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The distributions and variations of Quaternary Thames River Terrace deposits of Greater London

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Abstract: A database containing *c.* 27 000 records of Quaternary lithostratigraphy extracted from *c.* 5800 boreholes drilled to a variety of depths has been compiled from information contained in logs recorded and held by the British Geological Survey (BGS) and from the Crossrail project. After 'cleaning' and quality assessment the raw borehole log data have been investigated for patterns in distribution, and variations in the Quaternary facies across Greater London. In particular, the analysis of Quaternary River Terrace Deposits has been focused on here and a summary of relevant published terminology and nomenclature is also included in this Technical Note, as an aid to understanding. The spatial distributions of each major Quaternary lithostratigraphic interval, as identified in the log descriptions, are also presented as point locations in map form, and in comparison with the corresponding BGS mapped outcrop patterns of the respective lithostratigraphic units. The presence of various specific clasts in the log descriptions (e.g. cobbles and chalk clasts) is also presented at stratigraphic member levels against their apparent source outcrops. For instance, cobbles recorded from the Boyne Hill Terrace intervals are concentrated in the eastern outcrops and reflect the Wealden source and former river system of the Darrent–Wid towards the Essex coast at Maldon. Similarly, the presence and distribution of shell and chalk clasts within river terrace sands and gravels reflect the geology of the underlying subcrop strata of Lower Shelly Clay and Chalk respectively. The Crossrail data also include some grain-size information from sieve analysis and some engineering *in situ* test values, which require careful analysis beyond the scope of this work but are potentially useful. The grain-size distributions for some of the samples from the river terrace sands and gravels show fining-up and coarsening-up sequences, and geographical grain-size trends in various stratigraphic intervals. The recorded presence of faults, fractures and fissures, as identified by the drilling contractors or logging geologists, is also extracted and mapped. Supplementary evidence, from repeated stratigraphy or improbable spatial proximity changes in subcrop depths, suggests a cause other than deposition for such changes and, on the presumption that their cause is natural, is interpreted as likely to be representative of faulting of some kind, including low-angle thrust faults. Faulting is also considered to have controlled the distribution of several interglacial silt members and is the subject of considerable research in the deeper intervals of London stratigraphy, so is only briefly dealt with here. To define the period over which tectonic structures, now known to exist within the strata of the London Basin, were active requires an analysis of Quaternary deposits that overlie them. This Technical Note provides an initial review of the data available from boreholes for such work and for any other studies requiring knowledge of these deposits.

Supplementary material: Spreadsheets (and other files), and notes on the name and significance of each, are available at https://doi.org/10.6084/m9.figshare.c.6700313

Thematic collection: This article is part of the Geology of London and its implications for ground engineering collection available at: https://www.lyellcollection.org/topic/collections/geology-of-london-and-its-implications-for-ground-engineering

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This Technical Note documents the compilation, evaluation and analysis of a database of borehole records that intersect Quaternary sedimentary intervals, from across Greater London. This work complements the analyses and publications of many researchers and experts in the Quaternary of London and the Thames Basin.

Gibbard (1985, 1994) provided one of the first in-depth lithological and stratigraphic descriptions of the Quaternary River Terrace Deposits (RTDs) of the Thames Basin by mapping and connecting outcrops from the Upper and Middle Thames to those of the Lower Thames and Thames Estuary, and by discussing earlier courses of the rivers that now make up the Thames drainage system within London. His results are displayed in the various maps within his books (e.g. Gibbard 1994).

A great wealth of additional information is presented in other and subsequent works on the Quaternary geomorphology and geology of the Thames basin, such as those by Wiseman (1978), Devoy (1979), Gibbard (1983), Nunn (1983), Barton (1992), Whiteman and Rose (1992), Bridgland (2000), Maddy *et al.* (2001), Bridgland *et al.* (2004) and Gibbard and Clark (2011).

The British Geological Survey (BGS) holds a vast database of borehole records, dating back to the 1800s, for boreholes that have penetrated both solid and drift geology of London and surrounding areas and has underpinned the production of modern analogue and digital maps of the region.

Purpose of this Technical Note

In consideration of the above, it would be fatuous to attempt to replicate, in this document, the plentiful excellent Quaternary mapping work already undertaken by other researchers. Rather the authors considered it important and relevant to make available this large database of raw geological information from boreholes across London, in a form that has been compiled, quality assessed and analysed, and that is the purpose of this note. The borehole log data are available as raw scanned borehole logs and in electronic form from the BGS. In this Technical Note the compiled database up to August 2019 is presented as summary descriptions and borehole point distribution maps. The spreadsheets, which are the source of this information, are large and are not published here but are provided as Supplementary material.

The original purpose of the work was to assist those who wish to date the movement of known structures, but, as the work progressed, it became apparent that these descriptions and presentations would provide any interested parties, be they geologists or engineers, from industry or academia, with a representative selection of borehole data from both important Quaternary stratigraphic units (the river terrace gravels and associated regional silt deposits) and areas of important and potentially economic Quaternary deposits.

Lithostratigraphy of the Quaternary

Summary details of Quaternary chronostratigraphy are illustrated in Figure 1. The uppermost 781 000 years are expanded and cover the stratigraphic interval in which the Quaternary deposits of the Thames Basin (within the M25) fall. The bulk of the RTDs fall within the Thames Valley Formation (TVF). The boreholes in the database are representative of most of the Quaternary TVF stratigraphic members, as defined by the BGS Lexicon of Named Rock Units (https://webapps.bgs.ac.uk/lexicon/). It is assumed that the information taken from that Lexicon comprises the latest stratigraphic information available. Hence the ages quoted below and the stratigraphic intervals assigned to the rock intervals within the spreadsheet relate to those of the BGS.

A generalized lithostratigraphic framework for the Quaternary and Neogene for Great Britain and the Isle of Man has been formulated by McMillan *et al.* (2011) and adapted by Banks *et al.* (2015) and is shown in Table 1 for reference. Other notable work on the stratigraphic framework and chronology includes that by Bridgland (1994, 2000), Ellison *et al.* (1994), Jürgen and Gibbard (2004), McMillan (2005), Bondevik *et al.* (2006), Bridgland and Schreve (2009), Cohen and Gibbard (2011), Lee *et al.* (2011), Böse *et al.* (2012), McMillan and Merritt (2012) and Aldiss (2014), and most recently the chronological work on the tectono-climatic evolution of the landscape of England by Lee *et al.* (2018).

The relationship of each Quaternary member to another, in terms of precise age, is extremely difficult to determine, owing to the absence of any reliable palaeontological information, and thus the Member's absolute stratigraphic position is not always precise. Consequently, the Quaternary stratigraphic members as encountered in the London BGS and Crossrail borehole records are shown in approximate stratigraphic sequence, with oldest at the bottom, in Table 2.

The older Quaternary sections are not well represented in the database, so they have short descriptions. Each of the Anglian BPGR, WOGR, DHGR and GCGR sections is encountered in only a few boreholes (a total of *c.* 59), LOFT is present in very few and the Cromerian STGR in *c.* 25 boreholes.

The main stratigraphically distinct RTDs are well represented and described in detail. For instance, the Devensian KPGR is present in over 2000 boreholes, the Wolstonian TPGR in over 1000 boreholes and HAGR in over 250. The LHGR deposits are recorded in over 400 boreholes and the older Hoxnian–Wolstonian BHT in over 250.

In over 25% of the boreholes (*c.* 1300 boreholes) it has not been possible to determine which RTD Member the intervals represent; these are termed RTDU (River Terrace Deposit, Undifferentiated). The main bulk of these lie downstream of Woolwich, along the lower Thames floodplain and into the Thames estuary; that is, within TQ47NE, TQ48SE, through TQ58SW and TQ57NE to block TQ67. These boreholes are generally below sea level and thus ground observations for mapping and continuity are absent.

The interglacial silt deposits are also represented: Flandrian ESI (49 boreholes), Devensian LASI (over 200 boreholes), Ipswichian CFSI (nine boreholes) and Wolstonian ILSI (16 boreholes). Brief descriptions are given of each of these.

In some boreholes, Quaternary RTDs are absent but it is not known whether these were ever deposited, have been deposited and subsequently eroded, or have been removed through extraction or construction. The thickness of Made Ground may help in the analysis of the reason for the absence of the RTD; also, the lack of

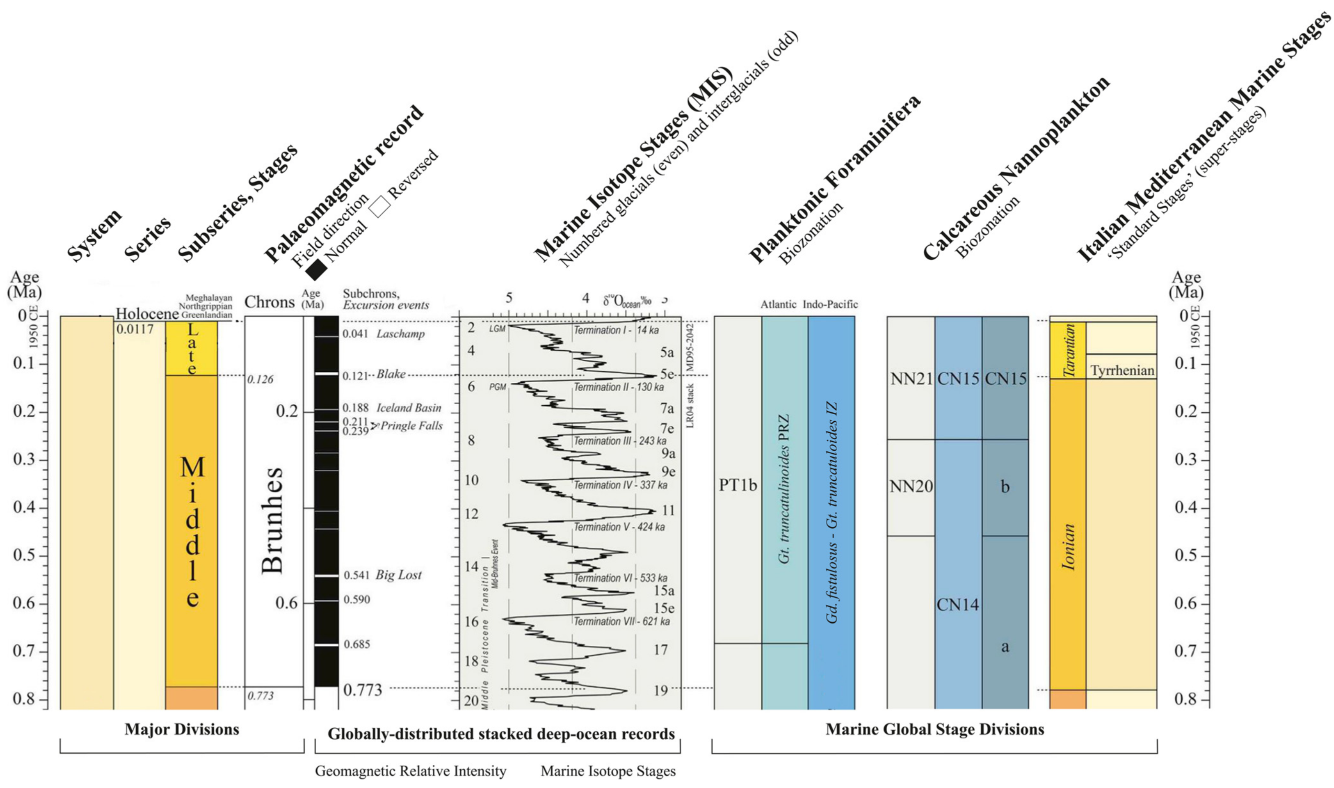

Fig. 1. Global chronostratigraphic correlation table of the last 781 kyr. Source: Cohen and Gibbard (2011).

Table 1. *Quaternary correlation chart for the Middle and Lower Thames (from Banks et al. 2015, which was adapted from McMillan et al. 2011, British Geological Survey Research Report)*

Chronostratigraphy			Middle Thames	Lea Valley
Epoch	British Stage	Marine Isotope Stage*		
Holocene		1	Thames Catchment Subgroup Maidenhead Formation	Catchment Subgroup Maidenhead Formation
				Alluvium
				Floodplain Gravel Bed
Late Pleistocene	Devensian–Welchsalian	Loch Lomond Stadial (2–1)	Shepperton Gravel Member	Lea Valley Member
		Windermere Interstadial (2)		Lea Valley Silt Member (Brickearth)
		Dimlington Stadial (2)	Kempton Park Gravel Member (terrace 1)	Langley Silt Member (Brickearth)
		3		
		4		
		5d–a		
	Ipswichian–Eemian	5e		Highbury Member
				Waterhall Farm Member
Mid-Pleistocene		6	Kempton Park Gravel Member (part)	Leytonstone Member
			Taplow Gravel Member (terrace 2)	Stamford Hill Member
		7		
		8	Taplow Gravel Member (part)	
			Hackney Gravel Member (terrace 3)	
			Lynch Hill Gravel Member (terrace 4)	
		9		
		10	Lynch Hill Gravel Member (part)	
			Boyn Hill Gravel Member (terrace 5)	
	Hoxnian–Holsteinian	11		
	Anglian–Elsterian	12	Boyn Hill Gravel Member (part)	Lowestoft Formation
			Black Park Gravel Member (terrace 6)	Hoddeston Member
			Kesgrave Catchment Subgroup of the Dunwich Group	
			Colchester Formation	
			Winter Hill Gravel Member	
Early Pleistocene		?61–13	Sudbury Formation	
			Gerrards Cross Gravel Member	
			Beaconsfield Gravel Member	
			Westland Green Gravel Member	
			Satwell Gravel Member	
			Stoke Row Member	
		103–?62	Stanmore Gravel Member	
Miocene to Early Pleistocene				

*Approximate correlation with Marine Isotope Stage (cold even and warm odd numbers).

Made Ground should indicate a genuine absence of the RTD, but it would not be known whether this was due to non-deposition or subsequent removal by erosion or faulting. Faulting should be invoked only where there is no other credible explanation or where there is evidence of fracturing and/or disturbance.

Borehole database

The database comprises records extracted from over 5781 borehole log records, the majority of which are from boreholes drilled since 1985. The raw information for each borehole record has been subdivided and presented according to BGS-defined lithostratigraphic intervals. All borehole records used in this note are provided in a shared folder from which users are free to download the data \Quaternary_BH_database.

Each lithostratigraphic interval and the depths at which it is observed forms a single row in the main reference spreadsheet entitled BGS-CR_RTD-BH_ALL.xlsx (in \BGS-CR-BH-data \Spreadsheets\All-BH-data); thus the borehole with ID 31922 (Fig. 2) has four recorded lithostratigraphic intervals, to depths of 22.91, 21.36, 18.86 and 15.25 m Ordnance Datum (OD), respectively. This spreadsheet contains 27 549 records from 5781 boreholes, and has two sheets (Microsoft Excel tabs), which present the entire lithostratigraphic records in ‘All data’ and a ‘Fissures’ sheet containing the extracted records from boreholes, which contains descriptions of fissures, faults or fractures; a section of this file is illustrated in Figures 2 and 3.

A further file in the same folder contains the outcrops of Quaternary lithostratigraphic intervals (BGS-CR_RTD-BH_outcrop-for-maps.xlsx) and in a sheet named ‘For-GIS’, in a ‘map-ready’ format suitable for display as points in 2D map form in ArcGIS (or other similar GIS platform). In this case, each row contains a unique record for each of the 5781 boreholes where the following information is given: DATAcat (record quality), Hole_ID (unique borehole number), Supplementary hole ID number, relevant Ordnance Survey TQ reference number, BGS number, easting coordinate (m), northing coordinate (m), borehole ground elevation (+OD(m)) and the Quaternary outcrop lithostratigraphic code (Main_Quat_Strat) for each borehole (one per row). A section of this file is illustrated in Figure 4.

Table 2. *Simplified summary of Quaternary stratigraphic members encountered in London borehole records, in age order*

Age order	Lithostratigraphic member	Lithostratigraphic code
9	Enfield SIlt Member (Devensian to Flandrian)	ESI
8	Kempton Park GRavel	KPGR
	Langley SIlt Member	LASI
	Shepperton GRavel Member (Devensian)	SHGR
7	CrayFord SIlt Member (Ipswichian)	CFSI
6	HAckney GRavel Member	HAGR
	TaPlow GRavel Member	TPGR
	ILford SIlt Member (Wolstonian–Saalian)	ILSI
5	Lynch Hill GRavel Member (Wolstonian)	LHGR
4	Boyn Hill GRavel Member (Hoxnian to Wolststonian)	BHT
3	Black Park GRavel Member	BPGR
	WOOdford GRavel Formation	WOOGR
	Dollis Hill GRavel Member	DHGR
	Gerrards Cross GRavel (Anglian)	GCGR
2	LOwestoFT Formation (Anglian)	LOFT
1	CRAG Group: the STanmore GRavel Formation deposits are within the CRAG Group (Pleistocene)	CRAG (STGR)

For map plotting, ESRI point shapefiles are also provided (in \BGS-CR-BH-data\Shapefiles and in \CR-BH-data\CR-clast-shapefiles) for the borehole locations and separated clast types and other features.

Notes on the name and significance of each spreadsheet (and other files) can be found in the Supplementary material: \BGS-CR-BH-data\README-BGS-spreadsheets.docx and \CR-BH-data\README_CR_spreadsheets.docx

The cores and samples recovered from boreholes are most commonly obtained in southern England from either cable percussion or rotary drilling. The former need not use a drilling fluid whereas the latter does, and the circulation of this fluid through the drilling bit and against the sample within the core barrel can wash away fine material. A borehole log will normally record the method of drilling used. Descriptions and their implication, particularly of mixtures (some, occasional, with, etc.) and material strength (strong, weak, etc.) have evolved over the past 25 years and subtle differences now exist between old and more recent descriptions of the same material. Users of this database are advised to check such details when comparing logs.

Data source and quality

The database described in this note has been compiled from two distinct sources:

(1) borehole logs held in the BGS digital database available online via the BGS GeoIndex web portal (https://mapapps2.bgs.ac.uk/geoindex/home.html?layer=BGSBoreholes), which intersect and are representative of the main Quaternary stratigraphic intervals;

(2) trial-pit and borehole logs captured during the Crossrail project (CR), which also included some analytical results (grain-size and engineering *in situ* tests).

The information available from each borehole record has largely been taken 'at face value' as time has not permitted scrutiny of every single aspect of every single borehole. The values and descriptions represent the raw data recorded by the driller and/or geologist, during or after the drilling of the borehole. Many older boreholes contain only simplified lithological names and/or descriptions made by the drilling contractor, which include little or no reliable stratigraphic interpretation. These simplified descriptions have often been reviewed by a geologist or other supervisor before being finalized, but not always; the quality of the geological descriptions is therefore variable.

The most obvious anomalies and inconsistencies have been corrected for this note. Typically, these have included incorrect ground level entries, which, after reference to the Ordnance Survey (OS) Digital Terrain Model (DTM, Terrain 5 product), have been corrected to reliable values above OD. Similarly, ground surface heights, which are missing entirely from the original borehole data, have been estimated from the Terrain 5 DTM using the borehole coordinate location.

The CR borehole positions were recorded using a unique 'local' CR georeference system, which is related to the UK National Grid (OSGB30) by a transformation in *x*, *y* and *z*; these CR positions have been transformed to six-digit British National Grid (BNG) coordinates and are included in this database The six-digit BNG coordinates (e.g. [559490/193760]) can be used as a search key on GeoIndex. Online records include scanned copies of the original borehole log (pdf or multi-layer tiff files), which contain the raw, often handwritten records of the driller's or geologist's

GTCH_HOLE_ID	HOLE_ID	QS	NUMB	BSUFF	Eastings (m)	Northings (m)	HOLE_GL (m OD)	DEPTH_TOP_OD	DEPTH_BASE_OD	Group	Formation	Member	LITHOSTRAT_CODE	LITHOSTRAT BASIC	LITHOLOGY_CODE	LITH BASIC	BRK	HEAD	L (cobble)	P (peat)	SH (shell clasts)	CH (chalk clasts)	Fissures	Geological_Description
31922	625	TL30SE	50	.	535000	200000	23.16	23.16	22.91		MGR		**MGR**	MGR	MGR	MGR	D	D	D	D	D	D	D	No Informattion - Assume SOIL, ALLUVIUM or MADE GROUND
31922	625	TL30SE	50	.	535000	200000	23.16	22.91	21.36	BCAT	MNHD	ESI	**ESI**	SILT	CS	C	D	D	D	D	D	D	D	Stiff brown sandy CLAY with flecks of carbonaceous matter.
31922	625	TL30SE	50	.	535000	200000	23.16	21.36	18.86	BCAT	MNHD	ESI	**ESI**	SILT	CS	C	D	D	D	D	D	D	D	NO INFO - assume CS as above or C as below
31922	625	TL30SE	50	.	535000	200000	23.16	18.86	15.26	BCAT	MNHD	ESI	**ESI**	SILT	C	C	D	D	D	D	D	D	D	Soft grey silty CLAY.
31926	630	TQ39NE	16	.	535210	199950	21.43	21.43	19.63		MGR		**MGR**	MGR	MGR	MGR	D	D	D	D	D	D	D	No Information - Assume SOIL or MADE GROUND
31926	630	TQ39NE	16	.	535210	199950	21.43	19.63	17.93	BCAT	MNHD	ESI	**ESI**	SILT	CS	C	D	D	D	D	D	D	D	Soft brown sandy silty CLAY.
31931	636	TQ39NE	17	.	535560	199980	20.33	20.33	16.93		MGR		**MGR**	MGR	MGR	MGR	D	D	D	D	D	D	D	No Informattion - Assume SOIL, ALLUVIUM or MADE GROUND
31931	636	TQ39NE	17	.	535560	199980	20.33	16.93	15.83	THAM	LC		**LC**	LC	CS	C	D	D	D	D	D	D	D	Stiff grey silty CLAY with veins of sand. (BLUE LONDON CLAY).
31935	645	TQ39NE	22	.	535907	199992	20.27	20.27	19.37		SOIL		**SOIL**	MGR	SOIL	SOIL	D	D	D	D	D	D	D	TOPSOIL
31935	645	TQ39NE	22	.	535907	199992	20.27	19.37	19.17		KPGR		**KPGR**	RTD	VC	V	D	D	D	D	D	D	D	Clayey GRAVEL (GLACIAL GRAVEL)
31935	645	TQ39NE	22	.	535907	199992	20.27	19.17	15.07		KPGR		**KPGR**	RTD	VS	VS	D	D	D	D	D	D	D	Dense slightly sandy GRAVEL (GLACIAL GRAVEL)
31935	645	TQ39NE	22	.	535907	199992	20.27	15.07	14.52	THAM	LC		**LC**	LC	C	C	D	D	D	D	D	D	F	Stiff grey fissured silty CLAY with silt in fissures. (BLUE LONDON CLAY).

