The application of 3D geological models: The BGS experience

David Entwisle and a host of BGS staff

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Public lecture, Nanyang Technology University, Singapore, 15 January 2019

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This version of this talk '**The application of 3D geological models: The BGS experience'** by David Entwisle, with contributions of many others from the BGS, contains all the slides presented at the public seminar at Nanyang Technology University, Singapore, 15 January 2019. A few changes and additions have been made to take into consideration the animations used and to anonymizes some of the slides. The talk lasted about 53 minutes of the allocated hour. It also contains additional slides that provide more background to the talk, helping explain a number of points.

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Synopsis

Introduction

Why 3D models?

Applied 3D geological models at the BGS some applications

Geology

Planning and engineering (also GIS)

- Crossrail Farringdon station model
- Glasgow

Groundwater and aquifer vulnerability

Environmental geology and engineering

Resources

Others

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About models

"All models are wrong, **some are useful**"

George Box, statistician (1976)

Journal of the American Statistical Association

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Why 3D geological model?

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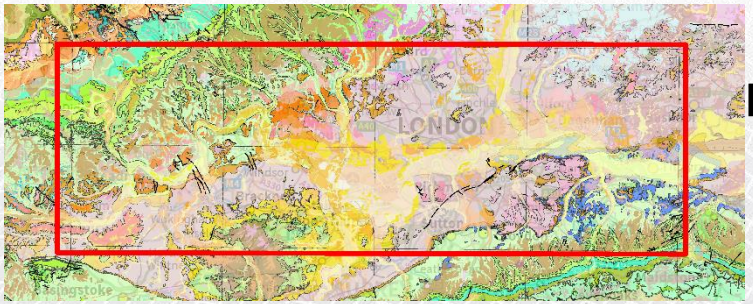

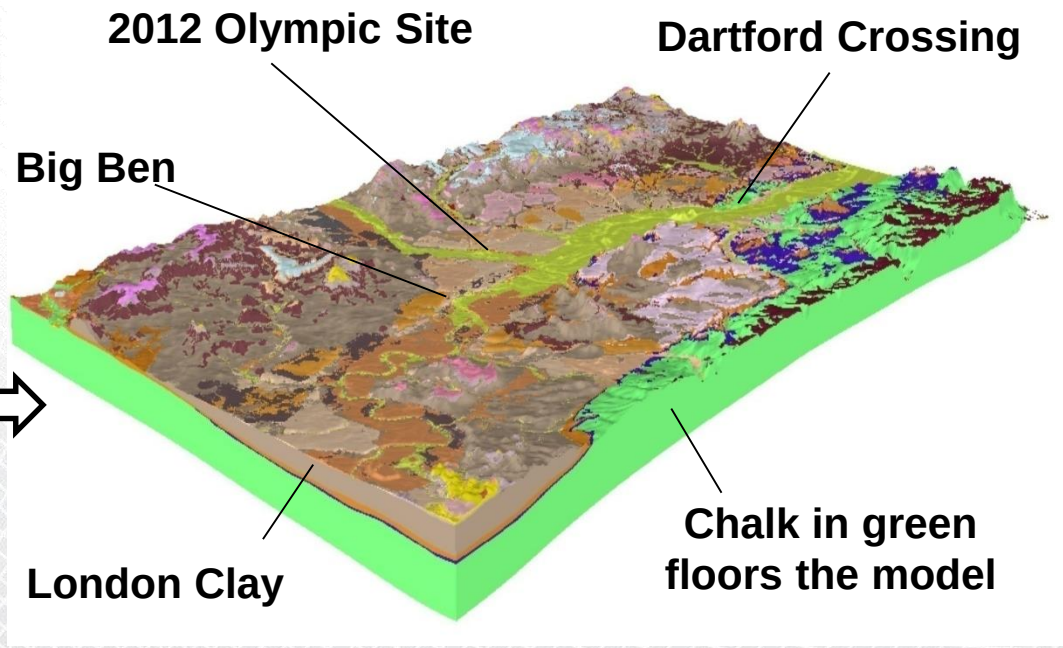

- Geologist – understand the geology and relationships between units, faulting, geological structures etc.
- Communicate to other-geologists and **non-geologists**
- **Examine ground conditions and inform planning decisions on proposed development**
- **Desk study tool, ground model, does not replace ground investigation**
- Thickness and volumes – Aggregates and Minerals
- Aquifer – relationship to other units

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Application of 3D geological models at the BGS

Examples of:

- Ground engineering (planning)
- Hydrogeology (resources) and ground water protection
- Resources – minerals and energy

Others not covered here e.g.

- Improving geological understanding
- Carbon capture and storage
- Geothermal energy – ground source heat pumps
- Ground stiffness
- Groundwater flooding

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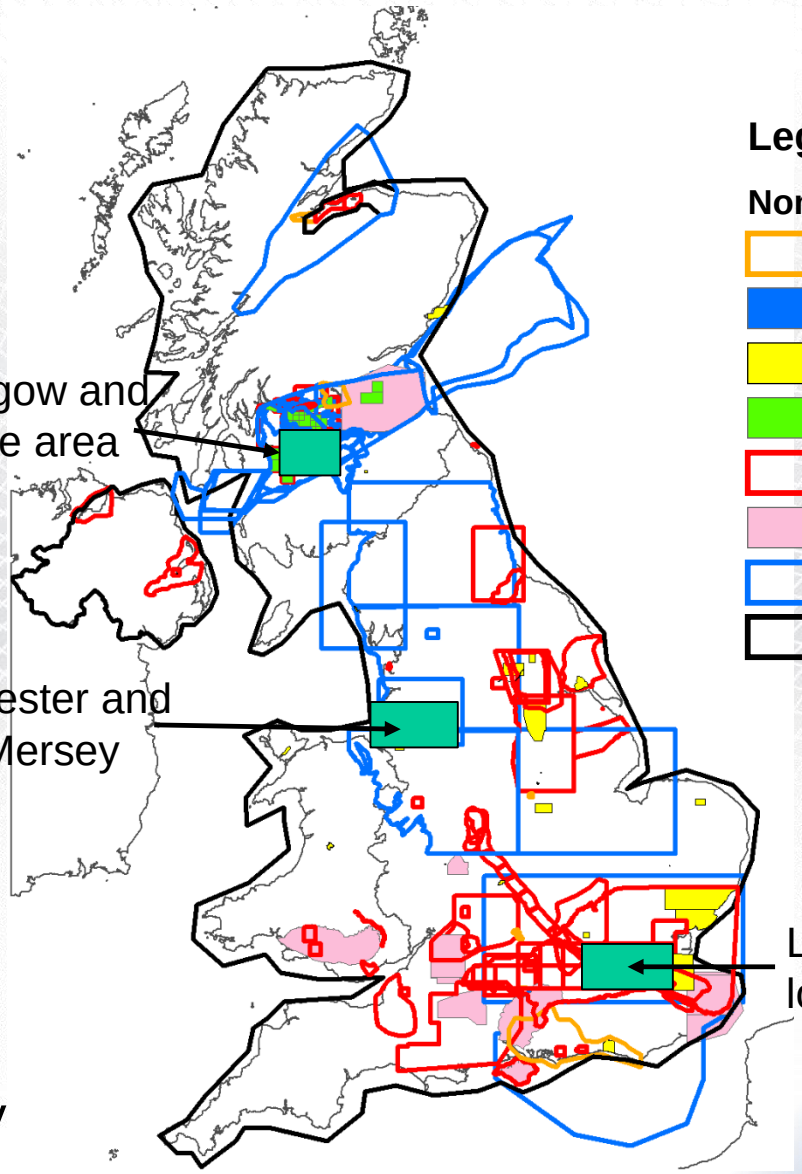
BGS UK Geological models:

Systematic coverage plus

Urban areas, aquifers, civil engineering etc.

First model 1992-93
London - LOCUS



Urban areas include
London – Thames
Manchester and lower Mersey
Glasgow and the Clyde

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Geological Modelling and Visualisation - BGS Industry and Consultancy

- Dr Sauer Group/CrossRail – Farringdon Station
- Singapore (Building and Construction Authority) – 3D geological Model
- High speed rail – Formation Expertise, Rayleigh Wave Assessment
- Tata Steel – Leeds to York Electrification
- Arup – UAE Offshore
- Ministry of Energy (Abu Dhabi) – Abu Dhabi Geological model
- Keynetix/Atkins – BIM for the Subsurface
- Vale/Coffey Mining – Mineral Exploration
- Wardell Armstrong – TELLUS HOW
- Anglo American – Visualisation Training
- Arup/Yorkshire Water - Doncaster

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Geological Modelling and Visualisation - BGS Local/National Government and Agencies

- Glasgow City Council – ASK Network
- Radioactive Waste Management - Geological Screening
- Environment Agency:
- National Geological Model – UK 3D
- Aquifers and Shales
- Manchester
- Knowsley
- Holderness
- Chichester
- Doncaster
- North Kent
- London Chalk Model
- British Waterways – Monmouthshire and Brecon Canal
- Forres-Moray (Moray Council) – Flood Prevention
- CO_2 storage - CASSEM
- Department of Energy and Climate Change – Shale Study Midland Valley (Scotland)
- Oil and Gas Authority – Bowland Shale Gas
- Oil and Gas Authority – Jurassic Shale of the Weald Basin
- Scottish Government - Geothermal Energy
- Ordnance Survey – 3D workshops/Project Iceberg

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Geological Modelling and Visualisation - BGS Geological Survey Organisations and Universities

- Swedish Geological Survey (SGU) – Esker Pilot Study
- Illinois – Visualisation and Modelling

Geological Survey of Finland (GTK) – Groundhog Desktop Development

- Chile – Digital Mapping Workflow
- University of Newcastle – Groundwater Flooding
- Volcano Research – STREVA
- University of East Anglia DTCs- Wensum
- Kingston University - Visualisation Training
- Universiti Tenaga Nasional UNITEN (Malaysia) – Visualisation Capability and Training
- European 3D Geological Modelling Community
- Sub-Urban – Consortium of Geological Survey Organisations, Cities and Research partners - management of ground beneath cities.

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3D geological model – bulk attribution

Model geological units –

- Lithostratigraphy, lithology

Engineering characteristics

- **Engineering geological characteristics (basic)**
- Permeability
- Plasticity
- Hazards

Others

Weathering characterisation

Engineering design characterisation ideas

- Foundations, excavatability, bulking, use as engineering fill

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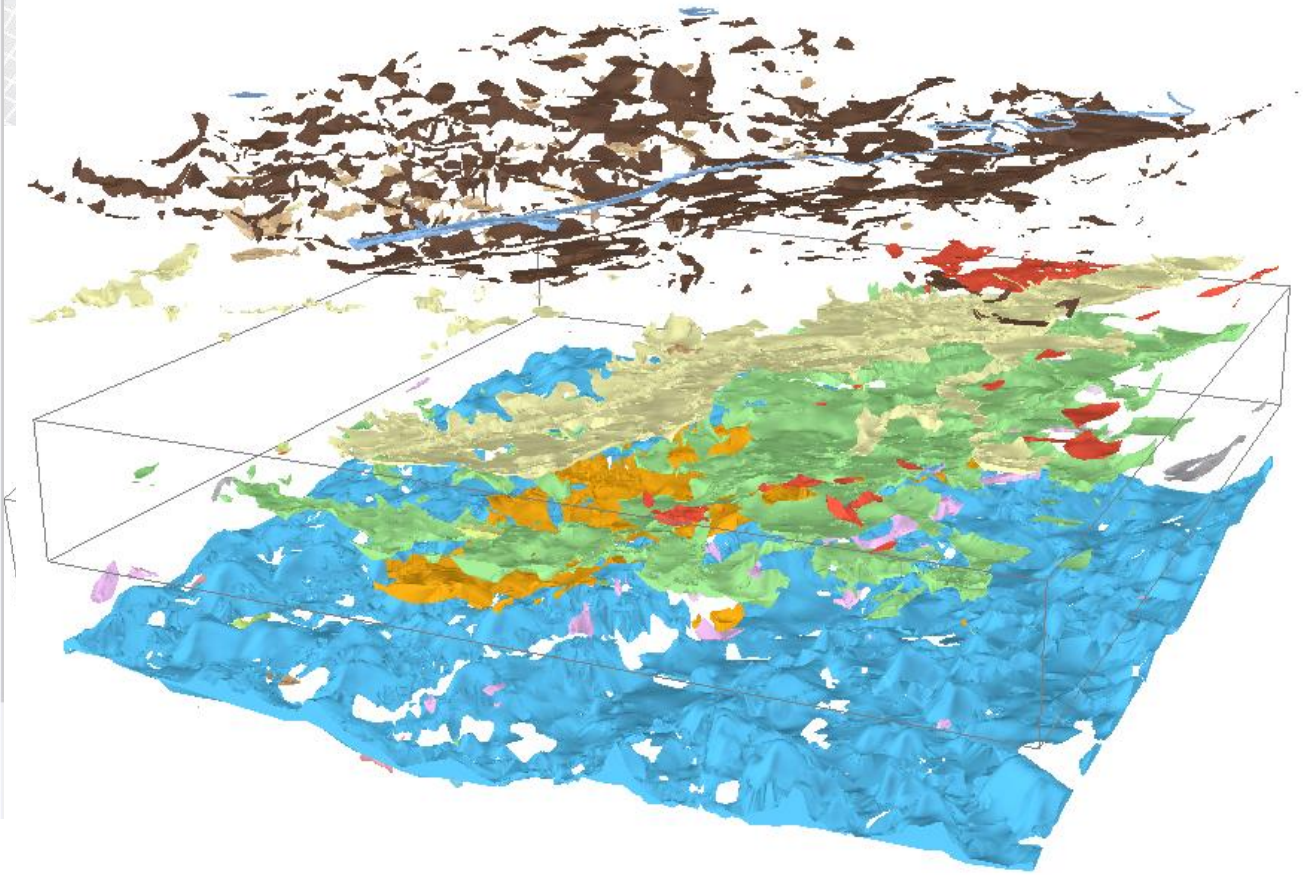
Central Glasgow 3D geological model 10 km x 10 km – GSI3D

Superficial (Quaternary)

- water
- Made and Worked Ground and topsoil
- Head
- Peat
- Lacustrine deposit
- Law Sand and Gravel Member
- Strathkelvin Clay and Silt Member
- Gourock Sand Member
- Killearn Sand and Gravel Member
- Linwood Clay Member
- Paisley Clay Member
- Bridgeton Sand Member
- Ross Sand Member
- "Ross Sand Member, silty sand"
- Bellshill Clay Member
- "Broomhouse Sand and Gravel Formation, undivided"
- "Broomhouse Sand and Gravel Formation, sand"
- Wilderness Till Formation
- Cadder Sand and Gravel Formation
- Broomhill Clay Formation
- Baillieston Till Formation
- Sand and gravel



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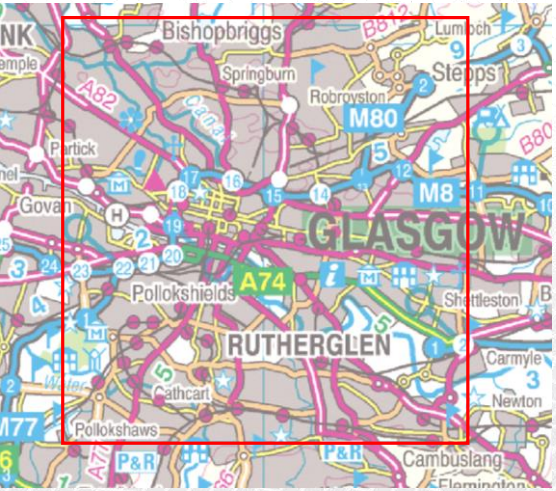
Engineering Geology classification Central Glasgow



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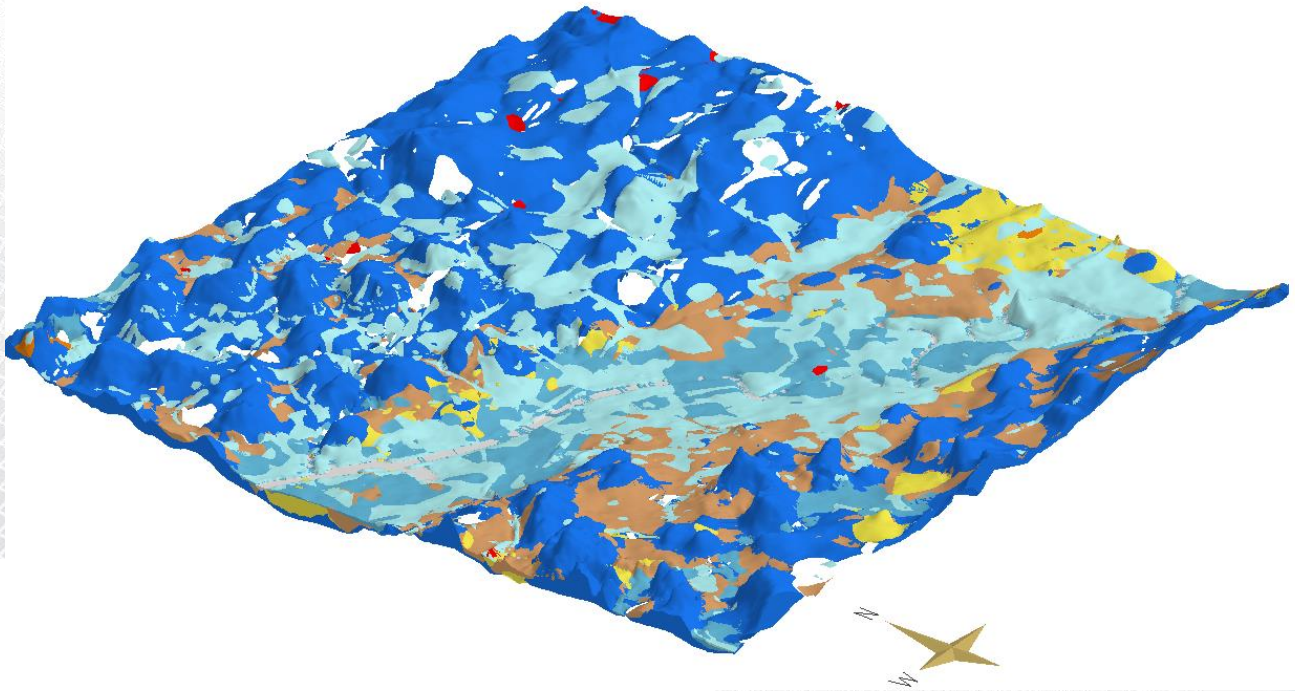

Key

Organic material

- Peat

Mixed fine and coarse

- Very soft to very stiff/loose to very dense: Made Ground
- Very soft to very stiff/loose medium dense CLAY or SILT, SAND or GRAVEL: Law and Gourock Formations
- Firm to stiff/dense very dense gravelly sandy CLAY or SAND and GRAVEL: Wilderness Formation

Mostly fine grained

- Very soft to firm/(loose) laminated (sand) SILT and CLAY: Paisley Formation
- Firm to stiff laminated SILT and CLAY: Bellshill and Broomhouse (fine grained) Formations

Coarse-grained

- Loose to medium dense silt SAND and SAND: Bridgeton, Ross and Killearn Formations
- Medium to very dense silty gravelly SAND and/or GRAVEL: Broomhouse Formation

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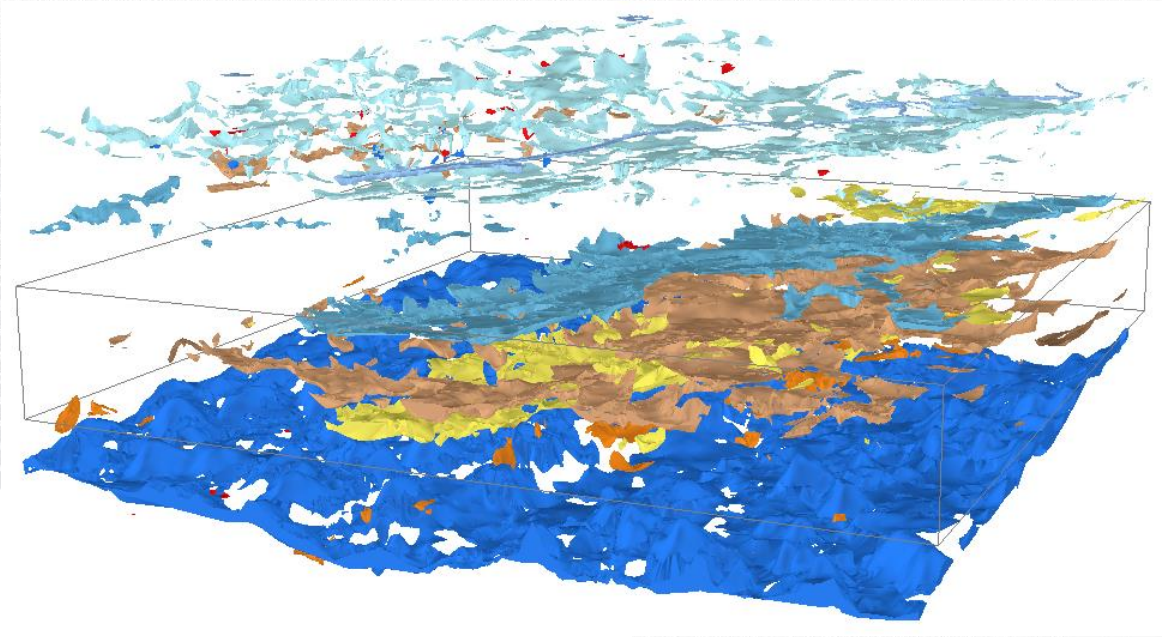
Engineering Geology classification Central Glasgow



