Drift-filled hollows in the London Basin: Characteristics, Origins and Assessment of Risk

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Abstract

Anomalous geology creates sub-surface risk to engineering projects. Within the London Basin, anomalous geological depressions, named drift-filled hollows (DFHs) have been identified and inducing sub-surface risk for the last century. DFHs are depressions identified at an anomalous depth to the local bedrock, infilled with largely unconsolidated sediment and occasionally local bedrock. The features range in size from 5-500 m wide and up to 75 m deep, narrowing with depth. Not visible from ground level, DFHs are often missed during site investigations which induces sub-surface risk on construction projects. Not addressing the features if and once encountered could lead to failure through differential subsidence, tunnel face collapse, impact on nationally-significant infrastructure, excessive and unplanned costs, damage to groundwater resources and loss of life. This thesis compiles information to create the largest DFH dataset of 89 features and their known characteristics. A multi-disciplinary approach is employed to further understanding of the physical characteristics of DFHs as well as to use an evidence-based approach to determine their origin and processes which have shaped their current form. The results illustrate the high level of variability between features and within a single feature. Data quality restrictions and methodological limitations are discussed in detail throughout. These limitations are then amplified with highly variable sediments, such as the infill of DFHs. Further outcomes of the research include furthering the understanding of London's geology, not solely through identifying further anomalies, but through mapping the sub-surface of two differing areas and showing notable differences in depth to bedrock and presence and absence of strata within relatively short distances. A guide for the site investigation sector has also been created to readily identify and characterise DFHs and so reduce risk. All of the outcomes reduce sub-surface risk through an increased knowledge of the features and London's geology as a whole. Finally, the enlarged dataset and the recognition of the high level of variability within a single feature and between features has enabled the existing and potential process hypotheses to be analysed and a new formation hypothesis is proposed for features with a diapir being formed through an increase of water and gas pressure.

Acknowledgments

Throughout my PhD I have been supported by every single person who I have spoken to about my research. Whilst I cannot thank them all, I am extremely appreciative.
Bearing that in mind, there are several people who I would like to thank in name. Dr Philip Collins, Peter Reading and Dr Lorna Anguilano for their knowledge, guidance and support throughout the entire process. I do not think there is another subject discipline which will have you hanging off of a sediment corer in a field with your supervisor and giving him a hernia. John Davis and Dr Jackie Skipper from the Geotechnical Consultancy Group, not just for the access they have given me to their data and industry connections, but for their support and knowledge. Pagani and MGS, who gifted the university with a CPTu drill rig. My amazing, supportive friends who I have made on this journey, Alaa Al-Isawi, Rand Al-Janabi, Mustasin Khan and Susanna Venditti, all of whom are incredible, intelligent people and I am extremely thankful that they are in my life. Last, but definitely not least, my extremely supportive and loving family. My loving parents, sister, Lucy and my supportive aunts, uncles and grandparents. Most notably, my Dad, John, who without I would not have started this PhD let alone finished it. Thank you.

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Research Presented

1. Engineering in Chalk conference (2018).
   Oral presentation and paper.
   "The role of the chalk in the development of buried ("drift-filled") hollows" (2018)
2. 20th Congress of the International Union for Quaternary Research (INQUA) (2019)
   Oral presentation
3. Quarterly Journal for Engineering Geology and Hydrogeology – Journal Article
   "Buried (drift filled) hollows in London – a review of their location and key characteristics" (2020)

1. Introduction

Geological anomalies pose a risk to civil engineering projects across the globe. In addition to generating risk for construction projects, the features also present a scientific mystery surrounding the processes which formed them.

This research focuses upon a geological anomaly identified within the London Basin, south England, UK, that is commonly termed a “drift-filled hollow” (DFH), but which has also been known as a “scour feature” (Berry 1979) or “pingo” (Hutchinson, 1980). The features within this project will be referred to as DFHs, as explained later in this chapter (section 1.1).

The project uses a multi-disciplinary approach to advance understanding of DFH features. In particular, it considers their physical properties and uses an evidence-based approach to further knowledge on their identification, genesis and the processes which lead to their current forms.

1.1. Explanation of the feature

Prior to this research project, DFHs were understood to be steep sided, cone shaped geological features developed into and sometimes breaching the local bedrock (most often, the London Clay Formation) (Figure 1. 1). These range from 5-500m wide (narrowing with depth) and up to 75m deep, and are infilled with unconsolidated, superficial sediment that is often, but not always, differing in lithology from the strata surrounding the feature. The infill type is typically a mélange (varied lithologies, mixed as one). In some features, a diapir (material intruding vertically into higher strata) is present, usually of Chalk Group (hereon Chalk) or Lambeth Group and often the lower strata are upwelling towards the centre of the hollow (Ellison et al. 2004, Royse et al. 2012, Banks et al. 2014).

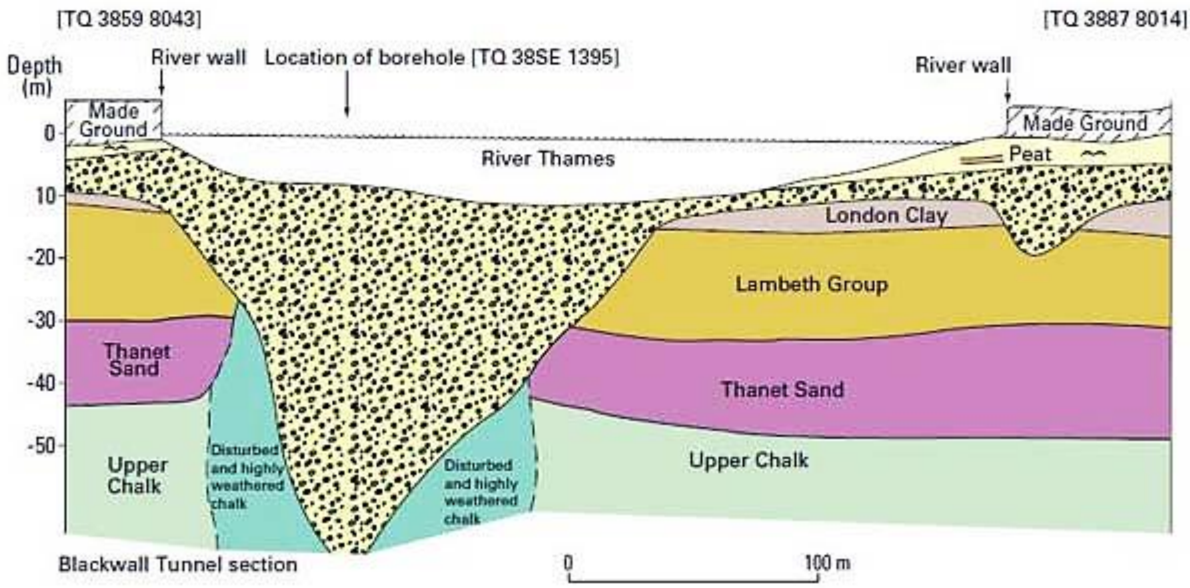


Figure 1. 1 - A simplified cross section of a DFH identified during the construction of the Blackwall Tunnel DFH (Ellison et al., 2004).

A DFH is defined within this project as an "anomalous closed form depression in the pre-Quaternary rockhead surface" (Flynn et al., 2020) located within the London Basin. The term is deliberately non-genetic and is used for its descriptive nature as it does not infer a mode of formation. All features identified within this project are grouped under the term DFHs due to their anomalous depth to the local bedrock.

The London Basin is here defined as the region surrounded by the outcrop of Cretaceous Chalk (Sumbler, 1996 and Royse et al. 2012), to the south by the North Downs and to the north by the Chilterns. It lies within the synclinal structure of Cretaceous and Eocene strata, confined or formerly confined lower aquifer (Chalk and Thanet Formation) and the overlying London Clay Formation (hereon London Clay)(Figure 1. 2). Although the term is now not used by the British Geological Survey (BGS), "drift" is here used informally to describe the infilling material, again due to the term being non-genetic. Key to note is that "drift" is not the only infilling material of a DFH. "Anomalous" is stated in place of any fixed dimensional criteria and is relative to the immediate local rockhead surface. The term 'closed form' is used so as to exclude any channel-like erosional features or rockhead steps within current or former Quaternary floodplains.

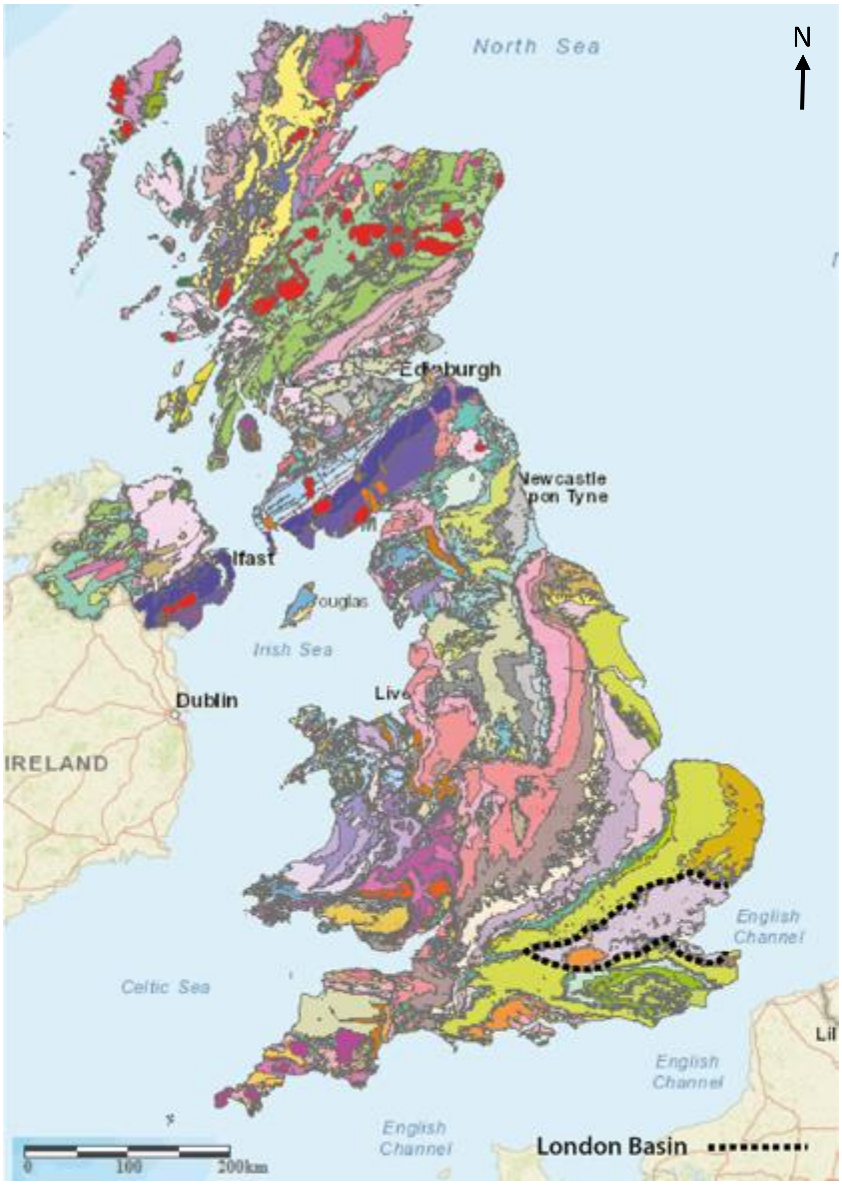


Figure 1. 2 – The outline of the London Basin as defined within this project. The basin is approximately 250km long and up to 75km wide (British Geological Survey, 2019)

The vast majority of DFHs have been identified through borehole exploration. An example cross-section is shown in Figure 1. 3, illustrating an anomalous depth of infill to 17.5m (depth from ground level) in comparison to the local level of London Clay at 8m (depth from ground level). This demonstrates how DFHs in built up areas are not identifiable from above ground, but identified through their anomalous depth to local bedrock.

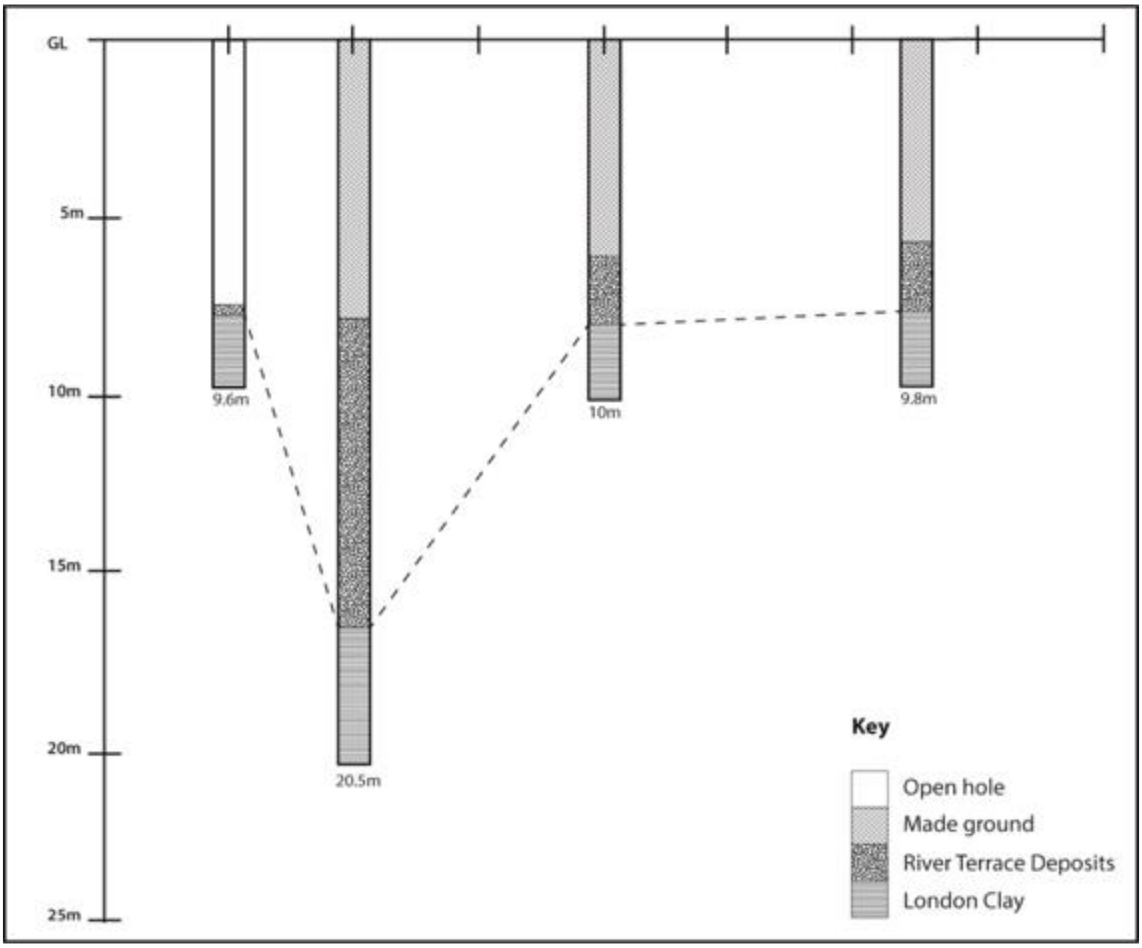


Figure 1. 3 – Identification of a DFH feature from anomalous depth to bedrock. Cross section drawn from borehole logs from the Battersea Power Station smaller feature (Created from data provided in Appendix A).

1.2. Engineering significance

At present, 89 DFHs have been identified in the London Basin and this number is growing (Chapter 5, Results). Numerous factors lead DFHs to become significant to engineering projects, all of which are due to the increase in risk due to the anomalous nature of the features causing unexpected ground conditions. This risk is further induced by the inability to identify a DFH from above ground. Moreover, there is also the potential for the anomalous geology to be missed during a site investigation primarily due to borehole spacing or misinterpretation of the sediment. When DFHs are identified as part of a site investigation, the diameter, depth and infill of each DFH differs in its geotechnical properties from the surrounding strata. These unexpected ground conditions in both surface and sub-surface construction (e.g. tunnelling projects) have the potential to cause delays and issues once construction projects have begun, including broken machinery, tunnel face collapse or water ingress, all of which are costly and potentially a danger to life (Figure 1. 4).

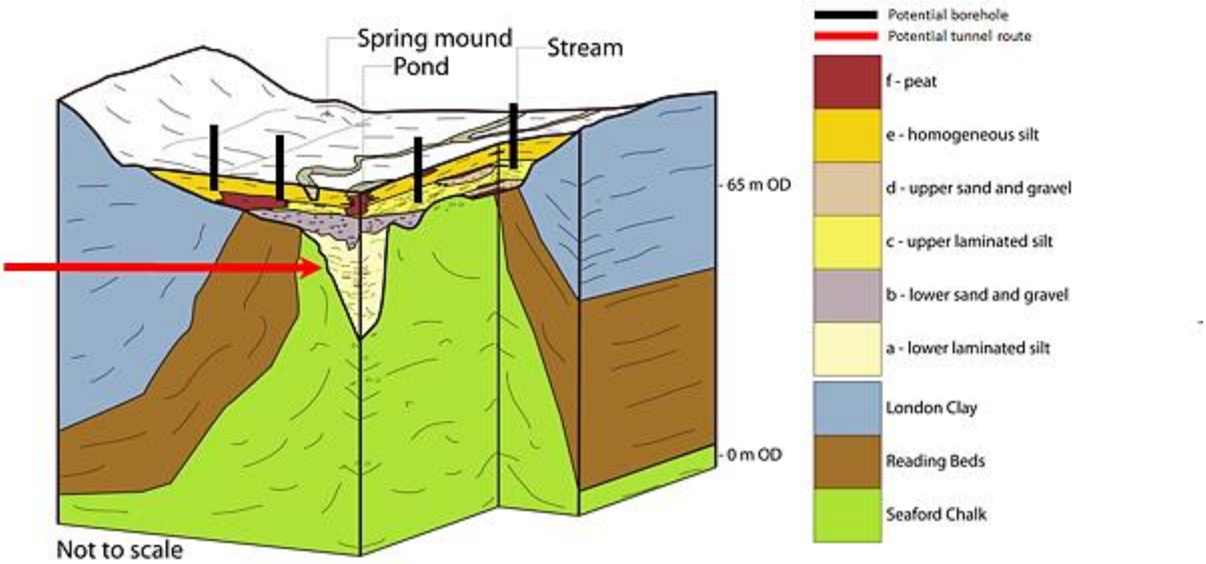


Figure 1. 4 - Diagram illustrating the DFH at Ashford Hill and the potential implications on site investigation and engineering projects. Examples shown are missing a feature through borehole exploration due to spacing and in turn not identifying the anomalous geology prior to tunnelling (adapted from Collins, 2017, pers. comm.).

Currently there is a lack of available information on the location and form of DFHs due to financial constraints, confidentiality within companies and/or a fear of legal action from clients. This is furthered by a location bias due to larger scale engineering projects that are mainly taking place in central London in comparison to the rest of the London Basin.

Site investigations are often limited financially, therefore once they reach what is deemed ‘normal’ London strata the boreholes cease. This is an issue both geotechnically for the individual construction project and research-wise for identifying the extent of these features individually and across London as it limits the availability of data.

At present, it is unknown how extensive construction work (in particular increased surface load or the removal of load and in turn pressure below surface when tunnelling) will impact on DFH features, as well as the infrastructure above, adjacent to and possibly below it. This is a prime example of where clients may not report identifying a DFH due to its potential, unknown knock-on effects in the immediate area and consequently a potential fear of legal action.

Tunnel construction projects across the United Kingdom (UK) are becoming more common (e.g. Thames Tideway, Crossrail, sections of HS2). This is especially the case in central London due to a high demand for infrastructure and a lack of space. If hollows are not identified during the site investigation phase or if they are underestimated in size or extent, unexpected ground conditions and subsurface movement can occur. This can lead to water ingress and tunnel face collapse, both of which are dangerous to human life and costly for the contractor (Newman, 2009). Even when features are identified there is still the potential for them to cause an issue for both above ground and tunnelling projects. This was the case for the Thames Water Ring Main, where sections of the tunnel had to be redesigned due to the presence of DFHs (Newman, 2009). Furthermore, where a diapir is present, there is the potential for contamination of the chalk aquifer.

If a diapir is present under what is believed to be “normal” strata (as identified at several locations), this can lead to issues not just within the immediate area of the feature, but possibly elsewhere within the basin. A study site within this project (section 2.4.1) located outside of central London, is a Natural England Nature Reserve (Ashford Hill) and untouched by construction work. A pond is located above what is believed to be the centre of the hollow. Indicating ongoing subsidence and increasing risk. During personal communications with a geotechnical engineer, it was noted that at one site in London where a DFH was present, dewatering was undertaken and it led to measurable subsidence of another feature 1km away. When the dewatering pump was switched off the feature returned to its previous standing. Although no research has been completed on this phenomenon as of yet, it provides evidence for a possible connection between the features and also suggests that DFHs may not be dormant.

Several large scale construction projects have encountered DFHs, these include:

- Crossrail, named the Elizabeth line (Lenham et al., 2006; Menkiti et al., 2015);
- Thames Tideway (Newman, 2009);
- HS2;
- Northern Line extension (Toms, Mason, & Ghail, 2016);
- Lee Tunnel (Bellhouse, Skipper, & Sutherden, 2015; Newman, 2008; Skipper, Newman, & Mortimore, 2008);
- The London Underground (Paul, 2009).

1.3. Scientific significance

DFHs are also significant in relation to their presence and how they formed. The mode of their formation has been hypothesised since the 1970s (Berry, 1979) and has ranged from fluvial scour (Berry, 1979), to ground ice depressions (Hutchinson, 1980). Due to their geomorphic shape and ability to store infill material, DFHs provide an archive of environmental change (similar to lacustrine and fluvial basins) as well as being a record of landscape evolution, with the potential to further understanding of London's geology and the basin's history.

1.4. Project scope

This project focusses upon both the engineering risk and geomorphological unknowns created by DFHs. DFHs have been identified as anomalous geology within the basin since the 1800s (Baker, 1885). The features were first studied as a group in relation to their formation by Berry (1979). Since Berry's paper, around 60 additional DFHs have been located across the London Basin, yet other than a feature at Woolhampton (Collins et al., 2006) there has been no comprehensive, evidence-based, analytical research undertaken on the characteristics or formation of the features in their entirety. Research has more recently focused upon individual features identified during a construction project and the impact on the specific projects (e.g. Thames Tideway - Newman, 2009).

This project builds on existing research and undertakes a multi-disciplinary analysis of the features as well as furthering the understanding of London's geology whilst acknowledging the limitations, considered in detail in chapter 4. The overarching aim is therefore to improve understanding of:

- Sub-surface risk associated with anomalous geology;
- Formation processes associated with DFHs;
- Data quality for study of the sub-surface and its associated methodologies;
- London geology.

1.4.1. Aims and Objectives

This research's aims and objectives are as follows:

- *What are the spatial and physical characteristics of DFHs?*
  Identify the physical characteristics of DFHs through an enlarged DFH dataset and a multi-disciplinary analysis of DFH material (using geotechnics, logging, petrography, mineralogy and microscopy).
- *What processes were involved in the formation of DFHs?*
  Using the updated and extended evidence base, develop further understanding in the processes involved in DFH formation through undertaking the multi-disciplinary assessment noted above to provide evidence for their formation.
- *What risks are associated with DFHs?*
  Identify and evaluate the surface and sub-surface risks associated with the DFH features as well as interpretation of the features undertaken by individuals. A guide for the site investigation sector will be presented to understand indicators of DFHs from borehole sediment and provide information on their characteristics through primary and secondary analysis undertaken throughout the thesis.

Through undertaking the above, it is expected that the increased understanding of DFHs, their physical characteristics and the understanding of data quality issues surrounding the features will contribute to the mitigation of sub-surface risk for surface and sub-surface development. Furthermore, the improved understanding of these features will advance scientific understanding of the geological history of the London Basin.

1.5. Thesis Structure

The research project undertaken combines a detailed case study investigation with a broader multidisciplinary analysis approach. The structure of the thesis follows a traditional arrangement across seven chapters.

Chapter 1 introduces the concept of DFHs, their significance in both the scientific and engineering fields as well as the aims, objectives and proposed outcomes of the research.

Chapter 2 provides an examination of the current state of knowledge on DFH features, together with a background to the London Basin region where they are identified.

Chapter 3 outlines the methodologies used within the research project. This includes the approach followed for primary and secondary data collection and analysis.

Chapter 4 provides a critical validation of the methods used in this project and in related research, focusing in particular on data quality and usability issues.

Chapter 5 presents the results of the methodologies outlined in Chapter 3 alongside any explanation, where required. Discussion is reserved for analysis in Chapter 6.

Chapter 6 discusses the results of the research in relation to literature and further information outlined in Chapter 2. The chapter focuses upon the delivery of the objectives and outcomes of the research, limitations identified throughout the project as well as recommendations for site investigations.

Chapter 7 provides conclusions to the research and identifies future research suggestions in and around the topic. This is then followed by a list of cited sources and appendices.

2. Background to the literature

2.1. Existing research on DFHs

Research on DFHs has largely focused on central London. With the exception of Berry's work in 1979, Hutchinson's pingo hypothesis the following year and Banks et al., (2015) research has since been driven by the engineering sector when coming across the features in engineering projects.

Hutchinson (1980) and Berry (1979) will be discussed later in this chapter within the formation hypotheses subsection (section 2.5). This subsection (2.1) will focus upon individual features which have had research undertaken on them (Ashford Hill, Denham and Lea Valley) followed by research undertaken in Central London, largely identifying DFHs through engineering projects.

2.1.1. Ashford Hill

Outside of London, several DFHs have been identified within the Kennet Valley, to the west of the London Basin. Ashford Hill (SU 56366 61711), one of these features, lies on the county border of Hampshire and Berkshire. The DFH lies in a narrow valley within a Site of Special Scientific Interest (SSSI) and a Natural England Nature Reserve.

The Baughurst Stream which lies in the middle of the valley is around 5.6 km long. The stream is a tributary or the River Enborne and flows to the north. Starting in Ewhurst and joining the River Enborne between Hyde End and Brimpton Common. The valley itself is prone to flooding and the floodwaters can cover the majority of the valley floor (Pers. Comms. Dr Collins and individuals local to the area). Conversely, when fieldwork was undertaken in 2018 the pond had completely dried out, which according to the locals was unusual to be that dry.

As the valley is only 300m wide, its sedimentological history is likely to be affected by the activity on the valley sides (Collins, 1994). The valley's geology includes the Bagshot Beds, which comprises of fine to coarse sand, with some clay and gravel in areas, overlying approximately 35m of London Clay, followed by the Lambeth Group and then into the Seaford/Newhaven Chalk Fm. (Figure 2. 1).

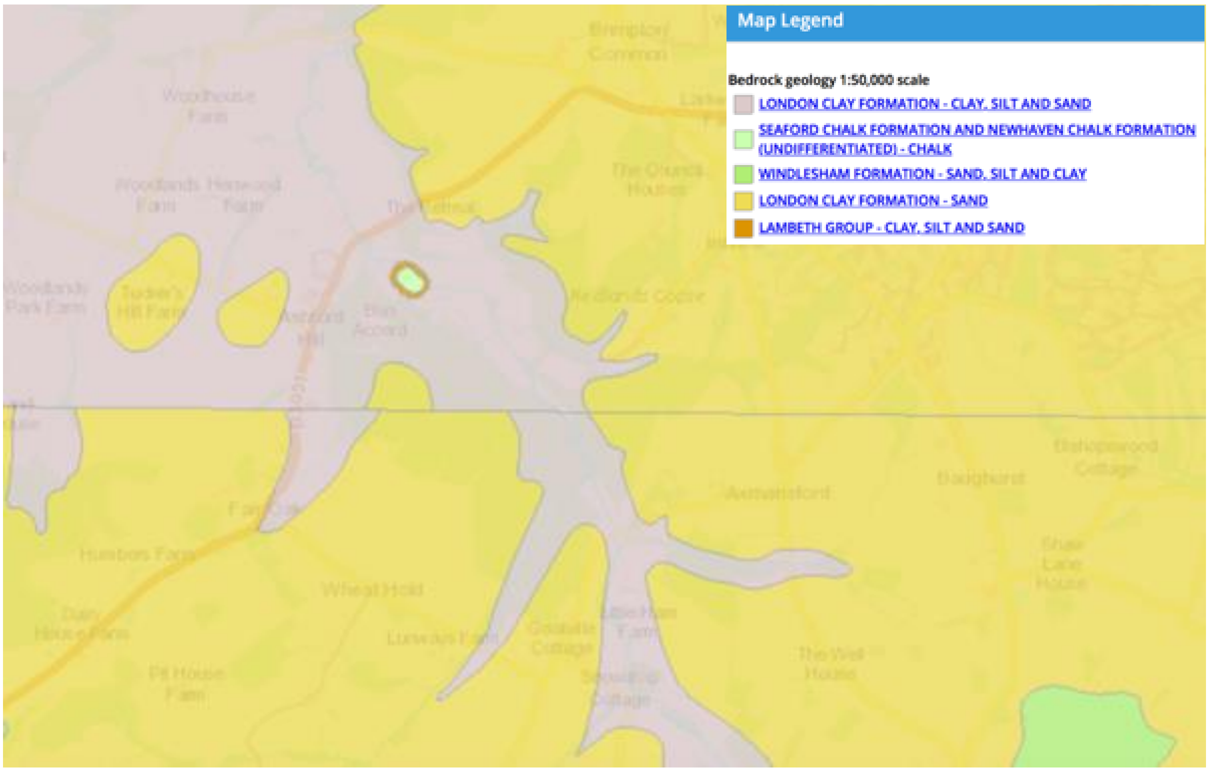


Figure 2. 1 - Ashford Hill bedrock geology. The shape of the anomaly is an artefact of the data and software (discussed in chapter 4). The line across the centre of the image is from two different maps being joined by the server (BGS, 2017).

In the late 1940s and early 1950s the local water board undertook an extensive geological survey of the area which included numerous boreholes for a potential reservoir. This formed the basis for Hawkin's, a professor at the University of Reading, research and led to the identification of a chalk "pinnacle" within the middle of a depression on the valley floor, 46m above local level. Cross-sections derived from Hawkin's work are shown in Figure 2. 2. He offered a tectonic eruption origin for the feature through localised valley bulging.

Hill (1985) undertook his PhD on the feature at Ashford Hill and took further boreholes to complement Hawkins' work (Figure 2. 3). Using the new borehole data, Hill created updated cross-sections (shown in Figure 2. 4). He proposed that the DFH was formed via ground ice activity through the following process: frost-shattering of the chalk occurred due to permafrost at depth, the chalk then deformed upwards due to high water pressure, (through possibly incised Paleogene strata). Ground ice development may then have resulted in a pingo. The decay of the ice feature ensued and the migration of the stream within the valley eroded any potential pingo rim and brought gravel into the system. Finally, a pond/lake formed within the depression and lead to the accumulation of laminated silts identified within the boreholes (Figure 2. 5).

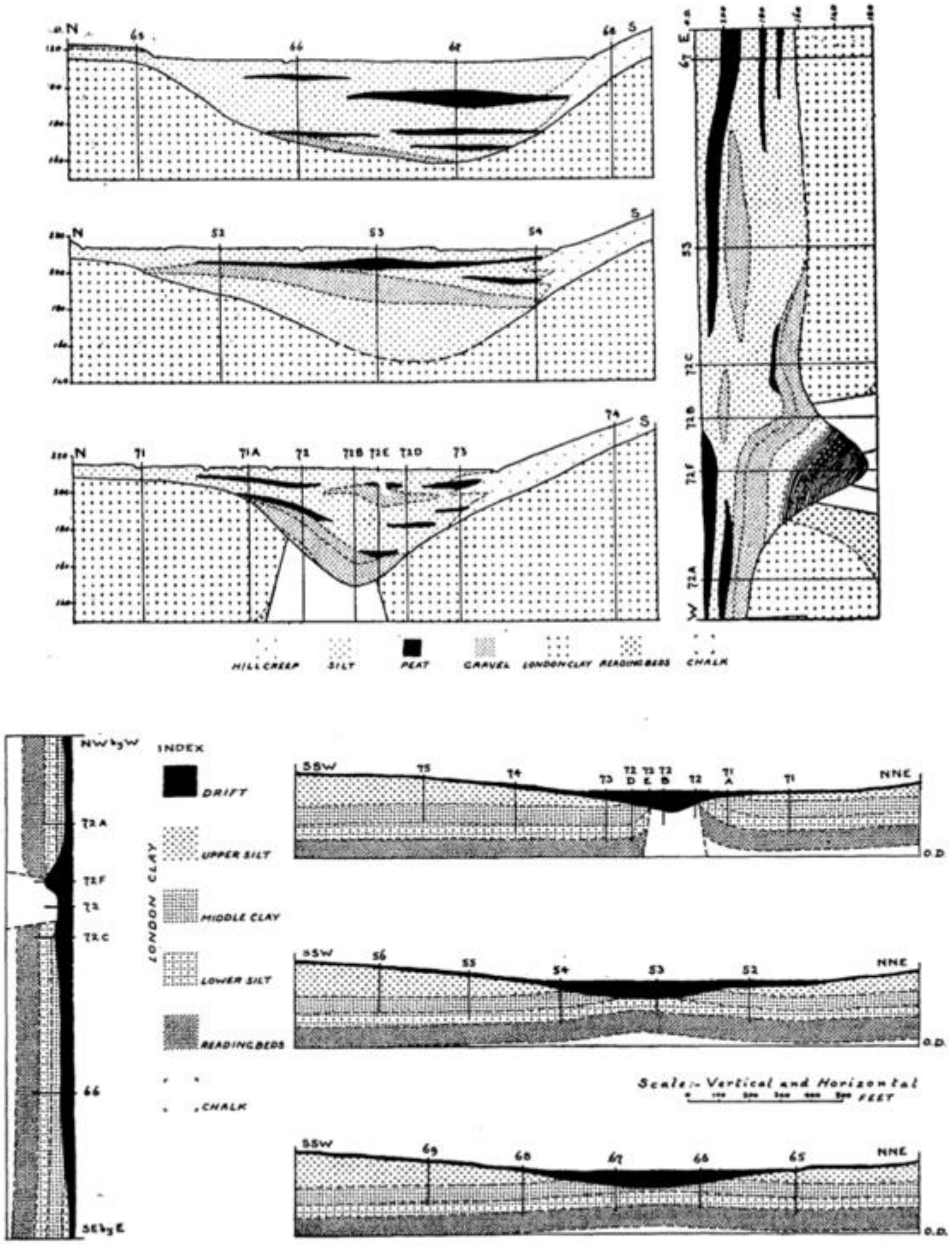


Figure 2. 2 – Hawkins' (1952) cross-sectional diagram of the DFH at Ashford Hill from borehole data.

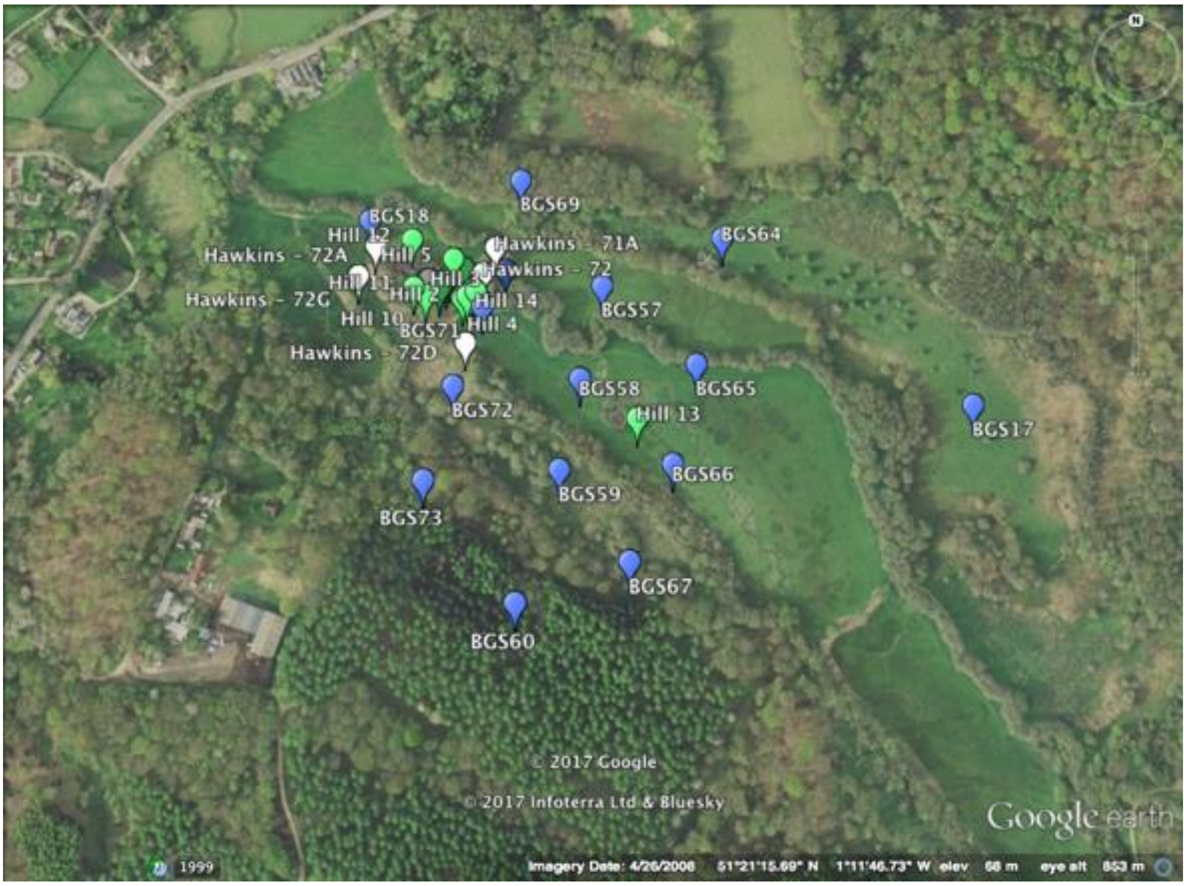


Figure 2. 3 - A map displaying the existing boreholes, prior to this project at Ashford Hill taken by Hawkins (1952) and Hill (1985). The features shown as BGS are stored on the BGS' GeoIndex and were taken during the site investigation phase for the project studied by Hawkins, but not noted in his research (Google Earth, 2017).

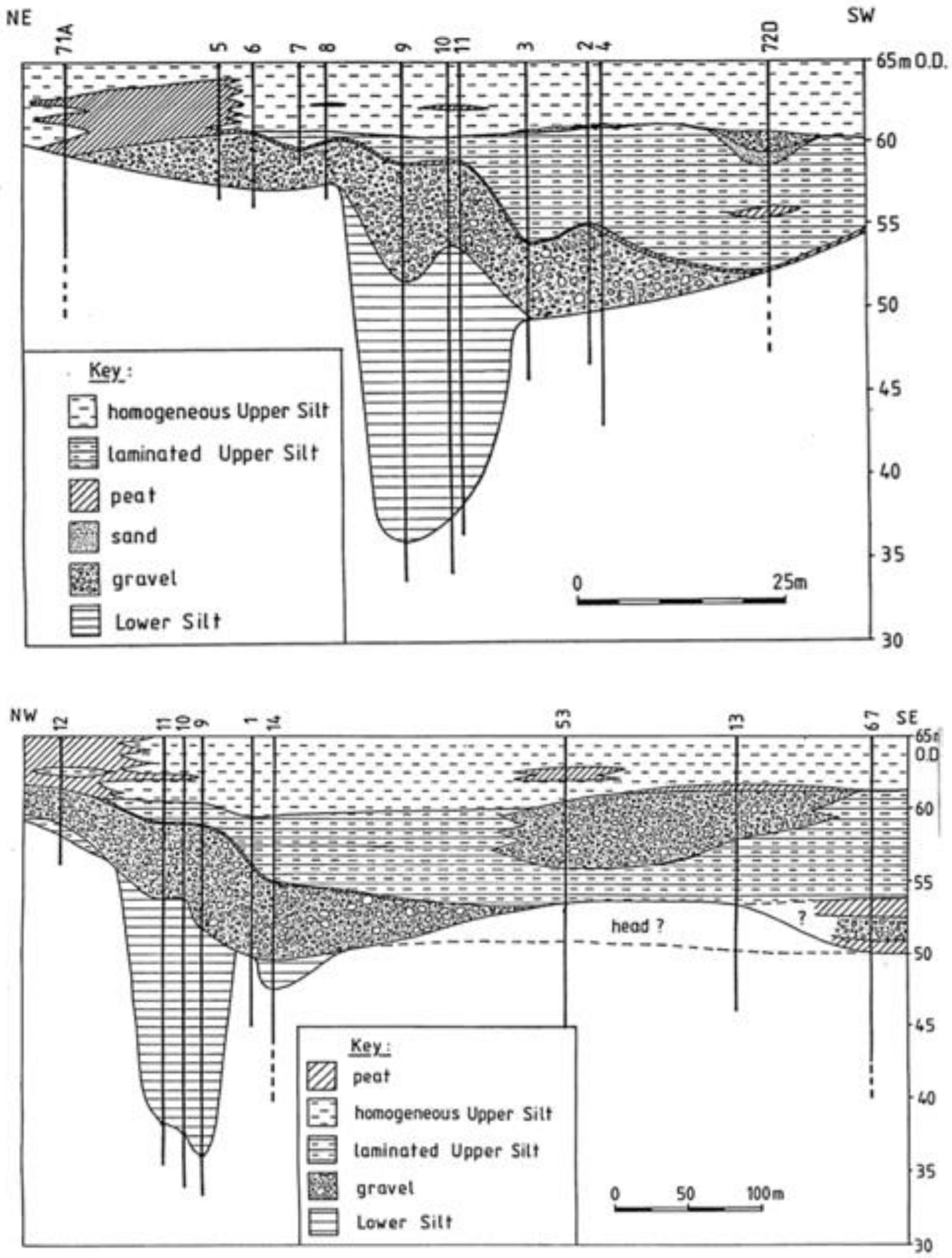


Figure 2. 4 – Hill's (1985) cross-sectional diagram of the DFH at Ashford Hill from borehole data.

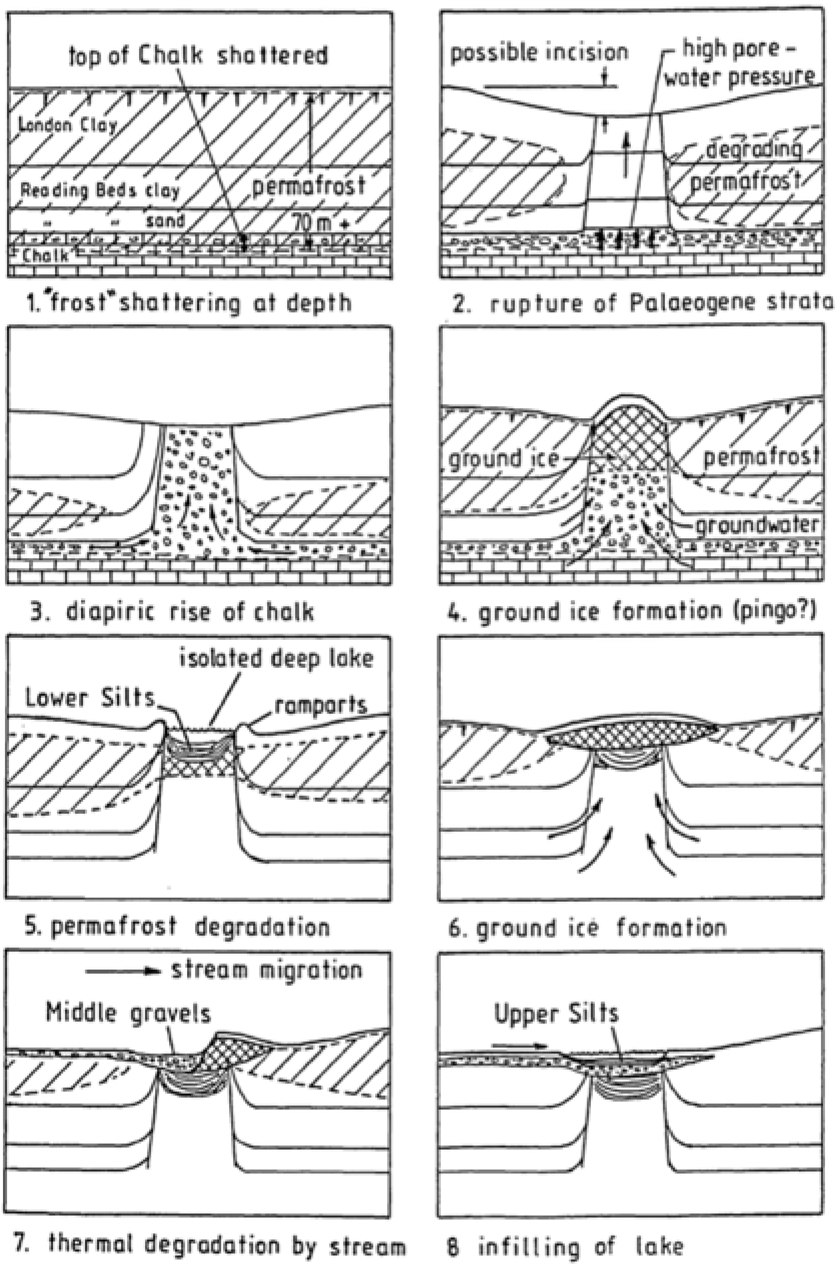


Figure 2. 5 – Formation hypothesis proposed by Hill (1985) for the anomalous ground conditions at Ashford Hill.

Based upon pollen analysis and work undertaken by Hawkins and Hill, Collins (1994) proposed that the DFH at Ashford Hill was infilled during the Devensian Late Glacial.

In 2015, the BGS used geophysics (a passive seismicity sensor) at Ashford Hill to map the extent of the feature using a Tromino (Raines et al., 2015). This appeared to show the chalk diapir feature upwelling through the overlying strata, but further geophysical transects are required to understand the feature's morphology and extent in full (Figure 2. 6).

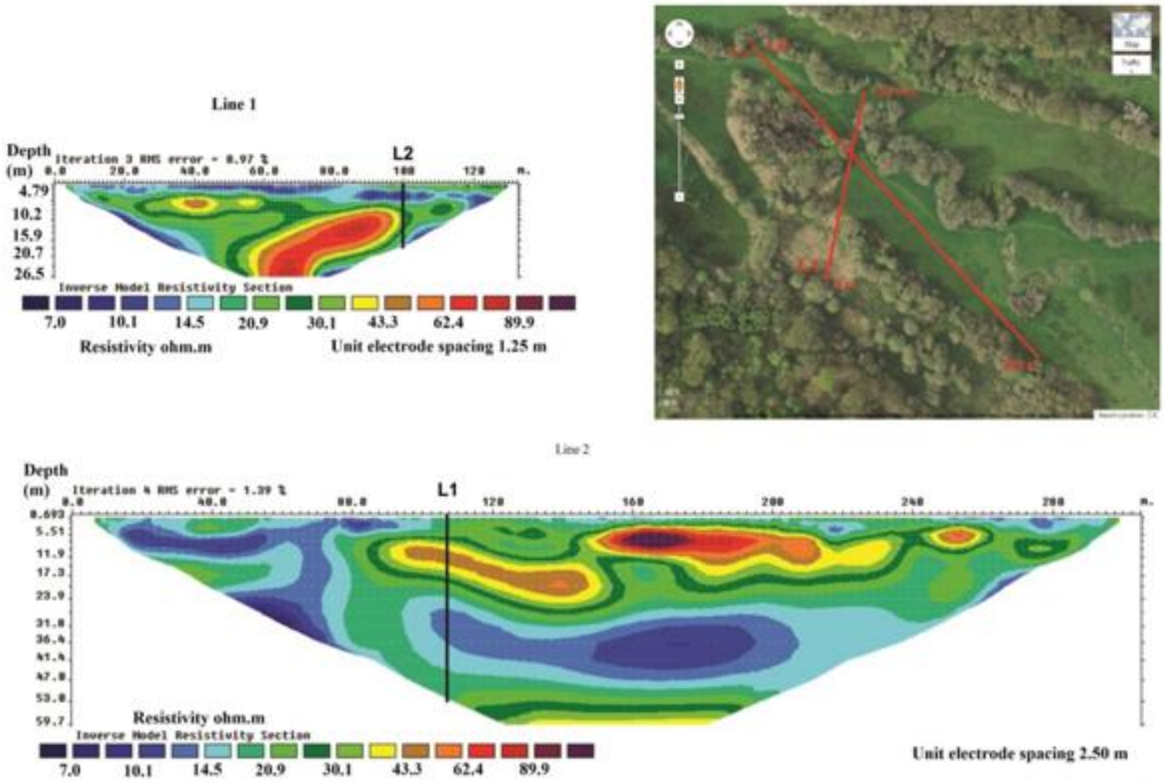


Figure 2. 6- A geophysical survey of the DFH at Ashford Hill and the transect plane (Raines et al., 2015).

Further hollows have been identified north of Ashford Hill at Woolhampton (Worsley & Collins, 1995; Collins et al., 1996) which showed tilting within the infilling material and Brimpton (Bryant et al., 1982; Collins, 1994) which was logged as “normal” fluvial deposits. These features were dated through their infill to the late glacial and early Devensian, respectively. The identification of these features west of central London suggests that their occurrence may be more common than originally thought within the basin. It is plausible that the fewer features are identified outside of central London due to lack of deeper construction and therefore ground investigation. This bias will be discussed later within the thesis.

2.1.2. Denham

Closer to London, a 40m wide and 37.5m deep DFH type feature was identified in Denham, Middlesex whilst site investigations were underway for the M25 motorway. The feature was infilled with gravel, sand and partially laminated silt and clay (Figure 2. 7). Gibbard et al., (1986) who first studied the feature, attributed the formation to a doline formed into the limestone chalk beneath. His theory was justified by the shape of the feature having steep sides and its distance from the Pleistocene ice sheet ruling out a glacial formation. Spink (1991) hypothesised that the same feature was a periglacial depression due to the shearing of its sides and reworked material within. Differences in research for the same feature prove the complexity of studying DFHs. Defining the features physical characteristics through limited data (largely borehole logs) and therefore attributing processes to cover all of the hollows will prove difficult.

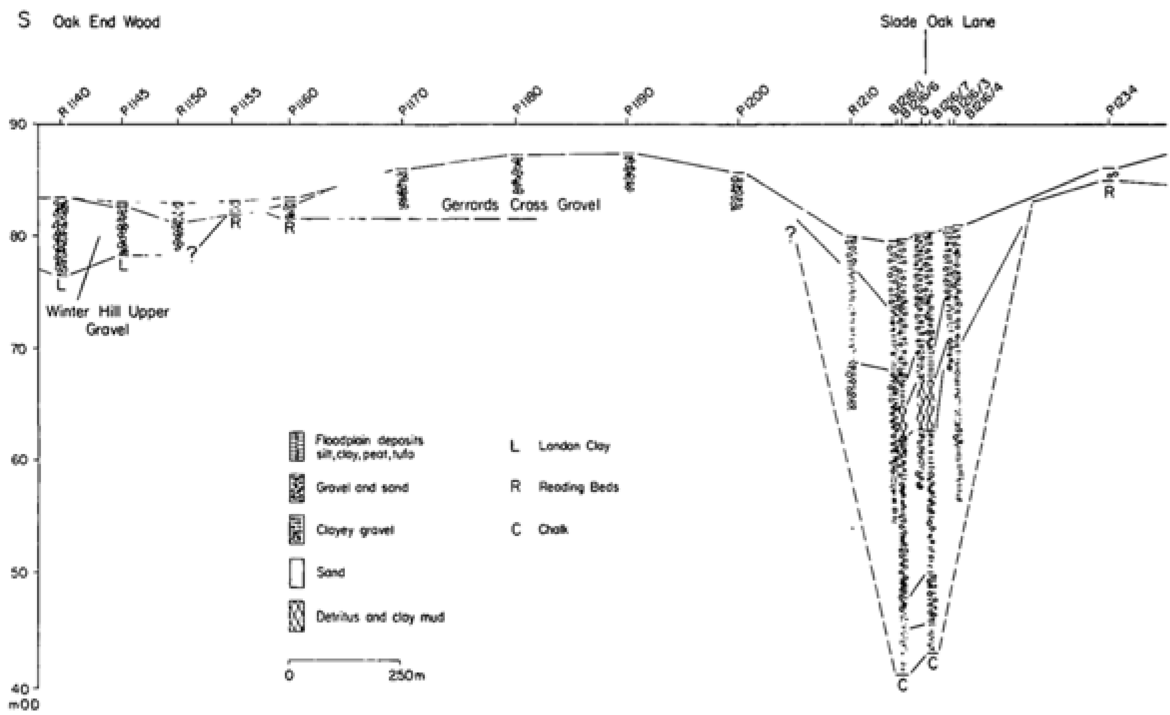


Figure 2. 7 – Cross-section of the DFH at Denham (Gibbard et al., 1986).

2.1.3. Lea Valley

Lee and Aldiss (2012) studied the Lea Valley DFH under the velodrome within the Olympic Park and hypothesised a pingo formation or potentially a combination of fluvial scour and ground ice formation. The borehole studied was the same borehole as the one being used in this project (TQ38NE 1366). The authors report that the chalk is 20m higher in this borehole than the immediate area (usually at 25m OD) and the 43m of mélange type infilling material is made up of chalk, sand, clay and gravel.

Several findings within the boreholes were of note. In particular, the chalk ranges in size and consistency from clasts, to very small, fragile nodules, to putty chalk. The authors attribute this to the material being frozen during formation. The variation in the characteristics of the weathered chalk are likely to reflect differences in original structure and porosity as well as freeze thaw history. Vein quartz and brown flint were also identified throughout the borehole, up to 50m below ground level, both of these materials are usually only identified within RTDs (Bridgland, 1994). This indicates a downward movement of the infilled sediment and confirms mixing. It is possible, the two materials are from the Upnor Fm., but this is less likely due to vein quartz being in higher abundance in the RTD than the Paleogene strata.

The authors identified a minimum of five depositional cycles, fining upwards each time. They attributed this to an open water depression at the top of the hollow at the time of infill. It could also represent several cycles of formation.

Finally, Lee and Aldiss used the RTDs within and above the feature to date the hollow. They propose a late Devensian age for the formation of the feature due to the position of the Taplow Gravel Member. However, using the RTDs as a dating method proves problematic and should be interpreted cautiously due to the mixing of the RTDs within and around the features and the accuracy of identifying specific RTDs in some areas of London (discussed further in chapter 7).

Flynn et al., (2018) furthered this work and identified elemental, mineral and physical structural differences of the chalk within the diapir structure at the Olympic Park site in comparison to 'normal' Seaford and Newhaven Chalk Fm. The differences were attributed to the mixing and vertical movement of the chalk through the Thanet Sand Fm. and the Lambeth Group as well as the deformation of the sediment in a liquid or plastic state. The full hypothesis is provided in chapter 7.

The history of the Olympic Park site is important to understand as it explains potential confusion whilst logging of what is deemed made ground at a greater than usual depth for London. Humans have been using the land in the Lea Valley since the Mesolithic era. Clearance of forest began around 1,500BC and land management within the area is traceable through to present day. After the Blitz in the Second World War, the Lea Valley area was used for dumping building debris and it was used as a landfill site until the end of the 20th Century causing the ground level to be increased by 9m (Unknown, Current Archaeology, 2016).

2.1.4. Central London

The large majority of DFH features have been identified within the M25 and in central London (Flynn et al., 2020). In this area, the majority of DFHs are located in areas of Kempton Park and Taplow Gravel Member RTDs (Banks et al., 2014). Within central London DFHs are largely identified through site investigations, usually from large scale construction projects due to the increased depth of the intrusive techniques. For that reason, research papers have focused on project specific DFH identifications and their implications on the design. Examples of this include the Lee Tunnel (Bellhouse et al., 2015 and Newman et al., 2016, Scoular et al., 2020), Northern Line Extension (Toms et al., 2016), Crossrail (Davis et al., 2018; Linde-Arias et al., 2017; Menkiti et al., 2015; Liew et al., 2016; Skipper et al., 2015; Lawrence and Black, 2019). These papers prove the engineering significance and issues surrounding DFHs and why further research on them is required.

A key example is the Lee Tunnel which is currently the deepest tunnel in London (70m below ground level). During tunnelling as well as the Plaistow Graben, a DFH was encountered (Newman et al., 2016; Bellhouse et al., 2015). Yellow chalk and “rounded flint with a brown rind” were reported at the tunnel face and two further boreholes were drilled. The sediment recovered showed lacustrine and marsh type, laminated sediment below the alluvium which is not common within the London Basin. Fossils within the laminations were dated to early Devensian age. Below this was RTDs (believed to be Taplow, 200,000 years old) mixed with Tertiary strata and then into a mélange of sand, chalk and RTDs. The DFH was not identified in a borehole taken 50m from the feature itself (Bellhouse et al., 2015) showing the ease of missing these features during the site investigation phase.

Further research has also been undertaken to map known DFH features within the London area (Strange et al., 1998; Banks et al., 2014; Flynn et al., 2020). It is generally accepted that more open communication within the engineering industry is required to reduce sub-surface risk by making the locations of these features known once identified. The approach to map hazard susceptibility (such as DFHs) in geology has been put forward since the 1980s (Edmonds, 1988), yet still relatively little has been done in regards to London due to confidentiality within the sector.

From the examples above, features similarities include anomalous depth to bedrock and the infill consisting of largely granular material. Each feature differs in regards to its known width, depth, range of the type of infilling material and the presence or absence of upwelling material beneath the depression.

It is evident from the above that this research project is required to bring together existing work undertaken on DFHs and to further it with evidence and analytical based research. This will both aid the site investigation and geotechnical sectors understand the features physical characteristics and further scientific knowledge on the processes which formed them.

2.2. Engineering Risk

Problematic ground conditions create engineering risk in construction projects across the globe (Van Starveren, 2018). The main risk created by the sub-surface is due to unexpected geology and therefore uninformed design. Uncertainty in engineering is inevitable. Even after undertaking a site investigation to gain an understanding of both the geological conditions and ground parameters it is not feasible, financially or otherwise, to physically test the entire site's sub-surface and therefore fully understand the sub-surface on a minute level (Nadim, 2007). Data acquisition and quality are discussed in detail in Chapter 4. This includes consideration of site investigation practice, the use of boreholes, cone penetrometer tests, sample retrieval methods, ground models (two and three dimensional), the variability of sediment (horizontally and vertically) and difficulties these factors impose for geotechnical testing, engineering and scientific research. In Europe, Eurocode 7 aims to standardise ground investigation practice to reduce risk and increase reliability of the findings. However, the following human factors remain, causing uncertainty and risk in ground engineering (Fookes, 1997):

- A lack of understanding between disciplines (e.g. geological knowledge by a civil engineer);
- Incorrect or insufficient advice between disciplines;
- Insufficient subsurface investigation;
- Communication issues including: lack of understanding, personality clashes, lack of communication between disciplines, not asking correct questions to enable understanding;
- Overworked individuals;

- Human errors in data, design or construction;
- Low quality data collection and recording of information;
- Computing software and outputs not understood.

Although this project focuses on the London Basin, elsewhere within the UK anomalous geology creates sub-surface risks to engineering projects. Examples of this include the chalk (limestone) bedrock which covers large proportions of England and the subsequent genesis of solution pipe features and dolines. Table 2. 1 shows the complexity between subsidence in the chalk and engineering risk. Edmonds (2018) also expressed the need for caution during ground investigations and subsequent design when engineering in chalk due to the increased risks of anomalous geology, in this case subsidence features.

Table 2. 1 –The relationship between subsidence and engineering risk (Edmonds 1988).

PHASE 1	PHASE 2	PHASE 3	PHASE 4
Open undeveloped Countryside	Urban Development (Construction Phase)	Urban Development (End of Construction)	Urban area (Post-Development Phase)
No construction	Active construction. Services, drains and soakaways not fully operational. Active and static loading by construction plant, traffic and materials. Increasing % of ground surface being rendered relatively impermeable.	Construction completed. Services, drains and soakaways operational. Static loading by buildings. Active loading by normal road traffic. 50-80% of ground surface rendered relatively impermeable.	As before
Groundwater concentration dependent on natural ground surface contours.	Groundwater concentration dependent on increasing artificial ground surface contours; installation of drains, soakaways and services; reduction in % of permeable ground surface.	Groundwater concentration dependent on natural and artificial ground surface contours; linear zones where services installed; soakaways and drains; remaining permeable ground surface.	As before. Plus leaking pipes mainly due to long term ground settlement after development.
	Relative subsidence activity level		
Occasional subsidences.	Increased number of subsidences due to collapse of shallow metastable cavities as ground is overstressed.	Increased number of subsidences due to new groundwater flow regime causing destabilization of loose zones and deeper seated metastable cavities.	Lower number of subsidences as deepest seated loose zones and metastable cavities gradually migrate upwards.

A way to mitigate risk is through an increase in understanding of the sub-surface. A key way to improve understanding is to combine differing engineering and scientific disciplines. In 1969, Glossop defined geotechnics as the border of knowledge between geology and civil engineering based within the soil sciences. Since then, geotechnics has grown as a discipline. In the first Glossop lecture Fookes (1997) depicts the relationship between geotechnical engineers, engineering geologists and civil engineers extensively. Hoek (1999) explains the ability of making geology a quantitative science for further analysis by geotechnical engineers and the larger engineering community. The value of geotechnics is expressed by De Freitas (2009), through its comprehension of the sediments' history to understand its parameters and geological controls.

Ground models are often employed to visualise the sub-surface information gained from the site investigation phase, in particular borehole logs. However, uncritical overreliance on ground models, particularly of varying quality can increase risk instead of reducing it. This is particularly true where knowledge of the ground models limitations are not known or communicated to those reading or interpreting it. Fookes' Glossop lecture in 1997 stated that a ground model is the link between "landforms, weathering, climate and engineering soils". He expresses that communication of the ground model can be a cause for concern as there are often misunderstandings between geologists, engineering geologists and civil engineers. Fookes concluded that the quality of the ground model depends on the quality of the data inputted, education and communication of the information held within the model, including potential risks.

Culshaw's Glossop lecture in 2005 touched upon the variability within a single geological unit. He stated that using depth plots to visualise this variation is not detailed enough to fully understand the changing characteristics of the soil or provide sufficient understanding of the risk. Fookes (1997) and Culshaw (2005) concluded the need for detailed and high quality ground models as well as effective communication and information sharing of both the ground model and its associated sub-surface risk between disciplines in order for effective engineering judgement to be made.

All of these matters raised demonstrate the relationship between unexpected and anomalous geology and sub-surface risk for engineering projects. This thesis will focus on DFHs within the London Basin as an example of sub-surface risk created through anomalous and often unexpected ground conditions.

2.3. Background

2.3.1. London Basin

All identified DFHs to date, have been located within the London Basin. The London Basin is defined here as the area between the chalk outcrop to the north in the Chilterns, the North Downs in the South and as far west as the London Clay Fm. is still present. The basin began to form during the Late Cretaceous (100.5–66 Ma) and deformed extensively into its current form through northward compressional tectonics during the Alpine Orogeny. Its main syncline runs in a north-easterly direction (Royse et al., 2012) (Figure 2. 8).

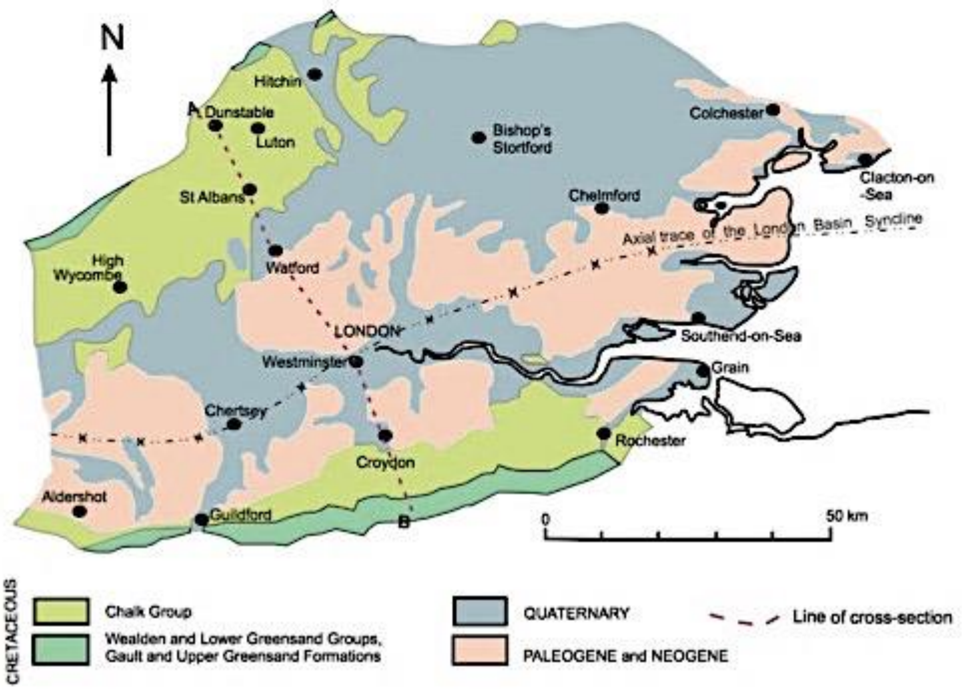


Figure 2. 8 – Simplified London geological map showing the basin syncline (Royse et al., 2012).

More locally, through detailed lithological description, several faults have been identified within the chalk in the southeast of England (Figure 2. 9) (Mortimore et al., 2011). The distinct colour and pattern of the Lambeth Group also enables faults to be identified across relatively small areas (Royse et al., 2012) within the London Basin. The main identified faults in London are the Greenwich fault, the Streatham fault and the Wimbledon fault (Figure 2. 9). Most recently the Plaistow Graben has been identified to the east of central London during the site investigation for the Lee Tunnel (De Freitas, 2009; Newman, 2008).

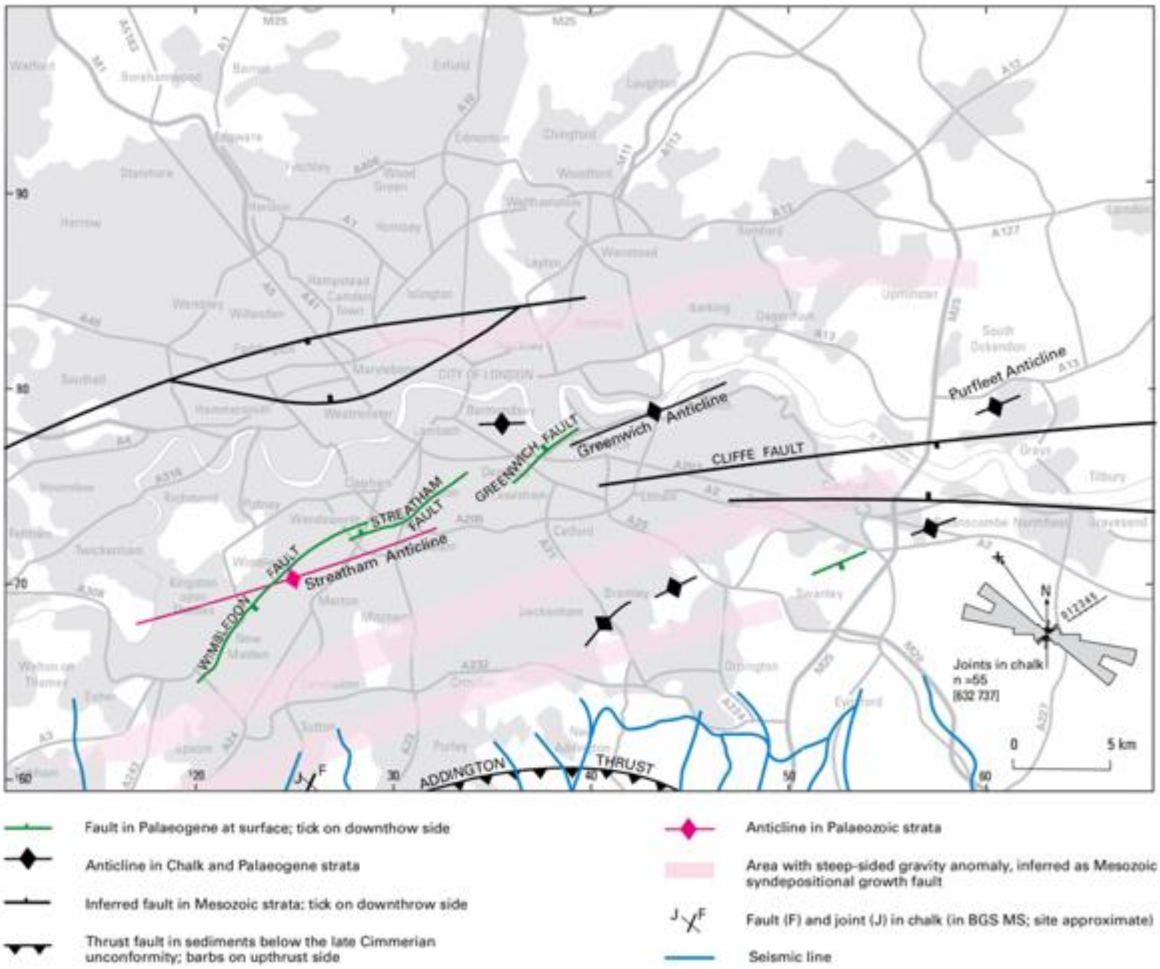


Figure 2. 9 – Key tectonic structures identified across the London Basin (Ellison et al., 2004).

Although London is often presumed to be tectonically stable in recent history, research now suggests otherwise (Aldiss, 2013). This faulting may be due to the proposed inversion of the basin, especially to the northeast of London where displacements of up to 10m have been observed across individual faults and dated (through River Terrace Deposits (RTDs)) within the last 100ka (Ghail et al., 2015). RTDs have also cumulatively uplifted by around 140m. Furthermore, current research using InSAR data, shows that small scale tectonics are still occurring and influencing England, and the London Basin in particular, to present day (Mason et al., 2015).

Until recently, the geology of London was believed to be relatively simple (Sumbler, 1996). In 2004, Ellison et al., published the London Memoir which brought together geological research for the region, advancing understanding of the basin as a whole. Royse et al., (2012) also published a review paper covering the geology of London. More recently, the complexity of the London Basin is becoming better understood through more research, such as on DFHs (Flynn et al., 2020), the Harwich Formation (Skipper & Edgar, 2019) and faulting (Aldiss, 2013 and Morgan et al., 2021).

2.3.2. Climate/glaciations

Climatic fluctuations across the globe have caused repeated glacial and interglacial cycles (Milankovitch, 1938). The last global glacial maximum occurred around 21,000 years ago, causing global sea level to drop by 130m and much of the northern part of the UK to be covered by an ice sheet ca 840,000 km^2 (Clark et al., 2012).

The two UK glaciations focused on within this project are the Anglian (around 450,000 BP, Marine Oxygen Isotope Stage (MOIS) 12) and the more recent Devensian (c. 110,000 to 11,000 ka BP, MOIS 4-2). The Anglian was the largest and most extensive glaciation during the Pleistocene to affect the British Isles. This ice sheet reached as far as St Albans, around 20km north of central London according to Gibbard (1977) and Pawley et al. (2010) and further advances into London (Finchley and Hornchurch) according to research undertaken by Baker and Jones (1980) and Bridgland (1994) (Figure 2. 10).

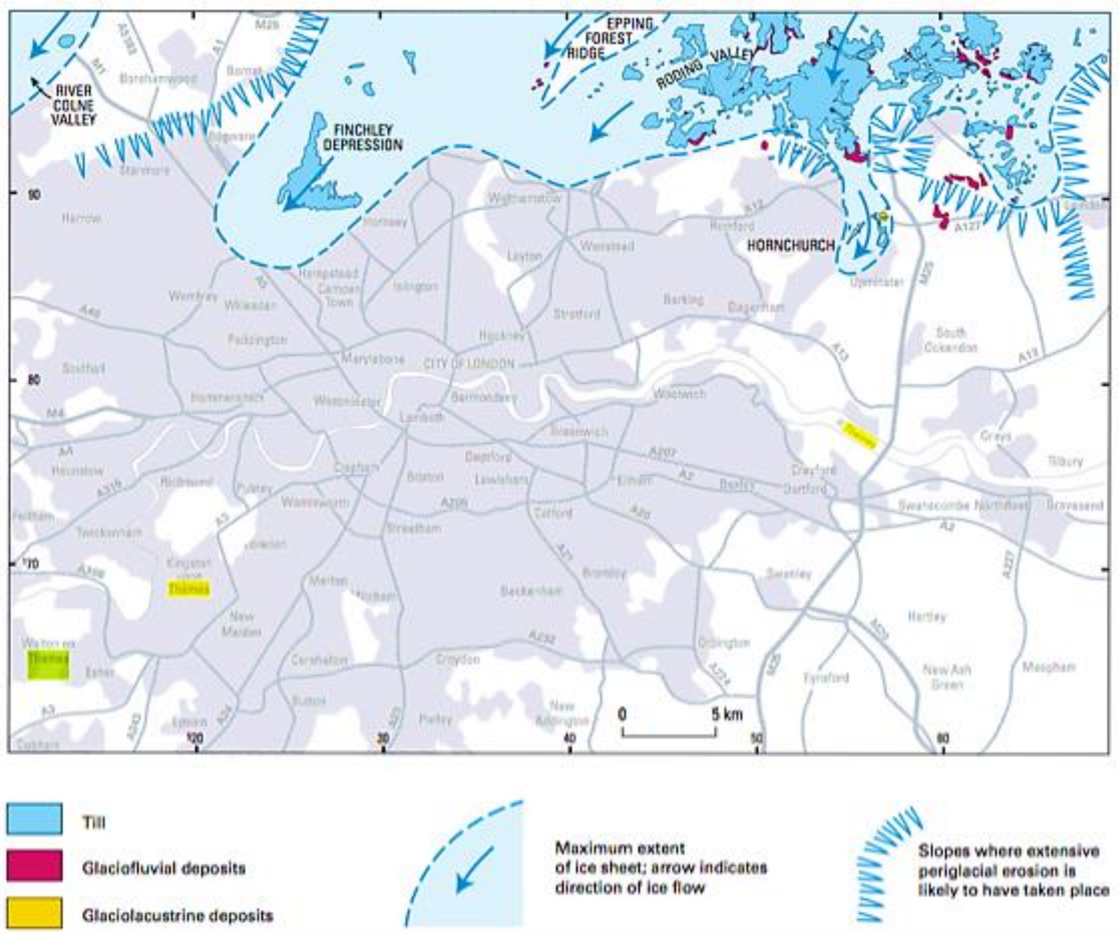


Figure 2. 10 – Map showing the limit of the Anglian ice sheet and its associated features (Ellison et al., 2004).

The Devensian glaciation (Figure 2. 11) is the most recent glaciation in the UK. Although there were several episodes of ice growth, its glacial maximum was around 22ka BP (Bowen et al., 2002). Although it did not extend as far south as the Anglian ice sheet, Murton and Ballantyne (2017) state that the south of the UK, including the London Basin was a periglacial environment, most likely affected by cold temperatures (ranging from -10 to -28°C, Gao et al., 1998) and the glacial system itself.

Beyond the glacial limit is the periglacial environment. Affected by the harsh climatic conditions and aeolian dominant environments, periglacial environmental conditions produce numerous associated features, some of which are discussed later as possible hypotheses for the formation of DFHs. Former periglacial processes cause unexpected problems for present day engineering projects (Higginbottom and Fookes, 1970; Engineering Group Working Party Report, 2017).