Fig. 2. Snapshot of the 'All data' sheet in the BGS-CR_RTD-BH_ALL-master.xlsx spreadsheet.

GTCH_HOLE_ID	HOLE_ID	QS	NUMB	BSUFF	Eastings (m)	Northings (m)	HOLE_GL (m OD)	DEPTH_TOP_OD	DEPTH_BASE_OD	Formation	LITHOSTRAT_CODE	Fissures	Geological_Description	PYRITE	Spacing: C- CLOSE, VC V CLOSE - XC EXTREMELY CLOSE EXTENSIVE - SF/SF SLIGHT / OCCAS IF - indistincly fiss'd	DESCRIP OF FISSURES/FRACS
61975	904T	TQ38SE	1276	.	539714	180568	1.68	-7.12	-8.22	LC	LC	F	Firm brown ext. to v. closely fiss. CLAY. Fissures subvertical planar smooth occ. loc. sl. polished.		XC	Fissures subvertical planar smooth occ. loc. sl. polished.
61976	905	TQ38SE	1277	.	539579	180564	1.58	-7.32	-13.12	LC	LC	F	V. stiff brown grey ext. closely fiss. CLAY with occ. partings (<1mm) of brown fine sandy silt. Fissures randomly orientated smooth planar clean with occ. black mottling.		XC	Randomly orientated smooth planar clean with occ. black mottling.
61979	908	TQ38SE	1280	.	539785	180695	1.73	-3.72	-9.77	LC	LC	F	Firm to stiff grey brown thinly lam. ext. closely fiss. CLAY		XC	
61982	911	TQ38SE	1284	.	539741	180713	2.19	-4.41	-8.81	LC	LC	F	Stiff becoming v. stiff by 7.70m depth grey brown ext. closely fiss. CLAY with occ. black silt partings (<20mm). Fissures randomly orientated clean planar occ. undulose.		XC	Randomly orientated clean planar occ. undulose.
61984	913	TQ38SE	1286	.	539754	180747	1.47	-5.13	-12.33	LC	LC	F	V. stiff grey v. to (predominately) ext. closely fiss. thinly lam. CLAY. Fissures randomly orientated grey mott. black sl. polished smooth. Occasional black silt lenses (<40x10mm). Occasional bioturbation.		XC	Randomly orientated grey mott. black sl. polished smooth.
61985	913A	TQ38SE	1287	.	539755	180745	1.52	-5.18	-21.98	LC	LC	F	Stiff grey brown ext. closely fiss. CLAY with some lenses of light grey silty fine sand (<30x3mm) and loc. with thin laminae of light brown v. silty clay. Fissures randomly		XC	Randomly orientated clean to lightly dusted planar

Fig. 3. Snapshot of the ‘Fissures’ sheet in the BGS-CR_RTD-BH_ALL-master.xlsx spreadsheet.

observations. This online database has been used to quality assess and confirm the stratigraphy of many (but not all) boreholes.

Where there are multiple (different) borehole records with identical grid references, the borehole with the best or most complete information and fullest log descriptions has been used in any further analysis.

The quality of the borehole records can thus vary greatly, so each record has been quality assessed using the simple schema described here. Where anomalies, discrepancies or ambiguities were identified, the data were downgraded; for example, from best to good, or from good to useful.

(1) Best quality data: these are the most recent boreholes and they consequently benefit from modern or improved drilling techniques, more accurate sample collection, better or more detailed descriptions and representation of the lithologies encountered, and better retention of ‘fines’ material. These tend to include logs recorded since 2000, which benefit from borehole positioning recorded using Global Positioning Systems (GPS) and are believed to be accurate to within 10 m. They are shown as: B-1, best quality data from BGS website source; C-1, best quality data from the CR source. The latter include some analytical results (i.e. grain-size distributions, water contents and mechanical properties), and these have largely been collected from records ascribed to the Lynch Hill Gravel Member (LHGR). These analytical data are included in CR-LHGR_grainsize-analysis.xlsx (in directory \Quaternary_BH_database\CR-BH-data\CR-LHGR-grainsize-data).

(2) Good quality data: these boreholes are older, but have been drilled within the last 25 years; the sample collection techniques and/or lithological descriptions may be of reduced quality; the grid references may be less accurate but are still believed to be accurate within 50 m (acquired using early GPS in the era of US selective availability) but at worst within 200 m. It might be that the data are as good as

DATAcat	HOLE_ID	Supp_hole_ID	TQ-etc-no	BGS_No	Eastings(m)	Northing(m)	+OD(m)	MAIN_QUAT_STRAT
B-1	72707	18	TQ39SE	251	538434	190951	22.05	WOGR
B-1	72708	19	TQ39SE	252	538441	190911	21.75	WOGR
B-1	72709	20	TQ39SE	253	538495	190953	22.30	WOGR
B-1	55134	BH 701	TQ07SE	66	505070	174656	20.60	TPGR
B-1	55182	TP 702	TQ07SE	67	505026	174664	20.30	TPGR
B-1	55287	TP 298	TQ07NE	243	509315	176875	24.10	TPGR
B-1	89796	DCS07	TQ18SE	418	519595	183734	21.75	TPGR
B-1	89795	DCS06	TQ18SE	417	519570	183700	22.80	TPGR
B-1	89767	CP09	TQ18SE	411	519617	183681	34.90	TPGR
B-1	89766	CP08	TQ18SE	410	519581	183665	34.80	TPGR
B-1	89764	CP06	TQ18SE	408	519609	183645	29.55	TPGR
B-1	89793	DCS04	TQ18SE	415	519578	183615	24.25	TPGR
B-1	89761	CP02	TQ18SE	405	519612	183601	29.65	TPGR
B-1	89762	CP03	TQ18SE	406	519681	183591	30.35	TPGR
B-1	89792	DCS03	TQ18SE	414	519605	183577	24.90	TPGR
B-1	89765	CP07	TQ18SE	409	519683	183555	30.15	TPGR
B-1	89791	DCS02	TQ18SE	413	519632	183538	26.05	TPGR
B-1	88121	TP44	TQ18SW	224	514005	181765	27.50	TPGR

Fig. 4. Snapshot of the BGS-CR_RTD-BH_outcrop-for-maps.xlsx spreadsheet, showing records of the topmost lithostratigraphy that crops out in each borehole.

those in B-1 category, but where the ground level or grid reference has had to be modified. These are shown as B-2 and C-2.

(3) Useful data: these boreholes have information that is generally good, but the quality for mapping is poorer because: the boreholes are a lot older and grid references are less accurate or absent (pre-GPS); these are generally within 100 m, but at worst within 500 m; ground level may be approximate or uncertain; generally, the lithological descriptions are less detailed. Nonetheless, they would be helpful in any mapping or analytical exercises. These are shown as B-3 and C-3.

These quality codes have been incorporated into the BGS-CR_RTD-BH_outcrop-for-maps.xlsx spreadsheet.

The dataset described in this note does not include any records from boreholes marked on BGS GeoIndex as 'confidential', as far as is known.

Lithostratigraphic and lithological code system

The lithostratigraphic codes used in the spreadsheets are those defined and provided by the BGS Lexicon (https://www.bgs.ac.uk/technologies/the-bgs-lexicon-of-named-rock-units). For the majority of boreholes, either the authors or MSc students at Imperial College London (during project work) have correlated and confirmed the lithostratigraphic interpretation in the log with BGS mapped outcrops, or have identified the stratigraphy of bodies logged as 'uncertain' or 'undifferentiated' or 'unidentified' gravel bodies. No subcrop information was provided with the Crossrail data; many of the 'RTDU' gravels interpreted in BGS logs indicate that the borehole did not penetrate the subcrop. In some cases, the authors have been able to identify a subcrop from the logged descriptions and notes.

The majority of borehole records are organized and described with the following information: location (TQ square number, easting and northing), ground level (in metres above OD), lithostratigraphic interval thickness and interpreted lithostratigraphic code of the main Quaternary interval, plus a description where present. Where two Quaternary lithostratigraphic units have been recorded as present, these are entered separately (e.g. LOFT with overlying BPGR or KPGR with overlying LASI).

The varied lithostratigraphic units and detailed descriptions have been supplemented, where possible and in separate additional columns, by codes representing the presence of peat (P), cobbles (L), shell clasts (SH), chalk clasts (CH) and fissures (F)/fractures (Fr) and faults (Fa). These again have been derived from the descriptions provided by the drilling contractor or geologist and have been incorporated into BGS-CR_RTD-BH_ALL.xlsx by the authors.

A series of five separate spreadsheets (prefixed Clast-Map-) provides separated records of boreholes where cobbles, shell and chalk clasts are identified, and which are also provided in map- or GIS-ready format and used to produce maps of the spatial distributions of the various clasts (in directory \Quaternary_BH_database\BGS-CR-BH-data\Spreadhseets\Clast-separation). A sixth sheet is provided for borehole records where fissures and fractures have been observed and described in the log descriptions; this also includes the locations where faults are suspected to be present, or where faults are identified by the authors.

Adopted digital mapping approach

Ordnance Survey British National Grid map reference framework

The borehole ID numbers in this Technical Note and database all refer to areas by reference to the BNG 'TQ' square number, which relates to the Ordnance Survey (OS) classification, using metric six-figure BNG grid references (e.g. [559490, 193760]). The OS division of the UK into 100 km × 100 km squares, where London lies in square TQ, and further subdivision into 10 km × 10 km squares (e.g. TQ 06), is illustrated in Figure 5. Each of the squares, such as TQ 06, is finally subdivided into four geographical regions: NW, NE, SW and SE.

The London Basin Forum (LBF) study has concentrated on the area within the M25 (within OS square TQ) but this study includes several data points located just north of the M25, in OS square 'TL', which lies to the north of OS square TQ (these are not shown in Fig. 5).

Digital British Geological Survey map data

All geological map information presented in this Technical Note has been extracted from BGS digital 1:500 000 scale published digital solid and drift geological sheets, available on the BGS website at https://www.bgs.ac.uk/information-hub/bgs-maps-portal, and from Digimap (via subscription, https://digimap.edina.ac.uk), as ESRI shape files. The BGS map sheets of outcrops of Mesozoic and Quaternary sediments and subcrop strata are used in the discussion below on the various Quaternary sedimentary packages. The Quaternary lithostratigraphic units that crop out in the Greater London area are illustrated in the simplified map in Figure 6.

Quaternary deposit lithostratigraphic distribution maps

The borehole record database 'cleaned' as described above and in 'map-ready' form was imported into ESRI ArcGIS. The data were then split according to lithostratigraphic code to identify the boreholes in which specific mapped lithostratigraphic units had been interpreted from the logs. These were then plotted as point entities in 2D map form for the 2D visualization of the spatial distribution of each unit. The point features were overlain on the outcrop of the relevant lithostratigraphic unit to which they were likely to be related or sourced from, or to which they had been classified. For example, all boreholes in which KPGR terrace deposits had been interpreted at some depth were plotted and overlain on the surface outcrop of the mapped KPGR, so that any likely mis-identifications could be spotted, and so that likely cases of subcrop KPGR could be discriminated from the outcrop of KPGR.

All the plotted lithogratigraphic units are shown overlain on a basemap consisting of linear features representing the M25 motorway and the tributary rivers of the Thames plus the Thames itself, along with the BGS mapped lithostratigraphic unit(s) that crop out shown as filled (grey) polygons.

Quaternary RTD sedimentary nomenclature

As the database comprises exclusively borehole data, it is considered worth providing the reader who is new to Quaternary deposits with descriptions of typical examples of the sedimentary facies, as well as the top and bottom surface features and any internal disturbances, as these features are not always determinable from any particular borehole description. All these features have been well described by Gibbard in the treatise of 1985 from his field observations (Gibbard 1985).

The surface on which the deposits now rest (the bench), the deposits themselves and the top terrace surfaces may or may not be discernible. Apart from the obvious pre-depositional subaerial erosion of the underlying strata and post-depositional erosion of the RTDs themselves, there are many other reasons for local variations in thickness. The RTDs have frequently been disturbed by post-depositional processes, particularly cryoturbation and solifluction. The user therefore needs to be aware of the possibility of such occurrences.

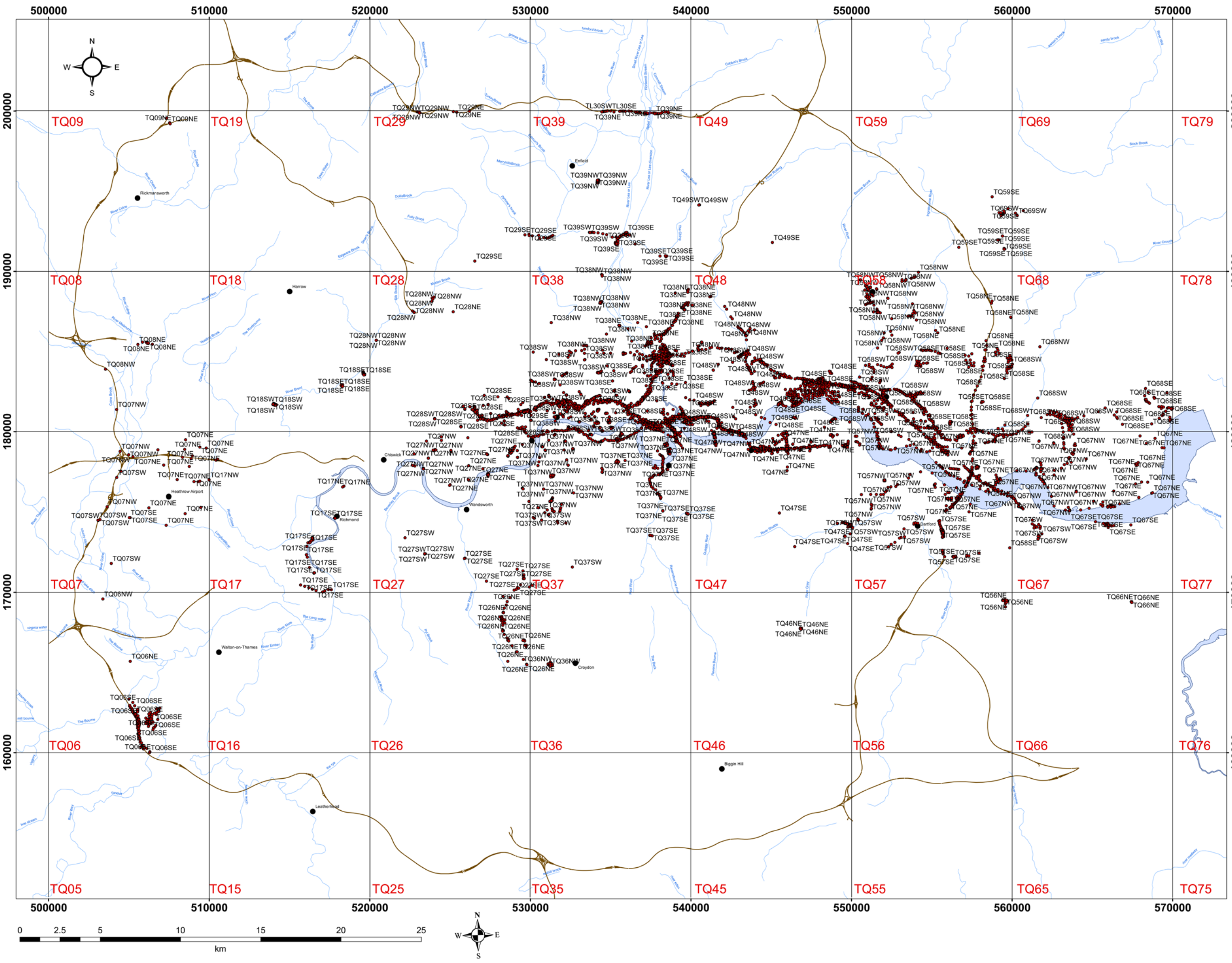

Fig. 5. Point locations of the entire borehole database, showing OS BNG TQ reference squares used and referred to in both the database and this Technical Note. For example, grid reference [563200/179560] lies in TQ67NW. The route of the M25 motorway, Thames and minor rivers are plotted here and on all subsequent maps as a navigation aid.

Facies descriptions

The facies associated with Quaternary deposition, which would probably be present within the RTDs of the River Thames and its tributaries, include the following types: massive or crudely bedded gravel (most common facies); interbedded, tabular, cross-bedded gravel and sand; trough cross-bedded pebbly sand alternating with gravel; scour fill sand (scours are <50 cm deep and <1.5 m wide); and horizontally bedded, often massive, sand (very local extent and <20 cm thick).

Terrace surfaces and internal structures

Uneven bedrock surfaces (benches)

Also recorded is the relative morphology, on a local scale, of the basal surface of the gravel or sand deposit (the bench), and the degree of unevenness of that surface. Similarly, the upper surface of a unit can be very variable. The relevant descriptions of these phenomena, summarized below, are from Gibbard (1985):

(1) fluvial scouring and channelling:
- 'irregular channelled surface of the Reading Beds';
- 'over 2 m of poorly stratified gravel filling channels scoured into the Reading Beds';

(2) solution of the bedrock and subsequent collapse of the overlying gravels, particularly dolines or funnel-shaped hollows:
- 'large infilled funnel-shaped hollow contained pebbly clays as well as disturbed gravel and sand. The hollows … extend through … and into the bedrock beneath … [suggesting] that they originated by bedrock solution collapse';
- 'the gravel bedding was much disturbed by collapse into a solution hollow in the underlying Chalk';

(3) doming, diapirs and pillars of bedrock protruding up into the overlying gravels:
- 'the gravel being penetrated' 'seemingly from below by irregular pinnacles (up to 2 m high) composed of disintegrated Chalk … diapiric-like structures';

(4) erosion along fault or fracture systems:
- see descriptions below in the section 'Disturbances to the internal structure of the RTDs', solution collapse.

Deep scour hollows, funnel-shaped hollows (dolines) and other overthickened sequences of gravels associated with solution collapse (see (2) above), as a group, are relevant to Buried Hollows or Drift-Filled Hollows (DFHs), which are described in the section 'Buried or Drift-Filled Hollows' below. They are found in this database and are reviewed below. As this Technical Note is considered to be important as a reference for deposits of potentially economic significance, particularly thick sections of gravel and sand (i.e. >10 m thickness) are also identified and reviewed below; some of these may actually represent 'over-thickened' sequences, as most RTDs are far less than 10 m thick.

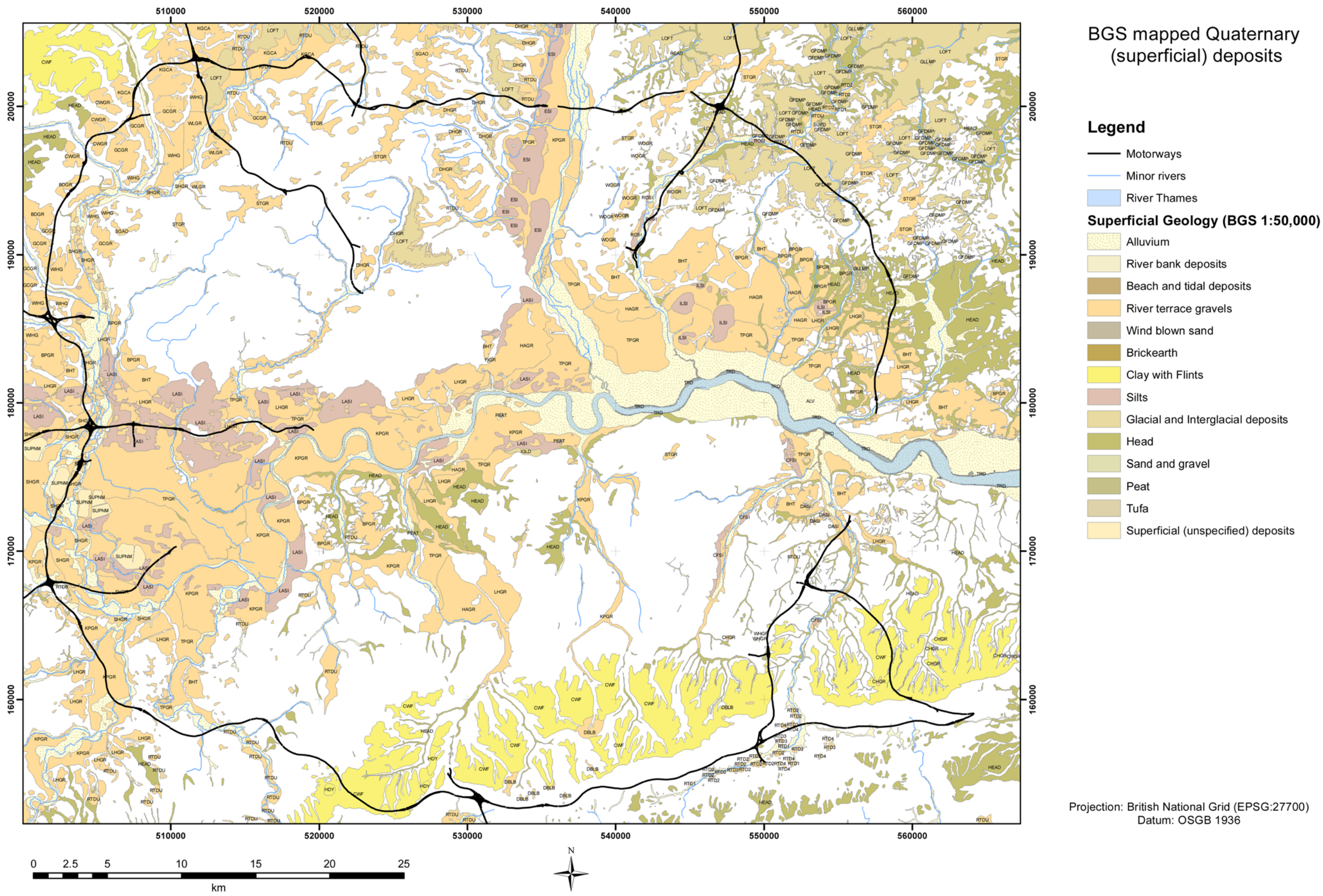

Fig. 6. Simplified Quaternary lithostratigraphic units that crop out in the Greater London area.

Degradation and dissection

Gibbard (1985) has provided useful descriptions of the following as evidence of degradation and dissection of Quaternary deposits: 'the surface is dissected by dry valleys and degraded by solution collapse', 'degraded remnants of a previously thicker aggradation', or 'been dissected by later stream erosion'. These descriptions have been used to identify borehole records and lithostratigraphic intervals that show signs of such activities.