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Civil Engineering Project application - Tunnelling
3D models and reducing risk - Crossrail Farringdon Station

Europe's largest construction project

- Links 41 stations over 100 km
- 42 km of new tunnels, 10 stations over 50 km of new track

See http://www.crossrail.co.uk/route/maps/
http://www.crossrail.co.uk/

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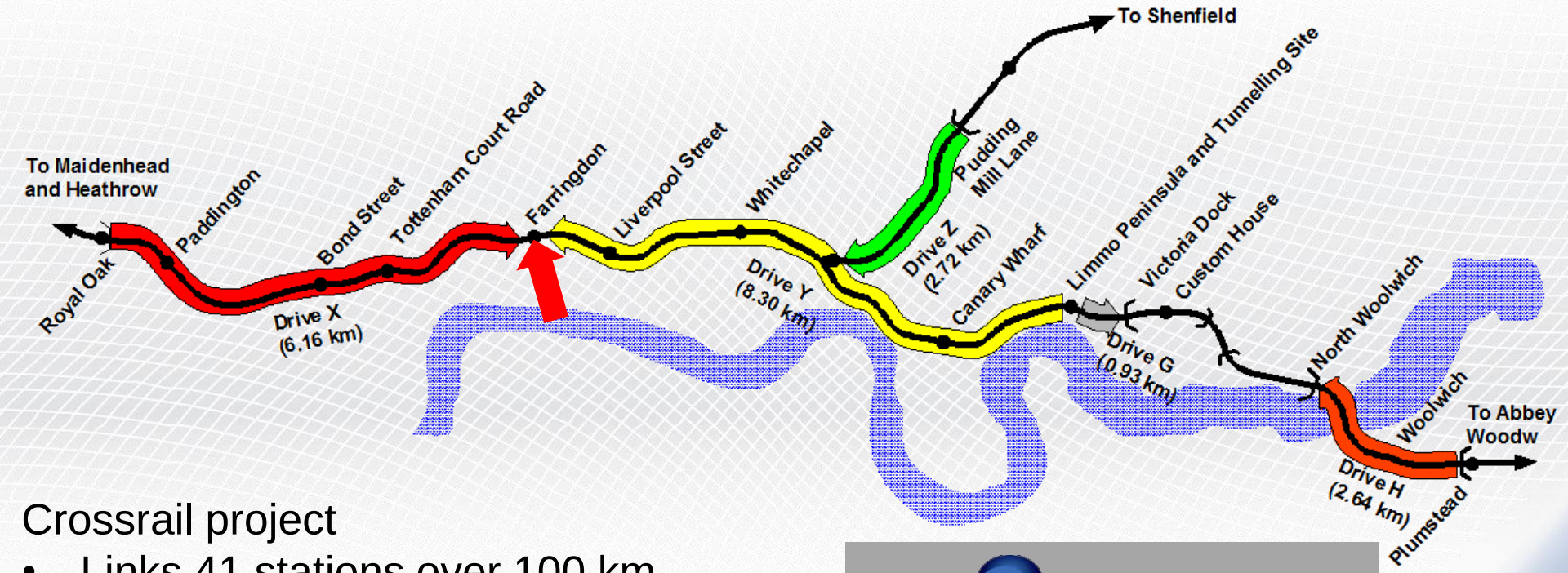
Reducing risk – Ground models Crossrail Farringdon Station
Open face tunnel sprayed concrete lining



Crossrail project

- Links 41 stations over 100 km
- 42 km of new tunnels, 10 stations
- Over 50 km of new track

BFK Bam | Ferrovial | Kier — Main Contractor

Dr. SAUER & PARTNERS — SCL specialists

https://www.bgs.ac.uk/news/events/geologyUnderLTV/GakisandCabrero_UseOfThe3DGeologicalModelWithSCL.pdf

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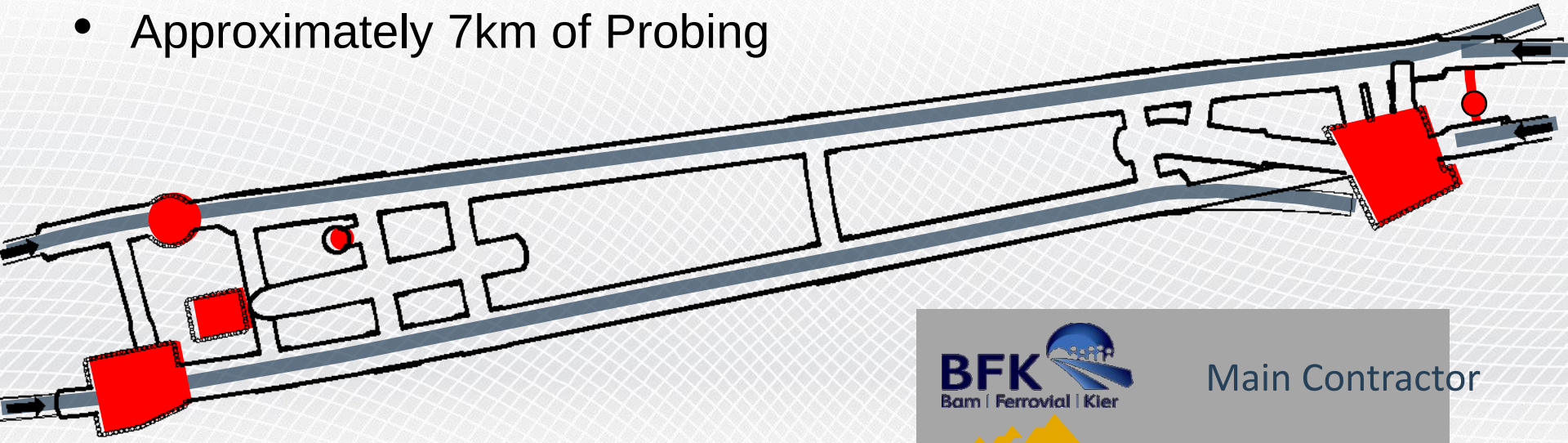
Reducing risk – Ground models
Crossrail Farringdon Station

- Approximately 1km of SCL tunnels
- Approximately 7km of Probing



BFK Bam | Ferrovial | Kier — Main Contractor

Dr. SAUER & PARTNERS — SCL specialists

- 6 Shafts
- 4 TBMs (Drives X/Y)

Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

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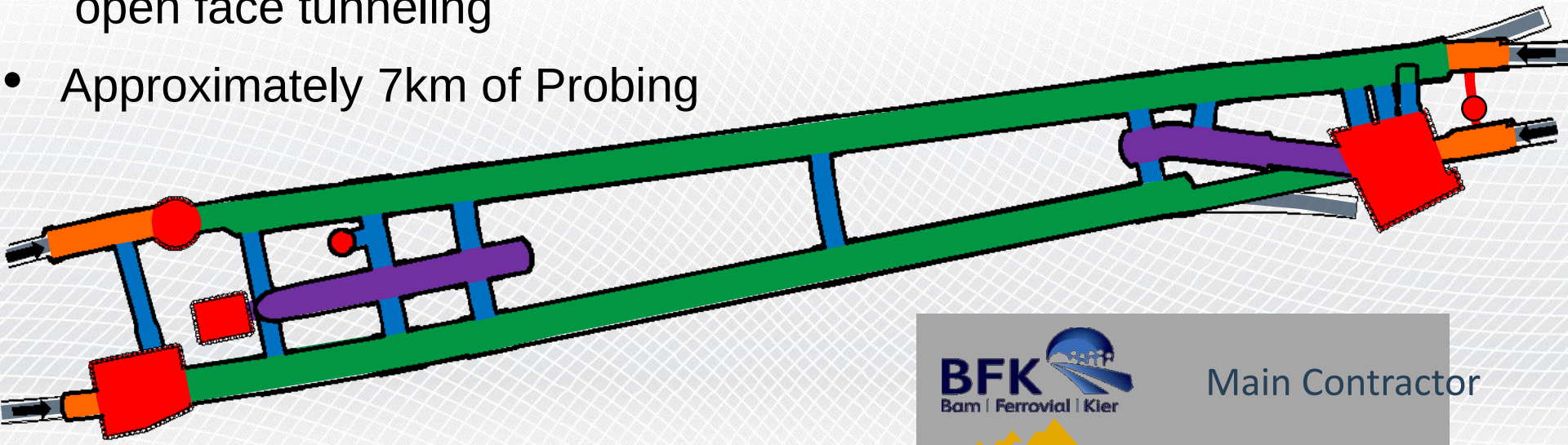
Reducing risk – Ground models
Crossrail Farringdon Station

- Approximately 1km of Spayed concrete lined tunnels – open face tunneling
- Approximately 7km of Probing



BFK Bam | Ferrovial | Kier — Main Contractor

Dr. SAUER & PARTNERS — SCL specialists

- 6 Shafts
- 4 TBMs (Drives X/Y)
- 2 Platform Tunnels
- 8 Cross Passages + 2 Ventilation Adits
- 2 Escalators/Concourse Tunnels
- 4 Stub Tunnels

Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

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Example – Crossrail Farringdon Station

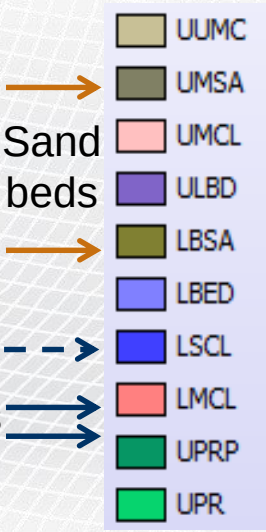
Farringdon Street Station in the lithological complex Lambeth Group (Palaeocene ~)

- Hard beds, water bearing sand channels, faulting

Interpretation of initial ground investigation (pre 2009) – no coherent ground model established

- Zones of ‘disturbed ground’ (faults) – number, character and orientation uncertain
- Water-bearing sand units ‘random’ distribution and thickness

Risk -
Further intrusive investigation was needed but where to locate the boreholes?



BGS commissioned to produce a 3D geological model in 2009

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3D Geological modelling

Expert geologist

Inputs

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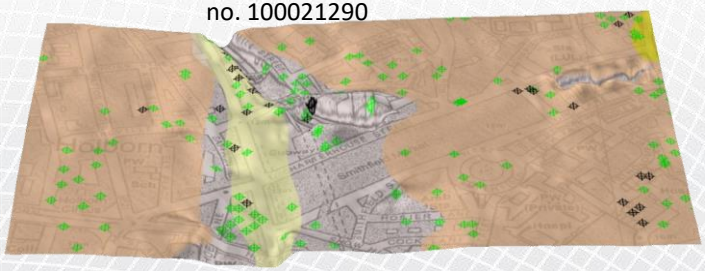
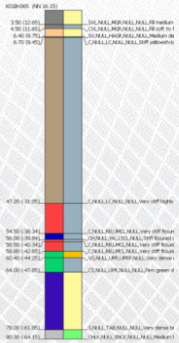


136 BH (52 not used)

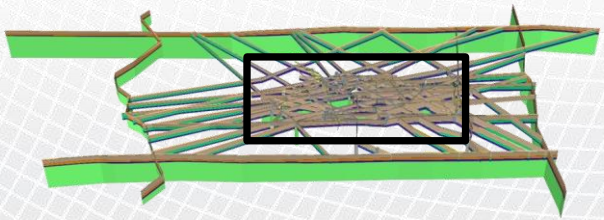


Modelled units

Rules

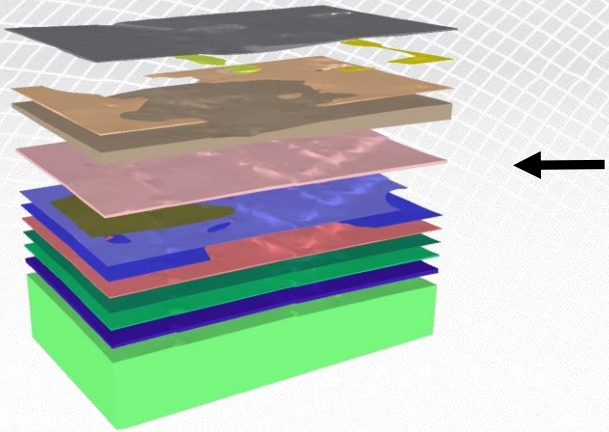
Construction

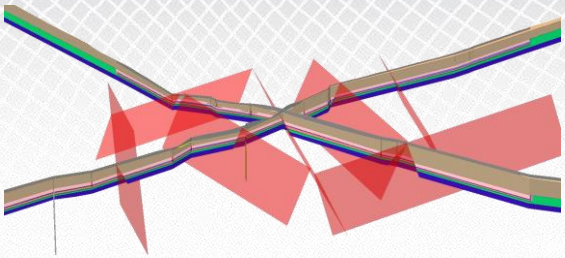
Model 800 m x 500 m

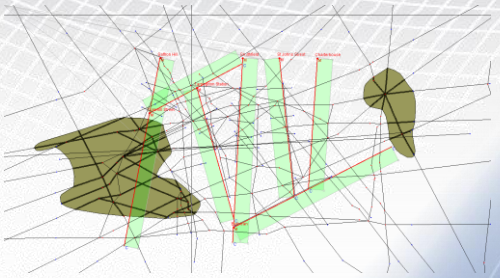


Fence diagram

Mapped and modelled Geology + DTM + boreholes + GSI3D







3D model ('exploded')

Model calculation

Unit distribution and faults

Modelling

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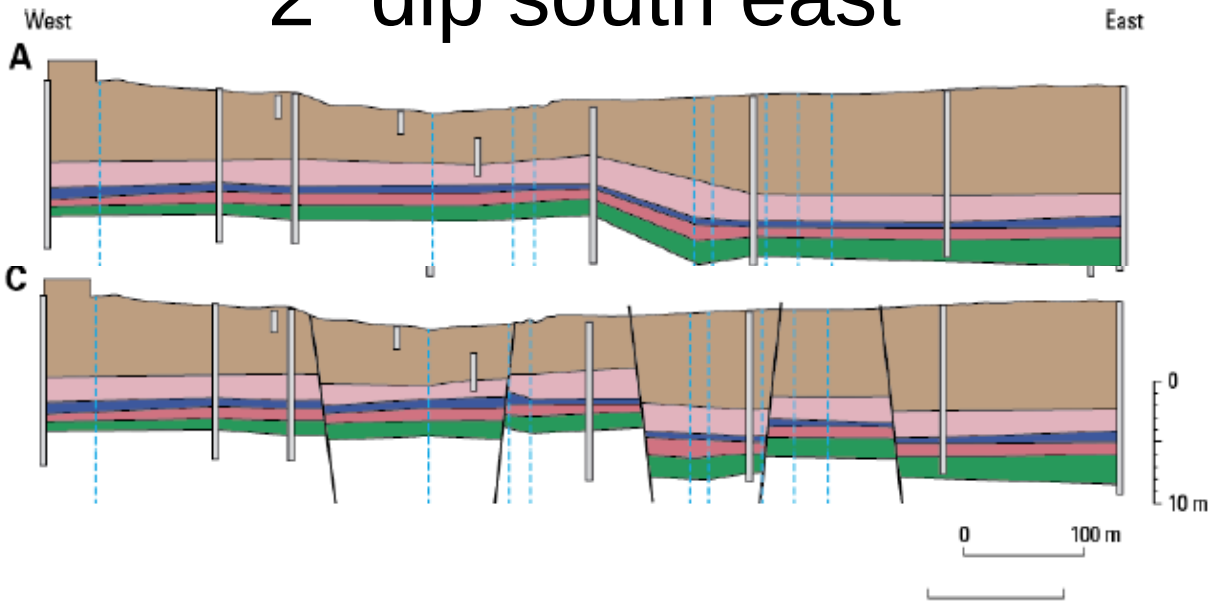
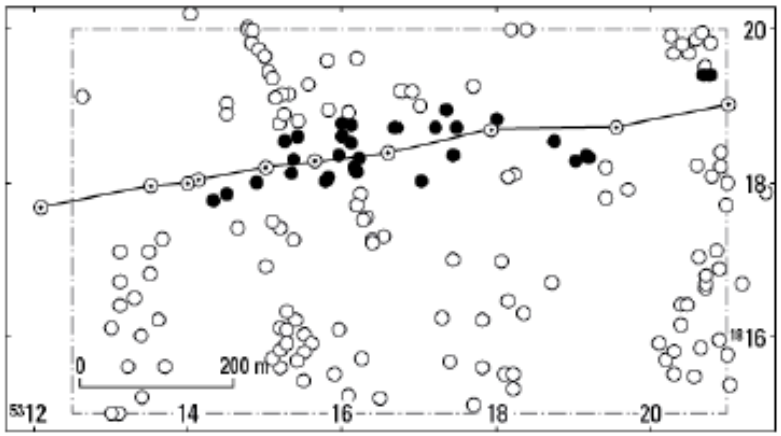
Cross-section – construction
2° dip south east

No faults, partly constrained by cross-cutting sections (dashed)

Same as A but with faults





London Clay Formation

Upper Mottled Clay

Woolwich Formation

Lower Mottled Clay

Upnor Formation

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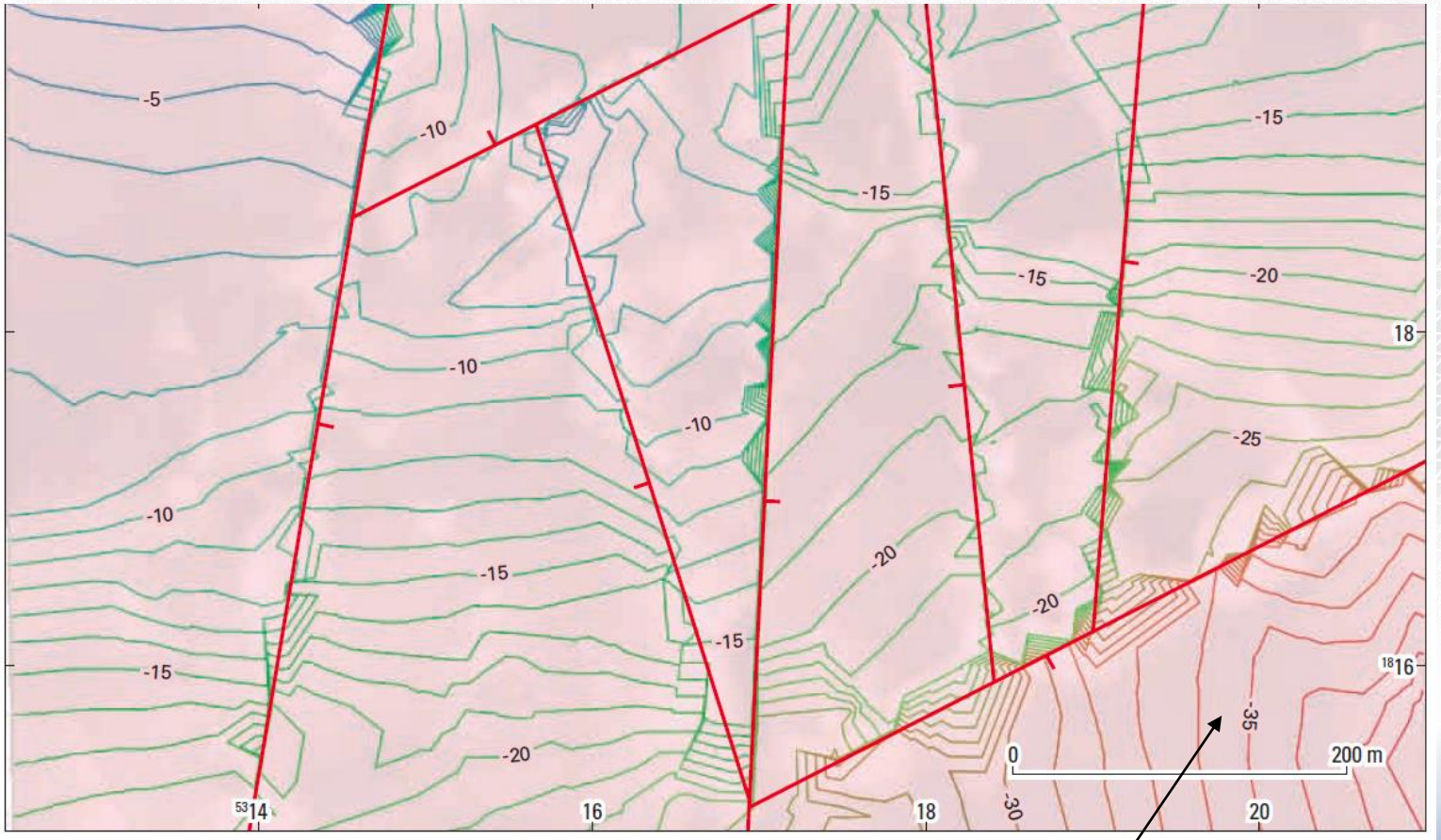
Modelled structure 1 m contours – Base Upper Mottled Clay (Beds) ~dip 2° to south