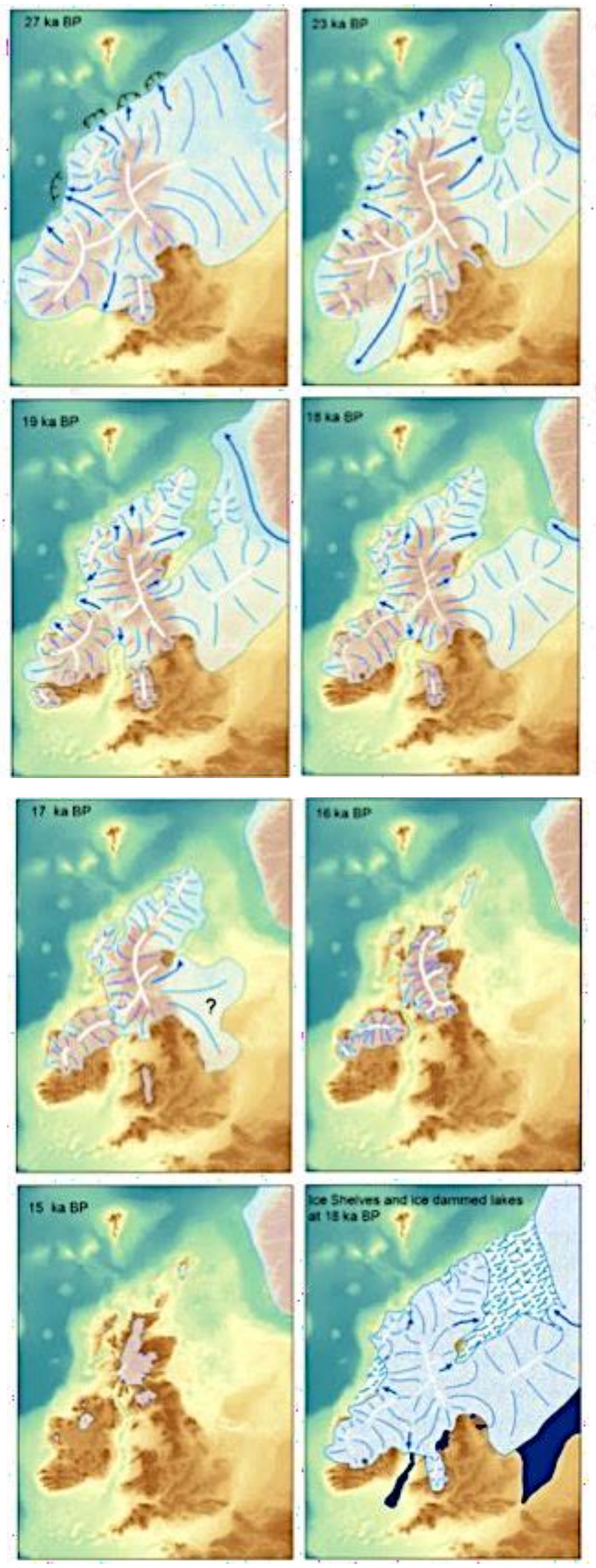


Figure 2. 11 – Devensian glacial ice extent and retreat across the UK from Clark et al. (2012). Ice divisions are shown via the white lines, ice streams are shown in the blue arrows and ice flow via blue lines.

2.3.2.1. Permafrost

Permafrost is defined as ground which is at 0°C or lower for a minimum of two successive years (French 2013). It is present in many periglacial environments across the globe and can play a significant role in the creation of cryostratigraphic features.

Within the UK, glacial ice limits during both during the Anglian and the Devensian are still not precisely known for certain and permafrost estimations are based upon these ice extents. Hutchinson and Thomas-Betts (1990) mapped the UK's permafrost limits showing "extensive permafrost" across the London Basin (Figure 2. 12) based upon a heat flow map by Wheildon and Rollin (1986), however it is not based upon physical evidence from the London Basin. Murton and Ballantyne (2017) furthered understanding of periglacial conditions and segregated the UK into regions of periglacial activity for both the Anglian and the Devensian glaciations (Figure 2. 13).

Recent advances in mapping permafrost using numerical models across Great Britain has shown that permafrost depths could have reached up to 100m closest to the glacial limit (Busby et al., 2016). This study used geothermal heat flux, a similar methodology to Hutchinson and Betts (1990). However, no sites within either study fell within the London Basin and were all in areas with proven permafrost from physical evidence. The presence of permafrost in the Basin and south coast is suggested through brecciation of chalk at depth (Hutchinson, 1991), however breccia can also be caused by high water pressure or localised syn-sedimentary tectonics (Van Loon et al. 2013; Aubrecht and Szulc, 2006), therefore it is not conclusive evidence for permafrost. Furthermore, Murton and Belshaw (2011) state that the top of the permafrost has the most ice rich layers, particularly in silt and clay strata due to the high permeability, and these lenses decrease with depth. An additional point to note from the paper is that they have stated the RTDs prevented the permafrost active layer from reaching the London Clay Fm. With the chalk at a depth most often below <75m across the London Basin (in particular, central London where the DFH features have been identified in mass) it decreases the likelihood that the chalk in central London deformed due to permafrost.

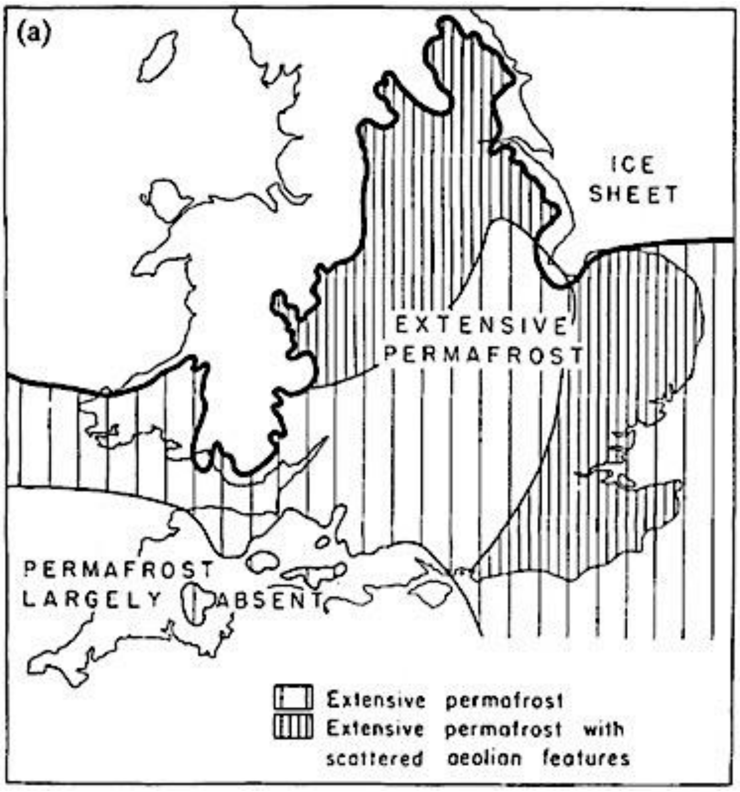


Figure 2. 12 – Modelled permafrost limits of the late Devensian maximum mapped by Hutchinson and Tomas-Betts (1990).

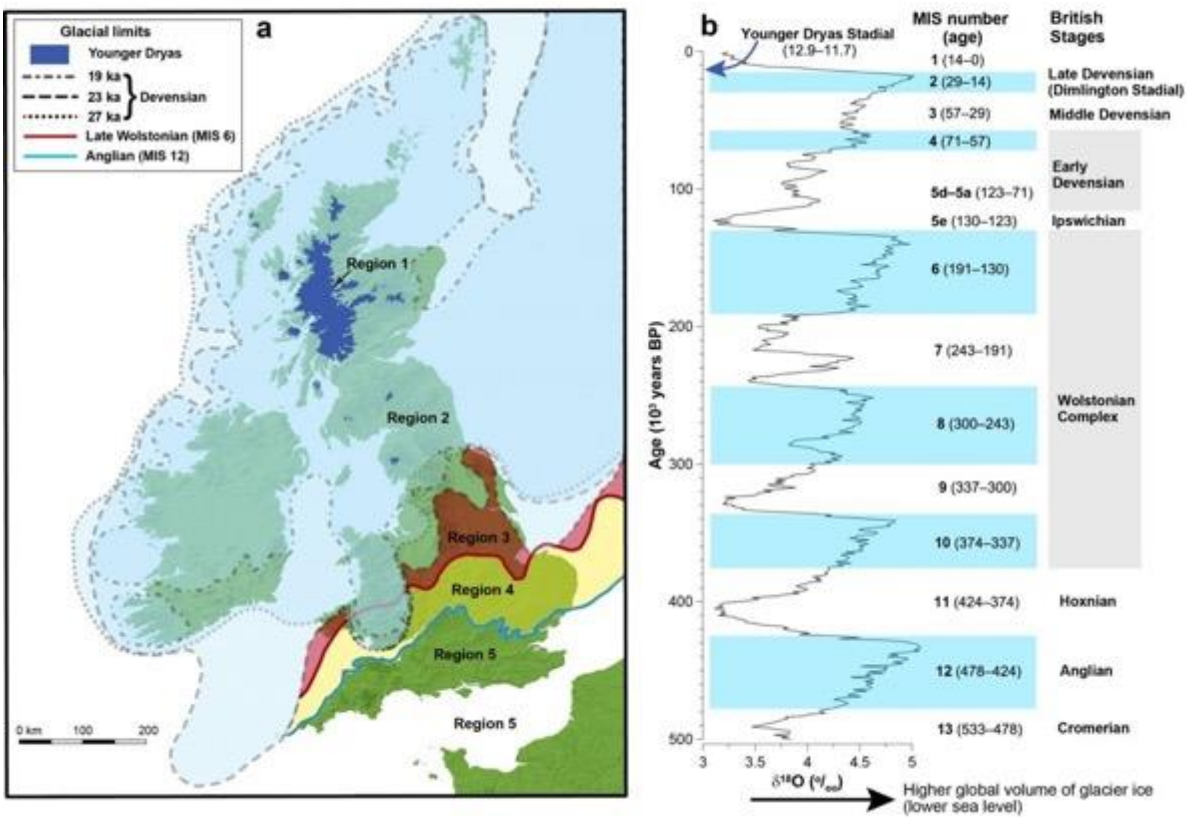


Figure 2. 13 – Permafrost environments across Britain during the Anglian, Wolstonian and Devensian glaciations (a). The associated timescales discussed throughout the project (b) (Murton & Ballantyne, 2017).

Permafrost affects soils due to its discontinuous behaviour. For example, its decay can induce slope failure through enabling excess pore water pressure within the surrounding sediment (Hutchinson, 1991). Harris et al., (2008) undertook an experimental study on the effect of permafrost on soil and concluded that excess pore water pressure during permafrost decay causes shearing and in the longer term deformation of sediment structures. The deformation is largely due to frost creep and is more abundant in sandy soils with low clay and silt content. Harris' research was undertaken using low pressures (simulating shallow environments). This demonstrates that even with low pressures deformation is possible. Harris et al., (2008) also noted that gelifluction is more likely in finer grained soils. Chamberlain and Gow (1979) similarly undertook a laboratory experiment on freezing and thawing of soil and found that repeated thawing and freezing can lead to a reduction in void space and an increase in permeability due to shrinkage cracks. Both of these studies are good indicators of soil behaviour in permafrost conditions, however, caution of the findings should be employed due to their controlled nature.

Identifying historic permafrost is reliant on the presence of periglacial features such as ice wedges, pingos, palsas or lithalsas (Isarin, 1997). Periglacial features are widespread across the UK and several sites have been identified within 100km of the London Basin (Clay, 2015; Murton and Lautridou, 2003). An example of permafrost evidence through relict periglacial features in the UK is provided by Worsley (2015). He identified ice and sand wedge structures in Chelford, Cheshire from now relict features of ice and sand-wedge casts and the features were dated to cold periods (c. 100 ka, c. 25 ka and c. 18ka). This indicated that permafrost was present within the area at those times. Without these features, or similar, it is not possible to state that permafrost was present within the London Basin.

Research demonstrates that factors which influence periglacial processes include climate, topography, sediment material, time, human activity, snow/ice cover, liquid moisture (and its availability), and vegetation. These physical relationships, in particular between permafrost and sedimentary behaviour are important when discussing DFHs, their formation as well as their current geotechnical characteristics.

2.3.3. Fluvial activity

The River Thames is the main drainage of the London Basin and encompassing its tributaries, is the largest river system in Britain. Often in literature it is split into the Upper, Middle and Lower Thames; with the last two falling within the London Basin flowing eastwards to the North Sea (Royse et al., 2012).

Originating during the Cenozoic (Gibbard & Lewin, 2003) the Thames, or proto-Thames (as often referred to), once flowed from northwest England, draining the Midlands. Until the late Anglian, the River Thames flowed through the Vale of St Albans, north of London (Gibbard, 1977). Due to glacial ice advance during the Anglian, the river moved southwards to its current valley and has resided for around 500,000 years (Figure 2. 14) (Gibbard, 1985). During this time, it has changed in many fluvial aspects. For example, the present day lower reaches of the river are tidal, whereas this was not the case during Roman times (Ellison et al., 2004).

In the current Thames Valley, the river has had and lost many tributaries (Figure 2. 15). Detailed work on the Thames and its tributaries during the Holocene has been undertaken by Nunn (1983). This was followed by Barton's (1992) work on the lost rivers of London.

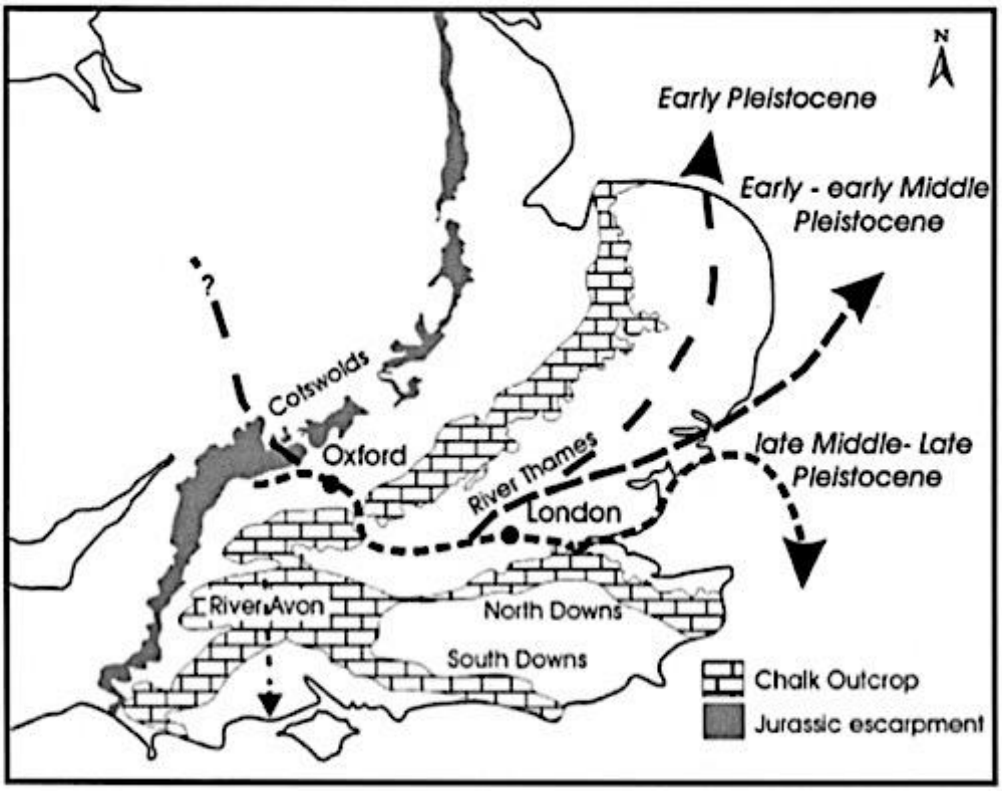


Figure 2. 14 – The southwards migration of the River Thames (Maddy et al., 2000).

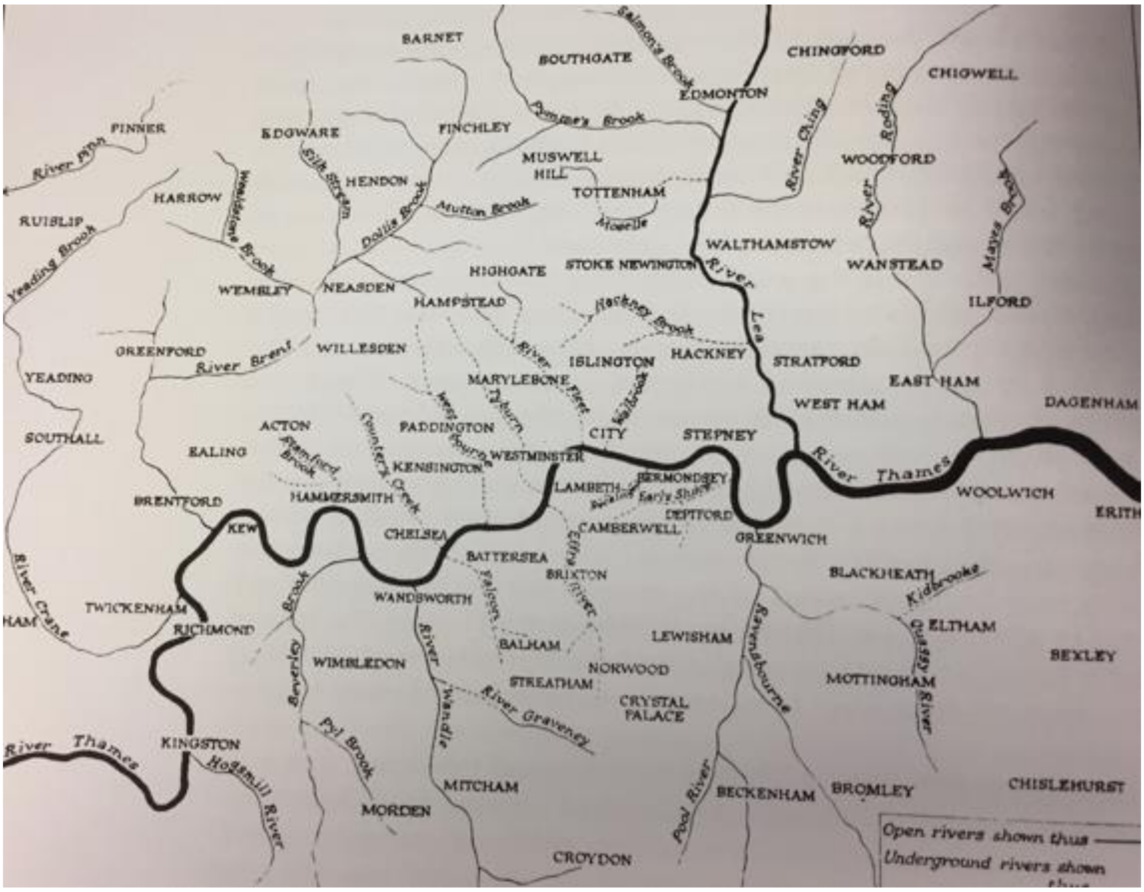
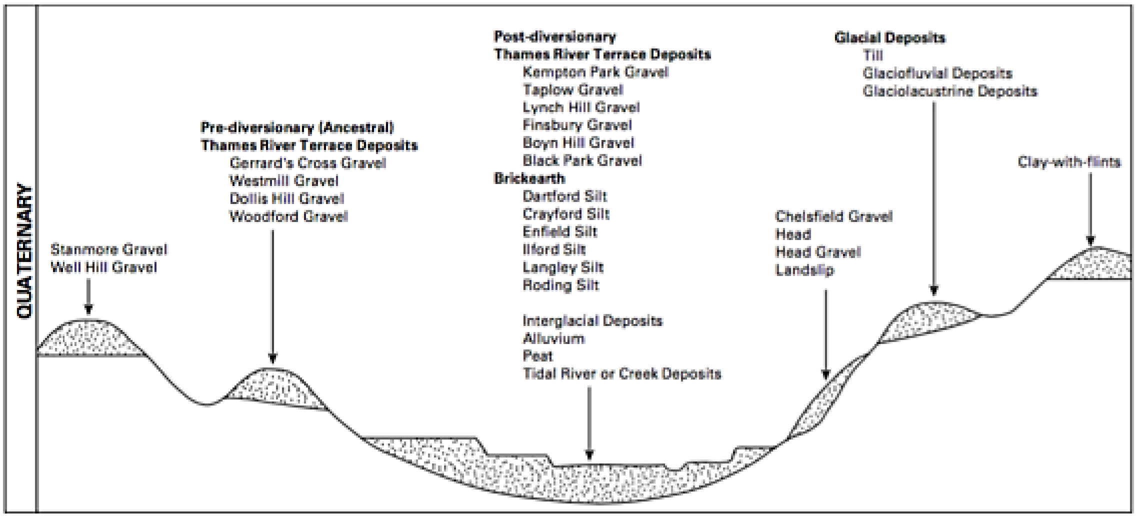


Figure 2. 15 – The River Thames tributaries, present and historic, identified in the figure through the dashed line (Barton, 1992).

2.4. London Geology

An overview of the London Basin's geology relevant to this research can be seen in Figure 2.16.



Period	Group	Formation	Thickness
PALAEOGENE		Bagshot Formation: sand, fine-grained with thin clay beds	10–25
	Thames	London Clay Formation: clay, silty; fine sand clay at base. *Claygate Member*: interbedded sand and clay at top	90–130
		Harwich Formation: sand, clayey fine-grained sand and pebble beds	0–10
	Lambeth	Reading, Woolwich and Upnor formations: clay mottled with fine-grained sand, laminated clay, flint pebble beds and shelly clay	10–20
		Thanet Sand Formation: sand, fine-grained	0–30
CRETACEOUS	Chalk	Undivided mainly Seaford Chalk Formation: chalk soft, white with flint courses	Up to 70
		Lewes Chalk Formation: chalk, white with hard, nodular beds	25–35
		New Pit Chalk Formation: chalk white to grey with few flints	30–40
		Holywell Chalk Formation: chalk white to grey, shelly, hard and nodular	13–18
		Undivided Zig Zag Chalk Formation and West Melbury Marly Chalk Formation (formerly Lower Chalk): chalk, pale grey with thin marls; glauconitic at the base	65–70
		Upper Greensand Formation: sand, fine-grained, glauconitic	Up to 17
		Gault Formation: clay, silty	50–70
	Lower Greensand	Folkestone Formation: sandstone, fine- to medium-grained	60
Concealed strata	Lower Greensand	Sandgate, Hythe and Atherfield Clay formations: sandstone and mudstone	34
	Wealden	Weald Clay Formation: mudstone Hastings Beds: sandstone and mudstone	Up to 150
JURASSIC		Limestone and mudstone	0–c.750
SILURIAN AND DEVONIAN		Sandstone and siltstone	

Figure 2. 16 – Simplified overview of the geology of London. Thickness is shown in metres (Ellison et al., 2004).

2.4.1. Bedrock

For this project the bedrock is defined as the pre-Quaternary deposits due to its denser material properties in relation to the overlying superficial deposits.

2.4.1.1. Chalk Group

This research will focus solely upon the Seaford Chalk Fm. and the Newhaven Chalk Fm. previously together termed the Upper Chalk. The chalk formations were deposited in deep marine conditions during the Late Cretaceous and are comprised of fine grained limestone, with flints and marl bands. Mortimore (1986) and Mortimore et al., (2011) mapped the stratigraphy of the two formations and, in turn, the faults identified within the strata within the south east of England. The Cretaceous deposit underlies the entire London Basin, up to 200m in thickness (with the Seaford and Newhaven Fm.s being up to 70m thick), outcropping to the north at the Chiltern Hills and the south at the North Downs (Royse et al., 2012). During the Cretaceous Period, the sediment underwent episodes of deposition, folding, uplift and erosion (Ellison et al., 2004) leading to its current faulted state, which is unconformably overlain by the Thanet Sand Fm.

GEOCHEM OF CHALK

The Chalk Group forms part of the Lower or Deep aquifer which underlies the basin alongside the Thanet and Upnor Formations, unconfined at its perimeter and confined in the centre by the overlying clay (London Clay Fm. and Lambeth Group). The aquifer has been heavily influenced by groundwater abstraction since the 17th Century (Ward, 2003), linked to the mass population growth in London (Ellison et al., 2004). Additionally, the aquifer's groundwater movement is heavily influenced through basin tectonics and the basement blocks (north-south crustal extension and the east-west basement block fractures). Royse et al., (2012) proposed that these faults and fissures have the potential to create a "flow regime". Flow regime meaning a pattern and type of flow structure.

The presence of flints and marl bands hamper deep engineering projects due to their hard nature and physical impact on tunnel boring machines (TBMs). Faulting also has implications on the movement of groundwater and therefore causes issues for sub-surface development (e.g. Haswell, 1969). However, the Seaford and Newhaven Chalk formations are softer in nature than chalk formations identified elsewhere (e.g. Yorkshire and Norfolk; Bell, 1977) which enables a better engineering medium.

2.4.1.2. Thanet Formation

The Chalk Group was overlain unconformably by the Thanet Fm. during the Palaeocene (58-56ma). The unconformity is due to multiple uplift and erosion events of the chalk prior to and during the deposition of the Thanet Sand Fm. (Knox, 1979). The formation consists mainly of fine, grey sand which coarsens upwards, with a maximum thickness of 30m at the east of the basin and thins in the northwest (Ellison et al., 2004). The formation was deposited under marine conditions. The unit's heavy mineral assemblage indicates the leaching of minerals at the top of the formation is due to uplift and emergence of the stratum post deposition (Morton, 1982).

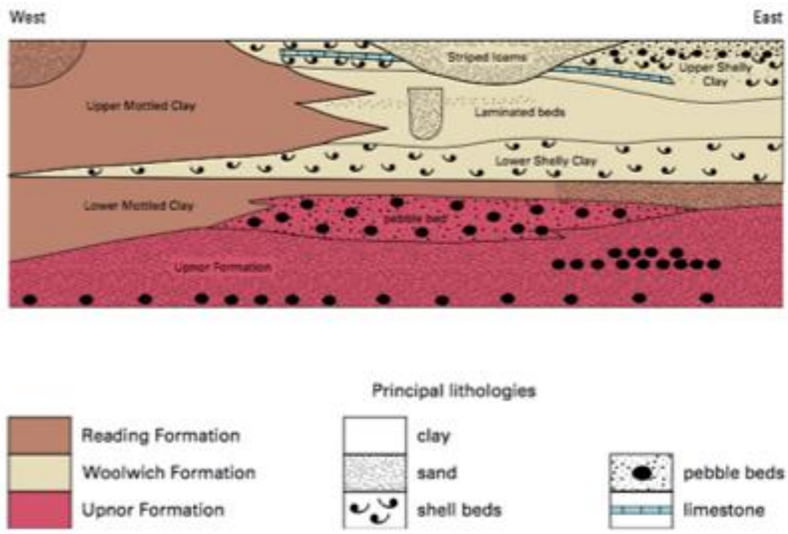
At the base of the formation are the Bullhead Beds, formerly named the Thanet Base-Bed (Whitaker, 1866). These beds range from 0.1 to 1.2m in thickness and comprise of flint (derived from the chalk), clay, silt and sand (Royse et al., 2012). A thin layer of volcanic ash is also present in some locations at the base of the Thanet Sand Fm. (Ellison and Lake, 1986; Knox, 1979).

The Thanet Fm. is non-cohesive with a high bearing capacity (Ventouras and Coop, 2009). For engineering purposes, the stratum is problematic due to the potential for running sand if below the water table (Ellison et al., 2004).

2.4.1.3. Lambeth Group

The Lambeth Group is Thanetian to Ypresian in age, between 59 and 46ma (Pearce et al., 1998). Previously known as the Upnor, Woolwich and Reading beds (Figure 2. 17), the three combine to form a strata of discontinuous clays, silts and sands which at their maximum are 30m thick. The irregularity of the formation is due to its depositional environment of brackish and marginal marine waters. Its mottled appearance is attributed to the deposition of iron bearing minerals and the subsequent uneven oxidisation occurring during alternating waterlogged and drier conditions (Skipper, 1999; Entwisle et al., 2013).

The mineralogy of the clay and non-clay material which makes up the Lambeth Group is summarised in Entwisle et al. (2013).



Formation	Previous nomenclature	Informal units used in this account
Reading Formation	Reading Beds	Upper Mottled Clay†‡ Lower Mottled Clay†‡
Woolwich Formation	Woolwich Beds	Upper Shelly Clay† Laminated beds† 'striped loams'* Lower Shelly Clay†‡
Upnor Formation	Bottom Bed	'pebble bed'†

† Ellison et al., 1994.
* Dewey et al., 1924.
‡ Skempton and Chrimes, 1994.

Figure 2. 17 – A diagram depicting the Lambeth group across London with the previous nomenclature and sub-units of the group below (Ellison et al., 2004).

For engineers the variability of the Lambeth Group has several implications. This is mainly due to non-constant or predictable ground conditions. Moreover, the deoxygenated Upnor Fm. leads to extreme health and safety risks and has resulted in deaths (Lewis & Harris, 1998; Newman et al., 2013). In 2013, the BGS released a report on the "engineering geology of the Lambeth Group" which extensively covered the mineralogy of the varying sediment, cross-sections, geotechnical properties, hazards and geophysical techniques for understanding the sequence. The report also covered data quality when studying the sediment as well as presentation of the data (discussed further in chapter 4, Data Quality).

Skipper et al., (2015) highlighted multiple engineering challenges arising from the Lambeth Group including anomalous geology, not visible from the ground surface such as: sand channels, calcrete beds and faulting. They concluded by highlighting the importance of training, education and, in turn, high quality logging when engineering the highly variable group of strata.

2.4.1.4. Harwich Formation

The Harwich Fm., comprising of, and previously known as the Blackheath Member (Beds), Oldhaven Member (Beds) and Swanscombe Member lies unconformably on the Lambeth Group and is overlain by the London Clay Fm. discontinuously throughout the basin. Deposited during the Eocene, the marginal and marine sediment infilled the irregular channels and the depositional environment left by the Lambeth Group prior to the sea level rising. The stratum is at a maximum 24m thick, but most commonly less than 2m and consists of gravel, sands, shells and clay (Royse et al., 2012; Skipper & Edgar, 2019).

All of the Harwich Fm. Members contain calcareous concretions, alongside its compositional variation and the higher permeability of this layer between the London Clay Fm. and the Lambeth Group make the Harwich Fm. significant to engineers (Skipper & Edgar, 2019). Particularly in regards to excavating, tunnelling projects and pile foundations, several large scale engineering projects (Crossrail and Thames Tideway) in London have encountered issues in relation to the Harwich Fm. These include the cemented layers (due to calcareous concretions) impeding grouting necessary for the TBM to be protected from the higher permeability present within the Harwich Fm. and TBMs being deflected off course due to the concretions (Skipper & Edgar, 2019).

2.4.1.5. London Clay Formation

The London Clay was deposited during the early Eocene in a marine environment across the entirety of the London Basin (Hight et al., 2003). At its maximum thickness, the clay can be up to 200m and has a low permeability (Kemp & Wagner, 2006). Its relative homogeneity across the basin makes the formation an ideal medium for tunnelling and sub-surface development (Royse et al., 2012). The thick strata is divided into several sub-units (King, 1981) which aids site investigation geologists to distinguish between its relatively consistent firmness and grey, blue colour. The clay mineralogy consists of kaolinite, smectite, illite, chlorite, montmorillonite, and pyrite while the silt is comprised of quartz (Hight et al., 2003).

Numerous researchers have studied the physical characteristics of the London Clay and the impacts these geotechnical variables have on engineering projects (Gasparre et al, 2007; Barnes, 2013). Although constant in colour there are differences in plasticity across the basin. This increases from west to east, as does the degree of over-consolidation.

Furthermore, Chandler's Glossop lecture (2000) was based upon the clay cycle (mainly focusing upon the London Clay Fm.) and its geotechnical implications including the effect of erosion and weathering evident through the red/brown colouring of the clay. It is understood that weathered London Clay material is the result of the weakened soil structure by reducing yield stress, stiffness and strength which can lead to structural collapse of the sediment.

While it is acknowledged that the London Clay is well understood, there are still unknowns. For example, whilst linked to permeability, its swelling potential is still not fully understood (Hight et al., 2013). This impacts on understanding of its history and behaviour since being lain.

Evidence of faulting is apparent within the formation through the presence of polished surfaces. Not only does the polished clay surface show that the basin has been tectonically active in recent geological time (since the London Clay was deposited 56ma), it also provides discontinuities in the geotechnical characteristics (reducing the friction resistance and in turn shear strength) of the clay sediment (Mesri & Shahien, 2003) and the potential for water movement within the usually highly impermeable strata.

2.4.2. Superficial Deposits

Since the end of the Pliocene and Early Pleistocene, deposition within the London Basin has been dominated by river terrace deposits (RTDs), alluvium and more recently made ground.

2.4.2.1. River Terrace Deposits

RTDs are lain by the current and palaeorivers within the basin through depositional processes depending on the environment and material available (Figure 2. 18). Within the London Basin, the RTDs range from 2 to 15m in thickness and the majority were deposited during cold periods through aggradation and incision (Maddy, 1997; Maddy et al., 2000). Key to note is that one RTD may represent more than one glacial cycle (Lewin & Gibbard, 2010). Controls on the rate and location of the gravel deposits include the availability of sediment and transportation power, these are often associated with glacial and periglacial processes. Further information can be found in Figure 2. 19.

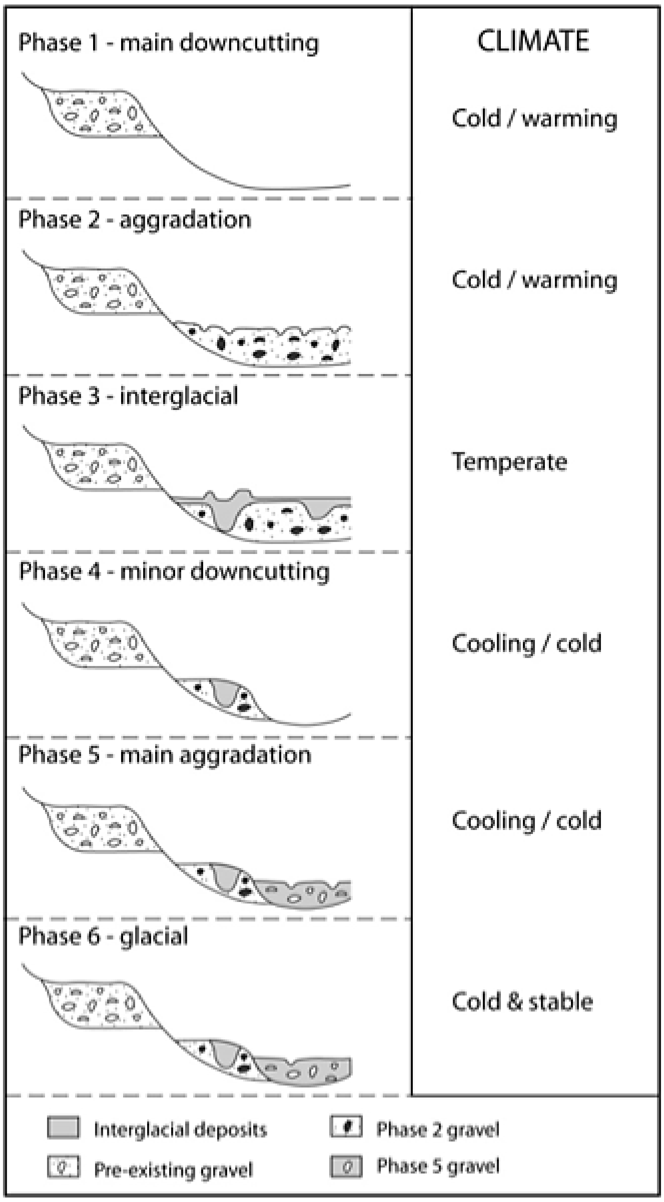


Figure 2. 18 - River Thames terrace formation in relation to climate (Murton & Belshaw, 2011).

For the River Thames, the older, lower deposits consist of more exotic clasts showing the greater extent of the Thames and proto-Thames, whereas the more recent deposits consist of local lithology (Royse et al., 2012). It is proposed that further incision of the Thames and its deposits has taken place within southern England due to crustal uplift (Maddy et al., 2000; 2001).

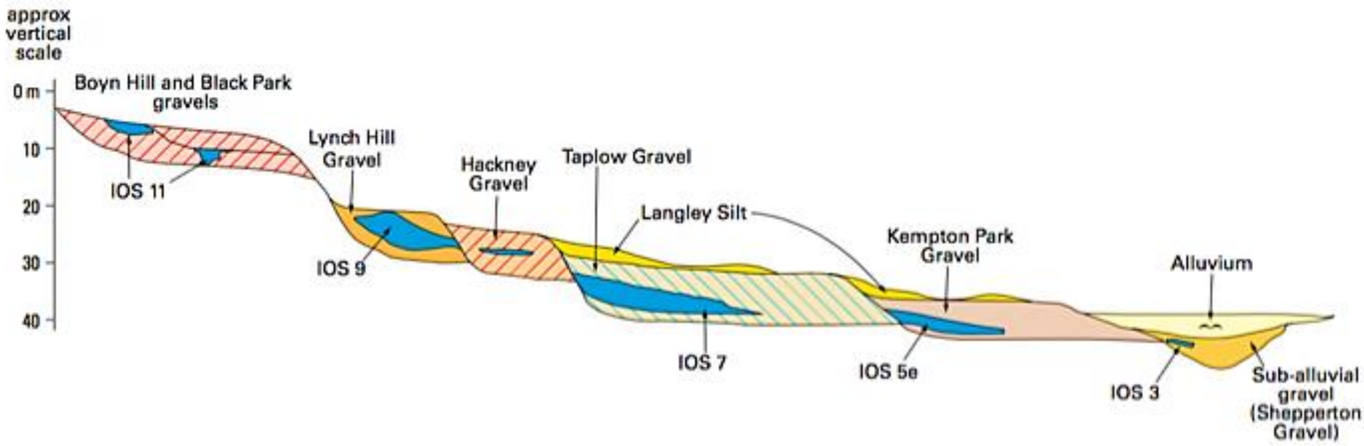


Figure 2. 19 – Cross section of the Thames RTD and their MOIS, identified within the sections coloured blue in the figure (Royse et al., 2012).

2.4.2.2. Alluvium

Alluvium is the most recent deposit within the London Basin and was mostly deposited during the last 8000 years. It can be up to 15m thick in areas and lies unconformably above the RTDs (Ellison et al., 2004). The fine silt and clay sediment is deposited in river and estuarine environments (Devoy, 1977; Ellison et al., 2004) and is occasionally interbedded with peat. The material is normally consolidated and is highly compressible, particularly when peat is present. The presence of alluvium is an indicator of previous fluvial activity and assisted with the mapping of the lost rivers (Barton, 1992).

2.5. Formation hypotheses for drift filled hollows

Hypotheses have been proposed for the formation of DFH features in literature. These include fluvial scour (Berry, 1979) and pingos (Hutchinson, 1980). These hypotheses, as well as further potential processes involved in the formation and modification of the features' morphology today are discussed here. These include alternative ground ice features, tectonic structures, dolines, water and gas pressure, mud volcanoes, soft sediment deformation and meteorite impacts. Each of these is described below alongside the diagnostic features required to provide evidence for their occurrence and necessary to identify their relict form. Each hypothesis in relation to DFH morphology will be discussed later within chapter 7 in relation to new evidence collated within this project.

2.5.1. Fluvial scour

Fluvial scour, or the resultant scour holes or hollows are depressions formed into a river channel bed through erosional processes. These features are largely identified at confluences where a tributary joins another fluvial system or downstream of bars and islands. Their size and shape is diverse and largely dependent on the size of river and confluence channel, the angle of confluence, the material of the river bed and the amount of energy present within the system (Figure 2. 20) (Ferrarin et al., 2018, Sambrook Smith et al., 2019).

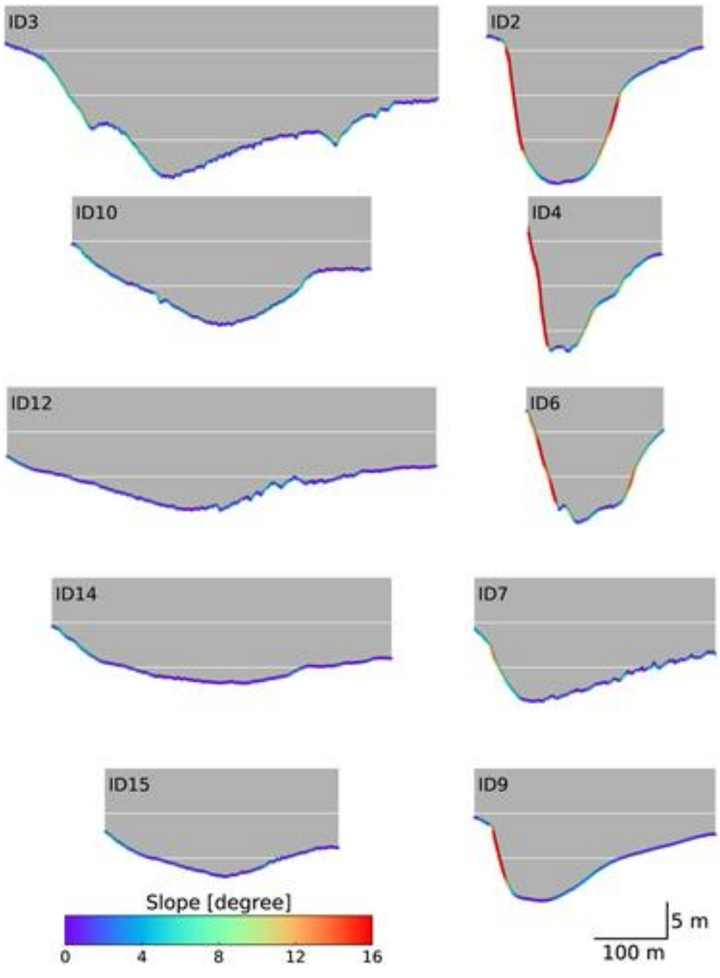


Figure 2. 20 – A range of shapes identified in scour hollows (Ferrarin et al., 2018).

Scour hollows have been experimentally studied by Liu et al., (2015) and although laboratory based experiments have shortcomings due to the level of control and not being in a natural environment, three key outputs are worth noting. Their flume experiment showed that the development of a scour hollow is dependent on the confluence angle (the higher the angle, the deeper the hollow), the amount of sediment supplied by the tributary (the presence of sediment reduces the ability of the discharge to scour due to deposition within the hollow at the same time erosion is occurring) and the level of discharge (the higher the discharge ratio the deeper the scour).

Numerical modelling of scour depressions (Sambrook Smith et al., 2019) has proved problematic due to the complex nature of the infilling material and subsequent reworking of the sediment due to ongoing fluvial processes. This evidences the difficulties in understanding present ongoing scour as well as the potential to identify relict features accurately (also acknowledged by Ferrarin et al., 2018). For relict fluvial scour holes to be identified it is likely that the characteristics to hypothesise their existence are a closed-form (no inlet or outlet) depression and the presence of superficial material indicative of fluvial processes within the vicinity. Scour holes also migrate which may cause confusion over historic fluvial activity. An example of this could be through mis-identification of a fluvial scour hole because a river was not known to be in such position.

The first systematic research which considered the formation of DFHs in London was by Berry (1979) who examined 26 features located within central London. His research identified that the majority of the hollows are located within close proximity to current or buried river channels. Berry hypothesised that the hollows formed when there was an influx of water into the river channels due to snow and ice melt, this led to scour at river confluences. Berry then proposed two options for the presence of a diapir: erosion of the overlying material occurred through fluvial scour, this then reduced the overhead stress below allowing the chalk and lower formations below to intrude vertically. His second proposal was that the cold conditions post scour created the conditions necessary for a sediment plug, freezing then the sediment rising through cryogenic processes.

Pollen analysis from two DFHs studied by Berry suggests the deposition of sediment within the hollows occurred during interglacial warming. Berry stated that the formation of the hollow prior to the infill deposition occurred during the colder stage prior to this. However, caution must be taken when using the infill as evidence for dating of the features as the infill is more than often a mixture of sediment types and therefore possibly reworked, potentially discrediting the reliability of the pollen derived ages.

The conclusions from the experimental study (Liu et al., 2015) question Berry's theory that confluence scour caused the formation of DFHs across London as during glacial melt, the discharge ratio would have been high, however sediment transport would have also increased (even if intermittent as suggested by Lewis and Maddy, 2004) and therefore the two have the potential to reduce the effect of the other and reduce the likelihood of scour hollows forming.

2.5.2. Ground ice

2.5.2.1. Pingo

"Pingos are intrapermafrost ice-cored hills, typically conical in shape, that can grow and persist only in a permafrost environment" (Mackay, 1998, p.2). The periglacial features range from 20-1000m in diameter and around 10m deep (De Gans, 1988; Mackay, 1988). There are two main types of pingo, open (hydraulic) or closed (hydrostatic) (Figure 2. 21).

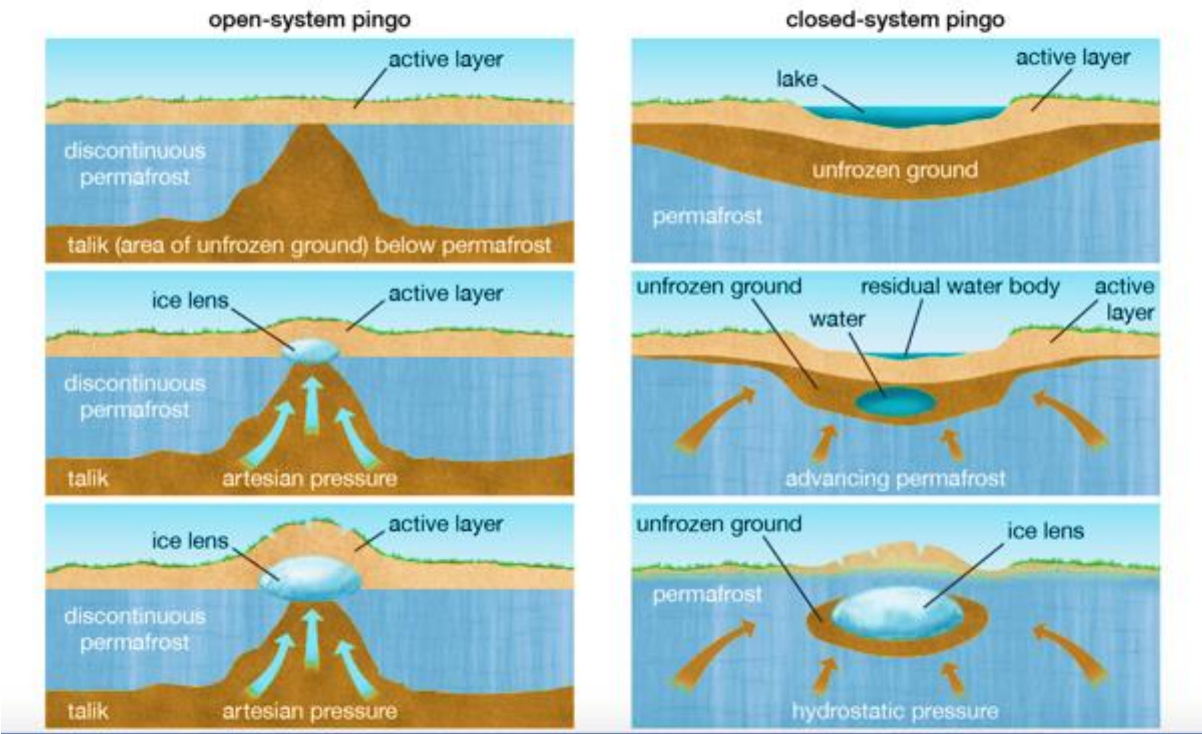


Figure 2. 21 – Diagram depicting the two types of pingo, open (hydraulic) and closed (hydrostatic) (Encyclopaedia Britannica Inc., 2016).

The classification of pingos is dependent on their formation process, in particular the water supply to the feature. Open pingos form via groundwater supply and therefore lie within close vicinity to higher relief. Upwelling occurs through a hydraulic head or under artesian pressure. Most open pingos are located in areas of discontinuous permafrost as this enables a talik to form within the permafrost and the hydraulic pressure to upwell and cause an ice lens beneath the ground surface. As the ice core grows, the ground above (the active layer) is pushed upwards, leading to a dome shape visible from the surface. Once the sediment above has reached its physical limit, tension cracks appear, exposing the ice core beneath. Mass movement often occurs along the sides of the pingo leading to an increase in rim size and as temperatures increase the core melts leading to collapse, leaving a pond feature for sediment to accumulate within (Ballantyne & Harris, 1994; Mackay, 1998).

Closed system pingos originate most commonly above lakes or rivers (sometimes drained) (Mackay, 1998). Water accumulates beneath the lake sediment and above the zone of permafrost. During colder months the sediment above the water lens freezes and permafrost aggradation occurs towards the ground surface. A combination of both frozen entities causes the water lens to freeze, expansion causes pressure within the sediment and in turn uplift at the ground surface. Warmer summer months cause the ice lens to melt and a dip within the mound to become visible at surface. Dilation cracks occur along the dipped surface and when temperatures rise the dip collapses, forming a pond where the former feature once stood.

Mackay (1988) and De Gans (1988) agreed on two criteria which define pingo remnants. These are a rim, partial rim and the isometric shape. Within the UK, pingo-like remnants have been identified in Wales, the Isle of Man (Watson, 1971; Watson & Watson, 1974; Ross et al., 2011) and Norfolk (Clay, 2015). All of these have rims present and evidence of permafrost within the region.

The two sites identified in Norfolk, East Walton and Thompson Common (Clay, 2015), both share the same relief from high ground to the north enabling the hydraulic system required to enable growth of an open system pingo. Both features were also similar geomorphologically, with Thomspon Common being slightly smaller. However, the latter was reclassified as a lithalsa (described in section 2.3.2.3) due to highly impermeable Lowestoft Till overlying the feature. Clay (2015) interpreted the dense Till as the reason the sediment could not uplift enough for a pingo to form.

Hutchinson (1980) proposed that the DFH features identified by Berry (1979) were instead pingo relicts. He attributed the hypothesis of DFH formation in London to Late Devensian open-system pingos and based this theory on the following:

1. The distribution of relict pingos across southern Britain.
2. The presence of reworked London Clay within the hollows interpreted as being due to collapse of the pingo mound.
3. The majority of the features are located in areas of former artesian water flow.
4. Their location being within less than 35m of London Clay and in areas where it thins towards the Deptford pericline.

A major limitation of the pingo hypothesis is the lack of rims identified in any of the remnant features in London. In Moscow, Russia rims of 2-5m in height are identified in relict pingos (Makkaveyev et al., 2015). These features are bases upon sand or sandy loam. Hutchinson does note that the morphology of the features seen today has been heavily modified by “swollen rivers” during glacial melt and that the remnants are of the root of the pingo affected by fluvial processes. If this is the case, with an enlarged dataset of DFH features, an indication of the required diagnostic characteristics would more than likely be present in at least a few of the features. Particularly where features are not identified in close proximity to fluvial activity.

Furthermore, if the impermeable Lowestoft Till is the reason for a lack of pingo growth in Norfolk (Clay, 2015), then similarly the London Clay, a highly impermeable layer within the London Basin (with a maximum thickness of 200m) would restrict pingo growth and therefore cast doubt on Hutchinson’s pingo theory.

It is important to point out that Hutchinson’s research is purely based on trends and assumed conditions in the past without physical analytical evidence for the hypothesis. The following points are also noted:

1. No ramparts are identified around the proposed pingos which are identified in relict forms elsewhere around the globe.
2. Diapirs are not present in all of the DFHs, questioning the location of the “root” of the pingo and the forming mechanism.
3. London Clay is not identified (reworked or otherwise) within the infill in all features. This would be expected if the pingo formed within the London Clay material.

4. Some features are not located within areas of thinning (<35m) London Clay. Although Hutchinson states the hollows are not located within London Clay thicker than 35m, the London Clay is a dense, impermeable formation and therefore it is difficult to accept pingo growth within the strata due to its geotechnical properties. Moreover, no known research has been carried out on pingos within dense clay and therefore it is unknown whether they can form or exist.
5. Whilst research has been published for evidence of permafrost to the east and south of the London Basin, there is no unambiguous physical evidence for permafrost within the London Basin and by definition, open pingos only originate in discontinuous permafrost regions.

2.5.2.2. Palsas

Palsas are between 2-150m in diameter and circular or elongated in shape. Comprising largely of peat, the mounds are usually around 3m in height, but can grow up to 12m and have a permanent ice core within their structure (Kujala et al., 2008; Allaby, 2013).

Palsas form via a build up of segregation ice in mineral soil with peat due to its thermal insulation properties. The features are located in periglacial regions (most often peat bogs), in areas of a thin snow layer, discontinuous permafrost and are highly dependent on the thermal properties of the peat for the maintenance of the frozen core (Washburn, 1983; Seppälä, 2011). They also do not rely on water injection as a water source as they are largely identified within boggy regions and therefore cryosuction enables their growth (Pissart, 2002).

Relict palsas are notoriously difficult to identify in relict form as once they have collapsed peat infills the depression extremely quickly and then there is little evidence left of their existence (Lundqvist, 1969 and Seppälä, 2003, in Pissart, 2002).

Due to the relict features being a depression, their shape can account for some of the smaller DFH features identified in the London Basin. However, without evidence for permafrost within the Basin, there is a reliance on the infilling of peat to aid in supporting or refuting the theory as a formation process for DFHs.

2.5.2.3. Lithalsas

Lithalsas are mounds, up to 8m in height which occur in areas of mineral enriched soil and discontinuous permafrost (Wolfe et al., 2014).

They are formed through the process of ice segregation via cryosuction (the result of water being drawn through soil to the freezing front, suction, in turn is caused by the ice formation) and often, but not always contain an ice lens (Pissart et al., 1998). Similar in size to palsas, their difference is the mineral material which makes up their mass, whereas a palsa is largely peat (Harris, 1993).

A long-term study showing the growth, life and decay of a lithalsa was undertaken in Quebec, Canada. It identified that the features often form as palsas then due to peat decay become lithalsas (Calmels et al., 2008). This emphasises the similarity between the two features and the difficulty in identifying the features when in relict form.

The diagnostic features for their identification is demonstrated by Pissart (2000; 2003 and 2011) and Bromfield (2017) from two sites in Belgium. These diagnostic characteristics are depressions surrounded by a rampart, in Pissart's case, up to 4m in height. However, it is likely that only the larger features would have had a noteable rampart surrounding the feature due to sediment slumping and accumulation, but this is not always the case with smaller features.

As discussed above, lithalsas have been identified in southern England (Clay, 2015) and are found worldwide in permafrost regions where the average annual temperature lies between -4 and -6°C (Pissart, 2003). Furthermore, it is also plausible that if these features did exist within the London Basin they could have been enlarged through chemical weathering during wet climate conditions which followed the periglacial period (Prince, 1964) and account for the relict features present today. However, without evidence for permafrost within the London Basin or a rim lithalsas cannot be proven or refuted.

2.5.3. Water and or gas pressure

The occurrence of water and gas pressure beneath ground level is caused by an increase in water or gas within a system and the inability to escape overhead. The lack of outlet for the water or gas can be due to thick, impermeable strata overhead. The pressure would in turn build up until a vulnerable point is exploited and the energy can be released.

A large increase in water pressure within a basin occurs due to an increase in water flowing into the system, whether it be above ground (e.g. fluvial) or through groundwater flow. This increase will be above normal levels and beyond the capacity of the system. This would then lead to the sediment in which the water is being carried (aquifer) to deform due to an increase in pore water and behave in a liquid or plastic behaviour (Seed et al., 1966). The relationship between an increase pressure due to water and deformation of the Chalk requires exploring in future research for increased understanding.

Gas accumulation and pressure within a system is caused by a drawdown and recharge within the basin (Standing et al. 2013). Again, without an outlet the pressure would build up until there is a point of release. There is not yet evidence as to where the groundwater table dropped to during low sea level periods. It is anticipated that there would be some decrease. If the groundwater table did drop during colder periods due to low sea level and drier conditions, this would change sub-surface water flow which would also impact on ground thermal conditions.

A recent example of gas pressure causing crater like structures has been researched in Siberia (Kizyakov et al., 2020). Here, all of the features formed in permafrost areas and are located either at gentle (1-15 degrees steep) slope foots, within streams or rivers. They range in size from 20 to 55m in diameter and consist of a lower cylindrical shape into a funnel like shape towards the surface.

Both the presence of water and gas pressure within a basin is difficult to identify in relict features and largely relies on structures or the physical properties of the soil to exhibit the pressure forcings in the past such as soft sediment deformation (Frey et al., 2009 and Shanmugam, 2017).

During glacial stages there is a drastic change in groundwater levels and behaviour from present day due to available water being held in glacial ice and permafrost in periglacial regions. As temperatures warm, glacial melt can lead to a sudden influx of water. In the London Basin this would be greatly amplified by the chalk valley sides to the north and south of the basin and the aquifer beneath. Flynn et al., (2018) propose that a large increase of liquid water within the basin led to the deformation of the chalk through an increase of pore water pressure, potentially aided by gas pressure at the base of the Lambeth Group. The chalk, in a liquid or plastic state (evident from the microscopy work viewing the physical structures of the chalk sediment in comparison to 'normal' chalk) exploited a vulnerable point within the overlying strata (such as a fault, spring or fluvial scour) and upwelled vertically through the sediment. Once the amount of available water decreases, vertical movement ceases due to a drop in pressure and water migrates into the surrounding strata leading to a volumetric change of the diapir. This creates the depression above via dewatering-induced consolidation and subsidence. Numerous processes could have then entailed to explain the mixing of the diapir and depression infill sediment. These include: the movement of the chalk through overlying strata in a pressurised state, slumping of sediment within the depression above, liquefaction and/or hydro fracturing. This hypothesis explains the formation of the diapir, the mixing of the sediment within the diapir, as well as the infilled depression above. As this hypothesis is based upon one feature (Olympic Park DFH), the study of further features with a diapir will enable further assessment, some of which will be undertaken within this project (see section 2.4.3).

Deoxygenated, pressurised gas has been identified during the site investigation phase of the Thames Tideway project within the Upnor Formation in the Lambeth Group, in particular within sand channels at the base of the sequence (Newman et al., 2013). This poses a potentially fatal hazard as it can lead to hypoxia in confined spaces often encountered when tunnelling or engineering the sub-surface. The accumulation of the gas is attributed to rapid dewatering of the London Basin during the Industrial Revolution (Standing et al., 2013). If correct, then it is also feasible that rapid dewatering during glaciations could also have caused pressurised gas within the base of the Lambeth Group.

The water pressure discussed above has the potential to have been aided by the pressurised gas at the base of the Lambeth Group.

A further potential hypothesis is that the water and/or gas pressure exploited a vulnerable point leading to a blow out at the surface. The original blowout may not have resulted in the morphology present today, but similar to Berry's research, the feature may have been modified by river scour, faulting, cryogenic or another process yet to be identified.

2.5.4. Tectonism

Localised tectonic movement can be seen in faults and fractures in geological strata. The faults and fractures can be arranged in differing ways depending on the forces acting upon the sediment and its properties. Two examples that are relevant for examining DFHs are flower structures and grabens.

Flower structures are “a series of convex-upward thrust or reverse faults found in transgressional strike-slip zones” (Allaby, 2013) (Figure 2. 22). The structures lead to an uplift or downward movement of sediment, depending on the pressures acting upon the structure. Negative structures can lead to a funnel shaped depression within sediment due to the structural collapse caused by faulting (Van Vliet-Lanoe et al., 2004).

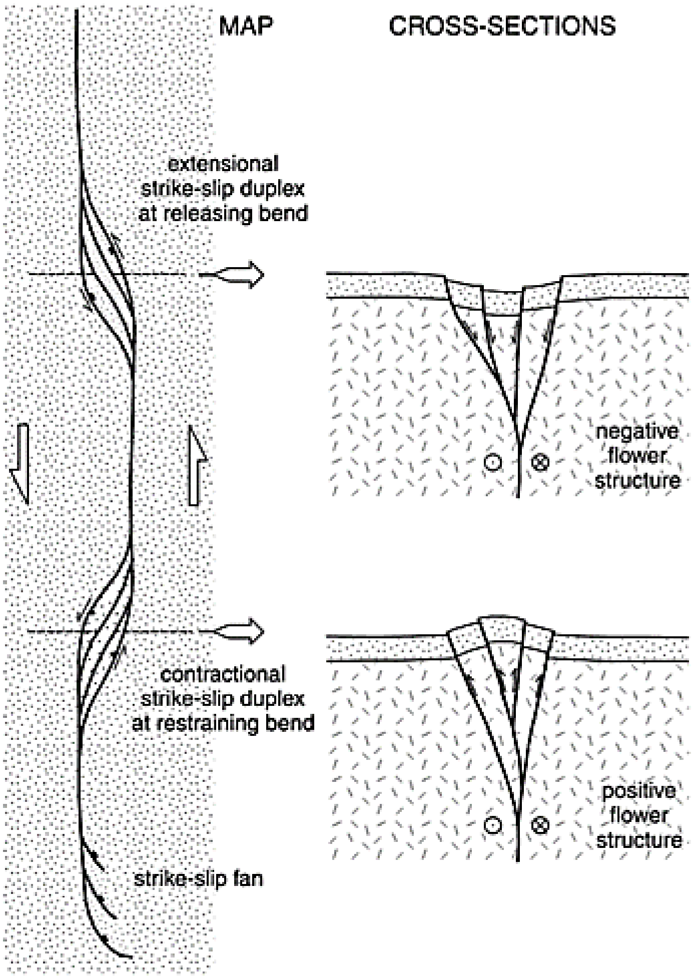


Figure 2. 22 – Diagram depicting the two main types of flower structure, positive and negative (Woodcock & Rickards, 2003).

Grabens are formed through the compression and extension of strata through tectonic forces. This can lead to localised depressions in extension zones (De Freitas, 2009). An example from the London Basin can be seen in Figure 2. 23.

Both flower structures and grabens are identified through the presence of faulting or fractures in the local bedrock material. This proves problematic when boreholes are the main method of exploration and will be discussed in detail in chapter 4.

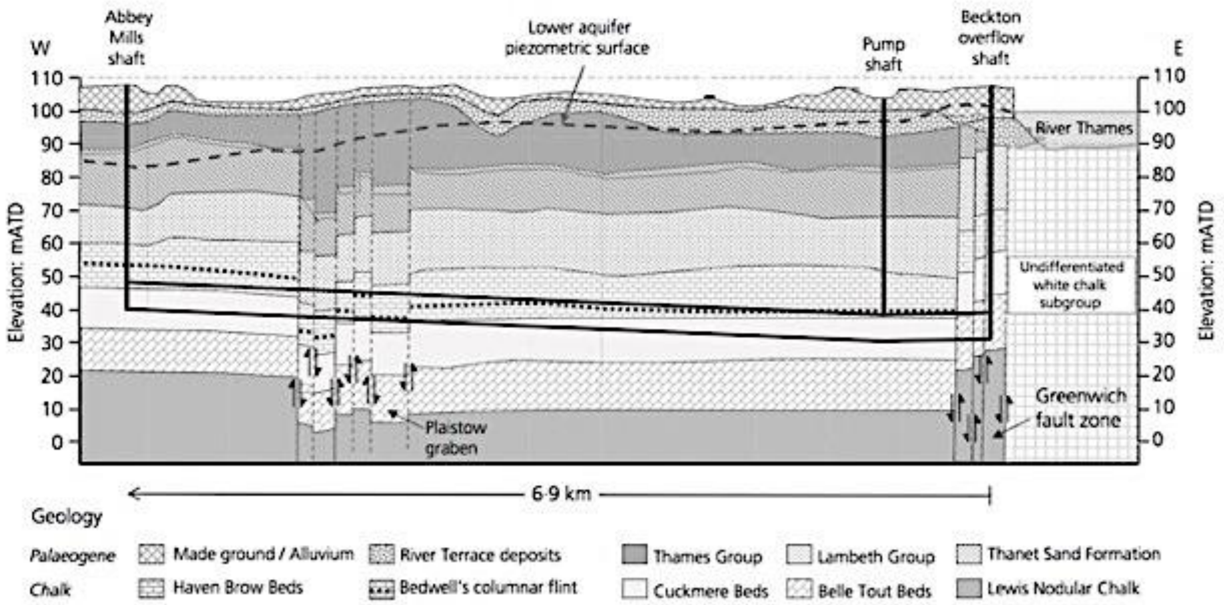


Figure 2. 23 – Plaistow graben, East London (Newman et al., 2016).

In relation to this project, localised faulting within the London Basin is becoming more frequently identified through extensive site investigations for major engineering projects (e.g. Thames Tideway; Newman et al., 2016).

Along the Tibetan Plateau pingos form and move along fault zones creating large scale uncertainty and hazard for engineering projects (Wu et al., 2005). Other research has also suggested a link between faults and pingo formation worldwide (Yoshikawa et al., 1996; Hamilton & Obi, 1982). However, many do not state whether the faults are active or remnant and therefore further understanding of the timing of the relationship cannot be reached.

Banks et al., (2014) identified a correlation between the location of DFHs and faults. The research found that of 31 hollows studied, 15 are within 1000m of a known fault and suggested that their proposed morphology orientation (NE-SW and NW-SE) are also orientated with the faults. It is key to note that this research is observational and at present there is no physical evidence to support the link between DFH formation and faulting. Moreover, the correlation of the 15 hollows to known faults does not represent a causal relationship between the two for their formation. Additionally, only 31 hollows were studied out of a now much larger dataset, and of these 31, over half of the features lay over 1000m away from any known faults. According to Aldiss' (2013) paper, it is believed that faults are under recognized within London and therefore the other hollows may be within close proximity to an unmapped fault, but again, without evidence this cannot be proven or refuted.

Faults could also create a vulnerable point (or pathway) within usually constant highly impermeable sediment for water or gas to move. This has the potential to facilitate a release of pressurised water or gas leading to the vertical movement of sediment as is proposed for DFHs with a diapir such as the Lea Valley (Flynn et al., 2018).

The depressions formed by a negative flower structure are similar in shape to DFHs, making the flower structure a possible mechanism for their formation. At present there is no evidence to support this theory apart from personal correspondence with an individual who has encountered a DFH based within what appears to be a flower structure. It is plausible that flower structures create the depression and other processes enable the infilling and mixing of sediment within. However, further DFHs need to be studied for surrounding faults to support or refute this hypothesis and this proves difficult when using boreholes as the exploratory method of sampling.

Figure 2. 23 depicts the Plaistow Graben identified during Thames Tideway, HS1 and Crossrail projects and studied further through extra borehole investigation. This feature is approximately 104m in width, at least 6km in length across north east London (Mortimore et al., 2011) and created mixed-face tunnel conditions for the Thames Tideway tunnelling project (Newman et al., 2016; Bellhouse et al., 2015). Further smaller grabens are also known within the London Basin, for example in the Fleet Valley (Paul, 2016). Similar to the flower structures discussed above, these localised tectonic depressions could be possible formation mechanisms for DFHs. Additional investigation into the known DFHs' surrounding structure is again needed for this hypothesis, however at present it is unlikely as the majority of known DFHs are reported to have 'normal' strata within metres of their location.

2.5.5. Doline

Dolines, commonly known as sinkholes, are subsidence features usually found within carbonate bedrock. Ranging between 0.5-500m in width there are broadly four main types (Figure 2. 24) depending on their formation (Culshaw & Waltham, 1987).

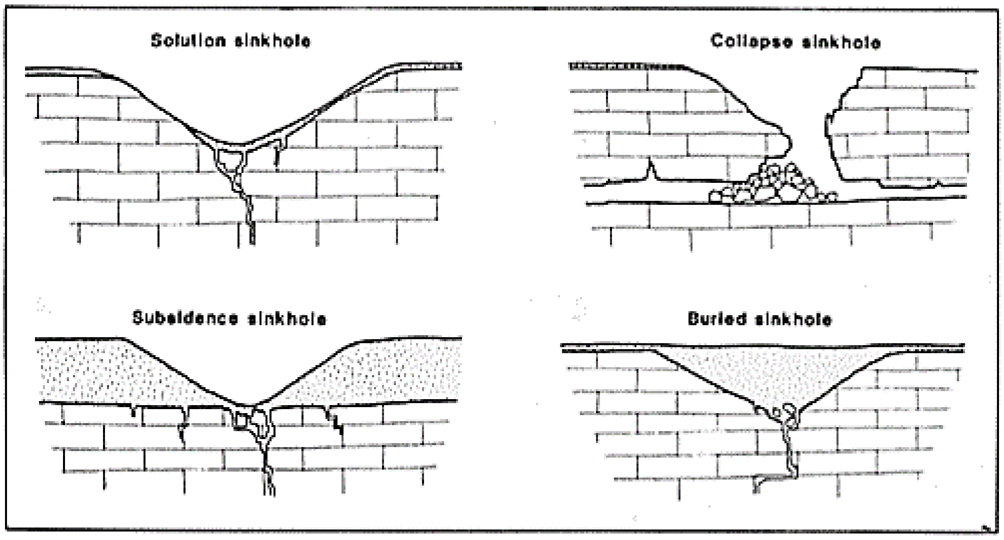


Figure 2. 24 – The four types of doline (from Culshaw & Waltham, 1987).

Dolines can be either natural or anthropogenic. Anthropogenic features are largely created through mining of the sub-surface and subsequent collapse from the overlying strata into the cavity (Edmonds, 2018). Naturally occurring dolines occur through the dissolution of limestone beneath the surface, with the rate of this solution varying depending on the movement of water across the surface of the material (McDowell et al., 2016, Edmonds, 2018). This can occur at both a small scale (usually resulting in buried or subsidence sinkholes) and larger scale with karstic networks beneath the surface (usually resulting in collapse type sinkholes). Collapse type sinkholes in chalk are rare due to the high strength of the material (Mcdowell et al., 2008). However subsidence type sinkholes are relatively common in areas of south east England and small-scale collapse events may also occur into the already subsided material (Edmonds, 1983).

Dolines are identified across large areas of the UK due to the presence of carbonate rock and their distribution is mapped and discussed in detail by Edmonds (1983, 2001) and Edmonds et al. (1988). The features are typically identified through a depression of the surface. In relict form, where there has been the energy and availability of sediment, infilling of the depression occurs. Evidence of subsidence post infilling of a cavity or hollow can be identified through the angle of which the infilling bedded material is identified (if not mixed) or if collapse structures within the infilling sediment are present.

Carbonate rocks such as the Seaford and Newhaven Chalk Fm. studied within this project are predisposed to dissolution due to susceptibility to chemical weathering, most often within fissures. Prince (1964) argued that the process of solution would be at its greatest at the end of interglacials. Solution and in turn dolines have the potential to enhance depressions already present (pingos, palsas and lithalsas) during postglacial times potentially leading to the DFHs present within the London Basin today.

In 1986, Gibbard et al., studied an infilled depression at Denham, Middlesex with similar characteristics to a DFH, but deemed the feature to be a doline formed through solution of the chalk bedrock during the early Hoxnian Stage, approximately 400 ka BP. They attributed the formation to be formed via dissolution as the strata beneath the feature had not been upwelled and there was a lack of fluvial system or water source to form a pingo. This will be discussed further in section 2.6.2.

The most likely type of doline for DFH formation are subsidence and buried sinkholes due to a lack of large scale cavity networks below and dense geological strata above.

2.5.6. Mud volcano

Mud volcanoes are geological structures formed due to gas and or water upwelling from deeper geological strata (Dimitrov, 2003). They range in size from a metre to several kilometres in length and have associated nomenclature depending on their dimensions. All mud volcanoes emit methane made up of modern and fossil carbon and the amount depends on their size and rate of eruption. Their shape is dependent on their origin, sedimentary material and duration of eruption (Murton & Biggs, 2003).

Mud volcanoes originate through several triggering factors or events including tectonics, slope failure and faulting, however they are all formed through the upwelling of sediment due to a high pore water pressure through an area of instability (Niemann & Boetius, 2010). The presence of water is a key component of mud volcano formation as the features are reliant on water for the energy required to form the features. The higher the material density, the more energy is required (Wan et al., 2017).

For the identification of relict mud volcanoes it is crucial to acknowledge the water source, availability of the amount required and its ability to move within the strata being studied (e.g. through fractures). For the London Basin, this is through dense, largely impermeable strata. Mud volcanoes can be acknowledged through the geochemical composition of the sediment. In northwest China and Taiwan the features (including gravel filled depressions) have been proven to have elevated levels of sodium and chlorine (Wan et al., 2017; You et al., 2004). Therefore, geochemical analysis can aid the identification of mud volcanoes.

For DFH formation, there are many factors which link to a mud volcano origin. Gas and water pressure, faulting, sediment instability and slope failure are all variables which are considered whilst discussing DFHs and their formation. This does not lead to a causal relationship, however there are similarities there to look further into this hypothesis.

2.5.7. Meteorite

Meteorite impacts lead to craters, otherwise known as impact structures on the earth's surface (Osinski and Pierazzo, 2013). The craters can range in size from 100m to tens of kilometres in width and around one hundred to tens of kilometres in depth. The features can range from a simple depression shape or a complex shape with upwelled material beneath the crater shown in Figure 2. 25 (French, 1998).

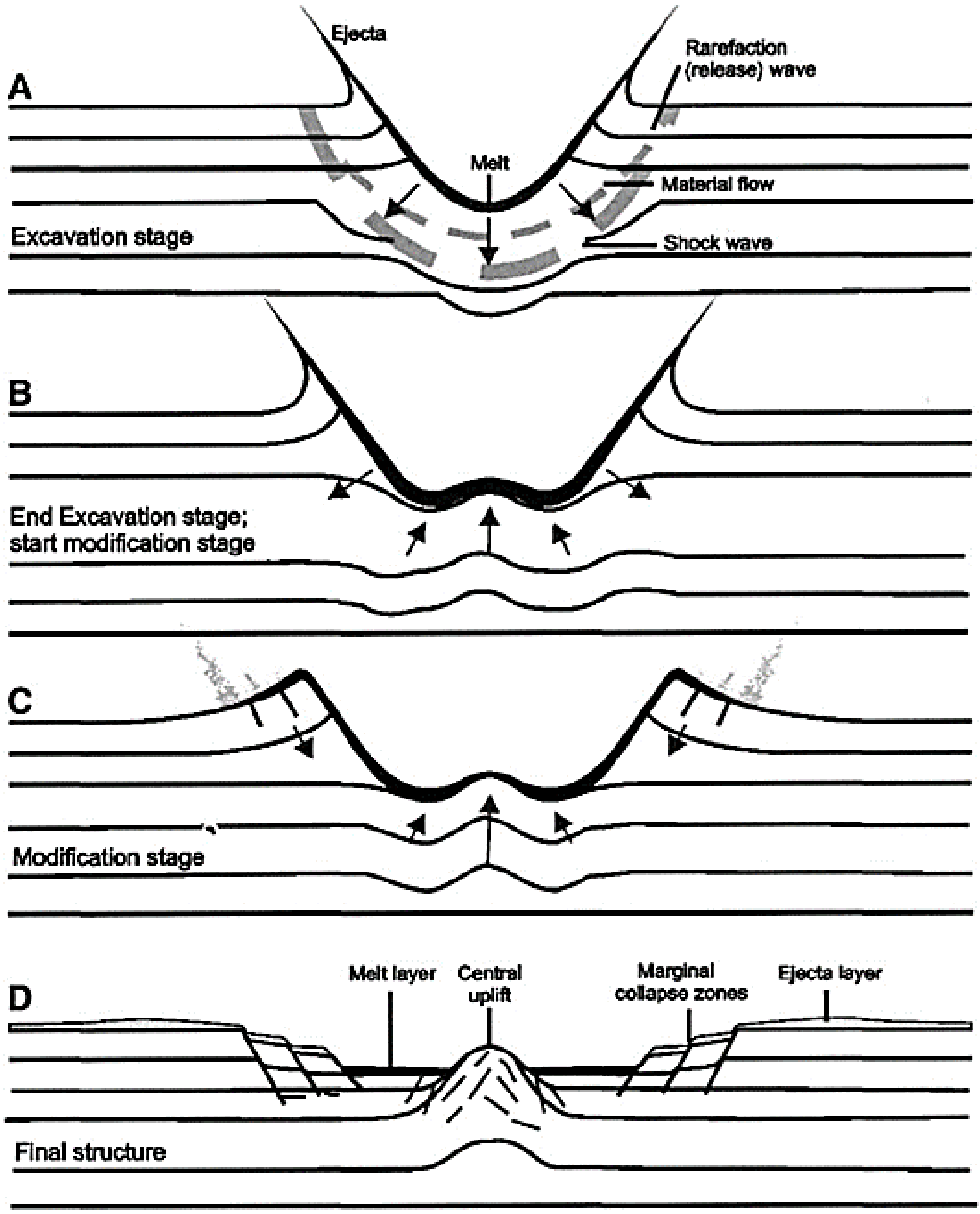


Figure 2. 25 – Complex impact structure formation (French, 1998).