Disturbances to the internal structure of the RTDs

The following descriptions are recorded by Gibbard (1985); again, these have been used to identify borehole records and lithostratigraphic intervals that show signs of such activities:

(1) cryoturbation (disturbance owing to frost action) causes disturbance within the RTDs:
- 'The … contact between the deposits being heavily disturbed by cryoturbation';
- 'the upper 60 cm of the gravels … was disturbed by cryoturbation';
- 'the uppermost 1.8 m was much disturbed';

(2) solifluction (slow downhill flow of soil, in periglacial regions) causes disturbance within the RTDs:
- '[the gravels] included large rafts of Reading Beds';
- 'the brown silt … appears to represent a slope wash deposit, … from its indistinct stratification and variable thickness';

(3) solution collapse of the underlying bedrock and disturbance of overlying sediments is also common, particularly above Chalk bedrock:
- 'Observations of steeply dipping strata … showed evidence for large-scale collapse of the deposits into bedrock solution cavities … some of the collapse was post-depositional … shown by a large thickness of the silt … filling a funnel-shaped hollow in the gravels at least 3 m deep and 6 m wide in one place';
- 'this suggests that solution occurred during or even prior to gravel and sand deposition;

(4) solution collapse associated with faulting and dolines (sinkholes):
- 'Throughout the pit, the sediments were disturbed by much small-scale normal, step faulting. The faulting increased in intensity downwards and indicated collapse by release from beneath. … It appears … that this and probably the other collapse features result from syn-depositional bedrock collapse';
- 'the upper part of the sequence is highly fissured … from its form, position and size, … the basin [probably] originated by bedrock solution. Its funnel-like shape and proportions closely resemble those of dolines … [which are] thought to form by intense solution activity along joint planes or fissures in the rock';
- 'The faulting … suggests that the basin was actively subsiding during this time';

(5) cryoturbation and solifluction may be described together in the same deposit:
- 'The upper 1 m of the gravels was cryoturbated and overlain by 20 cm of very clayey, probably solifluction gravel';

(6) cryoturbation, solifluction and solution hollows may be described together in the same deposit:
- 'the upper 1 m of the gravel was cryoturbated, beneath it was undisturbed except by two large hollows filled with brown pebbly clay. These features, up to 2 m wide and

3 m deep, penetrated the entire thickness of the bedded deposits and extended into the Chalk beneath. The form of these hollows suggests that they are solution features.'

Eroded, reworked and irregular landforms

Small disconnected areas of RTDs have been identified and described by Gibbard (1985) as 'remnants on either side of the … valley', 'extensively worked outliers', 'the dissected surface of the outlier' and 'terrace remnants'. The original extents of such areas cannot be determined but the spatial distribution of their occurrence may hint at the course of the palaeo-fluvial channel(s) that once connected them.

Measured thickness of RTDs

Factors that may have affected the original depositional thickness of any RTD unit include, as a minimum:

(1) scouring during deposition and post-depositional effects of erosion; many pre- and post-depositional solution and collapse features noted in (4) above;
(2) pre-, syn- and post-depositional effects of faulting;
(3) effects of extraction, locally for construction projects and regionally by extraction companies.

Consequently, the RTD thickness recorded in the database at any one location may be original, with or without geological modification, or may be remnants, or may be absent, owing to removal by human intervention. In short, the RTD sequence may be the original thickness or what is left now, or anywhere in between. Thicknesses are provided in the lithostratigraphic summaries below as minimum, average and maximum, but these must be treated with caution for the reasons cited above.

Lithostratigraphic descriptions and distribution analyses

The lithostratigraphic distribution maps are composed from BGS 1:50 000 solid and drift geological digital map sheets, over which any boreholes with records including the relevant lithostratigraphic unit are overlain. The locations of the boreholes that include specific stratigraphic or lithological features are overlain on relevant outcrop lithostratigraphy in a series of maps that are referred to in each subsection below. All mapping is necessarily limited by the database available:

(1) base Quaternary outcrop map;
(2) distribution of borehole data against specific lithostratigraphic units (e.g. boreholes encountering KPGR over the KPGR outcrops);
(3) distribution of specific lithological features: cobbles, chalk clasts, shell clasts against relevant outcrops;
(4) distribution of Buried (Drift-Filled) Hollows (hereafter DFHs) and thick sand and gravel sequences;
(5) distribution of tectonic features: fissures, fractures, faults.

Quaternary RTD Members

The following sections describe each of the RTD stratigraphic units in turn, using first the description from the BGS Lexicon of Named Rock Units, then pertinent descriptive facts from analysis of the database. These facts are based on the raw information provided by the operations team who drilled the borehole and information and/or analysis from the Crossrail contractors. Their descriptions are summarized, from oldest to youngest, in the following sections.

Stanmore Gravel Formation (STGR)

The STGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness distribution, parent unit, previous names and type area and/or section.

Age range	Pleistocene Epoch (QP)
Lithological and sedimentological description	Gravel and sand, clayey near base. Gravel mostly composed of flints, up to 150 mm in diameter, with a little quartz, quartzite and Lower Greensand chert in the fine fractions. Matrix of orange–brown, pale grey, red mottled clay and sandy clay, with pockets of coarse sand. Locally with layers of silt, clay or peat. Interpreted as offshore or beach gravels or possibly fluvial
Lower boundary	Rests unconformably on London Clay; base of deposit is at 105–128 m OD
Upper boundary	Overlain in places by Anglian till of the Lowestoft Formation, but generally at surface
Thickness	To 7 m; average 3 m (4.8 m is recorded in the BGS Stanmore Common borehole; TQ19SE)
Geographical limits	Thames Valley and Colne and Lea valleys; plateau cappings from Stanmore, Middlesex to Billericay, Essex, and Shooter's Hill, SE London (North Kent)
Parent unit	Crag Group (CRAG)
Previous name(s)	Pebble Gravel; Stanmore Member; Pebble Gravel Formation; Stanmore Pebble Gravel; Warley Gravel; Plateau Gravel; Sand And Gravel Of Unknown Age
Type area	Harrow Weald Common
Partial type section	Stanmore Common, described in BGS boreholes TQ19SE (TQ 1550/9394) and (TQ 1647/9360). Some 4.80 m recorded in BGS Stanmore Common borehole (TQ19SE)

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	<50
Distribution of boreholes	TQ29NE, TQ59SE, TQ69SW
Quality of data	All from BGS database, mainly good quality
Thickness variations	<0.5 to 4.6 m, average 2.55 m
Good descriptions	These are at Brentwood, where they are as follows:
TQ59SE [559490/193760]	Fine, medium and coarse GRAVEL in matrix of soft to firm to stiff light brown and brown–grey–red mottled slightly silty–sandy CLAY, becoming soft to firm very sandy CLAY at base
TQ59SE [558760/194650]	Fine light brown clayey SAND overlies fine, medium and coarse GRAVEL with a little fine and medium brown very clayey sand
TQ69SW [560700/193780]	Fine brown and grey, clayey, silty SAND overlies firm brown and grey, very sandy, silty CLAY with fine and medium gravel
Other comments	No cobbles, chalk or shell clasts have been reported. The STGR Member overlies Bagshot Formation mainly, but also London Clay Formation. The Lowestoft Formation overlies STGR in TQ 58NW

Lowestoft Formation (LOFT)

The LOFT is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Age range	Anglian Stage (QA)
Lithological and sedimentological description	The Lowestoft Formation forms an extensive sheet of chalky till, together with outwash sands and gravels, silts and clays. The till is characterized by its chalk and flint content. The carbonate content of the till matrix is about 30%, and tills within the underlying Happisburgh Formation have less than 20%
Lower boundary	The Lowestoft Formation unconformably overlies a large range of Mesozoic, Paleogene, Neogene and early Pleistocene bedrock formations, and in eastern East Anglia also unconformably overlies the older glacigenic Happisburgh Formation (formerly Corton Formation on some maps) and the fluvial sands and gravels of the Dunwich Group. The tills within the Lowestoft Formation typically contain a significantly higher percentage of chalk than the underlying tills. The gravels in the Dunwich Group contain a significant amount of quartzose lithologies and only very minor quantities of erratics and chalk, whereas the gravels in the Lowestoft Formation contain common erratics from Scotland and northern England, and abundant chalk where not decalcified
Upper boundary	The Lowestoft Formation is overlain unconformably by deposits of the Britannia Catchments Group and in northeastern East Anglia by the Sheringham Cliffs Formation. Where the uppermost part of the Lowestoft Formation comprises sand and gravel, it is not always easy to determine its upper boundary if overlain by younger sand and gravel, but in general the younger sand and gravel is better sorted and chalk free
Thickness	Extremely variable. It is thickest in buried valleys where locally up to 60 m may be present. Thick accumulations are also more generally present beneath much of northern Essex and south Suffolk
Geographical limits	There is some debate as to the extent of the Lowestoft Formation. It is extensive over East Anglia, having its southern limit near Romford, Essex. It is probable that most of the chalky tills in central East Anglia are also part of the Lowestoft Formation. In northern East Anglia the very chalky tills commonly referred to informally as the 'marly drift' were generally included within the Lowestoft Formation, but recent work has indicated that these may belong to a younger glaciation. Likewise, chalky tills in the south and east Midlands have commonly been linked with the Lowestoft Formation, but these may also be younger. It is also uncertain how the pre-Devensian tills in Lincolnshire relate to the Lowestoft Formation
Parent unit	Albion Glaciogenic Group (ALBI)
Previous name(s)	Lowestoft Till Group; Lowestoft Boulder Clay; Cromer Till; Lowestoft Till Formation
Type section	Cliff sections at Corton, Norfolk

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. LOFT is present in about five boreholes in TQ58 NW and 59SE, where it is up to 3.4 m thick. It is described as boulder clay: firm, brown and grey, sandy clay with gravel; no cobbles or shell clasts are recorded but chalk clasts are present in TQ58NW. It overlies London Clay and is overlain by BPGR in TQ58NW.

Black Park Gravel Member (BPGR)

The BPGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Anglian Stage (QA)
Lithological and sedimentological description	Sand and gravel, with possible lenses of silt, clay or peat (generic description). Horizontally stratified, matrix-supported gravel with thin tabular cross-bedded sand channels. Gravel assemblage is characterized by abundant angular flint (75–89%), sparse rounded flint (3–9%), sparse vein quartz (4–10%) and sparse quartzite (1–6%)
Lower boundary	Rests unconformably on bedrock geology
Upper boundary	At surface
Thickness	1–6 m, average 3 m
Geographical limits	Thames Valley and associated tributaries
Parent unit	Thames Valley Formation (TV)
Type area	Black Park Country Park, Slough
Stratotype	Up to 4 m of gravel and sand (Gibbard 1985)

Number of boreholes	<50
Distribution of boreholes	Dominantly in TQ58NW; also in TQ08NE, TQ27SW and TQ68SE
Quality of data	All from BGS database and good quality
Thickness variations	<0.5 to 15.75 m; average 2.62 m
Good description	Clayey sand, overlies clayey sand with gravel, passes down into sand, and then sand and small gravel
Other comments	No cobbles, shell or chalk clasts are reported. Most boreholes have a subcrop of London Clay, a few near Thurrock overlie Lambeth Group beds, and several near Hornchurch overlie LOFT

Woodford Gravel Formation (WOGR)

The WOGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, previous names and type area and/or section.

Age range	Cromerian Stage (QC)–Anglian Stage (QA)
Lithological and sedimentological description	Sand and gravel, locally with lenses of silt, clay or peat and organic material (generic description)
Lower boundary	Rests unconformably on bedrock geology
Upper boundary	Overlain in part by Anglian till, otherwise at surface
Thickness	1–10 m, average 5 m
Geographical limits	Tributary of pre-diversionary (ancestral) River Thames, Woodford–Epping
Previous name(s)	Glacial Sand and Gravel (GSG)
Type area	North Circular Road, Woodford, series of boreholes

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	<10
Distribution of boreholes	TQ39SE to TQ49SW, near South Woodford
Quality of data	All from BGS database and good quality
Thickness variations	<0.50 to 1.90 m; average 1.21 m
Good description	Firm to stiff brown fissured silty clay overlying medium dense orange–brown silty medium to coarse sand and angular to subrounded fine to coarse gravel
Other comments	No cobbles, chalk or shell class have been reported. Subcrop of London Clay, sometimes fissured

Dollis Hill Gravel Member (DHGR)

The DHGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Cromerian Stage (QC)–Anglian Stage (QA)
Lithological and sedimentological description	Gravel, sandy and clayey in part, with some laminated silty beds. Sand and gravel, locally with lenses of silt, clay or peat and organic material (generic description)
Lower boundary	Rests unconformably on bedrock geology
Upper boundary	Overlain by Anglian Till in many places; otherwise at surface
Thickness	1–15 m
Geographical limits	Tributary of ancestral River Thames in the Finchley–Hoddesdon area of North London
Parent unit	Sudbury Formation (SBRY)
Previous name(s)	Dollis Hill Gravel Formation; Glacial Sand And Gravel (GSG)
Type section	Temporary exposure on Dollis Hill near Hendon

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	<5
Distribution of boreholes	TQ28NE, TQ29SE; St Pancras
Quality of data	All from BGS database, good quality
Thickness variations	0.8–1.90 m
Good description	Soft to firm becoming soft brown slightly gravelly clay with thin bands of medium yellow–brown sand. Gravel comprises fine to medium subrounded flint or quartz. Firm brown slightly gravelly clay with thin bands of medium yellow–brown sand. Gravel comprises fine to medium subrounded gravel
Other comments	No cobbles, chalk or shell clasts have been reported. The subcrop is of London Clay

Gerrards Cross Gravel Member (GCGR)

The GCGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Cromerian Stage (QC)–Anglian Stage (QA)
Lithological and sedimentological descriptio	Sand and gravel, locally with lenses of silt, clay or peat and organic material (generic description)
Lower boundary	Rests unconformably on bedrock geology
Upper boundary	At surface
Thickness	1–10 m, average 4 m thick
Geographical limits	Ancestral Thames course (Vale of St Albans)
Parent unit	Sudbury Formation (SBRY)
Previous name(s)	Gerrards Cross Gravel Formation
Type section	Quarry face at Gerrards Cross Quarry

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	<5
Distribution of boreholes	TQ09NE; close to junction 19, M25
Quality of data	All from BGS database, good quality
Thickness variations	1.7–7.0 m; minimum thickness did not penetrate subcrop
Good description	Very dense orange brown, becoming dark orange brown, slightly to very clayey, silty, fine to coarse sandy, fine to coarse subangular to rounded gravel, with occasional cobbles and carbonaceous staining
Other comments	One borehole at TQ09NE (507570/199200) has a very heterogeneous sediment including cobbles. The boreholes did not penetrate the bedrock

Boyn Hill Gravel Member (BHT)

The BHT is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Hoxnian Stage (QX)–Wolstonian Stage (QO)
Lithological and sedimentological description	Sand and gravel, with possible lenses of silt, clay or peat (generic description). Poorly sorted, stratified gravel and locally tabular cross-bedded sand beds. Gravel assemblage is characterized by abundant angular flint (77–81%), sparse rounded flint (5–10%), sparse vein quartz (4–7%), sparse quartzite (1.5–5%), sparse Greensand chert (2.5–4%) and less than 1% of other types
Lower boundary	Rests unconformably on bedrock geology or older superficial deposits
Upper boundary	At surface
Thickness	1–9 m, average 5 m
Geographical limits	Thames Valley and associated tributaries
Parent unit	Thames Valley Formation (TV)
Previous name(s)	Boyn Hill Terrace; Boyn Hill Gravel Formation
Type section	Section near cemetery on Boyn Hill, Maidenhead (Gibbard 1985)
Illustrated in Figure 7	

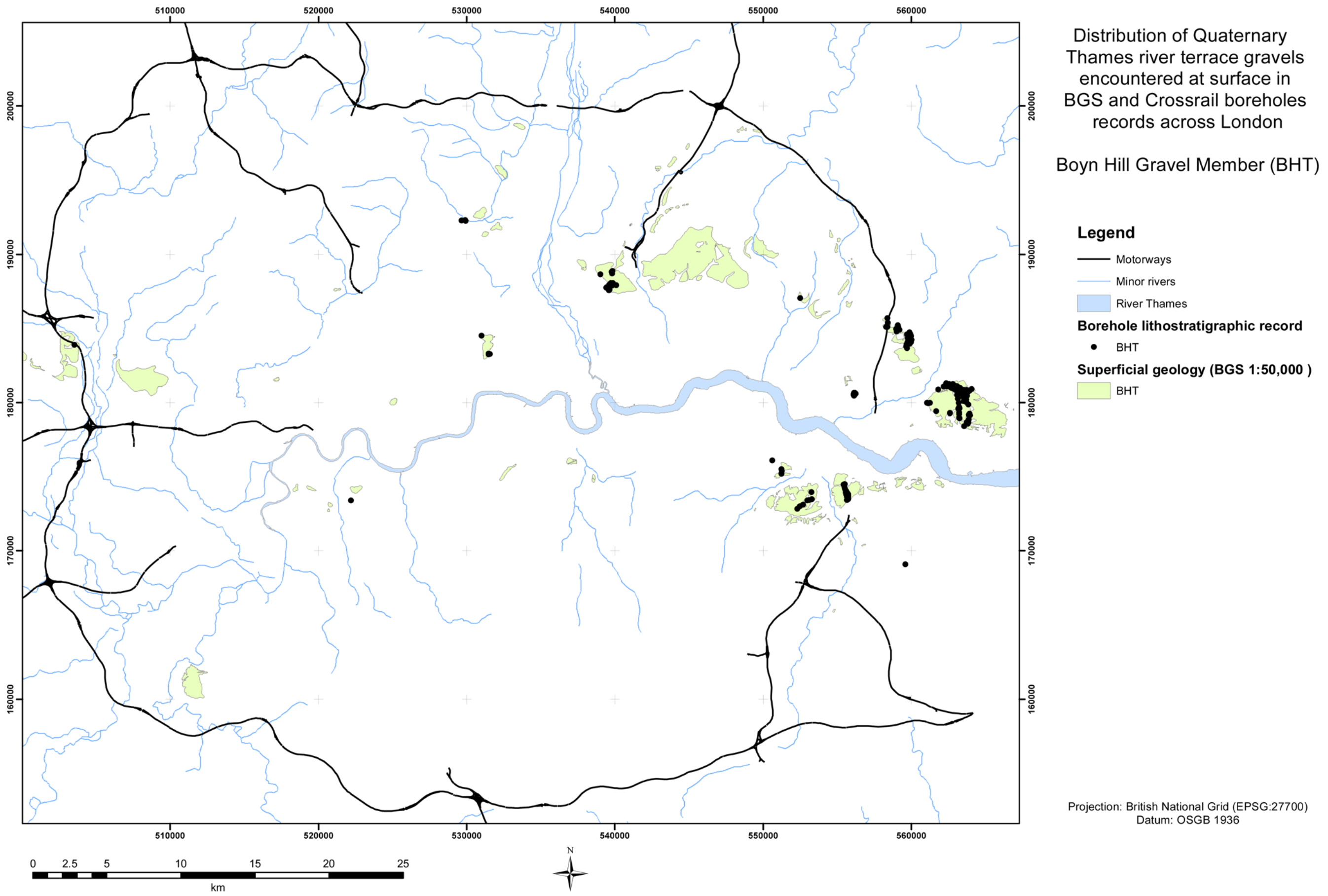

Fig. 7. Outcrops of Boyn Hill Terrace (BHT) sands and gravels, and boreholes encountering BHT.

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these are particularly detailed. Such information is summarized below.

Number of boreholes	>250
Distribution of boreholes	Varied (see Fig. 7); thickest sections in TQ57SE near A282 and Watling Street
Quality of data	All from BGS database and of good quality
Thickness variations	<0.5 to >25 m; average 5.59 m
Good descriptions	These include one from a very thick interval
TQ57SE [555657/173714]	Medium dense orange brown silty sand with angular to rounded fine and medium gravel. With coarse gravel below
TQ57SE [555715/173697]	Dense to very dense brown silty fine and medium sand with angular to rounded gravel and occasional small cobbles; passing down into very dense angular to rounded gravel and cobbles with some brown silty sand
TQ57SE [555727/173640] (BHT 22.55 m thick)	Stiff, brown mottled orange/brown and grey, slightly sandy, clay with pockets of grey slightly silty, fine sand and a little fine subrounded gravel (sieve analysis); passes down into medium dense, orange/brown, very silty fine to medium sand with pockets of orange/brown clay (sieve analysis). Medium dense, orange/brown and light brown fine sand passes down into soft grey, silty sandy clay with pockets of grey, silty, coarse sand and occasional medium to coarse gravel. Medium dense, orange/brown, silty fine to coarse sand with traces of medium, rounded gravel and pockets of orange/brown clay and, underneath, firm to stiff, orange/brown, very sandy clay (sieve analysis) with a little subangular medium flint gravel
The lower section is recorded as	Dense, orange brown and black, clayey fine to coarse sand and fine to coarse angular to rounded flint gravel. Medium dense to dense, angular to rounded, fine to coarse flint gravel and cobbles with some brown, slightly silty. Fine to coarse sand with a little brown, slightly silty, fine to coarse sand (sieve analysis) becoming dense to very dense, sand content increasing with cobbles at base with occasional pockets of brown silty clay, becoming medium dense to dense, with gravel-sized chalk fragments and flint gravel content decreasing. NB: it may be that this thick section is divided into an upper silty, clayey, sandy section (possibly one of the interglacial Silts Members) such as the ILSI, and a lower true sand and gravel river terrace section of sands and gravels (13.5 m thick)
Other comments	Shell clasts: one borehole has small shells within a sandy, gravelly clay, which may have been eroded from the underlying clay. The BHT sediments overlie the following: London Clay in mainly TQ58SE, 58NE, 58NW and in TQ38NE, 38SW; Reading Formation in TQ68SW; Upnor Formation and Woolwich Formation in TQ68SW; Thanet Formation in TQ57NW, 57SW, 67NW and 68SW; Chalk Group mainly in TQ57SE, 57SW, 58NE
	Chalk clasts are frequently present when BHT beds overlie a Chalk subcrop
	Cobbles are particularly abundant in TQ57SE as at TQ57SE [555727/173640], Watling Street Cemetery (22.75 m thick); and also common in boreholes in TQ58SE [556110/180520], Aveley; and TQ67NW [562590/179310], Little Thurrock. They are usually present in the basal strata

	Cobbles are also found in boreholes in square, as at TQ38NE [539789/188799], Epping Forest but only a few boreholes record cobbles. Occasionally cobbles are present throughout the RTDs, as at TQ57SE [555660/173728], Watling Street. The outcrops of BHT gravels in the eastern area, squares TQ57, TQ58, TQ67, in which cobbles are common, appear to be in a relatively upstream location but if the Thames River were the source, they should be in distal setting and the western outcrop should be in a more proximal setting with many cobbles, but here few cobbles are recorded. This suggests that the eastern outcrops may be part of a separate drainage system from those of the western outcrops. The presence of cobbles in eastern TQ57, TQ58, TQ67 squares is consistent with a southerly source upstream along the Darent River, which has a source in the Westerham area of the Weald. Further, the abundance of cobbles in the BHT deposits of these squares would suggest that there was uplift of the Wealden drainage source area prior to their deposition. The distribution of cobbles supports the proposed early Darrent river, which continues in a NNE direction through the Thurrock area to join probably the Crouch or Wid and to enter the North Sea along the Essex coast, possibly near Southend-on-Sea (see Figs 8 and 9). Thus, this evidence suggests that the western outcrops are part of the drainage system of the ancestral River Thames, whereas the eastern outcrops are part of the ancestral Darrent River drainage system. The ancestral Darent River system, from a Wealden source, through Essex to a North Sea estuary, flows along a separate route to, and is separate from, the ancestral Thames and its drainage system. Consequently, it would appear that the RTDs along the River Darrent may have been misclassified as part of the Boyn Hill Terrace Member, and thus part of the Thames Valley Formation and Thames tributaries, whereas they should probably be renamed the Darrent River Terrace Deposits
BHT deposits overlie	London Clay in the areas to the west of TQ38 and under the Essex outcrops in TQ58SE, 68SW Chalk in TQ57; Thanet Sand Formation in TQ67NW, Lambeth Group beds in TQ68SW
BHT overlain by	No silts are found overlying the BHT deposits

Lynch Hill Gravel Member (LHGR)

The LHGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Wolstonian Stage (QO)
Lithological and sedimentological description	Sand and gravel, locally with lenses of silt, clay or peat (generic description)
Lower boundary	Rests unconformably on bedrock geology
Upper boundary	At surface
Thickness	Average 7 m, range 1–12 m
Geographical limits	Thames Valley and associated tributaries
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Lynch Hill Gravel Formation
Alternative name(s)	Denham Valley Terrace
Type section	Lynch Hill, Slough
Illustrated in Figure 10	

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these are particularly detailed. Such information is summarized below.