Block with different dip direction

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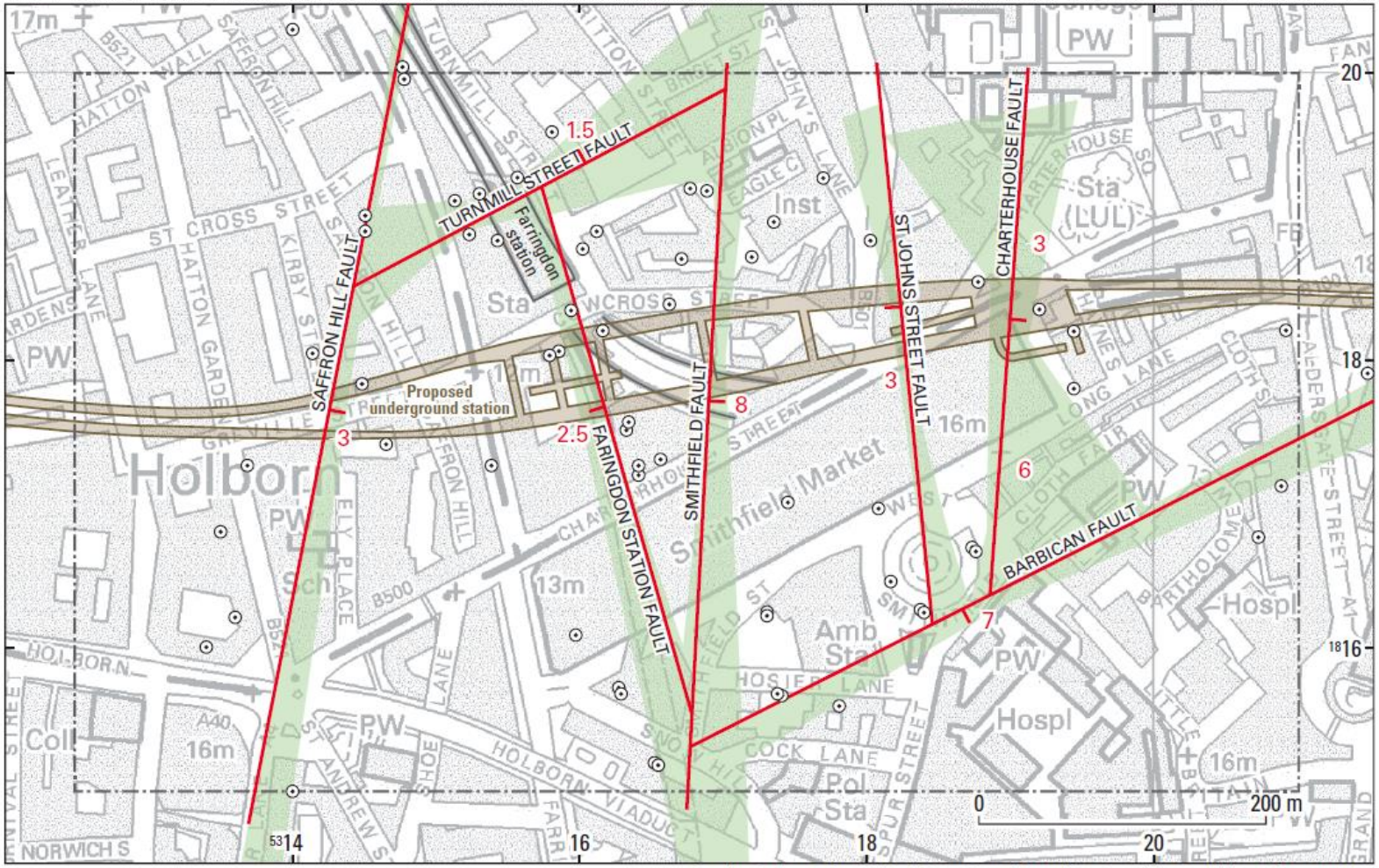
Fault envelopes – range at proposed Crossrail Farringdon station



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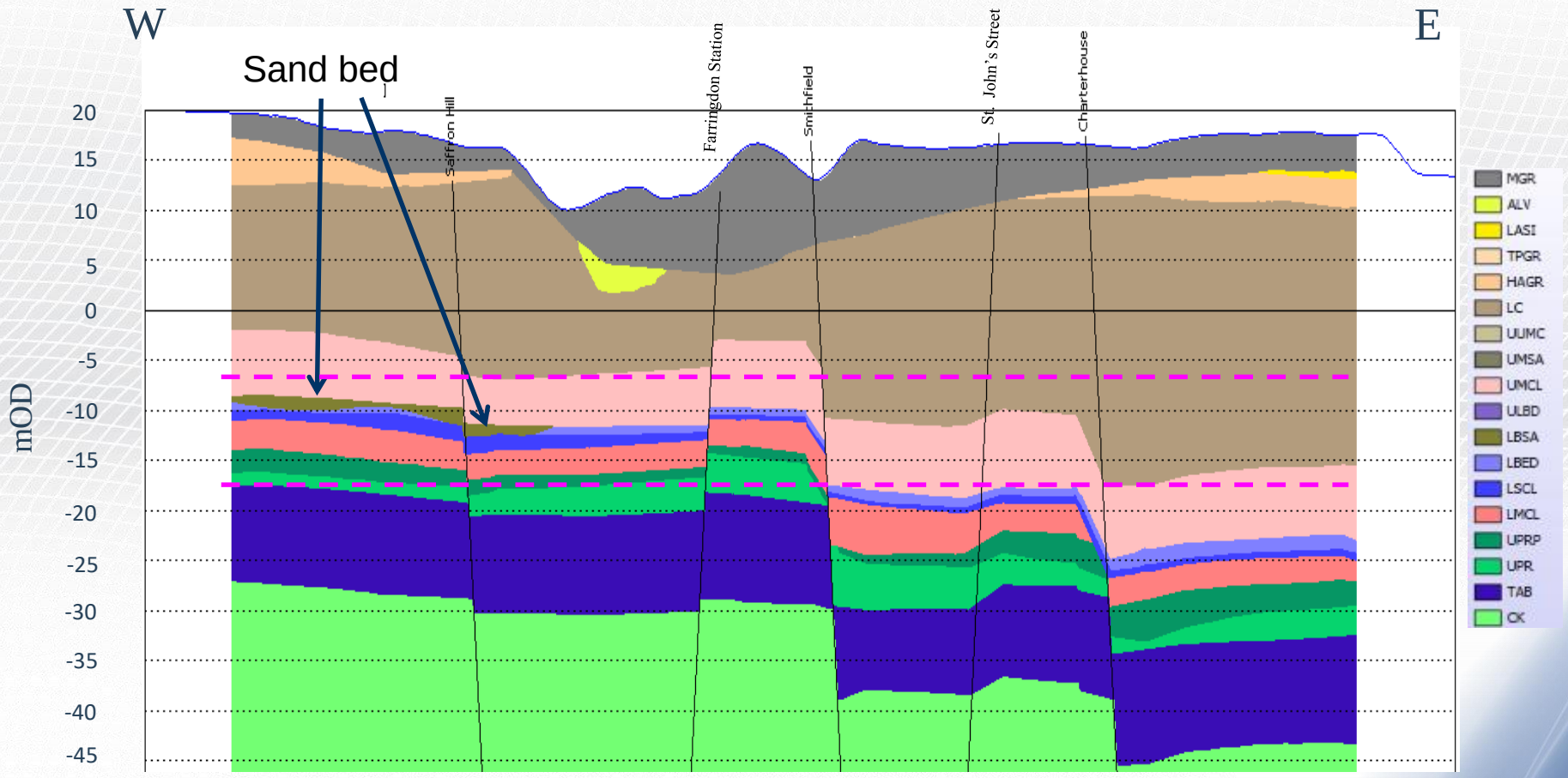
Synthetic cross-section ~ along tunnel line



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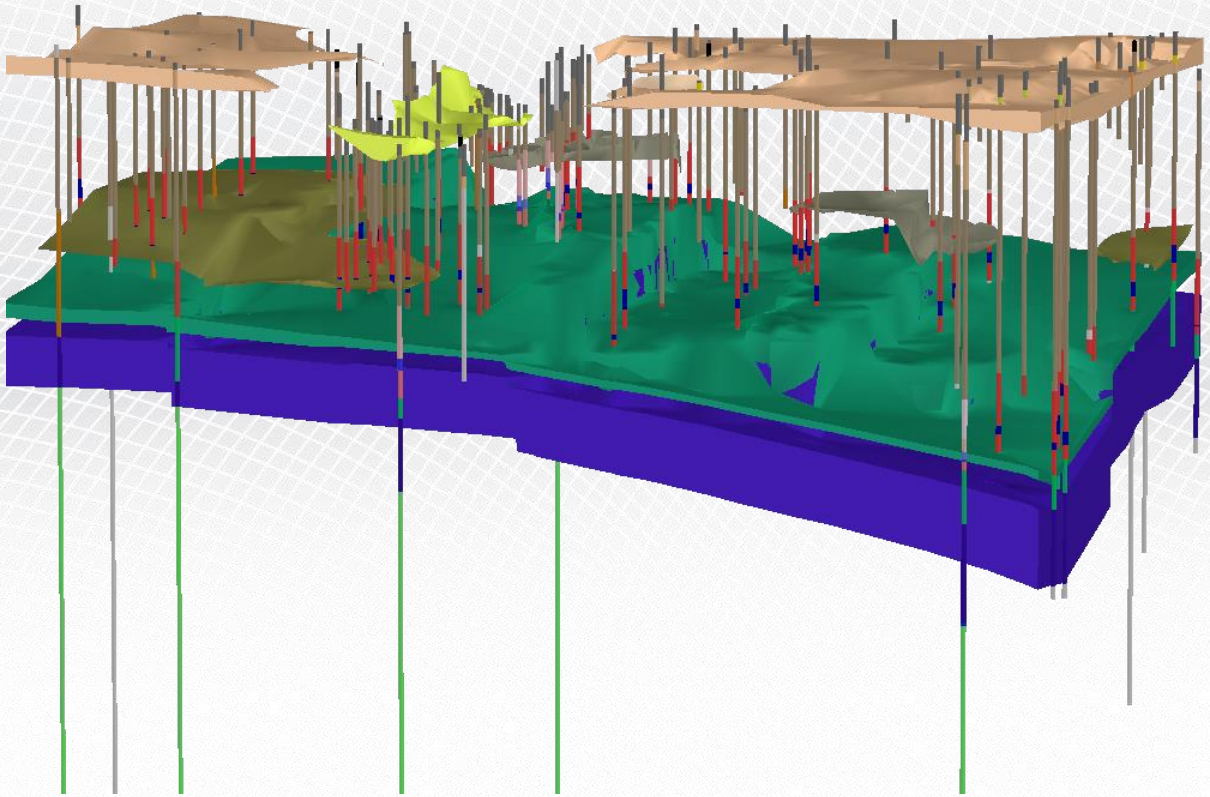
Derived from the 3D geological model For a tunnel showing the coarse soils



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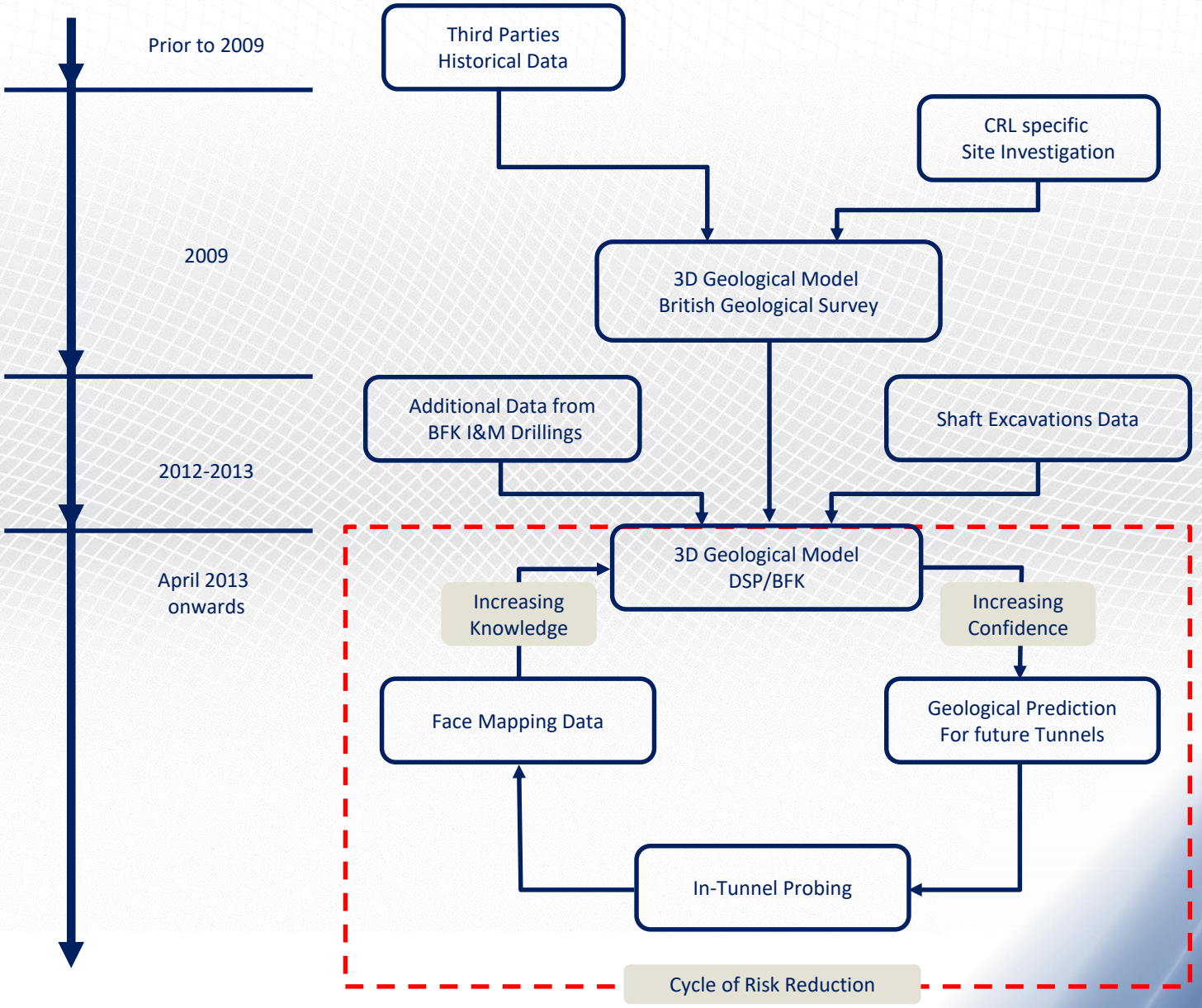
Development



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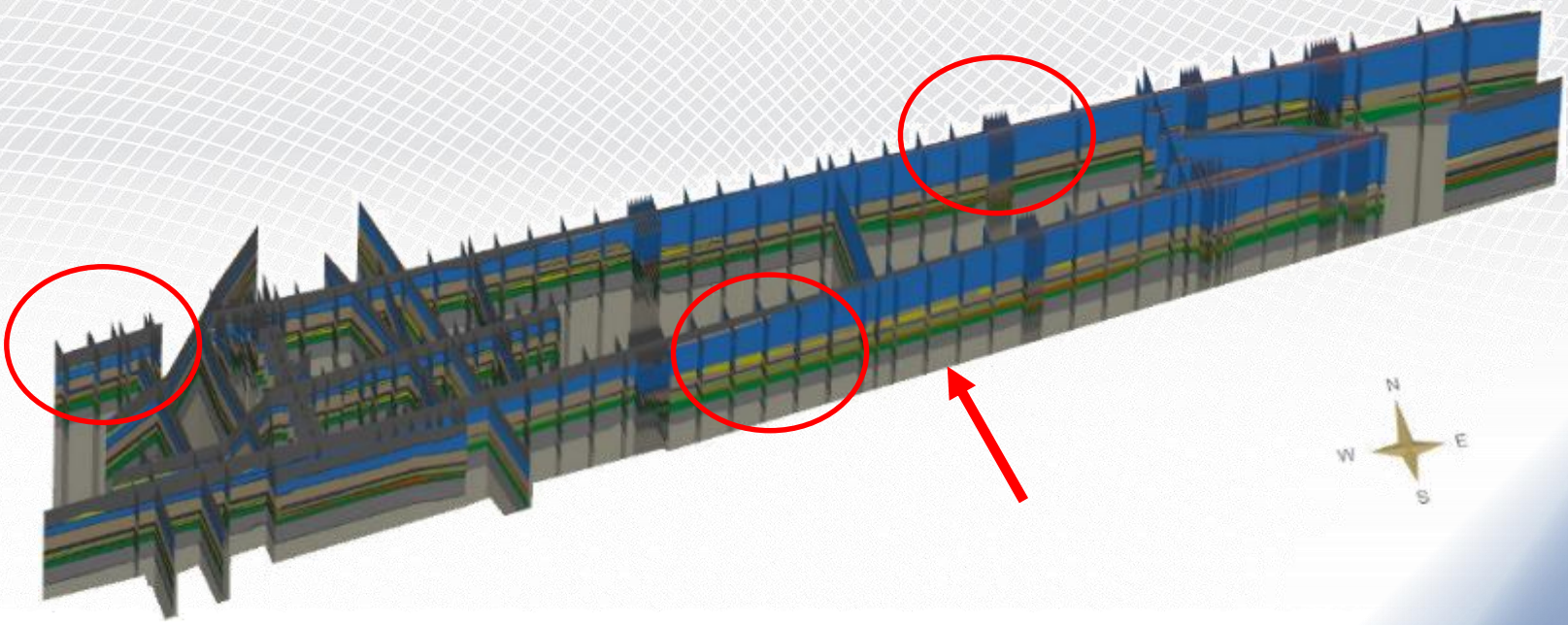
Integrating the data - tunnel face descriptions

- Long Tunnels – 1 face log/10m
- Short Tunnels – min 3 face logs
- Fault/Sand Lens areas – 1 face log/m
- Longitudinal section included upon completion of a tunnel
- All intersecting (affected) sections were subsequently updated



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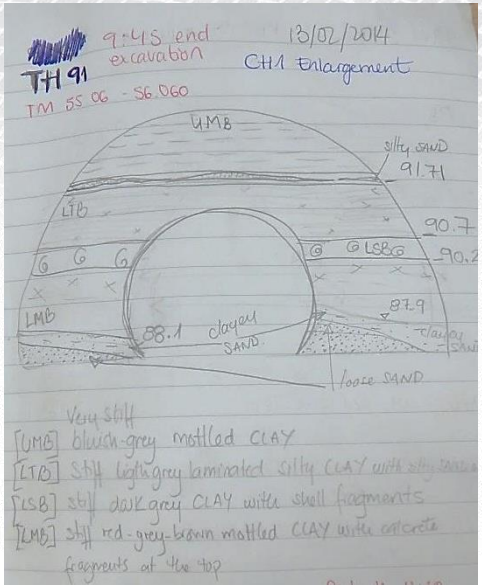
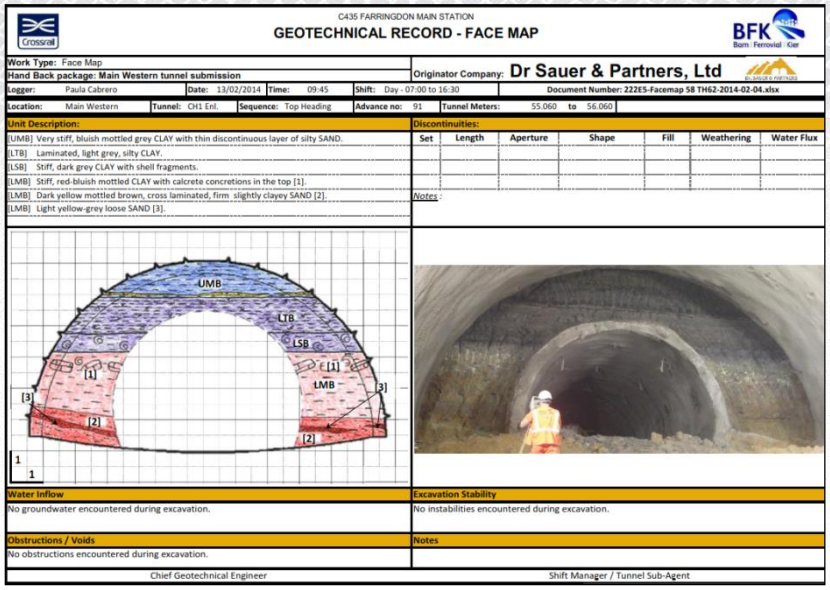
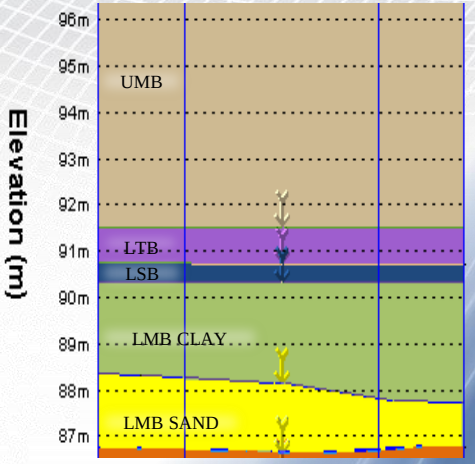
Tunnel face data

