



## **Modelling shallow urban geology using reservoir modelling techniques: voxel-based lithology and physical properties of the greater Glasgow area**

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Conventional 3D geological models of lithostratigraphy undertaken by BGS have facilitated a significant step forward in understanding of the 3D sedimentological and structural controls in the subsurface of the UK.

However, when lithostratigraphic units are mapped or modelled in 3D, intra-unit variability is often not recognized and may be substantial, particularly in sedimentologically heterogeneous successions. Because of this BGS has been testing voxel grid-based approaches in urban areas with high borehole density. A city-scale lithology model of shallow, unconsolidated sediments in Glasgow, Scotland has been developed as a test of the applicability of these techniques to aid geological understanding and possible future applications. This is of particular significance in this location due to the complex fluvial and glacial history of the superficial geology which alternates between inter-fingering sedimentary packages and short-scale variability of subsurface materials.

The model has been created by developing a stochastic model of clastic geology on a voxel support, based on upscaling of observed borehole lithology, independent of lithostratigraphy. Multiple realisations of lithology were generated, each honouring the borehole observations. Lithology information has therefore been used to both develop a model of the distribution of lithology throughout the grid, but also to develop an understanding of the associated uncertainty by providing estimates of the probability with which a particular lithology occurs at a given node. This lithological model compares well with 'traditional' deterministic lithostratigraphic 3D models created in the same area, and with field-based geological maps.

This lithological voxel model has been used as a matrix through which physical property data can be attributed within the grid by stochastic modelling and simulation of the variability of properties within the lithological units. Several different property datasets have been populated across the grid, including geotechnical parameters, such as density, derived directly from site investigations, and properties derived from particle size distribution such as hydraulic conductivity. This can be augmented in deeper parts of the succession with borehole geophysical log derived property data.

This model may be applied to understanding of both the strength of the subsurface materials to aid development, and also hydrogeological properties to inform 4D process models, thus extending BGS's capabilities to deliver scientific understanding of geological problems. For example, with ongoing large-scale redevelopment of post-industrial sites across the Greater Glasgow area, these techniques have the potential to provide a clearer understanding of both the risks and opportunities of these sites. This project will act as an exemplar of the applicability of voxelated representations of lithology and physical property data to subsurface planning as a precursor to the wider rollout of the techniques to many UK cities.



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British Geological Survey

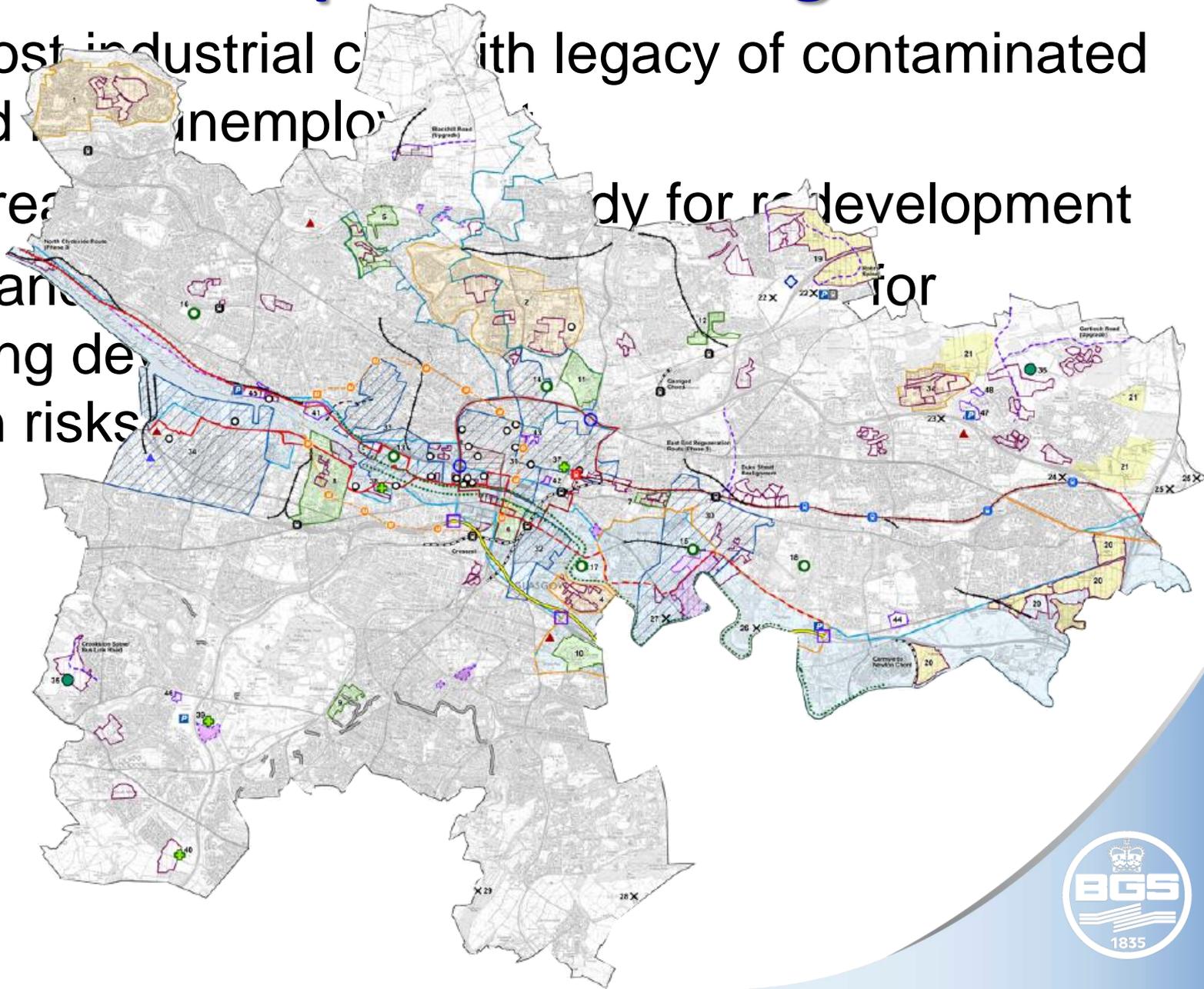
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# Redevelopment of Glasgow

- Large post industrial city with legacy of contaminated land and high unemployment
- Large areas of land ready for redevelopment
- Understanding and managing pollution risks for

