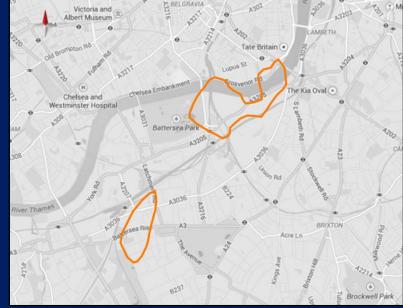
Drift-Filled Hollows in Battersea Investigation of the structure and geology along the route of the Northern Line Extension, London

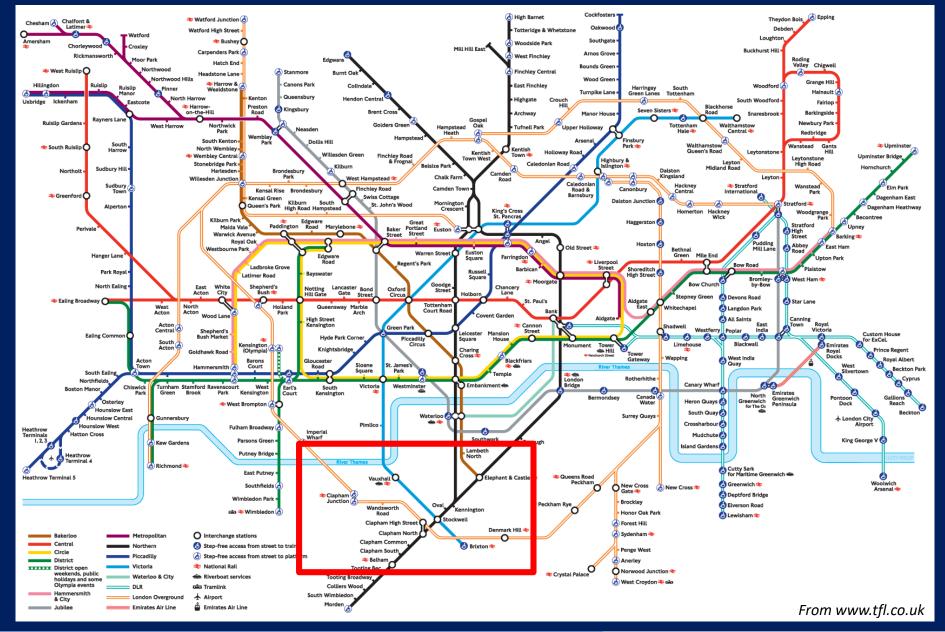
Emma Toms¹, Philippa J. Mason¹ & Richard C. Ghail²

¹Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK ²Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK



Imperial College London





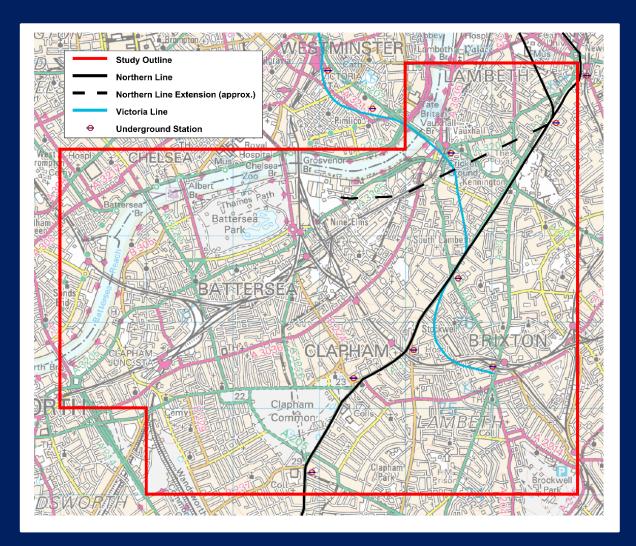


Northern Line Extension





Study Area Outline





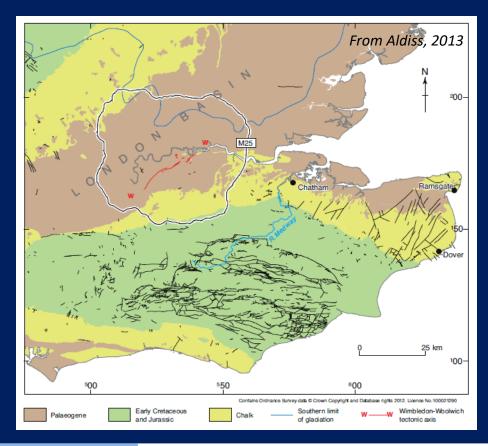
Project Aims

- To investigate the sedimentology, lithostratigraphy and structure along the Northern Line Extension (NLE) from Kennington to Battersea
- Create a 3D model using borehole logs
- Identify any potential geohazards:
 - Thames tributaries
 - Pingos
 - Faults



Geohazards in the London Basin

- 1. Mapped faults
- 2. Drift-Filled Hollows (DFHs)
- 3. Variable groundwater conditions



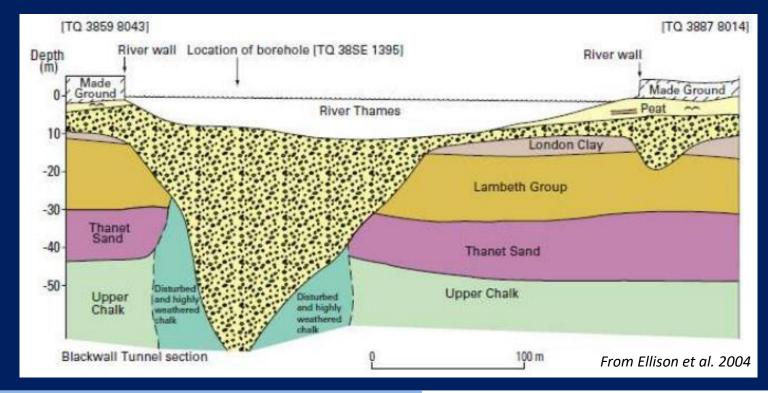
2. Geohazards in London

Imperial College London



Geohazards in the London Basin

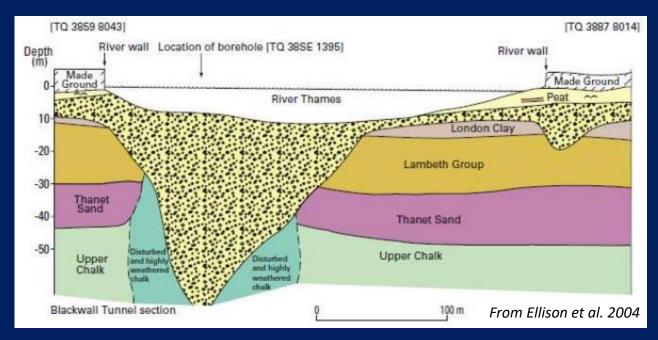
- 1. Mapped faults
- 2. Drift-Filled Hollows (DFHs)
- 3. Variable groundwater conditions





Why are DFHs a hazard to subsurface construction?

