Summary and outcomes

Workshop on 3D geological modelling methodologies

Utrecht - 17th – 18th September 2013

A good 3D geological model should be geological

Richard Thomsen – Utrecht September 2013

Foreword

The main players in the field of geological modelling in Northern Europe met to discuss state-of-the-art techniques and best practices. Discussion topics ranged from model construction, property attribution, storage, uncertainty estimation and model delivery.

The attendance of representatives from five countries was a significant achievement and resulted in very productive discussions that were deemed highly valuable and worthwhile. Given the success of this inaugural meeting, further workshops are envisaged. A key observation from the workshop was that each GSO has the same overall vision, to build a national 3D Geological Model (or knowledge base) to underpin decision-making. However, the methods employed by the GSOs are highly diverse as a consequence of differences in geology, data availability, funding mechanisms, corporate objectives and prior investment in technologies. These diverse approaches reflect those in other parts of the world (Berg et al 2011 http://nora.nerc.ac.uk/17095/1/c578.pdf). For this reason, we do not believe it is feasible to agree on common standards and methodologies at this point, however there are several elements of the 3D geological modeling workflow (data management, uncertainty research, exchange formats, model delivery, parameterization, incorporating "proxy" information, like geophysics) where collaboration would be valuable. For this work to continue, funding to develop such pan-European approaches should be sought.

The meeting initiated potentially valuable collaborative partnerships. Significant benefit from such workshops could be realised by building relationships where successes and problems can be honestly shared and used as learning points for the whole GSO community; this will inevitably lead to improved best practice, methodology, cost savings and most importantly an increased understanding of the subsurface.

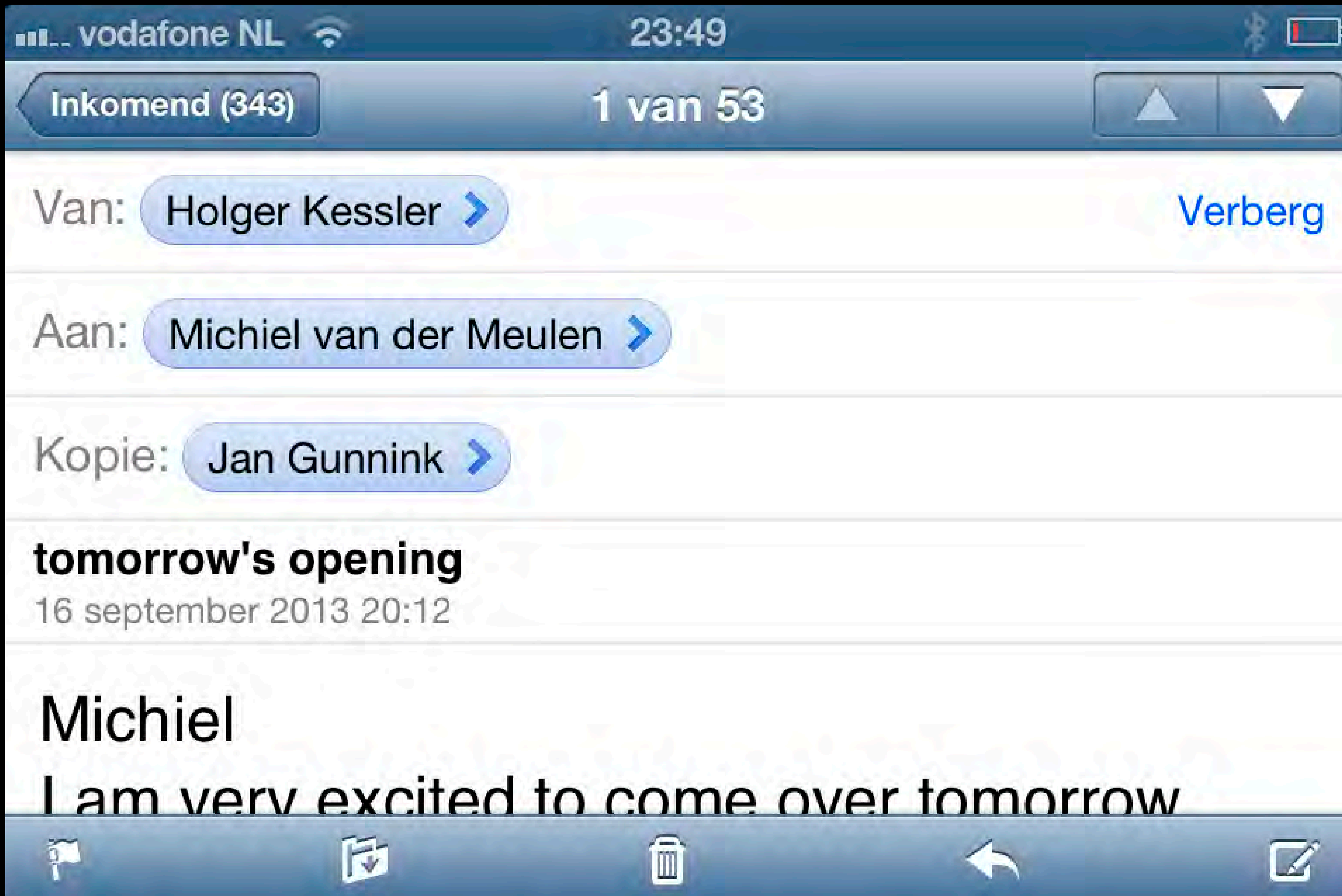
To facilitate cooperation on specific topics, we would suggest to establish a few "working-groups", with the aim to bring together expertise on topics like uncertainty, delivery, model management and proxy-data. These groups could work on their subject and report back on progress made at the next meeting of the GSO's. It is not clear yet how this should work in practice (meetings, staff-exchange, publishing papers) but we think it is a way to put flesh to the bones of our meeting.

Jan Gunnink and Holger Kessler

"We know more about the movement of celestial bodies than about the soil underfoot"