- Face Observation
- **Draft Sketch**
- **Detailed Face Log**
- **Data Input in the Model.**







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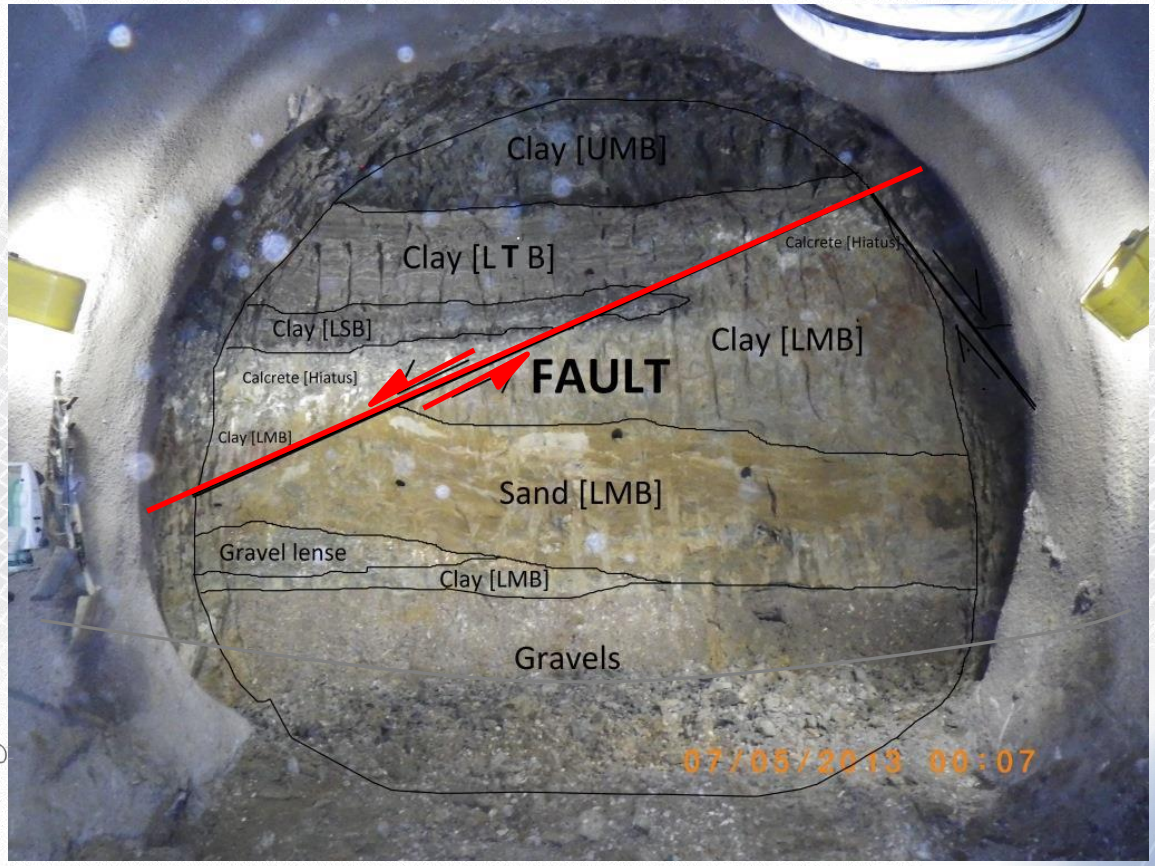
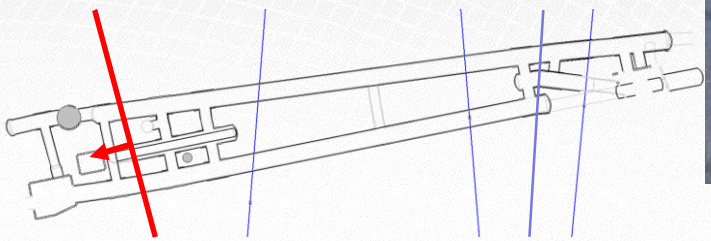
Farringdon Fault - face

- Farringdon Fault
- Smithfield Fault
- St. John Street Fault
- Charterhouse Fault
- Lindsey Street Fault





Lambeth Group

UMB – Upper Mottled Bed
LTB – Laminated Bed
LSB – Lower Shelly Bed
LMB – Lower Mottled Bed
Gravels belong to the Upnor Formation (UPR)

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Farringdon Fault

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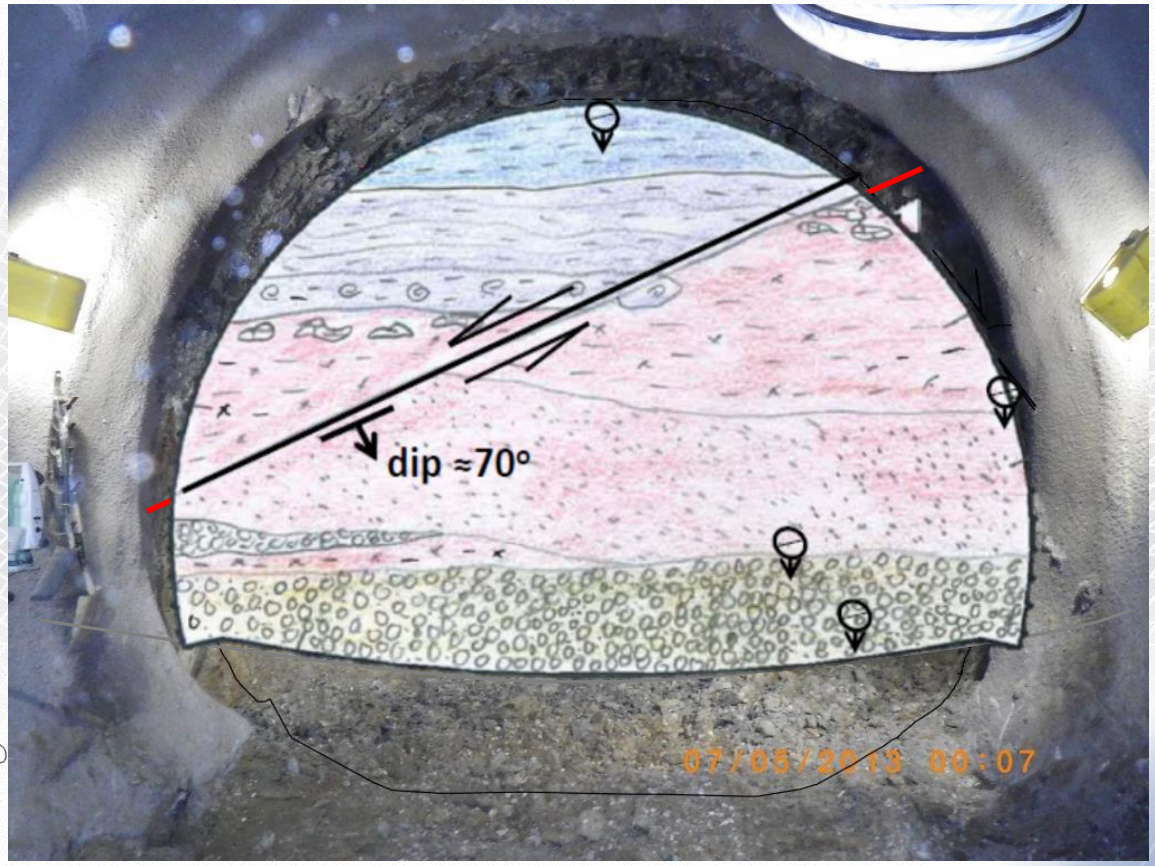

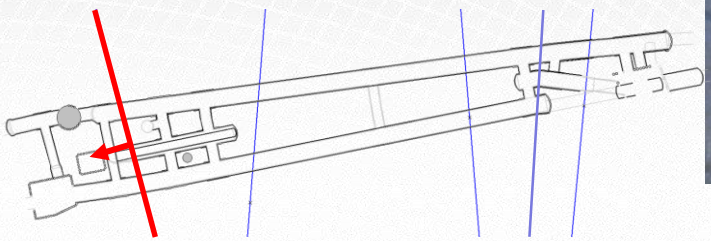

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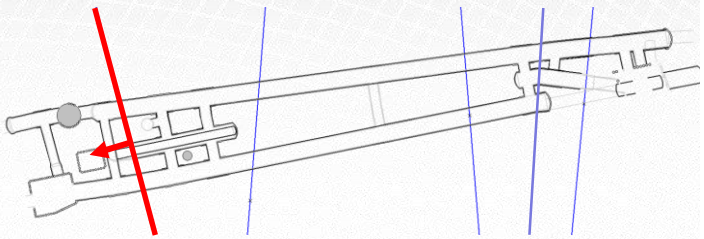

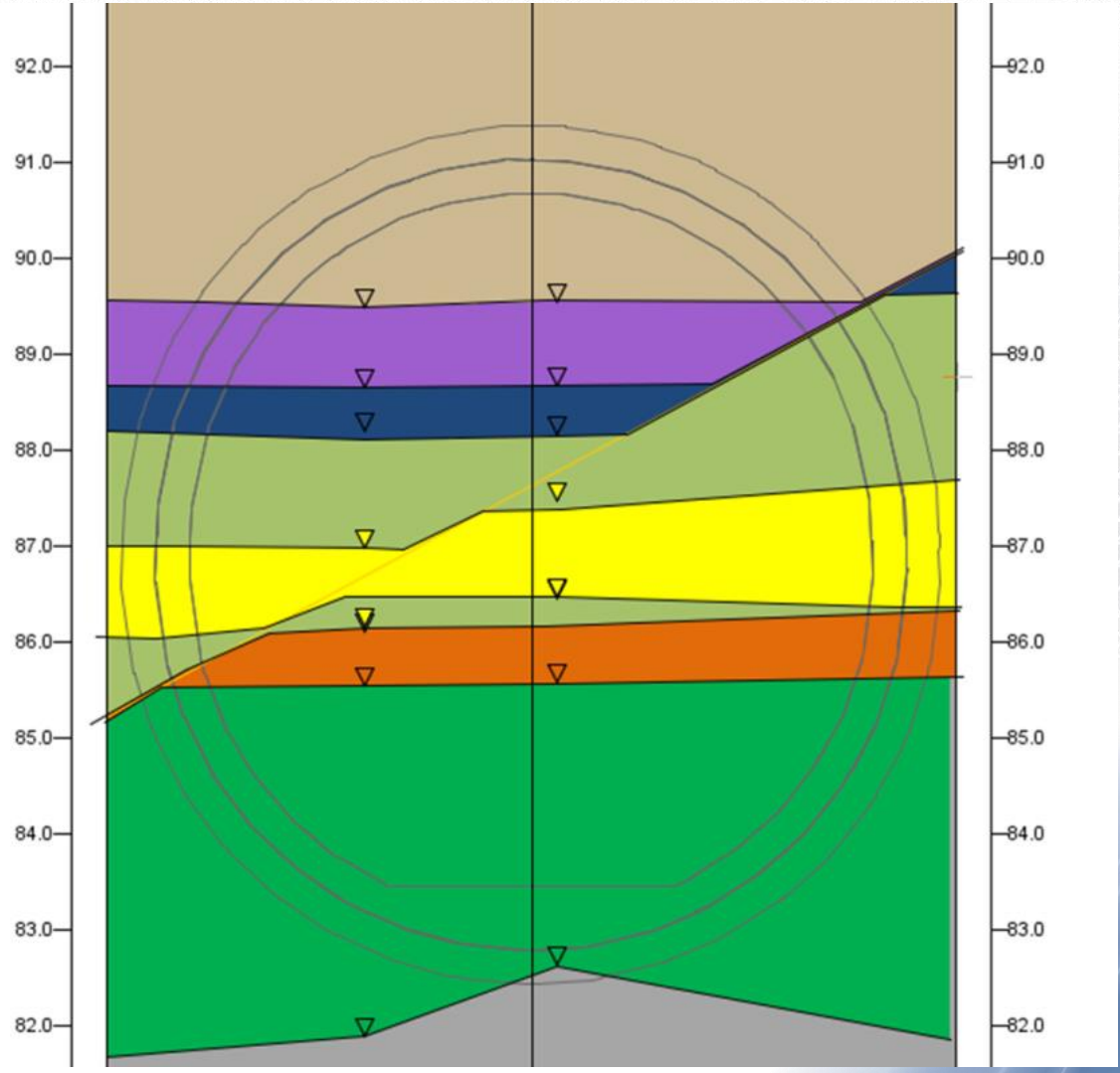

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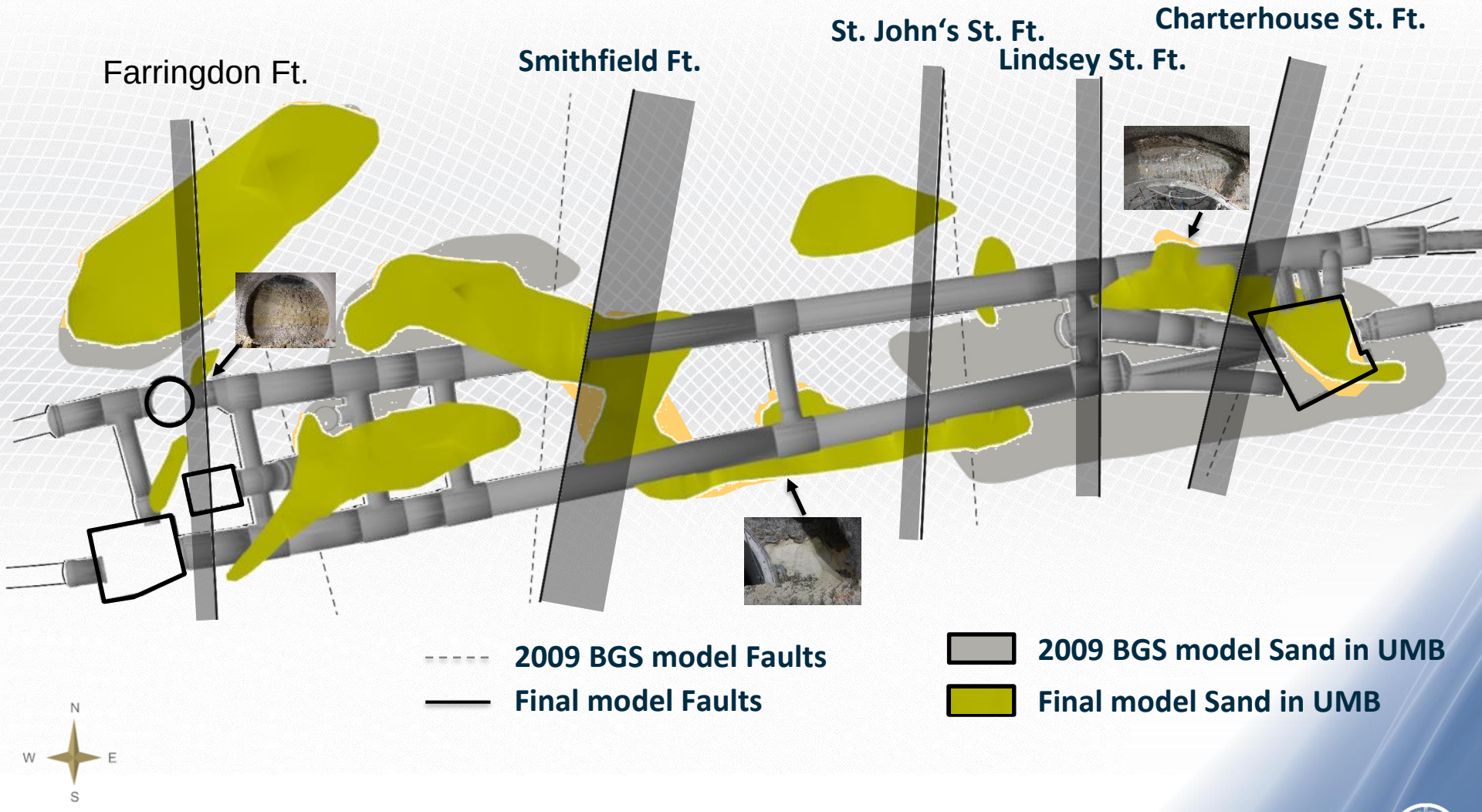
Comparison of models Faults and Sand



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Sand – removal of water

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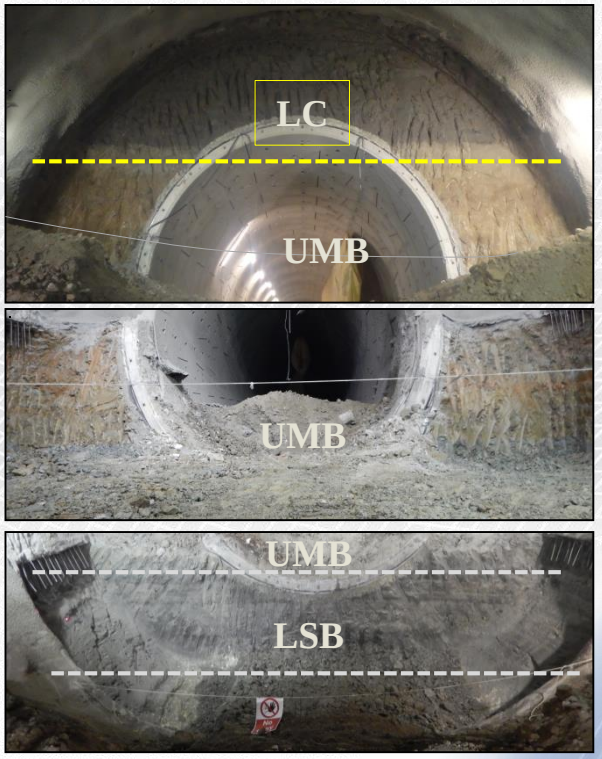
Lessons – Geology to engineering

Unit	Description	Engineering considerations
LONDON CLAY		
 *London Clay*	Stiff to very stiff closely fissured dark grey CLAY with occasional thin shelly beds and pockets. Up to 15m thick.	Ideal tunneling medium. Prone to wedge failures 'greasy backs' due to fissuring
 *Upper Mottled Clay*	Stiff to very stiff slightly fissured grey bluish mottled CLAY. Lignite at base (platform tunnels	Ideal tunneling medium. Not prone to wedge failures '
 *Sand Lenses in the Upper Mottled Clay*	Loose to dense, yellow-grey, silty SAND. Moist to water bearing. Up to 4 m thick	Significant mitigation measures required – water – problematical depending on position and hydraulic conditions
LAMBETH GROUP		
 *Laminated Beds*	Stiff laminated, silty CLAY/clayey SILT with occasional thin silty sand lenses up to 0.4m thick. Up to 1.2m thick	Issues encountered with crown occasionally, laminations resulted in shotcrete fallout, spraying adhesion poor. Sand thin no problems
 *Lower Shelly Clay*	Stiff to very stiff, dark grey CLAY with white shell fragments. Up to 0.6 m thick.	Good tunneling medium. Encountered in thin layers



Platform Tunnel West Enlargement

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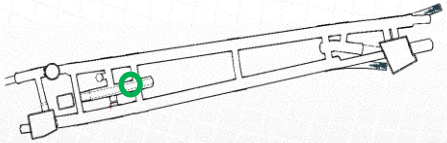
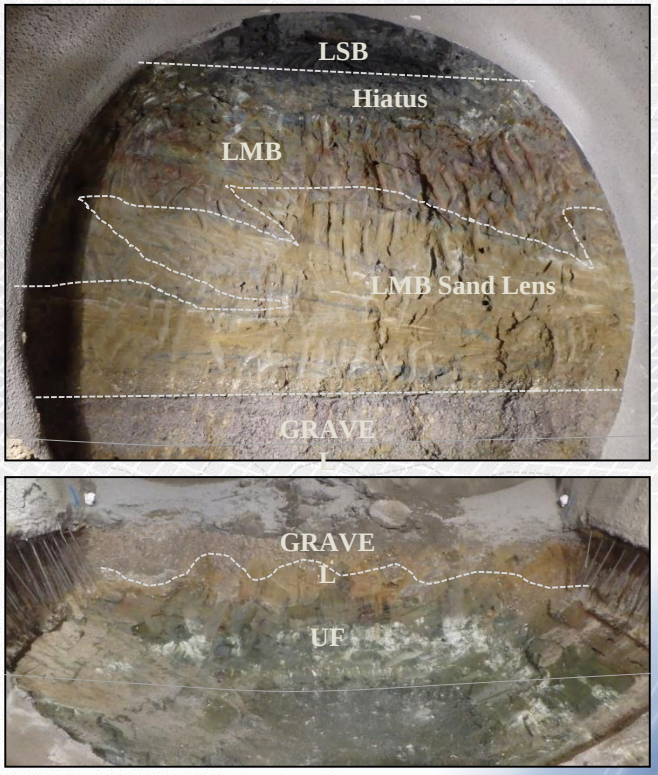
Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Geology to engineering

Unit	Description	SCL Considerations
 *Lower Mottled Clay*	Stiff to very stiff, slightly fissured reddish-brown grey mottled CLAY calcareous fragments near top. frequent dry to moist clayey sand lenses with thin gravel. Up to 4 m.	Ideal tunnelling medium.
 *Sand Lenses in the Lower Mottled Clay*	Loose to dense, cross-laminated, yellow-brown clayey SAND. Dry to moist. Up to 3 m thick	Predominantly dry/moist in lowest part of the tunnels- not significant instabilities. But problematical might require significant mitigation measures Depending on position and water content
 *Upnor Formation*	Dense, brownish green, clayey, fine to medium SAND with very thin gravel beds. Localised carbonate concretions. GRAVEL layer with slightly cemented beds (0.2 – 1.5 m) at top. Up to 5 m thick.	Predominantly dry but local seepage and instability at top of Gravel layer. Required minor mitigation measures.
 *Thanet Sand*	Dense, light grey silty SAND. Up to 2.5 m thick (invert of the platform tunnels	Dry not unstable but sprayed concrete 'fell off' depending on position and hydraulic condition.





