Drift-Filled Hollows in Battersea

Investigation of the structure and geology along the route of the Northern Line Extension, London

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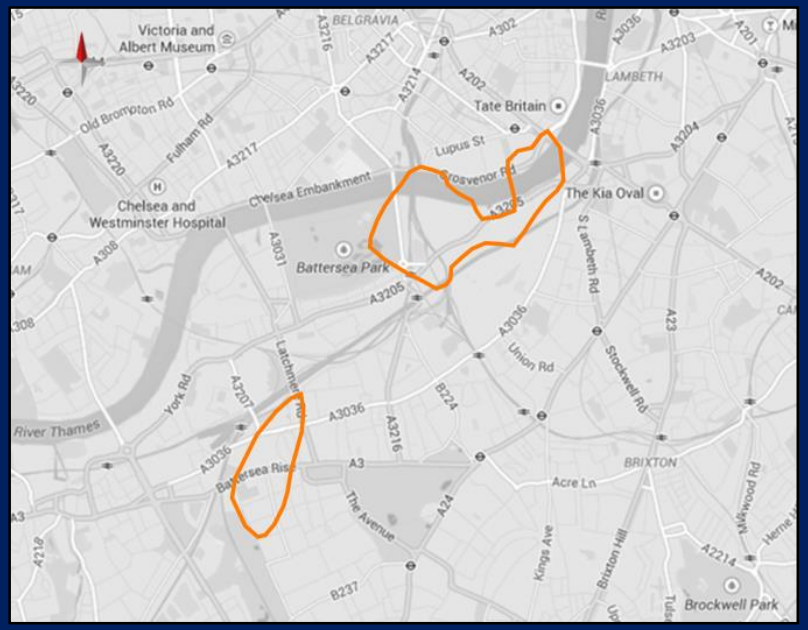

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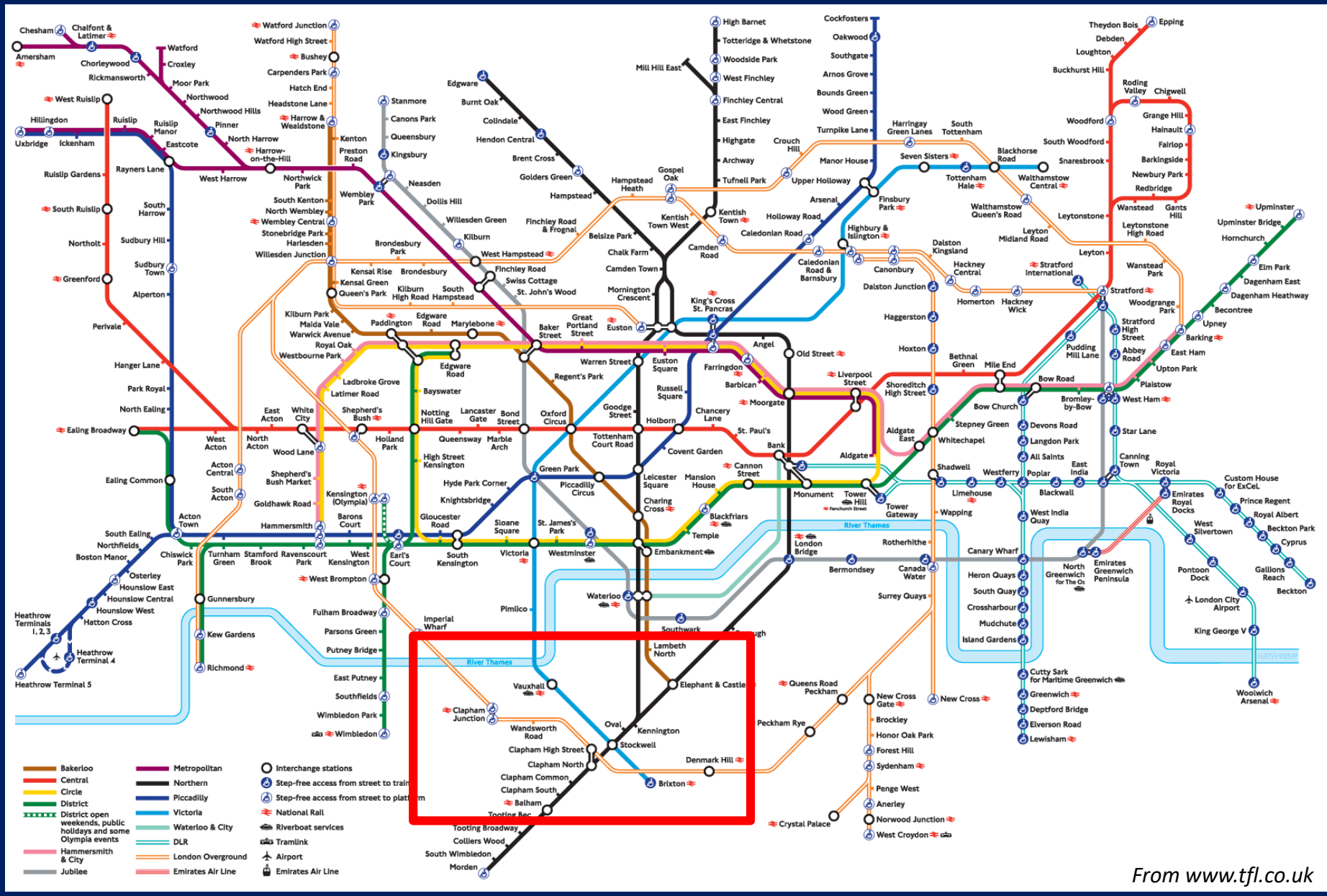

From www.tfl.co.uk

1. Introduction

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Northern Line Extension

1. Introduction

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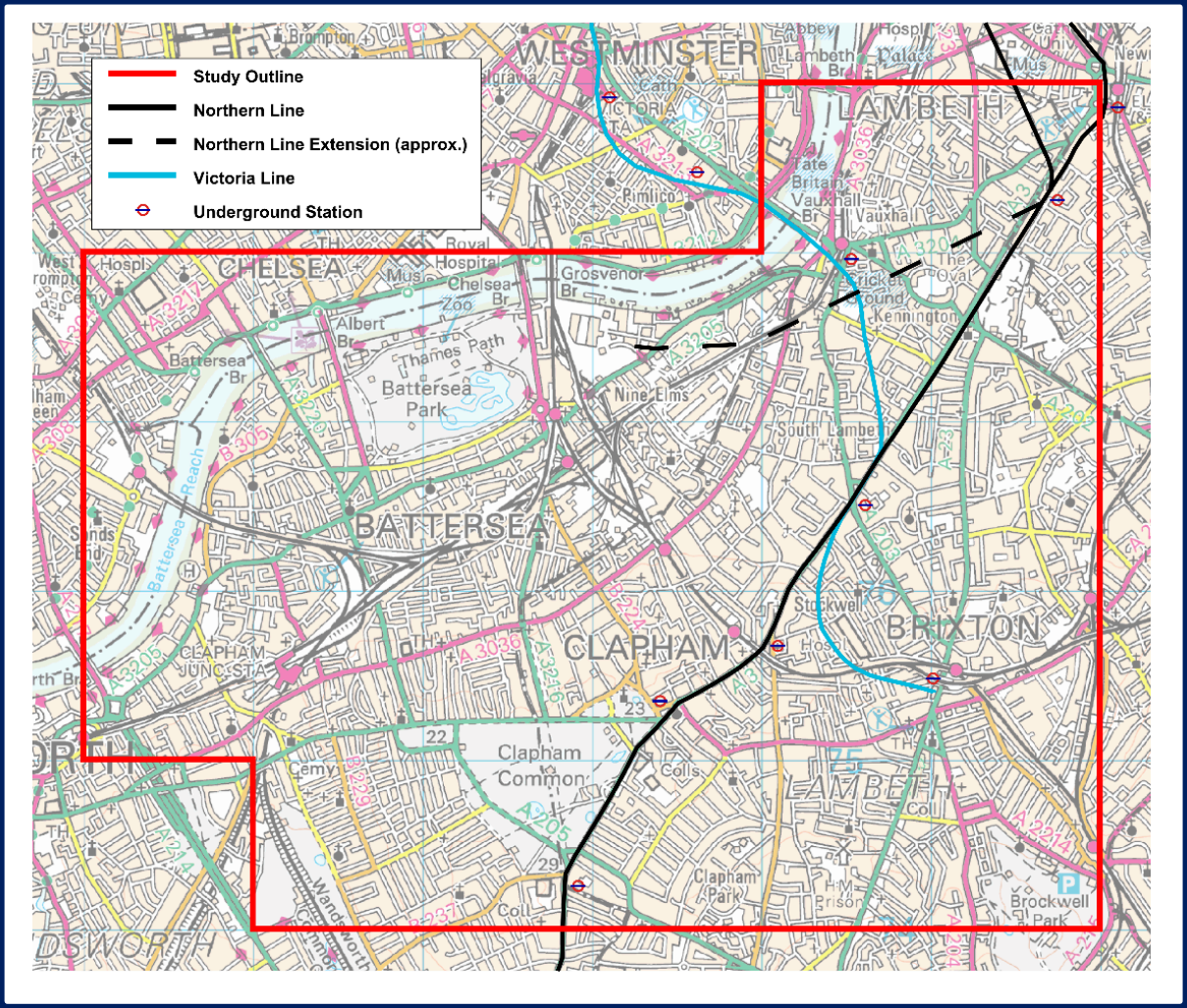
Study Area Outline



1. Introduction

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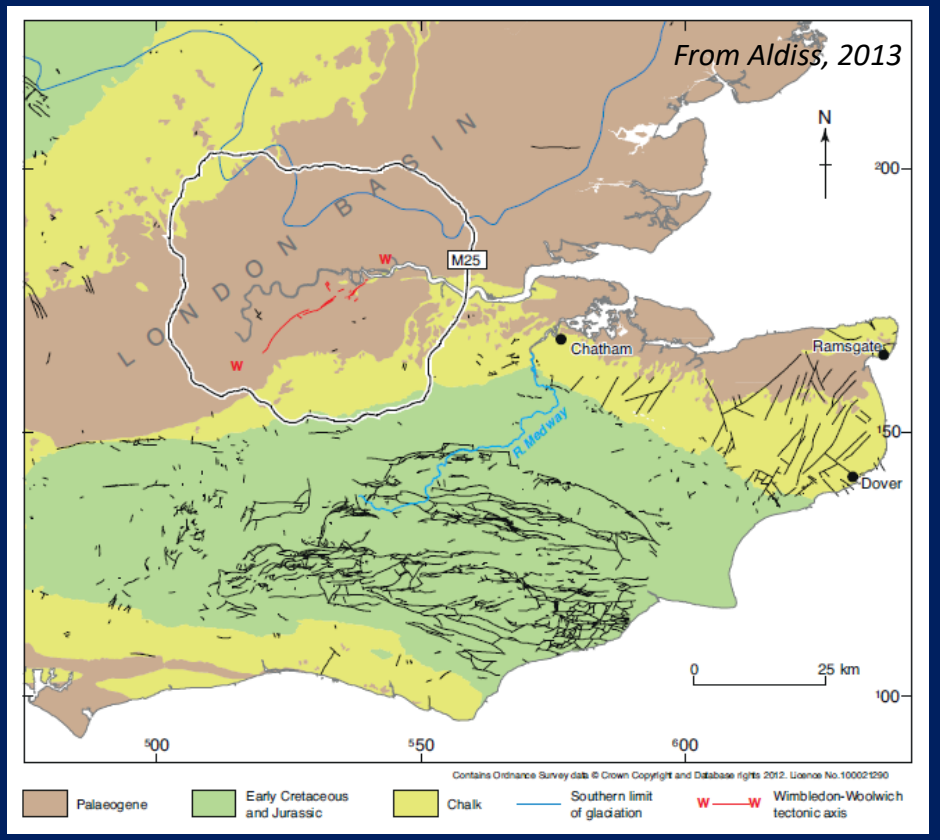
Project Aims

- 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

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Geohazards in the London Basin