Leonardo Da Vinci, circa 1500's

velkommen
willkommen
welcome
bienvenue
welkom



vodafone NL 23:49

Inkomend (343) 1 van 53

Van: Holger Kessler Verberg

Aan: Michiel van der Meulen

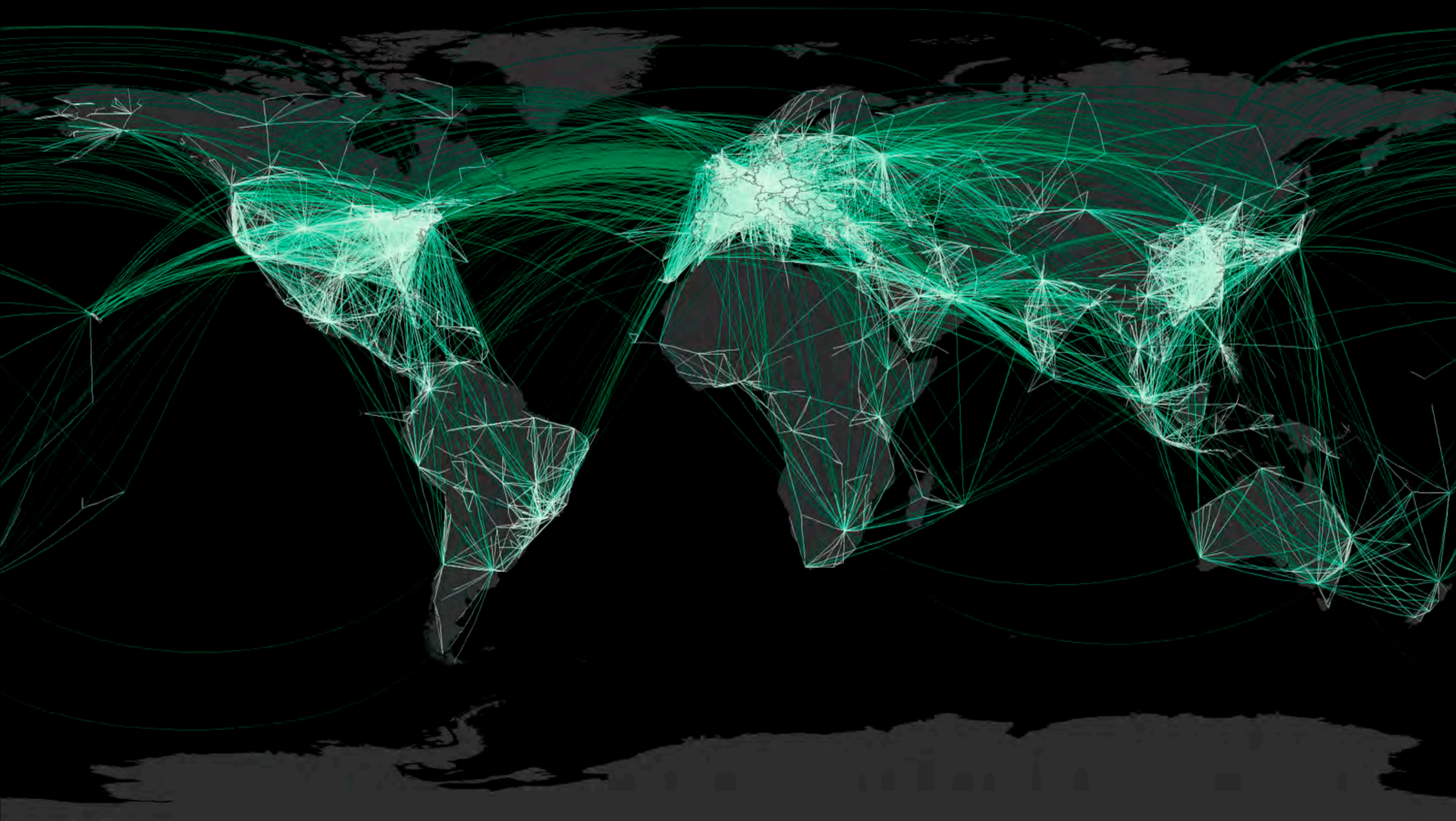
Kopie: Jan Gunnink

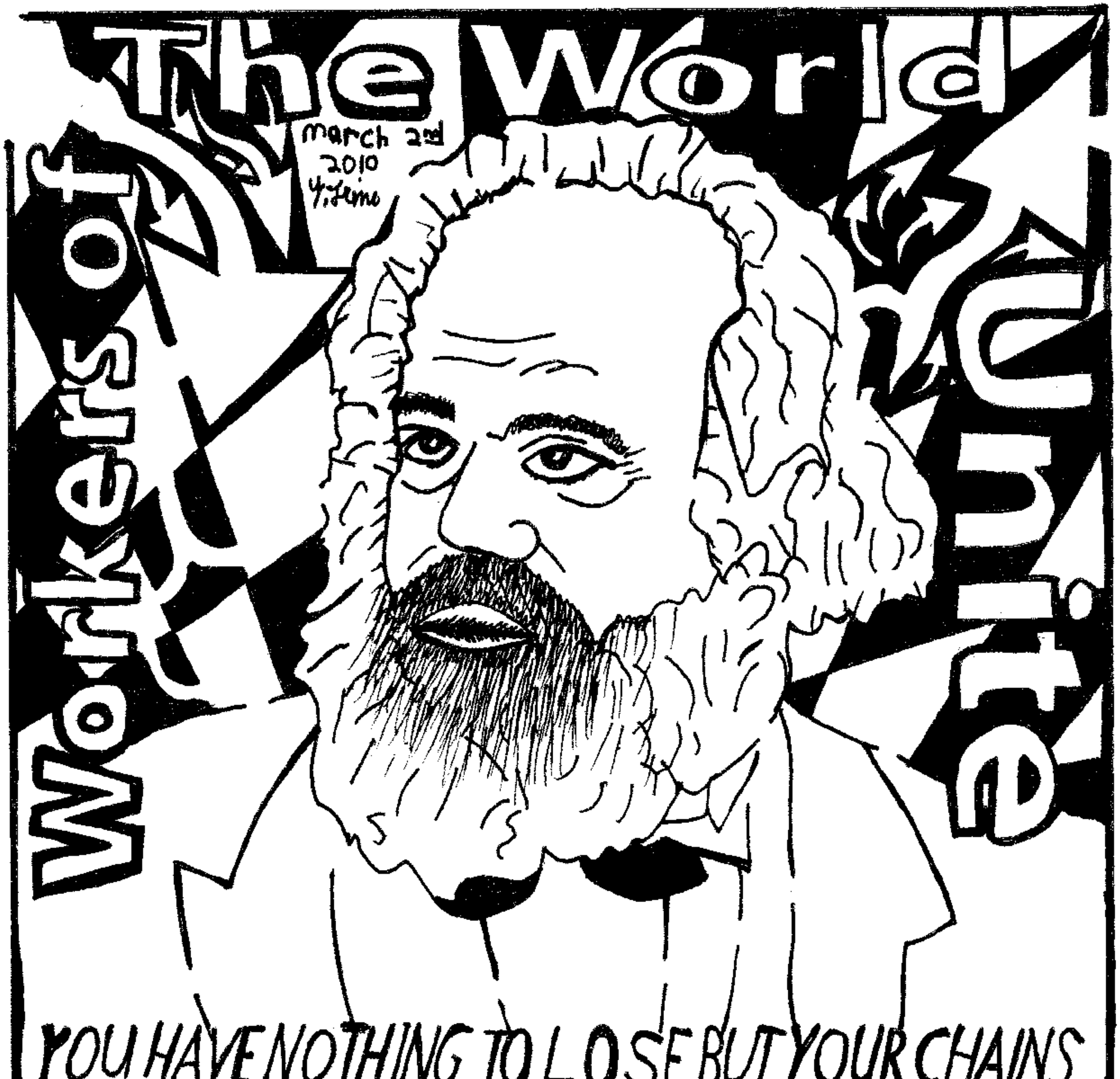
tomorrow's opening

16 september 2013 20:12

Michiel

I am very excited to come over tomorrow





Workers of
The World
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Y. Frimo
YOU HAVE NOTHING TO LOSE BUT YOUR CHAINS


Brand BIER
GRAND CAFÉ QUIGNON


6
Fermentatietank
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ВСЯ ВЛАСТЬ
МЫ ПРИДЕМ К ПОБЕДЕ КОММУНИСТИЧЕСКОГО ТРУДА!
СССР
СССР

Summary notes from break-out sessions

Session A Day 1 - Property modelling: populating geological models with properties - Facilitator - Flemming Jorgenson -

Team: Anne-Sophie Høyer, Stephan Steuer, Andy Kingdon, Ingelise Møller Balling, Antonio Guillen, Sunsearé Gabalda, Martin Nayembil, Jan Gunnink, Jeroen Schokker, Ronald Vernes, Jan Stafleu, Denise Maljers, Hans Doornenbal, Bernd Linder.

Property modelling: populating geological models with properties

- To incorporate geological expert knowledge into property models.
- How to quantify implicit knowledge
- Database should allow integration to enrich sparse properties with more abundant variables
- Small-scale heterogeneity needed for proper upscaling
- Scaling from measurement to model scale
- Borehole quality check
- Validation; how to?
- No more maps and models: risks and probabilities! Look for the extremes for a certain application

Session B Day 1 - Judging the quality of our models: uncertainty assessment, error propagation, quality assessments - Facilitator - Michiel van der Meulen

Team: Rachel Dearden, Holger Kessler, Murray Lark, Courrioux Gabriel, Gesa Kuhlman, Richard Thomsen, Diarmad Campbell, Peter Sandersen, Giulio Vignoli, Bruce Napier, Katie Whitbread, Maryke den Dulk.

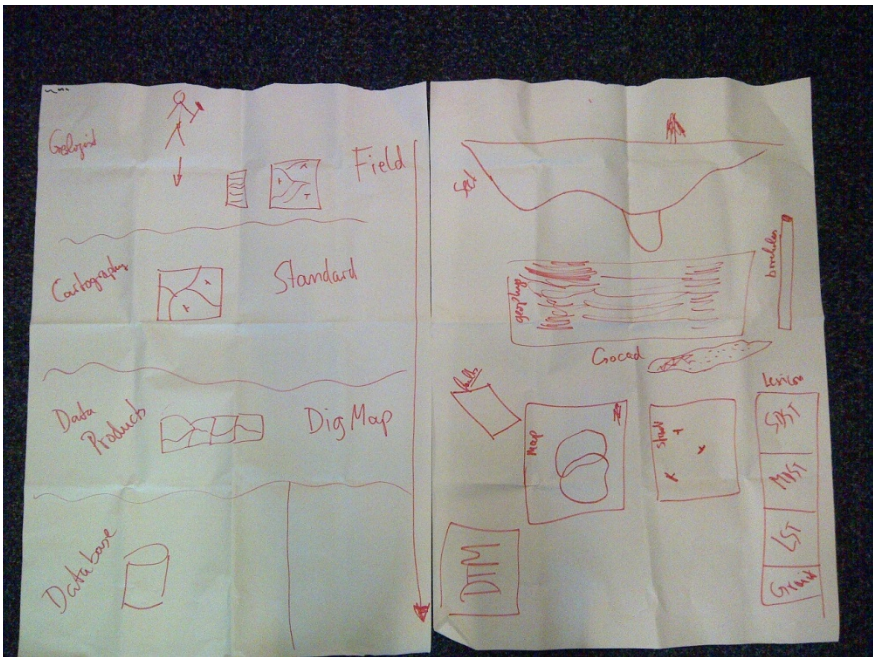
Day 2 session A2 - Versioning and management of geological models: challenges and solutions - Facilitator Holger Kessler

Team: Ingelise Møller Balling, Antonio Guillen, Sunsearé Gabalda, Richard Thomsen, Martin Nayembil, Michiel vd Meulen, Giulio Vignoli, Denise Maljers, Bernd Linder

Holger Kessler gave an overview of BGS attempts of model storage, we discussed whether to store observations and algorithms or interpretations. Holger presented that the current approach is to store and manage geological objects (see image below on the right) and not the final calculated model surfaces.

The left hand side of the image below tries to show that the traditional workflow of creating a map cannot be simply converted to facilitate the creation and maintenance of a dynamic, muslti scaled 3D geological model. There are differences in that:

- we need to work with others and not by ourselves on one sheet, to create the model
- the outputs from a model are not single scaled maps, but vary with end use
- a 3D model has to take into account a lot more input data than traditional mapping
- validation and sign-off happen on individual objects of interpretation not on a final product
- Storage does not mean “print it and store it” but continuous revision of the entire dataset and all its components (shown on the right)
- Eventually the aim is to open the model store and its components to the outside, so that it can become a shared knowledge base with an editorial board guaranteeing the QA.



Further discussions revolved around uncertainty between different interpretations and that someone has to decide what is approved, and that this person needs to have „knowledge of the Geology“

Day 2 session A1 - 3D layer-based vs. voxel-based modeling: techniques and pitfalls - Facilitator Peter Sanderson

Team: Anne-Sophie Høyer, Murray Lark, Stephan Steuer, Andy Kingdon, Flemming Jørgensen, Bruce Napier, Hans Doornenbal, Maryke den Dulk

In the process of determining whether to use voxel or layer-based modeling – or a combination – there inevitably will be certain constraints on our choices. A lot of factors can interfere and force us to choose modelling procedures that will represent compromises. The discussions we had were focused around the following topics (constraints):

Modelling software capabilities
• Voxels
• Layers/surfaces
• Structures
• Algorithms

Automatic or manual interpretation?
• Preferences/possibilities?
• Budget constraints
• Model update?

Geological complexity
• Layers/surfaces?
• Voxels?
• Combination?

"Politics"
• Budget
• Software restrictions
• Level of ambition
• Legislation

Data density/data types
• Do you have enough detail?
• Is the geology resolved in the data?
• Can the data you HAVE give you the model you WANT?
• Can you create the model you WANT from the data you HAVE?

Model purpose
• High detail?
• Low detail?
• Specific purpose?

Model update procedures
• Complex model = time consuming update

End-user preferences?
• Technical skills of end-users?
• Are we using the same software?
• Will the end-users "downsample" our detailed models anyway?

Notes from the discussions:
• A general agreement was that the time frame is very important. Generally there is always a need for more modeling time; maybe we do not have the time for the complex model we dreamed about?
• It is important to find a balance between modelling ambition and budget

- We have to consider future updates of the model and remember that very complex models can be very difficult to update
- We have to consider what the end-user expects from our models. Do the end-users use the same software as we are? Are the end-users skilled enough to understand and use our (sophisticated) models?
- Normally we all use more than one software package in the modelling process. Therefore it is very important to standardize the modeling procedures (choice of software, workflow…). We all agreed that there are no perfect solutions….
- We all have to be trained in using multiple software packages
- Modelling using a 100% automated approach can be used occasionally as a first look at data, but we all agreed that manual interpretation is necessary

Day 2 session B1 - Delivery of geological models: viewers, WWW and augmented reality -- Facilitator - Bruce Napier

Anne-Sophie Høyer, Sunsearé Gabalda, Martin Nayembil, Michiel vd Meulen, Giulio Vignoli, Hans Doornenbal, Maryke den Dulk, Bernd Linder

Notes:

We need to deliver intelligible models.

Badly conceived delivery can mislead, which would be our fault, not the customer's.

MvdM : Shale gas pilot example (confusing clash of vertical exaggeration on buildings and cross-sections)– can be misleading to those incompetent in the field.

Intelligible and intelligent delivery is key.

What sort of clients do we have...public – free viewing – more for fun perhaps? Professional – need answers.

Two distinct groups: no idea about geology

Model is not enough –

Most cases, the model is there and is used to provide advice. Can be built 'already there' - unanswered questions.

The model is there to help provide an answer. So the model is not always provided. Model is means to an end .

Present users with a suite of secondary products. Explain that answers are derived from a model...

Models help us understand the subsurface and describe it to clients.

Internal delivery. – get different disciplines together.

Building trust in the model by demonstrating to clients the processes in modelling. One of the major uses of 3d visualisation facilities.

Deliver data also. Model is interpretation. So the data is a valuable resource to show where we have constraints. Hard evidence versus interpolated or geofantasy..the data helps explain constraints and uncertainty.

Working vs just looking – consultants took geotop and built subsidence layer...chain begins with data and ends with a product:-real model delivery.

Delivery for emotive issues?

Don't underestimate users....uses can come out of unexpected directions...

Can be several delivery phases...steps are crucial in the process – do we need to deliver these as well?

Extreme model delivery...what if error in model causes death?

Augmented Reality – will get important – geo-tourism, education – maybe find uses for professionals. Needs time to catch on

Pay or not to pay? Discussion.. up to a point...free...national good. After a point must pay. Not noticed perception of quality lowering with offer of free data.

