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Possible Late Pleistocene pingo development within the Lea Valley: evidence from Temple Mills, Stratford, East London

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Possible Late Pleistocene pingo development within the Lea Valley: evidence from Temple Mills, Stratford, East London

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Summary

This report describes and discusses a borehole drilled at the Olympic Park development site at Temple Mills, in the Lea Valley near Stratford in East London. The original borehole number is MBHCZ6A-159. It has been registered as TQ38NE 1366 in the BGS Single Onshore Borehole Index.

The borehole penetrates a 70 metre-thick sequence which, from the top downwards, passes through made ground and Quaternary fluvial deposits before revealing a 43 metre-thick zone of bedrock mélange. This mélange includes material from the lower part of the Lambeth Group, the Thanet Formation, and the Chalk. It is interpreted as being the product of pervasive soft-sediment deformation formed during a series of short-lived elevated pore water events, based upon the presence of diagnostic geological structures characteristic of ductile deformation, probably during rapid ejection of groundwater under artesian pressure. During these events, fragments of chalk were carried to within 17 metres of the surface, some 20 metres above where the top of the Chalk was encountered in nearby undisturbed sequences. Conversely, the presence of glauconitic sand at 69 m depth apparently derived from the adjacent Palaeogene bedrock, more than 30 m below the top of the Chalk nearby, implies that there was also some downwards movement during mélange formation. The presence of such a thick disturbed sequence beneath superficial deposits is extremely unusual although not unique.

A model is proposed where this structure and internal deformation is explained by processes of pingo formation and decay in a part of the Lea Valley where the bedrock aquifer (Chalk) is confined by an aquitard as little as 3 m thick. Alternatively, it is possible that the structure formed during release of artesian groundwater pressure following fluvial scour. In either case, it is very likely that the structure lies above a fault zone including fractured, possibly karstic chalk, with high groundwater conductivity.

The structure is most likely to have formed during Late Devensian times, during the deposition of the Shepperton Gravel, but it might be older, possibly pre-dating part or all of the Devensian Kempton Park Gravel.

1 Introduction

The Stratford area of East London is currently undergoing a major re-development as part of the construction of infrastructure for the 2012 Olympic Games. The Temple Mills area is situated in the northern sector of what will be the main Olympic Park, which will encompass the Olympic Stadium and other sports venues. Temple Mills, including Development Zone 6A of the Olympic Park, will be the location of the Olympic Velodrome.

As part of the construction process, a large number of site investigations have been undertaken to determine the nature of ground conditions.

Most of the ground investigation boreholes in Zone 6A of the Olympic Park, for example MBHCZ6A-158 (TQ38NE 1365), proved the expected sequence of made ground, alluvium, river terrace deposits (with base at about -1 m Ordnance Datum (OD), Palaeogene Lambeth Group (Laminated Beds, Lower Shelly Clay, Lower Mottled Beds, Upnor Formation) and Thanet Sand Formation overlying Late Cretaceous Chalk Group. The top of the Chalk is typically at about -25 m OD in this part of the Park.

However, two cable percussion boreholes about 39 m apart in the eastern part of Zone 6A, MBHCZ6A-104 (TQ38NE 1362) and MBHCZ6A-106 (TQ38NE 1363), found an anomalous sequence. Here, no typical alluvium or river terrace deposits were found beneath made ground, although there is instead an approximately equivalent interval of 3.6 m of sandy silt/clay (base at -6.4 m OD) in 104, and 5.6 m of gravelly sandy clay and sand (base at -6.6 m OD) in 106. The remained of the core sampled unstructured clayey gravelly sand and clayey sandy gravel with a variable content of chalk in a more or less comminuted state. Both boreholes terminated without touching in situ bedrock (at -25 m OD in 104 and -28 m in 106).

A series of sonic percussion boreholes (MBHCZ6A-157 to 159; TQ38NE 1364 to 1366) were then drilled to investigate this anomalous sequence further. Boreholes 157 and 158 found the expected sequence; 159 sampled the anomalous sequence. The BGS registration numbers for all these boreholes are given in Appendix 1, and their locations are shown on Figure 1. Borehole 159 is about 15 m south of borehole 104 and 33 m east of borehole 106. Borehole 162, which is the nearest known borehole to have sampled a 'normal' sequence, is about 87 m west of borehole 106.

Examination of these borehole samples, and others from the vicinity, suggested to Mr Alan Smallwood, then working on site on behalf of Atkins, that the anomalous sequence marks a relict open system pingo, analogous to the structure found during ground investigation for the Blackwall tunnel (Ellison et al., 2004, fig. 36). Through his help and encouragement, core samples from the relevant boreholes were released by the Olympic Development Authority and brought to BGS Keyworth for further study, and for possible long term storage within the NGDC materials collection.

This report is to describe the highly unusual sequence sampled by borehole MBHCZ6A-159 (TQ38NE 1366) and to discuss its geology.

