British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

The challenge of capturing multi-component uncertainty in 3D geological models

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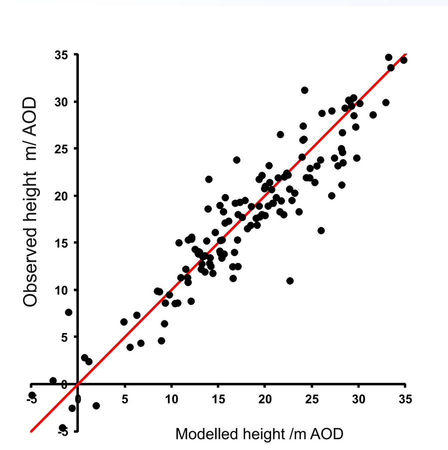
Introduction

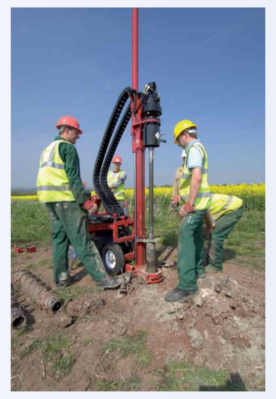
The British Geological Survey develops 3D geological models that support real-world decision-making. It is essential that model end-users can adequately assess the uncertainty within the models, but representing the multi-component uncertainty inherent in geological models is non-trivial. The sources of uncertainty can include the quality of the raw geological data, the experience of the modelling geologist, the complexity of the geology being modelled and the scale at which that complexity is conveyed, the geological modelling methodology and finally the way in which the model data is applied.

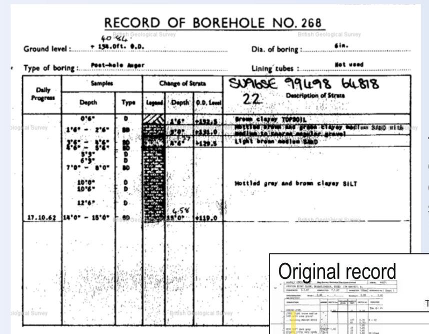
The plot below shows the combined effects of all sources of uncertainty by comparing modelled and observed geological depths in a model of southern East Anglia, UK. However, in order to control this uncertainty, and to quantify it in cases where such a validation is not possible, we need to understand the various factors that contribute to model uncertainty.



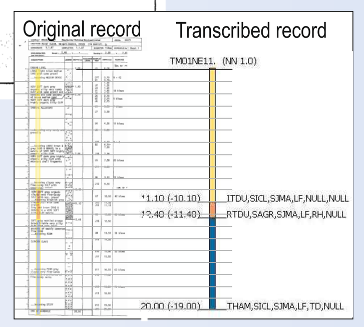
Establishing the uncertainty is the first challenge. The second, perhaps greater challenge, is conveying that uncertainty to the end-user in a useful and understandable manner.

Uncertainty in raw geological data

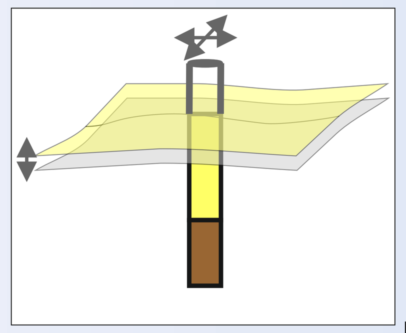




Transcription of borehole data into a digital database often requires significant geological interpretation



The spatial distribution of borehole data is typically highly variable.



Uncertainty associated with borehole start height

BGS relies to a large extent on borehole records from external sources. The data varies in age, quality and distribution, resulting in significant potential for uncertainty.