Day 2 session B2 - Using other datatypes (e.g. geophysics, geological knowledge) in the modelling process -- Facilitator - Andy Kingdon

Team: Anne-Sophie Høyer, Stephan Steuer, Ingelise Møller Balling, Antonio Guillen, Jan Gunnink, Peter Sandersen, Jeroen Schokker, Ronald Vernes Boundary conditions for property modelling in each institution

BGS: (onshore UK only)
Modelling Types: Voxel modelling of physical and fluid properties
Geology: Shallow / unconsolidated (Quaternary) sedimentation; Cenozoic to Mesozoic sedimentary basins
Locations: Specific cities and basins depending upon strategic needs
Purpose: Undertaking physical and fluid property models of cities and understanding
Data types: Borehole data, Wireline logs; civil engineering data; water industry data; some 2D (vario us vintages) but only extremely limited 3D seismic data, some other geophysical surveying techniques
Access to data: Most required data for modelling provided to BGS by legislation
Software tools: GSI3D, GoCAD; Petrel and other seismic interpretation systems (for offshore work)
National limitations: Onshore and offshore modelling efforts undertaken completely separately by different parts of BGS

BRGM (France):
Modelling Types: Modelling opportunities in complex structures
Geology: Upload areas/ mountain belts around France.
Purpose: Physical and fluid property models; seismic hazard modelling; geothermal prospectivity; civil –engineering (in support of large scale infrastructure projects such as Lyon-Turin high-speed railways tunnels); flood modelling
Data types: National Scale gravity models; magnetics; limited regional 2D seismic; 700000 borehole data archive; field data (eg Fault locations)
Access to data: Necessary data collected by or provided to BRGM
Software tools: Geomodeller
National limitations: RGF programming is a national program but modelling efforts avoid major sedimentary basins and oil prospectivity the specific responsibility of IFP and not within remit of BRGM.

GEUS (Denmark, only peripheral discussion of Greenland):
Modelling Types: Hydrogeological modelling for aquifer mapping and protection
Geology: Cenozoic/ Quaternary, complex glacial / post-glacial sedimentation
Purpose: Mapping of shallow aquifers and ensuring their protection
Data types: JUPITER borehole database (heterogeneous input quality); aerial electromagnetic surveys; some 2D seismic of various vintages
Access to data: Necessary data available particular aerial aeromag' but borehole database has not been updated. Direct inversion of TEM for lithology
Software tools: 3D <name needed>
National limitations: Only 40% of the landmass which are designated by Environmental Protection Agency as having aquifer potential National mapping / modelling program ends in 2015.

TNO (Netherlands)

Modelling Types: Hydrogeological and physical properties modelling for aquifer mapping and protection
Geology: Cenozoic and in particular Quaternary fluvio-deltaics and Lower Cenozoic/ Mesozoic
Purpose: mapping of shallow aquifers, physical properties / economic facies models
Data types: All imaginable, large borehole database, geophysics and wireline log data
Access to data: Many data collected now must deposit data with TNO under statutory obligation
Software tools: Isatis and in-house software / scripts
National limitations: None mentioned but issues with completion of national models along borders especially the Netherlands / Germany border.

BGR / Lander Surveys: (Offshore Germany only)
Modelling Types: Hydrogeological modelling for aquifer mapping and protection
Geology: Southern North Sea Mesozoic/ Palaeozoic sediments
Purpose: Improved understanding of geology and hydrocarbon prospectivity of German Continental Shelf
Data types: maps derived from 2D and 3D seismics, geophysical log data
Access to data: Very limited, published data only (eg geophysical logs shown in open literature) not deposited
Software tools: Petrel and others
National limitations: Lack of consistency between Lander and Federal surveys, lack of national data deposit rules.

Challenges for Discussion

1. How to incorporate expert knowledge into property models
2. How to manage data choice and validations

Wider discussions

The opportunities for lessons learned between countries in property modelling is somewhat limited by the diversity of input datasets (based on different national data deposit and access rules), different national requirements and variability of modelled geographic and geological localities.

This was seen as difficult problems in all locations even when the models concentrated on shallow subsurface geology. There was a significant unresolved discussion about “proving” the interpretation of subsurface properties derived from such models. this is done by stochastic simulation (UK, Netherlands) or falsification processes eliminating model results that cannot be undertaken,

Only GEUS are currently populating models directly with lithological / physical properties derived directly from inversion of geophysical data into their model interpretations. In other localities properties are derived from lithological / geological record and upscaled into the wider geological models.

In all locations, apart from the UK, where this property modelling is well advanced a new lithostratigraphic framework was agreed at an early point before modelling was undertaken .

Day 2 session A3 - How to organize feedback from our models users to increase the usability of the geological / property model -- Facilitator Jan Gunnink
Team: Rachel Dearden, Gabriel Courrioux, Gesa Kuhlmann, Ronald Vernes, Jan Stafleu, Katie Whitbread

We did a small introduction by each of the Surveys:

- BRGM: contract research with clear defined goals of the project and close interaction with the client; larger-scale mapping projects in collaboration with universities; scientific committee and user committee (industry and e.g. civil engineering in ministries / departments); try to meet societal demands
- BGS: 2 examples: Glasgow model and London model; Glasgow model with very close cooperation with city-council, stipulating that private contractors working for the municipalities are obliged to use the Glasgow model and to give feedback, in terms of revision of the model with their own data. Revised model objects are stored in the BGS database. A community of users is established, encouraging the use of the model; London model: contractor uses the model and the software to update the model "on-the-fly", as they obtain new data during tunnel construction
- TNO: before starting a regional modeling, user group is established, consisting of regional authorities and other interest groups (drinking water companies, engineering companies, etc.). During the modeling, the user group judge "half-products", like borehole interpretation, areal extent of geological units etc

General remarks

- To ensure user-feedback, time to update a model should be minimal, which is often a problem. Model construction is time consuming, and competes with other duties of the Surveys.
- Regional models are often used for local applications and that causes problems.
- We need to put more effort in education our users about our models, and for which purposes it can be used. This also means explaining (sometimes in lay-men vocabulary) how the model is made and what choices we made in the modeling process
- Visualizing / publishing complex 3D models is an important issue. 3D PDF was mentioned as an option to use for this
- To get feedback, try to give the Geological Survey a "face". So, not an anonymous complaint-form on the web-site, but also a person the user can talk to and who can explain (behind the computer screen, face-to-face) about the model.

Day 2 session B3 - Making geological models useful for applied modellers (eg groundwater, engineers) -- Facilitator Richard Thompson

Team: Holger Kessler, Murray Lark, Gabriel Courrioux, Gesa Kuhlman, Flemming Jørgensen, Jan Stafleu, Denise Maljers, Katie Whitbread

The first part of the discussion was used to get an overview of the use of models in the counties that were represented in the session.

At TNO, BGS and BRGM it has a high priority that all models use the national frame models as reference.

The models have to useful to the user. The models are developed with close contact to the end-user, and the models are mission-oriented.

Statement from the discussion

Tomorrow the 3D geological models have to be developed to be the foundation for multiple uses and based on the same national reference.

The mission-oriented modelling of today often tempter the modeller to simplify the geology to early.

For hydrological modelling many modellers often only use simple lithological information ignoring useful geological information for estimating the hydrological parameters – closer co-optation between geologist and hydrologist is strongly recommended.

Some modeller hope that they can use geophysical measurements as a direct basis for hydrological modelling without having to spend time with a geologist to go through the process of transforming the geophysical measurements to geology. The result will be pure use of the geophysical data and a hydrological model that is impossible to verify with other data including geological information.

The challenge of tomorrow is to stress the important for modeller to use of all geological information and accept the concept of modelling based on multiple 3D geology models with the same national reference frame.

Additional notes and personal comments from participants:

Murray Lark

A common experience is that data users want an uncertainty "layer", but once provided with it do not know what to do with it. While point-wise measures of uncertainty (e.g. the standard deviation at a point) are useful summaries of model quality, most real-world applications of 3D modelling require statements about the uncertainty about the geological configuration over some region or vector. For example, "what is the probability that this route for a tunnel, which passes through unit A only in the model, actually passes through unit B over more than 1% of its length?" This multiple-point question cannot be answered by interrogating the single-point uncertainty measures. In order to answer it we might interrogate a set of realizations of an appropriate error model. This requires that these realizations can be stored along with the model, and accessed appropriately to answer users' questions.

Jan Gunnink

Some considerations regarding predicting / modeling

Recently, I read a book written by an American statistician , Nate Silver, called "The Signal and the Noise; the art and science of prediction". Don't worry, no formula's (only one about Bayes Theorem), but lots of stories about predictions gone wrong.
Examples he describes are about economics (nobody predicted the current recession) weather and climate (there is no accurate prediction of the weather for next week), earthquakes (an earthquake will come, but when?) and sports-bets. The funny thing about these subjects is that the most progress is made in the field of bets and he describes an American who makes a grand living from the profits he makes in this field.
One of the observation the author made was about the fact that in predictions, we rely heavily on data (often from past observations) and try to squeeze some kind of model out of the data by fitting a curve or applying sophisticated statistics. Very often, the people making predictions rely on the data at hand and hardly look at the underlying processes that generated the data. He makes a vigorous appeal for bringing in *a-priori* knowledge into the prediction and uses the Bayes Theorem to prove how useful it can be.

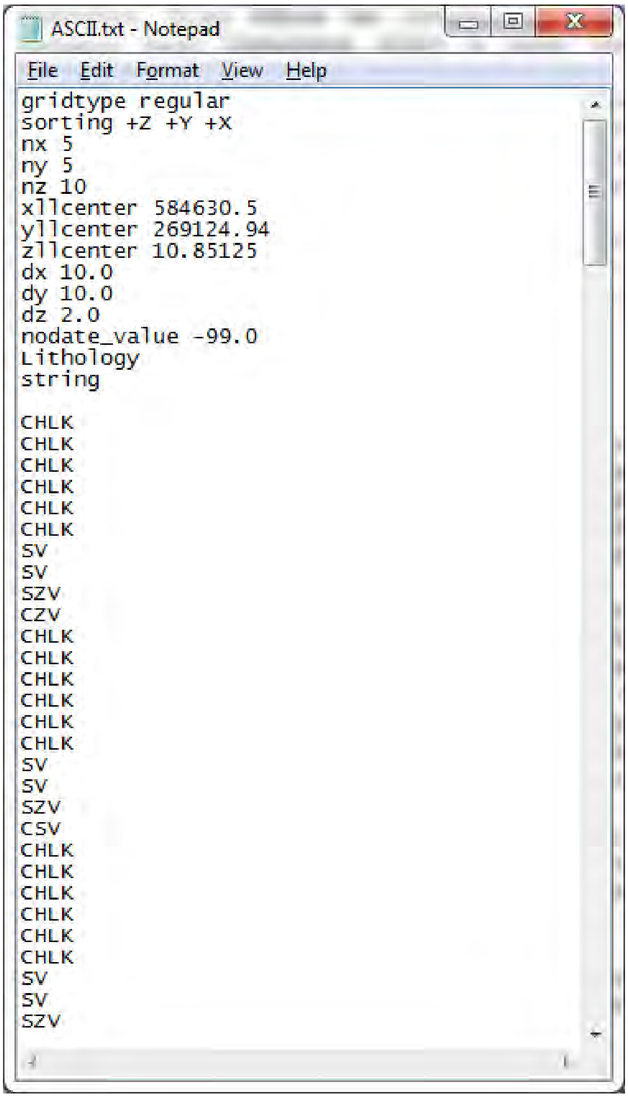
As you all know, modeling the subsurface is also about predicting. We are using a range of techniques to predict geological attributes at locations we have no data. We use all the data we have (good and poor) and try to assess the quality of our predictions. What I often find is that we are relying very much on our data and do not take time / effort to look at the greater picture. How often do we lean back and think conceptually about the geological environment we are trying to model / predict? Often, we just continue with the data we have, and after much data-squeezing and interpreting we create a model that we think is the best there is. One thing that sometimes worries me is: is it really a *geological* model we created? Is it geologically plausible? And did we put as much knowledge of the geological system as we have into the modeling procedure? In other words, do we bring *a-priori* knowledge in our predictions? We are trained geologists /

geophysicists, we should know from our background and experience what the subsurface should look like, at least approximately. To me, modeling is seeing the big picture through the data (noisy as it may be) and not to forget, with all the fancy modeling technique, that geology is a natural science that adheres to a certain set of rules.

