Model uncertainties in TNO’s subsurface modelling workflow

GSEU Workshop on Uncertainties in Geological Models

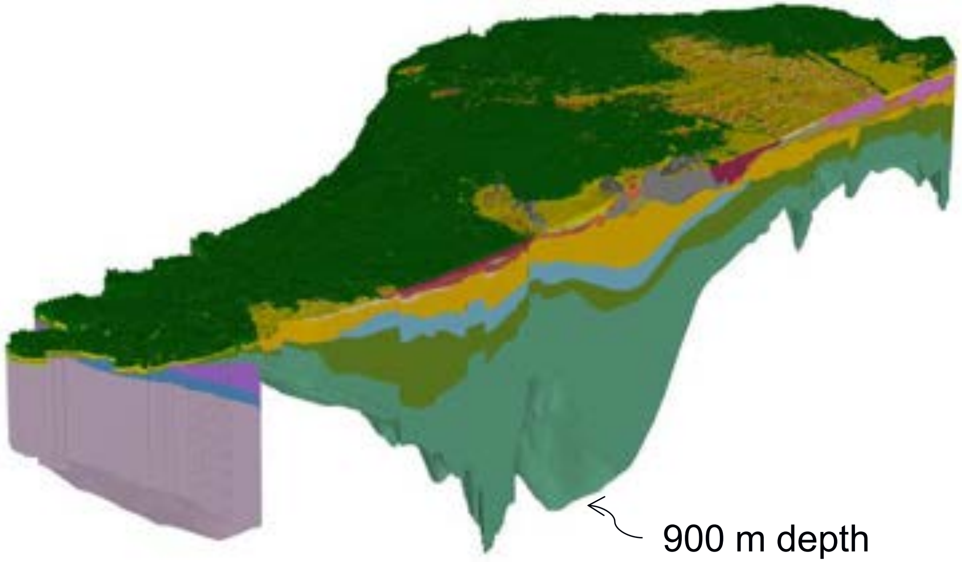
2 & 3 March 2026

Jan Stafleu

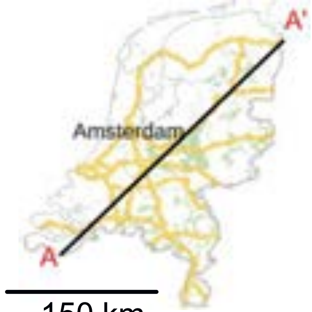
TNO Geologische Dienst Nederland

The national models

DGM: stratigraphical layers



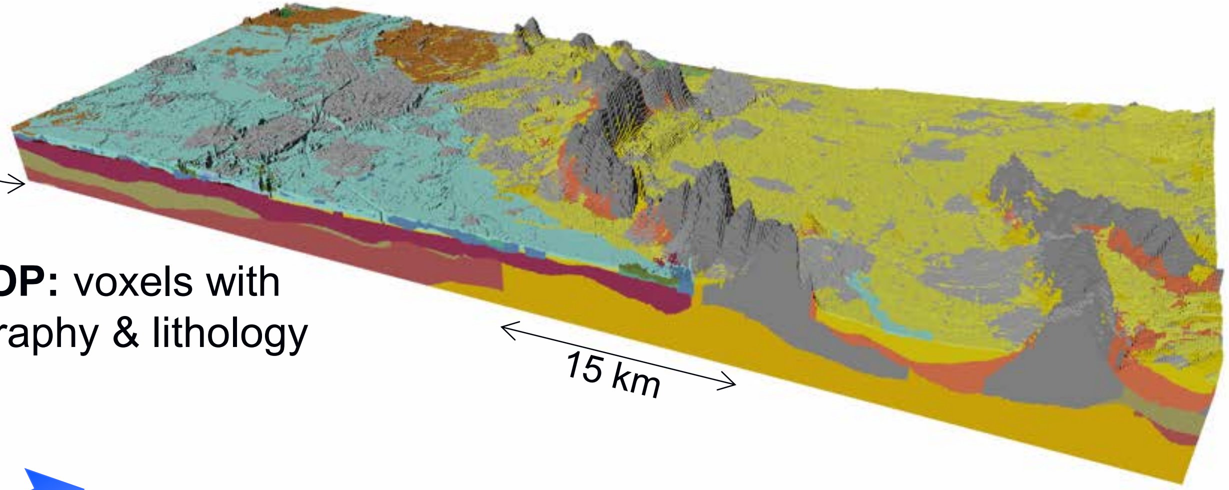
900 m depth



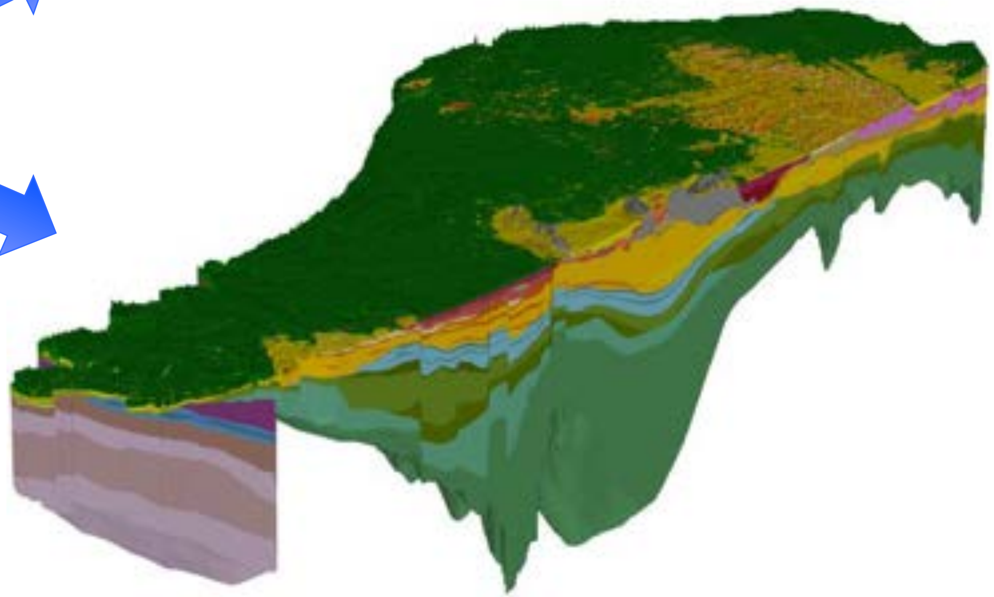
150 km

GeoTOP: voxels with stratigraphy & lithology

50 m depth

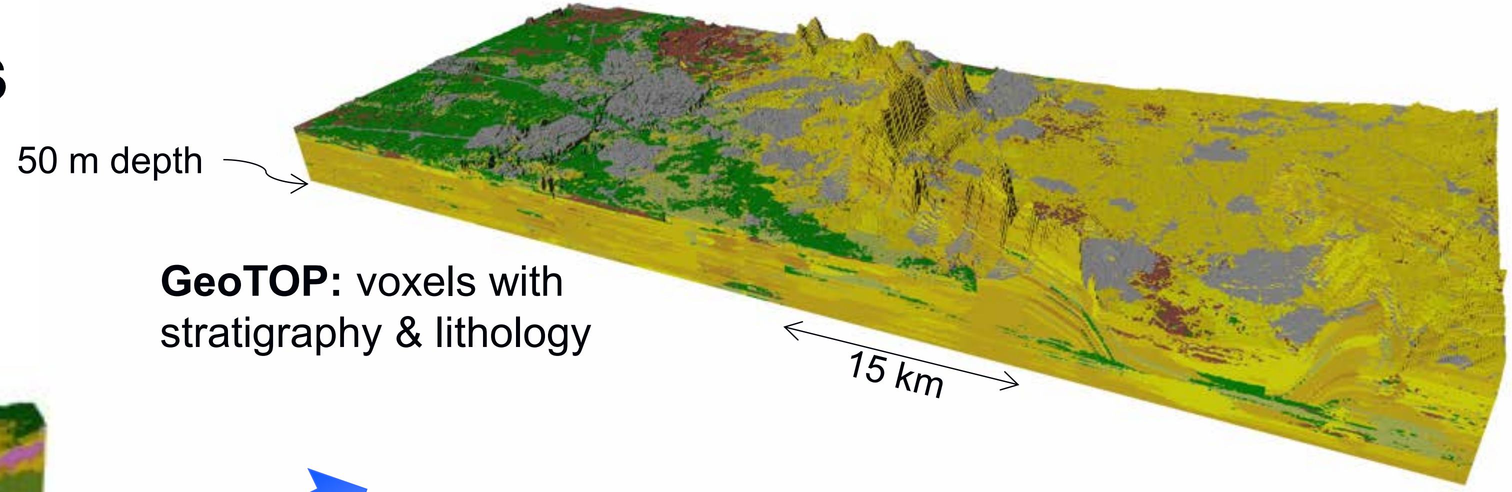


15 km



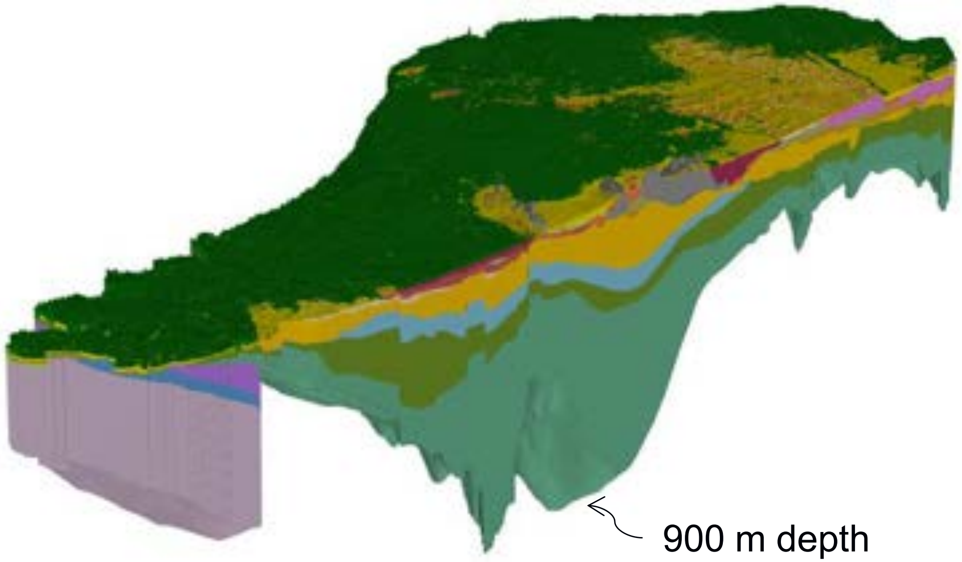
REGIS II: hydrogeological layers & properties