Relict craters are difficult to attribute to meteorite impacts due to weathering, erosion or burial since the craters formed (French and Koeberl, 2010). Other methodologies to determine a meteorite origin include geochemistry and surface texture analysis of sediment grains. For geochemical analysis, the presence or absence of the platinum group elements indicate an extra-terrestrial origin. In particular, iridium's (Ir) presence at the Cretaceous Tertiary (KT) boundary (Alvarez et al., 1982) or in excess of ≥1 ppb (French & Koeberl, 2010). Surface texture analysis can also be used to indicate a meteoric event through analysing the surface texture of the quartz grains to identify if planar deformation features are present (Boggs & Krinsley, 2006; Hamers & Drury, 2011). Both of the above methodologies are accepted as unambiguous identification for meteoric impacts and provide evidence to support or refute this hypothesis (French & Koeberl, 2010; McCall, 2009).

The similarity between groups of impact structures and bedrock depressions was suggested by Makkaveyev et al., (2015) who recorded the similarity between the morphology of scattered meteorite impacts and pingos identified in the Moscow region, Russia. This paper ruled out the depressions being formed by meteoric origin due to their rarity and the lack of evidence. In particular, the lack of impactites and the terrestrial origin of the sands within the lake's rim. DFHs are similar in form to the pingos in the Makkaveyev et al., (2015) paper and therefore the meteorite theory should also be considered for DFHs within the London Basin. Geochemical analysis and surface texture analysis will provide evidence to support of refute this hypothesis.

2.5.8. Combination

It is feasible that numerous of the above hypotheses played a role (simultaneously or consecutively) in forming the DFH features present today within the London Basin. This will be considered throughout the thesis whilst analysing newly collated evidence and evaluating formation hypotheses.

3. Methodology

3.1. General approach

89 anomalous features within the London Basin have been identified and are being studied as part of this project. Fieldwork within London is highly restricted due to land use and extensive engineering works. As a result, with the exception of three features (Ashford Hill, Battersea Power Station and the feature identified by Davis et al., 2018 from tunnel face logs), all research currently undertaken on DFHs has been from boreholes as the main and only evidence source. A discussion regarding the limitations of boreholes, cross-sections and ground models will be discussed in the data quality chapter (Chapter 4).

To complement the larger dataset, a largely undisturbed site at Ashford Hill, Hampshire, which contains a DFH of particular importance was investigated. All field work and subsequent testing and analysis at Ashford Hill was undertaken to increase understanding of an individual DFH feature. This is largely not possible in London due to the urbanised nature and the commercial interest of sites. Ashford Hill provides a case study of a DFH which has provided geotechnical (CPTu), geochemical, geophysical (Raines et al., 2015) and geological (Hill, 1985; Hawkins, 1952) understanding of an individual DFH furthering understanding of the features physical characteristics.

All secondary data and its subsequent analysis (DFH dataset and cross-sections) were collated to determine similarities or differences across large amounts of sparsely available information. This enables an increased understanding of the features spatial and physical characteristics as well as expanding understanding into processes which were involved in the formation of DFHs.

Laboratory techniques (geotechnical, geochemical and microscopy) were undertaken to determine the physical characteristics of the material within DFHs at differing scales. The techniques are also able to provide evidence for processes involved in the formation of DFHs and to increase understanding of their current form.

Geographic Information System (GIS) techniques were employed to visualise the data for portrayal and interpretation. The technique allows multiple variables (such as location of DFHs in relation to rivers, present and past, underlying bedrock and faults) to be visualised and comparisons made in relation to literature as well as increasing understanding into their spatial nature.

3.2. Field primary (Ashford Hill)

Preliminary fieldwork was undertaken in March 2017. Four cores were taken using a hand gouge at depths of up to 4.2 m. The hand gouge was 50 mm in diameter and the cores were logged according to the BS5930/2015 guidelines and sub-sampled in the field. Ideally, a Russian corer (a handheld gouge with a rotating fin which closes when turned within the soil; this seals the sample whilst extruding from the ground, providing a higher quality sample) would retrieve better samples from the site and stay within the permission for coring, however the clay was too dense to penetrate and therefore it was not possible to take samples with the larger diameter Russian corer. Further samples were retrieved using the Pagani CPTu TG63-150 drill rig in 2019 (Figure 3. 1).

Figure 3. 1 – Cores taken at Ashford Hill for this project (Google Earth, 2018).

3.2.1. Cone penetrometer tests

Cone penetrometer testing (CPTu) has been used as a methodology to determine the geotechnical properties of soils since the 1950s (Robertson, 2009). The piezocone itself collects raw data on tip resistance (Q_c), sleeve resistance (F_s) and pore water pressure (U_2). The use, interpretation, corrections and analysis of CPTu are described extensively by Lunne et al., (1997). Raw data acquired by CPTu can be used to determine soil type and behavior; mainly through graphs created and extensively studied by Robertson (1990, 2010 & 2016).

From the three values the CPTu acquires, the data can then provide information on further soil properties such as friction ratio, soil permeability and shear strength (Robertson, 1983 & 2010).

The methodology's major restriction, particularly in Britain, is that the cone cannot penetrate through gravel or rock and where it can, in softer rock, it destroys the piezocone. Because of this, and perhaps due to inertia in the UK ground investigation sector, there is little CPTu data for the London Basin, as a result of the RTDs above the softer clay strata below. However, for studying variable sediment, such as in the case of some DFHs (without gravel infill), CPTu is a good methodology to employ to understand the extent and rate of change between different strata and in turn geotechnical characteristics.

CPTu data was collected at Ashford Hill using the Pagani CPTu drill rig (TG63-150, with a push force of 150kN) once permission was granted by the site's manager, Natural England. Nine CPTu tests were undertaken at Ashford Hill (Figure 3. 2), with the help of SOCOTEC engineers with the Brunel University London *Pagani CPTu TG63-150* drill rig (CPTu tests 1-4) and InSitu with their own rig (CPT006 "Zoe" with a push force of 200kN)(CPTu tests 5-9). Table 3. 1 displays the key information regarding each CPTu test.

Figure 3. 2 – Location of the CPTu tests taken at Ashford Hill (Google Earth, 2018).

Table 3. 1 - Information on the CPTu tets undertaken at Ashford Hill.

ID	Final depth (m)	Date of test	Cone used	Dissipation depth (m)	Test remarks
CPTu 1	8.88	04/09/2018	MKj534		Final depth due to refusal - SOCOTEC drilled
CPTu 2	13.15	04/09/2018	MKj534	13.15	Final depth due to refusal - SOCOTEC drilled
CPTU 3	14.74	04/09/2018	MKj534	13.17	Final depth due to refusal - SOCOTEC drilled
CPTU 4	12.15	05/09/2018	MKj534	12.15	Final depth due to refusal - SOCOTEC drilled
CPTu 1	19.84	01/10/2018	S15CFIIP.1486		Final depth due to refusal - InSItu drilled
CPTu 2	18.53	01/10/2018	S15CFIIP.1486	14.50 & 18.51	Final depth due to refusal - InSItu drilled
CPTu 3	15.66	01/10/2018	S15CFIIP.1486		Final depth due to refusal - InSItu drilled
CPTu 4	21.62	02/10/2018	S15CFIIP.1360	13.98	InSItu drilled
CPTu 5	23.27	02/10/2018	S15CFIIP.1360	19.00	InSItu drilled

The positions selected to undertake the tests (Figure 3. 2) were chosen to gain as much information on the extent and infill of the feature as possible. The aim was to further knowledge on the variability of the infill which was previously unknown between the existing boreholes. A secondary aim of the fieldwork and CPTu testing was to compare the CPTu data with sediment retrieved from boreholes and analyse the reliability of the CPTu data in variable sediment. However, due to complications with the Pagani drill rig throughout the project, outside of the researcher's control, this comparison was not possible and is hoped to form part of future research.

The piezocones were calibrated (certificates of calibration are included in the appendices) to ensure reliability of the readings and the data produced. Set up of the piezocone was in accordance with training provided by Marton Geotechnical Services (MGS) who are the United Kingdom trainers for the Pagani CPTu rig.

Dissipation tests were undertaken to provide data on permeability and compressibility of the sediment and in turn aid the understanding of soil type and behavior (Robertson, 2010). The following equation is used:

$$U\ (100\%) = \frac{u_t - u_o}{u_i - u_o} \qquad [1]$$

Where

u_t – pore pressure at time t

u_o – equilibrium pore pressure in situ

u_i – pore pressure at start of dissipation test

The test was run until the degree of dissipation was at a minimum 50% (Lunne et al., 1997). On both the In Situ and the Pagani cone, the porewater sensor for the dissipation test is located at U_2 (shoulder of the cone tip).

3.3. Field secondary

The boreholes from Nine Elms and the Lea Valley (Figure 3. 3) have been imaged, cross-checked against the borehole logs to ensure accurate description and sub-sampled for further analysis explained throughout this document.

Figure 3. 3 – Map showing the locations of the two secondary field sites: Lea Valley and Nine Elms.

3.3.1. Lea Valley

A DFH was identified at the Olympic Park site in the Lea Valley in 2008 (TQ 38114 85569). The boreholes from the site investigation were given to the British Geological Survey (BGS) for research and sub-sampled as part of this project. Due to the cores being held in storage at room temperature for many years prior to this research and the restricted amount available to take from the BGS only petrographic and mineralogical analysis was undertaken on the sub-samples. This methodology had not been undertaken by Lee and Aldiss (2012). Geotechnical tests were not possible due to the sediment being dried out and the lack of weight required for tests to match British Standards. The DFH itself will be discussed later in the thesis (Chapter 6).

3.3.2. Nine Elms

In 2017 a DFH was identified on the perimeter of a confidential site in Nine Elms, London. This project was given access to three sediment cores (courtesy of Concept and Wanda) from the site investigation which were taken from within the feature (BH301, 302a and 303). The sediment cores were photographed using a colour card and tape as undertaken in industry and sub-sampled for further analysis. Again, due to the storing of the cores, geotechnical analysis would not have been accurate or reliable. Furthermore, due to the high level (often sub-centimetre) variability of the infill, the mass required for British Standards geotechnical tests to provide accurate and reliable data would not have been met for and the data it would have provided would not have been representative for the sediment horizontally or laterally. Petrographic and mineralogical tests were undertaken on the samples and cross-sections were created from all borehole logs taken during the site investigation.

3.4. Secondary data collection

Bar the three features mentioned above (Ashford Hill, Lea Valley and Nine Elms), all other data and information within this thesis was acquired from borehole logs, published articles site investigation and geotechnical reports. The borehole logs were mainly accessed through the BGS Geoindex tool (http://mapapps2.bgs.ac.uk/geoindex/home.html). All of these were vetted for accuracy regarding the geographic location and logging accuracy, dependent on the description given. The location of numerous features as well as additional borehole data, site investigation and geotechnical reports were kindly provided by the Geotechnical Consulting Group (GCG), the Robert Bird Group and SOCOTEC.

3.5. Laboratory

3.5.1. Geotechnics

Geotechnical analysis within this project is minimal due to the limitations of working with variable sediment (discussed in detail in Chapter 4, Data Quality). As well as CPTu, water content analysis was also undertaken to further understand the geotechnical properties of the sediment. Atterberg limits were also used for terminology purposes to further understanding in the formation of DFHs.

3.5.1.1. Atterberg limits

Atterberg limits are a measurement of the behavior of a soil in regards to its water content (Atterberg, 1911). The plastic limit is the point in which a sediment can be rolled out to 3 mm without breaking. The liquid limit is the stage at which the water content within a soil changes its behavior from plastic to liquid. The liquid limit is identified using the cone penetrometer test or the Casagrande method, both listed in the British Standards. A limitation of the Atterberg tests approved by British Standards are their dependence on the operator which can cause bias and lack of repeatability (Verstegui-Flores & Di Emidio, 2014).

Although Atterberg limits are key measurements in geotechnics and are employed throughout the sector, this project has not undertaken Atterberg limit tests due to the sediment within DFHs being highly variable and often a mixture of sediment types and the storage of the samples impacting on the water content and state of the material not being as in-situ. Therefore, it would not have met the requirements for the British Standard test (BS1377-2) or be representable of the sediment in question.

Atterberg limits are still used within this research to describe the behavior and movement of sediment in relation to water in regards to DFHs. The descriptive terms are based upon research undertaken on the Atterberg limits of similar sediment types to those identified within this project (Stone & Kyambadde, 2012; Barnes; 2013; Haigh et al., 2013; Nini, 2014; Çabalar & Mustafa, 2015).

3.5.2. Petrographic and mineralogical

Within this project three main geochemical methodologies will be used: X-ray fluorescence (XRF), X-ray diffraction (XRD) and scanning electron microscopy (SEM). A multi-disciplinary study of sand using mineralogy, surface texture analysis and other methodologies used within this research to look at quartz grains from borehole data sediment has been undertaken by Machadoet al., (2016) and Pan et al. (2016). The methodologies complement one another for understanding depositional palaeoenvironments and its potential is encouraging for this piece of research.

Mineralogical analysis has been undertaken on the main strata being studied in this project: London Clay (Kemp & Wagner, 2006), Lambeth Group (Pearce et al., 1998; Jones and Hobbs, 2004) and Thanet Sand Fm. (Menkiti et al., 2015).

XRF is undertaken on geological materials to determine their major element composition in projects across the globe in differing environments (Revenko, 2002; Margu et al., 2009; Oprea, 2015). Within this project the major elemental composition is identified qualitatively through XRF to enable accurate XRD data interpretation.

XRD determines the crystal structure and mineral composition (Rakovan, 2004). The analytical technique is used across many scientific disciplines including paleoclimate studies using clay (Song et al., 2014) and has been undertaken on the properties of clay minerals which will aid this piece of research (Zhang, et al., 2010). XRD is used here to identify whether the mineralogical composition of the sediments are as expected within London geological strata or if there if there is an anomalous composition within the DFH infill. In turn, this can inform on processes undergone by the sediment within and surrounding DFHs.

3.5.2.1. XRF

For XRF analysis the samples were prepared by drying them in the oven overnight at 110° then crushed using an agate pestle and mortar. Samples were then placed into the XRF sample holders and into the *Oxford ED2000* instrument at the Experimental Techniques facility Centre (ETC) at Brunel University London. All XRF set up and analysis was undertaken using the *Xpertease* software. A zinc calibration pellet was used at the start of each acquisition and then after every 12 samples to ensure accuracy of results and the calibration of the machine (Figure 3. 4).

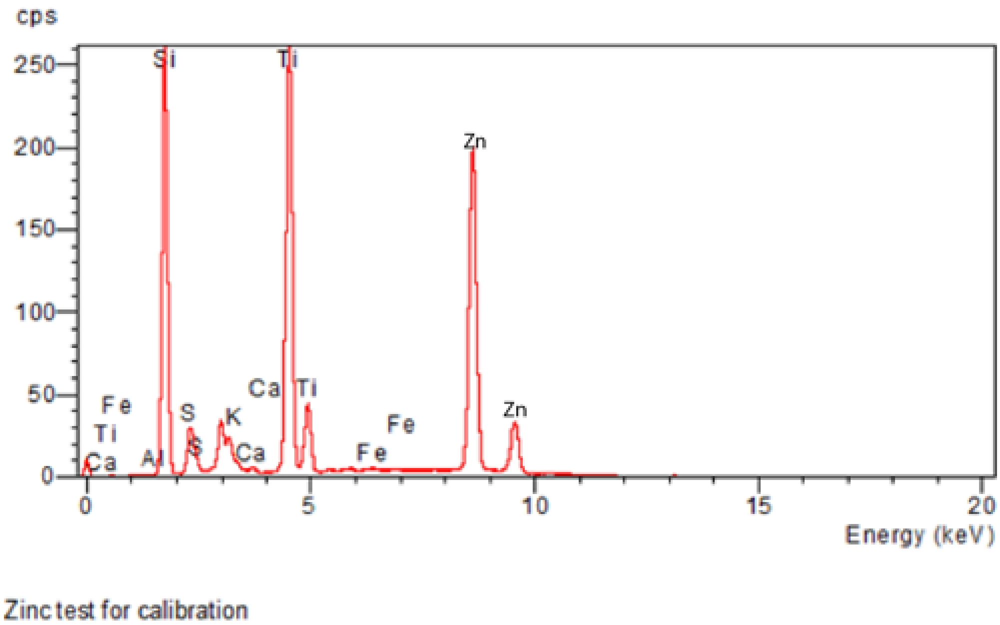


Figure 3. 4 – Zinc calibration spectrum used in XRF

Custom conditions were set for the entire project based upon the best resolution found during the experimental development/optimisation process (Figure 3. 5). The largest determining factors were between air and helium in the chamber and the voltage being 12 or 20 kV. A helium path and 20 kV of voltage enabled the lower energy region of the spectrum to have a higher resolution and as the samples are non-metallic this was deemed to be the best set up conditions for the project. All samples were acquired using a helium atmosphere, 20 kV voltage, 4.5 mm aperture, a 0-20 KeV spectrum energy range, 14 KeV as the upper energy limiter and with a pre-set livetime of 200 seconds (Figure 3. 6). The conditions remained the same throughout to ensure reproducibility and comparability of samples.

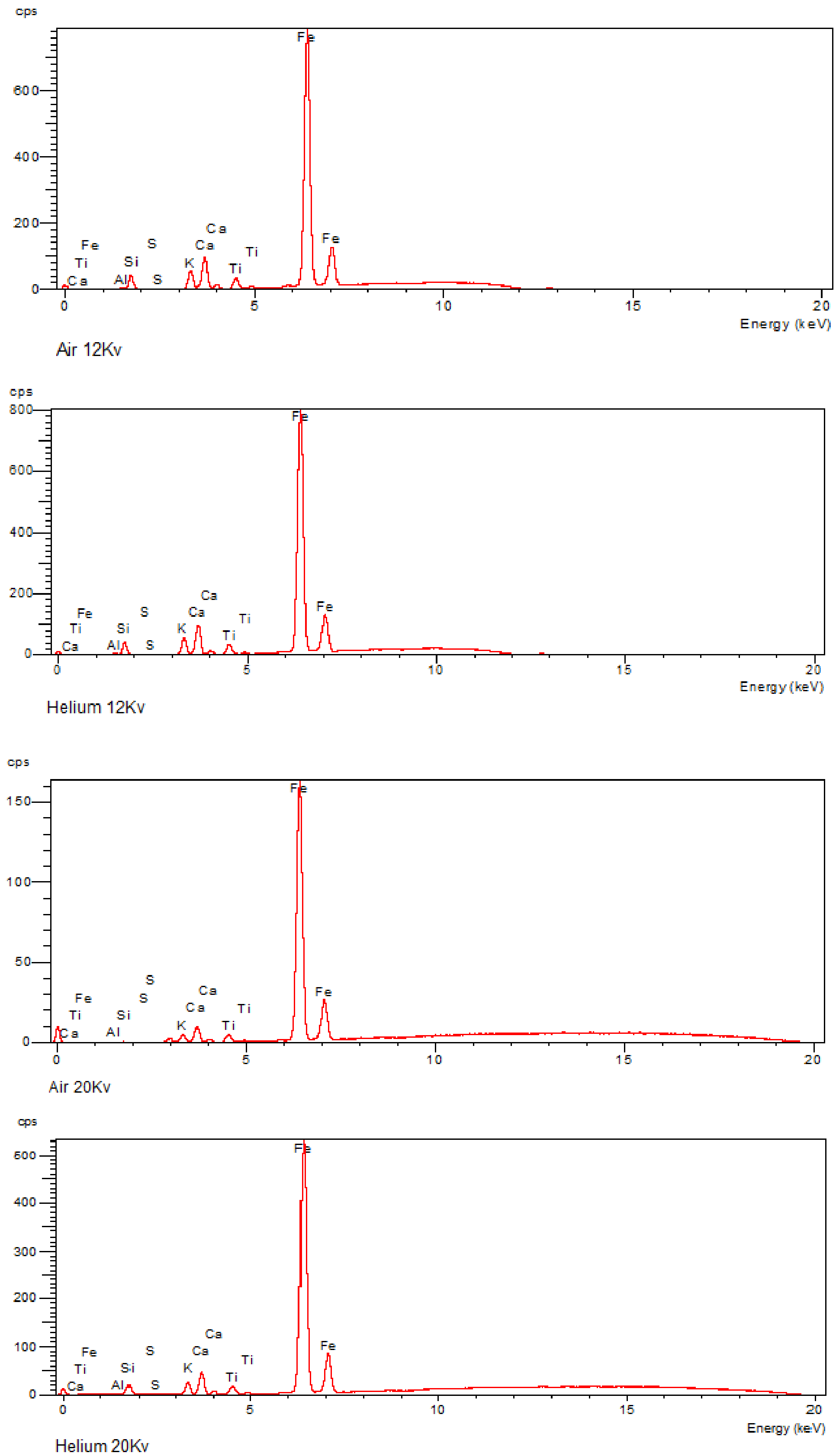


Figure 3. 5 –The outcomes of the custom conditions experimented with to establish the best resolution for samples used in this project showing the elements with the energy range 0-10.

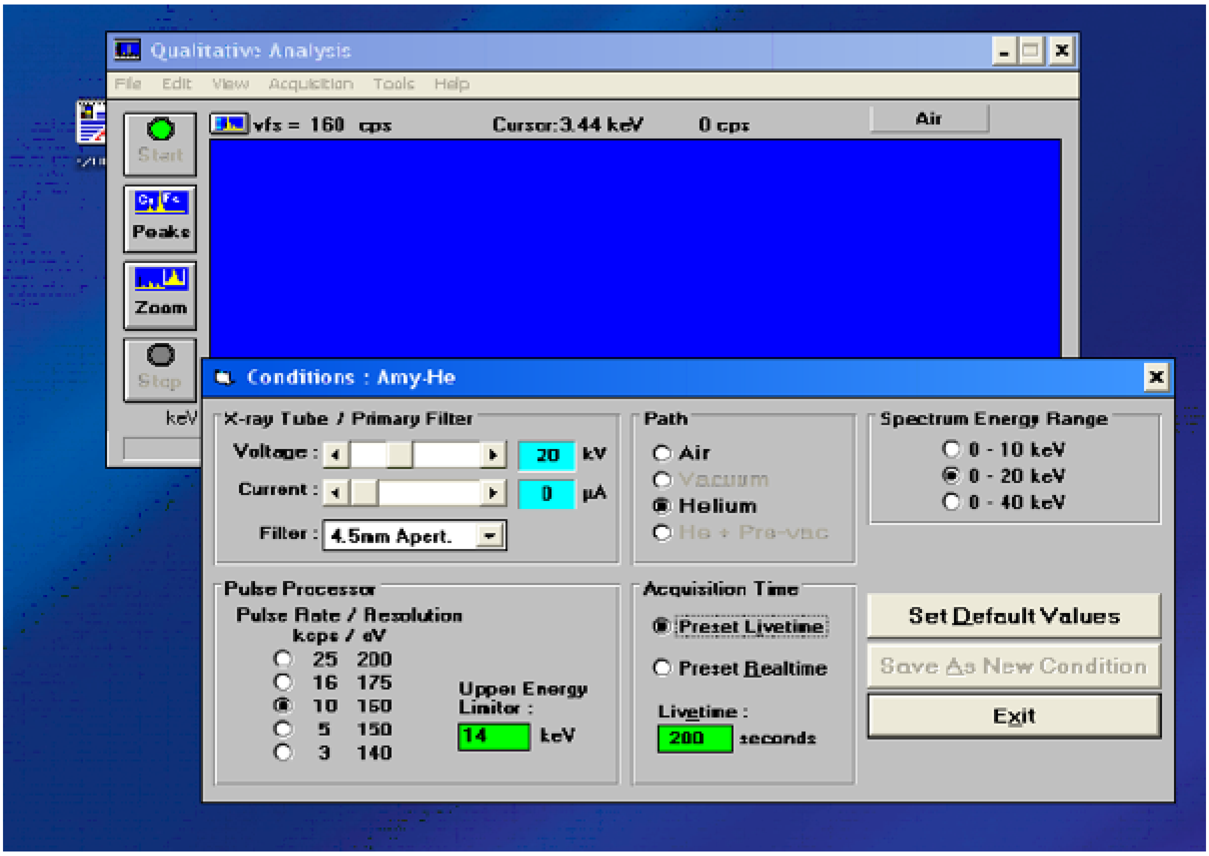


Figure 3. 6 – Image showing the custom conditions chosen within the Xpertease software for all samples used in this project.

3.5.2.2. XRD

Samples were dried, ground and sieved (sieved and centrifuged as necessary) as above. The dried sample is placed into a XRD holder and flattened as much as possible to ensure a plane surface. If the surface of the sample is not level the x-rays will comply with Bragg's law at a different angle impacting on the detector; this leads to the peaks in the analysis software to be offset and correction is then required using the *displacement tool* in the analysis software (Figure 3. 7 and Figure 3. 8). The *Bruker D8 Advance Power diffractometer* equipped with copper tube and LynxEye position sensitive detector is used alongside the *DIFFRAC Plus XRD Commander* software to set up the samples within the machine and set the scanning conditions. The following scanning conditions were used: *scan-lynxeye-5-100* acquired for 70 minutes whilst rotating for full sample coverage to achieve signal randomisation and avoid orientation effects.

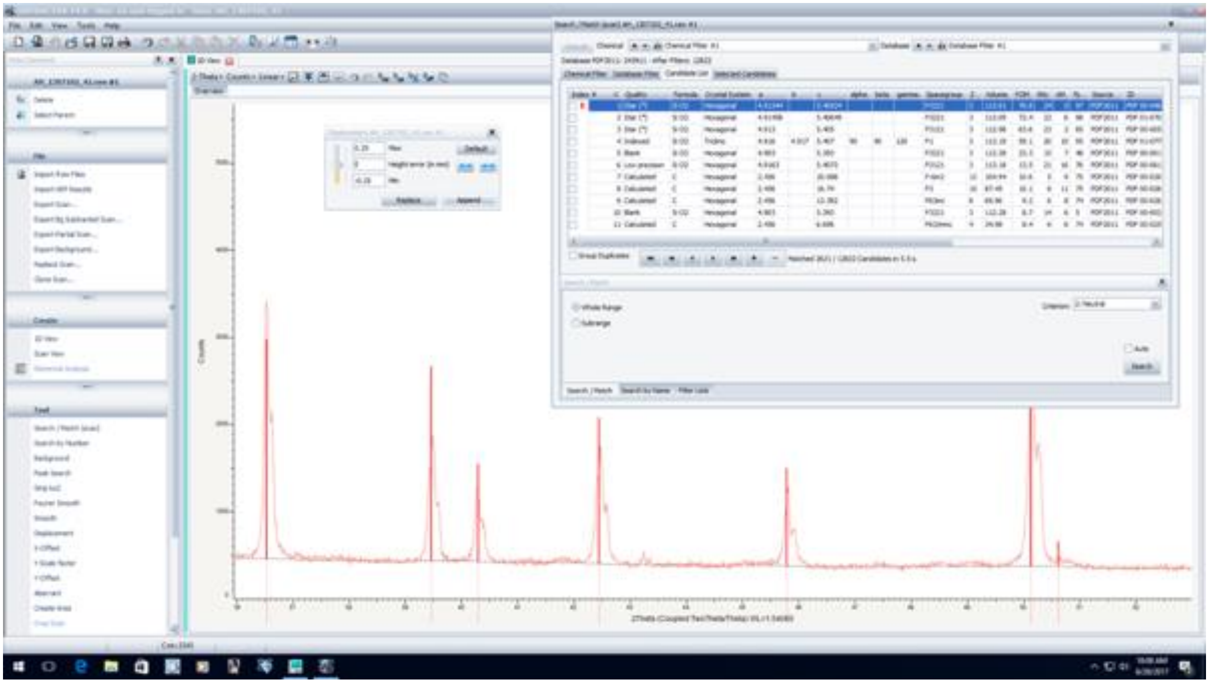


Figure 3. 7 - Image showing the slight offset of peaks in the XRD DIFFRAC EVA software (AH130710-2 4.1m). The displacement tool is used to correct the peaks alignment for analysis.

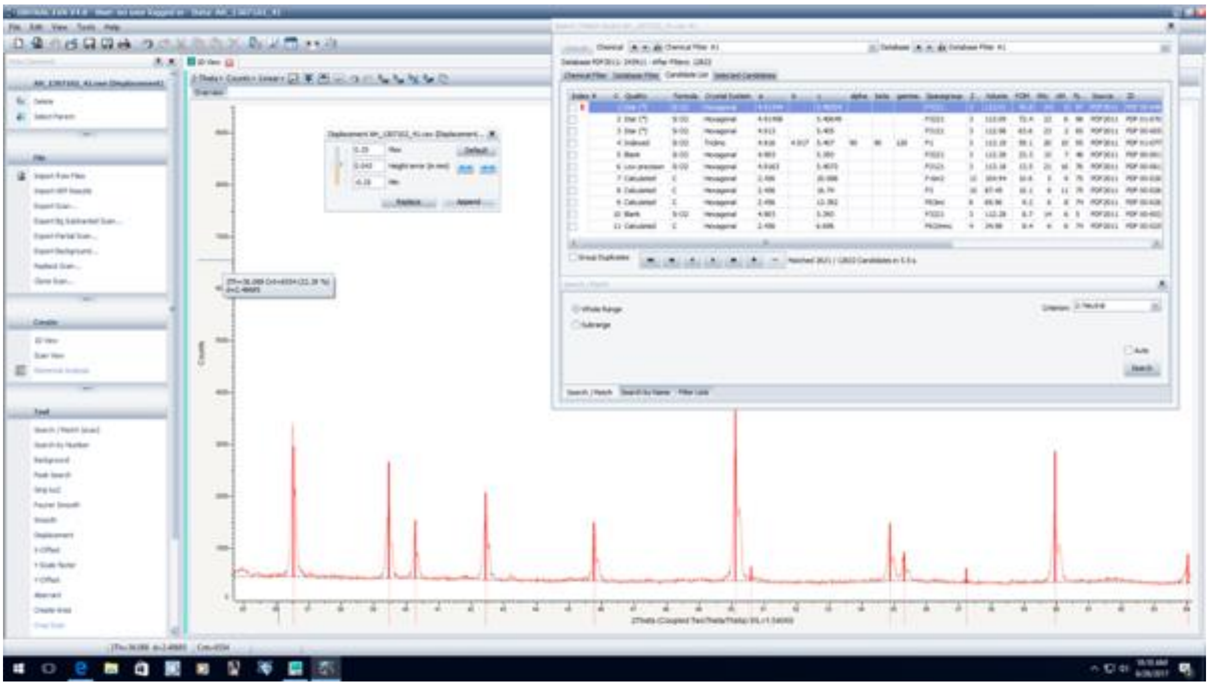


Figure 3. 8 – Peaks realigned from the image above using the displacement tool. A height error of 0.043mm is shown.

Once acquisition was complete the *DIFFRAC Suite EVA* software was used to analyse the XRD data. Each acquired sample is imported into the software and assessed using its elemental composition, which is identified from the qualitative XRF results and filtered for inorganic and mineral compositions.

The XRD analysis software is linked to the *International Centre for Diffraction Data – powder diffraction file – pdf 2 – 2011* database. The filters used above (elements and database section) narrow down the results of the database to what is applicable for the given sample which then enables peak analysis and mineral composition selection to take place (Figure 3. 9).

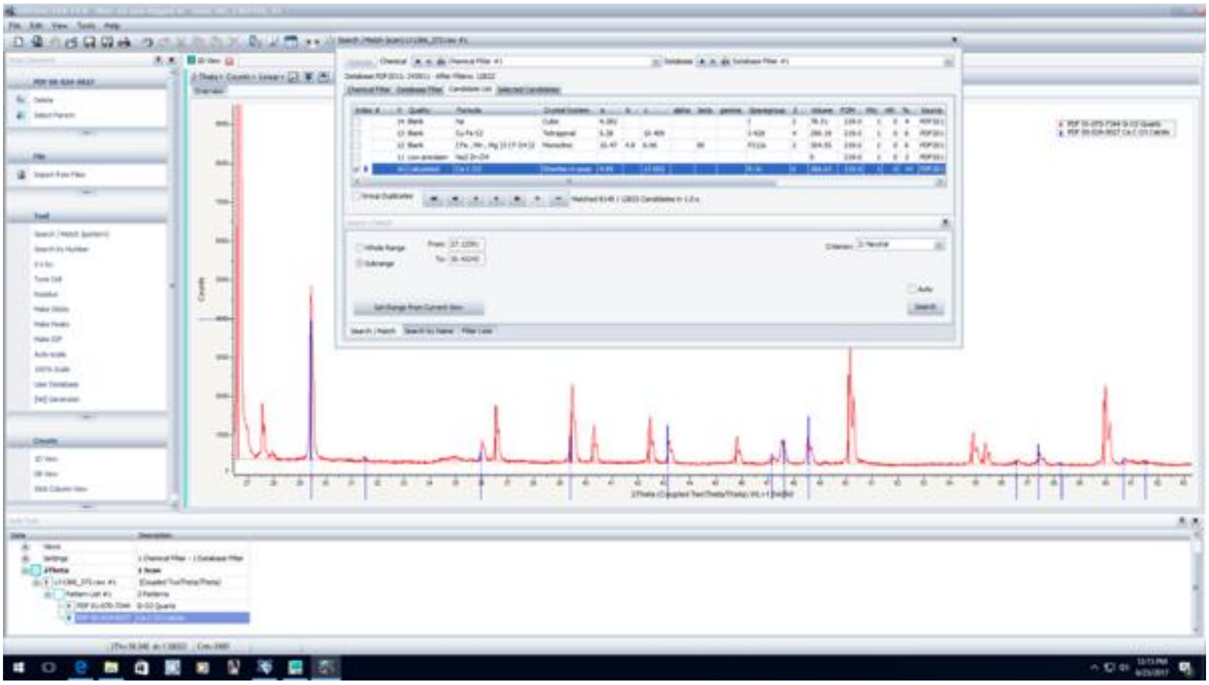


Figure 3. 9 – Print screen of peak analysis on a sample from the Lea Valley core.

3.5.3. Microscopy

3.5.3.1. SEM

The scanning electron microscope (SEM) *Zeiss Supra 35VP* was used to recognise morphological differences in chalk samples not visible to the naked eye from within and outside DFHs (Flynn et al., 2018). Sub-samples were taken from chalk identified within boreholes at the Nine Elms feature, the Lea Valley feature and intact Seaford/Newhaven Chalk from a HS2 site (an independent site which was deemed "normal" chalk).

The samples were sputter coated with gold to achieve a conductive surface and consequently increase the image resolution. The SEM was set up using the secondary electron detector (SE2), accelerating voltage of 10 Kv, with a lens aperture of 30 µm. Each sample was then observed at different magnifications and imaged.

3.5.3.2. Surface texture analysis

The same SEM *Zeiss Supra 35VP* was also employed to undertake surface texture analysis (STA) to observe and categorise the morphology of the quartz grains to determine the processes that the material has undergone and its depositional environment. A review of the methodology, use and analysis of the technique has been written by Vos et al. (2014). The technique itself can be quantifiable through numerous grains being analysed, however the technique itself is subjective due to an individual viewing the grains and deciding on the surface texture type identified. Figure 3. 10, Figure 3. 10 and Figure 3. 12 show the range of environments and processes which can be established through using the methodology.

Legend:
Abundant ■
Common ◢
Sparse ●
Rare –

		Mechanical																		
		1. Angular outline	2. Subangular outline	3. Rounded outline	4. Small conchoidal fractures (<10µm)	5. Medium conchoidal fractures (<100µm)	6. Large conchoidal fracture (>100µm)	7. Arcuate steps	8. Straight steps	9. Meandering ridges	10. Flat cleavage surfaces	11. Graded arcs	12. V-shaped percussion cracks	13. Straight/curved grooves and scratches	14. Upturned plates	15. Crescentic percussion marks	16. Bulbous edges	17. Abrasion fatigue	18. Parallel striations	19. Imbricated grinding features
Subaqueous: Fluvial	Low energy	◢	◢	◢	–	–	–	–	–	–	–	–	●	–	–	–	–	–	–	–
Subaqueous: Fluvial	High energy	●	◢	◢	■	◢	●	◢	◢	–	◢	●	■	◢	●	●	–	–	–	–
Subaqueous: Marine	Intertidal	–	◢	■	■	◢	–	◢	◢	–	◢	●	■	■	●	●	–	–	–	–
Subaqueous: Marine	Subtidal	●	◢	◢	–	–	–	–	–	–	–	–	●	●	–	–	–	–	–	–
Subaqueous: Marine	Tsunami	–	◢	◢	–	–	–	–	–	–	–	–	■	–	–	–	–	–	–	–
Eolian	Littoral dune	–	◢	■	◢	●	–	◢	●	◢	●	◢	●	●	■	◢	■	◢	–	–
Eolian	Desert dune	–	–	■	◢	●	–	●	●	◢	●	■	–	–	■	■	■	■	–	–
Glacial		■	–	–	■	■	■	■	■	●	◢	–	●	◢	●	–	–	◢	■	◢
Diagenetic/Alteration		–	–	–	–	–	–	–	–	–	–	◢	–	–	–	–	–	–	–	–

		Chemical							
		20. Oriented etch pits	21. Solution pits	22. Solution crevasses	23. Scaling	24. Silica globules	25. Silica flowers	26. Silica pellicle	27. Crystalline overgrowths
Subaqueous: Fluvial	Low energy	–	●	●	–	◢	◢	◢	●
Subaqueous: Fluvial	High energy	–	●	–	–	–	–	–	–
Subaqueous: Marine	Intertidal	◢	●	–	–	■	■	–	–
Subaqueous: Marine	Subtidal	■	◢	◢	–	–	–	–	–
Subaqueous: Marine	Tsunami	–	–	–	–	–	–	–	–
Eolian	Littoral dune	–	–	–	–	◢	◢	–	–
Eolian	Desert dune	●	◢	◢	●	–	–	◢	●
Glacial		–	–	–	–	–	–	–	–
Diagenetic/Alteration		◢	◢	◢	◢	◢	◢	◢	■

		Mechanical and chemical						
		28. Low relief	29. Medium relief	30. High relief	31. Elongated depressions	32. Chattermarks	33. Adhering particles	34. Arcuate/circular/polygonal cracks
Subaqueous: Fluvial	Low energy	–	■	–	–	–	–	–
Subaqueous: Fluvial	High energy	◢	■	◢	–	●	–	–
Subaqueous: Marine	Intertidal	–	■	–	–	●	–	–
Subaqueous: Marine	Subtidal	–	■	–	–	–	–	–
Subaqueous: Marine	Tsunami	◢	◢	–	–	–	–	–
Eolian	Littoral dune	■	◢	–	◢	–	●	–
Eolian	Desert dune	■	◢	–	◢	–	●	●
Glacial		–	◢	■	–	■	◢	–
Diagenetic/Alteration		◢	◢	–	–	–	◢	◢

Figure 3. 10 – STA SEM identification table (Vos et al., 2014) based upon samples from eight research articles.

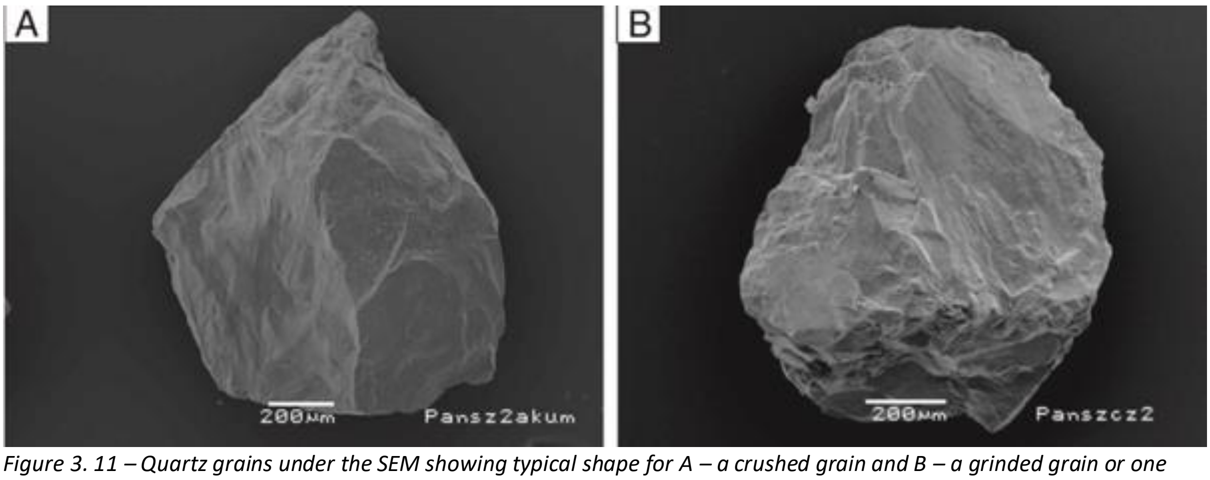


Figure 3. 11 – Quartz grains under the SEM showing typical shape for A – a crushed grain and B – a grinded grain or one which has undergone attrition (taken from Woronko, 2016).

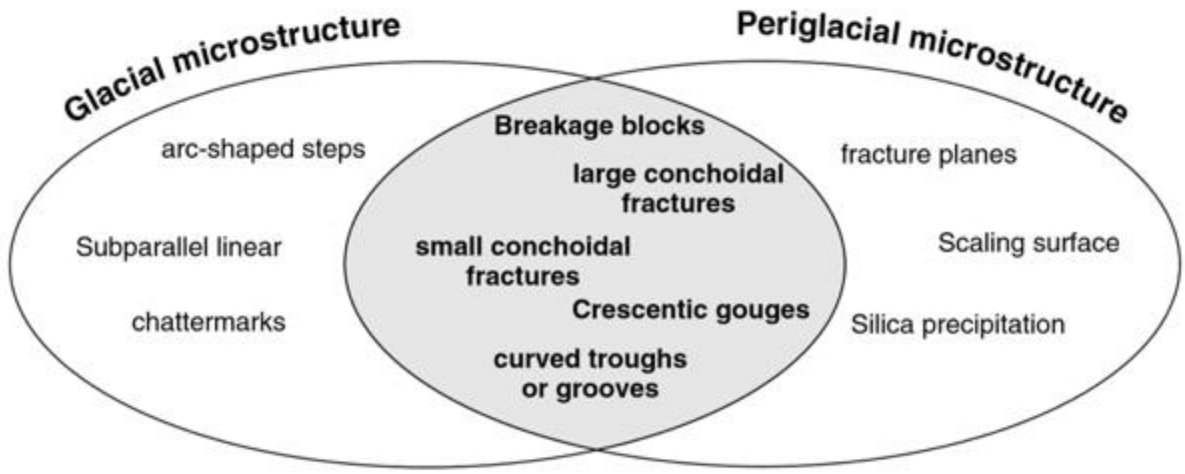


Figure 3. 12 – Common surface textures for quartz grains from glacial and periglacial environments (taken from Woronko, 2016).

STA of quartz grains has been undertaken in numerous studies around the world and across contrasting environments including glacial landscapes in Greenland (Helland and Holmes, 1997), alluvial environments in China (Helland et al., 1997), lacustrine sediments in Antarctica (Warrier et al., 2016) and periglacial environments in Poland (Kalińska-Nartiša et al., 2017).

A preliminary assessment was undertaken to determine the microscope setup and cleaning method required for the quartz grains to view the morphology under the SEM; these can be seen in Figure 3. 13 and Figure 3. 14. The images are of unsorted grains taken from Nine Elms at 21.5 m placed on carbon tape on the sample holder and sputter coated in gold to increase resolution by reducing the beam penetration, increasing conductivity and in turn decreasing the electrical charge of the sample surface (Krinsley & Doornkamp, 2011; Vos et al., 2014).

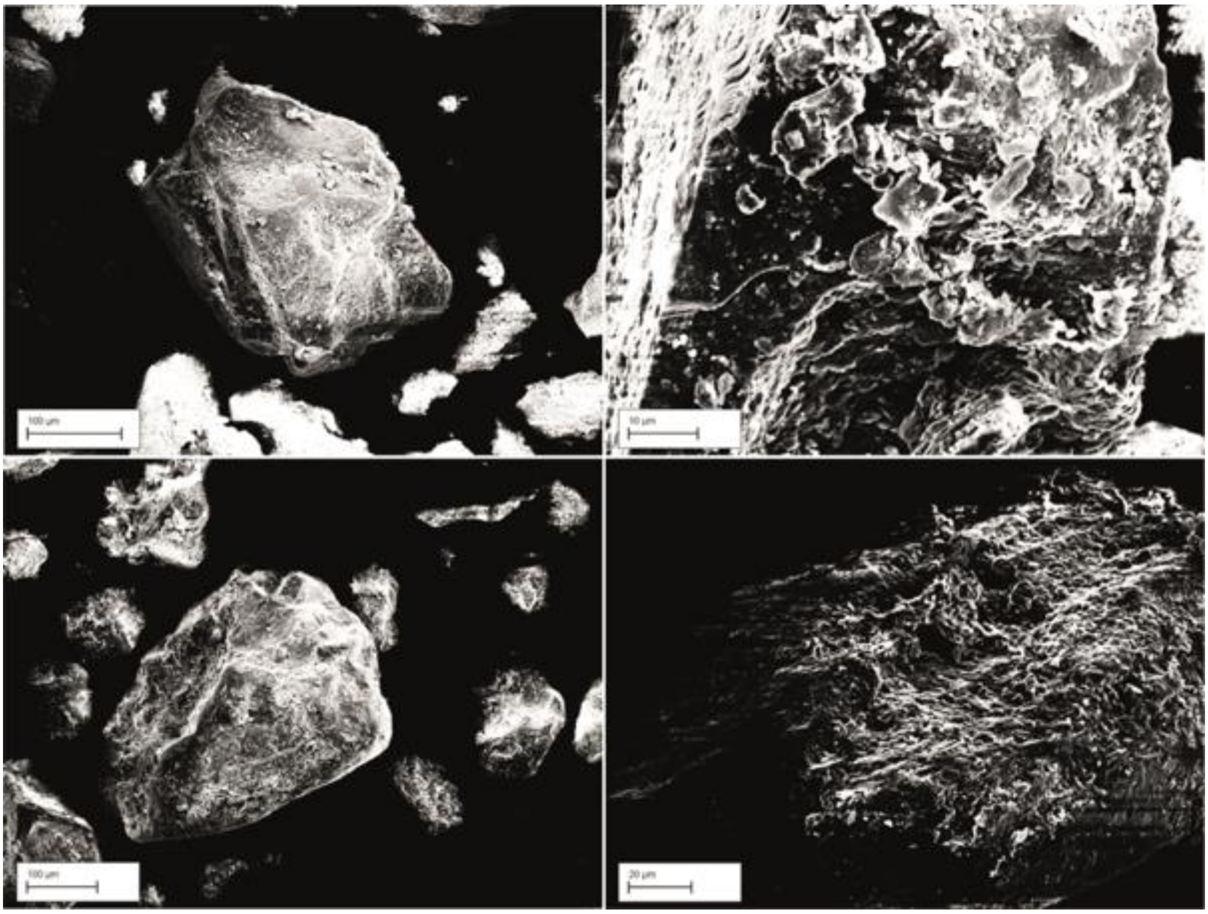


Figure 3. 13 – Four images of sand grains using the high current beam under the SEM (grains taken from samples from the Lea Valley DFH within this project).

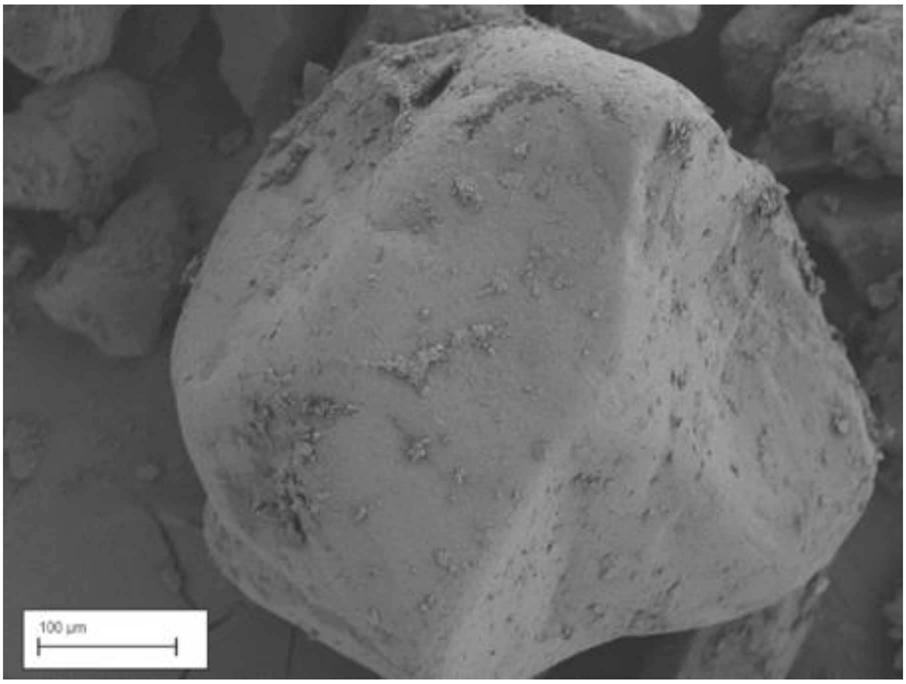


Figure 3. 14 – An individual grain under the SEM at 100um without the high current enabled. The darker patches underneath the lighter grey are the quartz underneath the coated (clay and silt) surface (grain taken from samples from the Lea Valley DFH within this project).

After viewing the images above and developing the methodology to optimise the conditions, it was decided that the microscope should be set up without the high current enabled, using the secondary electron detector, EHT at 5 kV, the aperture at 30 µm and a working distance of 7-8.5 mm as this provided the clearest images to analyse the surface texture of the quartz grains.

Additionally, the images show the surface of the quartz grains are covered by a layer of silt and clay material hindering the clear imaging of textures on the grains surface. Using the Vos et al., (2014) paper as guidance, the samples for analysis were cleaned using the following method:

1) Sieve the sample to retrieve the sand grains from the larger mixed samples.
2) Boil 10 g of the sand sample in 15% hydrochloric acid to remove iron oxides and carbonates.
3) Place the grains in sodium hexametaphosphate ($(NaPO_3)_6$) for 12 hours (Lewis & Armstrong, 1994) (if not enough, leave for 24 hours; Helland & Holmes, 1997) to remove the clay and silt particles.
4) Using deionised water wash the grains until the water runs clear (at least three times).
5) Dry the sample in an oven at 60°.
6) Using a regular binocular microscope, pick 30 grain sizes of approximately similar grain size and place on the carbon tape on the sample holder.
7) Sputter-coat the sample in gold.
8) Analyse and image the samples in the SEM.

3.6. Data management

3.6.1. Spreadsheets

Microsoft Excel was used to compile all known data on the DFH features, the data sources and notes on each individual feature. A master spreadsheet was created (the full spreadsheet is shown in the appendices due to size, Appendix A, Table 1.) providing all known information on each DFH. A reduced spreadsheet has also been presented in Flynn et al. (2020) for features within central London. This paper redacted confidential features and limited itself to features within the M25 motorway as per Berry's (1969) paper. The following information is recorded within the master spreadsheet where available:

- Name of feature;
- Location (easting and nothing);
- Minimum width (m);
- Minimum depth (m OD);
- Minimum depth (m) below ground level;
- Is the full depth known;
- Strata within at top;
- Strata reached at base;
- Local bedrock;
- Does it breach the local bedrock;
- Thickness of bedrock above;
- Thickness of bedrock below;
- River terrace;
- Is there evidence of a diapir;
- If there is a diapir, height of upwelled strata above local level;
- Is there evidence of faulting;
- Infill type (mixed or layered);
- Infill material;
- Is the infill disturbed or undisturbed;
- Number of depressions;
- Date of site investigation;
- Source(s) of information;
- Key BGS boreholes;
- Notes of information not covered elsewhere within the table.

The following points are noted on the information within the spreadsheet and are discussed further in Flynn et al., (2020). "Disturbed" infill includes: disorganised material, disordered contents (e.g. Lambeth Group above the London Clay), uplifted or unusually discontinuous (possibly faulted) strata both of which are directly related to the DFH.

Evidence for faulting can be identified through sharp contact of different materials or strata, potentially inclined or material at a higher than usual level (caution must be taken as this may be upwelled material, not faulted).

Limitations to the spreadsheet are also noted in Flynn et al., (2019) and include:

- "Difficulties in establishing the absolute ground level at the time of drilling relative to Ordnance Datum;
- Historic, non-standardised soil descriptions that require retrospective interpretation;
- The tendency for older, non-standard records to try and fit the ground to the expected sequence when naming strata;
- A lack of knowledge of the adopted drilling techniques, the effect these techniques have on the samples retrieved and, in turn, interpretation for borehole logs;
- The limited number of boreholes and their often shallow depths hinders identification and characterisation of features;
- Confidentiality issues often limit access to historical borehole data and ground investigation data;
- The tendency for ground investigation at urban sites to be constrained within development boundaries and within project design requirements, limiting the understanding of the full lateral extent of features."

Further limitations are discussed in detail within chapter 4, data quality.

3.6.2. Naming of individual features

Differing names were given to the features throughout the projects duration, such as road names and the engineering project the feature was identified on. Due to confidentiality issues with some features and the potential for roads to have several DFHs, a numerical system was derived from west to east within the M25 for the purpose of Flynn et al. (2020). Within this numerical naming system, Berry's features have remained unchanged in name (e.g. as Berry 1a etc.) due to their locations and names already being known by many. Features outside of the M25 were not considered within the Flynn et al. (2020) paper and due to their locations at present being sparse, on account of the identification bias discussed previously, they are named by location e.g. Ashford Hill. Within this project, the names of each feature have remained as the road name, unless discussed in direct relation to a specific engineering project.

3.6.3. GIS

Information within the spreadsheets above were imported into a geographic information system (GIS) to both visualise and analyse the data. *ArcGIS 10.5.1* software was employed to undertake analysis on the data and create maps to visually represent the results. For all maps created as part of this project the following formatting was used:

- *OS_Open_Carto_2 - base* map;
- *Scale line 1* - scale bar;
- *ESRI North 3* - north arrow.

3.6.3.1. Location

All features were imported into the ArcGIS software via *Microsoft Excel* using their geographical co-ordinates. This enables all features to be shown at their geographic location.

A heat map was created using the *point density* tool within the software to show the distribution of DFHs across the basin (Figure 3. 15). The *point density* tool was also used to create heat maps for the distribution of DFHs across smaller areas such as Nine Elms and to display the location of boreholes used within the sub-surface models.

The default range for the tool, selected by the software set each data point with a radius of 2060 m. As the maximum known width of a DFH is 500 m for the purpose of a heat map the radius was set at 750 m to allow for the maximum size of the features (+ 50%) to be covered. Once the layer was created, it is then possible to change the classification method for the display of the data within the heat map and the number of intervals shown. Each classification uses a differing statistical method which suits a range of data types. The default *equal interval* setting displays the data in equal class breaks and therefore suits homogenously spread data. For identifying the location of DFHs the *defined interval* and *quantile* classification methods both suit the data. *Quantile* enables each individual feature to be displayed as an equal number of features (Figure 3. 16) and *defined interval* allows the user to select the distribution. For the purposes of identifying DFHs location to one another the interval was set at 1 (Figure 3. 17). The heat maps displayed in the results chapter will state which of the two classification methods are used per map.

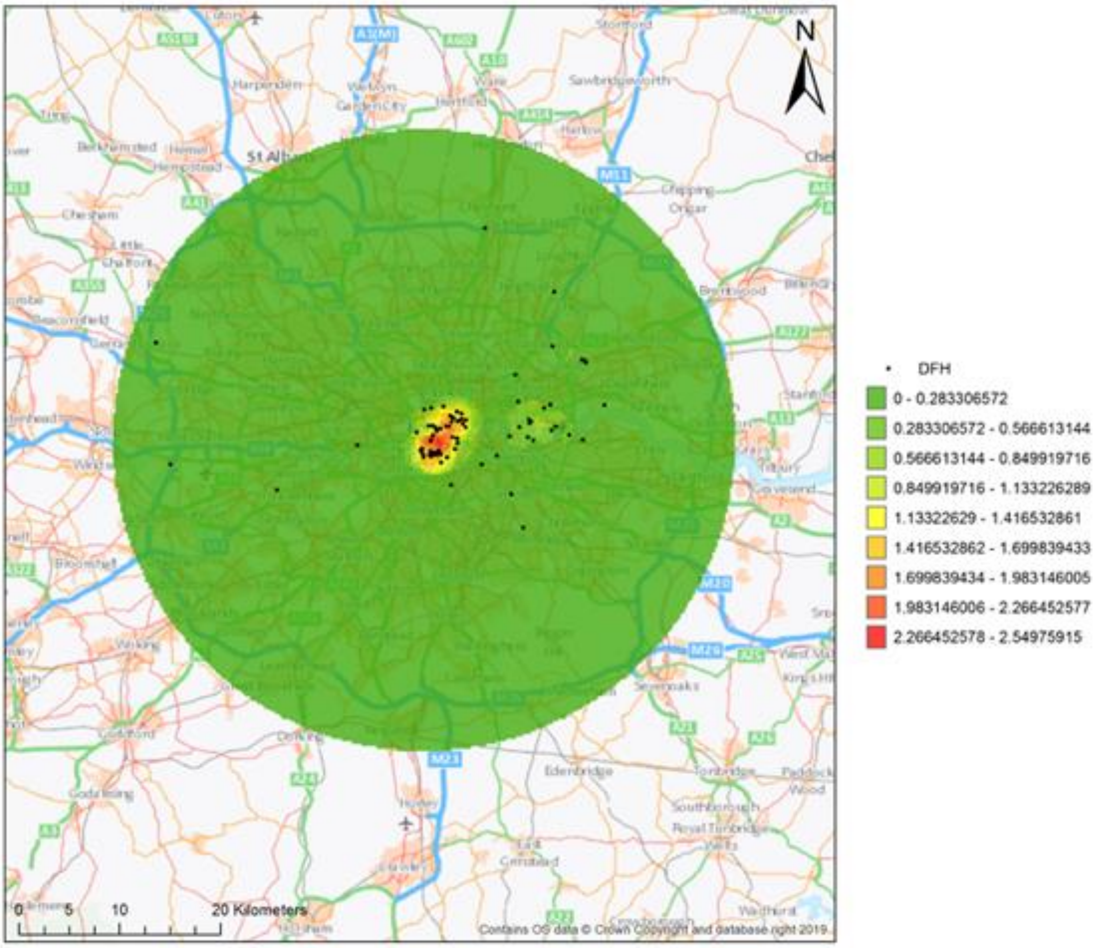


Figure 3. 15 – Heat map created using the point density tool for the distribution of DFHs within the M25. The data is here displayed using the default equal interval classification method and the radius of each point at the default 2060 m.

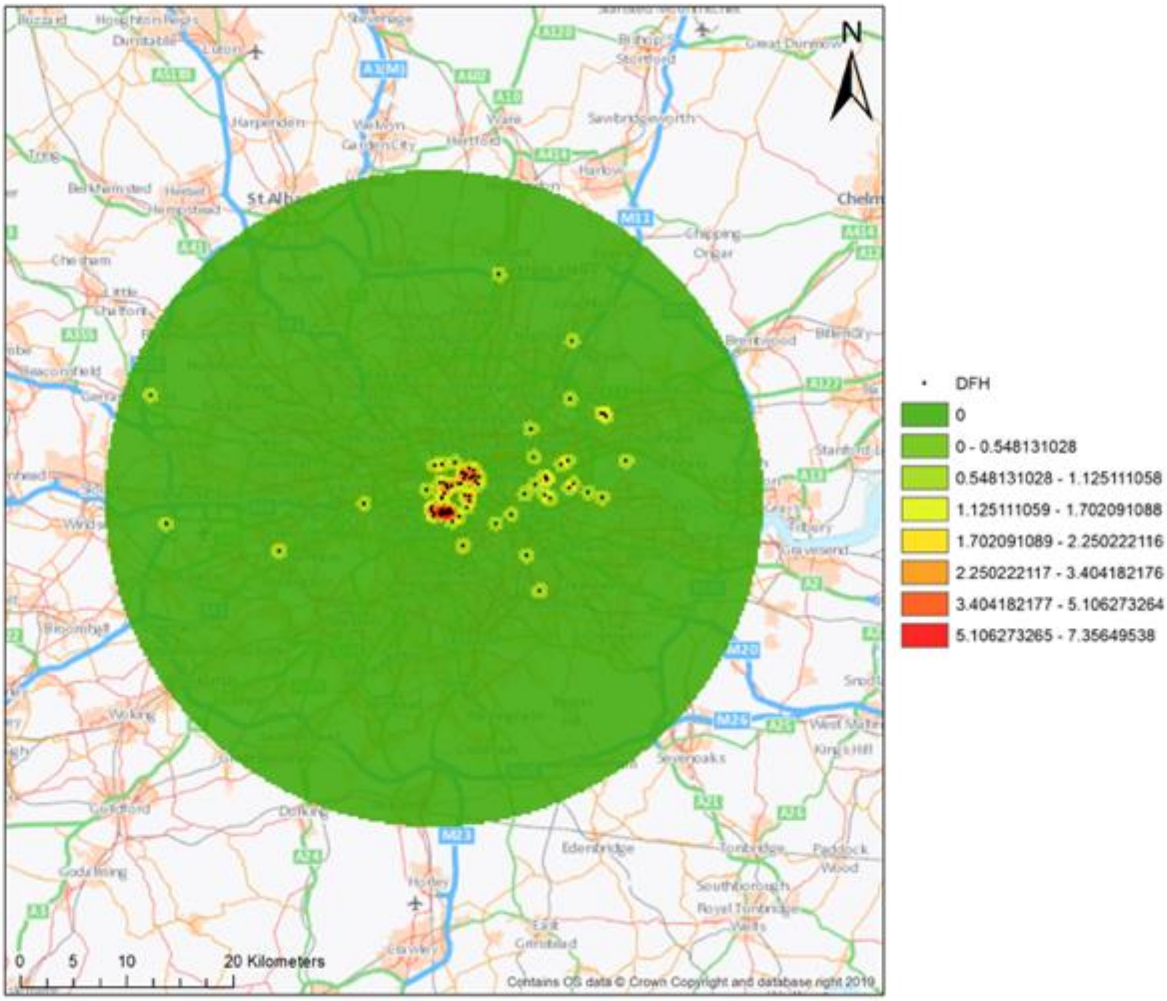


Figure 3. 16 – Heat map created using the point density tool and the classification method set as quantile and a 750 m radius for each data point.

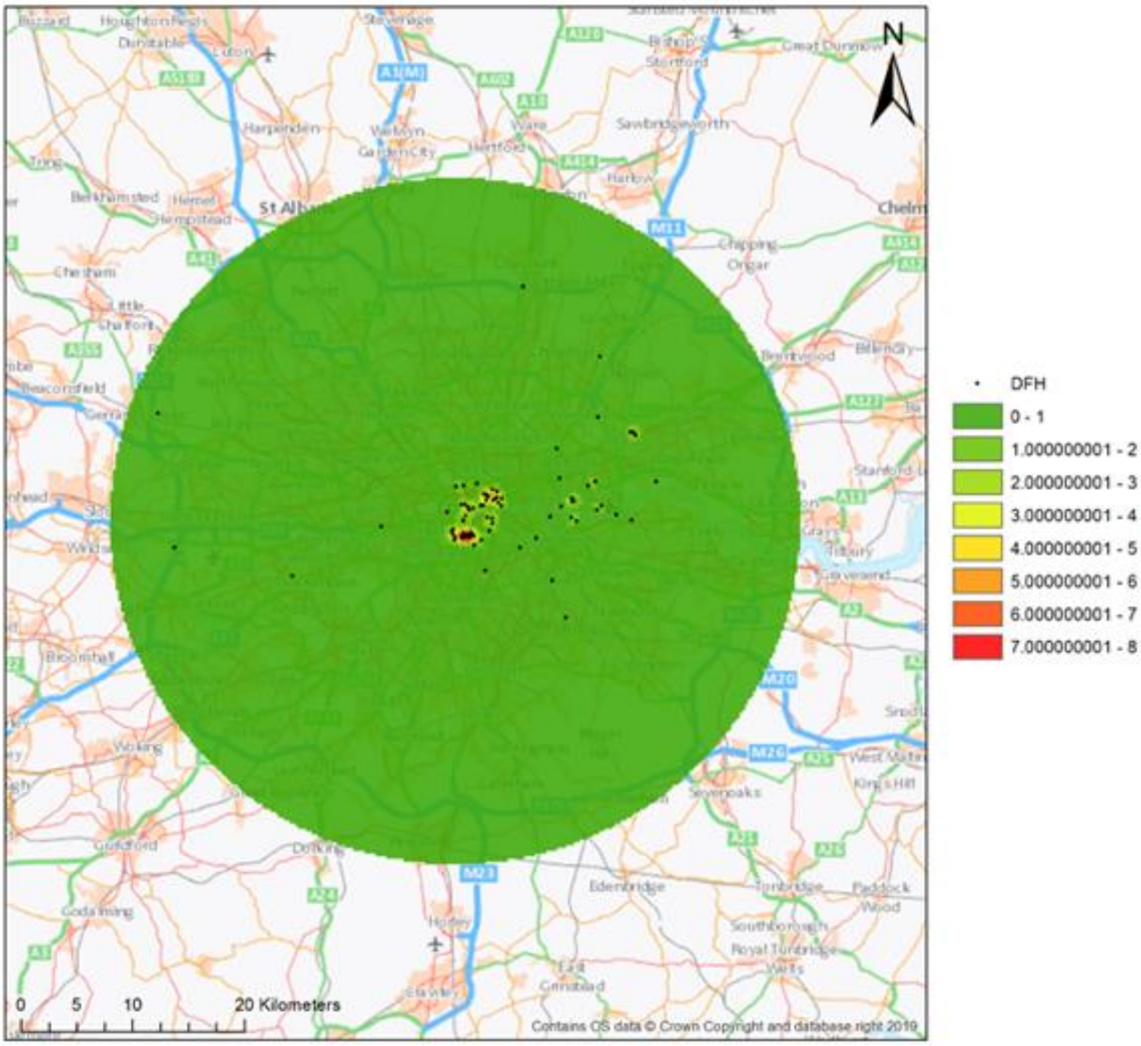
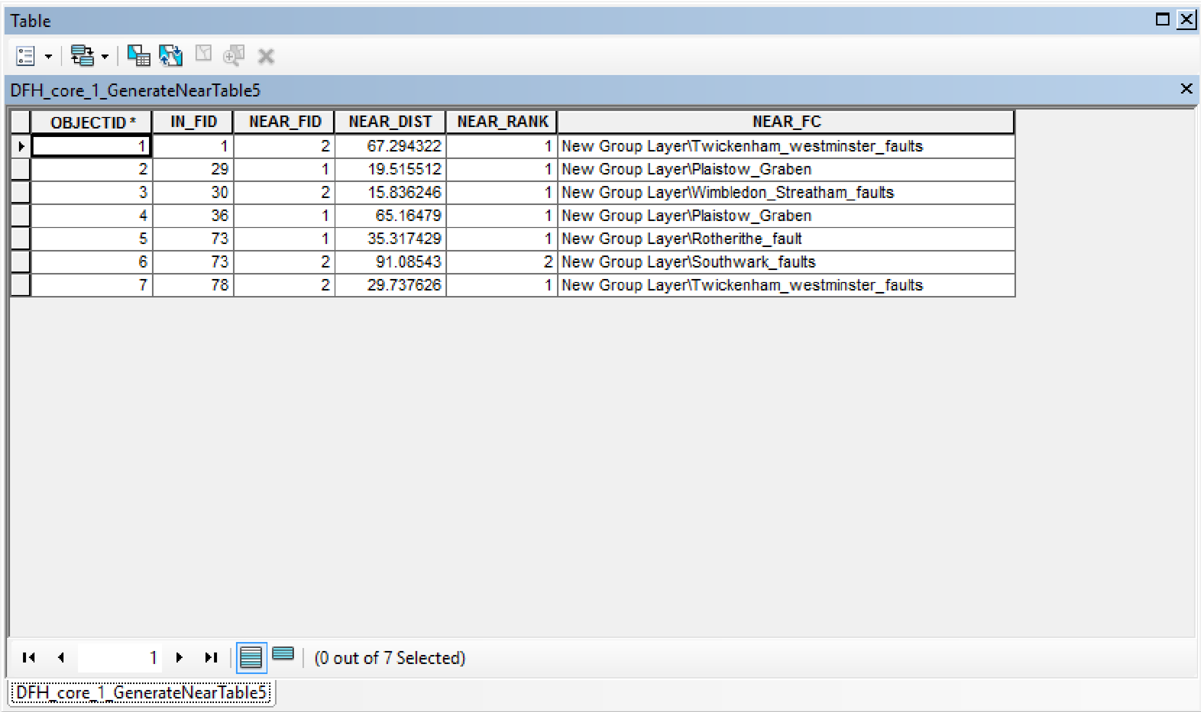


Figure 3. 17 – Heat map created using the point density tool and the classification method set as defined interval and a 750 m radius for each data point.

Known features such as palaeorivers, faults and glacial limits which may be related to the formation of DFHs, were also created in the software as layers. Palaeorivers were identified using Barton (1992), faults from Ellison et al., (2004) Royse et al., (2012), Mortimore et al., (2011) Aldiss et al., (2013) and Mortimore et al., (2011) and the maximum glacial limits from Ellison et al., (2004) and Clark et al., (2010). All features were carefully digitised onto the basemap using the draw toolbar and then converted from graphics into feature layers to enable analysis.

The layers of geographical features were then used to establish if there were relationships between the DFHs and the geographical entities which may have impacted on them. To identify the distance between DFHs and other features the *generate near table* tool (within the proximity toolset) was employed for faults and rivers (current and lost)(Figure 3. 18).



OBJECTID *	IN_FID	NEAR_FID	NEAR_DIST	NEAR_RANK	NEAR_FC
1	1	2	67.294322	1	New Group Layer\Twickenham_westminster_faults
2	29	1	19.515512	1	New Group Layer\Plaistow_Graben
3	30	2	15.836246	1	New Group Layer\Wimbledon_Streatham_faults
4	36	1	65.16479	1	New Group Layer\Plaistow_Graben
5	73	1	35.317429	1	New Group Layer\Rotherithe_fault
6	73	2	91.08543	2	New Group Layer\Southwark_faults
7	78	2	29.737626	1	New Group Layer\Twickenham_westminster_faults

Figure 3. 18 – The table created by the 'generate near table' tool showing distance of individual DFH features to faults (within 100 m).

3.6.3.2. Sub-surface ground modelling

Ground/geological models are used by geologists, geotechnical and engineering geologists to display sub-surface information (usually gained from boreholes and an understanding of the local geology) for engineering purposes, usually for a given site. The models have been used in two-dimensional (2D) and three-dimensional (3D) form extensively within the industry, in particular since Fookes' (1997) Glossop lecture.

This project created two larger scale ground models using the *ArcGIS 10.5.1* software to map the sub-surface using borehole data. The aim of modelling areas within central London was to establish whether the bedrock was at a constant level below the surface as often believed and subsequently whether DFHs are anomalous individual depressions or normal for certain areas. Two areas in central London were chosen to map the depths of geological strata (Figure 3. 19). The Battersea and Nine Elms area was selected as it is known for an abundance of DFHs. In contrast, Bermondsey to the Isle of Dogs was chosen for having no identified DFH features. 3.72 km^2 was mapped for Battersea, Nine Elms and 3.51 km^2 for Bermondsey.

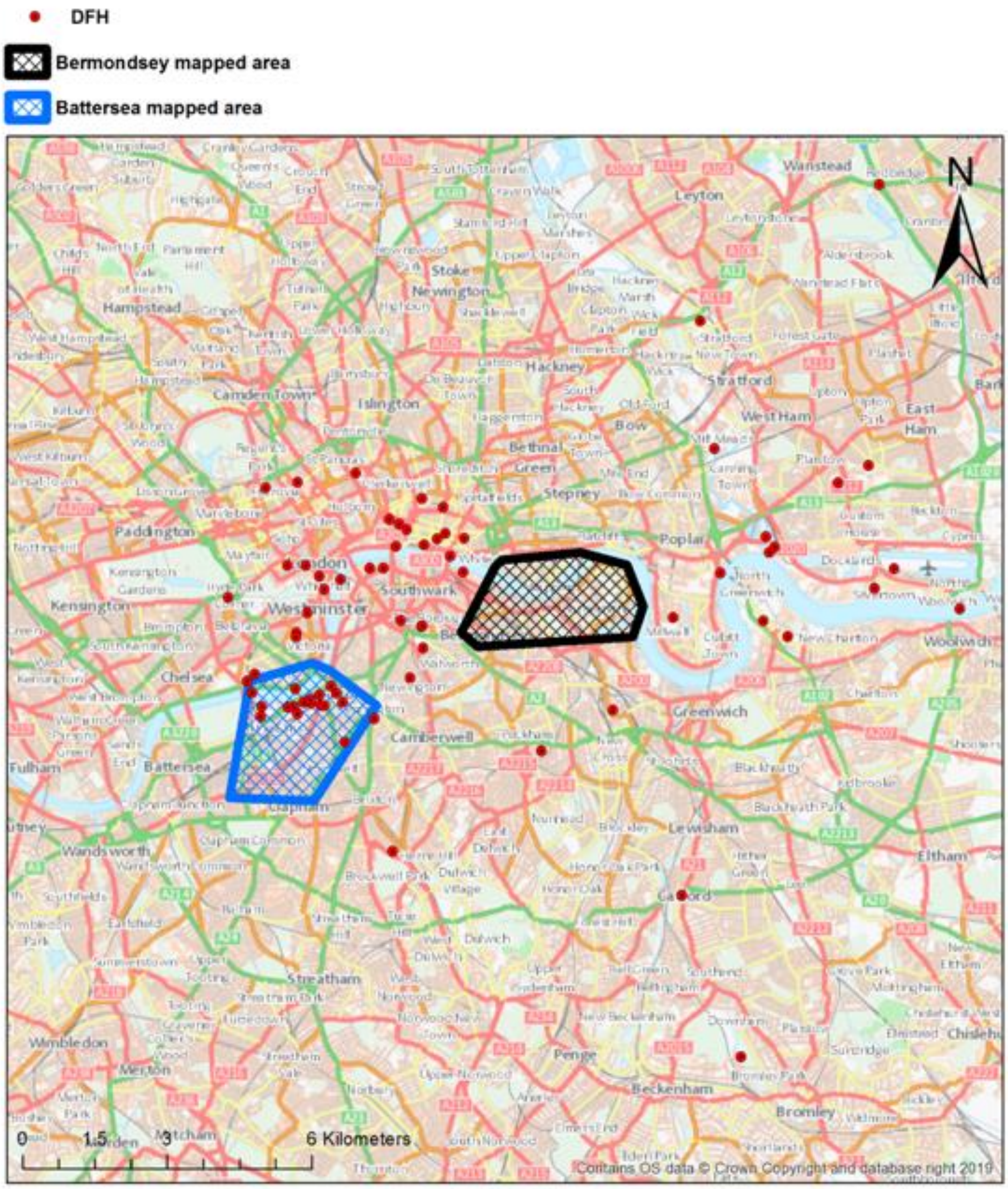


Figure 3. 19 – Area extents chosen to be mapped

Borehole data was collated in Microsoft Excel from independent borehole records within the BGS GeoIndex tool (http://mapapps2.bgs.ac.uk/geoindex/home.html), desk studies, geotechnical reports, journal articles and site investigation data provided by other individuals (Table 3. 1). 384 boreholes were included for the Battersea, Nine Elms region and 738 for the Bermondsey model. Boreholes were only included where the following information was available within the borehole log:

- Accurate geographical location;
- Ground level (Ordnance Datum);
- The borehole reached the bedrock;
- Definite identification of the London Clay or Lambeth Group.