- Dewatering of perched water from the gravels
- Slumping of the walls of the DFH
- Differential compaction





Models for DFH Formation

There are several proposed theories for the formation of these DFHs:

- 1. Periglacial pingos
- 2. Fluvial scour
- 3. Faulting
- 4. Combination



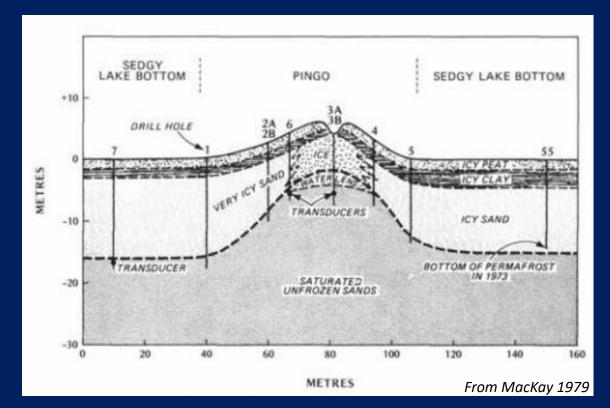




Models for DFH Formation

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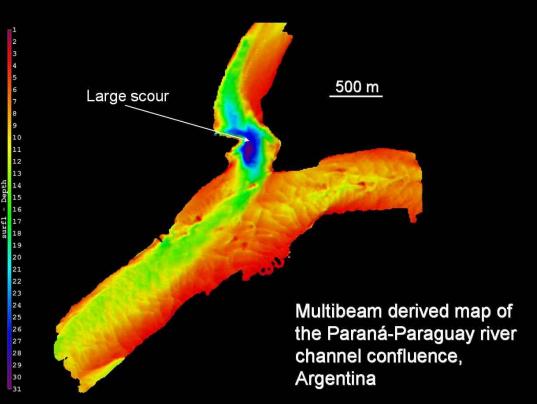




Models for DFH Formation

There are several proposed theories for the formation of these DFHs:

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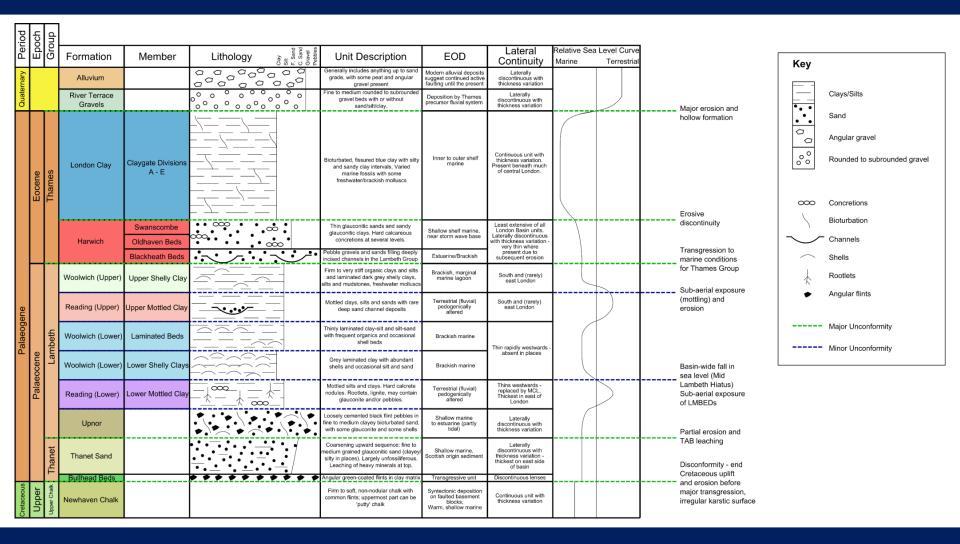


Daniel Parsons, University of Leeds





London Basin Stratigraphy





Data Collection

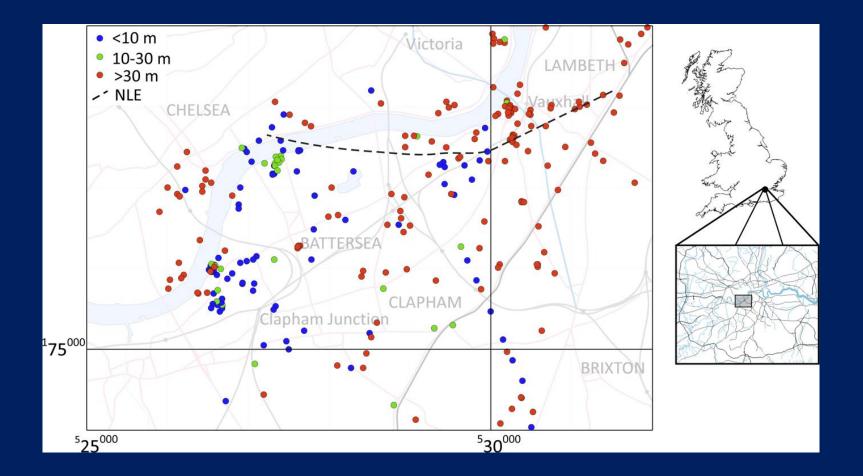
- 283 borehole records, with depths of 10-188m, were collected:
 - GeoRecords+
 - Halcrow site investigation
- Spreadsheet database held all information available on the borehole logs

| itish Geological : | Samples | | Ch | ange of S | itrata sh Geological | Survey Description of Strata |
|--------------------|--|----------------|--------|------------|-----------------------------|--|
| S Progress | Depth | Туре | Legend | Depth | O.D. Level | Description of Strata ' |
| | 2.6* | D | | | | FILL (soft brown sandy clay, becoming firm dark grey silty clay with ash; brick and flints |
| | 5*0* | D | | | | throughout) |
| | British Geological Si | rvey D | **** | 8 6 | 0.5 | British Geological Survey British |
| | 9'0" - 10'0" 9'0" - 10 0" | C(35) D | 0.00 | | | * |
| | 12 0" - 13'0" 12 0" - 13 0" | C(37) D | 0.00 | | <u>.</u> | Dense to very dense medium to coarse SAND and |
| | 15'0" - 16'0" 15'0" - 16'0" | C(56) D | 0000 | | | fine to medium GRAVEL |
| itish Geological : | 18'0" - 19'0" 18'0" - 19'0" | C(33) D | 0.0.0 | 20'0* | h Geological | Survey British Geological Survey |
| | 21 0" - 22 6" 22 6" | U(4) | | 20.0. | -11.0 | · · |
| | 22 6* 23 6* | D | | | | |
| | 26'0" - 27 6" 27'6" | U(4) D | X | r 1 | | |
| | 28 6* | D | ÷, č | | | |
| | British Geological S 31'0" - 32 6" 32'6" | U(4) D | | | | British Geological Survey British |
| 18.5.67 | 33'6" | D | | | | |
| | 36 0" - 37 6" 37'6" | U(4) D | | | | |
| | 38 6" | D | | | | |
| itish Geological : | 41'0" - 42'6" Urvey 42'6" | υ(μ) D | | • Briti | h Geological | Survey British Geological Survey |
| | 4316" | D | | | | Stiff, becoming very stiff, fissured dark grey silty CLAY with some fine sand partings below 90ft depth |
| | 46'0" - 17'6" 47'6" | U(41) D | | | | |
| | 48 6" | D | | | | • |
| | 51'0" - 52 6" 52'6" | υ(μ) D | | | | |
| | Britis 5 9 = 6 = gical S | irvey D. | | | | British Geological Survey Britis |
| | 56 0" - 57'6" 57'6 | U(4) D | | | | |
| | 58 6" | D | | | | · · · · |
| | 61 ^{°0} - 62 6" 62 ^{°6} 63 6" | υ(4) D D | | | - | |
| itish Geological : | 66 0" - 67 6" | U(4) | | Briti | h Geologica | Survey British Geological Survey |
| Key to type | 67°6" e of sample : | D | Rem | arks : (0 | Observati | (see over) |
| U (4) | in. dia. undisturber 11 in. dia. disturbed sample. | ~" | | | | and a second and a second data and a second data and a second data as a second data as a second data as a second |
| (× ()= | bulk disturbed samp vane test, standard penetration | n gest. | | | | |
| C () | dynamic cone penet test. tkets is No. of blows for given in depth column age 1). | | | Fro | om GeoRecords+, BGS website | |
| Use Notes, p | age 1). | | | | × × | |





