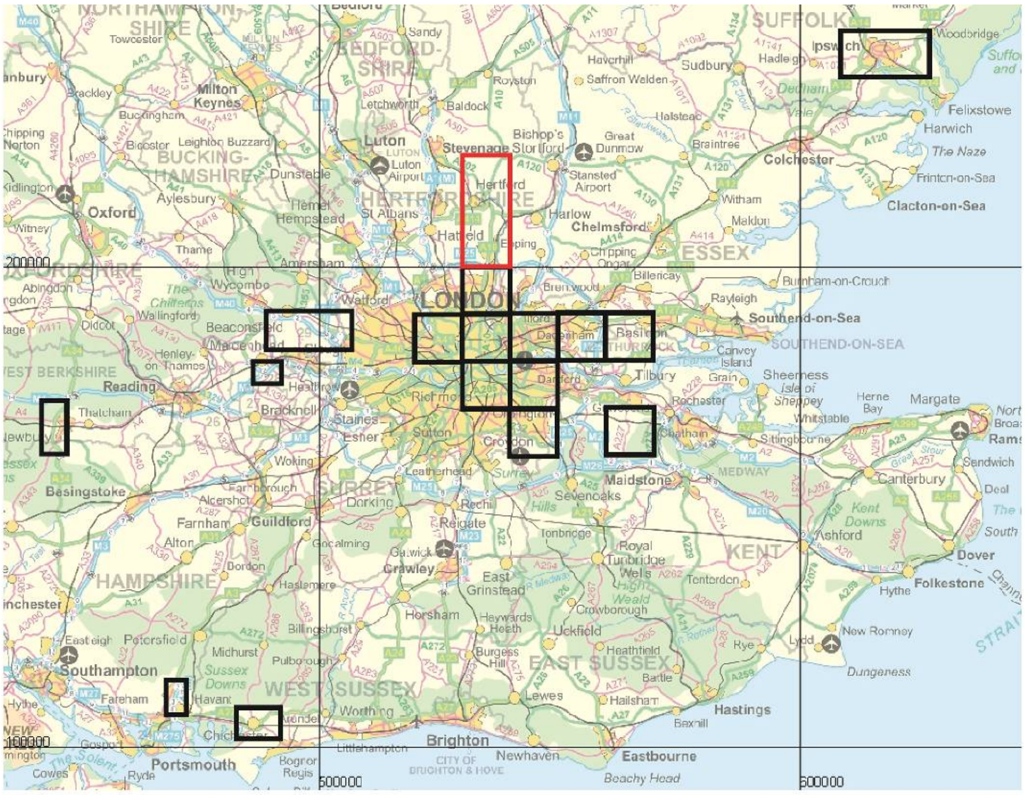


Figure A.3. 4. West of London, M25 - M40.



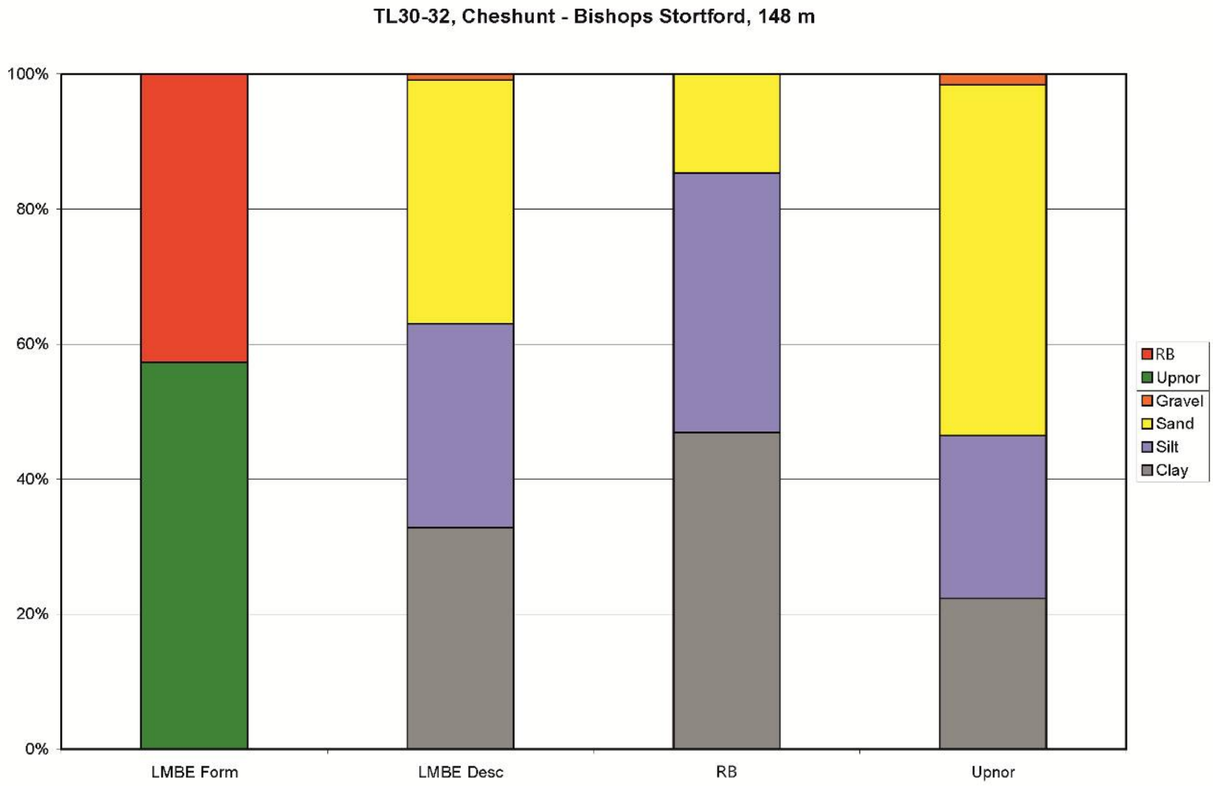
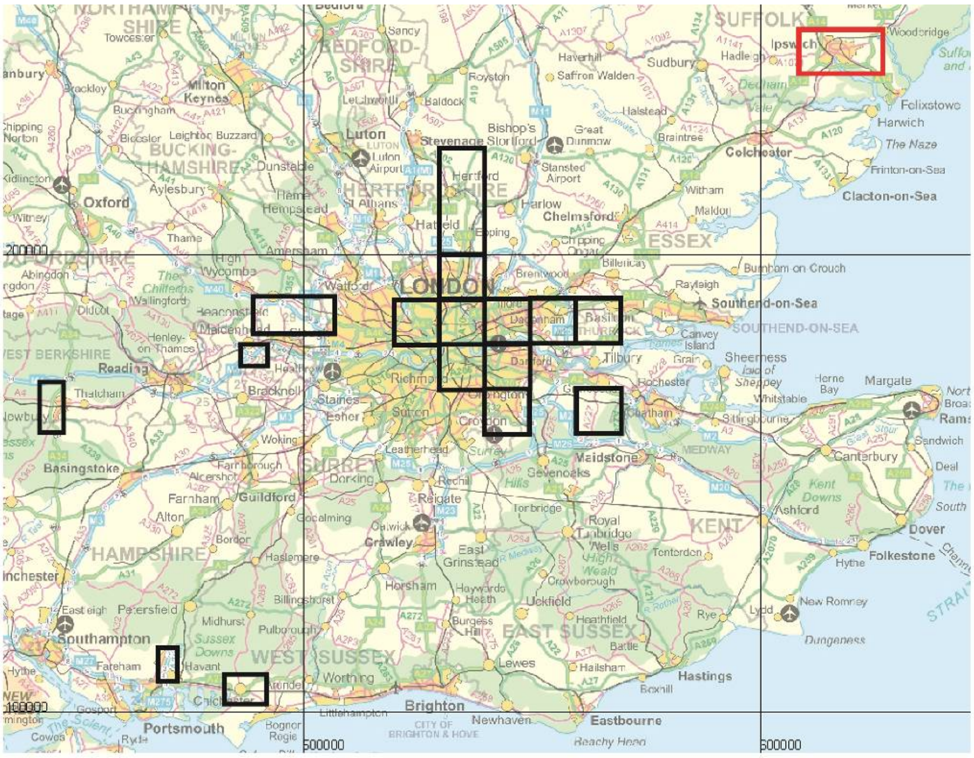


Figure A.3. 5. TL30 - TL32, Cheshunt to Bishop's Stortford.



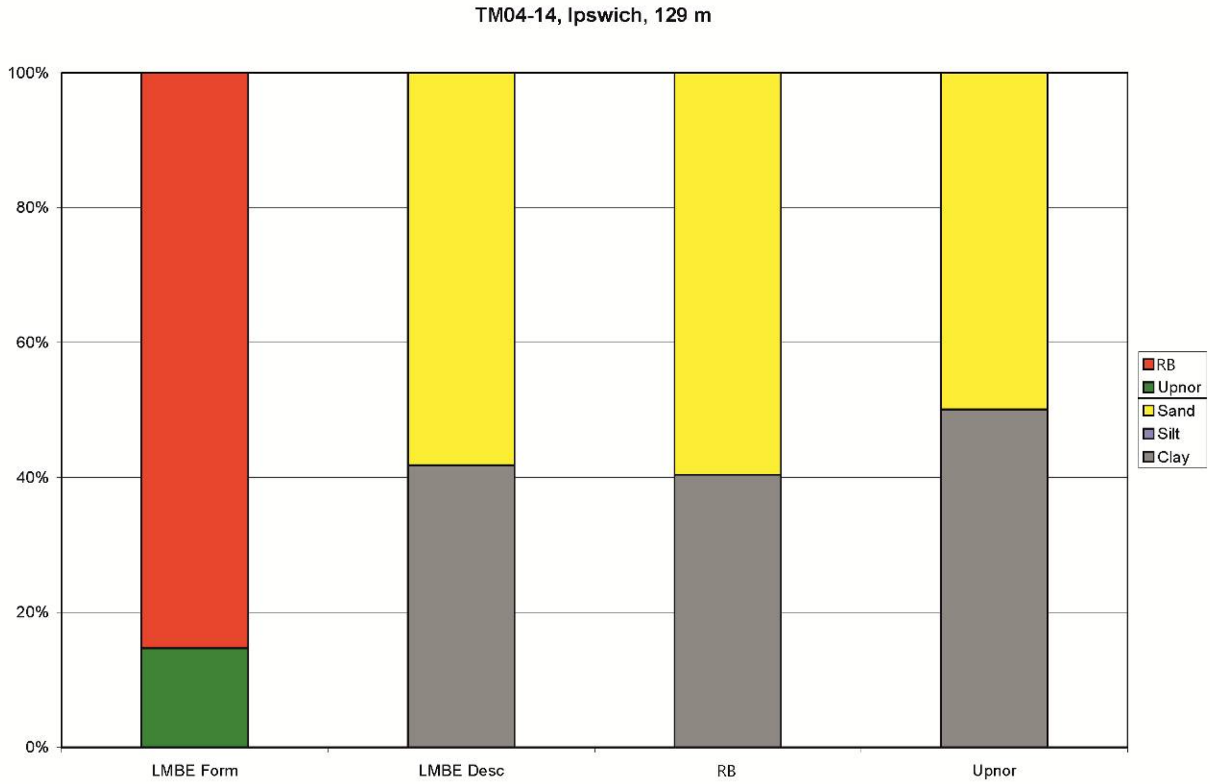
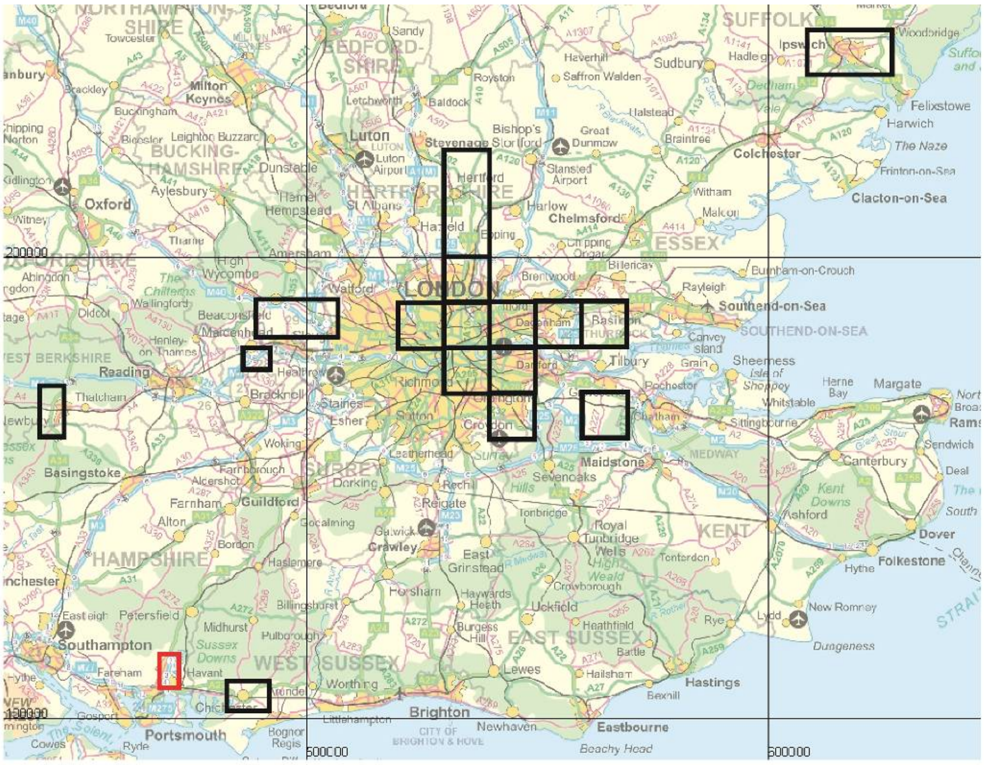


Figure A3.6. TM04-14, Ipswich.



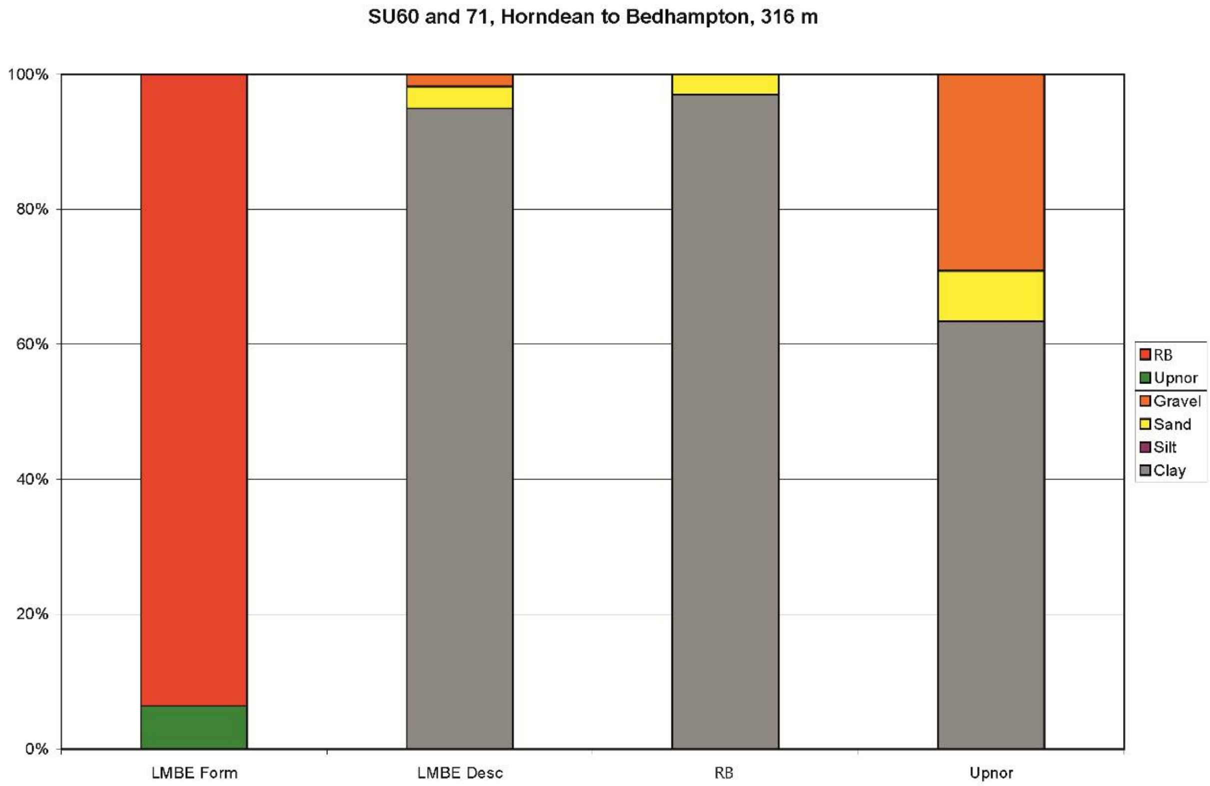
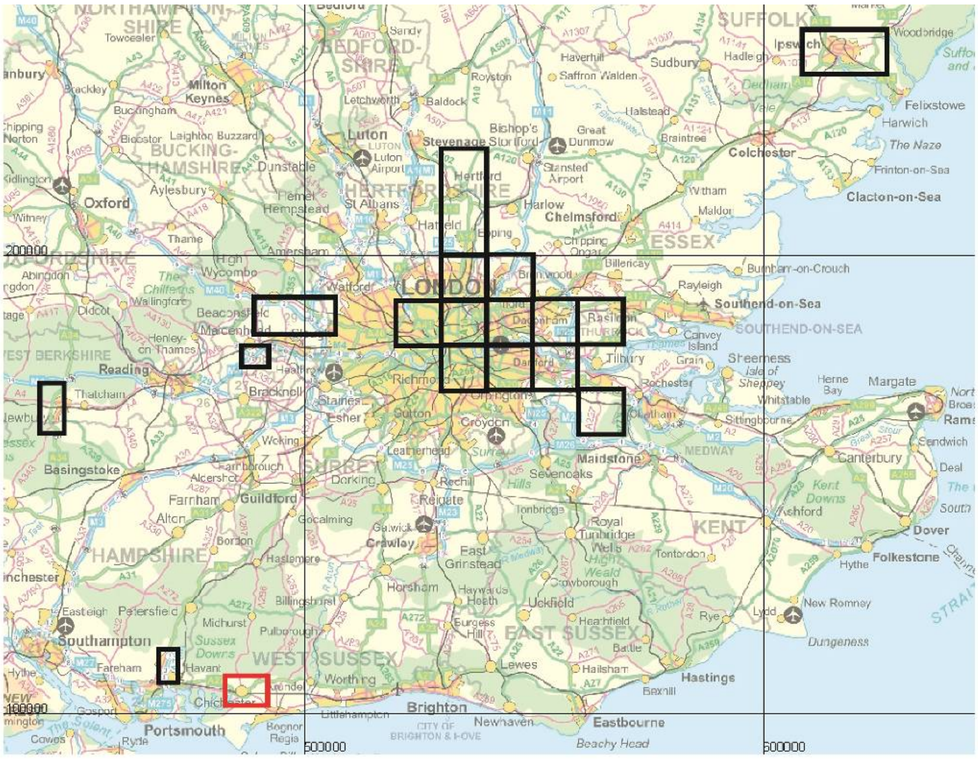


Figure A3.7. SU60 and 71, Horndean to Bedhampton.



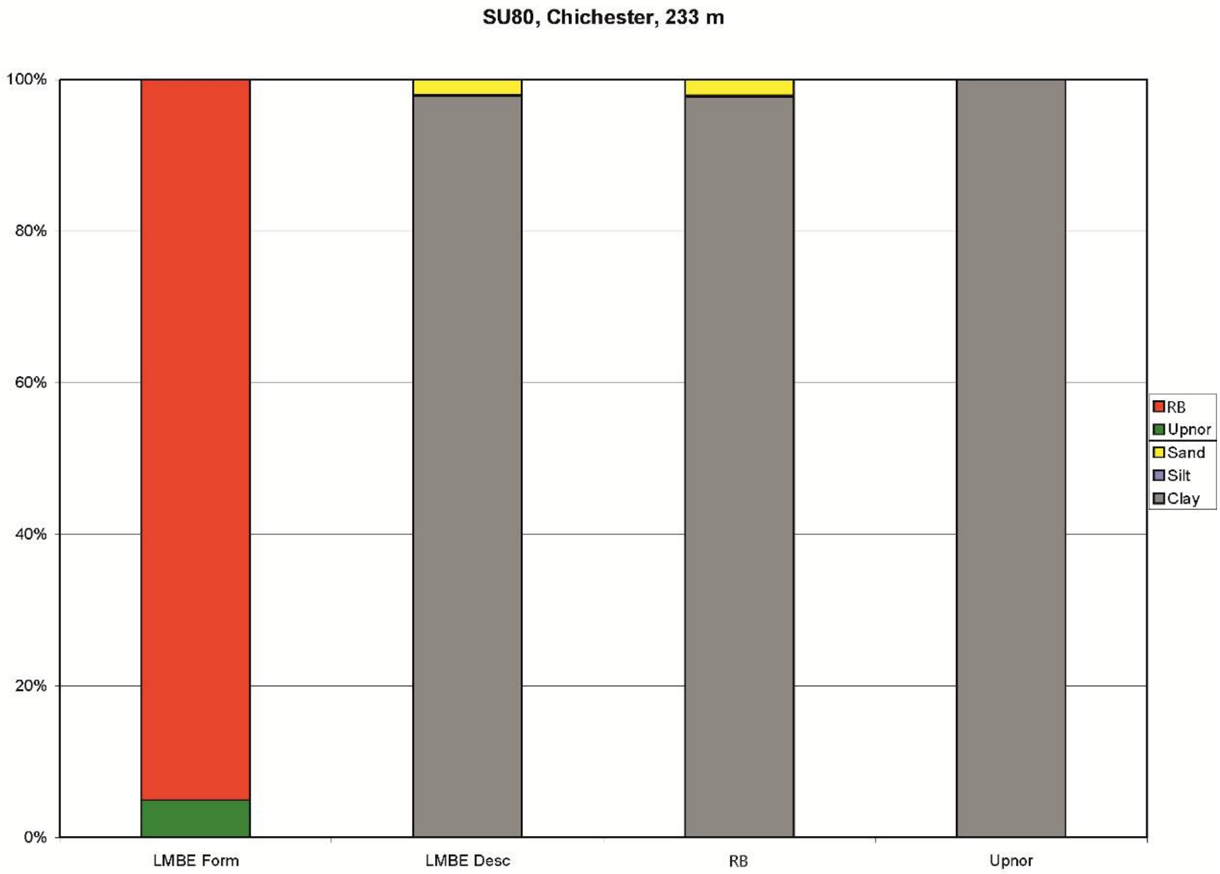
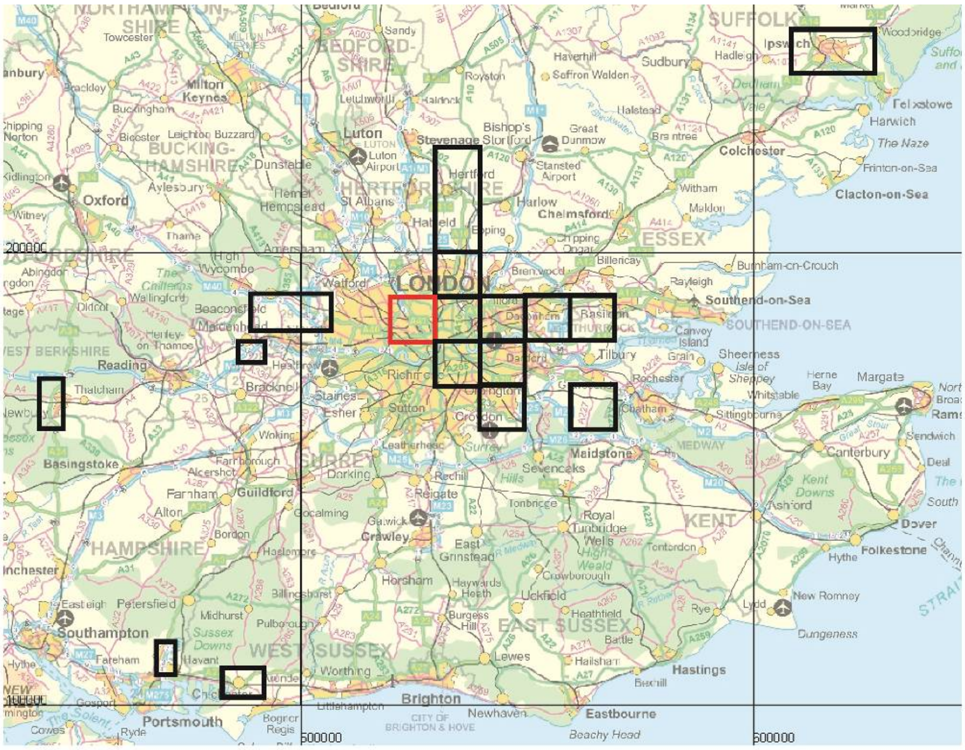


Figure A.3. 8. SU80, Chichester.