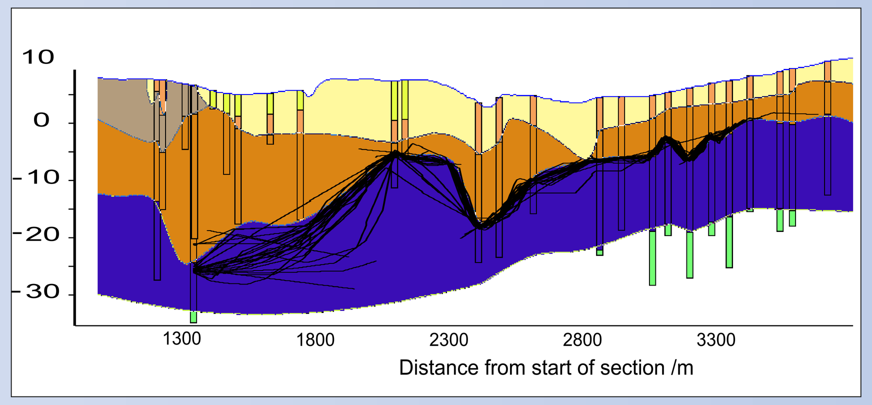
To minimise these uncertainties, the borehole data is interpreted both in the context of the surrounding geology and surrounding borehole data. Through this process we can often eliminate errors involving inaccurate start heights, borehole record to database transcription errors and poor quality records.

Data accuracy

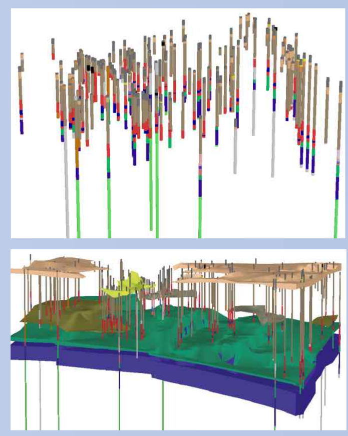
Accuracy of x,y,z measurements in field
Study goal
Expert added/ interpreted data
Inaccurate measurement
Expert experience
Data conversion
Illegible or inconsistent
Incorrect records
Poor sampling distribution
Anomalies
Typographical error
Clustered data points
Data entry

Uncertainty in expert interpretation

To create geological models from sparse borehole datasets, BGS rely on geologists to interpret the space between the boreholes. This requires significant geological expertise, scientific background and an ability to interpret geology in three-dimensions. Nevertheless, the interpretations of geologists still vary significantly. BGS is currently undertaking research to quantify this uncertainty.



The elevation of the base of the Lambeth Group (orange) in London was interpreted along a cross-section by 28 geologists. The base was proven by boreholes at the locations indicated by the borehole sticks. The interpretations vary to some extent, particularly where the borehole density is sparse. Most experts interpreted the base as continuous but some inserted faults.



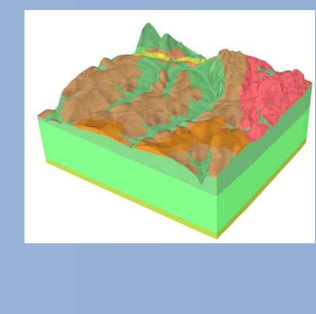
The images to the left show borehole data (top) that was interpreted to create a faulted geological model (bottom). Interpreting the strike, position and dip of the faults in this model required significant interpretation.

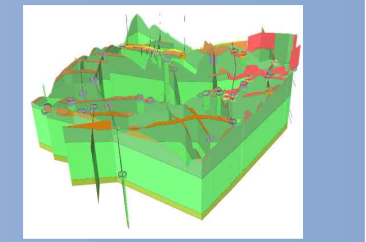
Expert input

Conceptual model uncertainty
Experience
Scientific background
Interpretation
Interpreted data points

Uncertainty is inherent in the source data, the extent of geological complexity, the expertise of the geologist, the 3D modelling software and the way in which the model is applied

Uncertainty in 3D geological models





Processed data accepted as accurate
Lack of connectivity between modelling process and usage
Ignorance of model granularity
Acceptance of print-outs