CH1 Pilot Tunnel

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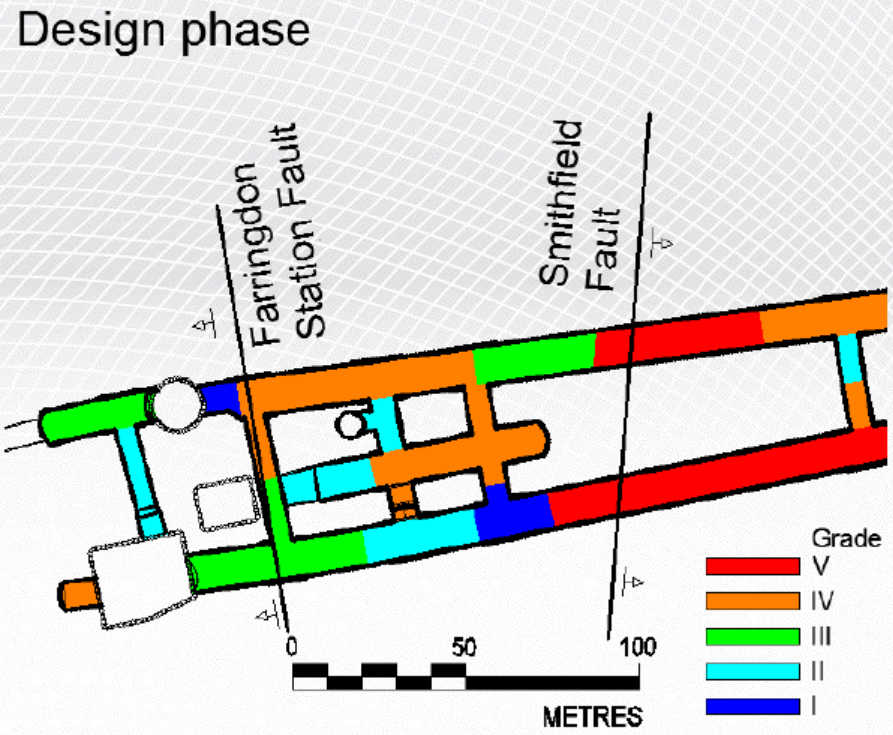
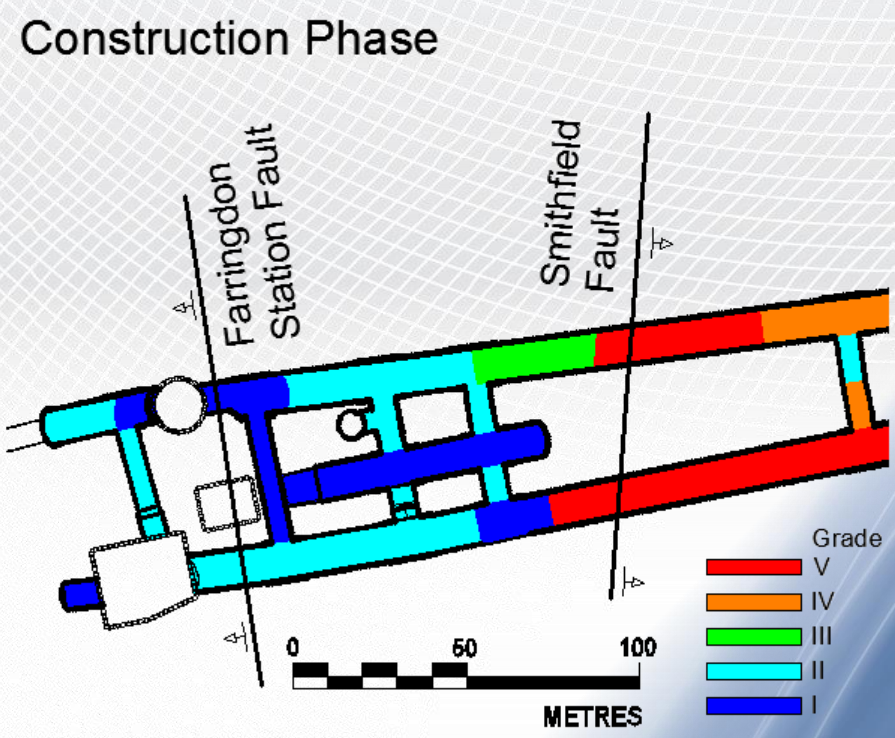
Ground model – benefits risk management and reduction

- Key element of the geotechnical risk management framework.
- Geotechnical risk mapping along the station.





Additional data added during construction reduced risk

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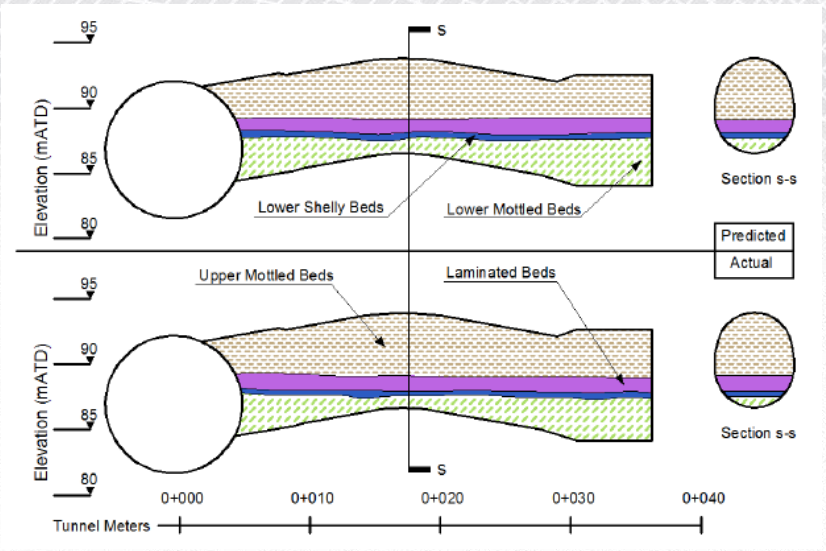
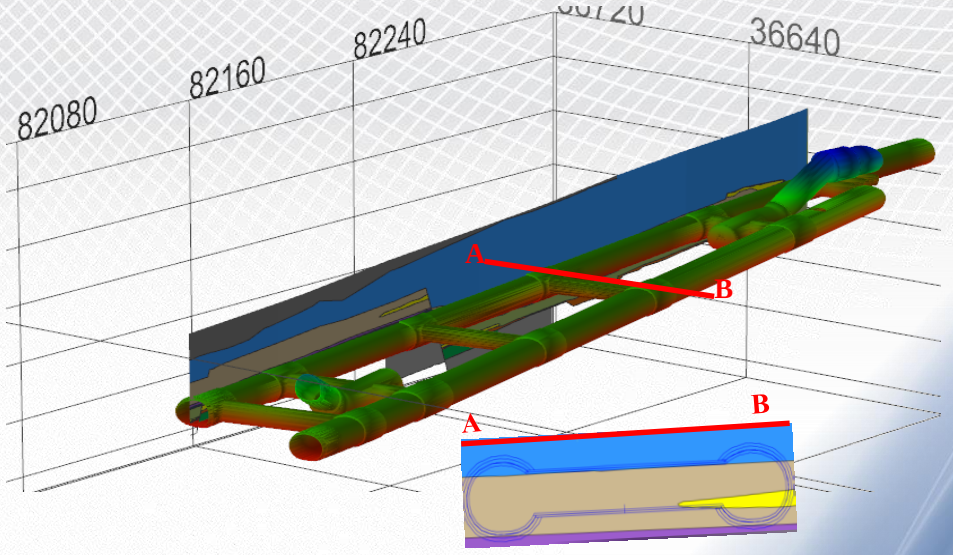
Benefits – risk reduction

- Increased accuracy and reliability with time.
- Examine and assess existing records, generate synthetic boreholes and section in areas of interest/risk.
- Geological predictions ahead of the excavations of each tunnel.





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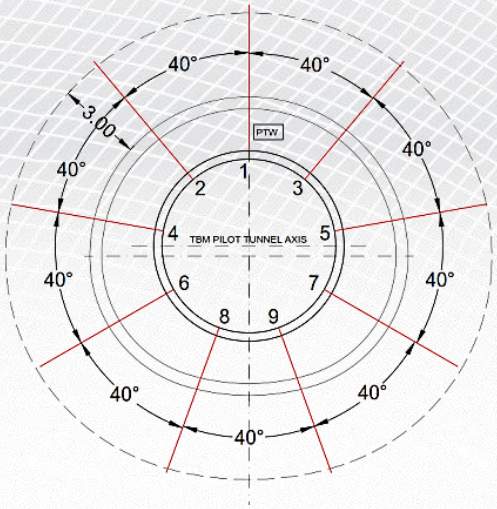
Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Benefits – cost and time saving

- 70% reduction of in-tunnel probing from that originally planned.
- **Directed additional in-tunnel probing and depressurisation wells in the 3D space.**



Initial probing proposal Platform Tunnels:

14 no. probe holes @3.0m - TOTAL: 3100 holes=22 km.

Final probing proposal Platform Tunnels:

9 no. probe holes @9.0m - TOTAL: 950holes=6.1 km.

Reduction ≈ 70%

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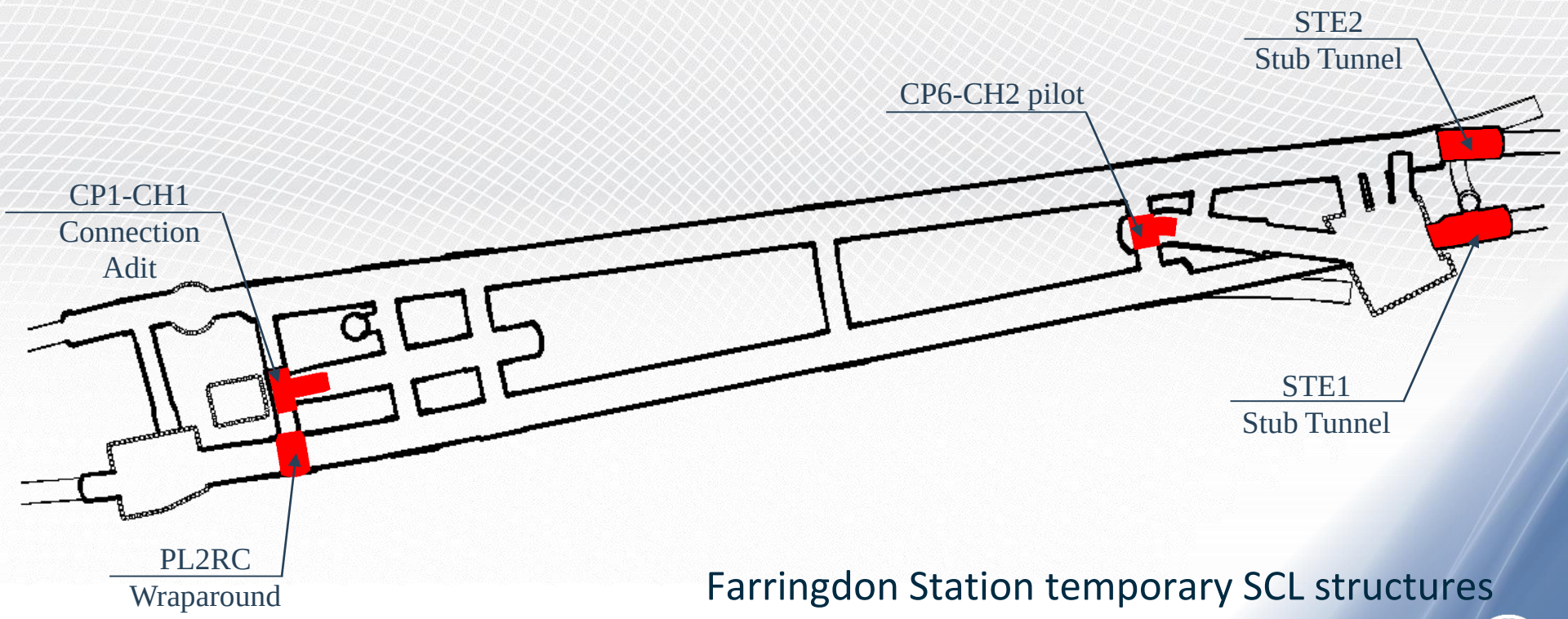
Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Benefits - efficiency

- Supported more efficient SCL design for 5 additional tunnels.
- ✓ Two 9.5m wide tunnels without a pilot.
- ✓ 5 openings without additional reinforcement or thickening.



Farringdon Station temporary SCL structures

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Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Crossrail Farringdon – further information

Papers

Ground model

http://nora.nerc.ac.uk/id/eprint/20346/

During construction

http://nora.nerc.ac.uk/id/eprint/515514/

Presentation

https://www.bgs.ac.uk/news/events/geologyUnderLTV/GakisandCabrero_UseOfThe3DGeologicalModelWithSCL.pdf

Other

https://www.geolsoc.org.uk/GeositesFarringdon

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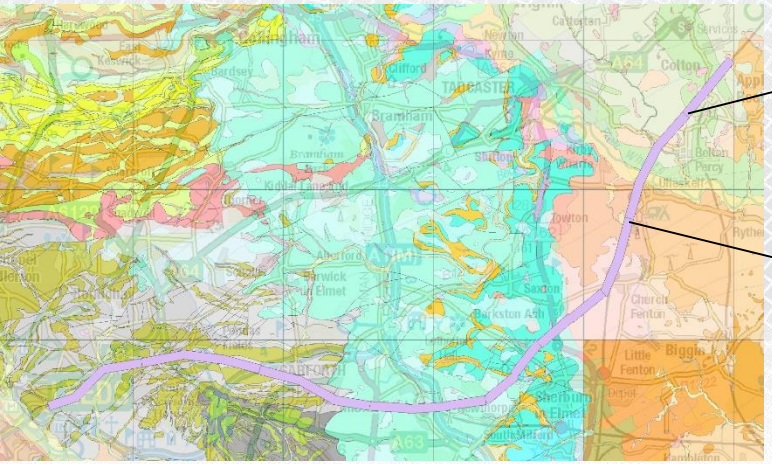
Project conceptual/preliminary observational ground model
Linear infrastructure TSP – Leeds to York rail line electrification

Model about 30 km long, 80 m wide and 30 m below track level



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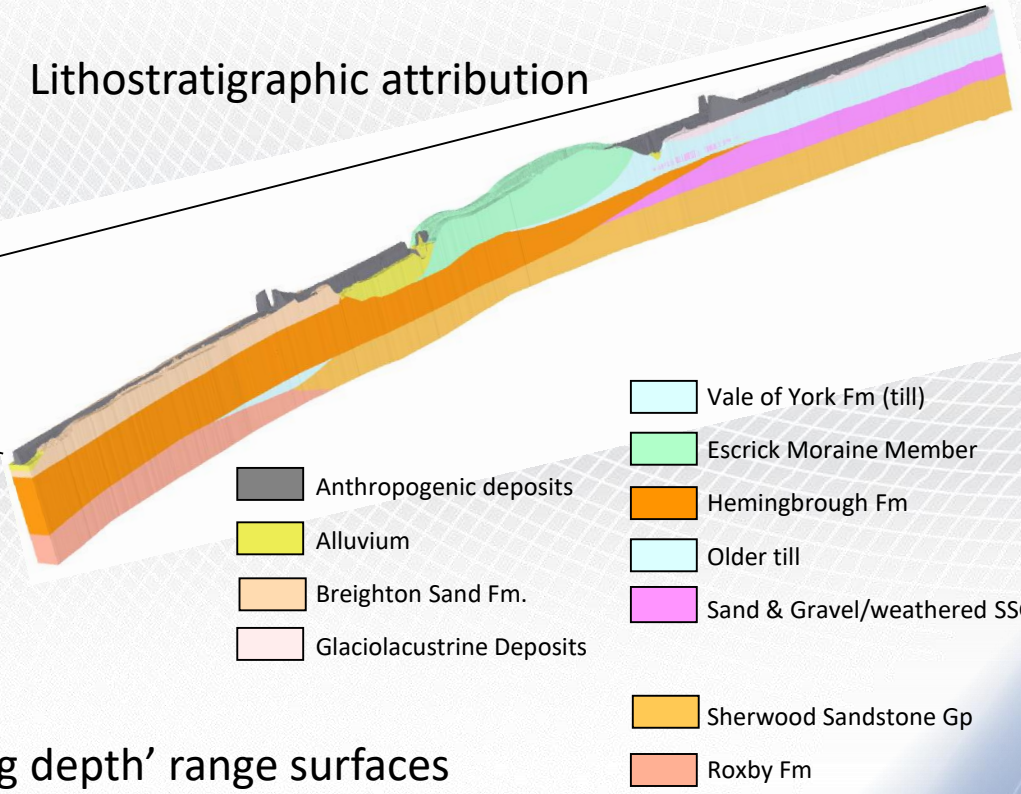
Lithostratigraphic attribution



Included potential ‘bedrock weathering depth’ range surfaces

Model supplied in software as required by the client as well as Adobe 3D pdf

http://nora.nerc.ac.uk/id/eprint/509777/

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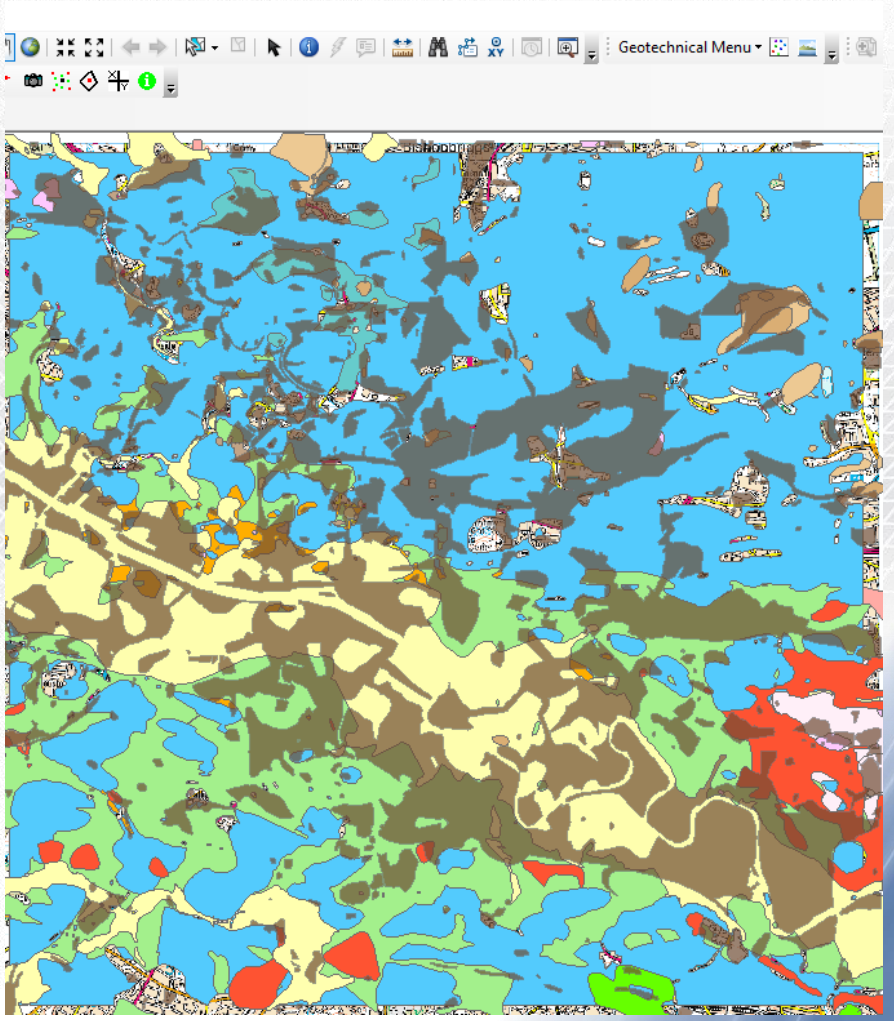
Model data and GIS

Geotechnical GIS - Glasgow

From 3D geological model exported as shp files

- mgr
- head
- peat
- lac
- law
- kel
- guf
- karn
- liwd
- pais
- bron
- ross_sand
- ross_sz
- bill
- bhse
- bhse_clay
- bhse_sand1
- witi
- cadr
- brll
- bnti
- sagr1