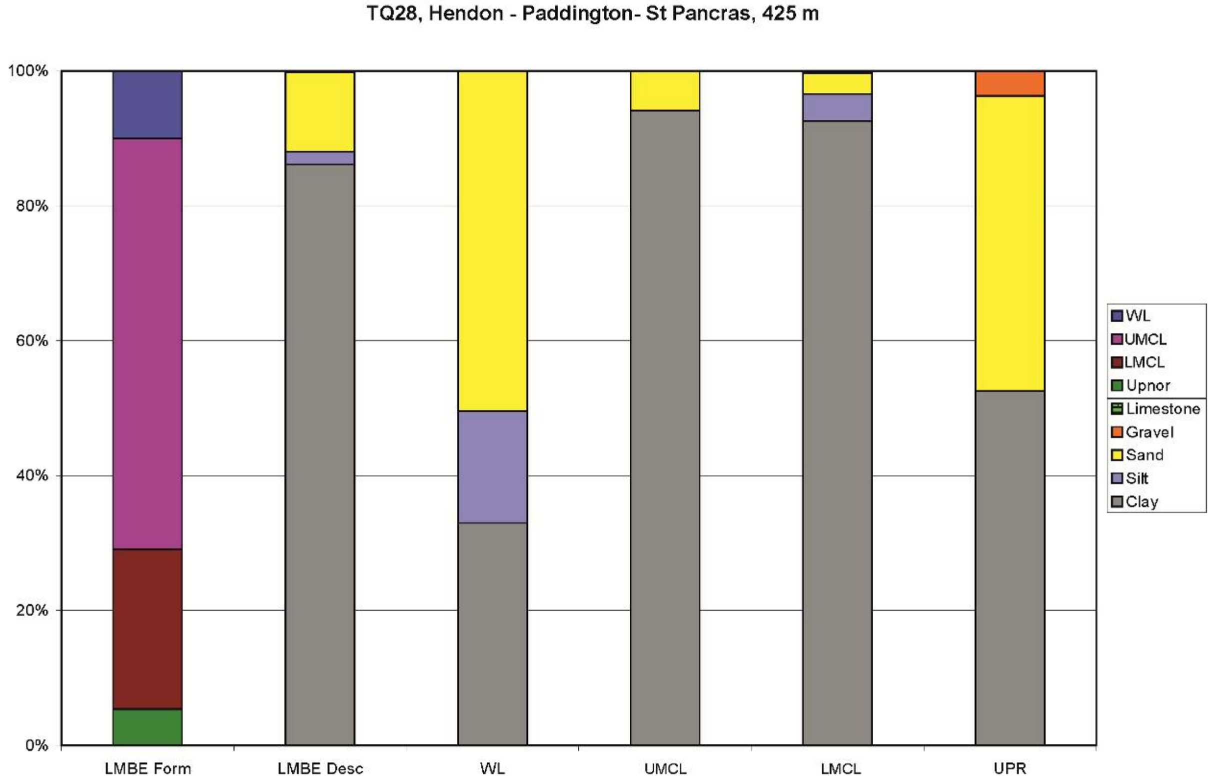
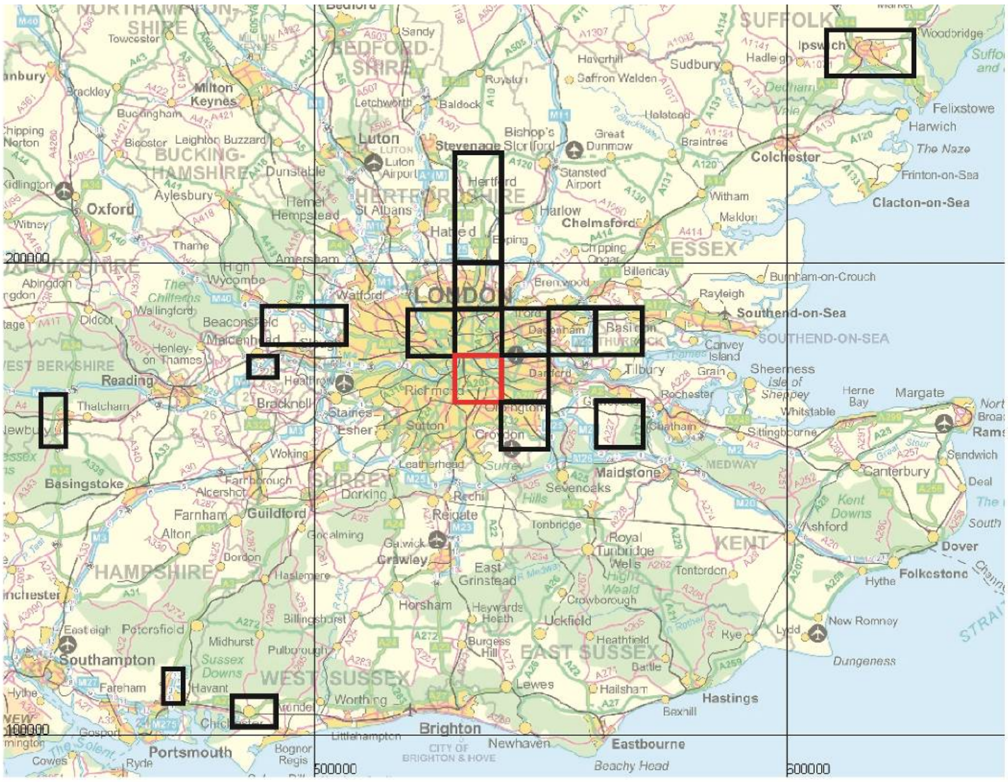


Figure A.3. 9. TQ28, Hendon - Paddington - St. Pancras.



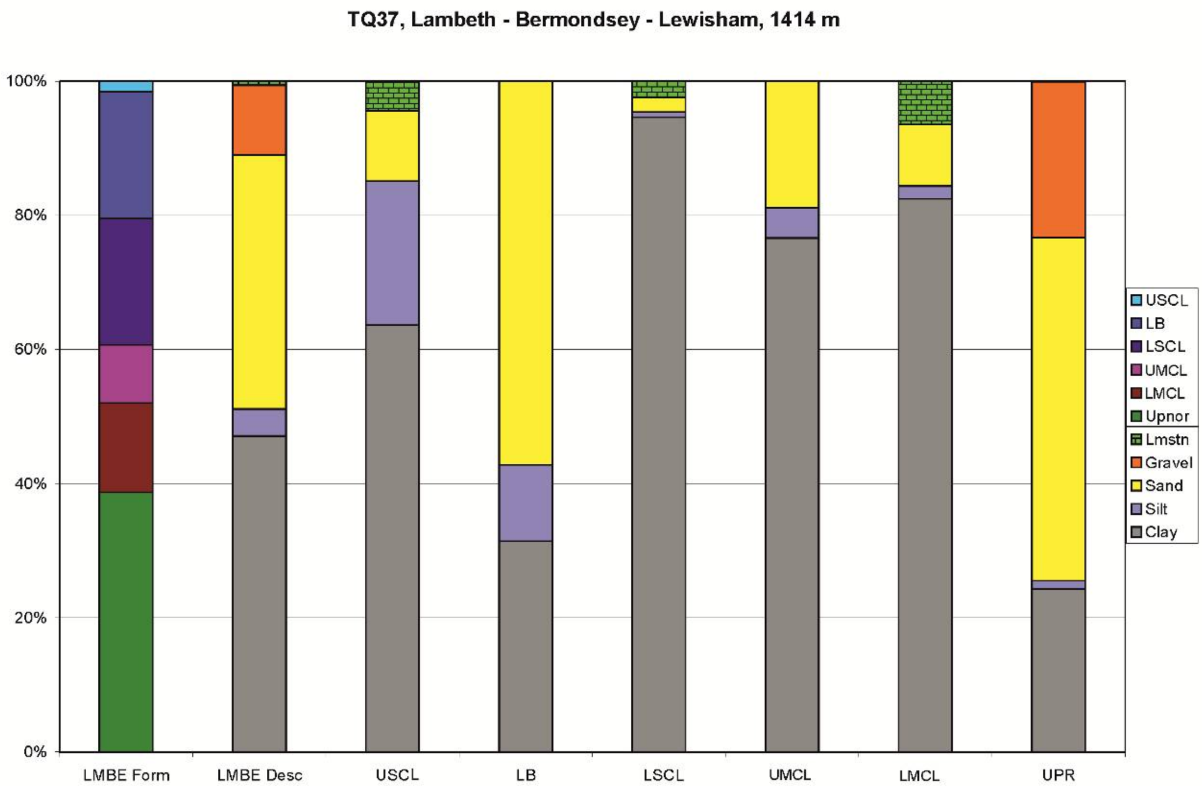
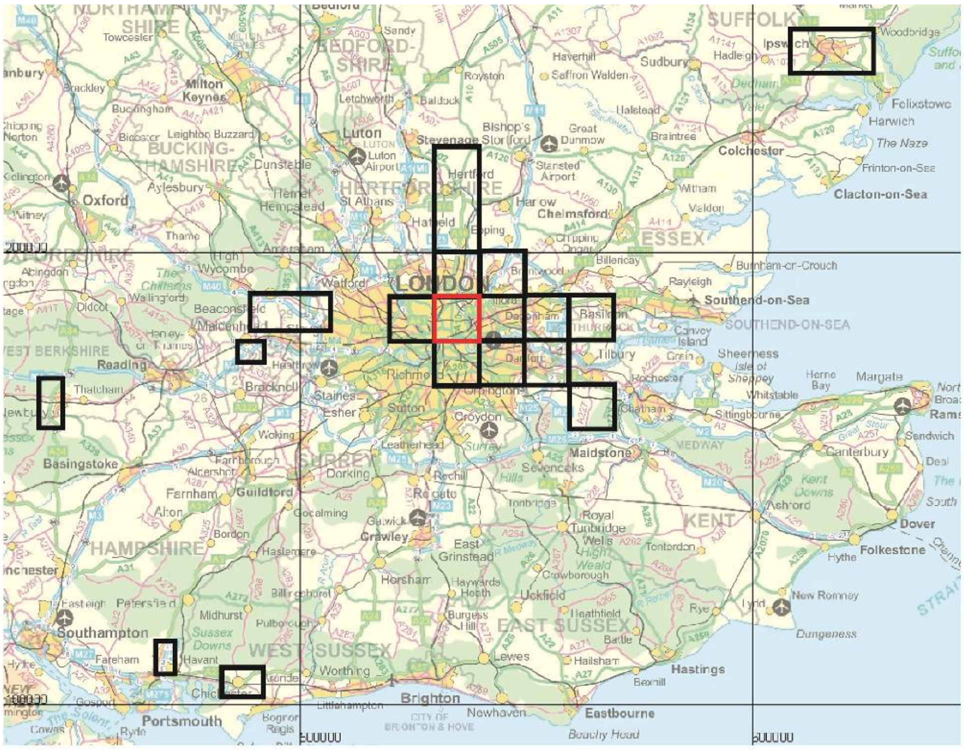
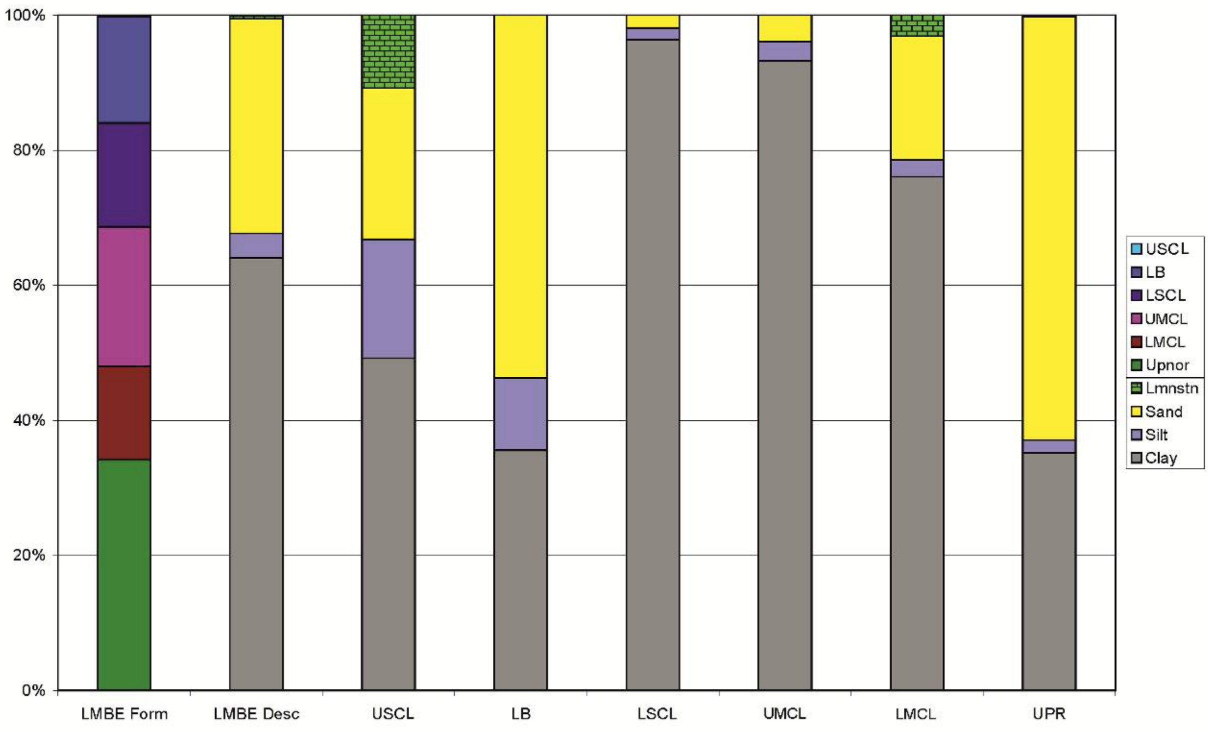


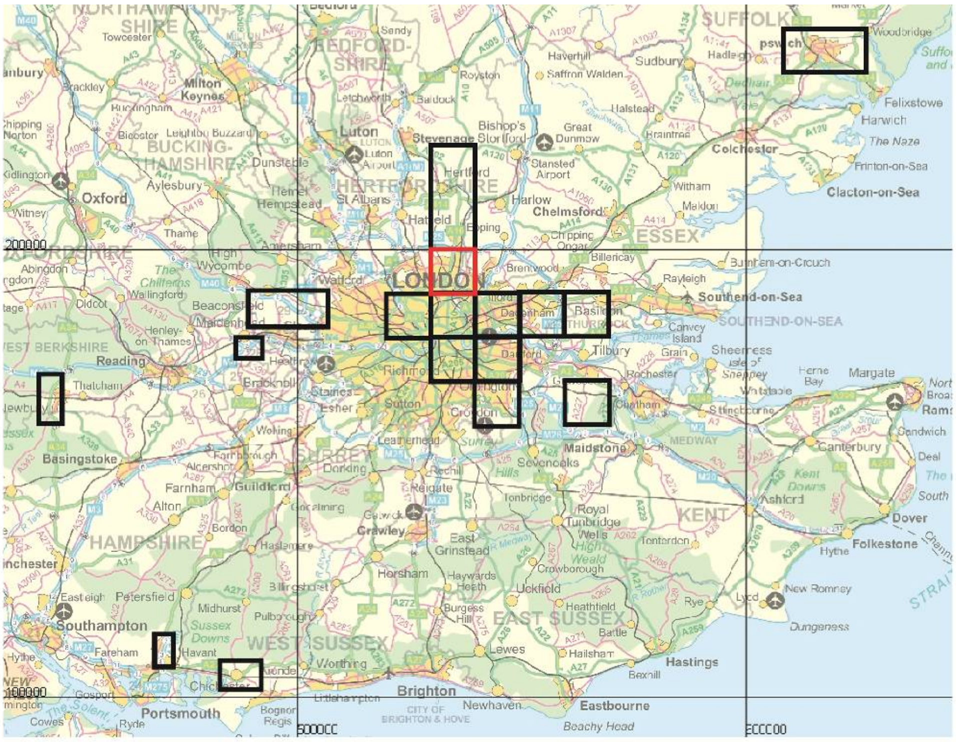
Figure A.3. 10. TQ37, Lambeth - Bermondsey - Lewisham.



TQ38, Finsbury - Blckwall - Leyton, 5500 m



A3. Figure 1. TQ38, Finsbury - Blackwall - Leyton.



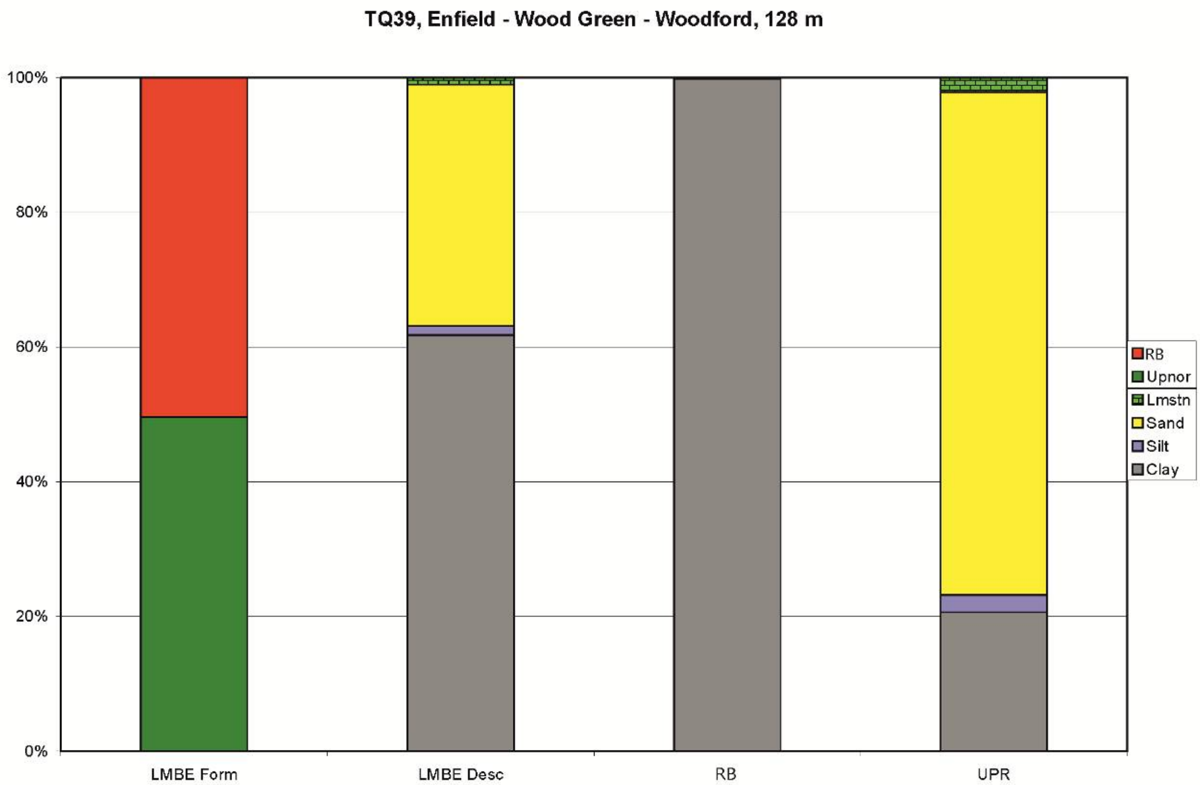
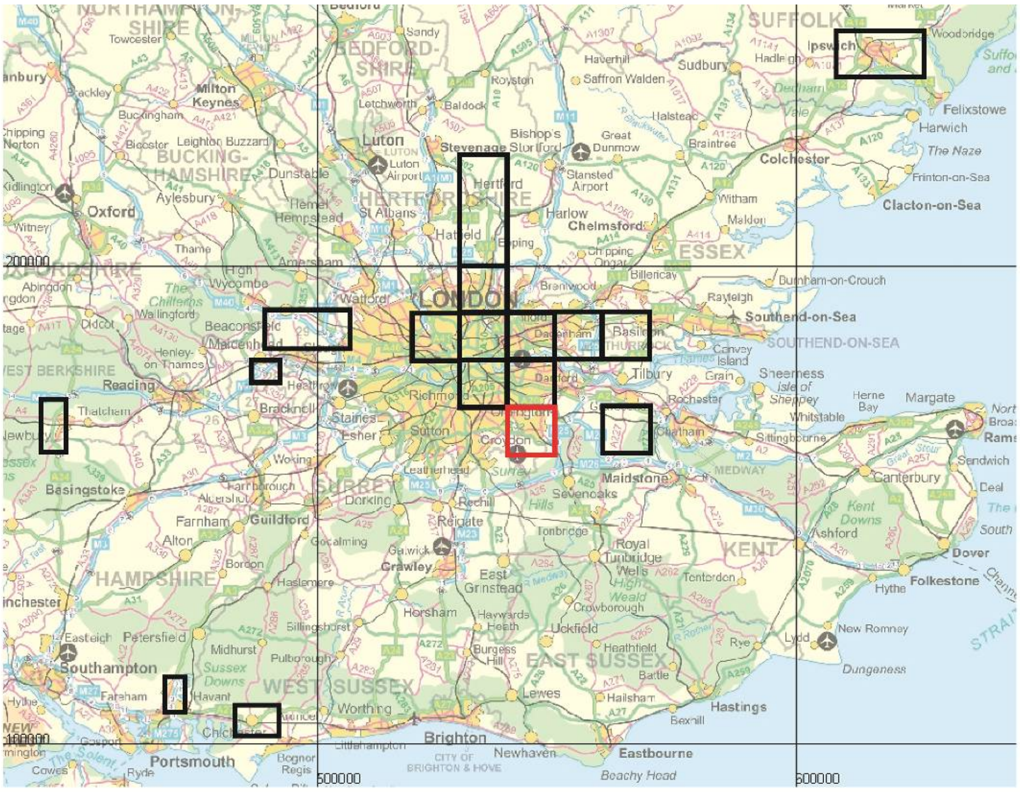


Figure A.3. 11. TQ39, Enfield - Wood Green - Woodford.