For each borehole the following was recorded:

- Borehole reference as per the BGS;
- Easting and northing;
- Ground level (m OD);
- Depth of the RTDs;
- Depth of the LC;
- Depth of the LG;
- Depth of the TS;
- Date of borehole retrieval.

Table 3. 2 - An extract from the spreadsheet collating the Battersea, Nine Elms borehole data.

BH ref.	Easting	Northing	GL_OD	RTD_top	LC_top	LG_top	Date
TQ37NW178	531100	177657	4.7	2.87	-3.45		1863
TQ37NW1231	530800	177780	4	1.87	-3.6		1950
TQ37NW110	530680	177760	4.57	-0.23	-1.53	-28.93	1870
TQ37NW1225	530640	177870	3.66			-25.6	1903
TQ37NW1203/A	530490	177960	5.18	4.57	-0.61	-31.09	1926
TQ37NW1203AB&D	530490	177962	4.27	1.53	-3.25	-40.84	1937
TQ37NW1203/C	530490	177900	5.18	3.05	-1.22	-32.01	1936
TQ37NW2561	530470	177910	4.26	1.82	-2.14	-29.26	1969
TQ37NW2340	530470	177890	4.9	2.65	-1.4		1982

Table 3. 3 - Extract of the information imported into ArcGIS for the location and analysis of DFHs. Full dataset is shown in the appendices.

Object_ID	Easting	Northing	LAT	LONG	TQ
Barbican	532257.9	181822.7	51.51984	-0.09517	TQ3225781822

Bromley Park (Beckenham)	539367.4	169580.8	51.40813	0.002418	TQ3936769580
berry 1a (Battersea Power Station)	528939.9	177510.9	51.48186	-0.14454	TQ2893977510

The spreadsheet containing all the information above was imported into ArcGIS and the *slope analysis* tool was used to map the top of the RTDs, London Clay and Lambeth Group within the given areas (Figure 3. 20). As above, the classification method was chosen as *defined interval* as it suited the depth data.

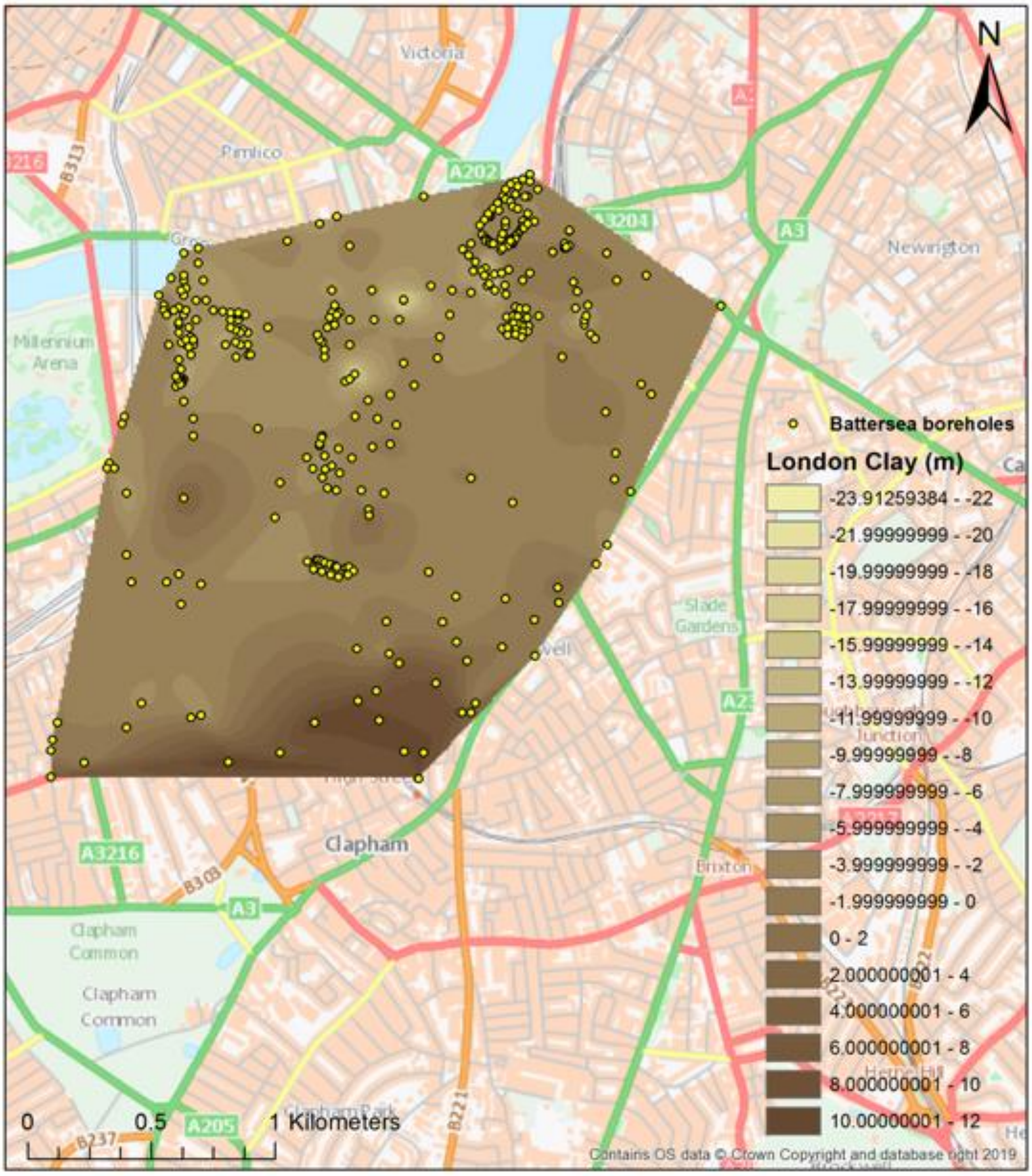


Figure 3. 20 - The results from the slope analysis tool showing the top of the London Clay in the Battersea mapped area. The classification method is shown as defined interval with an interval of 2 m.

The *contour* tool was another method employed to display the depth of strata data within the GIS software (Figure 3. 21). However, due to the highly irregular and non-constant distribution of the boreholes across the area, the contours were found to not be a reliable method to visualise the change in depth. Further limitations, including the use of boreholes, borehole spacing and extrapolating the data from boreholes into ground models are discussed in detail in chapter 4, data quality.

Figure 3. 21 - The contour results for the top of the units for the Battersea mapped area including the boreholes used for the analysis.

Once the strata were mapped in ArcGIS in two dimension (2D), the layers were imported into *ArcScene 10.5.1* to create a three dimensional (3D) subsurface model. As can be seen in Figure 3. 22 ArcScene enables the user to view all layers imported as one with the z value being offset by the depth data, meaning an accurate representation of an area's subsurface can be produced whilst remaining geographically accurate. Furthermore, the model can be zoomed and maneuvered 360° to enable a thorough understanding of the data in graphic form.

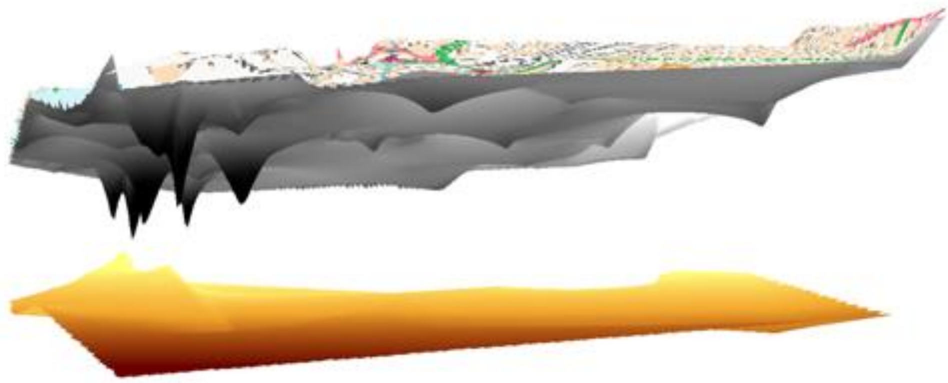


Figure 3. 22 – Print screen showing the sub-surface 3D model created in ArcScene 10.5.1 of Battersea, Nine Elms. The overlaid map shows ground level, the grey, London Clay and the orange, Lambeth Group.

3.7. Summary of methodology

Logging the cores enables both a visual understanding of the cores being studied as well as identifying the strata boundaries to enable an understanding of what is anomalous for a local area. This is furthered by the ability to interpret features and structures visible to the naked eye (e.g. mixing of distinct layers) which can be evaluated with geological and earth surface processes research and knowledge. Logging also allows identification of plant macrofossils and mollusca and enables effective sub-sampling of appropriate sections of the cores for further analysis.

Geotechnics provides an understanding of the physical properties of the sediment which aids understanding on the physical characteristics of DFHs as well as their formation. This primarily provides evidence on the variability of DFHs for the site investigation industry as well as how to engineer the features. It also provides information on the sediment's history, in particular, post-depositional processes undergone (e.g. mixing and deformation).

GIS enables the data compiled in spreadsheets to be analysed on a spatial scale and to deem whether there is a relationship with the location of geographical features such as faults and fluvial systems. The map and model outputs then enable visualisation of the data to further understanding and provide evidence for certain hypotheses.

Petrography and mineralogy in itself are a multi-proxy analytical tool. XRF provides knowledge on chemical composition qualitatively, which then enables XRD data to be interpreted. XRD determines mineral composition as well as crystal structure which furthers the understanding on the sediment's composition, behaviour and history. For example, the type of clay mineral identified can inform on the swelling capabilities of the material, this in turn informs what processes the sediment has undergone and its physical parameters within its mineralogical constraints.

Microscopy enables a visual understanding of smaller scale structures. This, alongside the STA, advances understanding of depositional environments, mixing and the physical processes which the sediment has experienced.

The combination of the methodologies above provides a multi and interdisciplinary project which will enables a well-rounded understanding of DFHs location and physical characteristics.

4. Data quality, availability and interpretation

Issues arising from data quality affect both the engineering sector (site investigation, geotechnical, design etc.) and scientific understanding as they can lead to uncertainty and risk. Whether undertaking an engineering project or scientific research, using primary or secondary data, reliability should always be questioned and evaluated. Issues arise throughout the process and range from human bias and error to data acquisition and processing with a wide array of factors affecting the outcomes in between.

A series of data quality, availability and interpretation issues are examined within this chapter. Encompassing both engineering practice, scientific research and in direct relation to this project on DFHs. Potential improvements are suggested based upon evidence of good practice within certain projects, academic journals and Glossop medal lectures (Fookes, 1997; Culshaw, 2005; De Freitas, 2009).

4.1. Ground investigation

A ground investigation is compulsory prior to any above ground or sub-surface structure being engineered as stated in Eurocode 7. The aim of the ground investigation is to provide information on the physical, chemical and biological properties of the sub-surface to enable informed decisions on materials and design. Inadequate ground investigations often lead to unexpected ground conditions triggering a large increase of project costs and delays (Rowe, 1972). According to Clayton (2009), an effective ground investigation depends on the client’s willingness to spend on high quality data and employing knowledgeable professionals. This is evident in a study undertaken by Mott MacDonald and Soil Mechanics Ltd. in 1994. It was found that the majority of engineering projects spend less than 1% of costs on the ground investigation phase. In-turn, the more money spent on the ground investigation, the less likely it was for the project’s overall costs to exceed predicted expenditure. This was particularly the case in the tunnelling sector. Furthermore, it was concluded that the organisation and interpretation of the ground investigation, not the drilling, sampling or testing were to blame for the ground investigation being flawed and leading to increased costs.

BS 5930:2015 sets out the standard for which the site investigation process must be undertaken and covers a wide range of information, from the suitability of a site for the project to in-situ testing and how to store samples. The first stage required in the standard is a desk study. This is to identify all existing, available information on the site and its surrounding area including existing boreholes (identifying 'normal' strata depths and any potential geological hazards), aerial photographs, topographic maps, groundwater levels, contamination and risks to the project. Issues during the desk study phase mainly arise from data availability. This can be due to confidentiality or historic information not being available electronically. With a strict timeframe to undertake the desk study due to financial constraints information is often lost if not available electronically.

The BGS provides a tool named 'GeoIndex' (http://mapapps2.bgs.ac.uk/geoindex/home.html) which enables free access to over a million borehole logs nationwide on and offshore. The tool is useful for construction project desk studies and scientific research to understand the sub-surface prior to any exploratory work. The major limitation of the resource is that it only provides borehole records from projects which have submitted data to the BGS. Consequently, due to submission of borehole records not being compulsory, there are many areas where exploration has been undertaken, but the data was not submitted. The impact of this will be discussed in due course.

After the desk study, ground investigation techniques are then decided upon. These include boreholes, geophysics and in-situ tests. Most often, boreholes are used to retrieve sediment cores and establish the groundwater level. The retrieval method is then decided upon, as are the boreholes spacing and locations. Boreholes are positioned based upon information gained during the desk study and the preliminary engineering design. Limitations then follow for both the positioning of boreholes and the retrieval method. For example, rotary drilling is not effective at retrieving unconsolidated sediment (Pers. Comm. Peter Reading).

Once the sediment has been bored, sub-samples of the cores are taken to be tested in the laboratory for geotechnical tests governed by BS 1377:2015. These tests aim to classify the samples in order to understand their physical properties and behavior in relation to the design. The tests and their limitations are discussed later within this chapter under geotechnical testing.

Once the testing has been undertaken the factual report on ground investigation is created. This comprises of the borehole logs, field reports, laboratory results and interpretation of the ground if required. These reports are crucial as they often are the only remaining information from the ground investigation once the borehole cores have been disposed of. The ground conditions, any groundwater monitoring and test results are summarised in a ground investigation report (GIR). Throughout the ground investigation, communication between engineers and geologists is essential (Fookes, 1997; Culshaw, 2005). The ground model is updated between periods of ground investigation. This enables a furthering of understanding at each point where additional knowledge of the site or sub-surface is identified, reducing risk through creating fewer unknowns.

4.1.1. Ground investigation and DFHs

Undertaking a ground investigation in urban environments is more challenging than for rural areas for numerous reasons. In London these include, but are not restricted to, the impact on existing surrounding infrastructure and services (both above and below ground), previous land use (e.g. foundations from previous buildings, archaeological remains and redundant tunnels), groundwater abstraction and undiscovered war bombs (Figure 4. 1). Additionally, sites are more often limited for space and therefore access for large drilling rigs is restricted (Clayton, 2009). This amplifies the issues surrounding investigating DFHs.

Figure 4. 1 – An excavation at Battersea Power Station with the previous structures piles exposed. Showing additional implications for site investigations and developing a site that has been previously developed.

As DFHs are not visible from the ground surface, if a DFH has not been previously identified and documented publicly, the site investigation is the only method to identify the feature prior to construction. Often boreholes associated with ground hazards are confidential as they are deemed to be commercially sensitive and have the potential to impact on the selling price.

A desk study will ensue and standard ground investigation methods will be used if there is no prior knowledge of the feature on site. This could lead to borehole spacing being wider than on a site with suspicious ground conditions and it is possible for the feature to be missed during the ground investigation phase. Figure 4. 2 provides an example of how this is possible within central London and three redeveloped sites. All four of the developments in the figure would have only identified a maximum of one borehole available publicly on the

BGS' Geoindex and as they are all located on the edge of the development and the feature may not have deemed a small change in bedrock depth anomalous.

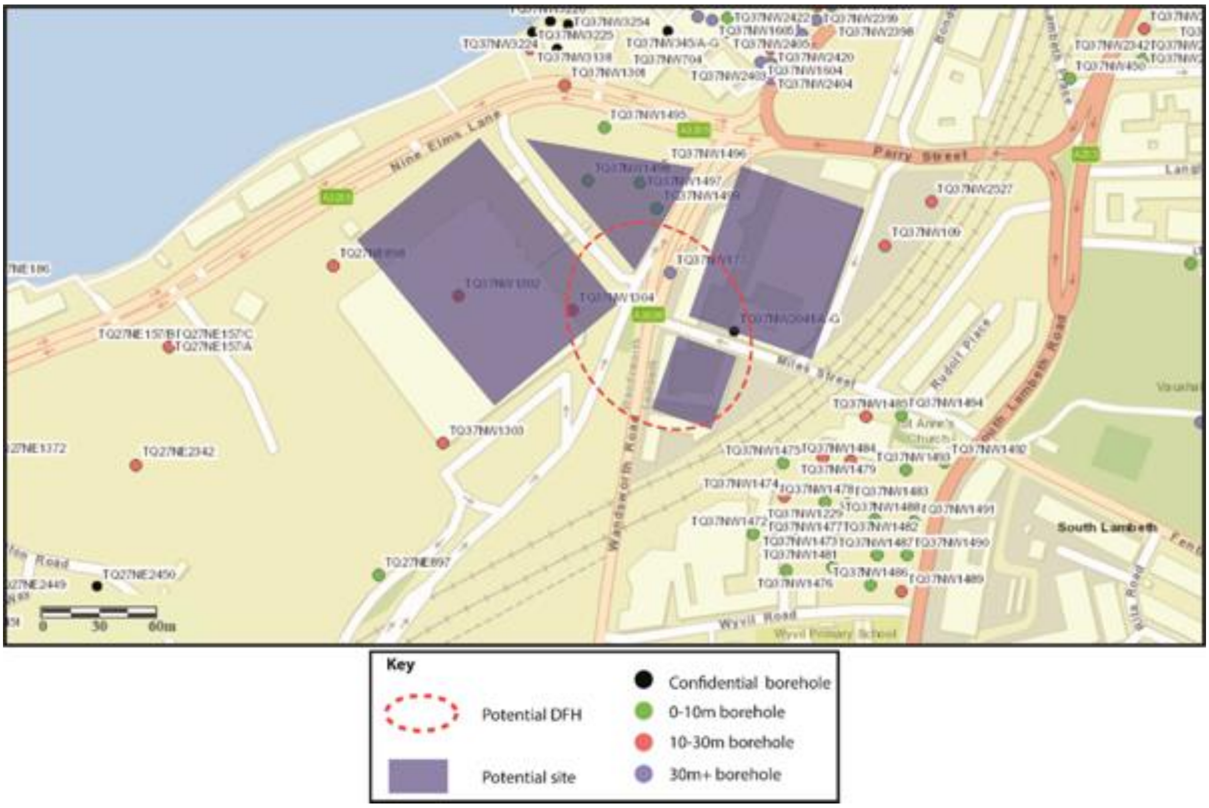


Figure 4. 2 - A map depicting the potential and often realistic occurrence that a DFH is located on the edge of several construction sites within an area of restricted borehole data publically available.

Once more, if the DFH is on the edge of a site or is unknown prior to the site investigation and construction it can initiate ground issues elsewhere in and above the feature as well as impacting on surrounding structures and services. As the majority of features are infilled with unconsolidated sediment how DFH feature is engineered could impact on surrounding sites and infrastructure. For example, if on the edge of a site and excavated, the unconsolidated infill of a DFH could cause subsidence elsewhere (possibly leading to the road above the feature to subside in Figure 4. 2) through collapse of the material into the site whilst excavating or alterations to the groundwater level if retaining walls are constructed, such as localised perched water tables.

If there are publicly available documents on the feature, the desk study would gather all information obtainable to ensure a thorough site investigation to understand the feature within the land boundary of the site.

4.2. Boreholes

Boreholes are a method to retrieve sediment and understand the sub-surface for both scientific research (more often termed sediment core) and engineering purposes. The technique is an effective way of understanding what lies beneath ground level. This is particularly the case for constant and unchanging ground conditions.

It is key to note that on average the amount of sub-surface sampled during a ground investigation via boreholes is typically <1 part in 10^6 (Broms, 1980). Consequently, the largest limitation of using boreholes is that they are not representative of a site (or large area), but are often believed to be so (Fookes, 2012). Eliminating uncertainty is practically impossible in urban areas where a full excavation is not possible in the large majority of cases. Thus, the sediment retrieval needs to be of a high quality and representative of the sites ground conditions in order to keep uncertainty to a minimum as far as possible.

For a site investigation, boreholes usually range from 100-200 mm in diameter and can be retrieved using several drilling methods. These include: cable percussion, rotary, sonic and dynamic sampling, each of which favour distinct types of sediment as well as having limitations (Table 4. 1).

Table 4. 1 - The advantages and disadvantages of difference borehole retrieval methods.

Drilling method	Advantages	Disadvantages
Cable percussion	Around 90m depth achievable Core retrieval via piston sampling, SPT Reasonable at retrieving gravel Can add inclinometers, piezometers etc.	Class 1 samples not possible Not capable in hard rock
Rotary	Deep drilling (100m+ possible) Good at drilling in hard sediments (rock) SPT capable, some are equipped for dynamic sampling Inclinometers and piezometers etc. can be installed in rotary boreholes	Not good at retrieving gravel and unconsolidated material unless equipped for dynamic sampling

	Numerous flush types possible (air, mud, water, polymers) Can also do inclined drilling	
Sonic	Can drill through all types of soil and rock Faster retrieval than rotary and cable percussion methods No lubrication required - minimising effect on sediment	Vibrations can disturb the samples structure and porosity
Window sampling	Cheap method of sampling up to 15m Low cost in comparison to a drill rig Sampling and probing for in-situ tests (including SPT) Smaller rigs for restricted sites or slopes	Casing required in unstable material Cannot sample rock

For scientific research, hand or motorised augers are usually employed to retrieve sediment from the sub-surface, these methods are also used for engineering purposes. The augers are usually smaller in diameter depending on type (50 – 100 mm) and similarly are chosen depending on the soil type being sampled and the desired depth to be achieved. For example, a Russian corer retrieves soft, consolidated sediments such as peat or clay more effectively than coarse grained sediments.

There are many limitations to using boreholes for both scientific research and engineering projects. In uniform sediment these include:

- Mode of drilling – Each sediment retrieval method favors differing sub-surface conditions. Table 4. 1 shows the limitations of each drilling method and Figure 4. 3 shows a rotary cored borehole and the lack of coarse grained sediment retrieval;
- A lack of familiarity of the chosen drilling techniques, the effect these drilling methods have on the retrieved sediment and consequently interpretation for borehole logs;
- Limited number of boreholes and borehole depth – the understanding of the sub-surface of an entire feature or site may be restricted due to only a small amount of sediment retrieved;

- Driller experience – reliant on the quality of the drilling itself, the driller's log records, accurate sub-sampling and careful storage of samples and cores;
- Difficulties in establishing the absolute ground level at the time of drilling relative to OD. This creates difficulties in comparing depths and establishing the 'normal' local level of strata;
- Urban sites are constrained within development boundaries and project design requirements – restricting the understanding of the lateral scope of strata and features.

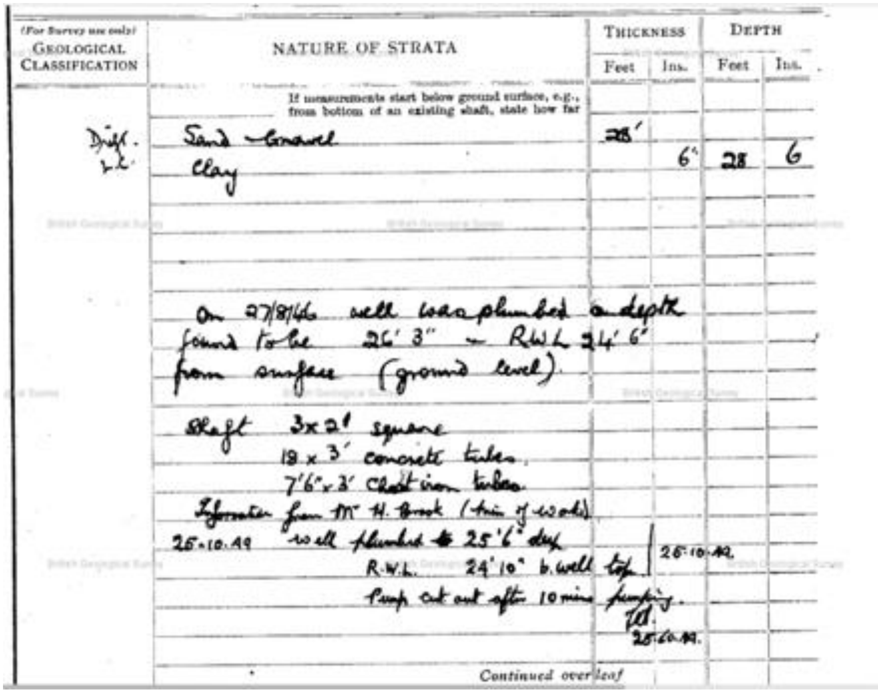
Figure 4. 3 - Images depicting gravel retrieval via a rotary drill rig. Image A shows a lack of retrieval of the unconsolidated gravel sediment. Figure B shows the retrieval of gravel sediment when there are finer particles present to consolidate the larger gravel sediment.

Once the sediment is retrieved, borehole logs are documented in both the scientific and engineering sector to record composition, strata changes, ground water level and any geological structures (such as faults, orientation of strata etc.). The Eurocodes e.g. EN ISO

14688 and EN ISO 14689 have established guidelines for the logging of soil and rock for the site investigation industry. The BGS' field description guides are used for geologists and researchers e.g. The Geological Society of London's handbook series "The Field Description of Sedimentary Rocks" (Tucker, 1982).

Limitations of borehole logs include:

- Historical borehole logs – drilling methods and knowledge of the strata has improved and therefore the older records should be treated with caution in regards to accuracy of depth, location, description and strata names. Furthermore, older records and retrospective interpretation of these logs often try and fit the ground to the expected sequence when naming strata. Figure 4. 4 shows a water well log written in 1941. However, this is not the case for all historic records. Many are extremely descriptive and can be more informative than present day records which are restricted by the need to produce logs quickly.
- Logger – the quality of borehole log and logging depends on the individuals training, experience and understanding of local geology, their time constraints and motivation to undertake the task well.
- Miscommunication - differences in discipline (e.g. geologists and engineers) and in turn terminology can impact on accurate information being retrieved from borehole logs for design purposes. Therefore, information within the log may be misinterpreted or misunderstood and can lead to increased risk.
- Access - confidentiality and non-electronic formatting often limit access to borehole and ground investigation data, particularly where borehole logs are not submitted to the BGS for their publically accessible GeoIndex database.
- Reason for drilling – shallow foundations will mean shallow boreholes and tunnelling or deeper foundations will result in deeper exploration.


(For Survey use only) GEOLOGICAL CLASSIFICATION | NATURE OF STRATA | THICKNESS | DEPTH

		Thickness Feet	Thickness Ins.	Depth Feet	Depth Ins.
	If measurements start below ground surface, e.g., from bottom of an existing shaft, state how far				
Drift.	Sand Gravel	28'			
	Clay		6"	28	6

On 27/8/46 well was plumbed a depth found to be 26' 3" – RWL 24' 6" from surface (ground level).

Shaft 3x2' square
19 x 3' concrete tubes,
7'6" x 3' cast iron tubes.
Information from Mr H. Brook (...)
25.10.49 well plumbed to 25'6" dry
R.W.L. 24'10" b. well top | 25.10.49.
Pump cut out after 10 mins pumping.
25.10.49.

Continued overleaf

Figure 4. 4 - Example of a drillers water well installation log and classification (TQ28SE1471).

Cross-sections are drawn from the borehole logs to visualise the sediment conditions across a given area identified from the boreholes and cores taken. These will be discussed later on in the chapter (4.4 Ground Models).

For both researchers and engineers, assuming constant ground conditions based upon boreholes and cross sections leads to a restricted view of the sub-surface. Missing out on vital evidence which could inform on understanding and physical properties which may impact upon design or formation hypotheses. This restricted view is largely caused by the exploration of the subsurface being through boreholes and the limitations of this method and the subsequent logs as previously discussed. Assumptions between borehole locations and the following restricted interpretation causes uncertainty and in turn induces risk.

4.2.1. Boreholes in relation to DFHs

Section 4.2 describes the restrictions of using boreholes in generic site investigations and exploratory work. These limitations go further when studying anomalous, highly variable sediment such as with DFHs.

Bar the excavation at Battersea Power Station and Woolhampton (Collins et al., 1996 and 2006), boreholes are the only method that have been employed to gain access to the material within and surrounding DFHs. This limits a full understanding of the physical composition of the infill, impacting on construction potential as the geotechnical properties are not fully understood. For researchers, it limits understanding of the formation of the features as it would often mean indicators of processes are unidentifiable through boreholes or missed altogether.

Limitations of using boreholes with anomalous, variable sediment include:

- Loggers – more so than in unchanging sediment, the loggers experience and accuracy when recording the geology in detail is crucial to documenting the variable sediment effectively. A thorough understanding of London geology would aid this by knowing what is normal and anomalous within a core.
- Mode of drilling – variable, unconsolidated sediment is difficult to retrieve (Figure 4. 3 above).
- Site restrictions – as mentioned previously, ground investigations in urban areas are constrained within development boundaries and design requirements. Not only does this limit understanding of the full extent of DFHs, but it restricts the knowledge the impact of external variables has on a sites sub-surface (e.g. fluvial). Further site restrictions include physical restrictions such as relict foundations, archaeological or environmentally sensitive areas and existing buildings.
- The limited number of boreholes and their often limited depths hinders identification and characterisation of features. Most importantly it does not allow for the extent of the features to be known, creating uncertainty for both engineering projects and scientific research.
- Geological structures - It is difficult to identify faults, dipping beds (Figure 4. 5) and the interaction of the sediment types in boreholes.
- Battersea excavation, Figure 4. 6 shows large clast of London Clay within the unconsolidated infill of the feature. This change in ground conditions was random throughout the infill and would most likely have been missed by a borehole.

- Access – as noted above, access to historic boreholes is largely only possible if freely available electronically (such as the BGS' Geoindex). Without access to borehole logs within or surrounding DFHs borehole spacing for a site investigation may miss the feature, especially if on the edge of a site. Moreover, if there are available boreholes, but on the edge of a feature, the extent may not be known and construction could impact on the feature outside of the site's boundaries. Several examples of borehole access issues in relation to known DFHs are noted within this chapter.

Figure 4. 5 - The dipping sand layers, indicated by dashed lines, would not have been able to be interpreted from a borehole. This larger exposure aids scientific research to understand previous processes associated with the feature and its infill which otherwise would not have been possible. Exposure is approximately 2.5 m wide and 2 m high.

Figure 4. 6 - Large clast of London Clay within the DFH infill at Battersea Power Station, consisting of mainly unconsolidated, disordered sand, silt and gravel. Due to the site being excavated, it is clearer to see the variability, the relationship between the differing sediment types and other indicators such as oxidation/iron staining in comparison to within a borehole. Exposure is approximately 2 m high and 1 m wide.

If identifying DFH features from publicly available borehole records such as the BGS' Geoindex for a desk study or scientific research, then many features and their extent would be unknown. For example, there are several features identified in the Nine Elms area, but only known through site investigation reports not publicly available. Therefore, if only using the BGS Geoindex tool as many desk studies do, the features alone, let alone their extent would not be identifiable (Figure 4. 7).

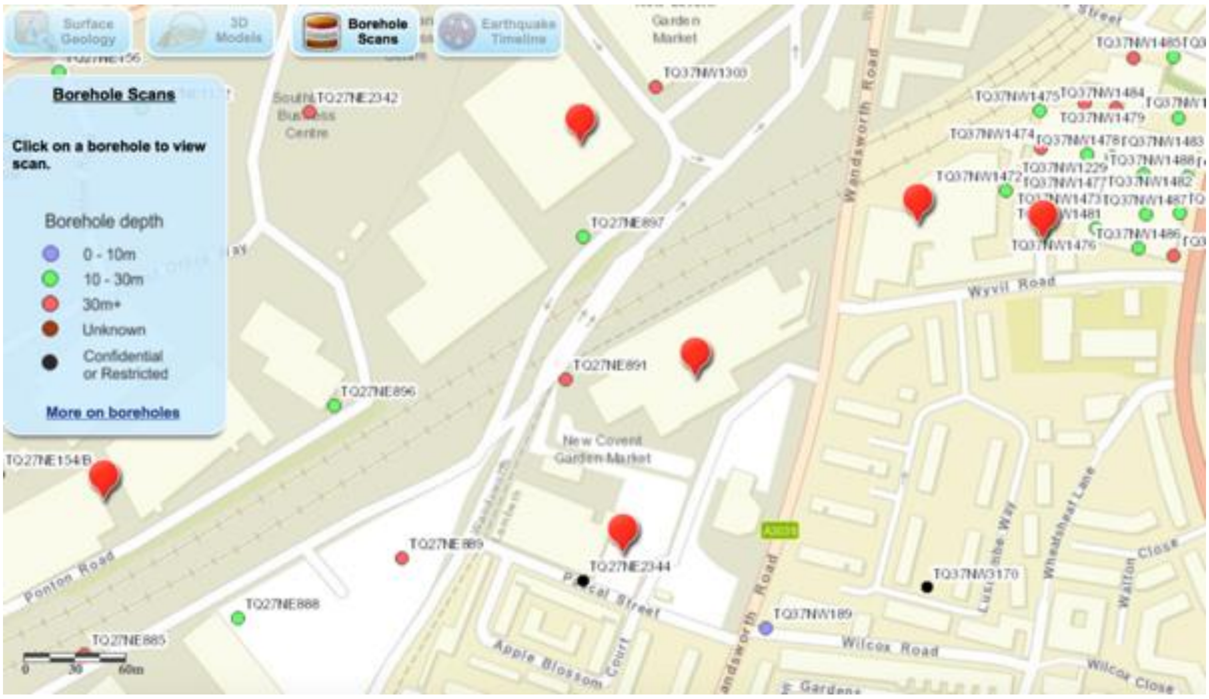


Figure 4. 7 - Potential DFHs identified (marked with the red indicators) in the Nine Elms area of London, with no boreholes in between to identify the DFH features, their extent or the 'normal' local level of strata confidently.

A further issue with access to boreholes is where there is no borehole data available between two features which are documented. It is unknown whether the Chigwell gravel pit cited at the end of Berry (1979) paper and the Albert Road DFH are separate features or one. No boreholes are known to have been taken between the two and the evidence for both features is extremely limited (Figure 4. 8).

Figure 4. 8 - New Barns Farm gravel pit identified at the end of the Berry paper and the Albert Road DFH (shown in red stars) showing that there are no publicly available BHs accessible for the feature or in between the two.

A final issue with borehole access is where there is only one borehole which identifies anomalous depth to the bedrock. The Elverton Street DFH is based solely upon one borehole log and there are no obtainable borehole logs available for at least 500 m. For a construction project, a full site investigation would follow. For research purposes it is questionable whether to include this one data point as a feature due to a lack of further data or the resources to gain more. The Lea Valley (Olympic Park) DFH is also based on one borehole for all data relating to the diapir and again must be treated with caution.

To conclude, often boreholes are restrictive, not accessible and can miss DFH features or only retrieve the edge (e.g. Bellhouse et al., 2015). However, it is not feasible or possible to extract an entire DFH using boreholes or excavate every feature to view its entirety. Hence, boreholes and cores must suffice for both engineering projects and scientific research whilst acknowledging and being cautious of the restrictions.

4.3. Testing of samples

Once sediment has been retrieved from the sub-surface, analysis of the sediment is undertaken to further understand the samples for numerous variables. Due to financial and time constraints the entire core is rarely tested. Sub-samples are taken, tested and the results inferred for the given strata. This project will focus on both geotechnical and geochemical testing and the limitations with such techniques.

4.3.1. Geotechnical tests

For construction projects, geotechnics is required to quantify the physical characteristics of the sub-surface in order to use the data to inform on construction above or through the sediment and determine how it will behave. Geology and geotechnics are both disciplines in which there are many unknowns and rely extensively on experience of professionals to exercise judgement based upon the known limitations of the data (Duncan & Sleep, 2016).

Geotechnical tests are employed to determine values for different variables in relation to soil behaviour. There are two types of geotechnical tests: in-situ and laboratory. In-situ tests include the standard penetration test (SPT), dynamic cone penetrometer test and the cone penetration test (CPT/CPTu) to name a few.

A piezometer cone is used to acquire CPTu data most commonly via a static drilling rig. The data itself has the potential to limit the need for an increased number of dearer boreholes through acquiring constant geotechnical data in place of sediment retrieval, but the methodology has several limitations. These include: operator experience and training (following of procedures such as rate of penetration and how to accurately set up the rig and cone for reliable data acquisition), contact with gravel affecting the inclination and data interpretation issues. Many of these limitations can be reduced by drilling (or having access to) one borehole within the immediate area. This enables validation of the data through comparison of the results to the borehole core sediment.

Data interpretation issues arise largely due to the knowledge, experience and training of the person deducing the data. Although the interpretation of the data is undertaken by a computer, humans are still required to check for any errors. Individuals have differing opinions and identify different strata boundaries and soil types from the data based upon experiences they have had previously and how they were educated in analysing the CPTu data. This matter can be overcome through taking a borehole in close proximity to a CPTu test, which is common practice.

In order for laboratory geotechnical tests to be undertaken sub-samples are taken from the retrieved sediment cores. These smaller samples are taken either at equal intervals throughout the core or at every stratum change. The drilling method impacts on the sediment quality retrieved. For some tests, it is crucial that the sediment taken for sub-sampling is undisturbed as far as possible. Methods to mitigate this include scraping away the outside of the core (removing the most likely disturbed layer) or taking the sample from the central area. Other tests, such as classification tests do not require undisturbed samples.

A major limitation of testing sub-samples is that only a small amount of the sediment is tested and then extrapolated to be representative of the entire strata. In constant and unchanging sediment, this is a relatively reliable method, however in variable sediments or where boreholes are spaced far apart, it is highly unlikely that the data recorded for the sub-sample represents the characteristics of the surrounding sediment in-situ.

Cores and sub-samples from boreholes are sent to a laboratory where geotechnical tests are undertaken following BS 1377. The type of tests undertaken are dependent on the soil type, planned construction and design. Additional limitations to note are that prior to geotechnical tests being undertaken the samples may have already been compromised for their reliability. The method of retrieval, handling and storage (not at a constant temperature or sealed in wax to keep in-situ moisture content within the sample) of boreholes and their sub-samples are crucial to guaranteeing the geotechnical test results are valid.

The data obtained from the geotechnical tests enables derivation of characteristic values which is then inputted into design software. This then enables the design of earthworks, foundations and the overall structural design based upon the sub-surface behavior, pre, during and post construction (settlement). Due to the restrictions of quantifying the sub-surface, discussed throughout this chapter, reliability calculations, such as factors of safety (FoS) and partial factors taken from the Eurocodes are employed to reduce the chance of failure of the given engineering design. Further reliability calculations can be found in Phoon (2017) and Duncan (2000). A FoS is a design parameter which allows for differing loading conditions based upon the known geotechnical parameters (any factor lower than one leading to failure and above one enabling a risk envelope). In uniform sediments factors of safety often lead to projects being over-engineered. However, the reduction in risk allows for the unknowns between boreholes and tested sediment samples to be accounted for. In variable ground, the design parameters are likely to be more conservative.

Basic equation for the FoS: $\frac{Restoring\ stress}{Disturbing\ stress}$

The British Standards and Eurocode provide factors of safety and partial factors for differing earthworks and structures. All of which depend on the structure itself as well as the sub-surface conditions (e.g. potential for earthquakes and slope failure) which impact on the probability of failure.

Geotechnical tests provide understanding of the behaviour of soils, in turn this can provide information on processes which the sediment has undergone in the past and provide an understanding of why it behaves in a certain way in the present. Geotechnical tests such as oedometer show whether a soil is consolidated or overconsolidated. If overconsolidated, this can indicate previous erosion, desiccation or a rise in groundwater in the past which now impacts on consolidation properties. The history of the sediment impacts on the physical characteristics of the sediment, including the shrink swell potential and rate and scale of consolidation to name a few.

4.3.1.1. Geotechnical testing in relation to DFHs

Geotechnical tests are effective because of their ability to quantify the behaviours of constant mass of sediment from a smaller sub-sample. In highly variable sediments, such as the infill of DFHs, the tests prove problematic for several reasons. As well as the limitations mentioned above, these include: retrieval method, sub-sampling, geotechnical test requirements and CPTu data acquisition and interpretation.

The retrieval method implications are amplified due to the inability to retrieve all types of samples. For example, where a rotary drill cannot retrieve unconsolidated sediment effectively it limits the amount of sample which can be tested geotechnically and therefore limits the understanding of its behaviour. Where sediment has been retrieved, sub-samples are taken. In variable sediment the location of sub-sample selection within cores is often more difficult due to fewer clear strata changes. Thus, there is an increased reliance on the engineer, laboratory technician or driller’s experience and knowledge to sub-sample at given intervals or within areas of sediment change.

The most crucial limitation of sub-sampling in highly variable sediment is that it is not representative of the surrounding ground conditions and therefore the test results will also not be characteristic or informative of the sediment's behavior. In geotechnical tests this reduction in representability is further enlarged due to the individual test restrictions. For the majority of geotechnical tests, the British Standards require a minimum amount of sample weight from sub-samples per test (table 4.2). Moreover, the majority of tests are not suitable for a range of sediment sizes (e.g. gravel and clay or silt). Therefore, the tests are either not carried out on variable sediment or their results are not representable due to the removal of larger or smaller sediments in order to run the test. Consequently, the reliability of the test results and the potential to extrapolate the findings from the small, variable samples to the wider sub-surface is reduced dramatically, particularly if the variability of the soil is on a centimetre scale horizontally and vertically such as with DFHs.

Table 4. 2 - Table showing geotechnical test suitability and requirements (based on BS 1377 from RSK, unknown date).

	Type of test	Derived parameters	Sample type required	Soil types	Mass required for: Fine grained soil	Medium grained soil	Coarse grained soil
Classification tests	Water content	Water content	D, U	C, S, G	50g	350g	4kg
	Atterberg limits	Liquid limit (%) Plastic limit (%) Plasticity index (%)	D, U	C, S	500g	1kg	2kg
	Density (linear)	Density (kg/m^3)	U	C, S	500g	1kg	2kg
	Particle size distribution	Particle size distribution by weight	D, B	All	150g	1kg	2kg
Compaction tests	California bearing ratio (CBR)	CBR value	U, B	All	6kg	6kg	12kg
	Compaction (4.5kg)	Maximum density and optimum moisture content	B	All	10kg	25kg	50kg
	Compaction (2.5kg)		B	All	10kg	25kg	50kg
	Compaction (vibrating hammer)		B	All	50kg	50kg	50kg

Strength testes	Undrained unconsolidated triaxial	Shear strength/cohesion	U	C	6kg	6kg	12kg
	Consolidated undrained triaxial	Effective cohesion Effective angle of shear resistance	U	C	6kg	6kg	12kg
	Consolidated drained triaxial		U	C	6kg	6kg	12kg
	Laboratory vane	Shear strength/cohesion	U	C	100mm diameter>100mm long		
	Small shear box	Effective cohesion Effective angle of shear resistance	U, B	All	1kg	2kg	n/a
	Large shear box		U, B	All	35kg	35kg	35kg
Consolidation	Oedometer consolidation	Coefficient of volume compressability Coefficient of consolidation	U	C	500g	1kg	2kg
Chemical	pH and sulphate	pH value and sulphate content	D, B, U	All	150g	600g	4kg

Fine grained soil = not more than 10% .2mm	U = Undisturbed sample
Medium grained soil = 2-20mm (fine and medium)	B = Bulk disturbed sample
Coarse grained soil - 20-75mm (includes coarse gravel)	D = Small disturbed sample

CPTu data acquisition and interpretation is potentially compromised in variable DFH sediments. This is largely due to the rate of change in the variable sediment on both a horizontal and vertical scale (e.g. the DFH at Ashford Hill) and the potential for the piezocone being able to penetrate the sub-surface. The majority of DFHs are infilled with a mixture of unconsolidated sediment of varying size. Therefore, if gravel is present within the infill the machine will refuse as the piezocone is unable to penetrate and collect data if the push force of the rig is not adequate.

Interpreting CPTu data in variable DFH sediments proves problematic due to the rate of change. In coherent sediment the results can be sub-sectioned into strata changes and clear characteristics which are typical behaviour for that given strata. In highly variable sediment this is challenging due to the behavioural properties of the soil changing at an increased rate. Therefore, it is difficult to identify and characterise a particular sediment type (e.g. dense sand) and in turn its behaviour for both engineering and scientific purposes.

Notwithstanding the limitations, CPTu is an effective method of gaining quantitative data on the behaviour of the sub-surface sediment. This limits the need for unwarranted numbers of boreholes which not just increase costs and logistical issues to retrieve, but have follow up repercussions such as storage and disposal.

Although geotechnical tests in variable sediments are not always representative of the entire sediment mass (or strata), the tests provide quantitative data on the behaviour of soil through numerous variables. Once the raw geotechnical data has been assessed and characteristic values derived, a FoS or partial factors are then applied to the characteristic values. This reduces the risks associated with the test results being overestimated due to the varied nature of the samples and the inability of them being representative as an entire mass.

4.3.2. Petrographic and mineralogical

The use of petrographic and mineralogical analysis in both the engineering and scientific sectors is discussed within the methodology. In predictable and uniform sediment, the techniques are effective ways of furthering understanding of both the composition and the behaviour of sediments which in turn can also provide information on their histories.

As per geotechnical tests, geochemical tests are usually taken via sub-samples of a sediment core and the same limitations of sub-sampling apply. Exceptions to this include x-ray scanners (such as ITRAX; Croudace et al., 2006) which analyses the entire core and x-ray fluorescence (XRF) sensors on piezocones which enable in-situ data to be collected. Both of which provide major elemental composition.

For laboratory tests sub-sampling (as above in geotechnics) must be undertaken. As above, due to a smaller limited sample mass, this presents issues for the representation of entire strata and assumes continuity (and no change) both horizontally and vertically. A further limitation to geochemical tests is the sample size analysed. Typically, less than one gram of sediment is analysed, again limiting the representability of the sample tested. In constant, unchanging sediments numerous samples can be tested to ensure validity, but in variable sediments this proves more difficult to ascertain accurate chemical and mineral compositions.

Further issues have the potential to arise through machine and human error. Although calibrated, the machinery may have defects due to age or not being serviced. Moreover, geochemical analysis is highly dependent on the user setting up the machine's settings depending on the sample being analysed. The set-up of the machine will also favour certain elements and minerals. Although standards reduce this uncertainty, different users would likely favour different set-ups and accordingly reproducibility is potentially an issue with data outputs of similar materials. This is somewhat overcome by standards and the recording and publishing of settings used, but each machine will also have different set-up parameters impacting on results.

Human bias also arises through data interpretation. Energy peaks are the output of the majority of geochemical tests. The user selects the peak within the software and establishes the element which is related to that energy range. In techniques such as XRF, this is relatively simple as the peak is directly related to the element present. However, in methodologies such as XRD the user is more instrumental in the identification of the peak and attributing the data to given mineral composites. Even with relatively uniform samples of two to three mineral compositions, caution of results should be employed as certain minerals can have broad peaks at a low intensity (such as quartz) and this creates difficulties in identifying other minerals.

4.3.2.1. Geochemical testing in relation to DFHS

Alike to geotechnics, the limitations noted above for using geochemical tests in constant and unchanging sediment are present and become greater in DFH sediment. Again, largely due to the inability to extrapolate the results in highly variable sediments with minute samples. All limitations of geochemical results and analysis impact on both the engineering and scientific fields.

XRD and XRF were undertaken for geochemical analysis within this project. The limitations of these methodologies are expressed in Table 4.3. Both of these techniques use one gram or less of sediment and this is the largest limitation of the methodology. Similarly to geotechnical tests, due to the rate of change within DFH infill, the small amount of sample tested presents difficulties in inferring the geochemical results to the surrounding irregular sediment and therefore make the results from a single sample negligible. To increase the confidence in the results analysing numerous samples within the sub-sample and identify whether there are trends or similarities can be undertaken. As well as being time consuming and costly, it is still minute samples being analysed within a small area of a single borehole or core. Therefore, within variable sediment both horizontally and vertically, this additional testing may still not be representable of the larger infill or even a borehole sub-sample.

Table 4. 3 - Advantages and disadvantages of XRF and XRD.

	Advantages	Limitations
XRF	Relatively quick to prepare and acquire data on elemental composition.	Lower concentrations are often lost due to larger matrix effect and absorption.
	Good for identifying either major elements or trace elements within a single sample.	User set-up preferences differ.
	Can be calibrated with a zinc pellet.	Human bias for identification of peaks.
	A relatively low cost geochemical test.	-
XRD	Relatively quick to prepare and acquire data on elemental composition.	Relies on the user to establish identification of peaks – bias.
	In homogenous samples mineral composition is reliable and straightforward.	Difficult to establish mineral composition in highly variable sediments.
	Can c127haracterise crystal structure and fine grained sediments.	If the sample is not plane then the user must alter the peaks to identify minerals using the database – human bias.
	Needs to be calibrated by an engineer.	-

The machinery employed for the analysis also have limitations through background noise and the effect of the material leading to a favouring strong-signalled elements and minerals. In highly variable sediments this creates additional unknowns for the user in regards to set-up of the machines scanning conditions and when identifying peaks for both mineral and elemental composition. If the composition of the sediment is unknown because of its variability the user is unable to tell whether the results are accurate or background noise due to mechanical or software issues. This is particularly the case when using XRD as the user must identify which peak attains to which mineral composition through a large database.

4.3.3. Summary of testing

It is not feasible to excavate the sub-surface for every research and engineering project to understand its entirety. Nor is it practical to test entire cores due to both time and money constraints. As a result, the current testing methods used are deemed reliable when exploring uniform geological sequences. More so in construction where the use of risk factors allows for error in analytical tests and in turn data outputs. Although the factor of safety potentially leads to over engineering structures out of caution.

Conversely, for highly variable sediments, and DFHs, there are crucial methodological and data quality issues which need to be addressed for accuracy. Bearing this in mind, it is crucial that geologists and engineers do not assume uniformity of strata between boreholes and in turn presume that the results from tests are applicable to entire strata. If this uncertainty is understood and communicated effectively, understanding of the risk can be built into construction and design reducing the threat or at least enabling a plan for worse case scenarios. This also enables a well-rounded understanding research of anomalous features and does not limit knowledge to limited, potentially inaccurate evidence.

4.4. Ground models

Ground models are covered briefly in chapter 2. The diagrams portraying the sub-surface in models can be illustrated in 2D or 3D form with the first primarily being in the form of cross-sections. Cross-sections have been discussed above in relation to how the information within is acquired. The limitations noted above on cross-sections are also applicable to ground models. Similarly, all 2D limitations apply to 3D models.

The major limitation of cross-sections is that the sediment between the two cores is deemed constant. In particular, for a non-geologist or geotechnical engineer they would not fully appreciate the simplification of the cross-section and may deem it as certain. This is amplified where lines are drawn between the boreholes at strata changes. Figure 4. 9 shows the potential for vital sub-surface evidence to be missed (e.g. fault, edge of a DFH). This leads to an increase in risk as it can lead to a simplified construction design potentially causing further issues either once construction has started delaying time frames and causing an increase in costs or once complete could cause settlement issues.

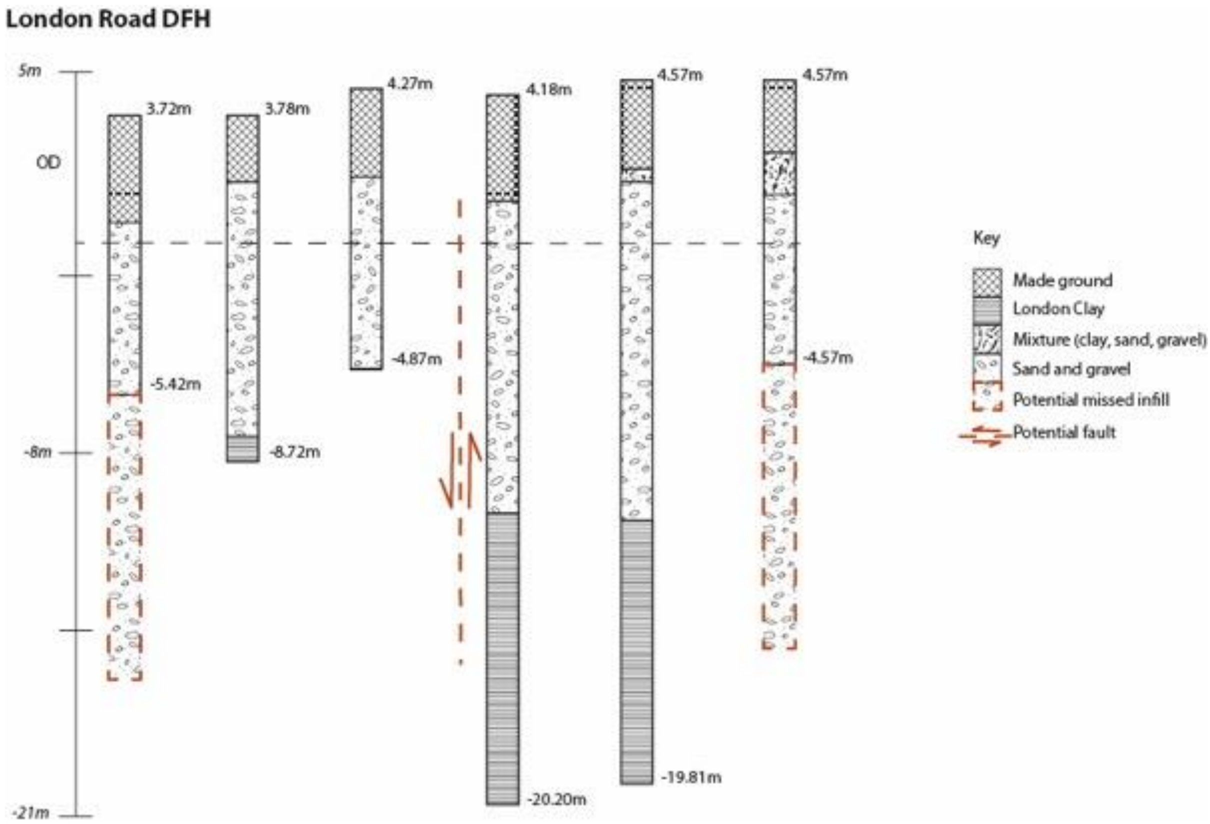


Figure 4. 9 - An example cross-section (edited from the London Road DFH) to show potential features missed from borehole investigation and how both the borehole methodology and the use of cross-sections have risks which need to be communicated.

An additional restriction of cross-sections in both engineering and scientific sectors is that as they are in 2D form and are drawn as a horizontal line. This is not representable of their geographic location when bored and again may lead to a misconception of the ground conditions and or location (Figure 4. 10).

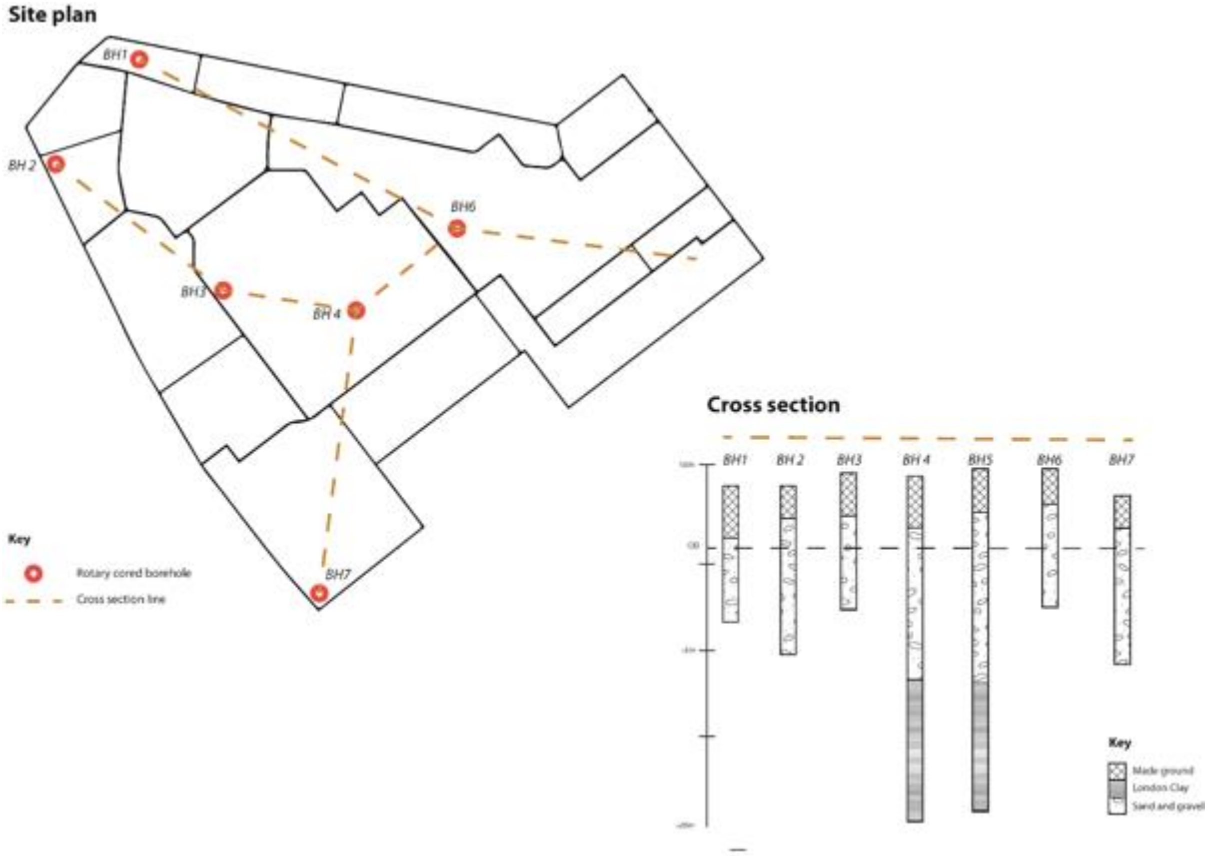


Figure 4. 10 - Site investigation borehole placing plan and the associated cross section diagram from the borehole logs.

An improvement on cross-sections and more geographically accurate are 3D models. Different types of 3D ground models exist depending on scale. These range from entire basins to smaller sub-surface models of local areas, usually undertaken by researchers (such as the Nine Elms and Bermondsey models in this project) and models based upon individual sites, usually based on the site investigation data. 3D models are still not commonplace within the UK ground investigation industry. This may perhaps be due to time and in turn cost restrictions, a lack of experience, access or training with modelling software.

As with cross-sections, 3D models are drawn up to increase understanding of the sub-surface conditions for both specialists and individuals who are not aware of geology or geotechnics. Thus, a key aspect of the model and also a potential major limitation is that they have a role in communicating risk. Differing disciplines have different educational backgrounds and therefore the ground model must be communicated between disciplines to ensure a thorough understanding. This is the case in both the engineering sector (e.g. geotechnical engineers, geologists, structural engineers) and in the research sector (e.g.

geology, geography, civil engineering). In particular regards to the risk associated both with the sub-surface unknowns (due to methodological restrictions) and how this is not illustrated within the model.

4.4.1. Ground models in relation to DFHs

Both cross-sections, 3D figures and models have been created for visual representation of DFHs from borehole logs for the engineering and research sectors. Limitations of ground models in relation to DFHs include:

- Only retrieved sediment can be logged and therefore modelled;
- Simplification of strata and boundaries – variability not fully illustrated;
- Illustrator dependent (e.g. training, experience of modelling non-uniform features, software available);
- Ineffective portrayal of risk and uncertainty;
- Unable to accurately map the extent of the features if the boreholes do not cover the full area;
- Communication between disciplines is necessary to enable understanding.

Once more, the major issue regarding DFHs and portraying standard geotechnical and geological techniques is due to the variability of the sediment and the restrictions of being able to retrieve, sample the sediment and accurately display its variability. Linked to this, a further crucial limitation is that only available data can be inputted into the ground models and there are vast unknowns between borehole locations. For both researchers and engineers understanding that the sediment and its properties between boreholes are unknown and therefore uncertain is a must and should always be communicated. Therefore, the lines in both cross-sections and 3D models for strata depths are also likely not accurate. Particularly with DFHs where the extent of the feature (both depth and width) and the type of infill (sediment grain size, composition and ordering) is most often unknown due to borehole spacing and depths reached as well as infill variability.

As mentioned previously, an issue with communicating understanding of the sub-surface through ground models is due to differing disciplines having different understanding. Often the data from borehole logs is simplified and therefore does not communicate risk. For DFHs, examples shown in Figure 4. 11 display how differing companies portray ground models. A standardised approach may aid the differing disciplines to understand the data and in turn its limitations more accurately.

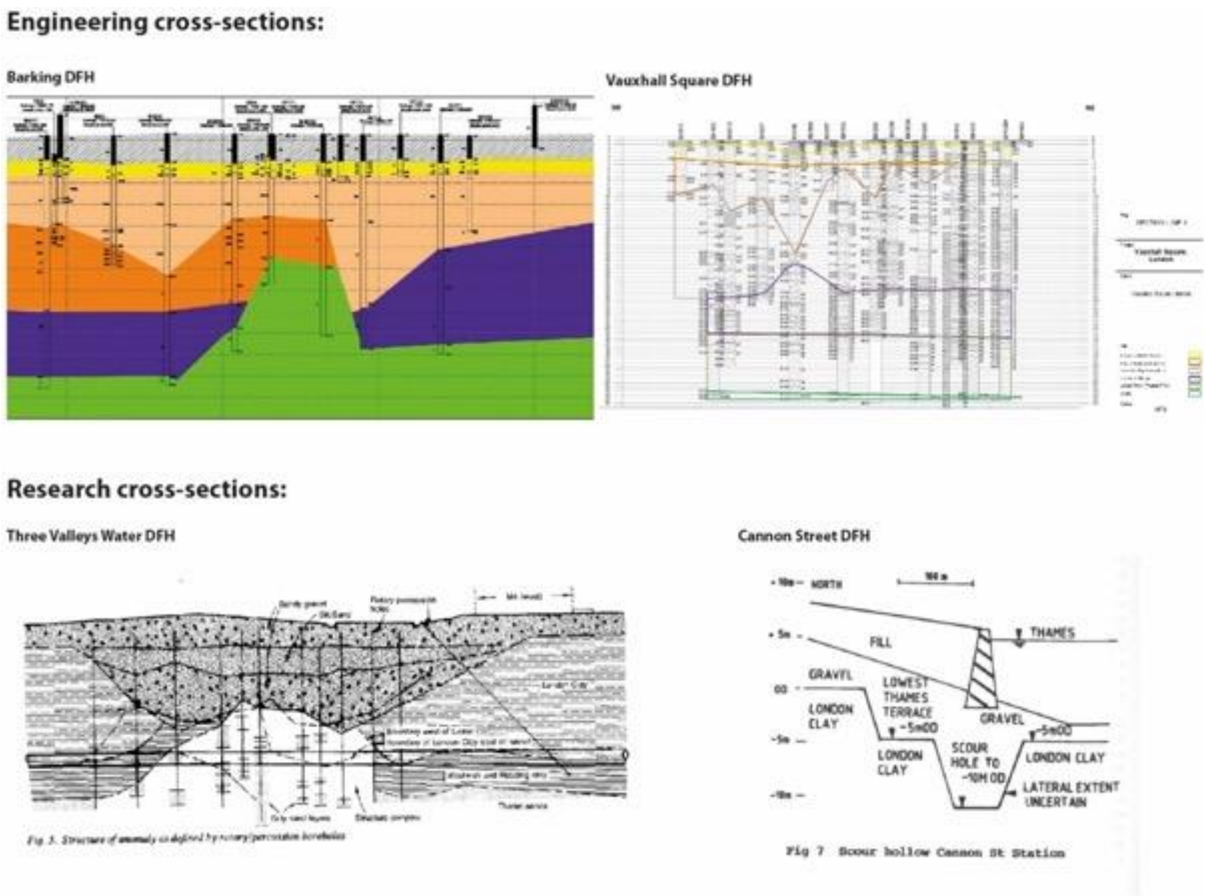


Figure 4. 11 - Differing illustrations of DFH cross-sections created by different companies. Evidencing the variation of styles and degree of simplification of the illustrations for what is deemed the same "DFH" feature.

4.5. Choosing information between sources

Secondary data is an invaluable tool for research and engineering projects. From corroborating hypotheses to desk studies for site investigations, secondary data enables validation and justification. Issues arise where there is conflicting information between differing and sometimes the same source, as well as where there is limited data available and the reliability of the single resource is questioned. Sources include, but are not limited to:

- Published articles (journal articles, conference proceedings etc.);
- Borehole logs;
- Tunnelling logs;

- Site/ground investigation reports;
- Geotechnical reports;
- Desk study reports.

To decipher between sources of information, judgement on reliability must be made and justified. Reliance on education, understanding of the topic and experience aid the quality of judgement decisions. These enable consideration of the reasons behind the errors and aid in judgement. Potential reasons for errors between sources include:

- Differing units (metric or imperial);
- Errors in figures;
- Different data sources used to conclude findings (e.g. publically available boreholes in comparison to a detailed, confidential site investigation);
- Borehole methodological limitations impacting on borehole logs/reports (e.g. lack of unconsolidated material retrieval);
- Age of the resource (conflicting strata names, quality of sediment retrieval etc.).

In regards to this project several examples have been identified where sources of information on the same DFH feature have arisen and how these cases were dealt with are explained:

1. Errors identified within papers – e.g. Gibbard (1986) on the Denham feature. The scale on the diagram (figure 2 in the paper) shows 250 m but the hollow is stated within the text as 40 m wide. Berry's (1979) paper also shows an error in figure 4 where features 7b and 7c are located in the other's geographical location. Where the boreholes used within the papers are available, corrections for this project have been made according to these.

2. Different sources providing differing information – e.g. Toms et al. (2016) states two large features within the Clapham and Nine Elms areas based upon borehole data taken from the BGS' Geoindex and mapped over a large area. On the contrary, numerous features are identified within individual site investigations within the Nine Elms area, not one large feature as implied by Toms et al. (2016). Due to more

condensed boreholes and the detailed nature within individual site investigations this project has deemed that the numerous features within Nine Elms do exist, but due to many of the borehole logs not being provided to the BGS the GeoIndex tool Toms et al. (2016) would not have been aware of the smaller, more localised features.

3. Conflicting information between scientific research - e.g. Hawkins' (1952) research paper and Hill's (1985) PhD thesis. Cross-sections produced for both research outputs are conflicting on the type of infill. This could be due to the retrieval method, age or logging of disturbed strata. The data used for this project has used the more detailed Hill (1985) where there are discrepancies as there is increased level of detail and information available in Hill's thesis to analyse for accuracy in comparison to Hawkin's paper where only cross-sections are present.

4. Existence of a DFH is dependent on one borehole - e.g. Grosvenor Waterside (Figure 4. 12) is only identifiable through a single borehole log and there are no surrounding borehole logs available for approximately 75m. These anomalies have not been ignored within this research project, but deemed questionable and treated with caution.

Figure 4. 12 - The location of the single borehole that identifies the Grosvenor Waterside DFH and the nearest surrounding boreholes available publicly on the BGS' GeoIndex tool.

4.6. Data clean up – this project

This project used extensive amounts of secondary data from borehole logs, tunnelling logs, desk study reports, site investigation reports, geotechnical reports and journal articles. All of these data types have the potential for errors or issues with data quality as discussed above. To mitigate for this risk, the following checks were undertaken:

- All imperial measurements checked for correct conversion to metric;
- Accuracy of borehole locations checked;
- Features of less than 5m depth are removed and considered as features likely to have been derived from fluvial scour;
- Definite identification of strata (no ambiguous borehole logs used, unless only source and if so then noted);

- Where only a single borehole represents all data for a feature, confidence in the borehole must be attained or noted as a questionable feature.

The following points are uncontrollable limitations of the current use of secondary data usage for studying DFHs. All known variables of the DFHs are based upon borehole or tunnelling data (sometimes single boreholes) and therefore cannot be verified as precise or representative of the features entirety. Positioning of the boreholes and the depths they reach limits true understanding of the dimensions (width and depth), infill composition, sorting and whether the depression breaches the bedrock. Reasons for these restrictions are largely due to the positioning and depths of the boreholes taken or are available and explained below:

- Widths are largely unattainable due to borehole restrictions (mythological and cost wise) not covering the entire feature. Therefore, they are the minimum knowns from the borehole data for each feature;
- Widths may also be restricted due to the removal of depressions <5m depth. These features may be fluvial scour or have the potential to be the edge of a deeper DFH feature;
- Depths are stated as the deepest known point of infill within a borehole. Borehole spacing or depth may have only identified the edge of a feature or missed the deepest point of infill;
- Infill type and sorting is dependent on the quality of logging;
- Identifying anomalous geology is problematic when publicly available boreholes are unavailable near suspected anomalous strata or the OD is not recorded. This creates difficulties in establishing the local ‘normal’ depths of strata (e.g. Grosvenor Waterside DFH).

4.7. Summary

Data quality has been identified and addressed throughout this project for various reasons stated within this chapter. Whilst the majority of the issues discussed can be mitigated in constant, unchanging geological conditions (e.g. employing factors of safety), it is apparent that data quality issues are amplified in variable conditions which are most often identified within or surrounding DFHs. Several DFH features have been given as examples throughout this chapter and the associated issues with data quality, availability, testing and interpretation identified due to their variable characteristics.

The core points to note are that all data quality issues lead to uncertainty and in turn risk in both the engineering and scientific research applications. In particular, this occurs where testing of the sediment is either not possible (due to a lack of retrieval or the inability to test the sediment due to its variable nature) or the results cannot be extrapolated to the wider sediment mass or geological unit. This is particularly the case in this project where the horizontal and vertical inconsistency of the sediment associated with DFHs does not allow for testing to fully represent the entire infill or surrounding units.

Scrutiny of the available data and awareness of the limitations enables mitigating techniques to be put in place as well as mindfulness of the research outcomes. Throughout the methodology chapter these issues have been addressed and in the discussion chapter the limitations have been recognised in relation to confidence in the results and outcomes.

5. Results

This chapter presents the results of the research starting at the largest scale, displaying the wider context of DFHs, where they are located across the basin (section 5.1) and the DFH dataset analysis. This is followed by the medium scale sub-surface mapping of Nine Elms and Bermondsey in section 5.2. Ashford Hill is the DFH where most evidence has been acquired and is therefore used to display the smaller, single DFH scale. The results from Ashford Hill are are provided in section 5.3. Sites where photography has been employed to provide detail of DFH infill (Battersea Power Station and One Nine Elms) are then shown in section 5.4. Section 5.5 provides cross sections of individual features and then section 5.6 onwards provides the smallest scale studied during this project from geotechnics (section 5.6) to chemical and mineralogical analysis (section 5.7) and finally microscopy (section 5.8).

Further raw data and supporting analysis is presented in the appendices (Appendix A - DFH dataset, B – cross-sections, and C - images) where size restrictions do not allow or if there has been extensive analysis and only part is shown within this chapter in direct relevance to the discussion.

5.1. Computed datasets

All computed datasets, analysis and models within section 5.1. are based upon the master spreadsheet of all known DFHs and their physical characteristics. Due to the size of the spreadsheet it has been placed in the appendices (Appendix A). GIS has been employed to display the data and relationships between variables.

5.1.1. Analysis of spreadsheet data

Table 5. 1 - Number of features identified with the given characteristic (total of 87 features).

	Yes	No	Unknown
Is there evidence of uplift (or a diapir)?	13 (15%)	14 (16%)	60 (69%)
Is there evidence of faulting?	18 (21%)	6 (7%)	63 (72%)
Does the depression breach the bedrock?	25 (29%)	51 (59%)	11 (12%)

Is the full depth of the feature known?	34 (39%)	29 (33%)	24 (28%)

Table 5. 1 shows that for the majority it is unknown whether there is upwelling of material or faulting associated with the feature. Where there is the uplift of strata (or diapir) this ranges in depth offset from 6-45 m above local expected level.

In regards to the breaching of bedrock, 88% of the features have a conclusive answer, this is the most known characteristic throughout the dataset. It also shows that the majority of features do not breach the bedrock they are identified within. This is in contrast to evidence being available for the full depth of the feature being known, with 61% of the features not having the evidence (through borehole depth restrictions) or data accessible creating unknowns.

Figure 5. 1, Figure 5. 2 and Figure 5. 3 show the minimum known widths and depths of the identified features derived from the available borehole logs. The minimum depth to OD ranges from 30 to -70 m OD showing a 100 m difference between the highest and lowest known feature. However, the majority of features are within 0 to -20 m OD. In Figure 5. 2 it shows the majority of features are identified between -10 and -30 m below ground level. Where the width of a feature is possible to gauge DFHs range from 3-500 m, most being lower than 200 m wide and only six above 400 m.

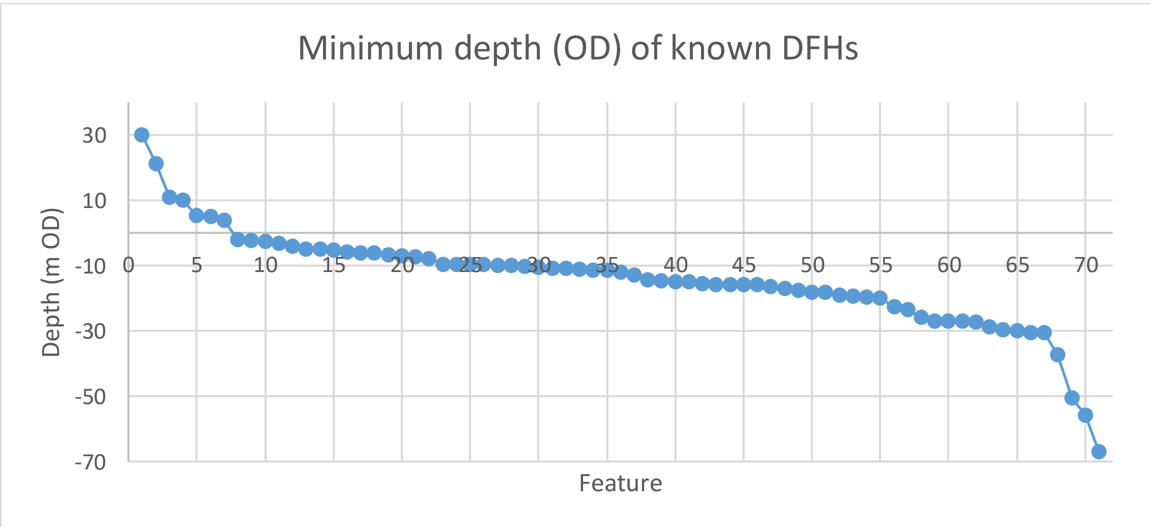


Figure 5. 1 - The range of minimum known depths against OD for the features.