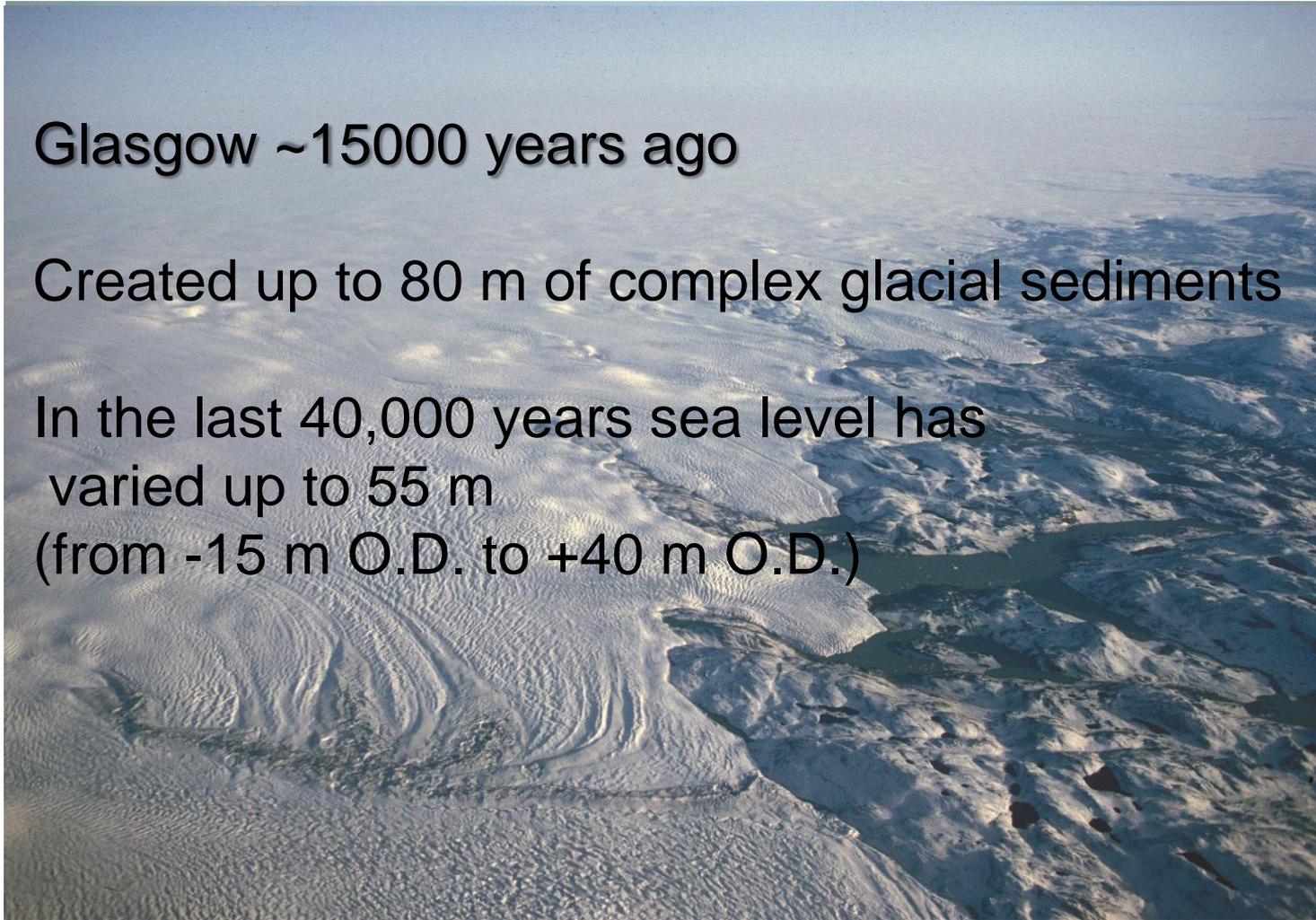


# Glasgow – Problems: Superficial Geology

Glasgow ~15000 years ago

Created up to 80 m of complex glacial sediments

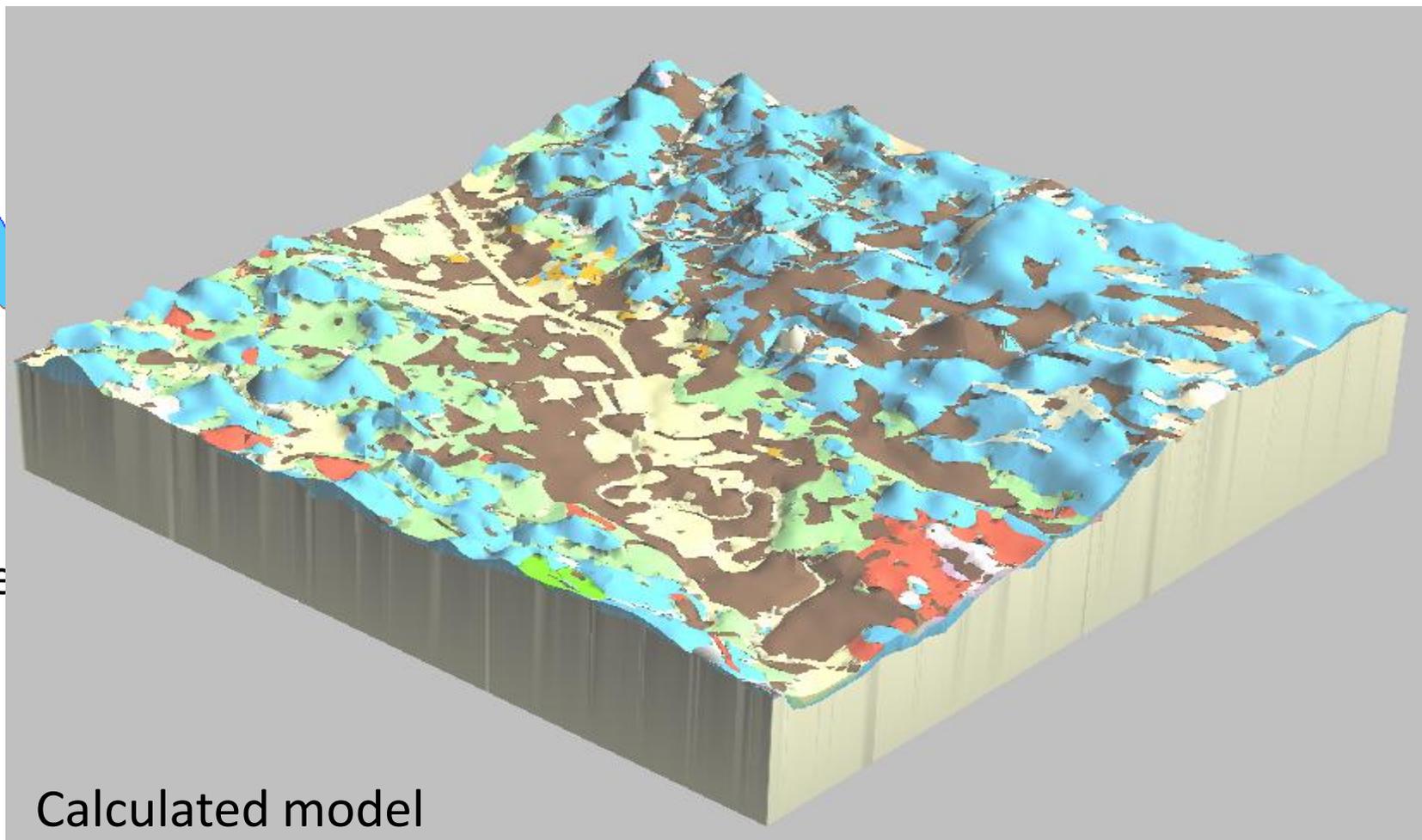
In the last 40,000 years sea level has varied up to 55 m (from -15 m O.D. to +40 m O.D.)



# 3D models – Deterministic Modelling



[www.gsi3d.org](http://www.gsi3d.org)