2 Location and methodology

The original borehole number is MBHCZ6A-159. This has been registered as TQ38NE 1366 in the BGS Single Onshore Borehole Index (Appendix 1; the remainder of this report uses only BGS Borehole Registration numbers). The borehole is located at National Grid Reference TQ 537986,185427 within Temple Mills, East London, within Zone 6A of the main development area for the new Olympic Park being built for the 2012 Olympic Games (Figure 1). The locality of the borehole is situated 35 metres north of Hennikers Ditch, which drains into a tributary of the River Lee called the Channelsea River. The ground elevation of the site is 13.21 metres OD.

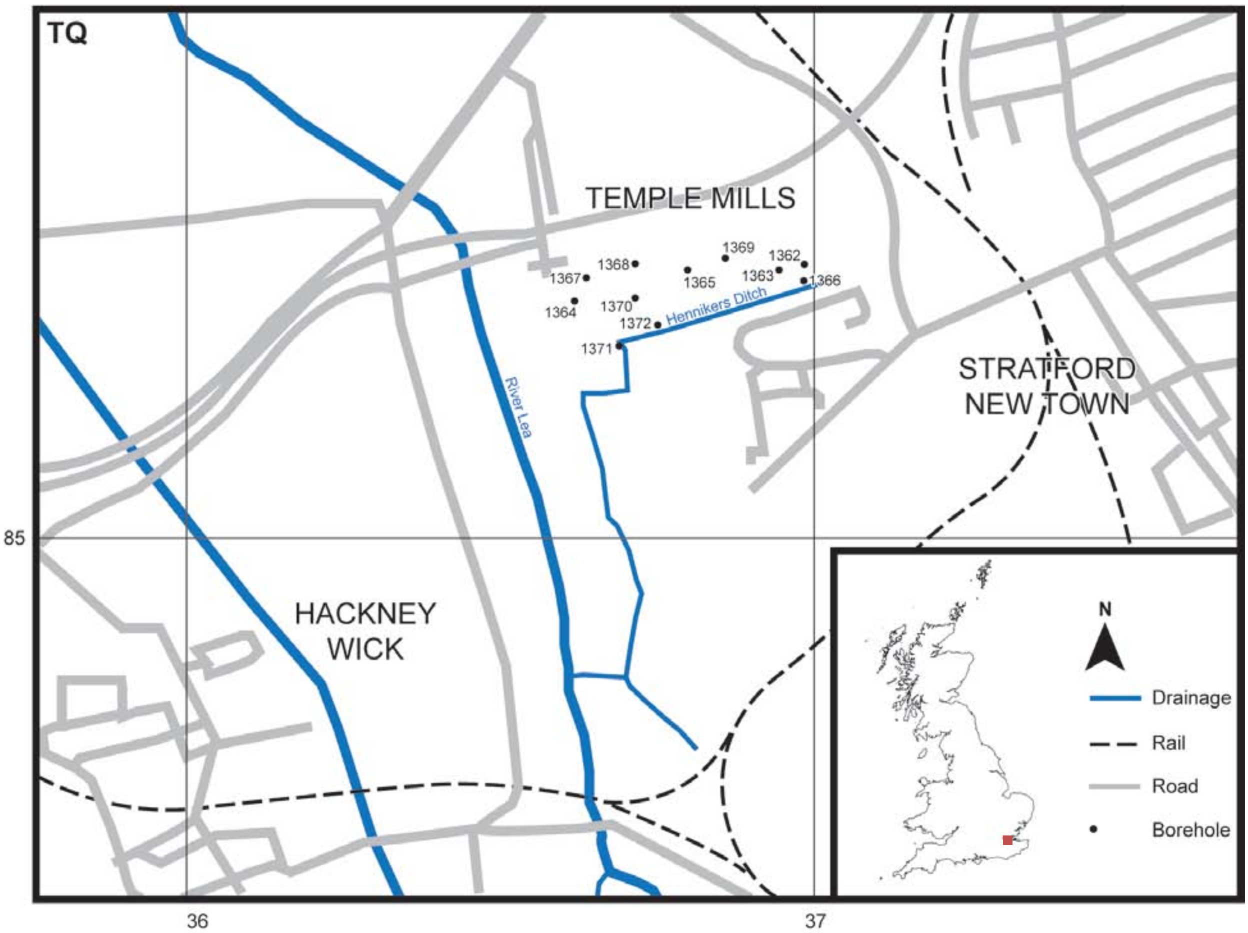

Figure 1: Location of the Temple Mills study area near Stratford, East London.

The position of borehole TQ38NE 1366 and adjacent borehole records cited within this report are also shown. See Appendix 1 for original and BGS borehole numbers.

The published 1:50 000 geological map (Sheet 256) suggests that the geology of the borehole site should include Holocene alluvium, overlying Quaternary river terrace deposits, which in turn should overlie the Palaeogene Lambeth Group and Thanet Sand Formation, and the Late Cretaceous Chalk.

The borehole was drilled between the 22 and 26 February 2008 using a sonic rig with cores retained within U100 tubes. The total depth of the borehole drilled was 69.00 metres with approximately 89% sample recovery. In general, recovery within the bottom 7.50 metres of the borehole was poor and only shoe samples exist between 69.00 and 62.55 metres at 69.00 and 64.30 metres respectively.