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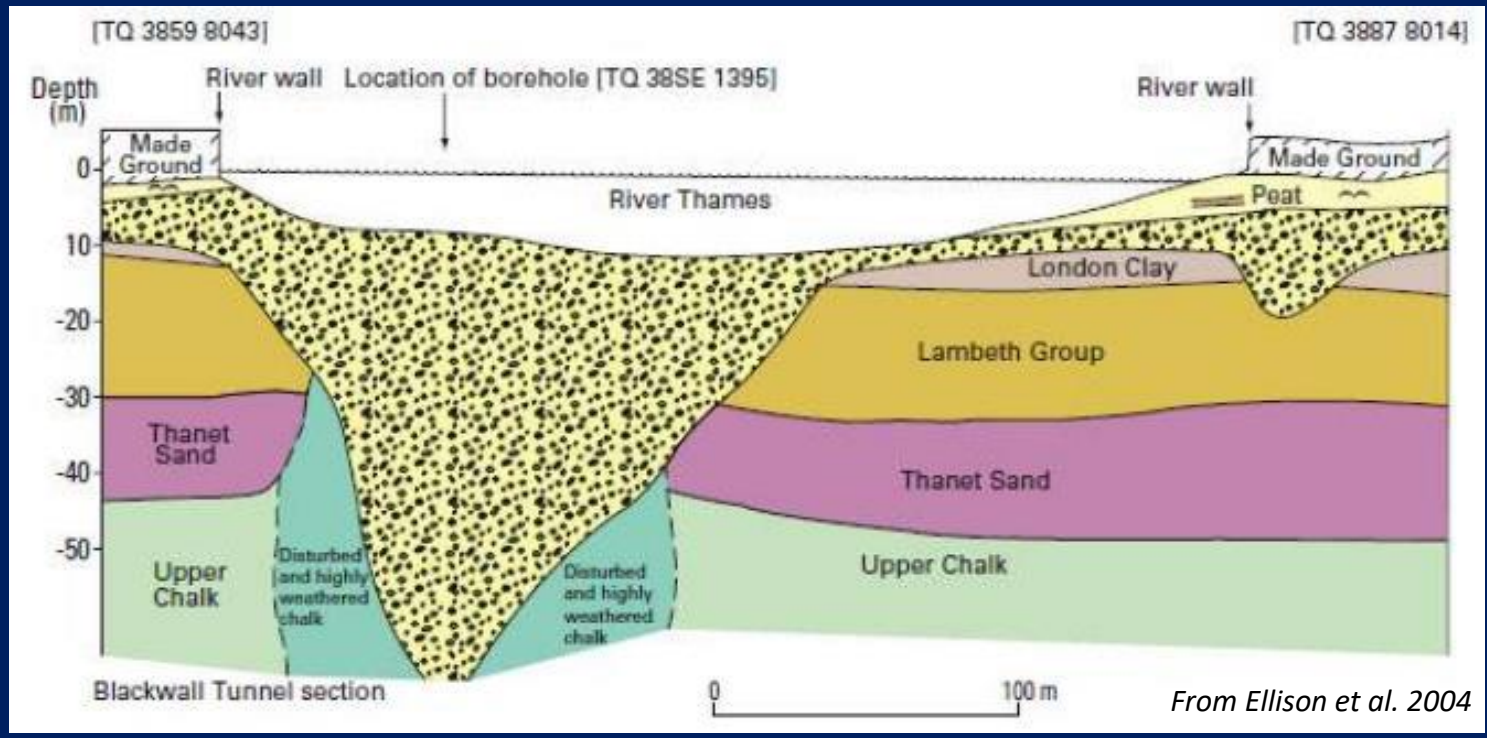
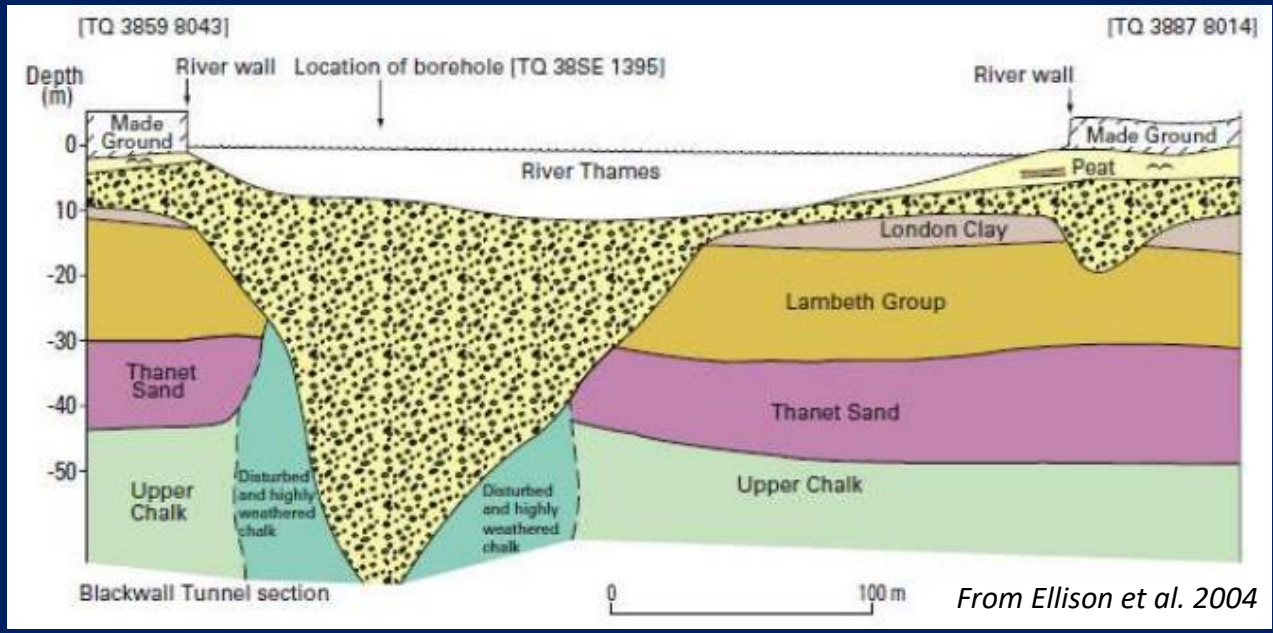


From Ellison et al. 2004

Why are DFHs a hazard to subsurface construction?

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



From Ellison et al. 2004

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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

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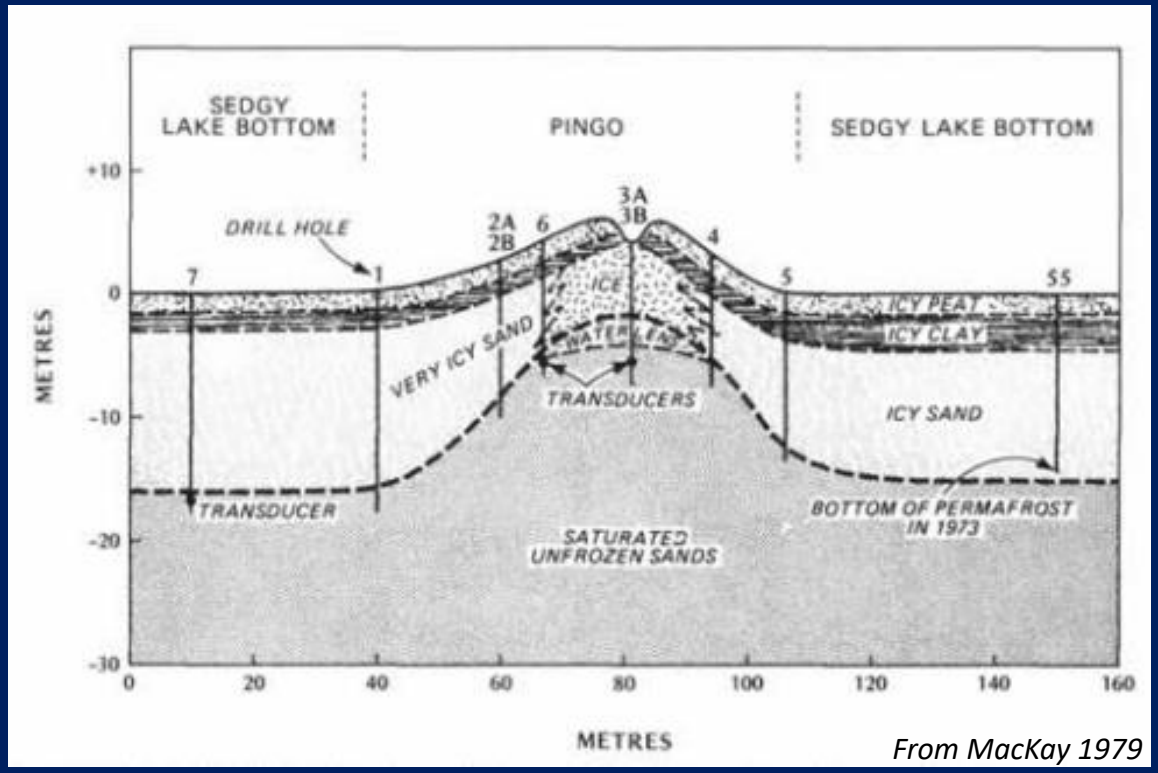

From MacKay 1979

Models for DFH Formation

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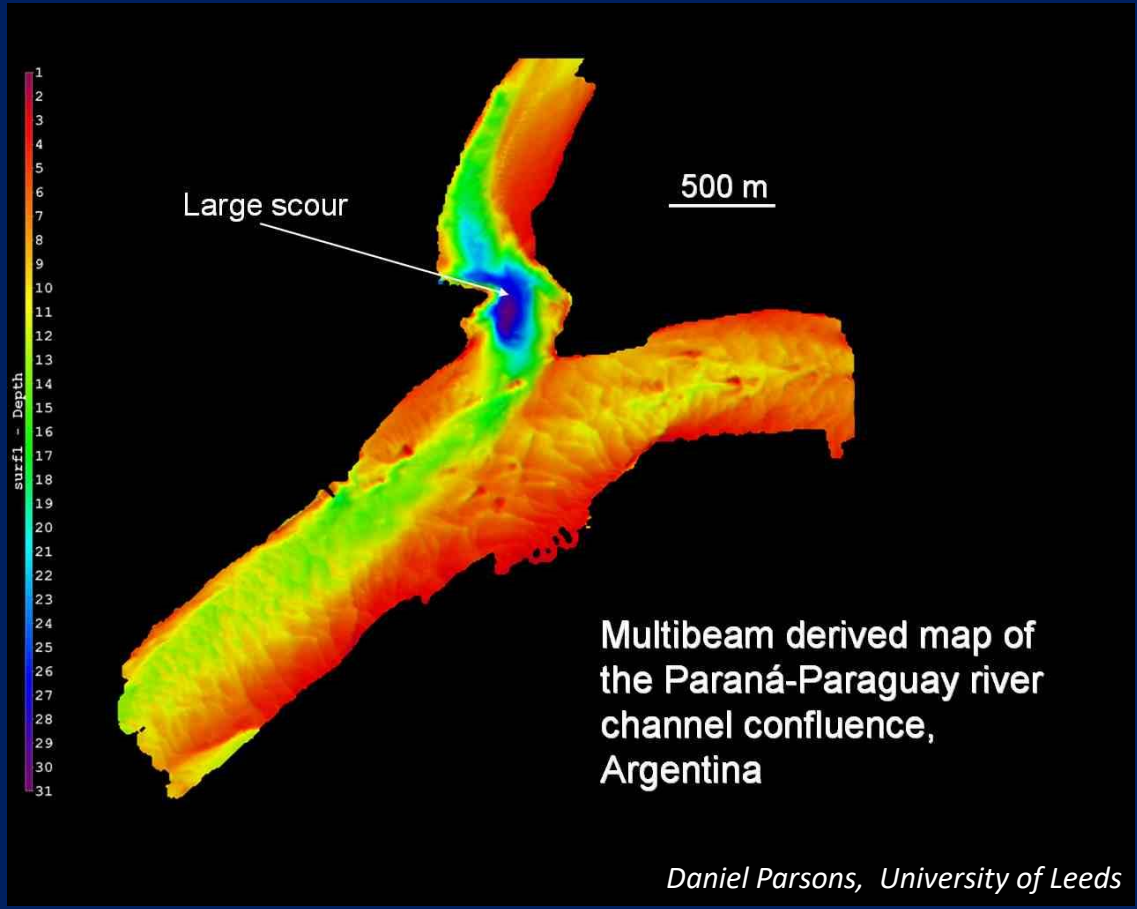
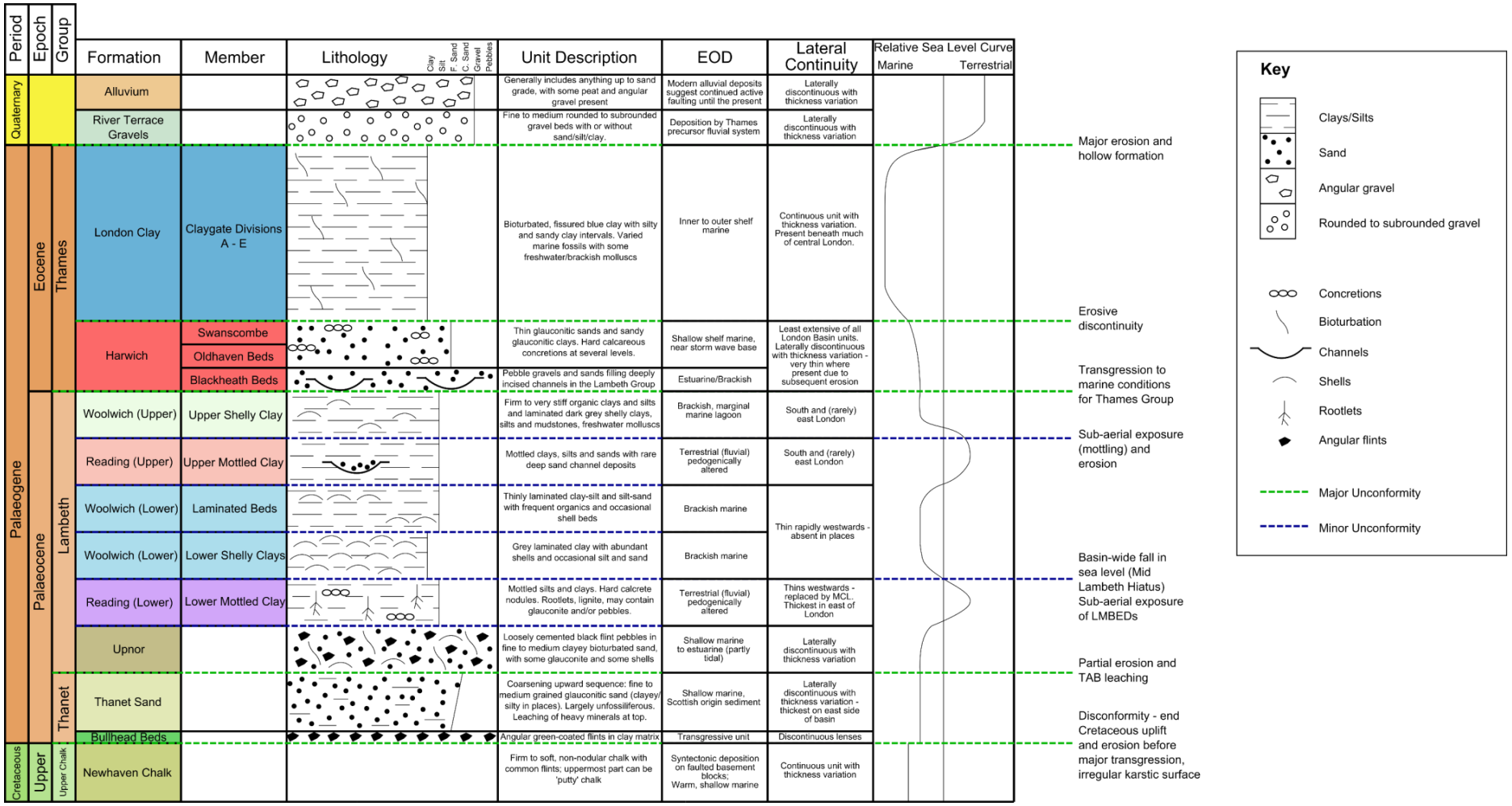