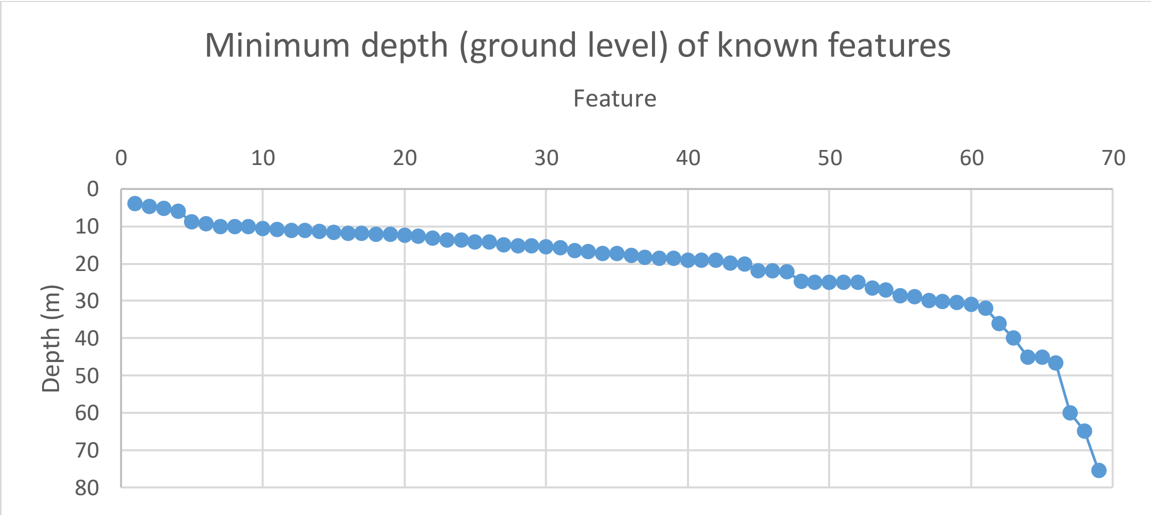


Figure 5. 2 - Graph showing the range of minimum known depths against (from ground level) for the features

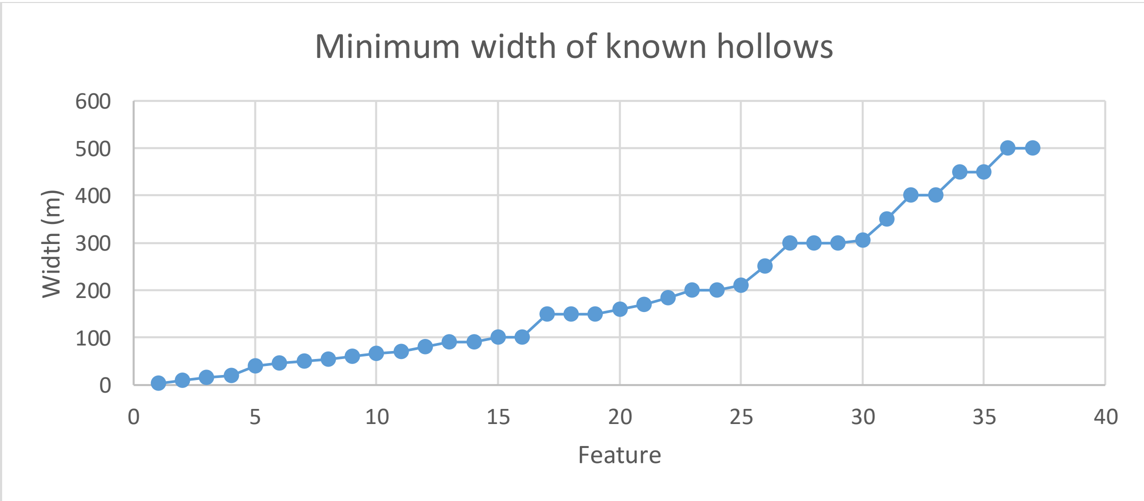


Figure 5. 3 – The range of minimum known widths of the identified DFHs. Note that borehole spacing and limiting numbers reduce the availability for this parameter to be established and therefore only 37 features data are displayed here.

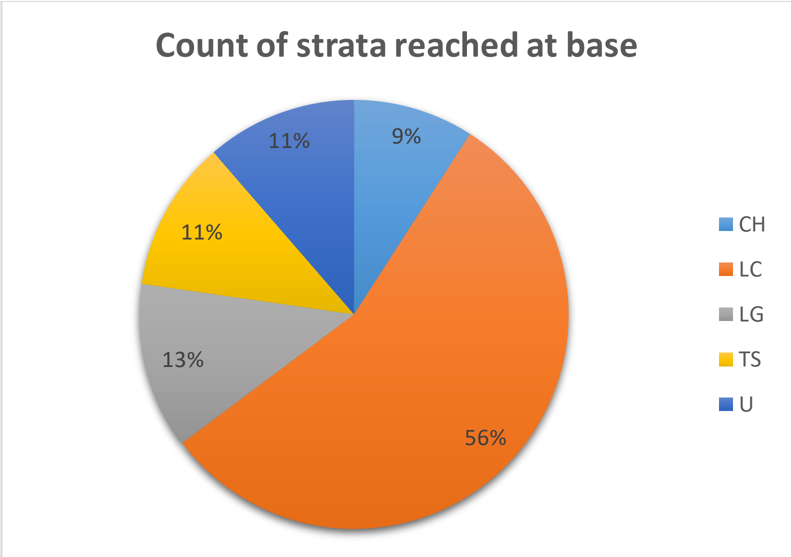


Figure 5. 4 – Bedrock in which the number of depressions reach. Over half are within the London Clay (LC) at the base of the depression. The remaining features are relatively evenly spread between Lambeth Group (LG), Thanet Sand (TS), Chalk (CH) and unknown (U) due to a lack of available data.

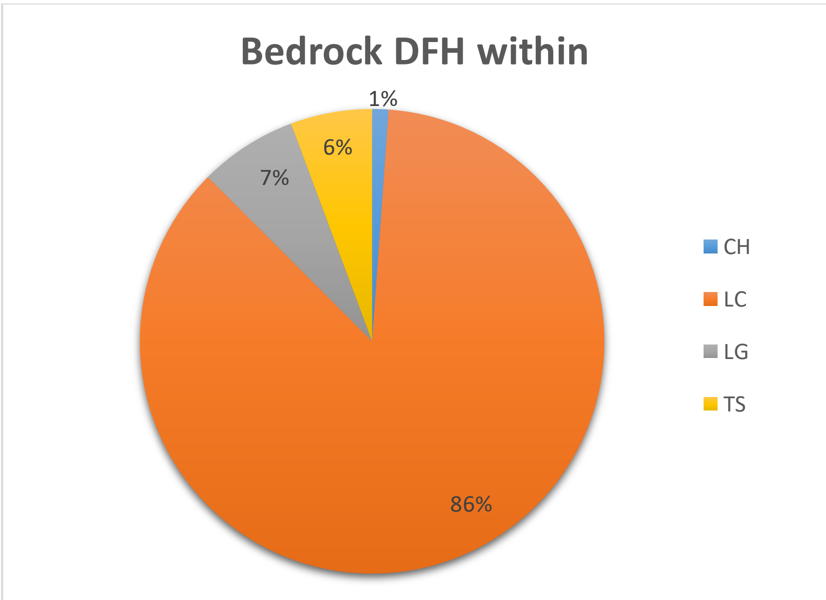


Figure 5. 5 – Percentage of features identified within each type of bedrock strata. The vast majority are identified within the London Clay Fm. and only 1% in the chalk.

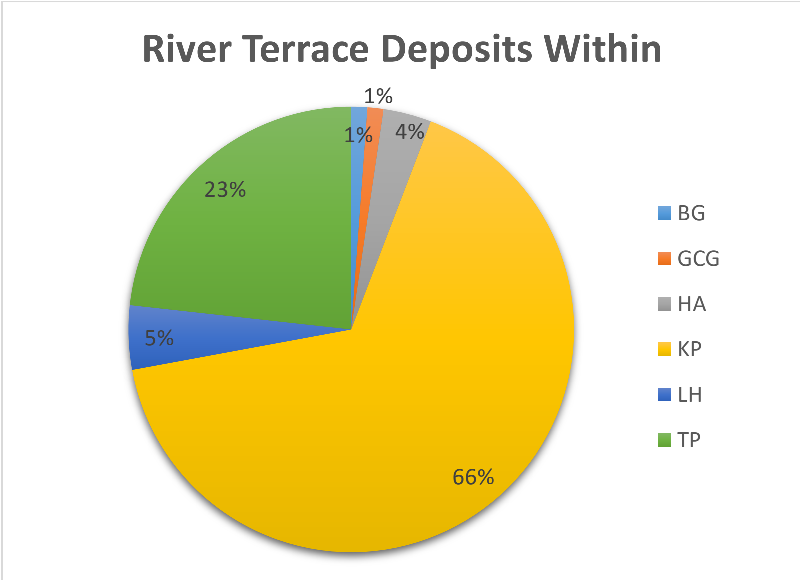


Figure 5. 6 – Percentage of features identified within each RTD. Key to note is the majority are located within the Kempton Park (66%) and Taplow Gravel (23%).

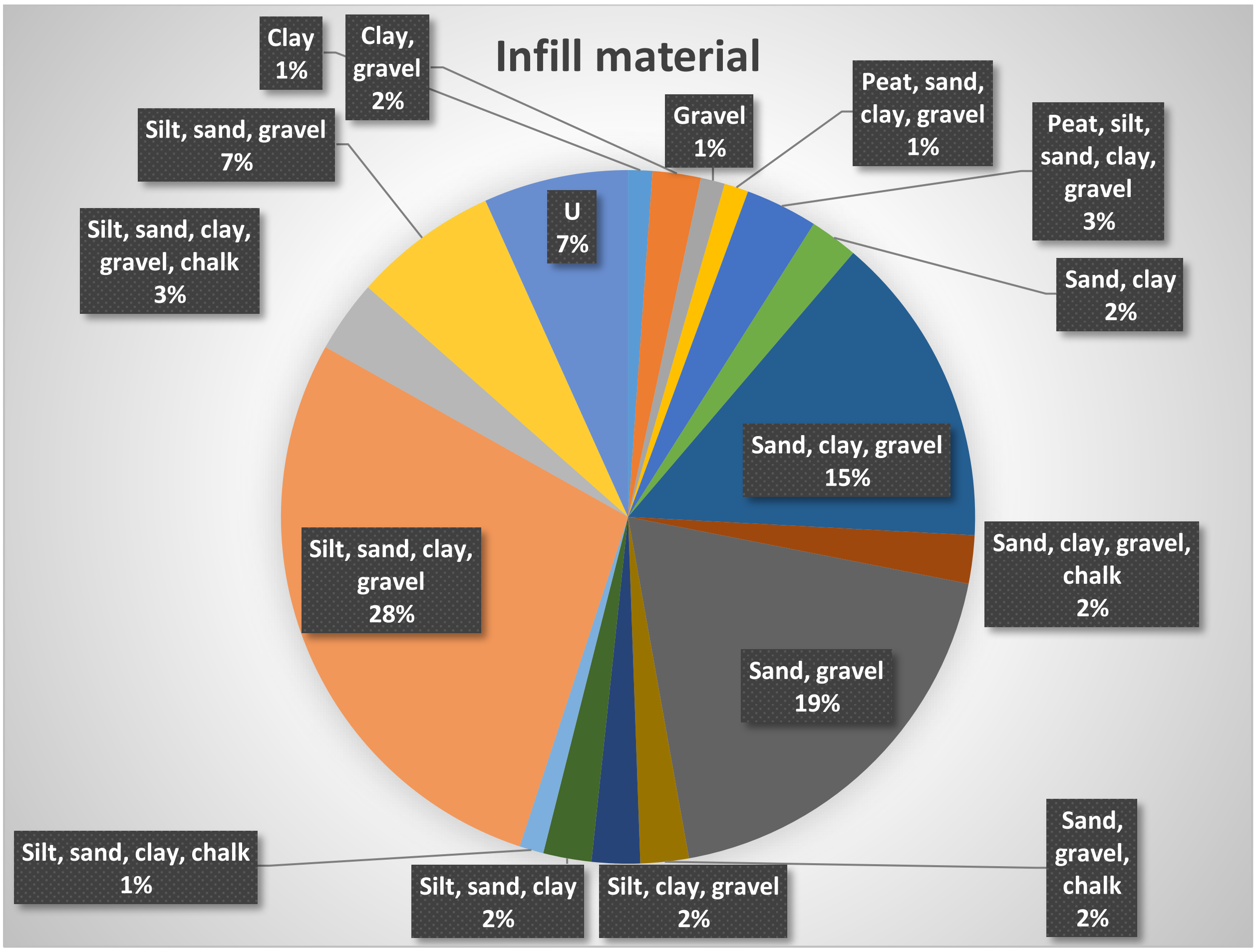
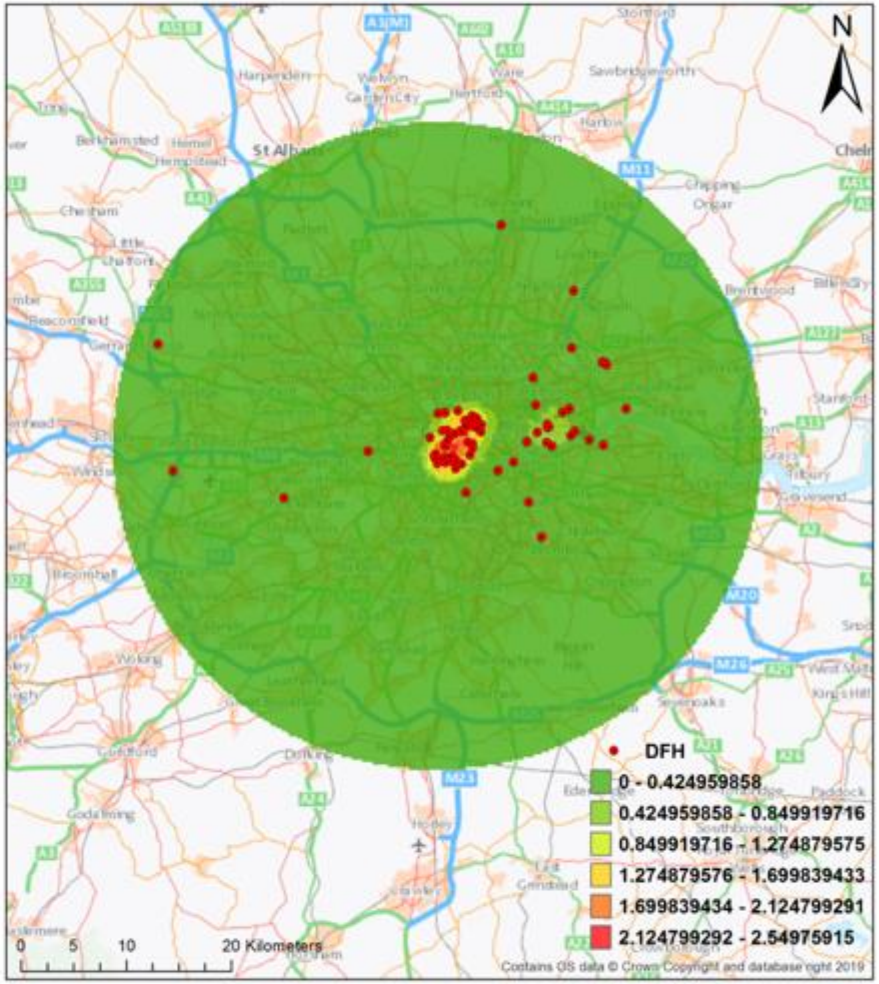


Figure 5. 7 – The wide range of infill material as recorded in borehole logs associated with DFHs.

5.1.2. GIS

ArcGIS is employed to visually represent the data collated through the methods discussed in chapter 3 (methodology) and establish relationships between different and individual variables in relation to geographic location. Figure 5. 8 identifies the largest cluster of identified DFH features in central London. A secondary hot spot for identified DFHs is around the tributary of the River Lea and the Thames. There is also a notable absence of DFHs identified in the north west of London outwards from Hyde Park and in the south of Teddington and Bromley. More centrally, there is also an absence of recognised DFHs between Whitechapel, through Bermondsey and towards the Isle of Dogs.



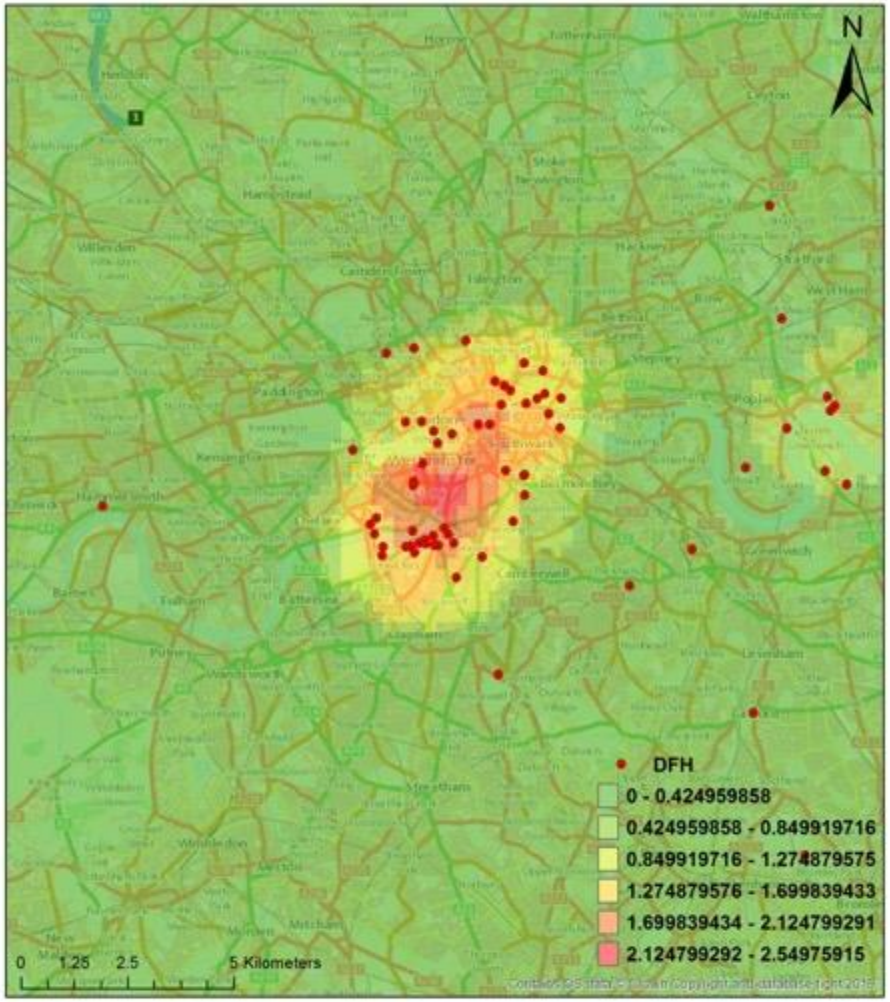


Figure 5. 8 – Heat maps showing the density of DFHs identified in a given area (within the M25 on the left and central London on the right) and the location of the features. Note the green depicts absence of evidence, not evidence of absence.

Figure 5. 9 – Location of DFHs in relation to major known faults and the rivers (including lost, taken from Barton, 1992) of London. The known limits of the lost rivers of London are shown within the dashed box.

Figure 5. 9 shows the relationship between the locations of identified DFHs, faults and river (present and lost). It is evident that the large majority of features are identified in

close proximity to a current or lost river. Where this is not the case, there is a high proportion of these features which are located near to known faults. Interestingly, if the known fault lines are extended following the previously identified angle and direction there are numerous faults within the extended fault path. Examples of this include the Wimbledon fault following its north easterly trend and coming in close proximity to the New Cross and Tiller Road features. Also the Westminster fault, north of the Thames extending in a south westerly direction and towards the Hyde Park Corner feature.

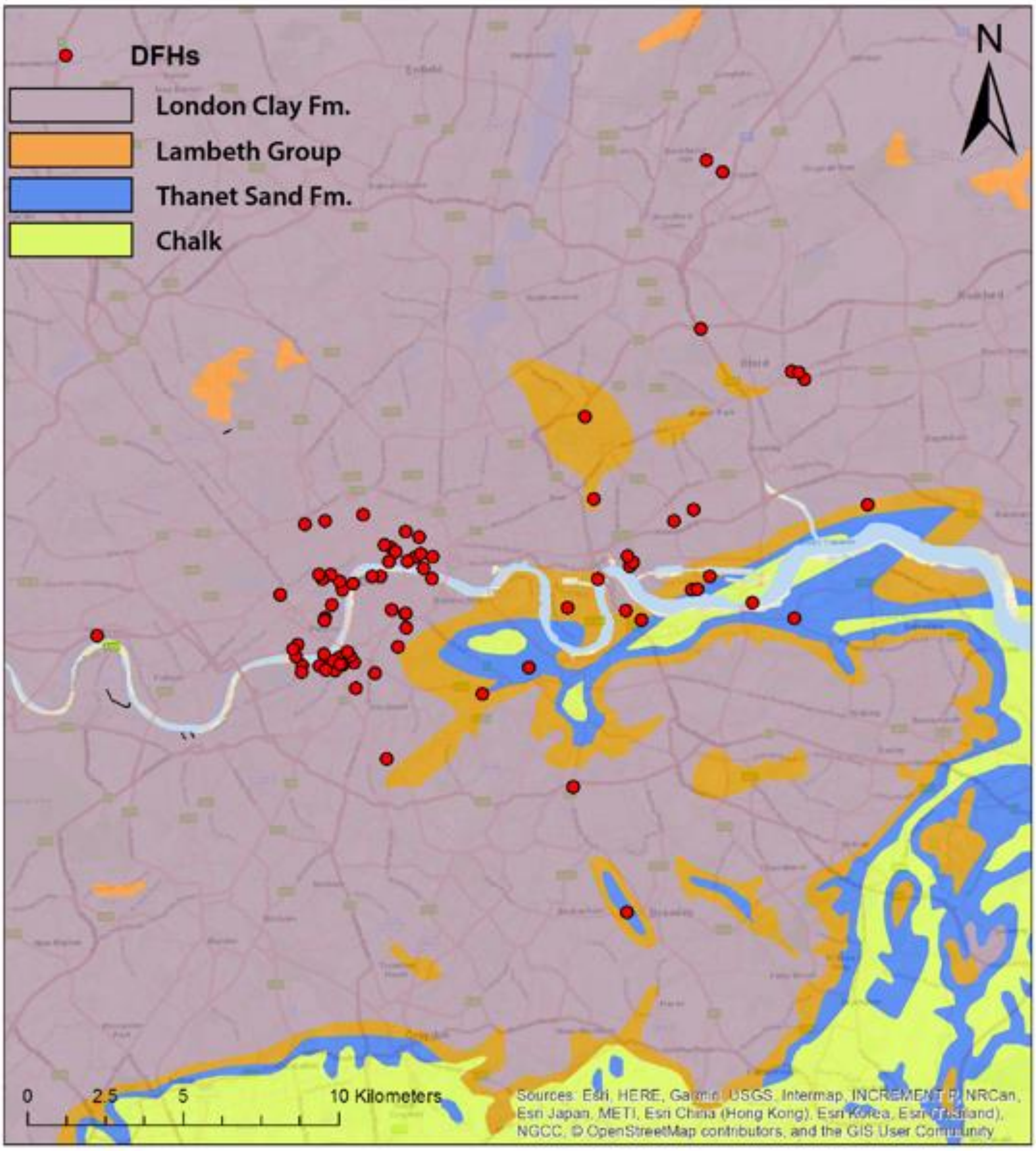


Figure 5. 10 – Map showing the location of DFHs in relation to the underlying bedrock strata taken from the BGS' ArcGIS layer.

Figure 5. 10 displays the relationship between identified DFHs and the underlying bedrock. Predominantly, as shown in Figure 5. 5, the vast majority of the features are identified within the London Clay and to the west and north of the Lambeth Group, Thanet Sand and Chalk outcrop. Outliers to this trend are present and include a feature identified within a small Lambeth Group and Thanet Sand outcrop to the south of the figure, to the west of Bromley.

To note from this figure is that, as is it zoomed out, the layer is not identifying known, small scale occurrences of Lambeth Group, Thanet Sand and chalk outcrops as shown in Figure 5. 43.

5.1.2.1. Near tables

	Distance from	Number of DFH features
River Thames	>300 m	17
	>500 m	36
River (current or lost)	>300 m	13
	>500 m	22
	>1 km	39
	1 km+	25
Known Faults	>100 m	4
	>250 m	11
	>500 m	22
	>1 km	39
	1-2 km	26
	2-5 km	17
	5 km+	6

Table 5. 2 – Number of known DFH features within given ranges of faults and rivers. Note that 64 identified DFHs are within the mapped lost rivers of London area and therefore included in distance from a lost or known river, not the full 88 DFHs.

5.2. Mapping of Nine Elms and Bermondsey

The geology underlying Battersea to Nine Elms and Bermondsey was mapped using borehole data as explained in chapter 3. Here the results are shown across the two areas in 2 and 3D form.

5.2.1. 2D

As shown in Figure 5. 11 and Figure 5. 12 the levels of London Clay and Lambeth Group below ground level are not constant and differ across both of the mapped areas. In the Battersea to Nine Elms region several isolated depressions of London Clay are identifiable with the deepest being in the north nearest to the current position of the River Thames. Towards the south of the mapped area, towards Clapham, the London Clay is at its highest level and this appears to become a constant. For the Lambeth group, this is also the case towards Clapham, but the strata is also found closest to ground level beneath the depressions of London Clay towards the north east. The Lambeth Group is also at its deepest in the west of the mapped area towards Battersea Park.

Bermondsey's sub-surface is shown in Figure 5. 12. A number of isolated depressions and higher points of identified London Clay and the Lambeth Group are apparent. The London Clay only covers the north west area of the mapped region. Within the small area, three clear depressions are recognisable as are areas of higher London Clay spread in a non-uniform pattern. The Lambeth Group is deeper where there is London Clay cover and thins to the west. There are also areas of deeper and higher Lambeth Group across the entire mapped area, showing it is not at a uniform depth.

The relationship between the depth of London Clay (m OD) and identified DFHs are shown in Figure 5. 13.

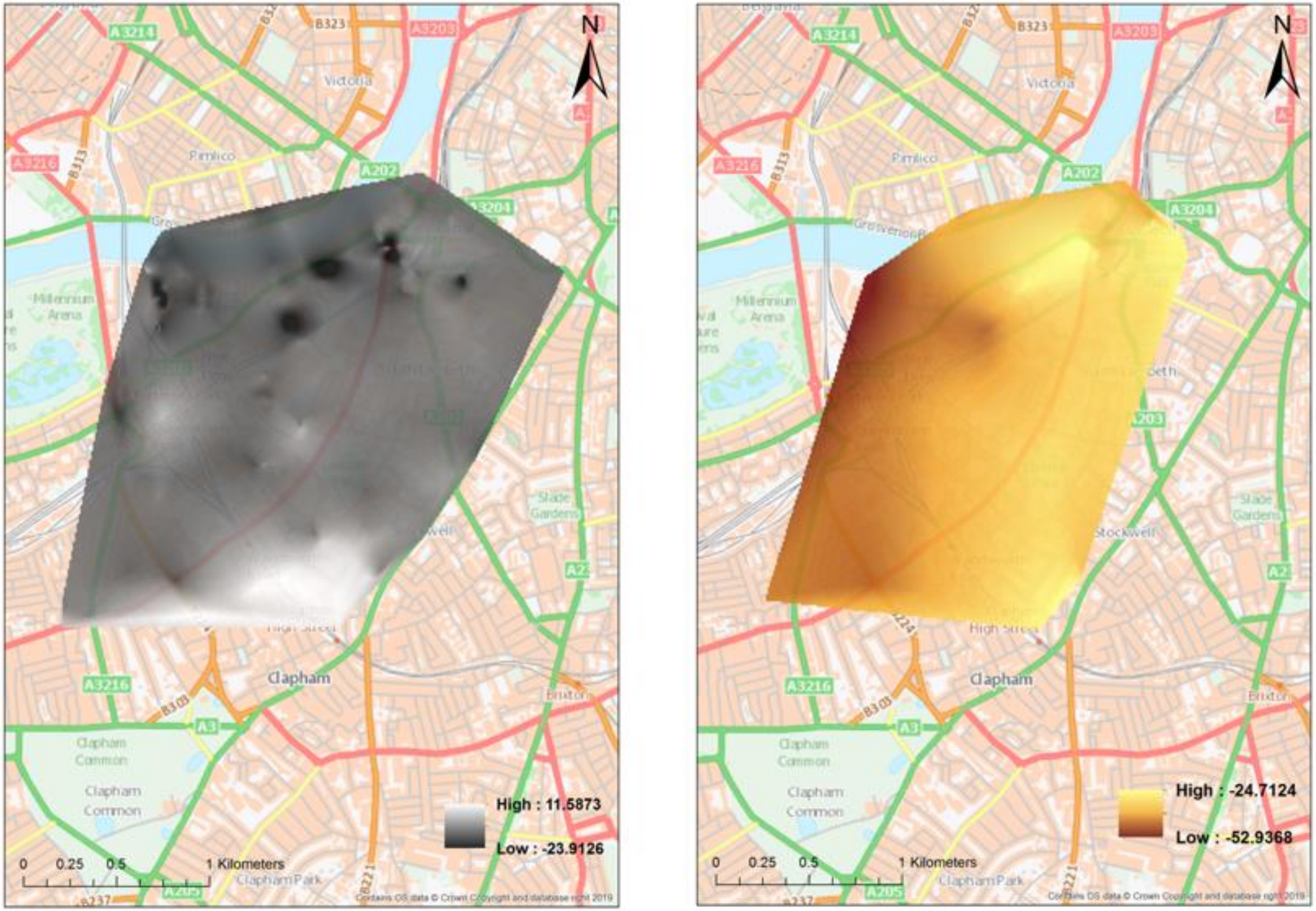


Figure 5. 11 – Maps showing the level of London Clay (left) and Lambeth Group (right) across the mapped Battersea to Nine Elms area derived from borehole data.

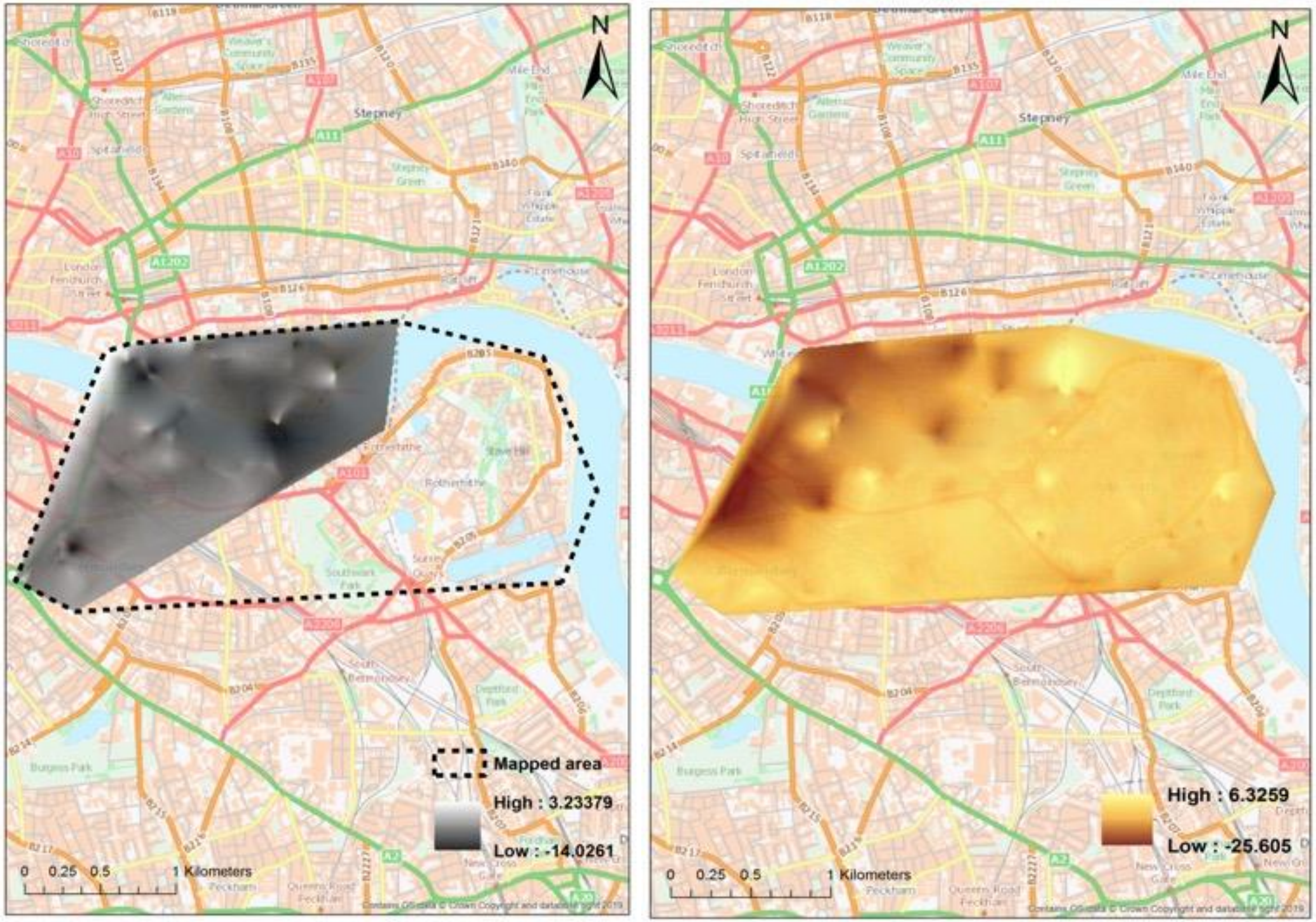


Figure 5. 12 - Maps showing the level of London Clay (left) and Lambeth Group (right) across the mapped Bermondsey area derived from borehole data.

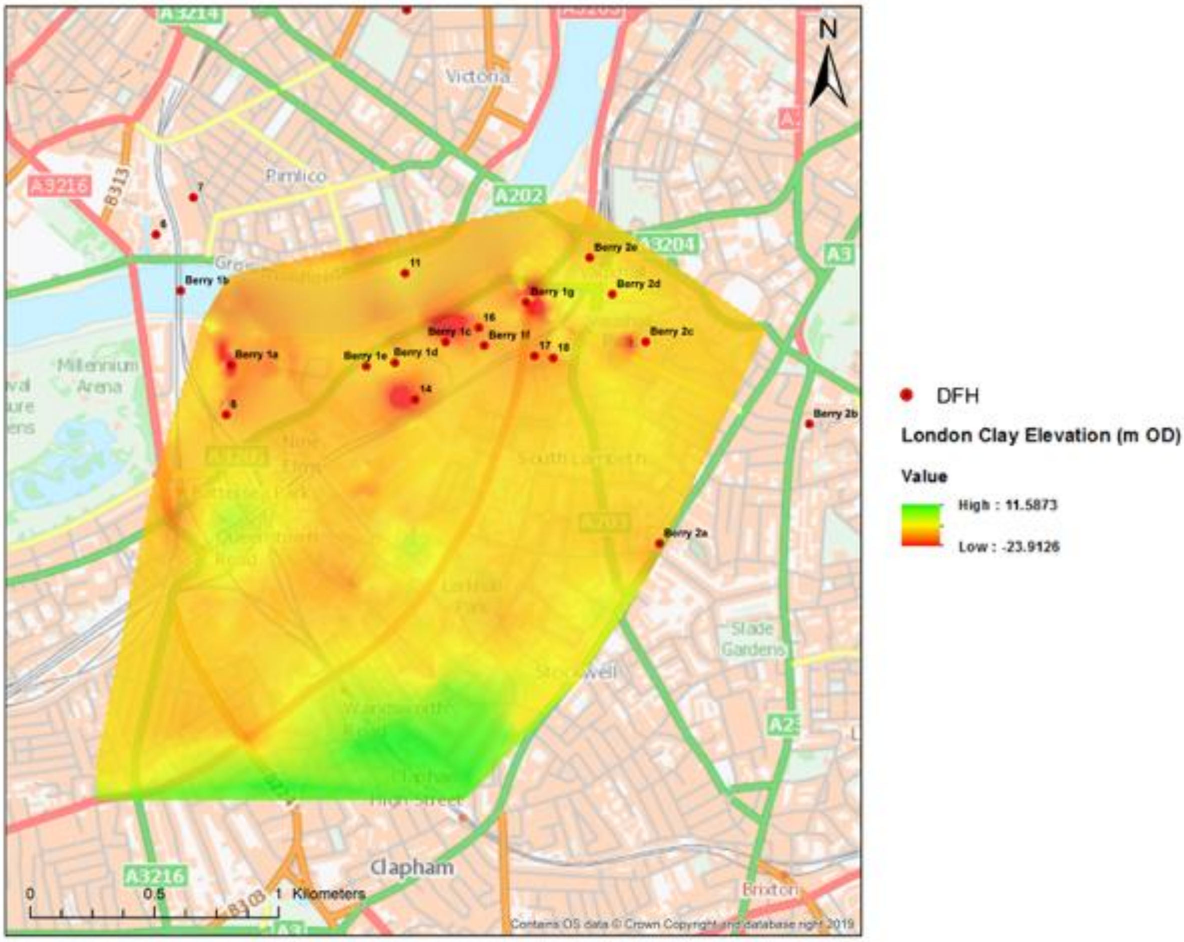


Figure 5. 13 – Identified DFHs in the Battersea to Nine Elms area overlying the depth of identified London Clay. Note that not all DFHs are visible through their depth to London Clay when mapping across large areas.

5.2.2. 3D

5.2.2.1. Battersea to Nine Elms

All figures within this section are print screens of the 3D sub-surface model created from the borehole data used in the 2D models above. For all Battersea to Nine Elms figures the base map tiles (TQ27 and TQ37) are offset in elevation by 17 m to the geological layers. The vertical exaggeration of the geological layers is set at 10.

Figure 5. 15 displays the 3D model from four differing angles as shown in Figure 5. 14. Key to note is the rising of the Lambeth Group towards the River Thames and its highest point being under the cluster of individual isolated depression of the London Clay. Also, the deeper isolated depressions are all located in a cluster to the north of the mapped area, and

shallower, wider depressions occur across the other region mapped. There also appears to be little deviance between the RTDs and the London Clay.

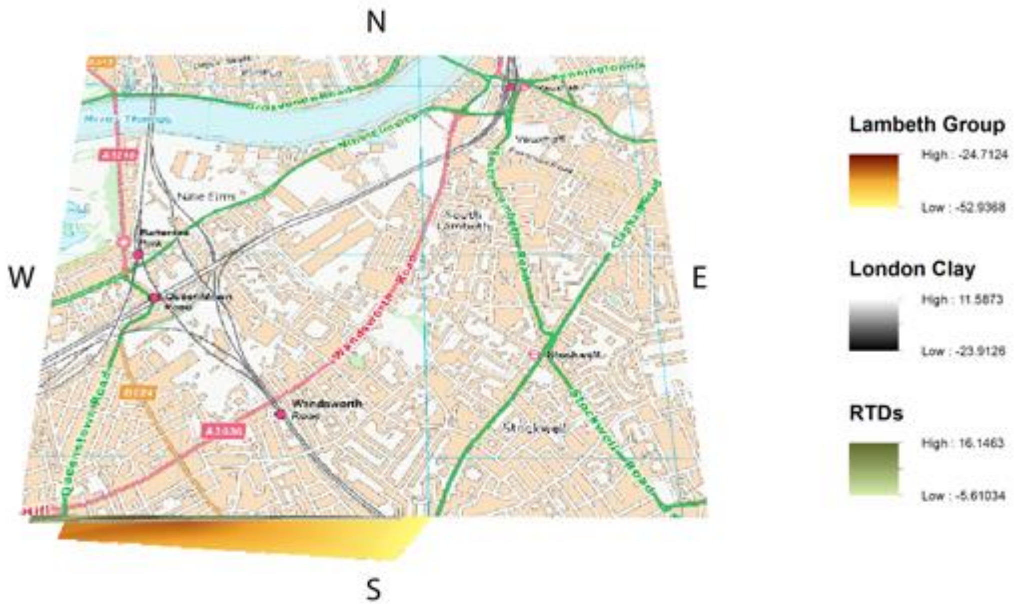


Figure 5. 14 – Area mapped across Battersea to Nine Elms with the key for figures 5.64 to 5.66 shown. Directions shown for understanding of orientation to direction and captions below.

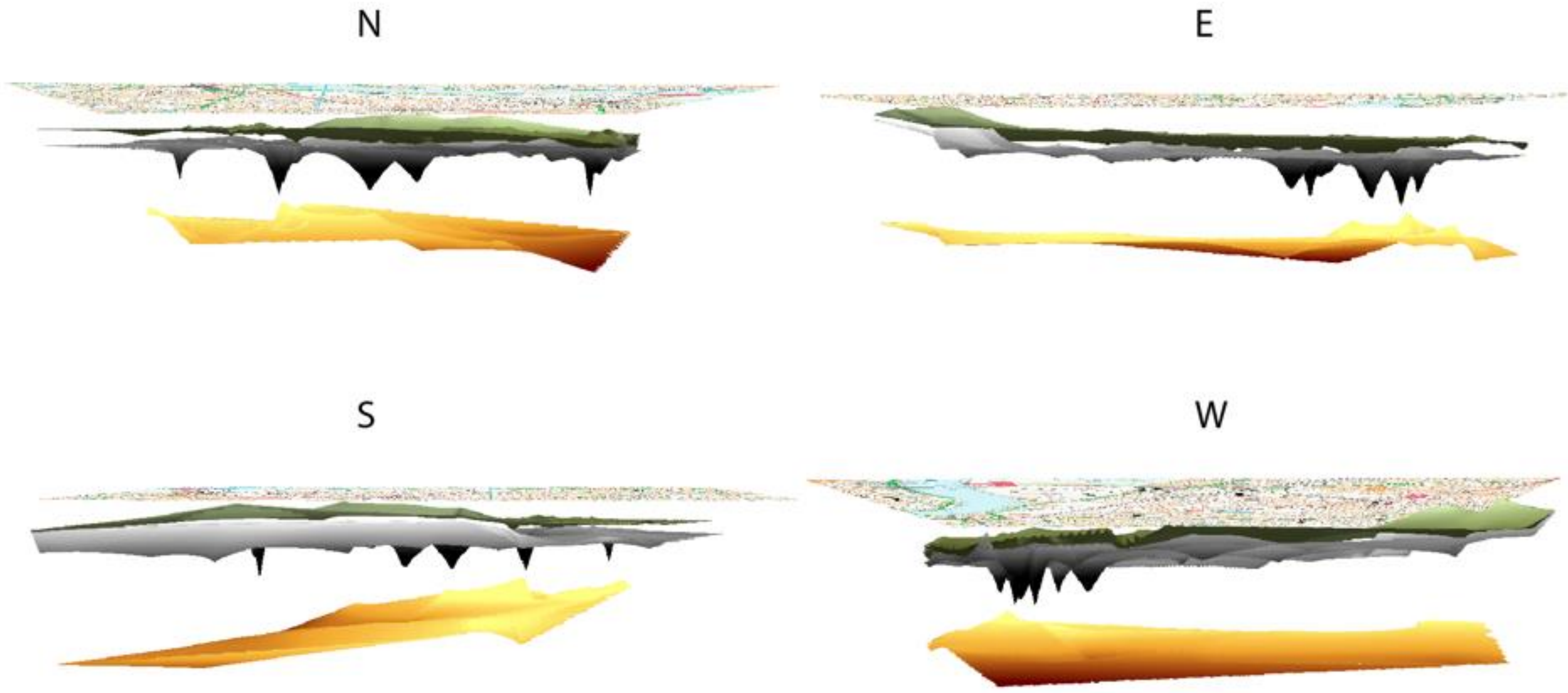


Figure 5. 15- The geology mapped under Battersea to Nine Elms from north (N), south (S), east (E) and west (W) perspectives.

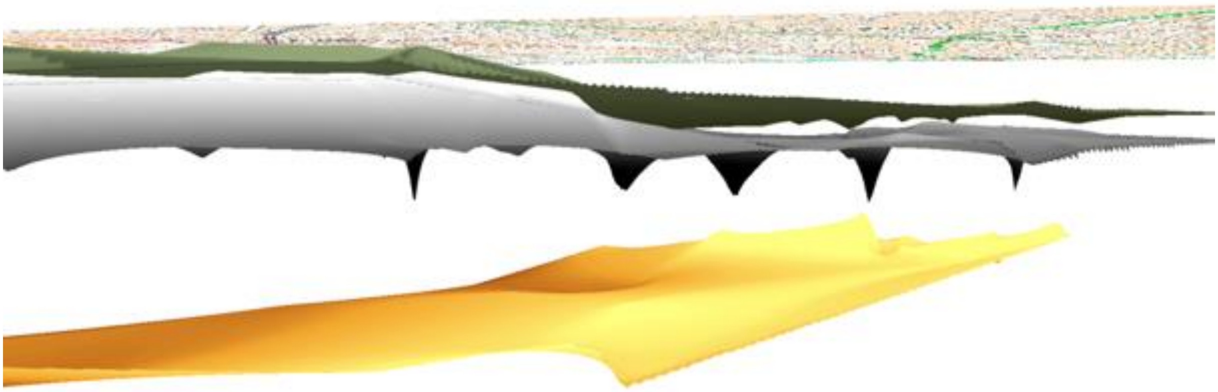


Figure 5. 16 – South east view of the sub-surface beneath Battersea to Nine Elms. Evident are the individual depressions in the London Clay and the higher level of the Lambeth Group beneath 3 of the depressions to the east of the mapped area. Also apparent is the higher Lambeth Group underneath the depressions and the lower depth on Lambeth towards the River Thames.

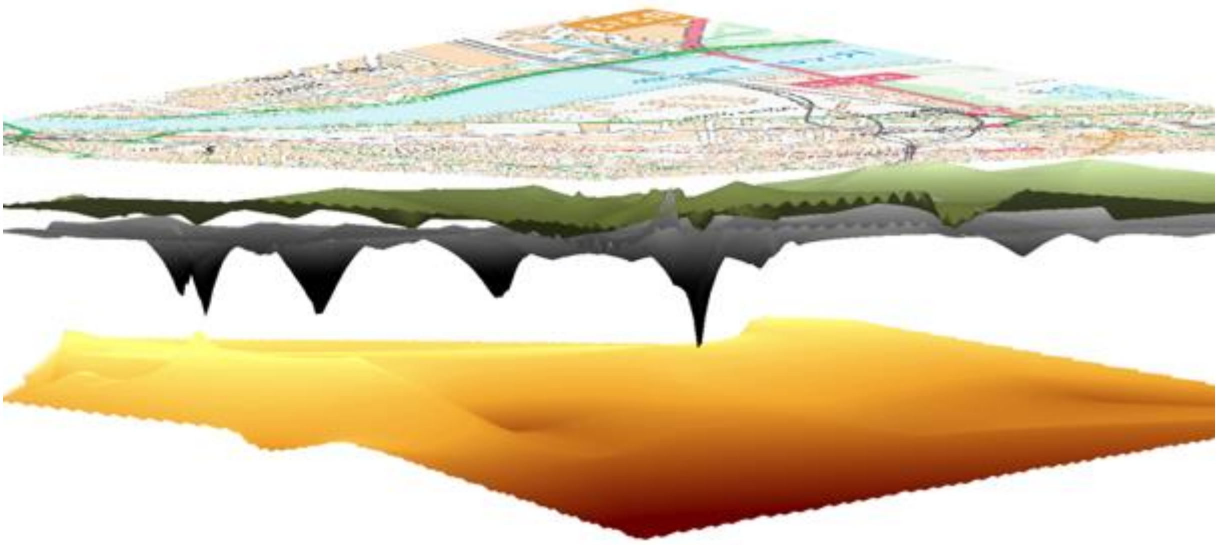


Figure 5. 17 - Sub-surface of Battersea to Nine Elms from the north west perspective. As shown in figure 5.60 the Lambeth group is higher where there is an abundance of isolated depressions. The Lambeth Group is at its lowest elevation towards the River Thames.

5.2.2.2. Bermondsey

For all Bermondsey figures the base map tiles (TQ37 and TQ38) are offset in elevation by 10 to the geological layers. The vertical exaggeration of the geological layers is set at 30.

Figure 5. 21 displays four different views from the sub-surface of the mapped Bermondsey area. Evident from all four angles is the lack of London Clay in the vast majority of the mapped area and its thinning from west to east. The Lambeth Group is also deeper in the west and is identified closer to ground level to the east. None of the three mapped

strata appear to underlie the area at a consistent depth. Furthermore, isolated areas of deeper (depressions) and higher (uplift) strata are also identifiable through all three strata across the mapped area. Finally, there appears to be little relationship or uniformity of depth between the RTDs, London Clay and Lambeth Group.

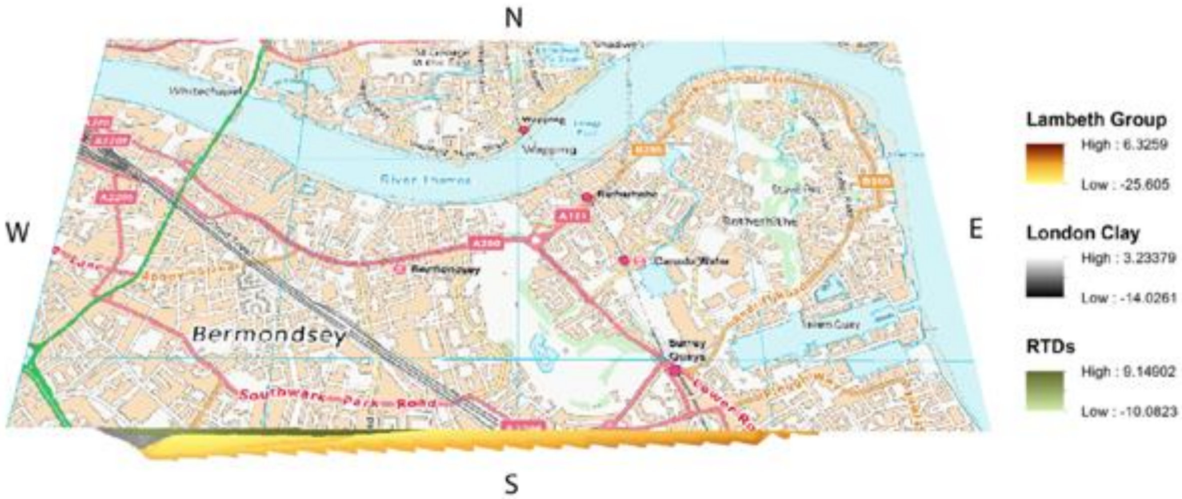


Figure 5. 18 - Area mapped across Bermondsey with the key for figures 5.68 to 5.70 shown. Directions shown for understanding of orientation to direction and captions below.

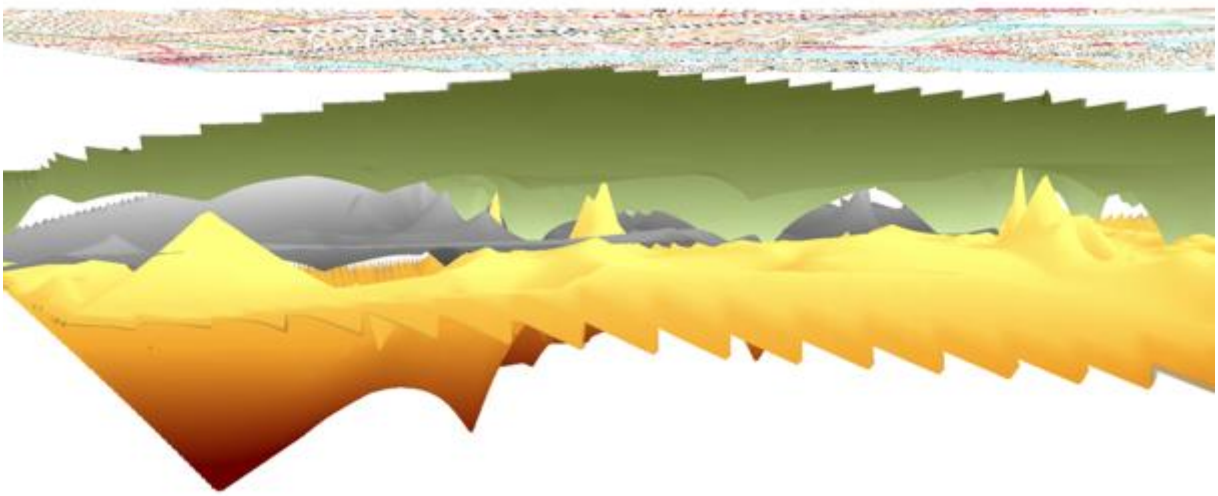


Figure 5. 19 – Sub-surface of Bermondsey from a south west perspective. Note the non-uniform nature of the RTD and the Lambeth Group, in particular, the deeper Lambeth Group to the south west and the individual peaks of Lambeth Group further north of this view. Also evident is the thinning and absence of London Clay cover across the studied area and its non-uniform relationship with the RTDs and the Lambeth Group.

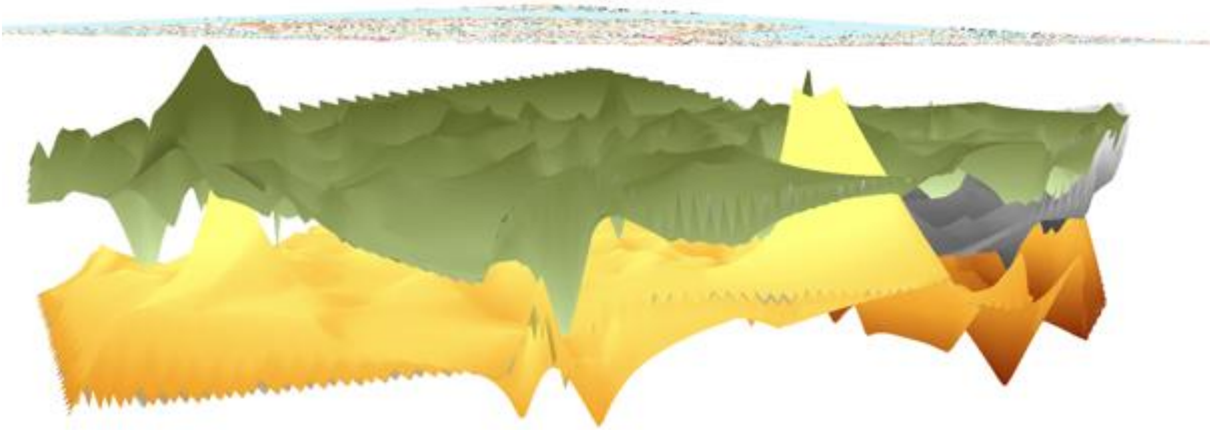


Figure 5. 20 – Sub-surface of Bermondsey from a north east perspective. The Lambeth Group is extremely erratic in its depth below ground level and there is little relationship between the Lambeth Group and the RTDs in relation to depth. Furthermore, the Lambeth Group is closer to ground level towards the north east and deeper towards the east of the modelled area.

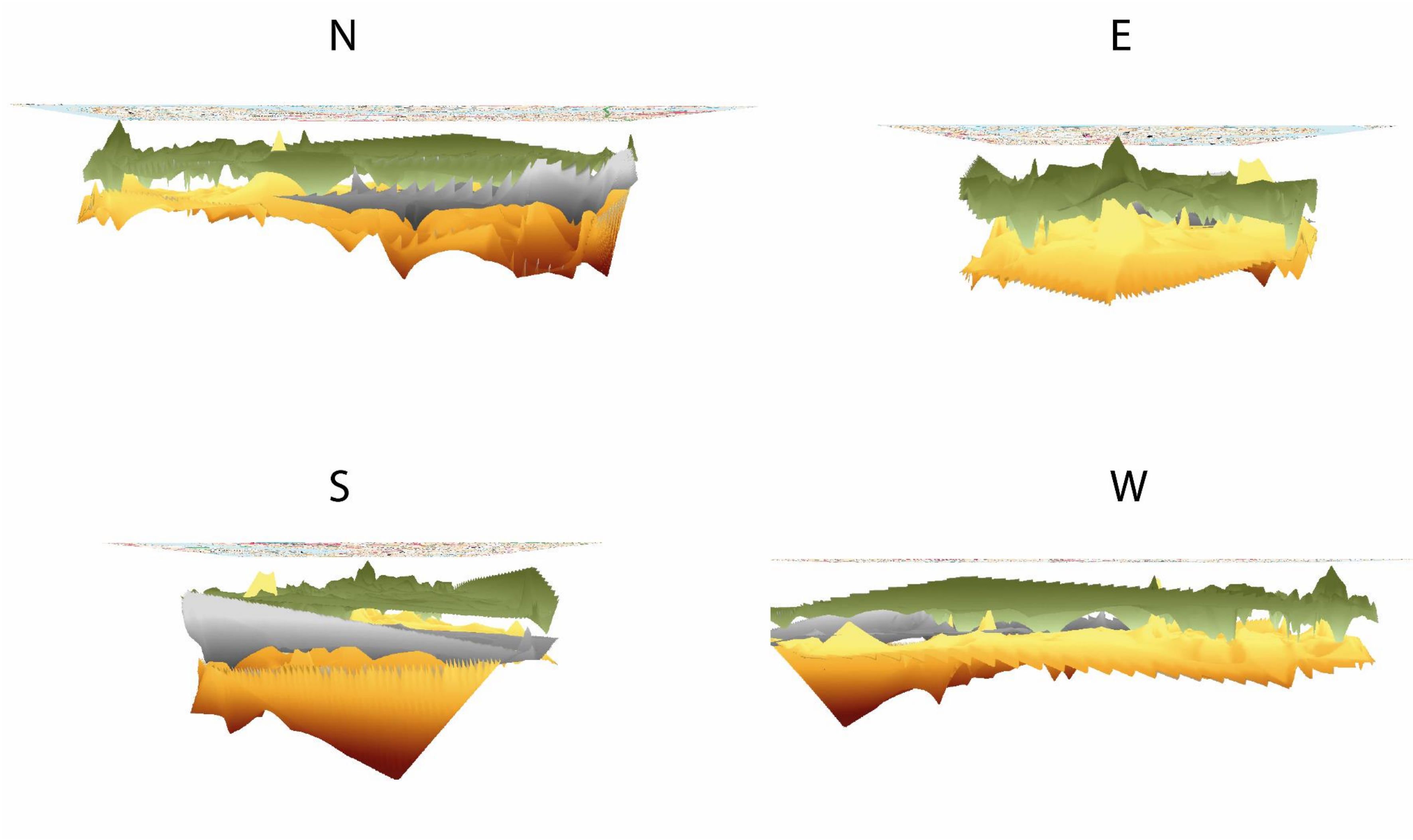


Figure 5. 21 - The sub-surface view of the geology mapped under Bermondsey viewed from the north (N), east (E), south (S) and west (W).

5.3. Ashford Hill

The DFH feature as Ashford Hill has been studied using a combination of methodologies undertaken in this research project. As explained in chapter 3 (methodology), these include new and historical boreholes which create cross sections, CPTu and dissipation. Elsewhere in this chapter results from the site are compared with other features using different variables (e.g. mineralogy and petrography).

5.3.1. Cross sections

Figure 5. 22 displays the borehole logs from this project alongside Hawkins' (1953) and Hill's (1985) data from northwest to southeast along the valley. Clay is present at the top of each borehole except for 72f which has peat down to 5 m. Peat is also identified in BH1, 71a, 11, 10 and 53 within the top 5 m. Sand and gravel is identified between 11 and 67 from around 10-12 m depth from ground level and extends to its deepest point in 9 at 25 m depth. Laminated silt is also present within boreholes 11, 10, 9, 1 and 67 between 8 and 12 m depth, but absent in 71a, 72f, 72c and 53.

Towards the deeper part of the feature, chalk is apparent in 11, 10, 72f, 9, 1 and 14. The highest level of chalk is recorded in 1 at 19 m depth. In comparison, the Lambeth Group is identified at 35 m depth in 72c and 53 which lie further southeast.

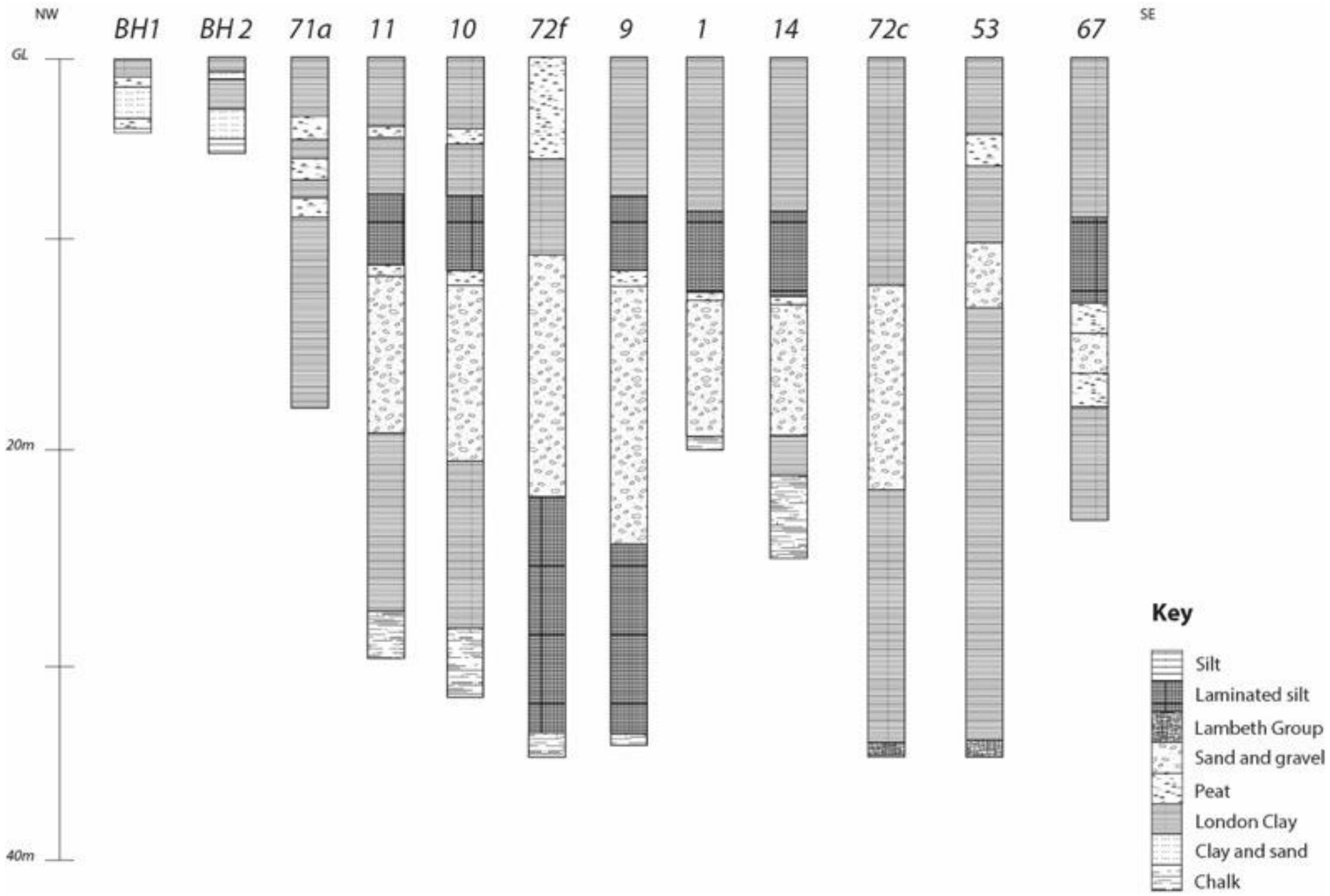


Figure 5. 22 – Cross section from northwest to southeast at Ashford Hill comprising of boreholes taken in this project, Hill (1985) and Hawkins (1952). The horizontal scale is not to scale. The locations of each borehole are shown in figures 3.2.

5.3.2. Cone penetrometer test results

5.3.2.1. CPTu graphs

All figures within this section use data from the four CPTus taken using the Pagani. This is to ensure consistency in the results by ensuring confidence in the data and not to risk interpretation of the data being skewed due to differing machinery. The locations of the CPTus are shown in Figure 3. 2 (Chapter 3, methodology).

Figure 5. 23 shows the CPTu outputs derived from the tests undertaken at Ashford Hill. Whilst the cone friction (q_c) values do not differ significantly between the four tests, the corrected pore water pressure and the friction ratio results show a wider range in results between the tests.

In particular, the friction ratio is higher within CPTu-1 in comparison to the three other tests with a peak of 16% between 50 and 100 cm. CPTu-3 also shows two peaks in friction between 350 to 400 cm and 850 to 875 cm. Both CPTu-2 and CPTu-4 show similar percentages for the friction ratio throughout. The corrected pore water pressure (u_2) also identified similarities between CPTu-2 and CPTu-4, and CPTu-1 and CPTu-3 showing different profiles. Apart from a peak at 30 cm in CPTu-4, both CPTu-2 and CPTu-4 have negative pore water pressure until 500 cm depth. From 400 cm onwards CPTu-2 decreases down to -80 kPa and CPTu-4 increases up to 40 kPa, with a short lived peak of 90 kPa at 750 cm. CPTu-3 has the overall highest pore water pressure, peaking at 295 kPa at 310 cm and dropping suddenly at 850 cm to below 0. CPTu-1 remains relatively consistent between 0 and 110 kPa until a drop at 550 cm. The pressure then increases back to 100 kPa before dropping to -85 kPa at 610 cm.

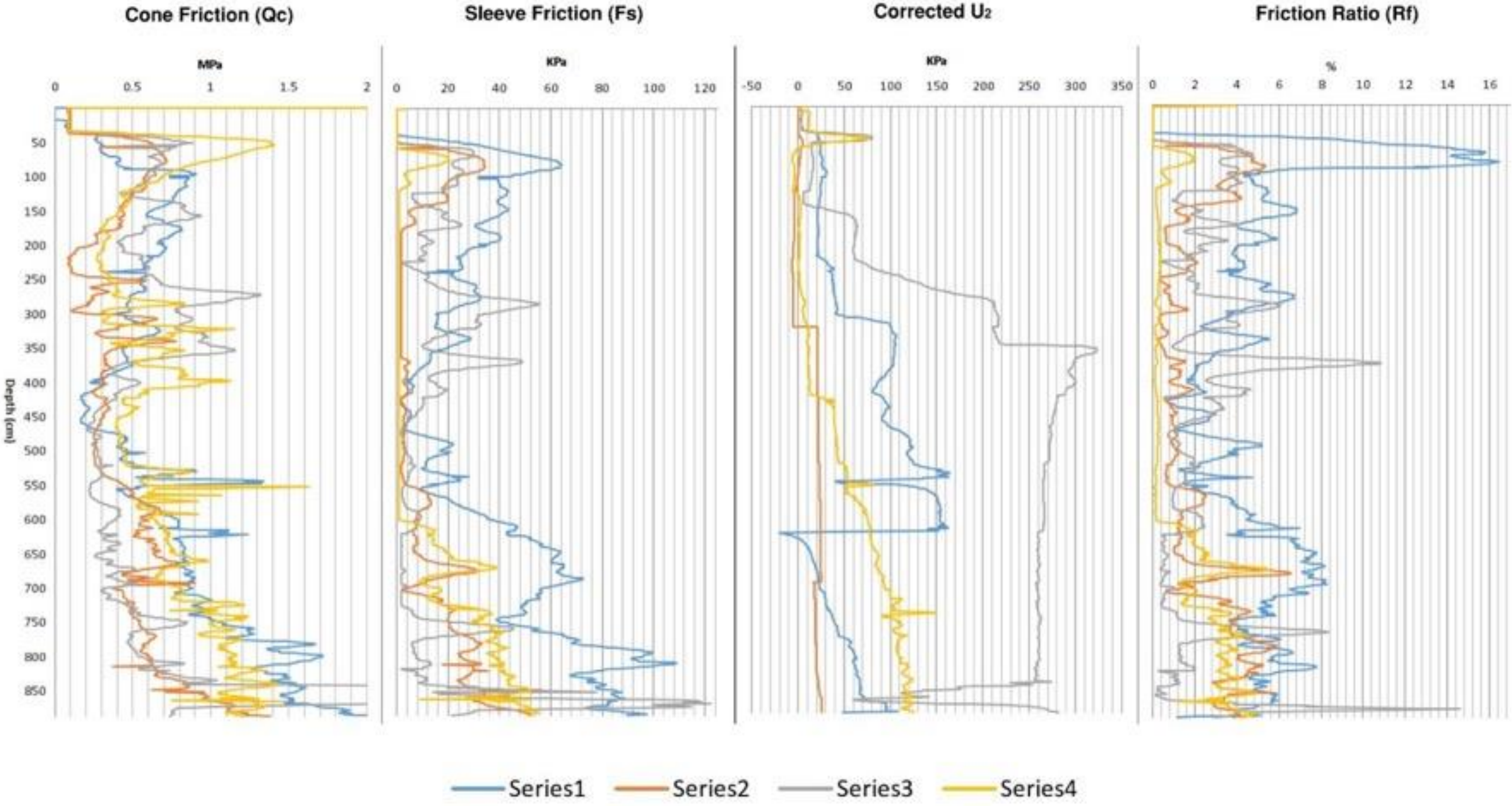


Figure 5. 23 – Results from the four CPTu taken at Ashford Hill. Showing cone friction (q_c), sleeve friction (f_s), pore water pressure (u_2) and friction ratio (R_f).

5.3.2.1.1. CPTu rate of change

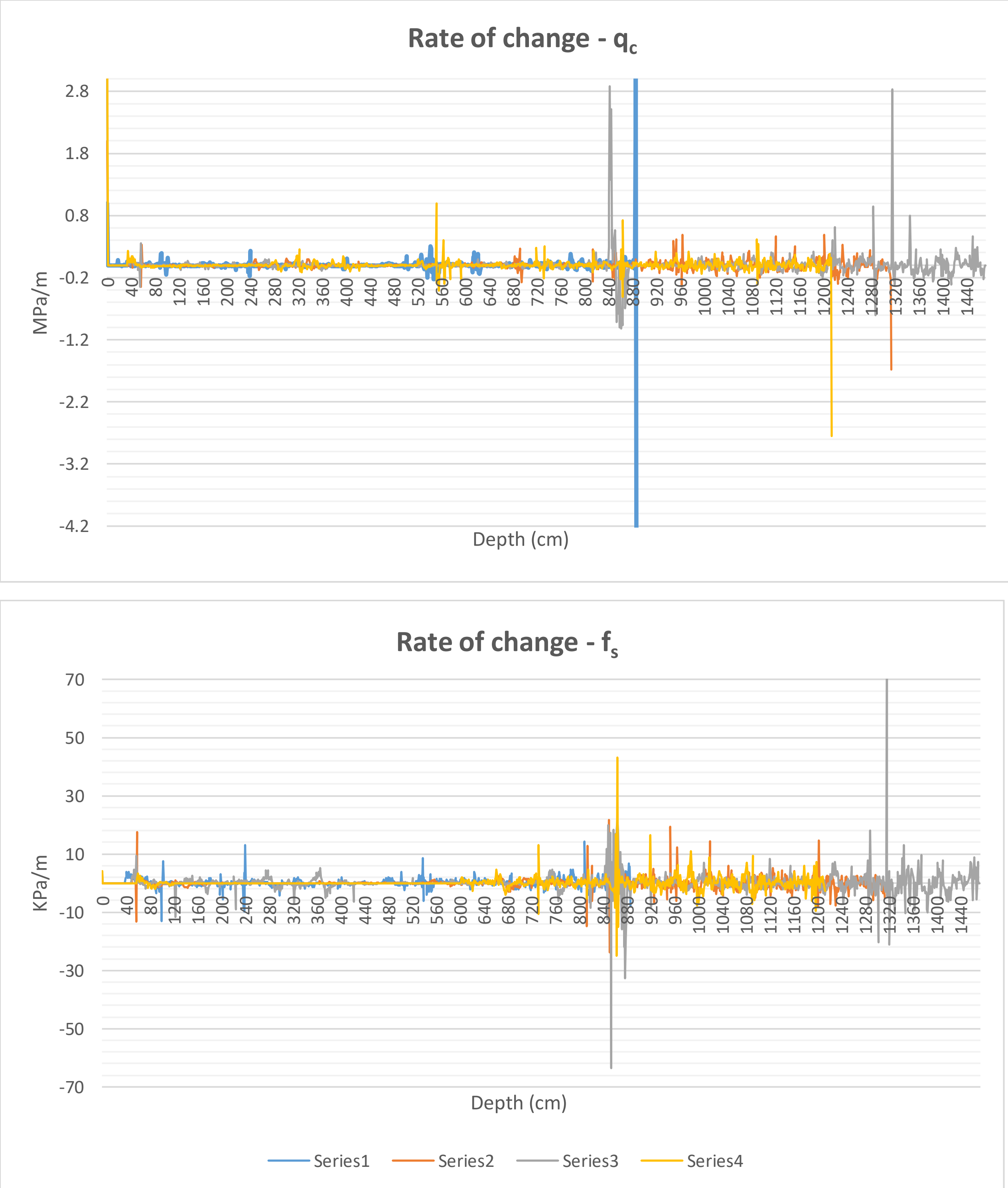


Figure 5. 24 - The rate of change from the cone and sleeve friction data from the four CPTus taken. Note the cone friction graph has a limited plotting range and does not show the full extent of the data.

Figure 5. 24 show the rate of change of cone and sleeve friction values with depth. The largest variability in cone friction is identified in CPTu-1 at 890 cm, CPTu-3 at 840 and

1310 cm depth. CPTu-4 exhibits the most variability throughout the test depth and CPTu shows little variation until 800 cm depth.

There is little variability in sleeve friction until 855 cm depth. Here CPTu-3 decreases and CPTu-4 increases significantly. Both tests become more variable after this point until the test ceases. CPTu-1 and CPTu-2 only vary by 20-30 kPa throughout with little variability in all tests between 250 and 720 cm.

5.3.2.2. CPTu cross-sections

Figure 5. 25 and Figure 5. 26 demonstrate the soil behaviour type attained through CPTu data taken at Ashford Hill. The locations of each test in relation to the site are shown in Figure 3. 2 (Chapter 3, methodology and below for reference). The tests were undertaken using two different machines: The Pagani, represented in the graphs with a “P” and the InSitu rig represented with an “I”.

The two figures exhibit the variable nature of the behaviour type with depth across the valley. This is evident in all CPTus through the non-constant depth of differing behaviour types identified. An example of this is where silty, sandy, clay is not identified in P3, but is identified at 17 m depth in I3, 12 m depth in I2 and 7 m depth in I1 (Figure 5. 25, A). Similarly, in figure 5.5 (B), clay is identified between 3-15.5 m in I5, ground level to 3 m in P3 and then between 1 to 3 m and 4.5 to 5 m in P1.

Figure 5. 26 (A) also shows some similarities, where in I5, I4, I3 and I2 silt and clay is underlain by silt, clay and sand. However, the depth at which these soil behaviour types are encountered differ in each test.

Figure 3.2 – Location of the CPTu tests taken at Ashford Hill (Google Earth, 2018).