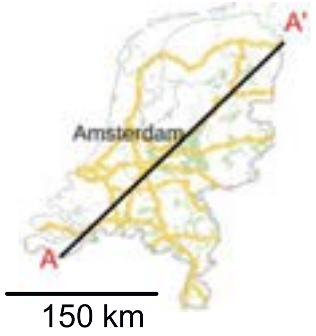
The national models

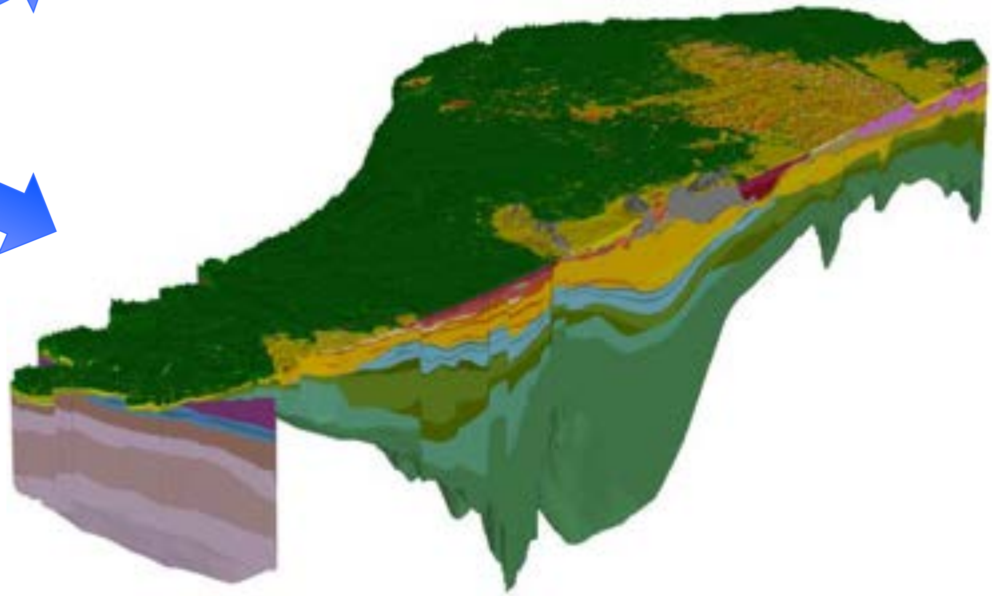


GeoTOP: voxels with stratigraphy & lithology

DGM: stratigraphical layers







REGIS II: hydrogeological layers & properties

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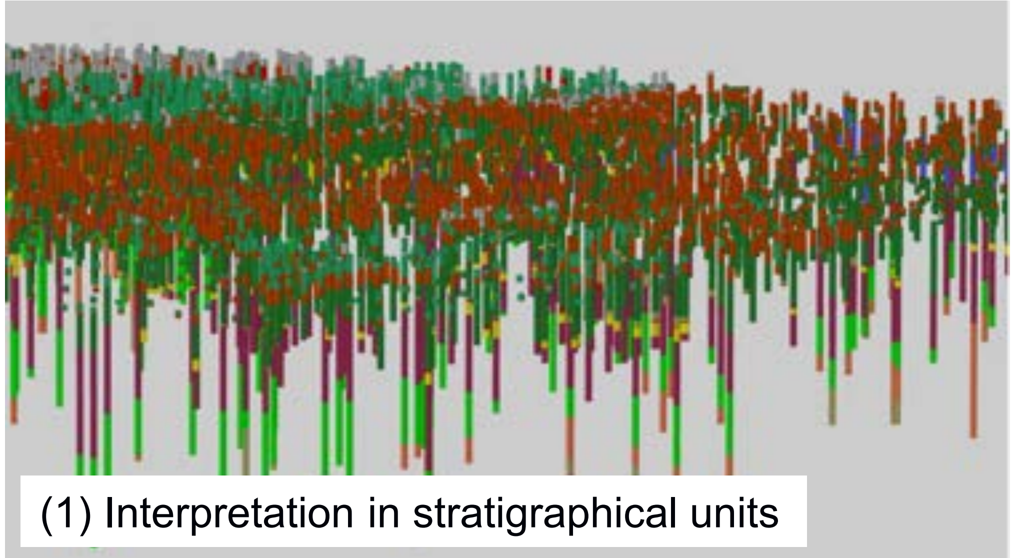
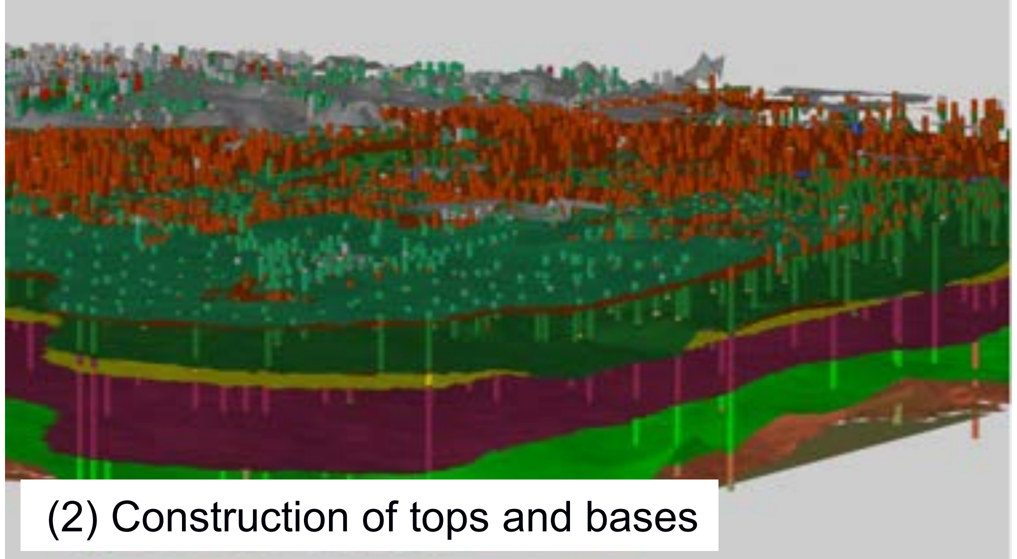
General workflow

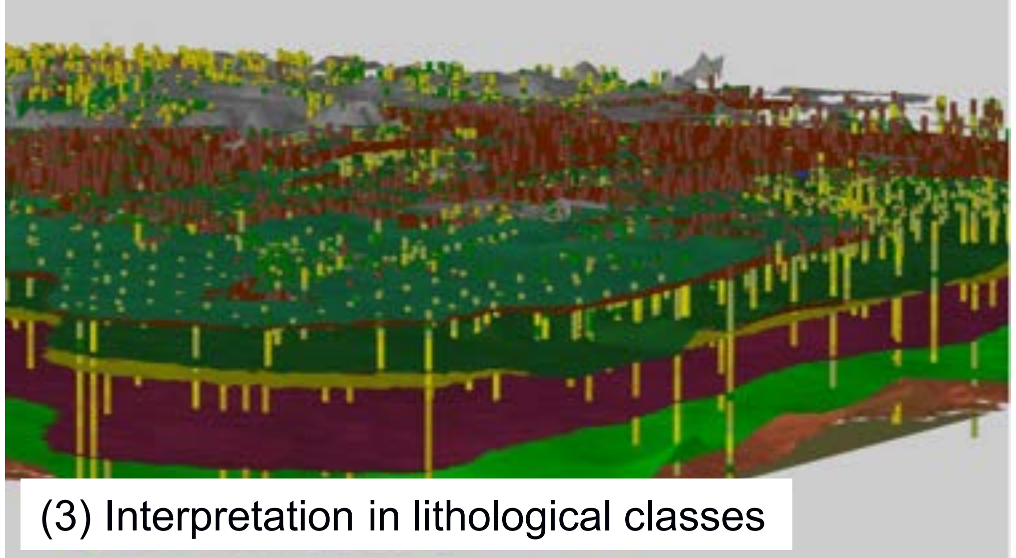


(1) Interpretation in stratigraphical units

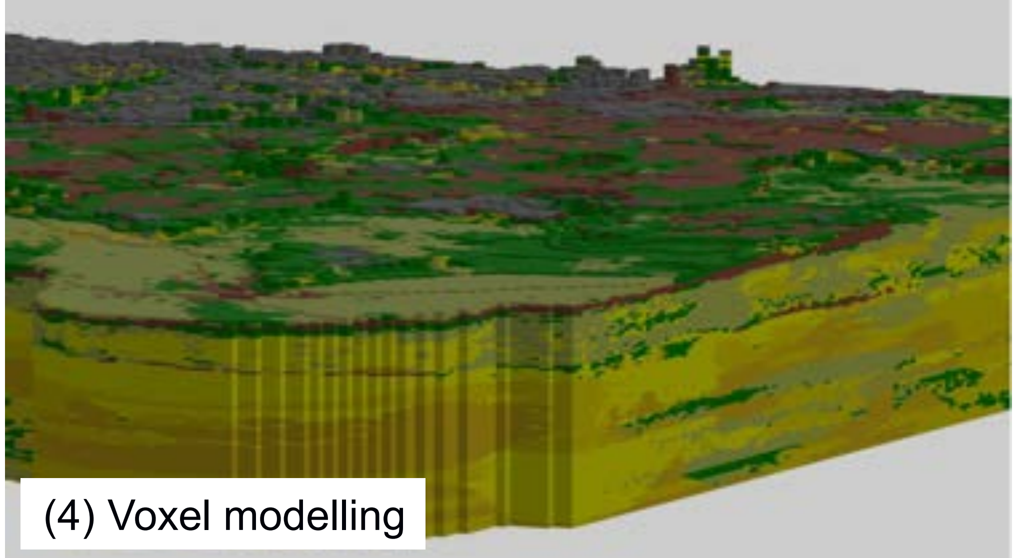


(2) Construction of tops and bases

Stratigraphical units
+
uncertainties



(3) Interpretation in lithological classes

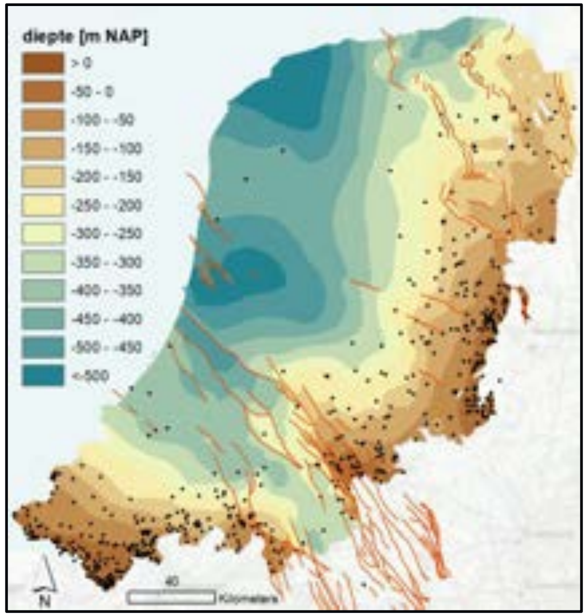


(4) Voxel modelling

Lithological classes
+
uncertainties

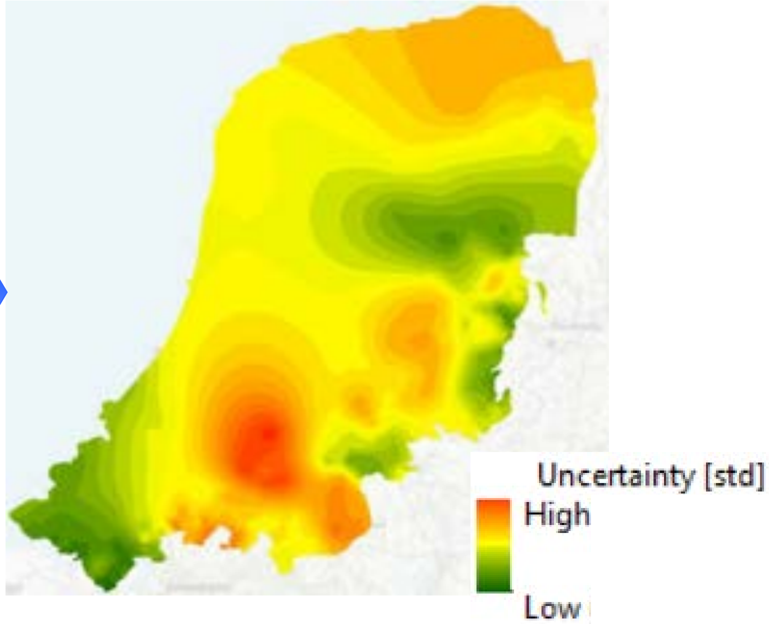
Uncertainty in layer models (DGM and REGIS II)

- **Regional uncertainty**
- Data density
- Regional & local uncertainty



Depth of base of formation

Cross-validation statistics



Regional uncertainty

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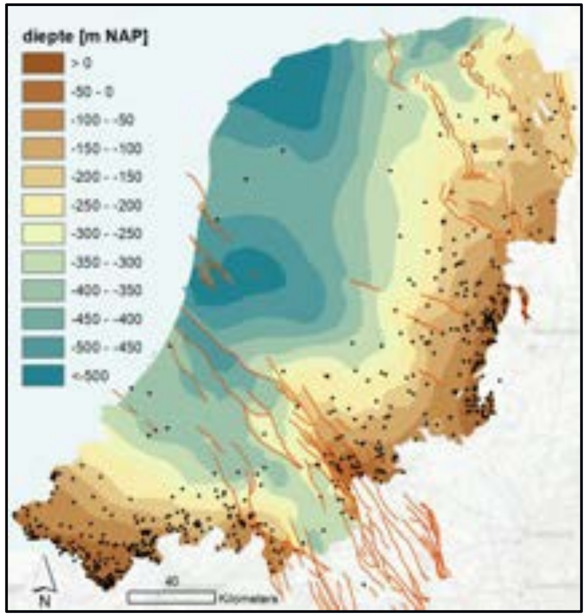
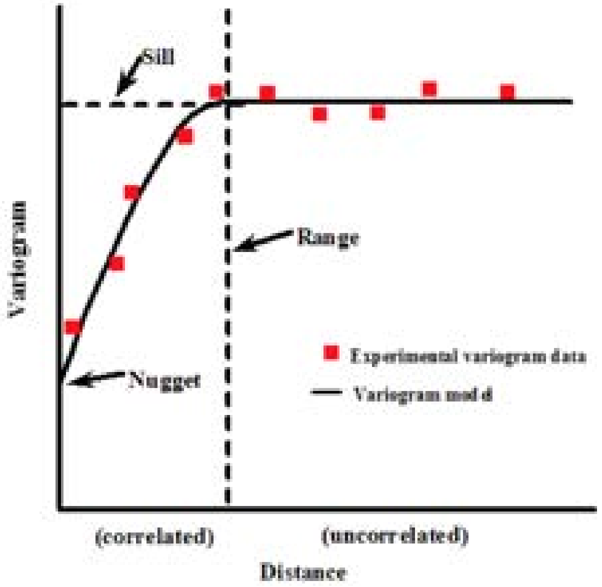
Uncertainty in layer models

