3D geological modelling at the British Geological Survey (BGS)

David Entwisle and many other BGS staff

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NTU-BCA Workshop on 3D Geological Modelling
BCA Academy, Building and Construction Authority, Singapore, 17 January 2019

This version of this talk ‘**3D geological modelling at the British Geological Survey (BGS)’** by David Entwisle, with contributions of many others from the BGS, contains all the slides presented at the NTU-BCA Workshop on 3D Geological Modelling BCA Academy, NTU, Singapore, 17 January 2019 for which permission was granted. 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.

An additional modelling method is also included i.e. voxel and other features of uncertainty/confidence.

After conversations at the meeting and elsewhere, the importance of understanding the geology (conceptual ground model), the quality of the data and the documentation about the model are also included.

BGS Minecraft is also mentioned.

Synopsis

Why do we want 3D models?

BGS models

- What is required to make 3D models?

Examples of models

Delivery

Uncertainty

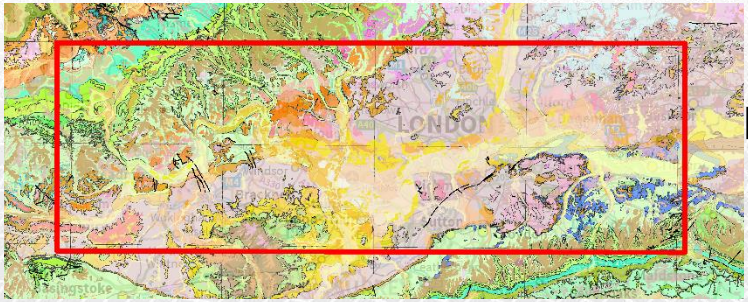
About models

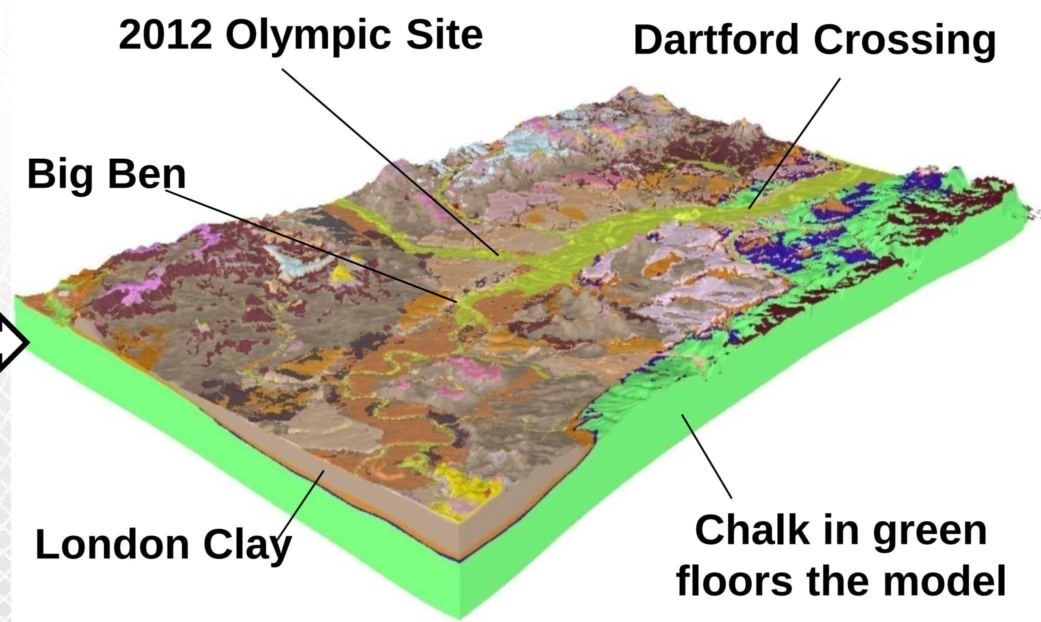
“All models are wrong, **some are useful**”

George Box, statistician (1976)

Journal of the American Statistical Association

Why 3D?





- Geologist – understand the geology and relationships between units
- Communicate to other-geologists and **non-geologists**
- Thickness and volumes – Aggregates and Minerals
- Aquifer – Lithology and relationship to above and below units
- **Examine ground conditions and inform planning decisions on proposed development**
- **Desk study tool – ground model (tests the conceptual ground model and informs investigations does not replace it)**

3D Modelling

Data processing for 3D modelling (e.g. GSI3D or Subsurface viewer)

Geological knowledge: Conceptual ground model

Relationships between units (erosional, folded, faulted etc.)

Data Preparation:

- DTM

Input data

- Boreholes (description, coding rules)
- *Geophysics – GPR and Seismic sections etc.*
- Geological map linework

Geological - general vertical section (GVS) and conceptual understanding of the ground model

Legend – to show the different modelled units

Others (as required)

Ground models for 3D geological modelling (after Parry et al. 2014)

Engineering Geology Model

Conceptual Engineering ground model

- Based largely on geological/ground information, **Desk study**;
- Anticipate what might be encountered on site and **relationships between the different units, faults, erosional surfaces, unconformities**

GI data — General GI DATA

3D geological model – preliminary observation model

- Based on conceptual ground model and collected data/information collected from various investigations. Not project specific.

Project DATA

Project observational engineering/geotechnical ground model

- Based on data/information collected from the project investigation;
- Identify and quantify(?) ground hazards; ground/groundwater conditions and uncertainties, also resources and material management. Project risk register.
- Inform further investigation;
- Can be further developed during construction.

• Analytical ground model

- Based on observational (conceptual) models
- Consolidates essential geology – support ground based engineering activity
- Analogue/mathematical models

Engineering geological models: an introduction: IAEG commission 25 http://nora.nerc.ac.uk/id/eprint/508530/

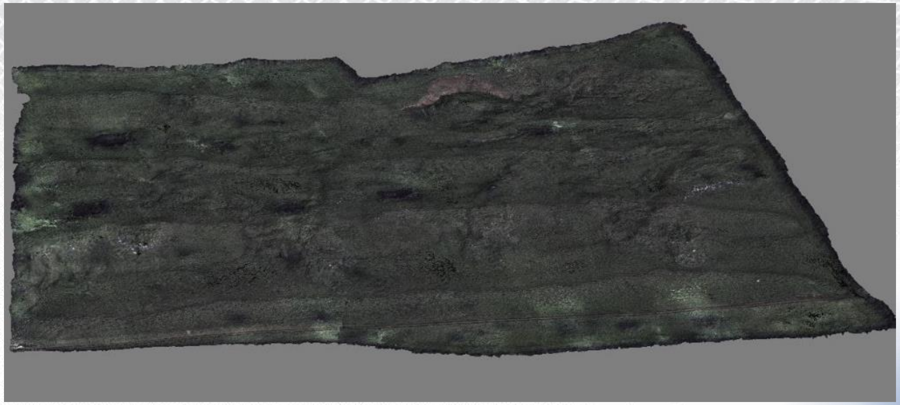
Data processing for 3D modelling - Digital Surface/Terrain Models

http://nora.nerc.ac.uk/id/eprint/8759

File formats often include:

- XYZs
- Gridded data
- Contours
- TINs/TRNs

Lidar DEM
Nottingham Castle



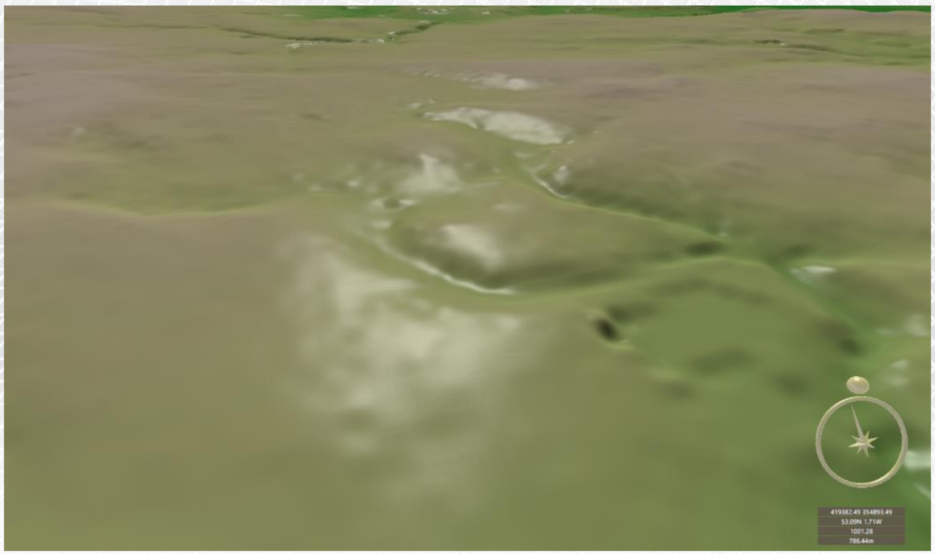
Lidar DTM of landslide

Need to select an appropriate point/mesh/grid/cell spacing size for the model area

Digital Terrain Model - scale

- Bare earth (no trees, no building, bridges etc.)
- Practical (balance between size and detail)
- Availability (price)

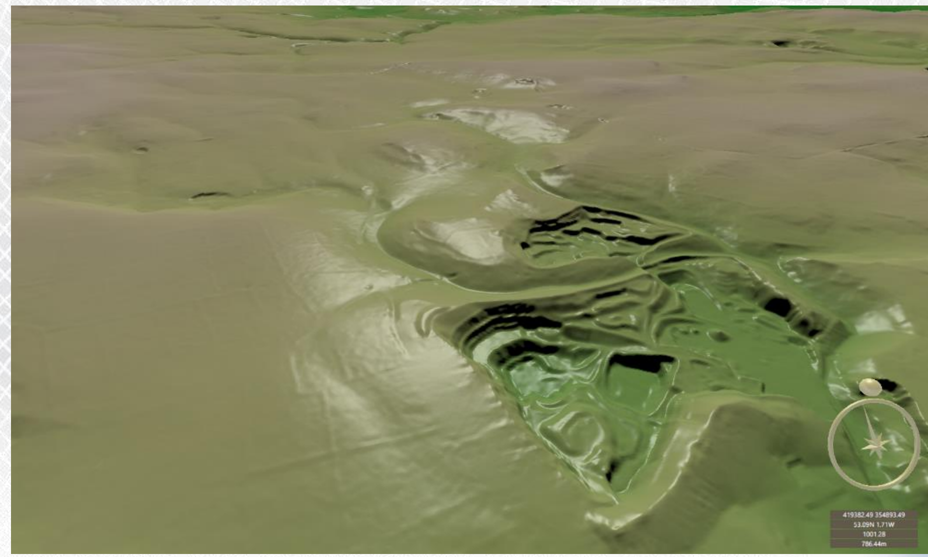
50 m



Contains Ordnance Survey data © Crown copyright and database rights 2010

Smaller files less detailed
Easier to use

5 m



NEXTMap Britain elevation data from Intermap Technologies

Larger files more detailed
Slows down the computer

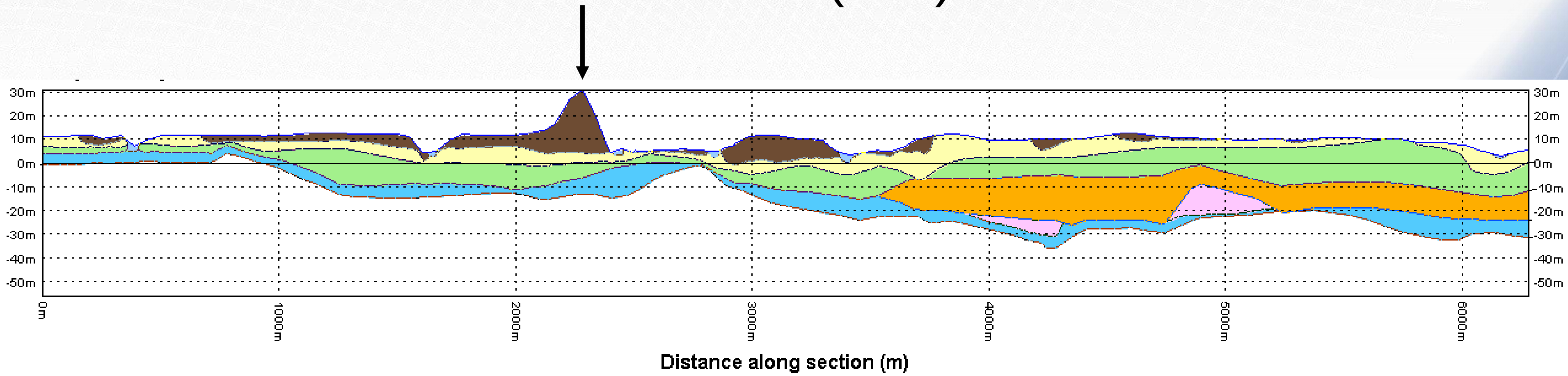
Digital Terrain Model - Artefacts

Digital elevation models contains non-ground structures such as man-made structures, vegetation etc.

DTM generally have various degrees of removal of these features:

Identify if there are artefacts (e.g. buildings, trees etc.)

Is this a building (should not be there)
or an embankment (OK.)



Borehole data

Ground investigation data –

Descriptions to National / International standards BS/EN/ISO (e.g. BS5930, EN ISO 14688-1, 14689-1)

Analogue information

- Paper reports
- pdf reports

Transcribing errors

AGS digital data transfer format
Ascii format (commas and quotes)

Rapid and easy to add to database (few errors)

Data processing for 3D modelling
Boreholes - different ages/quality (Standards)

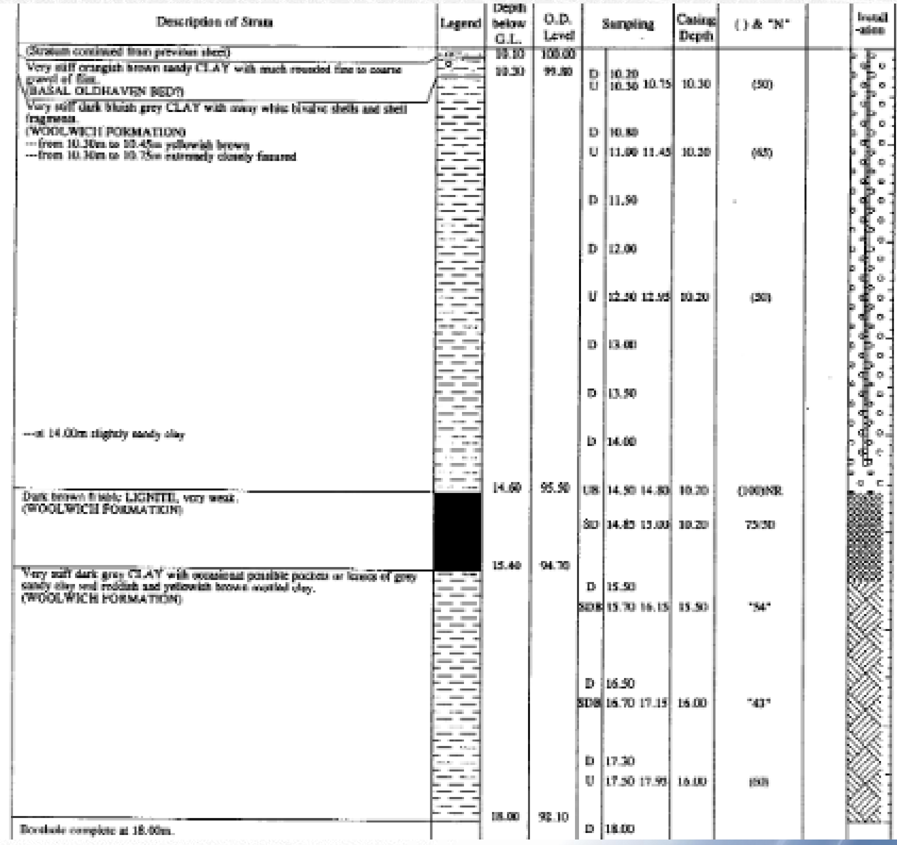
Suitable grid reference and ground level

Borehole description

Also consider the accuracy

(Singapore cable percussion drilling

Boundaries mostly to whole numbers)

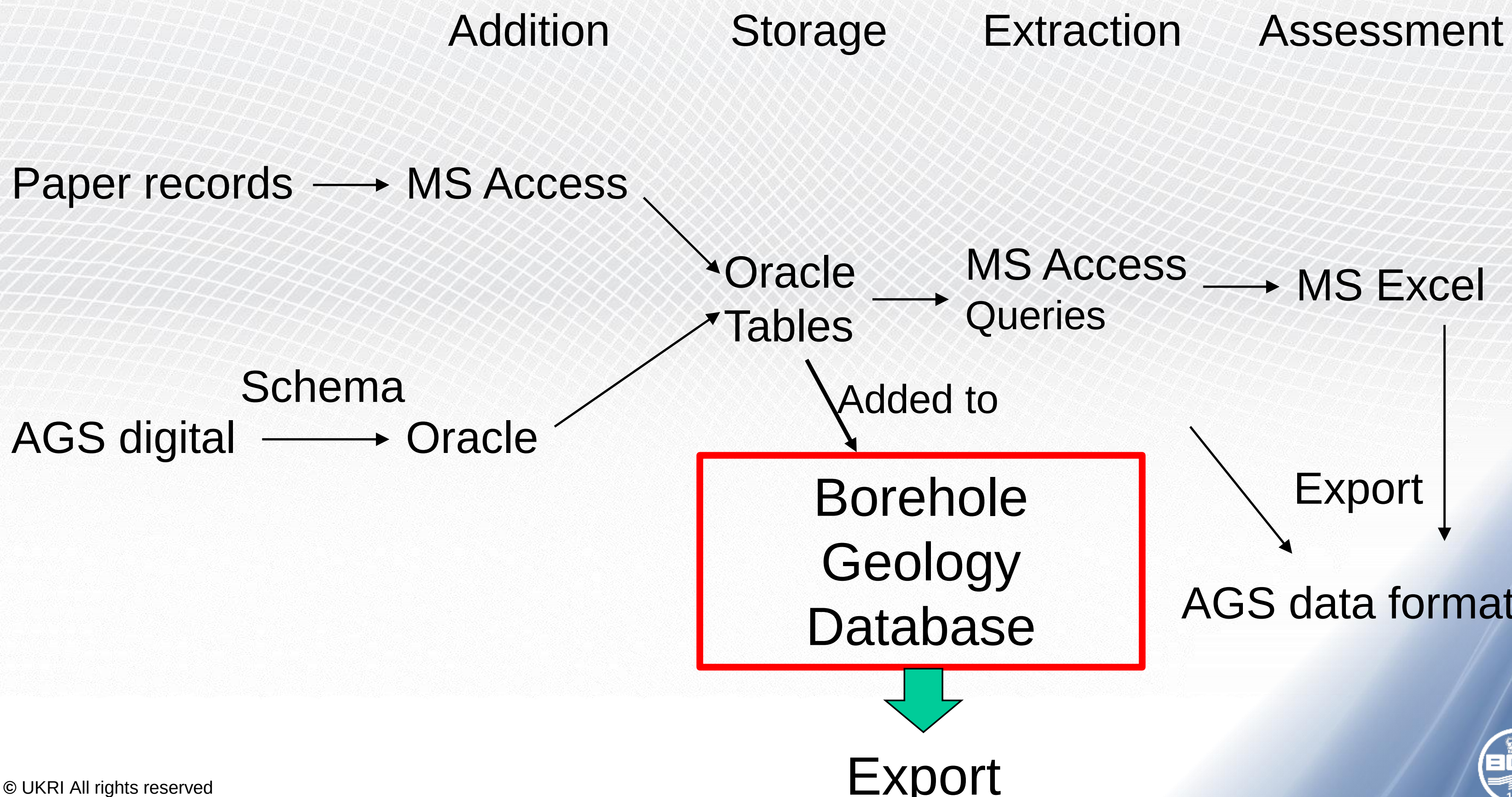


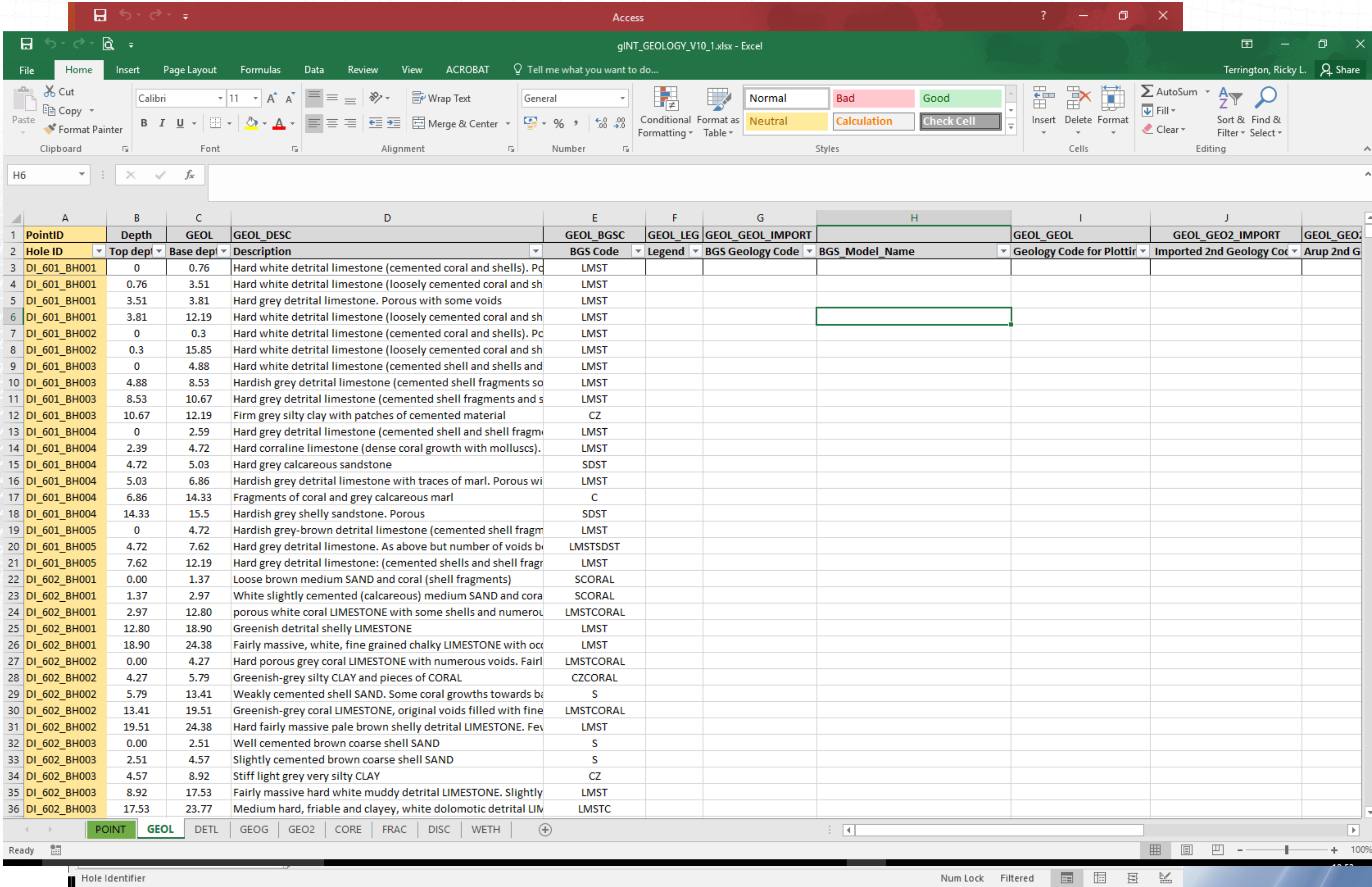
Description of Strata	Depth below G.L.	O.D. Level	Sampling			Casing Depth	( ) & "N"
(Stratum continued from previous sheet)	10.10	100.00					
Very stiff orangish brown sandy CLAY with much rounded fine to coarse gravel of flint. (BASAL OLDHAVEN BED?)	10.30	99.80	D	10.20			
			U	10.30	10.75	10.30	(50)
Very stiff dark bluish grey CLAY with many white bivalve shells and shell fragments. (WOOLWICH FORMATION) --from 10.30m to 10.45m yellowish brown --from 10.30m to 10.75m extremely closely fissured			D	10.80			
			U	11.00	11.45	10.20	(65)
			D	11.90			
			D	12.00			
			U	12.50	12.95	10.20	(50)
			D	13.00			
			D	13.50			
--at 14.00m slightly sandy clay			D	14.00			
	14.60	95.50	UB	14.50	14.80	10.20	(100)NR
Dark brown friable LIGNITE, very weak. (WOOLWICH FORMATION)			SD	14.85	15.00	10.20	75/50
	15.40	94.70					
Very stiff dark grey CLAY with occasional possible pockets or lenses of grey sandy clay and reddish and yellowish brown mottled clay. (WOOLWICH FORMATION)			D	15.50			
			SDB	15.70	16.15	15.50	"54"
			D	16.50			
			SDB	16.70	17.15	16.00	"43"
			D	17.30			
			U	17.50	17.95	16.00	(85)
	18.00	92.10	D	18.00			
Borehole complete at 18.00m.							