Borehole Distribution





Borehole Log Quality

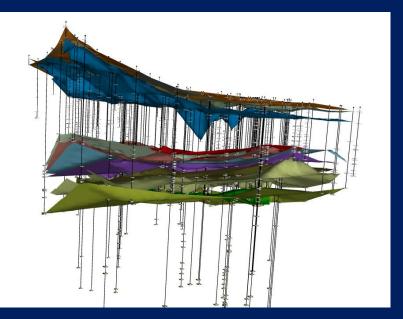
- Borehole log information was highly variable
- Historic log descriptions these differences had to be simplified for ground model construction





Ground Model Construction

- Boreholes were adjusted to the DTM surface (mAOD) to reduce false apparent displacements in the subsurface stratigraphy
- Stratigraphic units were correlated: surfaces interpolated using Delauney triangulation
- Faults interpreted this was initially carried out in 2D, as it was easier to see the vertical displacements







Stratigraphy: Upper Chalk & Bullhead Beds

| Epoch | Group | Formation | Member | | Unit Description | EOD | Lateral | | a Level Curve | |
|----------|-------------|--------------------------|-----------------------------|--|---|--|--|--------|------------------|---|
| t | 1- | Alluvium | | | Generally includes anything up to sand grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | Marine | Terrestrial | |
| | | River Terrace Gravels | | | Fine to medium rounded to subrounded gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation | | | Major erosion and |
| Eocene | Thames | London Clay | Claygate Divisions A - E | | Boturbated, fissured blue day with sity and sandy clay intervals. Varied marine fossils with some freshwaterbrackish molluscs | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | | hollow formation |
| | | | Swanscombe | | Thin glauconitic sands and sandy | Shallow shelf marine, | Least extensive of all London Basin units. | | | Erosive discontinuity |
| | | Harwich | Oldhaven Beds | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ | glauconitic clays. Hard calcareous concretions at several levels. | near storm wave base | Laterally discontinuous with thickness variation - very thin where | | | Transgression to |
| \vdash | | | Blackheath Beds | | Pebble gravels and sands filling deeply incised channels in the Lambeth Group Firm to very stiff organic clays and silts | Estuarine/Brackish Brackish, marginal | present due to subsequent erosion | | | for Thanes Group |
| | | Woolwich (Upper | Upper Shelly Clay | | and laminated dark grey shelly clays, silts and mudstones, freshwater mollusce | marine lagoon | South and (rarely) east London | | | Sub-aerial exposure |
| | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | Ι | \bigcirc | (mottling) and erosion |
| | heth | Woolwich (Lower |) Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | | |
| ocene | Lan | Woolwich (Lower |) Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in sea level (Mid |
| Palae | | Reading (Lower) | Lower Mottled Clay | | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | \triangleright | Lambeth Hiatus) Sub-aerial exposure of LMBEDs |
| | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | | Partial erosion and |
| | anet | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (clayey sitty in places). Largely unfossiliferous. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side | | | TAB leaching Disconformity - end |
| | ľ. | Bullhead Beds | | * * * * * * * * * * | | Transgressive unit | Discontinuous lenses | | | Cretaceous uplift |
| Upper | Ipper Chall | Newhaven Chalk | | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | major transgression, irregular karstic surface |



Stratigraphy: Thanet Formation

| Epoch | Group | Formation | Member | Tithology (State 1 - State | Unit Description | EOD | Lateral Continuity | Relative Sea Marine | Level Curve Terrestrial | | |
|--------|-------------|---------------------------|-----------------------------|--|---|--|---|------------------------|----------------------------|---|--|
| | | Alluvium River Terrace | | | Generally includes anything up to sand grade, with some peat and angular gravel present Fine to medium rounded to subrounded | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation Laterally | | | | |
| | | Gravels | | | gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | discontinuous with thickness variation | | | Major erosion and | |
| Eocene | Thames | London Clay | Claygate Divisions A - E | | Bioturbated, fissured blue clay with sitty and sandy clay intervals. Varied marine bosils with some freehwater/brackish moltuics | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | | hollow formation | A. |
| | | Harwich | Swanscombe Oldhaven Beds | | Thin glauconitic sands and sandy glauconitic clays. Hard calcareous concretions at several levels. | Shallow shelf marine, near storm wave base | Least extensive of all London Basin units. Laterally discontinuous with thickness variation very thin where | | | Erosive discontinuity Transgression to | and Barton |
| | | | Blackheath Beds | | Pebble gravels and sands filling deeply incised channels in the Lambeth Group | Estuarine/Brackish | present due to subsequent erosion | | | marine conditions | 7 June Jack Bar |
| | | Woolwich (Uppe | r) Upper Shelly Clay | | Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater molluscs | Brackish, marginal marine lagoon | South and (rarely) east London | | | for Thames Group | the state of the |
| | | Reading (Upper | r) Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | | \mathbf{D} | (mottling) and erosion | A start and a start and a start a star |
| Ŷ | heth | Woolwich (Lowe | er) Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards |] (| | 2 | |
| ocene | Lan | Woolwich (Lowe | er) Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in sea level (Mid | |
| Palae | | Reading (Lower | r) Lower Mottled Clay | <u> </u> | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | \supset | Lambeth Hiatus) Sub-aerial exposure of LMBEDs | |
| | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, | Shallow marine to estuarine (partly | Laterally discontinuous with | | | Partial erosion and | |
| | anet : | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (clayey sitty in places). Largely unfossiliferous Lanching of basis or places of the | r Shallow marine, Scottish origin sediment | Laterally discontinucus with thickness variation - thickest on east side | | | TAB leaching Disconformity - end | |
| | ÷., | Bullhead Beds | | * * * * * * * * * * | Angular green-coated flints in clay matrix | Transgressive unit | Discontinuous lenses | | | Cretaceous uplift and erosion before | |
| Upper | Jpper Chalk | Newhaven Chalk | ĸ | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | major transgression, irregular karstic surface | |