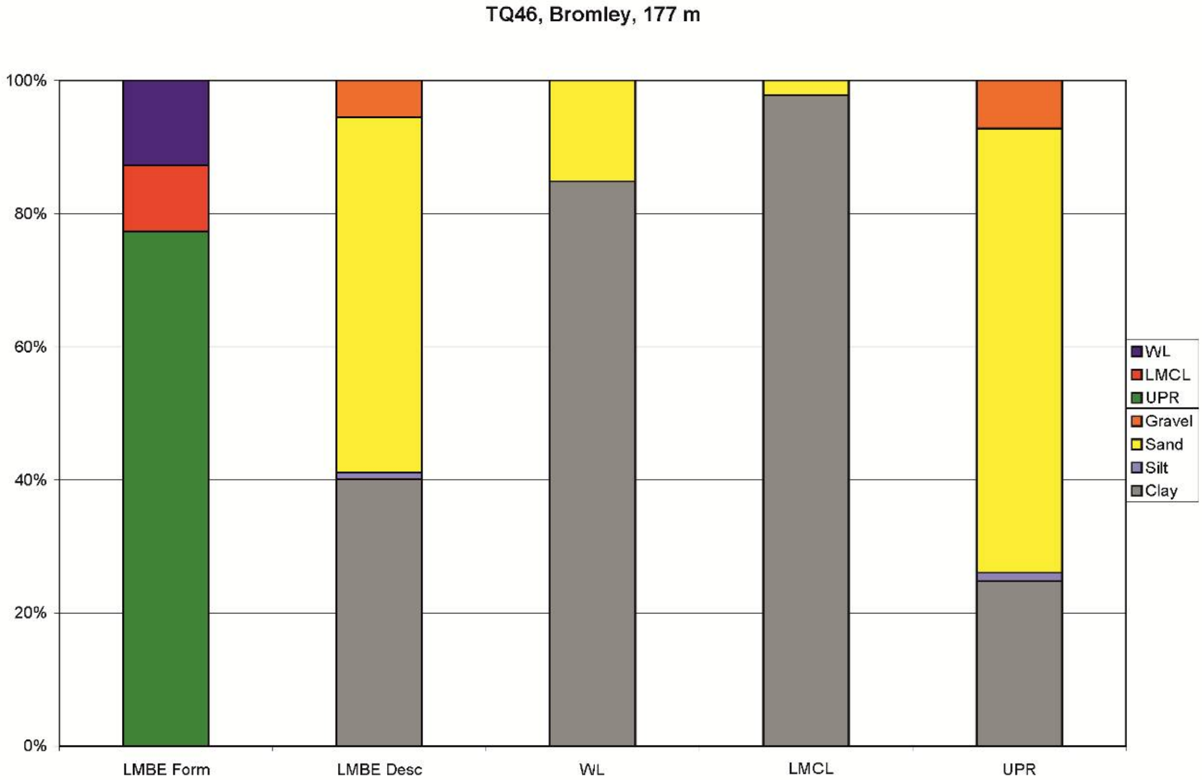
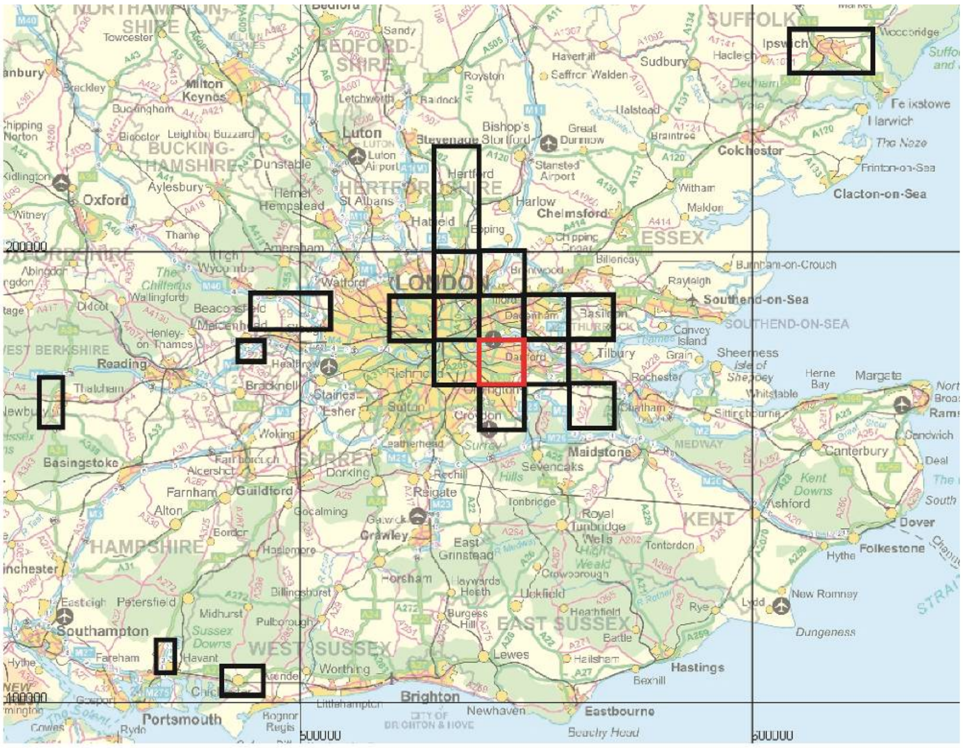


Figure A.3. 12. TQ46, Bromley.



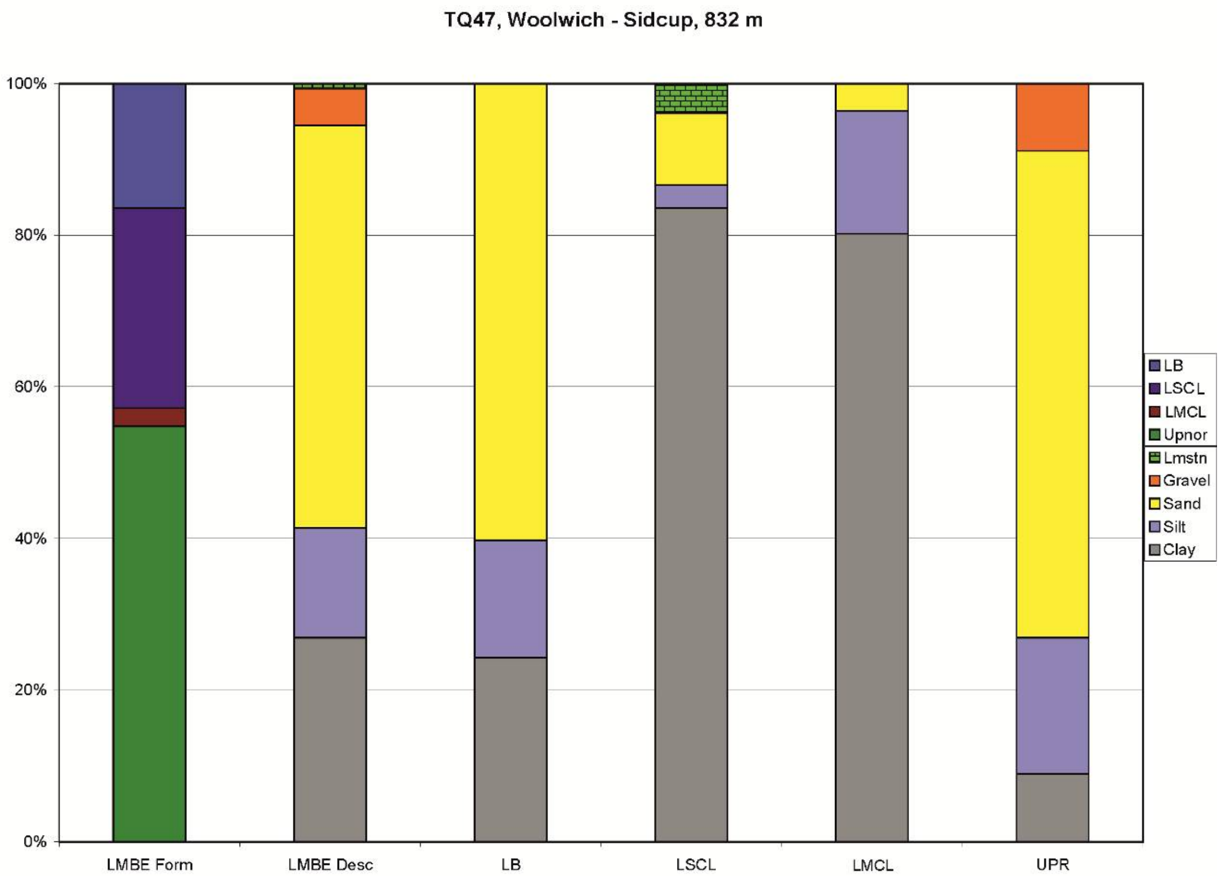
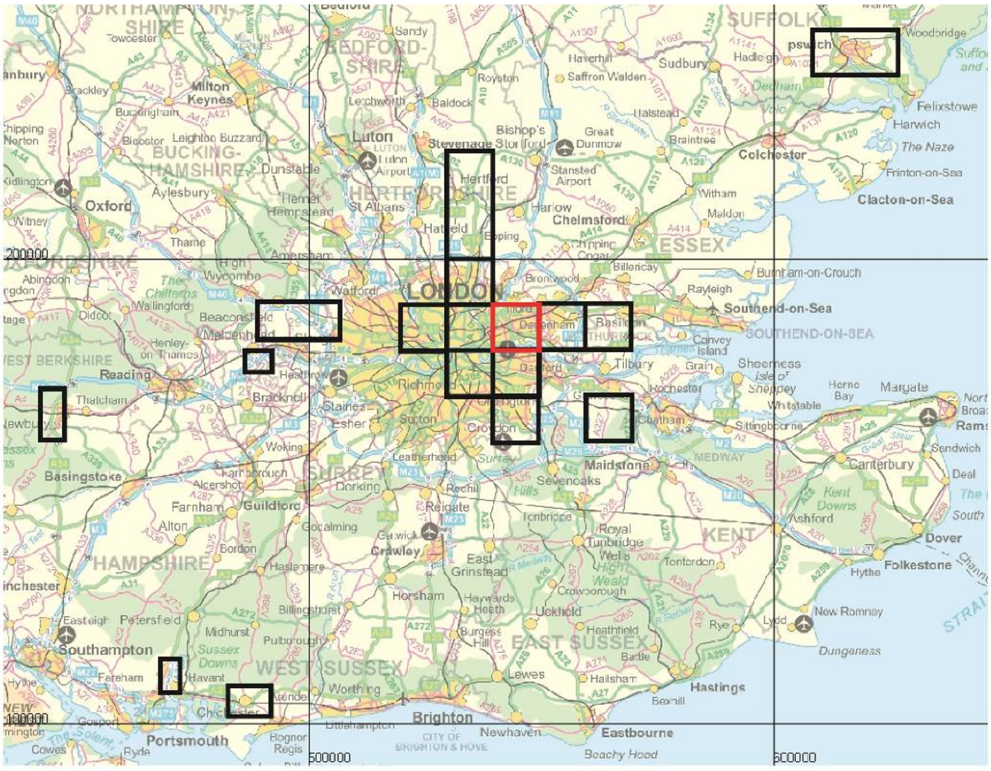


Figure A3.13. TQ47, Woolwich - Sidcup.



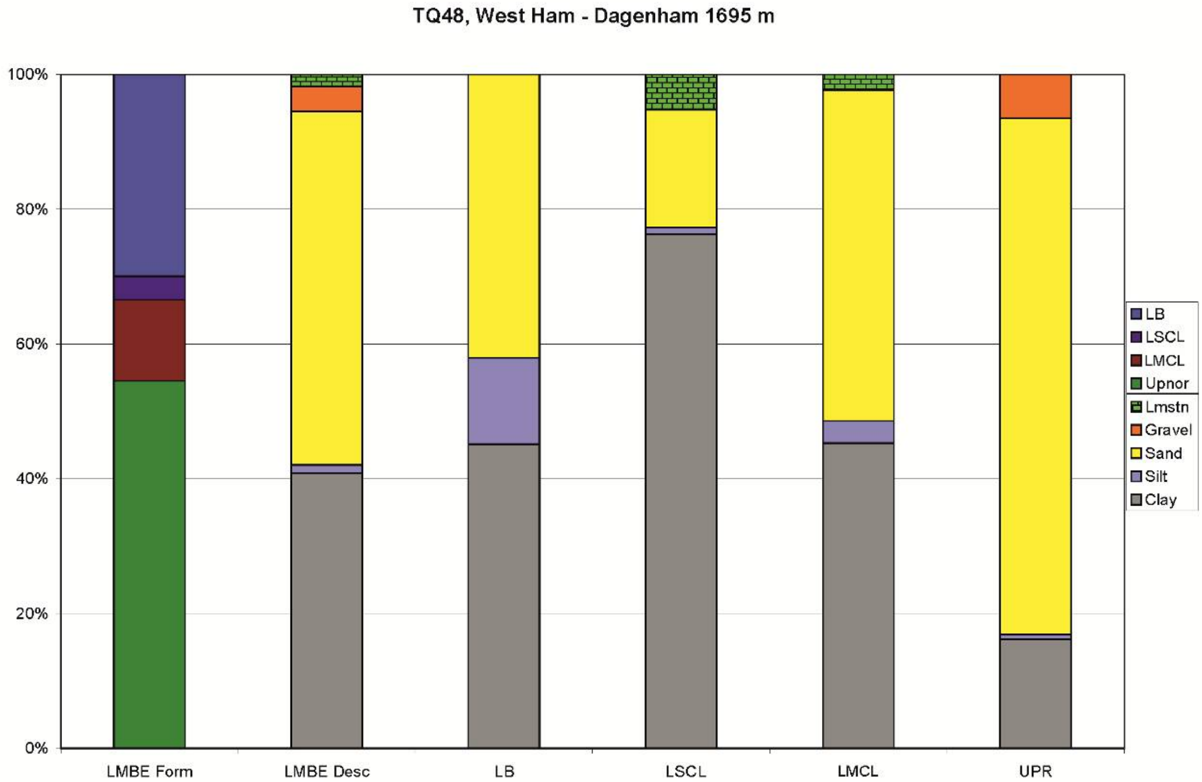
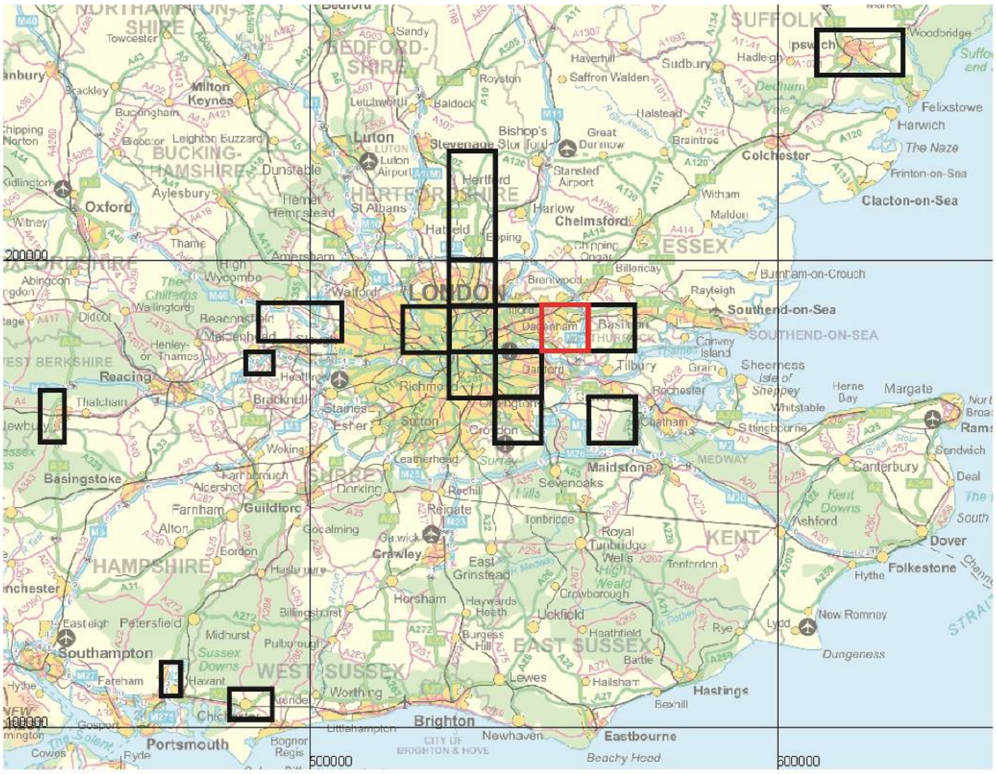


Figure A.3. 14. TQ48, West Ham - Dagenham.



TQ58, Rainham - Aveley, 679 m

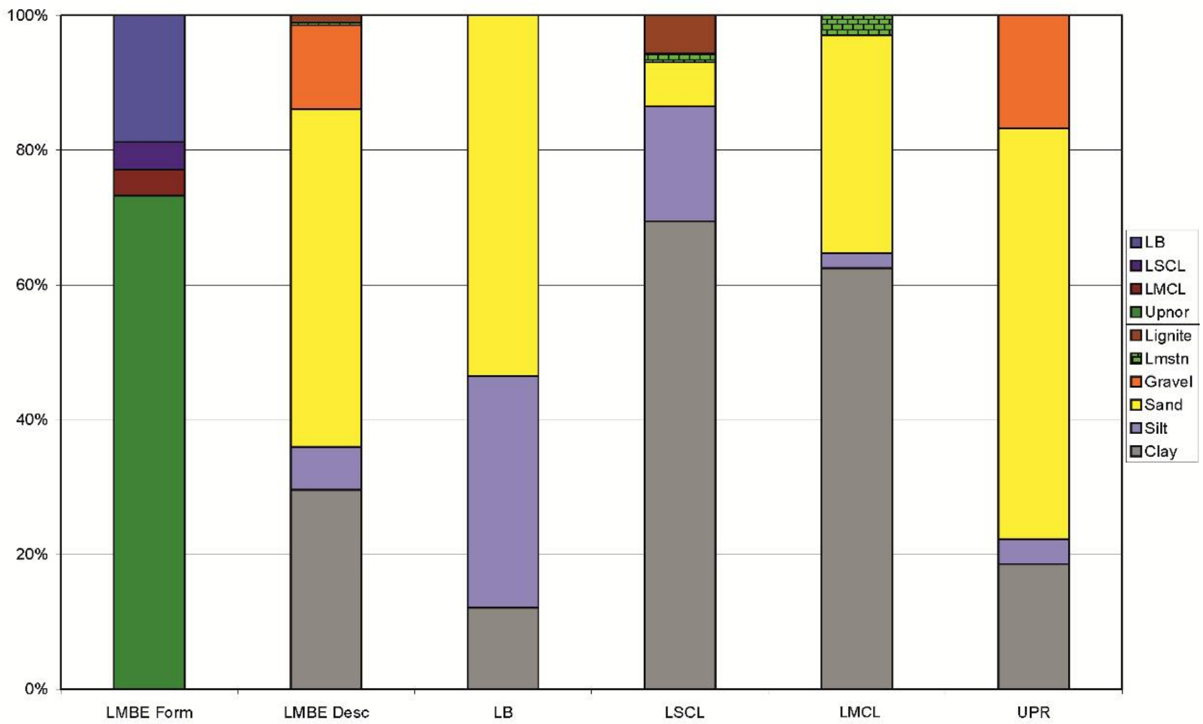
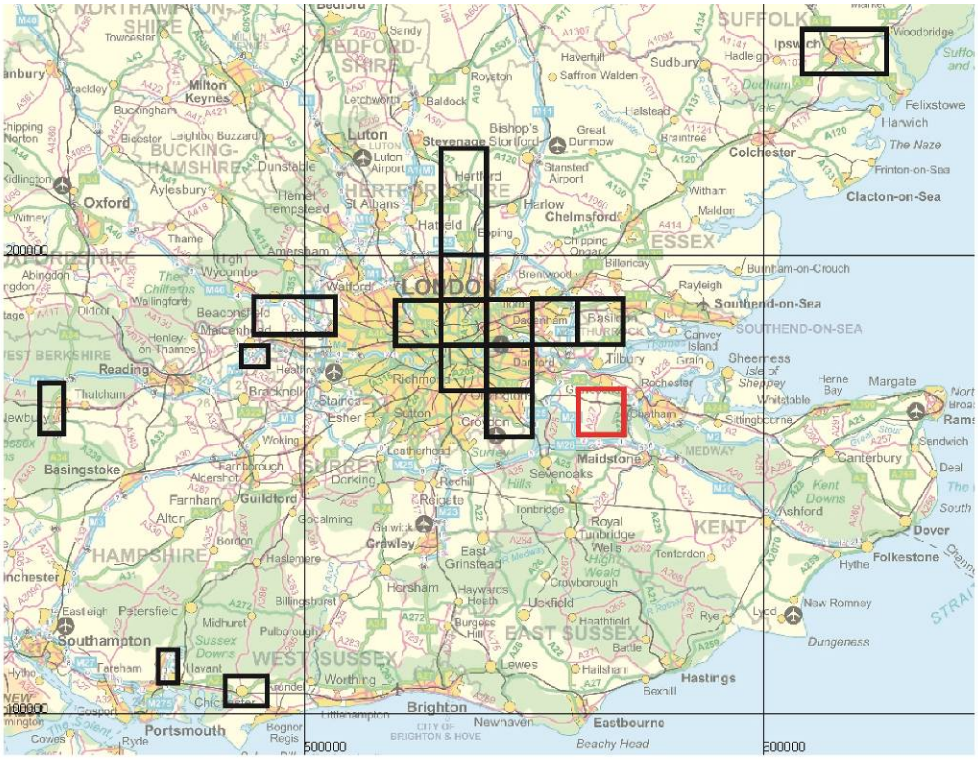


Figure A.3. 15. TQ58, Rainham - Aveley.