The cores were originally logged on site by a site geologist. The U100 samples were split with half of the core initially retained by Atkins, but passed to BGS upon relinquishment. Soon after receipt, on 1 July 2009, Don Aldiss, Alan Smallwood, Jonathan Lee and Kate Royse spent some hours making a preliminary examination of core material from TQ38NE 1365 and 1366. The contractor's geotechnical logs were to hand.

Various possible lines of research on the core, at the site, and on the geology of the surrounding area were then identified. These included a detailed review of the core by Jonathan Lee, the results of which are presented in this report. For this study, the split cores were cleaned using a sharp scalpel and the main lithological facies described based upon lithology, texture, Munsell colour and structure.

3 Stratigraphic summary of borehole TQ38NE 1365

A stratigraphic summary is provided from an adjacent 'undisturbed' borehole (TQ38NE 1365) to provide a relative geological context for borehole 1366. Borehole 1365 is located 184 m west of borehole 1366, with a start height of 14.34 m OD. The summary is based partly on the original borehole log, and in-part, on examination of the core now held at BGS.

The major subdivisions recorded in the original borehole log are all apparent in the core. Much of the core has a clearly marked margin, about 20 mm thick, attributed to drilling disturbance.

Made ground extends to 11.5 m depth, 2.84 m OD. Alluvium, comprising mainly organic or slightly to very sandy clay, with some gravel in places, extends to 12.7 m depth, 1.64 m OD. It forms a single fining-upwards unit that is 1.2 m thick. River terrace deposits, comprising variably clayey and sandy gravel, with some gravelly sand, extend to 15.2 m depth, -0.86 m OD, which is the base of the Quaternary sequence. These deposits include some oxidised gravel in a matrix of very well-sorted coarse sand (including sand-grade flint), as expected in a cold-climate high-energy fluvial deposit. They are 2.5 m thick.

The top Palaeogene surface is of irregular shape, apparently having been cryoturbated. The youngest bedrock unit, which is 1.22 m thick, has been assigned to the Laminated Beds of the Woolwich Formation (Lambeth Group). It comprises alternations of clay, some with occasional shell fragments, and clayey sand, some also with occasional shell fragments. This unit extends to 16.42 m depth, -2.08 m OD. It is underlain by clay with abundant shell fragments, representing the Lower Shelly Clay (Woolwich Formation), which extends to 16.8 m depth, -2.46 m OD, and which is 0.38 m thick.

The underlying green to brown slightly sandy clay, with calcareous concretions (presumably nodular calcrete) in the upper part, and gravelly in places, represents the Lower Mottled Clay of the Reading Formation (Lambeth Group). This is 1.5 m thick. At 18.3 m depth, -3.96 m OD, this unit rests on green, glauconitic clayey, sandy gravel, then clayey sand. This was originally assigned to the Lower Mottled Clay but is better placed within the Upnor Formation (Lambeth Group), which extends to 24.35 m depth, -10.01 m OD, making it 6.05 m thick.

The oldest part of the Palaeogene sequence comprises mainly silty sand, with some sandy silt, to 38.5 m depth, resting on sandy gravelly clay to 38.9 m depth, -24.56 m OD. This material belongs to the Thanet Sand Formation. Here, the Thanet Sand Formation is 14.55 m thick and rests upon the Chalk which was sampled to a depth of 49.5 m (-35.16 m OD) proving a thickness of 10.6 m. This interval is entirely composed of de-structured (partly disaggregated) chalk with sparse flint nodules, which typically are fractured but with the fragments still in approximately original relative position. No discolouration of the chalk or flints was seen. Parts of this core also show a narrow disturbed margin due to drilling.

This disaggregation of the chalk is probably natural, due to periglacial freeze-thaw effects (although variation in salinity might be considered as a possible alternative mechanism). The thickness of disaggregated chalk is comparable to those found at outcrop in places on the Norfolk coast, for example, and is not entirely unexpected in a valley-floor position.

The Chalk is the major aquifer in London. It is generally in hydraulic continuity with the Thanet Sand Formation and the Upnor Formation, although the clayey base of the Thanet Sand, here 0.4 m thick, and clayey portions of the Upnor Formation act as aquitards. At this locality, therefore, the main aquifer is separated from groundwater held in the Quaternary sequence by as little as 3.1 m of clay deposits of the Lower Mottled Clay, Lower Shelly Clay and Laminated Beds.

4 Description of BH TQ38NE 1366

The major lithological subdivisions recorded in the original log for borehole TQ38NE 1366 are all apparent in the core. During examination at BGS, six lithofacies were recognised within the core and these are detailed below. These are made ground (Lithofacies 6), 'alluvium' (Lithofacies 5), and various mixtures of the Palaeogene materials (Lithofacies 4-2) and Chalk (Lithofacies 1) that together form a mélange. A detailed lithofacies log is shown in Figure 7.