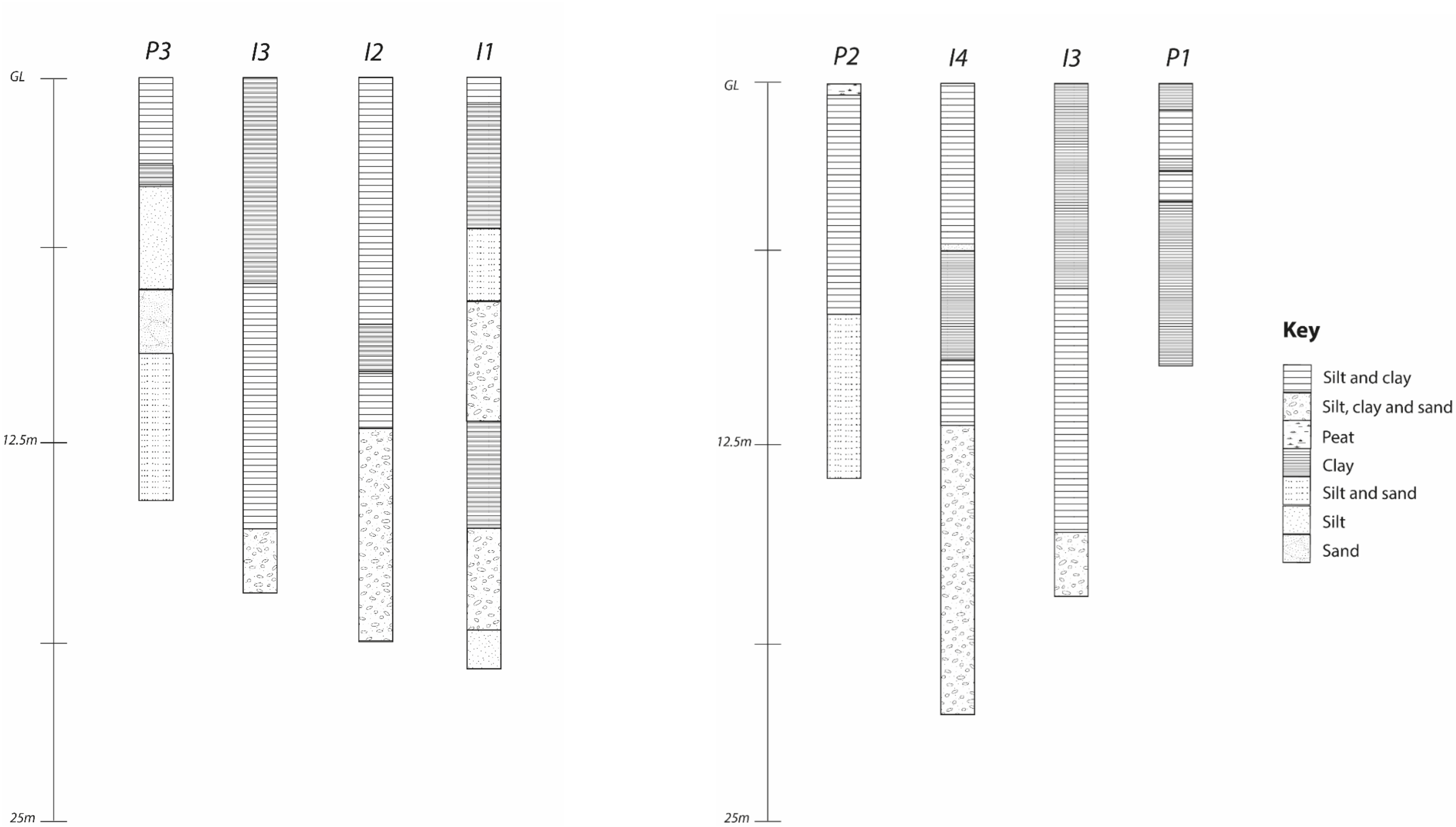


Figure 5. 25 – Cross section of the CPTu data showing soil behavior type from northwest to southeast along the valley (a) and southeast to northwest (b). I=Insitu and P=Pagani.

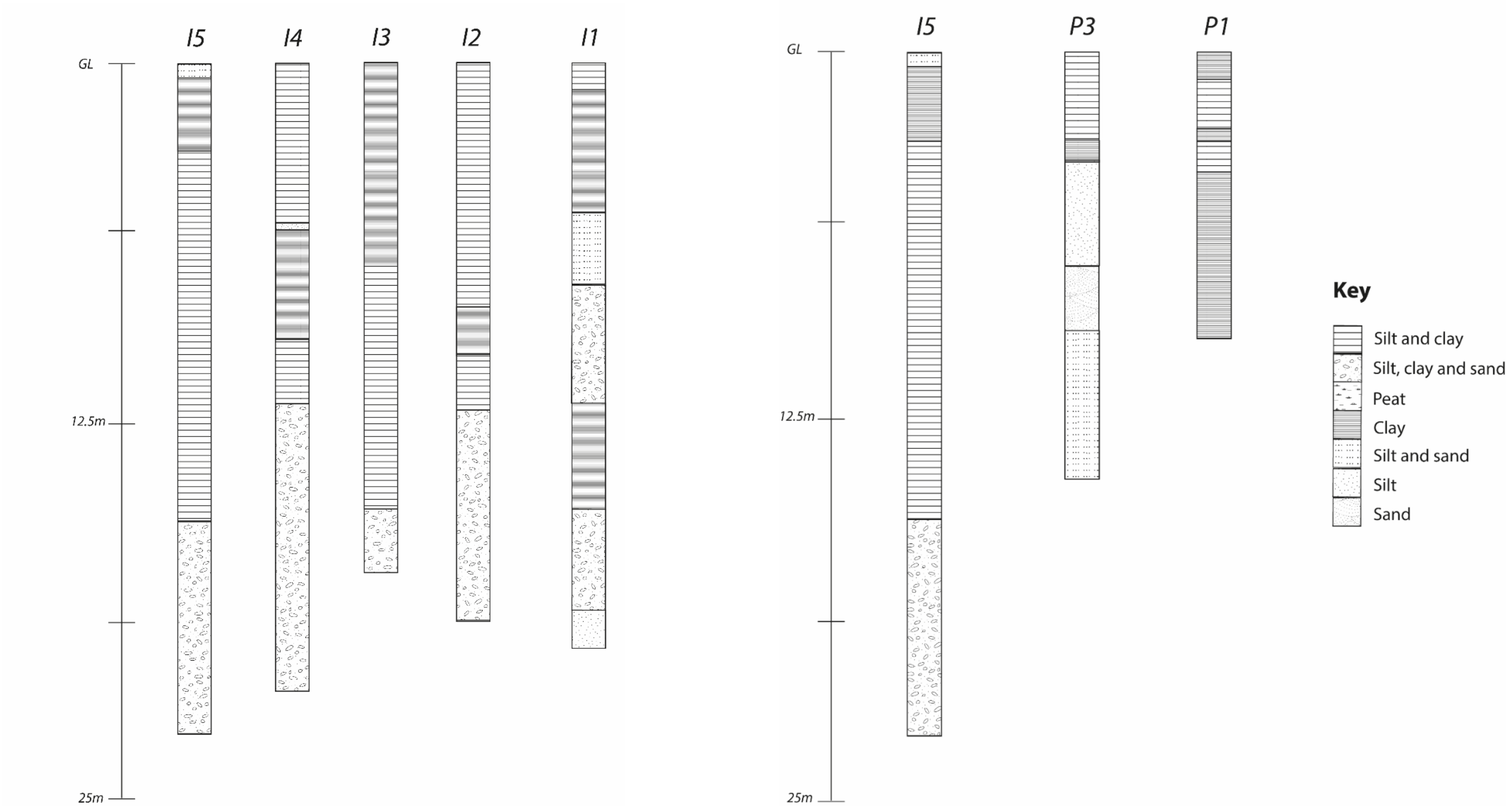


Figure 5. 26 - Cross section of the CPTu data showing soil behavior type from west to east (a) west to north (b) along the valley. I=Insitu and P=Pagani.

5.3.2.3. Dissipation tests

Dissipation tests identify the coefficient of consolidation and permeability in both a horizontal and vertical direction. This provides data on the rate of which a saturated soil will undergo compaction or consolidation whilst subject to a pressure increase. The dissipation graphs are shown in the appendices with all associated parameters beneath. Table 5.1 focuses upon the horizontal and vertical coefficient of consolidation in both horizontal and vertical direction.

Table 5. 3 – Coefficient of consolidation results derived from the dissipation tests undertaken with the InSitu rig.

Test no.	Test depth	Soil behaviour type within	Horizontal coefficient of consolidation (m^2/year)	Vertical coefficient of consolidation (m^2/year)
02	14.50	Melange of sand, clay, silt	7.95×10^0	2.65×10^0
02	18.51	Melange of sand, clay, silt	1.47×10^2	4.90×10^1
04	13.98	Melange of sand, clay, silt	1.01×10^1	3.36×10^0
05	19.00	Melange of sand, clay, silt	9.43×10^1	3.14 10^1

5.4. Photography

All images displayed within this section have been identified from boreholes, the excavation at Battersea Power Station Phase 3 or fieldwork at Ashford Hill. They have been selected due to the structures which have been identified within or surrounding the DFH infill.

Figure 5. 27 – Photograph taken from within the excavation at Battersea Power Station Phase 3 showing the DFH infill contact with the London Clay. Note the gentle slope angle (around 40°) and the relatively sharp contact between the gravel infill and the clay beneath.

Figure 5. 28 – DFH infill at Battersea Power Station Phase 3. Undisturbed horizontal horizons are identifiable within the sand and gravel infill beneath the excavator.

Figure 5. 29 – DFH infill material from Battersea Power Station Phase 3. Material ranging from sand and gravel to clay. Water movement through the material also shown and is not consistent throughout the materials in the image. Exposure is approximately 0.75m wide and 1.5m high.

Figure 5. 30 – Infill material at Battersea Power Station Phase 3. The infilling material shows two distinct sand layers where gravel is not present. The sand layers are dipping towards the centre of the feature. Exposure is approximately 2.5 m wide and 2 m high.

Figure 5. 31 – DFH infill at Battersea Power Station Phase 3. Gravel and sand beds dipping towards the centre of the feature. This dipping is not uniform throughout the infill on both a horizontal and vertical scale. The range of infill is also visible. From large rounded gravel to smaller angular gravel and sand. Exposure is approximately 2 m wide and 1.5 m high.

Figure 5. 32 – DFH infill at Battersea Power Station Phase 3. A large clay clast within the majority sand and gravel infill material. Exposure is approximately 2 m high and 1 m wide.

Figure 5. 33 – Material removed from a smaller clay clast with both angular and rounded flint within the clay. The clast was taken from the DFH infill at Battersea Power Station Phase 3.

Figure 5. 34 – Bubble-like structures identified within the fine sand, silty, clayey material at Ashford Hill. The largest bubble shown in the centre of the image is around 0.8 mm.

Figure 5. 35 – Borehole 302a from One Nine Elms at 30.4 m deep. Displaying a calcrete vertically embedded within the Lambeth group. "T" shown to identify the direction of the top of the borehole.

Figure 5. 36 – Borehole 303 from One Nine Elms at 21.5 m deep. Horizontal sand intrusions in the London Clay. "T" shown to identify the direction of the top of the split borehole.

Figure 5. 37 - One Nine Elms at 41 m deep. Calcretion, Lambeth Group and a dark grey layer (potentially the mid-Lambeth hiatus) unusually banded. "T" shown to identify the direction of the top of the borehole.

Figure 5. 38 – Borehole 302a from One Nine Elms at 28.7-30.2 m deep. Intact sections of mottled beds from the Lambeth Group within sand and gravel sediment. "T" shown to identify the direction of the top of the borehole.

Figure 5. 39 – Pond directly above the DFH depression and chalk diapir identified at Ashford Hill (image taken March 2017)

Figure 5. 40 – Aerial image taken via a drone of the dry Ashford Hill pond. Image taken in a southernly direction (image taken September 2018).

5.5. Cross sections

Two dimensional cross-sections have been employed in geotechnical reports and journal articles to display anomalous geology, including DFHs, from borehole data. Here several known DFHs have been created from borehole logs as 2D cross-sections to display the range in type of feature and the variability.

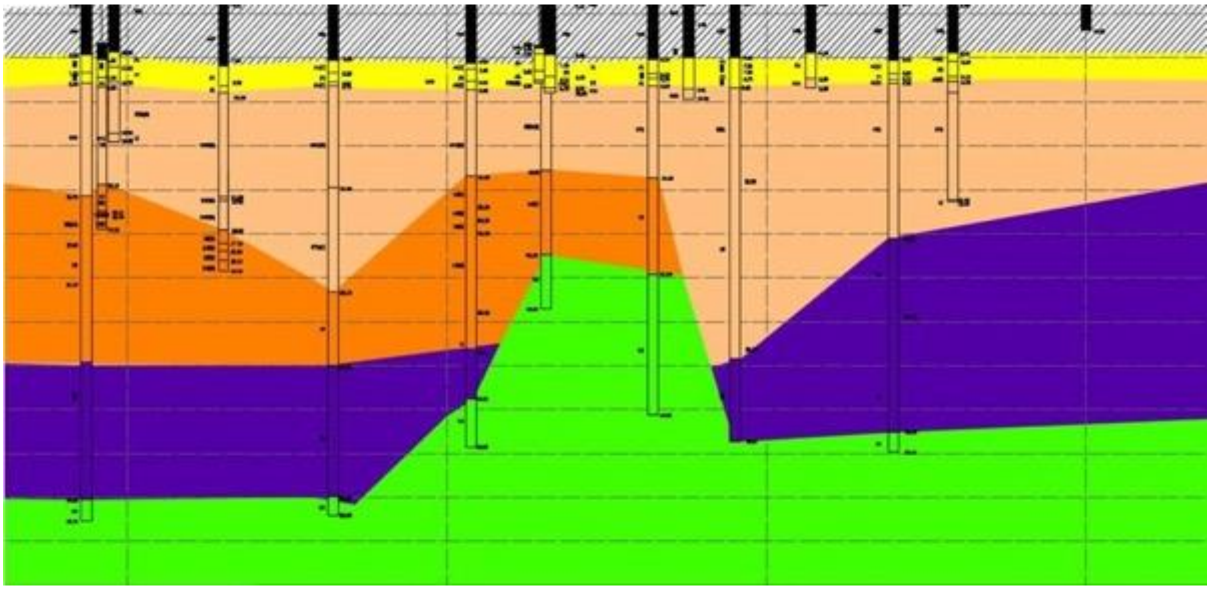


Figure 5. 41 – Barking DFH drawn from borehole logs. Vertical scale of 5m and horizontal scale at 10m. The chalk is represented in green, Thanet Sand in purple, Lambeth Group in orange, RTDs in cream, alluvium in yellow and made ground in grey hatched. Provided by Arcadis.

Figure 5. 41 displays a DFH feature with chalk material at a higher than local level. Key to note from the cross-section is that the diapir is offset from the deepest part of the depression (to the east of the upwelled chalk material) and also that the Lambeth Group is absent in the same direction. The Thanet Sand Fm. and Chalk is also identified closer to the ground level (15 m above) to the east of the upwelled chalk material in comparison to west. Finally, there is also a smaller second depression developed into the Lambeth Group (30m depth) to the west of the raised chalk. The DFH shown in Figure 5. 22 at Ashford Hill also shows a DFH feature with a diapir.

Features without a known diapir are shown in Figure 1. 3 (Chapter 1, introduction, Battersea Power Station Phase 3), Figure 4. 9(Chapter 4, data quality, London Road DFH), Figure 5. 42 and Figure 5. 44. It is possible that these features may have a diapir present beneath the depression, but it has not been identified by available borehole data.

Figure 5. 42 shows wide scale variability of infill, all within a distance of 200 m. This is evident through the presence and location of gravel within each of the boreholes as well as the differing levels of peat and London Clay. Note, the full depth of this feature is unknown due to boreholes not reaching bedrock in the deepest area of infill. Berry's feature 4a is also identifiable from the superficial geology in the BGS' Geology of Britain viewer as shown in Figure 5. 43.

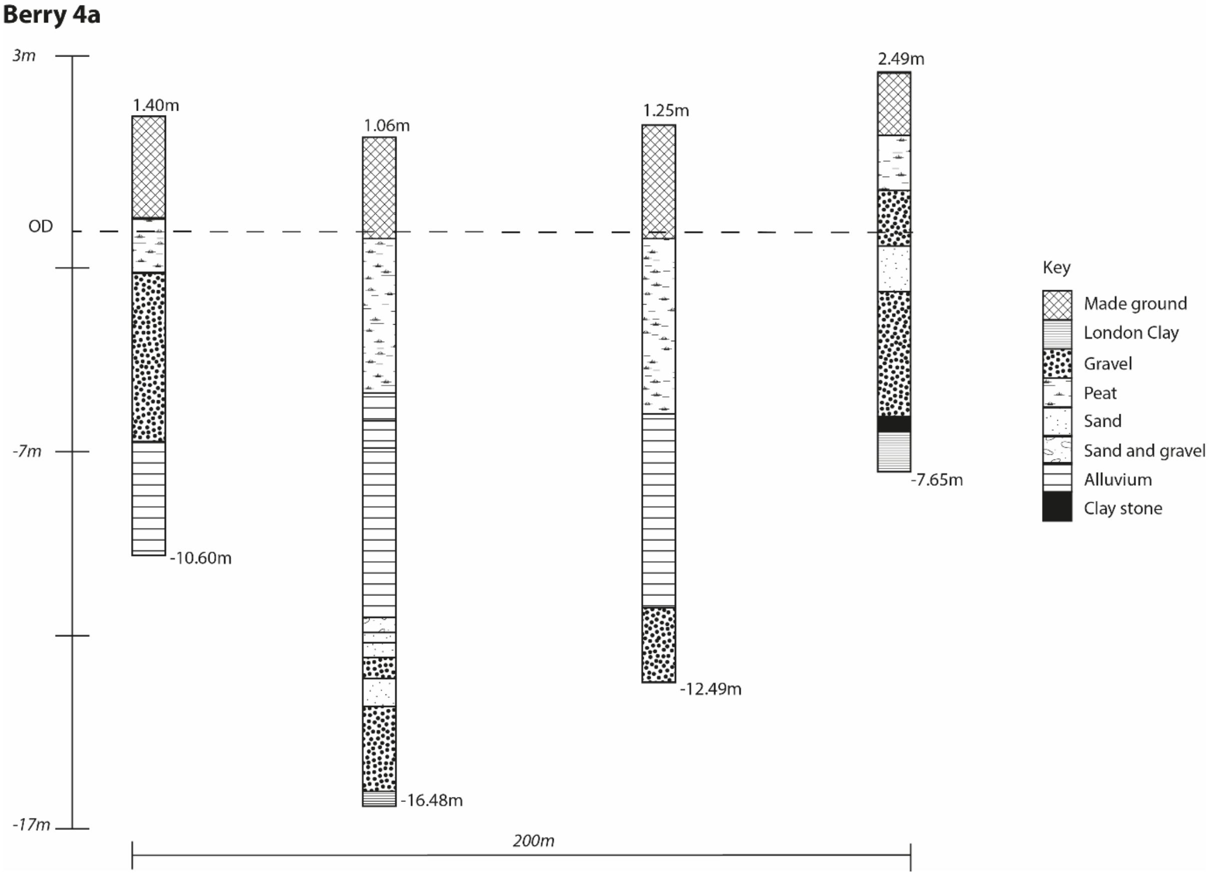


Figure 5. 42 – Cross section of feature 4a identified by Berry (1979).

Figure 5. 43 – The Berry 4a anomaly identified in the BGS' geology viewer is highlighted in the red circle. This shows the extent of this anomaly to be around 200 x 300m in diameter. Note that the viewer shows the infill to consist of peat and outer area of alluvium, yet figure 5.8 shows anomalous levels of peat identified at differing elevation OD and the near surface soils to consist of made ground. [BGS, 2019 - http://mapapps.bgs.ac.uk/geologyofbritain/home.html?]

Berry 2b

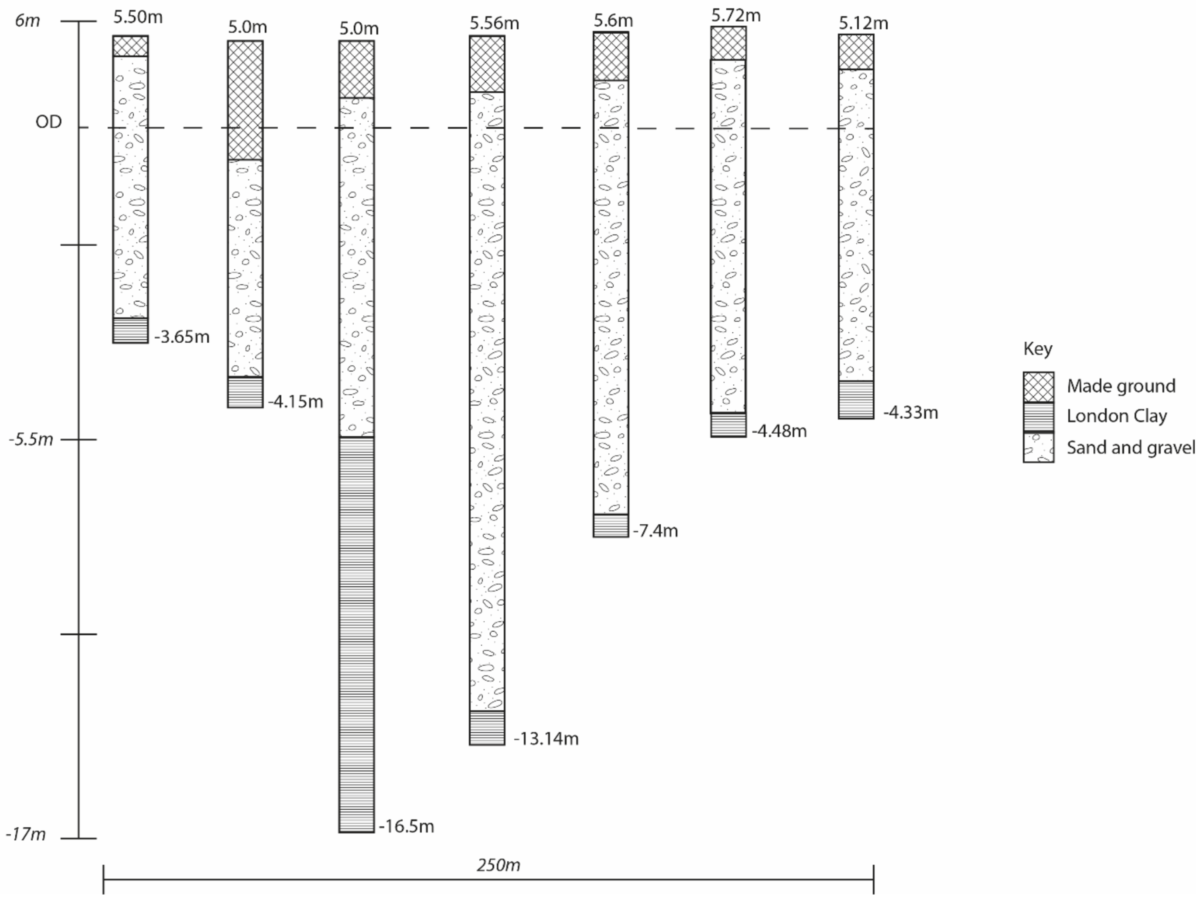


Figure 5. 44 – A 2D cross-section of the Berry 2b feature showing the range of depth in gravel before reaching London Clay.

Figure 5. 44 shows the Berry 2b DFH. Unlike Figure 5. 42 the infill of this depression to London Clay bedrock consists of sand and gravel with no peat or alluvium identified in the borehole logs. The depth of the feature here shows it reaching to -11.64 m OD.

5.6. Geotechnics

Due to the variability of the infill of DFHs, undertaking geotechnical tests which are representative and oblige to British Standards was often not possible (discussed in chapter 4, data quality). Results from the CPTu and dissipation tests undertaken at Ashford Hill shown above provide geotechnical data on one feature.

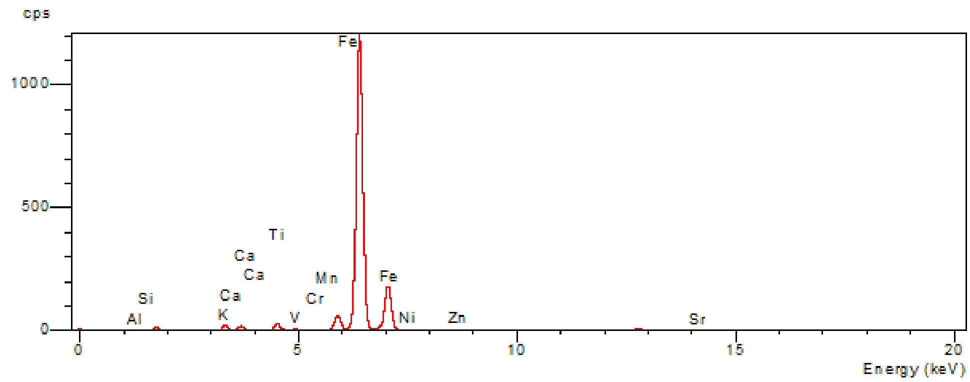
5.7. Chemical and mineralogical

Two types of geochemical techniques were used to attain the chemical (XRF) and mineral composition (XRD) of sub-samples taken from cores within the infill and on the edge of DFH features. The graphs displayed below are grouped in regards to individual feature and then ordered in relation to borehole number and depth the sample was taken within the borehole.

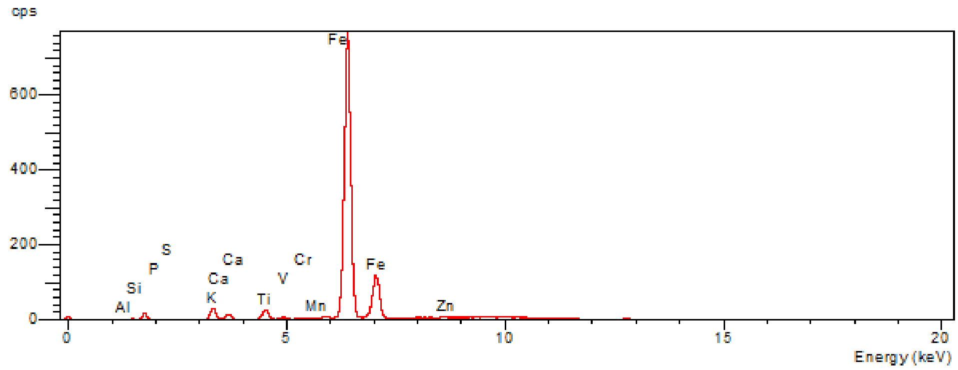
All XRF results shown within this chapter are qualitative and not quantitative. Therefore, the size of the peaks are not representative to the amount of element present within the given sample.

All tests shown in Figure 5. 45, Figure 5. 46, Figure 5. 47, Figure 5. 48 and Figure 5. 49 are silty clay material taken from Ashford Hill. Every sample has silicon (Si), iron (Fe), potassium (K), calcium (Ca), manganese (Mn), vanadium (V), aluminium (Al) and titanium (Ti) present. Magnesium (Mg) and chlorine (Cl) are only identified in the samples shown in Figure 5. 47 (borehole AH130710/4) as is sulphur (S).

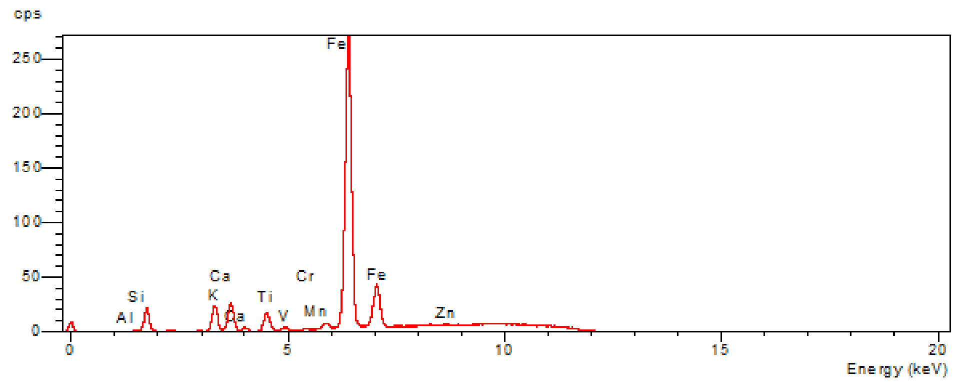
5.7.1. XRF



AH130710/2 1.3m

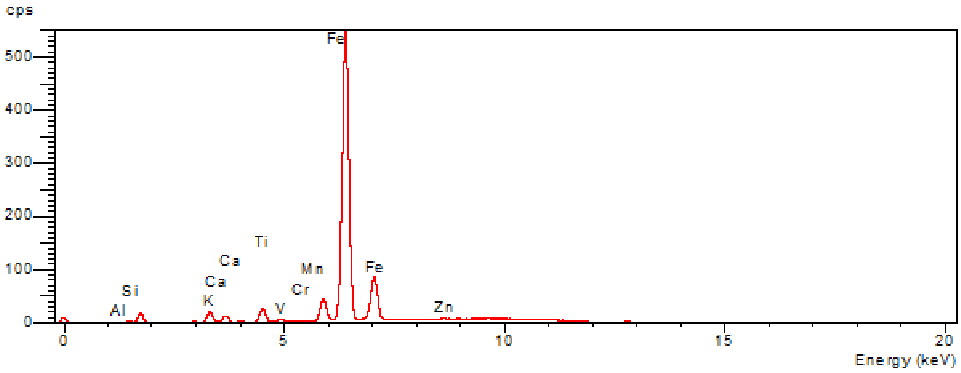


AH130710/2 2.6m



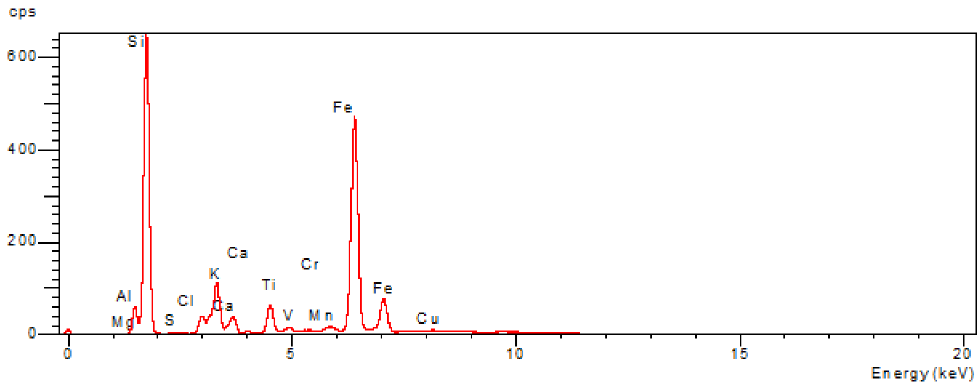
AH130710/2 4.1m

Figure 5. 45 – Qualitative XRF results from borehole AH130710/2 at Ashford Hill. The samples shown are all silty clay with a high iron component.

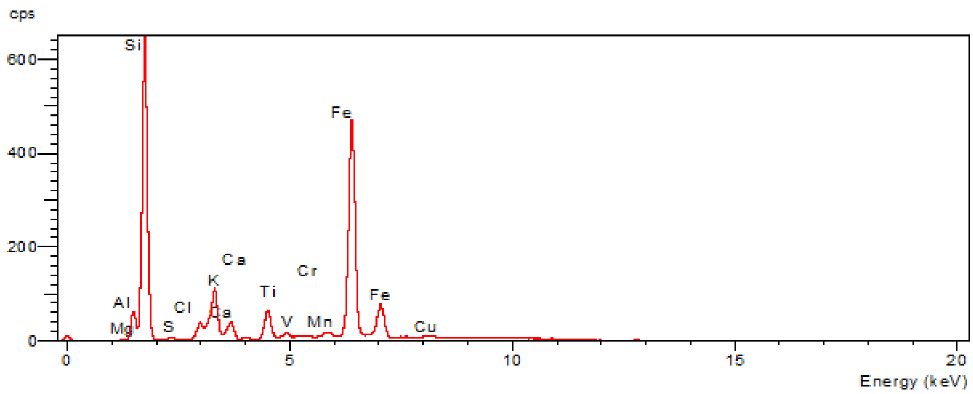


AH130710/3 1m

Figure 5. 46 - Qualitative XRF results from borehole AH130710/3 at Ashford Hill showing a silty clay.



AH130710/4 0.62m



AH130710/4 3.16m

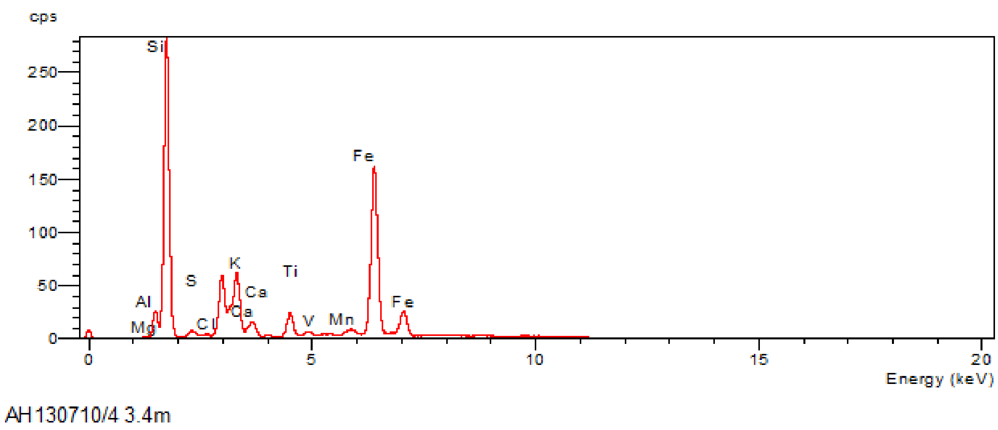


Figure 5. 47 - Qualitative XRF results from borehole AH130710/4 at Ashford Hill. The samples shown are all silty clay with a high silicon and iron content.

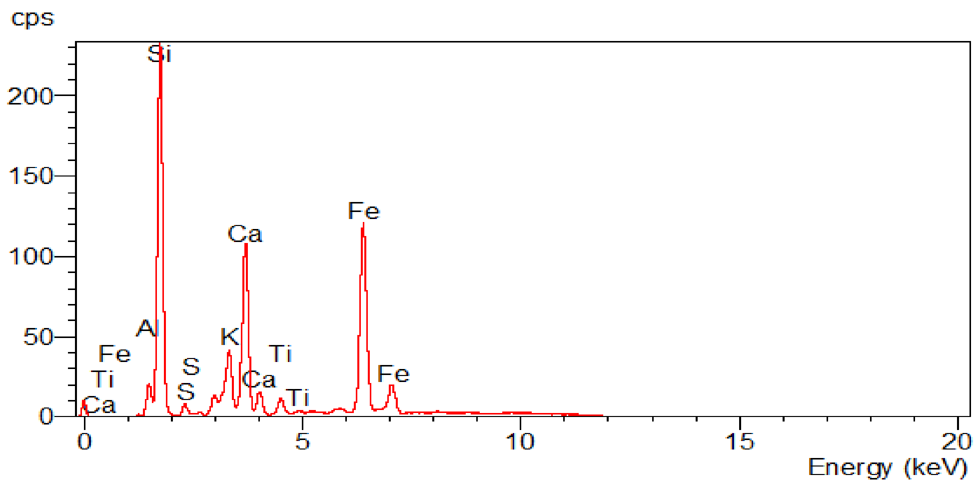


Figure 5. 48 - Qualitative XRF results from borehole 301 at One Nine Elms all showing the same chemical content at 21.5m depth. The sample is a clayey sand with a high silicon, calcium and iron content.

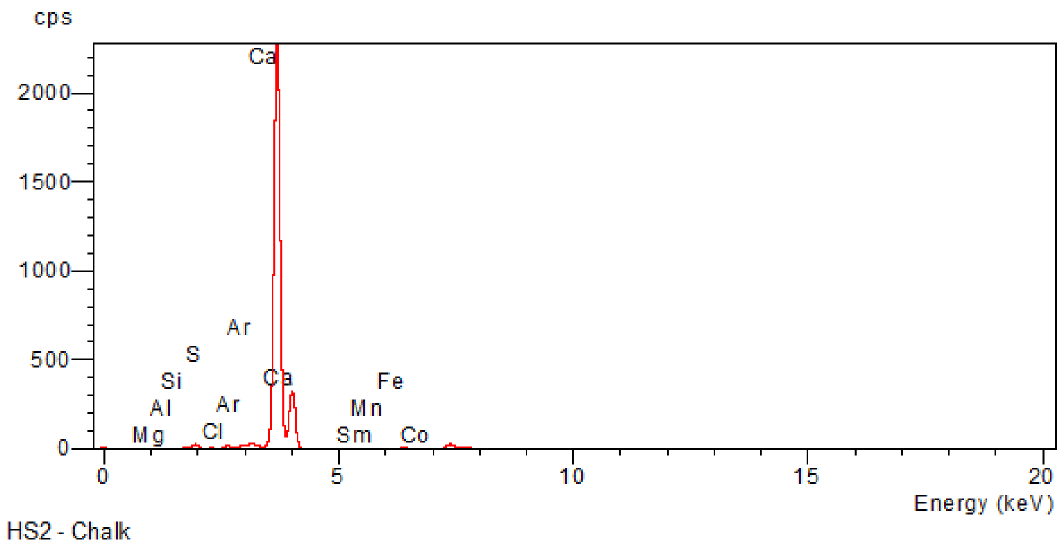


Figure 5. 49 - Qualitative XRF results from a borehole taken for HS2. The sediment is believed to be pure Seaford Chalk.

5.7.2. XRD

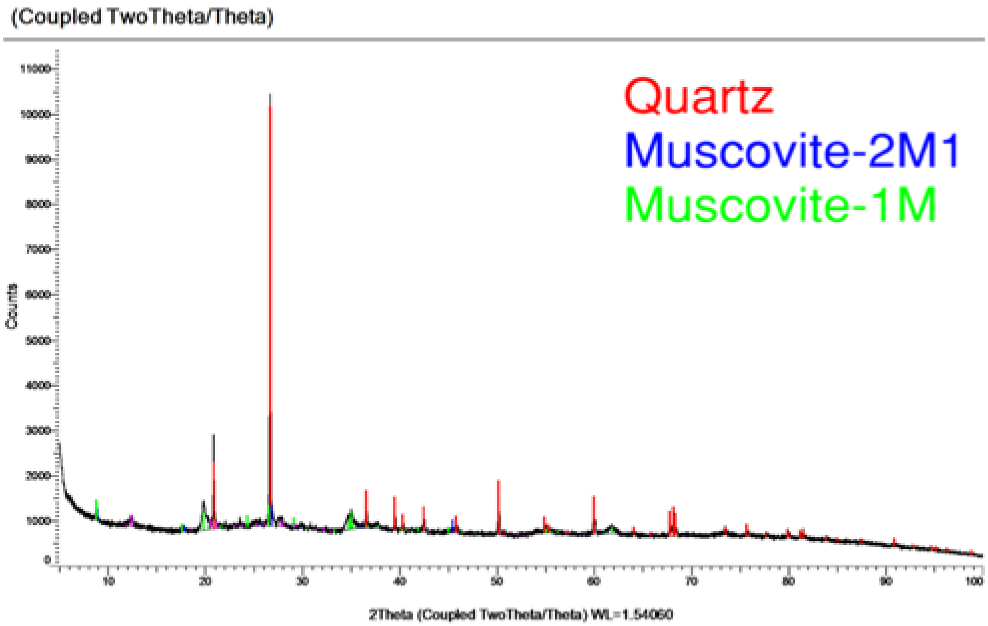


Figure 5. 50 – XRD results for AH130710/1 at 2.6 m. The sample comprises of quartz and muscovite.

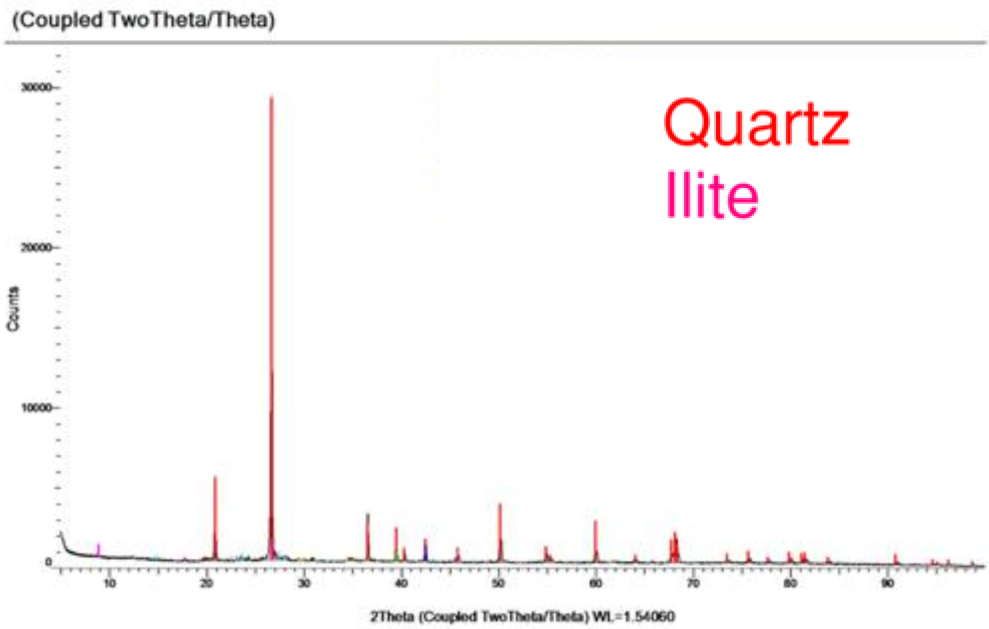


Figure 5. 51 – XRD results for the Ashford Hill feature, borehole AH130710/2 at 4.1 m. The sample has been analysed as having quartz and illite present.

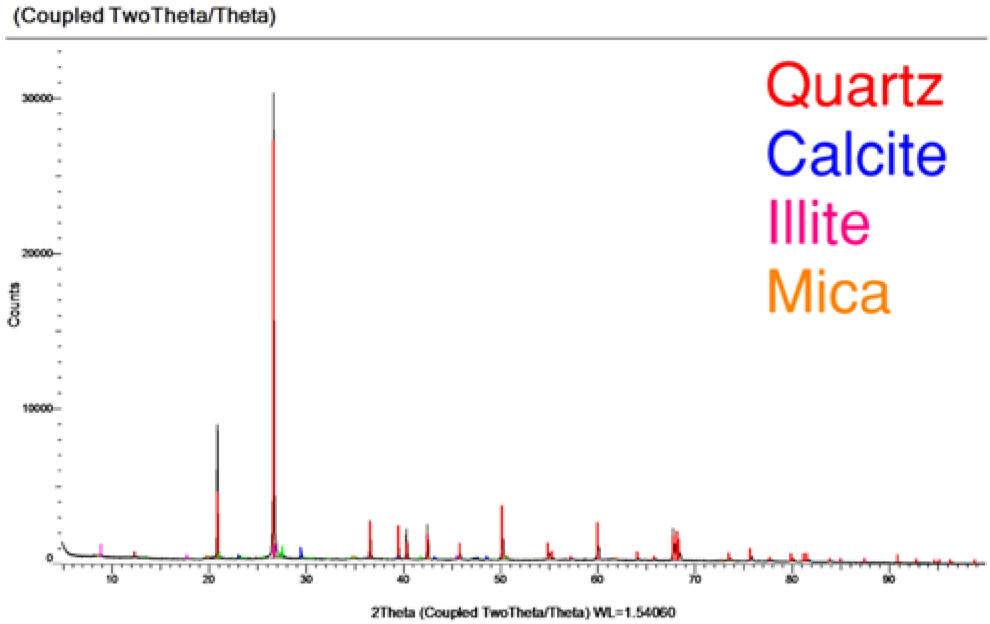


Figure 5. 52 - XRD results for the One Nine Elms feature, borehole 301 at 19.5 m. The sample comprises of quartz, calcite, illite, and mica.

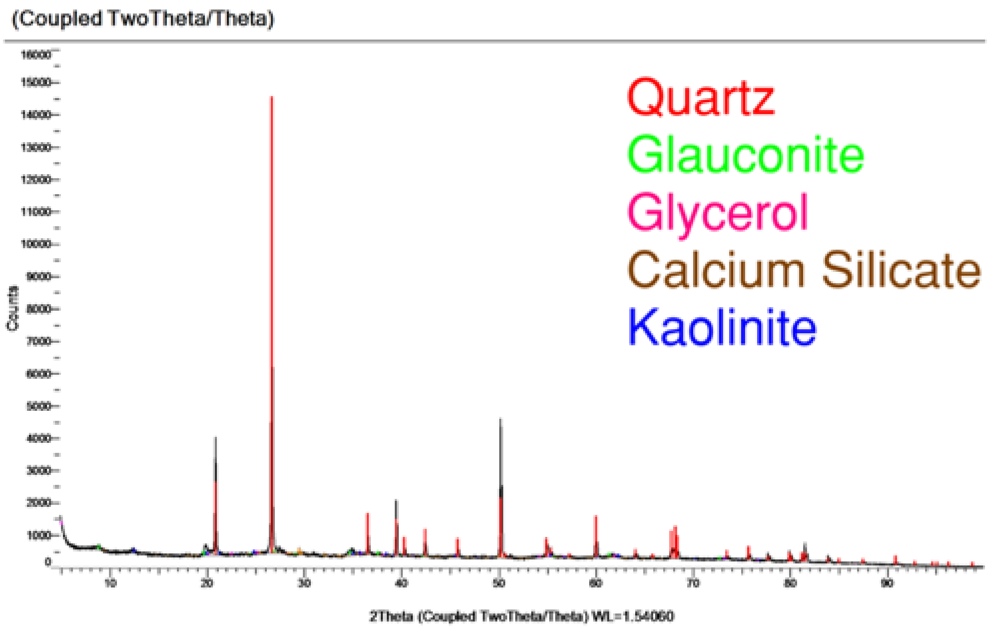


Figure 5. 53 – XRD results for the One Nine Elms feature, borehole 301 at 21.9 m. The sample consists of quartz, glauconite, glycerol, calcium silicate and kaolinite.

From all results shown in figures 5.30 to 5.33 it is evident that the samples are dominated by quartz and clay. The clay mineralogy identified is the clay mineralogy expected within the

London Clay and Lambeth Group (Section 2.4.1.5), therefore no unrelated stratum are identified via the technique.

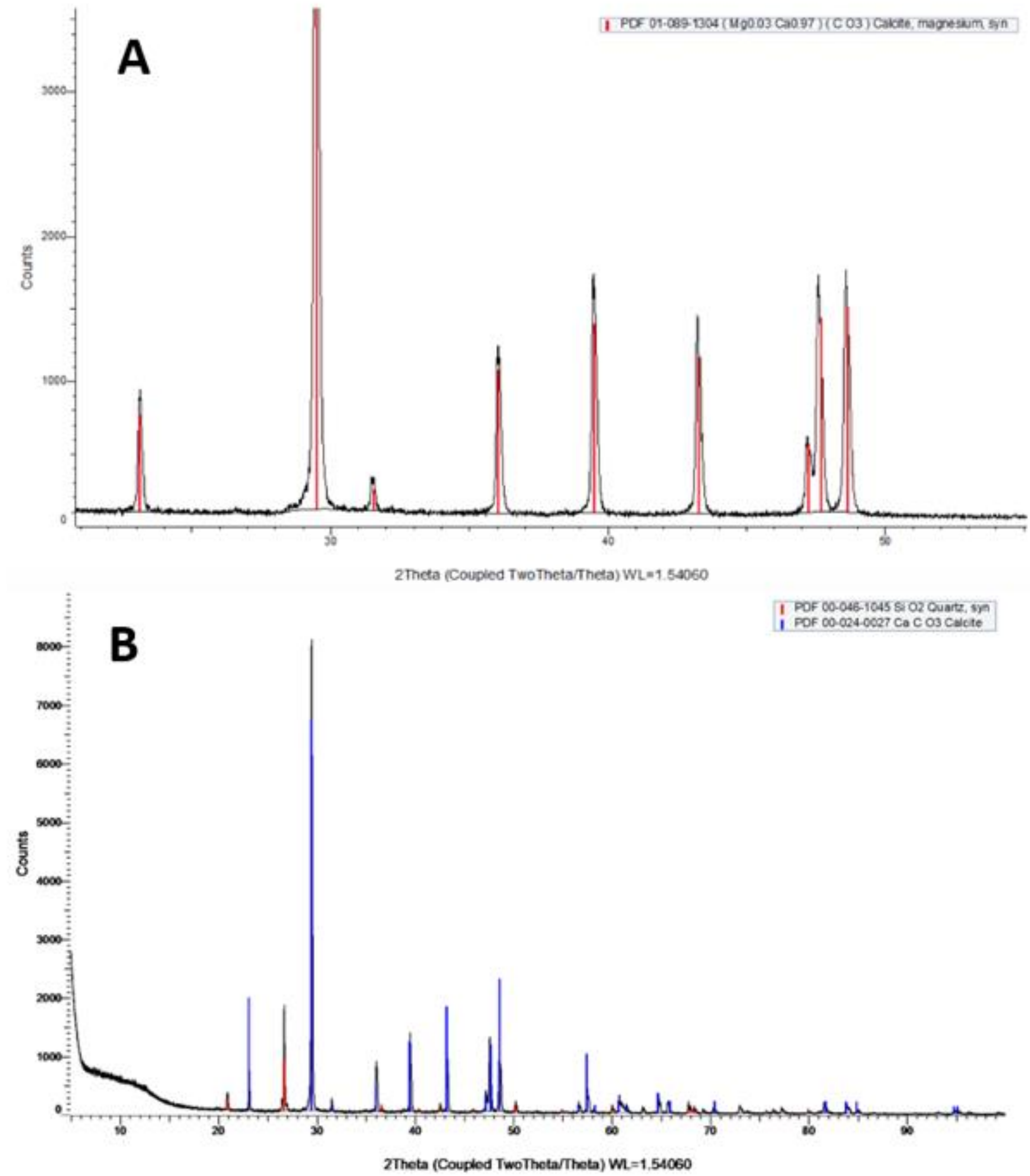
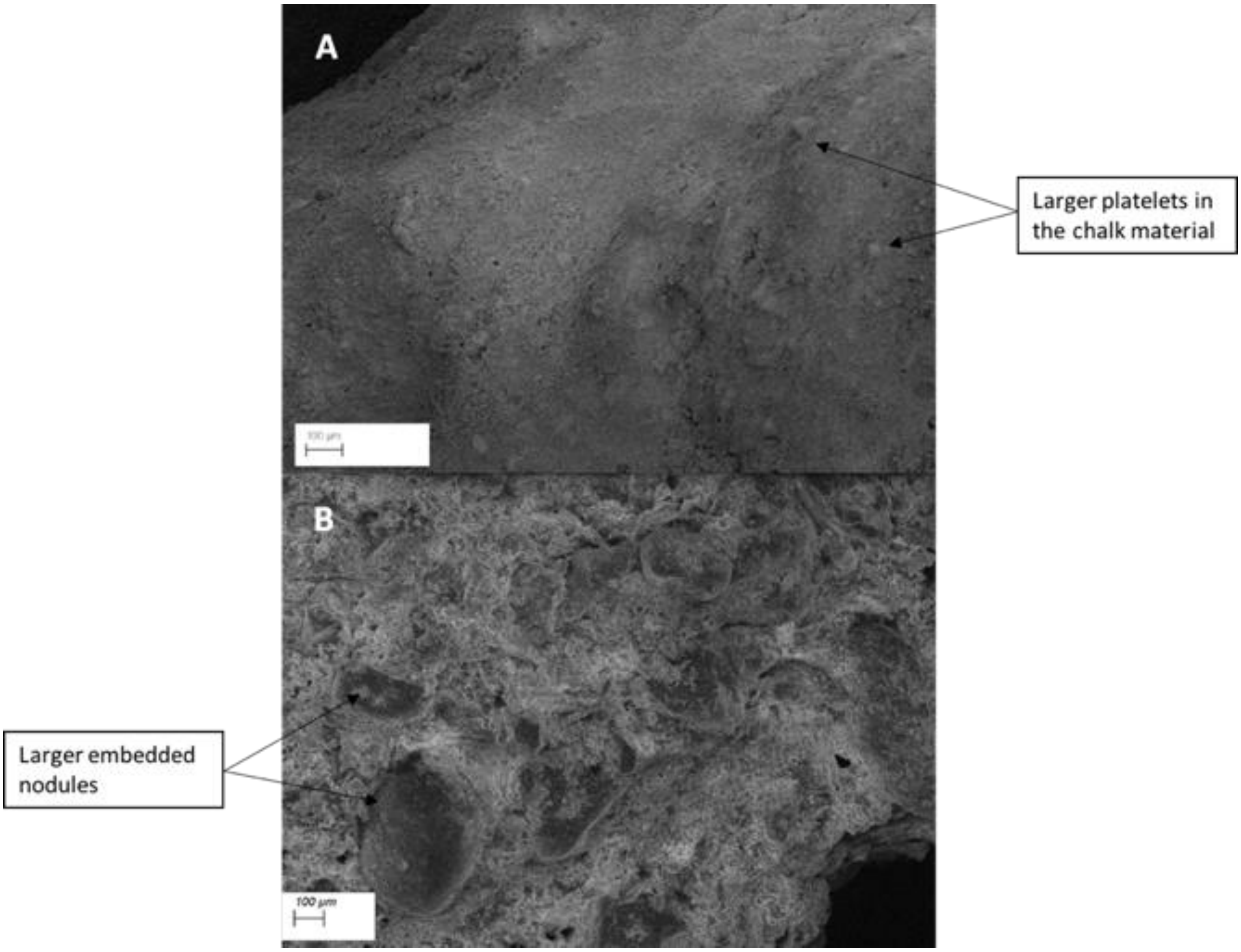


Figure 5. 54 - XRD results for intact Seaford chalk (A), taken from the HS2 chalk sample containing pure calcite and chalk diapir material (B) taken from the Olympic Park DFH comprising of calcite and quartz.

5.8. Microscopy

The scanning electron microscope (SEM) was employed for imaging purposes. The chalk material from the Olympic Park DFH diapir was imaged to analyse differences in the minute structures. The SEM was also used to enable surface texture analysis of quartz grains and imaging of the results.

5.8.1. Chalk imaging



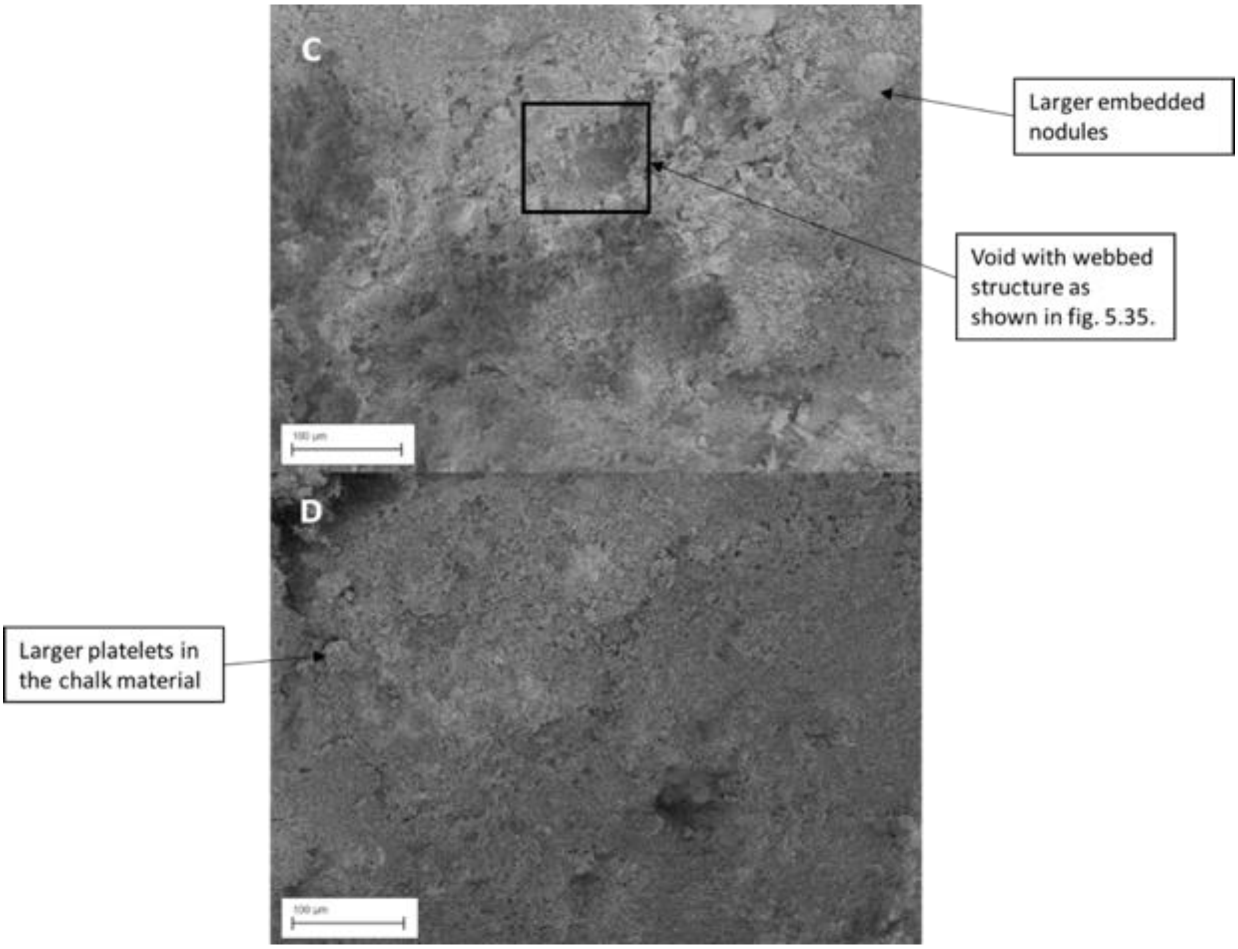


Figure 5. 55 – Chalk samples under the SEM: A - Intact Seaford Chalk, B - Chalk from the DFH, Lea Valley, C – Chalk from the DFH, Lea Valley, D - Chalk from the edge of a DFH taken from One Nine Elms.

Intact Seaford Chalk (A) shows a relatively constant granular appearance at 100µm with some larger and smaller angular platelets. This is in contrast to chalk material taken from the upwelled chalk at the Lea Valley DFH (B). This microscope image shows larger rounded nodules embedded within the chalk material. The nodules range in depth of embedment within the chalk material from near surface to barely visible. The second sample taken from the Lea Valley DFH (C) again shows the larger rounded nodules embedded in the chalk material. Also evident are voids within the chalk. A close up of this void is shown in Figure 5. 56. Finally, intact Seaford Chalk (A) shows the same physical appearance to the chalk sample from the edge of a DFH feature (D).

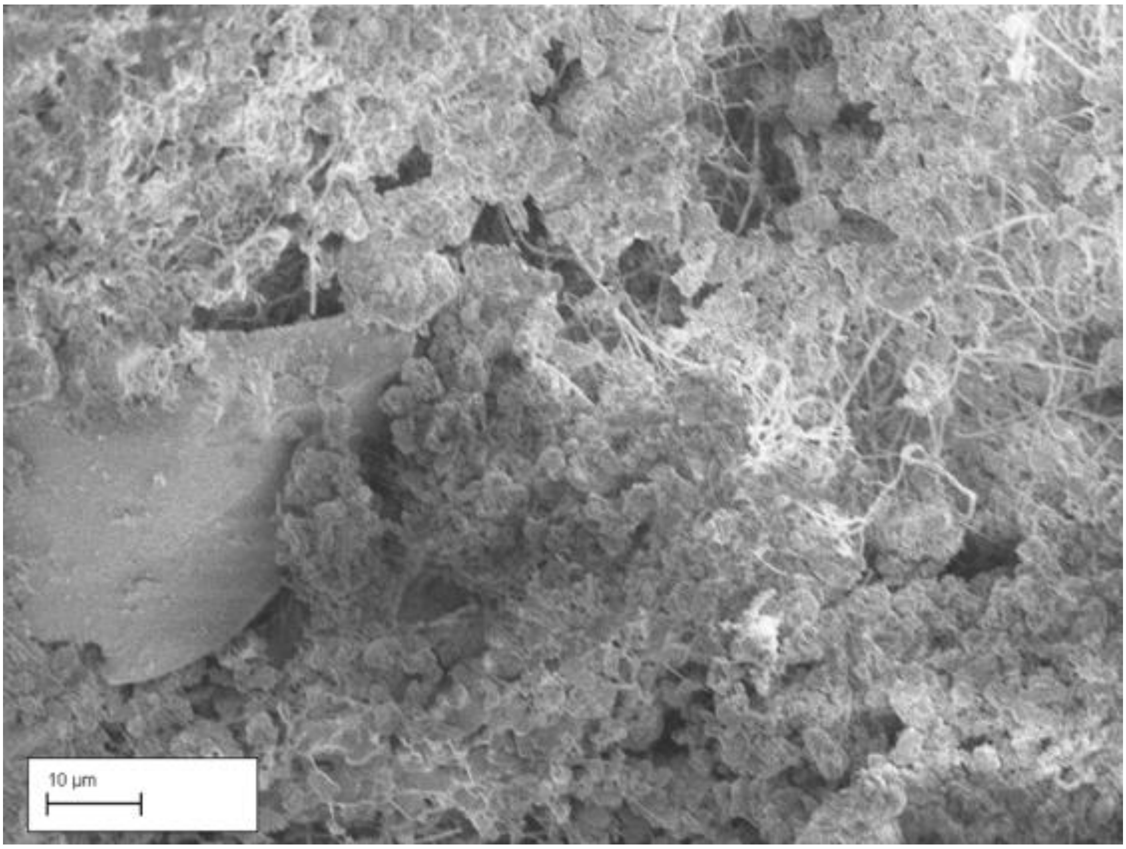


Figure 5. 56 – Web-like structure imaged under the SEM. The sample shown is zoomed in from image C in figure 5.35.

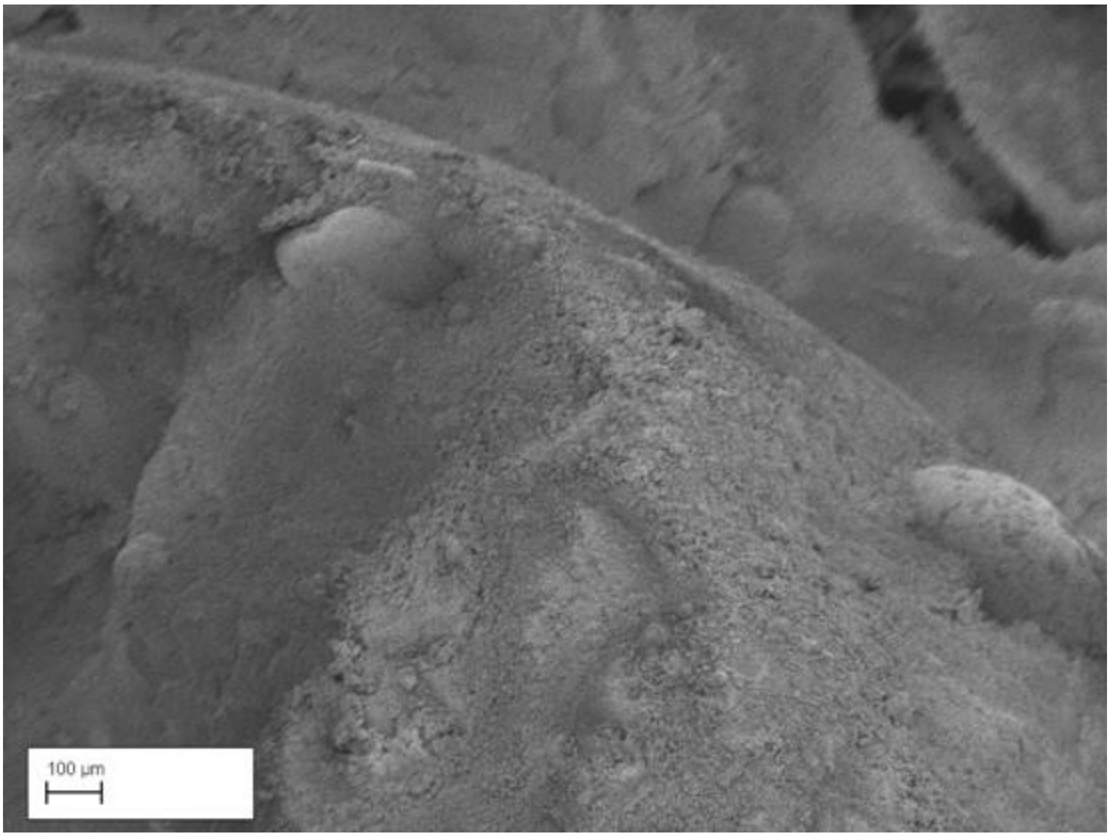


Figure 5. 57 – The microscope image shows the contact between two rounded quartz grains and the chalk material within the diapir material. The quartz grains are implanted into the chalk material.

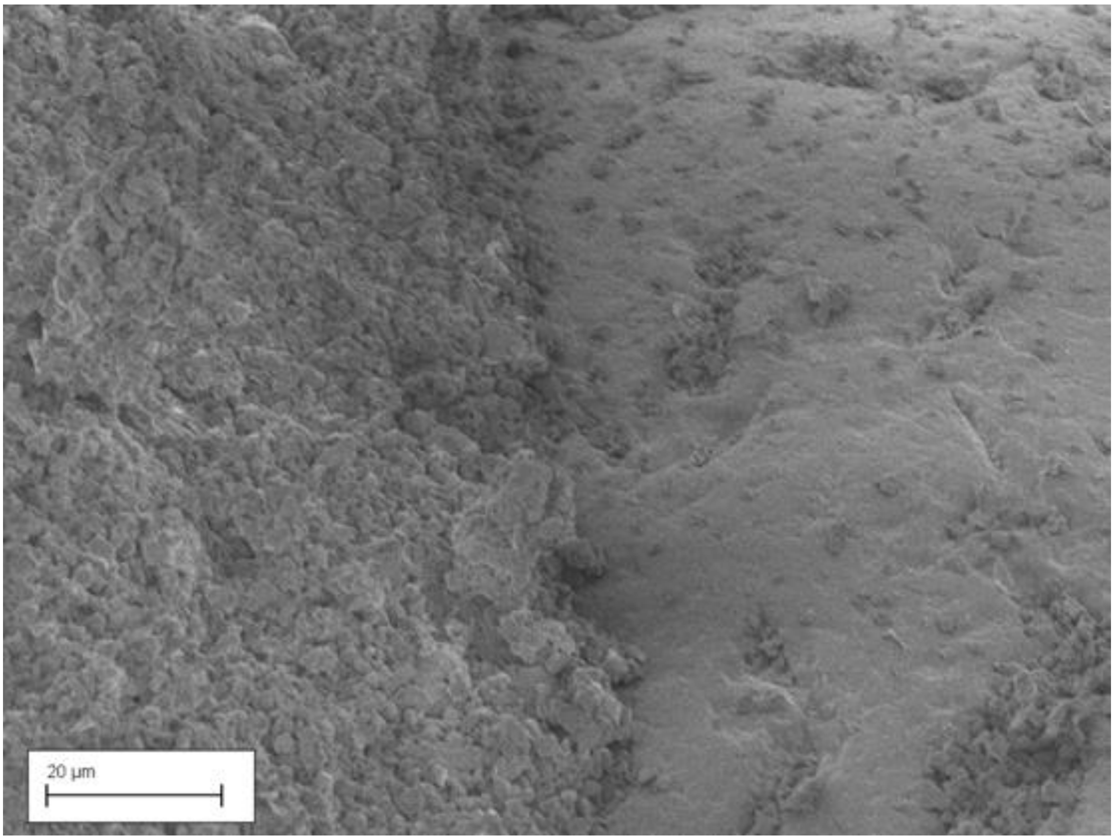


Figure 5. 58 - Contact between quartz grain and the chalk material within the diapir material. Image depicts the embedded nature of the quartz grain into the chalk material with chalk also on the quartz grain itself.

5.8.2. Surface texture analysis

The figures within the STA results section have been included for evidence of structures identified and recorded in Table 5. 4. All images within this section have been edited for visual representation using contrast and brightness adjustments.

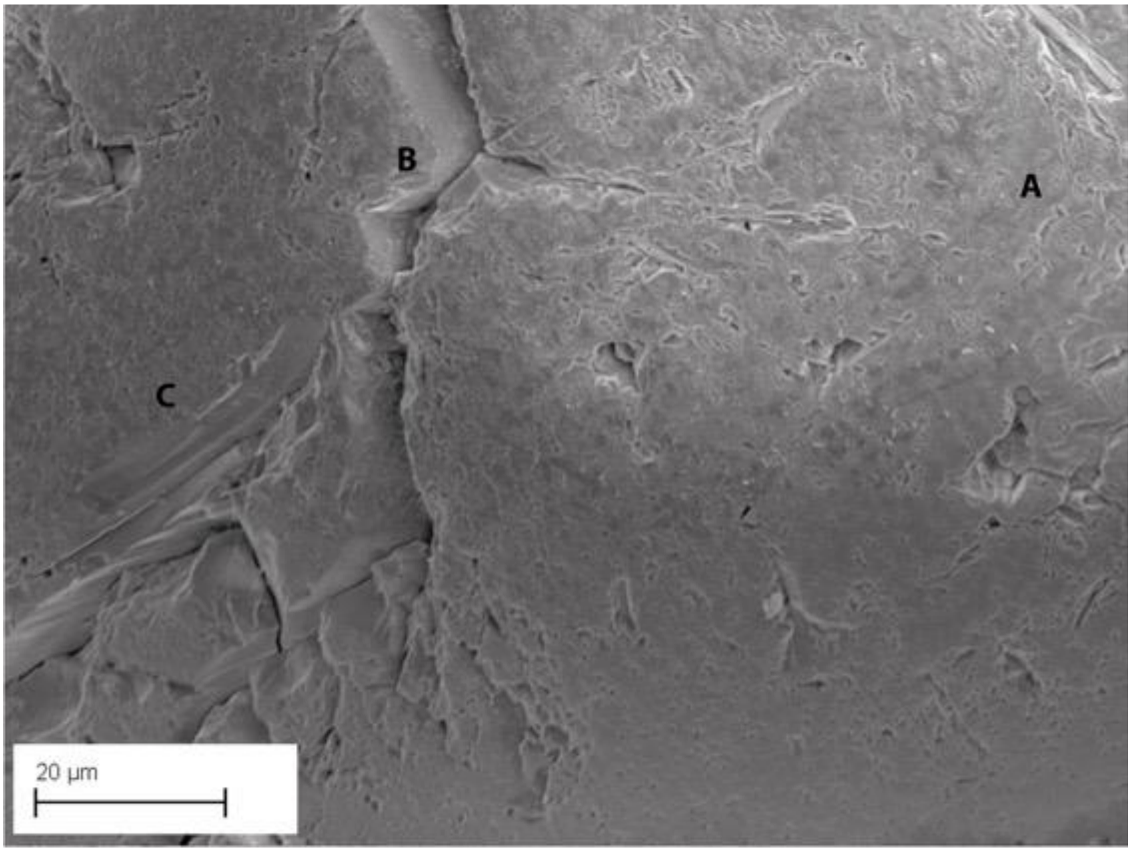


Figure 5. 59 – Quartz grain showing v shaped percussion cracks (A), polygonal cracks (B) and conchoidal fractures (C) (file number SE8_1_15344).

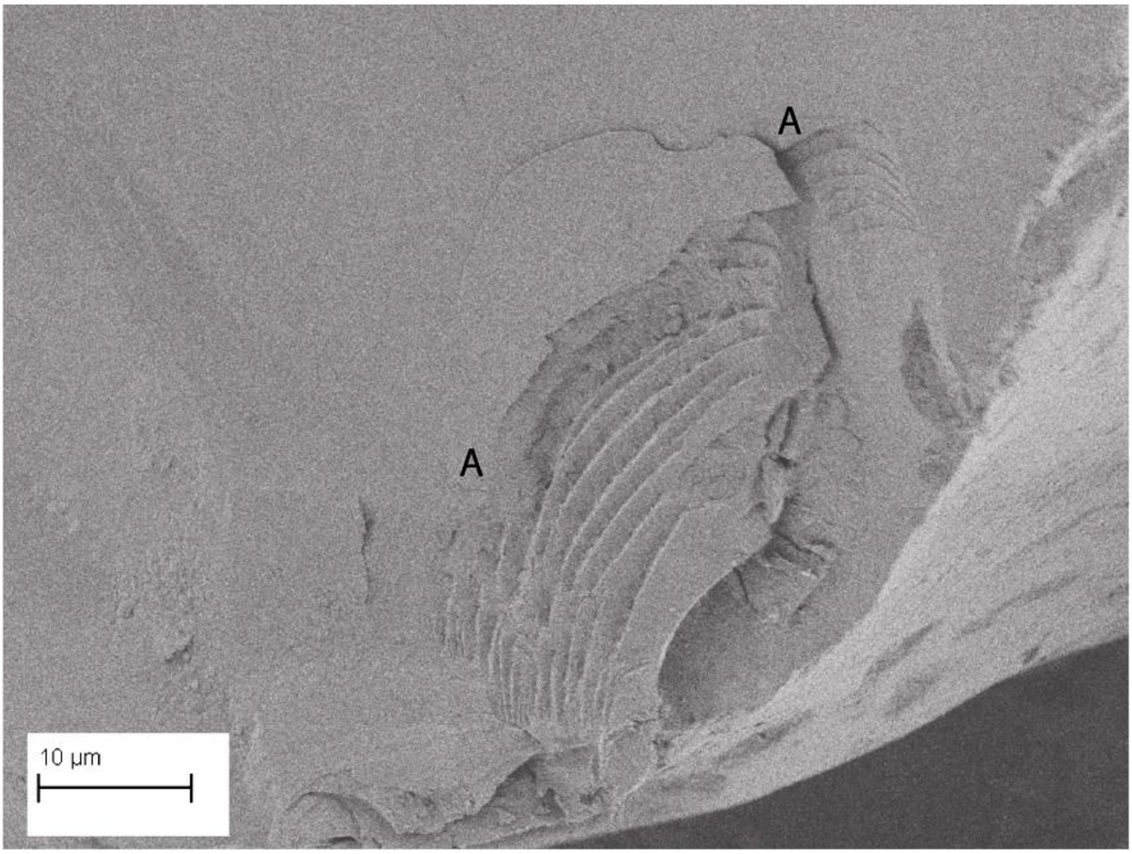


Figure 5. 60 – Quartz grain showing arcuate steps (A) (file name 1_2_se_2.31).