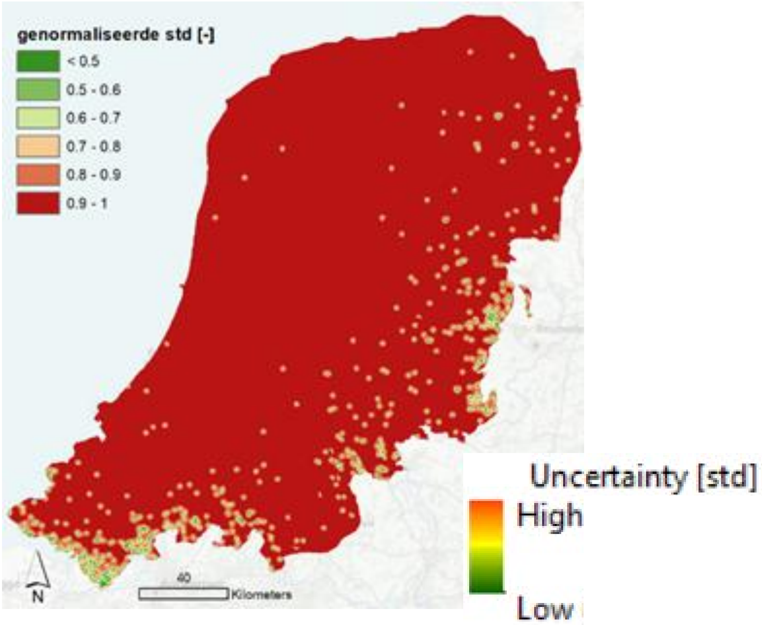
- Regional uncertainty
- **Data density**
- Regional & local uncertainty



Depth of base of formation



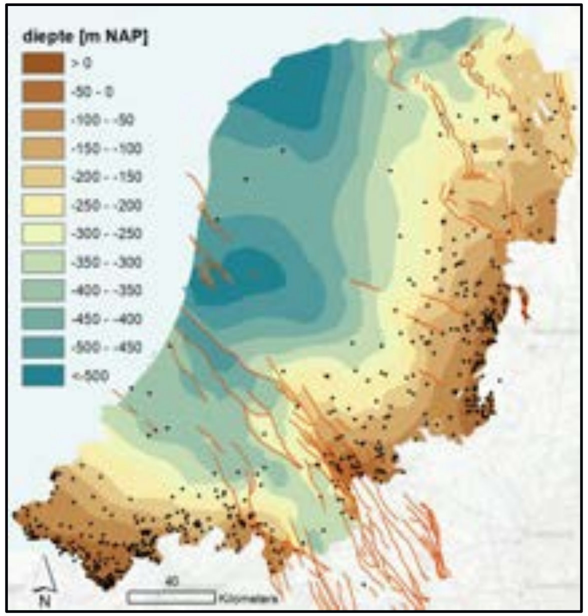
Normalised kriging variance



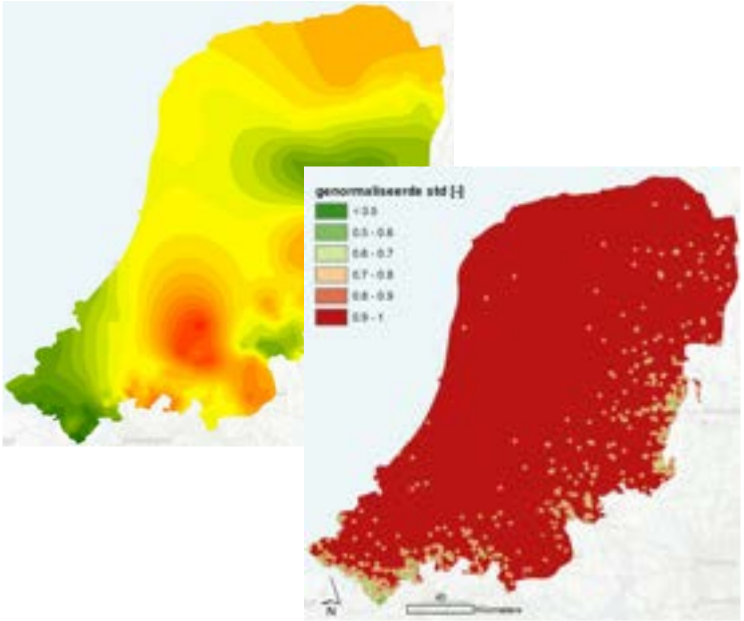
Data density, factor 0…1

Uncertainty in layer models

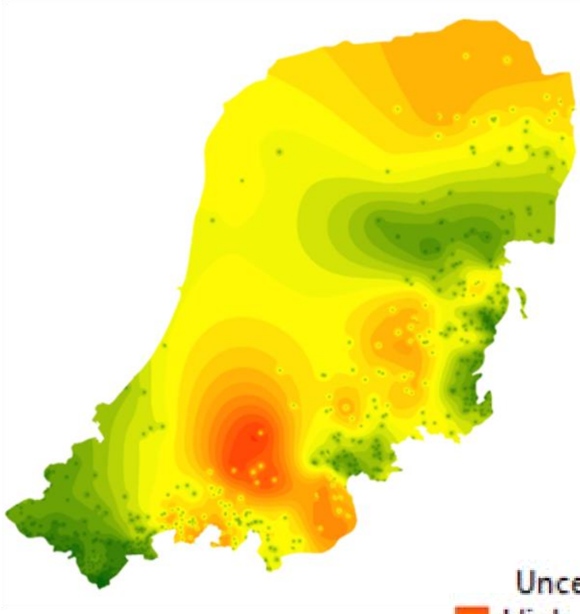
- Regional uncertainty
- Data density
- **Regional & local uncertainty**

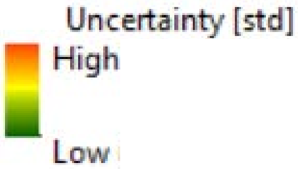


Depth of base of formation



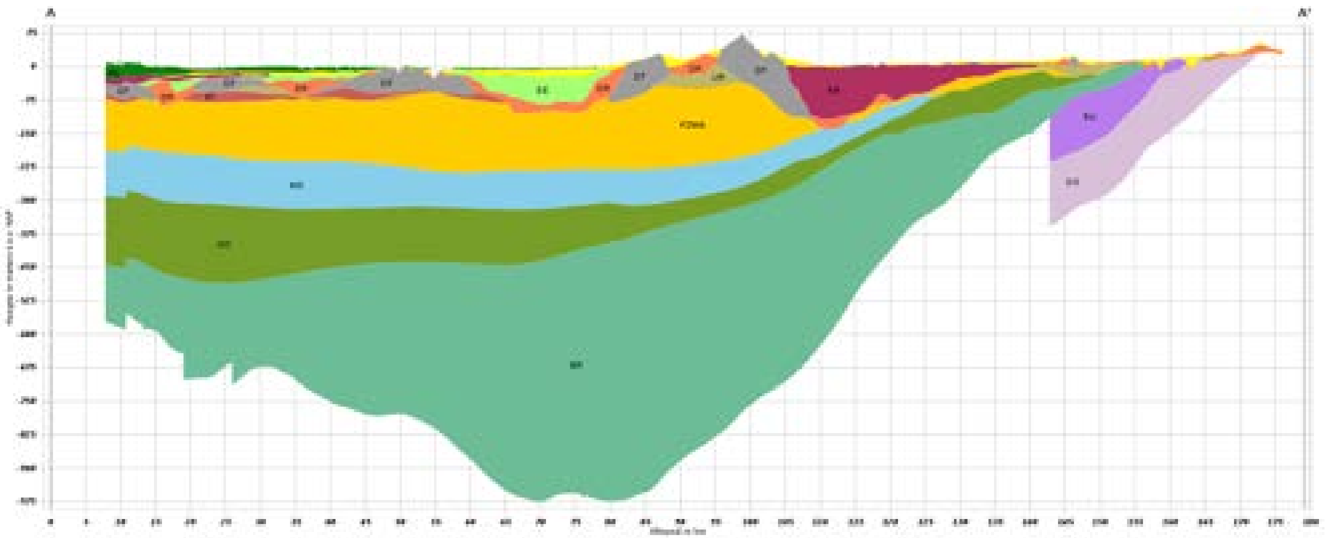
Regional uncertainty * Data density

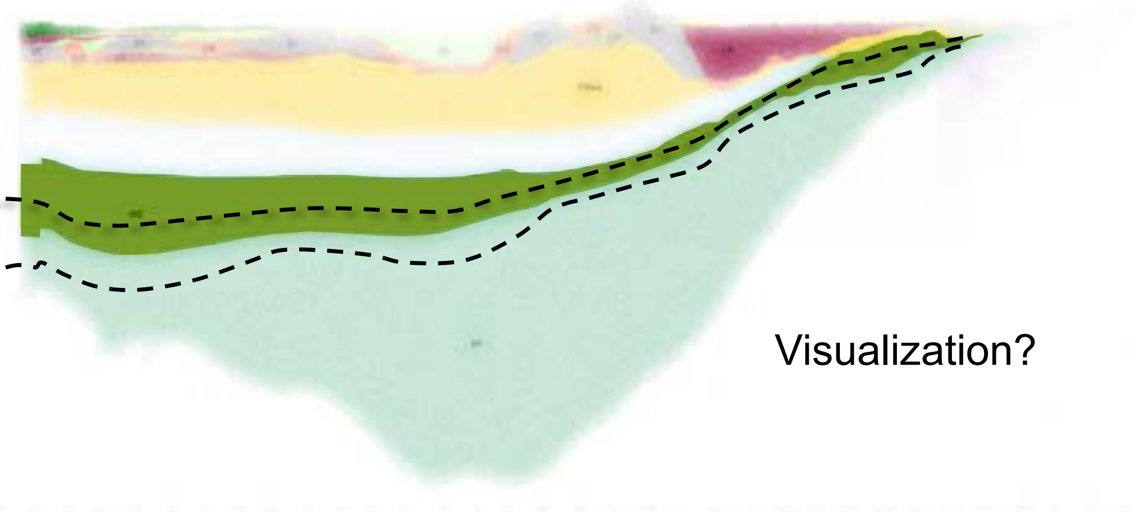




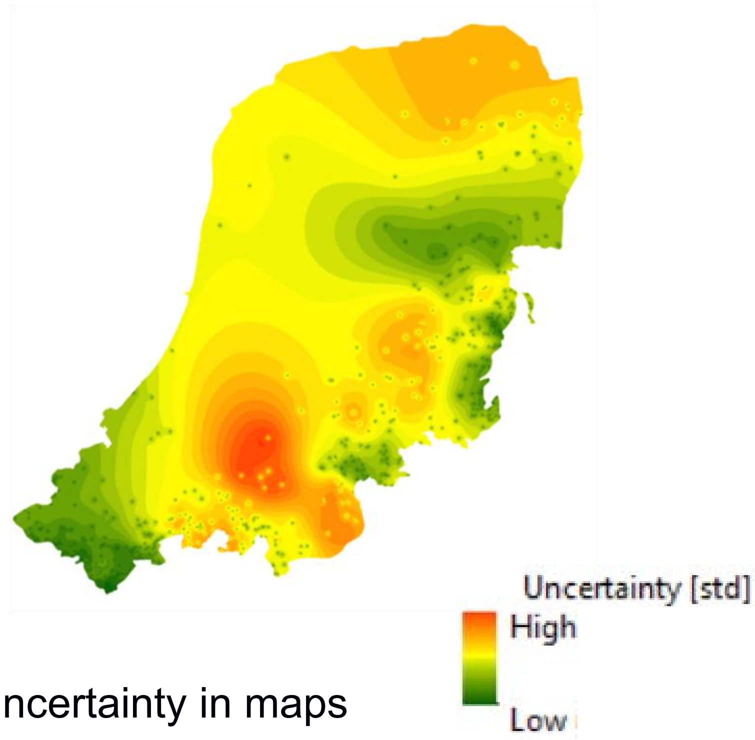
Uncertainty

Uncertainty in layer models – visualization?



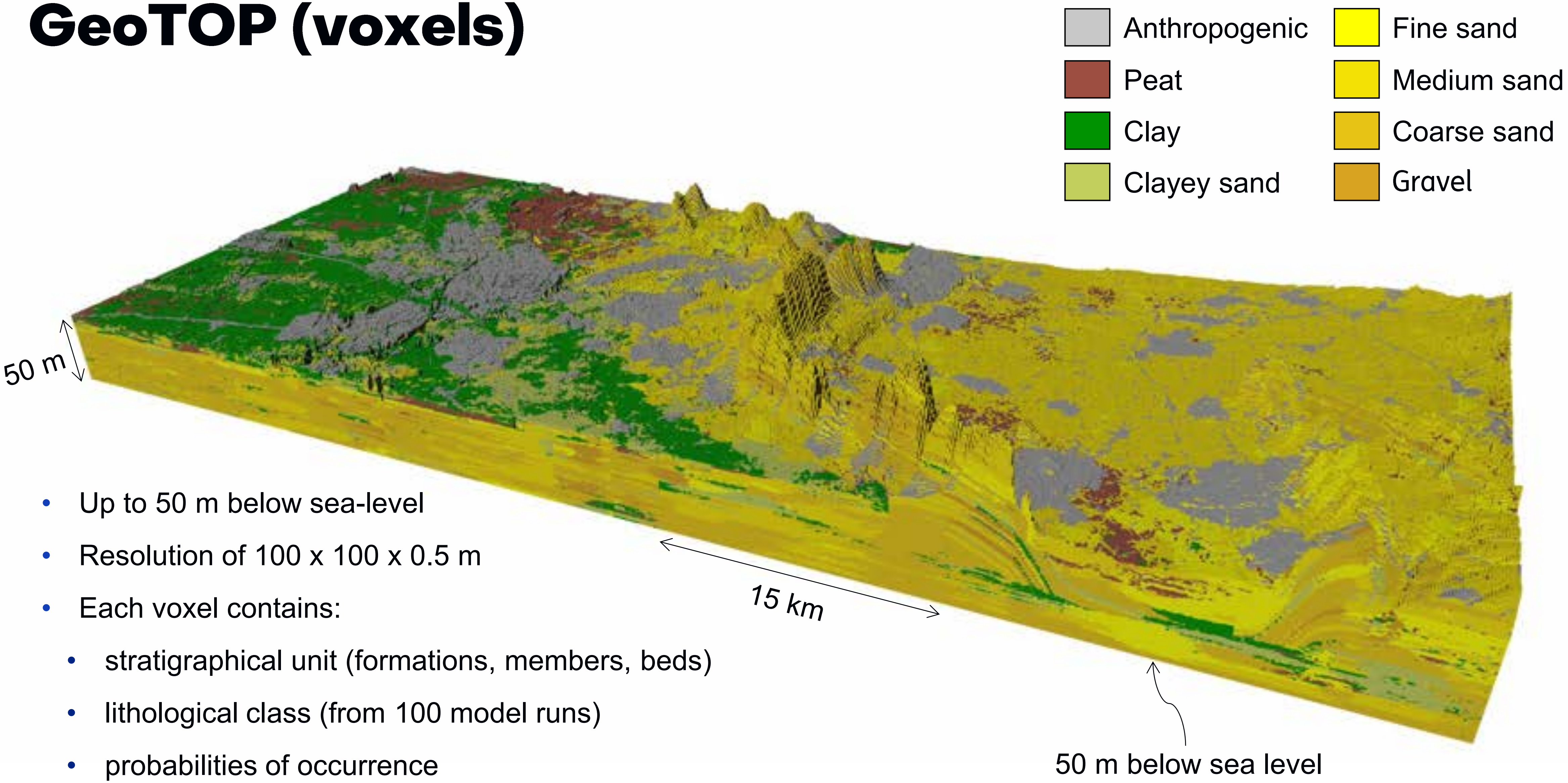


Visualization?