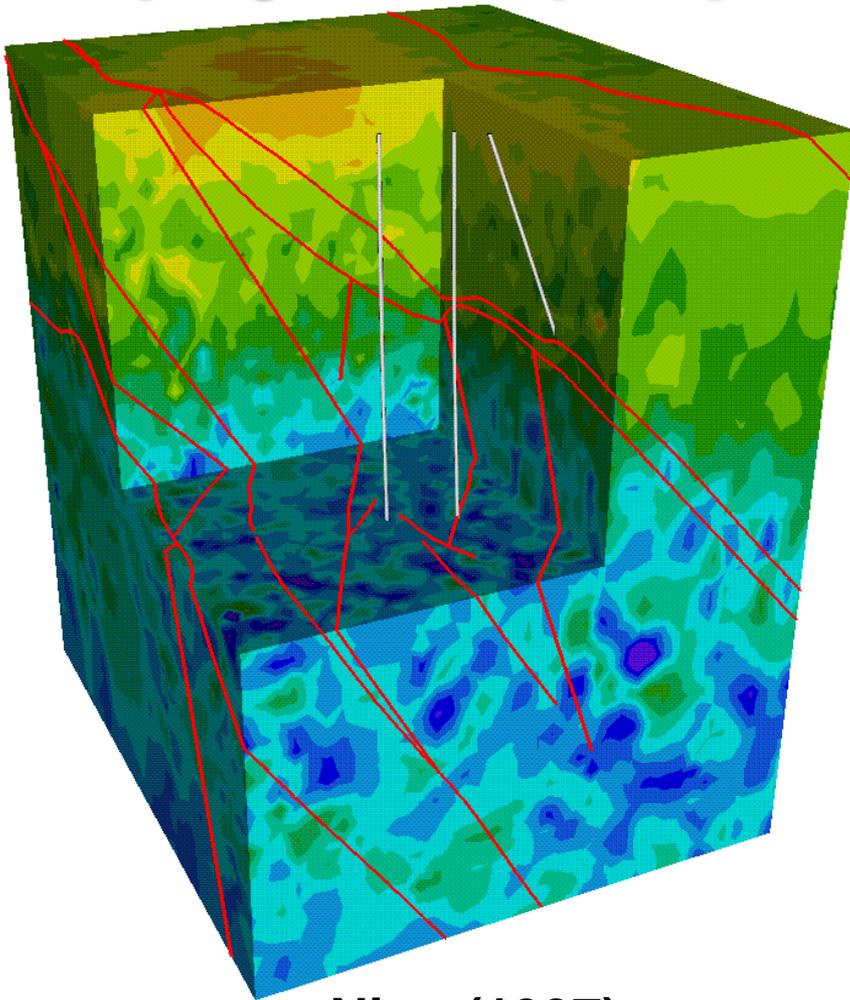


Interpre

Calculated model



# 3D physical properties model population



**Nirex(1997)**

**Sellafield acoustic impedance inverted seismic cube populated with upscaled rock strength**

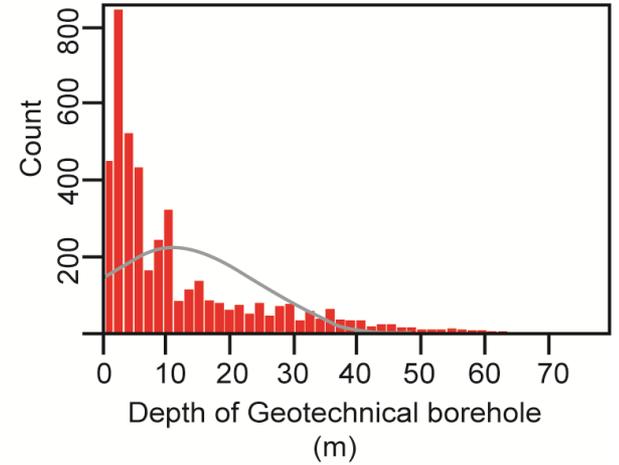
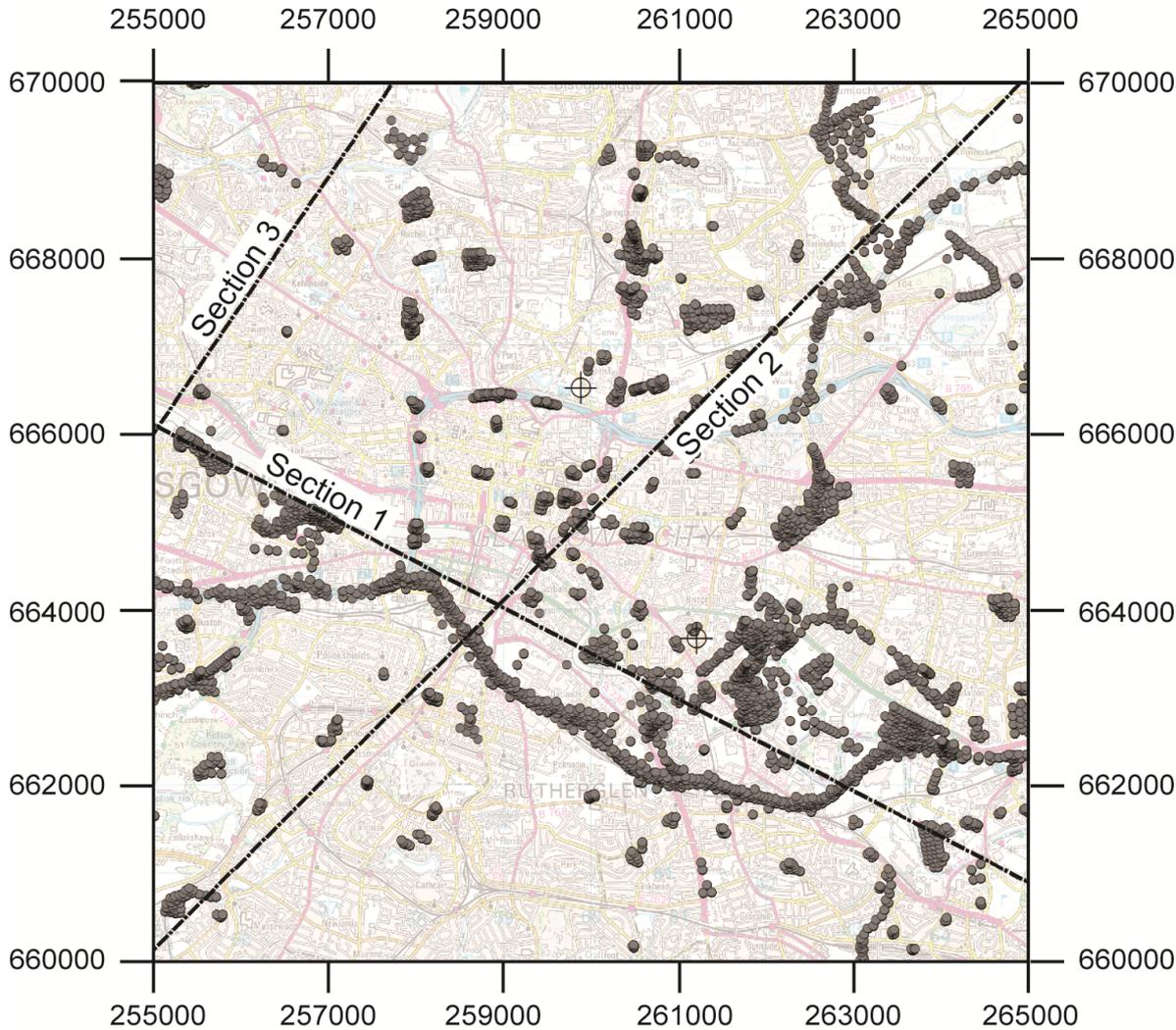
- Model shows 3D seismic models, may be unique in UK (>1% coverage)
- Ideally required for all UK landmass
- Creating UK property maps requires a different approach
- Need to build a pervasive matrix that properties can be propagated through

# Background to Glasgow Modelling

- Deterministic models limited in resolving complex superficial geology
- Stochastic models using voxels provides a possible alternative and as pathway to understanding physical properties
- Glasgow superficial geology provides best UK city to test this
  - Dense city-spanning borehole field area
  - high resolution property data derived from geotechnical testing
  - Long-term cooperation between BGS & Glasgow City Council
- Application of standard oil industry reservoir modelling techniques to shallow unconsolidated sediments
- Simulation methods derive statistical information from boreholes and develop models spatial variability
- Analyse vertical and horizontal spatial patterns of variance and populate a 3-D grid statistically using the variograms
- Similar techniques trialled by TNO for Dutch national models