Borehole data input and coding

Full description, lithology code, (lithostratigraphical code)

Useful to include geological at Group, Formation, Member (bed) level





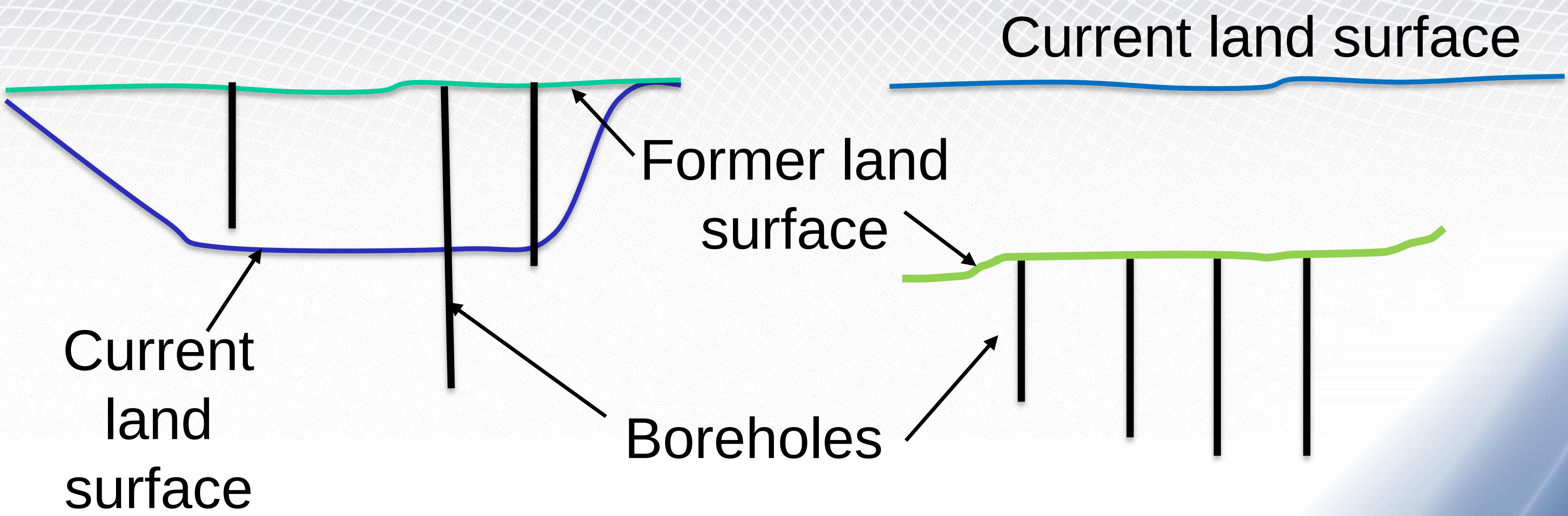
PointID	Depth	GEOL	GEOL_DESC	GEOL_BGSC	GEOL_LEG	GEOL_GEOL_IMPORT		GEOL_GEOL	GEOL_GEO2_IMPORT	GEOL_GEO2
Hole ID	Top dept	Base dept	Description	BGS Code	Legend	BGS Geology Code	BGS_Model_Name	Geology Code for Plottir	Imported 2nd Geology Coc	Arup 2nd G
DI_601_BH001	0	0.76	Hard white detrital limestone (cemented coral and shells). Pc	LMST						
DI_601_BH001	0.76	3.51	Hard white detrital limestone (loosely cemented coral and sh	LMST						
DI_601_BH001	3.51	3.81	Hard grey detrital limestone. Porous with some voids	LMST						
DI_601_BH001	3.81	12.19	Hard white detrital limestone (loosely cemented coral and sh	LMST						
DI_601_BH002	0	0.3	Hard white detrital limestone (cemented coral and shells). Pc	LMST						
DI_601_BH002	0.3	15.85	Hard white detrital limestone (loosely cemented coral and sh	LMST						
DI_601_BH003	0	4.88	Hard white detrital limestone (cemented shell and shells and	LMST						
DI_601_BH003	4.88	8.53	Hardish grey detrital limestone (cemented shell fragments so	LMST						
DI_601_BH003	8.53	10.67	Hard grey detrital limestone (cemented shell fragments and s	LMST						
DI_601_BH003	10.67	12.19	Firm grey silty clay with patches of cemented material	CZ						
DI_601_BH004	0	2.59	Hard grey detrital limestone (cemented shell and shell fragm	LMST						
DI_601_BH004	2.39	4.72	Hard coralline limestone (dense coral growth with molluscs).	LMST						
DI_601_BH004	4.72	5.03	Hard grey calcareous sandstone	SDST						
DI_601_BH004	5.03	6.86	Hardish grey detrital limestone with traces of marl. Porous wi	LMST						
DI_601_BH004	6.86	14.33	Fragments of coral and grey calcareous marl	C						
DI_601_BH004	14.33	15.5	Hardish grey shelly sandstone. Porous	SDST						
DI_601_BH005	0	4.72	Hardish grey-brown detrital limestone (cemented shell fragm	LMST						
DI_601_BH005	4.72	7.62	Hard grey detrital limestone. As above but number of voids b	LMSTSDST						
DI_601_BH005	7.62	12.19	Hard grey detrital limestone: (cemented shells and shell fragr	LMST						
DI_602_BH001	0.00	1.37	Loose brown medium SAND and coral (shell fragments)	SCORAL						
DI_602_BH001	1.37	2.97	White slightly cemented (calcareous) medium SAND and cora	SCORAL						
DI_602_BH001	2.97	12.80	porous white coral LIMESTONE with some shells and numerou	LMSTCORAL						
DI_602_BH001	12.80	18.90	Greenish detrital shelly LIMESTONE	LMST						
DI_602_BH001	18.90	24.38	Fairly massive, white, fine grained chalky LIMESTONE with occ	LMST						
DI_602_BH002	0.00	4.27	Hard porous grey coral LIMESTONE with numerous voids. Fairl	LMSTCORAL						
DI_602_BH002	4.27	5.79	Greenish-grey silty CLAY and pieces of CORAL	CZCORAL						
DI_602_BH002	5.79	13.41	Weakly cemented shell SAND. Some coral growths towards ba	S						
DI_602_BH002	13.41	19.51	Greenish-grey coral LIMESTONE, original voids filled with fine	LMSTCORAL						
DI_602_BH002	19.51	24.38	Hard fairly massive pale brown shelly detrital LIMESTONE. Fev	LMST						
DI_602_BH003	0.00	2.51	Well cemented brown coarse shell SAND	S						
DI_602_BH003	2.51	4.57	Slightly cemented brown coarse shell SAND	S						
DI_602_BH003	4.57	8.92	Stiff light grey very silty CLAY	CZ						
DI_602_BH003	8.92	17.53	Fairly massive hard white muddy detrital LIMESTONE. Slightly	LMST						
DI_602_BH003	17.53	23.77	Medium hard, friable and clayey, white dolomotic detrital LIN	LMSTC						

Borehole Issues – Urban Areas

- Age of borehole
- Location (National grid reference, Accuracy?)
- Ground level start height of borehole (changes?)
- Units used - feet/metres (consistent conversion)
- Drilling and description quality

Quarry or cutting

Reclaimed land/embankment

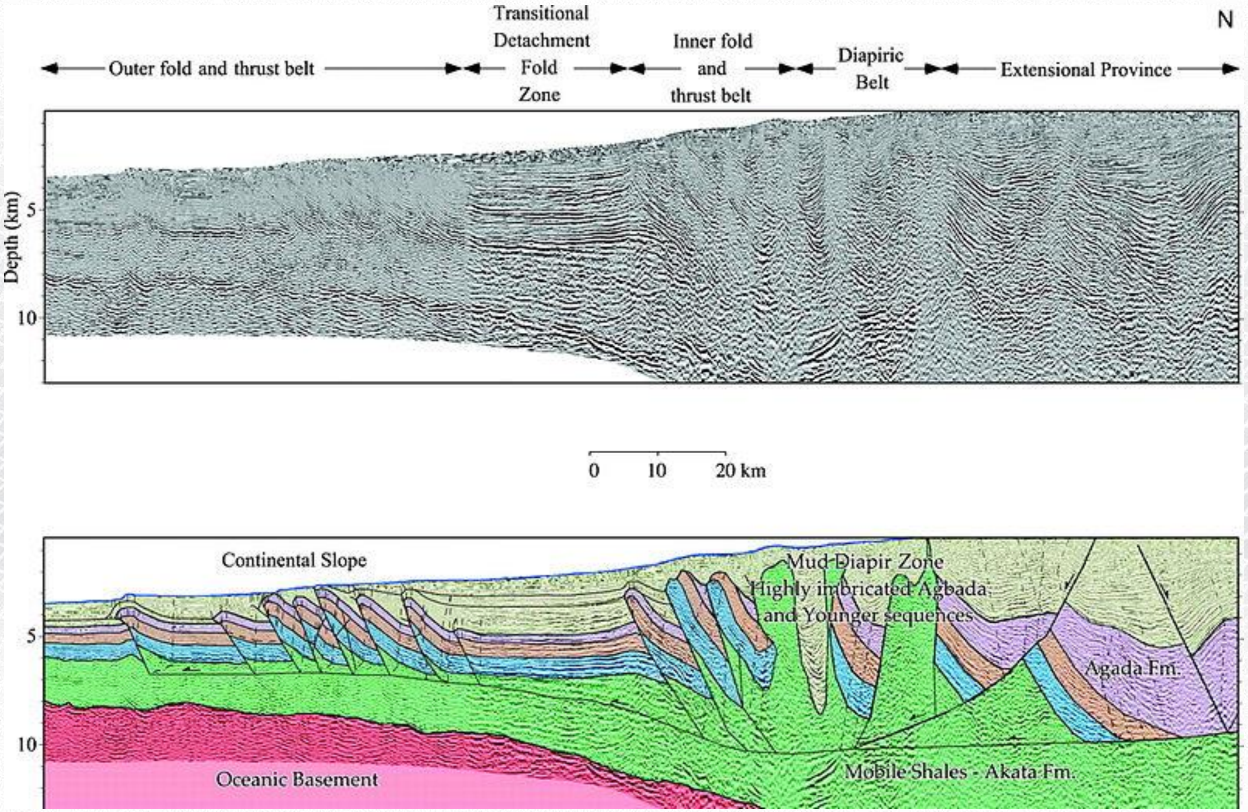


Deeper geology – interpreted seismic sections

Generally for implicit models

Seismic section

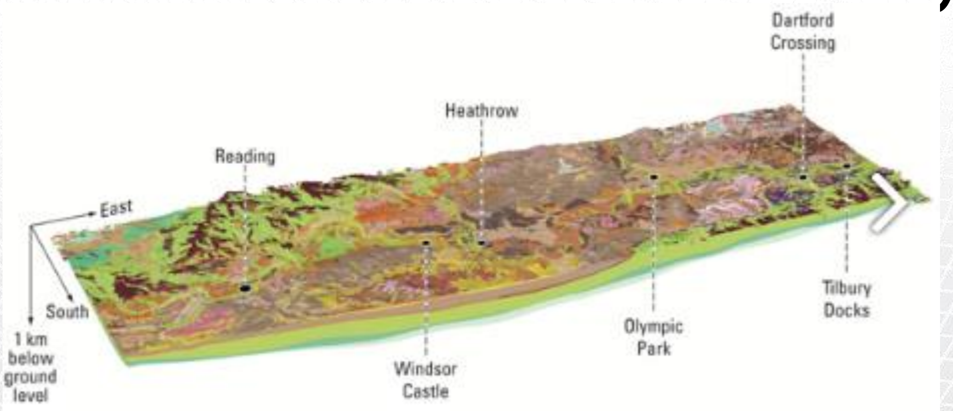
Interpretation



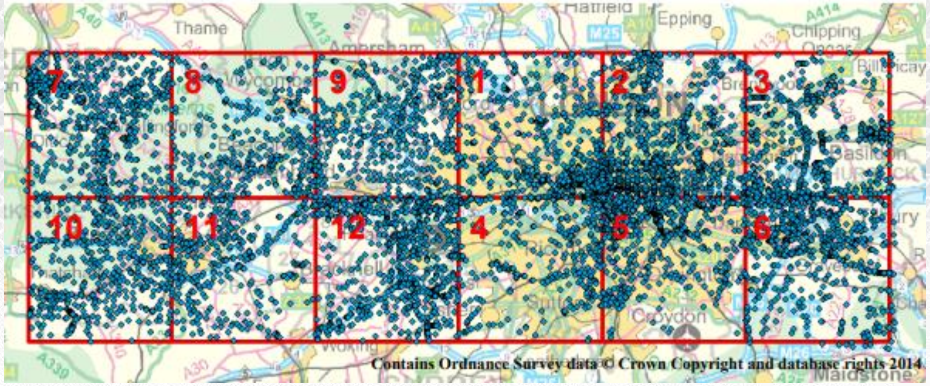
Example from the Niger delta https://commons.wikimedia.org/wiki/File:Niger_Delta_Tectonic_structure.jpg

Interpretation - Identification of units
Geological structures including faults, folds etc.
Also need borehole control

Borehole and section density
Modelling of the London and Thames Valley



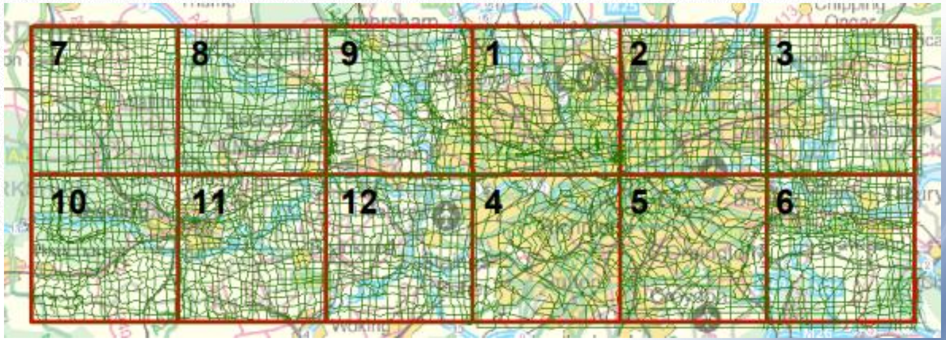
120 km x 40 km



7,174 boreholes considered

922 cross-section up to
3 km spacing

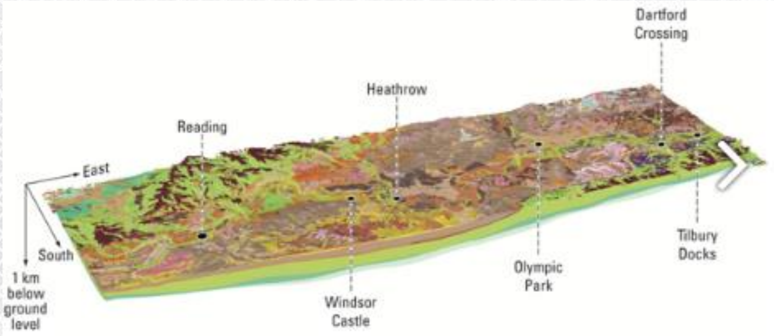
Do they maximise the data
for the geology?



Units to be modelled: general vertical section GVS in stratigraphical order (top to base)

Detail required for model use or uses

Modelled units (lithology, lithostratigraphy (Group, Formation, Member, bed)



120 km x 40 km x -100 mOD

London and Thames Valley model 76 units

- 5 Anthropogenic units
- 59 Superficial units (Quaternary)
- 12 Bedrock units (Tertiary and Cretaceous)
  1 Group, 7 Formation, 2 Members, 2 Beds

Report nora.nerc.ac.uk/507607/

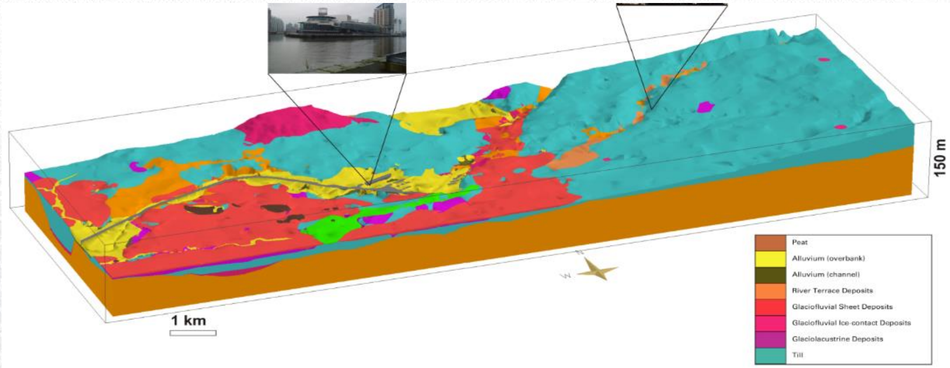
GVS – Manchester model

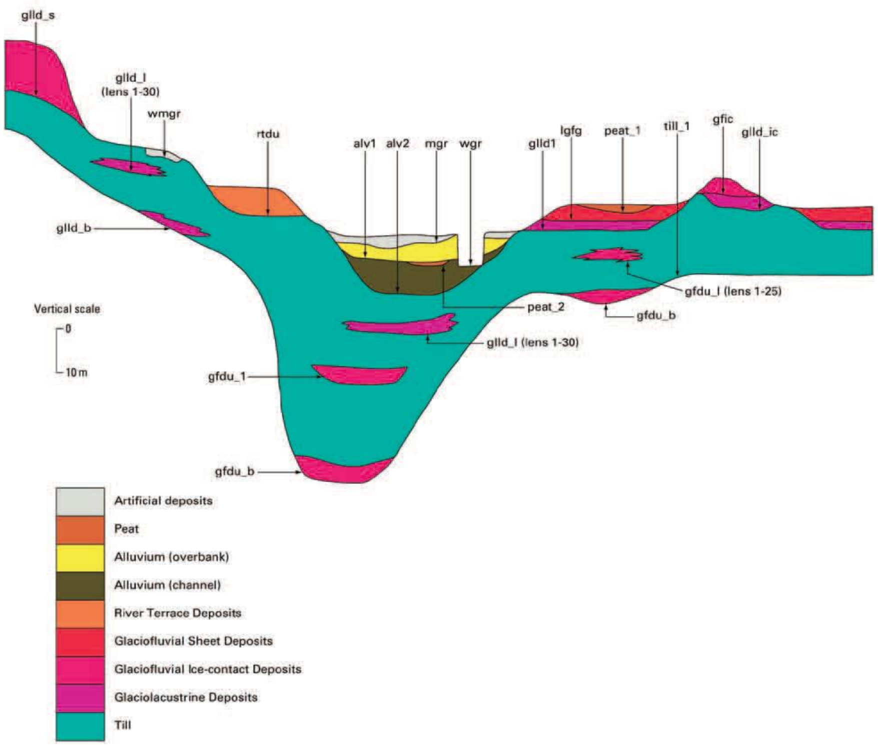
Manchester-Salford superficial model
15 km x 7 km to base of Quaternary

191 units – 160 Glacigenic units

Sand and gravel beds (glaciofluvial)
Clay and silt beds (glaciolacustrine)

https://www.bgs.ac.uk/downloads/start.cfm?id=1733





GVS – central Glasgow superficial model

10 km x 10 km to base of superficial deposits

Additional characteristics

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Name**	**id**	**Geological_Unit**	**Compositio**	**LEX_CO**	**Origin**	**Age**	**Aquifer_Produc**	**Permea**	**Enginee**	**Running**	**Plasticit**	**Geotech**
2	water	5	water	water	NULL	water	water	water	water	water	water	water	water
3	MGR-ARTDP	10	Made and Worked Groun	Made and Wor	MGR	Made and Worked Ground an	Recent	Non Aquifer	Variable	ENG1	RUN2	PLAS4	VAR
4	HEAD-XCZSV	15	Head	CS	HEAD	Mass Movement Deposit	Flandrian	Null	Moderate	ENG3	RUN3	PLAS4	VAR
5	PEAT-P	20	Peat	organic	PEAT	organic	Recent	Non Aquifer	Low	ENG8	RUN2	PLAS5	PEAT
6	LDE-XCZSP	25	Lacustrine deposit	CZS	LDE	Lacustrine	Recent	Null	Low	ENG4	RUN2	PLAS1	SFTFRM
7	LAWSG-XCZSVP	30	Law Sand and Gravel Mem	S	LAWSG	Present fluvial deposits	Flandrian	High	High	ENG2	RUN2	PLAS3	LOOSE
8	KELV-XCZSP	35	Strathkelvin Clay and Silt	CZ	KELV	Lacustrine	Flandrian	High	Low	ENG4	RUN2	PLAS1	SFTFRM
9	GOSA-XCZSV	40	Gourock Sand Member	SV	GOSA	Marine_estuarine	Flandrian	Moderate	High	ENG2	RUN2	PLAS3	LOOSE
10	KARN-XSV	65	Killearn Sand and Gravel I	VS	KARN	Raised beaches raised marine	Devensian	Moderate	Moderate	ENG6	RUN3	PLAS7	DENSEV
11	LIWD-XCZS	70	Linwood Clay Member	CZ	LIWD	Glacimarine	Devensian	Non Aquifer	Low	ENG4	RUN2	PLAS1	SFTFRM
12	PAIS-XCZS	75	Paisley Clay Member	CZ	PAIS	Glacimarine_estuarine	Devensian	Non Aquifer	Low	ENG4	RUN2	PLAS1	SFTFRM
13	BRON-XSVZ	80	Bridgeton Sand Member	S	BRON	Glacimarine delta	Devensian	Moderate	Moderate	ENG6	RUN1	PLAS3	VAR
14	RSSA-XSV	90	Ross Sand Member	S	RSSA	Glaciofluvial_Glaciolacustrine	Devensian	Moderate	High	ENG6	RUN1	PLAS3	DENSEM
15	RSSA-XSZ	95	Ross Sand Member, silty s	SZ	RSSA	Glaciolacustrine_deltaic	Devensian	Moderate	Moderate	ENG6	RUN1	PLAS3	DENSEM
16	BILL1-XZCS	100	Bellshill Clay Member	CZ	BILL	Lacustrine	Devensian	Non Aquifer	Low	ENG5	RUN3	PLAS6	FIRM
17	bhse_terrace	105	Broomhouse Sand and Gr	SV	NULL	Fluvial	Devensian	High	High	ENG6	RUN1	PLAS6	VAR
18	BHSE-XSV	110	Broomhouse Sand and Gr	VS	BHSE	Fluviodeltaic_ice contact	Devensian	High	High	ENG7	RUN2	PLAS7	VAR
19	BHSE-S	115	Broomhouse Sand and Gr	SV	BHSE	Fluviodeltaic_ice contact	Devensian	High	High	ENG7	RUN2	PLAS7	VAR
20	WITI-DMTN	135	Wilderness Till Formation	CZSVLB	WITI	Glacial	Devensian	Non Aquifer	Low	ENG3	RUN2	PLAS2	STIFF
21	SUPD-XZC	140	Clay and silt	ZC	null	Glaciolacustrine	Devensian	Non Aquifer	Low	NULL	NULL	NULL	FIRM
22	CADR-XSV	145	Cadder Sand and Gravel F	SVB	CADR	Glaciofluvial	Devensian	High	High	ENG7	RUN3	PLAS7	DENDENV
23	BRLL-XCZ	150	Broomhill Clay Formation	XCZ	BRLL	Glacimarine_estuarine	Devensian	Non Aquifer	Low	ENG5	RUN3	PLAS6	STIFF
24	BNTI-DMTN	155	Baillieston Till Formation	CZSVLB	BNTI	Glacial	Devensian	Non Aquifer	Low	ENG3	RUN2	PLAS2	STIFF
25	SUPD-XSV	160	Sand and gravel	SV	NULL	Glaciofluvial	Devensian	Unknown	High	ENG7	RUN1	PLAS7	DENDENV

nora.nerc.ac.uk/500548

Modelling software - Interpretation Tools & Techniques

Implicit (probabilistic or stochastic) & Explicit (deterministic) Modelling

Implicit models (statistical, stochastic, voxels etc.)
Data used to calculate the model

- \+ totally objective, reproducible, suitable for numerical data
  e.g. contouring grades in an ore body.
- Easy to quantify uncertainty
- Obeying laws of maths, physics and statistics but calculated models.

\- However, might not make geologically sensible.

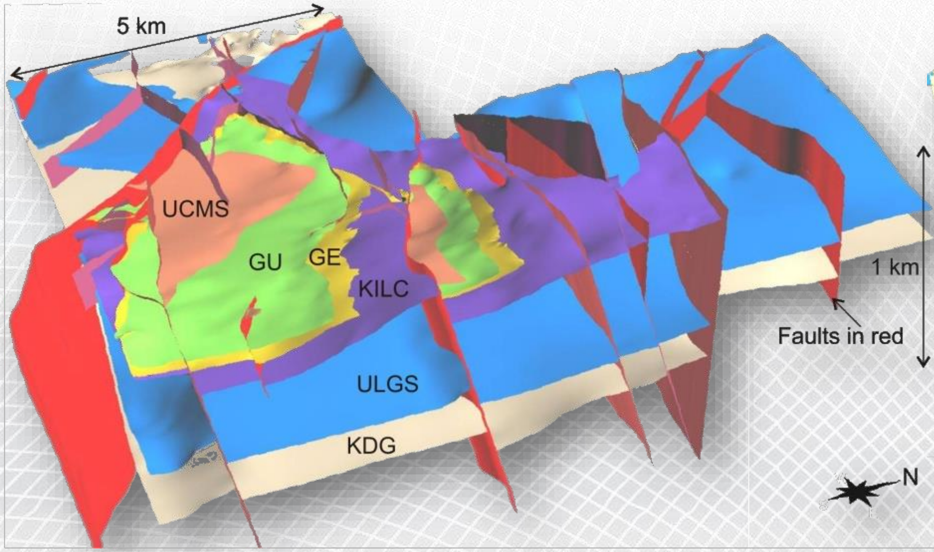
- No or little interaction by the geologists knowledge and understanding.
- Is the data (interpretation) correct?