Number of boreholes	>375
Distribution of boreholes	Along the Thames Valley in the central part of the study area from TQ08 to TQ68 and along the Lea and Wandle Valleys (see Fig. 6)
Quality of data	From both BGS and Crossrail data and are generally very good quality
Thickness variations	Sand and gravel, locally with lenses of silt, clay or peat (generic description); <0.5 to 15.4 m; average 3.71 m
Good descriptions from thick sequences	
TQ58SE [557550/180200]	*c.* 5 m. Medium dense, brown clayey, fine to medium sand and fine to medium to coarse gravel overlies soft brown, fine sandy, silty clay with a little fine gravel. Some grey patches. Becoming very silty and sandy near base then passing down into firm, dark grey, shaly silty clay with shells. Tends to break easily along shaly planes. Brown fine to medium sand and fine to medium to coarse gravel with some red patches passing down into firm to stiff mottled grey–green and rusty brown silty sandy clay and clayey coarse sand and gravel. Some silty pockets. Firm, brown, fine, sandy silt, clayey in places with some fine gravel overlies brown, silty, fine sand with some dark specks. A little gravel at 3.80–3.90 m below top of the LHGR beds
TQ58SE [558270/184580]	*c.* 15 m. Firm to stiff brown very sandy silty clay, with some fine to medium gravel overlies firm brown very sandy silty clay, with some pockets of grey fine sand. Firm brown/grey mottled slightly silty clay, with occasional pockets of light grey fine sand passes down into soft to firm brown very sandy clay, with some red patches. Soft to very soft brown sandy very silty CLAY with some greenish mottling in places. Laminations noticed in drilling. Soft to firm brown sandy and silty clay dark grey silty fine sand with some brown patches. Brown, very clayey, fine sand. Loose brown fine to medium sand with occasional fine gravel overlying soft to firm dark grey, sandy very silty organic clay (with traces of peat) loose brown fine to medium sand with some fine gravel soft dark grey/brown very silty clay. Soft, dark grey, very silty clay, with occasional brown patches. Small shells at 14.50–15.00 m and a trace of fine gravel. Becoming very soft in places. Grey fine to medium gravel with some coarse sand
Other comments	Shell clasts: one borehole in TQ58SE records shell clasts Chalk clasts are present in TQ58SE and 57NE HEAD (this is a poor term but is included here as many drilling teams use it) is described as overlying the LHGR outcrops in TQ27SE and in TQ57NE, 58SE Cobbles are noted in TQ27SE, 28SE in particular and also from boreholes in 37SW, 38NE, SW; also further east in many boreholes in TQ57NE, SE and a few in TQ68SE LHGR beds overlie London Clay, which is present throughout the area (TQ27SE, TQ28SE, TQ37, 38, 58SE, 58NW, 68SE); Lambeth Group, Upnor, Woolwich and Reading Beds; (TQ58SE and TQ68SE); Thanet Sand Formation (TQ57NE); and Chalk (TQ57NE) LHGR beds are overlain by LASI, mainly in TQ28SE and also in TQ38SW

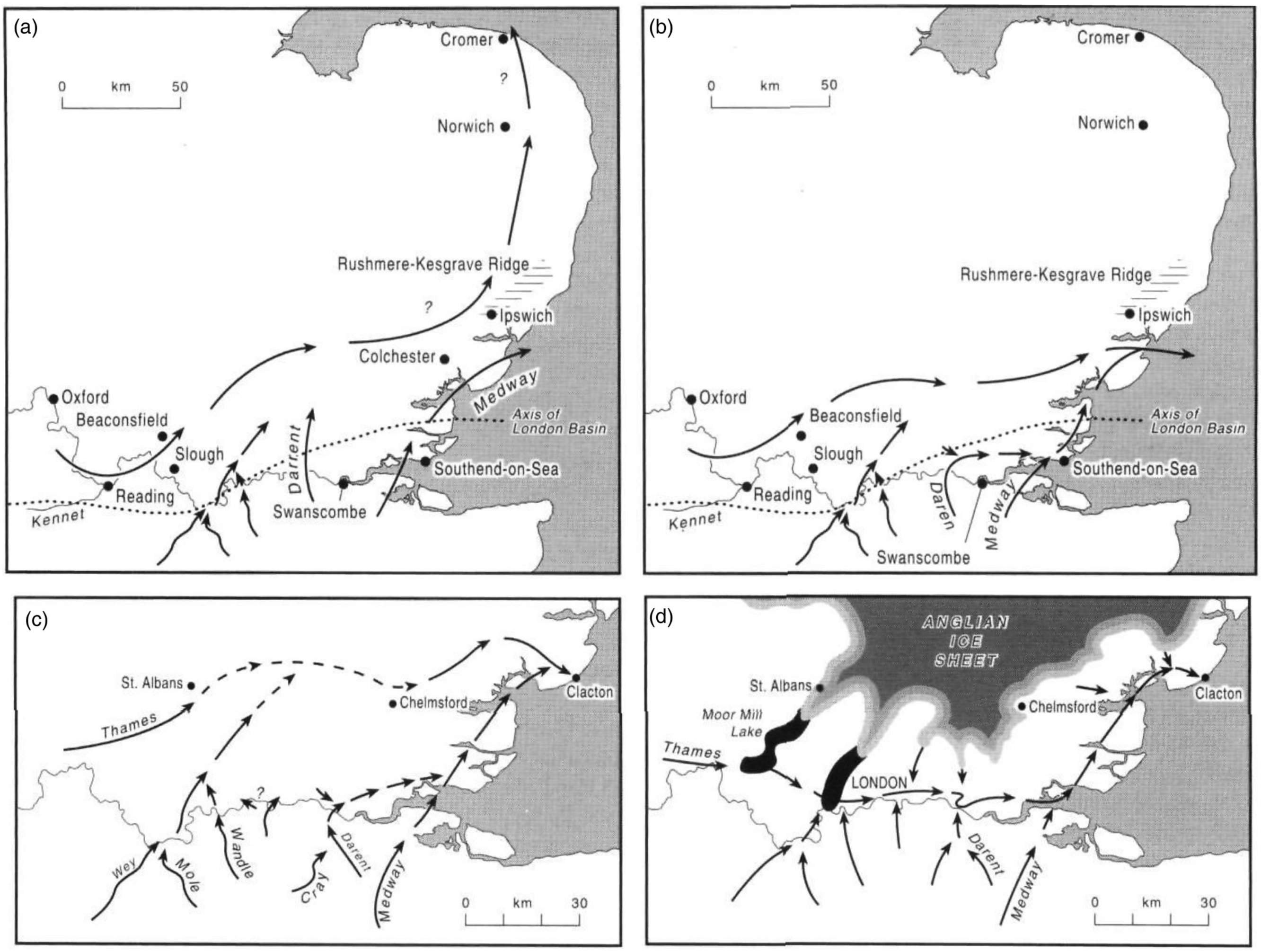

Fig. 8. The Pleistocene evolution of the Lower Thames drainage basin. (**a**) Early Pleistocene; (**b**) Early to Mid-Pleistocene (Cromerian); (**c**) Early Anglian–Esterian; (**d**) Anglian–Esterian glacial maximum, showing initiation of the post-diversion Thames drainage system. The proposed course of the River Darent should be noted. Source: Bridgland and Gibbard (1997).

Hackney Gravel Member (HAGR)

The HAGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, distribution, previous names and type area and/or section.

Age range	Wolstonian Stage (QO)
Lithological and sedimentological description	Sand and gravel, locally with lenses of silt, clay or peat (generic description)
Lower boundary	Rests with unconformity on bedrock geology (e.g. London Clay)
Upper boundary	At surface
Thickness	Average 6 m, range to 10 m
Geographical limits	Thames Valley and associated tributaries
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Hackney Gravel Formation; Terrace 3a
Type area	Hackney Downs
Illustrated in Figure 11	

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log

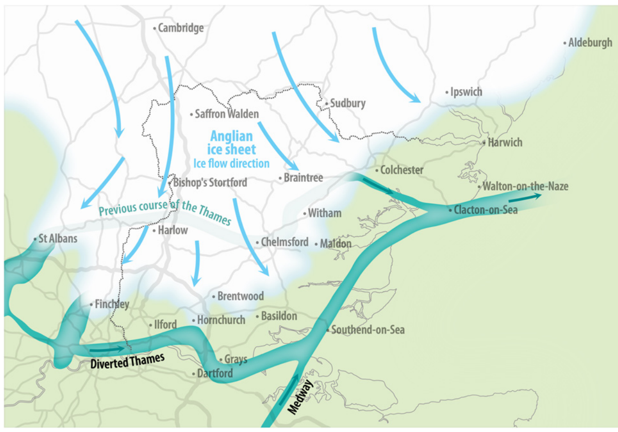

Fig. 9. Fig. 9. A proposed route for the palaeo-Thames and tributary rivers during the Anglian glacial maximum (Lucy 1999; Mercer and Mercer 2022). Source: Essex Rock and Mineral Society (ERMS), reproduced with kind permission.

descriptions and comments, where these are particularly detailed. Such information is summarized below.

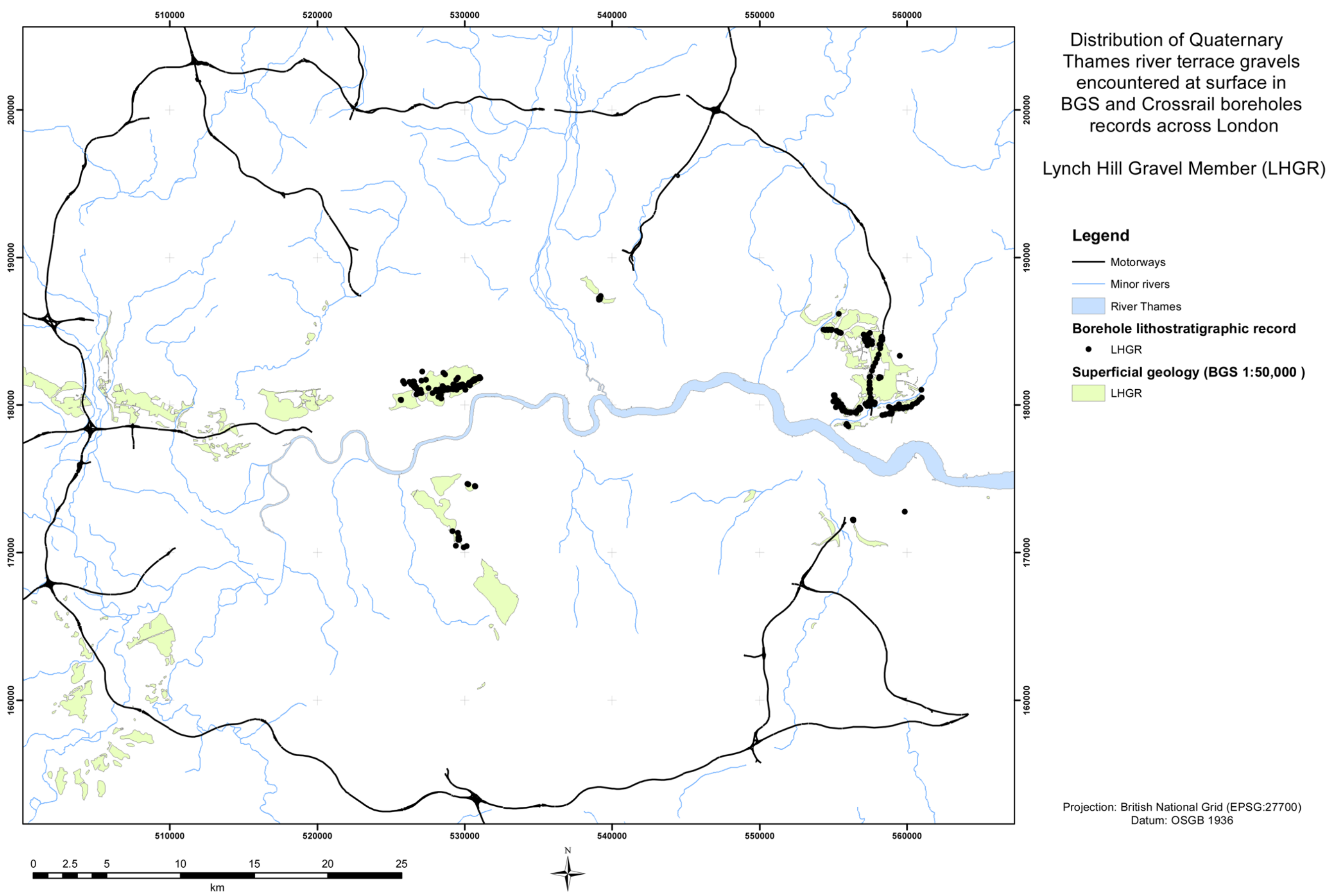

Fig. 10. Outcrops of Lynch Hill River Terrace Deposits (LHGR) and boreholes encountering LHGR.

Number of boreholes	>250
Distribution of boreholes	TQ26NE and from City of London eastwards, particularly in TQ38SW to TQ58NW (see Fig. 11)
Quality of data	From both Crossrail and BGS datasets and mainly of good quality
Thickness variations	<0.5 m to >14 m; with an average of 2.7 m
Good descriptions	
TQ38SW [531210/181768]	Brown sand and gravel passing down into flinty, brown sand and gravel. Very dense, grey and brown, fine to coarse, angular to subangular, flint gravel with some brown, medium and coarse sand and occasional subrounded cobbles. Becoming very dense, brown, medium and coarse sand (driller's descriptions)
TQ38NW [532814/185053]	Medium dense, brown, clayey sandy subrounded to rounded fine to coarse flint gravel passing down into medium dense to dense, brown clayey to very clayey, sandy, subangular to rounded, fine to coarse flint gravel. Dense brown sandy subangular to rounded fine to coarse flint gravel. Firm, brown, slightly fine to coarse, sandy clay with a little angular to rounded, fine to medium, flint gravel
TQ58NW [550830/188830]	Soft to firm, brown/grey, sandy, silty clay with pebbles passes down into soft to firm, brown, sandy clay and soft, grey, clayey silt and medium dense, sand and gravel
Other comments	No shell or chalk clasts are recorded. HEAD is recorded in boreholes from TQ58NW
	Cobbles are present, mainly at the base of the RTD and mainly in TQ 26NE but also in TQ38NE and NW
	HAGR deposits overlie, where recorded, dominantly London Clay Formation
	HAGR deposits are overlain by ILSI in TQ48NW, TQ38NW and SW

Taplow Gravel Member (TPGR)

The TPGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Wolstonian Stage (QO)
Lithological and sedimentological description	Sand and gravel, locally with lenses of silt, clay or peat (generic description)
Lower boundary	Rests with sharp base on bedrock geology (e.g. London Clay)
Upper boundary	At surface
Thickness	Average 5 m, locally to 9 m
Geographical limits	Thames Valley and associated tributaries
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Taplow Gravel Formation; Taplow Terrace
Type section	Gravel pit at Taplow Railway Station
Illustrated in Figure 12	

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these are particularly detailed. Such information is summarized below.

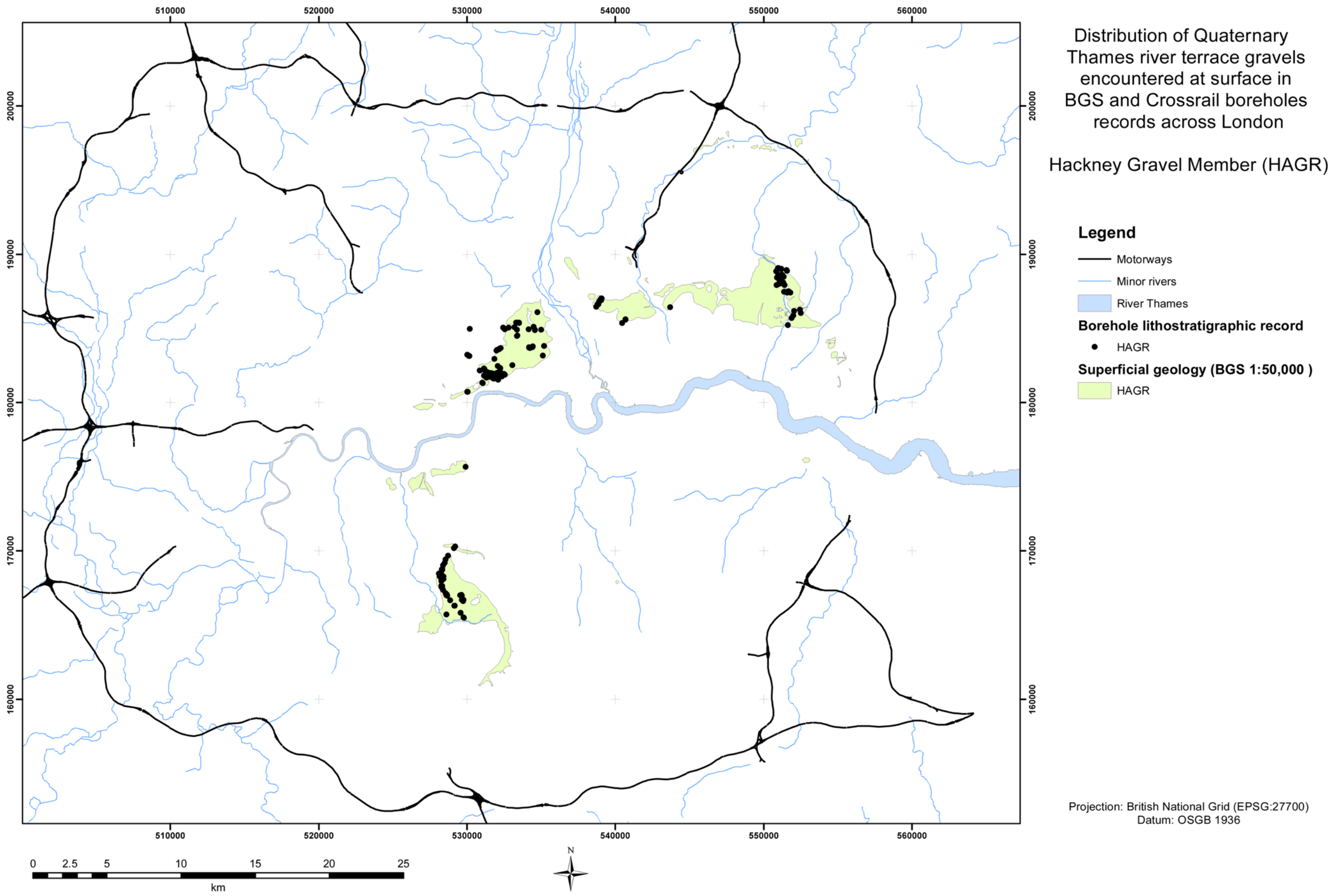

Fig. 11. Outcrops of Hackney Gravel Deposits (HAGR) and boreholes encountering HAGR.