# Input data



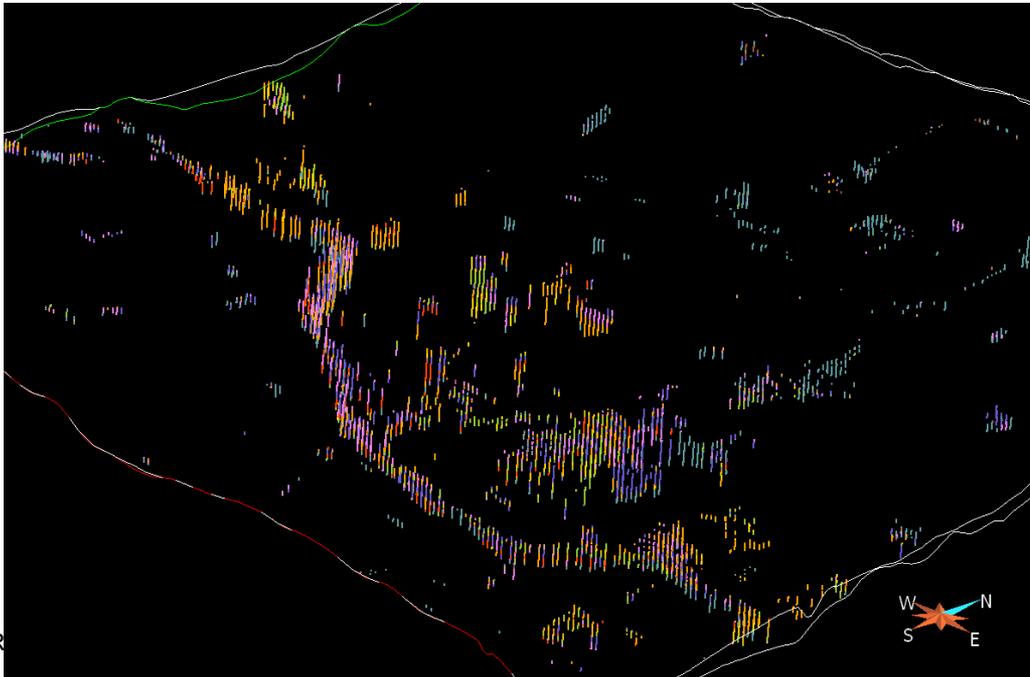
Key

- Geotechnical Borehole
- ⊕ BGS Borehole

# Lithological classification

- All Glasgow superficial geology (above rockhead) stored as BGS Rock Classification System codes
- Initial inspection showed 230 codes
- Code did not match descriptions one-to-one
- Radically simplified classification used
- Automatic processing then manual validation
- Focused on nine superficial classifications:

Code	Name	Color
2	SOIL	Brown
3	CLAY	Purple
4	CLAY_SAND	Pink
5	CLAY_DIAMICT	Teal
6	SILT	Red
7	SILT_SAND	Orange
8	SAND	Yellow
9	SAND_GRAVEL	Green
10	GRAVEL	Tan

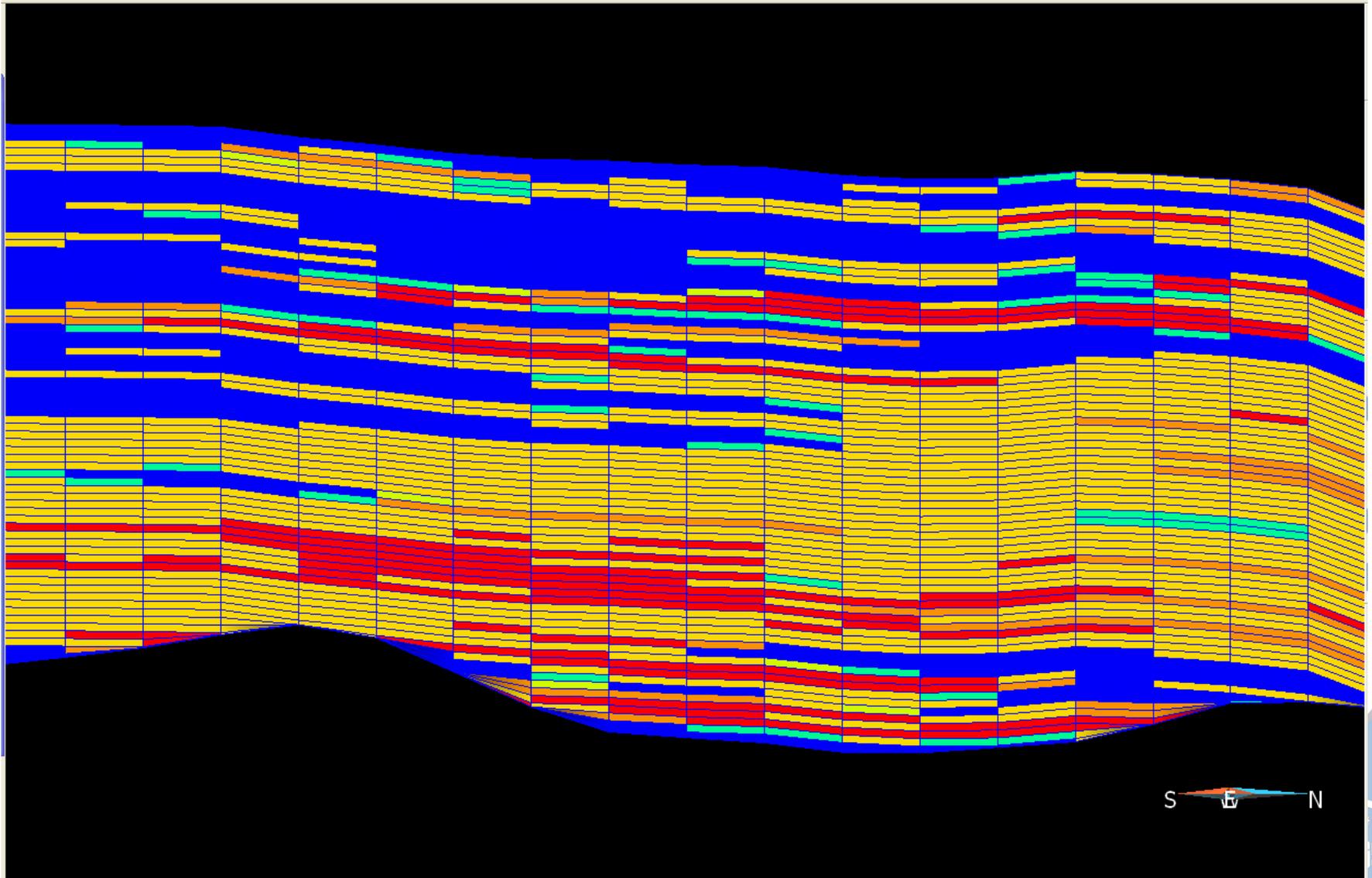


# “Reservoir Modelling” Simulation

- Application of oil industry techniques to unconsolidated sediments
  - Lithology
  - Density
  - Hydraulic Conductivity
- Derive statistical information from boreholes and develop models of spatial variability
- Analyse vertical and horizontal spatial patterns of variance
- Populate a 3D grid statistically guided by the variograms using Sequential Indicator Simulation (SIS) for lithology and Sequential Gaussian Simulation (SGS) for properties
  - Gives a statistical 3D extrapolation of the data
- Doing this rigorously requires a good understanding of both
  - the data and
  - its geostatistical properties