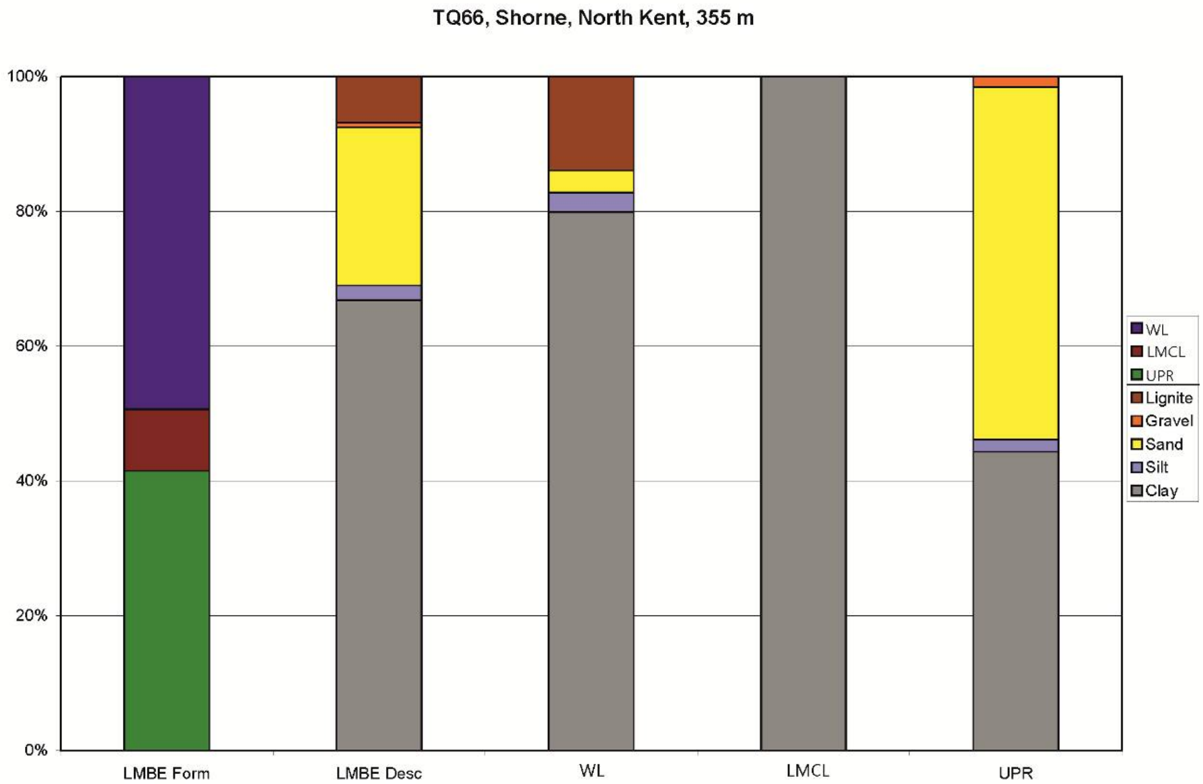
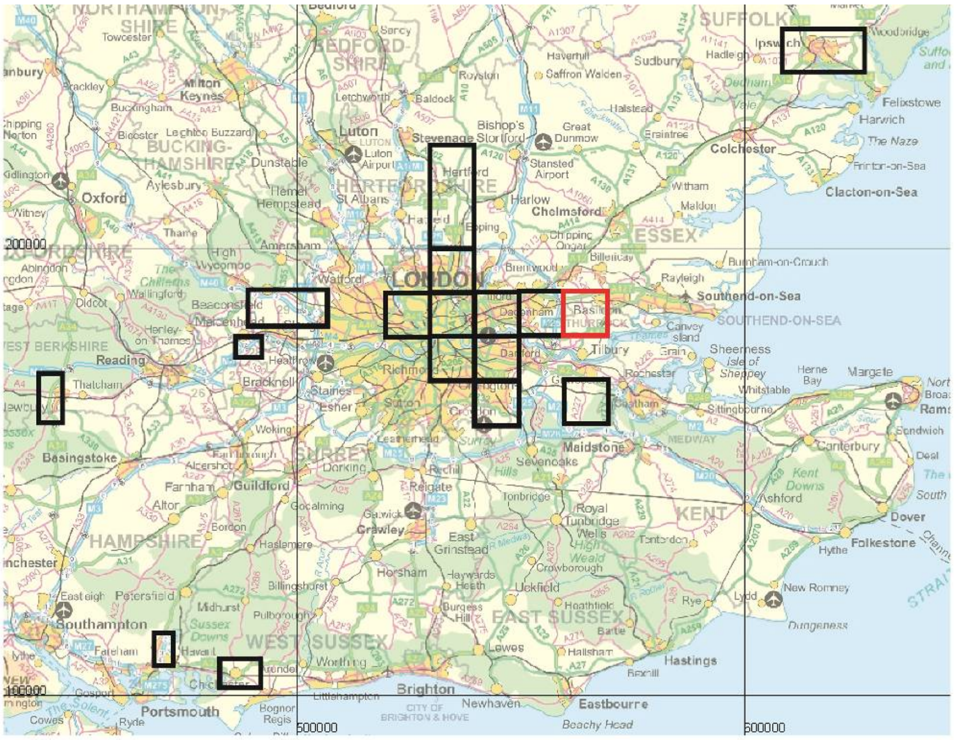


Figure A.3. 16. TQ66, South of Shorne, North Kent.



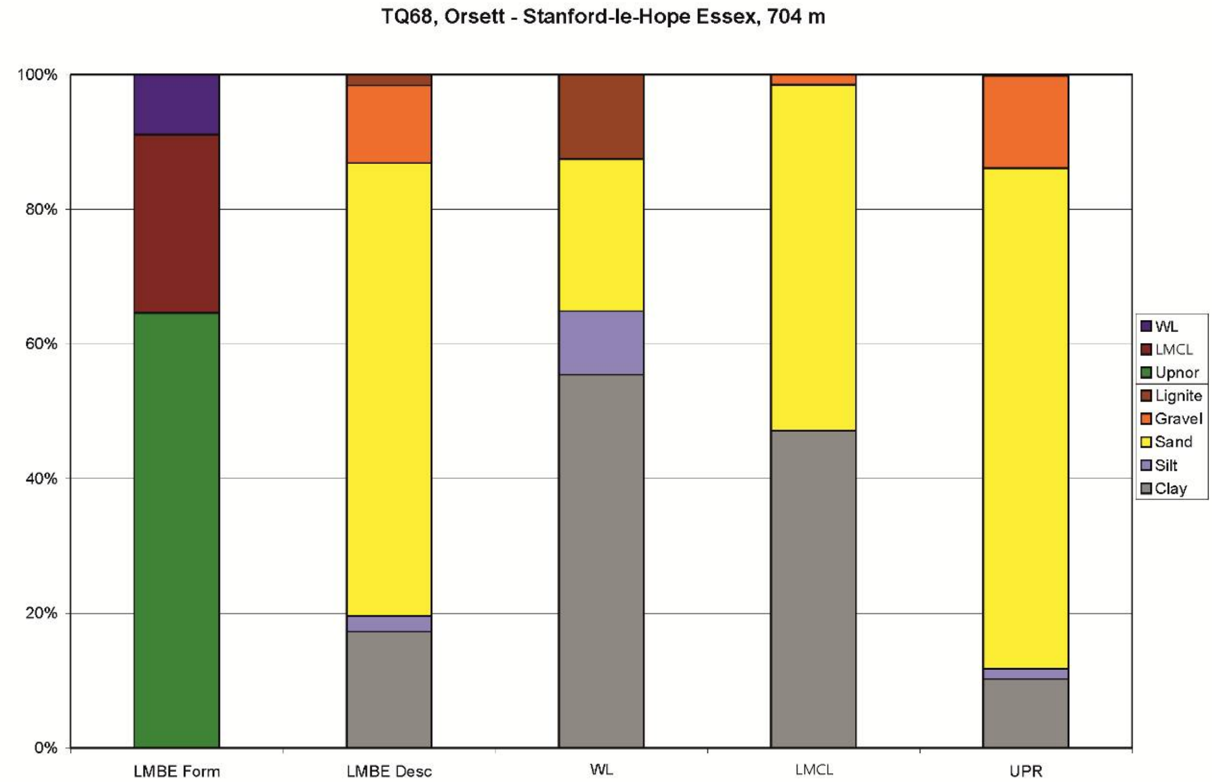


Figure A.3. 17. TQ68, Orsett - Stanford-le-Hope.

Appendix 4. Geophysical techniques:

RESISTIVITY

The electrical properties of earth materials are dependent on porosity, saturation, pore water resistivity and clay content and functions relating to the shape of the pores and the electrical conductivity of the clay. In general, saturated rocks and soils have lower resistivity than unsaturated rocks. In most rocks and soils electric current is conducted electrolytically by the interstitial fluid, and resistivity is controlled more by porosity, and pore water conductivity than by the resistivity of the rock matrix. However, many clay minerals are capable of conducting electrons; hence the current flow through a clay layer is both electronically (via the mineral) and electrolytically (via the bound water). A relatively low clay content (<10%) can significantly reduce measured resistivity in both weathered/fractured bedrock and clay or clayey deposits. Because of these phenomena the resistivity of rocks and minerals display a wide range that is unmatched by any other physical property.

Two resistivity survey modes are possible:

i) Conventional resistivity-depth soundings or 'vertical electrical sounding' (VES) is carried out using either Schlumberger, Wenner or Offset Wenner Arrays. The resistivity technique involves injecting a switched direct or low frequency current into the ground via two current electrodes. A potential difference is then measured between a pair of closely spaced inner, in line electrodes (see Kunetz 1966, Keller and Frischknecht 1966). When the current electrode separation is relatively small most of the current is constrained to flow close to the surface. By expanding the current electrode separation systematically about a fixed centre, successively deeper sections of the earth are investigated, thereby yielding a measure of the variation of resistivity with depth.

The measured resistance (voltage/current, V/I) is multiplied by a geometric factor, according to the disposition of current and potential electrodes, to give an apparent resistivity of the ground in ohm.metres (ohm.m). This represents a weighted average of the true resistivity of all lithologies through which the current passes.

The apparent resistivity sounding data are analysed in terms of a layered earth (1-D) model comprising a series of resistivities and comparable depths, or layer thicknesses. Automatic computer software, such as Interpex RESIX^{plus} use this initial approximate model to generate a theoretical apparent resistivity curve (Ghosh, 1971), which is then compared and matched to the observed field curve. After a series if iterations, the final interpretation will normally result in between three and five identifiable distinct electrical layers.

Apart from the assumption of lateral continuity an important problem confronting the interpreter of VES data is that of equivalent solutions. That is, a range of different arrangements of layer resistivity and thickness will yield very similar sounding curves. There is also a limited ability to resolve thin layers. The best way to resolve these ambiguities is to incorporate local borehole control (i.e. layer thicknesses and, where available, resistivities) at the modelling stage. In the absence of such control, data from complementary techniques (e.g. EM34 ground conductivity, see below in electromagnetic methods) may be used to constrain the model. A series of interpreted soundings can be combined to construct a geoelectrical section.

A further difficulty with VES interpretation could result from the lack of clearly defined resistivity contrast of the lithologies present. For example, there may be considerable overlap in the range of resistivities displayed by gravels (dry and saturated) and weathered bedrock.

Better results are obtained if resistivity measurements are positioned parallel to the geological strike and away from services such as water mains and metal fences. In addition measurements along the sides of roads invariably produce poor results (Anon, 1988, McDowell, *et al*., 2002).

ii) The resistivity tomography technique is useful for investigating areas of complex geology where the use of resistivity depth soundings and other techniques are unsuitable. The method is used to characterise vertical and lateral changes in subsurface electrical properties, by means of automated resistivity tomography or imaging technique. The main advantage results from an increase in resistivity information from the underlying strata, which can be plotted and interpreted in the form of a 2D section.

A 2D resistivity image is measured by moving the electrodes along a profile, whilst maintaining a constant separation between them. By repeating the profile at increasing electrode spacing or 'n' levels increases the depth of investigation and thus resulting values of apparent resistivity can be plotted against distance.

The pseudo-section is processed and inverted using a commercial software package, such as RES2DINV (Loke 1997, 1999, Loke and Barker, 1996b) for 3D inversions. This results in a colour contoured section, which reflects the qualitative spatial variation of true resistivity across the section.

ELECTROMAGNETICS

The electrical conductivity of the ground is determined by its response to an induced magnetic field. The technique (a variation of the conventional Slingram method) measures the terrain conductivity by passing an alternating current through a transmitter coil placed on or near the ground. This current produces a primary magnetic field that induces small currents in conductors in the underlying strata. These currents, in turn, produce a secondary magnetic field, which is sensed by the receiver coil together with the primary signal. The resultant field will have the same frequency as the primary field but, in general, not the same phase or direction. The ratio of the secondary to the primary field is approximately linearly proportional to terrain conductivity at low values of terrain conductivity, which, therefore, permits a direct readout at the instrument of apparent conductivity in milliSiemens per metre (mS/m). These readings are referred to the mid-point between the two coils. Resistivity (in ohm.m) is the reciprocal of conductivity (S/m) e.g.. 100 ohm.m = 10 mS/m; hence the two parameters are comparable and readily convertible.

As it is an induction method there are no grounded electrodes, and the problems of contact resistance, which can occur in galvanic resistivity prospecting, are avoided.

The Geonics EM31 and EM34 are non-contacting terrain conductivity meters, which operates on the principles of electromagnetic induction as described by McNeill (1980a). The EM34 is a two-man operation using two separate coils linked by a reference cable with measurements taken for coil operations of 10, 20 and/or 40 m length. McNeill (1980b) defines the depth range as 0.75 and 1.5 times the coil separation in a homogenous and conductive layer. Although this condition is rarely met, the effective penetration will be an average value. Hence, when operated in the vertical coil (Horizontal dipole) mode, approximate depths of investigations are 7.5 m, 15 m, and 30 m respectively. Similarly, there is a substantial increase in the depth of investigation when operated in the horizontal coil (vertical dipole) mode of approximately 15 m, 30 m and 60 m respectively.

The EM31 is operated by one man and comprises a transmitter and receiver coil at the end of a 3.66 m rigid boom, whilst a central console houses an analogue meter and data logger. The instrument is normally supported across the shoulder of the observer with measurements taken at waist height (approximately 1 m). When the boom is rotated from the vertical to horizontal coil position, (horizontal to vertical to dipole) the depth of investigation increases from approximately 3 m to 6 m respectively.

SEISMIC TECHNIQUES

The seismic methods (reflection and refraction) are the most effective and by far the most expensive of all the standard geophysical techniques. In the seismic method, an elastic pulse or a more extended elastic vibration is generated at shallow depth and the resulting motion of the ground at nearby points on the surface is detected by small seismometers or 'geophones'. Measurements of the travel-time of the pulse to geophones at various distances give the velocity of propagation of the pulse in the ground.

The ground is generally not homogeneous in its elastic properties, and this velocity will, therefore, vary both with depth and laterally. Where the structure of the ground is simple the values of elastic wave velocity and the positions of boundaries between regions of differing velocity can be calculated from the measured time intervals. 'Velocity' boundaries coincide with physical changes in the ground; usually coincide with geological boundaries and a cross-section on which velocities interfaces are plotted may, therefore, resemble the geological cross-section, although the two are not necessarily the same (Griffiths and King, 1981).

Seismic methods are of major importance in the fields of engineering site investigation and hydrogeology, where depths of interest lie in the range 10 – 200 m. Seismic refraction surveys are used for estimating the depth of high-velocity 'bedrock' or of a well defined water table, in addition to evaluating the mechanical and hydrogeological properties (degree of fracturing, porosity, degree of saturation etc.) of a concealed foundation material or aquifer.

ii) The Surface Wave Survey Method

When seismic waves are generated, there is a special type of wave propagating along the free surface called surface waves whose penetration depth is wavelength-dependent; the longer wavelength influences the deeper portion of the earth. Because of this property, surface waves are usually dispersive, meaning different frequencies have different propagation velocities, whereas body waves (refraction, reflection, head, etc., waves) rarely take such property to a noticeable extent. Two types of surface waves are generally known: Rayleigh and Love waves. The disturbance (vibration) direction of the former is mainly perpendicular to the surface, whereas it is parallel for the latter. Theoretically, the dispersion property of surface waves is determined by several elastic properties including density (rho), and depth-variation of S- and P-wave velocities (Vs and Vp). Among these parameters, the depth-variation of Vs is the most influencing factor. Because of this, surface waves are often used to deduce Vs properties of near-surface earth materials. In comparison to using conventional body-wave methods to achieve similar Vs information (for example, S-wave refraction, reflection, down-hole, cross-hole surveys), the surface-wave method has several advantages:

- Field data acquisition is very simple and tolerant because surface waves always take the **strongest energy**.
- The data processing procedure is relatively simple and easy even for the non-experienced.
- A large area can be covered within a relatively short time period.
- Because of all above reasons, it is highly cost effective and time efficient.

Utilization of surface waves for geotechnical engineering purposes has a history dating back to the early 1950s. Since the early 2000s a multichannel approach called the MASW (multichannel analysis of surface waves) method has been widely used (Park *et al*., 1999, 2007).

GROUND PENETRATING RADAR

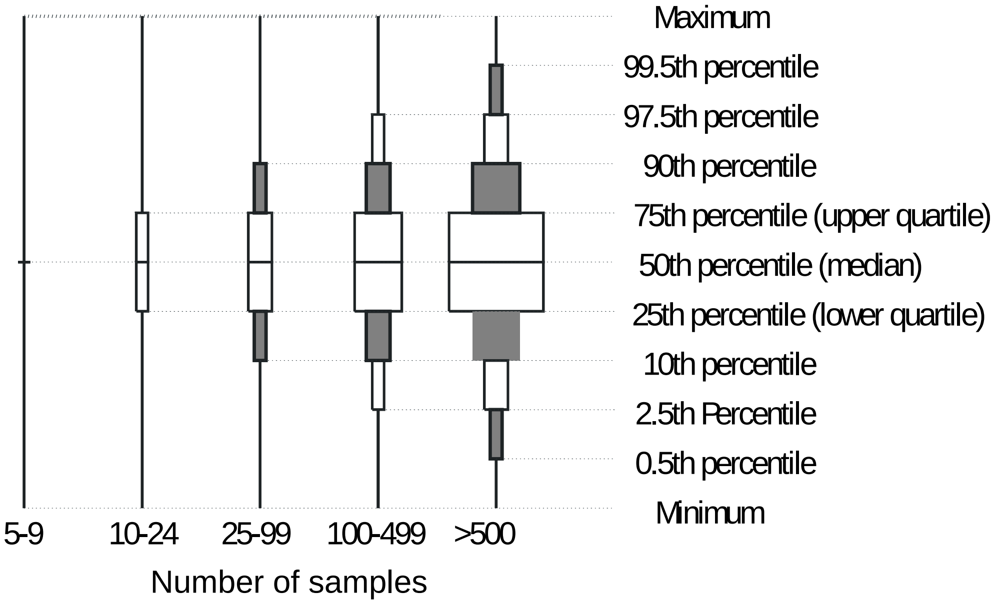
The GPR technique is similar in principle to sonar methods. The radar transmitter produces a short pulse of high frequency (25-1000 MHz) electromagnetic (EM) energy, which is transmitted into the ground through an antenna. Reflections are generated in the ground by changes in electrical impedance, which is dominated by changes in the relative permittivity or dielectric constant (K) of the ground. These reflections are subsequently detected at the ground surface by another antenna attached to the receiver unit. In general, the strength of the reflected signals is proportional to the degree of contrast of dielectric properties across the interface, the larger the contrast the stronger the signal reflected back to the ground surface (Davis and Annan 1989).

The results are plotted in section form as two way travel time (TWT) (i.e. the time taken for passage of the signal from transmitter to reflecting horizon and back to the receiver) against traverse position. The distance in metres is shown along the top of the profile section, whilst the left hand vertical axis indicates the TWT in nanoseconds (ns). The corresponding right hand vertical axis shows the depth in metres, derived from an average EM transmission velocity value for limestone of 0.1 metres/nanosecond (m/ns). It should be noted that ground surface is represented by the first thick black line of radar reflections.

Appendix 5. Extended box and whisker plots

Appendix 5 (Figures) App5.	Figure title
1	Water content
2	Bulk density
3	Dry density
4	Particle density
5	Liquid limit
6	Plastic limit
7	Plasticity index
8	Liquidity index
9	Total sulphate
10	Aqueous soluble sulphate
11	pH
12	Undrained triaxial shear strength
13	Standard penetration test - All
14	Standard penetration test – Coarse-grained materials

Key to 'Extended Box and Whisker' plots



Key to abbreviations

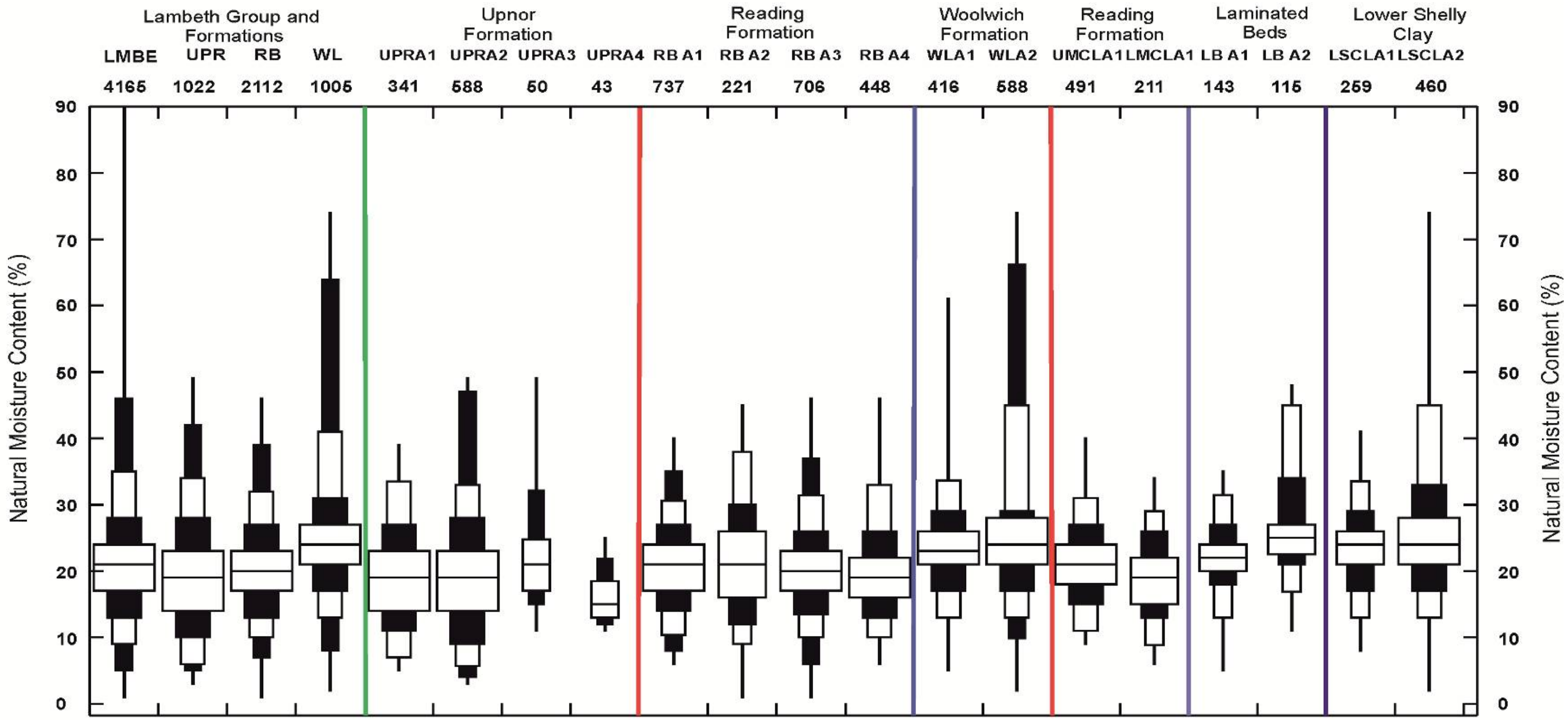
LMBE	Lambeth Group
WL	Woolwich Formation
LB	Laminated Bed
LSCL	Lower Shelly Clay
RB	Reading Formation
UMCL	Upper Mottled Clay
LMCL	Lower Mottled Clay
MCL	Mottled Clay

Area designations take the following form for instance in Area 1.