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Geotechnical GIS - Glasgow

From 3D geological model all units grids – Top, base and thickness

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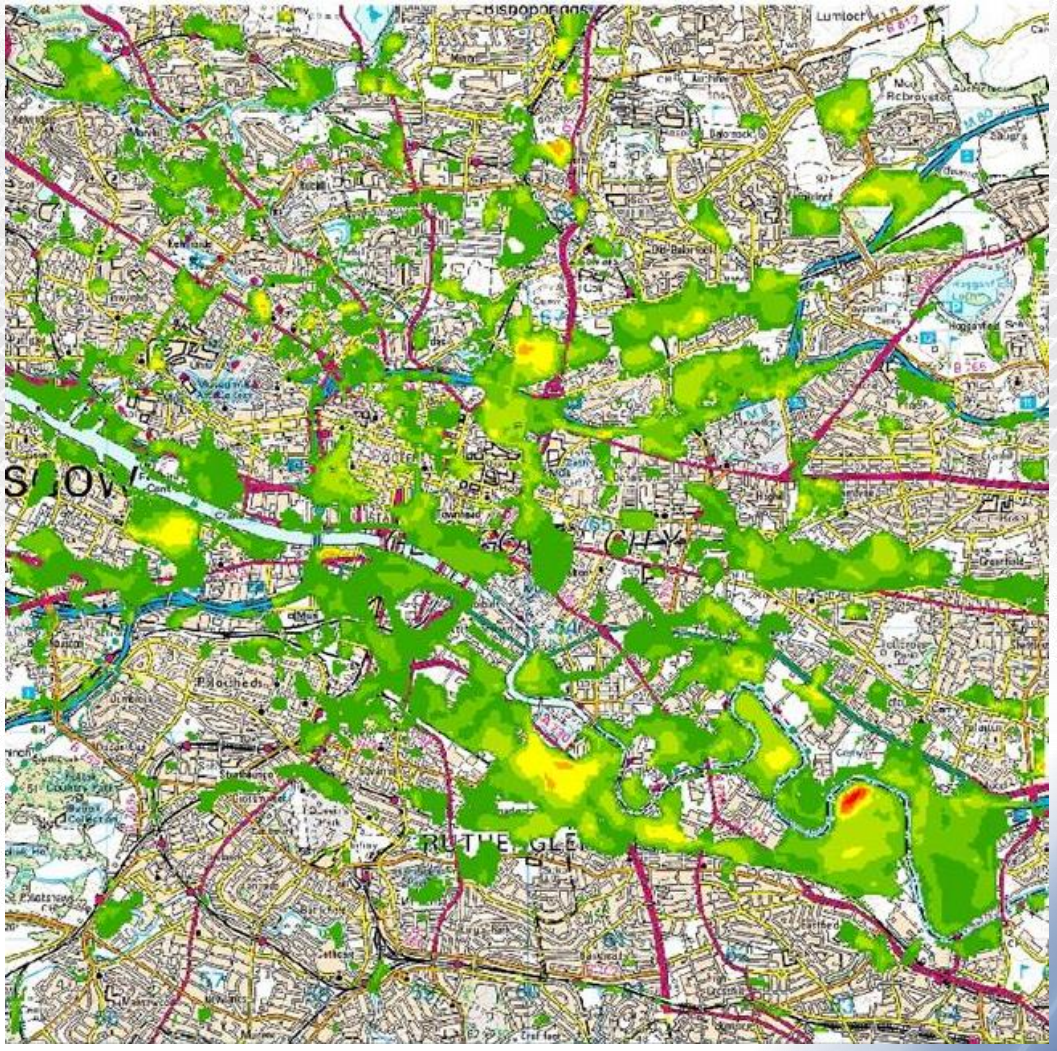
Anthropogenic deposit thickness (m)



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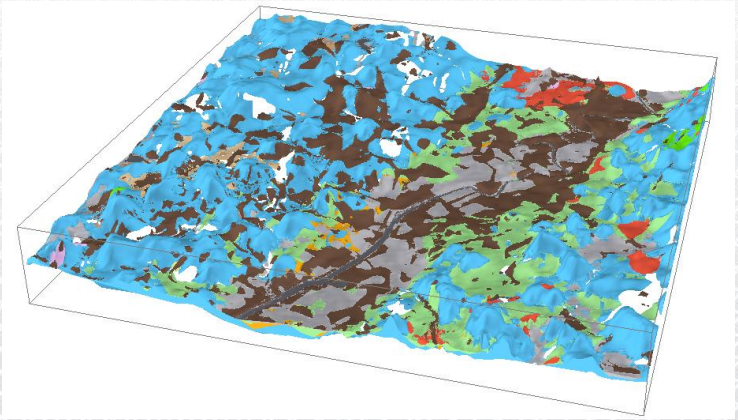
Near surface Coal mining Hazard – Glasgow

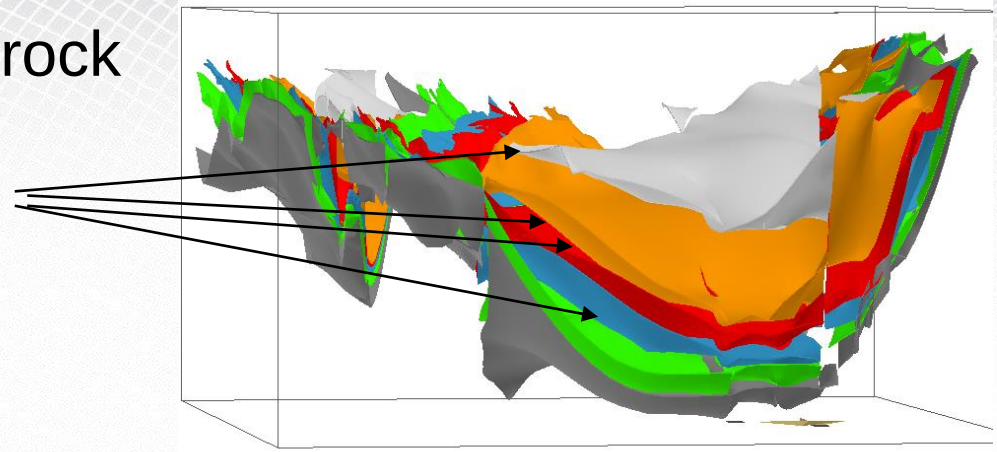
Identify where mining or potential mining is near surface

GSI3D Superficial (Quaternary)



GOCAD bedrock

Coal beds



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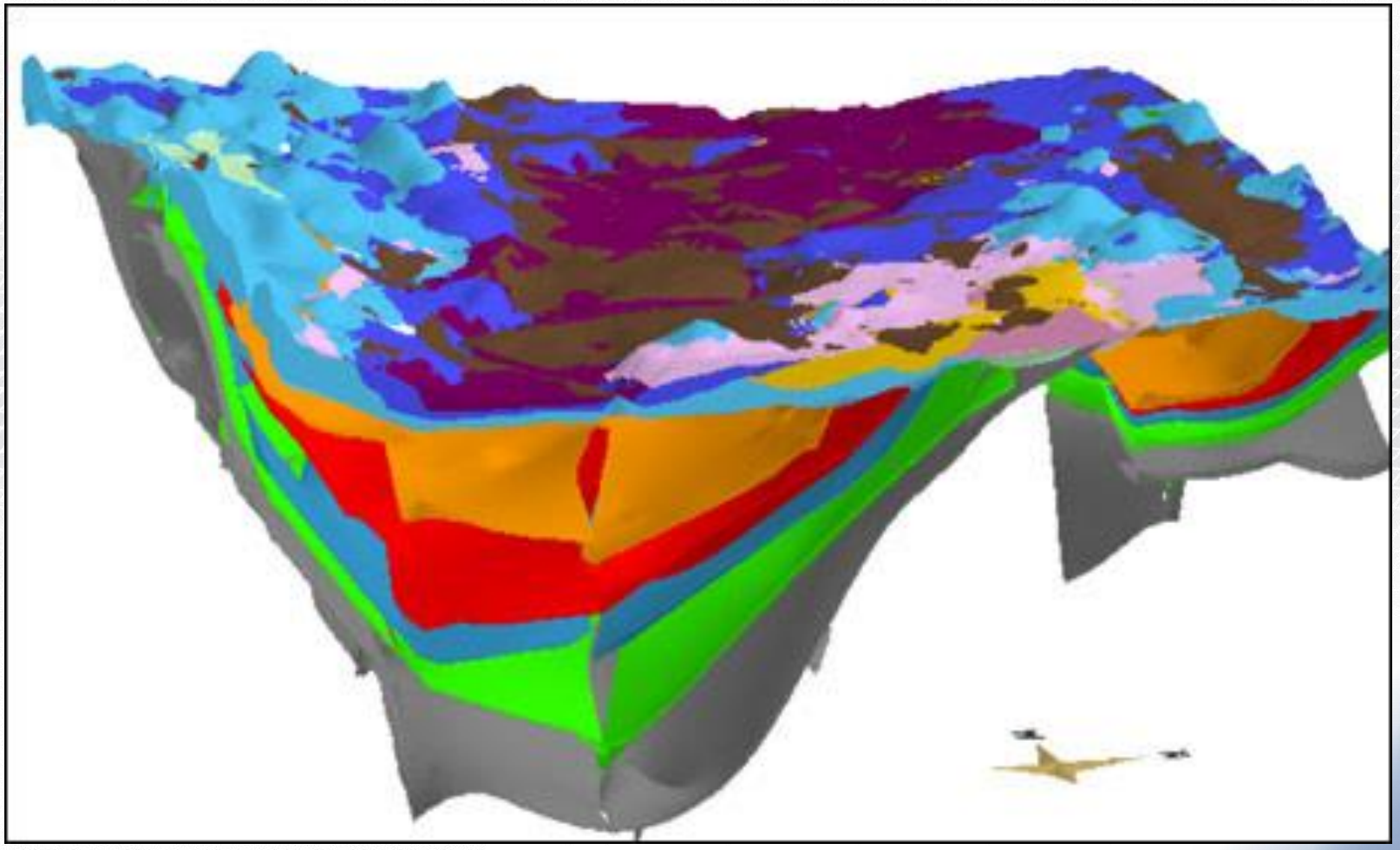
https://core.ac.uk/download/pdf/385097.pdf

Near surface Coal mining Hazard – Glasgow

Identify where mining or potential mining is near surface



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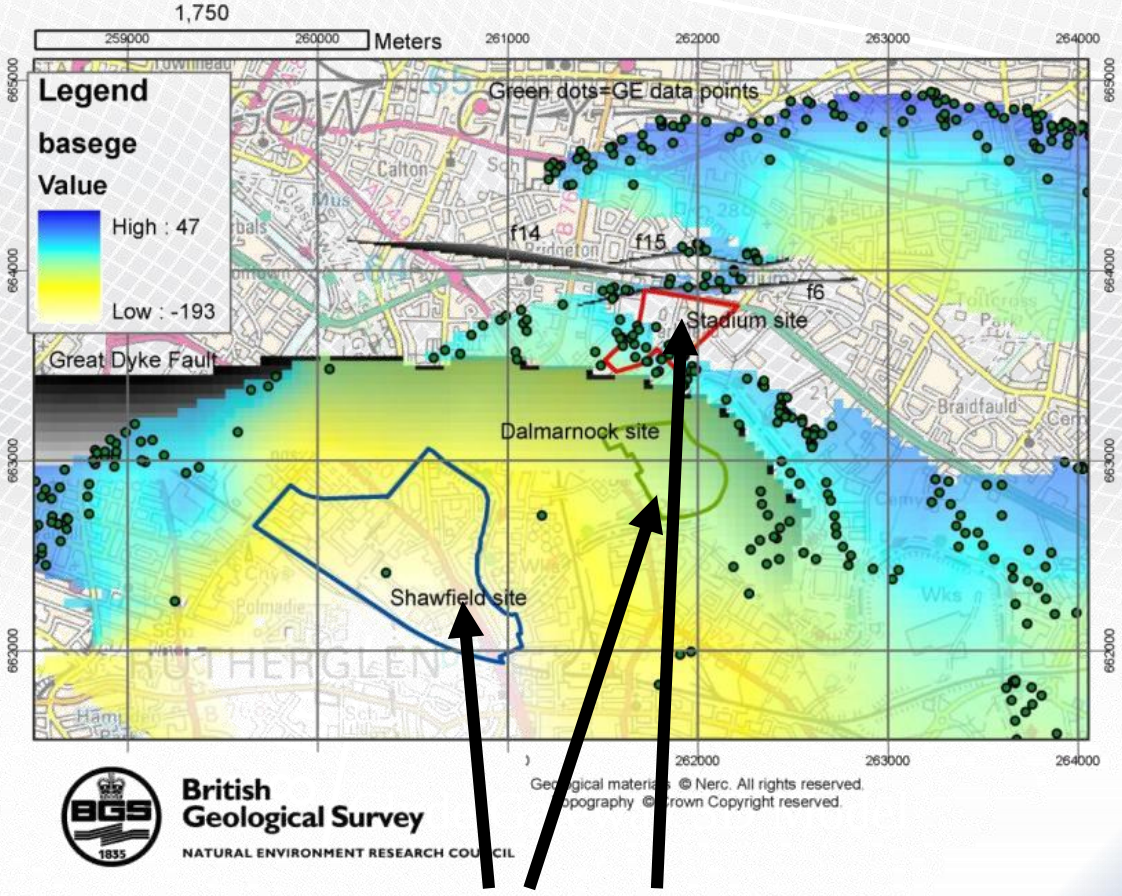
https://core.ac.uk/download/pdf/385097.pdf

3D modelling data used in GIS
Hazards - Depth of potentially hazardous shallow mine workings - Glasgow

Identify those areas that have coal mines/coal seams near bedrock surface and beneath x metres of Quaternary



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Clyde Gateway development sites

https://core.ac.uk/download/pdf/385097.pdf

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Hydrogeological applications of 3D models

Examples

1. Regional management of water from the Sherwood Sandstone Group. Environment Agency/BGS
2. Groundwater vulnerability and recharge

(urban groundwater flow)

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Hydraulic continuity and fault pathways - East Midlands

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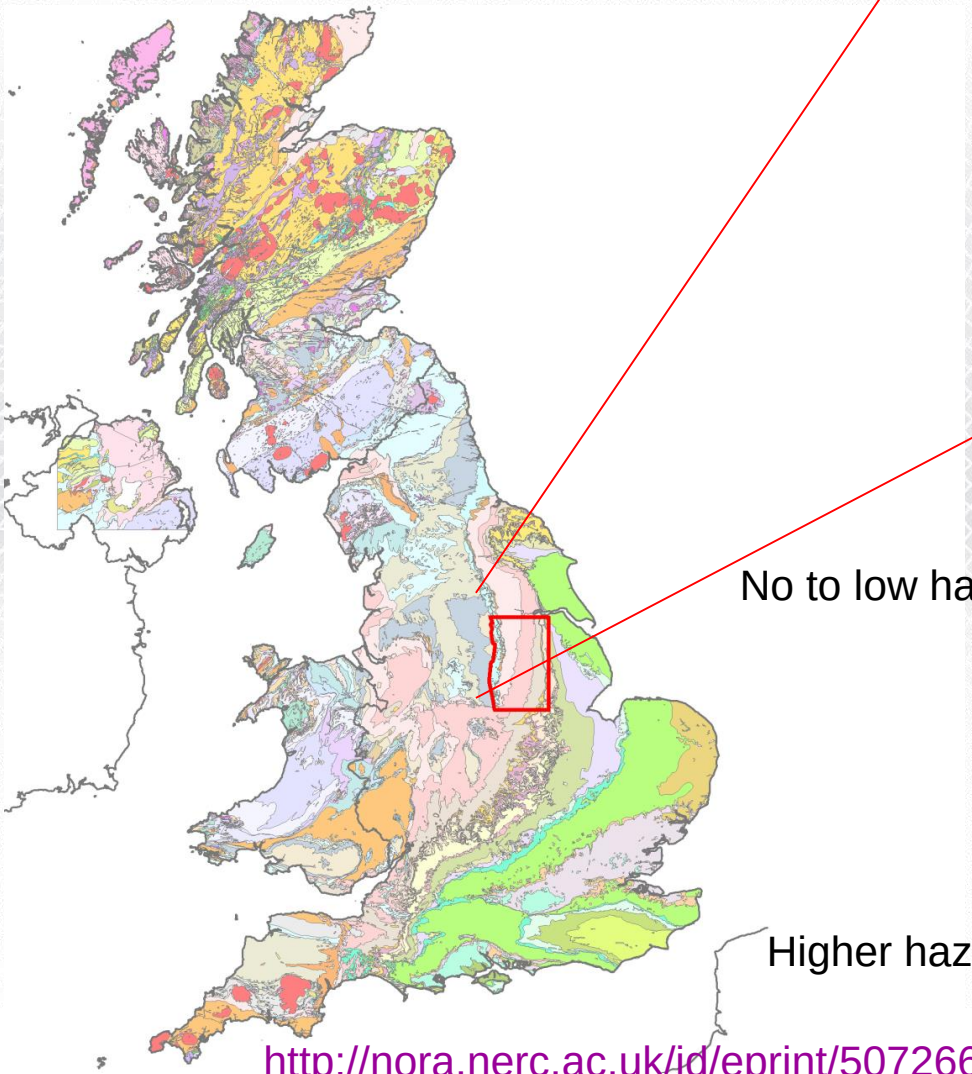
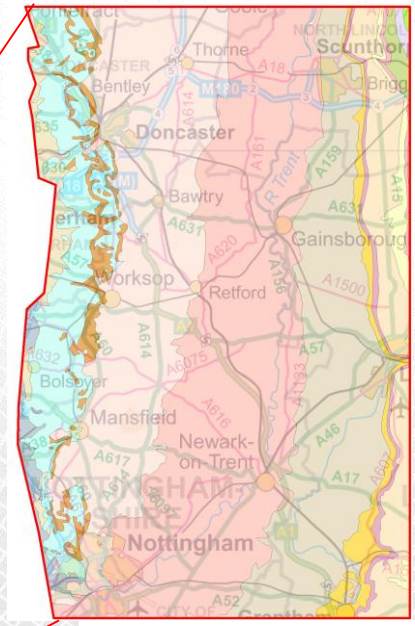
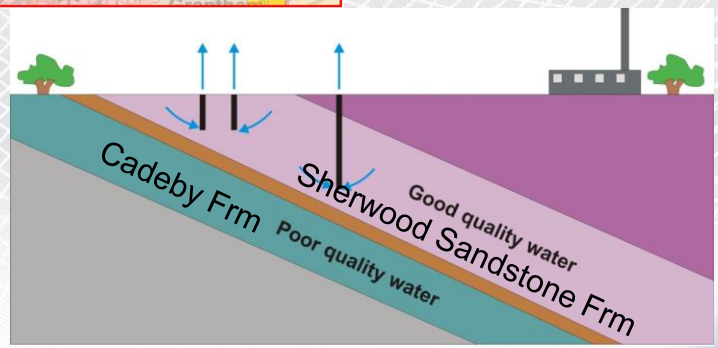
Environment Agency