As in borehole 1365, the core typically shows a narrow margin that has been disrupted by the drilling process. It appears, however, that in some sections, the cored material has been completely de-structured, possibly as a consequence of fluidisation during drilling. Beneath the 'alluvium' (Lithofacies 5), the core shows a similar deposit to that found in boreholes TQ38SW 1362 (originally 104) and 1363 (originally 106). In general, this comprises clayey sand with a variable content of comminuted chalk. Some parts of the core, including that below 64.3 m depth, are dominated by chalk. This chalk all includes pockets, veins, lenses of sand: no in situ chalk (or other bedrock) was found. Most of the sandy matrix contains visible glauconite grains, and appears to have been derived from the local Palaeogene formations. The chalk fragments and inclusions include some fairly coherent lumps of disaggregated chalk (like that seen in the lowest parts of 1365), some isolated sub-rounded fragments of soft to medium chalk ('chalk pebbles') and some angular fragments of chalk. Some of the latter are very small and delicate.

Chalk fragments occur at levels up to 17.1 m depth, or -3.89 m OD, which is more than 20 m above the top of the Chalk found in the 'normal' sequence of borehole 1365. Traces of glauconitic sand occur as deep as the end of the borehole, at -55.79 m OD, or more than 30 m below the oldest Palaeogene deposit found in borehole 1365.

There is a very small component of scattered flint pebbles, some at more than 50 m below ground level. Of particular significance is the presence of white vein quartz pebbles. They are likely to be derived from either older Quaternary Thames gravels ('Kesgrave Group'), or younger late Middle to Late Pleistocene Thames terrace deposits. It is not impossible that the flint pebbles were derived from the Palaeogene sequence (say the Upnor Formation or the Lower Mottled Clay) but they are very possibly derived from local Quaternary deposits. Vein quartz pebbles are rare in both the Palaeogene sequence and the river terrace deposits but are probably more typical of the latter. Some well-rounded, sub-spherical chatter-marked flint pebbles ('Tertiary pebbles'), some broken, are also present: these are likely to have been derived from Palaeogene deposits.

4.1 LITHOFACIES 1 – CHALK

Lithofacies 1 consists of beds of white (5Y 8/1 – Munsell Color value) chalk with occasional isolated sub-angular to angular black flint pebbles. Throughout the borehole, the Chalk appears to be de-structured with no obvious bedding structure.

4.2 LITHOFACIES 2 – CHALK PLUS SOME PALAEOGENE

This lithofacies is sporadically present throughout the entire core but is perhaps more common within the basal 20 metres. It consists of a light grey (5Y 7/2), highly calcareous slightly sandy silt with occasional thin wispy inclusions of light olive brown sand (2.5Y 5/3), which appears to have been derived from the local Palaeogene deposits. The lithofacies contains frequent sub-angular clasts of chalk and black flint. Scattered pieces of fresh, unweathered flint are present in places; either as fairly complete small nodules or as sharp angular pieces of broken flint. This flint material shows no indication of fluvial transport (Figures 2 and 3).

4.3 LITHOFACIES 3 – CHALK PLUS PALAEOGENE

Lithofacies 3 is composed of broadly equal proportions of light olive brown (2.5Y 5/3) glauconitic silty sand and white (5Y 8/1) chalk that occur throughout the lower part of the borehole as thin units (<1 metre), and within the upper part of the core as thicker (>1 metre) units. Structurally, this lithofacies is highly variable. In places the unit appears to be massive but is apparently an intermediate facies composed of glauconitic sand and chalk; whereas in other horizons it is very heterogeneous in structure. This heterogeneous facies includes inter-mixed and cross-cutting inclusions that typically exhibit a flame-like and wispy morphology. Rare disharmonic fold structures were also noted.

4.4 LITHOFACIES 4 – PALAEOGENE PLUS SOME CHALK

Lithofacies 4 is a common lithofacies within the borehole, especially between 44.10 and 30.00 metres depth, where it forms several generally thick units separated by thinner units of Lithofacies 1, 2 and 3. It is composed predominantly of light olive brown (2.5Y 5/4) glauconite-rich silty sand with flame-like and wispy inclusions of white (5Y 8/2) chalk material with occasional sub-angular chalk pebbles, sub-angular black flint, sub-rounded brown flint, chatter-marked flint, and white vein quartz (Figures 2, 3 and 4).

4.5 LITHOFACIES 5 – 'ALLUVIUM'

This lithofacies consists mainly of a light olive brown (2.5Y 5/3) to light yellowish brown (2.5Y 6/4) glauconite-rich silt and silty fine sand with rare sub-angular to sub-rounded pebbles of flint. It occurs between 21.00 and 16.80 metres depth. Sedimentary structures such as horizontal lamination and ripple-drift cross-lamination are preserved to varying degrees within this unit. In some instances the lamination appears to have been disrupted. At least five crude fining-upwards cycles, each topped by weakly laminated silty clays, occur within this interval. The interval also includes about six layers of chalk clasts, which are at the base of a cycle or within the lower, sandy part of the cycle, except for the topmost, which includes rounded chalk clasts up to 30 mm in observed diameter in sandy clay at the top of the unit (Figure 5).

This unit of material overlies Lithofacies 3 material and the contact between the two units is gradational over about 0.5 metres with a flame-like base.