UPRA1	Upnor Formation in Area 1
RB1	Reading Formation in Area 1
WL A1	Woolwich Formation in area 1
UMCLA1	Upper Mottled Clay in Area 1
LMCLA1	Lower Mottled Clay in Area 1
LB A1	Laminated Beds in Area 1
LSCLA1	Lower Shelly Clay in Area 1

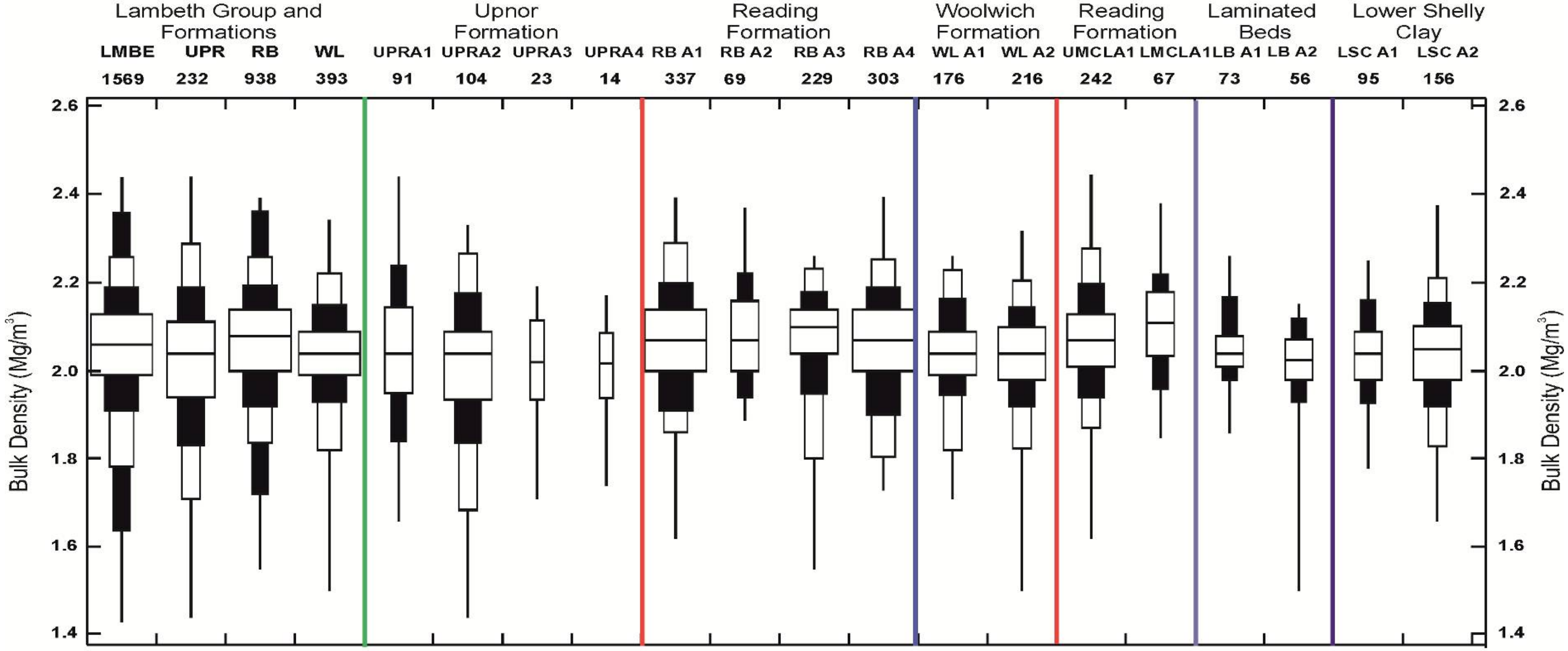
A5.1. Water content, w, (%)

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled B	Lower Mottled B	Laminated Beds		Lower Shelly Clay	
Area					Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Code	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WL A1	WL A2	UMCLA1	LMCLA1	LB A1	LB A2	LSCLA1	LSCLA2
No. of values	4165	1022	2112	1005	341	588	50	43	737	221	706	448	416	588	491	211	143	115	259	460
Minimum	1.0	3.0	1.0	2.0	5.0	3.0	11.0	11.0	6.0	1.0	1.0	6.0	5.0	2.0	9.0	6.0	5.0	11.0	8.0	2.0
0.005	5.0	5.0	7.0	8.0		4.0			8.0		6.0			9.9						
0.025	9.0	6.0	10.0	13.0	7.0	5.7			10.4	9.0	10.0	10.0	13.0	13.0	11.0	8.9	13.0	16.9	13.0	13.0
0.1	13.0	10.0	13.0	17.0	11.0	9.0	15.0	12.0	14.0	12.0	13.5	13.0	17.0	17.0	15.0	13.0	18.0	21.0	17.0	17.0
0.25	17.0	14.0	17.0	21.0	14.0	14.0	17.0	13.0	17.0	16.0	17.0	16.0	21.0	21.0	18.0	15.0	20.0	22.5	21.0	21.0
0.5	21.0	19.0	20.0	24.0	19.0	19.0	21.0	15.0	21.0	21.0	20.0	19.0	23.0	24.0	21.0	19.0	22.0	25.0	24.0	24.0
0.75	24.0	23.0	23.0	27.0	23.0	23.0	24.8	18.5	24.0	26.0	23.0	22.0	26.0	28.0	24.0	22.0	24.0	27.0	26.0	28.0
0.9	28.0	28.0	27.0	31.0	27.0	28.0	32.1	21.8	27.0	30.0	26.0	26.0	29.0	29.0	27.0	26.0	27.0	34.0	29.0	33.0
0.975	35.0	34.0	32.0	41.0	33.5	33.0			30.6	38.0	31.4	33.0	33.6	45.0	31.0	29.0	31.5	45.0	33.6	45.0
0.995	46.0	42.0	39.0	63.9		47.1			35.0		37.0			66.2						
Maximum	74.0	49.0	46.0	74.0	39.0	49.0	49.0	25.0	40.0	45.0	46.0	46.0	61.0	74.0	40.0	34.0	35.0	48.0	41.0	74.0
Mean	20.9	19.0	20.2	24.3	19.1	19.0	22.5	16.1	20.5	21.1	20.0	19.5	23.1	25.2	21.0	18.9	22.2	25.7	23.4	25.1



A5.2. Bulk Density, ρ, (Mg/m^3)

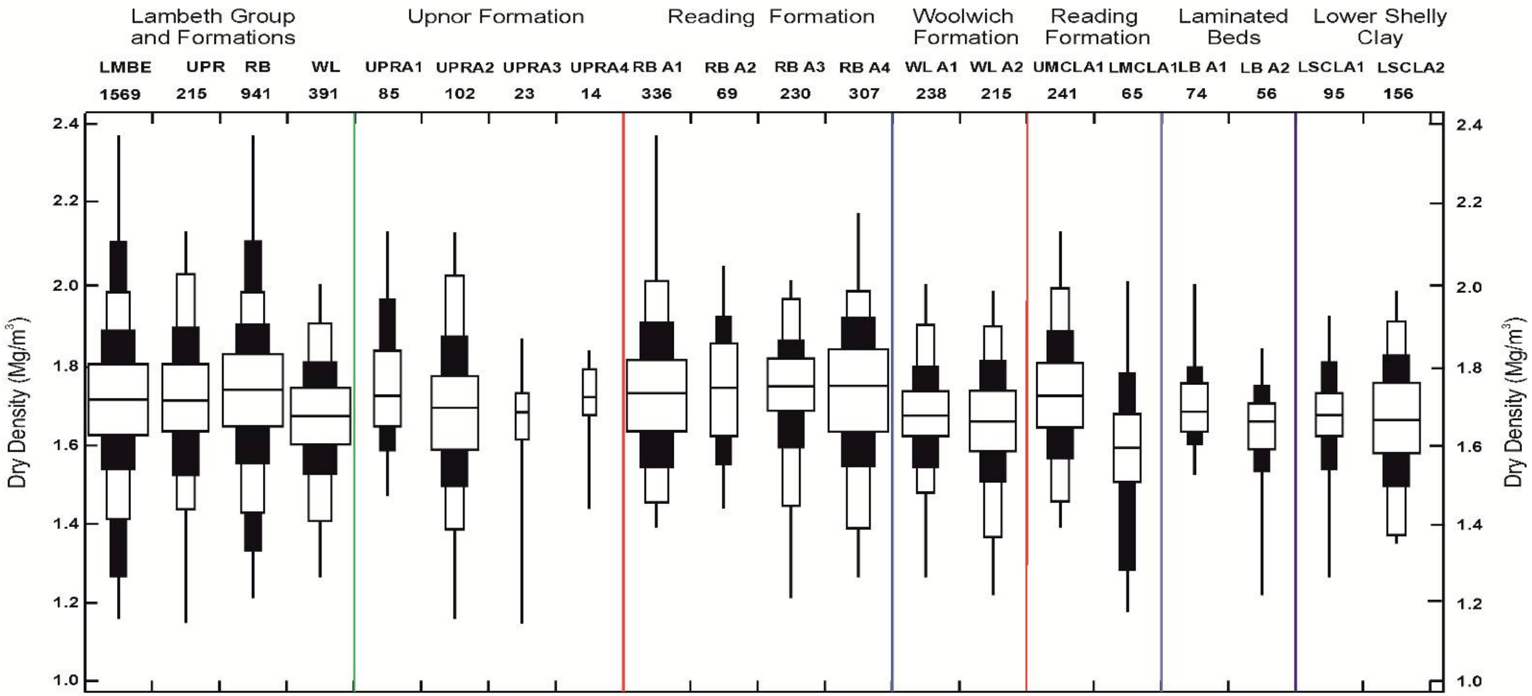
Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled B	Lower Mottled B	Laminated Beds		Lower Shelly Clay	
Area					Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Stats	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WL1	WL2	UMCL	LMCL	LB A1	LB A2	LSCLA1	LSCLA2
Count	1569	232	938	393	91	104	23	14	337	69	229	303	176	216	242	56	73	56	95	156
Min	1.430	1.440	1.550	1.500	1.660	1.440	1.710	1.740	1.620	1.890	1.550	1.730	1.710	1.500	1.620	1.500	1.860	1.660	1.780	1.660
0.005	1.637		1.720																	
0.025	1.782	1.708	1.835	1.820		1.683			1.860		1.801	1.804	1.819	1.824	2.068					1.829
0.1	1.910	1.831	1.920	1.930	1.840	1.836			1.910	1.940	1.948	1.900	1.945	1.920	1.746	1.930	1.889	1.920	1.780	1.920
0.25	1.990	1.940	2.000	1.990	1.950	1.935	1.935	1.939	2.000	2.000	2.040	2.000	1.990	1.980	1.870	1.980	1.940	1.980	1.800	1.983
0.5	2.060	2.040	2.080	2.040	2.040	2.040	2.020	2.018	2.070	2.070	2.100	2.070	2.040	2.040	1.940	2.025	1.980	2.050	1.928	2.050
0.75	2.130	2.113	2.140	2.090	2.145	2.090	2.115	2.087	2.140	2.160	2.140	2.141	2.090	2.100	2.010	2.073	2.013	2.103	1.980	2.100
0.9	2.190	2.190	2.194	2.150	2.240	2.177			2.200	2.222	2.180	2.190	2.165	2.145	2.070	2.120	2.040	2.155	2.040	2.153
0.975	2.260	2.290	2.260	2.222		2.267			2.292		2.233	2.255	2.230	2.206	2.130					2.212
0.995	2.360		2.363																	
Max	2.660	2.440	2.660	2.630	2.440	2.330	2.190	2.170	2.660	2.370	2.260	2.440	2.260	2.630	2.270	2.150	2.204	2.630	2.230	2.630
Mean	2.053	2.021	2.070	2.037	2.038	2.011	2.007	2.006	2.067	2.084	2.080	2.061	2.041	2.035	2.354	2.019	2.245	2.042	2.250	2.042



A5.3. Dry density, ρ_D, (Mg/m^3)

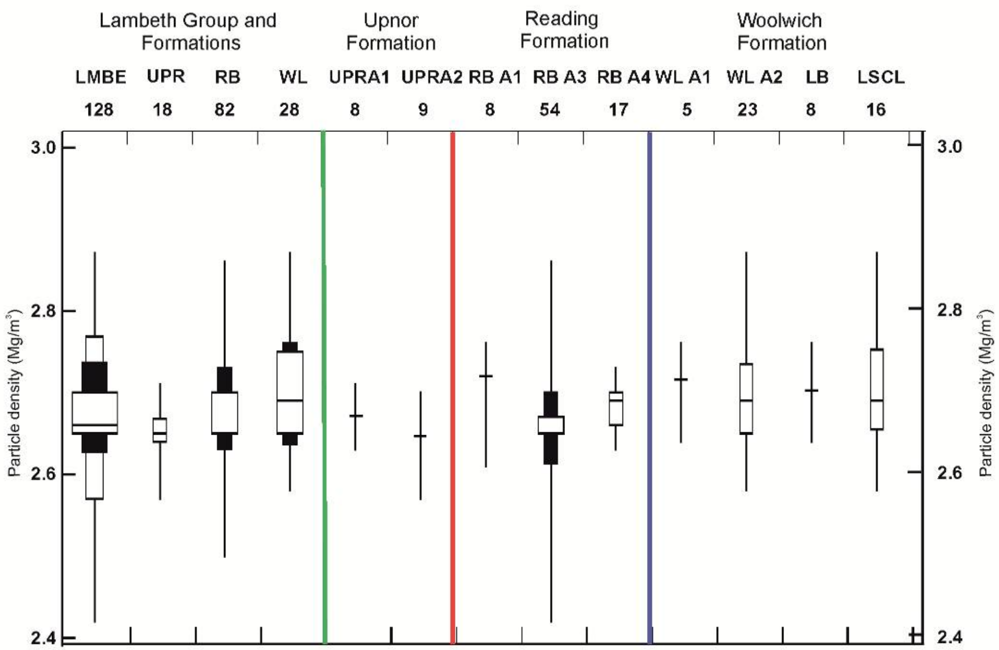
Stratigraphy / Area	All	Upnor F	Reading F	Woolwich F	Upnor Formation Area 1	Upnor Formation Area 2	Upnor Formation Area 3	Upnor Formation Area 4
Stats	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3	UPRA4
Count	1569	215	941	391	85	102	23	14
Min	1.158	1.148	1.211	1.265	1.469	1.158	1.148	1.438
0.005	1.265		1.329					
0.025	1.409	1.433	1.426	1.404		1.383		
0.1	1.534	1.520	1.551	1.523	1.583	1.492		
0.25	1.621	1.630	1.642	1.598	1.642	1.584	1.610	1.671
0.5	1.711	1.708	1.736	1.669	1.720	1.690	1.678	1.718
0.75	1.800	1.800	1.826	1.740	1.833	1.770	1.727	1.788
0.9	1.885	1.892	1.900	1.805	1.963	1.870		
0.975	1.982	2.027	1.982	1.903		2.024		
0.995	2.109		2.110					
Max	2.375	2.132	2.375	2.000	2.132	2.130	1.862	1.832
Mean	1.709	1.710	1.730	1.664	1.748	1.686	1.633	1.701

Stratigraphy / Area	Reading Formation Area 1	Reading Formation Area 2	Reading Formation Area 3	Reading Formation Area 4	Woolwich Formation Area 1	Woolwich Formation Area 2	Upper Mottled C Area 1	Lower Mottled C Area 1	Laminated Beds Area 1	Laminated Beds Area 2	Lower Shelly Clay Area 1	Lower Shelly Clay Area 2
Stats	RB1	RB2	RB3	RB4	WL1	WL2	UMCLA1	LMCLA1	LB A1	LB A2	LSCLA1	LSCLA2
Count	336	69	230	307	238	215	241	65	74	56	95	156
Min	1.390	1.439	1.211	1.265	1.265	1.219	1.390	1.176	1.523	1.219	1.265	1.350
0.005												
0.025	1.451		1.443	1.385	1.476	1.364	1.453					1.368
0.1	1.539	1.546	1.590	1.543	1.540	1.504	1.563	1.280	1.599	1.530	1.535	1.493
0.25	1.630	1.619	1.682	1.630	1.619	1.580	1.640	1.502	1.629	1.586	1.618	1.575
0.5	1.727	1.740	1.744	1.746	1.670	1.656	1.720	1.589	1.680	1.656	1.672	1.659
0.75	1.810	1.852	1.815	1.838	1.732	1.733	1.803	1.675	1.752	1.701	1.727	1.753
0.9	1.905	1.919	1.860	1.918	1.793	1.809	1.883	1.776	1.792	1.745	1.804	1.822
0.975	2.011		1.965	1.985	1.899	1.896	1.991					1.908
0.995												
Max	2.375	2.046	2.009	2.179	2.000	1.982	2.134	2.007	2.000	1.838	1.920	1.982
Mean	1.725	1.734	1.736	1.735	1.672	1.655	1.721	2.133	1.695	1.633	1.670	1.663



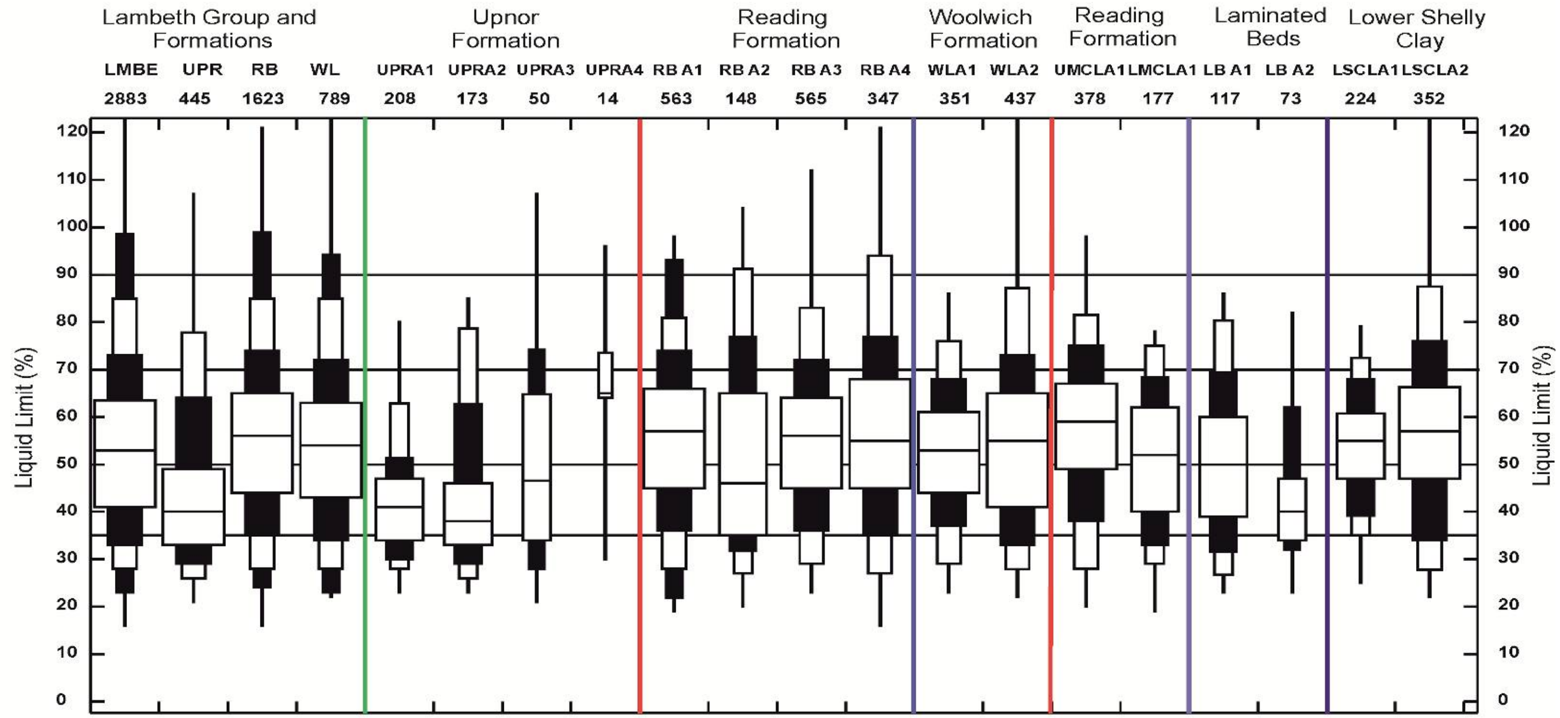
A5.4. Particle density, ρ_S, (Mg/m^3)

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation				Reading Formation				Woolwich Formation		Laminated Beds	Lower Shelly Clay
Area					Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2		
Stats	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WL1	WL2	LB	LSCL
Count	128	18	82	28	8	9	1	9	8	3	54	17	5	23	8	16
Min	2.420	2.570	2.500	2.580	2.630	2.570	2.650	1.495	2.610	2.640	2.420	2.630	2.640	2.580	2.64	2.580
0.005																
0.025	2.570															
0.1	2.627		2.631	2.637							2.613					
0.25	2.650	2.640	2.650	2.650							2.650	2.660		2.650		2.655
0.5	2.660	2.650	2.650	2.690	2.665	2.640	2.650	1.705	2.725		2.650	2.690	2.720	2.690	2.700	2.690
0.75	2.700	2.668	2.700	2.750							2.670	2.700		2.735		2.753
0.9	2.736		2.730	2.760							2.700					
0.975	2.768															
0.995																
Max	2.870	2.710	2.860	2.870	2.710	2.700		1.800	2.760	2.680	2.860	2.730	2.760	2.870	2.76	2.870
Mean	2.671	2.649	2.670	2.697	2.669	2.631		1.702	2.713	2.660	2.656	2.684	2.706	2.695		2.710