Number of boreholes	*c.* 1000
Distribution of boreholes	Along the modern River Thames corridor from TQ07 to TQ67 (see Fig. 12)
Quality of data	From both Crossrail and BGS databases and are generally of good quality
Thickness variations	<0.5 m to 16.54 m with an average of 3.26 m
Good descriptions in borehole records	
TQ38NE [539662/184890]	Yellow brown, fine to coarse sand with a little angular to rounded, fine to medium flint gravel. Becoming orange brown, sandy (fine to coarse) flint gravel and then sand and gravel
TQ48NW [542351/185170]	Medium dense, orange brown, very sandy, subangular to subrounded, fine to coarse, flint gravel. Rare flint cobbles
TQ48SW [544306/184373]	Medium dense light brown medium to coarse sandy angular to subrounded fine to coarse flint gravel. Medium dense brown medium to coarse sandy subangular to subrounded fine to coarse flint gravel. Greyish brown clay with very closely spaced thin laminae of orange brown very silty fine sand
TQ57	Medium dense, dark brown, fine, sandy very clayey silt with occasional rounded to angular flint gravel passing down into light brown fine sandy silt and medium dense, orange brown, slightly silty, fine to coarse sand with subangular fine to coarse flint gravel and rare chalk clasts. Medium dense rounded to sub-angular flint gravel with some brown fine to coarse sand. Occasional flint cobbles and chalk gravel. Cobbles increase towards base
Other comments	Shell clasts: no shell clasts are recorded. HEAD is recorded from TQ07NE, but mainly from TQ58 and TQ66, TQ68
	Chalk clasts are not common and they are recorded exclusively from TQ57; where the subcrop has been penetrated, it is Chalk
	Cobbles are present throughout the outcrops from TQ38 to TQ67, but over 50% of the boreholes where cobbles are recorded are in TQ38, and there is just one record in TQ67
	TPGR beds overlie almost exclusively, London Clay Formation within and to the west of TQ39; between TQ39 and TQ57, subcrops of London Clay Formation, Thanet Sand Formation, and Woolwich, Reading and Harwich Beds exist below the TPGR; whereas TPGR beds overlie Chalk Formation almost exclusively within and to the east of TQ57
	TPGR beds are overlain by CFSI in TQ59NW; ILSI in TQ48SW; LASI in TQ07NE, TQ18SW, TQ38SE and SW

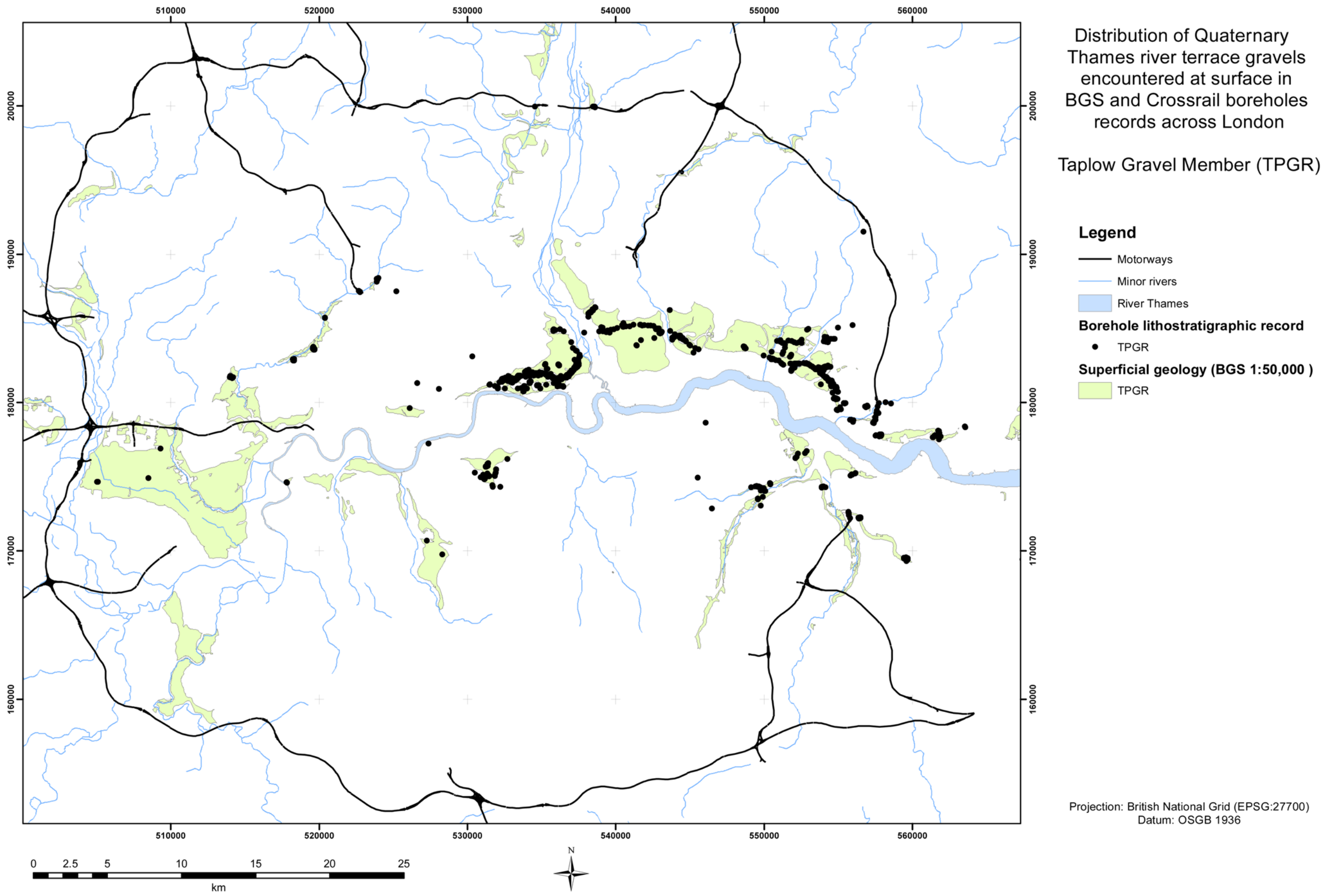

Fig. 12. Outcrops of Taplow Gravel Deposits (TPGR) and boreholes encountering TPGR.

Kempton Park Gravel Member (KPGR)

The KPGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Devensian Stage (QD)
Lithological and sedimentological description	Sand and gravel, locally with lenses of silt, clay or peat (generic description)
Lower boundary	Rests on bedrock geology of London Clay, or Woolwich and Reading Beds
Upper boundary	At surface
Thickness	Average thickness 6 m, but much thicker where infilling deep hollows
Geographical limits	Thames Valley and associated tributaries
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Kempton Park Gravel; Kempton Park Member; Kempton Park Gravel Member (KPGR); Upper Floodplain Terrace; Flood Plain Gravel (FPGR)
Type section	Kempton Park, former gravel workings at Kempton Park Racecourse (Bowen 1999)
Illustrated in Figure 13	

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these are particularly detailed. Such information is summarized below.

Number of boreholes	*c.* 2000
Distribution of boreholes	In TQ06SE and then mainly from TQ37 to TQ67 along the modern River Thames and Lea valleys (see Fig. 13)
Quality of data	From both Crossrail and BGS datasets and generally of good quality
Thickness variations	<0.5 m to >30 m, average of >5 m; the thick deposits are associated with DFHs
Good descriptions in borehole records	
TQ06SE [505620/ 161560]	Brown, silty fine sand with scattered gravel. Cobbles; black pebbles and gravel and brown coarse sand. Brown fine gravel and coarse sand. Grey coarse to medium sand with scattered fine gravel
TQ38SE [539284/ 180993]	Dense, dark grey and black slightly sandy, slightly silty, rounded to sub-angular fine to coarse gravel of flint and quartzite with occasional cobbles. Sand is fine to coarse. Rare pockets (20 mm by 20 mm) of soft, dark grey clay. This overlies medium dense becoming dense dark grey and black sandy rounded to sub-angular fine to coarse gravel of flint and quartzite with occasional cobbles.

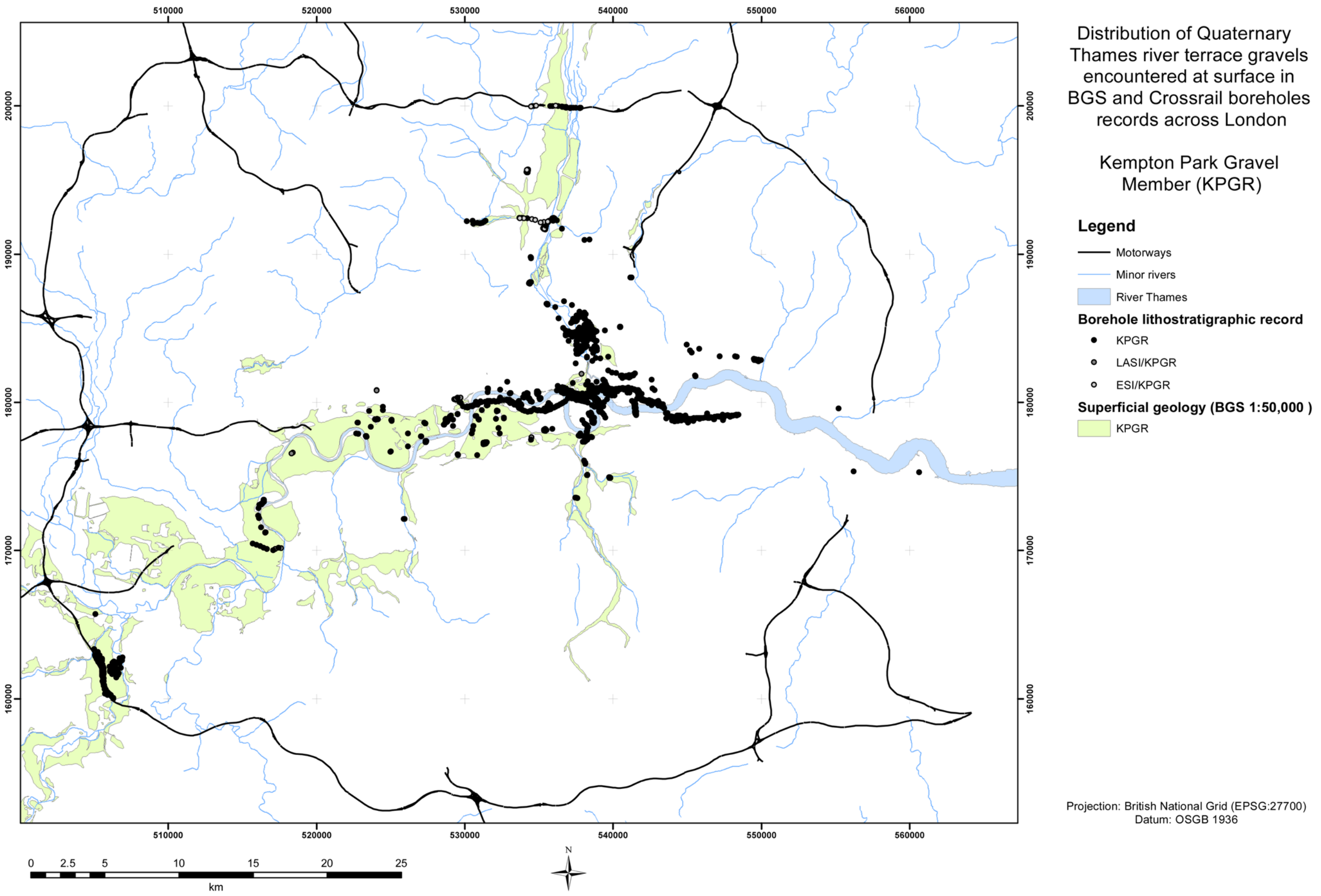

Fig. 13. Outcrops of Kempton Park Gravel Deposits (KPGR) and boreholes encountering KPGR.

TQ38SE [538652/ 1805452]	Medium dense, brown, silty, sub-angular to rounded gravel of flint, quartzite and chalk, with some generally medium to coarse sand. Medium dense, light brown, generally medium to coarse sand, with some mainly fine to medium, sub-angular to rounded, flint gravel. Below about 11.50 m with rare flint cobbles
TQ47NE [546459/ 178993]	Dense, brown, sandy angular to rounded fine to coarse gravel of flint. Sand is fine to coarse. Dense, brown, slightly gravelly, fine to coarse sand. Gravel is subangular to rounded, fine to coarse flint. Occasional shell fragments (<20 mm). Medium dense brown sandy angular to rounded fine to coarse gravel of flint. Sand is fine to coarse. Occasional shell fragments (<10 mm). Medium dense, brown angular to rounded, fine to medium gravel of flint. Medium dense, brown, very sandy, angular to rounded, fine to coarse gravel of flint. Sand is fine to coarse. Rare sub-rounded to rounded cobbles of flint
TQ48SE [545531/ 181798]	Medium dense to dense, rounded to sub-angular, coarse to medium to fine gravel with coarse sand; coarse to medium to fine sandy gravel with bands of grey sand
TQ56NE [559595/ 169396]	Orange brown, speckled white, clayey, silty, fine and medium sand with much angular fine flint gravel. Orange brown angular fine and medium flint gravel
TQ67NW [560625/ 175279]	Grey brown, slightly clayey silty fine and medium sand with occasional angular to rounded fine and medium flint gravel. Recovered as very soft dark grey brown sandy (fine) clay with some angular to rounded fine chalk and fine to coarse flint gravel. Light brown slightly silty fine and medium sand and angular to sub-rounded fine chalk gravel with occasional fine to coarse gravel and cobbles of flint. Light brown very sandy (fine to coarse) angular to sub-rounded fine chalk and fine to coarse flint gravel with occasional flint cobbles. Brown sandy (fine to coarse) angular to rounded fine to coarse flint and fine chalk gravel with occasional flint cobbles
Other comments	Shell clasts are recorded from <5% boreholes; these usually occur in the basal beds and usually overlie, and are probably eroded from, the Woolwich Formation (often the Lower Shelly Clay)
	In other boreholes, shell clasts are recorded throughout the sequences of sands and gravels, particularly in the thick sequences in TQ47NE overlying Thanet Sand Formation (TAB). For example, at TQ47 [544863/178925] and TQ47 [545953/178630] where the KPGR overlies TAB, and at TQ47 [545953/179413] and TQ47 [546005/ 179413] where RTDU also show thick sequences with several shell horizons overlying TAB. These sequences are believed to indicate deposition within a submerged estuarine location
	Chalk clasts are recorded from <5% boreholes; these consistently overlie the Chalk Formation and are believed to have been eroded from the underlying Chalk beds during transportation
	Cobbles are relatively common (*c*. 15% boreholes); they are present in TQ06; they are very common in TQ37, TQ38 (50% of the boreholes with cobbles are from these squares); they also occur in TQ47, TQ48
	Drift-Filled Hollows (DFH): the boreholes that are described by BGS as DFHs all occur close to the Blackwall Tunnel
	Head: one or two boreholes in TQ58SW record Head overlying the gravels

KPGR is overlain by Enfield Silt in TL30 and TQ39NW, SE, SW; and Langley Silt in TQ17NE, NW; 27NE, NW; 28SE; 37NW and 38SE
KPGR overlies Bagshot Sand Formation, TQ06; London Clay Formation, throughout the area from TQ27, 28 through TQ37, 38 and 39 to TQ48SW and in TL30; Lambeth Group (Upnor Formation Reading Formation Woolwich Formation), dominantly in TQ38SE, NE and TQ37NE but also in TQ48SE, 48SW; Thanet Sand Formation, in TQ67NW, TQ48SE, and particularly in TQ47NW and TQ37NE; and Chalk Formation in mainly TQ47NW and also in TQ37NE

Shepperton Gravel Member (SHGR)

The SHGR is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Devensian Stage (QD)
Lithological and sedimentological description	Gravel with clay and sand
Lower boundary	Erosional surface cut into Tertiary–Cretaceous bedrock
Upper boundary	Lies beneath Thames floodplain alluvium (Staines Alluvial Deposits)
Thickness	0–8 m, locally 12–14 m
Geographical limits	Thames Valley, Abingdon–London
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Shepperton Gravel; Valley Gravel (VLGR)
Type section	Shepperton Quarry

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	<10
Distribution of boreholes	TQ07NW, SW and TQ06NW
Quality of data	All from BGS database; good quality data
Thickness variations	*c.* 1 m to >13 m
Good descriptions	Medium dense to very dense, brown sand with sub-angular to rounded fine to medium flint gravel; passes down into green brown sand with some pockets of very soft orange brown silty clay and occasional pockets of soft green brown sandy clay
	Dense brown, very sandy, slightly silty, sub-angular to rounded, fine to coarse gravel, passes down into silty fine to coarse sand with much gravel and occasional dark brown, sandy clay
Other comments	No chalk or shell clasts recorded. Cobbles are present in only two boreholes. SHGR deposits overlie London Clay Formation. SHGR are not recorded as being overlain by any interglacial silt deposits.

River Terrace Deposits (Undifferentiated) (RTDU)

Some 1461 borehole logs record the presence of undifferentiated river terrace deposits, dominantly along the lower Thames floodplain but also in central and north London. By comparing their distribution with the mapped superficial outcrop geology, it was hoped to reveal the likely parents of these undifferentiated RTDs and there appears to be a close association with the TPGR (see Fig. 14).

Database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	1461
Distribution of boreholes (see Fig. 10)	Several boreholes with RTDU occur west of the Isle of Dogs, or TQ48, in TQ06, TQ36, TQ37, TQ38 and TQ39
	The majority of the boreholes lie in a swathe from TQ48SE and TQ47NE through TQ58SW to TQ57NW and NE, and on to TQ67 and TQ68SE. The RTDU in these boreholes lie beneath thick alluvium/peat sections or within the River Thames estuary and thus not visible at the surface for comparison with other outcrops
Quality of data	All from BGS database and are generally of good quality
Thickness variations	<0.5 m to >25 m, average of 4.6 m
Good descriptions	
TQ47NE, [549701/179156], 5.3 m thick	Medium dense grey and brown, very sandy gravel. Gravel is flint, from 8.0 m becoming dense; from 9.50 m becoming dense to very dense and with occasional chalk gravel
TQ48SE, [549978/182751], 12.0 m thick	Dense to medium dense (variable) light brown; fine to coarse sand with a little to some fine to coarse flint gravel
TQ58SW [550290/183064], 15.65 m thick	Very dense brown sandy fine to coarse subangular to rounded gravel with occasional cobbles. Clayey and silty in upper 0.30 m. Soft grey organic clayey silt with rare subangular gravel and traces of peat. Medium dense dark greenish brown silty fine to medium sandy shelly subangular to subrounded gravel. Medium dense dark grey silty fine sand with rare angular gravel. Dense grey silty fine to medium sand with rare angular gravel. Very dense grey fine to medium sandy clayey silt and silty sand with occasional shell fragments
TQ57NE [555659/177727], 6.7 m thick	Medium dense black brown coarse, medium and fine gravel
TQ68SE [569310/181570], 9.60 m thick	Brown silty fine sand. Coarse, medium and fine brown sandy gravel, with a few cobbles
RTDU deposits overlie	London Clay in TQ29NW, TW38SW and TQ39NE; TQ48SE and 48SW; TQ58SE and 58SW; TAB (and LMBE) in TQ36NW and TQ37NE; Chalk in TQ46NE, TQ37NE, TQ57NE and in TQ67; Chalk, TAB (and WL) in TQ47NE; and LC, RB, HWH, WL, TAB, UOR, LMBE, CK in TQ48SE and TQ58SW
RTDU deposits are overlain by	There is no record of them being overlain by Quaternary silt deposits, but they are extensively overlain by the thick alluvium and peat sequences of the Holocene Flandrian

Silt Members

It should be noted that many of the intervals described as 'brickearth' are probably associated with one of the following silt members.

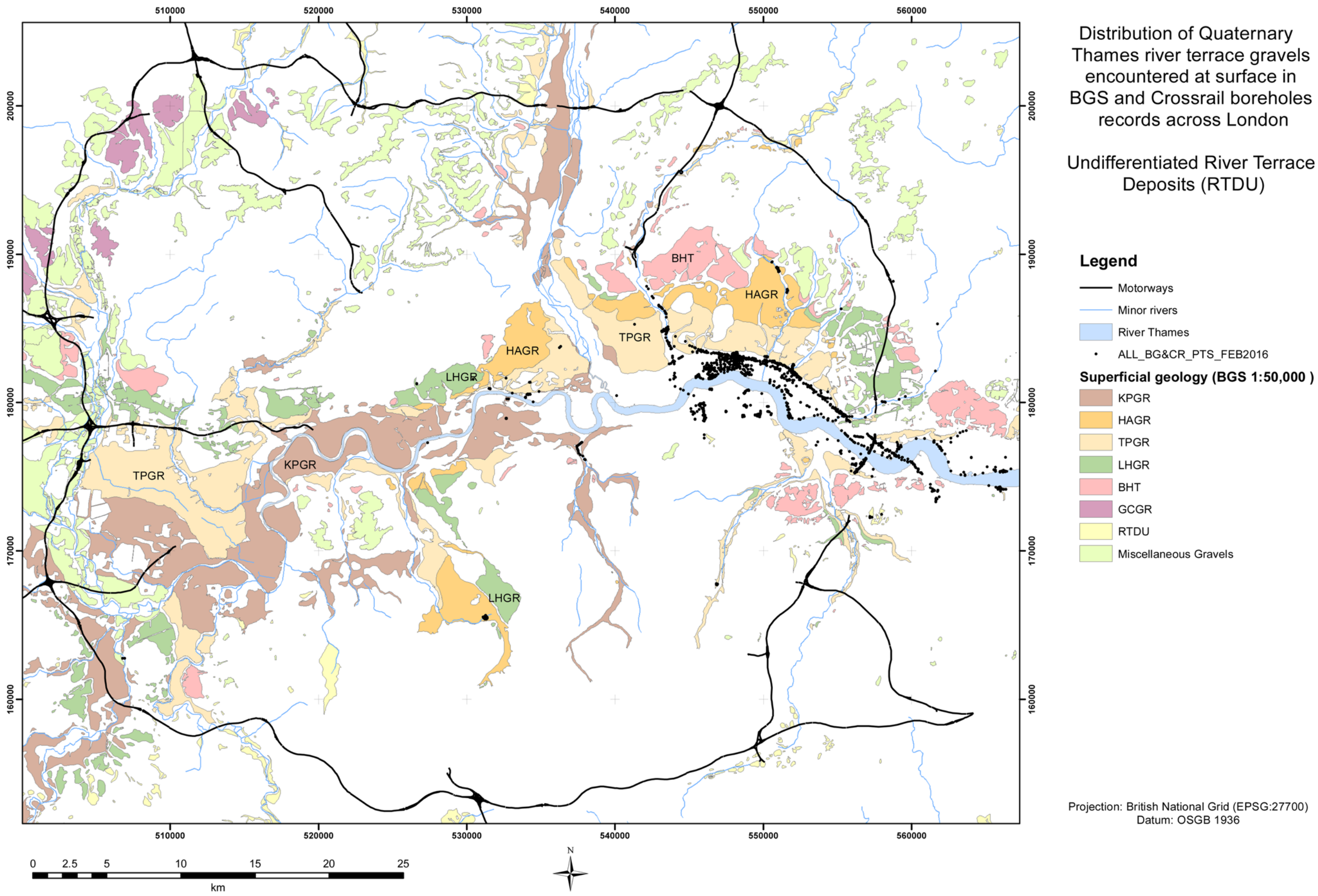

Fig. 14. Distribution of the boreholes in which Undifferentiated River Terrace Deposits (RTDU) are recorded.