4.6 LITHOFACIES 6 – MADE GROUND

Lithofacies 6 occurs between 16.80 and 16.00 metres within the retained core. (Core from above 16 m depth was classified as made ground and was not brought to BGS). It consists of dark grey (2.5Y 4/1) to dark yellowish brown (10YR 4/6) beds of sandy silt, sandy gravel (containing vein quartz; brown, white and black flint clasts) and thin beds of black (2.5Y 2.5/1) material.

This interval was originally logged as 'made ground', with abundant ash and rare timber fragments noted. It is in part dark grey and sulphurous-smelling. The present investigation found fragments of fabric, probably leather, and a piece of broken china about 20 mm long at about 16.3 m depth (Figure 6).

Figure 2: Mélange: irregular ‘soft-edged’ chalk blocks and chalky smears in clayey fine-grained sand, depth of 41 m.

Figure 3: Close-up of chalky smear in centre of Figure 4 with tiny angular flint shards, depth of 41 m. Scale in millimetres.

Figure 4: Slightly abraded, broken, sub-rounded, oxidised flint pebble from 35 m depth.

Figure 5: 'Alluvium': Layer of calcareous clasts in weakly laminated silty clay, depth of 17.33 m.

Figure 6: Made ground: clayey sandy gravel with fragment of glazed pottery from depth of 16.3 m.

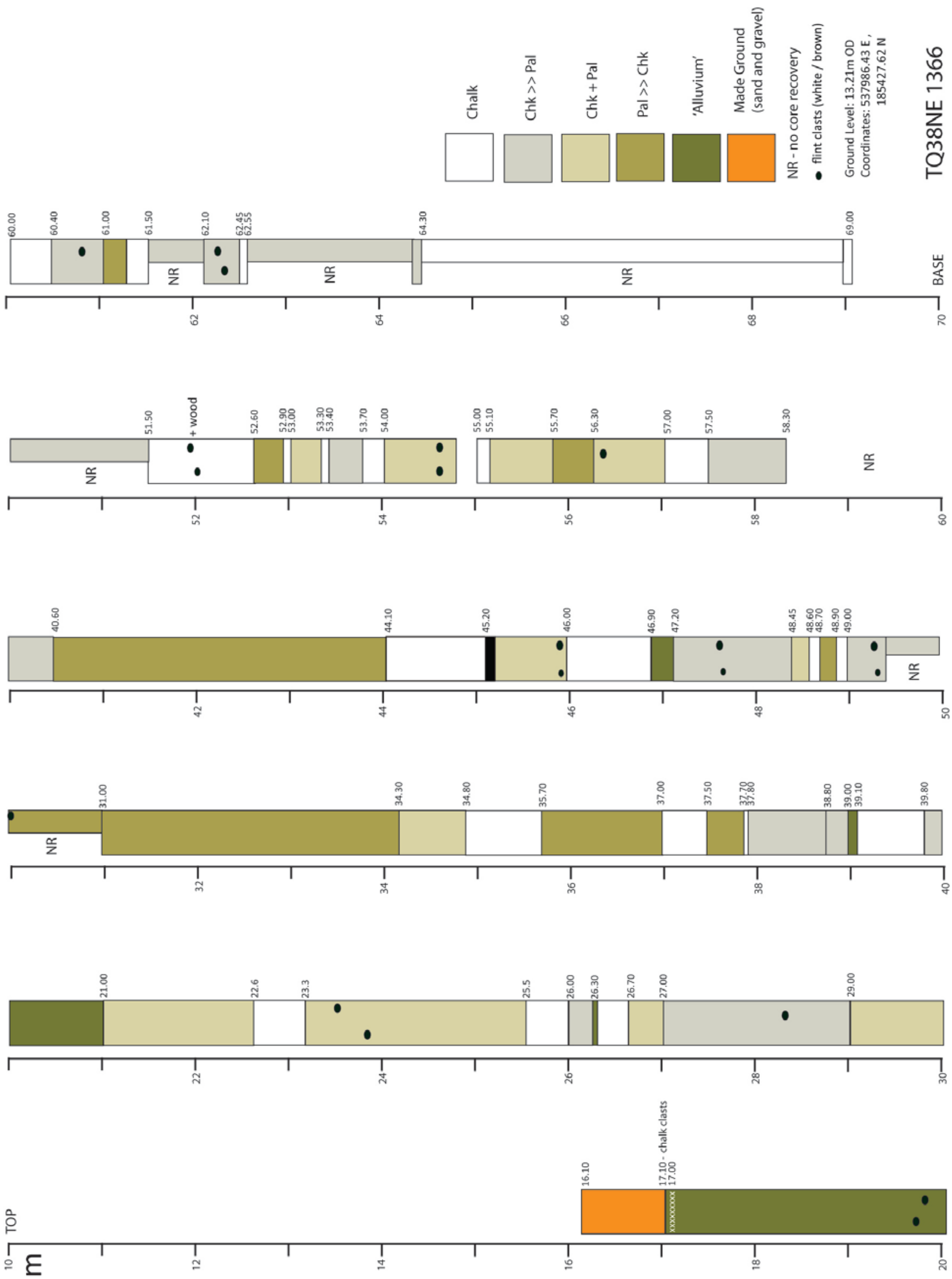

Figure 7: Major lithofacies in borehole TQ38NE 1366 showing Palaeogene and Chalk end-members, and several transitional facies. The scale shows the depth within the borehole. The top 10 m of the borehole was not recovered.