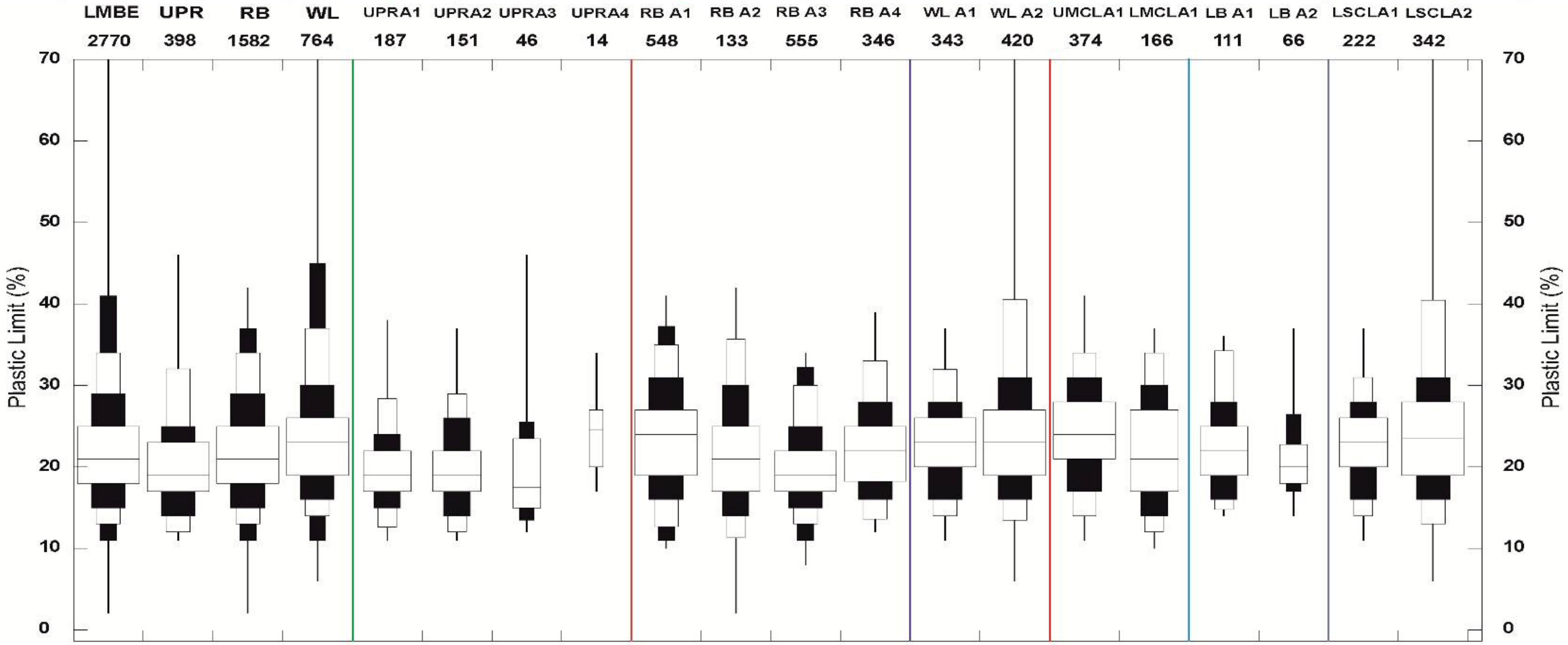
A5.5. Liquid limit, w_L, (%)

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled C	Lower Mottled C	Laminated Beds		Lower Shelly Clay	
Area					Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Code	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WL A1	WL A2	UMCLA1	LMCLA1	LB A1	LB A2	LSCIA1	LSCIA2
No. of values	2883	445	1623	789	208	173	50	14	563	148	565	347	351	437	378	177	117	73	224	352
Minimum	16.0	21.0	16.0	22.0	23.0	23.0	21.0	30.0	19.0	20.0	23.0	16.0	23.0	22.0	20.0	19.0	23.0	23.0	25.0	22.0
0.005	23.0		24.0	23.0					21.8											
0.025	28.0	26.0	28.0	28.0	28.0	26.0			28.1	27.0	29.0	27.0	29.0	27.9	28.0	29.0	26.7		35.0	27.8
0.1	33.0	29.0	35.0	34.0	30.0	29.0	27.9		36.0	31.7	36.0	35.0	37.0	33.0	38.0	33.0	31.6	32.0	39.2	34.1
0.25	41.0	33.0	44.0	43.0	34.0	33.0	34.0	64.0	45.0	35.0	45.0	45.0	44.0	41.0	49.0	40.0	39.0	34.0	47.0	47.0
0.5	53.0	40.0	56.0	54.0	41.0	38.0	46.5	65.0	57.0	46.0	56.0	55.0	53.0	55.0	59.0	52.0	50.0	40.0	55.0	57.0
0.75	63.5	49.0	65.0	63.0	47.0	46.0	64.8	73.5	66.0	65.0	64.0	68.0	61.0	65.0	67.0	62.0	60.0	47.0	60.8	66.3
0.9	73.0	64.0	74.0	72.0	51.3	62.8	74.2		74.0	77.0	72.0	77.0	68.0	73.0	75.0	68.4	69.4	62.0	68.0	76.0
0.975	85.0	77.8	85.0	85.0	62.8	78.7			80.9	91.3	83.0	94.0	76.0	87.2	81.6	75.0	80.4		72.5	87.4
0.995	98.6		98.9	94.2					93.2											
Maximum	123.0	107.0	121.0	123.0	80.0	322.0	107.0	96.0	98.0	104.0	112.0	121.0	86.0	123.0	98.0	78.0	86.0	82.0	79.0	123.0
Mean	53.0	43.2	55.2	53.7	41.4	43.4	49.6	66.9	55.8	51.1	55.2	56.1	52.5	54.5	57.8	51.4	50.2	42.9	53.9	56.6



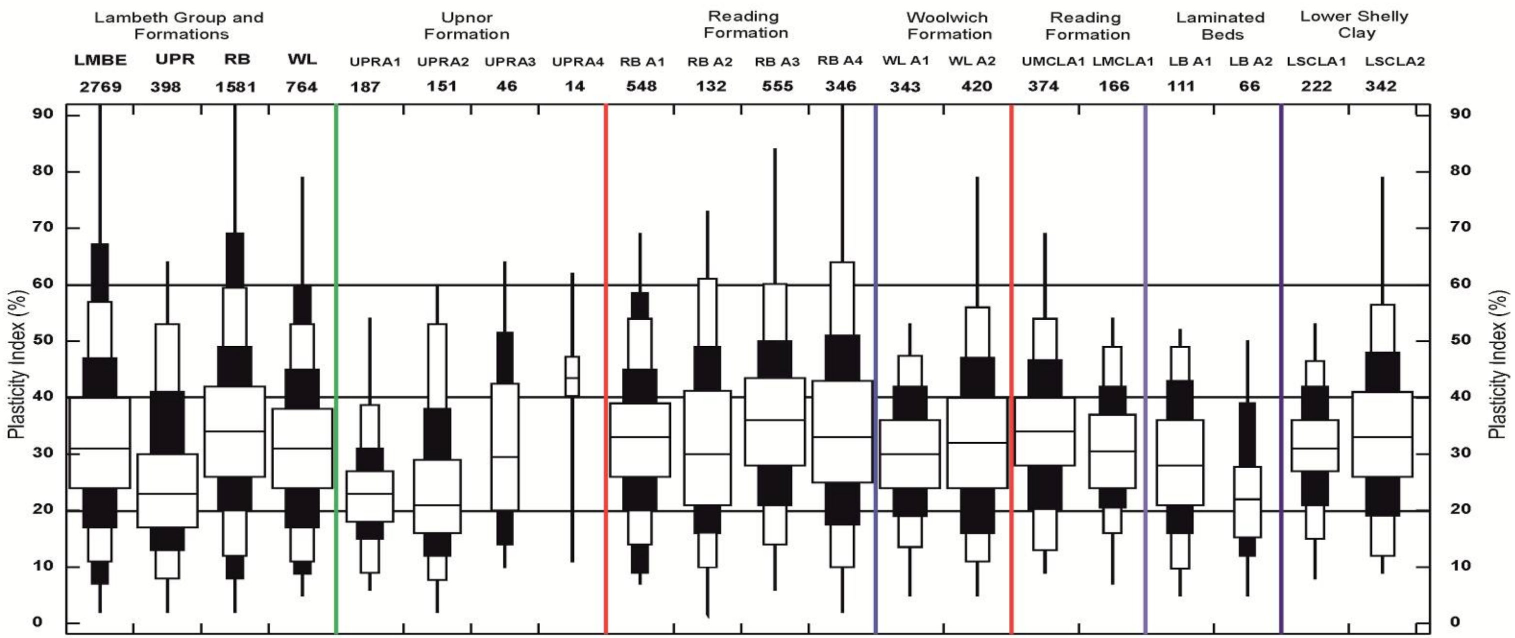
A5.6. Plastic limit, w_P, (%)

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled C	Lower Mottled c	Laminated Beds		Lower Shelly Clay	
Area					Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Code	LMBE	UPR		WL	UPR A1	UPR A2	UPR A3	UPR A4	RB A1	RB A2	RB A3	RB A4	WL A1	WL A2	UMCLA1	LMCLA1	LB A1	LB A2	LSCLA1	LSCLA2
No. of values	2770	398	1582	764	187	151	46	14	548	133	555	346	343	420	374	166	111	66	222	342
Minimum	2.0	11.0	2.0	6.0	11.0	11.0	12.0	17.0	10.0	2.0	8.0	12.0	11.0	6.0	11.0	10.0	14.0	14.0	11.0	6.0
0.005	11.0		11.0	11.0					11.0		11.0									
0.025	13.0	12.0	13.0	14.0	12.7	12.0			12.7	11.3	13.0	13.6	14.0	13.5	14.0	12.0	14.8		14.0	13.0
0.1	15.0	14.0	15.0	16.0	15.0	14.0	13.5		16.0	14.0	15.0	16.0	16.0	16.0	17.0	14.0	16.0	17.0	16.0	16.0
0.25	18.0	17.0	18.0	19.0	17.0	17.0	15.0	20.0	19.0	17.0	17.0	18.3	20.0	19.0	21.0	17.0	19.0	18.0	20.0	19.0
0.5	21.0	19.0	21.0	23.0	19.0	19.0	17.5	24.5	24.0	21.0	19.0	22.0	23.0	23.0	24.0	21.0	22.0	20.0	23.0	23.5
0.75	25.0	23.0	25.0	26.0	22.0	22.0	23.5	27.0	27.0	25.0	22.0	25.0	26.0	27.0	28.0	27.0	25.0	22.8	26.0	28.0
0.9	29.0	25.0	29.0	30.0	24.0	26.0	25.5		31.0	30.0	25.0	28.0	28.0	31.0	31.0	30.0	28.0	26.5	28.0	31.0
0.975	34.0	32.1	34.0	37.0	28.4	29.0			35.0	35.7	30.0	33.0	32.0	40.5	34.0	34.0	34.3		31.0	40.5
0.995	41.0		37.0	45.0					37.3		32.2									
Maximum	70.0	46.0	42.0	70.0	38.0	37.0	46.0	34.0	41.0	42.0	34.0	39.0	37.0	70.0	41.0	37.0	36.0	37.0	37.0	70.0
Mean	21.8	19.8	21.7	23.1	19.6	19.7	19.8	24.4	23.5	21.5	19.8	21.9	22.7	23.4	24.3	21.7	22.4	20.9	22.9	23.8



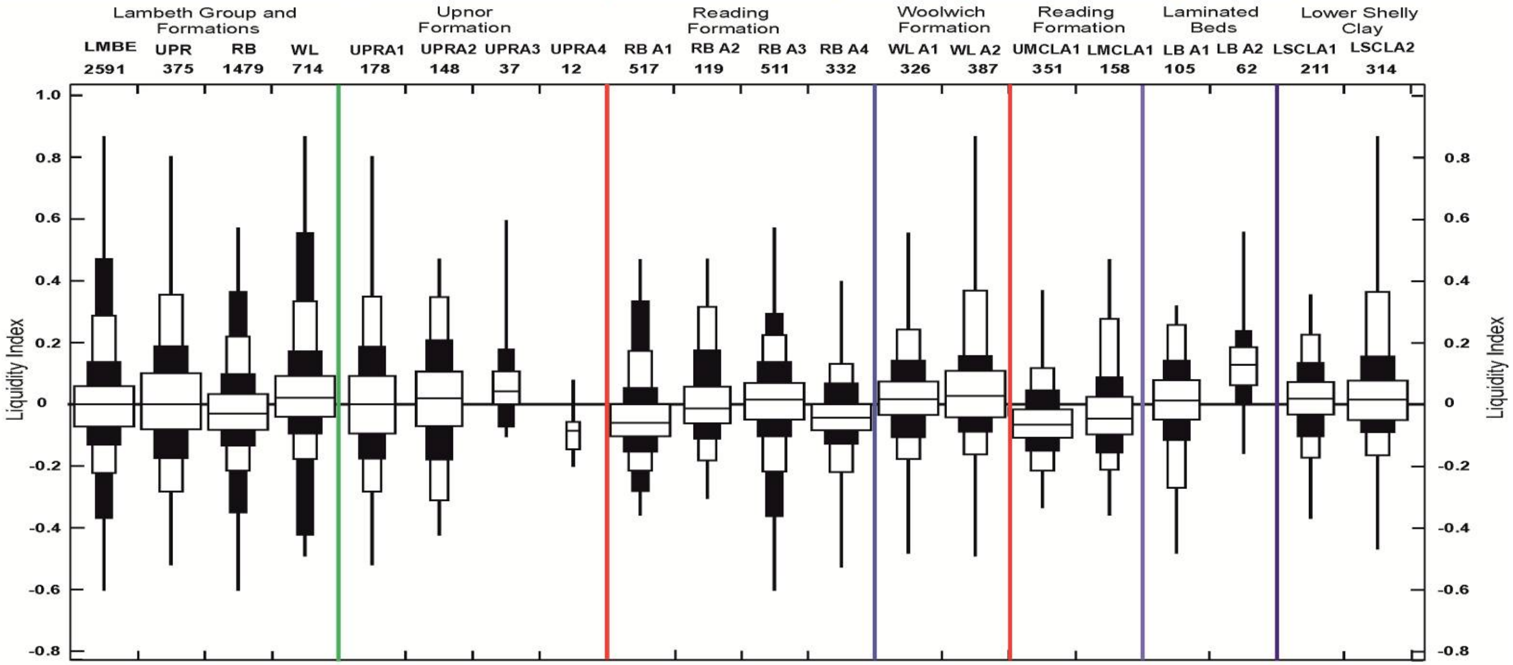
A5.7. Plasticity Index

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled B	Lower Mottled B	Laminated Beds		Lower Shelly Clay	
Area					Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Code	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WL A1	WL A2	UMCLA1	LMCLA1	LB A1	LB A2	LSCLA1	LSCLA2
No. of values	2769	398	1581	764	187	151	46	14	548	132	555	346	343	420	374	166	111	66	222	342
Minimum	2.0	2.0	2.0	5.0	6.0	2.0	10.0	11.0	7.0	7.0	6.0	2.0	5.0	5.0	9.0	7.0	5.0	5.0	8.0	9.0
0.005	7.0		8.0	8.8					9.0											
0.025	11.0	8.0	12.0	11.0	9.0	7.8			14.0		14.0	10.0	13.6	11.0	13.0	16.0	9.8		15.0	12.0
0.1	17.0	13.0	20.0	17.0	15.0	12.0	14.0		20.0	16.0	21.0	17.5	19.0	16.0	20.3	20.5	16.0	12.0	21.0	19.1
0.25	24.0	17.0	26.0	24.0	18.0	16.0	20.0	40.3	26.0	21.0	28.0	25.0	24.0	24.0	28.0	24.0	21.0	15.3	27.0	26.0
0.5	31.0	23.0	34.0	31.0	23.0	21.0	29.5	43.5	33.0	30.0	36.0	33.0	30.0	32.0	34.0	30.5	28.0	22.0	31.0	33.0
0.75	40.0	30.0	42.0	38.0	27.0	29.0	42.5	47.3	39.0	41.3	43.5	43.0	36.0	40.0	40.0	37.0	36.0	27.8	36.0	41.0
0.9	47.0	41.0	49.0	45.0	31.0	38.0	51.5		45.0	49.0	50.0	51.0	42.0	47.1	46.7	42.0	43.0	39.0	42.0	48.0
0.975	57.0	53.0	59.5	53.0	38.7	53.0			54.0		60.2	64.0	47.5	56.0	54.0	49.0	49.0		46.5	56.5
0.995	67.2		69.1	60.0					58.5		69.7									
Maximum	92.0	64.0	92.0	79.0	54.0	60.0	64.0	62.0	69.0	73.0	84.0	92.0	53.0	79.0	69.0	54.0	52.0	50.0	53.0	79.0
Mean	32.0	24.9	34.2	31.3	23.0	23.7	31.3	42.4	33.0	31.7	35.8	34.4	30.3	32.0	33.8	31.0	28.7	23.1	31.3	33.7



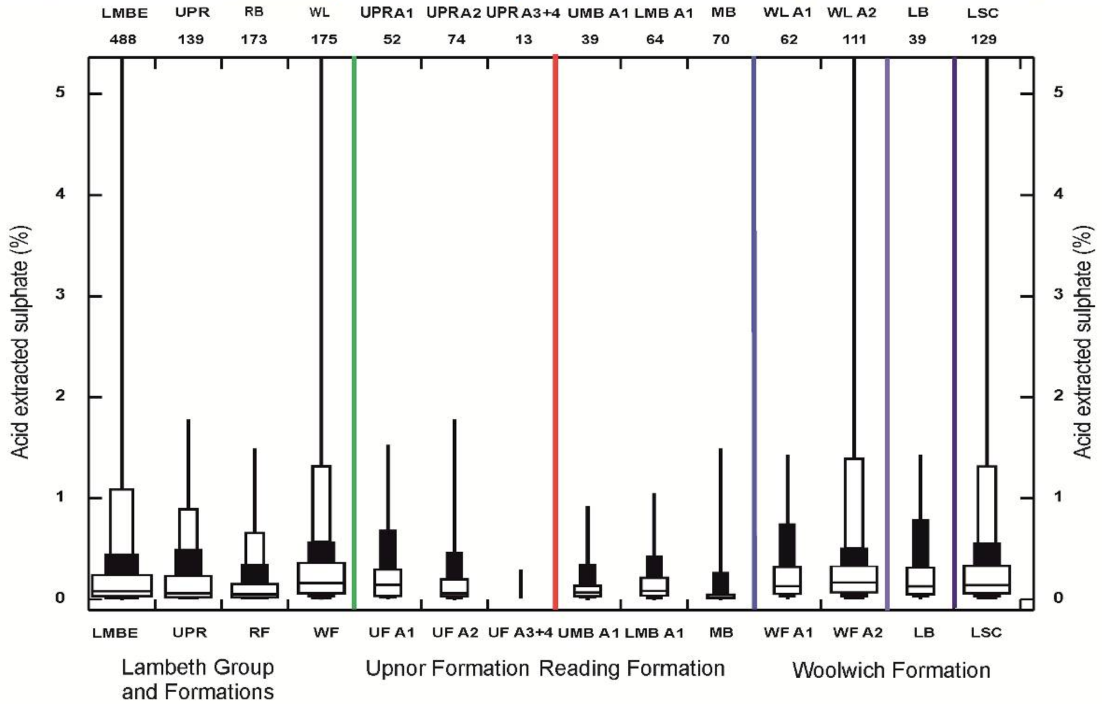
A5.8. Liquidity index, I_L

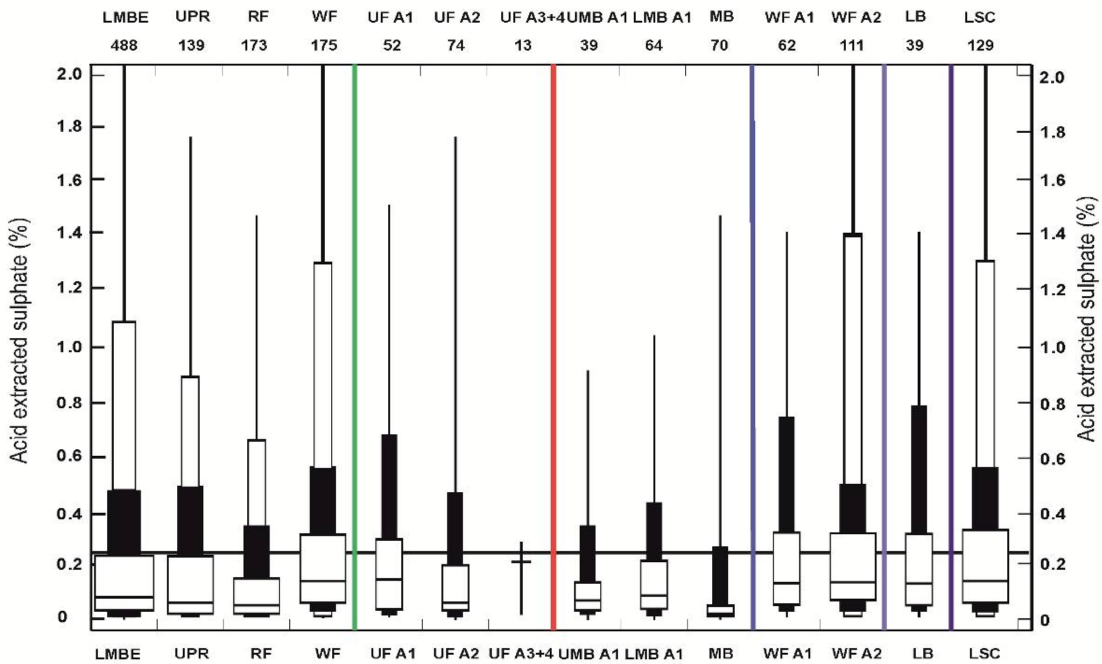
Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled C	Lower Mottled C	Laminated Beds		Lower Shelly Clay	
Area					Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Stats	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WL1	WL2	UMCLA1	LMCLA1	LB A1	LB A2	LSCIA1	LSCIA2
Count	2591	375	1479	714	178	148	37	12	517	119	511	332	326	387	351	158	105	62	211	314
Minimum	-0.60	-0.52	-0.60	-0.49	-0.52	-0.42	-0.10	-0.20	-0.36	-0.30	-0.60	-0.53	-0.48	-0.49	-0.33	-0.36	-0.48	-0.16	-0.37	-0.47
0.005	-0.37		-0.35	-0.42					-0.28		-0.36									
0.025	-0.22	-0.28	-0.22	-0.18	-0.28	-0.31			-0.22	-0.18	-0.22	-0.22	-0.18	-0.16	-0.22	-0.21	-0.27		-0.17	-0.16
0.1	-0.13	-0.17	-0.13	-0.09	-0.18	-0.18	-0.07		-0.15	-0.11	-0.10	-0.13	-0.11	-0.09	-0.15	-0.16	-0.12	0.00	-0.10	-0.09
0.25	-0.07	-0.08	-0.08	-0.04	-0.10	-0.07	0.00	-0.15	-0.10	-0.06	-0.05	-0.08	-0.04	-0.04	-0.11	-0.10	-0.05	0.06	-0.03	-0.05
0.5	0.00	0.00	-0.03	0.02	0.00	0.02	0.04	-0.09	-0.06	-0.01	0.02	-0.04	0.02	0.03	-0.07	-0.05	0.01	0.13	0.02	0.02
0.75	0.06	0.10	0.03	0.09	0.09	0.11	0.11	-0.06	0.00	0.06	0.07	0.00	0.07	0.11	-0.02	0.02	0.08	0.19	0.07	0.08
0.9	0.14	0.19	0.10	0.17	0.19	0.21	0.18		0.05	0.17	0.14	0.07	0.14	0.16	0.04	0.09	0.14	0.24	0.13	0.15
0.975	0.29	0.35	0.22	0.33	0.35	0.35			0.17	0.31	0.22	0.13	0.24	0.37	0.12	0.28	0.26		0.23	0.36
0.995	0.47		0.36	0.55					0.33	0.42	0.29									
Maximum	0.86	0.80	0.57	0.86	0.80	0.47	0.59	0.08	0.47	0.47	0.57	0.40	0.55	0.86	0.37	0.47	0.32	0.56	0.35	0.86
Mean	0.00	0.01	-0.02	0.03	0.01	0.02	0.07	-0.09	-0.05	0.01	0.01	-0.04	0.02	0.04	-0.06	-0.03	0.01	0.13	0.02	0.03