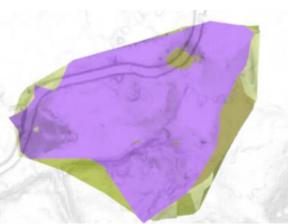
Stratigraphy: Upnor Formation

| Epoch | Group | Formation | Member | | Unit Description | EOD | Lateral | Relative Sea | | | |
|--------|------------|--------------------------|--|-----------------------|--|--|---|--------------|-------------|---|-----------|
| | | Alluvium | | | Generally includes anything up to sand grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | Marine | Terrestrial | | |
| | | River Terrace Gravels | | | Fine to medium rounded to subrounded gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation | | | Major erosion and | |
| Eocene | Thames | London Clay | Claygate Divisions A - E | | Bioturbaidd, fissured blue clay with ailty and sandy clay intervals. Varied marine fossils with some freshwater/brackish molluscs | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | | hollow formation | |
| | | Harwich | Swanscombe Oldhaven Beds Blackheath Beds | | Thin glauconitic sands and sandy glauconitic clays. Hard calcareous concretions at several levels. Pebble gravels and sands filling deeply | Shallow shelf marine, near storm wave base Estuarine/Brackish | Least extensive of all London Basin units. Laterally discontinuous with thickness variation very thin where present due to | | | discontinuity Transgression to | a fin how |
| | | Woolwich (Upper) | Upper Shelly Clay | | incised channels in the Lambeth Group Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater molluscs | Brackish, marginal marine lagoon | subsequent erosion South and (rarely) east London | | | marine conditions for Thames Group | and and |
| | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | | Ď | Sub-aerial exposure (mottling) and erosion | A STA |
| | nbeth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | | Solar Stan | |
| eocene | Lan | Woolwich (Lower) | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in sea level (Mid | - PA |
| Pala | | Reading (Lower) | Lower Mottled Clay | | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles | Terrestrial (fluvial) pedogenically altered | Thins westwards replaced by MCL. Thickest in east of | | \supset | Lambeth Hiatus) Sub-aerial exposure of LMBEDs | |
| | | Upnor | | | Loosely cemented black fiint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | | Partial erosion and | |
| | Thanet | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (clayey) sity in places). Largely unfossiliferous. Leaching of heavy minerals at top. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side of basin | | | TAB leaching Disconformity - end | |
| | ¥ | Bullhead Beds | | * * * * * * * * * * * | 1 | Transgressive unit | Discontinuous lenses | | | Cretaceous uplift and erosion before | |
| Upper | Upper Chal | Newhaven Chalk | | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | major transgression, irregular karstic surface | |



Stratigraphy: Lower Mottled Clay

| | Epoch | Group | Formation | Member | Lithology keys sis c.c. Samo | Unit Description | EOD | Lateral Continuity | Relative Sea Level Curve Marine Terrestria | |
|---|--------|----------|--------------------------|-----------------------------|--|--|--|---|---|--|
| | | | Alluvium | | | Generally includes anything up to sand grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | | 1 |
| | _ | _ | River Terrace Gravels | | °°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°°° | Fine to medium rounded to subrounded gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation | | Major erosion and |
| | Eocene | Thames | London Clay | Claygate Divisions A - E | | Bichurbated, fissured blue clay with sity and sandy clay intervals. Varied marine fossils with some freshwaterbrackish molluscs | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | hollow formation |
| l | | | Harwich | Swanscombe Oldhaven Beds | | Thin glauconitic sands and sandy glauconitic clays. Hard calcareous concretions at several levels. | Shallow shelf marine, near storm wave base | Least extensive of all London Basin units. Laterally discontinuous with thickness variation - very thin where | | Erosive discontinuity |
| L | | | | Blackheath Beds | \cdot | Pebble gravels and sands filling deeply incised channels in the Lambeth Group | Estuarine/Brackish | present due to subsequent erosion | | Transgression to marine conditions |
| l | | | Woolwich (Upper) | Upper Shelly Clay | | Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater mollusce | Brackish, marginal marine lagoon | South and (rarely) east London | | for Thames Group Sub-aerial exposure |
| l | | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | | (mottling) and erosion |
| | | ambeth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | ~ |
| | cene | Lan | Woolwich (Lower) | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | Basin-wide fall in sea level (Mid |
| Ì | Pala | | Reading (Lower) | Lower Mottled Clay | | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauccnite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | Lambeth Hiatus) Sub-aerial exposure of LMBEDs |
| | | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | Partial erosion and |
| | | Thanet : | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (clayey sitty in places). Largely unfossiliferous, Leaching of heavy minerals at top. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side of basin | | TAB leaching Disconformity - end Cretaceous uplift |
| t | | halk | Bullhead Beds | | * * * * * * * * * * | Angular green-coated flints in clay matrix Firm to soft, non-nodular chalk with | Transgressive unit Syntectonic deposition | Discontinuous lenses | ┫╴╸╸┍┶╺╸┝╺╸╸╸╸ | and erosion before major transgression, |
| | Upper | Jpper CI | Newhaven Chalk | | | common flints; uppermost part can be 'putty' chalk | on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | irregular karstic surface |





Stratigraphy: Lower Shelly Clays & Laminated Beds

| Ер | ğ | Formation | Member | Clay SI Sind Graved Pebbles | Unit Description | EOD | Lateral Continuity | Relative Sea Marine | a Level Curve Terrestrial | | |
|--------|-----------|--------------------------|-----------------------------|---|--|--|---|------------------------|------------------------------|---|---|
| | | Alluvium | | | Generally includes anything up to sand grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | | | | |
| | | River Terrace Gravels | | | Fine to medium rounded to subrounded gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation |] | | Major erosion and | |
| Eocene | | London Clay | Claygate Divisions A - E | | Bioturhated, fissured blue clay with ally and sandy clay internal. Varied marine basis with some freshwater/brackish molluscs | Inner to outer shelf marine | Continuous unit with thickness variation. Present breast much of central London. | | | hollow formation | Z |
| | | Harwich | Swanscombe Oldhaven Beds | | Thin glauconitic sands and sandy glauconitic clays. Hard calcareous concretions at several levels. | Shallow shelf marine, near storm wave base | Least extensive of all London Basin units. Laterally discontinuous with thickness variation - very thin where | | | Erosive discontinuity | 6 |
| | | | Blackheath Beds | $\sim \sim $ | Pebble gravels and sands filling deeply incised channels in the Lambeth Group | Estuarine/Brackish | present due to subsequent erosion | | | Transgression to marine conditions | |
| | | Woolwich (Upper) | Upper Shelly Clay | | Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater molluscs | Brackish, marginal marine lagoon | South and (rarely) east London | | | for Thames Group | |
| | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | | | Cub-aerial exposure (motting) and erosion | |
| | heth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | | Sant Yes | |
| ocene | Lan | Woolwich (Lower) | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in sea level (Mid | |
| Pala | | Reading (Lower) | Lower Mottled Clay | | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | \square | Lambeth Hiatus) Sub-aerial exposure of LMBEDs | |
| | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | | Partial erosion and | |
| | Thanet : | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (dayey silty in places). Largely unfossilferous. Leaching of heavy minerals at top. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side of basin | | | TAB leaching Disconformity - end Cretaceous uplift | |
| _ | | Bullhead Beds | | * * * * * * * * * * * | Angular green-coated flints in clay matrix | Transgressive unit | Discontinuous lenses | ┫╾╾╼┍┶╼╼ | + - | and erosion before | |
| Jpper | per Chall | Newhaven Chalk | | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | major transgression, irregular karstic surface | |