London Basin Stratigraphy



2. Geohazards in London

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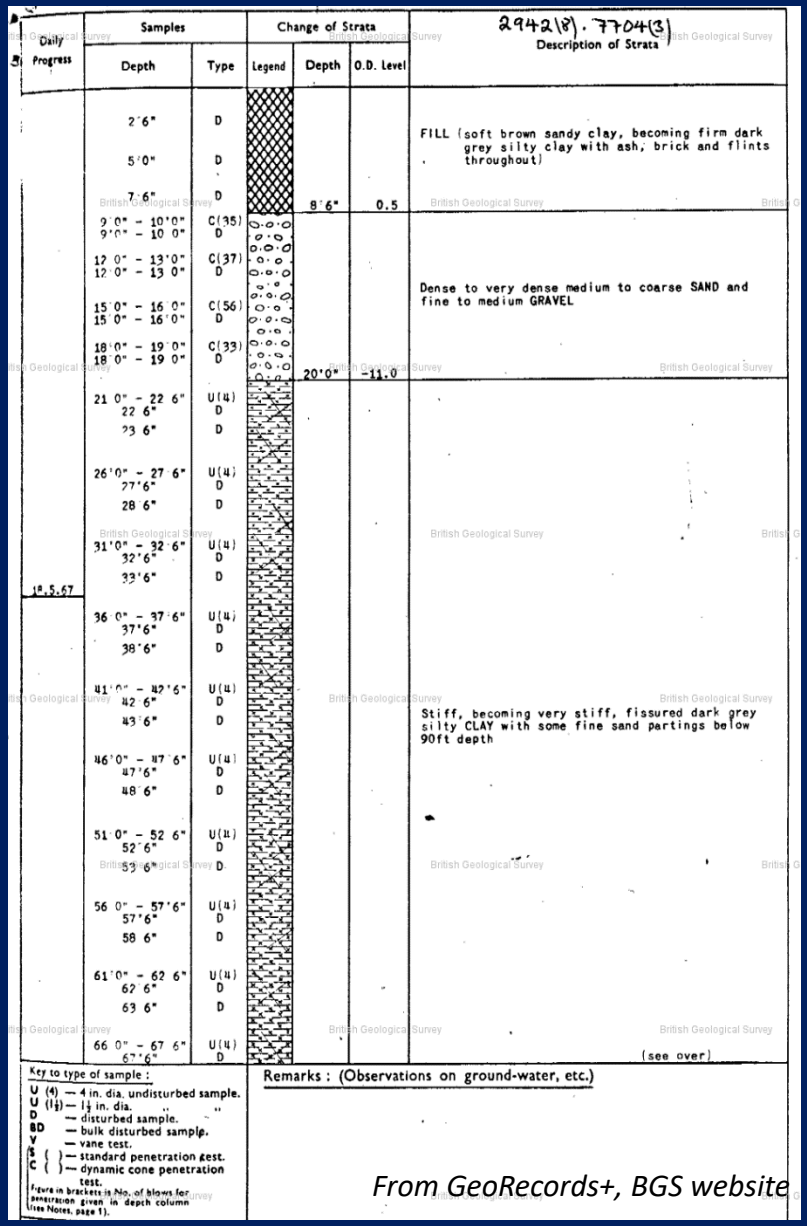
Data Collection

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



From GeoRecords+, BGS website

3. Model Construction

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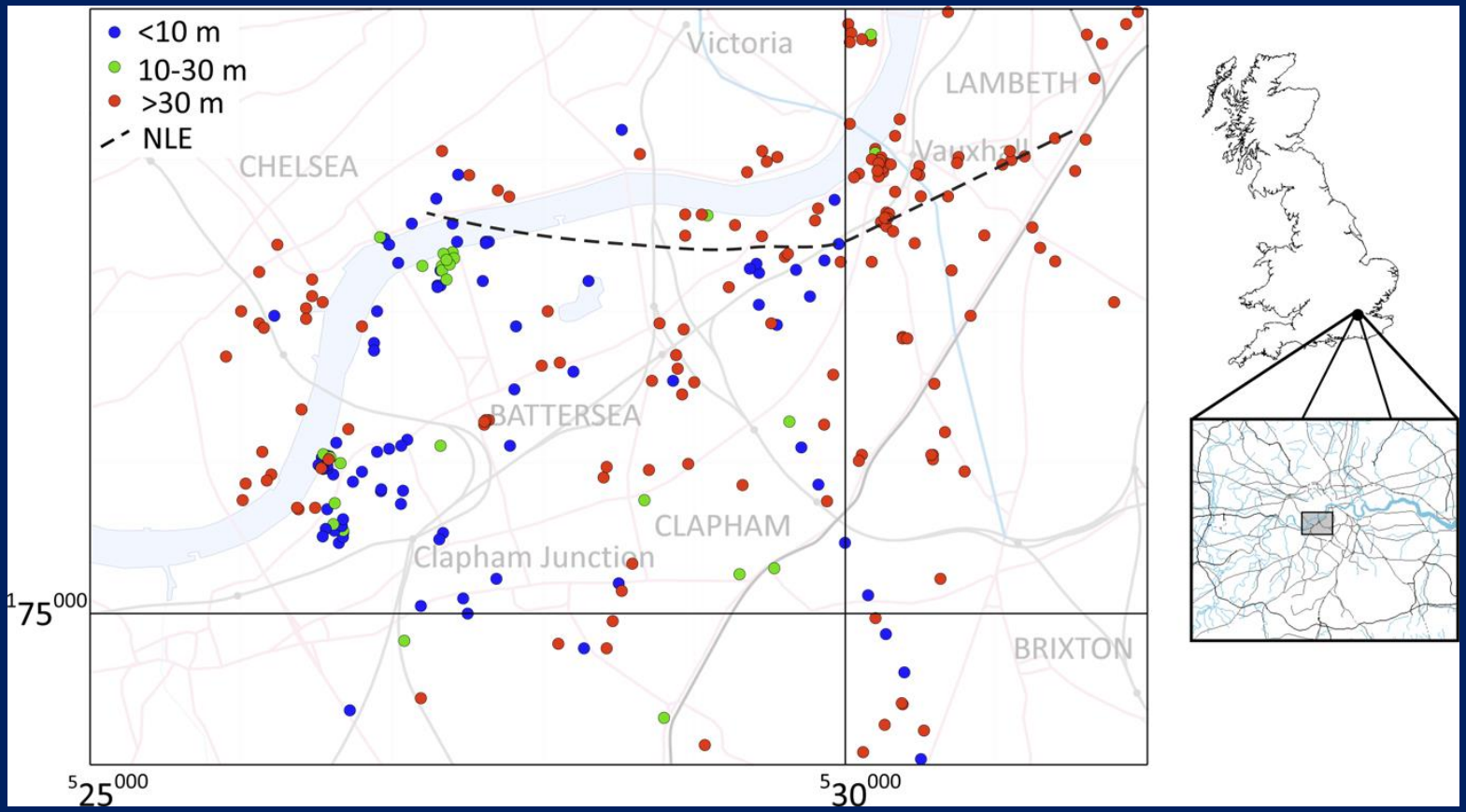
Borehole Distribution



3. Model Construction

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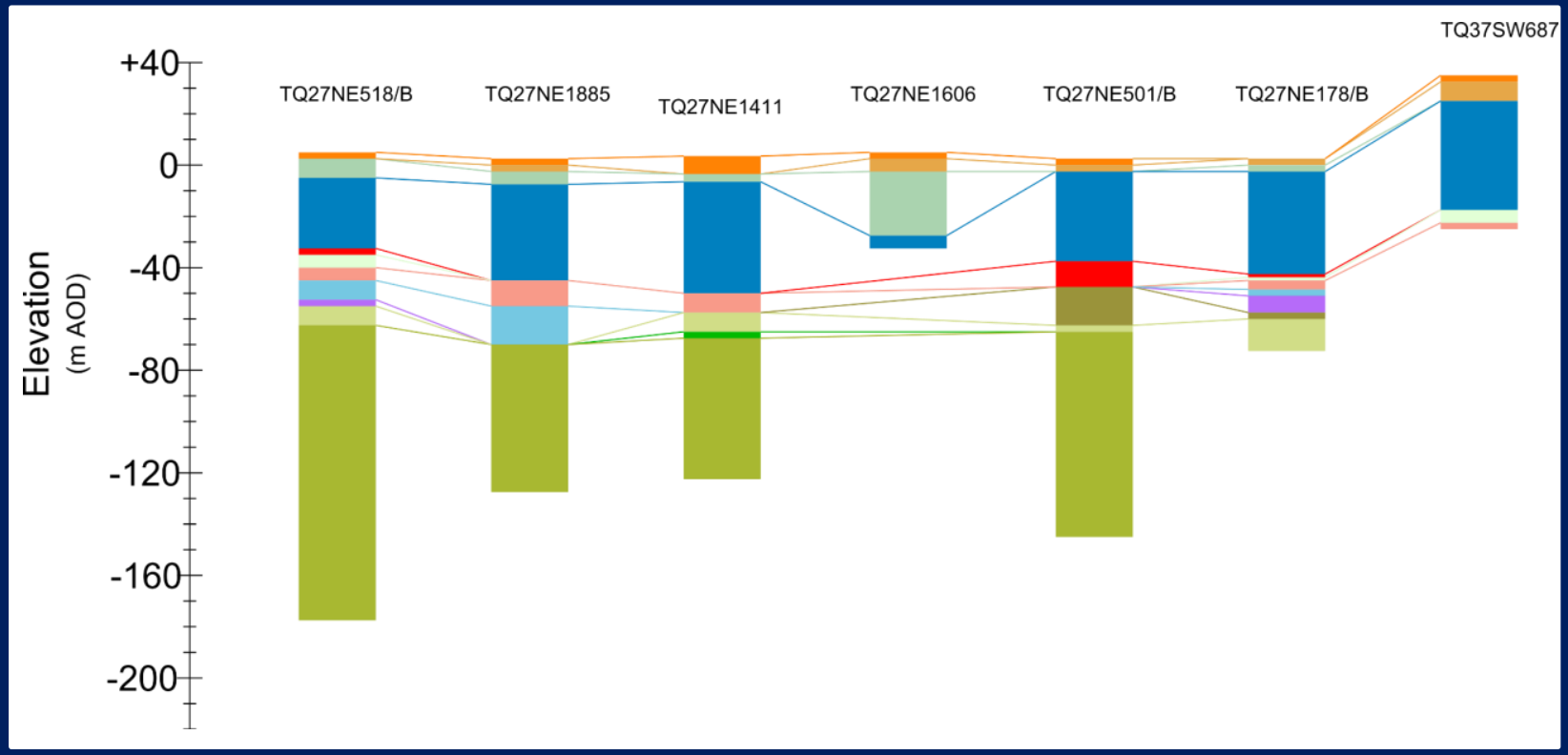
Borehole Log Quality

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



3. Model Construction

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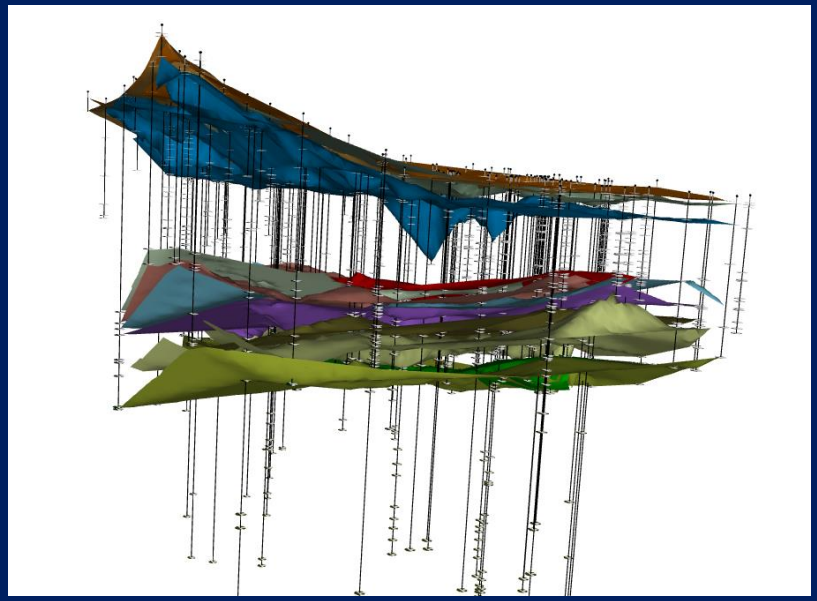
Ground Model Construction