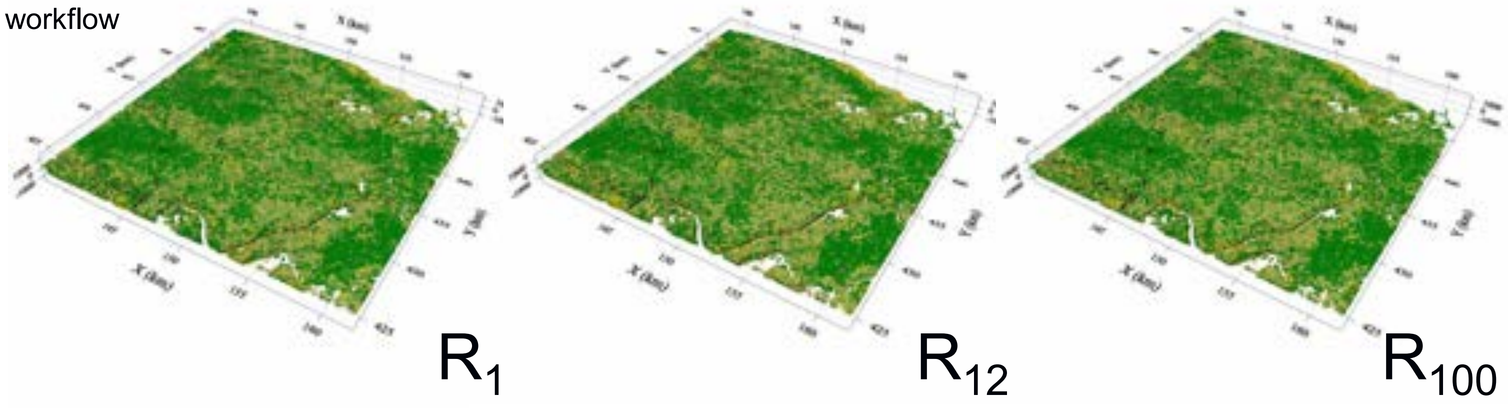
Uncertainty in maps

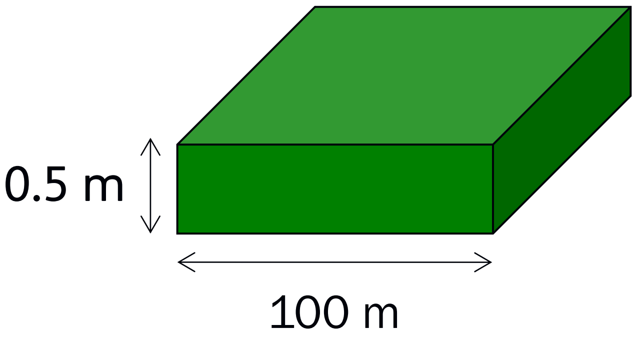
GeoTOP (voxels)



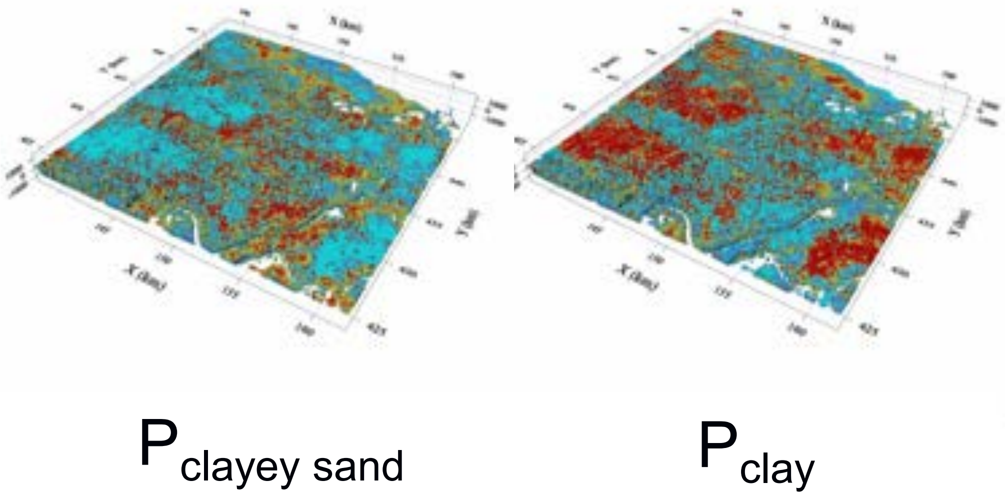
- Up to 50 m below sea-level
- Resolution of 100 x 100 x 0.5 m
- Each voxel contains:
  - stratigraphical unit (formations, members, beds)
  - lithological class (from 100 model runs)
  - probabilities of occurrence
  - model uncertainties

Voxel attributes

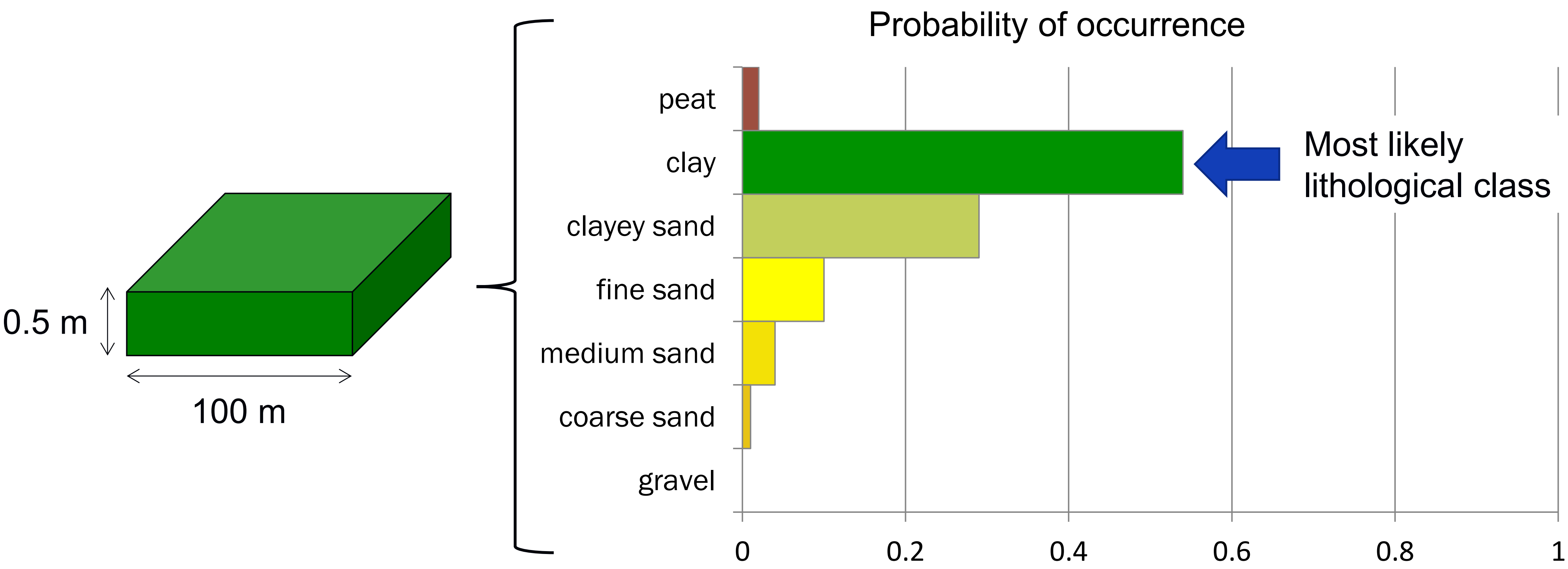




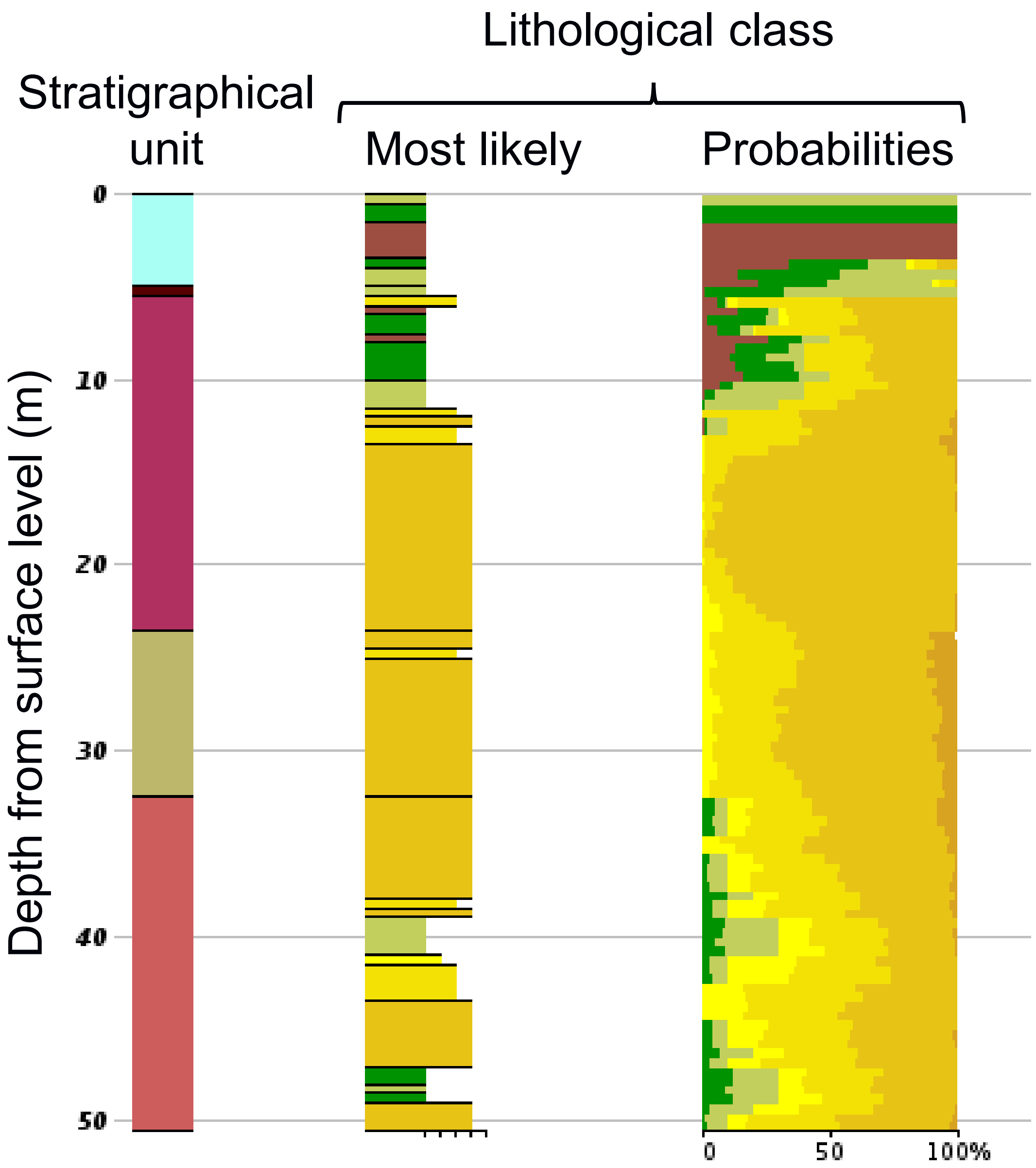
- Stratigraphical unit (from layer model)
- Most likely lithological class (from 100 model runs)
- Probabilities of occurrence:
  - peat
  - clay
  - clayey sand and sandy clay
  - fine sand
  - medium sand
  - coarse sand
  - gravel