Stratigraphy: Upper Mottled Clay

| Period | Epoch | Group | | | | | | | | | |
|-----------|------------|------------|--------------------------|---|---|---|--|---|------------------------|----------------------------|--|
| Pe | щ | ū | Formation | Member | Pebbles Clay Clay Sill Sill Clay Clay Clay Clay Clay Clay Clay Cl | Unit Description | EOD | Lateral Continuity | Relative Sea Marine | Level Curve Terrestrial | |
| ernary | | | Alluvium | | | Generally includes anything up to sand grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | | | |
| Quate | | | River Terrace Gravels | | ° ° ° ° ° ° ° ° ° ° ° ° ° ° ° ° ° ° ° | Fine to medium rounded to subrounded gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation | | | Major erosion and |
| | Eocene | Thames | London Clay | Claygate Divisions A - E | | Bioturbahd, fissured blue clay with sitty and sandy clay intervals. Varied marine fossis with some freshwaterbrackish molluscs | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | | hollow formation |
| | | | Harwich | Swanscombe Oldhaven Beds | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ | Thin glauconitic sands and sandy glauconitic clays. Hard calcareous concretions at several levels. | Shallow shelf marine, near storm wave base | Least extensive of all London Basin units. Laterally discontinuous with thickness variation - very thin where | | | discontinuity |
| | | | | Blackheath Beds | $\sim \sim \sim \sim$ | Pebble gravels and sands filling deeply incised channels in the Lambeth Group | Estuarine/Brackish | présent due to subsequent erosion | | | Transgression to marine conditions |
| | | | | Firm to very stiff organic clays and silts and laminated dark grey shelly clays, | Brackish, marginal marine lagoon | South and (rarely) | | | for Thames Group | | |
| ene | | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | |) | Sub-aerial exposure (mottling) and erosion |
| Palaeo | | ambeth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-siit and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | | • |
| ٩. | Palaeocene | Lan | Woolwich (Lower) | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in |
| | Pala | | Reading (Lower) | Lower Mottled Clay | | Mottled sits and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | \supset | Lambeth Hiatus) Sub-aerial exposure of LMBEDs |
| | | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | | Partial erosion and |
| | | Thanet : | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glaucontic sand (clayey sitty in places). Largely unfossiliferous. Leaching of heavy minerals at top. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side of basin | | | TAB leaching Disconformity - end Cretaceous uplift |
| SL | | ž | Bullhead Beds | | | Angular green-coated flints in clay matrix | Transgressive unit | Discontinuous lenses | ┫╾╾╼┍┶╼╼ | | and erosion before |
| Cretaceou | Upper | Upper Chal | Newhaven Chalk | | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | major transgression, irregular karstic surface |





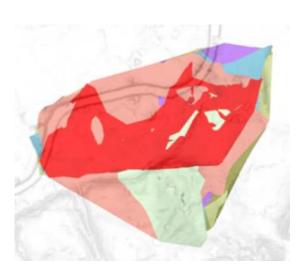
Stratigraphy: Upper Shelly Clay

| riod | och Jub | ţ | | | | | | | | | |
|------------|------------------|--------------------------|--|-------------------------------|---|--|---|------------------------|----------------------------|---|----------|
| Pei | Gro Gro | Formation | Member | Pebbes | Unit Description | EOD | Lateral Continuity | Relative Sea Marine | Level Curve Terrestrial | | |
| ernary | | Alluvium | | | Generally includes anything up to sand grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | | | | |
| Quate | | River Terrace Gravels | | | Fine to medium rounded to subrounded gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation | | | Major erosion and | |
| | Eocene Thames | London Clay | Claygate Divisions A - E | | Bioturbated, fissured blue clay with sity and sandy clay intervals. Varied marine fossis with some freehwater/brackish moltucs | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | | hollow formation | A Tr |
| | | Harwich | Swanscombe Oldhaven Beds Blackheath Beds | | Thin glauconitic sands and sandy glauconitic clays, Hard calcareous concretions at several levels. Pebble gravels and sands filling deeply incised chargets in the Lambath Group | Shallow shelf marine, near storm wave base Estuarine/Brackish | Least extensive of all London Basin units. Laterally discontinuous with thickness variation - very thin where present due to subsequent erosion | | | Erosive discontinuity Transgression to marine conditions | |
| | | Woolwich (Upper) | Upper Shelly Clay | | Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater moliusce | Brackish, marginal marine lagoon | South and (rarely) east London | | | for Thames Group Sub-aerial exposure | N. Call |
| ene | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | | \sum | (mottling) and erosion | Jan Karl |
| alaeou | heth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | | | |
| | eocene | Woolwich (Lower) | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in sea level (Mid | |
| | Pala | Reading (Lower) | Lower Mottled Clay | | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | > | Lambeth Hiatus) Sub-aerial exposure of LMBEDs | |
| | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | | Partial erosion and | |
| | Thanet | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (clayey silty in places). Largely unfossiliferous. Leaching of heavy minerals at top. Angular grean-coated films in clay matrix | Shallow marine, Scottish origin sediment Transgressive unit | Laterally discontinuous with thickness variation - thickest on east side of basin Discontinuous lenses | | | TAB leaching Disconformity - end Cretaceous uplift | |
| Cretaceous | Upper Chalk | Newhaven Chalk | | F. T. F. T. T. F. F. Y. F. F. | Angular green-coated flints in clay matrix Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | and erosion before major transgression, irregular karstic surface | |



Stratigraphy: Harwich Formation

| Period | Epoch | Group | | | pur see | | 505 | Lateral | Relative Sea | Level Curve | |
|------------|------------|-------------|--------------------------|-----------------------------|---|--|--|---|--------------|-------------|--|
| ₽. | ш | Ů | Formation | Member | | Unit Description | EOD | Continuity | Marine | Terrestrial | |
| rnary | | | Alluvium | | | grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | | | |
| Quate | | | River Terrace Gravels | | | Fine to medium rounded to subrounded gravel beds with or without sand/silt/clay. | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation | | | Major erosion and |
| | Eocene | Thames | London Clay | Claygate Divisions A - E | | Bioturbailed, fissured blue clay with sitily and sandy clay intervals. Varied maine focusis with some freshwater/brackah motusca | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | | hollow formation |
| Г | L | | | Swanscombe | •• ∞ • _∞ • | Thin glauconitic sands and sandy | Shallow shelf marine, | Least extensive of all London Basin units. | | | Erosive discontinuity |
| L | | | Harwich | Oldhaven Beds | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ | glauconitic clays. Hard calcareous concretions at several levels. Pebble gravels and sands filling deeply | near storm wave base | Laterally discontinuous with thickness variation - very thin where present due to | | | Transgression to |
| | L | L | | Blackheath Beds | | incised channels in the Lambeth Group | Estuarine/Brackish | subsequent erosion | | | marine conditions for Thames Group |
| | | | Woolwich (Upper) | Upper Shelly Clay | | Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater molluscs | Brackish, marginal marine lagoon | South and (rarely) east London | | | Sub-aerial exposure |
| ene | | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | | | (mottling) and erosion |
| Palaeogene | 1 | ambeth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | | |
| <u>م</u> | Palaeocene | Lan | | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in sea level (Mid |
| | Palae | | Reading (Lower) | Lower Mottled Clay | | Mottled sits and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | > | Lambeth Hiatus) Sub-aerial exposure of LMBEDs |
| | | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | | Partial erosion and |
| | | Thanet | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glaucontifs sand (clayey silty in places). Largely unfossiliferous. Leaching of heavy minerals at top. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side of basin | | | TAB leaching Disconformity - end Cretaceous uplift |
| 60 | | - | Bullhead Beds | | * * * * * * * * * * * | Angular green-coated flints in clay matrix | Transgressive unit | Discontinuous lenses | ╉╍╍╍┍┷╍╍┾ | | and erosion before |
| Cretaceous | Upper | Upper Chalk | Newhaven Chalk | | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | major transgression, irregular karstic surfac |