# Simulation Process for a voxel model

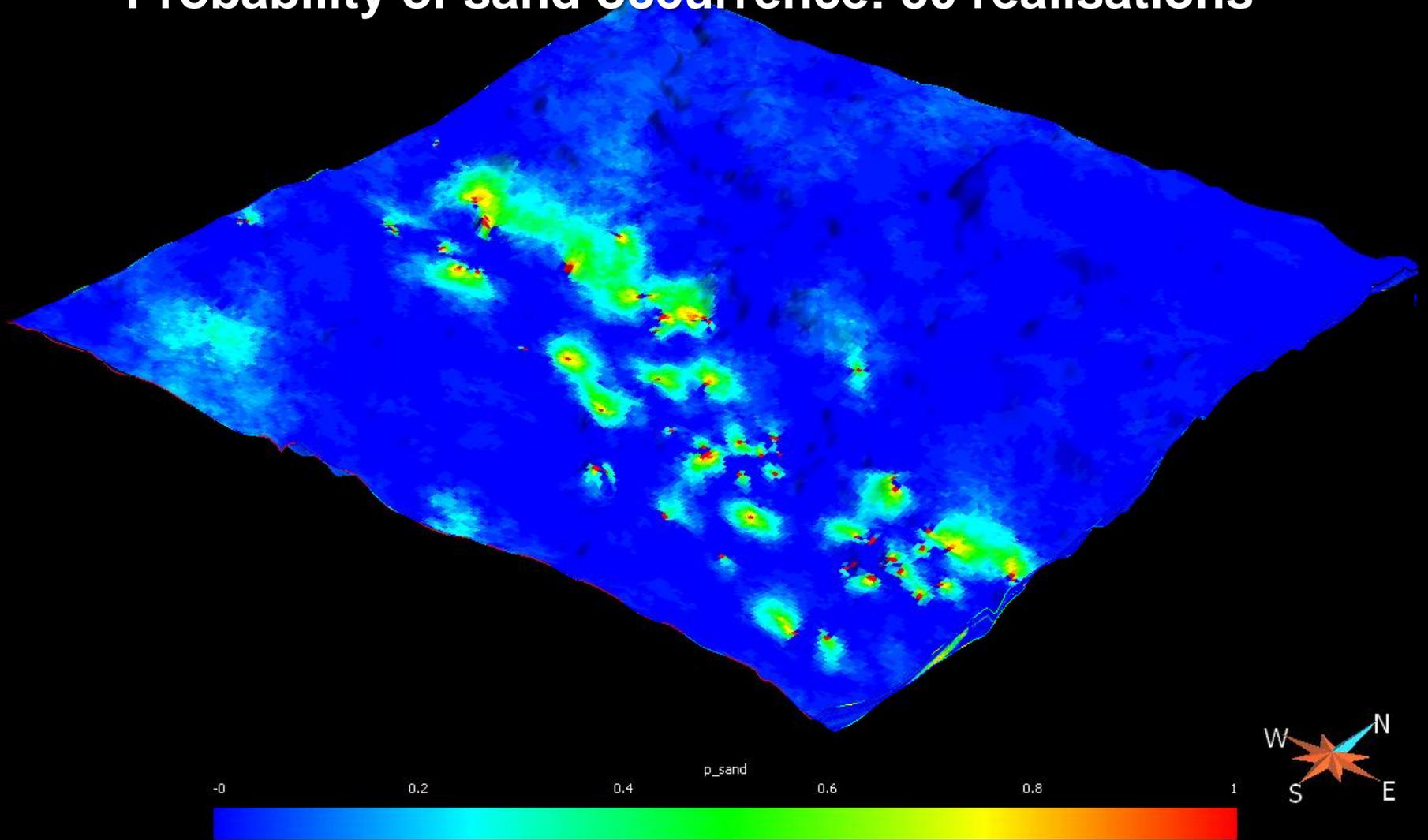


# Constraints on Simulations

- “Sand” variogram (reflects the orientation from the river valley)
  - oriented at 130 degrees azimuth,
  - max radius 2500m,
  - min radius 1500m,
  - vertical distance 1m
- Other variogram uniform
  - 1500m radius horizontally,
  - 1 m vertical range
- No account was taken of external drift, i.e. horizontal and vertical trends in the data.
- Multiple realisations computed in GOCAD
- Realisations post-processed into probability of lithology occurring

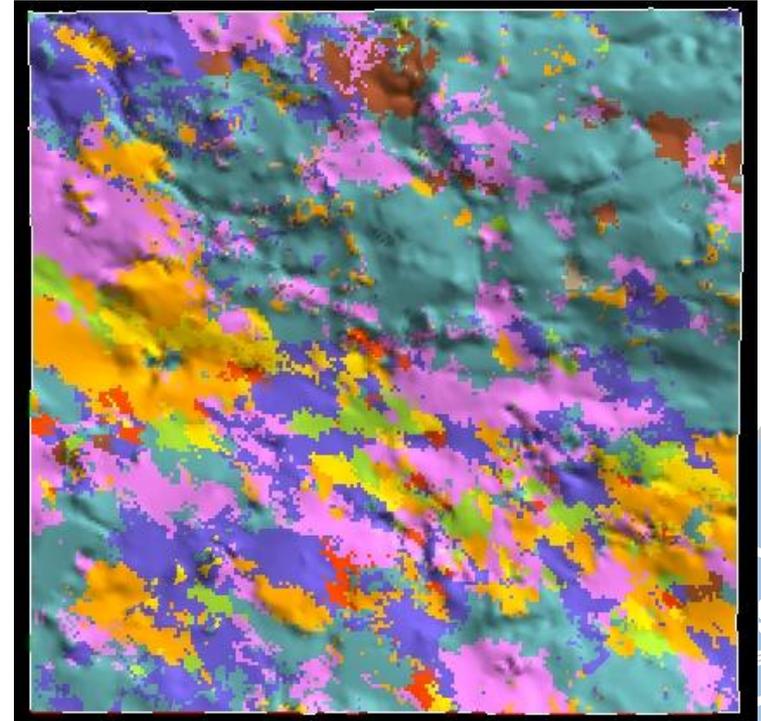
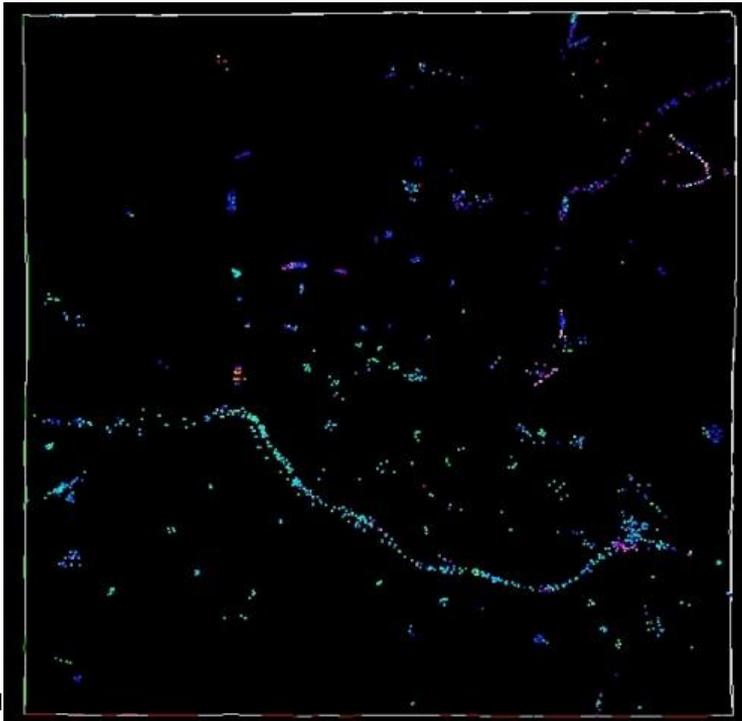
# Example 1: Lithology Modelling