- 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

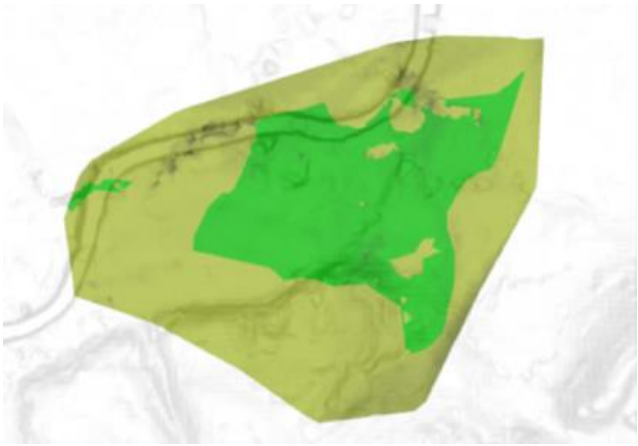


Stratigraphy: Upper Chalk & Bullhead Beds

Period	Epoch	Group	Formation	Member	Lithology	Unit Description	EOD	Lateral Continuity
Quaternary			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
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E		Bioturbated, fissured blue clay with silty 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.
			Harwich	Swanscombe		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 present due to subsequent erosion
				Oldhaven Beds				
				Blackheath Beds		Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish	
	Palaeocene	Lambeth	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
			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
			Woolwich (Lower)	Laminated Beds		Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
			Woolwich (Lower)	Lower Shelly Clays		Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine	
			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
			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
		Thanet	Thanet Sand			Coarsening upward sequence: fine to medium grained glauconitic 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
Cretaceous	Upper	Upper Chalk	Bullhead Beds			Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses
			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

Relative Sea Level Curve: Marine – Terrestrial

- Major erosion and hollow formation
- Erosive discontinuity
- Transgression to marine conditions for Thames Group
- Sub-aerial exposure (mottling) and erosion
- Basin-wide fall in sea level (Mid Lambeth Hiatus) Sub-aerial exposure of LMBEDs
- Partial erosion and TAB leaching
- Disconformity - end Cretaceous uplift and erosion before major transgression, irregular karstic surface



3. Ground Model

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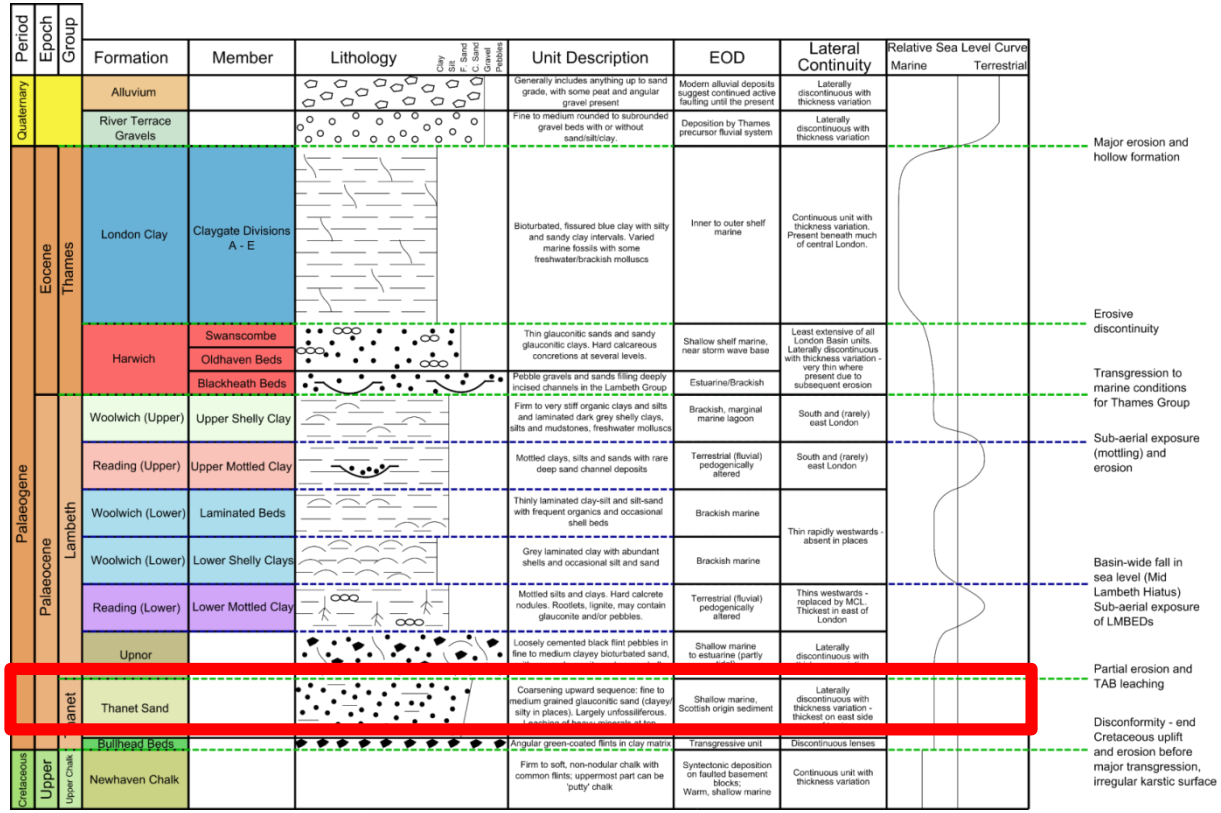
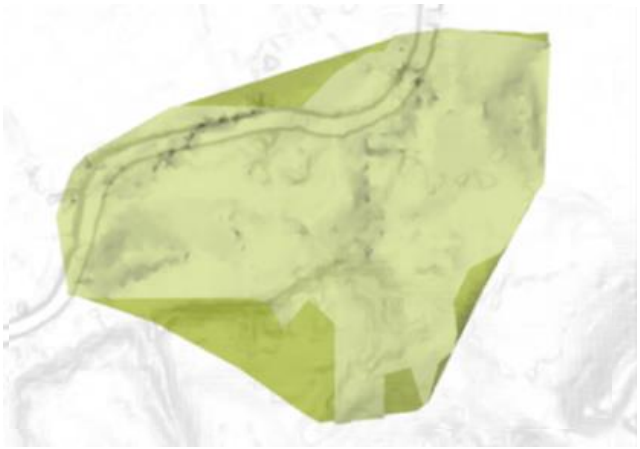
Stratigraphy: Thanet Formation





3. Ground Model

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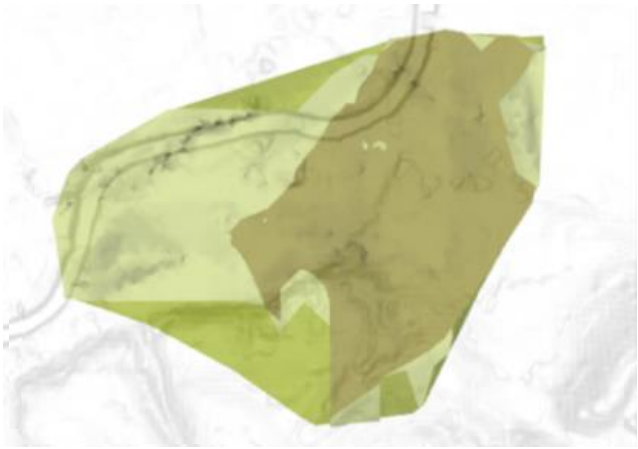
Stratigraphy: Upnor Formation

Period	Epoch	Group	Formation	Member	Lithology	Unit Description	EOD	Lateral Continuity
Quaternary			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
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E		Bioturbated, fissured blue clay with silty 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.
			Harwich	Swanscombe		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 present due to subsequent erosion
				Oldhaven Beds				
				Blackheath Beds		Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish	
	Palaeocene	Lambeth	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
			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
			Woolwich (Lower)	Laminated Beds		Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
			Woolwich (Lower)	Lower Shelly Clays		Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine	
			Reading (Lower)	Lower Mottled Clay		Mottled silts and clays. Hard calcrete nodules. Rootlets, lignite, may contain	Terrestrial (fluvial) pedogenically	Thins westwards - replaced by MCL. Thickest in east of
			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
		Thanet	Thanet Sand			Coarsening upward sequence: fine to medium grained glauconitic 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
			Bullhead Beds			Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses
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

Relative Sea Level Curve: Marine – Terrestrial

- Major erosion and hollow formation
- Erosive discontinuity
- Transgression to marine conditions for Thames Group
- Sub-aerial exposure (mottling) and erosion
- Basin-wide fall in sea level (Mid Lambeth Hiatus) Sub-aerial exposure of LMBEDs
- Partial erosion and TAB leaching
- Disconformity - end Cretaceous uplift and erosion before major transgression, irregular karstic surface



3. Ground Model

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Stratigraphy: Lower Mottled Clay

Period	Epoch	Group	Formation	Member	Unit Description	EOD	Lateral Continuity
Quaternary			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
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E	Bioturbated, fissured blue clay with silty 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.
			Harwich	Swanscombe	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 present due to subsequent erosion
				Oldhaven Beds			
				Blackheath Beds	Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish	
	Palaeocene	Lambeth	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
			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
			Woolwich (Lower)	Laminated Beds	Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
			Woolwich (Lower)	Lower Shelly Clays	Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine	
			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
		Thanet	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
			Thanet Sand		Coarsening upward sequence: fine to medium grained glauconitic 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
			Bullhead Beds		Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses
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

Relative Sea Level Curve: Marine – Terrestrial

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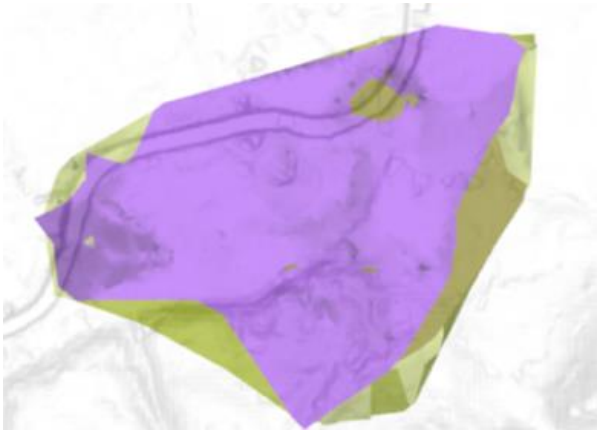

3. Ground Model

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Stratigraphy: Lower Shelly Clays & Laminated Beds

Period	Epoch	Group	Formation	Member	Lithology	Unit Description	EOD	Lateral Continuity	Relative Sea Level Curve (Marine – Terrestrial)	
Quaternary			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		
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E		Bioturbated, fissured blue clay with silty 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.		Major erosion and hollow formation
			Harwich	Swanscombe		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 present due to subsequent erosion		Erosive discontinuity
				Oldhaven Beds						
				Blackheath Beds		Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish			Transgression to marine conditions for Thames Group
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			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
		Lambeth	Woolwich (Lower)	Laminated Beds		Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places		
			Woolwich (Lower)	Lower Shelly Clays		Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine			Basin-wide fall in sea level (Mid Lambeth Hiatus) Sub-aerial exposure of LMBEDs
	Paleocene		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		
			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 TAB leaching
		Thanet	Thanet Sand			Coarsening upward sequence: fine to medium grained glauconitic 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		
			Bullhead Beds			Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses		Disconformity - end Cretaceous uplift and erosion before major transgression, irregular karstic surface
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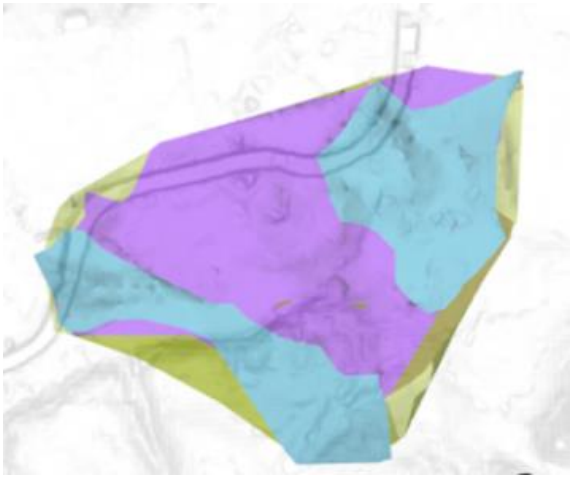

Stratigraphy: Upper Mottled Clay

Period	Epoch	Group	Formation	Member	Unit Description	EOD	Lateral Continuity
Quaternary			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
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E	Bioturbated, fissured blue clay with silty 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.
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			Woolwich (Upper)	Upper Shelly Clay	Firm to very stiff organic clays and silts and laminated dark grey shelly clays.	Brackish, marginal marine lagoon	South and (rarely)
			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
	Palaeocene	Lambeth	Woolwich (Lower)	Laminated Beds	Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
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			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
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Relative Sea Level Curve: Marine – Terrestrial

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3. Ground Model

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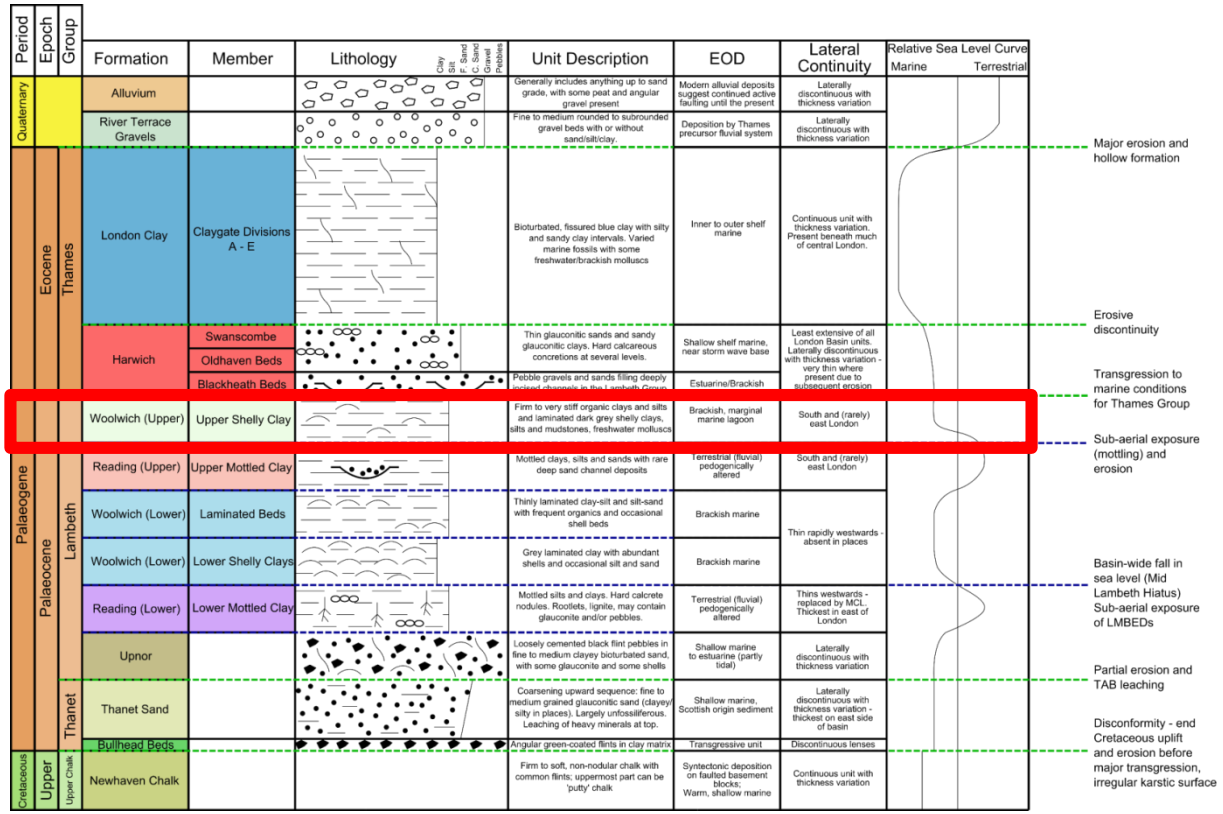
Stratigraphy: Upper Shelly Clay