Stratigraphy: London Clay Formation

| Epoc | Group | Formation | Member | Clay Clay San G an sand G an sand Petables | Unit Description | EOD | Lateral Continuity | Relative Sea Marine | Level Curve Terrestrial |] |
|--------|-------------|------------------|----------------------------------|---|--|--|---|------------------------|----------------------------|---|
| | | Alluvium | | | Generally includes anything up to sand grade, with some peat and angular gravel present | Modern alluvial deposits suggest continued active faulting until the present | Laterally discontinuous with thickness variation | | | |
| | | River Terrace | | | Fine to medium rounded to subrounded gravel beds with or without | Deposition by Thames precursor fluxial system | Laterally discontinuous with | 1 | | |
| Eocene | Thames | London Clay | Claygate Divisions A - E | | Bioturbined, fissured blue clay with sith and sandy clay intervals. Varied marine losals with some freahwaterbrackish mölascs | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneats much of central London. | | | Major erosion and hollow formation |
| | Т | | Swanscombe | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ | Inin glauconitic sands and sandy glauconitic clays. Hard calcareous concretions at several levels. | Shallow shelf marine, near storm wave base | London Basin units. Laterally discontinuous | | | discontinuity |
| | | Harwich | Oldhaven Beds Blackheath Beds | | Pebble gravels and sands filling deeply incised channels in the Lambeth Group | Estuarine/Brackish | with thickness variation - very thin where present due to subsequent erosion | | | Transgression to marine conditions |
| | T | Woolwich (Upper) | Upper Shelly Clay | | Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater molluscs | Brackish, marginal marine lagoon | South and (rarely) east London | | | for Thames Group |
| | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | |) | Sub-aerial exposure (mottling) and erosion |
| | ambeth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | | 15 |
| socene | 1- | | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | | Basin-wide fall in sea level (Mid |
| Palaed | | Reading (Lower) | Lower Mottled Clay | | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | > | Lambeth Hiatus) Sub-aerial exposure of LMBEDs |
| | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | | Partial erosion and |
| | Thanet | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (dayey silty in places). Largely unfossilferous. Leaching of heavy minerals at top. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side of basin | | | TAB leaching Disconformity - end |
| | 1 | Bullhead Beds | | * * * * * * * * * * | Angular green-coated flints in clay matrix | Transgressive unit | Discontinuous lenses | 1 | | Cretaceous uplift and erosion before |
| Upper | Ipper Chalk | Newhaven Chalk | | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | | major transgression, irregular karstic surface |

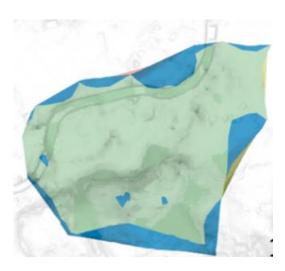






Stratigraphy: River Terrace Gravels

| Period | Epoch | Group | | | 9 5 5 | | | Latoral | Relative Sea Level Curve | 1 |
|------------|------------|-------------|--------------------------|--------------------------------------|--|--|--|---|--------------------------|--|
| Å | Щ | Ū | Formation | Member | Pebble Clay Clay Clay Clay Clay Clay Clay Clay | Unit Description | EOD | Lateral Continuity | Marine Terrestrial | |
| ary | | | Alluvium | | 0,0000000 | Generally includes anything up to sand grade, with some peat and angular | Modern alluvial deposits suggest continued active | Laterally discontinuous with | | |
| Quate | | | River Terrace Gravels | | | Fine to medium rounded to subrounded gravel beds with or without | Deposition by Thames precursor fluvial system | Laterally discontinuous with thickness variation | | Major erosion and |
| | Eocene | Thames | London Clay | Claygate Divisions A - E | | Bioturbailed, fissured blue clay with silty and sandy clay intervals. Varied marine fossis with some freshwaterbrackish molluscs | Inner to outer shelf marine | Continuous unit with thickness variation. Present beneath much of central London. | | hollow formation |
| | | | Harwich | Swanscombe Oldhaven Beds | | Thin glauconitic sands and sandy glauconitic clays, Hard calcareous concretions at several levels. Pebble gravels and sands filling deeply | Shallow shelf marine, near storm wave base | Least extensive of all London Basin units. Laterally discontinuous with thickness variation very thin where present due to | | discontinuity |
| | | | Woolwich (Upper) | Blackheath Beds Upper Shelly Clay | | incised channels in the Lambeth Group Firm to very stiff organic clays and silts and laminated dark grey shelly clays, silts and mudstones, freshwater molluscs | Estuarine/Brackish Brackish, marginal marine lagoon | subsequent erosion South and (rarely) east London | | marine conditions for Thames Group |
| ene | | | Reading (Upper) | Upper Mottled Clay | | Mottled clays, silts and sands with rare deep sand channel deposits | Terrestrial (fluvial) pedogenically altered | South and (rarely) east London | | Sub-aerial exposure (mottling) and erosion |
| Palaeogene | | ambeth | Woolwich (Lower) | Laminated Beds | | Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds | Brackish marine | Thin rapidly westwards | | |
| | Palaeocene | Lar | Woolwich (Lower) | Lower Shelly Clays | | Grey laminated clay with abundant shells and occasional silt and sand | Brackish marine | absent in places | | Basin-wide fall in sea level (Mid |
| | Pala | | Reading (Lower) | Lower Mottled Clay | | Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain glauconite and/or pebbles. | Terrestrial (fluvial) pedogenically altered | Thins westwards - replaced by MCL. Thickest in east of London | | Lambeth Hiatus) Sub-aerial exposure of LMBEDs |
| | | | Upnor | | | Loosely cemented black flint pebbles in fine to medium clayey bioturbated sand, with some glauconite and some shells | Shallow marine to estuarine (partly tidal) | Laterally discontinuous with thickness variation | | Partial erosion and |
| | | Thanet | Thanet Sand | | | Coarsening upward sequence: fine to medium grained glauconitic sand (clayey sitty in places). Largely unfossiliferous. Leaching of heavy minerals at top. | Shallow marine, Scottish origin sediment | Laterally discontinuous with thickness variation - thickest on east side of basin | | TAB leaching Disconformity - end Cretaceous uplift |
| S | | | Bullhead Beds | | | Angular green-coated flints in clay matrix | Transgressive unit | Discontinuous lenses | ┫╴╴╴┍┶╶╴┼╴╴╴╴╸╸ | and erosion before |
| Cretaceout | Upper | Upper Chalk | Newhaven Chalk | | | Firm to soft, non-nodular chalk with common flints; uppermost part can be 'putty' chalk | Syntectonic deposition on faulted basement blocks; Warm, shallow marine | Continuous unit with thickness variation | | major transgression, irregular karstic surface |