A5.9. Total sulphate, SO_{4TOT}, (%)

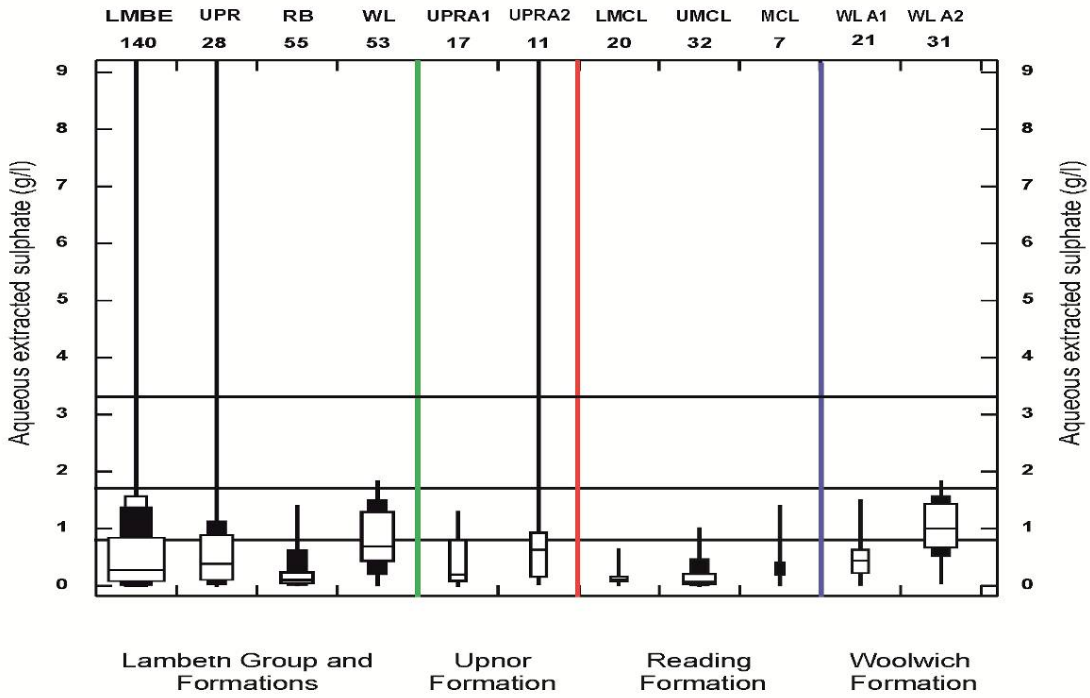
Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation			Reading Formation			Woolwich Formation		Laminated Beds	Lower Shelly Clay
					Area 1	Area 2	Area 3+4	Upper Mottled C	Lower Mottled C	Mottled C	Area 1	Area 2		
Stats	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3+4	UMCL	LMCL	MCL	WL A1	WL A2	LB	LSCL
Count	488	139	173	175	52	74	13	39	64	70	62	111	39	129
Min	0.00	0.01	0.01	0.01	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.01	0.01
0.005	0.01													
0.025	0.01	0.01	0.01	0.01								0.01		0.01
0.1	0.01	0.02	0.01	0.03	0.02	0.01		0.02	0.01	0.01	0.03	0.02	0.03	0.03
0.25	0.03	0.02	0.02	0.05	0.03	0.03	0.02	0.03	0.04	0.01	0.05	0.06	0.05	0.06
0.5	0.08	0.06	0.05	0.14	0.15	0.06	0.02	0.07	0.09	0.02	0.13	0.14	0.13	0.14
0.75	0.23	0.23	0.15	0.31	0.29	0.20	0.02	0.14	0.21	0.05	0.32	0.32	0.31	0.33
0.9	0.47	0.49	0.34	0.56	0.68	0.46		0.34	0.42	0.26	0.74	0.50	0.78	0.55
0.975	1.09	0.89	0.66	1.26								1.39		1.32
0.995	1.85													
Max	5.36	1.77	1.48	5.36	1.52	1.77	0.28	0.91	1.04	1.48	1.42	5.36	1.42	5.36
Mean	0.22	0.18	0.13	0.33	0.25	0.16	0.04	0.13	0.16	0.09	0.27	0.29	0.27	0.29

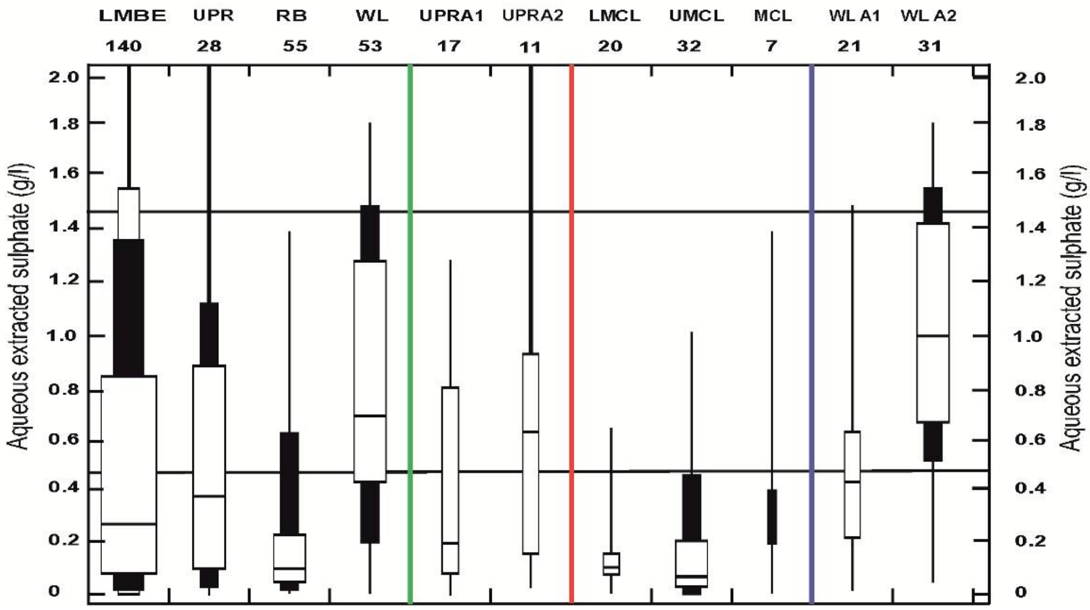




A5.10. Aqueous soluble sulphate, SO_{4aq}, (g/l)

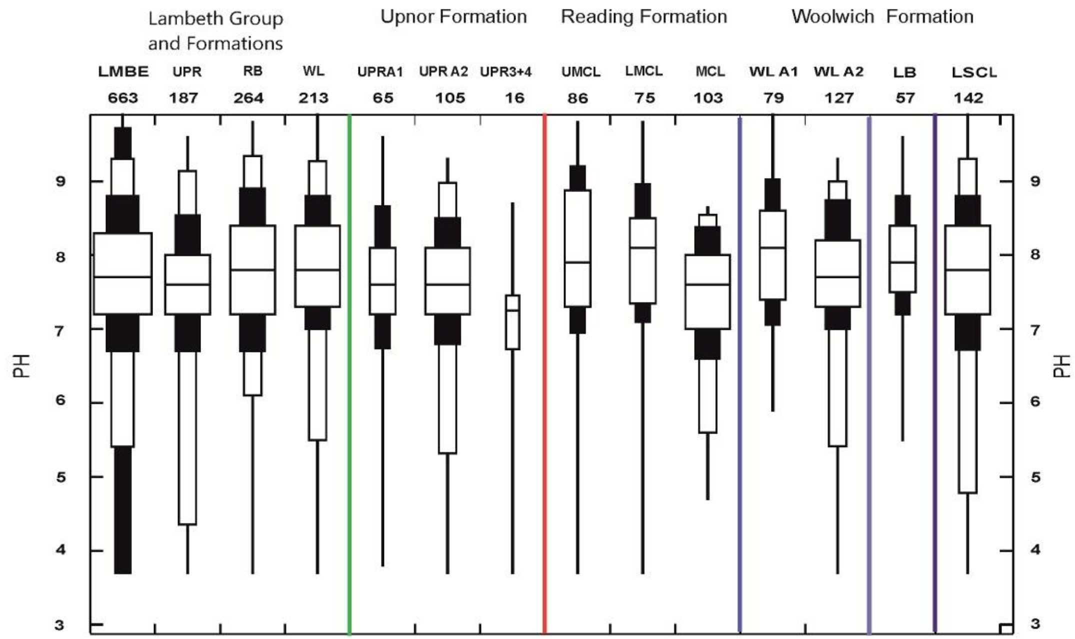
Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation Area 1		Reading Formation Lower Mottled C	Upper Mottled C	Mottled B	Woolwich Formation	
Stats	LMBE	UPR	RB	WL	UPRA1	UPRA2	UMCLA1	LMCLA1	MCL	WL A1	WL A2
Count	140	28	55	53	17	11	20	32	7	21	31
Min	0.00	0.00	0.01	0.01	0.00	0.03	0.01	0.00	0.01	0.02	0.05
0.005											
0.025	0.00							0.00			0.17
0.1	0.02	0.03	0.02	0.20	0.02	0.07		0.00		0.14	0.52
0.25	0.08	0.10	0.05	0.44	0.08	0.16	0.08	0.03		0.22	0.67
0.5	0.27	0.38	0.10	0.69	0.20	0.63	0.11	0.07	0.30	0.44	1.00
0.75	0.84	0.89	0.23	1.29	0.80	0.93	0.16	0.21		0.63	1.44
0.9	1.37	1.13	0.62	1.50	1.14	1.08		0.46		0.92	1.57
0.975	1.57							0.88			1.72
0.995											
Max	9.21	9.21	1.40	1.82	1.29	9.21	0.64	1.01	1.40	1.50	1.82
Mean	0.55	0.79	0.22	0.81	0.46	1.29	0.16	0.18	0.45	0.48	1.05





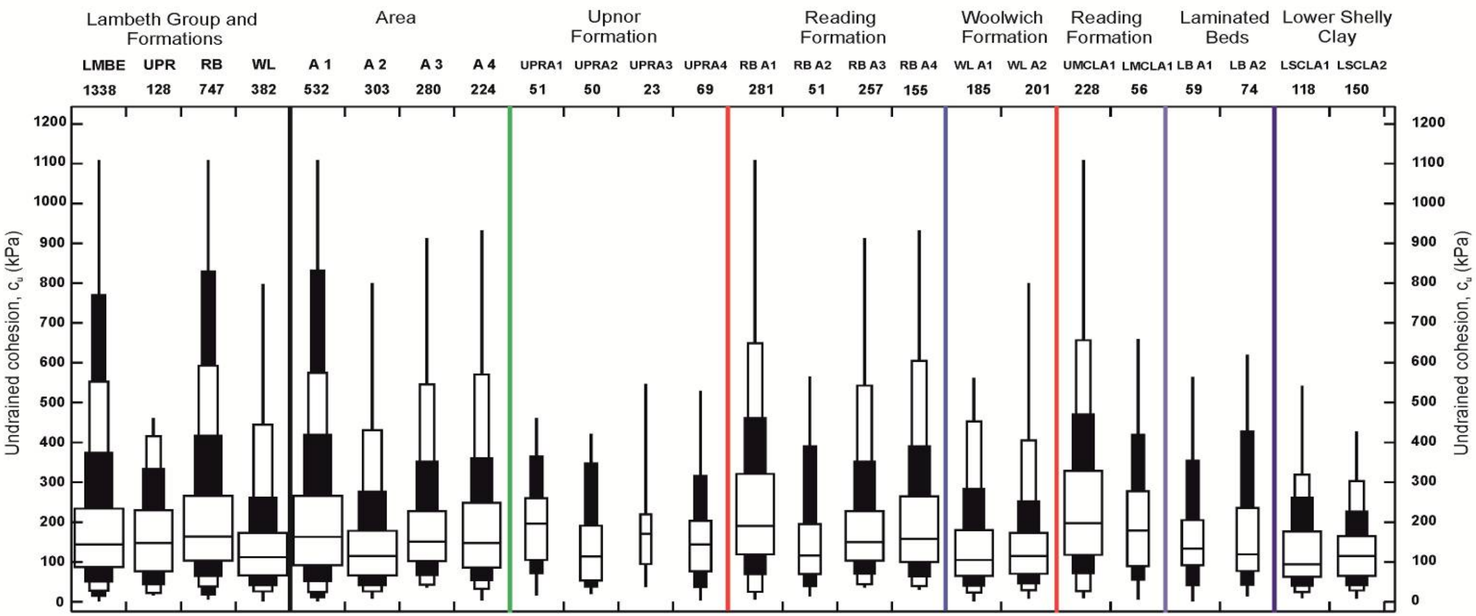
A5.11. pH

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Upnor Formation			Reading Formation			Woolwich Formation		Laminated Beds	Lower Shelly Clay
Area					Area 1	Area 2	Area 3+4	Lower Mottled C	Upper Mottled C	Mottled C	Area 1	Area 2		
Stats	LMBE	UPR	RB	WL	UPRA1	UPRA2	UPRA3+4	UMCL	LMCL	MCL	WL A1	WL A2	LB	LSCL
Count	663	186	264	213	65	105	16	86	75	103	79	127	57	142
Min	3.7	3.7	3.7	3.7	3.8	3.7	3.7	3.7	3.7	4.0	5.9	3.7	5.50	0.01
0.005	3.7					3.8							0.00	3.91
0.025	5.4	4.4	5.7	5.5	5.6	5.3				5.3		5.4	6.54	4.78
0.1	6.7	6.7	6.7	7.0	6.7	6.8		7.0	7.1	6.6	7.1	6.9	7.20	6.72
0.25	7.2	7.2	7.2	7.3	7.2	7.2	6.7	7.3	7.4	7.0	7.4	7.2	7.50	7.20
0.5	7.7	7.6	7.8	7.8	7.6	7.6	7.3	7.9	8.1	7.6	8.1	7.7	7.90	7.80
0.75	8.3	8.0	8.4	8.4	8.1	8.1	7.5	8.9	8.5	8.0	8.6	8.1	8.40	8.40
0.9	8.8	8.5	8.9	8.8	8.7	8.5		9.2	9.0	8.4	9.0	8.7	8.80	8.80
0.975	9.3	9.1	9.3	9.3		9.0				8.5		9.0	9.20	9.30
0.995	9.7												9.49	9.62
Max	9.9	9.6	9.8	9.9	9.6	9.3	8.7	9.8	9.8	8.7	9.9	9.3	9.60	9.90
Mean	7.7	7.5	7.8	7.8	7.6	7.6	6.8	8.0	8.0	7.4	8.0	7.6	7.91	7.73



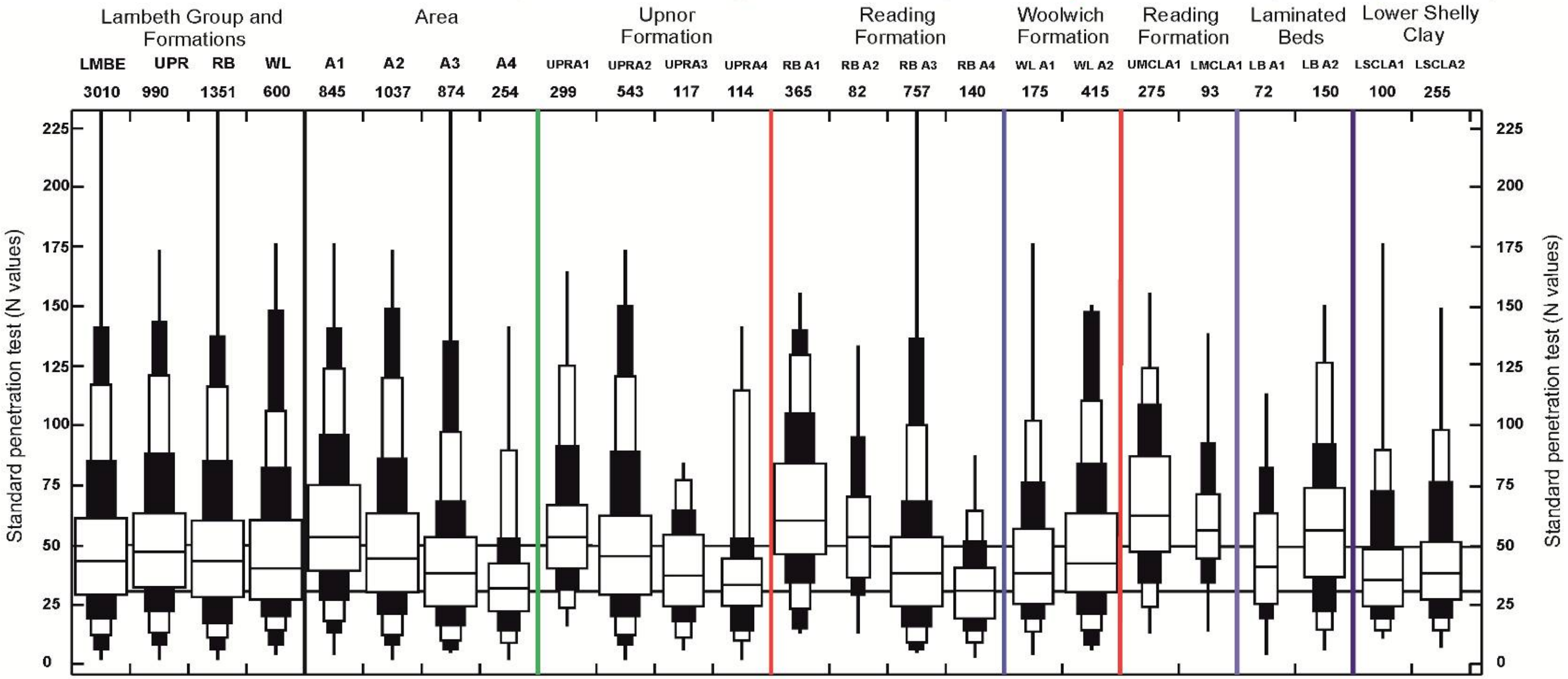
A5.12. Undrained triaxial shear strength (UU), c_u, (kPa)

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Area 1	Area 2	Area 3	Area 4	Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled C	Lower Mottled C	Laminated Beds		Lower Shelly Clay	
Area									Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Stats	LMBE	UPR	RB	WL	A 1	A 2	A 3	A 4	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WL A1	WL A2	UMCLA1	LMCLA1	LB A1	LB A2	LSCLA1	LSCLA2
Count	1338	128	747	382	532	303	280	224	51	50	23	69	281	51	257	155	185	201	228	56	59	74	118	150
Min	3.0	18.0	8.0	3.0	3.0	10.0	38.0	6.0	18.0	22.0	39.0	6.0	8.0	16.0	38.0	32.0	3.0	10.0	11.0	8.0	3.0	16.0	11.0	10.0
0.005	14.5		18.2		11.0																			
0.025	27.5	22.4	38.0	26.0	24.3	26.0	43.0	32.6					25.0		44.4	39.7	23.4	29.0	26.7				24.7	28.5
0.1	51.0	43.7	65.0	42.2	52.0	42.0	66.9	54.0	72.0	38.0		37.4	69.0	39.0	70.0	63.8	40.2	46.0	72.0	55.5	41.4	43.4	40.8	42.0
0.25	87.0	76.8	103.0	66.5	91.8	66.5	102.5	86.0	105.0	53.0	94.5	76.0	119.0	69.5	103.0	100.0	65.0	70.0	117.8	89.0	92.0	77.3	63.0	64.8
0.5	144.0	147.5	164.0	112.0	163.0	115.0	151.0	147.0	196.0	114.0	171.0	144.0	190.0	116.0	150.0	158.0	105.0	115.0	197.0	179.0	133.0	119.0	94.0	115.0
0.75	234.0	230.0	266.0	173.0	266.0	178.0	227.3	248.5	260.5	191.0	219.5	203.0	321.0	195.0	228.0	265.0	180.0	173.0	328.3	277.3	205.0	235.8	176.3	164.5
0.9	374.0	333.7	417.2	260.8	419.8	276.6	352.1	359.4	364.0	347.0		316.0	461.0	390.0	352.4	390.2	283.0	252.0	470.4	419.5	354.2	427.6	261.1	225.9
0.975	552.8	415.6	592.7	444.9	574.7	430.5	545.1	570.6					649.0		542.8	605.4	452.4	405.0	656.6				319.3	303.4
0.995	770.4		829.2		830.9																			
Max	1107.0	459.0	1107.0	798.0	1107	798.0	910.0	930.0	459.0	419.0	545.0	527.0	1107.0	563.0	910.0	930.0	575.0	798.0	1107.0	657.0	798.0	618.0	540.0	425.0
Mean	183.2	166.9	207.7	140.0	201.8	142.9	189.6	185.5	195.1	143.0	183.1	155.1	235.7	159.3	190.2	199.1	143.6	138.7	240.0	207.7	184.4	178.4	128.9	124.6