Period	Epoch	Group	Formation	Member	Unit Description	EOD	Lateral Continuity
Quaternary			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
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E	Bioturbated, fissured blue clay with silty 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.
			Harwich	Swanscombe	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 present due to subsequent erosion
				Oldhaven Beds			
				Blackheath Beds	Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish	
			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
	Palaeocene	Lambeth	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
			Woolwich (Lower)	Laminated Beds	Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
			Woolwich (Lower)	Lower Shelly Clays	Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine	
			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
			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
		Thanet	Thanet Sand		Coarsening upward sequence: fine to medium grained glauconitic 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
			Bullhead Beds		Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses
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



3. Ground Model

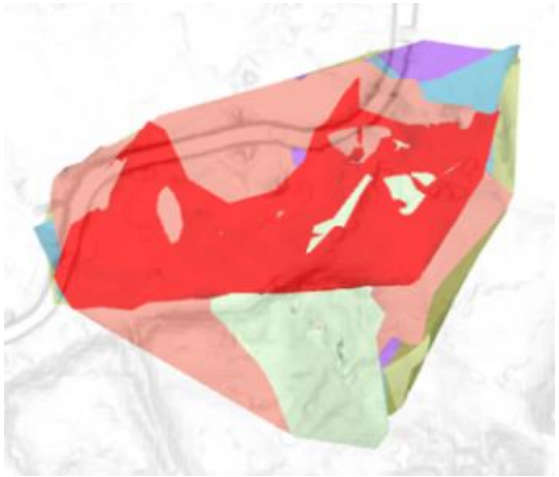
Imperial College London

Stratigraphy: Harwich Formation

Period	Epoch	Group	Formation	Member	Unit Description	EOD	Lateral Continuity
Quaternary			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
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E	Bioturbated, fissured blue clay with silty 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.
			Harwich	Swanscombe	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 present due to subsequent erosion
				Oldhaven Beds			
				Blackheath Beds	Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish	
	Palaeocene	Lambeth	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
			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
			Woolwich (Lower)	Laminated Beds	Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
			Woolwich (Lower)	Lower Shelly Clays	Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine	
			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
			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
		Thanet	Thanet Sand		Coarsening upward sequence: fine to medium grained glauconitic 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
			Bullhead Beds		Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses
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

Relative Sea Level Curve: Marine — Terrestrial

- Major erosion and hollow formation
- Erosive discontinuity
- Transgression to marine conditions for Thames Group
- Sub-aerial exposure (mottling) and erosion
- Basin-wide fall in sea level (Mid Lambeth Hiatus) Sub-aerial exposure of LMBEDs
- Partial erosion and TAB leaching
- Disconformity - end Cretaceous uplift and erosion before major transgression, irregular karstic surface



3. Ground Model

Imperial College London

Stratigraphy: London Clay Formation

Period	Epoch	Group	Formation	Member	Lithology	Unit Description	EOD	Lateral Continuity
Quaternary			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 fluvial system	Laterally discontinuous with
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E		Bioturbated, fissured blue clay with silty 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.
	Palaeocene	Lambeth	Harwich	Swanscombe		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 present due to subsequent erosion
				Oldhaven Beds				
				Blackheath Beds		Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish	
			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
			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
			Woolwich (Lower)	Laminated Beds		Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
			Woolwich (Lower)	Lower Shelly Clays		Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine	
			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
			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
		Thanet	Thanet Sand			Coarsening upward sequence: fine to medium grained glauconitic 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
			Bullhead Beds			Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses
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

Relative Sea Level Curve: Marine – Terrestrial

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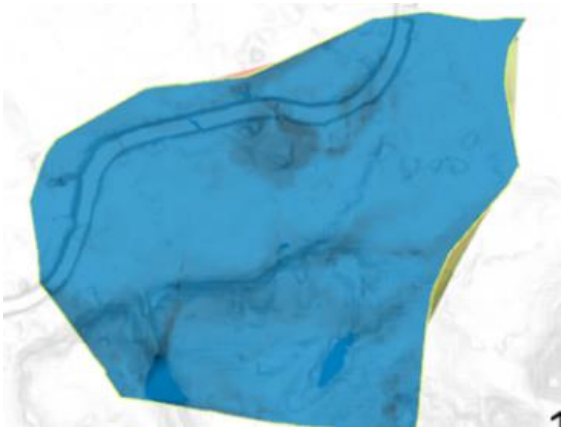
- Partial erosion and TAB leaching
- Disconformity - end Cretaceous uplift and erosion before major transgression, irregular karstic surface



3. Ground Model

Imperial College London

Stratigraphy: River Terrace Gravels

Period	Epoch	Group	Formation	Member	Lithology	Unit Description	EOD	Lateral Continuity
Quaternary			Alluvium			Generally includes anything up to sand grade, with some peat and angular	Modern alluvial deposits suggest continued active	Laterally discontinuous with
Quaternary			River Terrace Gravels			Fine to medium rounded to subrounded gravel beds with or without	Deposition by Thames precursor fluvial system	Laterally discontinuous with
Palaeogene	Eocene	Thames	London Clay	Claygate Divisions A - E		Bioturbated, fissured blue clay with silty 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.
Palaeogene	Eocene	Thames	Harwich	Swanscombe		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 present due to subsequent erosion
Palaeogene	Eocene	Thames	Harwich	Oldhaven Beds				
Palaeogene	Eocene	Thames	Harwich	Blackheath Beds		Pebble gravels and sands filling deeply incised channels in the Lambeth Group	Estuarine/Brackish	
Palaeogene	Palaeocene	Lambeth	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
Palaeogene	Palaeocene	Lambeth	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
Palaeogene	Palaeocene	Lambeth	Woolwich (Lower)	Laminated Beds		Thinly laminated clay-silt and silt-sand with frequent organics and occasional shell beds	Brackish marine	Thin rapidly westwards - absent in places
Palaeogene	Palaeocene	Lambeth	Woolwich (Lower)	Lower Shelly Clays		Grey laminated clay with abundant shells and occasional silt and sand	Brackish marine	
Palaeogene	Palaeocene	Lambeth	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
Palaeogene	Palaeocene	Lambeth	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
Palaeogene	Palaeocene	Thanet	Thanet Sand			Coarsening upward sequence: fine to medium grained glauconitic 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
Palaeogene	Palaeocene	Thanet	Bullhead Beds			Angular green-coated flints in clay matrix	Transgressive unit	Discontinuous lenses
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

Relative Sea Level Curve: Marine – Terrestrial

- Major erosion and hollow formation
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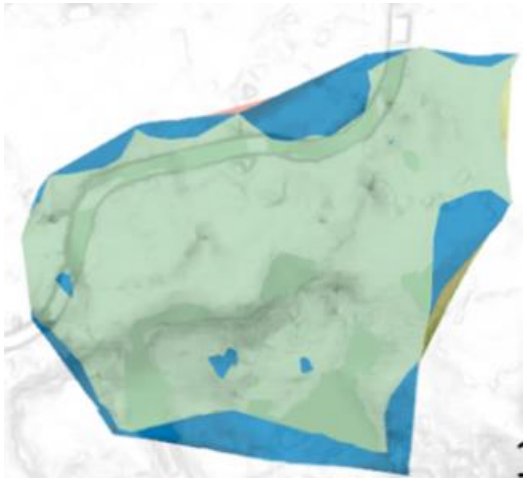
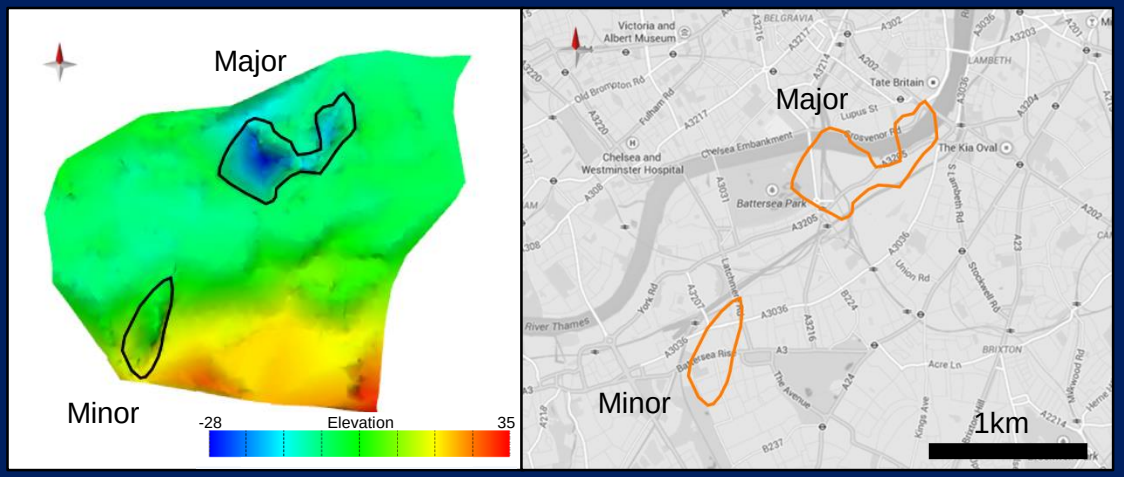
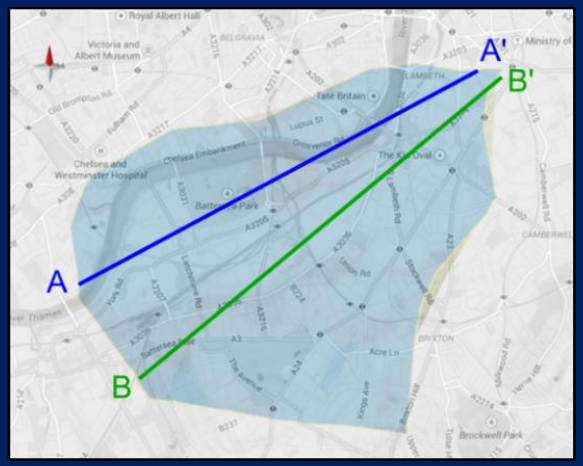