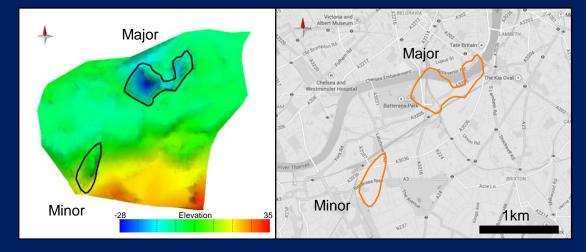


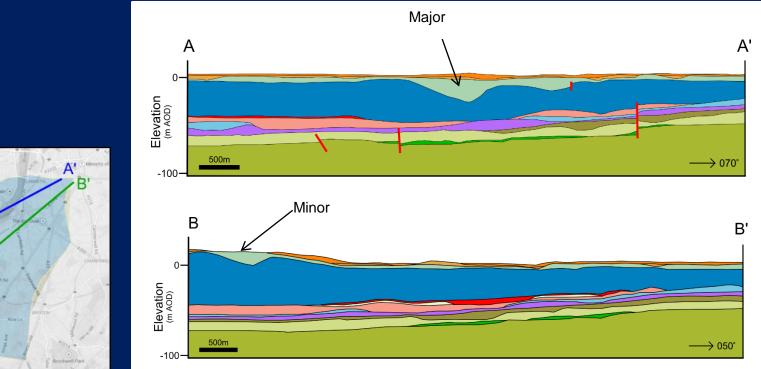




<u>DFHs</u>

A



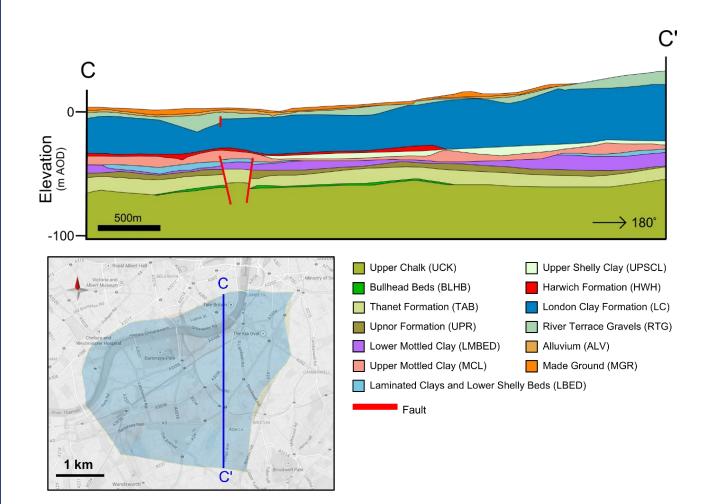


4. DFHs in Battersea



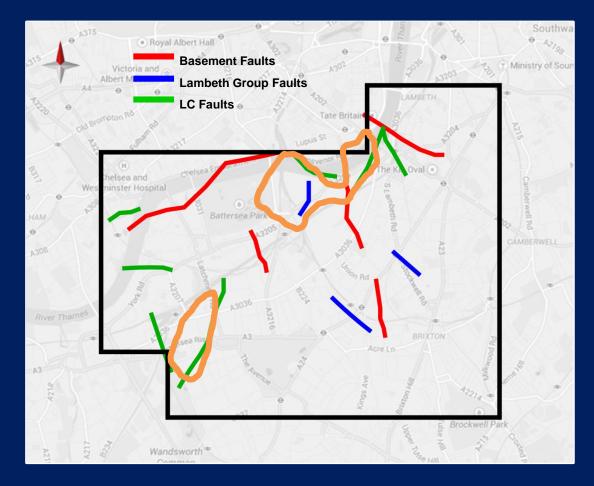
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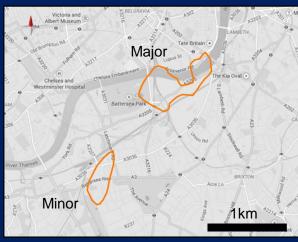
<u>DFHs</u>





Interpreted Faults



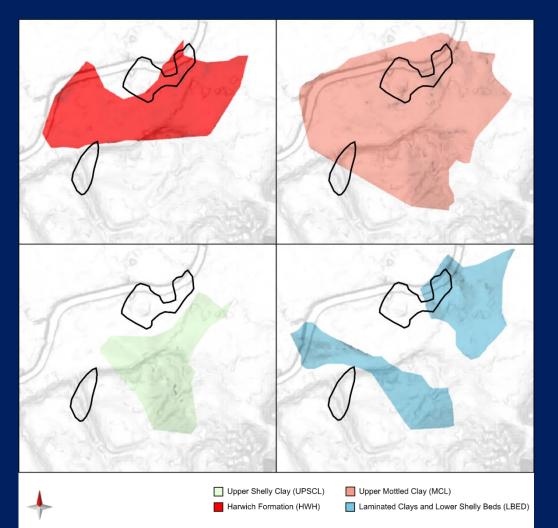


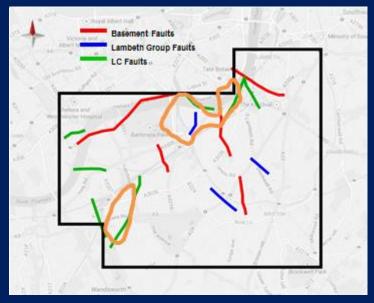
4. DFHs in Battersea





Lithological Control?