Explicit models (expert controlled, capturing knowledge)
hard and soft data to calculate the model
\+ Geological sensible results, drawing on the holistic knowledge of the most suitable geologist(s) available.
\- Non-reproducible, uncertainty difficult to quantify

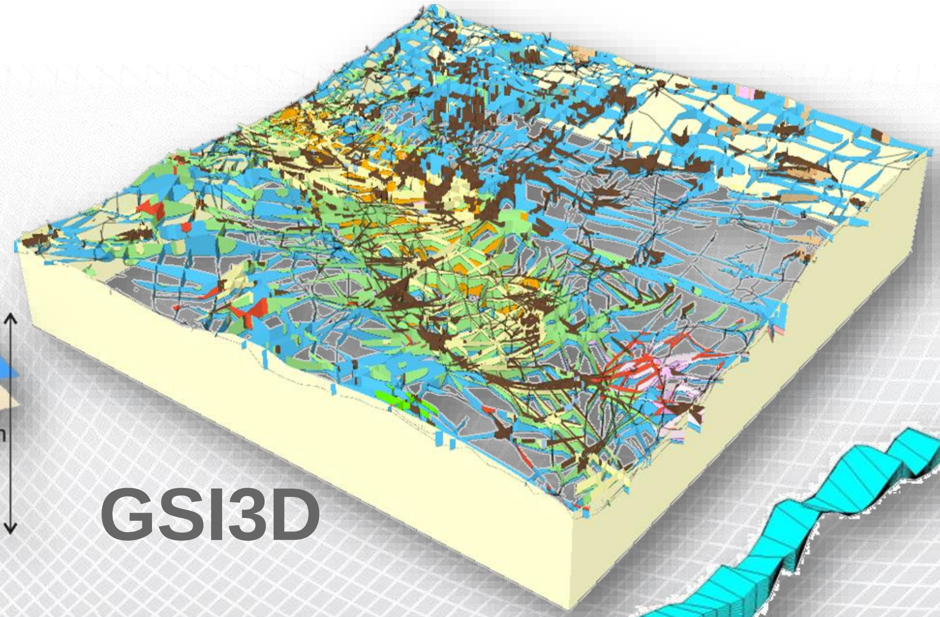
Explicit	Implicit
GSI3D (*Groundhog Desktop)	Leapfrog
AutoCAD	GOCAD-SKUA
MicroStation	GeoModeller
Subsurface Viewer	Petrel

Other software used (modelling, visualisation presentation)
Surfer, Voxler, Grapher, Strater, Slicer Dicer, AutoDesk 3dMax, Adobe Creative Cloud includes 3d pdf capability Unity, Engine

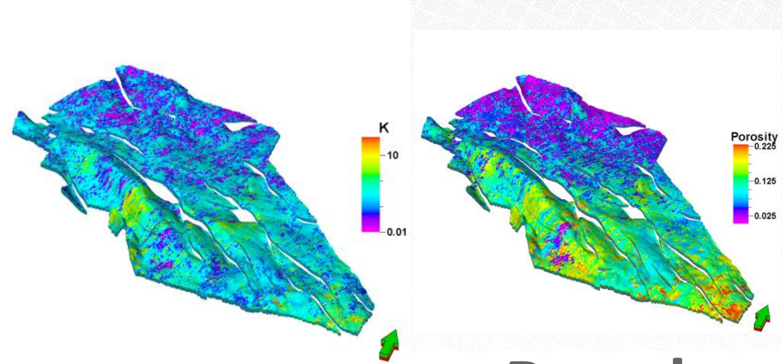
3D models



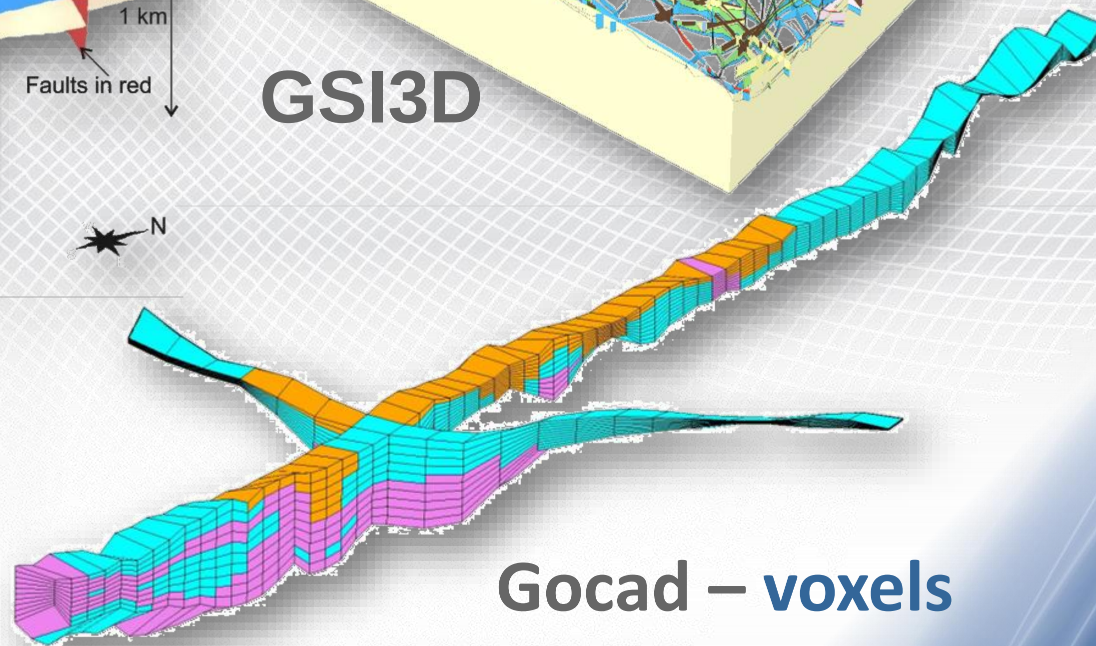
Gocad - surfaces



GSI3D



Petrel - voxels

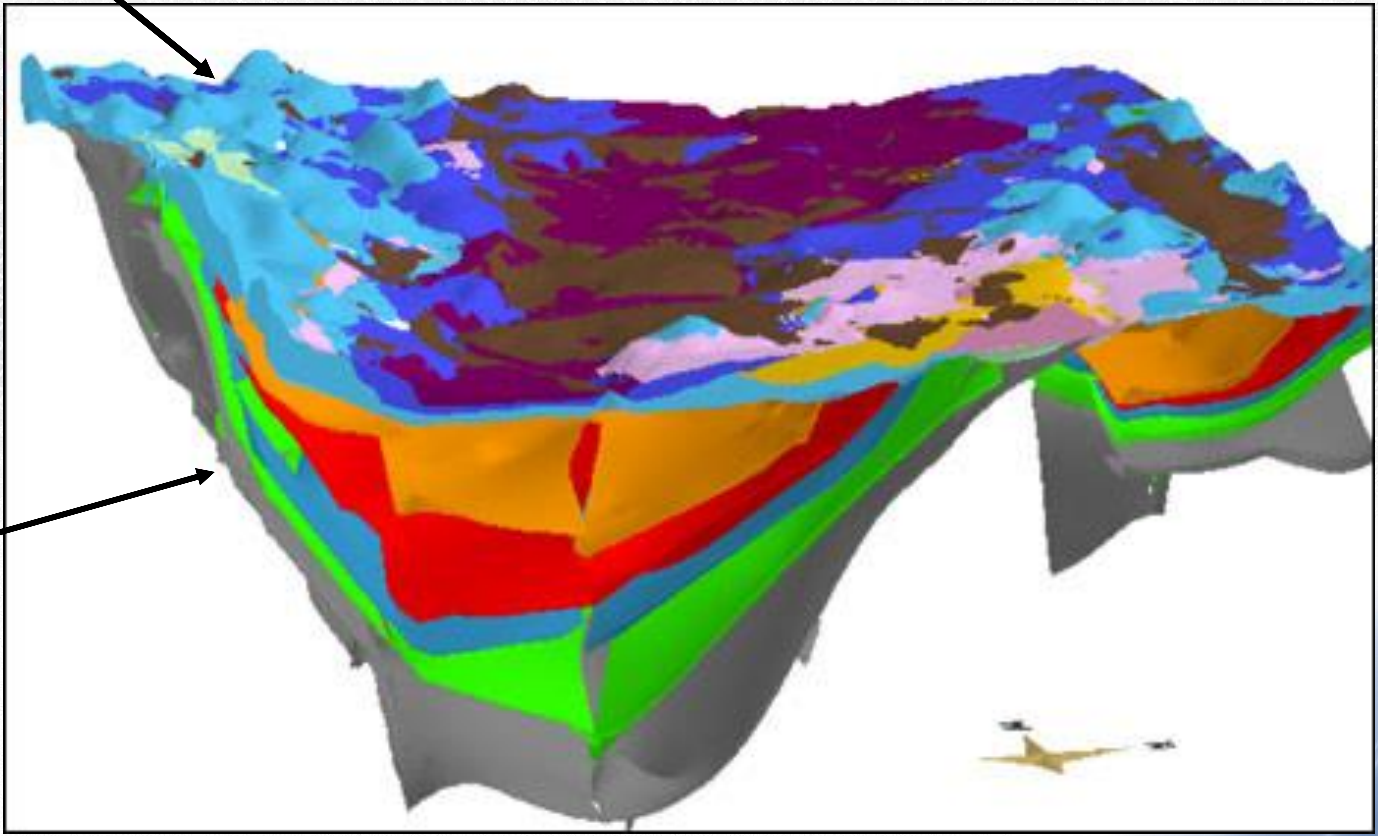


Gocad – voxels property data

Sources: C25: Parry et al., 2014, *Bull Eng Geol Environ*, doi:10.1007/s100064-014-0576-x

Central Glasgow model – deterministic and probabilistic models

Deterministic superficial model GSI3D



Probabilistic bedrock model (faulted) GOCAD

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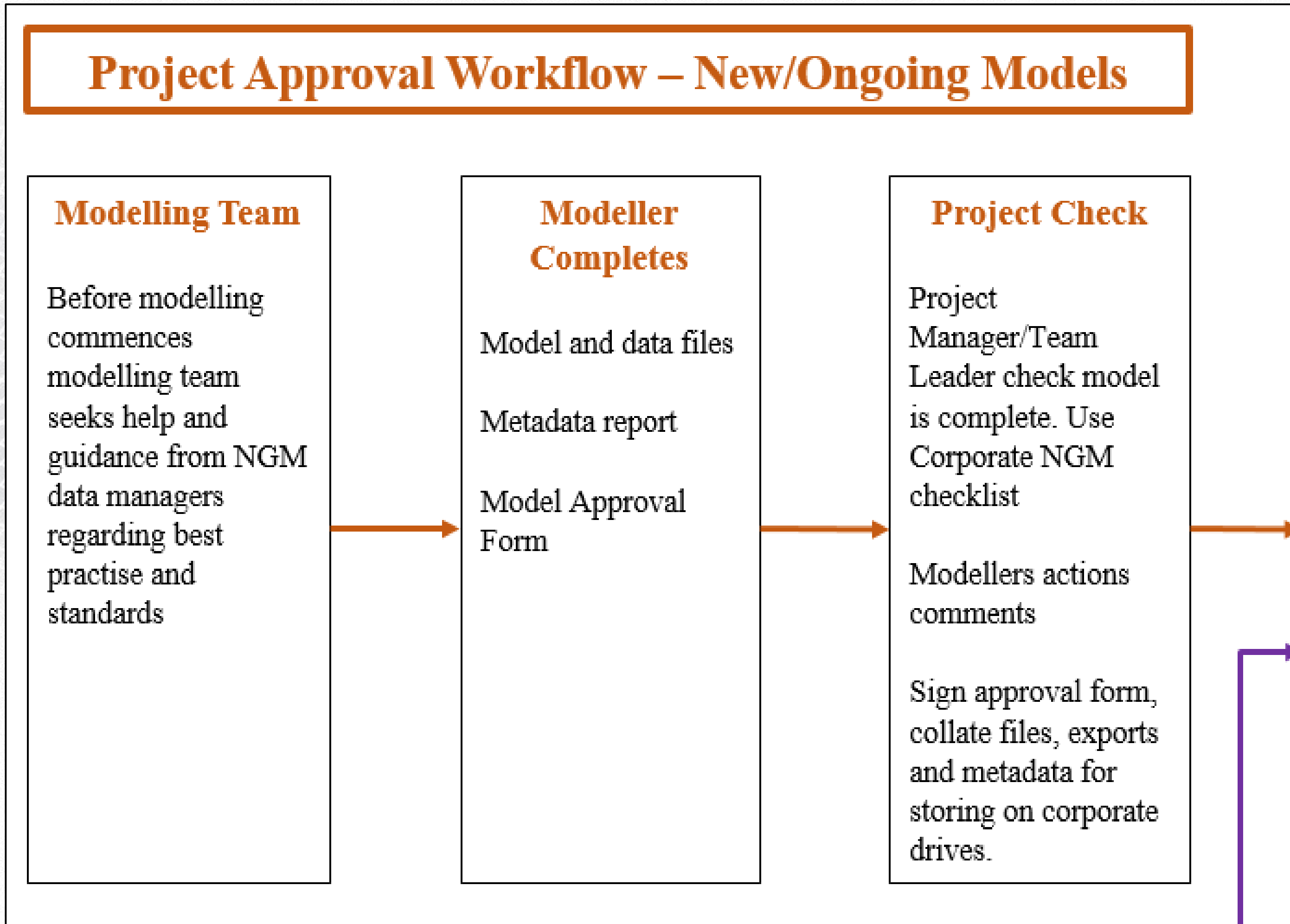
Which package to use?

Deterministic modelling
GSI3D/subsurface viewer/Groundhog (cross-sections)
For simple ‘layer cake’ geology perhaps with simple faults.
GOCAD is used to further investigate modelled surfaces.

Implicit modelling
GOCAD used for more complex geology such as folds, faults etc.
Petrel is used for seismic interpretation

Model checking and approval - project

- Completed approval form
- Metadata report



Model QA metadata for each model (software dependant)

What is metadata?

A set of data that describes other data

Purpose

Important to capture information about the spatial extent of the 3D model coverage (including details about each model)

https://www.bgs.ac.uk/data/publications/pubs.cfc?method=viewRecord&publnId=19867285

Metadata – GSI3D + Subsurface viewer

Metadata report includes:

- Modelling volume, purpose and scale;.
- Modelled surfaces/volumes (GVS) with description and units included.
- *Modelled faults*
- Model Workflow
- Model datasets
  - GVS, legend file, digital geological line work, DTM, Borehole data, interpreted geophysics
  - Other models
- Model assumptions, geological rules used etc.
- Model limitations
  - Model specific– data, geological units amalgamated or not included
  - General modelling
- Model QA
- Model images

http://nora.nerc.ac.uk/id/eprint/519288/

Sign off form

Gocad metadata report

- Modelling volume, purpose and scale
- Modelled surfaces/volumes
- Modelled faults
- Model datasets (Gocad Objects)
- Software used and model workflow
- Model limitations
- Model images

  http://nora.nerc.ac.uk/id/eprint/507028/

- Sign off form

3D Geological modelling GSI3D

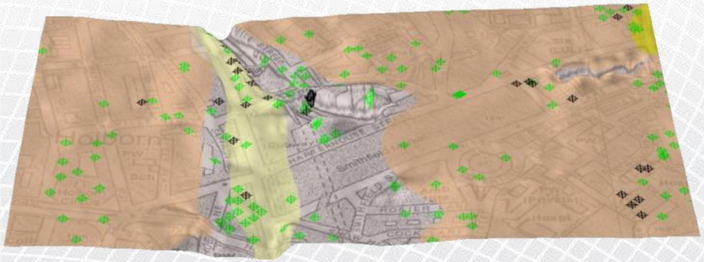
Expert geologist

Construction

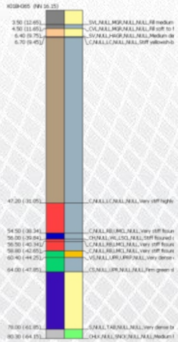
Model 800 m x 500 m

Inputs

136 BH (52 not used)

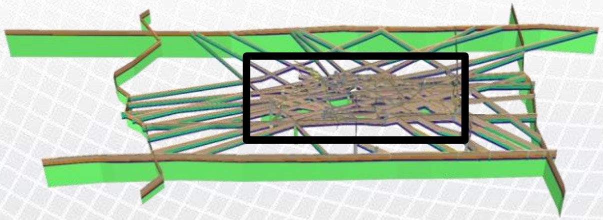


+



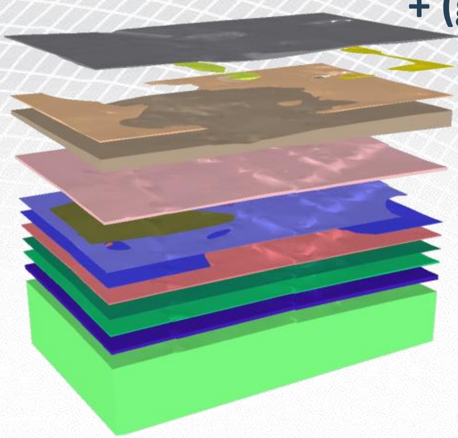
Modelled units

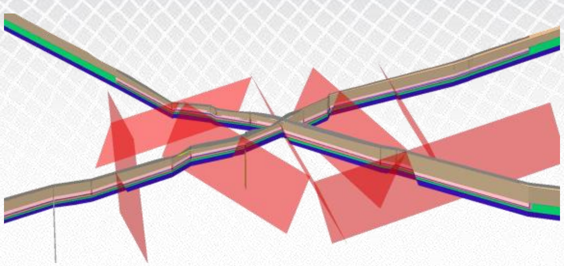
Rules

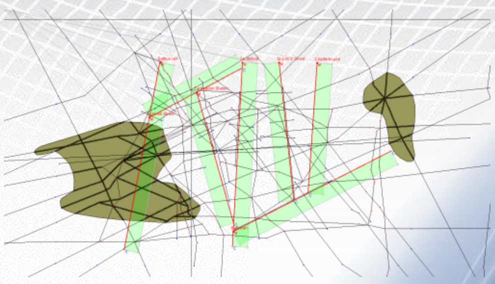


Fence diagram

Mapped and modelled Geology + DTM + boreholes + GSI3D + (geophysics)







3D model ('exploded')

Model calculation

Unit distribution and faults

Modelling

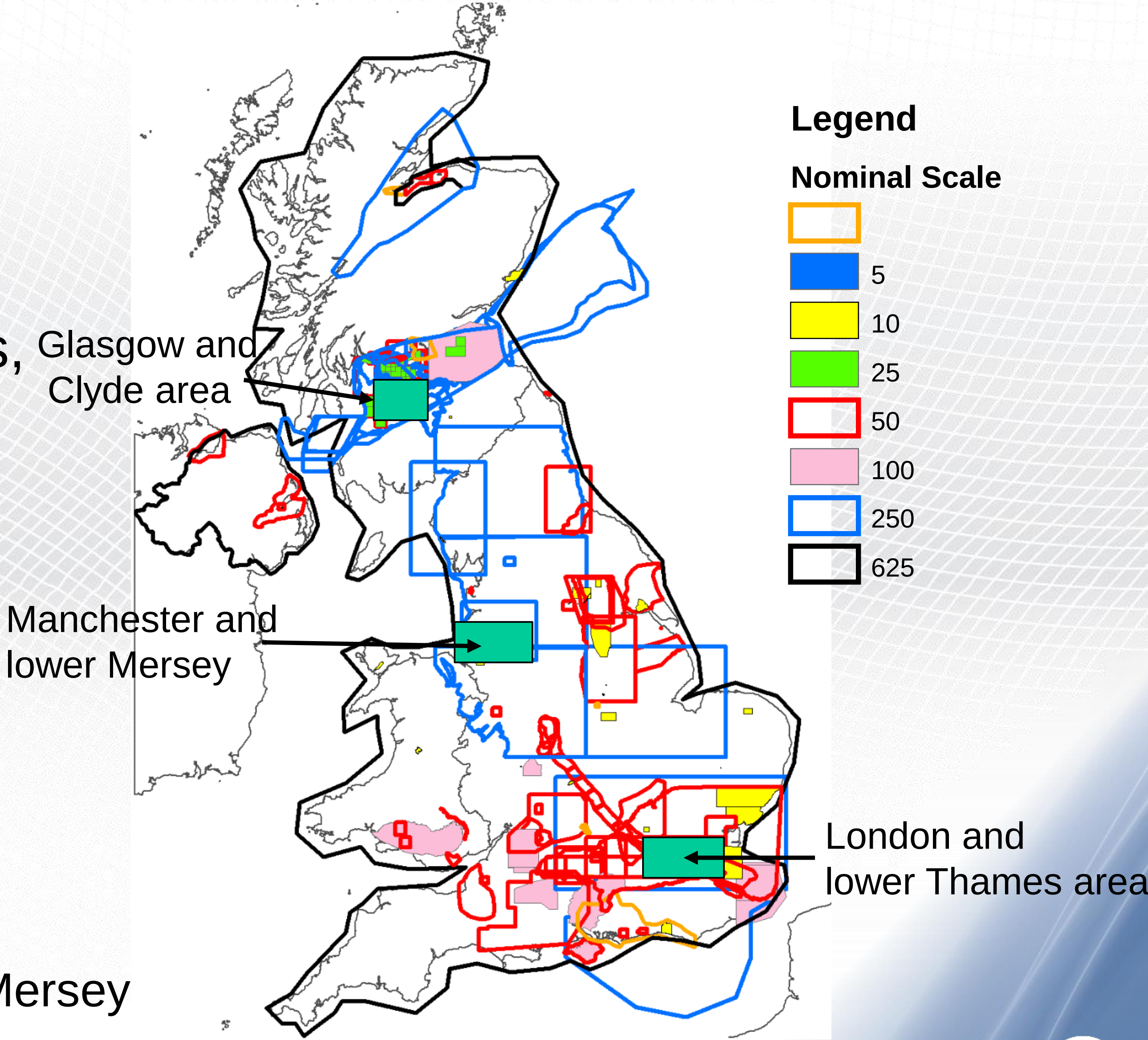
Expert geologist

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

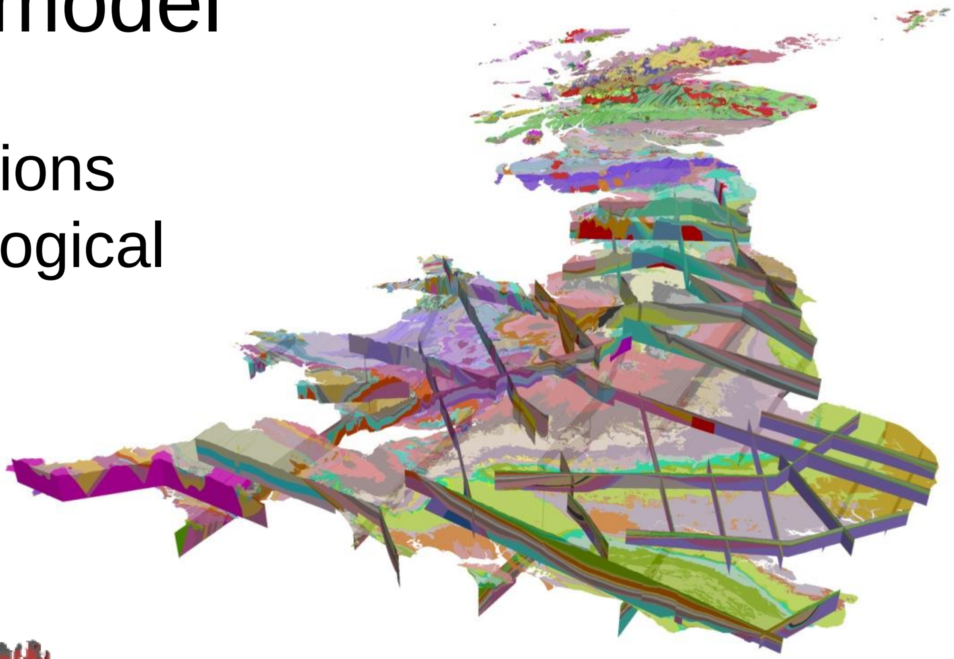
Scope of BGS geological models

- Framework models (mostly National Capability)
  - Systematic
  - Multi-purpose (can be limited)
  - Generalised geological subdivisions
  - Equivalent to geological maps at 1:50 000 to 1:625 000

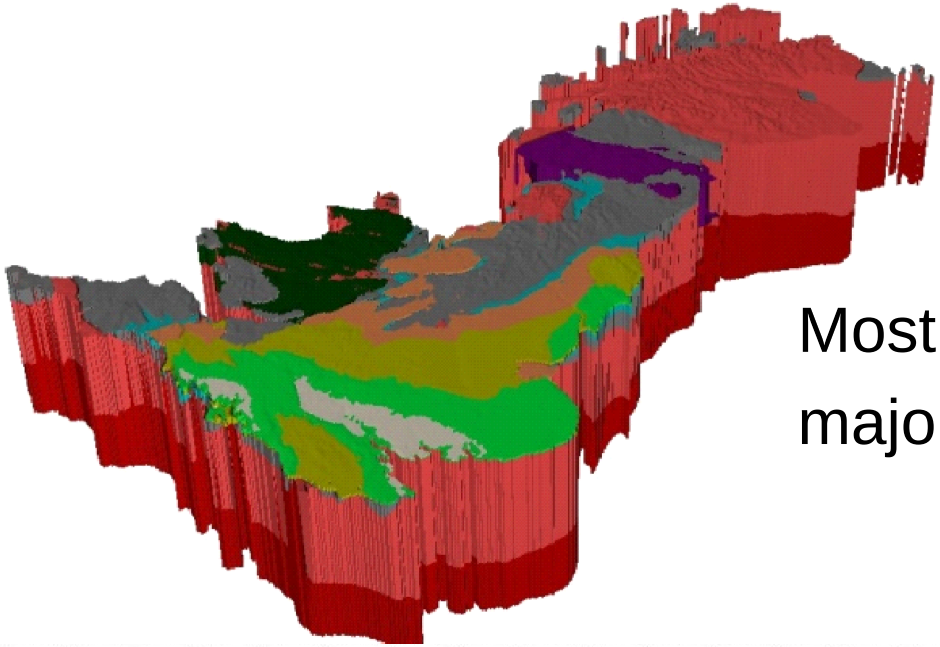
- Bespoke models (National Capability or commissioned)
  - On demand
  - Addressing a specific purpose(s)
  - Detail as required (as possible?)
- Regional [e.g. 100 km x 100 km x 1 km]
  - to local detail [e.g. 20 km x 20 km x 200 m]
  - to site-specific [e.g. 800 m x 400 m x 50 m]