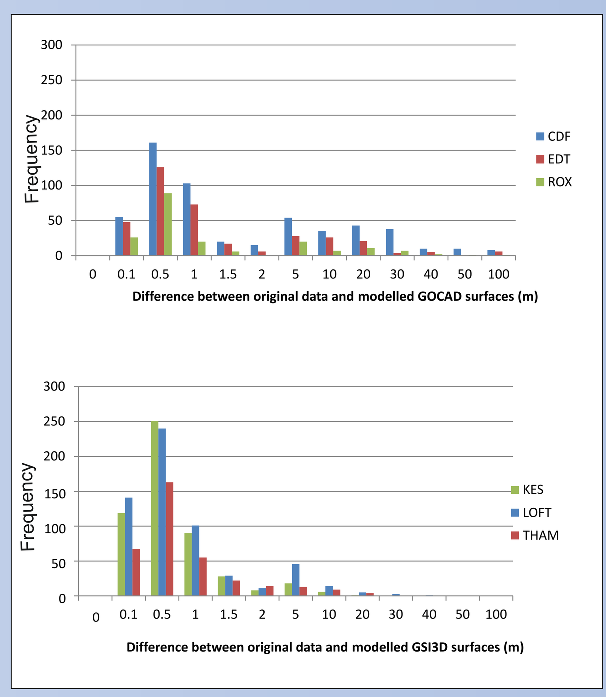
Model usage

Software experience
Modified
Proprietery
Blackbox
Expert decision on modelling process
Algorithm

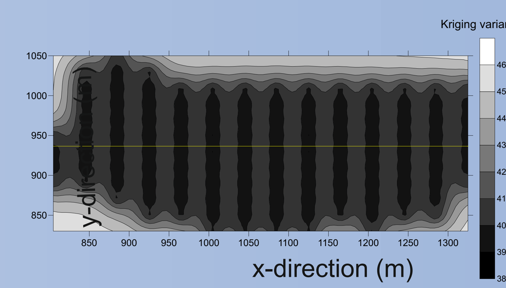
Modelling software

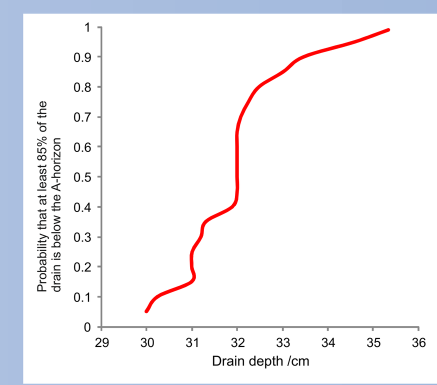
Uncertainty inherent in modelling methodologies

The modelling software employed to create 3D geological models can significantly affect the uncertainty inherent in the resulting surfaces. We took surfaces modelled by GSI3D and GOCAD and compared modelled surface elevations with the borehole interface depths used, or considered in the creation of that surface. Differences between the surfaces and modelled data of 0.5 m were common, but in some cases these differences totally 10s of metres.



Meaningful uncertainty measurements must be customised to answer the right questions



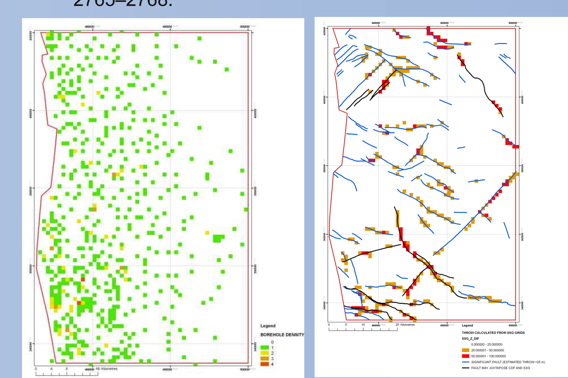


Data from Western, A.W., & Grayson, R.B., 1998. Water Resources Research, 34, 2765–2768.

It is possible to compute point-wise uncertainty measures and present these as a map but the uncertainty attached to a user's particular interpretation of a map, addressing a particular question, is unique and cannot generally be obtained from the point-wise information alone.