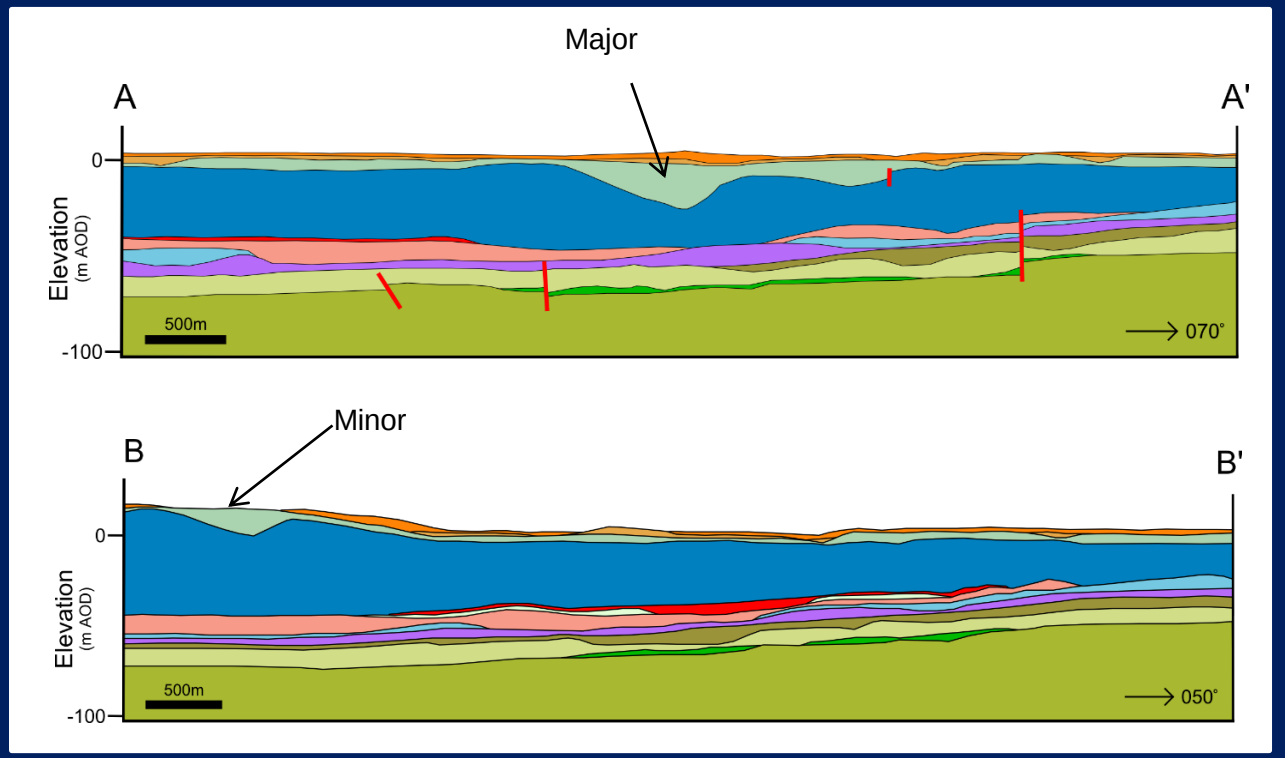
3. Ground Model

Imperial College London

DFHs



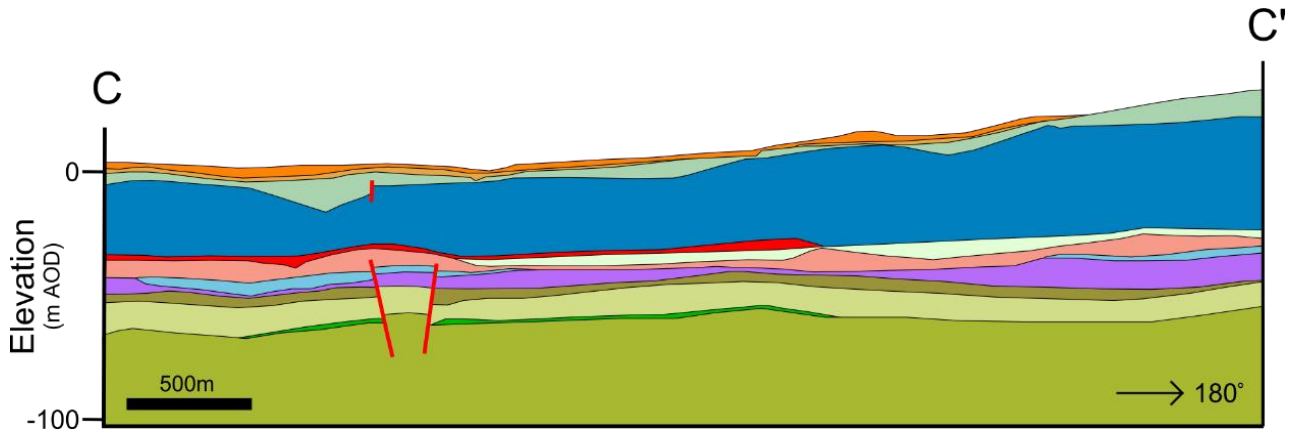


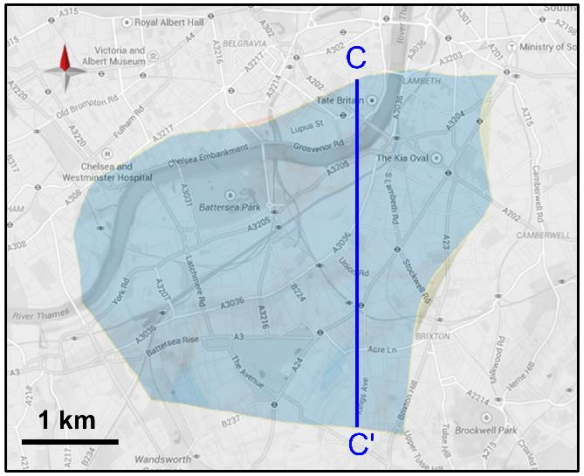


4. DFHs in Battersea

Imperial College London

DFHs



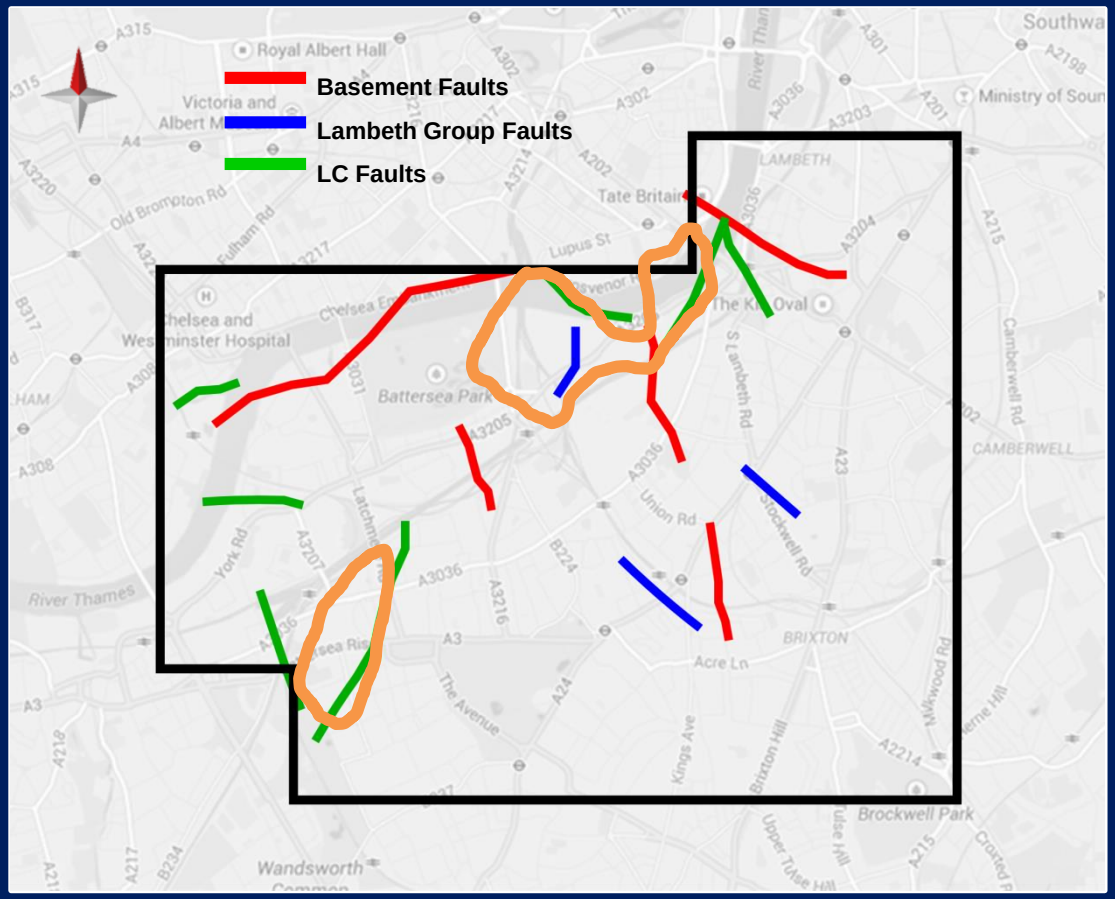


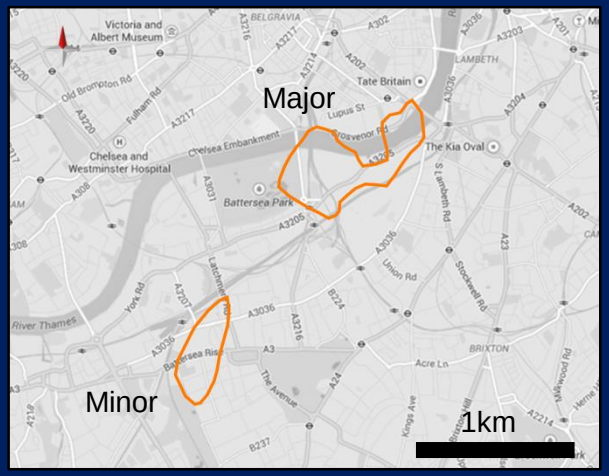
- Upper Chalk (UCK)
- Bullhead Beds (BLHB)
- Thanet Formation (TAB)
- Upnor Formation (UPR)
- Lower Mottled Clay (LMBED)
- Upper Mottled Clay (MCL)
- Laminated Clays and Lower Shelly Beds (LBED)
- Upper Shelly Clay (UPSCL)
- Harwich Formation (HWH)
- London Clay Formation (LC)
- River Terrace Gravels (RTG)
- Alluvium (ALV)
- Made Ground (MGR)
- Fault

4. Ground Model

Imperial College London

Interpreted Faults





4. DFHs in Battersea

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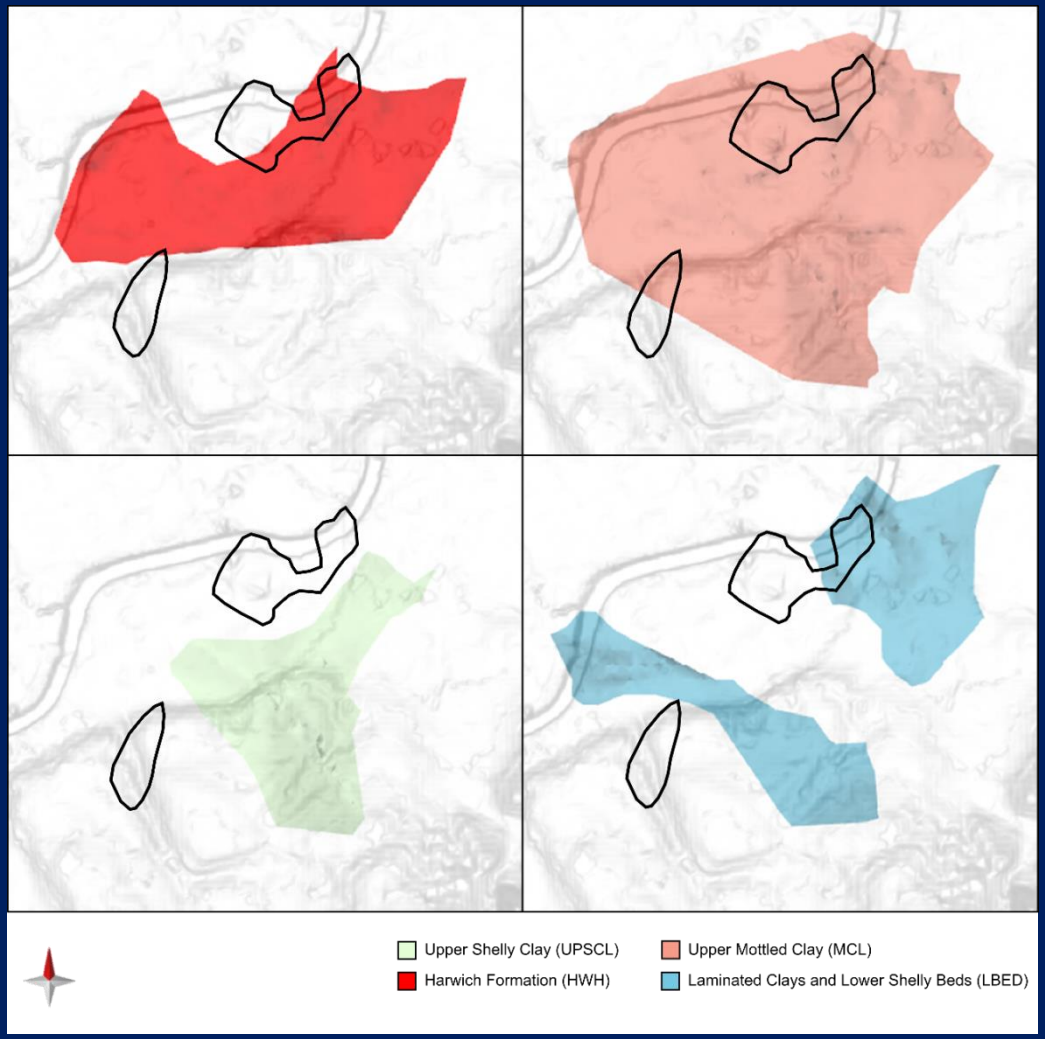
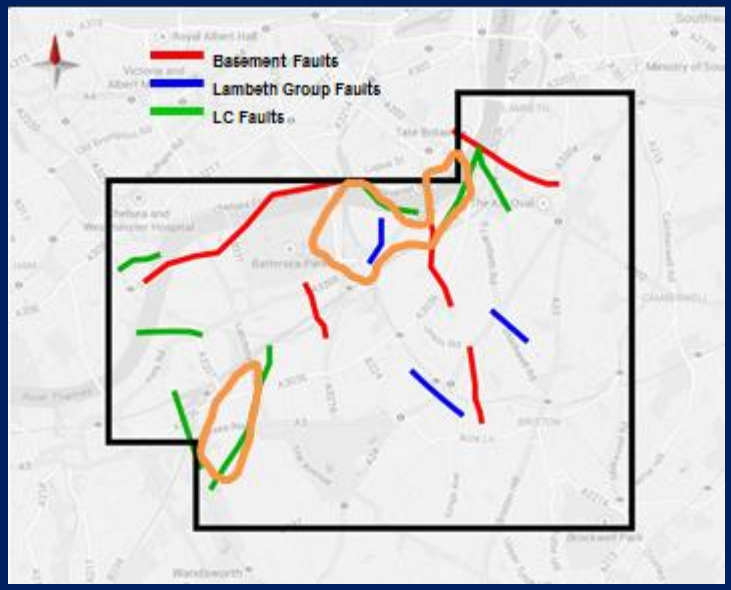
Lithological Control?