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

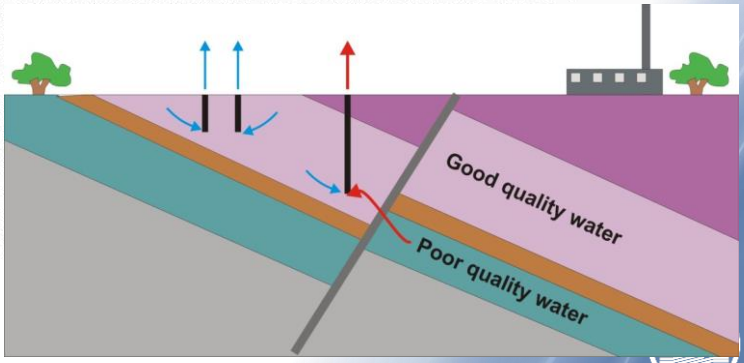




No to low hazard



Higher hazard



http://nora.nerc.ac.uk/id/eprint/507266/

http://nora.nerc.ac.uk/id/eprint/501836/

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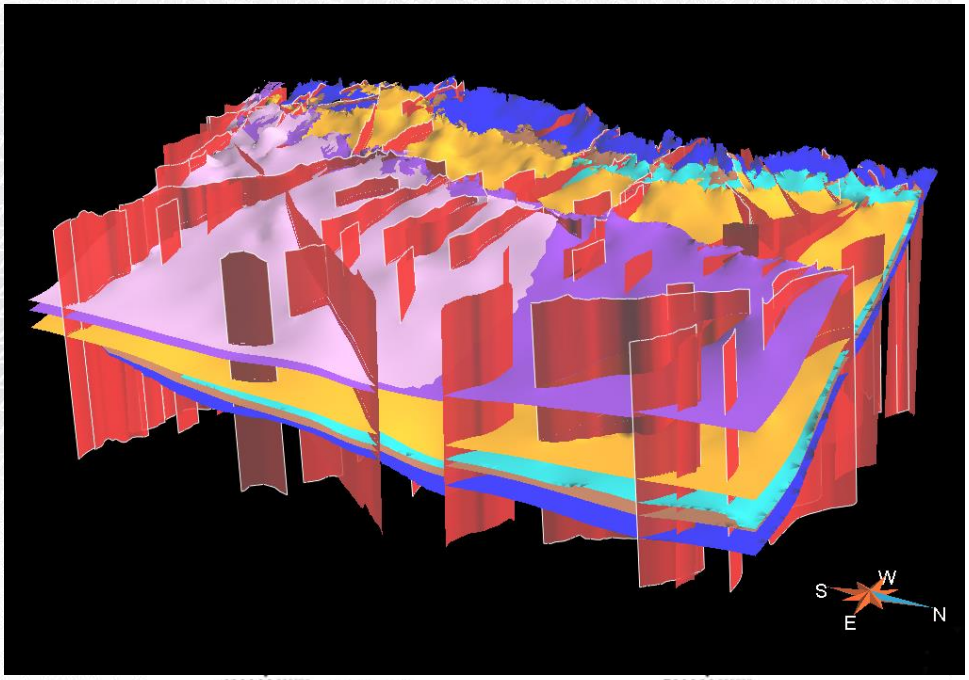
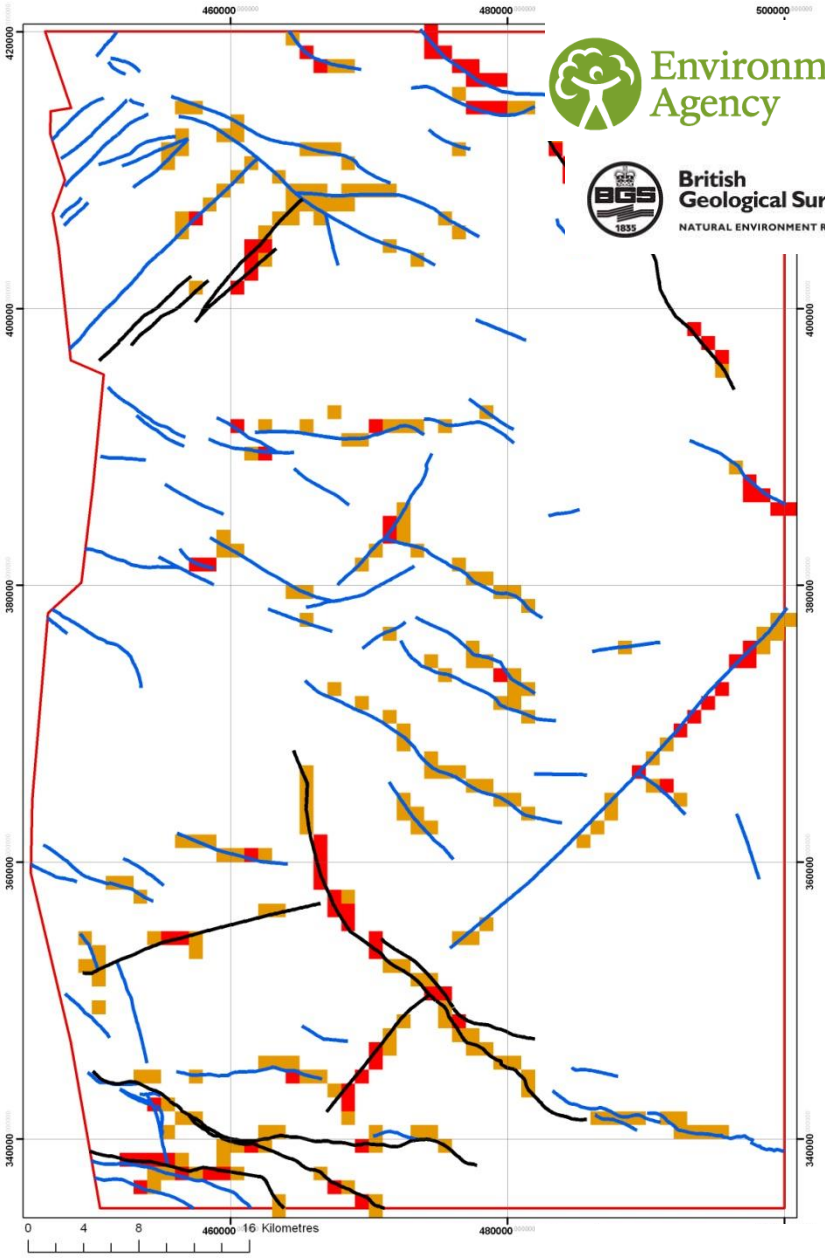
Hydraulic continuity and fault pathways

Interval thickness,
Thickness variation
Vertical separation





Environment Agency

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

480000 500000

Legend

THROW CALCULATED FROM SSG GRIDS

SSG_Z_DIF

0 - 25
26 - 50
51 - 100

SIGNIFICANT FAULT (ESTIMATED THROW >25 m)

FAULT MAY JUXTAPOSE CDF AND SSG

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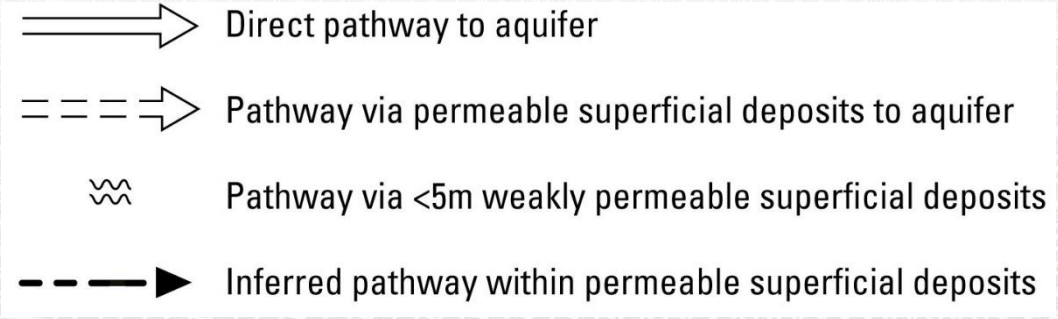
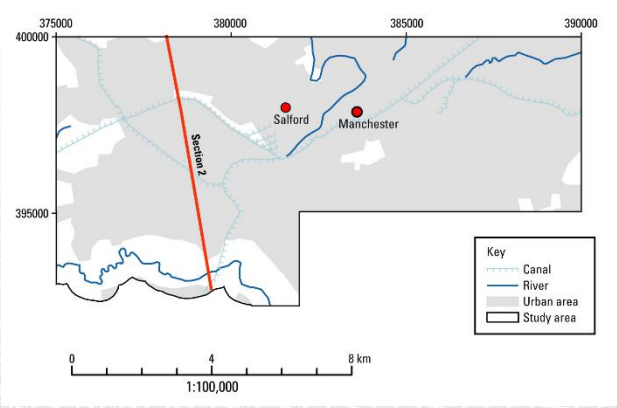
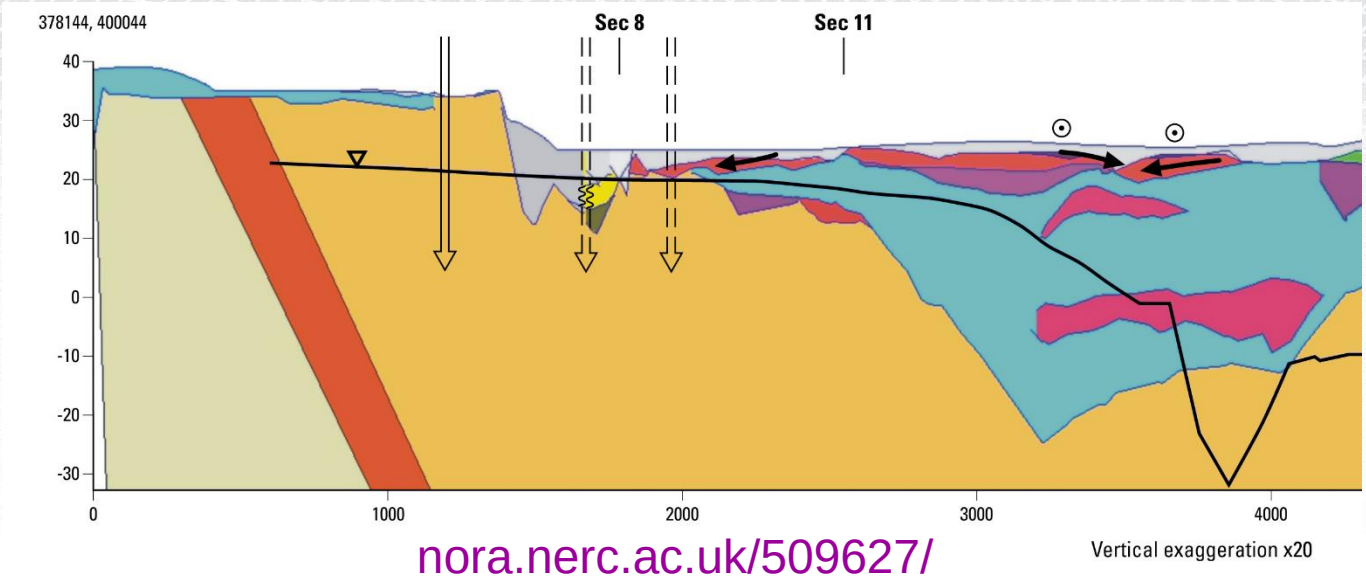
http://nora.nerc.ac.uk/id/eprint/507266/
http://nora.nerc.ac.uk/id/eprint/501836/

Groundwater vulnerability - Manchester

Development of conceptual model







nora.nerc.ac.uk/509627/

nora.nerc.ac.uk/16120/

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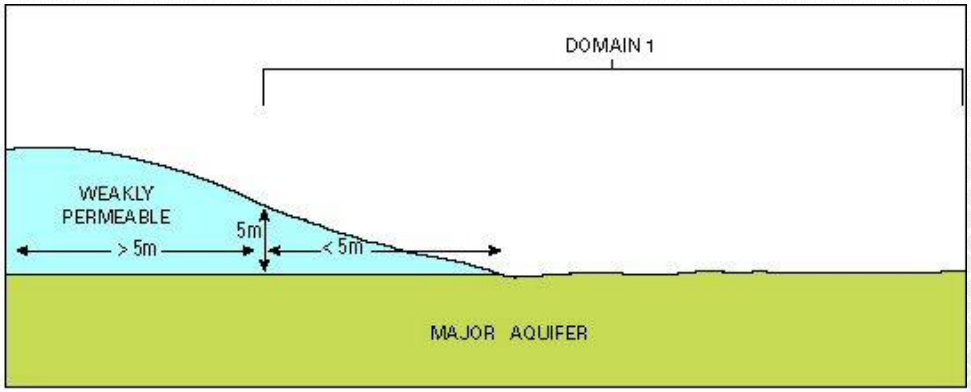
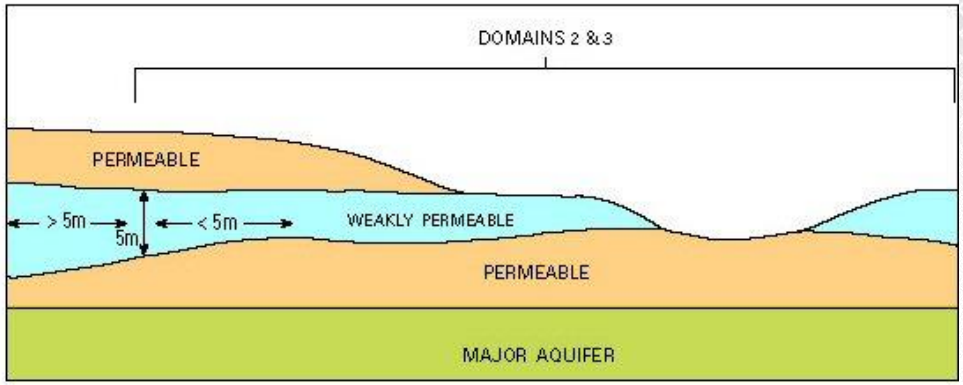
Groundwater vulnerability – Manchester Examples of the 9 domains



Domain 1

Major aquifer at outcrop or covered by less than five metres of weakly permeable deposits



Domain 2

Permeable superficial deposits on a major aquifer, or separated from it by less than five metres of weakly permeable deposits.

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nora.nerc.ac.uk/16120/

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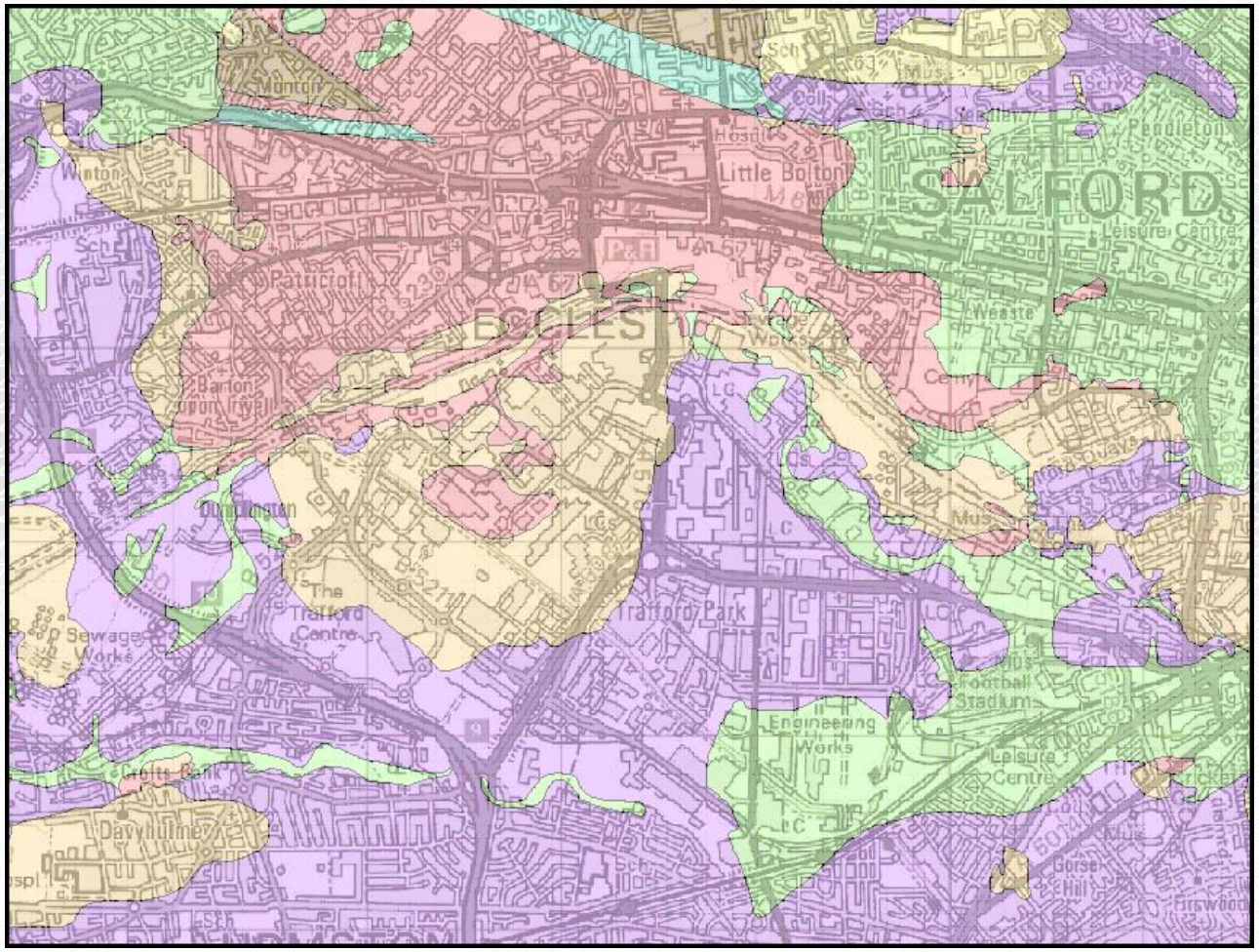
Groundwater vulnerability - Manchester



Decreasing vulnerability / recharge potential

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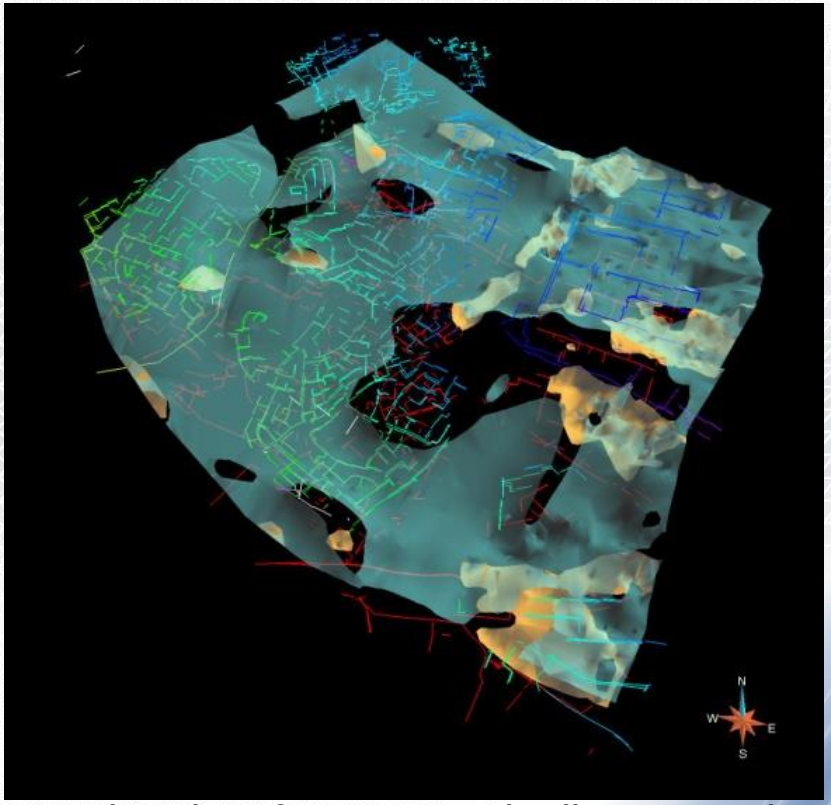
Aquifer vulnerability & buried infrastructure

Urban service pipes



Foul and surface water pipeline network with geological model, Knowsley, north-west England

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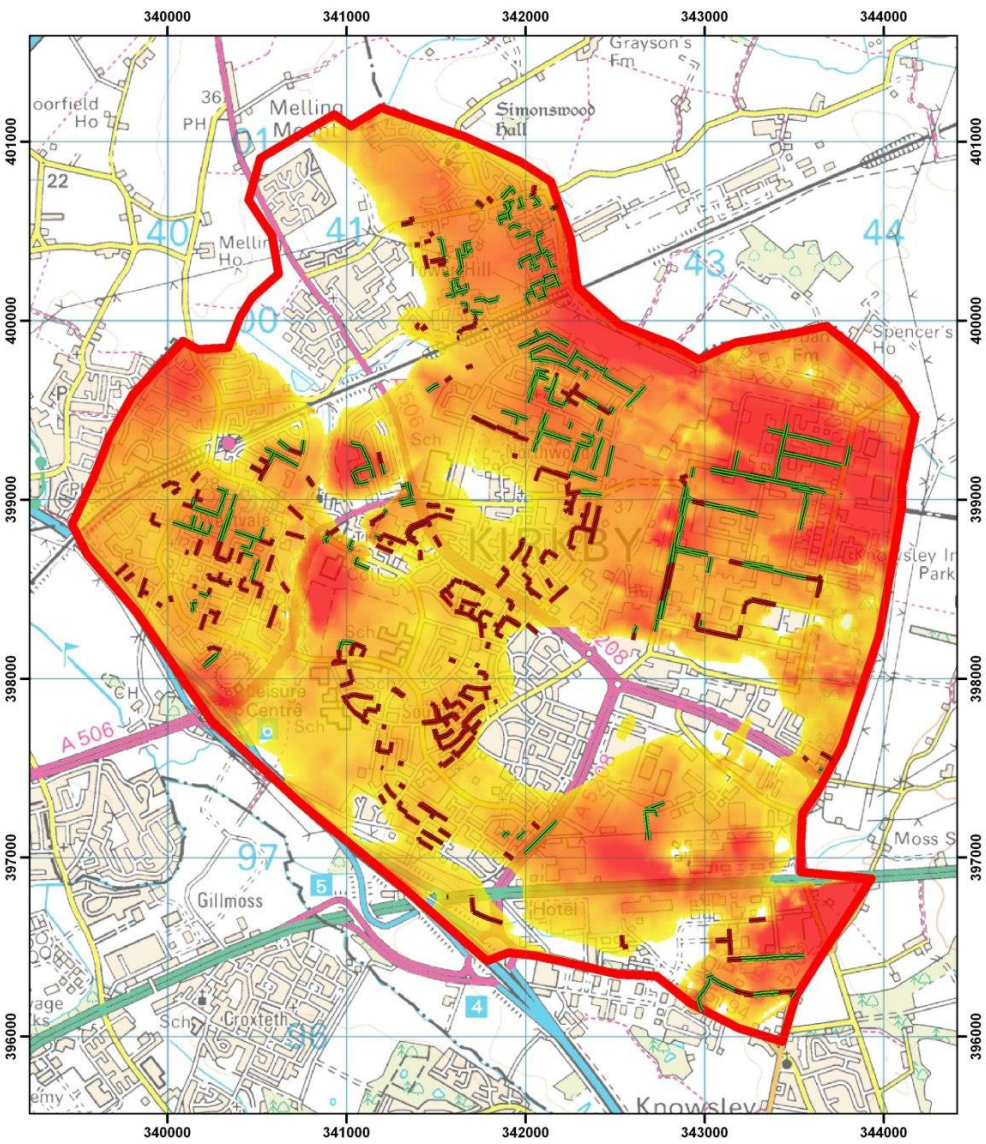
Glacial till (variable thickness) on Sherwood Sandstone aquifer

Environment Agency

Aquifer vulnerability =

Pipelines underlain by less than 2.5 m till

Prioritised utilities maintenance



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Legend

KNOWSLEY_PROJECT_BOUNDARY

PIPELINES_OVERLYING_<2.5m_TILL

PIPELINES_OVERLYING_>2.5m_TILL

TILL_THICKNESS_(m)

Value

High : 12.368013

Low : 0.000000

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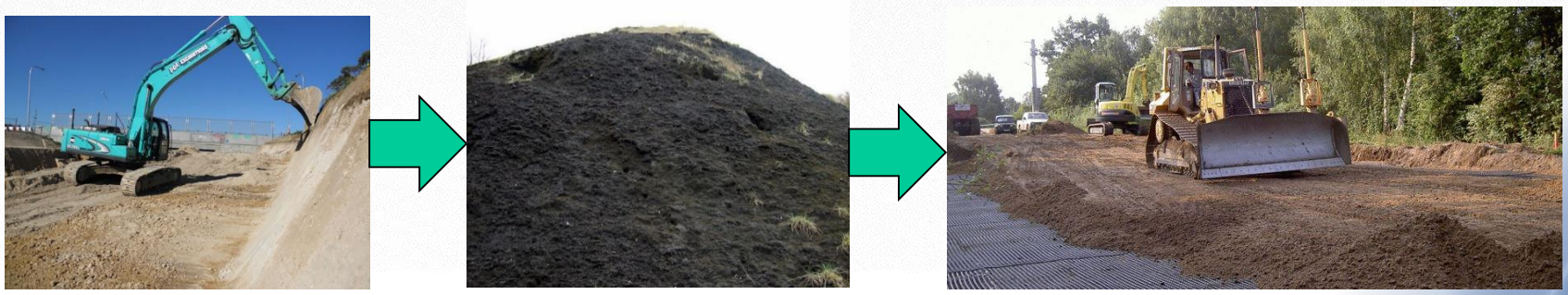
Civil engineering – chemical hazards
Excavated material and its reuse

Excavated/reuse material – chemistry and changes in chemistry or mixing with other material (oxidation, pH, redox, dissolution, etc.)