National 3D geological model

• National network of cross sections new 1:625 k scale national geological maps



National Geological Map (1:1 000 000 scale)



Most significant stratigraphic divisions, major faults and plutons

http://www.bgs.ac.uk/science/3dmodelling/lithoframe1mvis.html

Geological Modelling and Visualisation - BGS

Industry and Consultancy

- Dr Sauer Group/CrossRail – Farringdon Station
- **Singapore (Building and Construction Agency) – 3D geological Model**
- HS2 – 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

Local/National Government and Agencies

- Glasgow City Council – ASK Network
- Radio Active 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
- Dept Energy and Climate Change – Shale Study Midland Valley (Scotland)
- Oil and Gas Authority – Bowland Shale Gas
- Jurassic Shale of the Weald Basin
- Scottish Government - Geothermal Energy
- Ordnance Survey – 3D workshops/Project Iceberg

Geological Survey Organisations and Universities

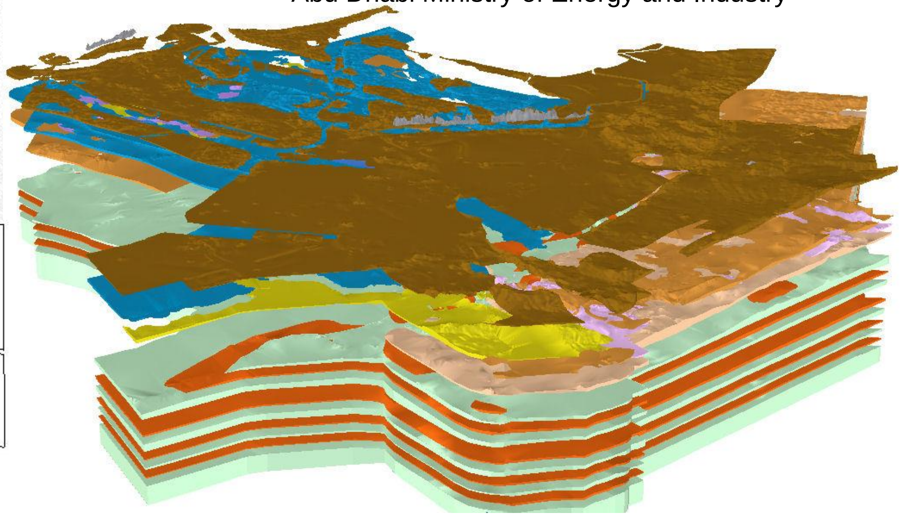
- SGU (Sweden) – Esker Pilot Study
- Illinois – Visualisation and Modelling
- GTK (Finland) – Groundhog Desktop Development
- Chile – Digital Mapping Workflow
- University of Newcastle – Groundwater Flooding
- Volcano Research – STREVA
- University of East Anglia DTCs- Wensum
- Kingston University - Visualisation Training
- UNITEN (Malaysia) – Visualisation Capability and Training
- European 3D Geological Modelling Community
- Sub-Urban – Consortium of GSOs, Cities and Research partners - management of ground beneath cities.

BGS international

https://www.bgs.ac.uk/research/international/UAE.html

Abu Dhabi - UAE

Abu Dhabi Ministry of Energy and Industry



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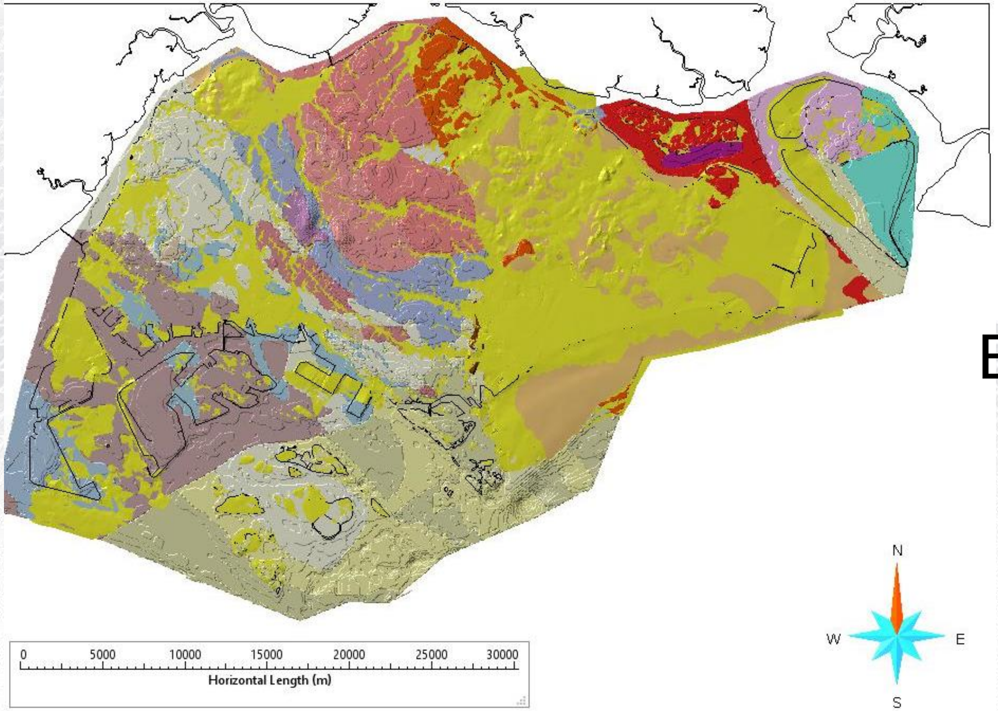
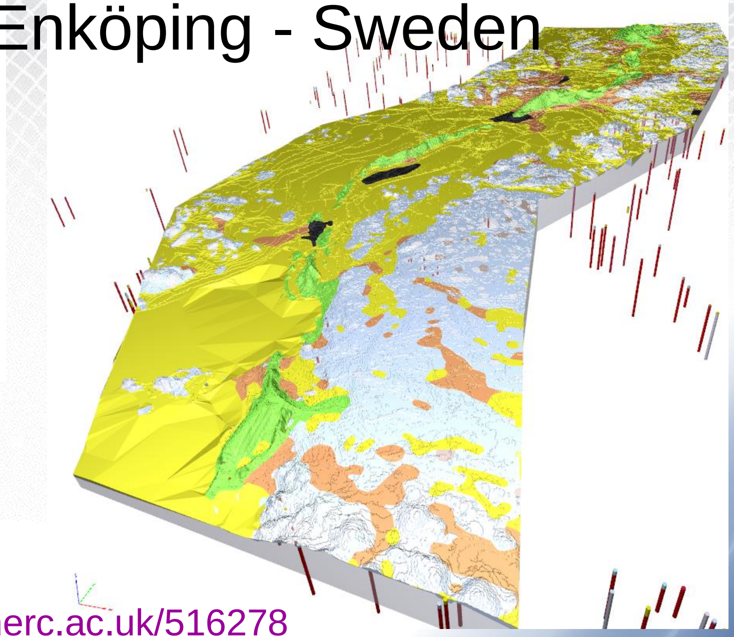


Singapore - bedrock

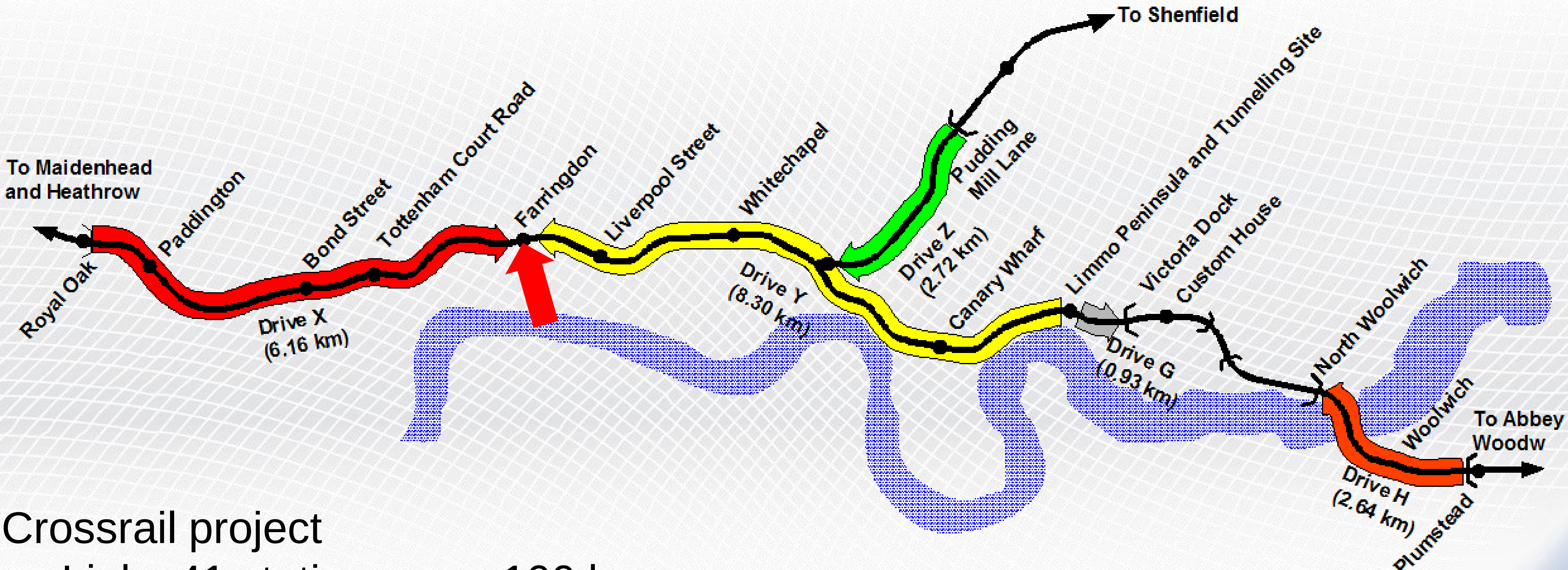
Enköping - Sweden



nora.nerc.ac.uk/516278

Case Study
Crossrail Farringdon station – London (UK)
(includes test of a model)

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

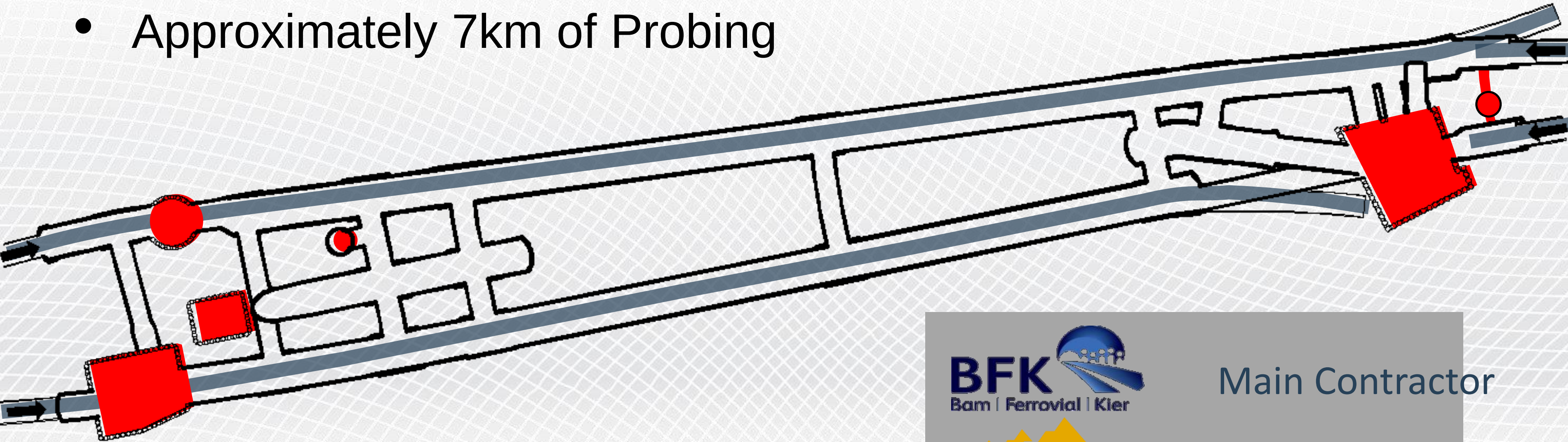
BFK Bam | Ferrovial | Kier — Main Contractor

Dr. SAUER & PARTNERS — SCL specialists

Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Reducing risk – Ground models
Crossrail Farringdon Station

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



BFK Bam | Ferrovial | Kier — Main Contractor

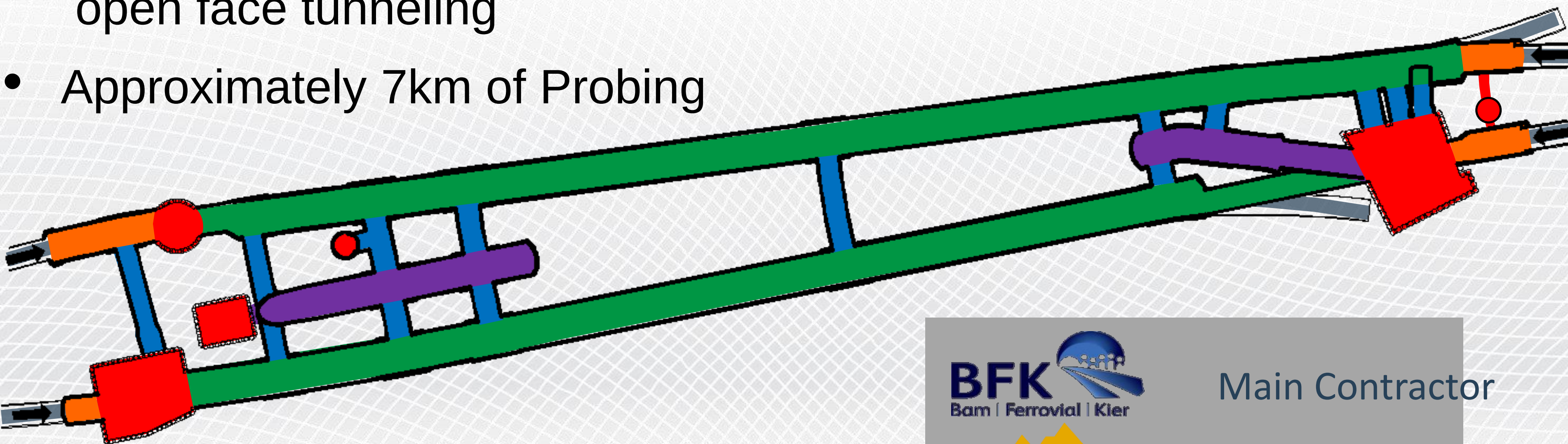
Dr. SAUER & PARTNERS — SCL specialists

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

Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

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

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

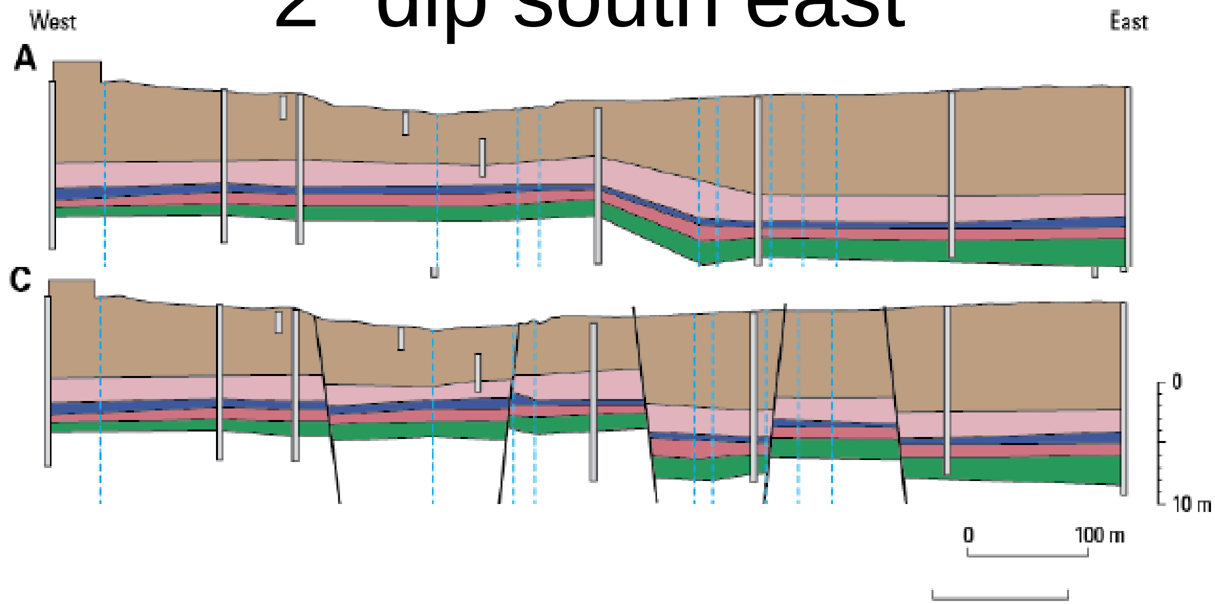
Sand beds

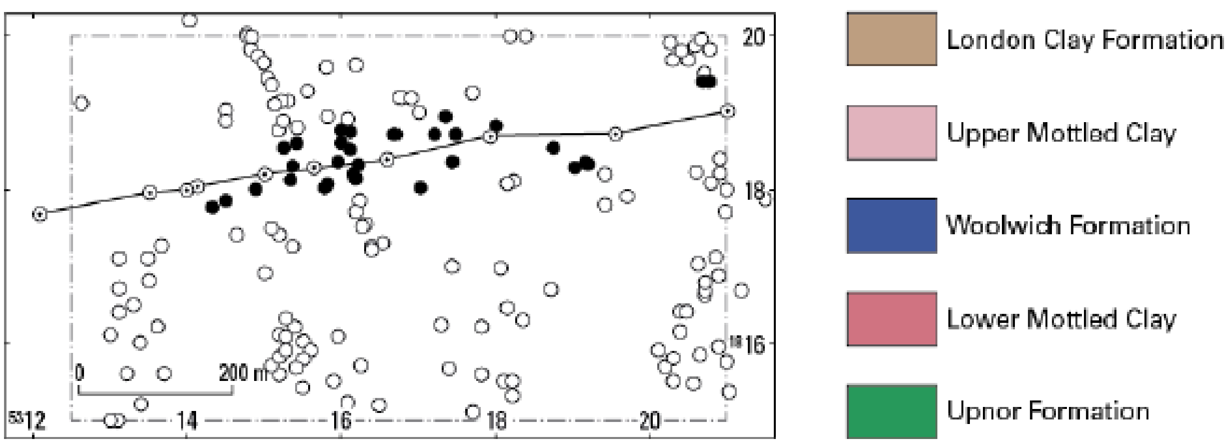
Potential zones with hard bands

Cross-section – construction
2° dip south east

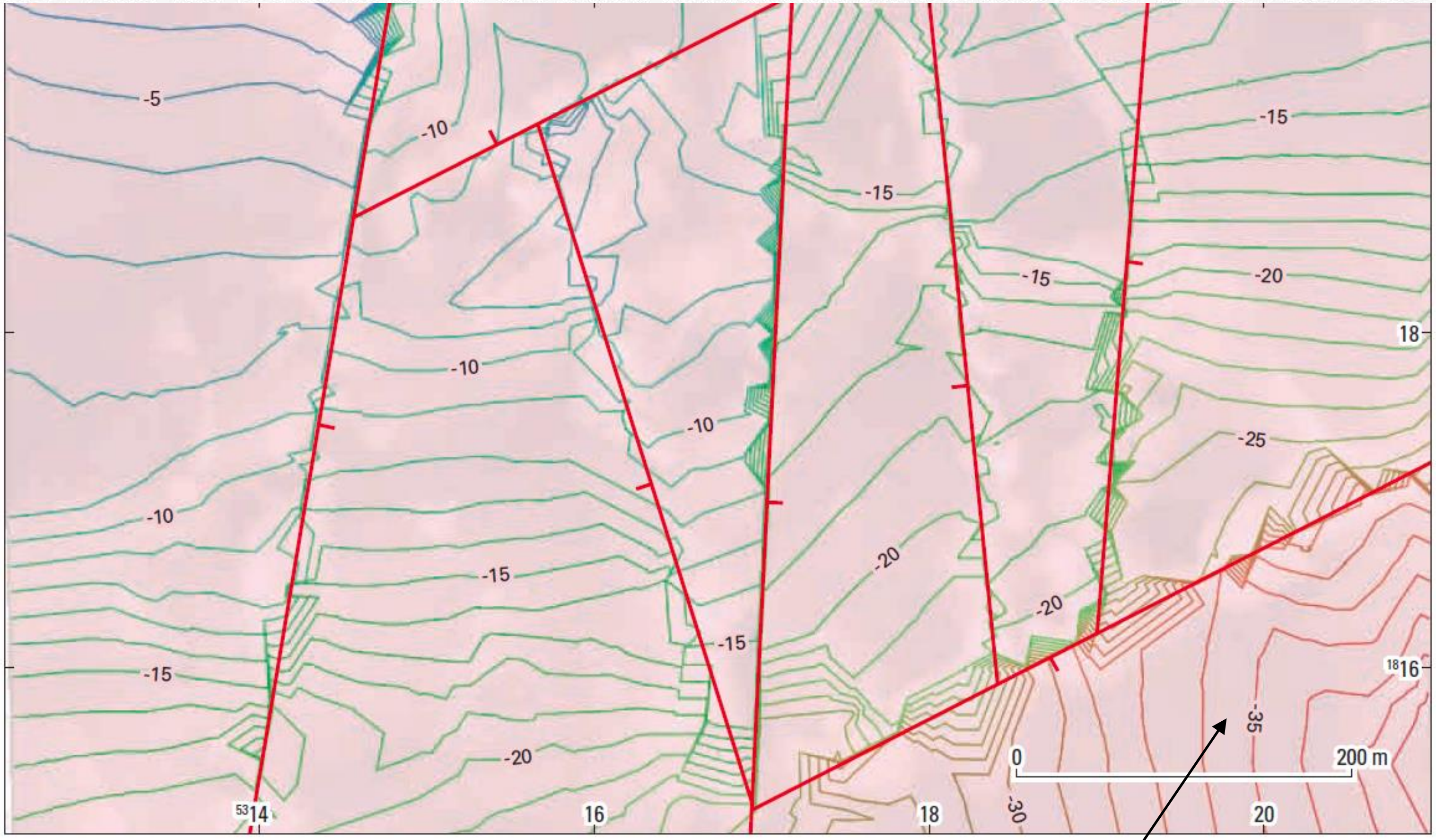
No faults, partly constrained by cross-cutting sections (dashed)