Jan Stafleu:

Hans-Georg Sobisch and I have developed two different voxel data formats that we use in the SubsurfaceViewer as well as in other applications.

The first (and oldest) data format concerns **regular voxels,** i.e. a 3D grid of rectangular voxels where each voxel has the same dimensions. This data format is a 3D extension of ESRI's Arc-ascii format. The format consists of header lines describing the grid structure (x,y,z of the origin, dx,dy,dz of the voxel sizes and nx,ny,nz of the number of voxels) followed by data lines containing the attribute values of the voxels. The format does not require the x,y,z-coordinates of individual voxels, which saves a large amount of storage space. However, it does require data lines describing empty voxels with nodata-values.


ASCII.txt - Notepad

File Edit Format View Help

```
gridtype regular
sorting +Z +Y +X
nx 5
ny 5
nz 10
xllcenter 584630.5
yllcenter 269124.94
zllcenter 10.85125
dx 10.0
dy 10.0
dz 2.0
nodate_value -99.0
Lithology
string

CHLK
CHLK
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An example of this format adopted by the BGS

Recently we developed a second data format, with which we are able to store **irregular voxels**, i.e. a 3D grid of rectangular voxels where each voxel can have its own dimensions. We have chosen a simple data structure consisting of a plain ASCII-file containing the x,y,z –coordinates of the lower left and upper right corner of each voxel followed by a list of property values (e.g. the geological unit the voxel belongs to, the lithological composition and the hydraulic conductivity). Irregular voxels are used to deliver voxel models that display more detail (i.e. smaller voxels) where data density is high, and less detail where data density is low. In general, data density in the Netherlands allows the construction of detailed voxel models with a resolution of 100 x 100 x 0.5 m for the upper 30 m. The incorporation of soil data (both maps and boreholes) allows an even higher resolution (25 x 25 x 0.1 m) in the upper 2 m.

Example:

```
*****************************************************************************
TEST DATASET IRREGULAR VOXELS                                             ***
(c) TNO Geological Survey of the Netherlands                              ***
*****************************************************************************
XY_irregular=false
nodata_value=-999.0
xmin      ymin      zmin       xmax      ymax      zmax       unit_name     unit_number
float     float     float      float     float     float      string    integer
182900    386900    24.57      183000    387000    25.59      AA        0
183000    386900    24.35      183100    387000    25.27      AA        0
183100    386900    23.89      183200    387000    24.67      AA        0
183200    386900    24.17      183300    387000    24.78      AA         0
183300    386900    25.02      183400    387000    25.53      AA        0
```

An interesting spin-off of the irregular voxels is that they allow the efficient storage and analysis of layer-based (framework) models. Using irregular voxels, the layer-based hydrogeological model of the Netherlands, for instance, can be stored in a single file rather than in a large set of separate raster-files of top, base, thickness and hydraulic conductivity for each of the 128 hydrogeological layers in the model (Figure 1).

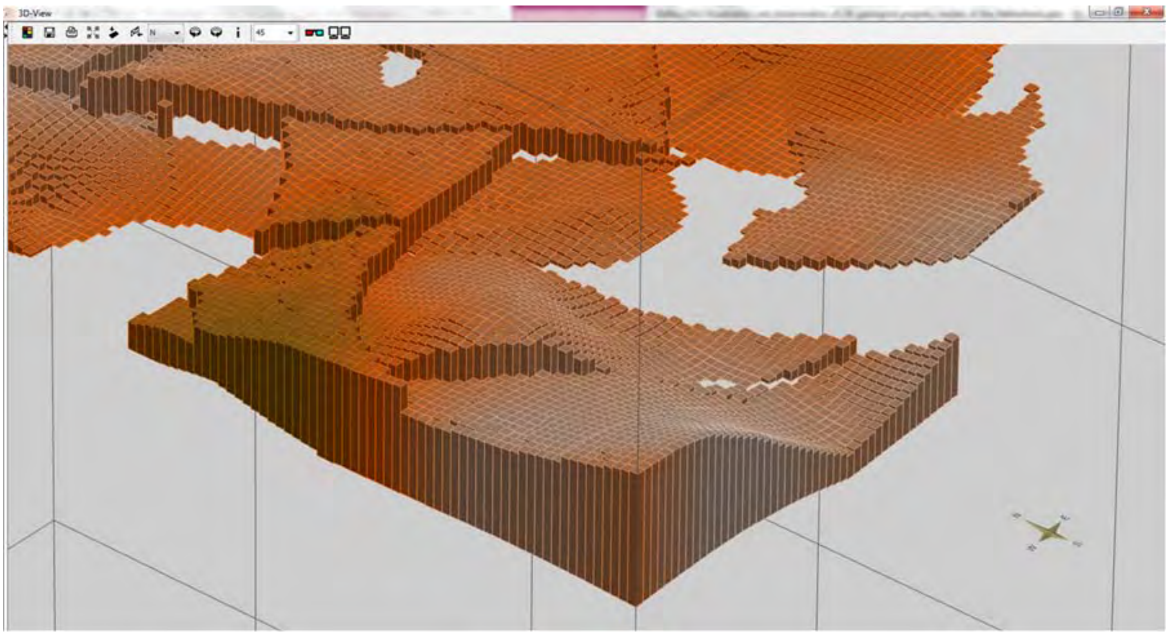


Figure 1: A hydrogeological layer described by irregular voxels (regular xy, irregular z). Hydraulic conductivity varies within the layer in horizontal directions.

Holger Kessler:

- I think it is extremely important that we think about our language and vocabulary when talking to our colleagues from different disciplines, backgrounds and cultures. The first day showed how quickly we can misunderstand each other when using terms such as "deterministic" or "model"
- I was very interested in the Danish "manual voxel editing" process which bridges the gap between data and expert driven modeling and I will follow this methodology up in the future
- It was fascinating to contrast the implicit approach in Geomodeller with the explicit approach of GSI3D, both create a model in the end, but the input is completely different and of course the method you chose depends on the data and knowledge you have in the first place
- I liked the idea of the TNO eye tracking experiment to see where Geologists look when analyzing a model – I will be in touch with Freek Buschers about this some time.
- One other important message (for management and Directors) is that we do still need Geologists with real-life experience of rocks to create and importantly approve meaningful models.
- We need to be open with our methodologies in order to ensure our models can be defended and true interoperability is ensured, http://www.sciencemag.org/content/340/6134/814.full.pdf
- I think we should have a regular workshop of a small team, perhaps every year or maybe we follow the model of our North American friends who have a workshop every 2 years connected to the GSA conference? http://www.isgs.uiuc.edu/research/3DWorkshop/index.shtml

Martin Nayembil

I enjoyed the experience and it was very good to hear the views from across different institutions and interesting science, especially from the non-modeller perspective.

It was interesting to see that data, data structures, formats and the overall data architecture facilitates the modelling process and was a common theme in most of the talks and in my interactions with participants.

It was evident that quality data is very critical to the modelling process but also, how and where to store and access this data together with modelled components are also very critical in streamlining the modelling process and delivering quality models.

As indicated at the meeting, we are developing a Geological Object Store (GOS) to facilitate our modelling work and the key high level requirements driving this are:

- Provide a secure corporate repository for centralised storage of models from where they can be retrieved easily.
- Provide appropriate metadata describing models to comply with ISO standards, and also to provide the necessary information needed to re-create the model at some point in the future (e.g. record the type of software and version used to build the model)
- Provide a means of storing models in their original proprietary formats, so that the complete model can be rendered in the original software used to create it.
- In addition to storing models in their original formats there is also a requirement to be able to store in a software independent format so that the model can be re-created in a different modelling tool if required, so improving interoperability, and ensuring continued usability of the data as new modelling software becomes available. This software independent format also allows us to provide 3D modelled data in a form which can be readily delivered to users who may not have access to the original software used to build the model.
- Provide access to the corporate repository of models for BGS scientists via appropriate software interfaces – and using appropriate metadata.