5 Interpretation of lithofacies and structure

Below 21 m depth, the complex arrangement in the mélange shows strong evidence for varying degrees of inter-mixing and homogenisation of locally-derived Palaeogene and Chalk material. The presence of wispy and flame structures plus disharmonic folding within most of the intermediate facies are suggestive of widespread pervasive soft-sediment deformation that occurred under elevated pore water conditions (Phillips et al., 2008). Occasional cross-cutting relationships between different soft-sediment deformation structures indicate that deformation did not occur as one single event, but as several, presumably driven by fluctuations in pore water content (Lee and Phillips, 2008).

As a consequence of the processes that led to this mixing, chalk fragments occur at levels more than 20 m above the top of the Chalk found in borehole 1365. Conversely, traces of glauconitic sand occur more than 30 m below the oldest Palaeogene deposit found in borehole 1365. It is clear that both upwards and downwards movement of the admixed material has taken place, implying a circulation of material that could have given rise to the observed cross-cutting relationships.

An intriguing consequence of this mixing is the presence of clasts of brown flint and of vein quartz within the core at various depths of as much as 56.5 metres (Figure 4). Brown flint and vein quartz are common constituents of the Thames river terrace gravels (Bridgland, 1994) and their presence here suggests partial downward reworking of lithologies during deformation. It is possible, however, that some of these pebbles have been derived from the Upnor Formation.

The chalk fragments and inclusions range from some fairly coherent lumps of disaggregated chalk, some isolated subrounded fragments of soft to medium chalk ('chalk pebbles') and some angular fragments of chalk. Some of the latter are very small and delicate: it is thought that these – and perhaps all the chalk – were frozen at the time of transport and deposition. In an unfrozen state, the most delicate pieces of chalk present would have been destroyed by even small movements of their sandy matrix (or by weathering or groundwater circulation).

Lithofacies 5, the 'alluvium', appears to be in situ, based on the preservation of the sedimentary structures (that are the right way-up). Based upon lithology, it is suggested that the glauconitic sand in this unit is derived from the Palaeogene age Upnor Formation (Lambeth Group). The occurrence of five or more fining-upwards depositional cycles, each containing chalk clasts, corroborates the suggestion of multiple events of soft-sediment deformation. It appears that during formation of the mélange, there was a open, water-filled topographic depression at the surface. Fluctuations in subsurface pore water pressure appear to have injected part of the mixed sediment into the water in this depression, where it was deposited as the observed in situ 'alluvium'.

Lithofacies 6, which forms the topmost unit, is interpreted as made ground. It seems unlikely that, prior to infilling with waste material, this site remained as a natural cavity or topographic depression open to almost 17 m below the surface. The base of made ground in boreholes 1362 and 1363 is also significantly below OD, whereas in 1365 and other nearby BHs it is mostly several metres above OD. Presumably, the 'alluvium' was buried by some deposit of enough economic value to be worth excavating. It is therefore likely that this site was once part of a gravel pit, presumably worked by dredging as was the case at the nearby Hackney Wick Pit, although topographic maps dated between 1873 and 1938 show no indication of such a pit. The present depth of the made ground presumably approximates to the original extent of the gravel deposit, or perhaps a little more, there being no apparent reason for the gravel pit workers to excavate far into the underlying 'alluvium'.

It is therefore suggested that the site was originally buried to a depth of about 16 m by sand and gravel of a river terrace deposit that post-dates the underlying ‘alluvium’ and therefore the formation of the topographic depression in which that alluvium was deposited. This river terrace deposit was presumably contiguous with that underlying the surrounding area. The made ground contains a high proportion of sand and gravel. While some of this could have been dumped as waste, a proportion might represent material that has sloughed-off the sides of the flooded excavation during the period of back-filling.

6 Correlation of the river terrace deposits and age

The river terrace deposits beneath alluvium in the Temple Mills area have been studied by unpublished 3D geological modelling of Area 6 of the Thames Gateway model, by Don Aldiss. This work shows that the sub-alluvial gravels in this part of the Lea valley can be divided into three by reference to the basal level of the deposit. The local correlative of the Kempton Park Gravel mostly extends down to a basal surface at about 0 to -0.5 m OD and appears to underlie the east of Zone 6A. It is bounded to the north-east by a step up to the base of the Taplow Gravel at about 2.5 to 3.6 m OD, close to the local edge of the alluvium. Most of the Taplow Gravel lies above the level of the alluvium. The local occurrence of the Kempton Park Gravel is bounded to the west and to the north by gravels typically resting on a basal surface at about -1.3 to -2.2 m OD, which can be correlated with the Shepperton Gravel.