Same as A but with faults



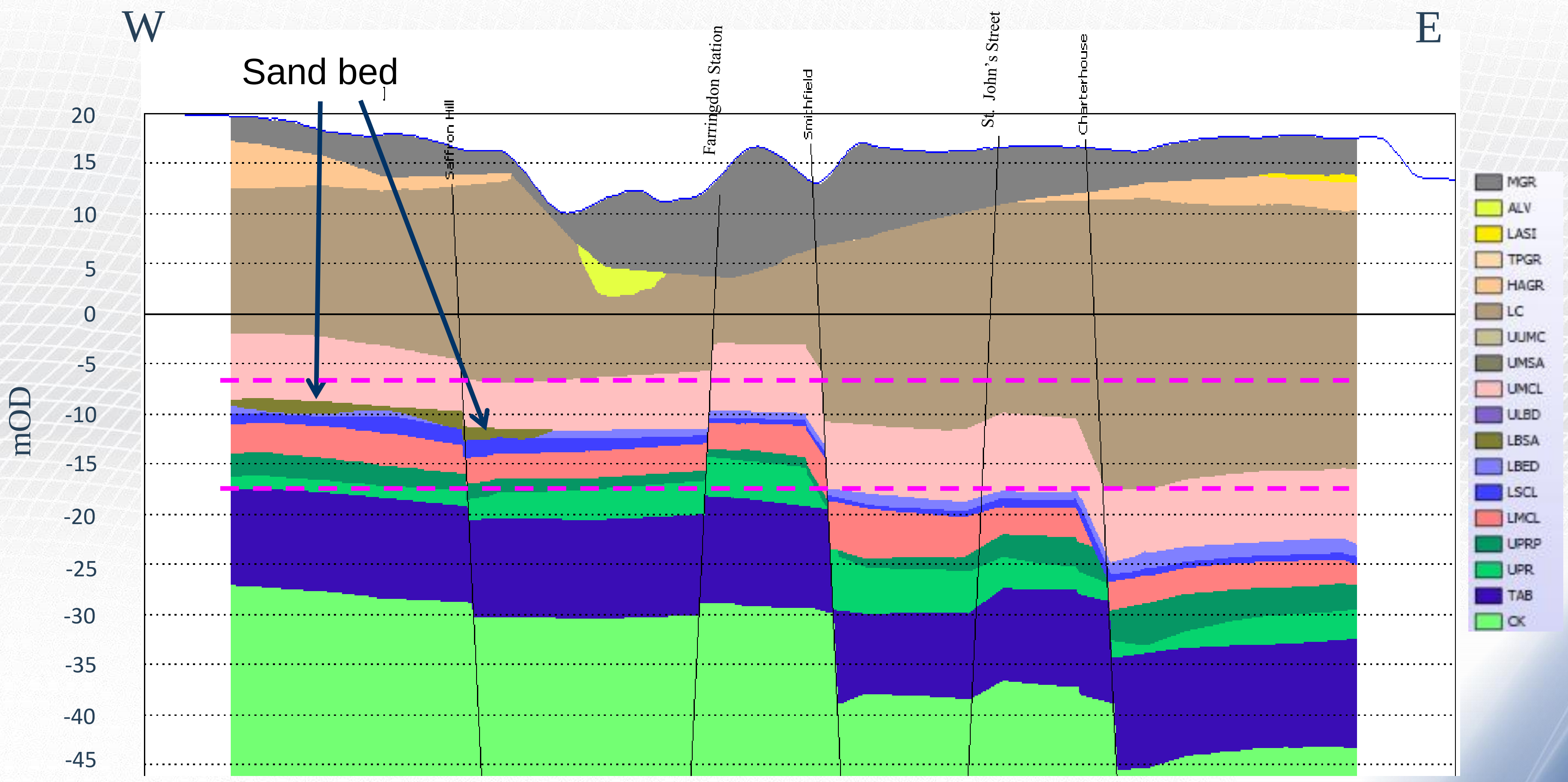


Modelled structure 1 m contours – Base Upper Mottled Clay (Beds) ~dip 2° to south

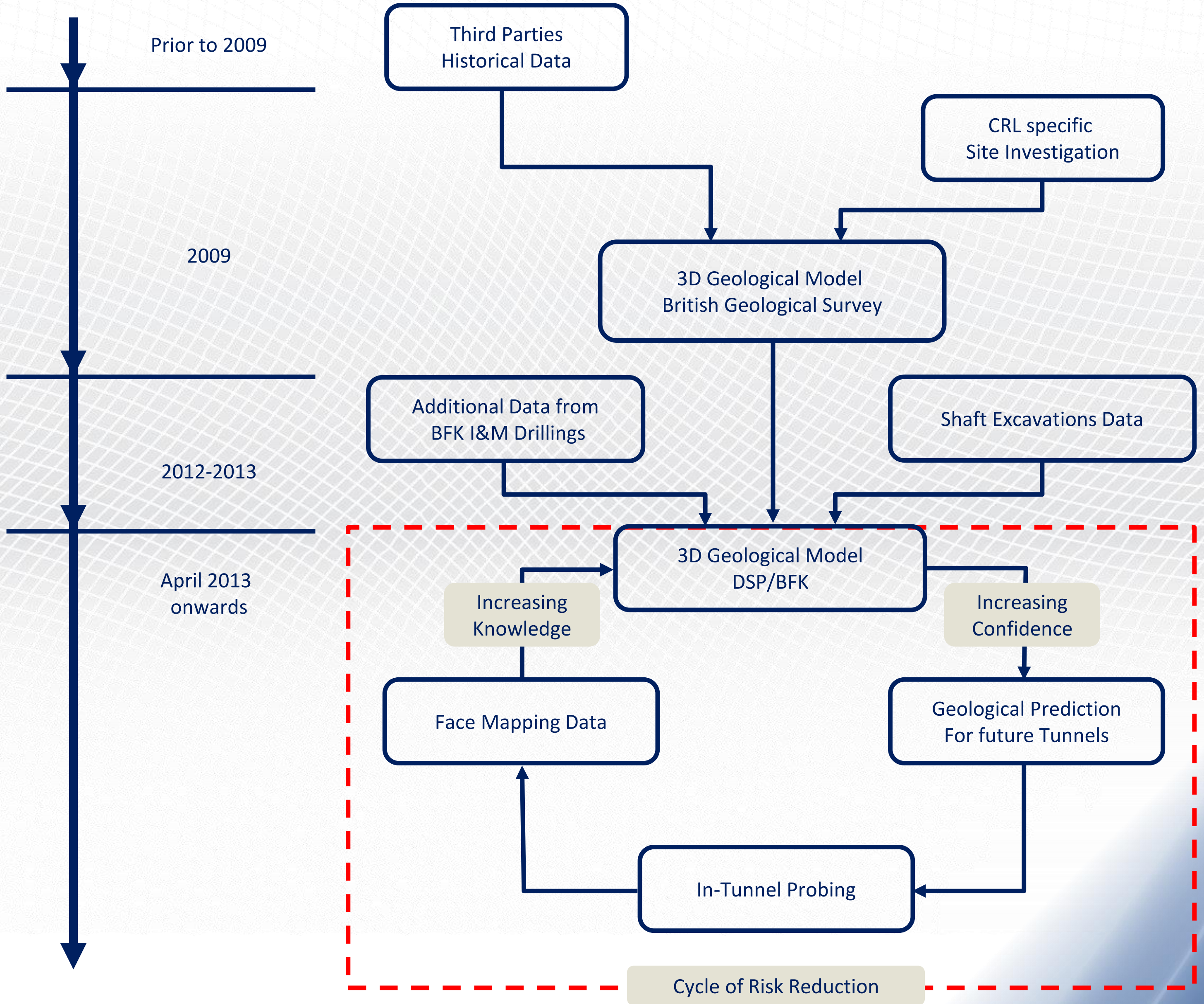


Block with different dip direction

Synthetic cross-section ~ along tunnel line



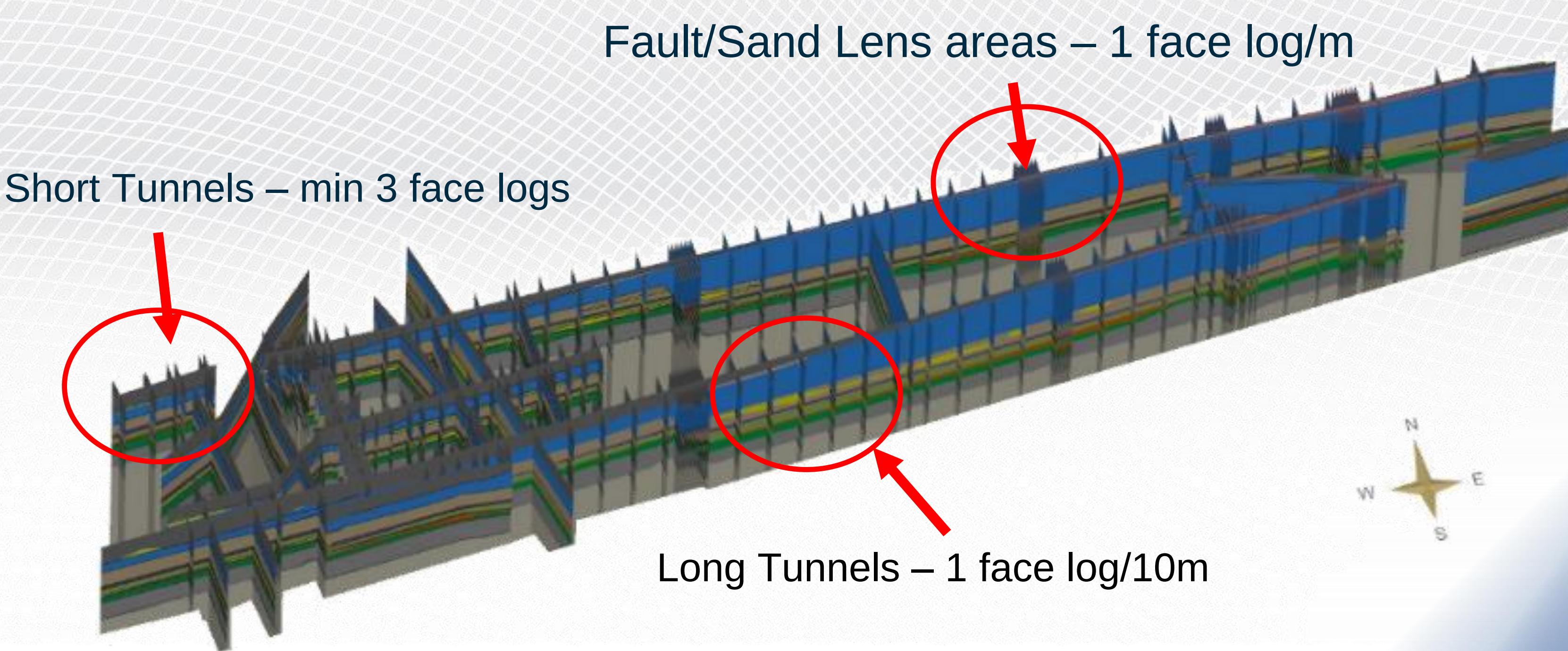
Model development



Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Integrating the data

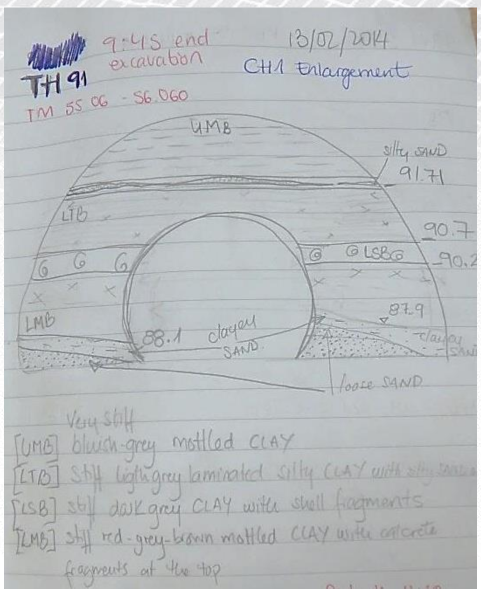
All intersecting (affected) sections were subsequently updated

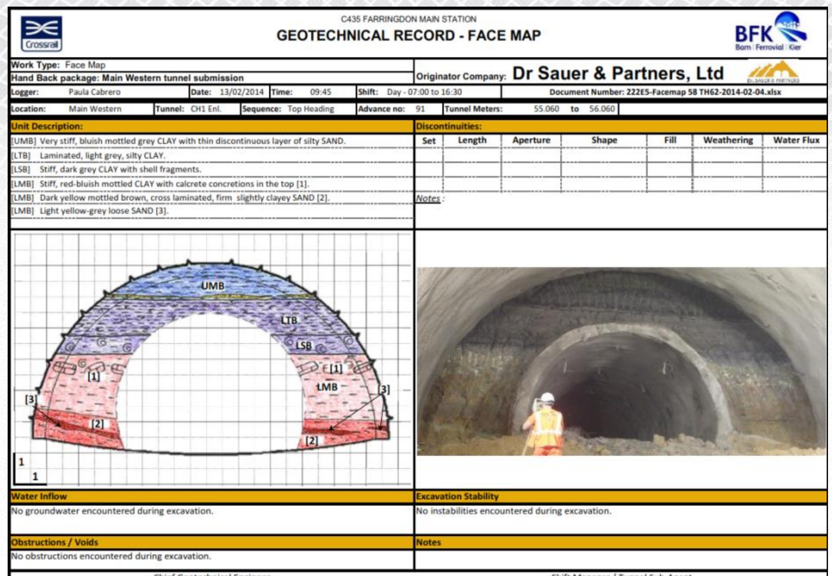


Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Integrating the data

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





C435 FARRINGDON MAIN STATION

GEOTECHNICAL RECORD - FACE MAP

Work Type: Face Map
Hand Back package: Main Western tunnel submission
Originator Company: Dr Sauer & Partners, Ltd

Logger:	Paula Cabrero	Date:	13/02/2014	Time:	09:45	Shift:	Day - 07:00 to 16:30	Document Number: 222E5-Facemap 58 TH62-2014-02-04.xlsx	
Location:	Main Western	Tunnel:	CH1 Enl.	Sequence:	Top Heading	Advance no:	91	Tunnel Meters:	55.060 to 56.060

Unit Description:

[UMB] Very stiff, bluish mottled grey CLAY with thin discontinuous layer of silty SAND.
[LTB] Laminated, light grey, silty CLAY.
[LSB] Stiff, dark grey CLAY with shell fragments.
[LMB] Stiff, red-bluish mottled CLAY with calcrete concretions in the top [1].
[LMB] Dark yellow mottled brown, cross laminated, firm slightly clayey SAND [2].
[LMB] Light yellow-grey loose SAND [3].

Discontinuities:

Set	Length	Aperture	Shape	Fill	Weathering	Water Flux

Notes:

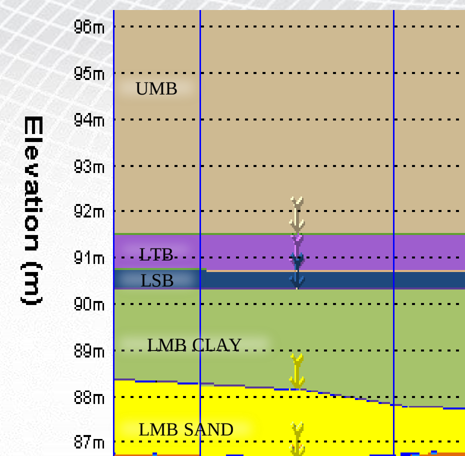
Water Inflow: No groundwater encountered during excavation.

Excavation Stability: No instabilities encountered during excavation.

Obstructions / Voids: No obstructions encountered during excavation.

Notes:

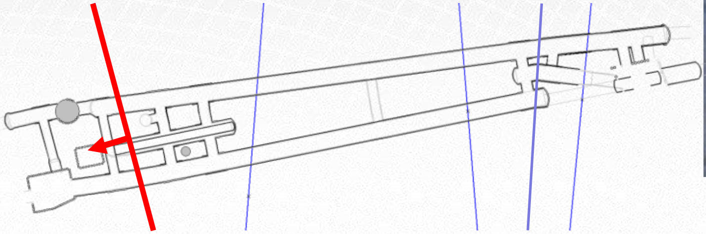
Chief Geotechnical Engineer   Shift Manager / Tunnel Sub-Agent

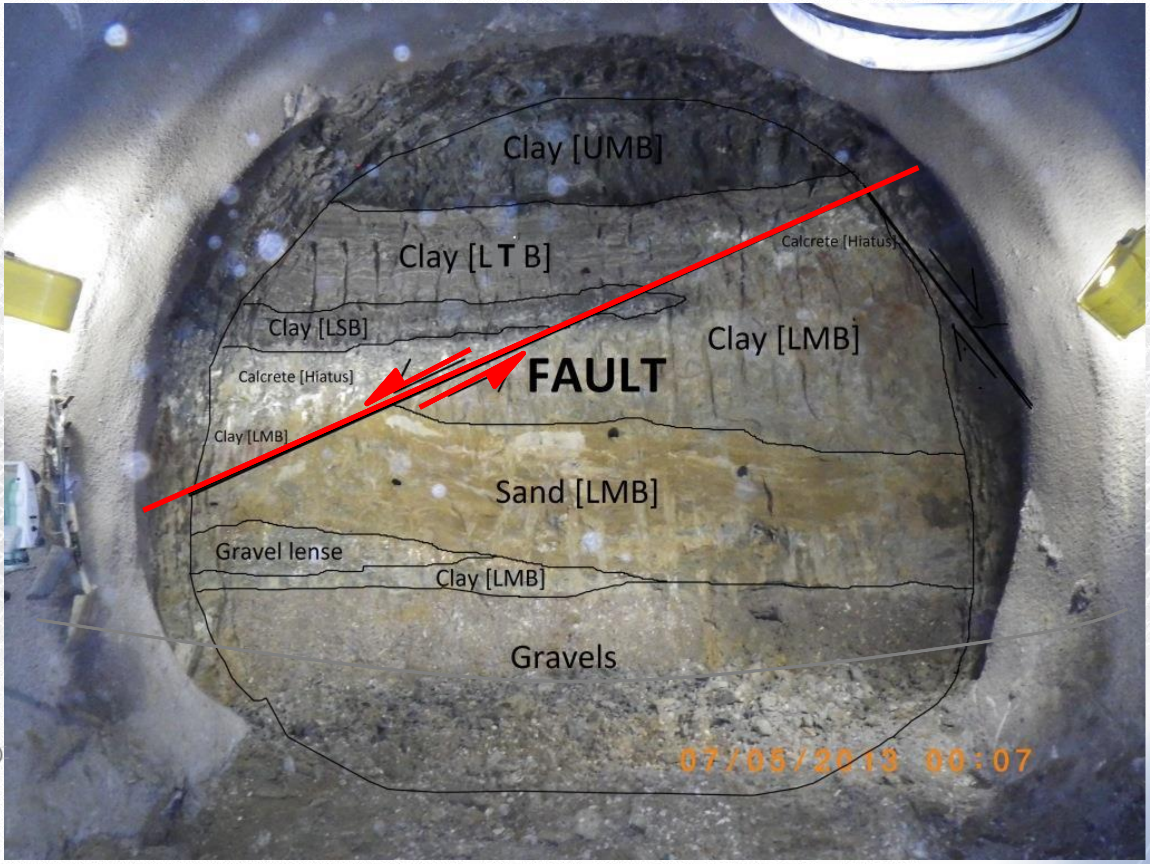


Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Farringdon Fault - face

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





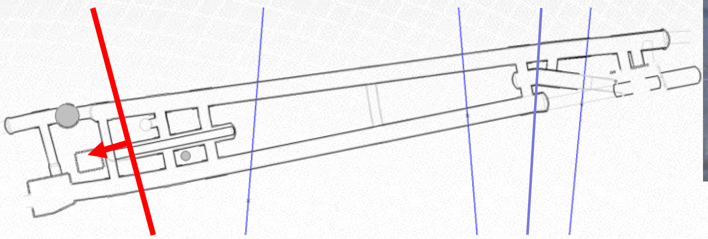
Lambeth Group

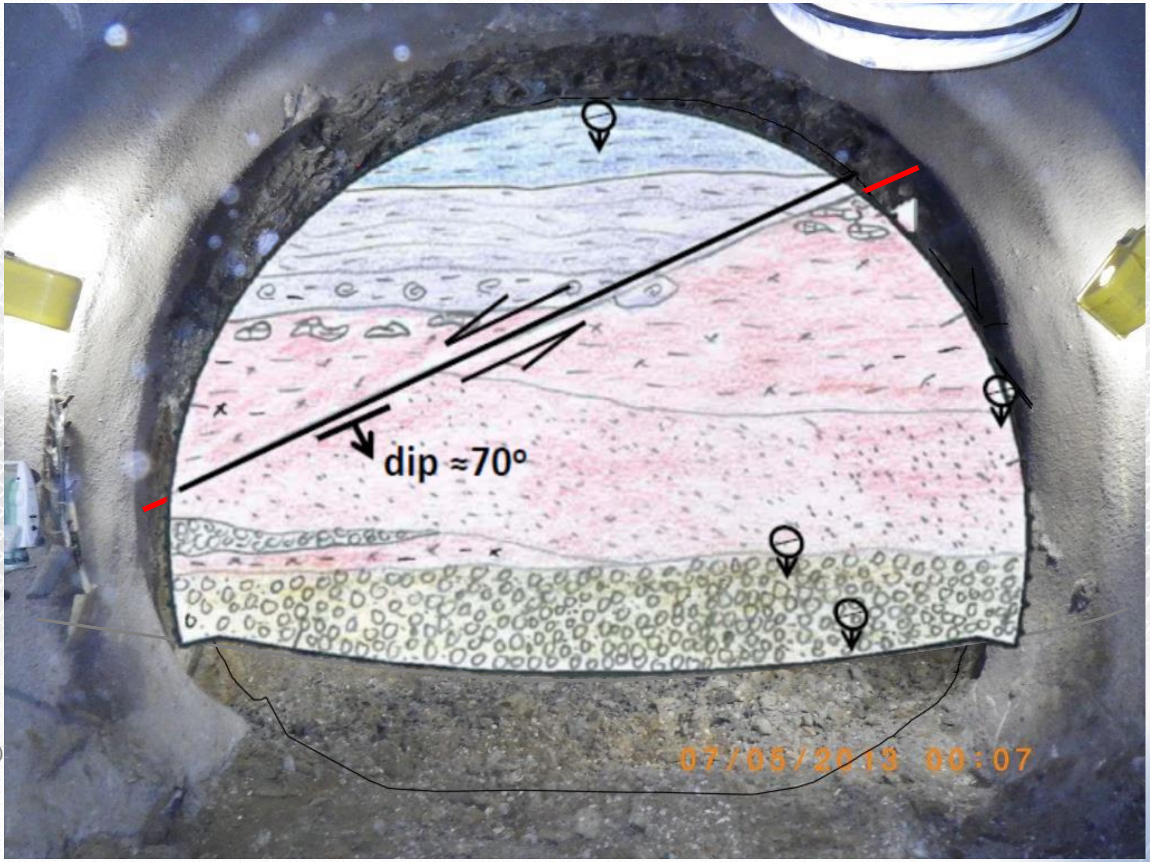
UMB – Upper Mottled Bed
LTB – Laminated Bed
LSB – Lower Shelly Bed
LMB – Lower Mottled Bed
Gravels belong to the Upnor Formation (UPR)

Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Farringdon Fault

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

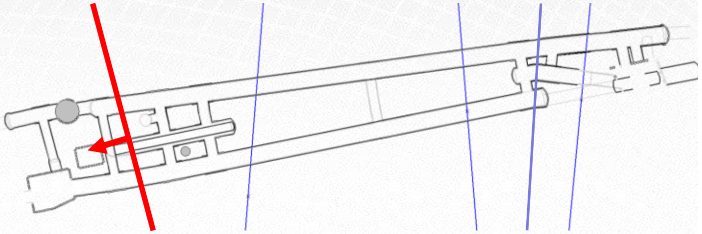


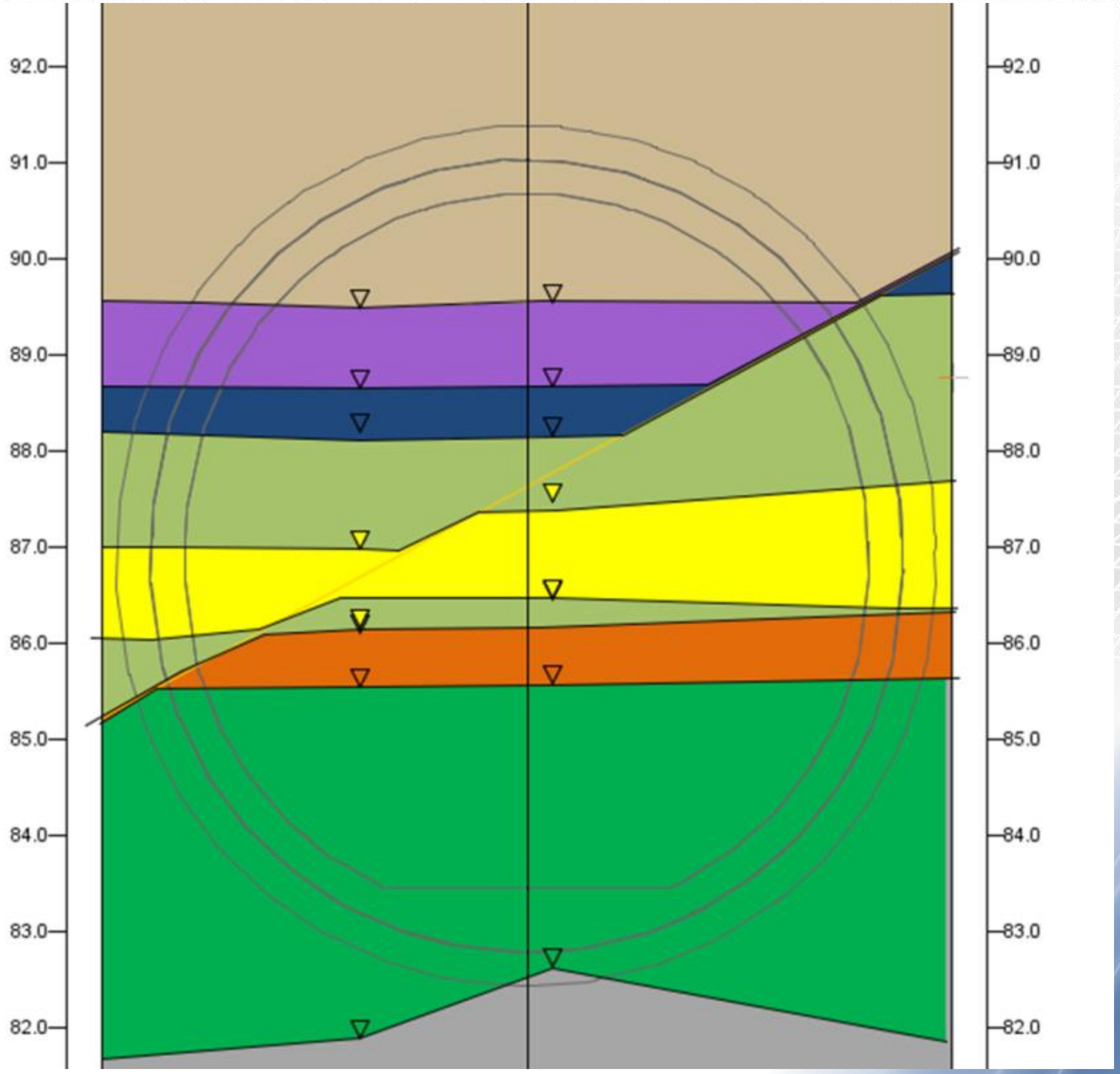


Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Farringdon Fault

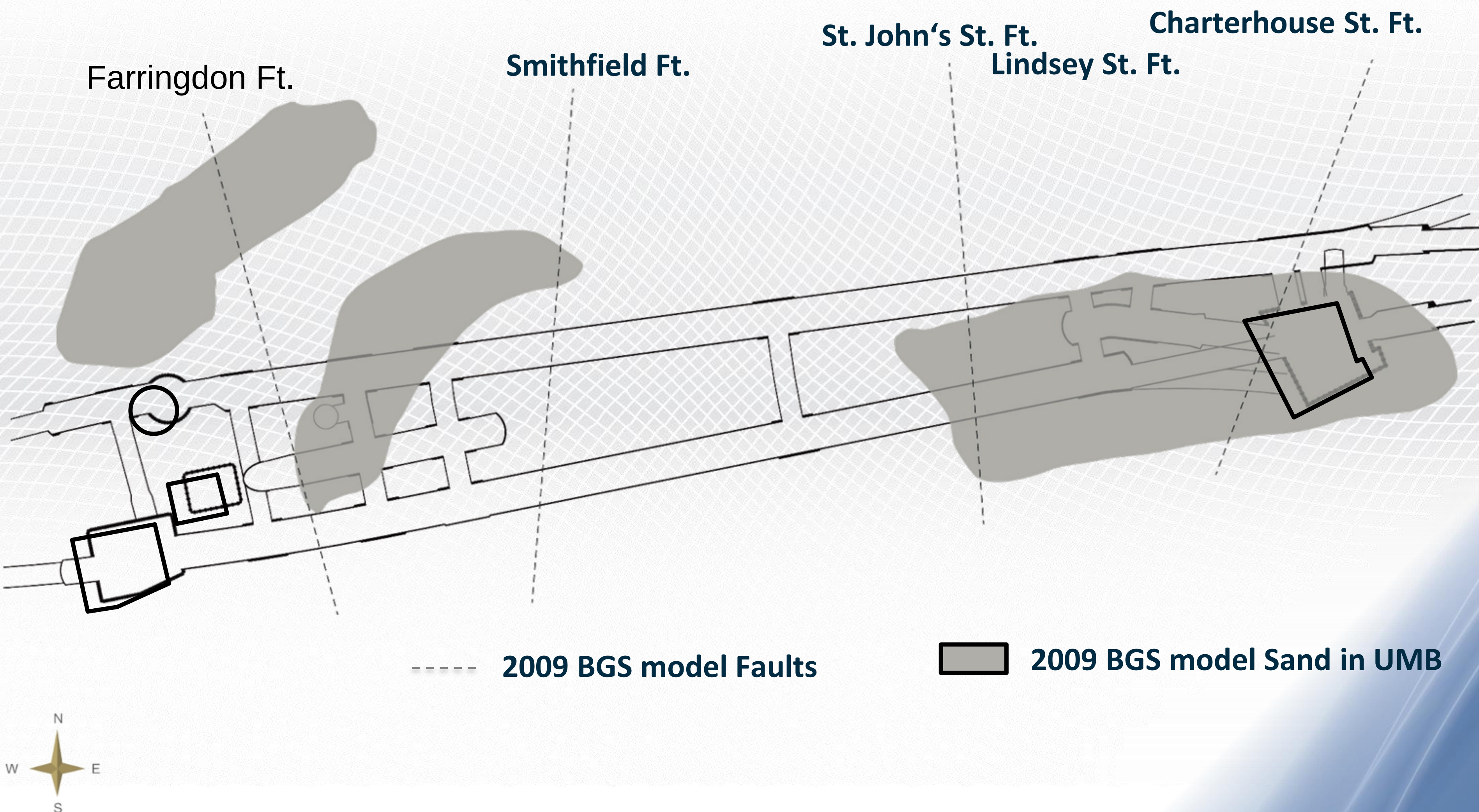
- Farringdon Fault
- Smithfield Fault
- St. John Street Fault
- Charterhouse Fault
- Lindsey Street Fault





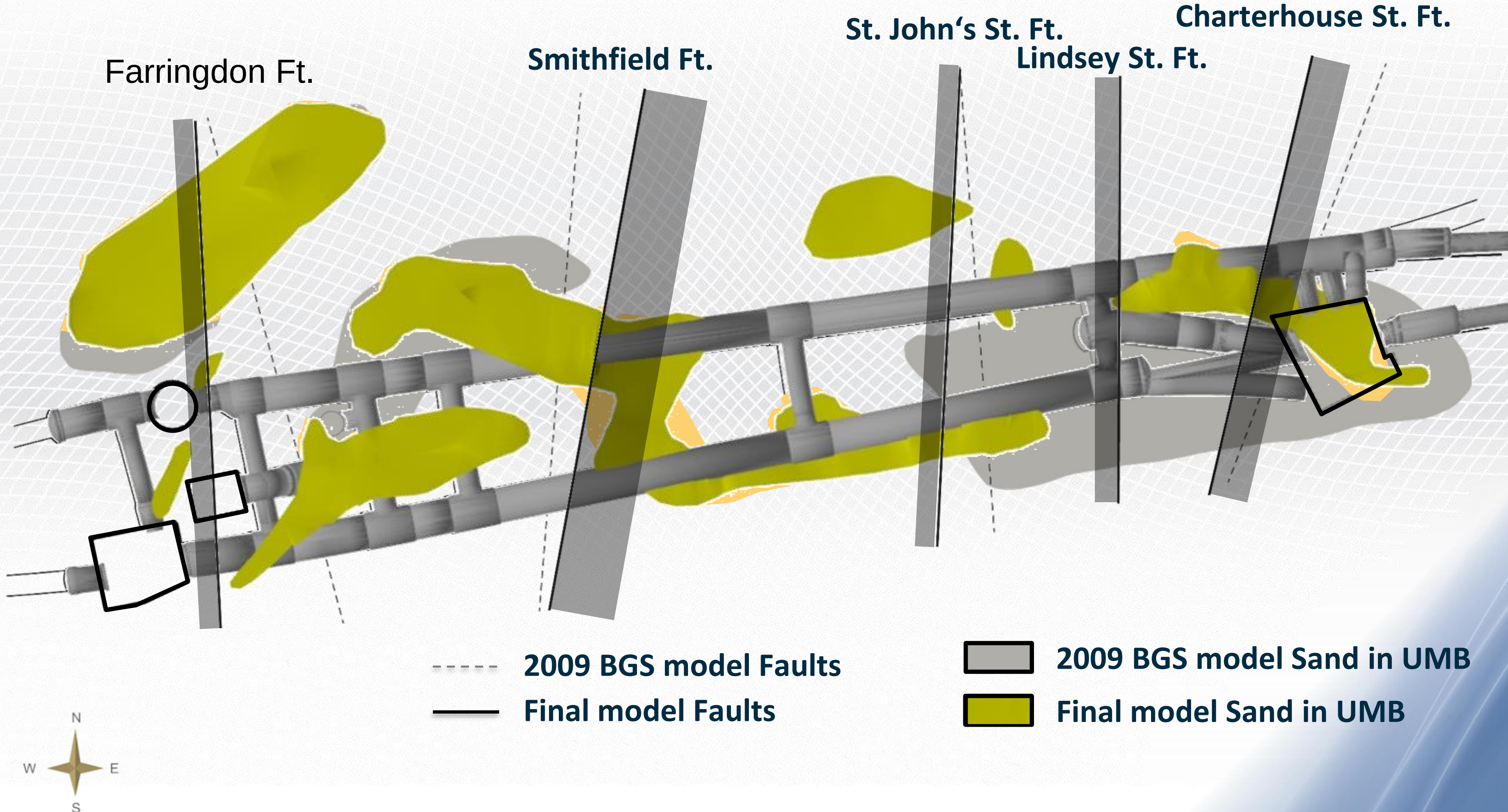
Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

BGS modelled - Faults and Sand
2009 model



Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

Final and BGS faults and sand



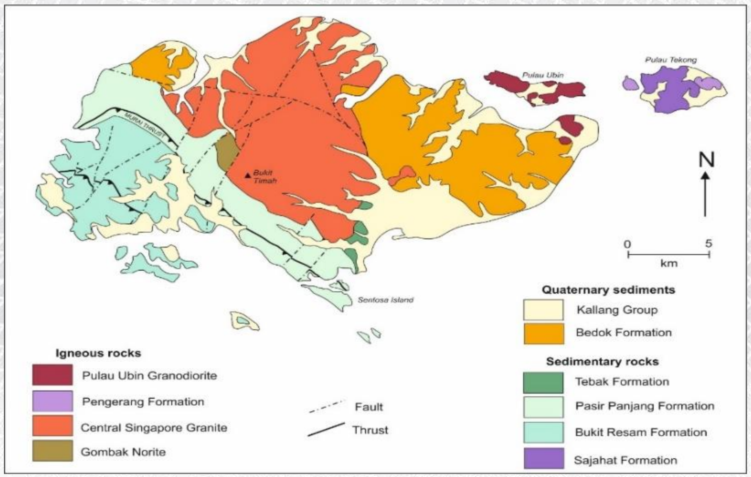
Thanks to Crossrail, Angelos Gakis, Dr Sauer & Partners

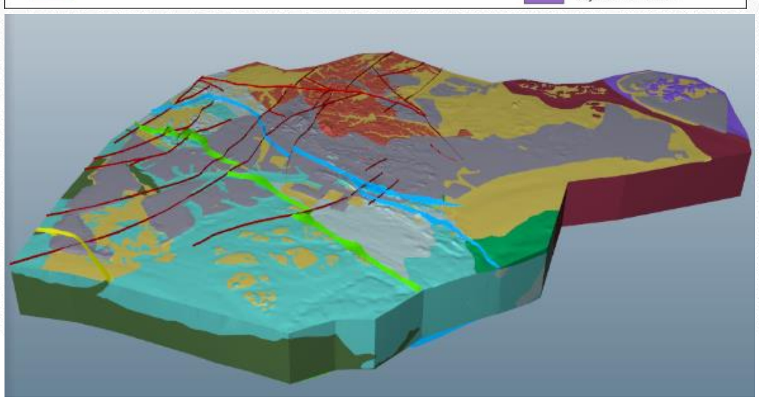
Example 2 Singapore – bedrock

BGS Involvement 2012-14

ICS is the International Commission Stratigraphy

- First project commissioned by the Building and Construction Authority (BCA)
- Desk study; fieldwork; digitisation geological maps; ICS lithostratigraphical framework; national scale 3D geological bedrock and superficial deposit models; training and knowledge exchange.





Building and Construction Authority

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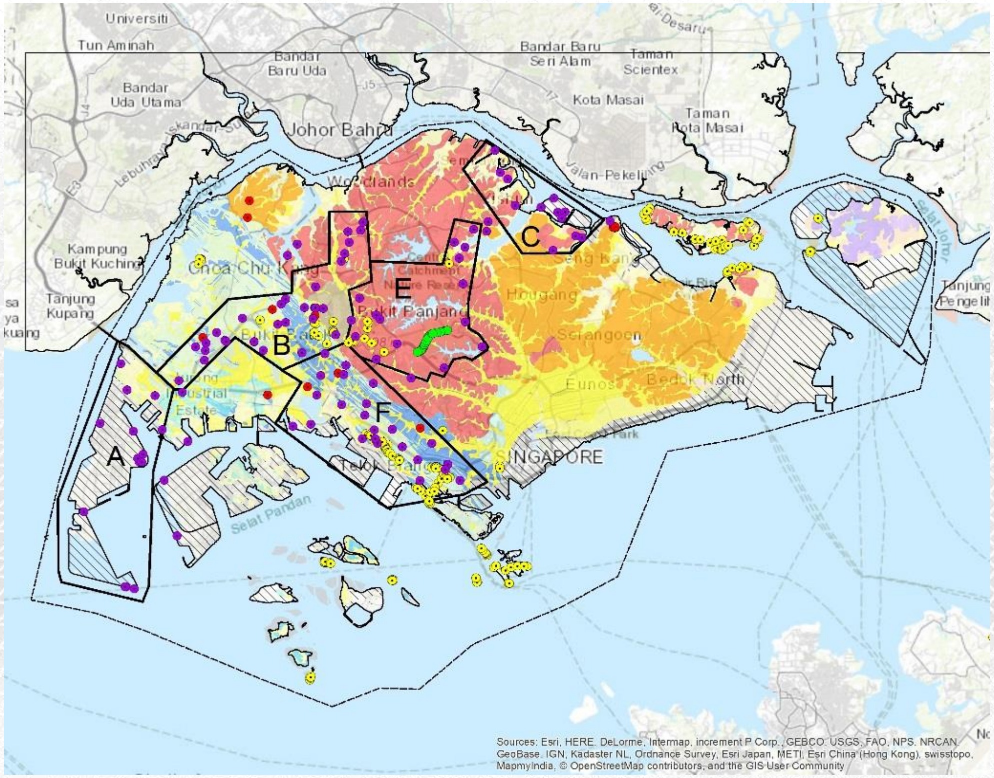
Building and Construction Authority

BGS Study 2016 -18



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Objective: Resolve bedrock geology of Singapore

Develop new more suitable lithostratigraphical framework and 3D geological models to aid subsurface development in Singapore.

New information including: new and new field observations collected by BGS across Singapore.

Main outcomes

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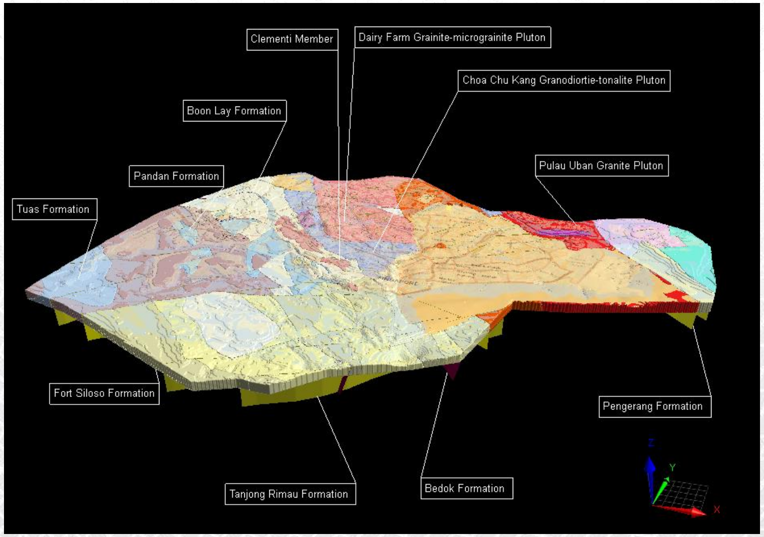
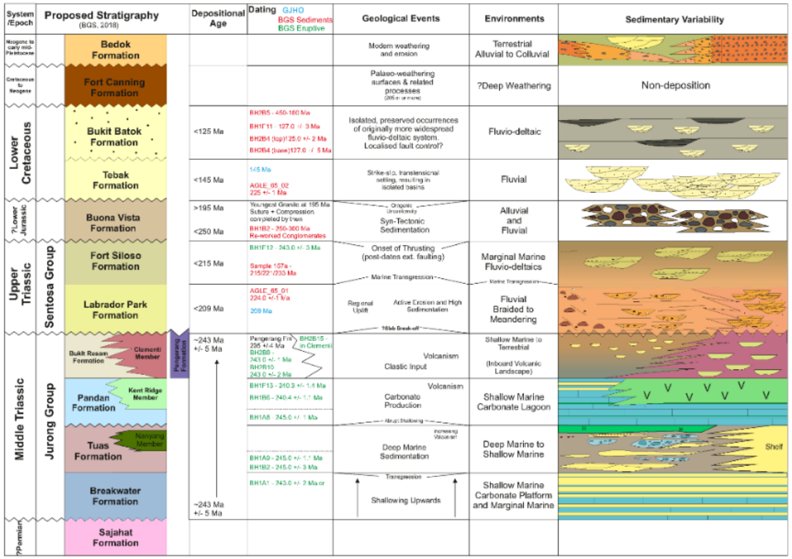
Chronostratigraphical divisions			Lithodemic units (rank and name)		
Period	Epoch	Age	4	5	6
Cretaceous	Upper Cretaceous	Cenomanian		Pulau Sekudu Quartz-monzonite Pluton	
Probably no older than Upper Triassic Epoch and no younger than Lower Cretaceous Epoch				Singapore Basalt–andesite Dyke-swarm	unnamed dykes
Triassic	Upper Triassic	Carnian	Bukit Timah Centre	Pulau Ubin Granite Pluton	
				Simpang Granite Pluton	
	Middle Triassic to Upper Triassic	Anisian to Carnian		Dairy Farm Quarry Granite–rhyolite Pluton	
Permian to Triassic	Guadalupian to Middle Triassic	Capitanian to Anisian		Gombak Gabbro–granite Pluton	
Permian	Cisuralian	Artinskian		Choa Chu Kang Granodiorite–tonalite Pluton	





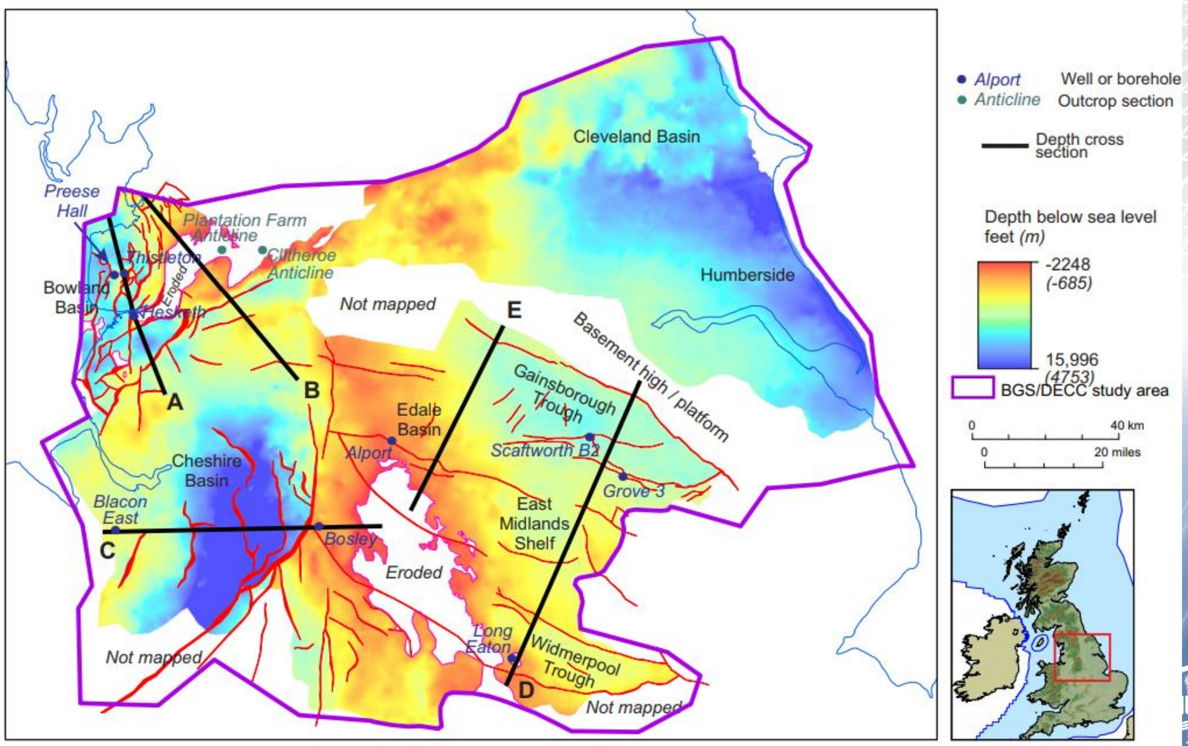
- Revised lithostratigraphical framework
- Substantial revision to the structural geological framework
- Comprehensive facies analysis of all sedimentary bedrock units
- Revised understanding of the evolution of the bedrock geology. Better constraint of ages of deposition and deformation

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



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)

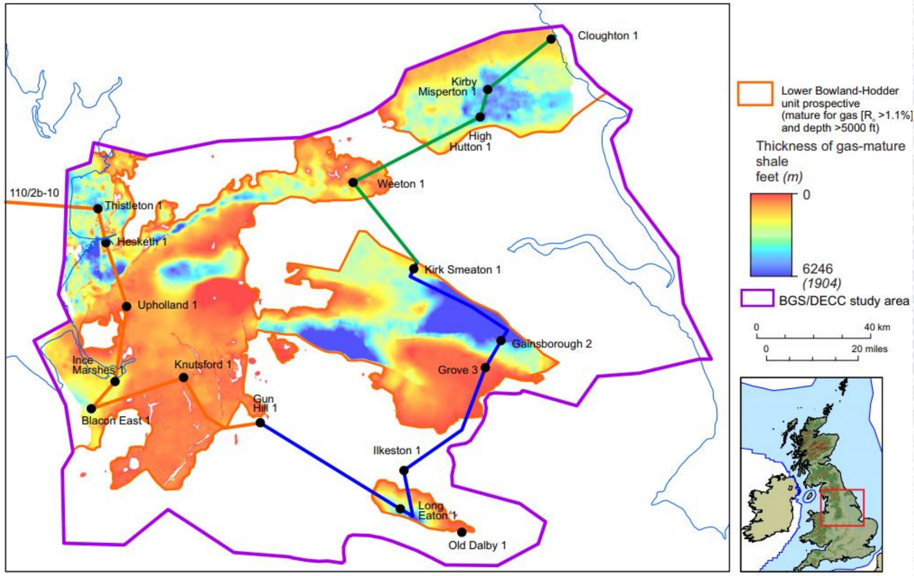


Figure 40. Thickness and distribution of shales of the lower Bowland-Hodder unit that are within the gas window and at a depth greater than 5000 ft.

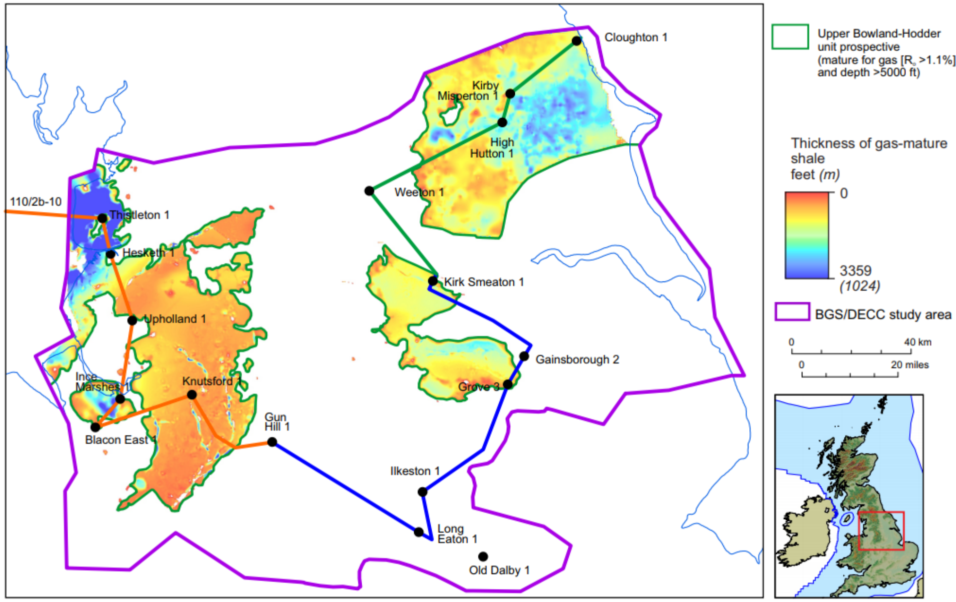


Figure 41. Thickness and distribution of shales of the upper Bowland-Hodder unit that are within the gas window and at a depth greater than 5000 ft.