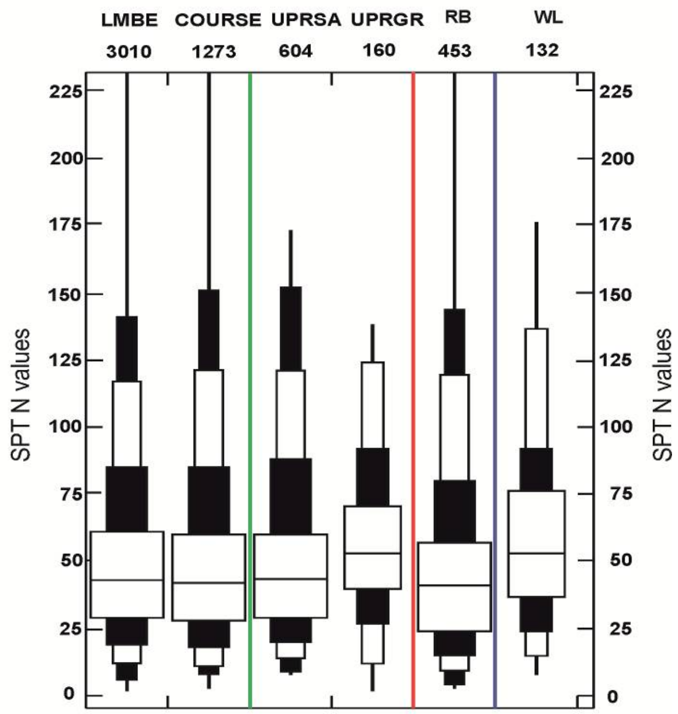
A5.13. Standard Penetration Test, SPT, (N-values), All

Stratigraphy	All	Upnor F	Reading F	Woolwich F	Area				Upnor Formation				Reading Formation				Woolwich Formation		Upper Mottled C	Lower Mottled C	Laminated Beds		Lower Shelly Clay	
Area					AREA1	AREA2	AREA3	AREA4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 1	Area 1	Area 1	Area 2	Area 1	Area 2
Stats	LMBE	UPR	RB	WL	A1	A2	A3	A4	UPRA1	UPRA2	UPRA3	UPRA4	RB1	RB2	RB3	RB4	WLA1	WLA2	UMCLA1	LMCLA1	LB A1	LB A2	LSCIA1	LSCIA2
Count	3010	990	1351	600	845	1037	874	254	299	543	117	114	365	82	757	140	175	415	275	93	72	150	100	255
Min	2	2	2	4	4	2	5	2	16	2	6	2	13	13	5	3	4	6	13	14	4	6	11	7
0.005	6	8	6	8	13	8	6			8					6									
0.025	12	13	11	14	18	12	10	9	23	12	11	10	23		9	9	13	14	24			14	14	14
0.1	19	22	17	20	27	21	16	14	31	20	18	14	34	29	16	14	19	21	34	34	19	22	19	19
0.25	29	32	28	27	39	30	24	22	40	29	24	24	46	36	24	19	25	30	47	44	25	36	24	27
0.5	43	47	43	40	53	44	38	32	53	45	37	33	60	53	38	31	38	42	62	56	41	56	35	38
0.75	61	63	60	60	75	63	53	42	67	62	54	44	84	70	53	40	57	63	87	71	63	74	48	51
0.9	85	88	85	82	96	86	68	52	91	89	64	52	105	95	68	51	76	84	109	93	82	92	72	76
0.975	117	121	116	106	124	120	97	89	125	120	77	115	130		100	64	102	110	124			126	90	98
0.995	141	143	137	148	141	149	135			150					136									
Max	232	173	232	176	176	173	232	141	164	173	84	141	155	133	232	87	176	150	155	138	113	150	176	149
Mean	48	51	48	46	58	49	41	34	57	50	40	48	66	57	41	32	44	48	68	61	47	58	41	43



A5.14. Standard Penetration Test, SPT, (N-values), Coarse-grained materials

Stratigraphy	All	Lambeth Coarse	Upnor Formation Sand	Upnor Formation Gravel	Reading F	Woolwich F
Stats	LMBE	COURSE	UPR SA	UPR GR	RB	WL
Count	3010	1273	604	160	453	132
Min	2	3	8	2	3	8
0.005	6	8	9			
0.025	12	11	14	12	9	15
0.1	19	18	20	27	15	24
0.25	29	28	29	40	24	37
0.5	43	42	43.5	53	41	53
0.75	61	60	60	71	57	76
0.9	85	85	88	92	80	92
0.975	117	121	121	124	120	137
0.995	141	151	152			
Max	232	232	173	138	232	176
Mean	48	48	49	57	45	59



Glossary

ATTERBERG LIMITS Consistency criteria for defining key water contents of a clay soil. They are: liquid limit, plastic limit and shrinkage limit.

BASIN A geological depression containing significant thicknesses of sediment, or in which sediment is able to accumulate.

BEARING CAPACITY The ability of a material to support an applied load. Ultimate bearing capacity is the pressure at which shear failure of the supporting soil immediately below and adjacent to a foundation. A foundation is usually designed with a working load that is some proportion of the bearing capacity.

BED. The smallest lithostratigraphical unit.

BEDDING The arrangement of sedimentary rocks in beds or layers of varying thickness or character.

BEDROCK. Unweathered rock beneath a cover of soil or superficial deposits.

CALCAREOUS Carbonate-rich.

CALCITE. The crystalline form of calcium carbonate, $CaCO_3$.

CALCRETE a generally white to light pink or light reddish brown hardened deposit of calcium carbonate formed by pedogenic processes or other mechanisms. Can form strong lenticular to rounded boulders or very weak to powdery concretions.

CLAY (particle size) A particle that is less than 0.002 mm across

CLAY (material description). A material that after the removal of coarse sand and larger particles can be rolled into a 3 mm diameter thread at a specific water content. In hand tests does not show dilatancy, the 3 mm thread has some strength, dry lumps are difficult or cannot be crushed between the fingers, feel smooth and takes a polish and lumps breaks up slowly in water. It contains a fair proportion of clay size particles.

CLAY MINERALS A group of aluminosilicate minerals with a layer lattice structure which are generally platy or fibrous crystals. These tend to have a very large surface area compared with other minerals, thus giving clays their plastic nature. They have the ability to take up and retain water and to may undergo base exchange. Commonly defined as being <0.002 mm in diameter. The same mineral may be larger than 0.002 mm in diameter for example illite is clay-size mica.

COEFFICIENT OF CONSOLIDATION A measure of the rate at which consolidation takes place.

COEFFICIENT OF VOLUME COMPRESSIBILITY A measure of the amount of compression that takes place during consolidation, measured as a change in dimension per log interval of applied stress.

COHESION Attractive force between soil particles (clay) involving a complex association of solid and water. Specifically, the shear strength of a soil at zero normal stress.

COHESIVE SOIL. A soil in which particles adhere after wetting and subsequent drying and significant force is required to crumble the soil.

COMPACTION The reduction of voids (densification) of a soil mass by engineering action to produce a more stable, stronger material.

COMPRESSION INDEX The slope of the normal consolidation line with respect to the change in voids ratio over a long cycle of applied stress.

CONSOLIDATION. The process in which pore water drains from a material under an applied load with a consequent reduction in volume of the material (see subsidence).

CROSS-BEDDING Horizontal units that are internally composed of inclined layers and indicates fluid flow. TROUGH CROSS BEDDING relatively low angle cross-bedding

DENSITY The mass of a unit volume of a material. Often used (incorrectly) as synonym for Unit weight. Usually qualified by condition of sample (e.g. saturated, bulk or dry).

DIGGABILITY Measure of the ability for an excavation to be made in a material by a mechanical digger.

DIP The inclination of a planar surface from horizontal. Usually applied to bedding planes.

DISCONTINUITY Any break in the continuum of a rock mass (e.g. faults, joints).

DOGGER Flattened calcareous or ferruginous concretion in a clay or sand deposit. Often stronger than the remainder of the deposit.

DRAINED Condition applied to strength tests where pore fluid is allowed to escape under an applied load. This enables an effective stress condition to develop.

DURICRUST Hard beds formed by pedogenic processes.

EFFECTIVE STRESS The total stress minus pore pressure. The stress transferred across the solid matter within a rock or soil.

ELASTICITY Deformation where strain is proportional to stress, and is recoverable.

EXCAVATABILITY A measure of the ability for an excavation to be made in a material by earth-moving equipment such as backhoe excavators, face shovels, scrapers, bulldozers etc. using digging, ripping and blasting as the difficulty of removing material increases.

EXPOSURE A visible part of an outcrop that is un-obscured by soil or other materials.

FAULTING The displacement of blocks of strata relative to each other along planar fractures. Movement may take place in several ways, depending on the direction of the compressive or extensional forces acting on the rock mass forming normal, reverse or strike slip faults.

FAULTS Planes in the rock mass on which adjacent blocks of rock have moved relative to each other. The relative vertical displacement is termed 'throw'. The faults may be discrete single planes but commonly consist of zones, perhaps up to several tens of metres wide, containing several fractures which have each accommodated some of the total movement. The portrayal of such faults as a single line on the geological map is therefore a generalization.

FERRICRETE An iron-rich hard bed formed by pedogenic processes.

FERRUGINOUS. Iron-rich. Applied to rocks or soils having a detectable iron content.

FILL. Material used to make engineered earthworks such as embankments and capable of acquiring the necessary engineering properties during placement and compaction.

FLASER BEDDING Heterolithic bedding characterized by cross-laminations draped with silt of clay typical of intermittent flow of tidal environments and rarely, fluvial conditions.

FLUVIAL/FLUVIATILE Of, or pertaining to, rivers.

FORMATION The basic unit of subdivision of geological strata, and comprises strata with common, distinctive, mappable geological characteristics.

GLACIAL Of, or relating to, the presence of ice or glaciers; formed as a result of glaciation.

GRADING A synonym (engineering) for particle-size analysis (see also Sorting).

GRAVEL (particle size) Particles from 2 mm to 63 mm.

GRAVEL (sample description) Material that does not stick together (cohesive) that has most particle of gravel size.

GROUNDWATER Water contained in saturated soil or rock below the water-table.

GROUP A stratigraphical unit usually comprising one or more formations with similar or linking characteristics.

GYPSUM Mineral consisting of hydrous calcium sulphate ($CaSO_4.2H_2O$), that occurs in deposits that contain sulphides and calcium carbonate, primarily dark gray or grey clay and mudstone. Formed by the reaction of oxidised sulphide minerals (usually iron sulphide) with calcium carbonate, which may be present as disseminated particles or in shells.

HEAD A deposit comprising material derived, transported and deposited by solifluction in periglacial regions. May include material derived also by hillwash, creep and other non-glacial slope processes. Composition is very variable and dependent on source material. Thickness is also very variable.

HOLOCENE The most recent subdivision of geologic time (RECENT) which represents time after the last ice age, approximately last 10,000 years.

HYDRAULIC CONTINUITY Juxtaposition of two or more permeable deposits or rock units such that fluids may pass easily from one to another.

ILLITE A 2:1 clay mineral, common in sedimentary rocks, not noted for susceptibility to shrink/swell behaviour. Clay size mica.

INDEX TESTS Simple geotechnical laboratory tests which characterise the properties of soil (usually) in a remoulded, homogeneous form, as distinct from 'mechanical properties' which are specific to the conditions applied.

IRONPAN Hard layer formed by re-precipitation of iron compounds leached from overlying deposits.

JOINT A surface of fracture or parting in a rock, without displacement; commonly planar and part of a set.

KAOLIN A group of 2 layer, 1:1 structure clay minerals usually of low plasticity (e.g. kaolinite). Can be larger than clay size.

LANDSLIDE A down slope displacement of bedrock or superficial deposits subject to gravity, over one or more shear failure surfaces. Landslides have many types and scales. Landslides may be considered both as 'events' and as geological deposits. Synonym of 'landslip'.

LIGNITE Soft, brown-black accumulation of vegetable matter that has been altered by earth processes but still retains high water content. Somewhere between peat and coal.

LINEAR SHRINKAGE The percentage length reduction of a prism of remoulded clay subjected to oven drying at 105C.

LITHOLOGY The characteristics of a rock such as colour, grain size and mineralogy. The material constituting a geological material.

LITHOSTRATIGRAPHIC UNIT A rock unit defined in terms of lithology/lithologies and age and not fossil content (Biostratigraphic unit).

LIQUID LIMIT The moisture content at the point between the liquid and the plastic state of a clay. An Atterberg limit.

LOWER LAMBETH GROUP Informal unit that includes the Lambeth Group units deposited below the mid-Lambeth Group Hiatus and includes the Upnor Formation and Lower Mottled Clay.

MARL A calcareous mudstone, *sensu-strictu* having > 30% carbonate content.

MEDIAN The 50th percentile of a distribution; that is, the value above and below which 50% of the distribution lies.

MEMBER A distinctive, defined unit of strata within a formation characterised by relatively few and distinctive rock types and associations (for example, sandstones, marls, coal seams).

MICACEOUS Containing mica, a sheet silica mineral.

MID-LAMBETH GROUP HIATUS The major break in deposition during the Lambeth Group between the lower Lambeth Group (Upnor Formation and Lower Mottled Clay) and upper Lambeth Group (Woolwich Formation and Upper Mottled Clay). The hard band (calcrete, silcrete and ferricrete) formed by pedogenic processes occur below the hiatus, shelly limestone occur above.

MINERAL A naturally occurring chemical compound (or element) with a crystalline structure and a composition which may be defined as a single ratio of elements or a ratio which varies within defined end members.

MOISTURE CONDITION VALUE (MCV) Test to determine suitability of soil as compacted fill. The test measures the minimum compactive effort required to produce a state of near-full compaction.

MOISTURE CONTENT See Water content.

MUDSTONE A fine-grained, non-fissile, sedimentary rock composed of predominately clay and silt-sized particles.

NATURAL WATER CONTENT The water content of a geological or engineering material in its natural or 'as found' state.

OEDOMETER Laboratory apparatus for measuring consolidation properties of a soil.

OUTCROP The area over which a particular rock unit occurs at the surface.

OUTLIER. A deposit or an outcrop of rock surrounded by the outcrops of older deposits or rocks and separated from the main body by erosion.

OVERBURDEN Material, or stress applied by material, overlying a particular stratum. Unwanted material requiring removal (quarrying).

PALAEOCENE The geological epoch from approximately 65.5 to 56 Ma which include the Thanetian stage.

PARTICLE-SIZE ANALYSIS (PSA) The measurement of the range of sizes of particles in a disaggregated soil sample. The tests follow standard procedures with sieves being used for coarser sizes and various sedimentation, laser or X-ray methods for the finer sizes usually contained within a suspension.

PARTICLE-SIZE DISTRIBUTION (PSD) The result of a particle-size analysis. It is shown as a 'grading' curve, usually in terms of % by weight passing particular sizes. The terms 'clay', 'silt', 'sand' and 'gravel' are defined by their particle sizes.

PEDOGENIC PROCESSES Soil forming processes – a variety of mechanisms contribute to soil formation including chemical and physical processes.

PERCHED GROUND WATER Unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone or above a very low permeability layer such as clay.

PERIGLACIAL An environment beyond the periphery of an ice sheet influenced by severe cold, where permafrost and freeze-thaw conditions are widespread. Fossil periglacial features may persist to the present day or may have been removed by subsequent glaciation or erosion.

PERMEABILITY The property or capacity of a rock, sediment or soil for transmitting a fluid; frequently used as a synonym for 'hydraulic conductivity' (engineering). The property may be measured in the field or in the laboratory using various direct or indirect methods.

PERMAFROST Permanently frozen ground, may be continuous (never thaws), discontinuous (with unfrozen patches, especially in summer) or sporadic (unfrozen areas exceed frozen areas). The surface layer subject to seasonal thaw is the 'active layer'.

pH Measure of acidity/alkalinity on a scale of 1 to 14 (< 7 is acid, > 7 is alkaline).

PLASTICITY INDEX The difference between the liquid and plastic limits. It shows the range of water contents for which the clay can be said to behave plastically. It is often used as a guide to shrink/swell behaviour, compressibility, strength and other geotechnical properties.

PLASTIC LIMIT The water content at the lower limit of the plastic state of a clay. It is the minimum water content at which a soil can be rolled into a thread 3 mm in diameter without crumbling. The plastic limit is an Atterberg limit.

PLEISTOCENE The first epoch of the Quaternary Period prior to the Holocene from about 2 million years to about 10.000 years ago.

POISSON'S RATIO The ratio of the strain parallel to an applied stress to that perpendicular to it [rock mechanics]

PORES The voids within a soil or rock.. The non-solid component of a soil or rock.. May be filled with liquid or gas.

PORE PRESSURE The pressure of the water (or air) in the pore spaces of a soil or rock. It equals total stress minus effective stress. The pore pressure may be negative.

PUDDINGSTONE A conglomerate formed of silcrete containing flint gravel.

IRON PYRITE The most widespread sulphide mineral, FeS_2.

QUARTZ The most common silica mineral (SiO_2).

QUARTZITE. A sandstone composed (almost) entirely of cemented quartz (silica) grains.

QUATERNARY A sub-era that covers the time from the end of the Tertiary to the present, approximately the last 2.0 Ma, and includes the Pleistocene and Holocene.

RESIDUAL SHEAR STRENGTH The strength along a shear surface (clay) which has previously failed or has undergone significant displacement. Generally the minimum shear strength. Tends to be constant for a given soil.

ROCKHEAD The upper surface of bedrock at surface (or its position) or below a cover of superficial deposits.

RUNNING SAND Fluidisation of sand and flow into an excavation below the water table or into a perched water table, under the influence of water flow into an excavation.

SAND (particle size) A soil with a particle-size range 0.063 to 2.0 mm.

Sand (material description) A course grained deposit that is predominantly sand-sized.

SANDSTONE Sandstones are clastic rocks of mainly sand-sized particles (0.063 - 2.0 mm diameter), generally with quartz being the dominant component. Sandstones exhibit some form of cementation.

SARSEN Silica cemented, (silcrete) sandstone blocks formed by pedogenic processes. Used by man in walls and in such ancient monuments as Avesbury and Stonehenge.

SATURATION The extent to which the pores within a soil or rock are filled with water (or other liquid).

SETTLEMENT The lowering of the ground surface due to an applied load (see consolidation).

SHEAR PLANES/SURFACES A series of closely spaced, parallel surfaces along which differential movement has taken place. Usually associated with landslides or stress-relief. May be polished (slickensides).

SHEAR STRENGTH The maximum stress that a soil or rock can withstand before failing catastrophically or being subject to large unrecoverable deformations.

SHRINKAGE The volume reduction of a clay (or clay-rich soil or rock) resulting from reduction of water content. Shrinkage may cause subsidence of shallow foundations.

SHRINKAGE LIMIT The water content below which little or no further volume decrease occurs during drying of a clay (or clay-rich soil or rock). The laboratory tests which measure shrinkage limit have largely fallen into disuse in the UK. An Atterberg limit.

SIDERITE Carbonate mineral of iron ($FeCO_3$).

SILCRETE an indurated hard band or duricrust formed by the redeposition of silica commonly formed by pedogenic processes. May be as cobble or lenticular boulders.

SILT (particle size) A soil with a particle-size range 0.002 to 0.06 mm (between clay and sand).

SILTSTONE A sedimentary rock intermediate in grain size between sandstone and mudstone.

SLAKE DURABILITY A measure of the ability of a rock to resist degradation by the combined action of wetting/drying cycles and mechanical abrasion.

SMECTITE A group of 2:1 clay minerals with a very high surface area (~780 m^2/g) noted for their high plasticity and susceptibility to shrink/swell behaviour. Commonly a product of alteration (argillisation) of volcanic ash. Sometime known as montmorillonite (from France) or bentonite, (from USA).

SOLID Old term used in geology to indicate mappable bedrock (see also Superficial).

SOLIFLUCTION The slow, viscous, down slope flow of waterlogged surface material, especially over frozen ground.

SORTING A descriptive term to express the range and distribution of particle sizes in a sediment or sedimentary rock, which has implications regarding the environment of deposition. Well-sorted = poorly graded indicates a small range of particle sizes, poorly sorted = well-graded) indicates a larger range of particle size.

STANDARD PENETRATION TEST (SPT) A long-established in-situ test for soil where the number of blows (N) with a standard weight falling through a standard distance to drive a standard cone or sample tube a set distance is counted. Used as an indication of lithology and bearing capacity of a soil.

STIFFNESS The ability of a material to resist deformation.

STRAIN A measure of deformation resulting from application of stress.

STRATIGRAPHY The study of the sequence of deposition of rock units through time and space.

STRESS The force per unit area to which it is applied. Frequently used as synonym for pressure.

SUBCROP The area over which a particular rock unit or deposit occurs immediately beneath another deposit, e.g. the Solid unit lying below Superficial Deposits (i.e. at rockhead).

SUBSIDENCE The settling of the ground or a building in response to physical changes in the subsurface such as underground mining, clay shrinkage or drained response to overburden (consolidation).

SUCTION The force exerted when fluid within pores in a soil or rock is subjected to reduced atmospheric (or other environmental) pressure.

SUPERFICIAL DEPOSITS Quaternary age deposits overlying bedrock; formerly called ‘drift’.

SWELLING The volume increase of a clay (or clay-rich soil or rock) resulting from an increase in water content. Swelling behaviour may cause heave of shallow foundations.

SWELLING INDEX The rebound (unloading) equivalent of the Compression index.

GLACIAL TILL An unsorted mixture which may contain any combination of clay, sand, silt, gravel, cobbles and boulders deposited by glacial action without subsequent reworking by meltwater.

THANETIAN The latest stage of the Palaeocene approximately 58.7 to 55.8 Ma which included the deposition of the Ormesby Clay and Thanet formations and the Lambeth Group.

TRAFFICABILITY The capacity of a soil to support vehicle movement. This is influenced by soil shear strength, water content, and surface friction, ground pressure and vehicle wheel or track configuration.

TRIAXIAL TEST A laboratory test designed to measure the stress required to deform a sample until it fails, or until a constant rate of deformation is obtained.

UNCONFORMITY A break in the sedimentary record indicating cessation of deposition.

UNCONSOLIDATED A triaxial soils strength test carried out without a consolidation stage (see Consolidation).

UNDRAINED Condition applied to strength tests where pore fluid is prevented from escaping under an applied load. This does not enable an effective stress condition to develop.

UNIAXIAL COMPRESSIVE STRENGTH The strength of a rock sample (usually a cylinder) subjected to an axial stress causing failure (usually in an undrained condition) in the laboratory.

UNIT WEIGHT The weight of a unit volume of a material. Often used (incorrectly) as synonym for Density. Usually qualified by condition of sample (e.g. saturated, dry)

UPPER LAMBETH GROUP The Lambeth Group units deposited above the mid-Lambeth Group Hiatus.

WATER CONTENT In a geotechnical context: the mass of water in a soil/rock as a % of the dry mass (usually dried at 105C). Synonymous with the moisture content.

WATER TABLE The level in the rocks at which the pore water pressure is at atmospheric.

WEATHERING The physical and chemical processes leading to the alteration of geological materials near surface (e.g. due to water, wind, temperature).

YOUNG'S MODULUS A measure of linear stiffness. The slope of the stress-strain graph for elastic deformation [soil and rock mechanics].

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