Environmental hazard – mobilisation of hazardous elements

Engineering hazards – Effects on concrete (mostly sulfide oxidation) changes in and sulfate Identification of potential natural chemical contamination



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Civil engineering – chemical hazards

Data and information sources

- 3D geological model (lithostratigraphy at Formation/Group level)
- Formational Geochemical domains (e.g. organic, limestone, pyritic clay, mudstone and mixtures)
- Background concentrations (geochemical database)
- Leaching potential (pH and eH)
- Potential mobility (mixing materials, engineering activities)

All into GIS 50 m pixel

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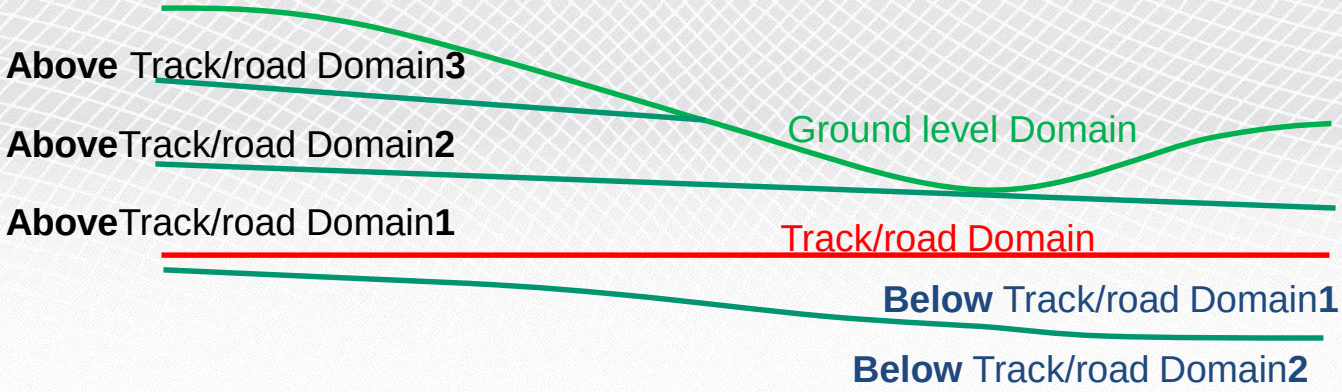
Civil engineering – chemical hazards
Linear structures – road and rail

Different structures require different input:

- Track/road at surface
- Track/road in shallow cutting
- Track/road in deep cutting
- Track/road in tunnel



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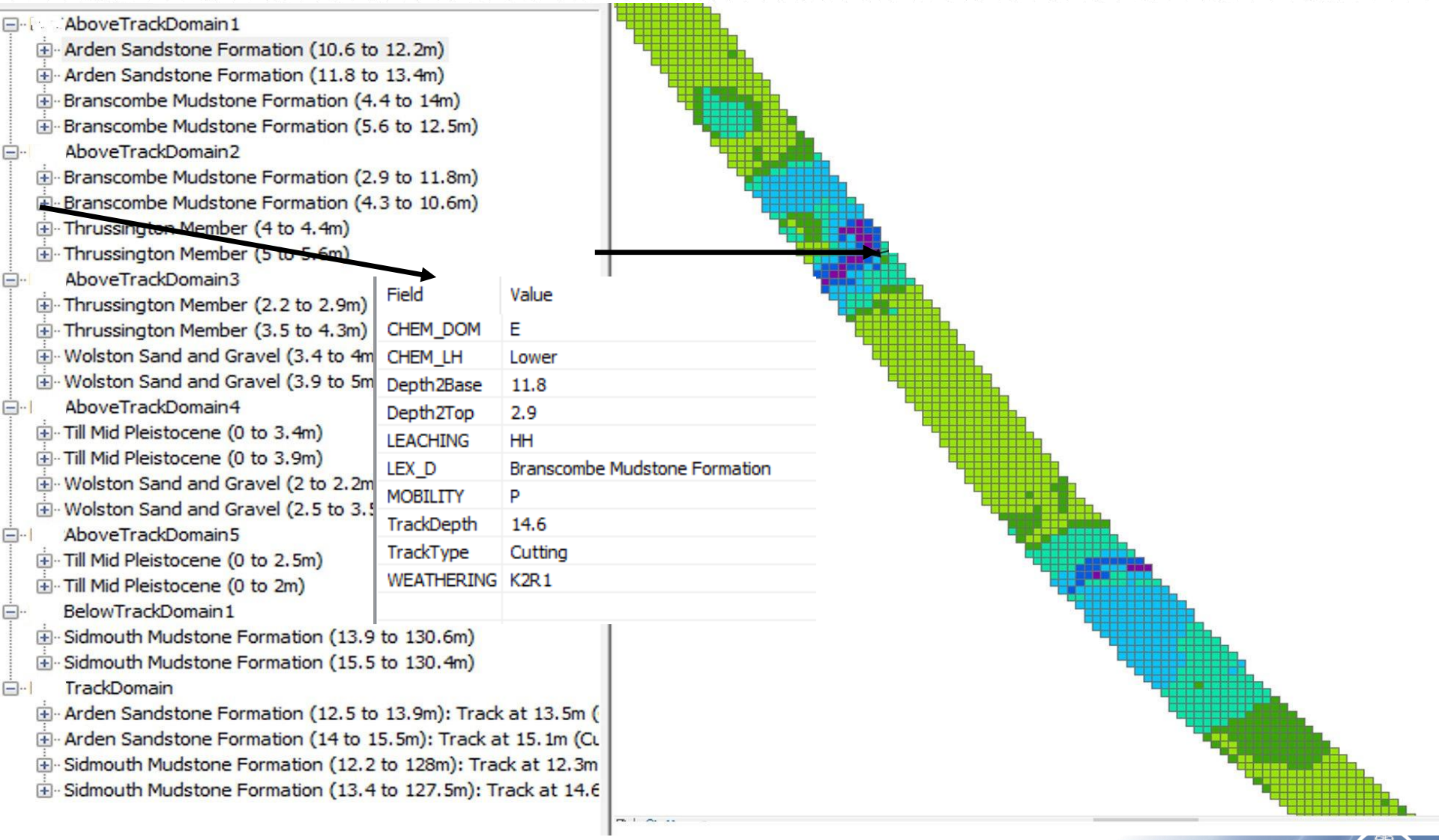
Civil engineering – chemical hazards
GIS assessment for road or rail



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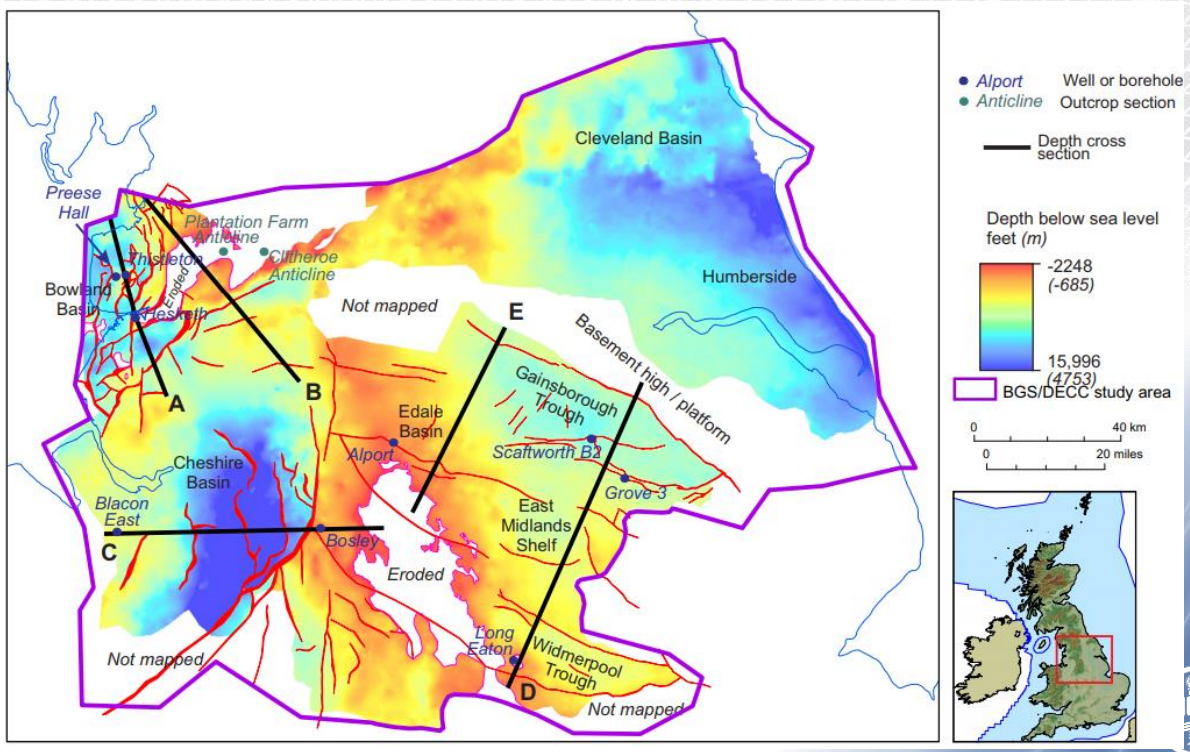
Carboniferous Shale Gas: Geology and resource estimation
Modelling down to >4 km depth

https://www.ogauthority.co.uk/onshore/onshore-reports-and-data/reports-bowland-shale-gas-study/

Modelling software: GOCAD and Petrel
Bowland Shale and Hodder Mudstone formations
Data

- Boreholes
- Surface geophysics e.g. 2 and 3D seismic (Landmarks' Seisworks)
  Gravity, Bouguer anomalies (geophysics)

3D geological model
Top, Base and thickness



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Resource
Carboniferous Shale Gas: Geology and resource estimation

Addition of other data and knowledge (chemistry, gas behaviour etc.)
Likely occurrence of gas (Thickness or area)

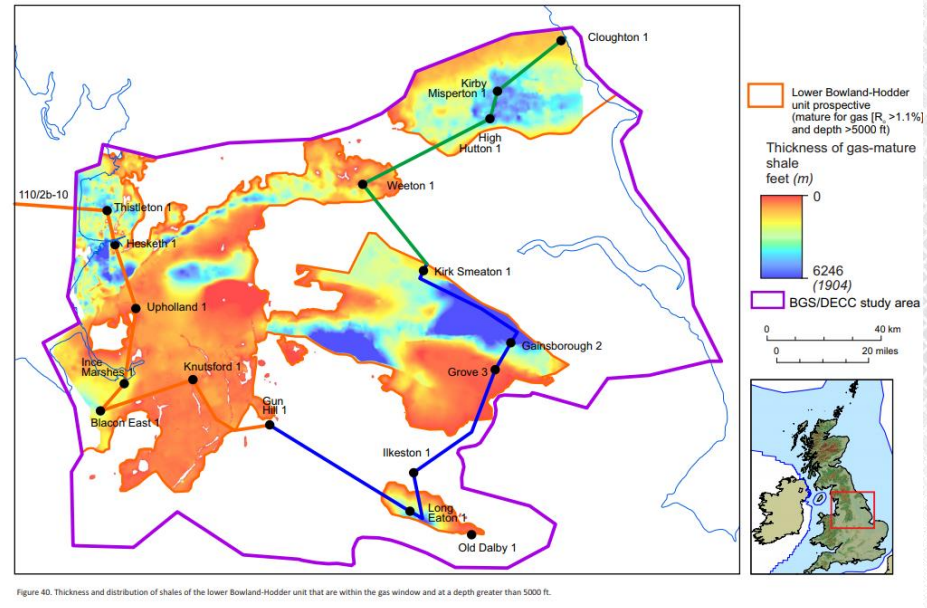

Figure 40. Thickness and distribution of shales of the lower Bowland-Hodder unit that are within the gas window and at a depth greater than 5000 ft.

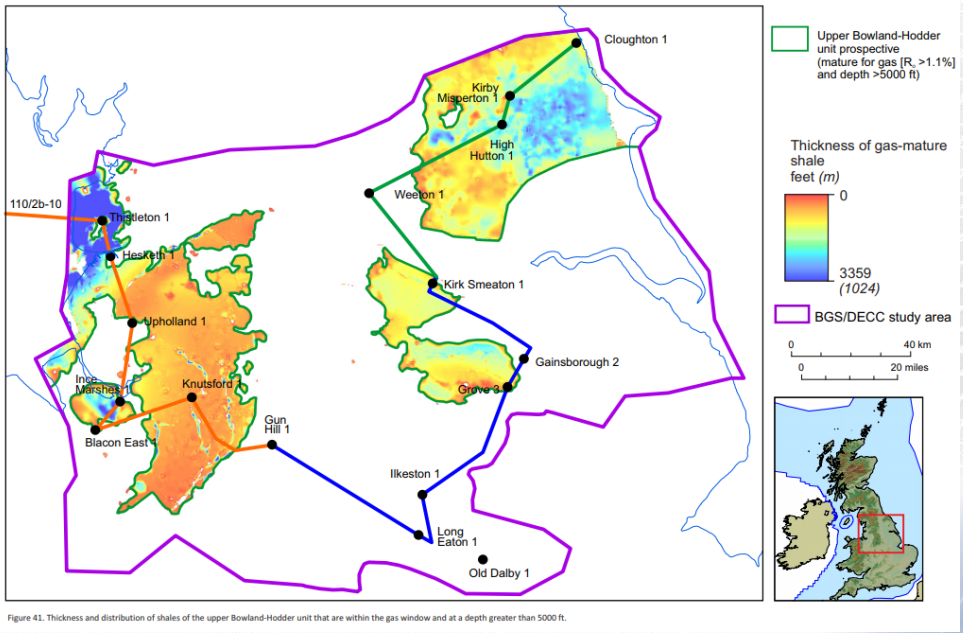

Figure 41. Thickness and distribution of shales of the upper Bowland-Hodder unit that are within the gas window and at a depth greater than 5000 ft.

Lower Bowland/Hodder unit

Upper Bowland/Hodder unit

https://www.ogauthority.co.uk/onshore/onshore-reports-and-data/reports-bowland-shale-gas-study/

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Resource
Carboniferous Shale Gas: Geology and resource estimation
Summary map

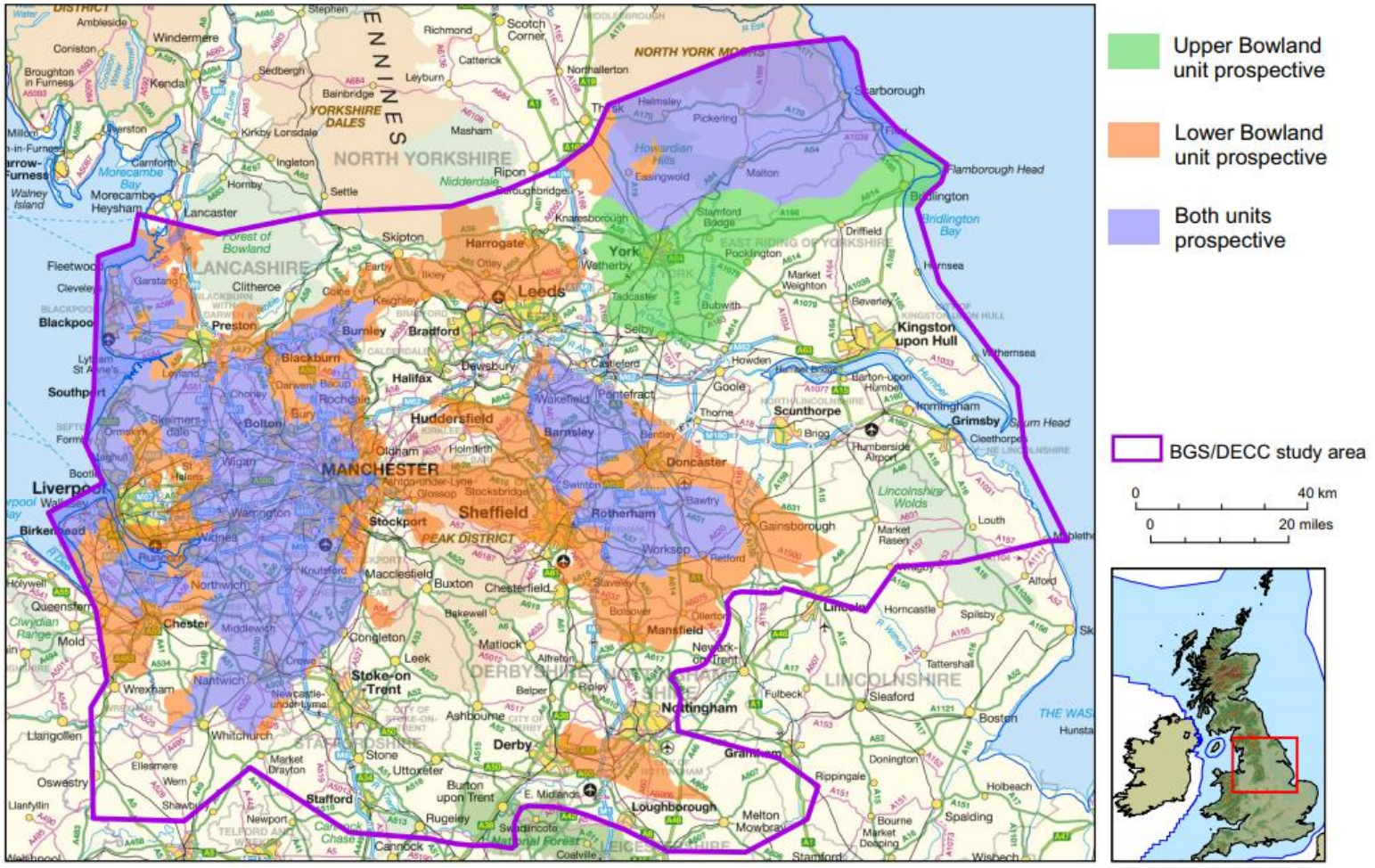

Figure 44. Summary of areas prospective for gas in the upper and lower parts Bowland-Hodder unit in relation to the urban areas of central Britain.

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https://www.ogauthority.co.uk/onshore/onshore-reports-and-data/reports-bowland-shale-gas-study/

Summary

BGS – developed many application for 3D geological models

Wide range of applications including:

Understanding of geology and geological process

- Planning and engineering (also GIS)
- Groundwater and aquifer vulnerability
- Environmental geology and engineering
- Resources

A geological model can have many application and should be

USEFUL

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