Lower Bowland/Hodder unit

Upper Bowland/Hodder unit

Resource
Carboniferous Shale Gas: Geology and resource estimation
Summary map

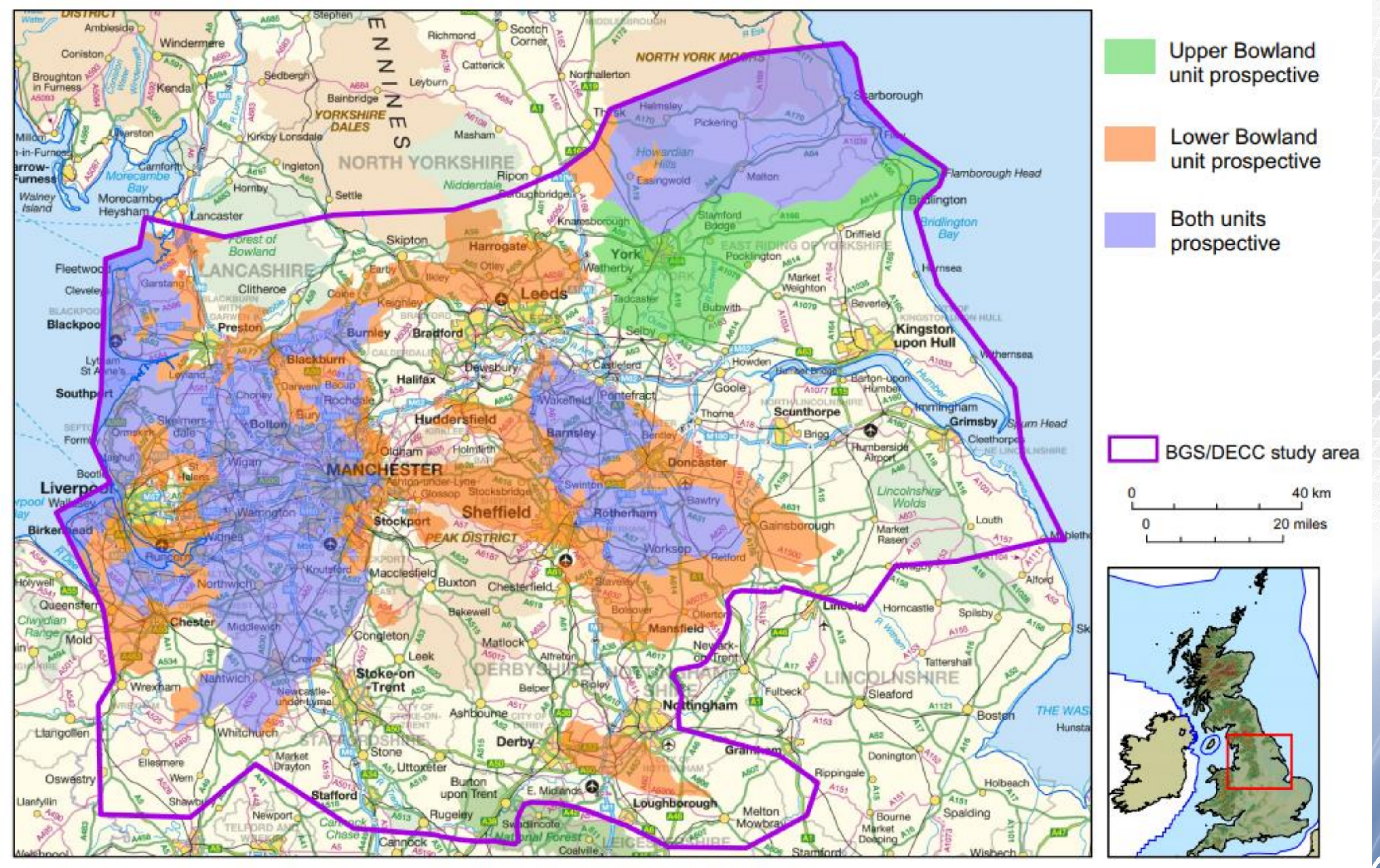


Figure 44. Summary of areas prospective for gas in the upper and lower parts Bowland-Hodder unit in relation to the urban areas of central Britain.

Physical property modelling – stochastic voxels

Voxel: a regular volumes (boxes) relative to other volumes - used in visualisation and analysis of values. (Used in oil and gas reservoir modelling)

BGS -

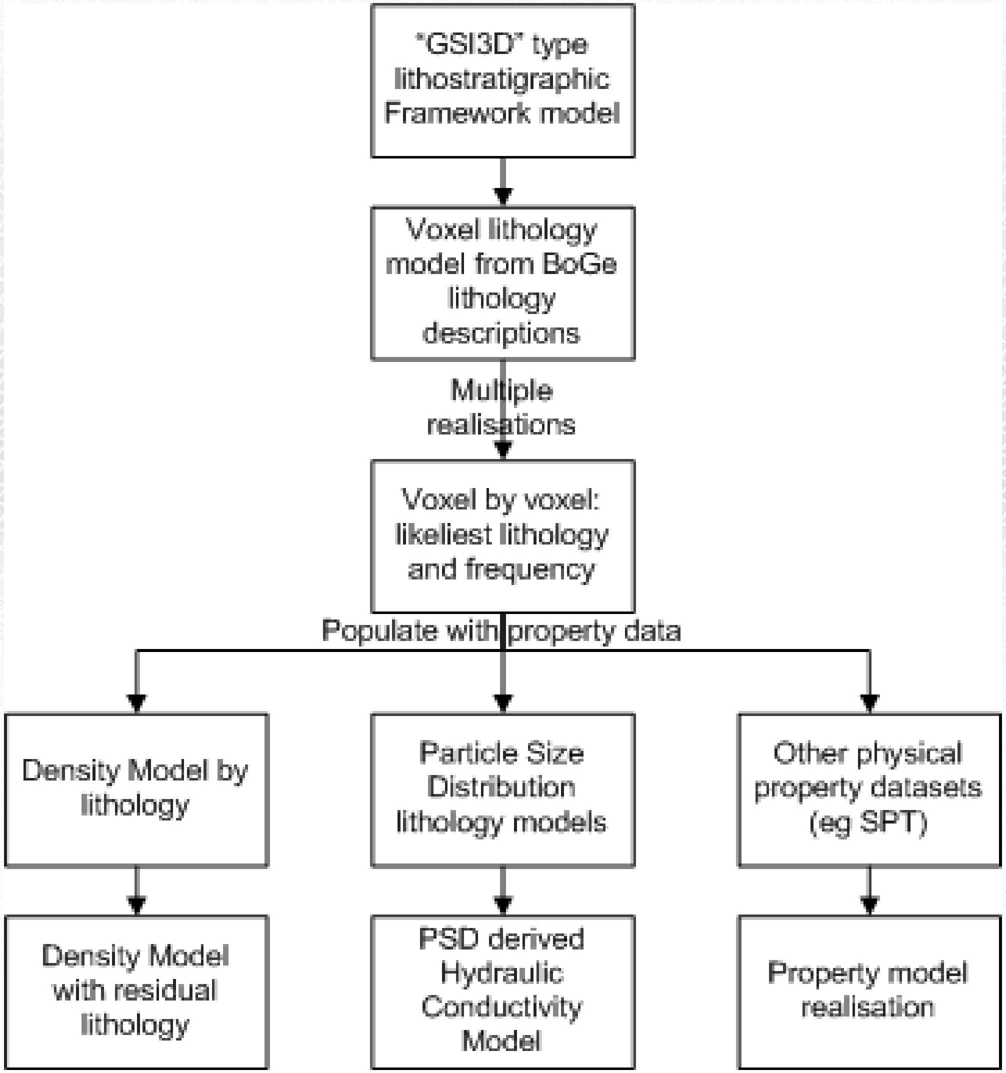
Based on upscaling observation (lithology, parameter values)

Assessment of uncertainty – multiple realisations

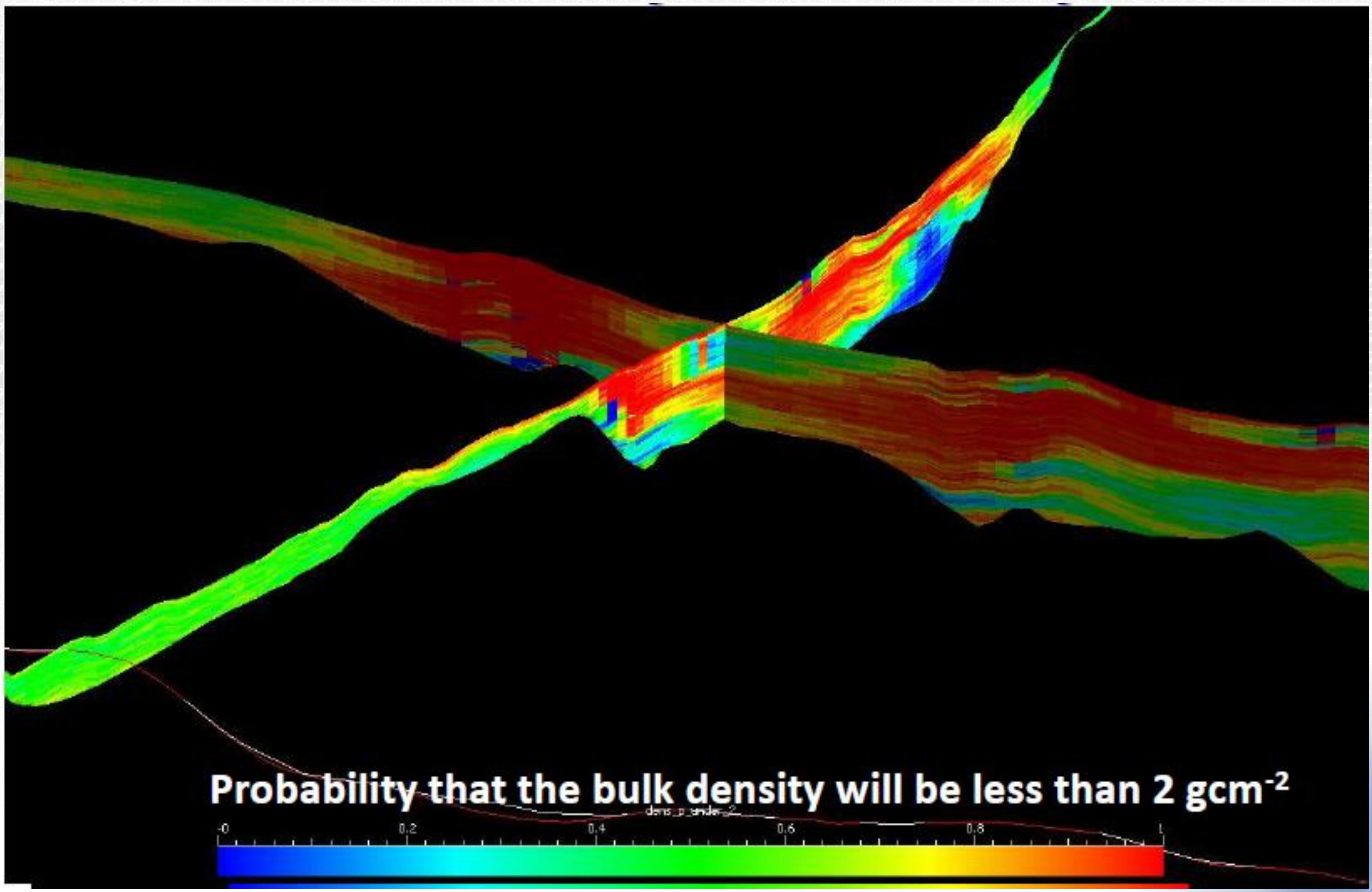
- Probability of a limited set of values in any voxel
- Constraints on simulations
- Example probability of sand occurring, bulk density is <2 Mg/m^3, hydraulic conductivity based on particle size

nora.nerc.ac.uk/501765/

Physical property modelling – stochastic voxels
Flowchart of property modelling

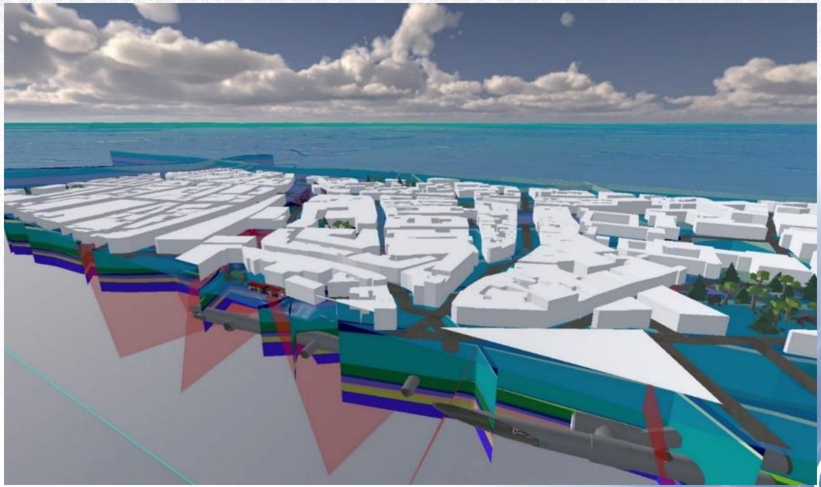


Physical property modelling – stochastic voxels Example – bulk density



GeoVisionary examples

- Data Integration
- CAD Models
- Lidar point clouds
- 3D Geological Model data



Model delivery

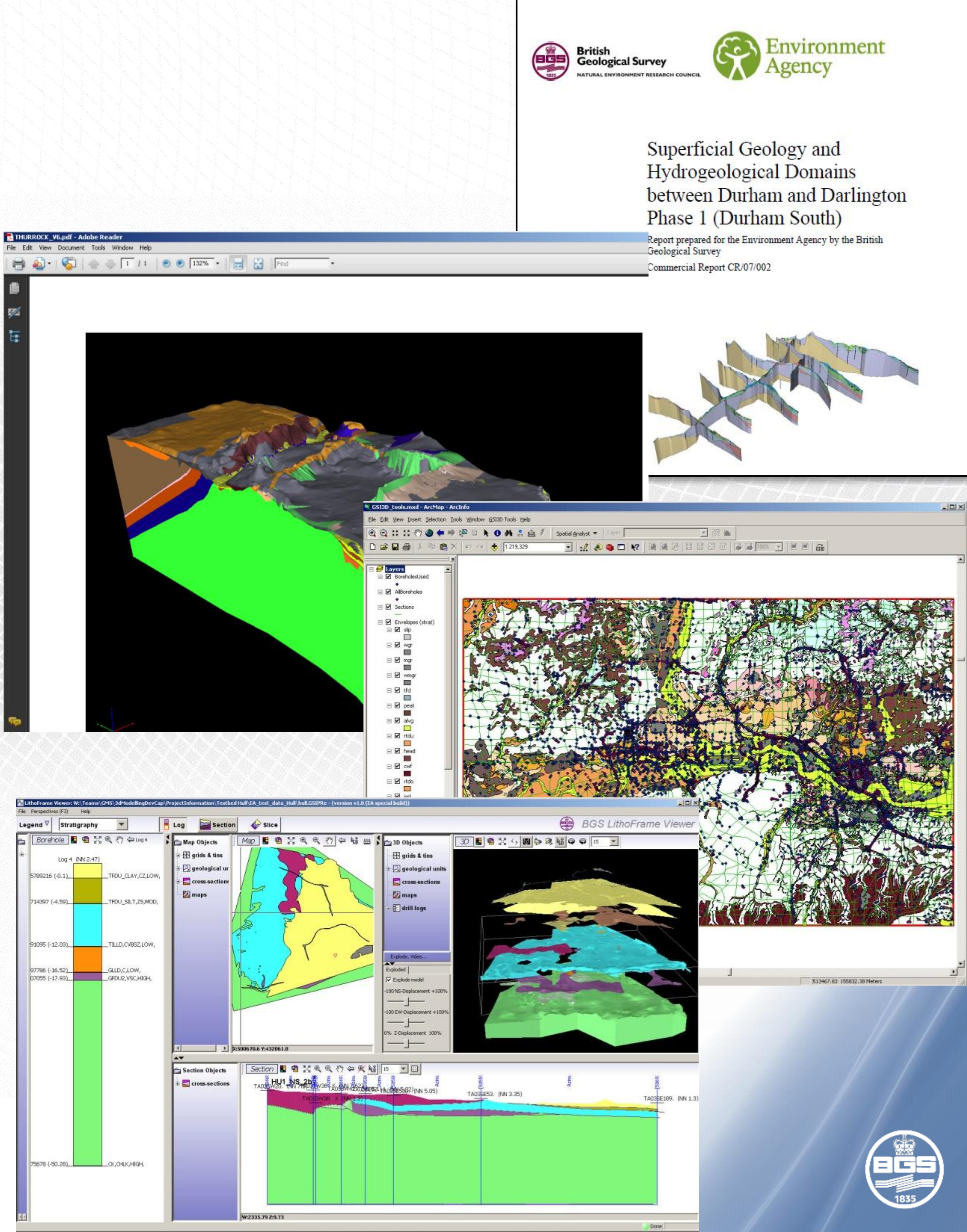
- Papers and reports,

Model

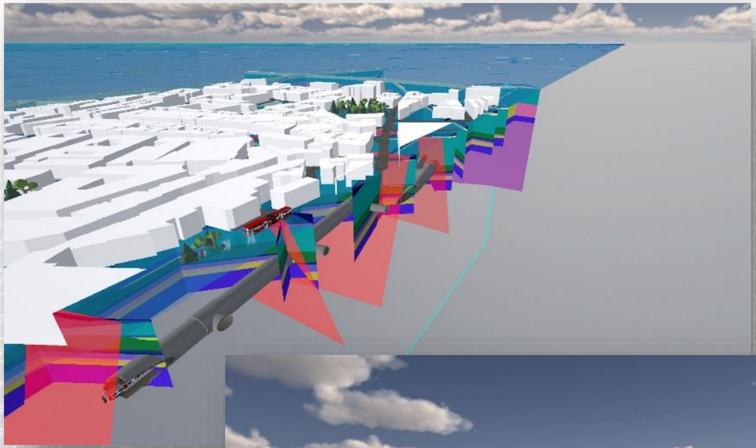
- GIS (.shp, .grid), 3Dpdf
- Model Viewers (Lithoframe viewer, synthetic cross-sections and boreholes),
- CAD,
- 3D software

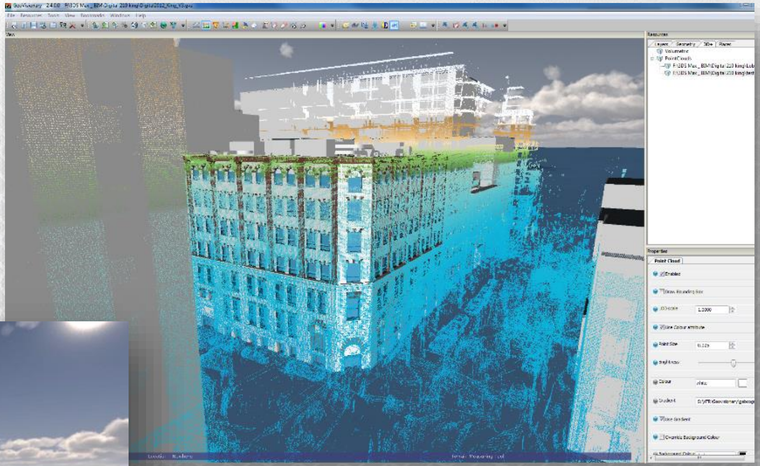
- Bespoke thematic outputs to address specific issues provided as required

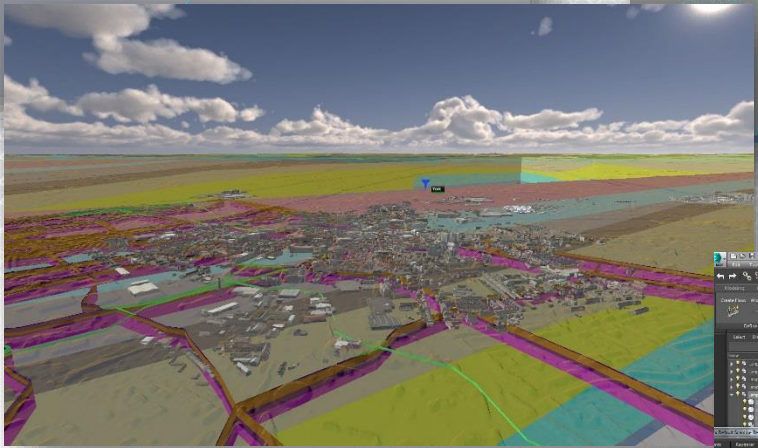
- Web enabled via extranet delivery

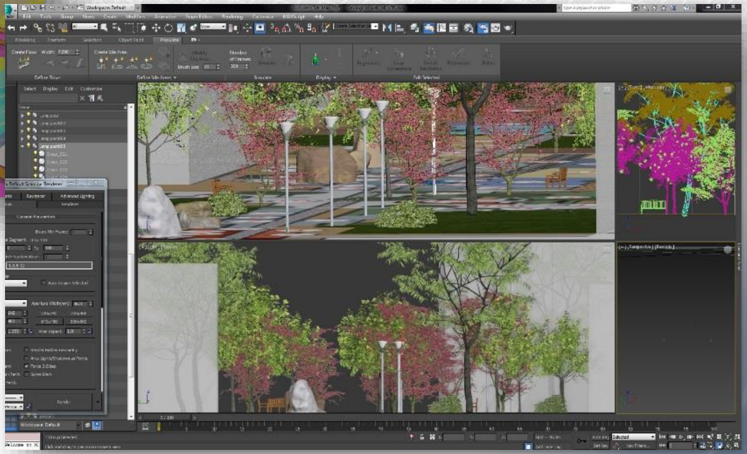


CAD model integration









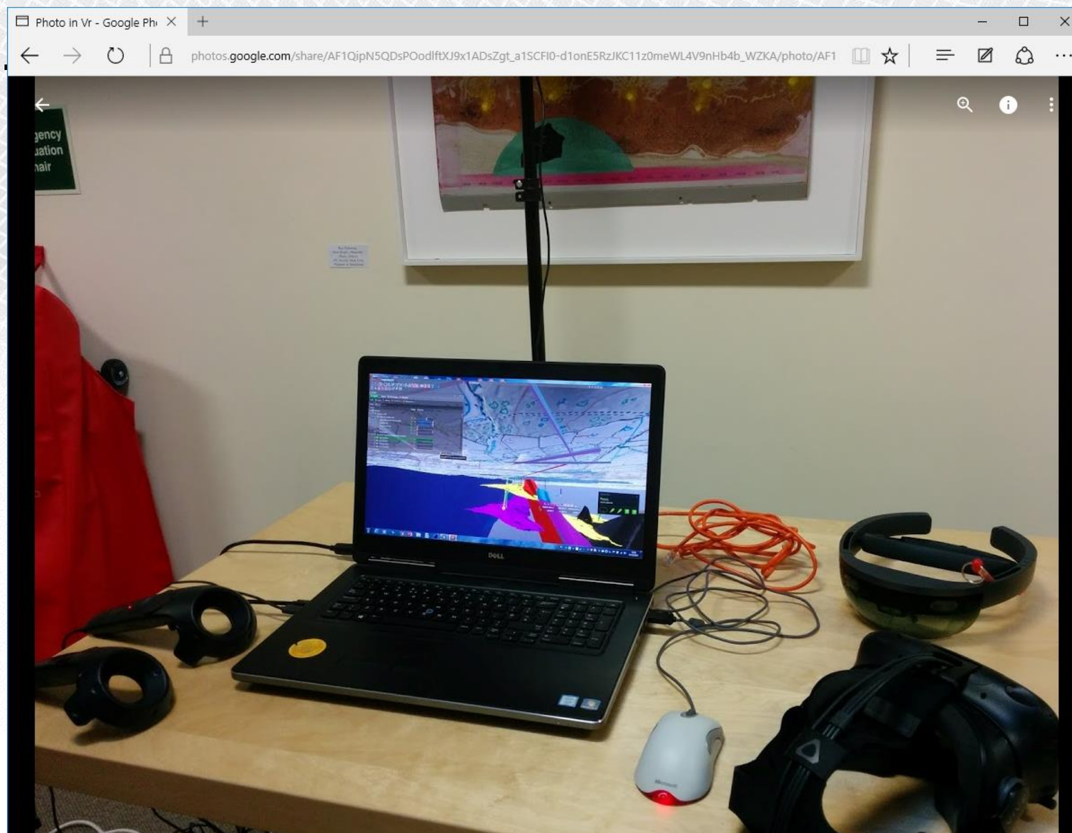
3DVS can bring together data from engineers and geoscientists, enabling better cooperation and understanding

Future Delivery Systems

Web Delivery (e.g. Geology of Britain Viewer 3D)
or bespoke web delivery systems
Plus – commercial delivery

Cloud served data

Augmented Reality



Provision of 3D models - Lithoframe viewer etc.

https://www.bgs.ac.uk/services/3dgeology/lithoframeSamples.html

LithoFrame samples

Sample LithoFrame models are available as free downloads in various formats.

Model data downloads

The sample downloads are also available to view in the virtual borehole and section viewer.

Visualisation of the 3D PDFs is recommended on PCs and laptops using a Windows operating system. The 3D PDFs use Flash Technology so is unlikely to work or will suffer poor performance on devices using IOS and Android operating systems.

Samples	3D pdf	LithoFrame Viewer	Other formats	Information
National Bedrock Fence Diagram (UK3D)	UK3D England North 3D pdf UK3D England South 3D pdf UK3D Northern Ireland 3D pdf UK3D Scotland 3D pdf UK3D Wales 3D pdf	UK3D LithoFrame model	UK3D individual sections (KMZ format)	Report describing the National Bedrock Fence Diagram
Thurrock	Thurrock 3D pdf	Thurrock LithoFrame model	• ASCII grids [Download] • ESRI shells [Download] • Gocad surfaces [Download]	Thurrock model information
York	York 3D pdf	York LithoFrame model	Not available	York model information

Uncertainty/confidence (explicit models)

What is uncertainty/confidence?