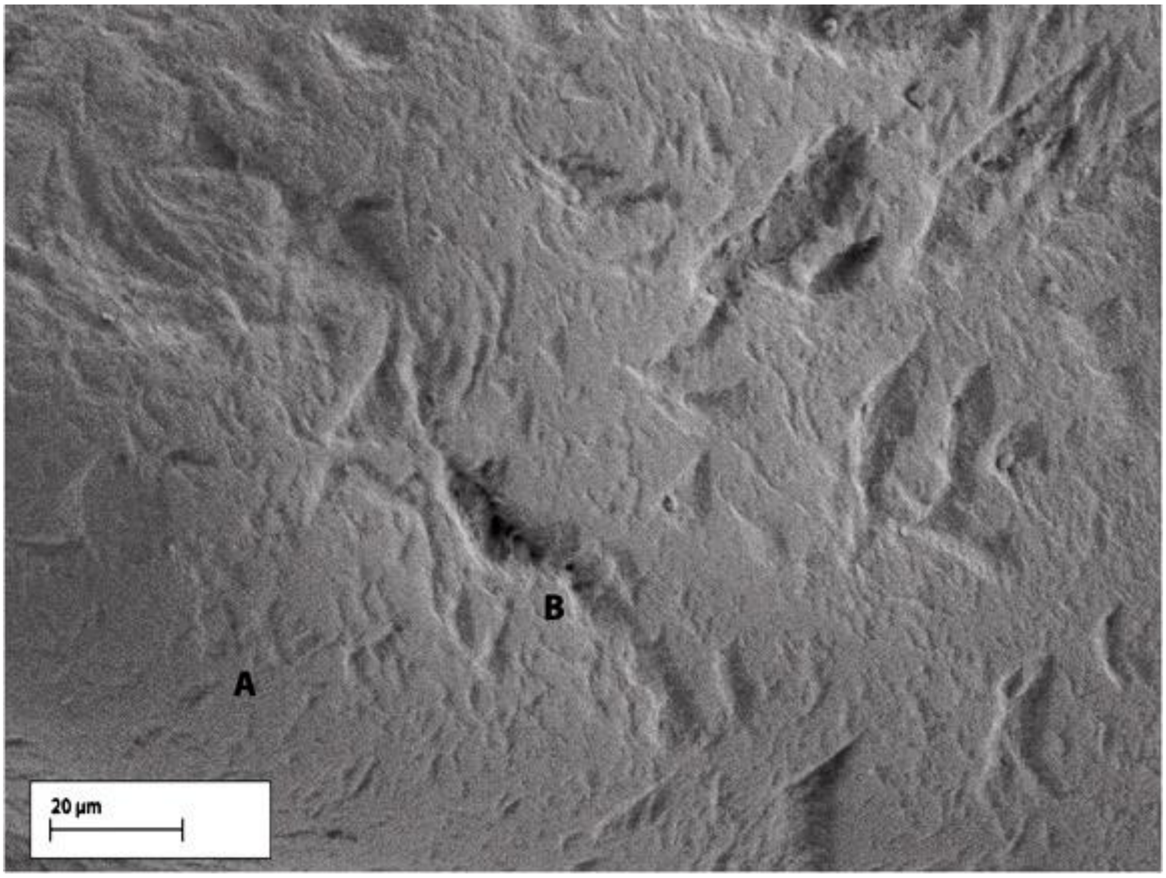


Figure 5. 61 – Quartz grain with v shaped percussion cracks (A) and straight grooves or scratches (file number 1_5_se_1.24).

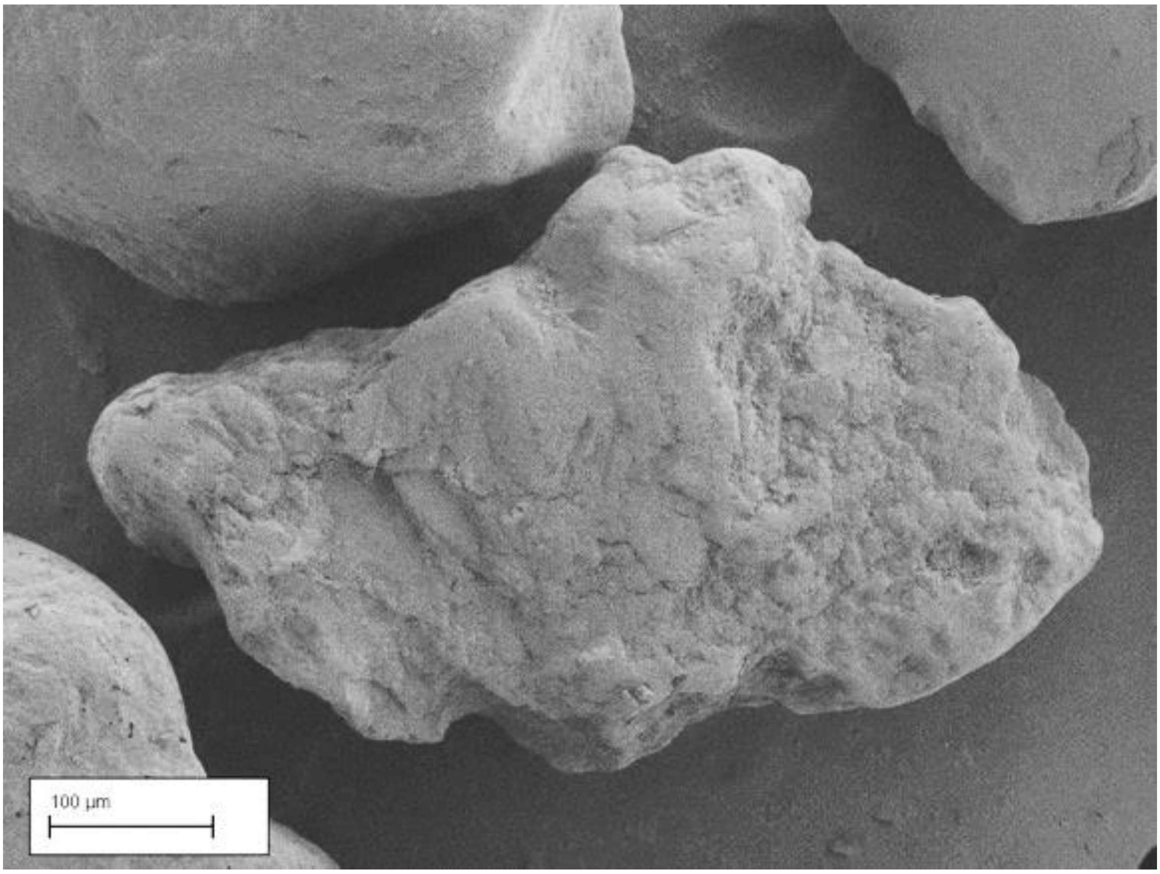


Figure 5. 62 – Angular quartz grain.

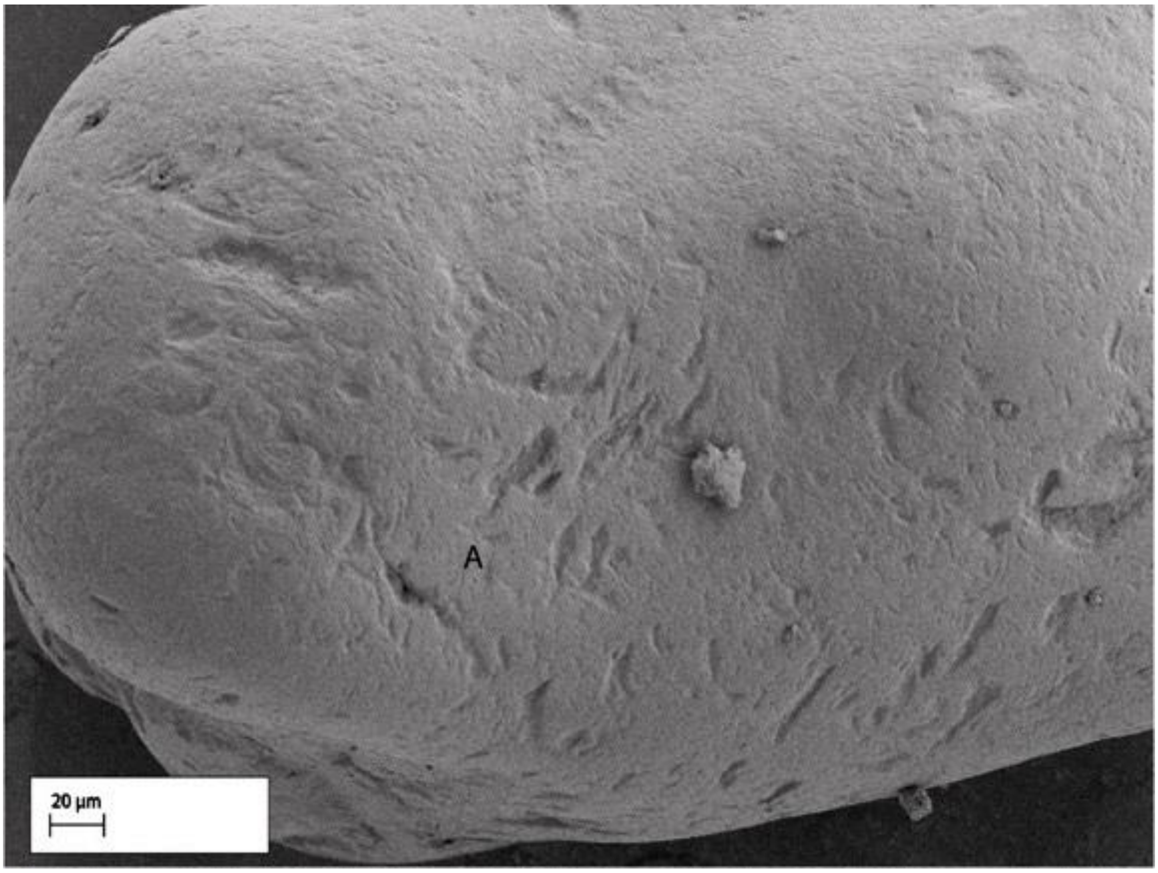


Figure 5. 63 – Rounded grain with low relief, V shaped percussion cracks (file number 1_5_se_506)

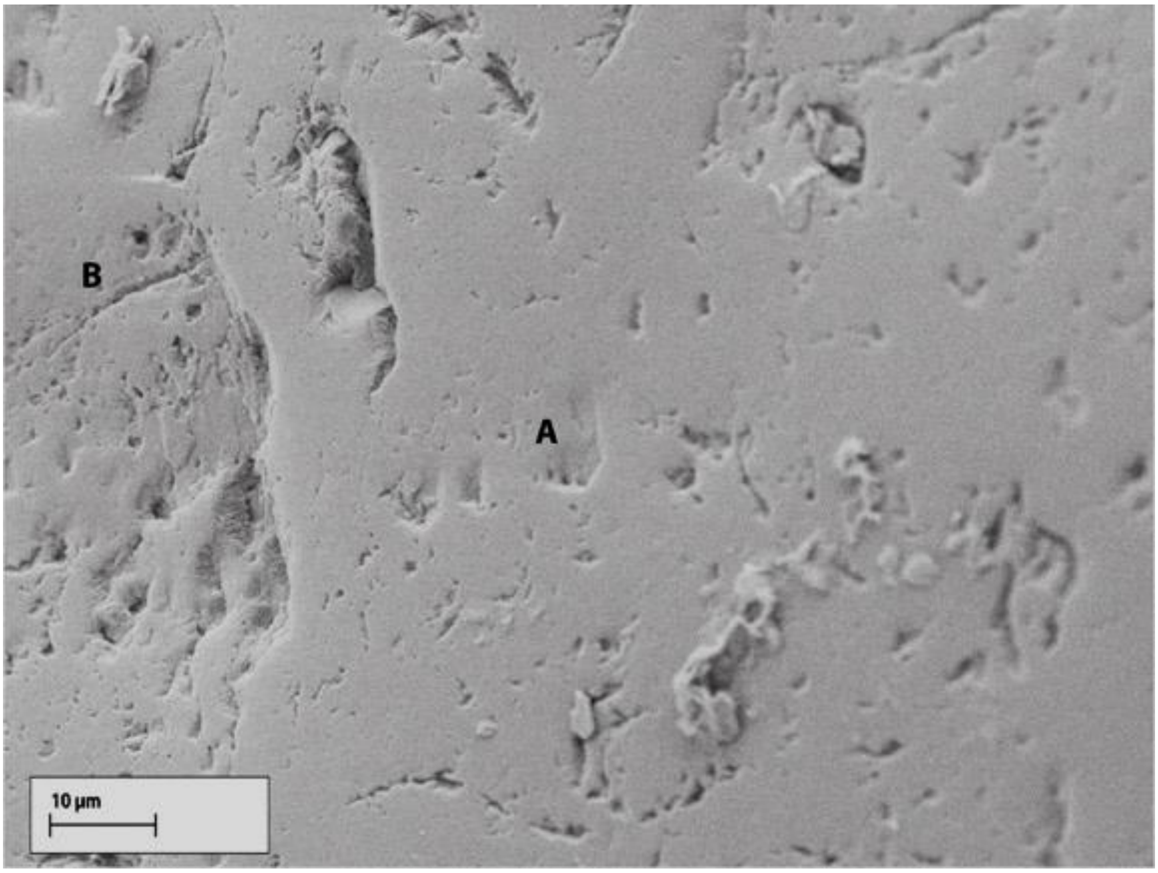


Figure 5. 64 – Grain exhibiting v shaped percussion cracks (A) and arcuate cracking (B) (file number S1_1_se_1.99).

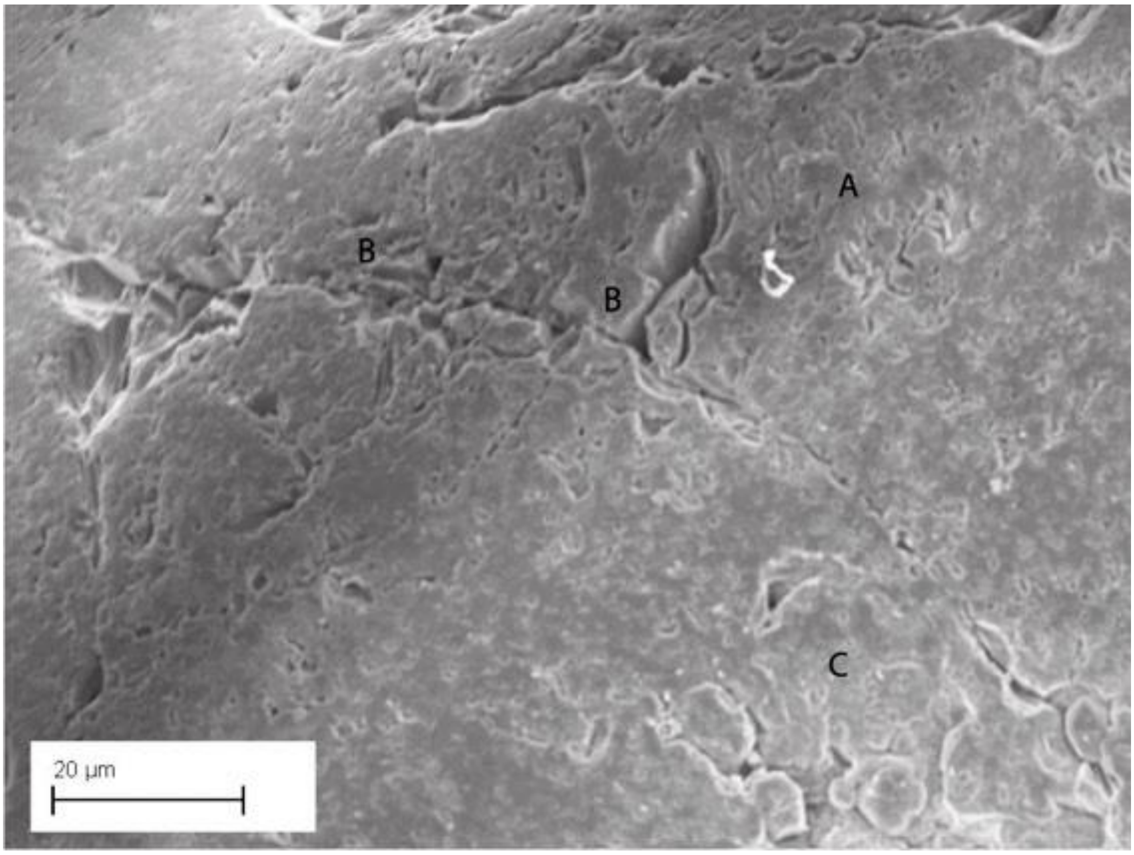


Figure 5. 65 – Quartz grain showing v shaped percussion cracks (A), polygonal/arcuate cracks (B) and upturned plates (C) (file number 8_1_se_24943).

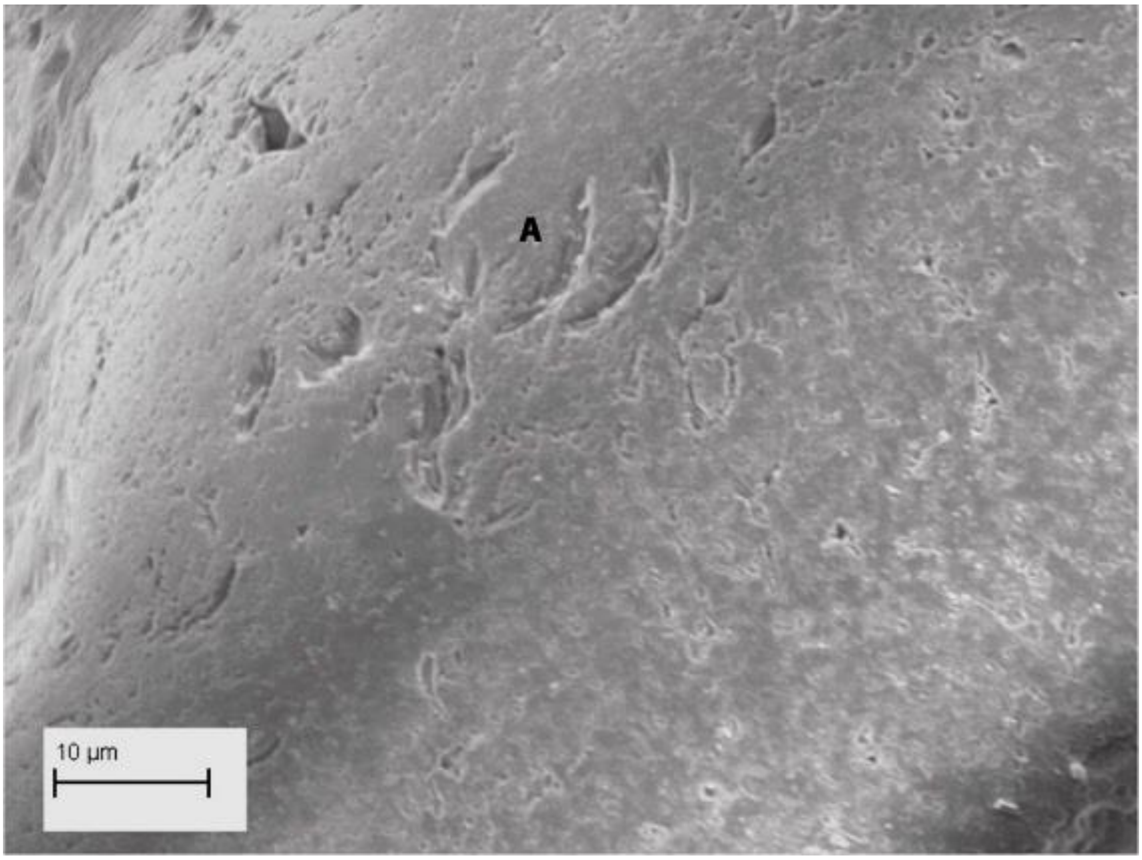


Figure 5. 66 – Quartz grain showing crescentic percussion marks on the surface (file number 8_1_21441).

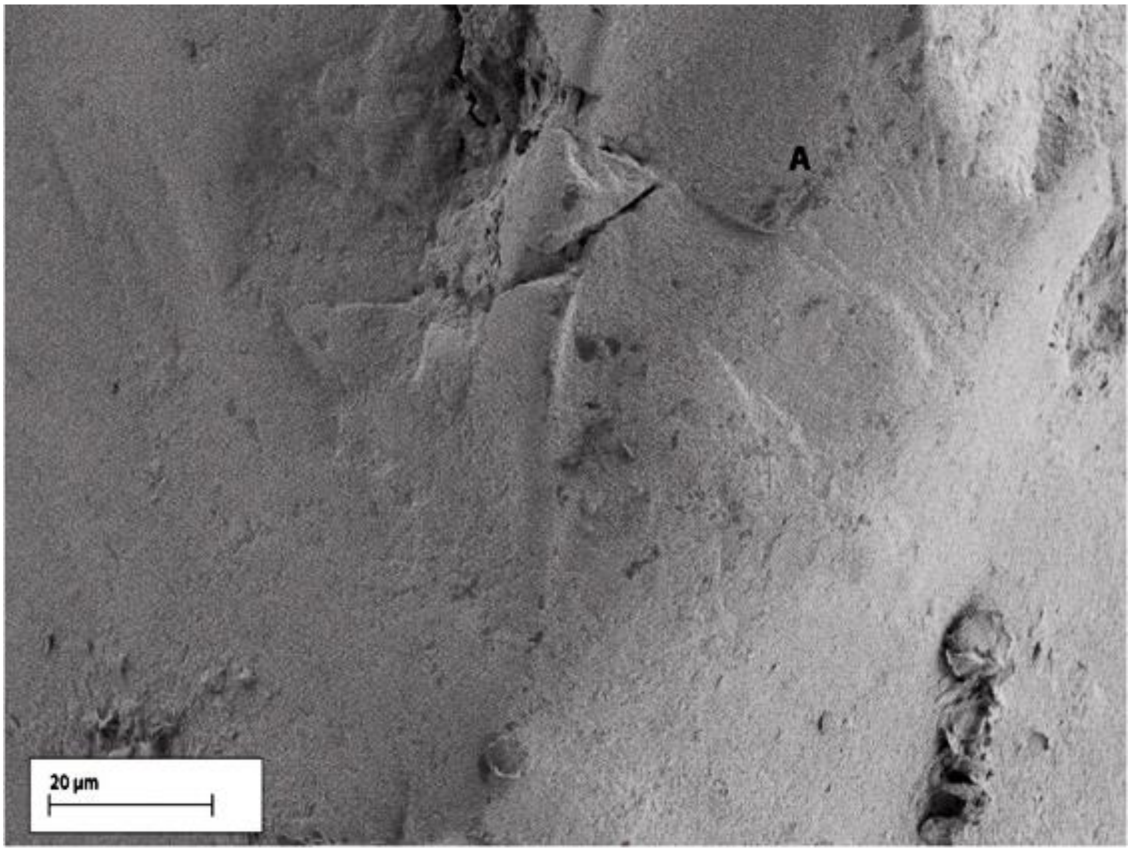


Figure 5. 67 – Grain showing straight (towards the bottom of the microstructure) and arcuate (towards the top of the stepped microstructure) steps (A) (file number 1_8_se_157 lines).

Table 5. 4 - Surface texture types identified within the DFH samples, the number identified and the environment the texture is indicative from as per Vos et al., (2014).

Surface texture type	Number of grains with identified markings	Indication of environment (according to Vos et al., 2014)
V-shaped percussion cracks	21	Subaqueous (Fluvial or marine) or glacial
Straight/curved grooves and scratches	6	High energy fluvial, intertidal marine, aeolian or glacial
Arcuate steps	14	High energy fluvial, intertidal, aeolian or glacial
Straight steps	13	High energy fluvial, intertidal, aeolian or glacial
Arcuate/circular/polygonal cracks	3	Desert dune or diagenetic/alteration
Conchoidal fractures	6	High energy fluvial, intertidal or subtidal marine, aeolian or glacial
Upturned plates	8	High energy fluvial, intertidal marine, aeolian or glacial
Chattermarks	1	High energy fluvial or intertidal marine, most likely glacial
Crescentic percussion marks	9	High energy fluvial, intertidal marine or eolian

Angular outline	11	Glacial, Low energy fluvial or possibly high energy fluvial or subtidal marine
Subangular outline	10	Subaqueous (Fluvial or marine)
Rounded outline	5	Subaqueous or eolian
Total no. grains	26	

Table 5. 4 shows the range of texture types identified on the sand grains analysed under the SEM. What is apparent is the commonality of high energy environments. This suggests that the grains have most likely been deposited and last disturbed under processes involving a high energy source. Fluvial and glacial are also two environments which are common amongst the grains indicative texture types.

5.9. Summary

All figures shown in this chapter are collated from the various methodologies undertaken throughout the project. Data quality implications of these results have previously been discussed in Chapter 4. In the next chapter, each figure will be assessed in relation to sub-surface risk, understanding of the physical characteristics of DFHs and the formation processes which potentially could have led to the features being created. The advancement of understanding of London's geology will also be discussed.

6. Discussion

This chapter evaluates all results from the methodologies used within this project, alongside existing knowledge and research, in the context of the engineering impacts and scientific knowledge. The outcomes are relevant to both the London Basin, where the DFHs have been identified and elsewhere where anomalous geology is present and engineering schemes are taking place, particularly in locations where space is already limited due to extensive existing construction.

The chapter discusses in detail the main outcomes of the research. These include methodological considerations variability of DFHs, both between features and within a single feature, sub-surface risk associated with anomalous geology. This leads into a guide for the site investigation sector for how to identify DFHs and the risks associated with the features. London geology, and the limitations to its current knowledge, as well as the classification of DFHs and hypotheses proposed for their formation are also discussed, and finally, issues surrounding nomenclature.

Data quality has impacted on the methodologies available, their results and usage in all aspects of researching DFHs and anomalous geology. These limitations have been discussed in detail in chapter 4 and will be touched upon where relevant throughout this chapter.

6.1. Methodological considerations

Data quality hampers understanding of the variability of single features as well as the dataset as a whole for the engineering and scientific sectors (discussed extensively in chapter 4). The main restriction is that due to boreholes being the main exploratory method analysis must be undertaken on samples. Due to spatial and vertical variability it would require an impractically large number of samples for testing to gain semi-reliable results which still may be not be representative of the infilling material. There would also be further issues such as sample bias and, not insignificantly, the large increased cost of any investigation, without adding much additional useful insight.

In addition, the volume or mass of material available is insufficient to produce results that meet the requirements of existing standards (see table 4.2). For this reason, the variability means that it was difficult to create detailed stratigraphic sequence histories, though it was generally possible to identify major stratigraphic units.

6.2 Nomenclature

The geological features discussed within this project have been subject to ongoing debate regarding their nomenclature. They have often been termed “pingos”, “scour features”, “drift-filled hollows” and “glacial” features (chapter 2, section 2.3.2). This project has amplified this debate and also established new issues concerning terminology due to the variability identified between the individual features and within them. In turn, this variability has led to several formation processes being hypothesised and therefore more ambiguity on their naming. This leads to further questions relating to nomenclature.

As it is hypothesised that the features have formed due to potentially differing processes, the features could be given different names to differentiate between types of feature. However, as the sole factor which groups these features is the anomalous depth to bedrock, the term DFH suits as an informal non-genetic term. Furthermore, a feature could be identified as a DFH with organised infill, without a diapir or associated faulting through little exploration and the feature could be misconstrued when engineered due to a lack of data, therefore increasing risk through uncertainty.

The key to preventing misunderstanding and misrepresentation of the sub-surface when identifying these features is to communicate the variability, both within a single feature and between DFHs. Therefore, terming the features as DFHs and communicating this variability should enable effective site investigation and scientific understanding to progress. In turn, this should lead to an increase in the understanding of the sub-surface and consequently decrease risk through fewer unknown characteristics.

This project has used the term drift-filled hollow (DFH) throughout due to its nomenclature not being related to formation as explained in section 1.1 (Chapter 1, Introduction). However, issues with this term do still remain, primarily due to its descriptive nature not covering every feature accurately. The use of the word ‘drift’ suggests that every one of the features is infilled with solely ‘drift’ material, which is not the case. Furthermore, the BGS has changed from using the word ‘drift’ to ‘superficial deposits’, but this term would also imply that there is no other infilling material. Again, communicating the variability of the features’ infill as shown in Figure 5. 32 should mitigate this terminological issue creating risk.

Furthermore, the literature review has not found any similar features in other surrounding areas with similar geology, fluvial and climatic histories e.g. the Hampshire-Dieppe Basin, Belgium, the Netherlands and Germany, where the London Clay extends to under different nomenclature (Brenchley & Rawson, 2006). For this reason, it is possible that they are deemed unique to the London Basin, yet it may be the terminology which leads to difficulties identifying similar or the same feature elsewhere.

The naming of individual features also creates debate due to ambiguity of their location. The system used within this project is expressed in chapter 3, section 2.6.2. Going forward, when a new feature is identified, it is plausible to use the west to east numerical system already in place and add a corresponding letter to the feature immediately west. For example, if a new feature was identified in Darlan Road, Fulham, the nearest feature to the west would be '4 – Hammersmith A4' and therefore this new feature would be termed feature 4a. The Berry features would not be used in this lettering system and it would be the nearest non-Berry DFH to the west of the newly identified feature.

6.3 Variability

6.3.1 Between features

The data collected in this investigation (Appendix A) show that every DFH identified is unique and differs to all the others in regards to its physical parameters.

The range of characteristics and the proportion of features with each one are shown in section 5.7.1. The high amount of unknown variables and the implications of this are discussed later within this section. From the insights that the data provides, it is apparent that it remains challenging to determine the presence of faulting and a diapir. This is most likely due to the retrieval method of the sub-surface being too small in diameter to gain this information with certainty. The lack of knowledge for these two variables induces risk to both the process of understanding and to the engineering works as the features could have faulting or uplifted strata, but the site investigation has not been conducted in a way that could identify these potentially hazardous geotechnical conditions.

The easiest characteristic to obtain is whether the feature breaches the local bedrock. Since 59% of the features are not breaching the bedrock, this implies that the majority of the features are located within the geological unit they are identified within. For engineering purposes this is important as for above ground construction projects foundations can still be anchored into the local bedrock, just deeper than local level. Nevertheless, for 61% of the features the full extent is still unknown and therefore caution should be taken over whether the feature extends below the deepest borehole in a large proportion of the DFHs.

The extent of the features (width and depth) is also difficult to identify through the intrusive methods currently used in built up, urban areas such as central London. The data show that the features range from 3 to 500 m wide and 3.8 to 75.5 m in depth (from ground level) with the majority falling between 10 to 20 m in depth. It is important to note that the width of the features is restricted by borehole spacing or tunnel positioning and only 37 features have a reliably established estimated width.

As shown in Figure 5. 5 and Figure 5. 6 the vast majority of identified DFHs are located within the Kempton Park Gravel Member and the London Clay (66% and 86% respectively), although this may be due to the location bias of where the features are currently identified (discussed below in section 7.2). It is clear, however, that the features are not limited to these geological deposits, but they are also present within a range of RTDs, the Lambeth Group and the Thanet Sand Fm.

The infilling material of DFHs has proven difficult to quantify for numerous reasons. Figure 5. 7 shows the range of material recorded in borehole logs associated with DFH infill. Whilst the largest percentage (28%) identify silt, sand, clay and gravel this does not provide information on the amount of each material and whether the infilling material is organised. These more specific characteristics of the infilling material are difficult to attain. This is due to the results showing a secondary interpretation of a borehole log, which is a prior interpretation undertaken by a logger. This secondary interpretation means there is a greater chance of error. The interpretation undertaken within this project is based solely on the borehole logs and therefore if these are inaccurate or incorrect this impacts on the secondary analysis.

Further evidence of the variability between features is shown through cross sections of individual features (Figure 5. 22, Figure 5. 41, Figure 5. 42, Figure 5. 44and Appendix B). It is evident that the features vary in almost all physical characteristics. For example, the Barking (Figure 5. 41) and Ashford Hill features have a chalk diapir present whereas the Berry 2b cross-section shows the feature does not have uplifted strata associated with the feature as far as the data allows us to interpret. They are also different in width being 100m, 350 m and 150 m respectively. Battersea Power Station (phase 3a), the sole DFH which has been excavated in London and its full extent known, also does not have a diapir beneath the infilled material. However, even within features with similar features, such as a diapir, there are major differences. For instance, the Barking feature has an absence of Lambeth Group to the east of the uplifted chalk material, as does the Ashford Hill feature above the laminated silts, whereas there is no evidence of this absence at the Olympic Park DFH.

The range in the physical characteristics of the features impacts on site investigation, construction and scientific hypotheses for the formation of the features due to their variability, meaning it is not possible to accurately predict the sub-surface conditions once a DFH is identified. For example, from the borehole records, feature “Berry 2b” (Figure 5. 44) shows an anomalous depth to bedrock (London Clay) with an approximately cone-shaped depression infilled with sand and gravel. In comparison, the Barking DFH shown in Figure 5. 41shows a feature with an absence of Lambeth Group on the east side of the uplifted chalk material and the Thanet Sand Fm. is identified at a higher than local level. The Thanet Sand Fm. has a higher water content and settlement rate in comparison to both the Lambeth Group and the London Clay. For engineering purposes, if both features were deemed to be less complex than the Berry 2b feature, additional boreholes may not have been placed on the right side of the depression to encounter the absence of Lambeth Group and the higher than normal Thanet Sand Fm. The Barking feature leads to more complex sub-surface works such as differing piles to be considered to bear the same load across differing geotechnical units, or deeper retaining walls if necessary to seal the water on one or both sides of the feature. Whereas with a feature such as Berry 2b, once the bedrock and the extent of the feature is identified it is not as difficult to seal off both piles and retaining wall structures into the London Clay. This example shows how understanding that all DFHs are variable and not identical to one another aids the engineering sector. Furthermore, it highlights the importance of needing to understand a features extent and physical characteristics.

At present, the only known similarity between every feature within the dataset is that they have an anomalous depth to bedrock and this is their sole reason for being grouped. Bar this, the features can only be grouped in regards to the level of disturbance identified within or surrounding the DFH, such the presence of uplifted strata or faulting associated with the depression or infilling material itself. This grouping will be discussed later within this chapter.

6.3.2 Within a single feature

As shown above, every DFH is unique and they vary from one another in regards to their physical state. The results shown in chapter 5 also show that an individual DFH is likewise internally variable in relation to its shape and infill.

This is shown in greatest detail through the data collected from the Ashford Hill DFH (Figure 5. 22 to Figure 5. 26). Both the borehole and CPTu data shows variability in the geological and, in turn, geotechnical characteristics with depth and also between the test locations. For the CPTu data the range of variability shown in Figure 5. 23, Figure 5. 25 and Figure 5. 26 are all within 100 m of one another. The lack of horizontal consistency of the geological types and units between boreholes in relatively close proximity, as well as the varied nature of sediment (peat, silt, clay and sand) within a single borehole or CPTu test, proves the extent of the variability of infill both horizontally and vertically. This is further seen in Figure 5. 24which shows the rate of change vertically within single CPTu tests. Ranging from sands to clays to silts and organic material at a single point within an individual feature, Figure 5. 22 to Figure 5. 26 show the rate and how vastly the infill of a DFH can change.

Table 5.1 displays the influence the variability of infilling sediment has on the movement of water through the Ashford Hill DFH and in turn the consolidation and permeability of the material. Even at a single test location (CPT02), 4m apart the dissipation values range from 7.95×10^0 to 1.47×10^2 (14.50m and 18.51 m depth respectively). This range could be due to ongoing consolidation of the lower materials over time through overburden and the reduced level of consolidation at 14.50 m in comparison. However, this range and variability of dissipation values is not normal for the surrounding bedrock material within the basin, be it London Clay or Lambeth Group and is attributed to the variability, and material properties of the infill.

Unfortunately, at Ashford Hill, due to technical difficulties it was not possible to compare a borehole core taken with the CPTu data within a very close proximity. Furthermore, due to the horizontal variability of the infill comparing the CPTu data and boreholes taken was not possible due to the variability and proximity of the test and cores taken (~20m between the CPTu tests and the boreholes).

Back within central London Figure 5. 35 to Figure 5. 38 show the variability within single boreholes, taken within DFH infilling material. The scale and range of abnormal occurrences, such as vertically embedded calcretes (Figure 5. 35) and larger sections of Lambeth Group mottled beds (Figure 5. 38) within sandy gravel material also provide evidence for how varied DFH material can be.

Other features showing horizontal and vertical variability within a single feature include Battersea Power Station, Barking, One Nine Elms, St James' Square and Vauxhall Square (shown in Appendix A, Table 1). These features' variability can be assessed as there is a larger availability of data in comparison to more historic features or DFHs where only a single borehole is taken within the infilling material. Variability within individual features can be identified through borehole logs, their cross-sections, SEM imaging of the chalk, images taken from the boreholes and the excavated Battersea Power Station DFH infill.

Figure 5. 41 shows the variability within a single feature from the absence of Lambeth Group to the east of the upwelled chalk material in the Barking DFH. Furthermore, the feature is variable in its depth to chalk. The cross-section through DFH 'Berry 4a' (Figure 5. 42) also shows the variability within a single feature. The gravel, peat and clay are all found to be at differing depths across the four boreholes shown as well as at differing thicknesses. The Vauxhall Square DFH (Appendix B6), also shows the variable depth of the infill within a site and a single feature. Sand is only identified in 2 boreholes and clay stone in just one.

Figure 5. 27to Figure 5. 33, Figure 5. 37, Figure 5. 38 and appendix C3 to C5 also demonstrate visually the variability present within a single feature, both identifiable within boreholes as well as in an excavation. Figure 5. 29 depicts the variability of infill within a relatively small area (>1m^2). This image shows both how variable the nature of the infill can be (ranging from silt to gravel) and the subsequent implications of the varied materials on the movement of water through the sediment. Figure 5. 33 also shows the varied nature of infill within smaller ranges and the potential for clay to be bedded with medium sized angular gravel.

It can be seen in Appendices C3 and C4 that not only does the infill vary within a single feature, but the contact between the infilling material and the bedrock (in the case of

St James' Square, London Clay) can also vary. For example, in Appendix C3, an approximately 70° angle is shown while, in Appendix C4, a sharper, vertical interface between the two materials at around 90° can be seen. Appendix C5 also shows the variability of the material and contact between the Langley Silt, RTDs and either the London Clay or alluvium. This image proves that the infilling material or sub-surface material associated with DFHs is not always in mélange form, but can also be varied yet intact within or surrounding a feature.

Petrographic and mineralogical analysis shown in both the XRF and XRD data (Figure 5. 45 to Figure 5. 49 and Figure 5. 50 to Figure 5. 54 respectively) also exhibit the variability within a single borehole and within the infill of a single DFH. Although the majority of minerals and chemicals identified are what is expected within the bedrock material, there is considerable difference in the chemical and mineralogical composition of samples over very short vertical distances. Furthermore, the presence of quartz in the large majority of samples exhibits its non-uniform state of the material and this has the potential to impact on the geotechnical properties as well as provide information on formation processes discussed later within this chapter.

For engineering, variability within a single feature and understanding its geotechnical implications is crucial with direct relation to design and to risk. For this reason, the entire DFH feature should not be characterised or refined based on understanding taken from a single borehole. As shown in the CPTu tests undertaken at Ashford Hill, the range of material differs from the local bedrock and is not consistent horizontally. Furthermore, the dissipation tests undertaken and shown in Table 5.1 also show the impact variability has on potential consolidation and permeability. Variability of a single feature in relation to engineering risk is discussed further in section 7.3.

For scientific understanding of how the features formed and also for providing an insight on previous environments, the variability of the infill both restricts and informs understanding. This will be discussed in detail in section 7.5.

Although there are limitations with every methodology employed due to the amounts required for the testing and the inconsistency within the infill of a DFH, the variability of the infill itself cannot be questioned. This variability between features and within a single feature will be discussed in relation to its impact on sub-surface risk and the implications for hypotheses on how these features formed throughout this chapter.

6.4 Sub-surface risk

As discussed in chapter 4 (data quality), sub-surface risk exists for all engineering projects due to the inevitable degree to which sub-surface information is unknown. This is amplified when variable sediment is encountered in boreholes due to issues surrounding accurate geotechnical figures being required and the limitations of existing testing procedures. For this reason, sub-surface risk discussed throughout this section is applicable to all potentially anomalous geology, particularly in built-up urban areas and not solely related to DFHs. This section will discuss the evidence gained in this project in relation to sub-surface risk associated with DFHs, the implications of these risks and how they can be mitigated through the use of the site investigation guide (section 7.3.1.).

The prime reason DFHs lead to an increased sub-surface risk for engineering projects is due to their unpredictability and the lack of understanding currently held on the features. DFHs should therefore be considered a potential risk to all sub-surface developments in London. This is due to their often unknown location, the variability of the infill, as well as poorly constrained information on their extent. This is apparent from the DFH spreadsheet (appendix A) and section 5.7.1 and has been discussed extensively in chapter 4. The prime reason as to why there is this limited knowledge on the known DFHs is attributed to the investigation techniques and previous information not being shared. The large proportion of unknowns (Table 5.3) leads to uncertainty and in turn risk for both the construction industry and scientific understanding being reliable, e.g. incorrect formation hypotheses. Every additional piece of information has the potential to change the understanding of an individual feature and the wider dataset. This could lead to a radical (and potentially expensive) change to design as it has the potential to change understanding of the actions and influences on a structure.

Flynn et al., (2020) provide an update to Berry (1979) as a resource to reduce sub-surface risk by increasing knowledge of the locations of the features. It also furthers understanding on the variability of DFHs both within a single feature and between features. By communicating this variability, the paper highlights the risk of assuming similarity between features for engineering projects and the need for a thorough site investigation to understand each individual feature.

Once a feature is identified, understanding the full extent of a DFH before technical design and construction begins is crucial to reduce risk and most likely cost. This is primarily due to the depth of the bedrock being expected if understood, leading to fewer problems such as pile test failures, retaining wall leaks and tunnel machine breakage.

It is important to note that the full depth (vertical extent) of the feature may not be truly understood simply by identifying depth of infill to bedrock. An example of this is Vauxhall Square (appendix B6), where London Clay is identified at -24 m OD, and Lambeth group is identified at -27 m OD at the deepest point of the depression in comparison to the Lambeth Group's local level of -34 to -37 m OD. This upwelled stratum is only identified in a single borehole and highlights the need for boreholes to not stop once identifying bedrock and also for multiple boreholes to be taken within the infilling material to gauge the true extent of a DFH. Once a borehole reaches what is believed to be bedrock it is also essential to not cease with exploration as it may be entrained bedrock, such as the nodes of London Clay identified within the DFH at Battersea phase 3a (Figure 5. 32) and not true bedrock level.

DFHs are not always constrained to the London Clay or the local bedrock and many have breached into lower lithologies. If this is the case, or if the boreholes miss the feature (often due to spacing), then construction may begin and problems, such as subsurface movement and foundation difficulties, may occur mid-way through a project. This leads to delays when the feature is identified mid-construction and in turn increases costs to the client as projects must be halted to find design solutions, repair broken equipment, equipment or materials not being available and to secure the unknown, possibly unconsolidated, strata. Even where the feature is confined to the local bedrock, problems can still arise where the full extent of the feature is unknown. An example of this is the Crossrail Moorgate box, a DFH (Moorgate, Davis et al., 2018) was identified, but the full extent was not known until during construction and permeation grouting had begun. Further ground investigation had to be undertaken in order to provide information for an effective design solution and this shows the impact of not understanding the full extent of a DFH prior to construction.

As discussed above and in chapter 4 (data quality), the variability of infill associated with the majority of DFHs creates sub-surface risk. This is due to the limitations associated with borehole exploration and the inability to quantify specific geotechnical parameters for the entire infill. Due to the horizontal and vertical variability of the infilling material, borehole exploration creates unknowns between each core taken and the results from individual boreholes cannot always be extrapolated in either direction. The differing type of DFH infill (mainly unconsolidated, coarse grained material) in comparison to the local bedrock (mainly clay) also induces risk. Examples of these include subsidence and differential ground water levels and will be discussed below.

The potential for differential subsidence occurs due to the difference in physical characteristics of the infill and the bedrock material. For example, if a gravel/coarse grained, unconsolidated infilled feature is located beneath part of a construction site and the feature extends outside of site limits, movement of the unconsolidated sediment within the site could lead to subsidence outside of site limits (potentially a road/building). Subsidence can also occur within site boundaries if a similarly unconsolidated filled feature occurs within part of a site, but the extent is not fully identified. The piles or other foundation methods may fail due to the differing properties of the expected bedrock material to what is actually present with the infill material. This has occurred at several sites within the Nine Elms area where piling difficulties (e.g. pile load test failures) have been encountered due to differing geotechnical properties of the ground (or depth of the local bedrock) due to a DFH covering part of the site. This could also arise if the bedrock identified in the borehole exploration is not the true depth of the feature's extent and there is underlying disturbance, such as a diapir or fault which could impact on the strength of the material being piled.

A further consideration when discussing subsidence, risk and DFHs is whether they are still active, dormant (i.e. could be reactivated) or in fossil form (i.e. cannot be reactivated) where the characteristics provide a passive control on ground conditions. This poses the question of whether there is ongoing subsidence, or if the features are linked through groundwater movement; this has been proposed by a geotechnical engineer in personal communications. As noted previously, change in groundwater levels was observed during a site investigation in central London where a DFH was present, whilst another site with a DFH within a few kilometres was undergoing groundwater pumping within a very short timeframe (less than a day) (Pers. Comms. Geotechnical Engineer). This indicates a potential connection of groundwater between features. This, however, is the only known occurrence of its kind and further investigation would be required to determine whether the link was causal.

If the features are still active and subsiding, then there are engineering implications such as ongoing subsidence and a differing water table. Ongoing subsidence can impact on the lifespan of a structure e.g. on a tunnel, inducing cracking or for above ground, differential settlement acting upon a multi-story building or subsidence under nationally significant infrastructure. The ground water level may also be impacted by constructing into or near to a DFH feature. If there is a chalk diapir present or faulting this can provide a pathway for water to migrate faster than usual through the largely clay bedrock present across London. There is also the potential for ponding of water at the surface if there is ongoing subsidence of the feature. The DFH at Ashford Hill provides an indication that ongoing subsidence is occurring within the features. Directly above the chalk diapir lies a pond (Figure 5. 39) and is the only known feature to have a depression visible from the ground surface (Figure 5. 40). Although the feature is located in a relatively small river valley, the pond being above the chalk diapir means that there is the potential for the pond to have a closer connection with the chalk aquifer below. This connection in turn is likely to have an impact on the flooding or drained nature of the pond and valley floor above.

Differing ground water levels are likely to be present due to the difference in permeability of the infill, largely gravel and coarser grained sediments, in comparison to the local bedrock, mainly the dense, highly impermeable London Clay. This may cause the ground water level across a single site to differ in the short-term, impacting on both basements with water ingress and implications to piling due to water ingressing on the pile base or shaft. Ground water may also move differently within the infilling material due to its variability. This then impacts on the sediments' behaviour due to differing materials within the infill acting in different states (e.g. liquid or plastic) as shown in Figure 5. 29.

Implications of sub-surface risk associated with DFHs can range from financial to life threatening. If the features are identified during the site investigation phase, they can be engineered through mitigation techniques, such as piles going deeper to reach higher end bearing stratum or if tunnelling the route could be modified to avoid the variable, granular material. As discussed, the main sub-surface risk associated with DFHs is not identifying them or understanding their full extent during the site investigation phase. This can lead to implications on foundations and the structures themselves.

For tunnel construction the risk is dependant on the tunnelling method used. If incorrect, tunnel face collapse can occur if the DFHs location and extent are not known prior to the tunnel being drilled. For example, if a tunnel was going through the Lea Valley area and the route went through the Olympic park DFH it would encounter chalk at a level 30m higher than the local level instead of the expected Lambeth Group (if the DFH was not identified during the site investigation phase). Similarly, if a tunnel was to go through Nine Elms or Bermondsey there would also be several locations where diapirs of Lambeth Group, Thanet Sand or Chalk are identified at anomalously high levels. In turn, the tunnel face collapse may also lead to sediment and/or water ingress depending on the ground water level and the DFH infilling material. Furthermore, it would prove costly if the tunnelling machine is built to drill through clay and encounters gravel or coarser grained materials and leads to breakage. Additional costs to the project would likely also include delayed timelines to secure the infill through methods such as grouting, changing of the route, fixing machinery and further site investigation.

The key to mitigating sub-surface risk associated with DFHs is knowledge of and communication of the risks discussed throughout this section and acknowledgement of the limitations of the exploratory method used during the site investigation phase. Understanding and communicating that each individual feature is unique and that within an individual feature there is a high chance of vast variability, increases the awareness of the unknowns associated with DFHs and should in turn reduce sub-surface risk. Appendices A, showing the DFH dataset and the Flynn et al., (2020) paper provides a resource for the location and known characteristics of currently identified DFH features. The paper should lead to a reduction in risk for future developments where the features identified in the paper are located within or near to site boundaries. Identifying the full extent of a feature, where possible within site limits, during the site investigation phase also reduces risk and a site investigation guide is proposed in section 6.3.1. to aid with further reducing subsurface risk associated with DFHs.

For research purposes, the unknowns discussed throughout this chapter and chapter 4 must be acknowledged when addressing hypotheses and be included when discussing their validation. This communication and acknowledgement of risk in both the engineering and scientific sectors can be used for all anomalous geology in urban areas and not solely DFHs.

6.4.1 Site Investigation Guide

Through collating and interpreting the information gained throughout this research project, the following section is guidance on a) how to identify a DFH feature during a site investigation, b) what risks should be considered if identified and c) recommendations on how to characterise and better understand the individual feature encountered. The purpose of this site investigation guide is therefore to help identify anomalous geology and reduce the sub-surface risk associated with these features. This guide is not intended as an engineering standard (British Standard or Eurocode) and is solely for consideration when conducting a site investigation within the London Basin or other sites where complex ground conditions are suspected.

For this project, and in turn this guide, the features have been grouped due to their only similarity, their anomalous depth to local bedrock. Their identification is primarily through boreholes, as this is the main explorative method for investigating the sub-surface in urban areas and in this case, London. Therefore, the guide is based upon borehole identification of anomalous geology, namely, DFHs. A simplified flow diagram on how to identify the differing types of DFH features through boreholes (classified in section 6.5) is shown in Figure 6. 1.

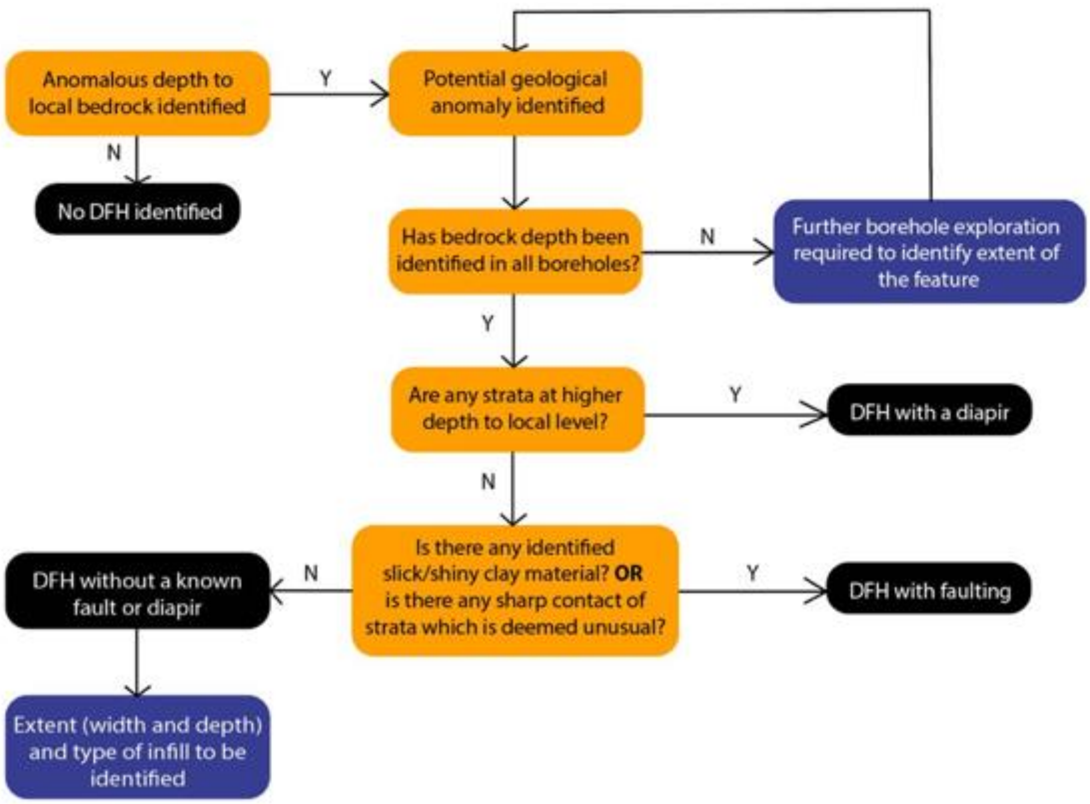


Figure 6. 1 – A flow diagram to indicate how a potential DFH can be identified through borehole investigation.

The following are indicators of the potential presence of a DFH feature from borehole sediment:

- Anomalous depth to local bedrock;
- Borehole containing mixed strata (usually RTDs, but can be other types e.g. peat, silt, sand, clay, chalk, Figure 5. 32);
- Strata/geological units identified above local level;
- Disordered contents (e.g. Lambeth Group identified above the London Clay such as One Nine Elms);
- Stained chalk (yellow, orange or red in colour), most often identified above local level. This has been noted in the logs from the Pettman Crescent DFH and the Lee Tunnel (see Table 9.1, Appendix A);
- Putty chalk (not disturbed due to drilling method), most often identified above local level;
- Sharp contact of strata at a non-horizontal angle (e.g. St James' Square DFH).

In addition to the examples given above, further images of faulting surrounding a DFH can be seen in appendices C1 and C2, non-horizontal sharp contact of strata in Figure 5. 37 and appendices C3-5, mélange material in Figure 5. 33 and the differential permeability within the infill material in Figure 5. 29.

If a DFH feature is identified through the indicators noted above, the following recommendations are made for site investigation:

- Identify the extent of the feature. Deeper boreholes to reach the depth extent of the infill (local bedrock) and more boreholes to identify the horizontal extent of the feature. The extent may reach beyond site limits and implications of this should be considered;
- Boreholes should provide as full of a profile as possible. Samples are required with minimal disturbance from the drilling method,

therefore techniques such as wireline rotary drilling or continuous sampling from dynamic sampling are preferred. Cable percussion drilling can provide good quality sampling using UT100s but the process is not continuous. Sonic drilling will provide a full profile, but the degree of disturbance will hinder identification and subsequent testing.

- Detailed logging of the infilling material and the contact between the infill and the bedrock;
- Photographing the borehole sediment for analysis, particularly where geotechnical tests are not possible;
- Where possible, geophysics can be considered to identify the extent, this is rarely achievable due to its limitations noted below.

Boreholes enable samples to be taken and inspected, however, whichever method is adopted it is essential to obtain samples with little disturbance. Pushed samples will provide the best sample quality, but this technique is rarely used in the UK. Often, the infilling material of the features can be varied and frequently derived from Terrace Deposits. This inclusion of gravel makes avoiding disturbance whilst sampling difficult. In general, a combination of investigation methods will produce the best compromise.

Geophysical methods have the ability to identify whether a DFH is present and potentially conceive its extent within a site (Culshaw and Waltham, 1987, Hutchinson, 2001). Although Raines et al. (2014) proved this at Ashford Hill, there are numerous limitations to using geophysics for understanding the features including: cost, availability of geophysical expertise, interpretation of results, the variability of the sediment and the need for a borehole to correlate the geophysical results accurately, which can prove problematic with variable sediments. Noise is also problematic due to London being a capital city with vibrations from above and below ground, as well as multiple active electrical sources and passive structures which distort electrical signals for electrical resistivity and ground radar surveys. Geophysics has not been considered on a larger scale for this project and is a potential area for future research with DFHs.

6.4.1.2 Risk Considerations

Table 6.1 considers the risks which can impact a site and where these may occur during a development. Ideally investigation should be designed to ensure these risks are identified at an early stage well before development begins.

Table 6. 1 - Potential risks to consider when engineering within, or near to a DFH.

Risk	If a DFH is identified during the SI phase	If a DFH is not identified during the SI phase (above ground construction)	If a DFH is not identified during the SI phase (sub-surface construction)
The full horizontal extent of the feature is not truly understood. E.g. unconsolidated infill goes outside of site limits and sub-surface works within the site can lead to settlement of the infill beyond the site boundary.	✓	✓	✓
The full depth (vertical extent) of the feature is not truly understood. E.g. a borehole reaches bedrock, but does not identify a potential chalk diapir or upwelled material beneath the bedrock, e.g. Vauxhall Square (appendix B6).	✓	✓	✓
The movement of water through the infill material may differ. Due to variability of the composition of infill or due to the presence of a diapir or localised faulting.	✓	✓	✓
The presence of faulting which can potentially lead to differing behaviour of clay material and in turn geotechnical capacity.	✓	✓	✓

Issues surrounding spatial and vertical variability in material properties leading to uneven settlement and heave.	✓	✓	✓
The presence of a chalk diapir and the potential increase in water movement and risk of polluting the aquifer.	✓	✓	✓
Differential settlement through piles failing or not creating the same friction between the bedrock and DFH infilling material.		✓	
Settlement of ground outside of the site boundary due to movement of the unconsolidated infill within the site.	✓	✓	✓
Pile load test failures due to misunderstanding of the geotechnical properties of the infill or water ingress into the base of the pile due to the bedrock not creating a seal.		✓	
Retaining walls not sealing due to an increased permeability of the infill.		✓	
Tunnel face collapse (potentially causing loss of life) due to unconsolidated sediment not being predicted and accounted for with remediation techniques such as grouting.			✓
Water ingress at the tunnel face, above or below the tunnel due to the presence of unconsolidated sediment where largely impermeable clay was predicted for the designed route.			✓
Breakage of machinery due to the physical difference between a largely clay bedrock and the potentially coarser grained material within the infill.		✓	✓
Increase in costs and delay of timelines.	✓	✓	✓

This guide is based upon knowledge gained from the increased number of features identified within this project. Recommendations for when DFHs are identified in the future are ways of increasing understanding of the features whilst still acknowledging their variability horizontally and vertically. It is important to note going forward that more detailed logging by trained personnel is required and the infill material imaged systematically for furthering understanding of the infill. This also aids the engineer to gain an understanding of the geotechnical properties where geotechnical tests are not possible on variable materials. Moreover, it provides evidence for processes which led to the formation and/or subsequent infilling of the features.

6.5 London geology

This project has furthered current understanding and identified numerous areas where differing aspects of the geology of London is not known or at least not publicised through literature. The unknowns discussed in this section are all linked to issues surrounding variability, expected or unexpected ground conditions and terminology. In turn these can impact on interpretation and subsequently risk.

Throughout this section differing scales will be discussed in relation to understanding. Large scale is deemed here as the understanding of the geology of London as an entire basin, as well as within the M25 motorway. The geology of London, at this basin wide scale, is understood in terms of the major faults, the synclinal structure and geological units being known for their location in broad terms across the basin. These units consist of the Cretaceous Chalk, Thanet Sand Fm., Lambeth Group, London Clay, the RTDs and superficial deposits making up the made ground as discussed in detail in chapter 2 (section 2.2).

Small scale is used for areas discussed which are single site specific. This scale is also locally relatively well understood where deeper construction has occurred in central London through site investigations and previous land use most often being man-made and therefore previously investigated.

Medium or intermediate scale is approximately 1 to 10 km^2 such as multi-site engineering projects or local boroughs. The medium scale is not as constant as the larger scale understanding would imply. What has become evident throughout this project is the absence of understanding or the lack of public recording (e.g. published journal articles) of the intermediate scale geology. Both basin wide and for an individual site or construction project the geological units are mapped, yet for areas of an intermediate scale this information is either not available or has not yet been collated and digitised for visual representation. The lack of this collation and visualisation leads to a lack of understanding and in turn can create risk. Examples of this include: geological anomalies (e.g. faulting and DFHs), depth to bedrock and presence or absence of strata being unknown.

Within this research project two sub-surface models were created from borehole data. The two areas were selected due to one being commonly thought of as being abundant with DFHs (Nine Elms, Figure 5. 11 and Figure 5. 13) and the other having no DFH features identified (Bermondsey, Figure 5. 12). Both Nine Elms and Bermondsey were not constant in their depth to local bedrock across the mapped regions (shown in Figure 5. 11 to Figure 5. 21), nor were isolated depressions just restricted to the Nine Elms area. This raises questions to not only how is a DFH identified, but from a wider perspective, what is classed as anomalous or "abnormal" geology and what is normal and expected.

The mapped Nine Elms area exhibits the 'expected' London geological sequence (RTD, London Clay, Lambeth Group, Thanet Sand Fm., Chalk) and therefore anomalous geology such as DFHs are easier to identify due to the anomalous depth to bedrock in what is the expected London Clay bedrock beneath the RTDs.

Bermondsey does not have the 'expected' geological strata sequence for London, with the thinning of London Clay into undulated Lambeth Group, which is not at a constant depth across the area. Although this is not what is expected for the geology of London, the occurrence seems 'normal' for this mapped area as the undulating pattern covers a wide region.

The two contrasting areas within a relatively close proximity raise several questions. What is 'normal' for London geology and how can anomalous geology (such as DFHs) be identified if there is no known 'normal' or 'abnormal'. In regards to DFHs it is plausible that it is easier to identify anomalous or "not constant" geology in areas such as Nine Elms due to the relatively constant depth to bedrock and the expected geological sequence being present. Therefore, more are recorded in this area because the anomalous nature of the DFH is established and definite. It is not easy to identify a DFH or anomalous geology in

Bermondsey or less constant sub-surface strata areas due to the bedrock not being as expected or at a constant depth across a given area. Consequently, it is more difficult to identify anomalous occurrences and therefore none are recorded or termed as DFHs.

This theory is backed up in part by the amount of available data known on the two areas mapped. Bermondsey to the Isle of Dogs has far more boreholes available. Therefore, understanding of the area and identification of geological anomalies should be greater than Nine Elms, but this does not seem to be the case. Hence, it is likely to be the non-constant nature of the Bermondsey area which is leading to the lack of identified DFHs.

On a broader scale, the two mapped areas within this project have shown that it is not possible to compare geology across London under a single blanket understanding. The sub-surface, particularly the type and depth to bedrock is more locally specific even within the M25 motorway and understanding needs to be more area and not basin specific. Bearing this in mind, if there is no 'normal' or expected sub-surface, because of a lack of understanding, there is great difficulty in identifying 'abnormal' or anomalous.

A further example of this is the London Docklands. The bedrock beneath the RTDs across the docklands ranges from the London Clay to the west into the Lambeth Group, Thanet Sand and the Chalk is lying as bedrock to the east. This change in bedrock is 'normal' for this given area shown in Figure 6. 2 and should therefore be expected during site investigations. However, three DFHs were identified across the docklands and further were suspected at the start of this project. Once further analysis of the site investigation boreholes and the surrounding boreholes available from the BGS' GeoIndex was undertaken, it was established that not all features were anomalous, and it was the lack of understanding of the transitional areas between the differing bedrocks as well as the deep levels of RTDs across the docklands which caused the confusion. This variability across the Docklands is problematic for engineering projects due to not knowing what bedrock is expected, and in turn can lead to the misidentification of DFH features or anomalous geology where in fact the identified bedrock from a borehole exploration is normal for that given area and simply not well known or documented. This shows that it is crucial to understand what is normal for a given area and what is truly anomalous.

Figure 6. 2 - The range of bedrock strata across the London Docklands area.

In contrast, true anomalous geology can also be identified through the BGS' GeoIndex tool. Figure 6. 3 shows an anomalous area of Lambeth Group in an area of London which is largely underlain by thick London Clay deposits. Although this is anomalous, similarly to the Elephant and Castle feature, it has not previously been termed a DFH. However, there is a similar anomalous bedrock area shown on the BGS' GeoIndex tool shown in Figure 5. 43 which is deemed a DFH termed Berry 4a. This shows that whilst there are anomalous depths to bedrock across London, not all have previously been termed DFHs.

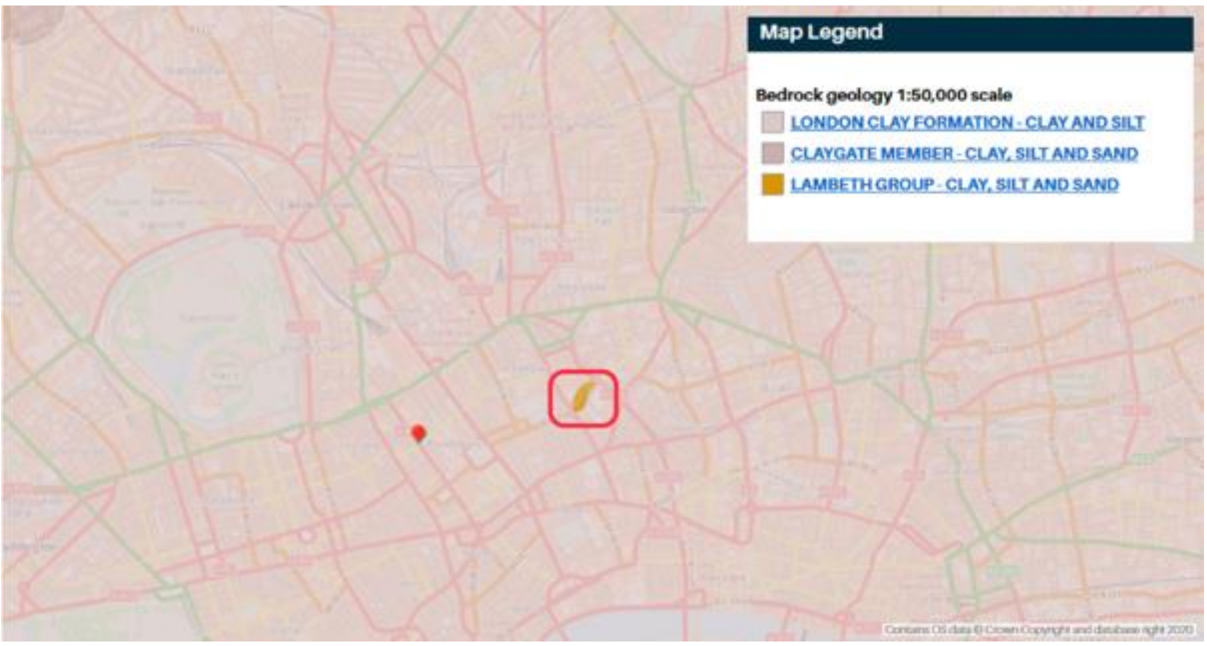


Figure 6. 3 - An anomalous bedrock of Lambeth Group in the largely London Clay Fm. bedrock (circled in red). The red point shows the Gower Street DFH.

For both an engineering and scientific viewpoint it is crucial to understand what is normal for a given area, and then in turn abnormal, to ensure thorough understanding and minimise risk. For this reason, unknowns should be not deemed anomalous just because there is no available information on a given area or site or it not as expected as per previous understanding. Examples of this include Figure 4. 7, Figure 4. 8 and Figure 4. 12. A lack of available data can lead to false identification of anomalous geology which is normal for an area, due to no evidence being accessible to conclude otherwise. The absence of data can also cause a single DFH feature to be identified as two or more separate features due to no ability to correlate between boreholes and sites. There is therefore a greater need to increase the understanding of the non-constant nature of the London Basin geology and have this communicated through literature.

A further crucial point to discuss is interpretation bias. If the individual analysing the borehole logs has a preconception of either London geology or a given area, anything outside of this expectation could be deemed anomalous. For instance, if an individual is anticipating variability in the borehole logs (such as in the Bermondsey area), any variation to the norm is simply expected and not deemed as anomalous. If the interpreter is expecting established London geology, any discoveries which deviate from this norm are deemed anomalous (Nine Elms).

Therefore, it is not solely the availability and quality of data, but the background (discipline), training and ability of the interpreter to establish and term what is normal and what is anomalous. Finally, it is then down to the individual and the company's time and willingness to record and publish new information, with or without interpretation.

Finally, scales are not solely physical area as discussed at the start of this section, but in relation to discipline area. Geologists may often think on the larger scale, such as the London Basin in its entirety and the larger structures, such as the faulting and synclinal structure of the basin. In contrast, engineers are most often focussed on the smaller scale with individual boreholes, site cross-sections or slightly larger for a multi-site construction project. This leads to a potential for bias based upon which discipline is looking at the information acquired or available and limits furthering of understanding into London geology and DFHs.

All points discussed within this section have bearing on the definition and identification of DFHs and other geological anomalies. Definite answers are not all possible within this project, but are crucial for understanding in the future. Some of these unknowns include:

- Are there numerous DFHs across the Bermondsey area or is there another process creating the undulated Lambeth Group and subsequent depressions in the area?
- Can DFHs be truly be deemed anomalous if there are so many identified within the London Basin, particularly within central London.

Going forward, increased independent recording (in models, journal articles etc.) is required of the intermediate scale geology for London to further understanding to what is normal for given areas. Only once this is understood can geological anomalies be truly understood across the entire basin reliably. The increase in understanding will also reduce uncertainty and risk for both construction projects and improve scientific understanding of the basin's geology and its history.

6.6 Hypotheses and classification

Throughout this project, additional information has been gathered to create the largest DFH dataset to date. From this additional information further evidence has been accumulated to enable a more thorough understanding of potential processes which led to the formation of DFH features. During this section all potential hypotheses (discussed in chapter 2) will be examined in relation to the current evidence and the evidence which is potentially missing and required for testing of formation hypotheses.

As established throughout this chapter, variability of the features, both within a single feature and between features is apparent. Although the only characteristic that groups the features under one term is their anomalous depth to bedrock, a broad classification scheme has been created within this section in order to gain a better understanding of the feature's characteristics. This also aids in furthering understanding the features once they are identified and exhibits the potential for sub-surface risk, particularly if the feature is not truly understood in its entirety.

6.6.1 Classification

The single characteristic which groups DFHs in their identification is their anomalous depth to bedrock. Once identified it is important to deem their extent to minimise sub-surface risk and further understanding.

Through the enlarged dataset, it has become apparent that although every feature is unique and no two features are the same, there are several DFH characteristics which do occur in some features, but not all. These include, the presence of upwelled material (potentially a diapir), association with faulting or no known faulting or upwelled material (Figure 6. 4). Each of these groupings can then potentially be further categorised through the type and ordering or infilling material.

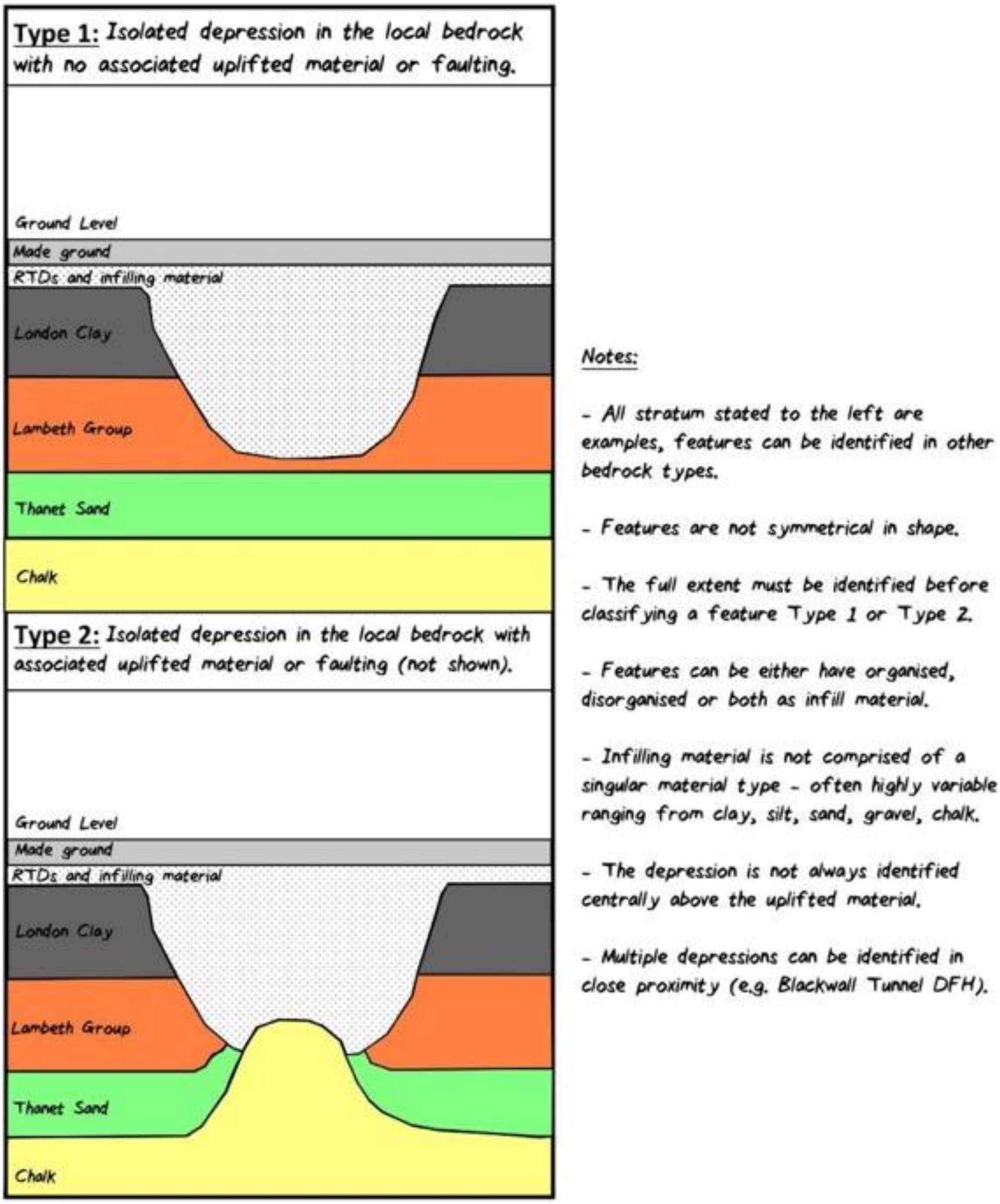


Figure 6. 4 - Classification into 2 types of feature, the third type of "uncertain" is not shown as it cannot be classified.

A large proportion of features could wrongly be deemed a Type 1 feature (without a diapir or association with faulting) due to a lack of knowledge of their full extent. For this reason, a third type of feature called "uncertain" is proposed. The DFH dataset has not been sectioned into categories or given a category to each individual feature for this reason as this could potentially have led to a misinterpretation of the sub-surface going forward and lead to increased risk due to the presence of further anomalous geology not being expected beneath a Type 1 feature.

Finally, it is possible that there are further characteristics which are common amongst several features, however at present with the limitations and availability of data these listed will be used for classifying the features.

6.6.2 Hypotheses

Numerous hypotheses have been theorised for the formation and current state of DFHs. For each of these hypotheses, evidence is required to establish their validity. Figure 6. 5 depicts the evidence required for a hypothesis to be verified, including the processes potentially influencing the hypotheses and methodologies which can be employed to provide the evidence. The figure shows the complex nature of not only gaining evidence to validate a theory of processes which lead to the formation. It also demonstrates the implications of other processes which likely could have been acting upon the strata and features, pre formation, during formation and since the features initially formed. Furthermore, numerous processes are also likely to have acted upon the feature since its initial genesis. Therefore, no hypothesis is likely to be definitive and all theories provided within this chapter acknowledge the limitations and complexity of DFHs and relict features in general.