Individual voxels



Vertical voxel-stacks



Plot created on: https://www.dinoloket.nl/en/subsurface-models/map

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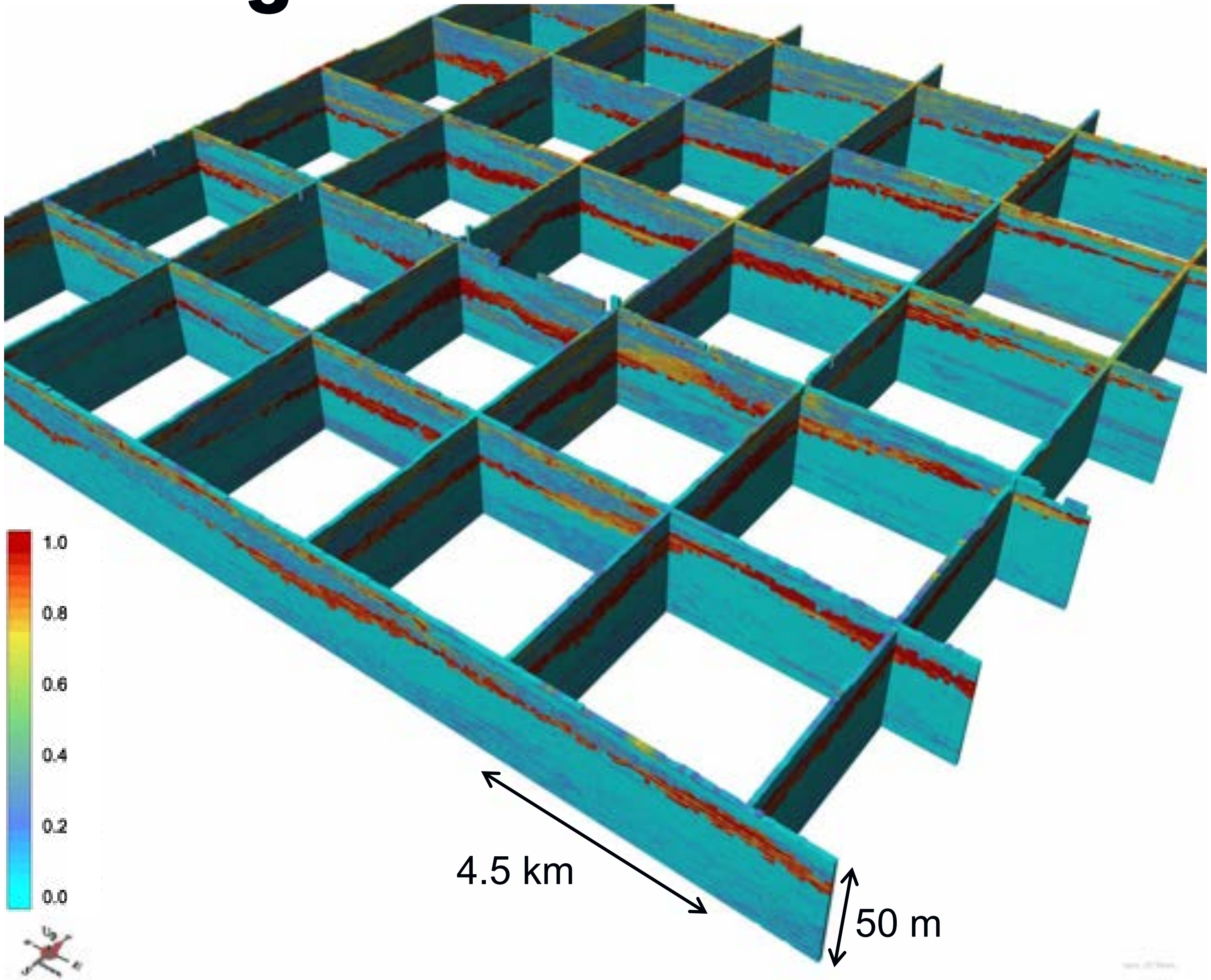
Model uncertainty – lithological class

- Probability of clayey sand



Model uncertainty for three lithological classes

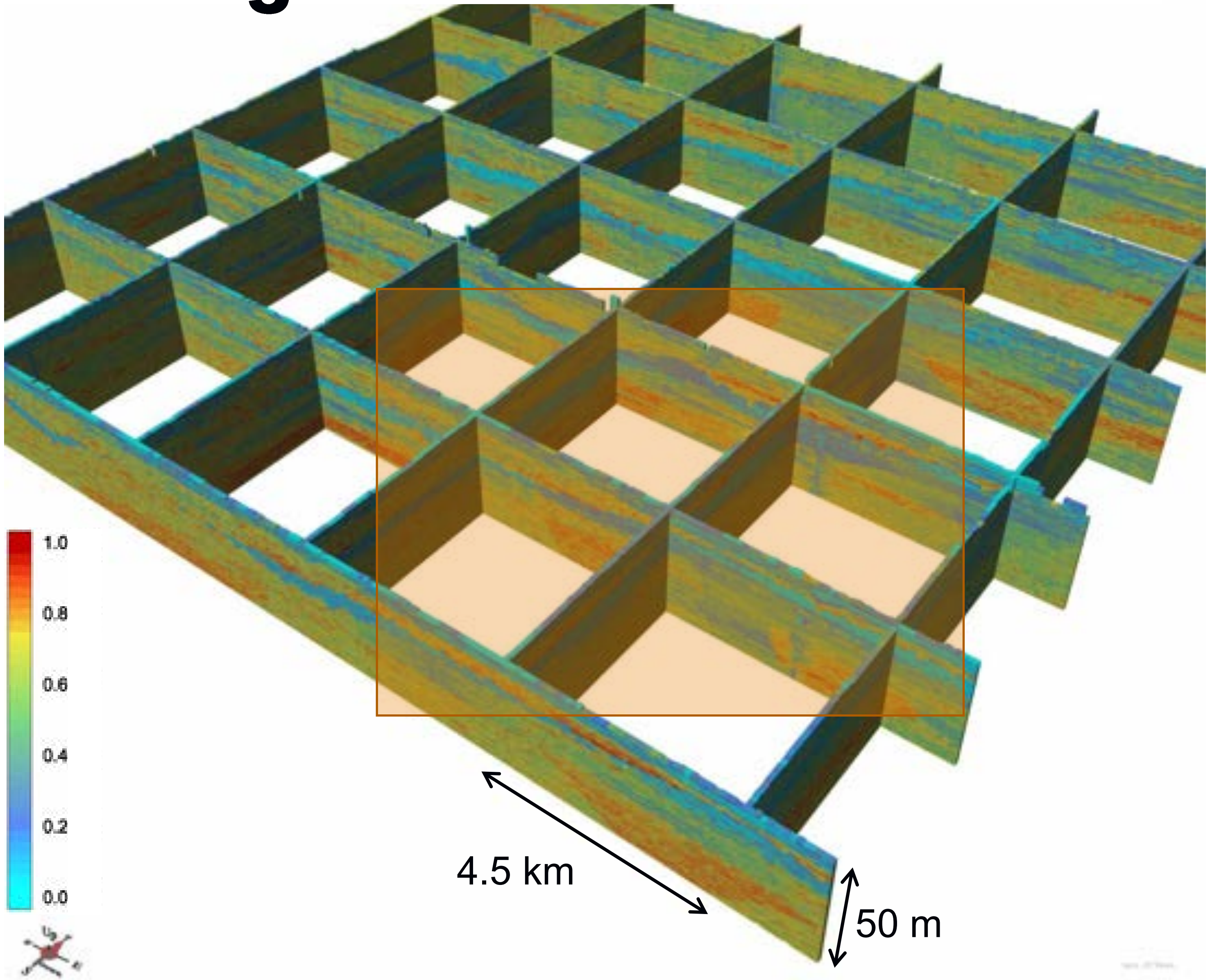
p_{peat}	p_{clay}	p_{sand}	Entropy (H)
1	0	0	0
1/3	1/3	1/3	1
0.5	0.5	0	0.63
0.49	0.49	0.02	0.71

$$H = -1 * (p_1 \, {}^3\log p_1 + p_2 \, {}^3\log p_2 + p_3 \, {}^3\log p_3)$$

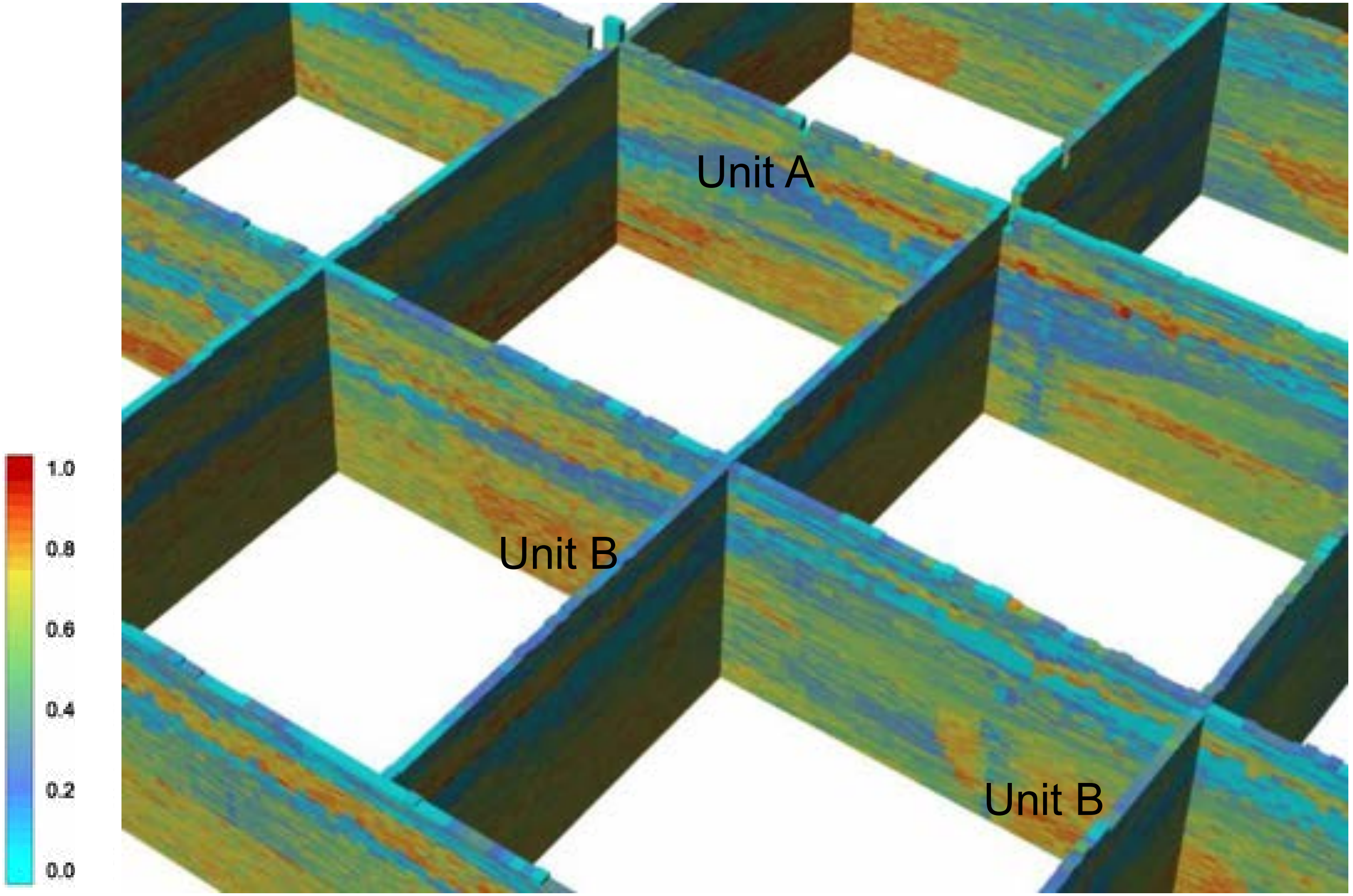
- *Concept of information entropy: Shannon (1948)*
- *Application in geological modelling: Wellman & Regenauer-Lieb (2012)*