Ilford Silt Member (ILSI)

The ILSI is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Saalian Stage (BS)
Lithological and sedimentological description	Sandy clay and silt
Lower boundary	Rests on Taplow Gravel, Hackney Gravel and Boyn Hill Gravel river terrace deposits
Upper boundary	At surface
Thickness	Typically 1–3 m but up to 6 m, possibly more
Geographical limits	Thames Valley, north shore, from Ilford, possibly as far as Grays
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Ilford Silt Formation; Grays Brickearth; Brickearth (BRK)
Type area	Old brickpits, Ilford to Seven Kings
Illustrated in Figure 15	

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	<20
Distribution of boreholes	TQ48NW and SW, 57NE, 58NW (see Fig. 15 for distribution of all silts)
Quality of data	All from BGS database and are good quality
Thickness variations	<0.5 m to >2.75 m; thickest occurrences are in TQ48SW and TQ57NE
Good descriptions	Orange–brown silty very sandy clay with some fine gravel Orange–brown, slightly clayey fine to medium sand varies from dense to very dense Brown slightly fine sandy clay with a little angular to rounded fine to medium gravel
Other comments	Overlies BPGR, HAGR, TPGR

Crayford Silt Member (CFSI)

The CFSI is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Ipswichian Stage (QI)
Lithological and sedimentological description	Generically it varies from silt to clay, commonly yellow–brown. Origin uncertain. Commonly includes a high percentage of wind-blown, silt-sized quartz (possibly loess). Locally represented by yellow to buff sand with shells at base passing up through brown, bedded sand with sandy silt to grey clay and shelly sand at the top
Lower boundary	Overlies Interglacial gravel and sand
Upper boundary	At surface or overlain by floodplain gravel
Thickness	2.4 m (average)
Geographical limits	Crayford, and Cray and Darent valleys
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Crayford Brickearth; Crayford Brickearth Formation; Crayford Silt Formation
Type area	Crayford area (Greater London) (Ellison *et al.* 2004)
Illustrated in Figure 15	

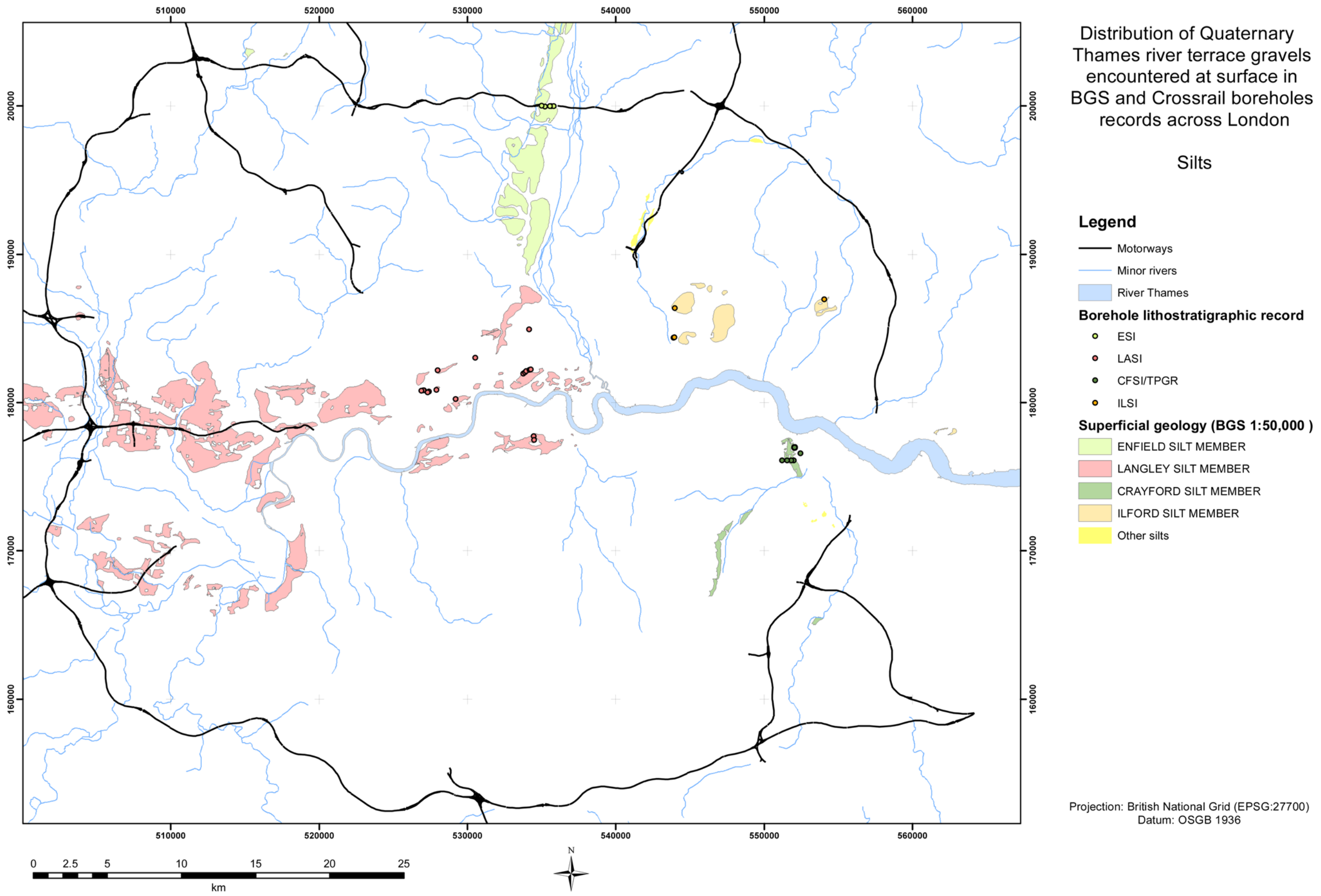

Fig. 15. Outcrops of Silt Members and boreholes encountering LASI, ILSI, ESI and CFSI.

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	*c.* 10
Distribution of boreholes	TQ57NW (see Fig. 15 for distribution of all silts)
Quality of data	All from BGS database, and are of good quality
Thickness variations	<0.5 m to *c.* 4 m
Good description	Stiff, brown, sandy clayey silt with some coarse to fine flint gravel. Medium dense, slightly clayey, medium to fine sand. Compact sand
Other comments	CFSI overlies TPGR

Langley Silt Member (LASI)

The LASI is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Devensian Stage (QD)
Lithological and sedimentological description	Varies from silt to clay, commonly yellow–brown and massively bedded (generic description)
Lower boundary	Rests on sand and gravel River Terrace Deposits, with sharp base
Upper boundary	At surface
Thickness	1–5 m, average 3 m
Geographical limits	Thames Valley from Goring to Thames Estuary
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Langley Silt Formation; Brickearth (BRK)
Type section	Gravel pit at Langley, Berks
Illustrated in Figure 15	

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	>200
Distribution of boreholes	The majority of the boreholes with LASI in them (almost 50%) are in TQ38SE, SW and TQ37NW. The remainder occur in TQ07, 17, 18, 27and 28 (see Fig. 15 for distribution of all silts)
Quality of data	From BGS database and Crossrail datasets and are good quality
Thickness variations	<0.5 m to 5.8 m, average of 1.3 m
Good descriptions	
TQ28SE [526550/181530]	Stiff, grey/brown clay. Stiff grey/brown mottled clay, silty in places and with small stones Mottled clay
TQ28SE [527031/180810]	Stiff orange brown mottled yellow brown silty sandy clay with a little flint gravel
TQ28SE [527083/180754]	Stiff, orange brown mottled yellow brown silty sandy clay with a little flint gravel
Other comments	LASI overlies mainly KPGR (inTQ28 and TQ37) and TPGR (in TQ07, 17, 18 and 38) but also LHGR (inTQ28), HAGR (inTQ38SW) and BPGR

Enfield Silt Member (ESI)

The ESI is classified and characterized by the following summary descriptions of age, lithostratigraphy, thickness, distribution, parent unit, previous names and type area and/or section.

Age range	Devensian Stage (QD) to Flandrian age (QF)
Lithological and sedimentological description	Varies from silt to clay, commonly yellow–brown and massive (generic description)
Lower boundary	Rests on river terrace deposits
Upper boundary	At surface
Thickness	1–5 m, average 2 m in thickness
Geographical limits	Lea Valley tributary of Thames, North London
Parent unit	Maidenhead Formation (MNHD)
Previous name(s)	Enfield Silt Formation; Brickearth (BRK)
Type section	Borehole sites at TQ 344 928 at Edmonton and 1200 m to the west (TQ 328 931)
Illustrated in Figure 15	

Other database information considered relevant to this unit includes the number and location of boreholes that encounter it, data quality, encountered unit thicknesses and the driller's or geologist's log descriptions and comments, where these contain other useful information. Such information is summarized below.

Number of boreholes	*c.* 50
Distribution of boreholes	Lea Valley, TQ39 and TL30 (see Fig. 15 for distribution of all silts)
Quality of data	All from BGS database, and are generally of good quality
Thickness variations	<0.5 m to 7.65 m but usually <3 m, average 1.18 m
Good description	Stiff brown sandy clay becoming very sandy at depth
Other comments	They overlie mainly KPGR but also TPGR locally

Alluvium and peat

Alluvium and peat is present all the way along the flood plain, but downstream of Woolwich particularly thick sequences of alluvium and peat occur overlying KPGR and RTDU sequences, as in TQ47NE and as at TQ [547286/179025] and TQ [547096/179037]; in TQ47NW, as at TQ [542925/179973]; in TQ48SW, as at TQ [542671/180031]; TQ [541423/180882] and at TQ [540306/180868]; also in TQ57NW at TQ [553550/177110] and TQ [552930/179790]; in TQ57NE at TQ [556809/176009]; also in TQ67NW, as at TQ [561709/177148] and TQ [562640/177580]. This area of thick alluvium and peat extends downstream to at least Rainham. Individual peat beds can probably be correlated between boreholes across various parts of this area, although this has not been attempted.

Depositional features and characteristic clasts

Shell clasts

Shell clasts are recorded in *c.* <5% of the RTDs. They are found in all the RTD members, one in BHT, and several in boreholes from HAGR, LHGR and TPGR, but most are found in the KPGR and RTDU boreholes. They are absent from the earlier Pleistocene to Anglian gravels (STGR, BPGR, GCGR, DHGR, WOGR) and from boreholes with LOFT deposits.

The shell clasts normally occur at, or near, the base of the gravel, which suggests that they have been eroded from underlying shell-bearing strata and included into the gravel deposit from erosion of the subcrop. These underlying strata include London Clay Formation, as at TQ58 [551282/181697], Lambeth Group, Lower Shelly Clay Formation, as at TQ38 [537672/180131], and Thanet Sand Formation, as in TQ48 and in TQ47 as at [545931/179440].

Figure 16 shows the distribution of shell clasts against the outcrop of the London Clay Formation, Harwich Formation and Lambeth Group rocks. As can be seen, there is a very close relationship between shell clasts and these underlying fossiliferous strata, particularly over the Shelly Clays of the Woolwich Formation, Lambeth Group.

The clasts are also recorded at the top of the RTD sequences, as at TQ47 [541460/179730], where they underlie shell-bearing alluvium and may well represent 'contamination' during cable percussion drilling, from the overlying alluvium.

Elsewhere shell-rich gravels are present; here shell clasts are recorded throughout thick Quaternary KPGR and RTDU gravel sequences. These thick and shell-rich gravels extend from TQ48SW and TQ47NE, as at [545653/178923], eastwards through TQ58SE, TQ57NW and NE, to TQ67. The presence of shell clasts throughout the RTDU sequences would suggest that rather than being clasts of underlying strata, the shells accumulated during deposition and thus, that these gravels were laid down in estuarine, marine or possibly intertidal conditions. These latter boreholes are often underlain by Thanet Sand Formation or London Clay.

Chalk clasts

Chalk clasts are present within <5% of the RTD sequences. They are found in the glacial tills of the Lowestoft Formation and all the main RTD Member sediments younger than the LOFT. Like the shell clasts, they are absent from the earlier Pleistocene to Anglian gravels (STGR, BPGR, GCGR, DHGR, WOGR).

Chalk clasts normally occur in the basal gravel beds, and usually are present in those boreholes that overlie, or are close to, a subcrop of Chalk strata; their distribution is shown in Figure 17. Again, the presence of the clasts at the base of the RTD would suggest that it has been eroded from underlying Chalk during erosion and deposition of the gravels. Nowhere are they found at different levels through the sequence of gravels.

Cobbles

Cobbles are recorded in boreholes within all the main sand and gravel RTD Members and their distribution as recorded in borehole log descriptions is shown in Figure 18. They are normally present in the basal beds as would be expected in fluvial deposits. Cobbles are absent from the LOFT tills and the earliest gravels of Pleistocene to Anglian age (STGR, BPGR, GCGR, DHGR and WOGR), except for one borehole within the GCGR deposits, in TQ09NE at [507570/199200], where cobbles occur at the base of the sequence.

Cobbles are present in all the later RTD Members. They typically occur in *c.* 10–20% of the boreholes and are assumed to represent proximal areas of fluvial deposition, close to glacial fronts or highland areas. Many clusters of boreholes recording cobbles occur in the terrace deposits to the south of the present Thames and these suggest that the Weald–North Downs area was an important uplifted source area relative to the present River Thames area, which was depressed (probably owing to isostatic movements caused by the thick ice sheet to the north).

BHT Member. Approximately 20% of the BHT boreholes record cobbles, these are mostly (*c.* 80%) in TQ57SE and TQ58), along the ancestral Darent River, flowing from its Wealden source in the Westerham area through Kent to Essex. The frequency of cobbles in TQ57NE boreholes suggests that they were deposited following uplift and erosion of the Wealden area. Cobbles are also present in the BHT deposits in TQ38NE, in the Leytonstone area, between the Lea and Roding Valleys. Clearly, this is a totally separate group of

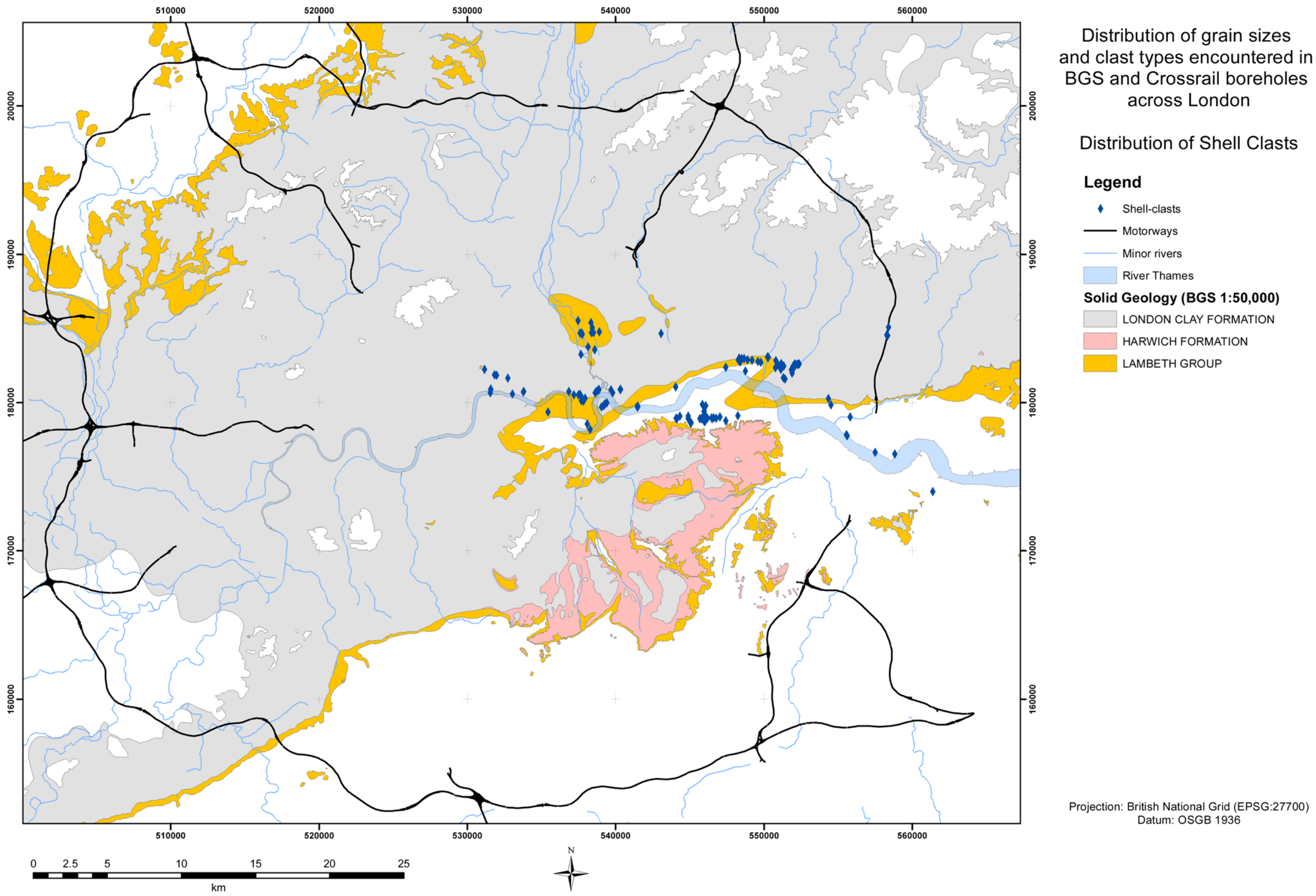

Fig. 16. Outcrops of Harwich Formation, Lambeth Group and London Clay Formation, and the distribution of boreholes in which Shell Clasts were identified in River Terrace Deposits.

sands and gravels from those of TQ57, but the source area for these deposits may well be from the north.

LHGR Member. Approximately 10% of the LHGR boreholes record cobbles, and these are located mainly (*c.* 80%) within the LHGR outcrops in TQ28SE, TQ38SW (Paddington to Holborn) and TQ27SE (Streatham), which may represent a lobe of an ice sheet to the north of this area. The remainder of cobbles (*c.* 20%) are recorded in a few boreholes within TQ57NE and TQ68SE in the Purfleet and Mar Dyke area, further supporting the notion that this area is probably part of the ancestral Darent drainage system.

HAGR Member. Also *c.* 10% of the boreholes with HAGR deposits contain cobbles. These boreholes are split approximately evenly (*c.* 50%) between two separate outcrops: that in TQ26NE (Beddington, near Carshalton, Wallington) to the east of the River Wandle and another in TQ38SW (Farringdon) to the west of the lower Lea Valley. This would suggest different source areas; the Beddington area deposits probably had a source from an uplifted southern, Wealden, area whereas the Farringdon area probably had a northerly glacial front source area. Surprisingly, none are recorded from boreholes within the outcrop area in TQ58NW.

TPGR. Approximately 10% of boreholes record cobbles, most of these (*c.* 70%) in the TPGR outcrop extending from west to east from TQ38SW through TQ38SE, TQ48NW and TQ48SW to TQ58SW and TQ57NE, suggesting a northerly source along a long glacial front to the north. A second cluster occurs from TQ56NE to TQ57SE, part of the Darent drainage system.

KPGR. Approximately 20% of the boreholes with KPGR deposits record cobbles. The majority of those (*c.* 80%) lie in the outcrop area between TQ37NW and TQ38SW (Victoria) through TQ38SE to TQ48SW (Poplar, Greenwich), to TQ47NE (Abbey Wood, Woolwich) and also in TQ37NE (Lewisham). These extend from west to east and probably reflect proximal fluvial deposition from a glacial front to the north. The remainder form a cluster in TQ06SE, in the Byfleet area on the River Wey, and probably reflect deposition from an uplifted Wealden source area, south of the North Downs.

SHGR. The only two boreholes with cobbles in SHGR deposits lie in TQ06NW (near the M4–M25 junction, near Harmondsworth), which is on the present River Colne.

RTDU. There are many boreholes where the RTD Member is unidentified and, of these, *c.* 15% are boreholes in which cobbles are recorded. Almost all of these (>95%) lie in the east, within an area defined approximately by TQ48NW (Ilford near the River Roding), TQ47NE (Woolwich), TQ58SW (Hornchurch, Rainham), TQ57NE (Dartford Tunnel area), TQ67 (Gravesend) and TQ68SE (Mucking, Stanford-le-Hope) in the Thames Estuary. Although their age is not known, the fact that they are distal to the Thames source area and are dominantly on the northern edge of the Thames suggests that they are probably related to a northerly glacial front source area.

Buried or Drift-Filled Hollows

Buried Hollow or Drift-Filled Hollow are terms given to an increasingly widely recognized geohazard in the UK and particularly in the London Basin. The ‘hollows’ are closed depressions in rockhead (often London Clay and sometimes Chalk), of varying size and shape, which are infilled by a range of Quaternary deposits, usually a non-laminated, non-structured mixture of clays, silts, sands and gravels (Hutchinson 1980; Bricker *et al.* 2013; Collins *et al.* 2015; Flynn *et al.* 2020). Buried Hollow is the term currently preferred by the BGS but DFH is still very widely

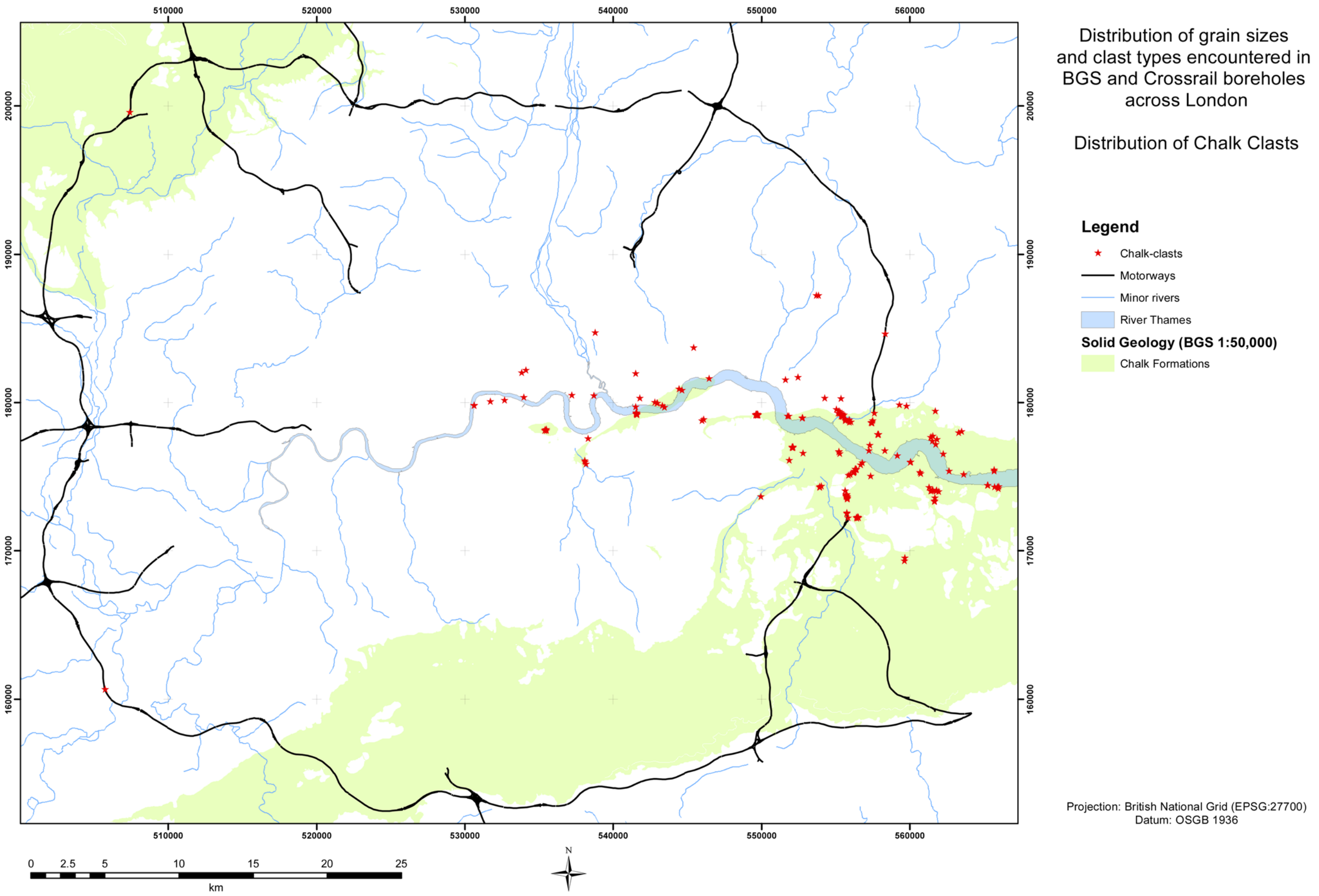

Fig. 17. Outcrops of Chalk and the distribution of boreholes in which Chalk Clasts were identified in River Terrace Deposits.