The current intention is that the key modelling information to store is the interpreted line work on which the model is based, not the 3D calculated surfaces and triangulations which we previously stored. Calculated surfaces , coverage and thickness maps are now considered to be information products, which will be are generated from the contents of the Geological Object Store using appropriate tools/workflows and representing our best understanding/interpretation at a particular point in time.

There was mention of a central database required in many of the talks, re-emphasising the importance of a sound data framework to support the modelling process. I'm very keen to share components of BGS's data architecture with others not only on modelling components but the overall data architecture involving data and information management. I'm also keen to learn how other institutions are doing this and will be making the necessary contacts for visitations both ways, so that we can collaborate more and provide sound data architectures to facilitate 3D modelling work and beyond for overall better science and impacts.

We've also started a website to share some of our data models at the following location: http://www.earthmodels.org and will be very happy to also host models from other institutions or link to any similar resources you may have, so just let me know.

Katy Whitbread:

Key action points from my personal perspective are:

1. The continuation of development of quantitative methods to deal with uncertainty
2. Initiating more proactive approach to user engagement (in respect of feedback) within the context of the ASK network – by visiting external users, and when the timing is suitable arranging user workshops/demos.

Detailed notes:

Day 1 Session B: Model quality, uncertainty, error and QA.

Distinction between data quality and model quality:

- QA and error identification of input data to enhance model quality
- QA and checking of geological interpretations – relies on experienced geologists.

Dealing with uncertainty needs to reflect key questions that will be asked of the data, e.g. probability of sand in this position, likelihood that contact occurs within ± 1 m of depth Z. It is an ongoing challenge to develop ways of representing this uncertainty in our models – and different types of modelling (voxel vs. 'deterministic' models will require different approaches).

Visualisations of uncertainty can be confusing to users. Visualisations of uncertainty may only be useful in terms of highlighting data density and therefore giving an indication of interpretation uncertainty in deterministic models. Development of statistical methods for assessing interpretational uncertainty is ongoing at BGS.

What uncertainty values can/should we include in web products e.g. synthetic cross-sections and boreholes? How do we present them?

Need to strike a balance between the need to QA models and the need to maintain flexibility in modelling approaches; to respond both to user needs and technological developments. There is potential that complex QA procedures could stifle development of modelling capability.

Day 2 Session A3: Organizing feedback from users

Distinction between feedback on geological interpretation and on the products or 'presentation' of the model:

- Still need to develop methods of displaying complex bedrock structures (BRGM, BGS)
- TNO and BGS already responding to user feedback on model presentation, products and delivery: use of web served data, ARC compatible products, 3D viewers.
- Feedback on geology and data encouraged by TNO through user groups during model development, but issues of engagement due to limited time available for external users to assess products and consider feedback.

- BGS engaging user community by building a user network (ASK Network in Glasgow) and working with specific commercial clients to encourage 'user' amendment to models. Need to address issues with QA and versioning of user edited models.

Need to empower/encourage users to give feedback through building of relationships directly between geo-modellers and users. Development of user groups and use of demos and workshops can raise understanding of modelling procedures and limitations within the user community and allow survey organisations to present a 'human face' to users. This should encourage direct engagement and build confidence in users that feedback will be acted on.

Day 2 Session B 3: Making geological models useful for applied uses

How to develop models for applied uses depends on application and purpose of model:

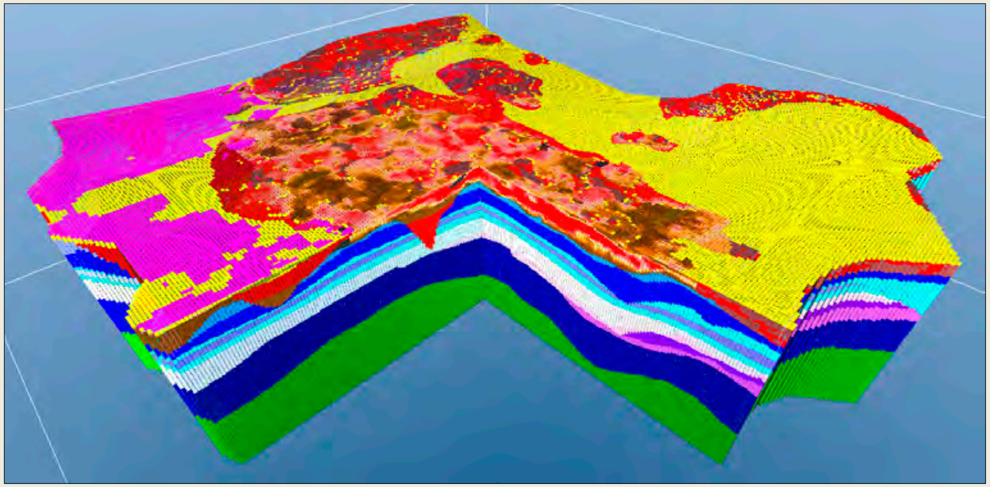
- GEUS model developed specifically for groundwater modelling
- BGS and BRGM develop(ing) both local applied models and national framework models

National framework models are based on geology but can be populated with key information that then allows them to be developed for a range of uses

- There is a need to identify a core set of attributes that can be used to populate framework models for a range of hydrogeological and engineering uses.