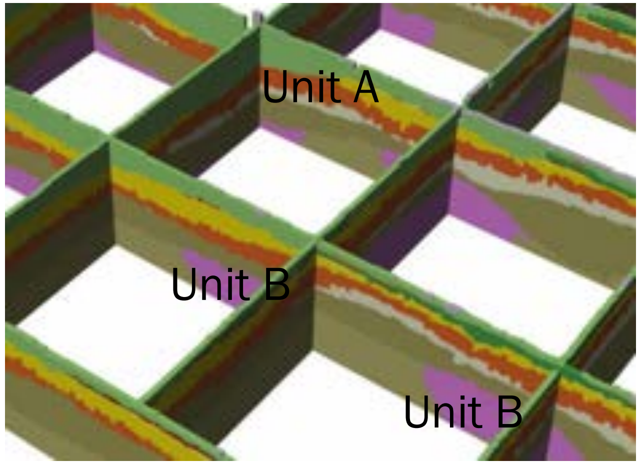
Model uncertainty – lithological class

- Based on 7 lithological classes
- Replaces 7 visualisations of probability



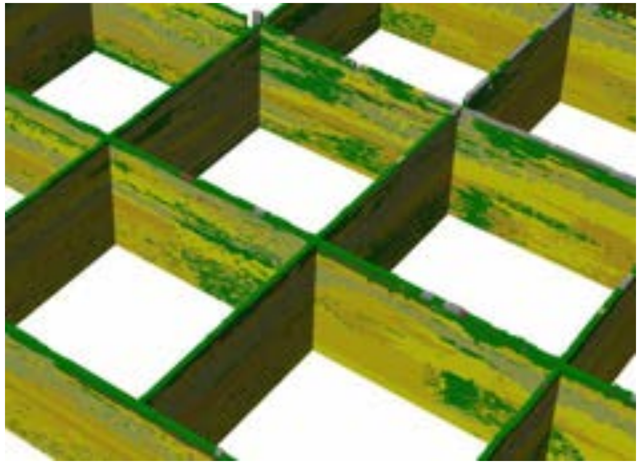
Model uncertainty – lithological class





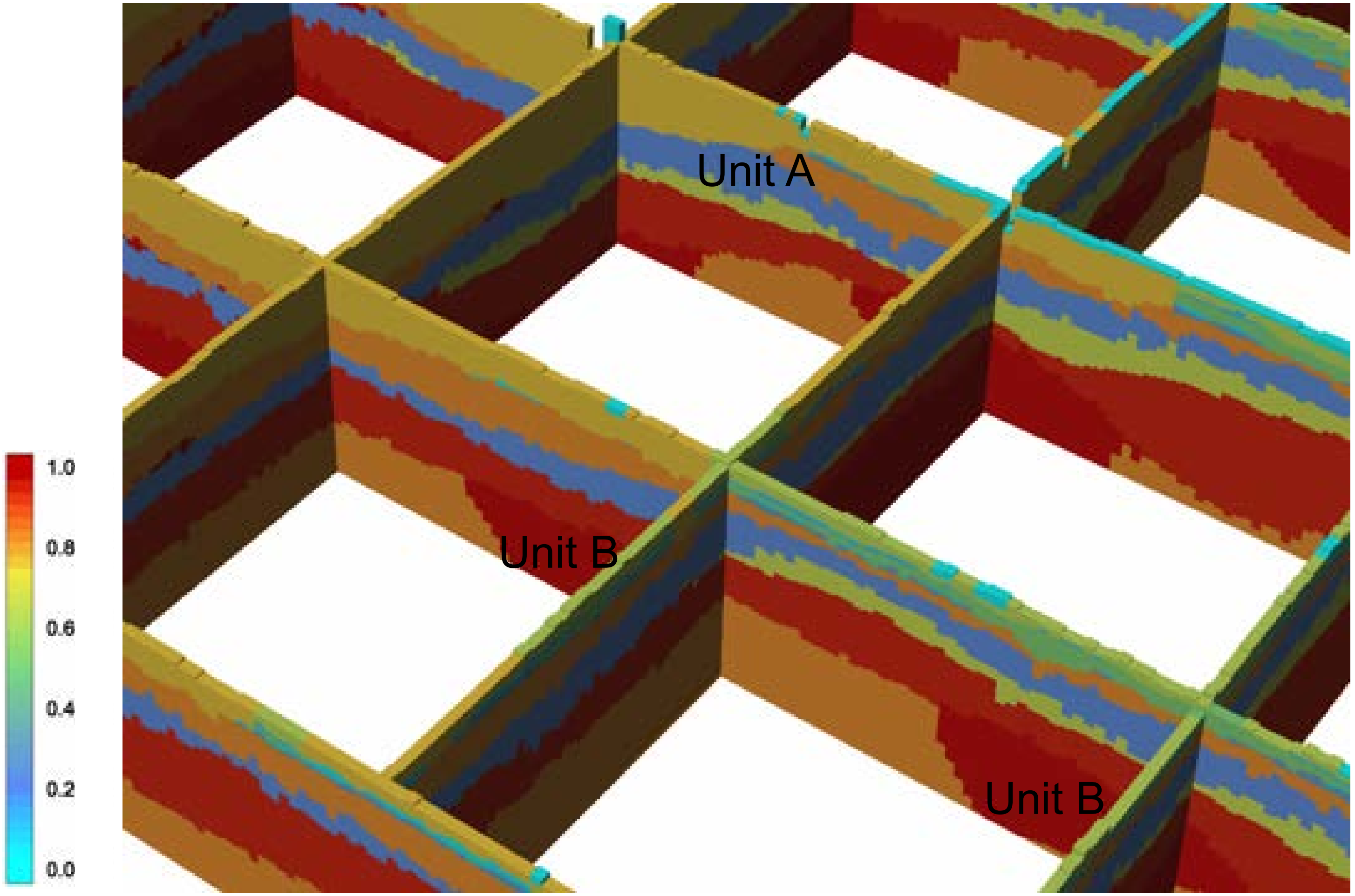
Stratigraphical units

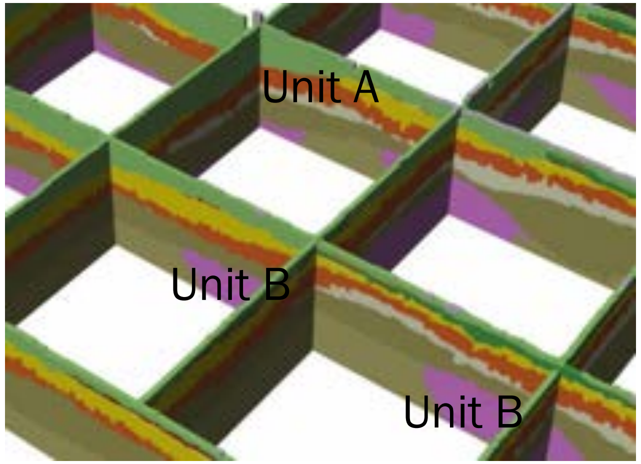
- Unit A
- Unit B



Most likely lithological class

Average for each stratigraphical unit





Stratigraphical units

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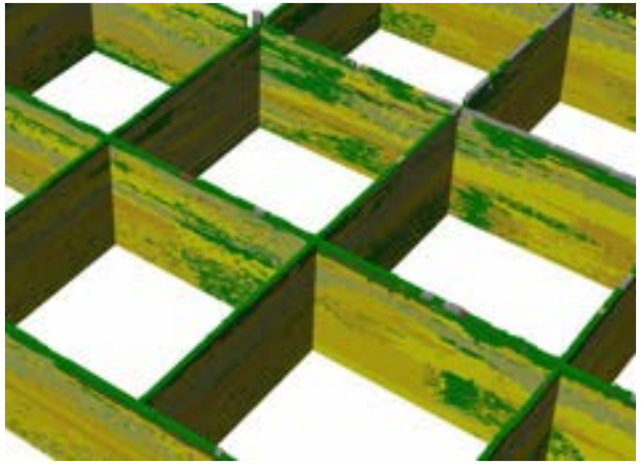

Most likely lithological class

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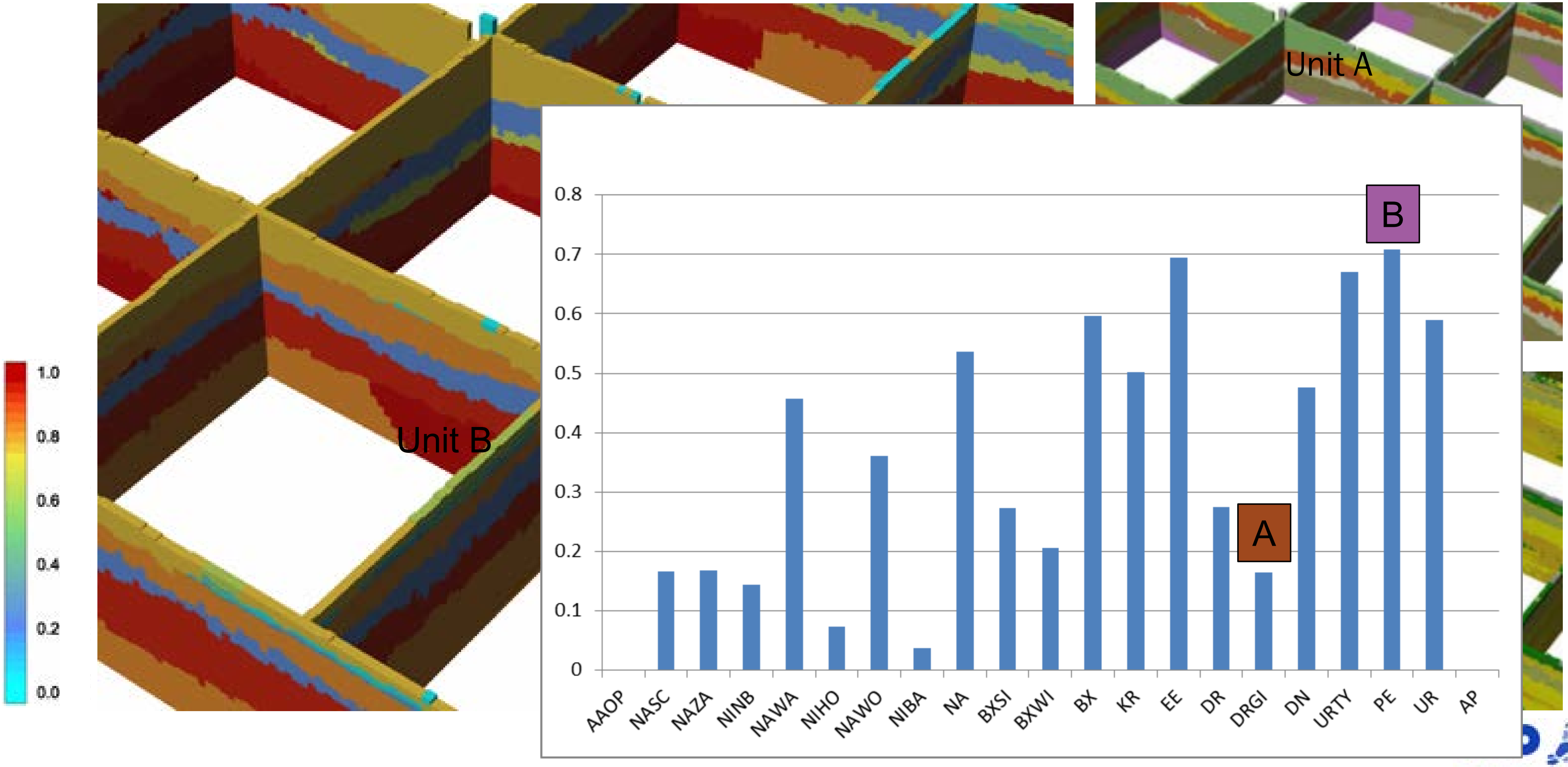


Stratigraphical units

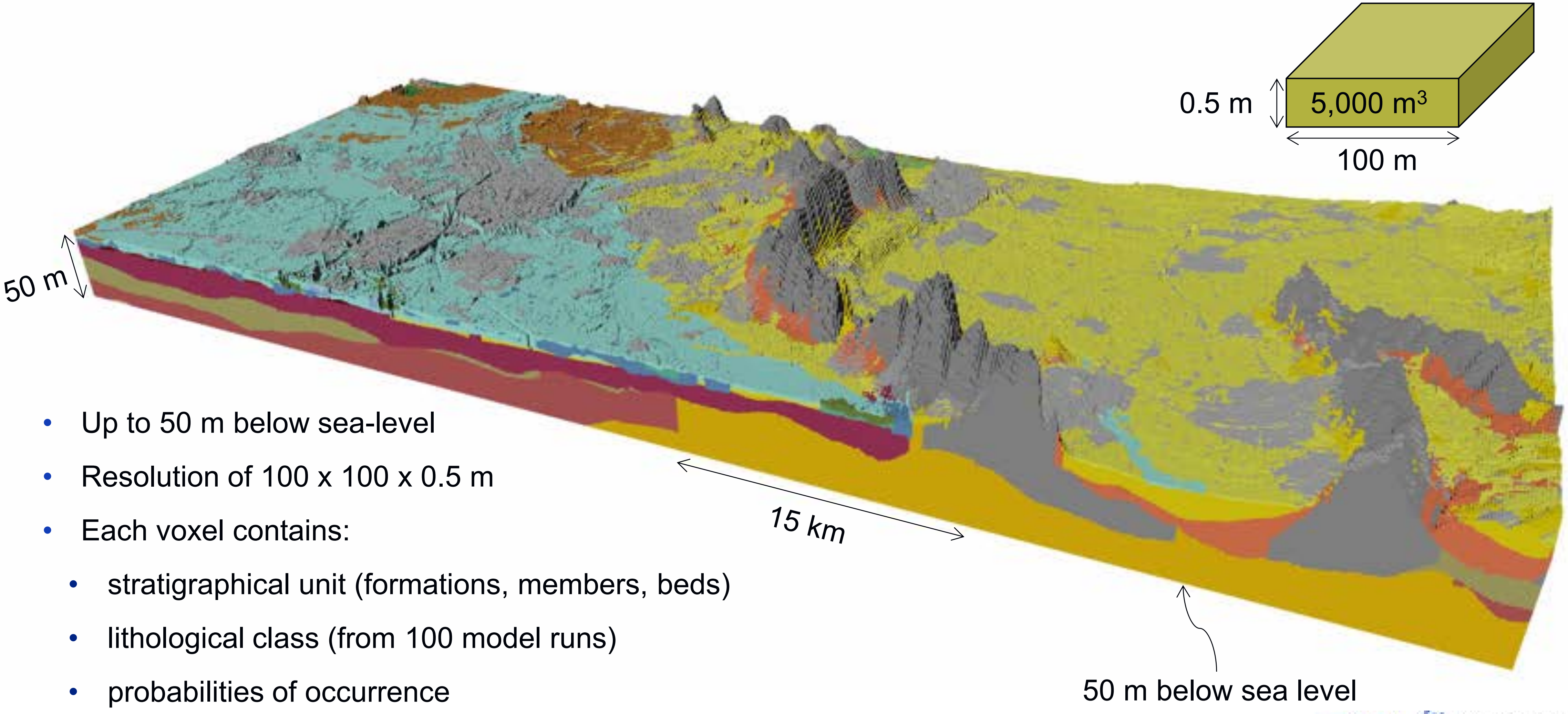
Unit A

Unit B

Most likely lithological class

Geologische Dienst Nederland

GeoTOP (layers → voxels)