Probability of sand occurrence: 50 realisations

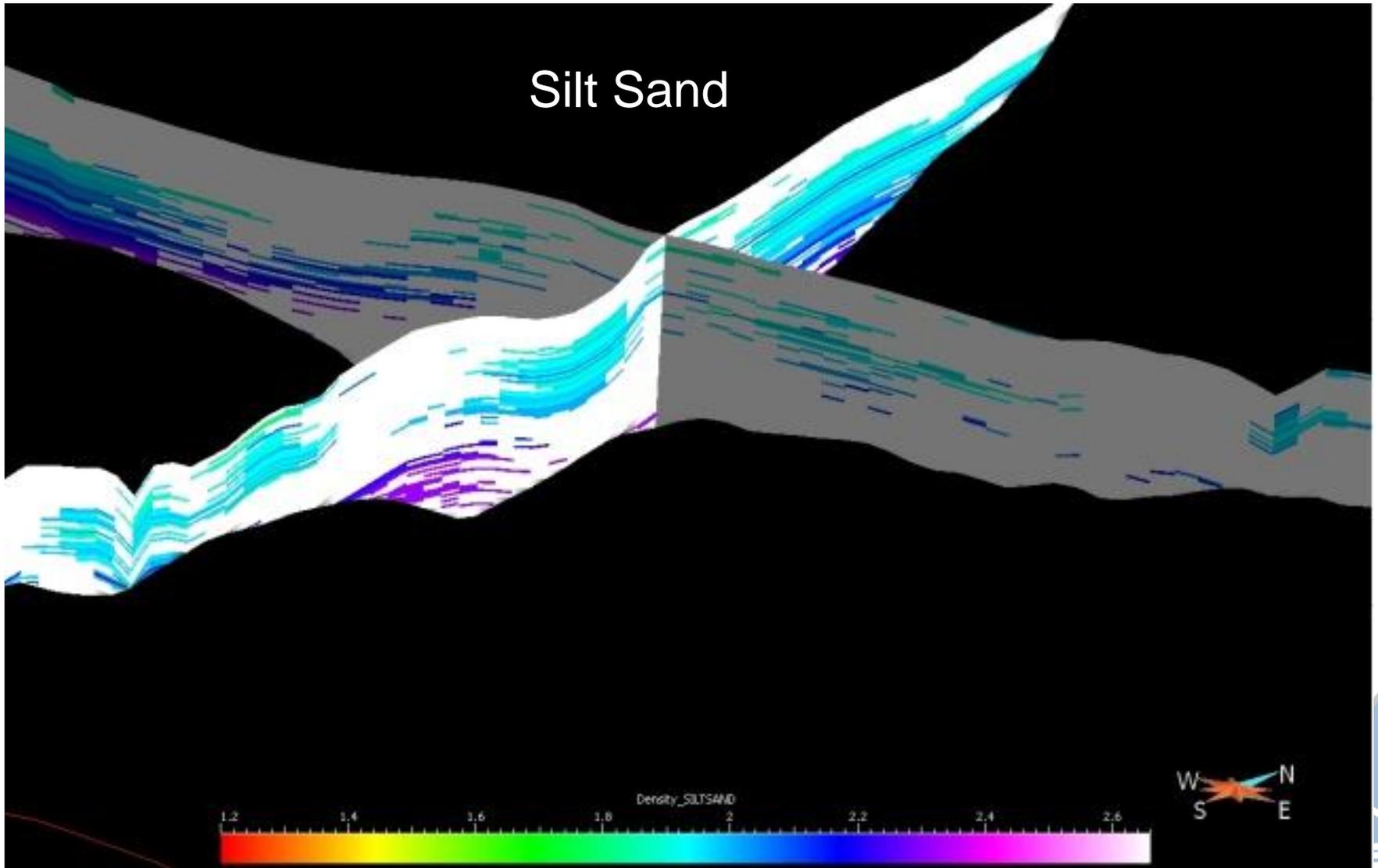


# Example 2: Bulk Density Data

- Density chosen as test physical property as BGS geotechnical properties database contains reasonable coverage: 12782 points
- Different ranges observed for different lithologies
  - Therefore **each lithology modelled separately**
- Distribution controlled lithology distributions