The map (top left) shows the kriging variance of the basal depth of the A-horizon of the soil in an Australian catchment and represents a point-wise uncertainty measure. If a user wants to install a drain across a particular route (shown on the map as a yellow line) and wants to know the probability that a drain, at some specified depth, would be below the A-horizon over at least 85% of its length, this must be calculated from the underlying uncertainty model (see left), and cannot be obtained from the kriging variance map. This highlights that general model uncertainty plots are not particularly useful for specific applications and thus instead, bespoke uncertainty plots must be generated.

Borehole density plots are typically used to indicate uncertainty in 3D models, but actually they only show one single source of uncertainty. Borehole density plots are therefore a poor indicator of total uncertainty.



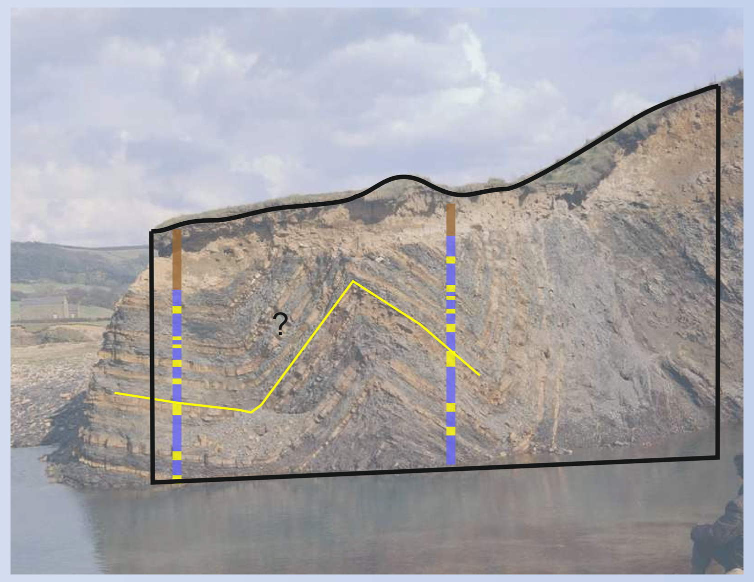
In the example to the left, the purpose of the model was to identify faults and displacement in the Permo-Triassic of Yorkshire and the East Midlands of the UK; the borehole density plot (far left) was provided as an indicator of uncertainty, however, in reality it did not give any explicit information about the uncertainty inherent in the fault objects (near left), and therefore had limited application.

Inherent predictability of geological complexity

The uncertainty inherent in geological models is influenced by the geological environment, in particular the type of depositional processes, the extent of diagenesis, and the presence of folds or faults. Greater certainty is inherent in deposits with more predictable sedimentary histories, such as lake or marine deposits, whereas the uncertainty is much greater when complex, relatively unpredictable processes act to create terminal moraine or faulted bedrock environments. In the predictable environments, extrapolation between boreholes over 100s or 1000s of metres is potentially acceptable, whereas in more complex environments, any extrapolation of borehole data may result in inaccuracies.

Faults
Unconformities
Irregular rock bodies
Folds

Geological complexity



Summary

Uncertainty inherent in 3D geological models is complex and challenging both to quantify and convey in an understandable manner. A key consideration is that general uncertainty models are of limited application, as the measure of uncertainty depends on how the model is used. Following significant engagement with users of 3D model data, conditions emerged that were deemed necessary for conveying model uncertainty.

a) For users who generate new data and conceptual knowledge during ground investigations, it is important that the original data and interpretations used in modelling are accessible. If users then add data to the geological model, they are better able to intuitively assess the inherent uncertainties in the data and interpretations, and have the opportunity to make informed revisions to the model.
b) If the geological model is used as input data to a numerical model or as part of a regional decision support system, model users require a more numerical assessment of uncertainty. A bespoke uncertainty assessment needs to be provided for the geological units of interest, to ensure that the uncertainty assessment is relevant.
c) If geological models are used for the communication of science, uncertainty is less important than an understanding of the geologists.
d) For all users, it is vital that methodologies employed in geological modelling should be fully open and transparent (Joppa, L. N. 2013. Troubling Trends in Scientific Software Use Science 17 May 2013: Vol. 340 no. 6134 pp. 814-815).

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