- Modellers must work with hydrogeologists and engineering geologists (within surveys and in user organisations) to identify key attributes.

The advantage of having a national framework model is that it provides continuity for local models and can be used to influence policy at a regional and national level. The National framework model must be compatible, at some level, with local applied models to ensure continuity. (This was discussed in response to a question posed by BRG that a national framework model may be of limited use when models are generally constructed on the basis of application to specific user needs.)

GEUS



Examples of hydrogeological and geological modelling from geophysical data

Flemming Jørgensen

Geological Survey of Denmark and Greenland

Translating resistivity to geology or hydrogeology – limitations:

- The degree of saturation
- The ion content of the pore water
- Clay content
- Clay type

- Vertical resolution capability
- Horizontal resolution capability
- Weak resolution of resistive layers
- Spatial variations in property

- Depth of penetration, DOI
- Coupled and noise-infected soundings
- Model equivalency, model uncertainty
- The type of model used – blocky or smooth model

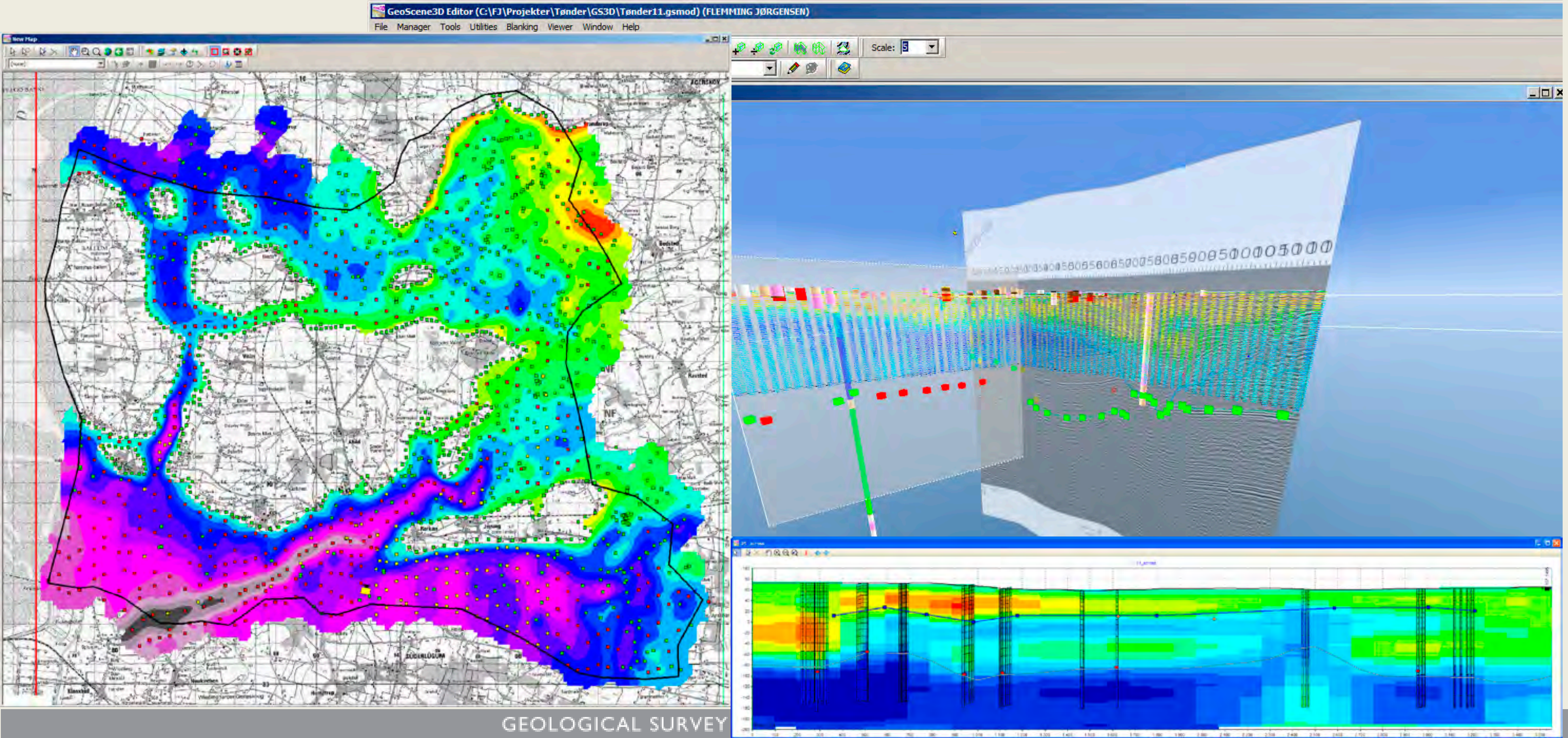
Data interpretation

Some Danish sediments:

Sediments	Resistivity (Ω m)
Meltwater sand and gravel	>60
Clay till	25–50
Glacio-lacustrine clay	10–40
Neogene mica silt/sand: Miocene	>40
Neogene mica clay: Miocene	10–40
Paleogene clay: Eocene–Oligocene	5–12
Paleogene clay: Paleocene–Eocene	1–7
Danian limestone	>80

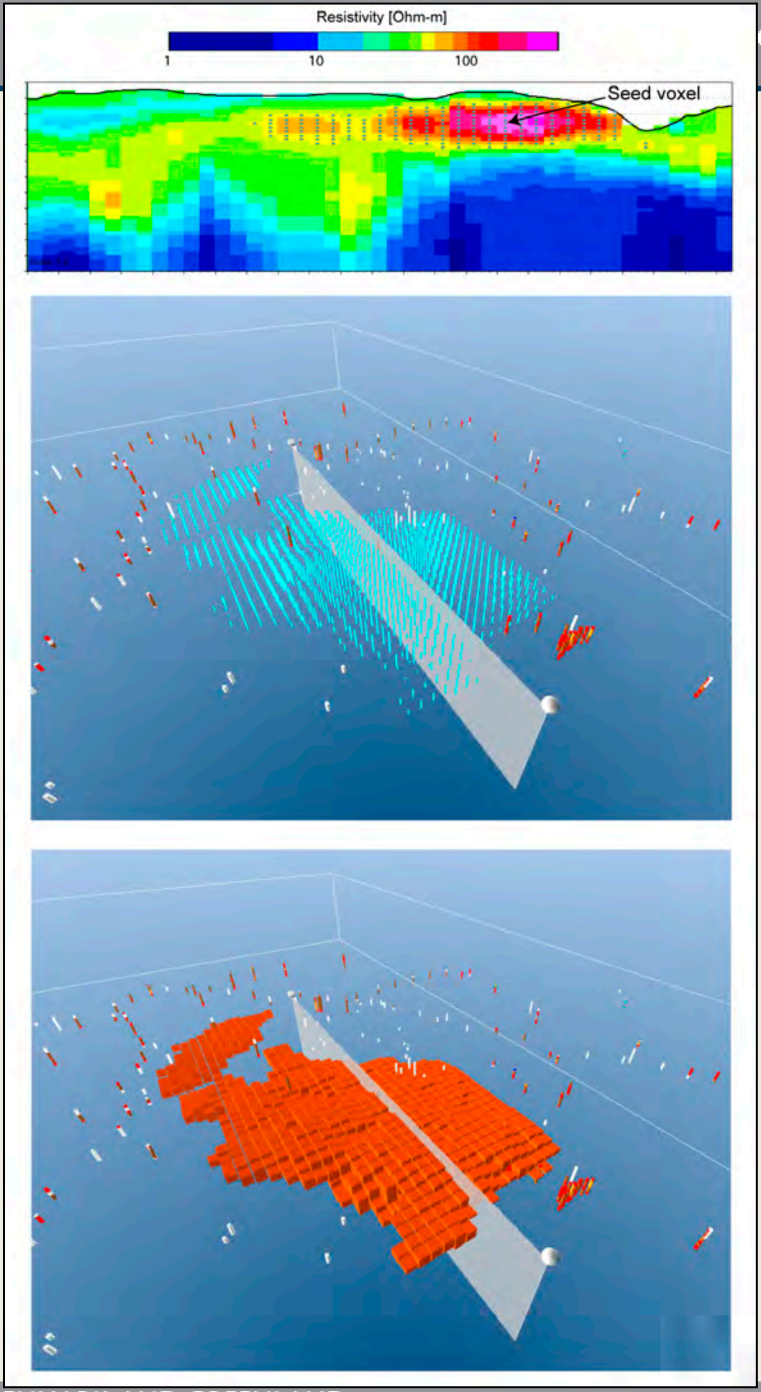
Layer-based modelling

Basic digitalisation of interpretation points on maps, profiles and directly in 3D space



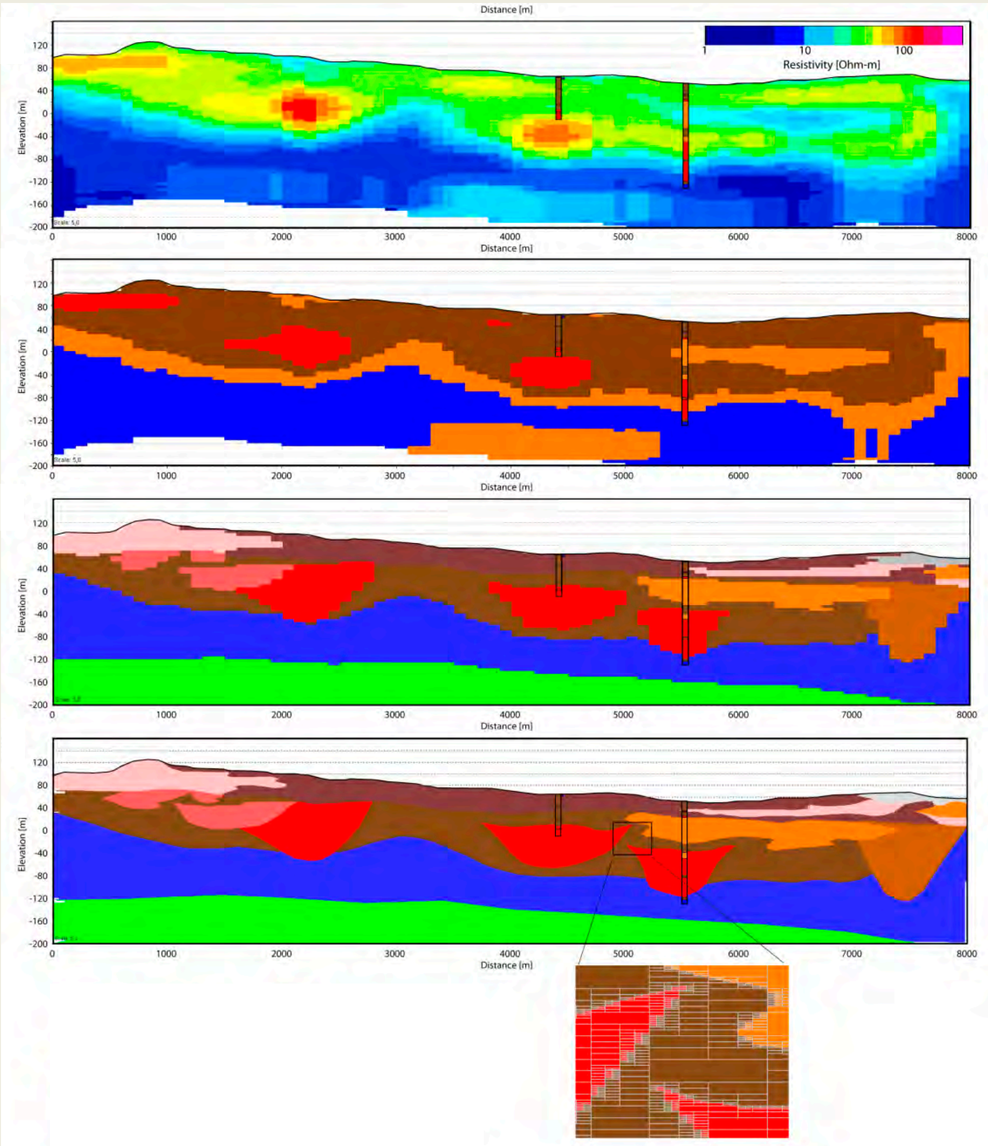
Voxel modelling tools

- Region grow selection

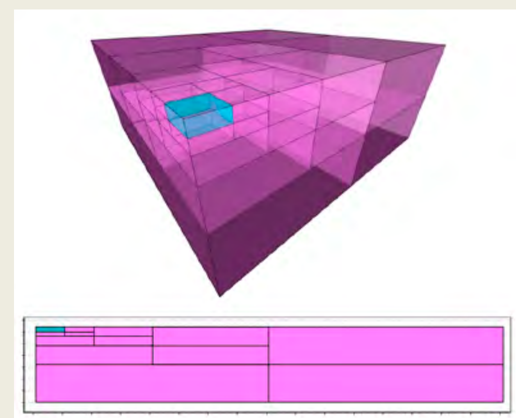


Jørgensen, F., Møller, R.R., Nebel, L., Jensen, N.-P., Christiansen A.V. and Sandersen, P.B.E 2013: A method for cognitive 3D geological voxel modelling of AEM data. Bulletin of Engineering Geology and the Environment.

Cognitive, manual voxel modelling, octree discretization



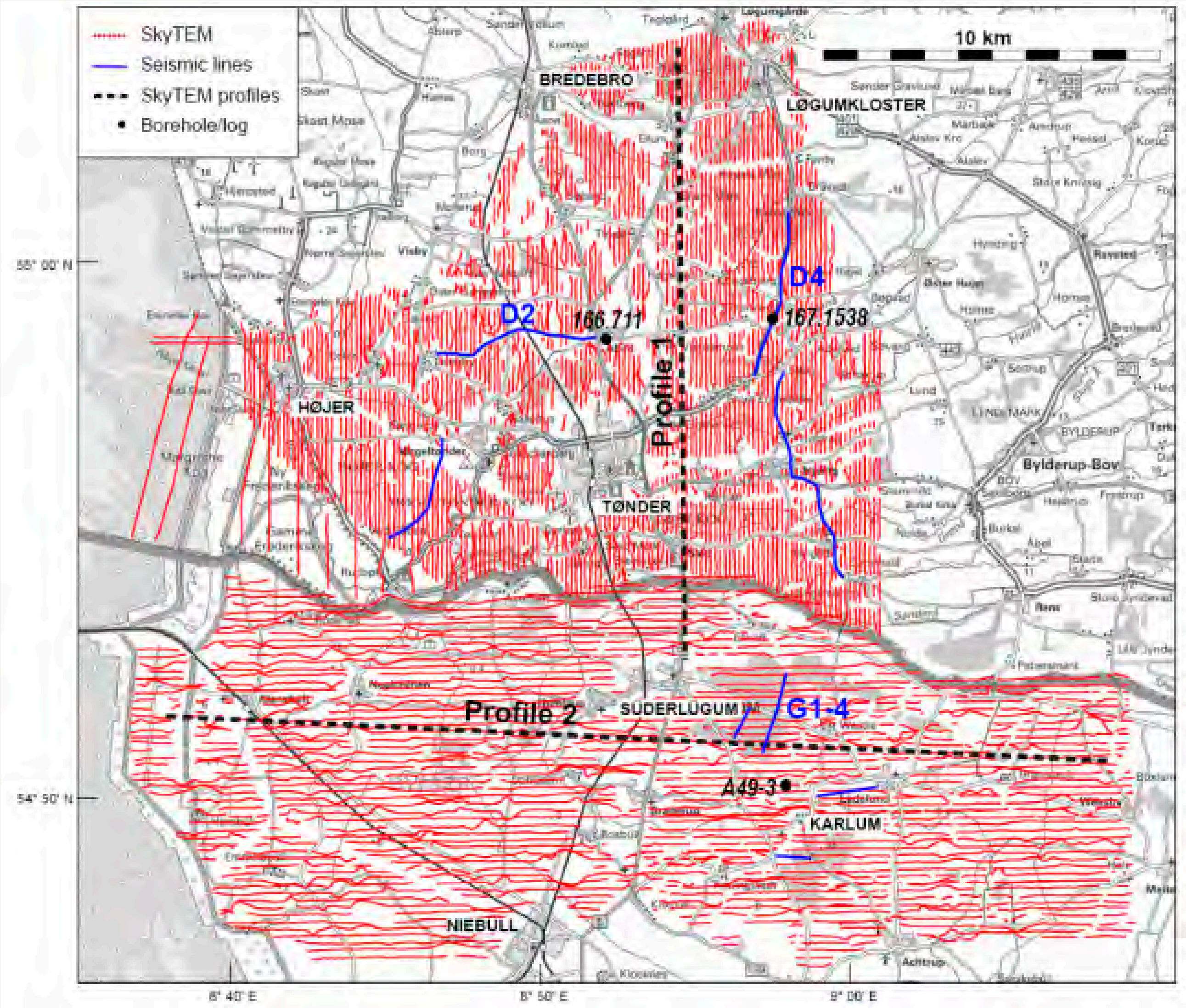
- Voxels can be divided into 8 equally-sized in order to increase the level of detail



Jørgensen, F., Møller, R.R., Nebel, L., Jensen, N.-P., Christiansen A.V. and Sandersen, P.B.E 2013: A method for cognitive 3D geological voxel modelling of AEM data. Bulletin of Engineering Geology and the Environment.

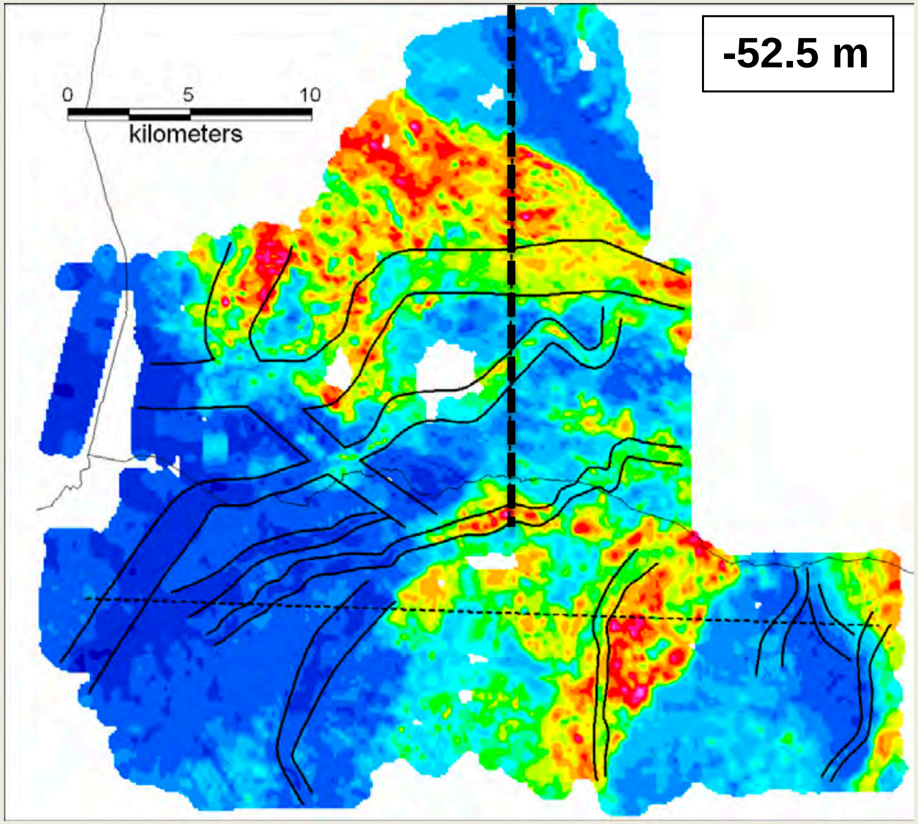
The Tønder-Leck survey

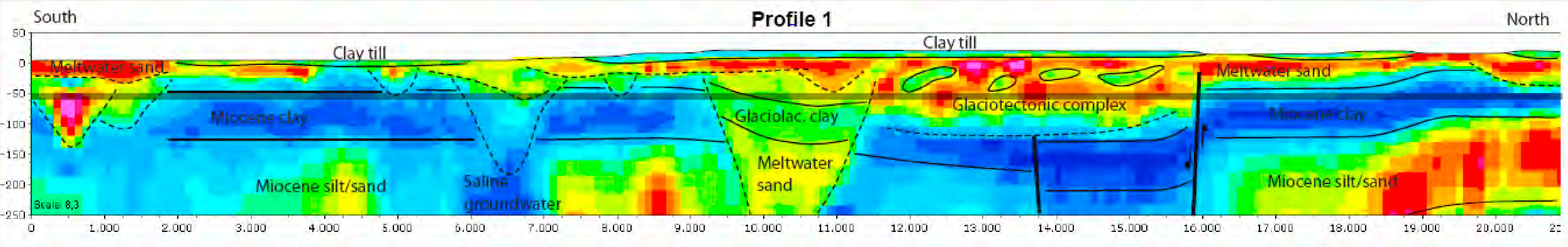
- 3230 line km
- 166 and 250 m spacing
- 721 km^2



Jørgensen, F. et al. 2012: Transboundary geo-physical mapping of geological elements and salinity distribution critical for the assessment of future sea water intrusion in response to sea level rise. Hydrology and Earth System Sciences, 1845-1862.

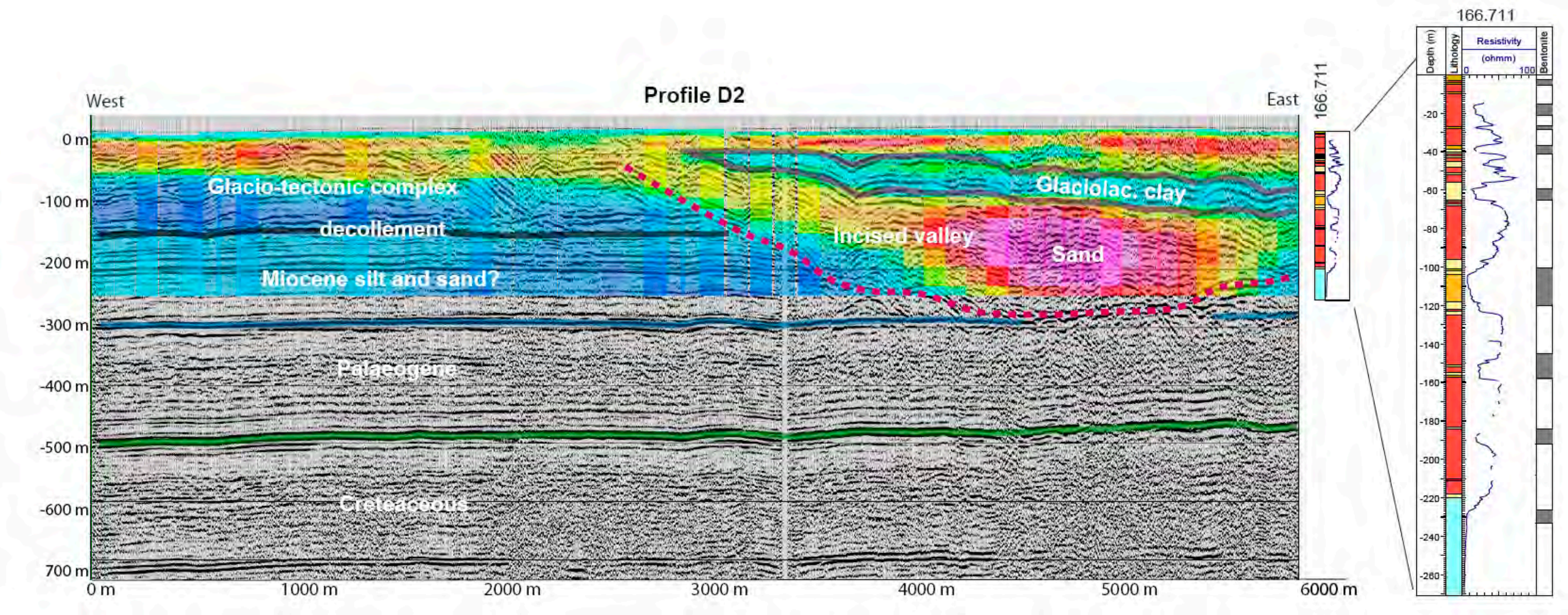
Geological interpretations

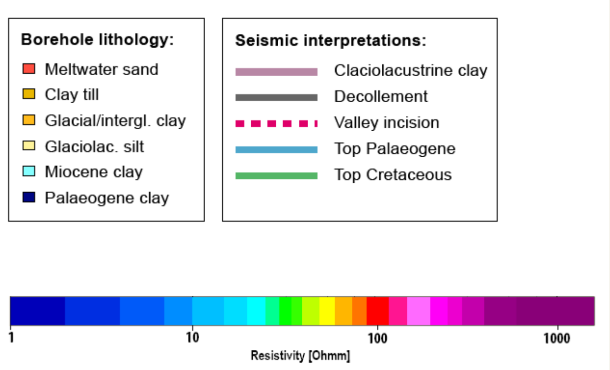




Jørgensen et al. 2012

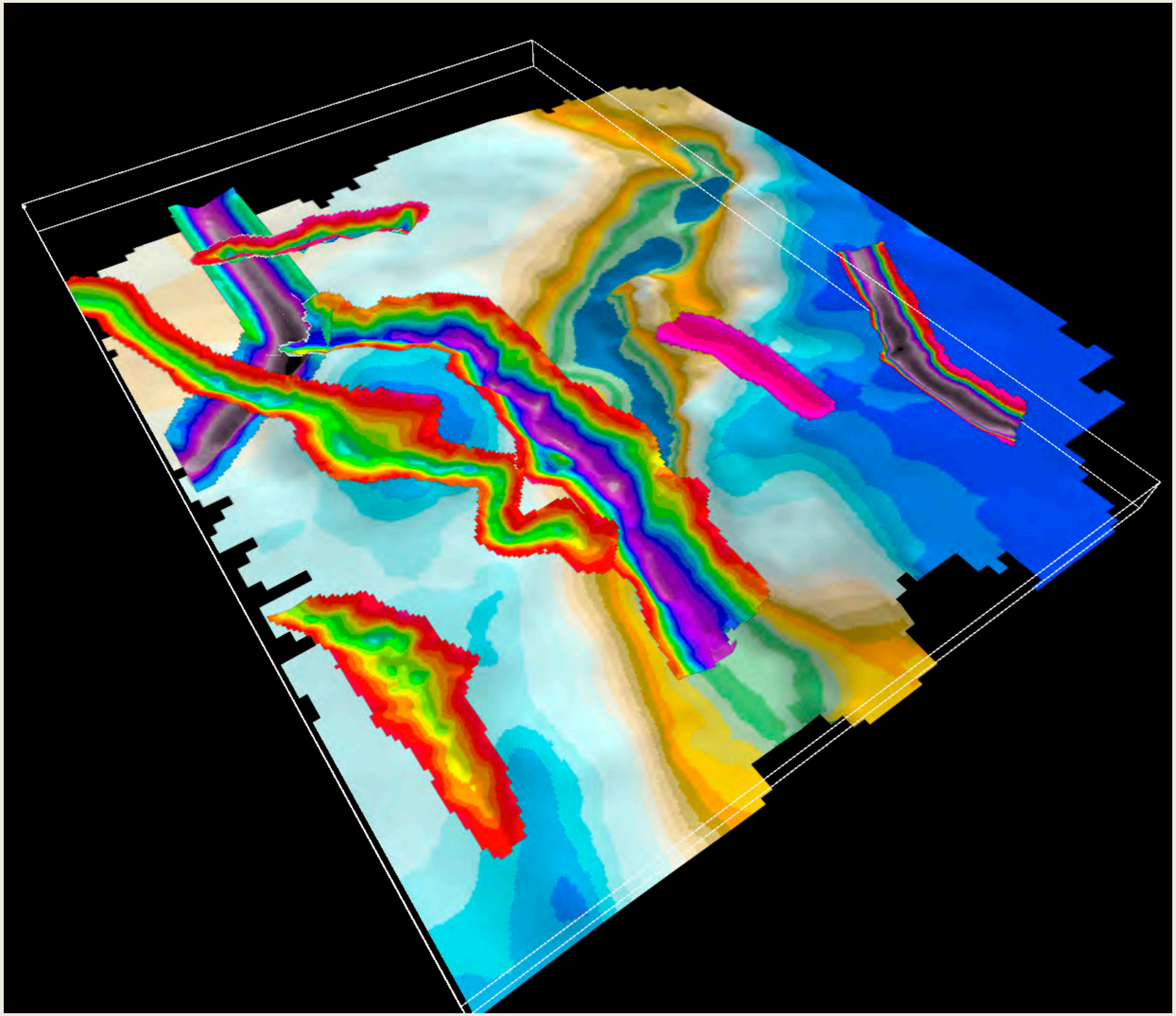
Geological interpretations



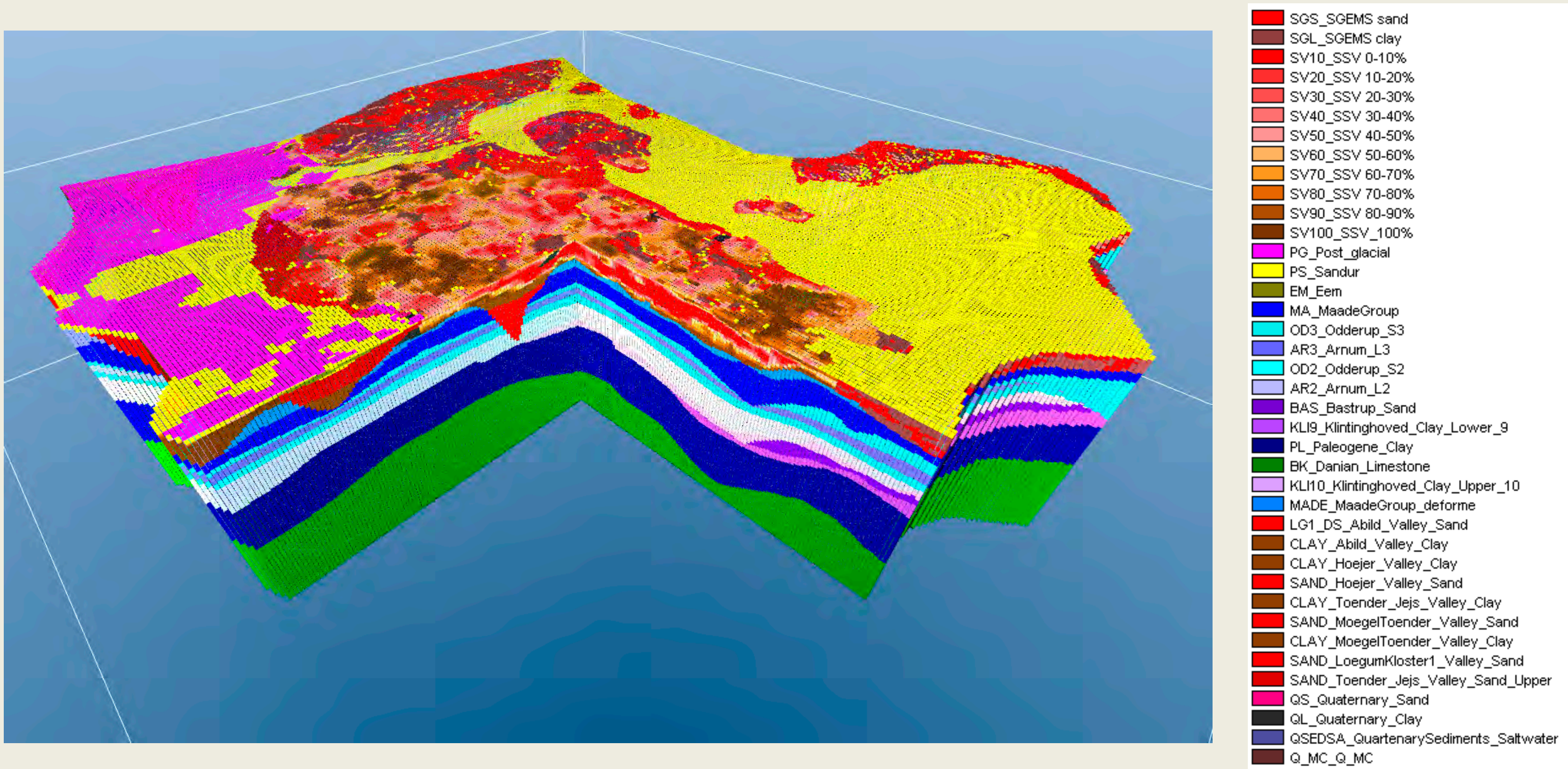


Jørgensen, F. et al. 2012: Transboundary geophysical mapping of geological elements and salinity distribution critical for the assessment of future sea water intrusion in response to sea level rise. Hydrology and Earth System Sciences, 1845-1862.

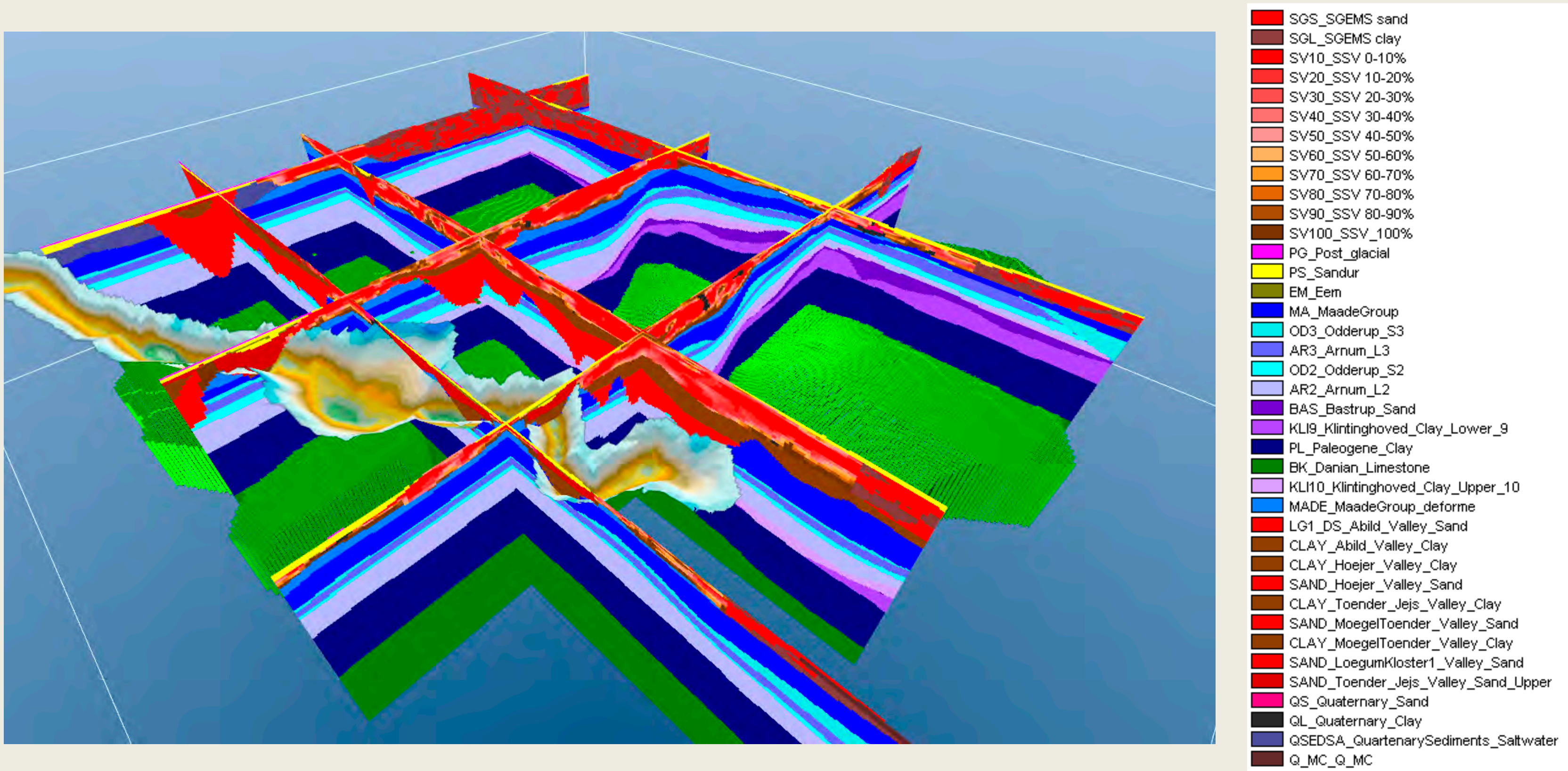
Buried valleys



Final voxel model



Voxel model, valley surface



Appendix

AGENDA

17th – 18th September 2013

TNO, Princetonlaan 6, NL-3584 CB, Utrecht

Aim: To exchange progress, problems and solutions in our quest to understand and communicate the 3D composition and properties of the subsurface to aid science-based decision making

AGENDA

Tuesday

13.00 Opening and Welcome, Michiel Van der Meulen

13.10 Overview presentations (20 mins max!) plus questions – Chairs Holger Kessler and Jan Gunnink

Geological modelling in Denmark - An overview – Peter Sandersen

The National Reference Framework and 3D modeling experiences at BRGM - **Sunseaié** GABALDA

Trends and perspective in 3D and 4D Geomodeling in the Netherlands – Michiel van der Meulen

Overview of 3D modelling activities in Germany and a case study from the German North Sea sector – Bernd Lindner and Gesa Kuhlmann

An overview of activities in BGS – Andy Kingdon

15.30 Break

16.00 Introduction to the workshop discussion sessions – (Jan Gunnink, Holger Kessler)

16.10 Facilitated discussion A and B

Session A Day 1 - Property modelling: populating geological models with properties - Facilitator - Flemming Jorgenson -

Team: Anne-Sophie Høyer, Stephan Steuer, Andy Kingdon, Ingelise Møller Balling, Antonio Guillen, Sunseaié Gabalda, Martin Nayembil, Jan Gunnink, Jeroen Schokker, Ronald Vernes, Jan Stafleu, Denise Maljers, Hans Doornenbal, Bernd Linder.

Session B Day 1 - Judging the quality of our models: uncertainty assessment, error propagation, quality assessments - Facilitator - Michiel van der Meulen