# Bulk Density Modelling



# Bulk density - Process

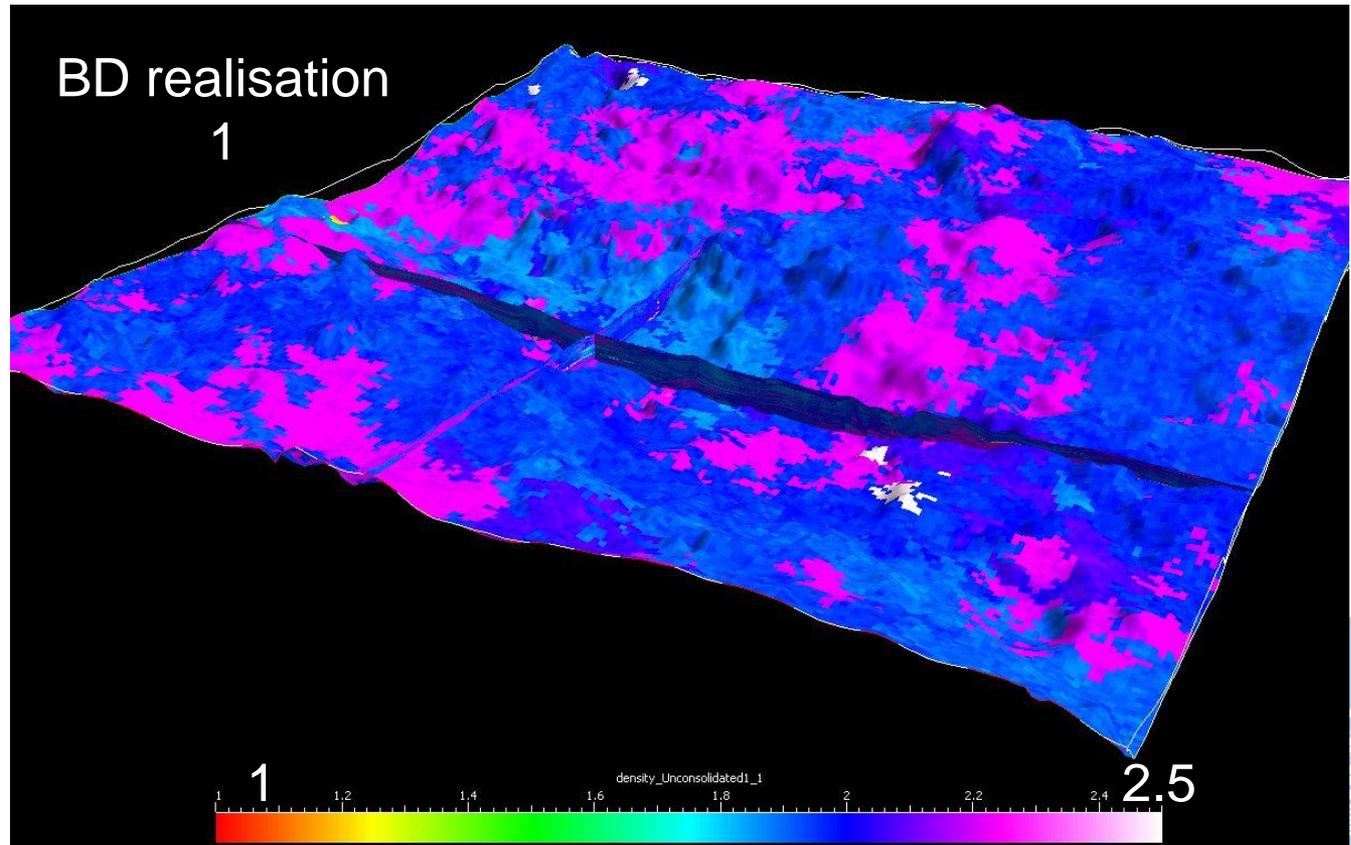
50 x lithology  
realisations

→ 50 x lithology  
class mean BD  
realisations

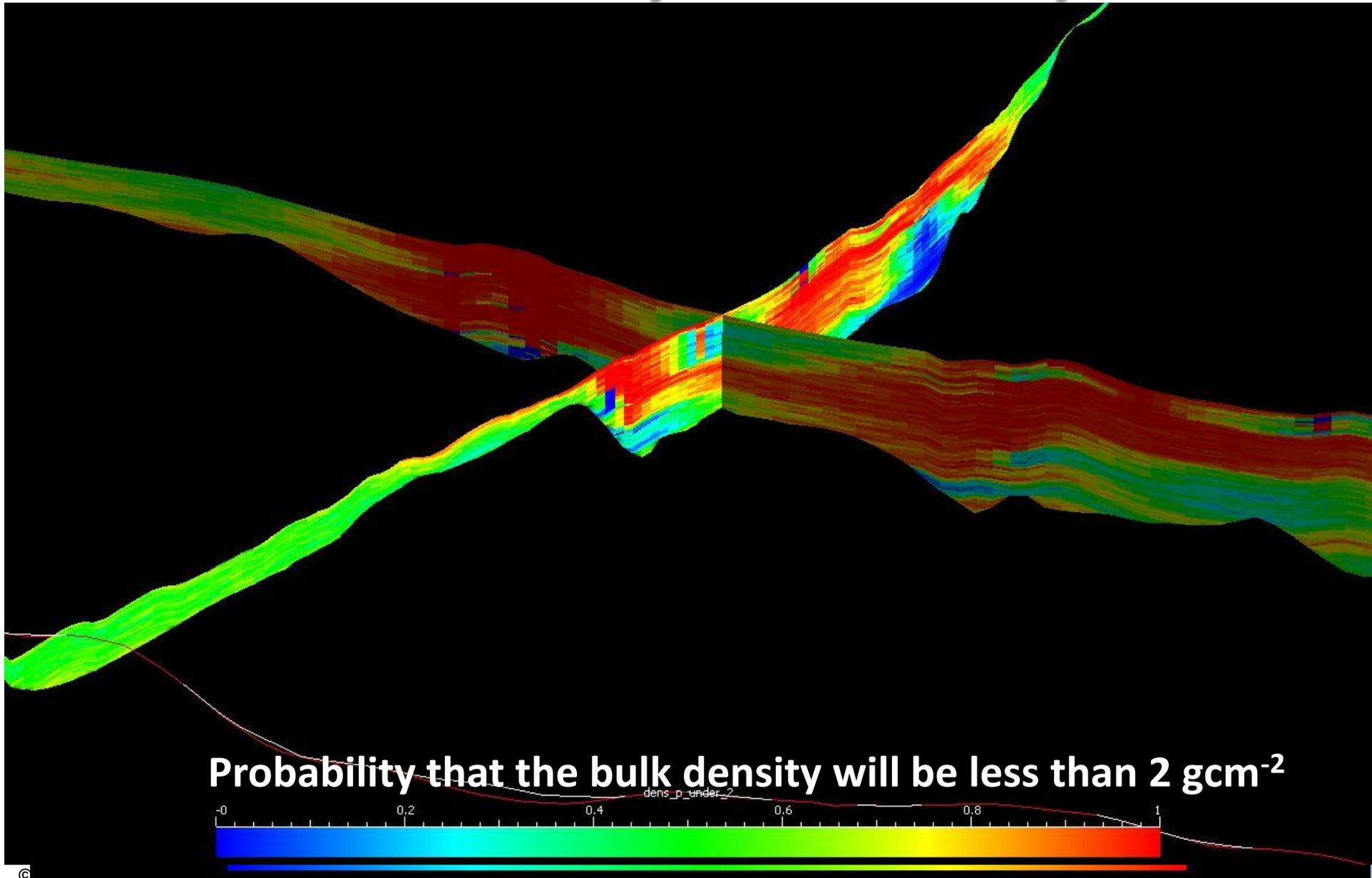
→ 500 x simulated  
BDR realisations

→ 10 x simulated  
BDR realisations  
added  
individually to  
each mean BD  
realisation

= 500  
different BD  
realisations



# Bulk Density - Probability



# Bulk Density

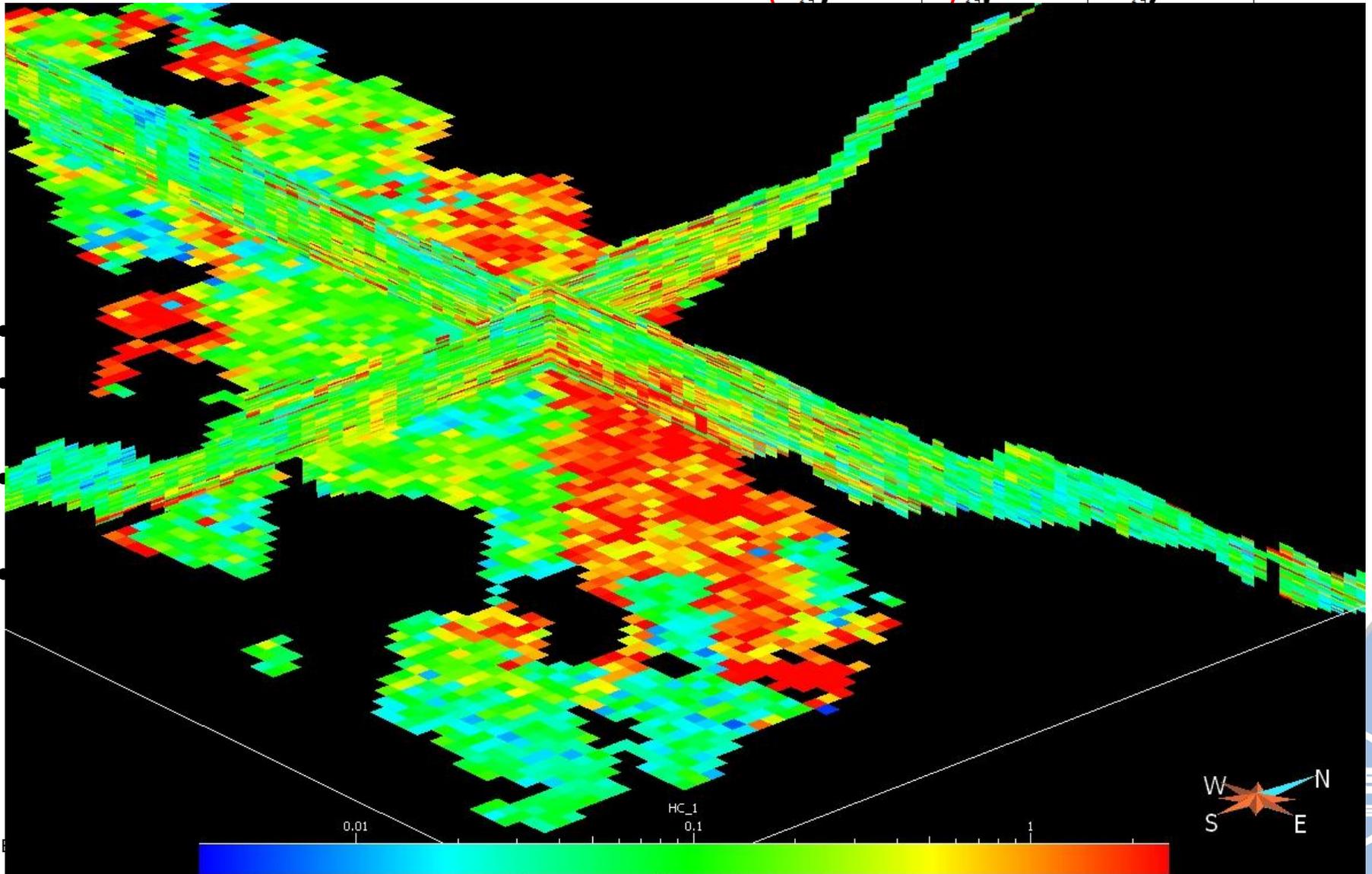
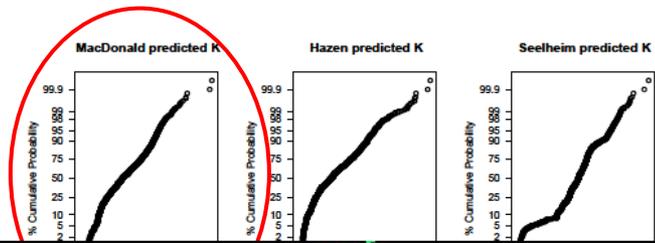
- Aside from probabilities other useful grid properties can be calculated from multiple realisations:
  - Mean and Standard deviation ('most-likely' value and uncertainty)
  - The min/max value for each cell (eg worst-case scenario).
  - Discretised property based on ranges (eg BS5930 classifications).