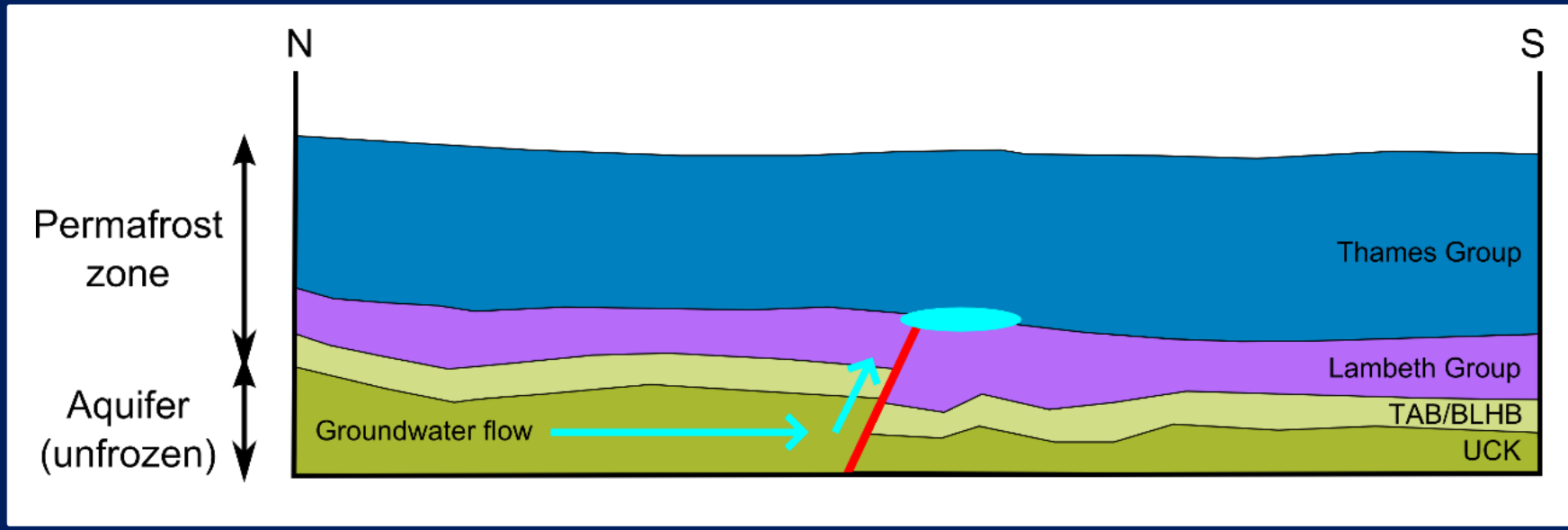




4. DFHs in Battersea

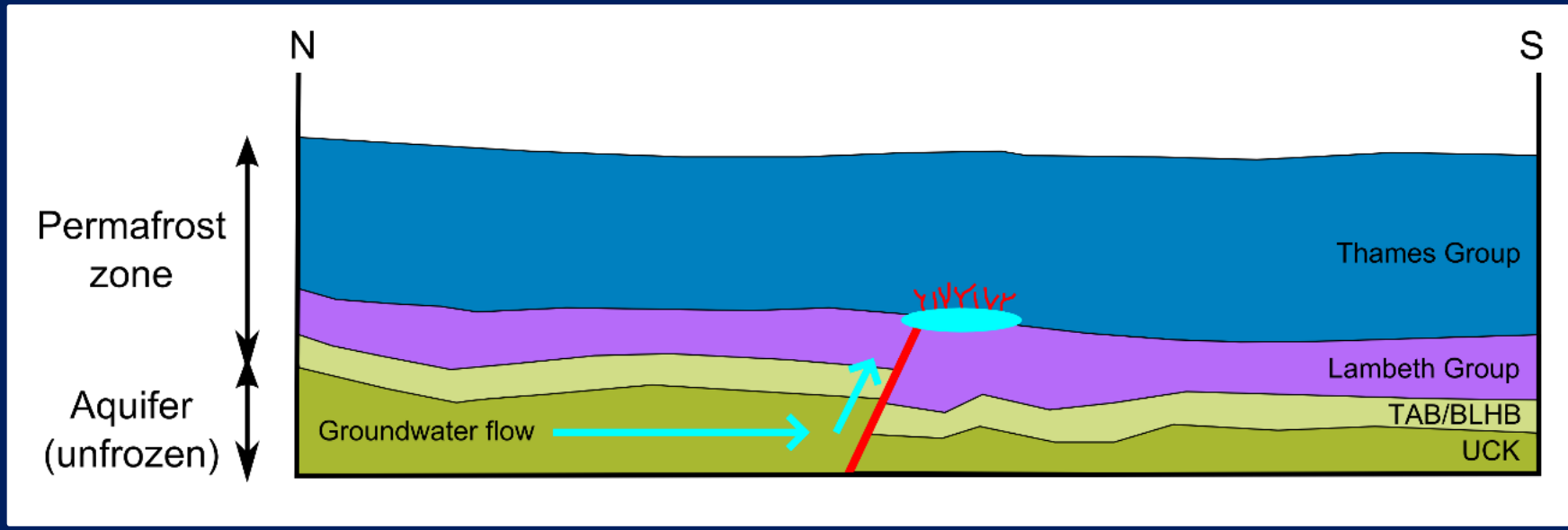
Imperial College London

DFH Formation



5. Discussion

DFH Formation



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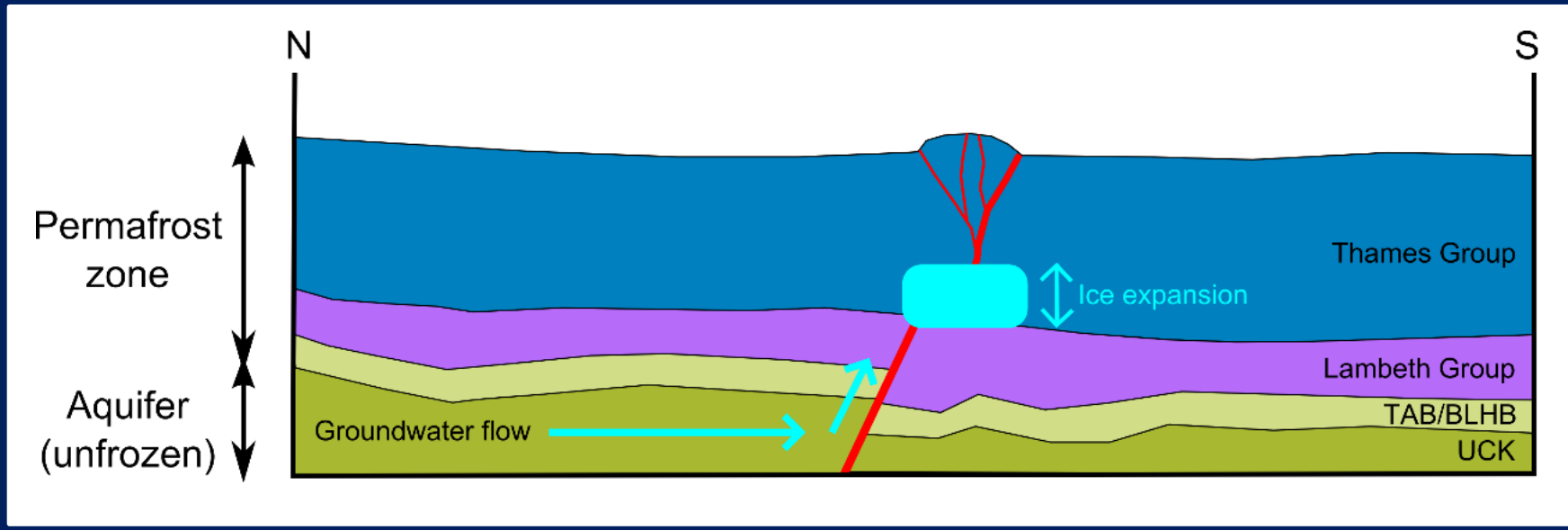
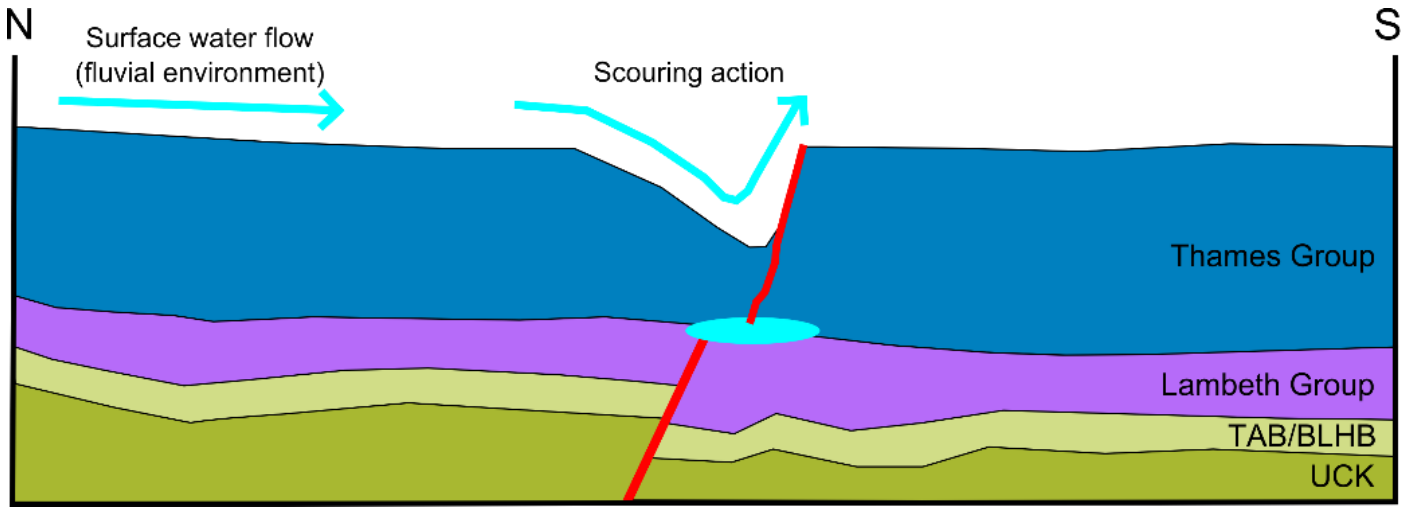
DFH Formation