This correlation with the Shepperton Gravel is demonstrated by a local occurrence of the cold-climate organic deposit known as the ‘Lea Valley Arctic Bed’ recorded by Warren (1916), and described by him as the Temple Mill section (his locality G). The Lea Valley Arctic Bed has been radiocarbon-dated as being about 21.68 ka (Coope and Tallon, 1983; Hayward, 1956-57; Shotton and Williams, 1971), 24.6 ka (Gibbard, 1994, p. 110) or 28 ka old (Godwin and Willis, 1960; Hayward, 1956-57). It therefore appears to post-date the greater part of the Kempton Park Gravel (which is Devensian in age, possibly as late as Dimlington Stadial (26.0-13.0 ka) (McMillan et al., 2010, table 18) and to pre-date the Shepperton Gravel (which is Late Devensian in age, correlated with the Loch Lomond Stadial / Younger Dryas (c.10.8-9.6 ka) (Ellison et al., 2004; McMillan et al., 2010, table 18).

The Temple Mill section was in a gravel pit ‘immediately south-west of the Great Eastern Railway’ [TQ 379 859], and about 400 m north of the present site. A small pit is shown on topographic maps dated 1873. It exposed about 4.6 m of gravel and sand, beneath 1.4 m of soil and alluvium, resting on Palaeogene bedrock at a depth of about 6 m or 0 to -1 m OD. Disrupted masses of the Arctic Bed occur towards the base of the gravel, which can therefore be correlated with the Shepperton Gravel.

The Hackney Wick Pit (locality H of Warren, 1916) is another disused, infilled gravel pit, which was about 750 m south-west of the present site, west of the River Lea [TQ3727 8500]. This is shown on topographic maps dated 1920. Although the pit was permanently flooded and worked by dredging, the section appears to be similar to that at Temple Mills, except that the organic deposits represent a post-glacial climate, albeit somewhat cooler than the present day (Warren, 1916). By inference, the gravel at Hackney Wick can also be correlated with the Shepperton Gravel, there extending down to -1 or -2 m OD.

Most of those boreholes in Zone 6A of the Olympic Park (the site of the Eastway Cycle Circuit in the north of the Park) proved the expected sequence of made ground, alluvium, river terrace deposits, extending to depths of between -0.59 m OD and -2.09 m OD, implying that most of the Zone 6A area is underlain by the Shepperton Gravel, perhaps in two or more channels with remnants of the Kempton Park Gravel between them. The rockhead surface has a somewhat irregular shape, which might be a consequence of proximity to the anomalous structure exposed in boreholes 1362, 1363 and 1366.

There are no boreholes to the east of the anomalous structure that show the presence there of the Shepperton Gravel, and so it is possible that the structure is within the outcrop of the Kempton Park Gravel, or even within the Taplow Gravel. However, the clayey fill at the top of the anomalous sequence suggests proximity to the contemporary surface, so that formation during Taplow Gravel, when the local land surface would have been several metres higher than at present (and the confining aquitard that much thicker) seems unlikely.

Therefore, although the relative age of the anomalous structure to the individual river terrace deposits is uncertain, it appears very probable that it post-dates the Taplow Gravel.

As discussed in the next section, it could be as old as parts of the Kempton Park Gravel or as young as the Shepperton Gravel.

7 Origin of the structure

The stratigraphy preserved within the borehole suggests that the structure is most likely to have formed during the Devensian, possibly the Late Devensian. During this and previous Quaternary glaciations, widespread discontinuous permafrost existed throughout much of south-eastern England. The nature and depth of the mixing and deformation within the cored material points to extreme and quite possibly rare groundwater conditions and suggests that the structure was probably formed over a comparatively short time interval. The inference that at least some of the chalk in the mixed deposit was frozen at the time of emplacement implies contemporary permafrost conditions, with frozen ground to several tens of metres depth.

The preferred interpretation is that the anomalous structure represents a relict open-system pingo, or cluster of such pingos, although this interpretation should be treated with caution.

An alternative hypothesis for such structures is suggested by Berry (1979), who proposed that some of the localised deep scour hollows that formed in the river channel systems prior to deposition of the river terrace gravels reached depths that allowed rapid pressure release of confined groundwater. In this hypothesis, the inferred depression at the site of anomalous bedrock structures such as that found in Zone 6A is a cause, rather than a consequence, of the formation of the structure.

Origin as a pingo

According to Ballantyne and Harris (1994), open-system pingos are usually round or elliptical in plan, reaching maximum widths of less than 500 m and heights of 35 m. Most reported examples of relict pingo scars (i.e. the surface expression of a relict pingo) are between 25 and 350 m in diameter, and between 1.5 and 17 m in depth. The distances between the three boreholes that sampled the anomalous structure in Zone 6A, of less than 50 m, are therefore consistent with this origin. Likewise, the inferred existence of a depression as much as 16 m deep on the site of the structure is also consistent with it being a relict pingo scar.

Individual pingos can be relatively short-lived, but can form clusters in which successive pingos disrupt the relicts of earlier ones. This is consistent with the inferred rapid formation of the mixed sediment, and with its multi-phase nature.

In this hypothesis, the pingo (or successive pingos in a cluster) is thought to have formed by freezing of groundwater confined (or partly confined) under artesian pressure by a permafrost layer. The de-structured chalk seen in borehole 1365 suggests that, at times, the ground was frozen to a depth of more than 37 m (vertical distance from base of alluvium to the end of borehole 1365). However, the pingo may have formed when the permafrost was thinner and possibly discontinuous.