Team: Rachel Dearden, Holger Kessler, Murray Lark, Courrioux Gabriel, Gesa Kuhlman, Richard Thomsen, Diarmad Campbell, Peter Sandersen, Giulio Vignoli, Bruce Napier, Katie Whitbread, Maryke den Dulk.

17.30 Wrap-up discussion led by the facilitators

18:00: Transport to city center (arranged by TNO) with drinks and dinner in "town-castle" Oudaen (http://www.oudaen.nl/web/en/1_home.htm). (Total cost per person 50 Euros, incl meal, drinks and beer tasting, each participants pays themselves)

Wednesday

9.00 Introduction to second day workshop sessions (Jan Gunnink and Holger Kessler)

9.10 First round of sessions

Day 2 session A1 - 3D layer-based vs. voxel-based modeling: techniques and pitfalls - Facilitator Peter Sanderson

Team: Anne-Sophie Høyer, Murray Lark, Stephan Steuer, Andy Kingdon, Flemming Jørgensen, Bruce Napier, Hans Doornenbal, Maryke den Dulk

Day 2 session A2 - Versioning and management of geological models: challenges and solutions - Facilitator Holger Kessler

Team: Ingelise Møller Balling, Antonio Guillen, Sunseaŕe Gabalda, Richard Thomsen, Martin Nayembil, Michiel vd Meulen, Giulio Vignoli, Denise Maljers, Bernd Linder

Day 2 session A3 - How to organize feedback from our models users to increase the usability of the geological / property model -- Facilitator Jan Gunnink

Team: Rachel Dearden, Gabriel Courrioux, Gesa Kuhlmann, Jeroen Schokker, Ronald Vernes, Jan Stafleu, Katie Whitbread

10.10 Short break

10.30 Second round of sessions

Day 2 session B1 - Delivery of geological models: viewers, WWW and augmented reality -- Facilitator - Bruce Napier

Anne-Sophie Høyer, Sunseaŕe Gabalda, Martin Nayembil, Michiel vd Meulen, Giulio Vignoli, Hans Doornenbal, Maryke den Dulk, Bernd Linder

Day 2 session B2 - Using other datatypes (e.g. geophysics, geological knowledge) in the modelling process -- Facilitator - Andy Kingdon

Team: Anne-Sophie Høyer, Stephan Steuer, Ingelise Møller Balling, Antonio Guillen, Jan Gunnink, Peter Sandersen, Jeroen Schokker, Ronald Vernes

Day 2 session B3 - Making geological models useful for applied modellers (eg groundwater, engineers) -- Facilitator Richard Thompson

Team: Holger Kessler, Murray Lark, Gabriel Courrioux, Gesa Kuhlman, Flemming Jørgensen, Jan Stafleu, Denise Maljers, Katie Whitbread

11.30 Reporting back from the work sessions – 10 minutes per facilitator

12.30 Lunch

13.30 Open Forum for feedback from groups (this can be in form of demonstrations, presentations, flip chart, a proposal, a discussion) – Chair to be decided

15.30 Break

16.00 Actions and close (Holger Kessler)

17.00 Depart

BGS Attendees

Bruce Napier – ITSpecialist - Team Leader – Visualisation Systems http://www.bgs.ac.uk/staff/profiles/1335.html -
Rachel Dearden – Hydrogeologist – Products and delivery systems development, knowledge exchange
Paul Williamson –Geophysisist - GOCAD and statistical modeller, algorithm developer

Katy Whitbread - Sedimentary Geologist

Holger Kessler – Geologist - Team Leader Geological Modelling Systems http://www.bgs.ac.uk/staff/profiles/2986.html -

Andy Kingdon –Geophysist – Team Leader Parameterisation and Statistics http://www.bgs.ac.uk/staff/profiles/0809.html -

Murray Lark – Environmental Statistician http://www.bgs.ac.uk/staff/profiles/40081.html -

Martin Nayembil – Geologist– Data Architect –

Diarmad Campbell – Chief Geologist Scotland

GEUS attendees

Peter Sandersen – Senior advisor, Geologist, - experienced geological modeller, interpretation of geophysical data, borehole data -
Anne-Sophie Høyer – Researcher Geologist/geophysicist, interpretation of seismic and airborne data, 3D geological modelling -
Giulio Vignoli – Senior researcher Geophysicist, inverse modelling, airborne data, surface waves -
Flemming Jørgensen – Senior researcher Geologist, 3D geological modelling, interpretation of geophysical data, borehole data -
Richard Thomsen – Chief consultant Groundwater mapping, hydrogeology, database management, administration, international projects
Ingelise Møller Balling - Senior researcher, Geophysicist, inverse modelling, airborne and ground based data, databases -

BGR/State Survey attendees

Gesa Kuhlmann – Geologist, GDPN project (Geopotential of the North Sea) -
Stephan Steuer – Geologist, GDPN project (Geopotential of the North Sea)
Bernd Linder – Geologist, Modeller - NorthRhein Westfalian Geol. Survey – representing the Federal Geological Surveys -

BRGM attendees

Sunseare Gabalda – Geologist - Project Manager National Geological Framework Programme -
Gabriel Courrioux– Researcher, Geomodeller -
Antonio Guillen – Researcher, Geomodeller -

TNO attendees

Denise Maljers – Geologist / Geomodeller, 3D geological modeling, property modeling
Jan Stafleu – Geologist, 3D model development, IT and geological modeling, 3D visualization – **Jan Gunnink** – Geologist / 3D modeller, property modeling, uncertainty analysis, using geophysical data in modeling –

Roula Dambrink – Geologist / Geomodeller –
Ronald Vernes – Hydrgeologist, Geomodeller –
Jeroen Schokker – Geologist, 3D modeler –
Maryke den Dulk - Geologist, seismic interpretion -
Hans Doornenbal – Geophyics. Project manager –
Michiel van der Meulen – Geologist, Head of Geomodelling department –