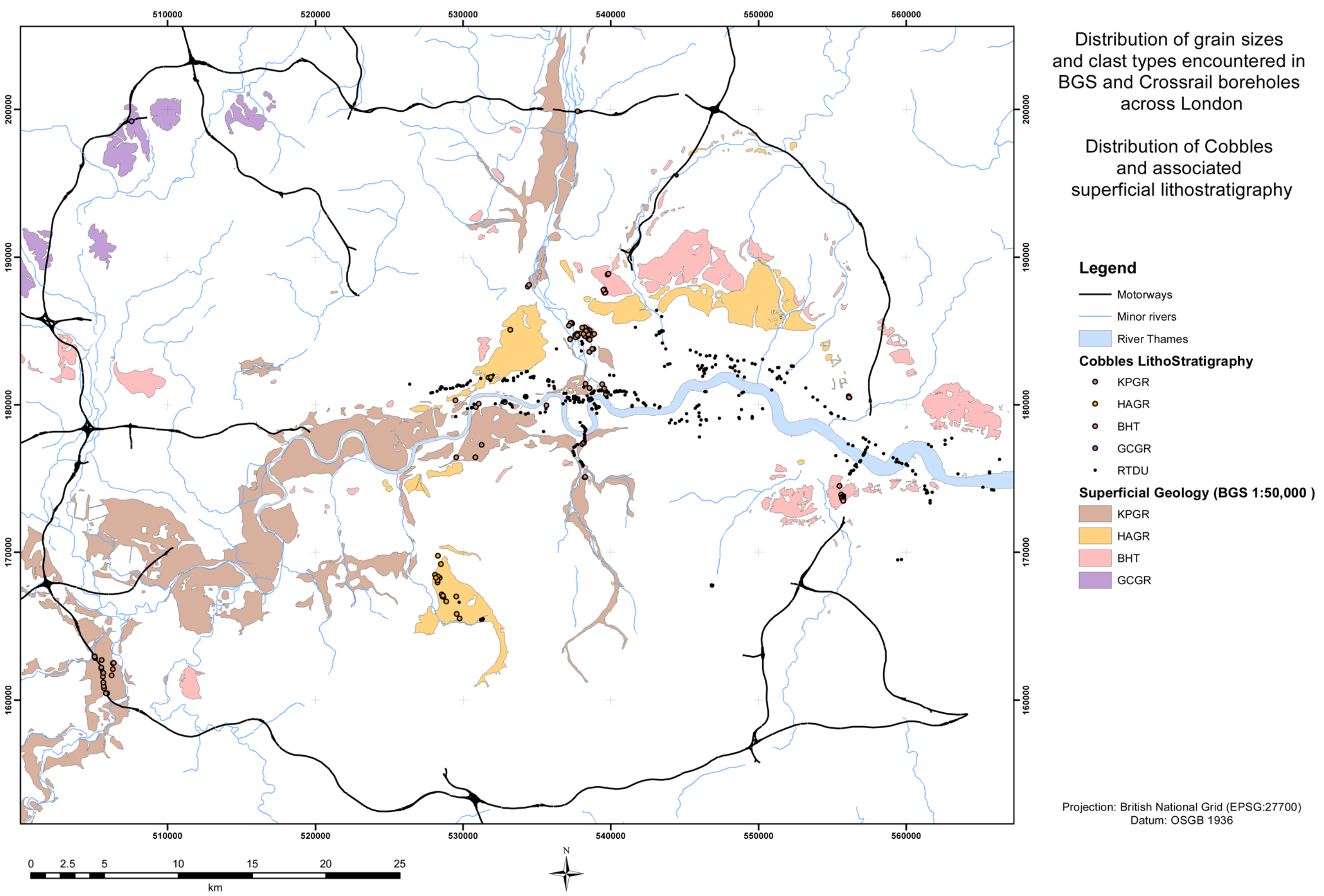

Fig. 18. Outcrops of major RTDs (KPGR, HAGR, GCGR and BHT) and the distribution of boreholes in which Cobbles were identified.

used. In the spreadsheet BGS-CR_RTD-BH_All-master.xlsx, these features are also commonly referred to by the drilling contractor team as Scour Hollow infill (SCHO). The genesis of Buried (Drift-Filled) Hollows is still under some debate and a number of recent works have revealed structural control, palaeogeographical correlation, relation to disturbance or folding of underlying strata, to movement of water, and that they may be connected with glacial processes.

DFHs can embody a variety of different genetic processes: scour features (deep erosional bases, probably along fracture zones), pingos (a mound of earth-covered ice in periglacial regions), dissolution hollows (sinkholes), diapiric structures (from frost heave and ice wedging) and from liquefaction of sediments owing to fault activity.

Berry (1979) worked on DFHs in central London (South Lambeth in TQ37NW, Battersea, Westminster in TQ27NE, Southwark in TQ38SW), which he concluded to be 'shallow buried "channels", now forming elongate closed hollows'; with most of the DFHs forming in the London Clay surface. 'They often appear to coincide with stream junctions in the Recent drainage pattern. Under-drainage may occur in some depressions through contact with underlying granular Lower Tertiary sediments. In some cases, these deposits appear to have risen above the adjacent levels as diapiric features, possibly at the time when deepening of the hollows occurred.' Berry's work, on a DFH at Gray's Inn Road, described fine-grained alluvial sequences containing fossils, with silts and clays reworked from London Clay, along with densely packed gravels and over-consolidated reworked London Clay, some of which could represent over-bank channel deposits.

Three particular DFHs, with slopes of *c.* 20–25°, along the Crossrail route were mapped by Flynn *et al.* (2020) and this summary is shown in Table 3 (see Figs 19 and 20). Banks *et al.* (2015) developed an updated geohazard susceptibility map for the London region, which compiles previously mapped DFHs in addition to several newly identified features. These have been included in the map shown in Figure 21. A further DFH is proposed in the Watling Street Area, in TQ57SE, and is compared with Davis' DFHs in Table 3.

The section shown in Figure 20 shows a very thick section of sands and gravels recorded in the borehole at TQ38SE [538642/180353], with the entire sequence forming one DFH. The log shows that this thick section of DFH sediments is described as 'Medium dense grey occasionally brown angular to sub-angular fine to coarse flint gravel with much very soft fine to coarse sandy clay'. This sequence is interrupted at −25 m to −27.5 m and at −34.97 m (−26.87 m drilled depth) to −39.90 m (−31.80 m drilled depth) by Chalk, which appears to be in the form of large blocks 'floating' within the thick sand–gravel sequence.

The upper section of Chalk (*c.* 2 m thick) is described as '(recovered as) structureless Chalk, composed of fine to coarse gravel sized (weak to moderately weak) chalk and flint fragments with some soft white comminuted chalk matrix and occasional cobbles (possibly SCHO)'. Below that a further *c.* 5 m section of Chalk is described as 'Off-white moderately weathered CHALK, moderately weak'. Below *c.* 7 m, the rock changes character even further, and some detail is provided by the presence of the following features:

- fractures, very closely to medium spaced, infilled up to 40 mm with brown clayey, silty fine sand and rare rounded fine to medium flint gravel;
- fissures at 29.85–29.98 m, 45°, rough, planar, infilled up to 10 mm with sand;
- fissures at 30.00–30.08 m, 45°, rough, planar, infilled up to 30 mm with sand;
- fissures at 30.46–30.50 m, subhorizontal, rough, planar, infilled up to 40 mm with sand;
- fissures at 30.85–31.80 m, very closely spaced, rough, irregular, locally infilled up to 20 mm with brown silty fine sand.

In this case, the uppermost 2 m section of Chalk probably represents the weathered or eroded Chalk subcrop surface, which had been buried beneath the Quaternary sands and gravels. The 5 m section below that is less weathered and more structured and appears to have come from a deeper part of the Chalk subcrop; it shows a consistent pattern of structures, in particular over the last 2 m where it is heavily fractured and fissured. The fissures become wider by dissolution, up to 30 and 40 mm, and were probably open at the time of dissolution. Furthermore, the fracturing and fissuring becomes extremely closely spaced with depth and is interpreted to be part of a deeper buried, faulted and fissured Chalk, with the 2 m fracture or fissure zone probably overlying a more extensive fault or zone of deformation. This interval, and others like it, would have been extremely porous and permeable owing to extensive and widely spaced fissuring. Any faulting and rupturing of the Chalk would cause any existing high water content to be sent upwards, causing intense disturbance to, and ultimate loss of, any bedding within the overlying Quaternary sands and gravels.

Faulted intervals, as recorded in logs at other locations, have descriptions that show similar patterns and they are always associated with subvertical and subhorizontal fissures and fractures; for example:

- 'at 27.84–28.08 m, subvertical rough irregular fracture infilled with soft grey clay and at 28.80 m, subhorizontal rough irregular HV fracture';
- 'at 31.27 m in WRB, subhorizontal rough SL planar fracture';
- 'in TAB at 35.60–35.75 m, subvertical, rough, irregular, fracture; and at 39.00–39.20 m, and at 39.90–40.10 m, subvertical, rough, planar fractures'.

Intervals of fracturing are frequently recorded in the TAB at 40.01–42.2 m, 45.43 m and 48.5–48.65 m, and these are variously recorded as 'subvertical' or as 'subhorizontal', 'rough planar fractures', and dips of 10° and 20° are noted.

In this database, drift-filled hollows are described in 15–20 boreholes, within the KPGR, and all near the Blackwall Tunnel. It is noticeable that they are all closely associated with fissures and fractures described as very closely spaced, smooth, planar and often cross-cutting and dipping typically from subhorizontal at 10°, 20° or 30°, but occasionally at 45° and 80°. A further 171 borehole records include descriptions of materials that resemble the DFH descriptions and/or that directly refer to the materials as 'Scour Hollow infill (SCHO)'; these are predominantly in central and east London. The distribution of the DFHs and SCHOs, identified in this project, in addition to a number of Buried Hollows described by Banks *et al.* (2015) (mainly from descriptions by Berry 1979), are shown in relation to the distribution of all RTDs in Figure 21.

Other typical descriptions of sands and gravels, described on the logs as being likely DFHs, are shown below.

- At TQ38SE [538583/180377], 16.71 m thick: loose, brown, sub-rounded to rounded, generally fine to medium, flint gravel with much medium to coarse sand. Below about 4.0 m, becoming medium dense gravel with rare cobbles. Medium dense, brown medium to coarse sand with much sub-rounded to rounded, fine to medium flint gravel. Below about 7.0 m, becoming slightly orange brown sand and gravel. Medium dense, becoming dense, below about 14.50 m, grey brown generally fine to medium silty sand, with occasional sub-rounded to rounded, fine to medium, flint gravel. Brown grey, fine to medium sand. Grey, thinly

Table 3. *Descriptions of drift-filled hollows from several locations across London*

Feature	Moorgate*	Limmo (mouth of R. Lea)*	Thames River Crossing*	Blackwall River Crossing†	Watling Street Bridge over M25 [555668, 173665]
Terrace	Edge of TPGR (*c.* 4 m thick); overlying alluvium possibly thicker in DFH	KPGR (usually *c.* 2 m)	KPGR	KPGR	BHT
Modern watercourse?	Yes, but minor	Yes	Yes, entirely within the current river course and elongated parallel to it	Yes	Not directly, east of River Darent
Faulting?	No obvious vertical component of faulting at depth	Yes, fault control over shape and location of hollows	Yes, minor faulting of the Chalk; subparallel to small anticline and syncline axes	Yes, fracturing and fault(s) within Chalk	Fissuring in Chalk subcrop, related to regional fault; extremely closely to closely fissured; brown silt infilling of fissures up to 2 mm
Depth	10 m	*c.* 23 m; complex shape	10 m	*c.* 60 m (base not reached)	27.5 m (base not reached)
Maximum width	70 m conical shape	*c.* 450 m; multiple coalescing hollows	400 m × 200 m	Unknown	>114 m × >332 m
Infill?	Alluvium, gravel, sand with large clay inclusions; higher levels gravelly, lower levels sandy	Alluvium, sand and gravel	Alluvium, sand and gravel		Alluvium, sand and gravel; sandy gravelly silt in top half; lower half gravel with sand
Subcrop	Thick LC (*c.* 30 m) *c.* 20 m below the DFH; possible LMBE channels	Thick (37 m) LC within faulted syncline; reduces to 1.5 m below DFH	Thick Chalk, weak comminuted in centre	Thin impermeable cover to Chalk aquifer	Chalk described variably as weathered, structureless, remoulded, blocky, hard, brittle, jointed of high porosity; black speckling on fissure faces
Clay layers or large inclusions?	Yes, ‘inclusions’ of clay, often with London Clay like descriptions in lower levels	No	No	Yes, mainly of large Chalk blocks, the lower heavily fissured	No, just chalk clasts
Scour, diapirism other association	Relationship of Lambeth Group channels and London Clay subcrop?	Faulting control dominant in the area	Possibly scour	Diapirism assisted by fissuring and fracturing with the Chalk subcrop	Diapirism, assisted by fissuring within the Chalk subcrop

*Flynn *et al.* (2020).
†Present study.

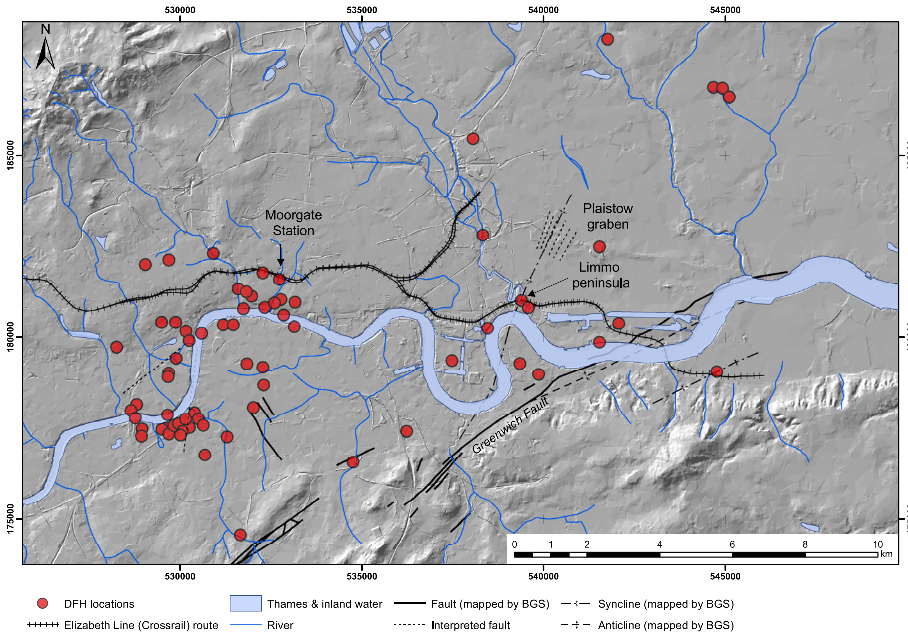

Fig. 19. DFH locations (red filled circles) and along the Thames valley, with respect to the route of the Elizabeth Line (Crossrail project), the Thames Tributaries and some major geological structures; using data from Berry (1979) and Flynn *et al.* (2020). Overlain on shaded relief map generated from LiDAR T5 Digital Terrain Model (DTM) © Crown copyright and database rights 2023 Ordnance Survey (100025252).

laminated, slightly sandy, very clayey, thinly laminated silt. At 16.71–16.72 m and 16.90–16.91 m, very stiff, grey, fissured clay: rounded, smooth, planar, fine. Brown grey, silty sand, firm, brown grey, fine, slightly sandy clay, locally fine to medium, very sandy clay and grey very thinly to thinly bedded, fine sand, becoming locally slightly silty, clayey, sand below 26.7 m and slightly silty with abundant pockets of light brown silty, fine sand below 29.25 m, sub-angular to angular, fine to coarse, flint gravel with cobbles with some slightly fine, sandy clay overlies Chalk.

- At TQ38SE [538675/180282], 19.20 m thick: loose, becoming medium dense, below 2.50 m, brown and grey sub-angular to rounded, flint gravel with some to much medium to coarse sand. Medium dense, brown sand with some to much sub-angular to rounded flint gravel. Brown, slightly clayey, becoming clayey below 13.20 m, sub-angular to rounded flint gravel with much sand. Here the underlying beds of TAB, between 25.05 and 31.46 m, have frequent fissures described as: fissures, rounded, planar, dipping from extremely closely spaced, subhorizontal to 10°, 30° and subvertical, and fractures dipping at 45°, 80° at 31.46 m. Similarly, in the underlying Chalk, fractures are common and described as dipping at 80°, 45°, 80°, 80°, 45° or 70°; these are commonly large, open fractures, smooth, planar, very closely spaced, with infillings up to 40 mm width of comminuted Chalk.
- At TQ38SE [538840/180174], 7.4 m thick: grey clay, locally sandy, with occasional to much angular to rounded, fine to coarse flint gravel. Slight tar odour. Immediately below the gravels, at 27.84 m–28.08 m, the sequence is described as a subvertical rough irregular fracture, infilled with soft grey clay and, at 28.80 m, subhorizontal, rough, irregular fractures. At 31.27 m in Woolwich, Reading Beds, subhorizontal, rough, slicken-sided, planar fracture. In TAB at 35.60–35.75 m, subvertical, rough, irregular, fracture and, at 39.00–39.20 m and at 39.90–40.10 m, subvertical, rough, planar fractures. Frequent intervals of fracturing are recorded from the TAB at 40.01–42.2 m, 45.43 m and 48.5–48.65 m; these are variously recorded as subvertical or as subhorizontal, rough planar fractures, and dips of 10° and 20° are noted.

The predominance of extensive fractures (commonly subhorizontal and steeply dipping) within the strata of many of the boreholes would suggest that this particular area is part of a fault zone (see discussion below under fissures, fractures, faults).

DFHs have also been recorded in the BHT. For example, within an area of *c.* 120 m × 350 m in TQ57SE, there are >30 boreholes that have very thick sequences of DFH material (9.7–27.95 m, average 13.2 m) and are all underlain by Chalk. Many of these boreholes have intervals described as 'Infill Solution Hollows'; a sample of these are described below.

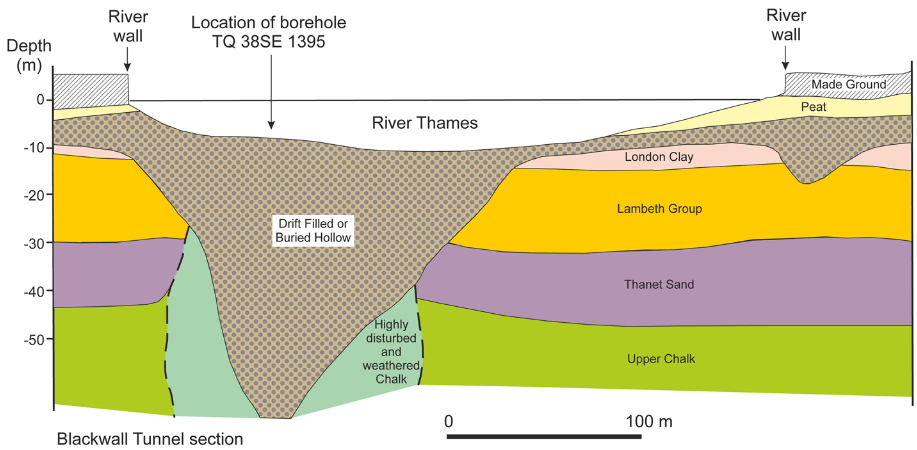

Fig. 20. The drift-filled hollow at Blackwall Tunnel, shown here as one thick DFH section, compared with the smaller DFH at Limmo. Source: Ellison *et al.* (2004).