5. Discussion

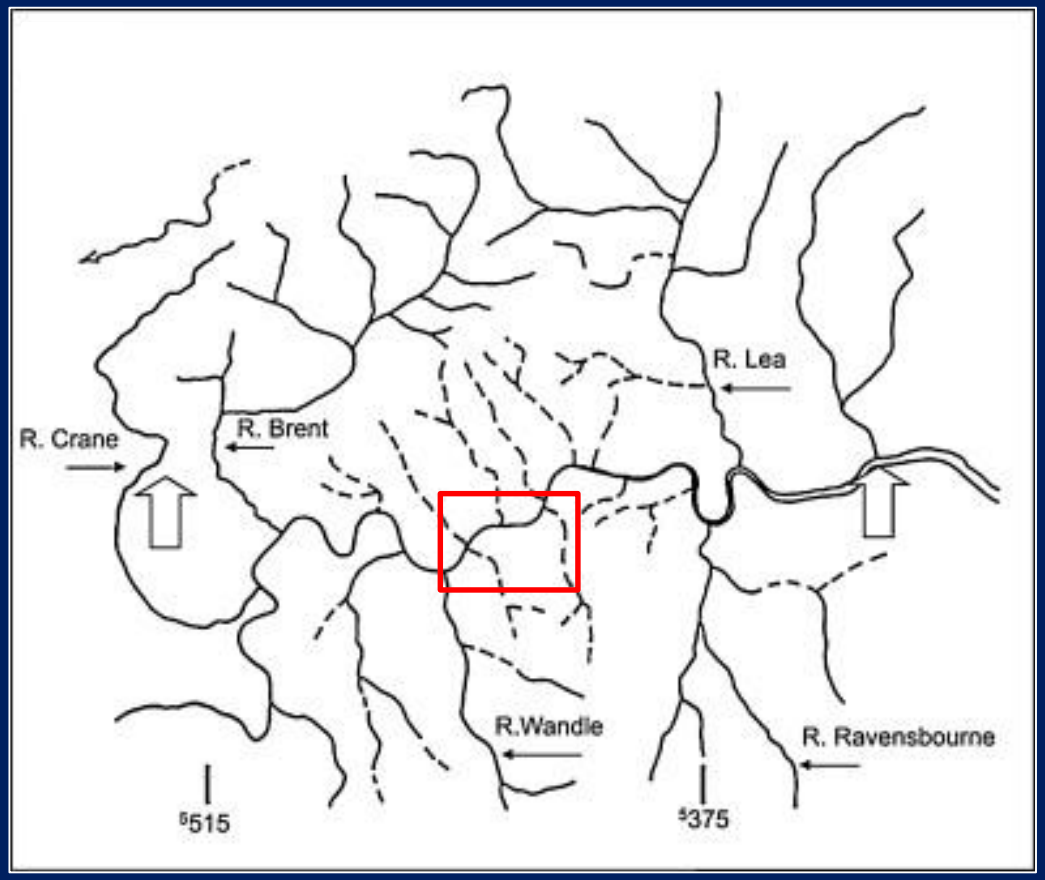
Imperial College London

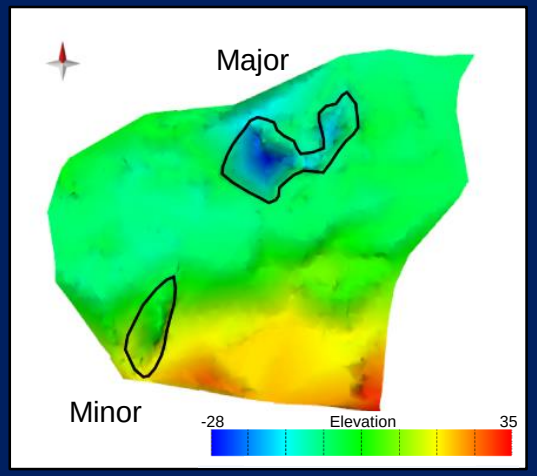
DFH Formation

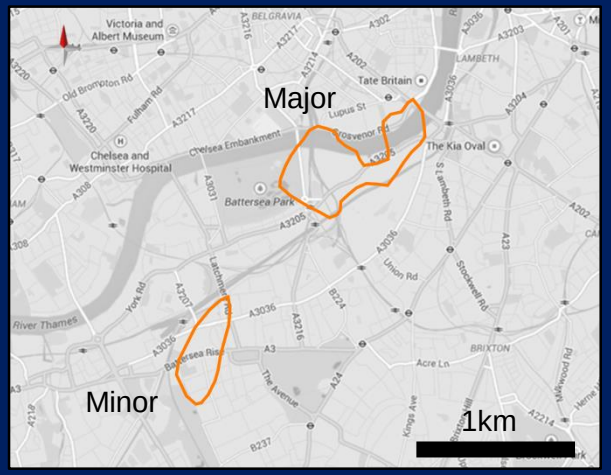


5. Discussion

DFH Formation: Scouring



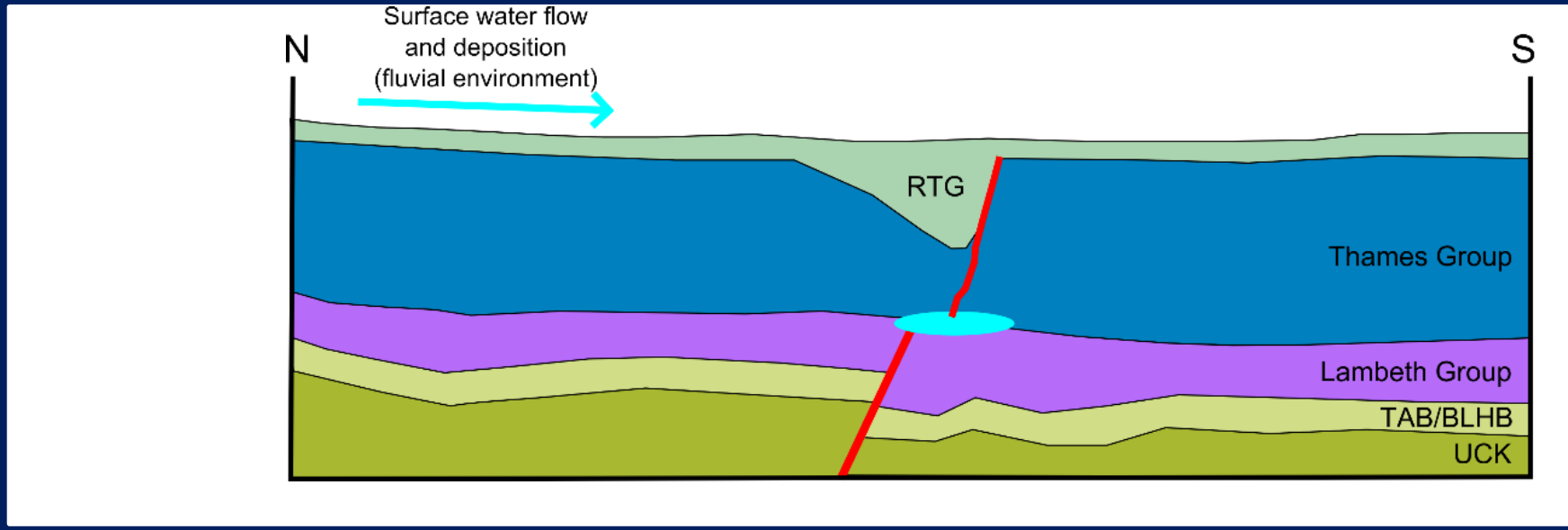




5. Discussion

Imperial College London

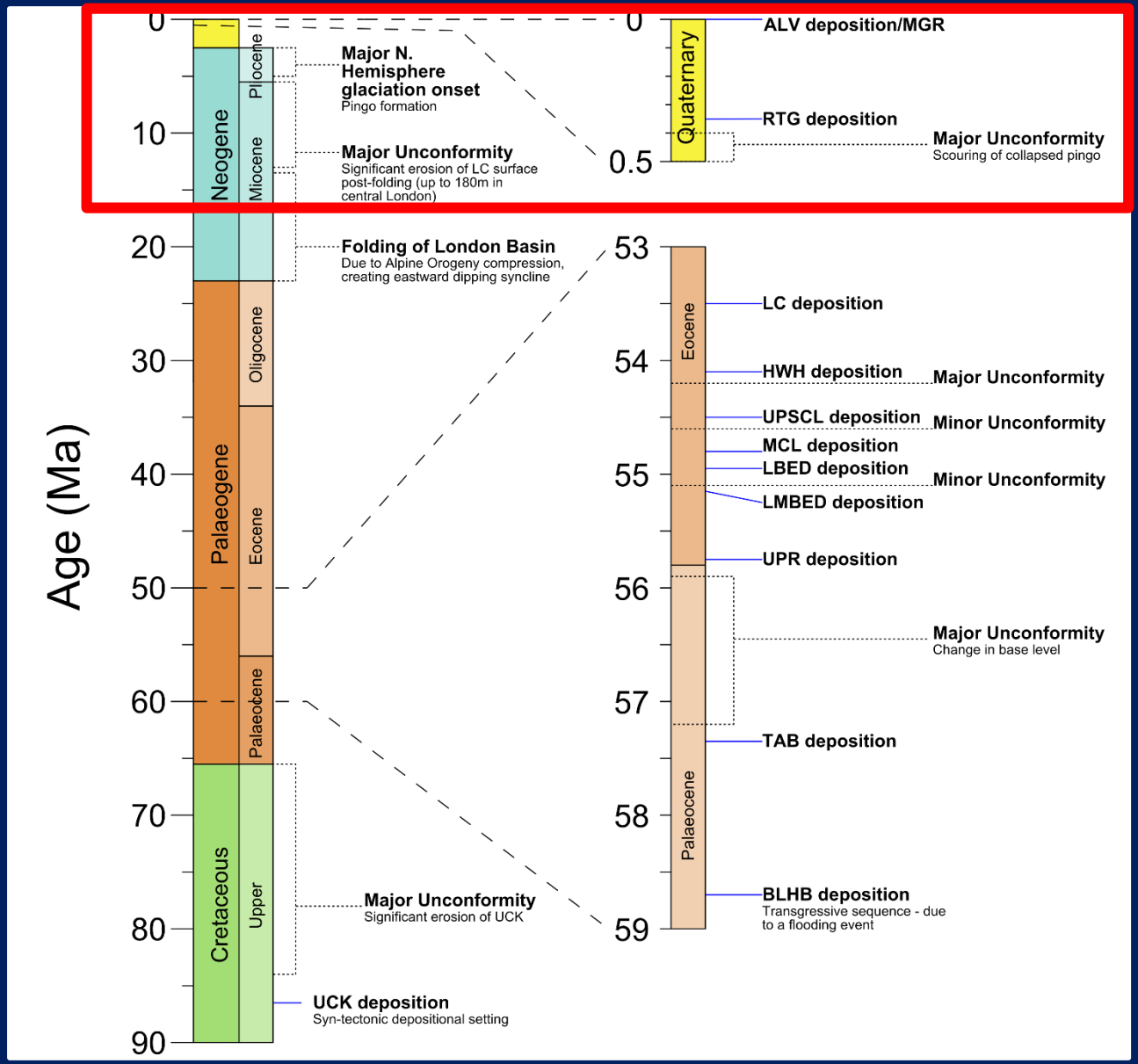
DFH Formation



5. Discussion

Imperial College London

Geological History of Battersea



5. Discussion

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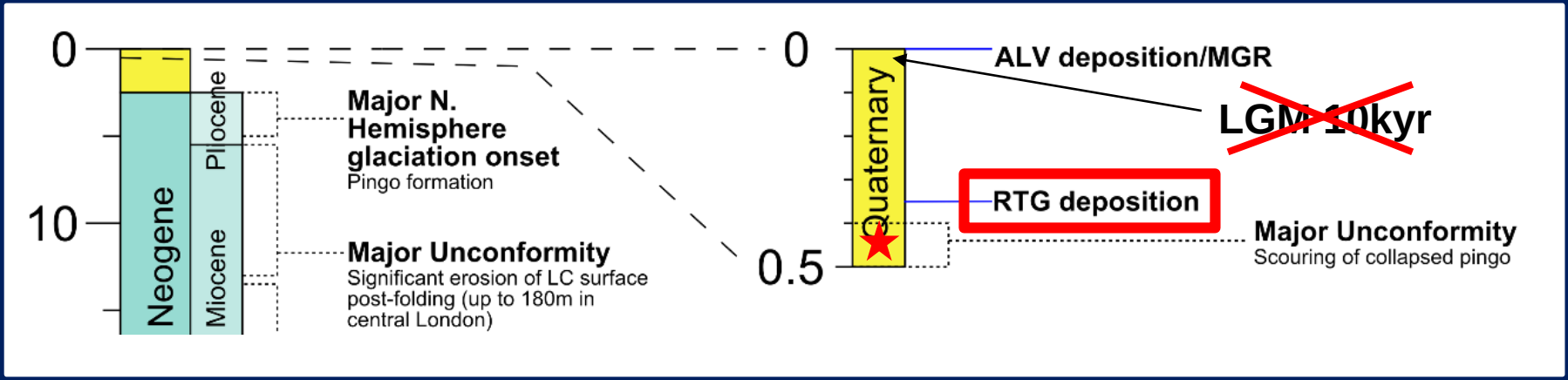
DFH Formation Timing



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

5. Discussion

Imperial College 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

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

Acknowledgements

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

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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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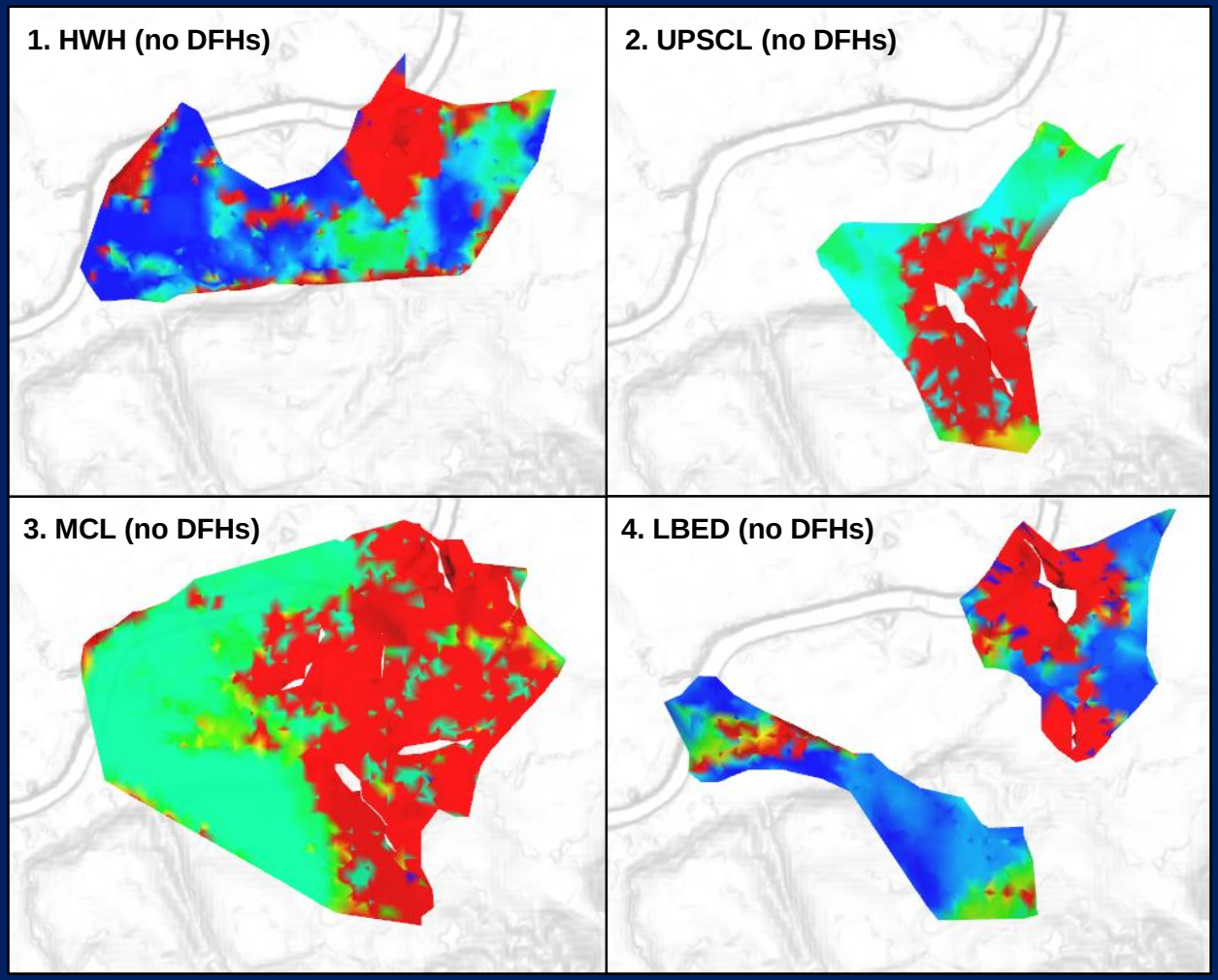

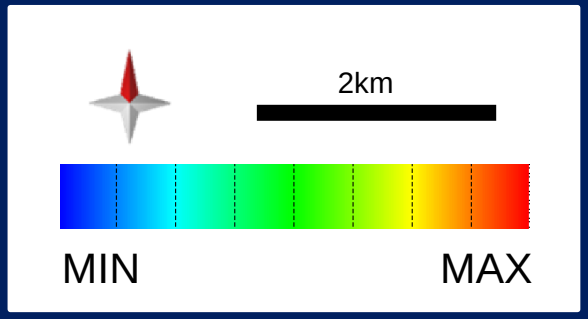

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