"A parameter associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the object being measured"

BGS Three primary methods of investigation

- A structured approach to the measurement of uncertainty in 3D geological models
- Statistical and Multi-component uncertainty in 3D models http://nora.nerc.ac.uk/id/eprint/503978/ http://nora.nerc.ac.uk/id/eprint/503860/
- Expert elicitation

Uncertainty/confidence (explicit models)

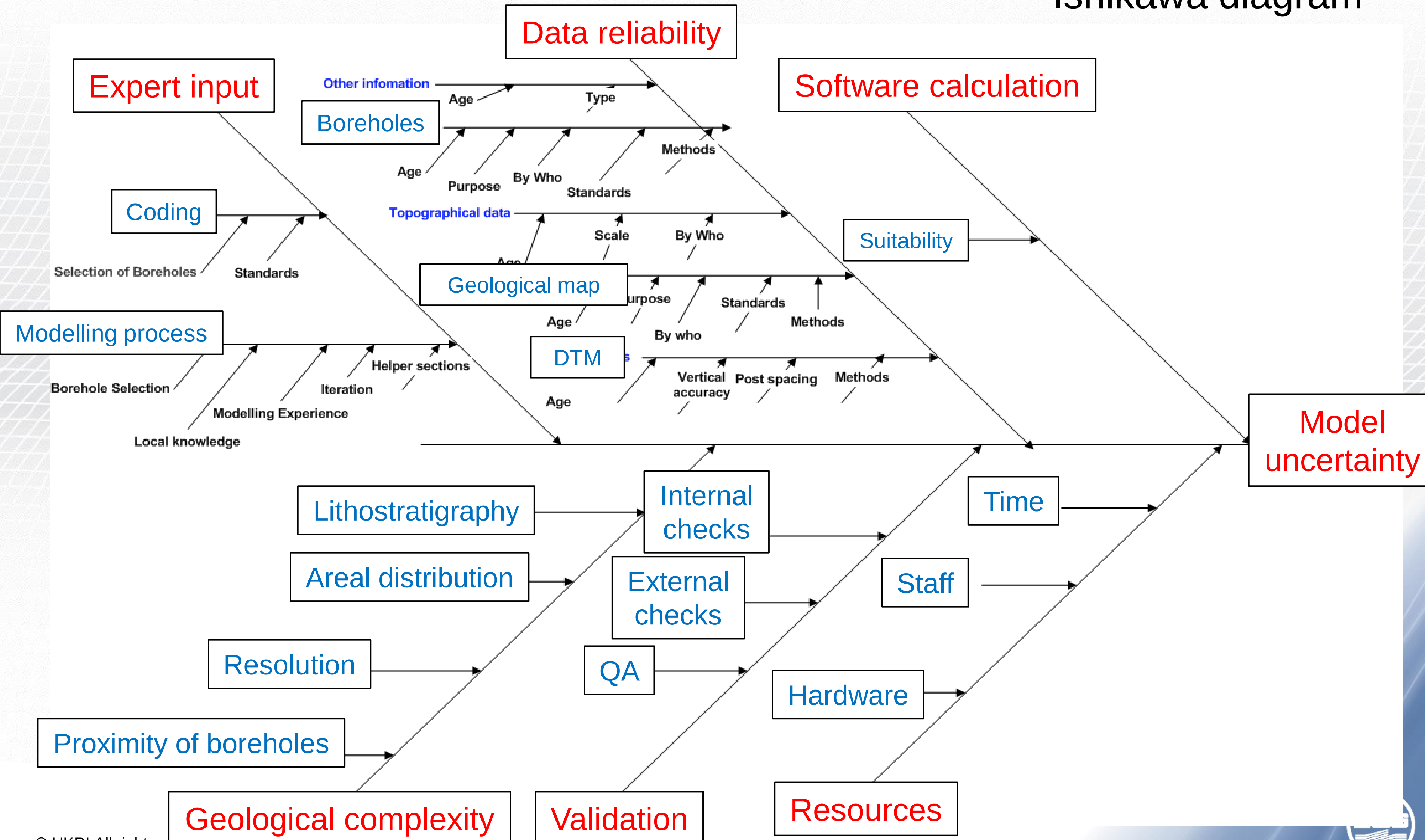
http://nora.nerc.ac.uk/id/eprint/6959/

- Identify all sources of uncertainty (Fish Diagram)
- Arrive at a definition of ‘Fit for Purpose’ for the project
- Identify qualitative and quantitative uncertainties
- Measure/model uncertainty from each branch of the Fish diagram (bootstrap, fuzzy logic)
- Combine the inputs to arrive at an overall uncertainty
- Decide how to represent the final uncertainty

https://www.bgs.ac.uk/research/environmentalModelling/ParametrisationAndGeostatistics.htm
http://nora.nerc.ac.uk/id/eprint/509482/
http://nora.nerc.ac.uk/id/eprint/503860/
sp.lyellcollection.org/content/specpubgsl/436/1/1.full.pdf

Understanding uncertainty –

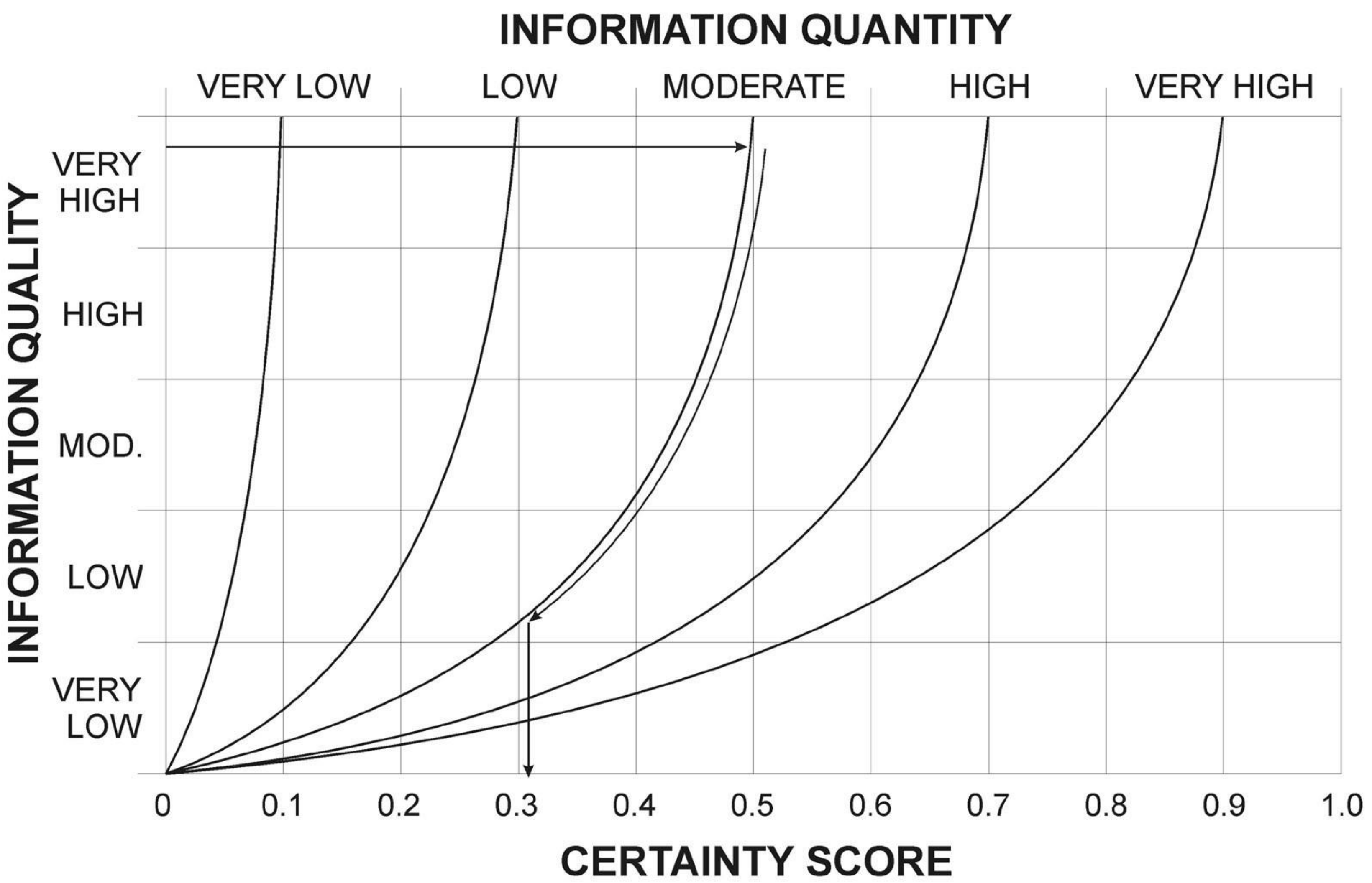
Ishikawa diagram



Uncertainty confidence Qualification of terms

		DATA	THEORY	METHOD	AUDITABILITY	CALIBRATION	VALIDATION	OBJECTIVITY	EXPERT
1.0–0.8	VERY HIGH	Measured or field data collected specifically for making this interpretation.	Well-established and highly accepted geological theories were used in the	Field survey or direct measure of data following appropriate *Best Practice* guide-lines.	Well documented, clear link between raw geological data and interpretation.	Interpretation correlates with all available raw geological data.	This interpretation is the only geologically sound interpretation of available	No discernible bias to preconceived geological understanding or interpretative	Interpreter is familiar with theories/metho ds and has the local geological knowledge required to
0.8–0.6	HIGH	Historical, or field measured data collected as part of the general survey process, or for another	Accepted theories with a high peer consensus.	Majority field survey or direct measure with iterative checking. Some additions from desk	Poorly documented but traceable link from interpretation to raw geological	Interpretation correlates with the majority of available geological data - anomalies can be	Interpretation is the strongest solution to available data but a few, less likely interpretations	Influence of understanding of the regional geology but not at the expense of evidence from data.	Interpreter is familiar with theories, methods required but unfamiliar with aspects of the
0.6–0.4	MOD.	Computed or derived/calcula ted geological data including statistically generated values.	Accepted theory but poorly tested, lacking in examples or with a low peer consensus.	Desk compilation from derived/ historical data with field-checking, or from	Raw geological data traceable in part.	Interpretation correlates with most available data but some small, local, unexplained anomalies	Interpretation is valid but a few, equally valid interpretations would fit the data just as well.	Moderate bias towards specific style of interpretation in data-poor areas but data evidence not	Interpreter is unfamiliar with aspects of the theory or method required to make the
0.4–0.2	LOW	'Standard' values or approximated numbers.	Preliminary theory, poorly tested and un-validated.	Desk compilation from historical, inappropriate or insufficient data with no field check.	Weak, unclear or ambiguous link to the raw geological data. Original data on which the	Interpretation correlates with most data but geologically significant and/or large-scale,	A significant number of plausible interpretations would fit the data.	Strong bias towards specific style of interpretation even the face of refuting geological	Interpreter is significantly lacking in understanding of theory or methods required to
0.2–0	VERY LOW	Ball-park approximation.	Crude speculation.	No discernable rigour, best guess interpretation.	No link to the raw geological data, no recorded input to interpretation.	Correlation with the minority of data or no apparent correlation.	The interpretation is speculative.	Obvious bias toward specific interpretation and disregard of significant geological data.	Interpreter has little or no knowledge of the theories or method required to make the

Estimation of information quality



Uncertainty Summary Documentation

Type of Uncertainty				Score	Explanation	
Main Branch	**Small branch**	**Twig**	**Leaf**			
Expert Input				9	For even the simplest models, expert input is essential	Poor (0-2.5) Medium Poor (1.5-4.5) Medium Good (4-7.5) Good (7-10)
	Interpretation			5	Uncertainty will arise from ones 'own' style of interpretation of all data available which will be different from an interpretation of the same data by some one else. The differences will depend upon other factors e.g. knowledge, timetable. For two persons of similar backgound one would generally get interpretations that are broadly the same but with minor differences	Low Confidence (0-2.5) Acceptable Confidence (1.5-4.5) Confident (4-7.5) High Confidence (7-10)
	Goal uncertainty			5.5	It is important to understand what the model is being made for. If you do not know what is the model being made for it will be unfocussed and not meet the requirements for that work. It is a big influence on both the interpretation and the model	Undefined (0-6.5) Defined (4.5-10)

Fuzzy Model

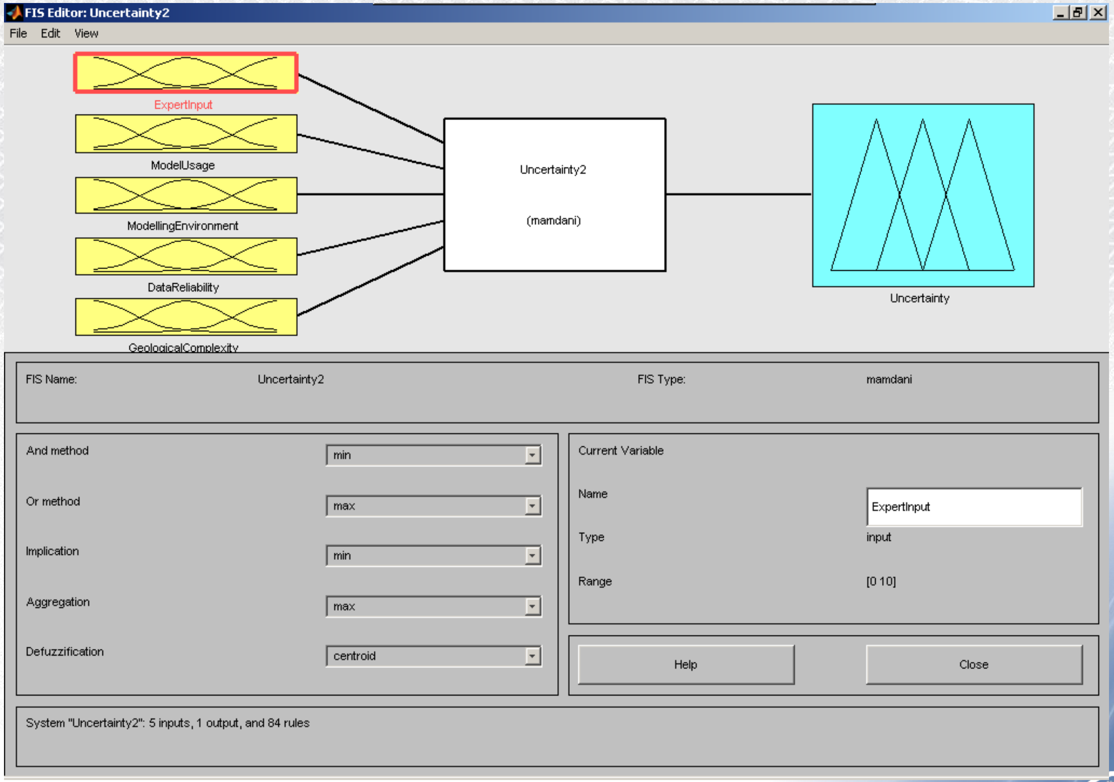
Fuzzy logic - Approach to computing base on ‘degrees of truth’ not true or false.

Used six fuzzy inference systems

30 input functions

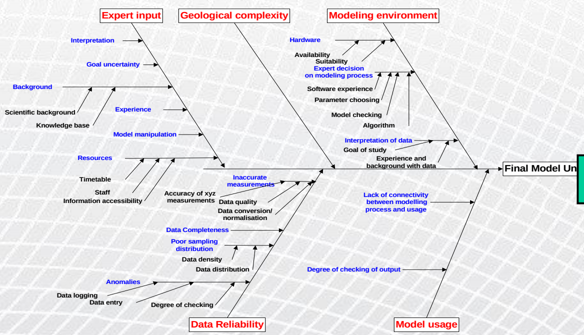
4 output functions

84 rules

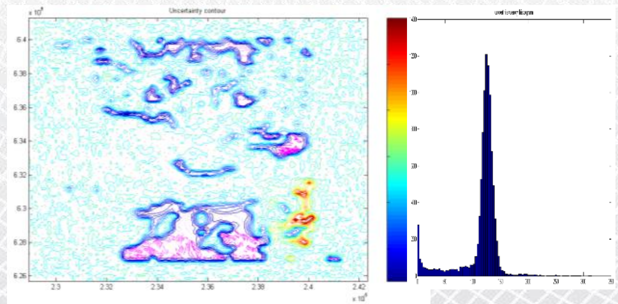


Uncertainty/confidence

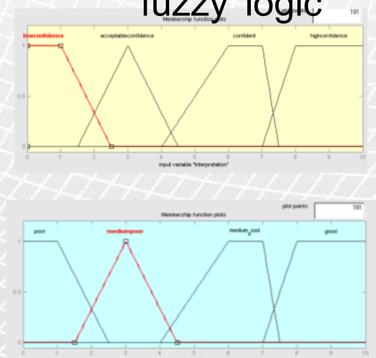
Cause and Effect Diagram



Assess data density and surface fitting uncertainty



Set up input and output membership functions – 'fuzzy' logic



Construct the uncertainty rules

1. If (Interpretation is highconfidence) then (Expertinput is good) (1)
2. If (Interpretation is lowconfidence) and (ModelManipulation is highlymanipulated) then (Expertinput is poor) (1)
3. If (Interpretation is lowconfidence) and (ModelManipulation is untouched) then (Expertinput is mediumpoor) (1)

Apply uncertainty scores to all data

Set up and run the combined uncertainty model

Nora.nerc.ac.uk/id/eprint/6959/

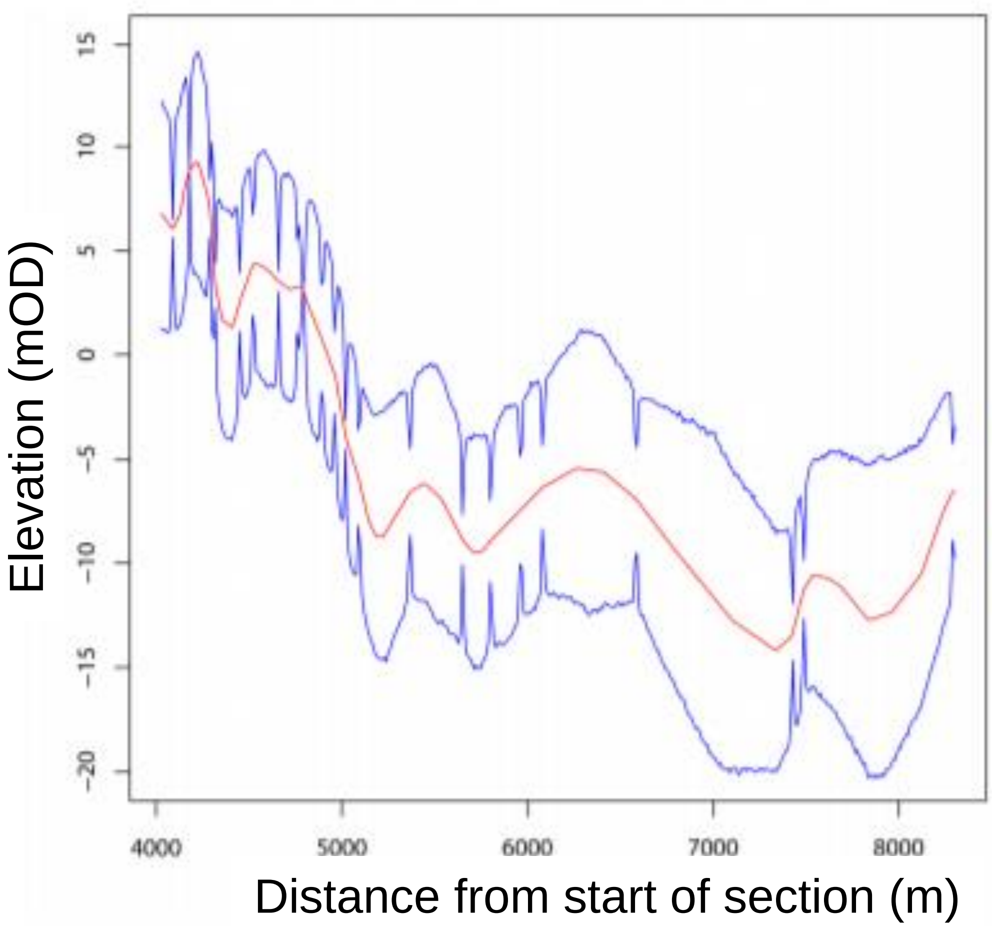
Uncertainty/confidence assessment
Expert Elicitation – borehole logs

Structured questioning of geologists – consensus for geological model and uncertainty.

Geologists create a model and inferring the uncertainty from differences in interpretations

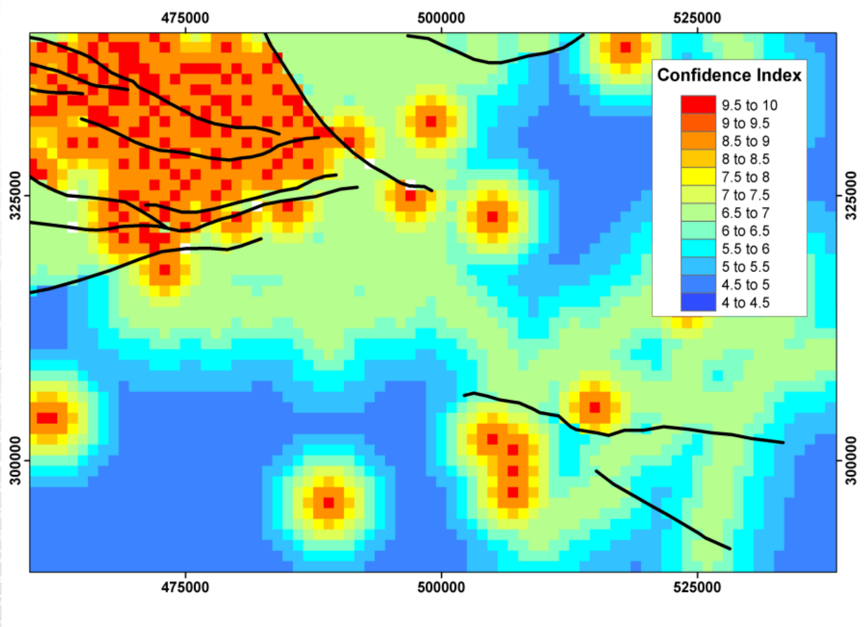
Solid Earth (2014) 5, 1189-1203

Solid Earth, 6, 727–745, 2015
www.solid-earth.net/6/727/2015/



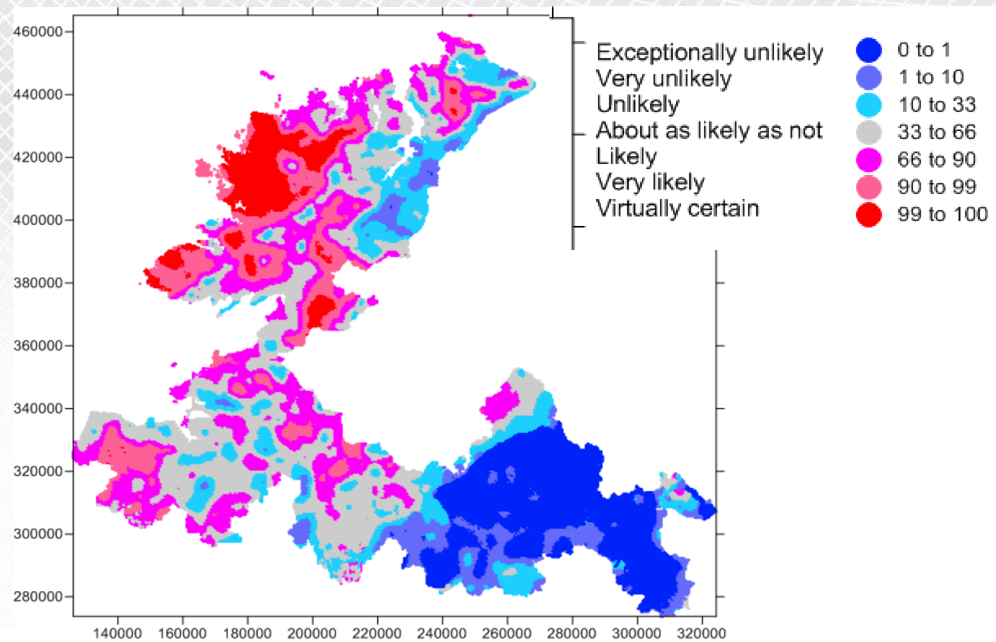
One geologist's interpretation of the base of the London Clay Formation (red) with 95% confidence intervals (blue)

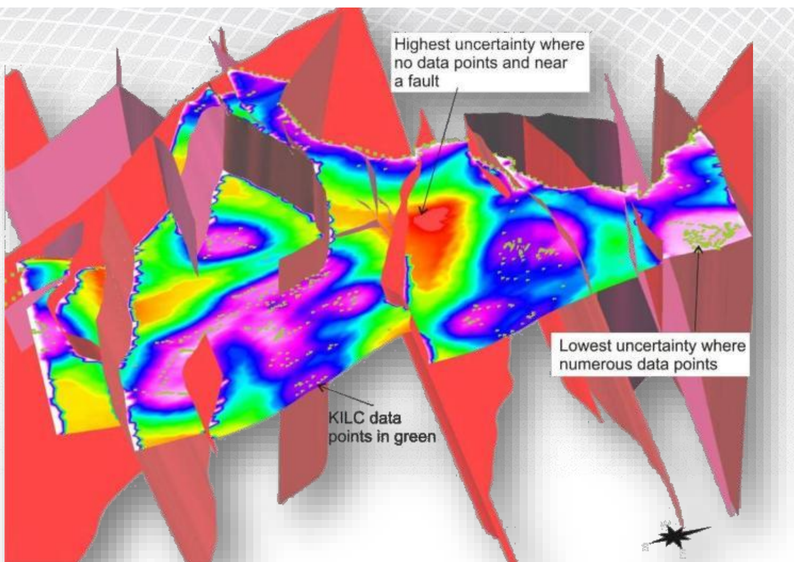
Presenting Uncertainty/Confidence



Probability not a quantitative value + or – 5 m

Work in progress





nora.nerc.ac.uk/510117/

nora.nerc.ac.uk/500548/

Summary

A snap shot of BGS 3D geological models and modelling

- Why a 3D model?
- Data, information and knowledge needed
- Software - Explicit & Implicit Modelling
- Metadata and reports
- Examples of models
- Model delivery
- Uncertainty/confidence

Not including:

Much of the BGS work!