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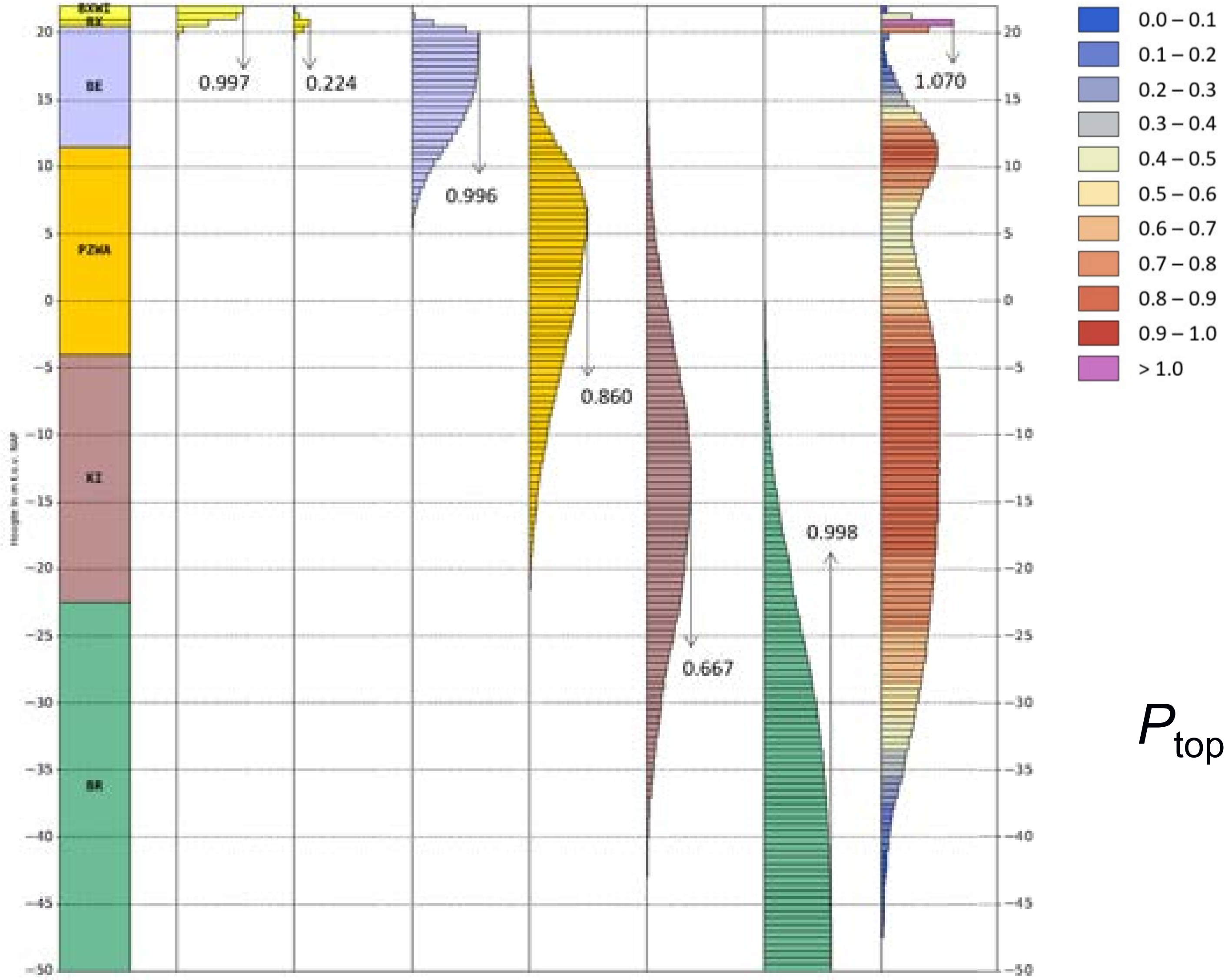
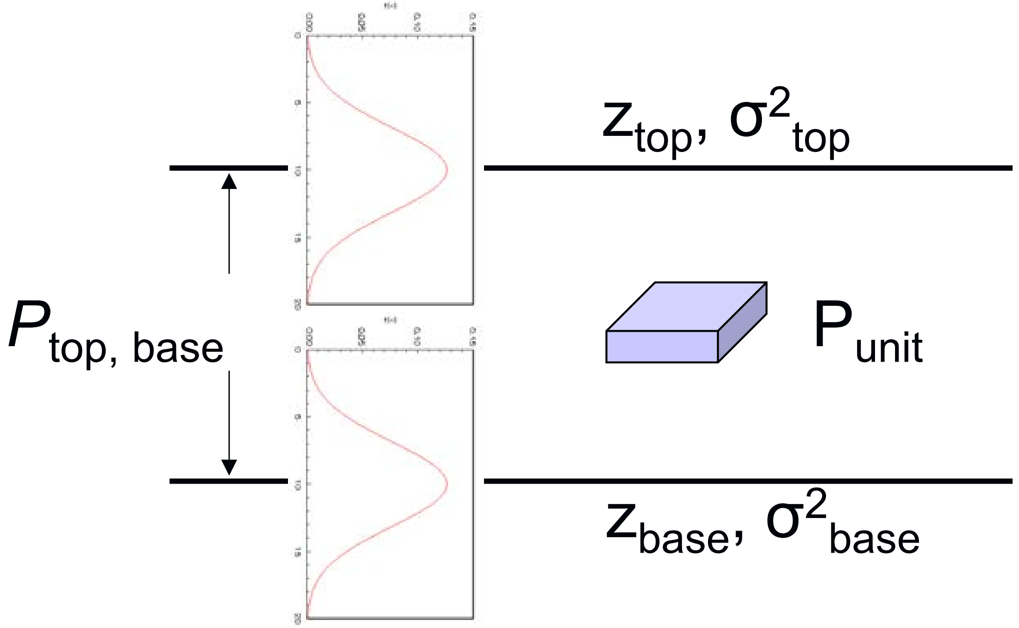
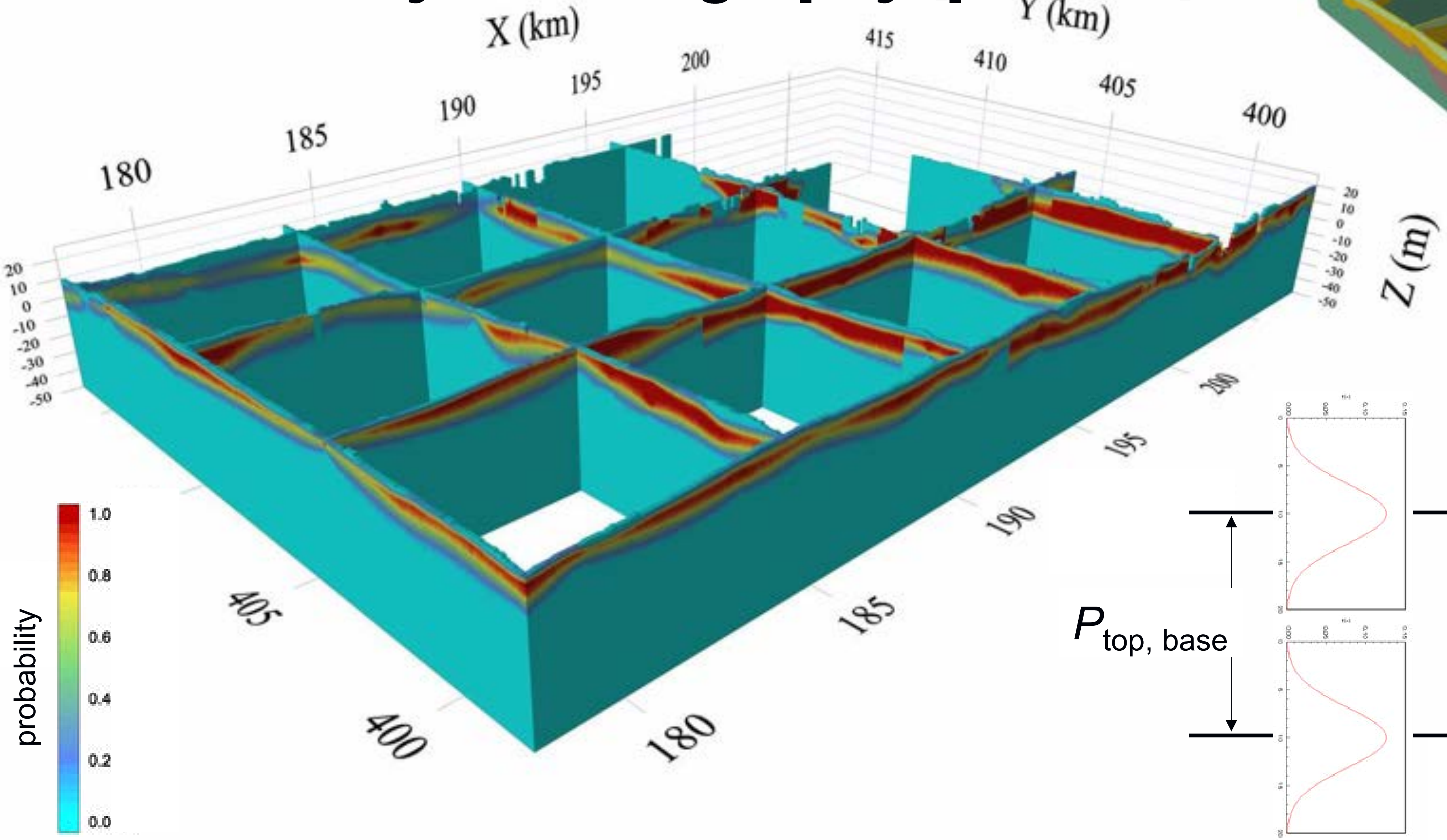
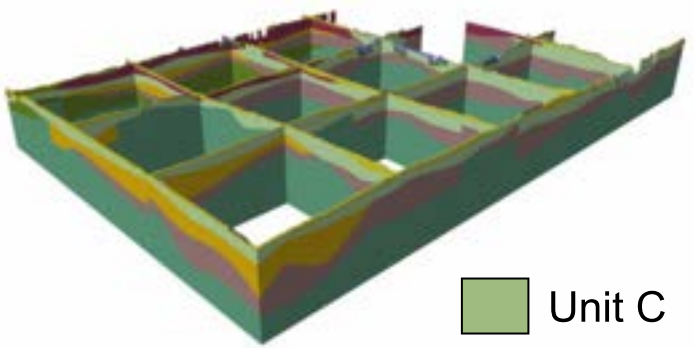
Probabilities and uncertainty – stratigraphy