# Example 3: Hydraulic Conductivity (HC)

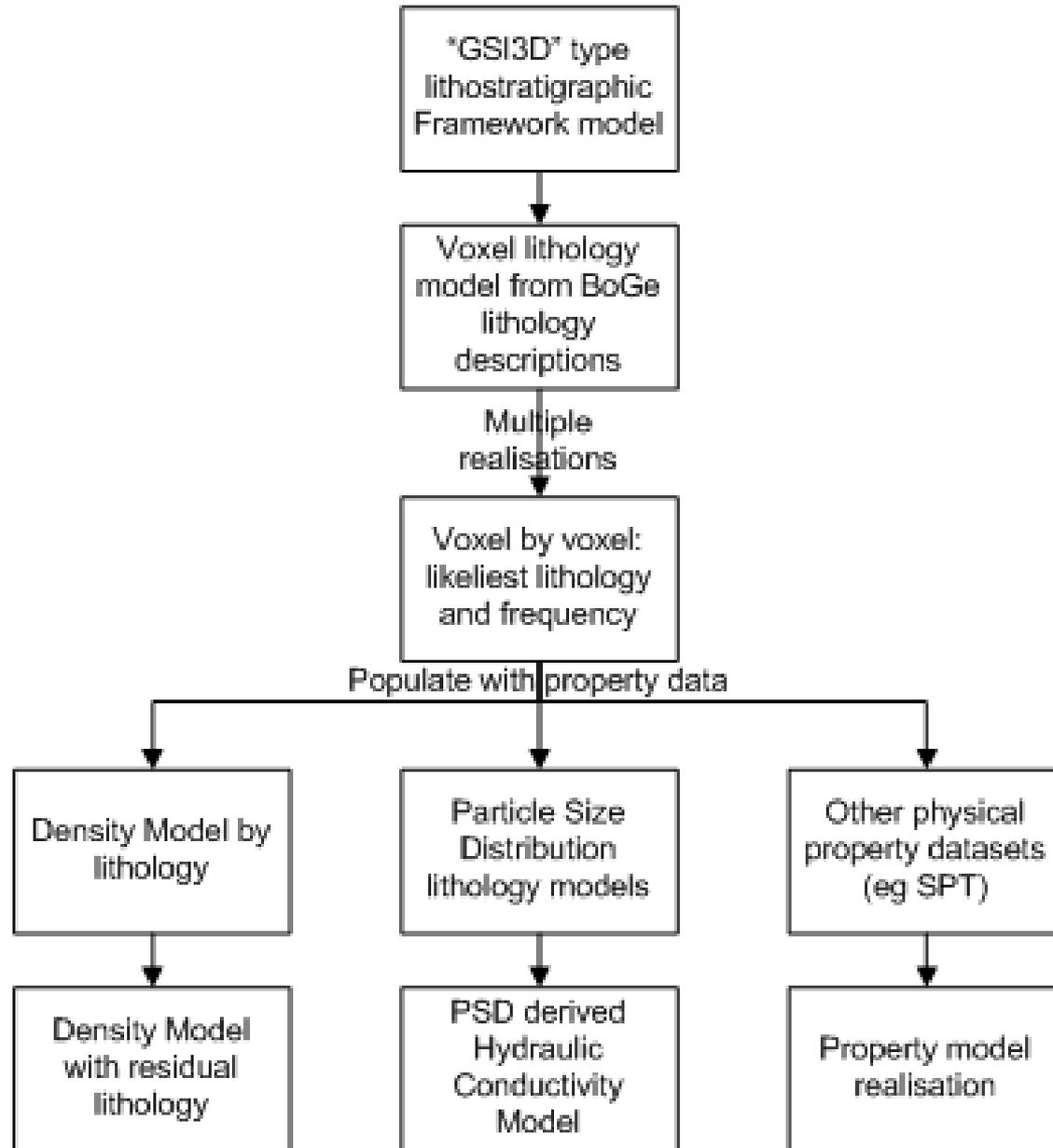
- Derive HC from geotechnical particle size distribution tests for Glasgow extracted from Nation Geotechnical Properties Db (NGPD)
- Calculated the HC for each samples using MacDonald Formula.  
(MacDonald, A.M., Maurice, L., Dobbs, M. R., Reeves, H.J. and Auton, C.A. 2012. Relating in situ hydraulic conductivity, particle size and relative density of superficial deposits in a heterogeneous catchment. Journal of Hydrology 434-435 130-141.)
- Empirical equation derived from samples and in situ testing of heterogeneous superficial deposits in Morayshire
  - $\log K = 0.79 \log d_{10} + (2.1 - 0.38 \text{ SSD})$
- K – hydraulic conductivity (m/day)
- $d_{10}$  – diameter of 10<sup>th</sup> percentile grain size (mm)
- SSD – Soil state description value
  - range of 1 – 5 depending upon description,
  - very loose coarse soil/very soft fine soil = 1
  - very dense coarse soil/very stiff fine soil = 5
- Result = 2345 points with hydraulic conductivity values, X, Y & Z coordinates and stratigraphy
- 1506 points within the grid of the model area which also have QAed lithology

# Best HC results?

- Macdonald Formula checked against 5 other formulae for deriving HC from



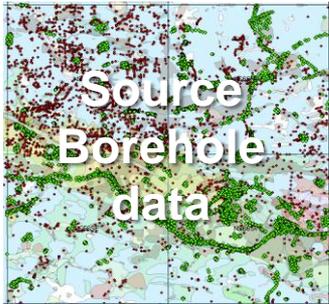
# Flowchart of property modelling process



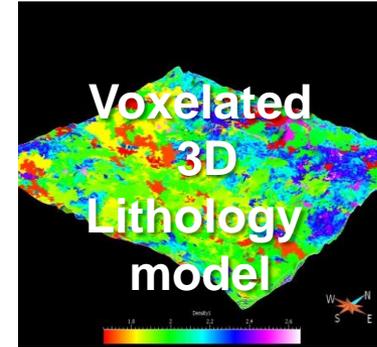
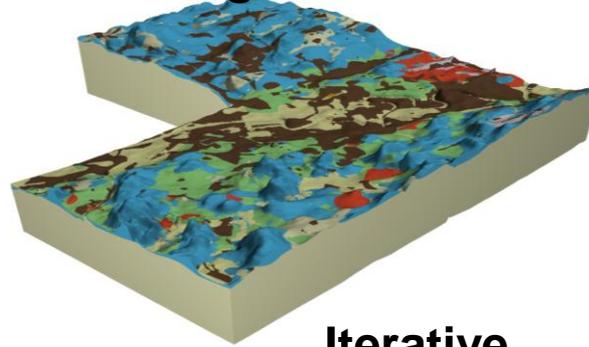
# Conclusions

- When modelling properties the number of simulations ‘needed’ depends on the dataset geostatistical characteristics
  - Degree to which data are dependent on other variables (Lithology)?
  - Do the data have a wide-range of values?
  - A given dataset might ‘require’ a higher number of realisations to capture the nature of possible variations.
  - 50 lithological realisations sufficient to predict likely lithology distribution within our model
  - May not be sufficient to capture the likely variability/uncertainty of continuous properties (i.e. BD) across multiple simulated realisations.
  - Ongoing work to determine the optimal number of realisations required for stochastic modelling of different datasets.

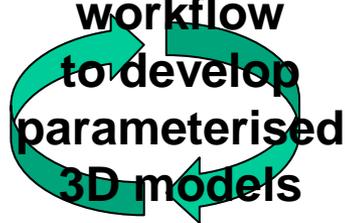
# BGS urban modelling workflow



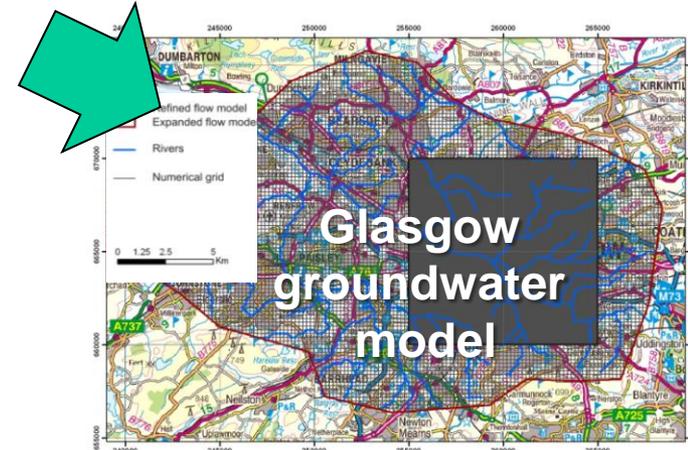
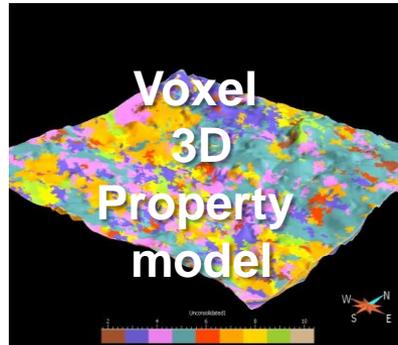
3D Framework  
Geological model<sup>1</sup>



Iterative  
workflow  
to develop  
parameterised  
3D models



A circular green arrow indicating an iterative workflow.



1: SDG Campbell, et al, 2010. 3D geological models and their hydrogeological applications: supporting urban development - a case study in Glasgow-Clyde, UK  
In: Special Volume, *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, 251-262.