In 1365, the main aquifer (the Chalk plus overlying granular portions of the Palaeogene) is confined by only about 3 m of Palaeogene clays. There are indications in the BGS 3D geological model of the Lower Lea Valley that the bedrock in the vicinity of Zone 6A is faulted; possibly with faults of more than one orientation intersecting. Arguably, these discontinuities created pathways of enhanced groundwater flow, possibly leading to springs in the contemporary valley floor. Formation of free ice within such springs, and within zones of high permeability in the bedrock, is thought to have lead to the formation of a pingo or a cluster of pingos.

With time, a pingo will degrade: the ice core will melt. Typically, this leads to the formation of a flooded depression with a peripheral rampart (a relict pingo scar) but it is expected that where such scars occur on a braid plain or floodplain then the rampart will be destroyed and the depression infilled. It seems possible that the clayey facies near the top of the anomalous sequence in boreholes 1362, 1363 and 1366 represents part of such an infill, reflecting deposition from still or slow-moving water, prior to the ingress of river gravels.

At some point in the degradation of a pingo, there could be an abrupt release of confined groundwater, with the potential for an outrush of water, rapid erosion of the walls of the space once occupied by the pingo core, now a conduit, and fluidisation of the contents of that conduit. It is thought that this process explains the upwards movement and mixing of chalk, unweathered flint, and material derived from the Palaeogene. Such rapid movement might last only for a matter of hours, but the process might be repeated if the pingo reformed and failed again.
The apparent presence of small amounts of material derived from surface superficial deposits could be explained by there being an element of downwards movement: either by sinking through a fluidised granular medium, or within the downwards portion of convection cells within the fluidised material.

The inferred presence of a spring, and of fluidisation and rapid emplacement of the mixed sedimentary fill, implies considerable rates of groundwater flow, in excess of that available in unfractured chalk or chalk with minimal karst development. So it is very likely that the inferred bedrock faulting in this area is accompanied by karst development in the fractured chalk, leading to the presence of a zone of high groundwater conductivity.

In this interpretation, the pingo might have been contemporary with, or prior to, the deposition of the Shepperton Gravel. It is also possible that it dates from Kempton Park Gravel times, and that the Shepperton Gravel was then laid across a remnant of Kempton Park Gravel preserved in the pingo scar. However, as the local confining aquitard would have been about 4.5 m thick, on average, prior to deposition of the Kempton Park Gravel, compared with about 3 m prior to deposition of the Shepperton Gravel, the later origin seems more likely.

Origin by scour and pressure-release
The probable relationship with karst within the confined Chalk leads to the suggestion of catastrophic pressure release following a build-up of hydrostatic pressure within cavernous karst beneath permafrost, perhaps as the permafrost was degrading. In this instance, the conduit would be formed solely by upwards water movement, not by ground ice formation in a pingo.

Normally, where chalk karst is infilled, it is with oxidised sediment, much of which has been carried from the surface. The absence of such material might suggest that the anomalous structure is not a doline (or related type of surface structure), but this type of infill would not be expected in karst that might exist beneath an intact Palaeogene cover.

It seems possible that alluvial down-cutting during late glacial times could have led to the formation of a localised deep scour hollow that enabled groundwater under artesian pressure to break through to the surface. Other circumstances would be similar to that suggested for the ‘pingo’ hypothesis. The main advantage of this alternative is that it does not require the postulation of pingo formation; its main disadvantage is that some explanation of the presence of a deep scour hollow is required instead.

8 Conclusions

Detailed analysis of borehole 1366 from the Olympic Park development at Temple Mill reveals that Palaeogene and Late Cretaceous bedrock strata have been fluidised and remobilised at depth. The origin of this phenomena are not known with any certainty but it appears to be related to a short-lived event associated with unusual groundwater conditions.

It appears most likely that the anomalous sequence marks a relict pingo scar, with the pingo having been formed at a spring under permafrost conditions. Alternatively, it is possible that the structure marks a fluvial scour hollow formed prior to deposition of overlying river terrace deposits, which allowed the outburst of groundwater under artesian pressure. In either case, the anomalous sequence is likely to have formed in a zone of fractured, probably faulted, bedrock with karstic dissolution of the Chalk leading to high groundwater conductivity.

The structure is most likely to have formed during Late Devensian times, prior to or during the deposition of the Shepperton Gravel, but it might be older, possibly pre-dating part or all of the Devensian Kempton Park Gravel.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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Appendix 1

BGS registration numbers for new Olympic Park boreholes

TQ38NE 1362	MBHCZ6A-104
TQ38NE 1363	MBHCZ6A-106
TQ38NE 1364	MBHCZ6A-157
TQ38NE 1365	MBHCZ6A-158
TQ38NE 1366	MBHCZ6A-159
TQ38NE 1367	MBHCZ6A-160
TQ38NE 1368	MBHCZ6A-161
TQ38NE 1368	MBHCZ6A-162
TQ38NE 1370	MBHCZ6A-163
TQ38NE 1371	MBHCZ6A-164
TQ38NE 1372	MBHCZ6A-165