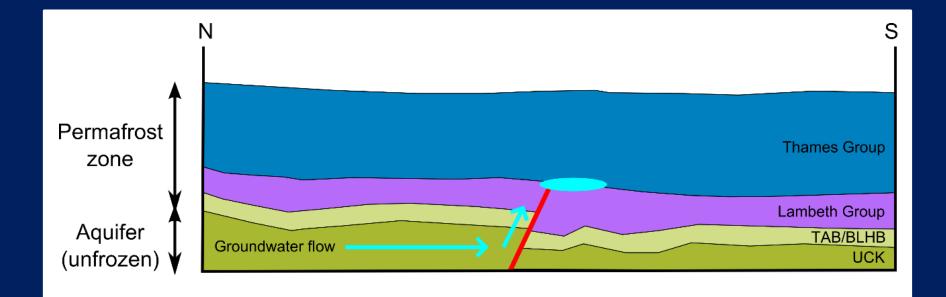




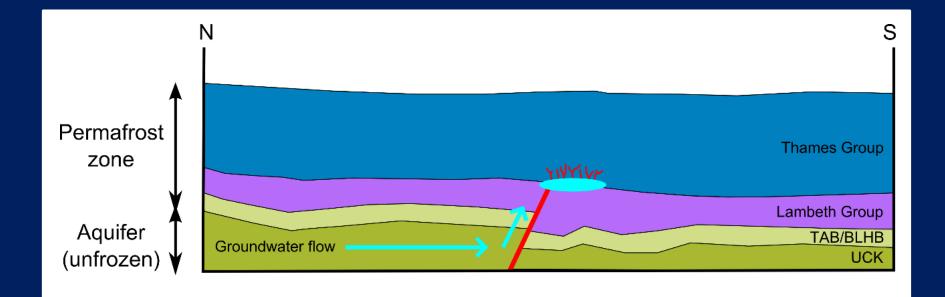
4. DFHs in Battersea

Imperial College

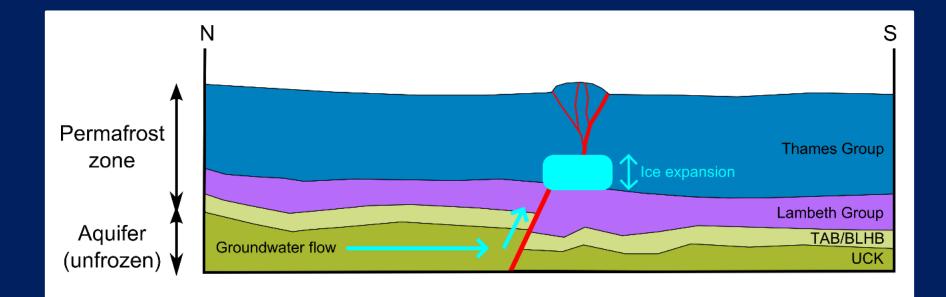




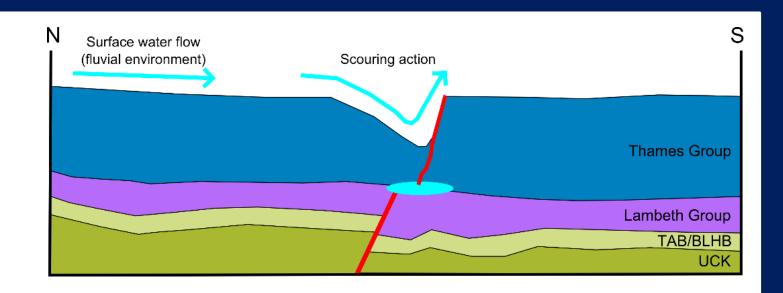






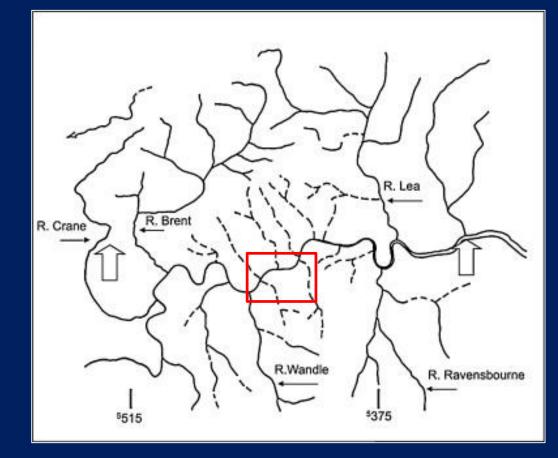


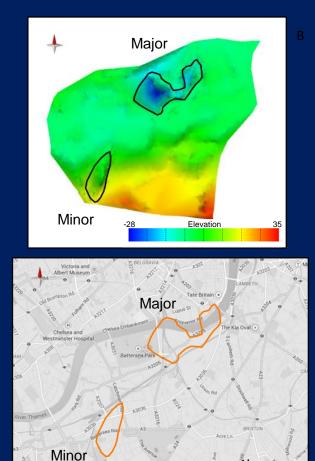






DFH Formation: Scouring

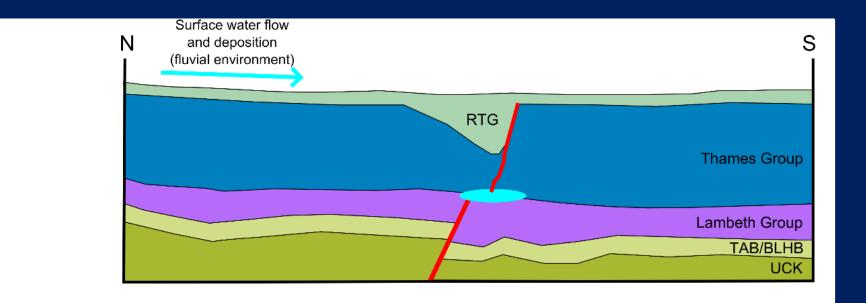




5. Discussion

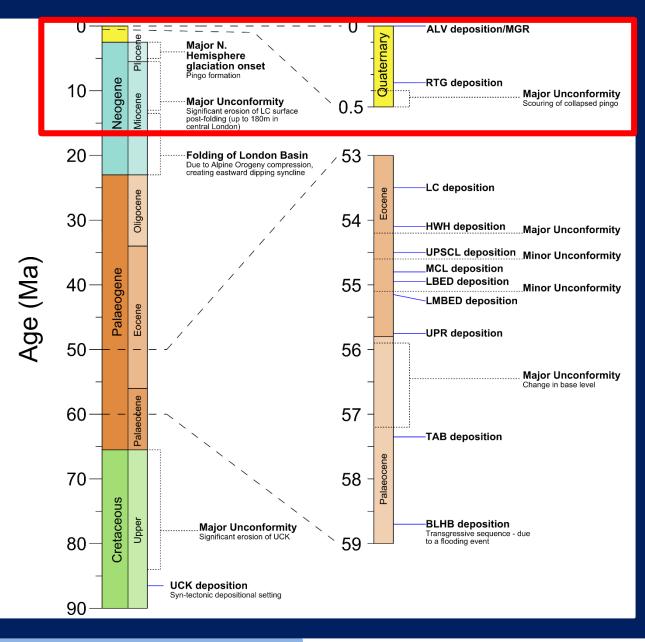


1km



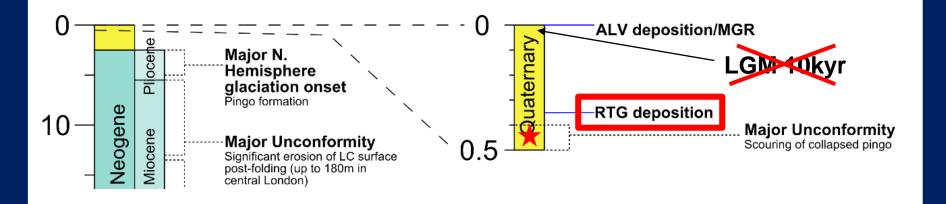








DFH Formation Timing



- Literature: pingo formation during LGM
- But River Terrace Gravels dated to 0.35Ma
- Anglian glaciation instead (when glacial ice reached north London)



Conclusions

- Geology of London Basin more complex than previously thought: faults, stratigraphy and DFHs
- DFHs are likely to have originated as both periglacial pingo features and in relation to scour
 - Probably formed earlier than the LGM
- Possible lithological control on the distribution of DFHs, as well as a relation to faulting
- DFHs can cause problems for construction this could be a problem in Battersea
 - Groundwater pumping and tunnel sealing may be required

6. Conclusions



Recommendations

- Investigate further if there is a lithological control on the location of DFHs (whether there are sand units below other DFHs)
- Drilling of additional boreholes to more accurately constrain the limits of the major DFH

<u>Acknowledgements</u>

- Philippa Mason & Richard Ghail
- Support team at Midland Valley, who helped solve the issues encountered with 3D Move software

6. Recommendations



Research article

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Drift-filled hollows in Battersea: investigation of the structure and geology along the route of the Northern Line Extension, London

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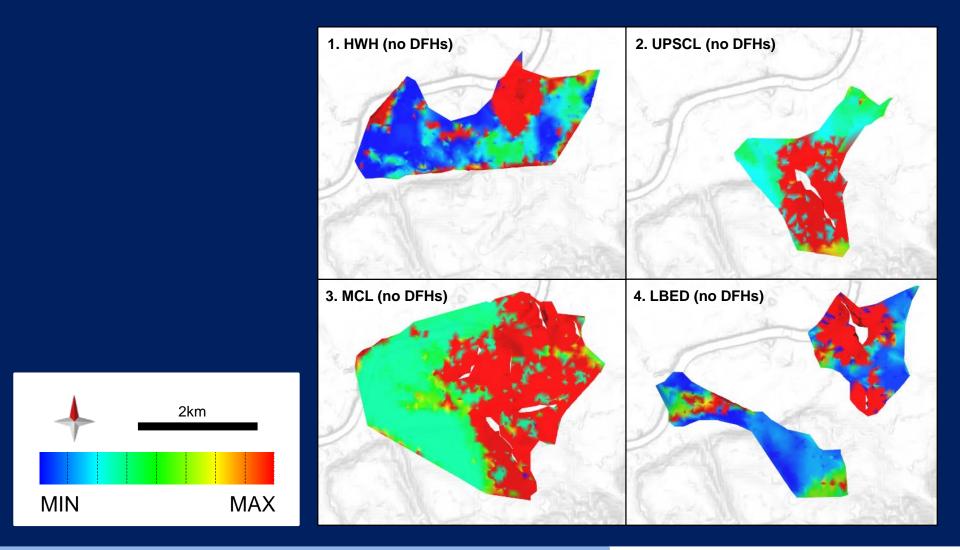
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