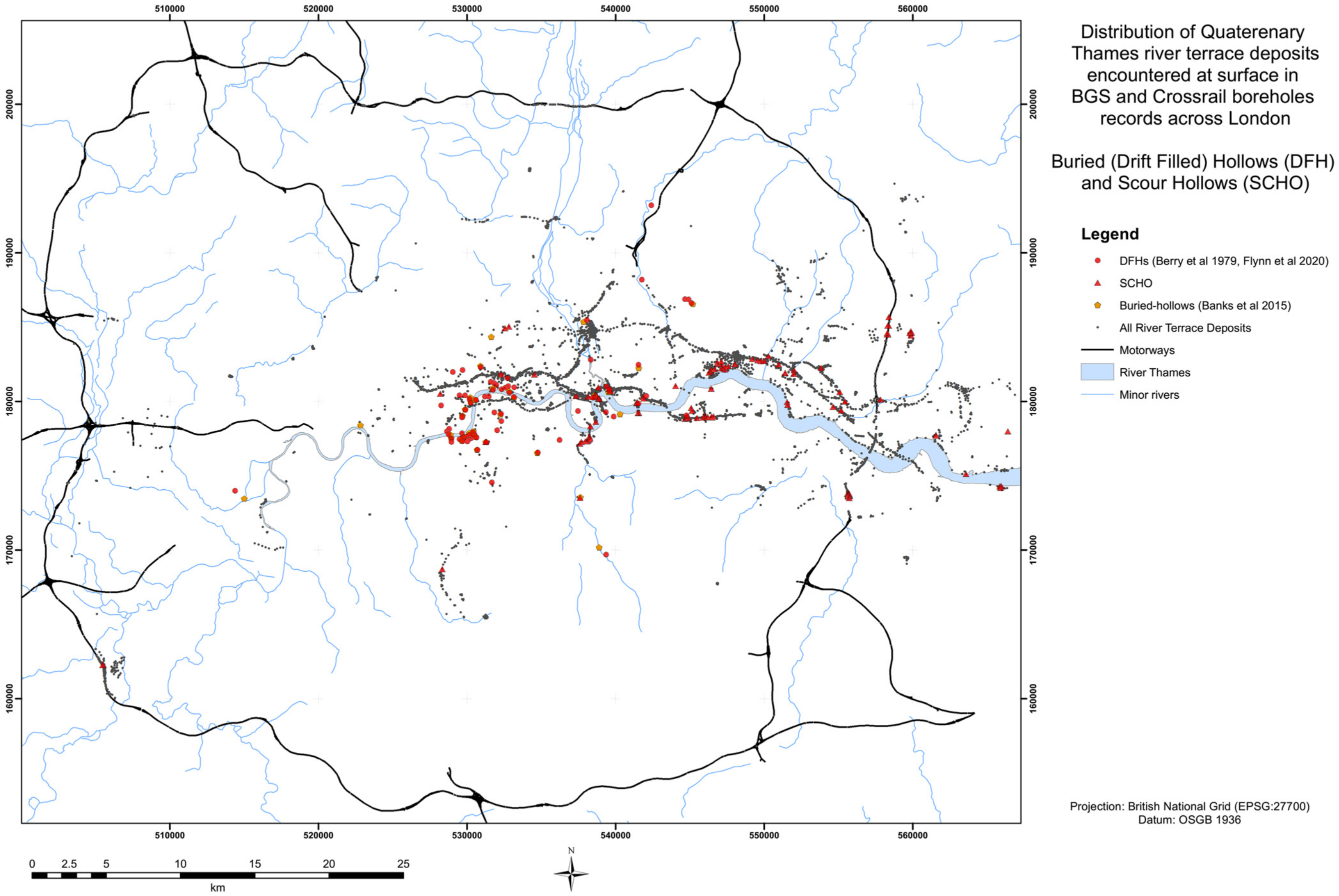

Fig. 21. Distribution of Buried (Drift-Filled) Hollows, Scour Hollows, from a variety of sources, and River Terrace Deposits.

- At TQ57SE [555668/173665], 27.95 m thick: medium dense to dense, light brown, fine, sandy, silt with a trace of clay. Medium dense, slightly dark brown, mottled light brown, fine sandy clayey silt below 2.2 m. Medium dense, yellow brown, fine, very sandy, silt with some sub-angular to rounded flint gravel. An increasing amount of black mottling especially below 7.50 m. Occasional traces of clay. Dense, angular to rounded, flint gravel with some brown silty fine-grained sand. Medium dense, orange brown, silty, fine- to medium-grained sand with some angular to rounded flint gravel. Traces of clay especially towards top. Becoming more gravelly. Dense, sub-angular to rounded flint gravel with some orange, silty, fine- to medium-grained sand. Occasional flint cobbles.
- At TQ57SE [555675/173828], 23.8 m thick: brown, slightly clayey, silty, fine sand with angular to rounded, fine and medium gravel. Some roots. Very loose to medium dense, brown, clayey silt with some angular to rounded, fine and medium gravel. Sometimes with some fine sand. Some black staining throughout. Medium dense, brown and grey mottled clayey silt. Some black staining. Dense brown clayey silt with angular to rounded fine and medium gravel. Dense to very dense, orange brown, clayey, silty sand with angular to rounded, fine and medium gravel. At 20.50 m sand, generally medium and coarse. Overlying Chalk.

The Chalk underlying DFHs is described, in multiple boreholes, as ‘white, fine grained, extremely closely to closely fissured, weak to medium hard fresh Chalk, of high porosity. Some brown silt infilling of fissures up to 2 mm. Black speckling, limonite or iron staining on fissure faces. Occasional flints.’

This area is clearly extensively fissured in weak, highly porous Chalk, the combination of fissuring and porosity giving rise to dissolution of the chalk and thus solution collapse structures (or sinkholes in modern parlance). Here the fissuring is important in generating a solution collapse feature, and the presence of extremely closely spaced fissuring in multiple adjacent boreholes would support a fault-related origin (see discussion below under fissures).

A recent study by Toms *et al.* (2016) on DFHs in the Nine Elms area finds that there are some 26 DFHs identified in the London area, which arrange in depth from a few metres to nearly 100 m, and whose origins are far from certain. This work found that the two DFHs in the Battersea area formed before the Last Glacial Maximum, contrary to published literature, and suggested that one is related to pingos in the London Clay, and the other caused by erosion of a palaeo-channel, and that both may be related to the existence of faults.

Banks *et al.* (2015) found that there are two groups of buried hollows: scours and ‘rooted’ hollows, and that there is rarely sufficient evidence to discriminate between them. They concluded that a nationwide study is needed to identify and characterize these and other related features.

Economically important thick deposits

The distribution of the boreholes with thick sand and gravel sections (>10 m thick), which may be of economic value, is shown in Figure 22. The majority of these boreholes are close to the drift-filled hollows noted above in the Canary Wharf, River Lea Mouth (Limmo) and Blackwall Tunnel areas, near Greenwich and on the southern edge of the Isle of Dogs, the last of which coincides with the folding structure or fault revealed by Crossrail. Another group of boreholes with thick RTD deposits occurs in TQ47NW in the Woolwich Reach area, Dagenham Reach area, both the north and south banks of Barking Reach and further east in the Plumstead, Abbey Wood area.

All these thick sequences are associated with the younger RTDs and lie within or along the banks of the present River Thames. Many of them include descriptions of heterogeneous deposits (i.e. sand, gravel, silt, clay pockets, etc.) and many of them overlie a subcrop (London Clay, Woolwich and Reading Beds, Harwich Formation and Chalk) that is described as having extremely closely spaced fissures and/or subhorizontal and subvertical fractures. The Chalk subcrop frequently shows expansion of the fissures to >2 cm, presumably through dissolution of the Chalk, and often these contain comminuted Chalk or other fine sediment. Thus some of these may also be drift-filled hollows, but the lack of seismic or 3D mapping prevents a certain answer.

Grain-size analyses of Crossrail boreholes

Some of the best quality borehole log records collected during the Crossrail project contain the sorted quantitative grain-size results from particle size dimension analysis (sieving), which was largely performed on LHGR deposits. Data collected include grain-size distributions, water contents and mechanical properties. The grain-size fractions are included in the file CR-LHGR_grainsize-analysis.xlsx. This file includes two separate sheets, as follows.

- CR-LHGR_ALL_grainsize-analyses, which includes all the analyses for each sampled interval in each borehole. Some boreholes have only one sampled interval. Some have multiple sampled intervals, and in these cases, each interval is presented vertically (i.e. with the same columns) with the analyses listed below one another according to depth. The sample analyses are described and arranged by the following information: borehole ID, sample top (metres below ground level (m bgl)), sample reference (ref), and sample type (B, U, LB, D); this information appears in Row4 of this sheet.
- Top-sample – geog-sort(WtoE): here the uppermost interval sampled from each borehole has been sorted by location and arranged in a broad sequence from west to east.

Such analyses may be characteristic of the sedimentary depositional environment and may reveal information about transport and deposition of the sediments, as well as porosity and permeability, and thus these data may be of considerable use to engineering geoscientists working in London. The grain-size fractions are presented in millimetre sieve sizes, rather than on the logarithmic phi scale, so the ISO 14688-1 scale equivalents and soil class descriptions have been included in a third sheet (ISO14688-1-scale) within this file. In addition, the equivalent phi (Φ) values have been inserted into the Top-sample – geog-sort(WtoE) sheet for plotting purposes.

Plotting reveals some complex patterns that have no particular west-to-east trend but some of the samples clearly show removal of the finer fractions of material, suggesting reworking and winnowing, whereas the majority show a much more gradual fining; some show fining upwards and other coarsening upwards.

Fissures, fractures and faulting

There is a growing body of work in support of the notion that faults are significantly under-represented on published BGS geological maps of the London area (De Freitas 2009; Aldiss 2013), and that the geology of London is altogether more structurally complex than was previously thought, and more than was previously shown on maps and cross-sections across London (Sumbler 1996; Royse 2010; Royse *et al.* 2012). Consideration of the palaeo- and current stress regimes of the London area would suggest that structures of

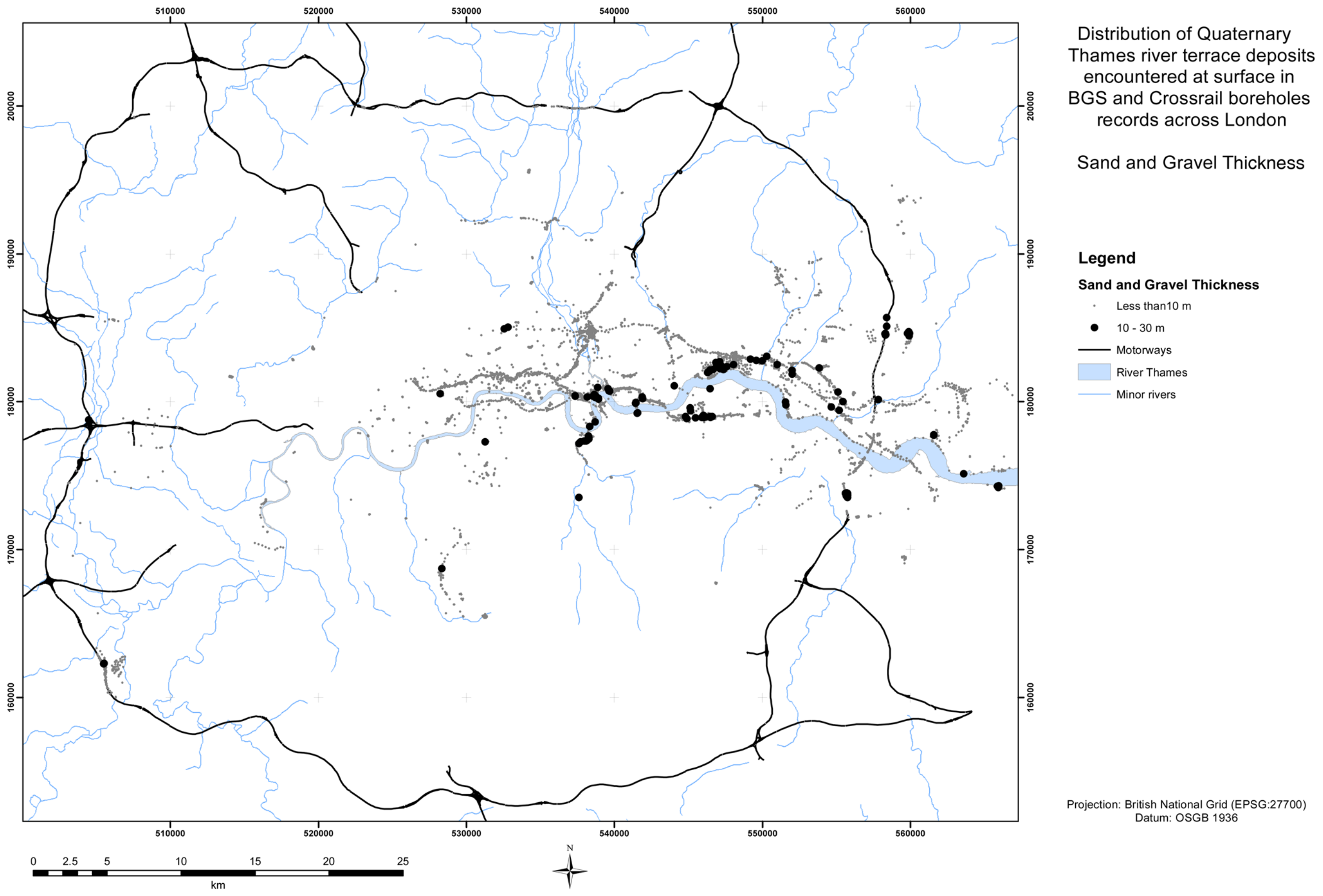

Fig. 22. Distribution and thickness of sand and gravels.

Caledonian, Variscan and Alpine origin should be present at depth and that some of these structures are likely to have propagated upwards into the younger stratigraphy (Vandycke and Bergerat 2001). This topic is the subject of other, much more detailed pieces of work (e.g. Morgan *et al.* 2020).

There is plentiful and widespread evidence of brittle deformation, which is highly likely to have been caused by fault movement, throughout this borehole database of Quaternary lithogratigraphic descriptions from the BGS and Crossrail borehole archive. From each borehole log examined by the authors, any descriptions considered to suggest fault deformation, whether specifically described by driller or geologist, or indirectly inferred from the detailed descriptions of the sediments affected, have been coded to allow the production of a separate spreadsheet of borehole locations where faults and/or fissures are observed; stored in BGS-CR_RTD-BH_All-master.xlsx in the 'Fissured' sheet. Here we provide only a selection of the relevant descriptions.

The map in Figure 23 shows the distribution of boreholes with records of fissures or fractures and the location of boreholes where faults are thought to be present, either where the strata are repeated, or where the boreholes are very close and yet the subcrop pattern is completely different.

Descriptions of open fractures within the Chalk subcrop are also common, and differences in adjacent boreholes may be due to faulting or to subcrop activity such as 'sink-holes'.

Boreholes at TQ38SW [532420/184780] show repeated sequences of LASI over KPGR. These appear to be genuine repeated sequences and are interpreted as reverse faults. They lie on a NNE–SSW trend, which continues SSW with consistent descriptions of highly fissured clay into the Westminster Reach of the River Thames and continues NNE to South Tottenham at the sharp corner of the Lea Valley, where the London Clay is described as extremely closely fissured and where a fault has been identified in two adjacent boreholes. This trend continues NNE along the Lea Valley.

Descriptions of the London Clay Formation in the borehole logs from around the mouth of the River Lea provide clear evidence of fissuring and of mechanical deformation. In this area faults have been proven and have been observed *in situ* by contractors working on the Crossrail tunnel construction and in the wall of the Canary Wharf station box at *c.* 30 m below current ground level (R. Ghail, pers. comm. 2017). Some relevant descriptions from logs in this area include the following.

- TQ38SE [539440/180724], −6.66 m to −10.56 m: firm to stiff, grey brown, extremely closely fissured clay. Fissures are subvertical to subhorizontal, slightly undulose.
- TQ38SE [539407/180660], −7.35 m to −9.95 m: stiff, grey brown, fissured clay with occasional sub-angular medium gravel sized nodules of pyrite. Fissures are extremely closely spaced, vertical to subhorizontal, undulose.
- TQ38SE [539497/180982], −8.76 m to −14.06 m: stiff, grey fissured clay with the occasional fissure containing grey fine sand.
- TQ38SE [539497/180633], −7.69 m to −14.99 m: stiff brown fissured clay, with rare sub-rounded medium gravel sized pyrite nodules. Fissures are extremely closely spaced, vertical, subvertical and subhorizontal. Undulose. … Very stiff, grey brown fissured clay with some partings of dark grey silt. Fissures are extremely closely spaced, subvertical and subhorizontal, slightly undulose.

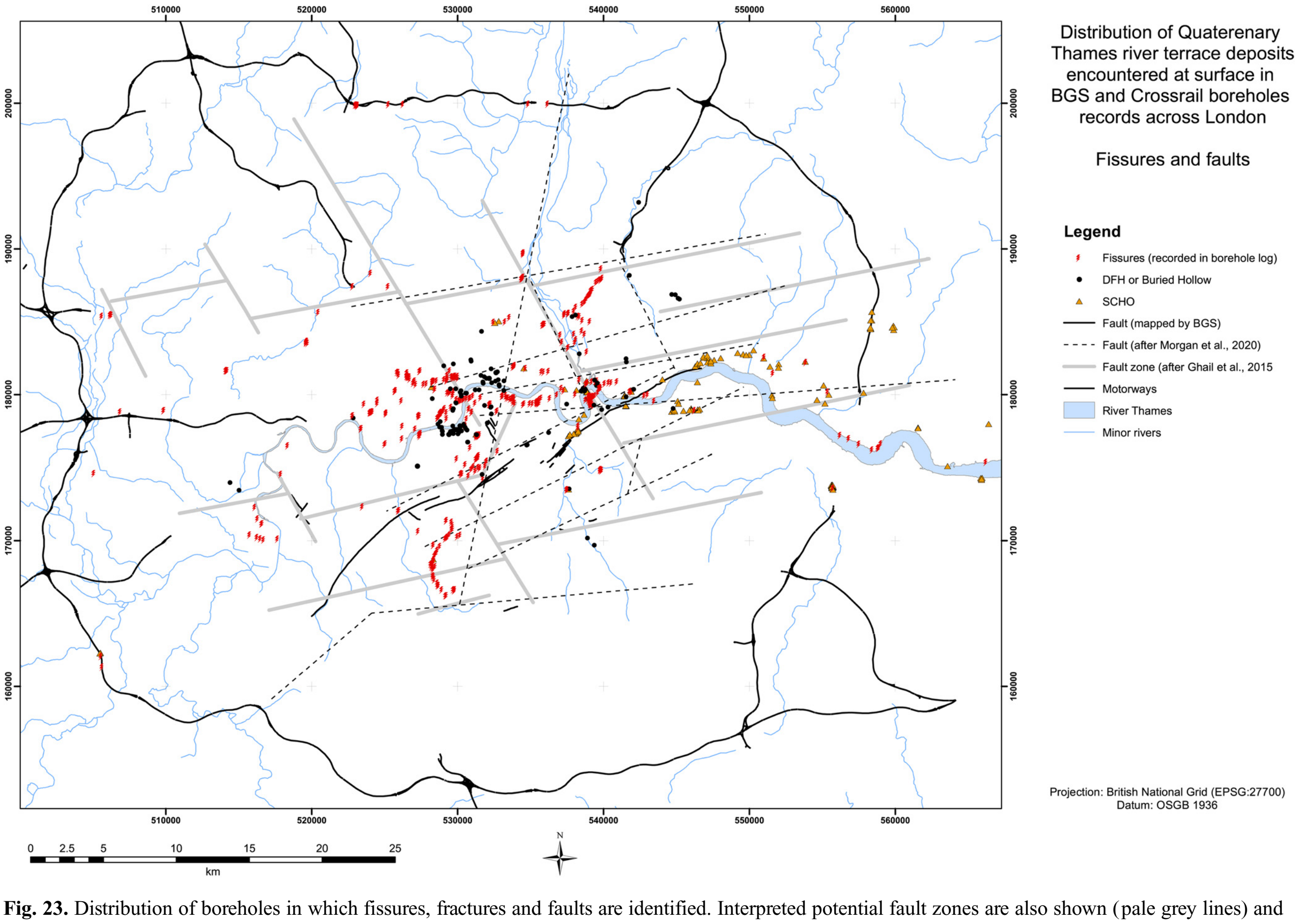

Fig. 23. Distribution of boreholes in which fissures, fractures and faults are identified. Interpreted potential fault zones are also shown (pale grey lines) and modified fault zones (dashed black lines). Sources: interpreted potential fault zones (Ghail *et al.* 2015) and after Morgan *et al.* (2020).

- TQ38SE [539213/180907], −4.04 m to −25.25 m: stiff, very stiff, grey brown closely fissured silty clay with occasional fine sandy partings.

Boreholes between the Blackwall Tunnels have a sequence of DFH sediments often overlain by Kempton Park Gravels, suggesting that the DFH was formed before the deposition of the KPGR beds. The underlying subcrop of these Quaternary deposits is the Woolwich Beds along the northern shore of the Thames, and variably Thanet Sand, Reading Beds and London Clay along the southern bank of the Thames, and with Chalk along the centre of the meander.

The Chalk in this and other cases is often heavily fissured, fractured and faulted. The descriptions from the *in situ* Chalk include 'fissures sub-horizontal, sub-vertical'; 'fractures extremely to very closely spaced'; 'fissures, rough, planar, dipping from (extremely closely spaced) sub-horizontal to 10°, 30° and sub-vertical and fractures dipping at 45°, 80°'; 'fractures are common, dipping at 80°, 45°, 80°, 80°, 45°, 70°, these are commonly large, open fractures, smooth, planar, very closely spaced, with infillings up to 40 mm width comminuted chalk'. Similar descriptions occur in the deeper rafted Chalk block within borehole TQ38SE [538642,180353]. Similar descriptions come from the subcrops of London Clay and Woolwich Bed.

From examination of this database, the occurrence of extremely closely spaced fissures as well as associated pyrite and fissure infill in the subcrop of other closely spaced boreholes is very common. These structures appear to be tectonic in origin and thus proximity to a fault would be a reasonable interpretation in each case; from the distribution of fissuring in the boreholes of this database, faults appear to be present across much of central London.

The constraint or provision of evidence for the timing of faulting is considered of great importance for understanding of the evolution of London and southern England; there is plenty of evidence for recent tectonic activity in this area (Ghail *et al.* 2015). Work by Morgan *et al.* (2020) suggested that the London Basin is an uplifted platform, rather than a basin as such, and that its basement geology is just as fractured as elsewhere in southern Britain. The geological evidence provided in the Quaternary lithostratigraphic descriptions in this database strongly supports fault activity during the Quaternary, and this supports continuing work, which also suggests that tectonic uplift and inversion has been occurring in SE England in the last 400 kyr (Blundell 2002; Aldiss *et al.* 2014; Ghail *et al.* 2015; Morgan *et al.* 2020).

Conclusions

This Technical Note provides a database of *c.* 27 000 borehole records of Quaternary lithostratigraphy, as recorded from drilling through the River Terrace Deposits of Greater London, for assessing the distribution of facies and eroded and deposited materials, and their implications for the reconstruction of Quaternary depositional environments and interpretation of neotectonics, and to aid understanding of geotechnics in this region. This database has been compiled from boreholes drilled by British Geological Survey and for the Crossrail project (in preparation for the construction of the Elizabeth Line). The data presented have been quality assessed, corrected and duplicates removed (where necessary), and have been selected and graded for quality as 'Best', 'Good' or 'Useful' from *c.* 58 000 such records publicly available in the BGS archive or acquired by the Crossrail project and made available to the authors.

Detailed analysis of these data has revealed how some drainage systems evolved during the Quaternary, the likely sources of their detritus and the nature of their fluvial environments. These analyses have revealed many patterns in the data that might not have otherwise been recognized, such as particularly thick sequences of sand and gravel, or the distributions of shell and chalk clasts that point toward the source material of the deposits. Our analyses also revealed that descriptive evidence of small-scale fracturing in the bored materials is widespread, and the authors suggest that this provides compelling evidence of faulting in the subsurface of London, which supports a growing body of evidence in other recently published literature. These data therefore provide a basis against which evidence from other sources (e.g. the location and nature of Drift-Filled Hollows and presence and character of faulting) can be compared.

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Data availability All data generated or analysed during this study are included with this published article and its supplementary information files.

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