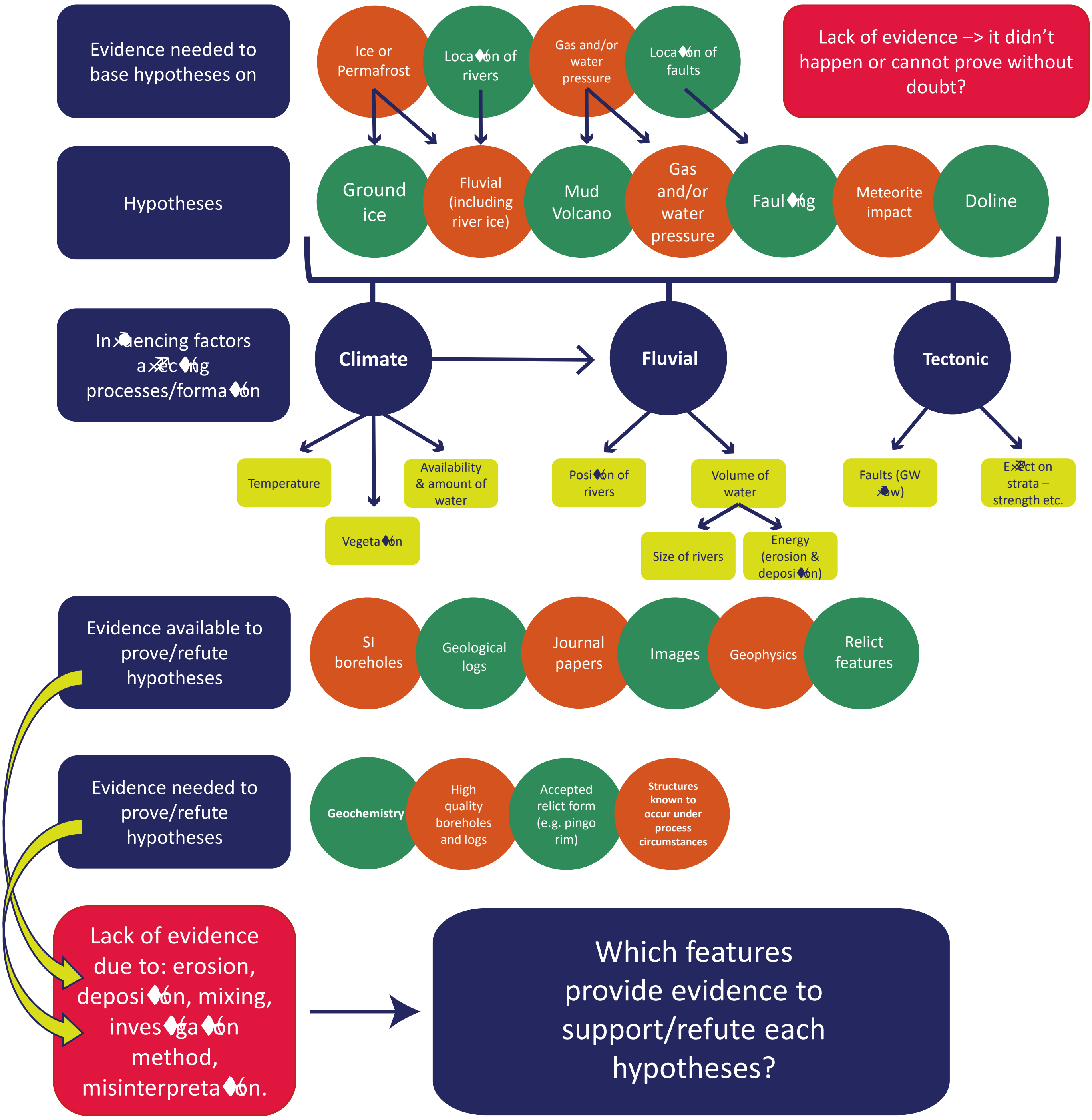


Figure 6. 5 – Figure depicting what is required for a hypothesis to be validated, the sources of information, methods in which this information can be gathered and examples of hypotheses which can be validated or rejected.

Bearing Figure 6. 5. in mind, Table 6. 2 shows each potential DFH hypothesis discussed in chapter 2 alongside the processes involved in their formation according to literature, the evidence required to acknowledge or refute its occurrence and any identified

DFH feature within this project which has evidence proving it formed through the given hypothesis.

Table 6. 2 - Each formation hypothesis with associated evidence for proving or refuting its validity and whether a given DFH feature exhibits this evidence.

Hypothesis	Image	Key research	Diagnostic features for identifying relict form	Potential hypothesis?	Why?
Ground ice					
Pingo	 (Haeberli, unknown date)	Hutchinson (1980); Mackay (1998)	• Depression surrounded by a rampart/rim	Unlikely	No unambiguous evidence of permafrost in the London Basin, no rim identified and not all features have a diapir which is described as the "root" by Hutchinson.
Palsa		Kujala et al., (2008); Seppala (2011)	• Depression surrounded by a rampart/rim • Peat infill	Unlikely	No rim or unambiguous evidence of permafrost in the London Basin. Peat is only identified in a minority of features and within the infill, therefore post hollow formation.

	(Calmels et al., 2008)				
Lithalsa	 (Calmels et al., 2008)	Pissart (2003); Calmels (2008)	• Depression surrounded by a rampart/rim	Unlikely	No unambiguous evidence of permafrost in the London Basin or rim identified.
Fluvial Scour		Berry (1979)	• A depression in an elongated shape. • Evidence of fluvial activity in the vicinity.	Y	Locality to existing or palaeo river channels, shape and narrowing with depth. Can explain the anomalous depth to local bedrock and fluvial processes can also explain subsequent infilling and mixing of superficial deposits.

Doline	 (Sahu and Lokhande, 2015)	Gibbard et al. (1985); Spink (1991); Culshaw and Waltham (1987)	• A depression overlying limestone.	Y	Can explain the depression in the local bedrock. Relies on other processes for infilling and diapiric movement of material beneath.
Tectonics					
Flower Structure	 (Ellero et al., 2012)	Bellhouse et al., (2015); Ghail et al., (2015)	• Fractures or faults mapped into the flower structure beneath and surrounding the depression.	Unknown	The use of boreholes as the investigation method limits the identification and subsequent understanding of faults and fractures.

Grabens	 (Structural Geology Blog, 2013)	Newman (2008)	• Fractures or faults surrounding the depression.	Unknown	The use of boreholes as the investigation method limits the identification and subsequent understanding of faults and fractures.
Mud volcano	 (Worldlandforms.com, 2015)	You et al., (2004); Wan et al., (2017)	• Geochemical signal (elevated levels of sodium and chlorine). • Large amounts of sediment deformed past its liquid limit.	N	No geochemical signal to confirm this theory. Furthermore, only the chalk has been identified as deformed into a fluid like state at a single site.
Gas or water pressure		Newman et al., (2013); Flynn et al., (2018)	• Deformed (plastic or liquid state) strata which has moved	Y	Features with a diapir. Chalk diapir material analysed from the Olympic Park DFH showed how the

			in a vertical direction		material had deformed and mixed with sand whilst moving vertically from its local level. Can explain all features with upwelled material.
Meteorite impact	 (New Scientist, 2013)	Makkaveyek et al. (2015); Mccall (2009); French & Koberl (2010)	• Impact craters • Geochemical signal (rare earth elements)	N	No geochemical indicators for a meteorite impact. No iridium was identified in the geochemical analysis and no STA indicated this process had occurred. The infill is largely relatively intact where cohesive material is identified and therefore no evidence of large-scale liquid behaviour (other than the diapiric material at the Olympic Park feature).

Based upon the literature discussed within chapter 2, summarised in Table 6.2 and the new evidence from the features identified across the London Basin the following observations have been made regarding the plausibility for the hypotheses to have formed the features.

- Pingo – Although the size of the majority of DFHs can be accounted for by a pingo there is a lack of diagnostic features which cast doubt on this theory. The shape of the diameter of a DFH, although not proven for an entire feature, is not symmetrical and largely not circular. Furthermore, not every feature has a diapir or upwelled material and therefore difficulty surrounds where the water source for the pingo would have come in a dense, largely impermeable clay bedrock. The lack of the diagnostic rim for any feature also questions this hypothesis as the mode of formation. Although Hutchinson (1980) states that erosion could have removed the rim, with now 89 identified and rims ranging from 2-5m in height elsewhere across the globe (Makkaveyev et al., (2015) it would be plausible to expect a minority of features to feature a partial rim if this hypothesis was accurate. Moreover, a pingo relies on the presence of permafrost for its formation. Without direct, unambiguous evidence for permafrost within the London Basin, particularly central London where the large majority of features have been identified, this hypothesis cannot be proven.

- Palsa - Although their size can account for the smaller DFH features, it cannot explain the larger features. Furthermore, to date, there has been no distinctive amount of peat identified within the vast majority of hollows in central London, therefore if evidence proves that they are palsas, it is likely that they will be of the mineral, lithalsa form.

- Lithalsa - It was previously thought that lithalsas only grew vertically through frost heave, however research has now proven that the features can grow laterally (Pissart et al., 2011) which adds to their formation being a possibility in DFH formation. Furthermore, it is also plausible that if these features did exist within the London Basin they could have been enlarged by chemical weathering during wet climate conditions which followed the periglacial period and lead to the features present today. However, without evidence for permafrost within the London Basin lithalsas cannot be proven or refuted.

The presence of permafrost plays a central role in all of the ground ice hypotheses discussed above. Many of the theories rely on permafrost at certain depths being a key factor in the formation of the feature, however without definitive evidence of permafrost activity within the London Basin these hypotheses cannot be proven or refuted indefinitely.

- Fluvial scour - The large majority of DFHs near to the Thames and its tributaries, historic or present does support the confluence scour hypothesis. However, not all of the features are identified within or near to river channels (or palaeo). Furthermore, confluence scour alone cannot explain the diapirs identified beneath and within some DFH features nor the upward movement of the Lambeth Group. It is plausible that fluvial scour was part of the initial process of formation which removed sediment from the top of the to-be hollow then further processes sculpted its more defined morphology pre or during infill.

- Doline – As stated within Chapter 2, collapse sinkholes are uncommon in chalk due to the low rock mass strength being incapable of sustaining large cavities (McDowell et al., 2008). Additionally, collapse dolines are often evident through the identification of oxidised sediment collapsed from the surface of the feature. Although some oxidised (often logged as weathered) London Clay has been recorded (e.g. Battersea and One Nine Elms), it is not commonly logged amongst DFH sediment. However, the two features where oxidised sediment is acknowledged are the highest quality samples and logging within this project. Therefore, it is possible that many DFHs have oxidised sediment within, but it has not been logged due to poor sample retrieval or logging quality. The two, combined, cast doubt on the doline hypothesis being the main process for DFH formation, in particular the collapse type. However, buried or subsidence dolines could explain the initial formation of the hollow if it were initially an open depression, which then infilled with locally available material. Similar to confluence scour, it cannot explain other associated characteristics such as the diapir or the mixing of sediment within the depression and can only be plausible for the initial formation if a depression formed first. Without further evidence, it is however acceptable to state that subsidence (creating dolines) is a possible triggering mechanism of the formation of the depression. Although this process cannot be ruled out due to a lack of evidence, it is difficult to state what evidence is required. If it were a cavity beneath the chalk, this may have been infilled If it were subsidence, then there is evidence for syn-sedimentary (deformation which occurs during or shortly after deposition of material) subsidence in some high-quality sediment retrieved via boreholes at One Nine Elms and at Woolhampton within the exposure. Although these do not confirm the theory, it provides enough evidence to leave it as a possible cause of formation.

- Tectonics - At present, there is no evidence that earthquakes are the primary cause of DFHs. However, their activity could have impacted on many processes which may be involved in their formation due to their potential to influence sediment, water and gas movement. Furthermore, it is plausible that in areas where faulting is known, such as along the Greenwich fault, tectonically-formed geological features could be interpreted as a DFH.

- Water and gas – whilst water and gas pressure cannot account for the anomalous depth to bedrock or the infilling of the feature, it can provide a source of energy for the upwelling of strata and an explanation as to why some feature have diapirs or lower strata upwelled, but not all. The hypothesis in full is provided below in section 6.6.2.1 and Flynn et al., (2018), but evidence for the presence of water and/or gas pressure has been provided through the enhanced dataset, as well as the sediment material analysed within this project. Key evidence includes the current location of lower stratum (chalk, Thanet Sand and Lambeth Group) identified closer to ground level in relation to the local area, e.g. the Olympic Park DFH where chalk is identified around 20m above the local level and Figure 5. 34 which shows bubble-like structures in DFH infilling material. Furthermore, the state of the chalk sediment within the Olympic Park feature also proves the material deformed in a liquid or plastic state and moved vertically through the overlying sediment (Thanet Sand and

Lambeth Group). This is evidenced in the chalk SEM images (Figure 5. 57) where chalk material located above local level is mixed with sand grains. This deformation and subsequent vertical movement would require a large increase in pore water pressure and potentially further energy which has the potential to be gas pressure, known to be apparent within the basin (Newman et al., 2013). Although there is no evidence for a large influx of water during or post Anglian glacial melt it is plausible, due to the close proximity to the glaciers maximum extent being in St Albans. This would provide enough water within the basin to lead to an elevated groundwater table to potentially create both artesian type conditions and an increase in pore water pressure which in turn would deform the upper layers of chalk. A vulnerable point would then be required for the liquid or plastic behaving material to exploit and move vertically (explained in the theory below).

Whilst numerous hypotheses have been proposed, using the enlarged dataset of DFHs now available it has been possible to rule several out altogether, cast doubt on published hypotheses such as pingos being responsible due to a lack of diagnostic features and establish some theories as potentially accurate from the available evidence.

Both confluence scour and dolines are potentially viable for the formation of a depression into the local bedrock, however neither explain the infilling material, nor the upwelled strata located beneath or within some features. Gas and water pressure is also a plausible energy source for the upwelled material. The next section will look at the infilling material and the evidence it provides in relation to formation hypotheses.

6.6.2.2 Infilling material

The infilling material and its nature is not explained in the majority of the theories above. The large majority of features are infilled with a mixture of sediment types (silt through to gravel) and most often the material is not stratified. Where it occurs, this unordered sediment suggests a mixing process has taken place. The mixed nature of the sediment and its varied state indicates a movement which requires energy bringing the sediment into the system and in turn mixing the sediment within the DFH basin.

Where the sediment is stratified it indicates that sediment was brought into the DFH, but there was no subsequent energy or processes to create the mixed sediment. Also identified, is the presence of both a mixed and non-mixed infill within a single feature, such as at Ashford Hill and Berry 3b. This indicates that several processes were acting upon individual features, whether this be at one time or over varying timescales.

Post depositional movement is also evident within the DFH infill. Syn-sedimentary disturbance has been identified in the Woolhampton feature (Collins et al., 1996) and within the One Nine Elms feature at both small and larger scales. At Woolhampton, tilted beds were identified within the lower infilling material, but not in the uppermost part (dating discussed later within section 6.5.3). At One Nine Elms, small scale, collapse structures can be seen and at the larger scale a potential explanation for the structure shown is reverse faulting of the lower material (Mid Lambeth Hiatus) (Figure 5. 37). There is also evidence of post depositional movement within the Battersea phase 3a DFH with the gravels showing a downward movement in Figure 5. 30 and Figure 5. 31. All of these individual characteristics across several DFHs suggest settlement of the feature during its lifespan, particularly post infilling.

A further occurrence identified within the infilling material is the presence of lower strata located above local level, by tens of metres, within the infilled unconsolidated material. This has been identified with the Lambeth Group mottled beds in One Nine Elms (Figure 5. 38) and large clasts of London Clay at the excavated Battersea phase 3a feature both intact (Figure 5. 32) and mixed with gravel (Figure 5. 33). Both of these occurrences lead to the conclusion that at some point within the DFH's history there has been a sufficiently energetic environment with the potential to remove dense clay and move it by tens of metres in a vertical direction. There are several potential explanations for this movement, but it is important to bear in mind that the London Clay and Lambeth Group clasts were identified within the infilled, unconsolidated material both in the borehole and excavation. Potential explanations for their position within the infilled material are that the clay clasts were removed either prior to infilling and transported into the DFH during subsequent infilling. Alternatively, the dense clay material was removed during infilling (potentially due to slope instability) and continued to mix with the unconsolidated sediment. Both processes could have occurred to differing material or at differing timescales. If there was wintertime freezing of the riverbed or banks within the London Basin, it is possible for ice rafted debris to have formed outside of the hollow and the processes which lead to infilling bringing in the frozen sediment. A potential explanation for this could be the iced rafted debris was transported through fluvial processes during spring thaw floods. This would lead to the relatively intact clay clasts to be identified within the infilled material and remain intact after being brought into the DFH from elsewhere. It is also possible that clay was removed during scour (e.g. a high energy flood event) and mixed with the unconsolidated infill, such as shown in Figure 5. 33.

These theories are also reinforced by the mapping of the Battersea to Nine Elms regions in London. From the mapping of the subsurface the area appears to be an interfluvial environment, evidenced by the London Clay lip to the south of the mapped area as a potential strath terrace (Figure 5. 11 and Figure 5. 13).

Additionally, there is also the potential for some of the larger DFHs near to the River Thames not being individual and isolated features, but large areas of deeper River Terrace Deposits or alluvium which have been reworked by fluvial activity over the years. Consequently, it is probably due to limited borehole logs available within the vicinity as to why they have been recorded or identified as DFHs or anomalous, but deep superficial deposits are potentially common for the area. An example of this is the Booth road DFH which is identified 80 m north of the River Thames. For 180 m northwards of the feature there is deep superficial sediment identified within boreholes and the London Clay is not identified for 180-200 m north of the feature and around a kilometer eastwards. If the depth to local bedrock is not anomalous then the term DFH should not be used due to a lack of knowledge of the area’s bedrock types or depth. This example exhibits the speculative nature of identifying these features retrospectively through limited borehole data.

To summarise, there is the potential for both confluence scour and subsidence to have created an initial depression to the bedrock. The subsequent infilling is then likely to have occurred through locally available unconsolidated sediment, most likely through fluvial processes. The infilling material is split into three categories depending on its sorting: mixed sediment, ordered (layered) sediment or a mixture of ordered and mixed within a single feature. Depending on which of the three is present within the DFH depends on the processes which acted upon the feature during or post infill. For mixed sediments, there would have had to be an energy acting upon the infilling sediment causing it not to be deposited in a uniform manner. For non-mixed, potentially stratified sediment, the infilling would have likely occurred in a lower energy environment and not disturbed by subsequent infilling. Where there is both ordered and mixed sediment infill, this suggests several processes acting upon the feature at the same time in an isolated manner. This shows the complex nature of the features within single timeframes and across timescales.

6.6.2.1 Diapir theory

Through analysing potential hypotheses in the process above and with the increased number of DFHs known, a new hypothesis which warrants further testing is here proposed for features with a diapir or upwelled material. 13 of 89 DFHs have an identified upwelled chalk or lower strata material and Figure 6. 6 shows the locations of these (excluding Ashford Hill and Iver). It is evident that bar the two features identified in Nine Elms (Berry 1c and 1g), which are around 350 m apart, features with a diapir are not located within close proximity to one another. The nearest other features are 1.1km apart. It is plausible that this may be due to the mechanism leading to the initial uplift of strata and the reason for which not all features have a diapir.

Figure 6. 6 – Features with a diapir identified within the M25.

It is here hypothesised that the following processes took place to form the DFH features with a diapir:

- An influx of water entered into the London Basin potentially during glacial melt and/or retreat as well as through ground ice melting;

- The influx of water above ground flowed via rivers, leading to excess fluvial scour in the bedrock material and sub-surface via groundwater flow causing a higher groundwater table and increased water in the chalk aquifer (artesian pressure conditions). Flow along existing faults could have also increased the speed in which excess water was available in certain areas within the centre of the basin. Dennis et al. (1997) proved the relationship between groundwater movement and faults within London;
- The increase in water in the basin leads to an increase in pore water pressure within the sediment below the surface (artesian pressures discussed in Hutchinson, 1991), increasing the likelihood for the sediments to behave and/or deform in a liquid or plastic state. Such as the Lea Valley DFH where the chalk has changed structurally and mixed with sand grains;
- Where there is scour above or localised faulting this leads to a reduced load above for the pressure below to break through and a vulnerable point for the excess water to exploit. This enables vertical movement of the sediment in its plastic or liquid state towards this vulnerable point overhead, causing a diapir or upwelling of sediment from below. This is shown in all DFHs where there is upwelled material;
- Due to a release in pressure at the location of the features with a diapir, the surrounding features had less pressure available in the given localised area and therefore not enough to upwell and break through the overlying (largely clay) material even where unloading above due to fluvial scour or faulting is present;
- Therefore, if one feature in an area “blows” (upwells) then the pressure is released locally, meaning that the surrounding features remained as scoured depressions and no diapir occurred below.

The limitation to this hypothesis is that only 15 of the known features have positively identified a diapir or upwelled material, 15 definitely do not and the remainder is unknown.

Although there are limitations to the available evidence, there is a developing picture that DFHs featuring diapirs are geographically isolated from one another. If this is correct, then a new model explaining their presence, and of nearby anomalous thicknesses of superficial deposits can be hypothesised.

6.6.3 Dating

A severe issue with verifying and understanding formation hypotheses is the lack of dating undertaken, or indeed possible, on DFHs. Several researchers have also dated the features based on the river terrace they are identified within or beneath (e.g. Lee and Aldiss, 2011). However, as discussed in chapter 2, this is not a reliable method of dating due to ongoing erosion and depositional events which would have modified the position or presence of RTDs over thousands of years, as well as the RTDs or strata member being difficult to verify, as they rely largely on location for identification.

For floodplain DFHs, such as Woolhampton, the features are buried beneath undisturbed alluvium and/or peat which can provide a minimum age bracket for those features and provide a higher degree of confidence in the dating. Woolhampton is also the only known feature to date to have dating techniques applied to the infill. Palaeoecological and radiocarbon dating methods established that the gravels identified towards the bottom of the feature (Heales Lock Member) were deposited prior to the Wasing Sand Bed which is dated to the Late Devensian Windermere Interstadial. Both of these lie beneath the Lateglacial Stadial sediments, which are overlain by the Holocene Midgham Member. This dating also aided understanding of when subsidence was ongoing within the feature. The tilted beds identified within the infill material and the associated dating showed that the site was active during the Lateglacial Stadial. This subsidence had ceased by the start of the Holocene, which is evidenced through the Midgham Member showing no tilted beds. (Collins et al., 2006).

Due to the mixed nature of the infill of the majority of features, confidence in the results of traditional techniques such as radiocarbon or optical luminescence is not possible. This is due to the infilling sequence from which the material is chosen for dating not being accurate or reliable. For example, sediment could have been lain when the infilling process began, but due to subsequent mixing of the sediment within the DFH that material could now be higher up the hollow towards ground level or lower, such as the Lea Valley DFH. The dating results would show an older date for material which is relatively close to surface and in turn impact on understanding of the feature and its environment at the time of infilling. Furthermore, for the RTDs and alluvium, the organic material could have been reworked from older deposits in the catchment, again providing inaccurate dating results.

Dating of mixed sediments is something which needs to be addressed in future research and then applied to DFHs for furthering understanding.

6.7 Summary

This chapter has discussed the variability of DFHs both within a single feature and between features, identifying that every feature is unique and the scale of variability within a single feature is also often substantial.

The understanding of the features and issues surrounding understanding of the wider London geology was then evaluated at differing scales and the impact and questions surrounding nomenclature were discussed.

Existing, potential and newly made formation hypotheses have been evaluated in relation to literature, together with newly collated data and results, whilst bearing in mind the restrictions associated with understanding past environments and data quality restraints of existing methodologies. This has led to a broad classification of type of DFHs, new hypotheses on the formation of DFHs, and a site investigation guide for when anomalous geology is identified within the London Basin and other areas with anomalous and complex near-surface geology.

7 Conclusions

This research project set out to answer the following research questions:

1. What are the physical characteristics of DFHS?
2. What is the subsurface risk associated with DFHs?
3. What processes were involved in DFH formation?

This chapter will summarise the outcomes of the research in relation to these questions and suggest the direction for future research based upon this project's findings.

89 DFHs have now been identified and all available information on their location and characteristics collated. Techniques including GIS, CPTu, logging, microscopy (imaging and STA) and geochemistry (XRF and XRD) were undertaken to analyse both the DFH dataset as well as the feature's infilling material.

The new results enhance knowledge of the features and their physical characteristics. In particular, this research has shown how every DFH identified is unique and not comparable to other features in relation to their width, depth, infill material, sorting, presence or absence of a diapir and faulting. Furthermore, it has also identified that within a single DFH feature there can be variability on both a horizontal and vertical scale.

Through the enlarged dataset it has been acknowledged that the only factor grouping all of the features is their anomalous depth to local bedrock. From this three types of DFH have been recognised. Type 1 – an isolated depression without a diapir or faulting associated, Type 2 – an isolated depression with a diapir or faulting associated (Figure 6. 4) and Type 3 – unknown due to lack of data or understanding.

The implication of sub-surface risk has been demonstrated through previous literature, identifying the impact anomalous geology has on engineering projects. This project has evidenced the sub-surface risk induced by DFHs within the London Basin. Hazards include, the anomalous geology not being identified during the site investigation phase. This is largely due to borehole spacing and a shortage of records on the location of the features. A further risk is the lack of understanding of the features physical characteristics (including variability) and extent.

To mitigate the sub-surface risk identified, this project has established methods which can reduce the risk associated with DFHs using several outcomes of the research. These include publishing the location of the DFHs identified within this project, their key characteristics and communicating the risks associated with the features (Flynn et al., 2020). A guide for the site investigation sector has also been produced to help more efficiently identify DFHs and anomalous geology within the London Basin as well as communicate the associated risks.

Based upon evidence from the numerous methodologies employed within this project and knowledge gained from previous literature, a hypothesis for DFH formation has been proposed specifically in relation to features with a diapir or upwelled strata. Several possible explanations for additional processes involved in forming the DFH features have also been addressed throughout. However, there is currently an absence of evidence to support several of them.

In addition to the aims and expected outcomes at the start of the project, two further topics became apparent whilst undertaking the research: Data quality restrictions and the current understanding of London Geology often being oversimplified.

Vital issues attaining to data quality whilst studying engineering geology, and geomorphology have been recognised. These are mainly due to the testing and accuracy of the results from variable sediment and the ability to extrapolate results to larger sediment masses.

This project has mapped the subsurface of two areas in central London (Battersea/Nine Elms and Bermondsey). The aim was to map an area abundant with DFHs and an area without identified features. Conversely, the results have illustrated the large scale variability in the level of strata depths across relatively small areas and shown that there is no "normal" London geology as often believed. The implications of this is that every site should be treated as an individual, as it is crucial to ascertain whether the geology identified within boreholes is normal for an area (e.g. no presence of London Clay towards the Isle of Dogs) or to identify anomalous geology, such as a DFH.

Two papers have been published on the results from this project. One based upon the role of the chalk in the development of buried (drift-filled) hollows (Flynn et al., 2018) and the other providing the locations and key characteristics of DFH features identified within central London (Flynn et al., 2020).

7.1 Future research suggestions

The research undertaken within this project has demonstrated the requirement for future research both on DFHs and on understanding, characterising and quantifying variability in geotechnics, geology and geomorphology.

As new DFHs are identified within the London basin increased amounts of borehole sediment, samples and data need to be made available for research purposes. This project encountered numerous restrictions due to limited access to data, whether it be borehole sediment, borehole logs or geotechnical reports due to confidentiality or unwillingness from the client to acknowledge unknown ground conditions. A better sharing of data would benefit the sustainable development of cities and further research understanding e.g. an increase in data submittal to the BGS for their Geoindex.

Where the identification of features was established and data was shared it was apparent that borehole logs were often the only method of information available. The number of boreholes was also often not sufficient to understand the features entirety. In particular, the extent (width and depth). Going forward, an increase in availability of data, deeper boreholes and testing of the sediment will hopefully aid further understanding of DFHs. This increase in understanding will aid both the geoscience and engineering sectors. The following questions and problems still remain unanswered due to technological or time constraints beyond this project:

- Are DFHs still active and evolving features? Are they still subsiding or is their current form dormant or relict?
- Methodologies to test variable sediments - to determine geotechnical characteristics, rate of change or scale of variability, quantifying variable sediment (extent and properties).
- The use of stratigraphical relationships between boreholes with high quality samples to infer and increase understanding of modes of DFH formation.
- Dating DFH formation (initial formation, particular processes or ceasing of formation) based upon more accurate dating techniques and not through the possible earliest or latest age via proximity to RTD.
- Variation of groundwater over time and the relationship with DFH formation.

- Furthering understanding and reporting or publishing of London geology at an intermediate scale (larger than a single site or feature and smaller than the entire city or basin).

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8 Appendices

Appendix A	Drift-filled hollow dataset
Appendix B	Cross-sections
Appendix C	Images

Appendix A

Table 9. 1 - Drift-filled hollow dataset of all known features with their known characteristics

	Easting	Northing	Length (m)	Depth (m OD)	Depth (m bgl)	Is full depth known?	Strata within at top	Strata reached at base	Bedrock	Does it breach the local bedrock?	Thickness of bedrock below (m)	River terrace	Diapir present	If yes - height of diapir above local level (m OD)	Evidence of faulting	Infill type	Infill material	Disturbed/ Undisturbed	Single or multiple of depressions	Date of SI	Source	Key BGS boreholes	Notes
Barbican	532257.9	181822.7	-	-	-	Y	MG	U	LC	U	U	HA	N	-	U	Both	Silt, sand, gravel	Y	2+	1865	Baker (1885)		
Bromley Park (Beckenham)	538869	170277	-	21.03	11	Y	MG	CH	LG	Y	U	KP	Y	20	U	Mix	Sand, clay, gravel	Y	1	1943-1992	Banks et al (2014), BGS	TQ37SE540 & TQ37SE161	Two main boreholes from BGS Geoindex noted here. No other boreholess within 0.6km. Even within 1km no London Clay identified. Boreholes show deep drift and then Lambeth Group, Thanet Sand, Chalk. Due to lack of BHs unable to identiy difference between normal and abnormal.
berry 1a (Battersea Power Station)	528939.9	177510.9	125	-27	36.2	Y	MG	LC	LC	N	U	KP	N	-	U	Mix	Silt, sand, clay, gravel	Y	2	1929	Berry (1979), Higginbottom and Fookes (1970), Edmunds (1931)	TQ27NE1606	Meanderine feature bounded by steep, cliff like sides into the London Clay up to 12.2m.
berry 1b (Battersea Cable Tunnel)	528739	177812.4	-	-14.9	-	N	AL	LC	LC	N	U	KP	U	-	U	U	Sand, gravel	U	U	1948	Berry (1979)		Berry (1979), very little information provided.
berry 1c (Meux's Brewery)	529805.8	177604.6	-	-31.7	-	N	MG	LG	LC	Y	12.19	KP	Y	6.1	U	Mix	Sand, clay, gravel	Y	2	1944	Berry (1979), Edmunds (1931 & 1952), BGS		Lambeth Group elevated by 6.1m according to Banks - 2 depressions (Edmunds, 1931).
berry 1c (Meux's Brewery) part 2	529805.8	177604.6	-	-31.7	-	Y	MG	LG	LC	Y	U	KP	Y	6.1	U	Mix	Sand, clay, gravel	Y	2	1944	Berry (1979), Edmunds (1931 & 1952), BGS		Lambeth Group elevated by 6.1m according to Banks - 2 depressions (Edmunds, 1931).
berry 1d (Battersea Gas Works)	529601.8	177520.6	-	-18.3	-	Y	MG	LC	LC	N	8.08	KP	U	-	U	Mix	Sand, gravel	Y	1	1929	Berry (1979)	TQ27NE154/B	Two features mentioned within the same paragraph, possibly linked - see below - infill noted as "drift".
Berry 1d (Battersea Gas Works) 2nd hollow	529601.8	177520.6	60	-17.6	28.8	N	MG	LC	LC	N	U	KP	U	-	U	Both	Sand, gravel	Both	1	1977	Berry (1979)	TQ27NE157/B	Two mentioned within the same paragraph, possibly linked - this one 183m North East of the above DFH.
berry 1e (Meux's Brewery)	529486.6	177506.2	-	-11.6	12.255	U	MG	LC	LC	N	U	KP	U	-	U	U	Sand, gravel	U	U	1974	Berry (1979)	TQ27NE625	Berry (1979), very little information provided.
berry 1f	529961.8	177590.3	-	-11.58	15.24	U	MG	U	LC	U	26.42	KP	U	-	U	U	Sand, gravel	U	U	1862	Berry (1979)		Cliff like sides into the London Clay up to 12.2m (Berry, 1979). Potentially linked to Berry 1f.

berry 1g (Market Tower) One 9 Elms	530130	177766.2	-	-27.4	30.5	Y	MG	LG	LC	Y	U	KP	Y	7.9	Y	Mix	Sand, clay, gravel	Y	1	1971	Berry (1979), Banks et al., (2014) GCG		London Clay and Lambeth Group elevated, narrow, deep focus bounded on one side by vertical cliff of London Clay 12m high (Berry, 1979). Banks et al., (2014) Lambeth Group elevated from surrounding area. Data from One Nine Elms site investigation shows evidence of faulting from shiny fissured LC and a reverse fault in the Lambeth Group. Lambeth Group uplifted, but Thanet Sand not a noteable amount. RTD identified within infill at differing depths within feature.
berry 2a (Clapham Road)	530667.6	176788.1	-	-16.1	21.8	N	MG	LG	LC	Y	11.35	KP	U	-	U	Mix	Silt, sand, clay, gravel	Y	3	1965	Berry (1979), Banks et al., (2014)	TQ37NW486-491	LC and LG elevated. Additional, shallow hollows in the vicinity. Broad, shallow hollow (Banks et al., 2014).
berry 2b(Brixton Road)	531270.6	177272.2	-	-10.2	15	Y	MG	LC	LC	N	U	KP	U	-	U	Mix	Sand, gravel	Y	U	1972	Berry (1979), BGS	TQ37NW610	Berry (1979) states 10.2m OD depth and BGS Geoindex logs show -11.64 OD m (16.75m depth).
berry 2c (Vauxhall Park)	530612.1	177605.5	-	-22.6	19	Y	MG	LC	LC	N	9.1	KP	U	-	Y	Both	Sand, clay, gravel	Both	U	1966	Berry (1979)	TQ37NW456-7	Berry (1979) "Elongated in the direction of the enclosing channel trends". Lower parts of fill are apparently slipped with recumbently foleded sands, showing evidence of faulting.
berry 2d (Lawn Lane)	530477.2	177797.9	-	-17.7	-	Y	MG	LC	LC	N	12.3	KP	U	-	U	Mix	Sand, clay, gravel	Y	2		Berry (1979), Wakeling & Jennings (1976)		Hollow separated by vertical London Clay wall - "two descending cone-shaped masses of sand and sandy gravel separated by a vertical wall of London Clay and clayey gravel, the latter following a trend similar to that of the boundary of the hollow" - there is also a sandy cluster close to the feature.
berry 2e (Vauxhall Station)	530385.9	177946.7	-	-10.7		Y	MG	LC	LC	N	U	KP	N	-	U	Dis	Clay	Y	1		Berry (1979)		Softened and oxidised London Clay as infill, then waterlogged silt below.
berry 3a (Horseferry Road)	529666.5	179041.6	150	-18.3	22.12	N	MG	U	LC	U	U	KP	U	-	U	Lam	Sand, gravel	N	1	1962	Berry (1979)	TQ27NE230	Base of alluvium above the hollow is slightly above local level.
berry 3b (Board of Trade)	529881.6	179464.7	75	-27.1	25	N	MG	LC	LC	N	U	KP	U	-	U	Both	Silt, sand, clay, gravel	Both	1	1951	Berry (1979), BGS	TQ27NE387	The main borehole log shows a cross section of boreholes with a large lense of silty clay amongst a depression of sand clay and gravel below and RTDs above.
berry 3c (Ministry of Defence)	530232.5	179943.2	-	-19.5	-	U	MG	LC	LC	N	U	KP	U	-	U	Mix	Sand, clay, gravel	Y	1	1968	Berry (1979)		Elongate hollow containing redeposited London Clay.
berry 3d (Whitehall Place)	530139.4	180217.4	-	-12	10.8	N	MG	LC	LC	N	U	TP	U	-	U	Lam	Alluvium, clay, gravel	N	1	1910	Berry (1979)	TQ38SW1247	Unusually level base - "apparent aggradation into post-glacial times" Berry (1979).
berry 3e (Hungerford Bridge)	530568.8	180147.6	130	-27.1	-	Y	AL	LC	LC	N	U	KP	N	-	U	Mix	Sand, gravel	Y	1	1901	Berry (1979)	TQ38SW1282	Lies entireley beneath the River Thames. Very difficult to read the cross-seciton in the borehole log record.
berry 3f	531719.8	180838.3	120	-9.7	14.1	Y	MG	LC	LC	N	28.3	KP	U	-	U	Mix	Sand, gravel	Y	1	1968	Berry (1979), BGS	TQ38SW762/H	Elongate, shallow hollow, parallel to channel.
berry 3g	532839.8	180628.8	-	-9.7	15.5	Y	MG/AL	LC	LC	U	25.4	KP	U	-	U	Both	Sand, gravel, chalk	Both	U	1964	Berry (1979), BGS	TQ38SW787	Borehole log notes chalk cobbles within melange.
berry 3h	531456	180383	-	-	-	N	MG	LC	LC	N	U	KP	U	-	U	U		U	U	1894	Berry (1979)		Small hollow with other minor hollows nearby, only identified in one borehole. Berry (1979) states others are known in the area but not discussed in paper.
berry 3i	533111	180302.1	60	-6	9.4	U	MG	LC	LC	N	U	KP	U	-	U	Both	Sand, clay, gravel	Both	U		Berry (1979)	TQ38SW1948	5m more of drift than immediate vicinity - "basal sandy deposit with pebbles and clay laminae 5.5m thick, overlain by coarse and finer gravels" Berry (1979) made an error with feet & metres on depth. Corrected here.
berry 4a	532253.7	179181.1	200	-19	-	N	MG	LG	LC	Y	U	KP	U	-	U	Both	Peat, silt, sand, clay, gravel	Both	U	1906	Berry (1979), BGS	TQ37NW2432	Feature with extended axis trending E/W, subsidence rate 1.4m/100y - known from roman times (Berry, 1979).
berry 5a (Greys inn rd)	530889.3	182350.4	240	13.5	6	N	MG	LG	LC	Y	U	HA	U	-	U	Both	Silt, Clay, Gravel	Both	2		Berry (1979), BGS, Wakeling and Jennings (1976)	TQ38SW1093	Long axis trending NE/SW, levels of London Clay locally variable. Differences between the two depressions infill with the west depression more laminated than the east. BGS borehole shows feature as a cross section.

berry 6a	537644.8	173614.1	200	-9.7	26.5	U	MG	LG	LC	Y	U	KP	Y	12.2-15.2	U	Mix	Sand, clay, gravel	Y	U	1970	Berry (1979), BGS	TQ37SE747	Broad and shallow, London Clay and Lambeth Group elevated 12.2-15.2m above local level. On BGS Geoindex the feature is on the edge of a lost river in KP gravel and is visible in the Geoindex surface geology as an anomaly. BGS log shows RTDs into Thanet Sand at 28m.
berry 7a Blackwall Tunnel	538443.2	180283.5	165	-30.5	60	N	AL	CH	LC	Y	U	KP	N	-	Y	Mix	Sand, gravel, chalk	Y	2	1891	Berry (1979), BGS	TQ38SE110-113 & 140-141	183m wide at -20m, strata are slipped, elongate, basin like feature, which veers away from the river Thames.
berry 7a Blackwall Tunnel part 2	538443.2	180283.5	165	-14	-	Y	AL	LC	LC	N	U	KP	N	-	Y	Mix	Sand, gravel	Y	2	1891	Berry (1979), BGS	TQ38SE110-113 & 140-141	The second smaller hollow noted in Berry (1979) paper south of the above feature.
berry 7b	539839.8	178971.3	-	-16	18.97	N	MG	TS	LG	Y	U	KP	U	-	U	Lam	Sand, gravel	N	U	1974	Berry (1979), BGS, TFL	TQ37NE1307/J	Infill of stratified sand and gravel.
berry 7c	539462.2	180705.6	-	-14.3	19.2	Y	MG/AL	LC	LC	N	U	KP	Y	-15.3	Y	Lam	Gravel	N	U		Berry (1979), BGS, TFL	TQ39498067	Chalk 15.3m below local trends. Could be associated with Blackwall tunnel DFH.
berry 8a	534736	176600.7	-	-11	18.6	U	MG	TS	TS	Y	U	TP	U	-	Y	Both	Alluvium, sand, clay, gravel	Both	2		Berry (1979), Banks et al., (2014)		Two elongate hollows form inliers of Thanet Sand in Lambeth Group and slumping in borehole core of the infill. The feature to the east is elongated and spindle-shaped. Evidence of faulting according to Berry (1979) and Banks et al., (2014). Berry mentions two DFHs at Camberwell-New Cross yet only talks about one.
Thee Mill Lane (BGS Lea)	538316.4	182858.2	-	-6.16	11.7	Y	MG	LC	LC	N	7.8	KP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	1988	BGS	TQ38SE2867 & TQ38SE1987	
Redbridge Station (BGS Redbridge)	541741.5	188329.1	-	5.576	3.8	U	MG	LC	LC	N	10.78	KP	U	-	U	Mix	Sand, clay, gravel	Y	U	1971	BGS	TQ48NW220	Berry notes 'diapiric' movement of the chalk. The confidential boreholes only reach the top of the London Clay and there are no other publically available deep boreholes in this location.
Cannon Street (Bloomberg)	532570.8	180985.8	11	21.03	32	Y	MG	Ch	LC	Y	17	TP	Y	16	Y	Both	Silt, sand, clay, gravel	Both	1	2012	Cox (1992), GCG		London Clay is heavily fissured. There is London Clay into Lambeth Group into London Clay again in borehole logs. Lambeth Group 16m higher than surrounding area. Silt pocket within depression goes down to 7.7m OD. Width and length based on infilled depression, not the silt pocket. Silt infill believed to be from Walbrook. The hollow is circular at the top and rectangular at base. Chalk level is also irregular across the site ranging from -64.83 to -81.87m OD. Lambeth Group is also around 10m higher in some areas compared to others.
New Barns Farm (Chigwell)	542452.8	193372.3	-	-	-	U	MG	U	LC	U	U	KP	U	-	U	U	Sand, gravel	U	U		Berry (1979)		Deep gravel pit discussed at the end of the Berry paper. Potentially the the same feature as the Albert Road DFH below. There are no boreholes in between the two availalbe.
Crossrail Ilford Depot	544661.9	186972.4	-	<-4	>25	U	MG	U	LC	U	U	TP	U	-	U	U	U	U	U	2012	GCG (Crossrail)		No BGS BHs between here and High Road (Ilford 3) and Green Lane to confirm normal levels.
Limmo1	539566.1	180819.7	-	-20	24.8	N	AL	LC	LC	N	7	KP	N	-	Y	Mix	Sand, gravel	Y	1	1990	GCG (Crossrail), Linde-Arias et al., (2017)		The two Limmo hollows are located close together. Evidence of faulting associated with both features shown in the LC. Linde-Arias shows this feature as a shallow one to the east of the double deeper feature with info below. Shown in appendices (B5).
Limmo2	539388.4	181034.2	-	-30	45	N	AL	LC	LC	N	2	KP	N	-	Y	Mix	Sand, gravel	Y	2		GCG (Crossrail), Linde-Arias et al., (2017)		The two limmo hollows are located close together. Evidence of faulting associated with both features shown in the LC . Arias shows this as a double deeper feature to the west of Limmo 1. Shown in appendices (B5).
Moorgate	532702.7	181637.8	-	-10	11.9	Y	AL	LC	LC	N	20	TP	N	-	N	Mix	Sand, clay, gravel	Y	1		GCG (Crossrail)		Broadly conical and not in an area of thinning LC. More gravel at top then base of feature.

North Woolwich on Thames (Woolwich)	543407.6	179534.7	200	-10	20	Y	AL	CH	CH	N	U	KP	N	-	Y	Mix	Alluvium, sand, gravel	Y	1	2003	GCG (Crossrail), Lenham (2006)		Lenham (2006) "The chalk was typically described as being weak, medium-density, white or off- white chalk" Chalk was also fractured with shear areas showing faulting. The feature is within the River Thames and elongated to the channel. Potentially scour.
Carburton Street (Gt Portland 1)	529023.8	182052.1	-	-15	-	N	MG	U	LC	U	U	LH	Y	U	Y	U	Clay, gravel	Y	U		Cox (1992)		Great Portland Street feature in Cox (1992). A diapir of LG identified 20m below ground level. Cox attributes this to a steep local anticline. West there is a gravel-filled hollow, in the centre is a diapir of highly disturbed Lambeth Group, east is a sharp anticline of London Clay.
Gower Street (Gt Portland 2)	529681.1	182165	-	5.2	4.8	Y	MG	LG	LC	Y	U	LH	N	-	Y	Mix	Silt, sand, clay, gravel	Y	1	1950	Cox (1992)		Euston Square - melange of London Clay and Lambeth Group in hollow. Fault identified as on one side of the hollow is London Clay and the other is Lambeth Group.
Green Lane (Ilford2) - Ilford Sports Club	545083.5	186708.9	-	-16	26.95	U	MG	TS	LC	Y	U	TP	U	-	U	Mix	Sand, clay, gravel	Y	U	2006	GCG, BGS		GCG boreholes note deep levels of RTDs
High Road (Ilford3)	544905.3	186934.8	-	10	-	U	MG	LG	LC	Y	3.5	TP	U	-	U	Mix	Silt, sand, gravel	Y	U	2016	GCG		Based on 2 boreholes from GCG - BHA and BHB - only known to depth of 2 boreholes.
Jenkins Rd Newham	540885.6	182153	-	-14.8	16.9	N	MG	LC	LC	N	U	TP	U	-	U	Both	Silt, sand, clay, chalk	Both	U	1952	GCG, BGS	TQ48SW408 & TQ48SW409	From BGS Geoindex - 2 BHs and no others to deem 'normal' - both note traces of soft white chalk and flint pebbles at around 17m depth - unable to determine if chalk diapir as nothing deeper nearby - Jackie "high suspect deep soft strata with chalk"
Tiller Road (JLE78 1)	537472.5	179363.5	-	-28.95	31	U	MG	CH	LG	Y	U	KP	U		U	Mix	Silt, sand, clay, gravel	Y	U	1977	BGS, Jubillee line extension (1978)	TQ37NE1452	Ends in structureless white chalk.
Boord Street (JLE78 2)	539331.9	179287.3	-	-17.1	18.2	U	MG	U	LC	U	U	KP	U	-	U	Mix	Peat, silt, sand, clay, gravel	Y	U	1965	BGS, Jubillee line extension (1978)	TQ37NE1470	
London City Airport (JLE78 3) - Hartmann rd	542044.4	180376.6	-	-12.95	17.7	U	MG	TS	LG	Y	14.5	KP	U		U	Mix	Silt, sand, clay, gravel	Y	U	1977	BGS, Jubillee line extension (1978)	TQ48SW466	
Pettman Crescent (JLE78 4)	544746.4	179037.3	-	-6.9	11	U	MG	TS	TS	Y	4.1	KP	N	-	Y	Mix	Silt, sand, clay, gravel	Y	U	1978	BGS, Jubillee line extension (1978)	TQ47NW401	From BGS Geoindex & JLE drawings. No LC or LG in the vicinity, straight into Thanet Sand bedrock, but in this instance the RTDs extend down lower than normal. Stained chalk fissure indicating faulting/weathering.
Lee Tunnel	541519.5	182511.4	-	-67.09	75.5	Y	MG	CH	LC	Y	U	TP	Y	20	U	Mix	Silt, sand, clay, gravel, chalk	Y	1	2007-2014	Bellhouse et al., (2015), GCG, BGS	TQ48SW2085	A melange of RTDs, LC, LG & TS. Chalk 20m higher than local area and TS 10m lower. RTDs within chalk and remoulded chalk also identified. In the report it states that below 27.5m it is highly irregular with blocks of Upnor Fm, LC, LG, TS and a matrix of Chalk from the Seaford Fm. The chalk is structureless and often stained yellow/orange. The chalk is recovered as silt/sand and gravel size
Lime St	533132.1	181001.3	-	4.95	12.2	Y	MG	LC	LC	N	U	TP	N	-	Y	Mix	Silt, sand, clay, gravel	Y	U	1933	BGS	TQ38SW5178	From Geoindex - borehole logs state numerous polished surfaces in clay of vertical and horizontal discontuinties.
Cornhill (LU Bank Station DS)	532746.7	181102.2	-	-	19.8	Y	MG	LC	LC	N	33.83	TP	N	-	N	Mix	Silt, sand, clay, gravel	Y	U	1946	BGS, Bank Station desk study	TQ38SW3074	TQ74 only borehole showing anomolous levels of drift.
Milton Road (Newman Brockwell)	531653.7	174519.4	-	-	11.8	Y	MG	LG	LC	Y	U	LH	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	1992-2005	Newman (2009)		
Sutherland Street (Newman Pimlico)	528790	178190	-	-	-	N	MG	LC	LC	N	U	KP	U	-	Y	Mix	Sand, gravel	Y	U	1986	Newman (2009) Dick and Jacques (1994)		Faulting shown either side of hollow in image of stage 2a.
Warren Road (Newman Whitton)	514361.2	174030.1	150	-16	30	N	MG	LC	LC	N	U	TP	U	-	U	Mix	Silt, sand, gravel	Y	U	1988	Newman (2009)		

																					Stanniforth (1994)		
South Lambeth Road (Wyvil Road)	530033.8	177453.4	-	-9.77	12.55	U	MG	LC	LC	N	U	KP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	2014	GCG (Northern Line Extension)		From the GCG document - Factual 01.
Post Office Way (NLE1)	529683.4	177371.7	-	-18.25	21.95	U	MG	LC	LC	N	18.75	KP	U	-	U	Mix	Sand, clay	Y	U	1906-1929	BGS, GCG (Northern Line extension)	TQ27NE154/B	
Battersea Power Station 2 (NLE 2)	528922.5	177309.9	-	-	10	U	MG	LC	LC	N	U	KP	U	-	U	Mix	Sand, gravel	Y	U		Robert Bird Group		From Battersea Power Station phase 3a. Smaller feature south of power station.
Old Bailey	531792	181288.7	-	-7	17.4	U	MG	LC	LC	N	U	TP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	1963	BGS	TQ38SW2703 & TQ38SW2716	From a single borehole.
Ave Maria La (St Pauls)	531939.7	181177.3	-	-4.15	17.25	U	MG	LC	LC	N	U	TP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	1962	BGS	TQ38SW2741	
Wards Wharf Silvertown	541456.4	179945.7	-	-	18.5	U	MG	TS	TS	N	U	KP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	Num	GCG		
Temple Mills Lane (Velodrome)	538031.4	185505.9	100	-56	65	N	MG	CH	LG	Y	U	TP	Y	20	U	Mix	Sand, clay, gravel, chalk	Y	1	2007	Lee and Aldiss (2012), BGS, GCG	TQ38NE1366	
Suffolk Street (Pall Mall)	529854.9	180439.9	-	-2.64	13.72	U	MG	LC	LC	N	U	TP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	1906	BGS	TQ28SE130	Anomalous when compared to close vicinity of LC being identified at 7.62m. Potentially linked to St James' Sq and Carlton Gardens DFH.
Albert Road (Berry Roding Buckhurst)	541925.6	193748.6	-	-	>20	Y	MG	LC	LC	N	U	none but at TP elev	U	-	U	Mix	Silt, sand, clay	Y	U	1987-2001	Berry (1979)		Weathered material at the top of the London Clay, but all boreholes show intact LC beneath. Potentially same feature as Chigwell New Barns Farm. No boreholes to compare in BGS Geoindex to know if it is anomalous or different features.
Waltham Cross (Great Cambridge Road)	535031	200064	-	-5.26	28.6	N	MG	CH	LC	Y	U	none but at LH elev	U	-	N	Mix	Silt, sand, clay, gravel, chalk	Y	U	1977	BGS (Pickard)	TL30SE136	Drift to 28.6m then structureless chalk in main borehole log. Six surrounding boreholes have gravel to a maximum depth of 20m. Borehole 300m away is very different yet still 'abnormal' for local area.
Grosvenor Waterside	528640	178040	-	-19.5	25	N	MG	LC	LC	N	U	KP	U	-	N	Both	Silt, sand, clay, gravel, chalk	Both	U	1992	BGS (Pickard)	TQ27NE1564	Only 1 borehole within 100m. Drift to 25m, then LG, then peaty clayey chalk, then TS, then off-coloured chalk.
Hyde Park Corner	528240	179780	-	-0.3	14.32	Y	MG	LC	LC	N	U	HA	U	-	U	Both	Silt, sand, clay, gravel	Both	U	1903-1964	BGS (Pickard)	TQ27NE33 & TQ27NE755	From BGS boreholes. The main log shows the cross section of the DFH. A borehole around 90m south east of main borehole show melange and red brick down to 13.9m.
London Road	531821	179300	60	-9.57	13.05	Y	MG	LC	LC	N	U	KP	U	-	U	Mix	Sand, gravel	Y	2	1968	BGS (Pickard)	TQ37NW1710	
Coin Street	531180	180380	-	-11.25	15.73	Y	MG	LC	LC	N	U	KP	U	-	U	Mix	Peat, silt, sand, clay, gravel	Y	U	1968	BGS (Pickard)	TQ38SW2992 & TW38SW6	
Pasley Park	532010	178110	-	-7.4	10.1	N	MG	LC	LC	N	2.7	KP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	1975	BGS (Pickard)	TQ37NW2321 & TQ37NW2325	From BGS boreholes - 2 main boreholes then none within 100m or more E+W and ~500m other directions.
Heygate Street	532280	178730	-	-7.43	10.7	N	MG	LC	LC	N	U	KP	U	-	U	Both	Silt, sand, clay, gravel	Both	U	1969	BGS (Pickard)	TQ37NW752 & TQ37NW753	
Farringdon Street	531580	181390	30	3.23	5.18	U	MG	LC	LC	N	U	TP	U	-	U	Mix	Silt, sand, clay, gravel	Y	U	1950	BGS (Pickard)	TQ38SW525/B	From BGS boreholes - main log shows the cross section of the DFH.
Little Trinity Lane	532310	180870	-	-4.9	8.7	U	MG	LC	LC	N	31.5	KP	U	-	U	Mix	Sand, clay, gravel	Y	U	1968	Pickard Site Investigation	TQ38SW1943/A & TQ38SW1943/B	One borehole showing drift levels stated. Others surrounding are at local level bar one around 30m away showing flint and chalk in MG for 9.5m.

Ponton Road	529940	177662	-	-8	12.3	Y	MG	U	LC	U	U	KP	U	-	U	Mix	Sand, clay, gravel	Y	U		Pickard Site Investigation		New Covent Garden Market - possibly extension of Berry's 1c.
St James Sq	529471	180434	-	-2	15.2	Y	MG	LC	LC	N	U	TP	U	-	U	Mix	Silt, gravel, clay	Y	U		Pickard Site Investigation		Potentially an overlap with Carlton Gardens and/or Pall Mall. Fill consists of Langley Silt, Kempton Park Gravel and London Clay.
Wandsworth Road	530164	177548	-	-9.8	13.6	U	MG	U	LC	U	U	KP	U	-	U	U	U	U	U		Pickard Site Investigation		CONFIDENTIAL Embassy Gardens - "infill material information is unavailable. Feature is apparently elongated terndin NE SW. Could be southern tip of larger feature" Pickard (2016)
Hammersmith A4	522354	178463	-	-24.7	30.05	N	MG	U	LC	U	U	KP	U	-	U	Mix	sand, clay, gravel	Y	U		Pickard Site Investigation		According to Pickard (2016), "An elongate, steep sided feature trending northeast southwest. Anticipated contact between drift and solid geology is at approximately -3.5mOD. A number of boreholes ended within drift at as deep as -24.7mOD. The fill material generally comprised loose to dense sand with subordinate gravel and clay layers predominantly throughout the middle and lower sections. The clay layers feature both fine to medium sized gravel and selenite crystals indicating re-deposited London Clay, whilst still retaining its structure and strength."
Renwick rd - Barking (left of diapir)	547115	182689.86	-	-29.4	36.1	Y	MG	LG	LG	N	10	AL or TP	Y	11	Y	Mix	RTD, clay	Y	2	2017	Arcadis (confidential)		Left of the 'fault' is approximately 40m of Superficial Deposits, the Superficial Deposits to the right of the fault are slightly shallower at 30m. The depression is not over the diapir, it is to the left.
Renwick rd - Barking (right of diapir)	547115	182689.86	-	-39.46	45	Y	MG	TS	LG	Y	10	AL or TP	Y	11	Y	Mix	Clay, gravel	Both	2	2017	Arcadis (confidential)		As above.
Ashford Hill	456041	162098	150	30	46.6	Y	LC	LC	LC	N	U	AL or BG	Y	45	Y	Both	Peat, sand, clay, gravel	Y	2	1951	Hill (1985), Hawkins (1952), BGS	SU56SE69-71	
Slade Oak Lane - Denham	502319	188685	-	-37.5	40	N	LG	CH	LC	Y	U	GCG	N	-	Y	Both	Sand, clay, gravel	Both	1	1978	Gibbard et al., (1986)		Gibbard et al., (1986) notes faulting present in infill.
Iver (Thames water)	503782	176576	-	-5	25	Y	MG	LG	LC	Y	U	AL or SH	Y	15	Y	Mix	Silt, sand, clay, gravel	Y	U	1986	GCG		LC absent from BH 9a where anomoly is located. Melange of silt sand and gravel into LG back to a melange then back to LG. LG is higher nearer to anomoly than surrounding area.
Elverton St	529650	178950	-	-15.9	11.3	U	MG	LC	LC	N	U	AL or KP	U	-	U	Mix	Silt, sand, gravel	Y	U	1946	BGS (Pickard)	TQ27NE516	From BGS Geoindex. Based on 1 borehole and limited in the surrounding area for comparison.
Three Valleys Water Tunnel - Thorney	*503098*	*179981*	-	-	32	Y	MG	LG	LC	Y	U	AL or SH	Y	12	U	Mix	Silt, sand, gravel	Y	1	1985	Banks et al., (2014) and Baker and James (1990)		Banks paper as 9a "Basal sands in horiztonal feature"
Woolhampton	456509	166145	500	-	10	N	MG	U	LC	N	U	AL or BG	U	-	U	U	Silt, sand, gravel	Both	U	1994	Collins thesis & Collins et al., (2006)		
Elephant & Castle	532270	179195	-	-15	-	Y	MG	LC	LC	N	U	KP	U	U	U	Both	Peat, silt, sand, gravel	N	1	1906	BGS	TQ37NW2432	From the BGS Geoindex showing a round peat anomaly in the superficial deposits
New Cross	536216	177449	100	-	16.6	N	MG	TS	TS	U	U	KP	U	U	U	Mix	Peat, silt, sand, clay, gravel, chalk	Y	1	1974	BGS	TQ37NE1271 & TQ37NE1677	From the BGS Geoindex where a moon shaped peat anomaly is shown in the superficial deposits. The logs show nodules/pebbles of Chalk within the infill and local Chalk level is at -100mOD

Appendix B

London Road DFH

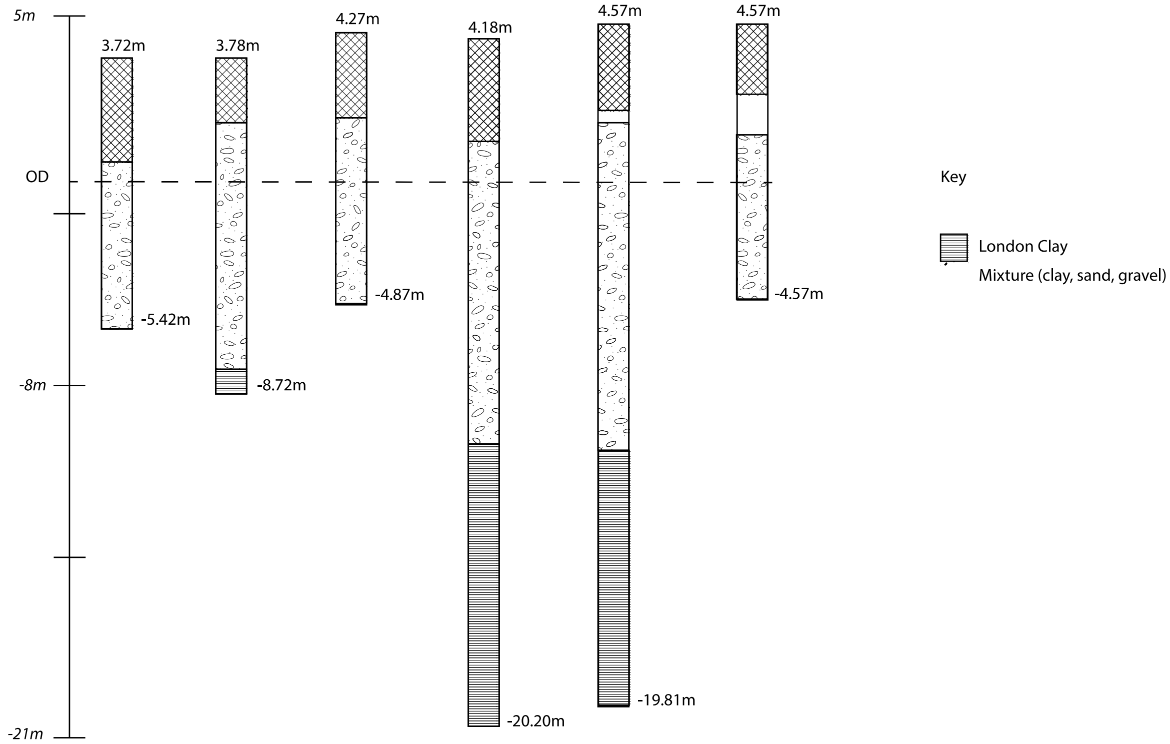

Figure 9. 1 – London Road DFH cross-section

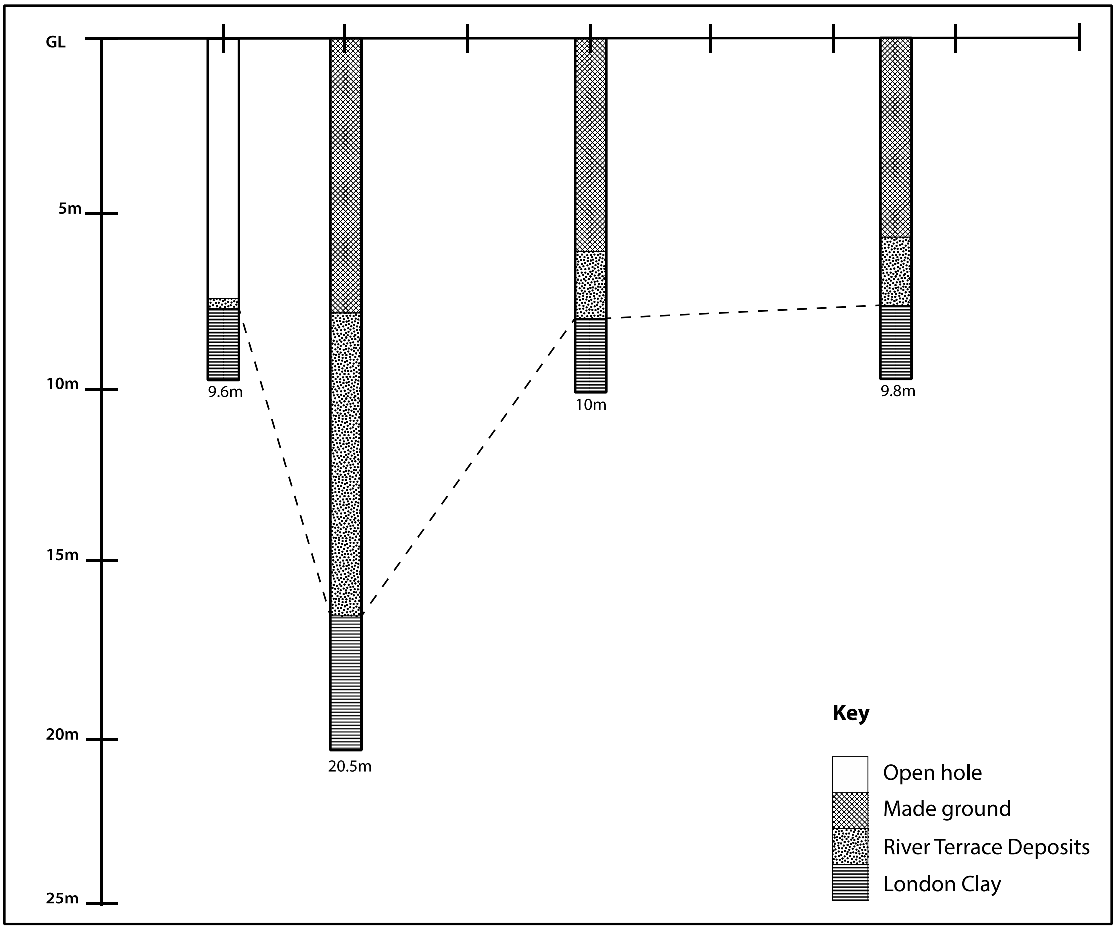

Figure 9. 2 - Battersea power station phase 3a DFH cross-sectionBattersea 3a

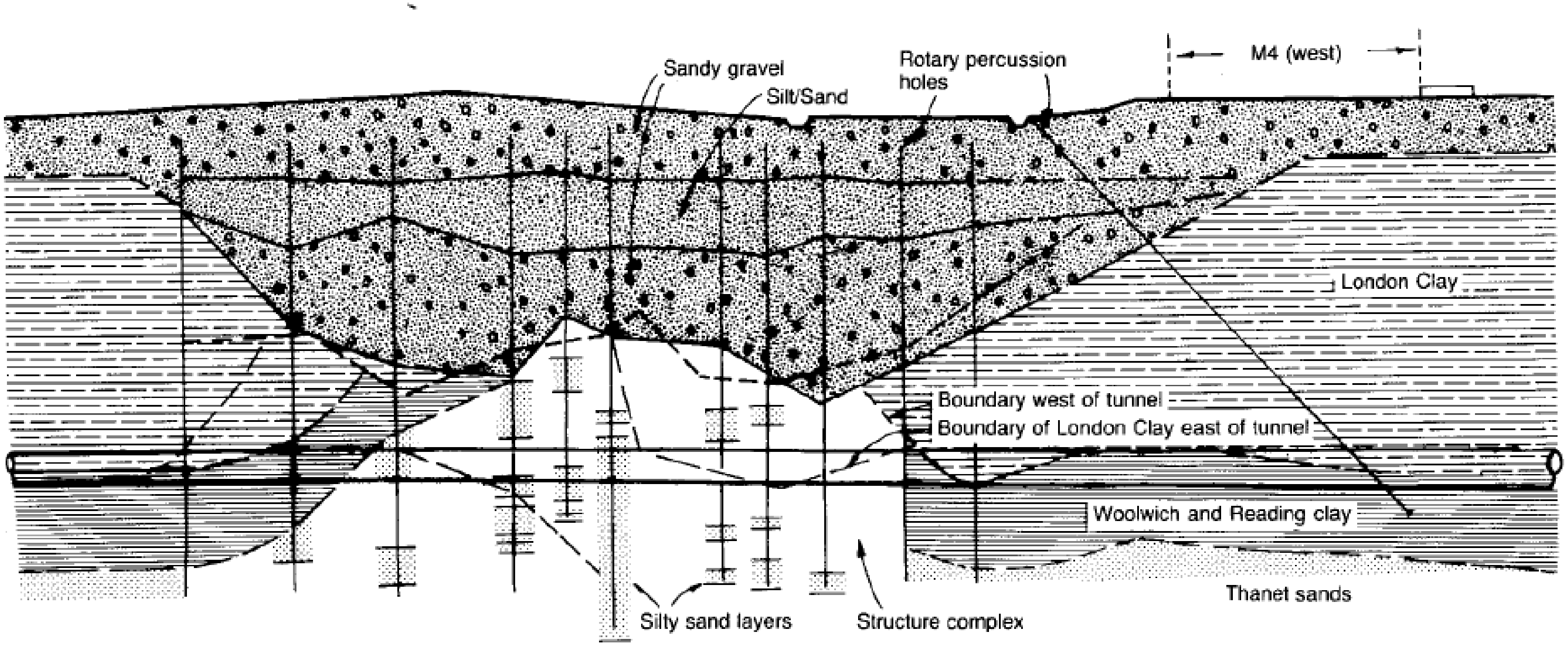

Figure 9. 3 – DFH cross-section

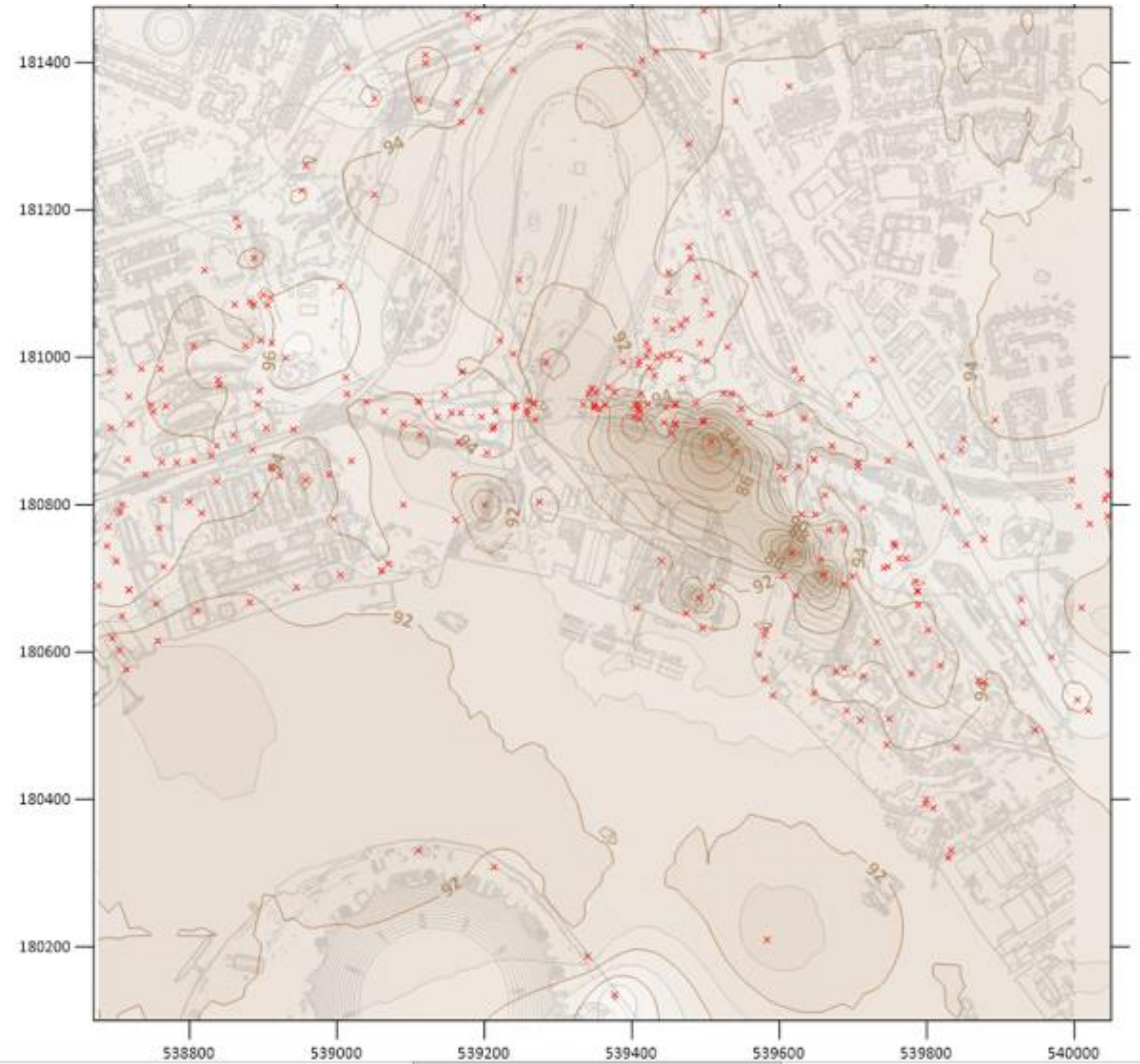

Figure 9. 4 - London Clay contour map for the Limmo feature

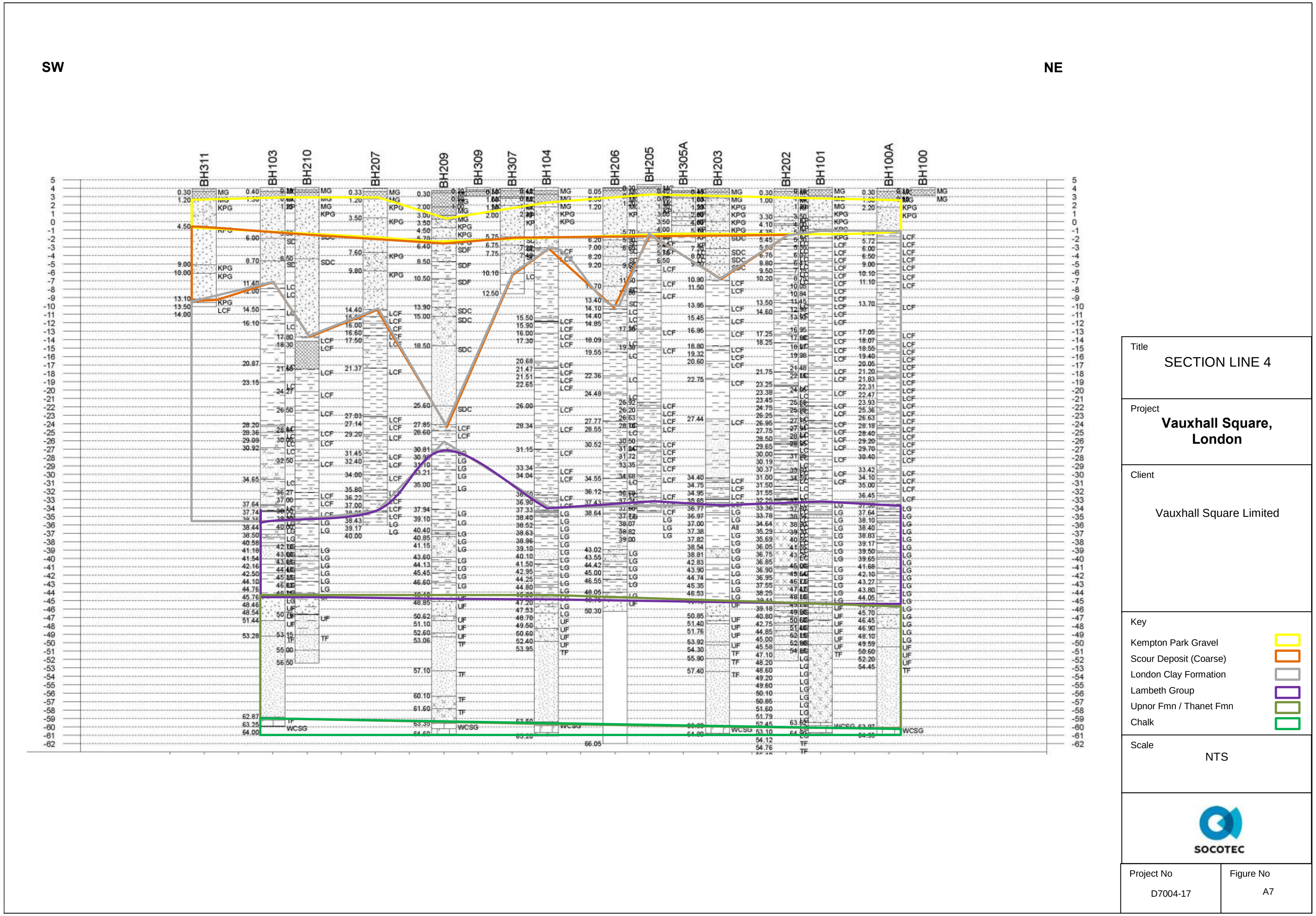

Figure 9. 5 - Vauxhall Square DFH cross-sectio

Appendix C

Figure 9. 6 – Offset London Clay at the edge of the Battersea Phase 3a feature.

Figure 9. 7 – Polished London Clay surface identified at the edge of the Battersea Power Station phase 3a feature.

Figure 9. 8 – Inclined contact between DFH infill to the left and London Clay to the right.

Figure 9. 9 – DFH infill showing vertical contact between clay, mixed deposits and oxidized, orange material to the right of the image.

Figure 9. 10 – DFH infill showing the contact between silt, clay and RTDs.