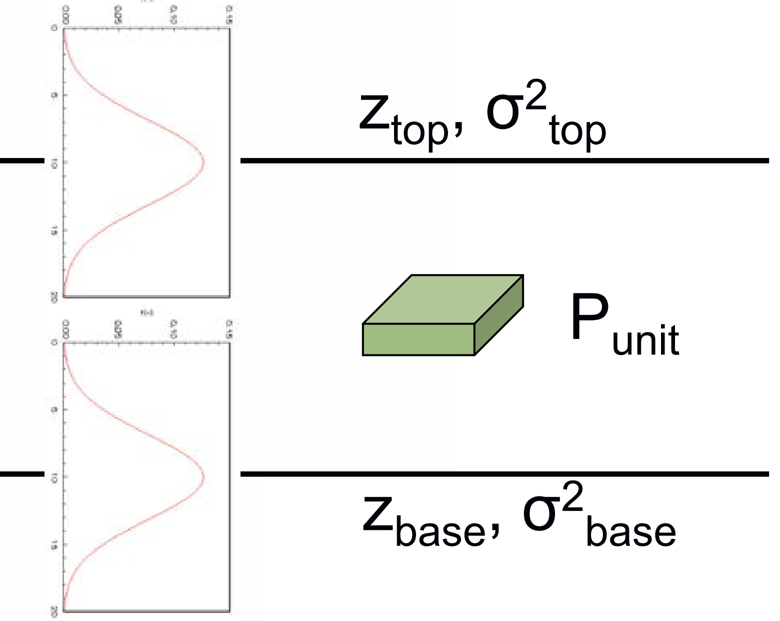




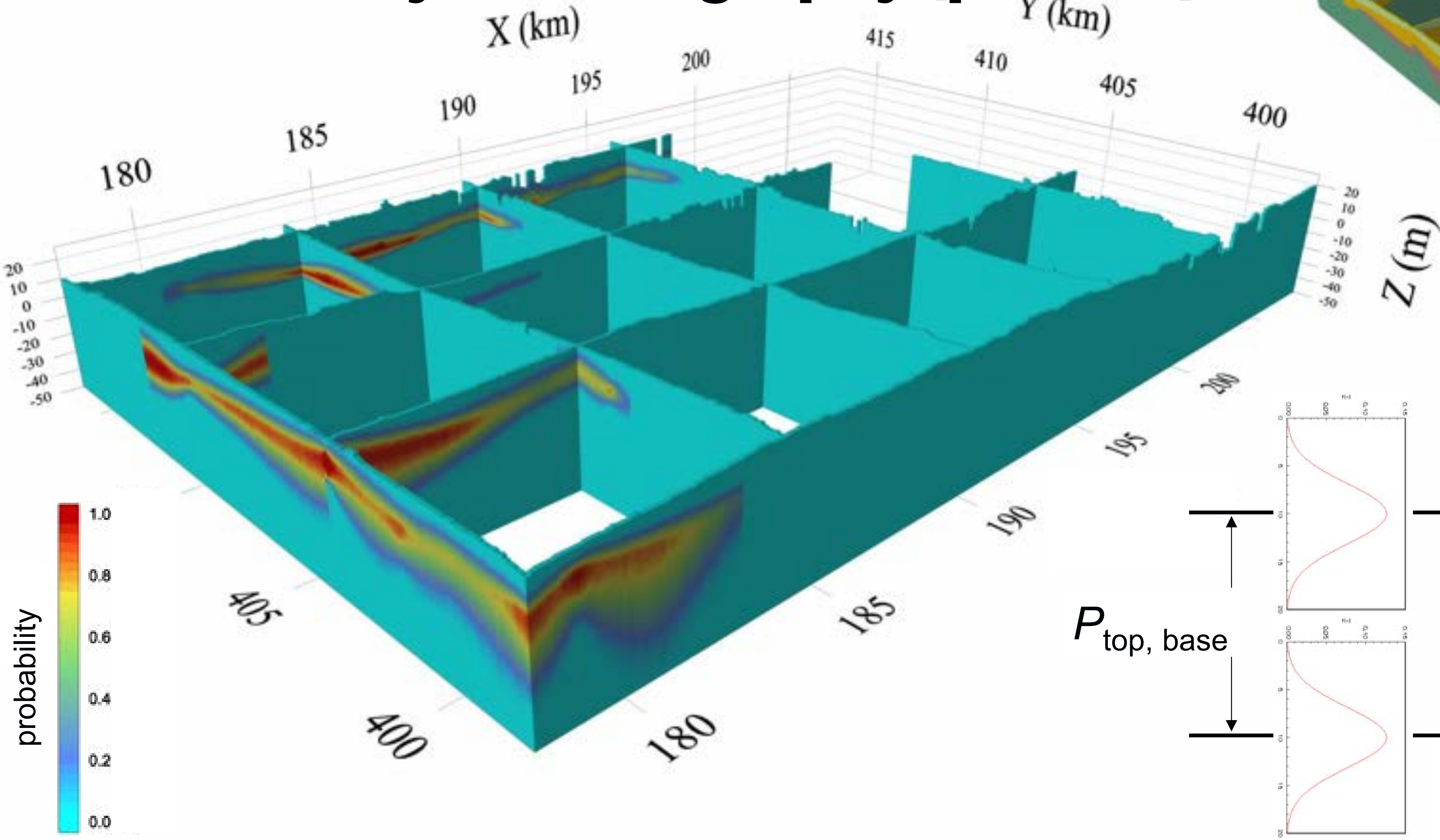
Probability of stratigraphy (per unit)

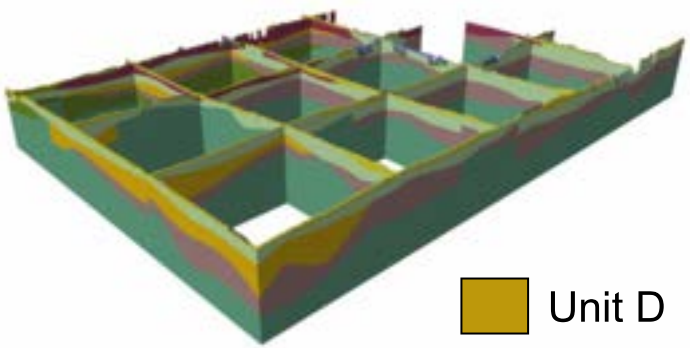


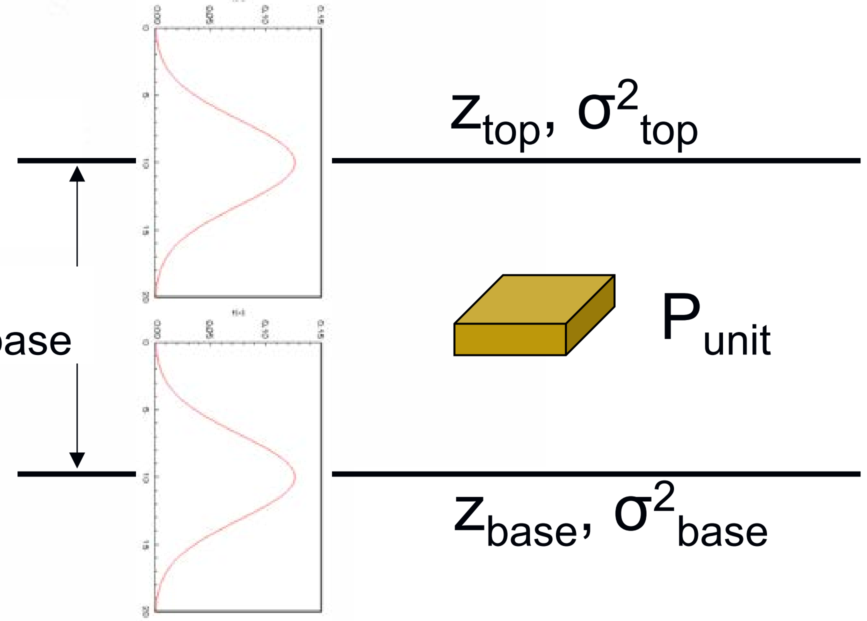




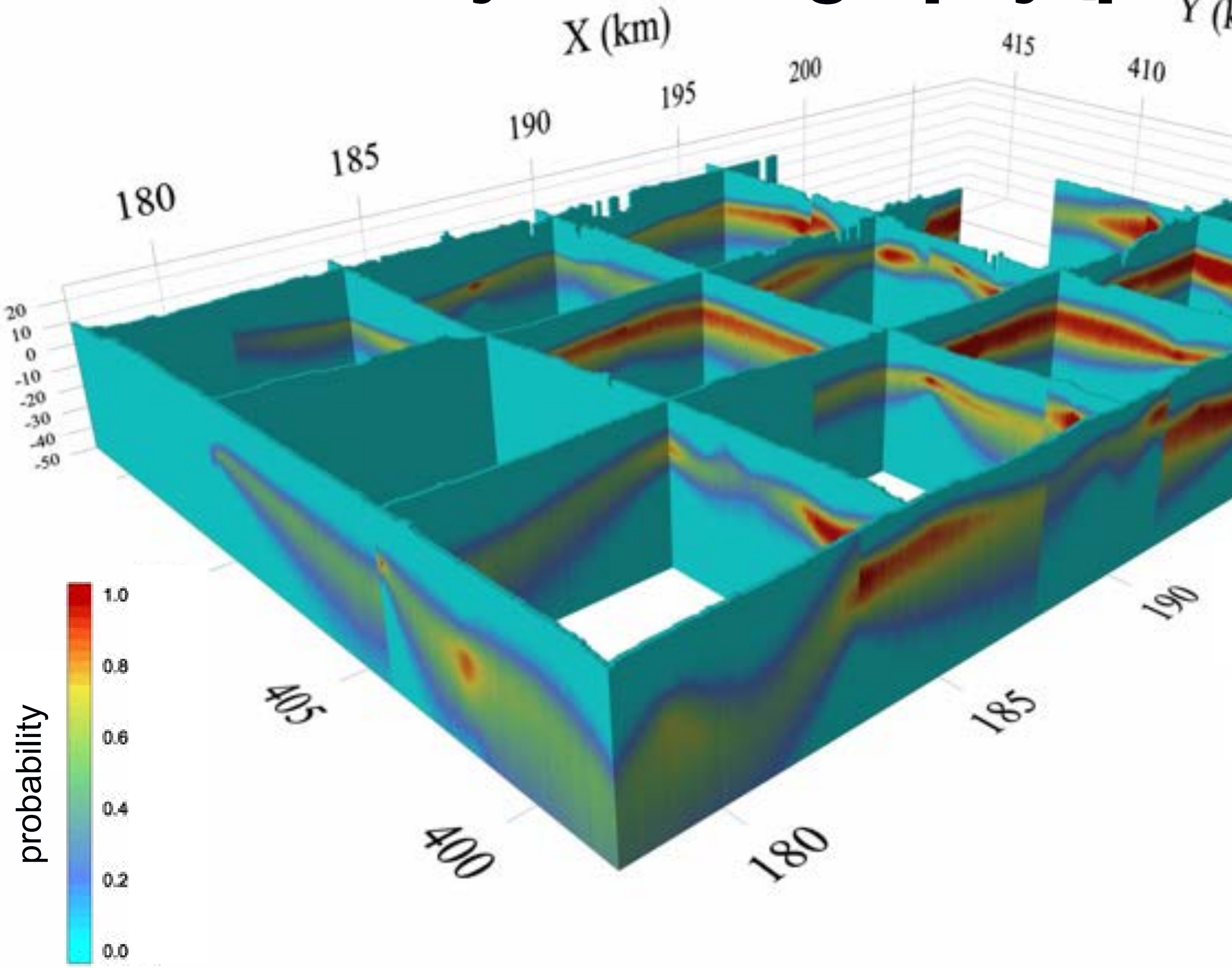
Probability of stratigraphy (per unit)

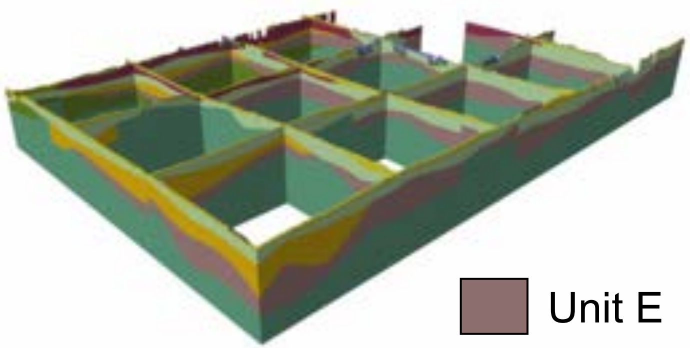


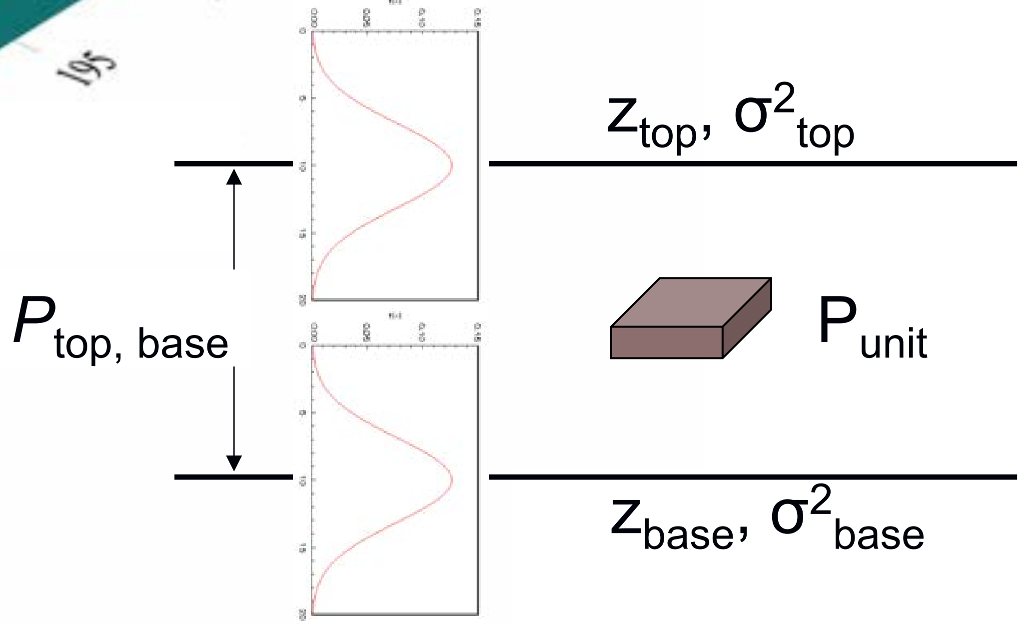




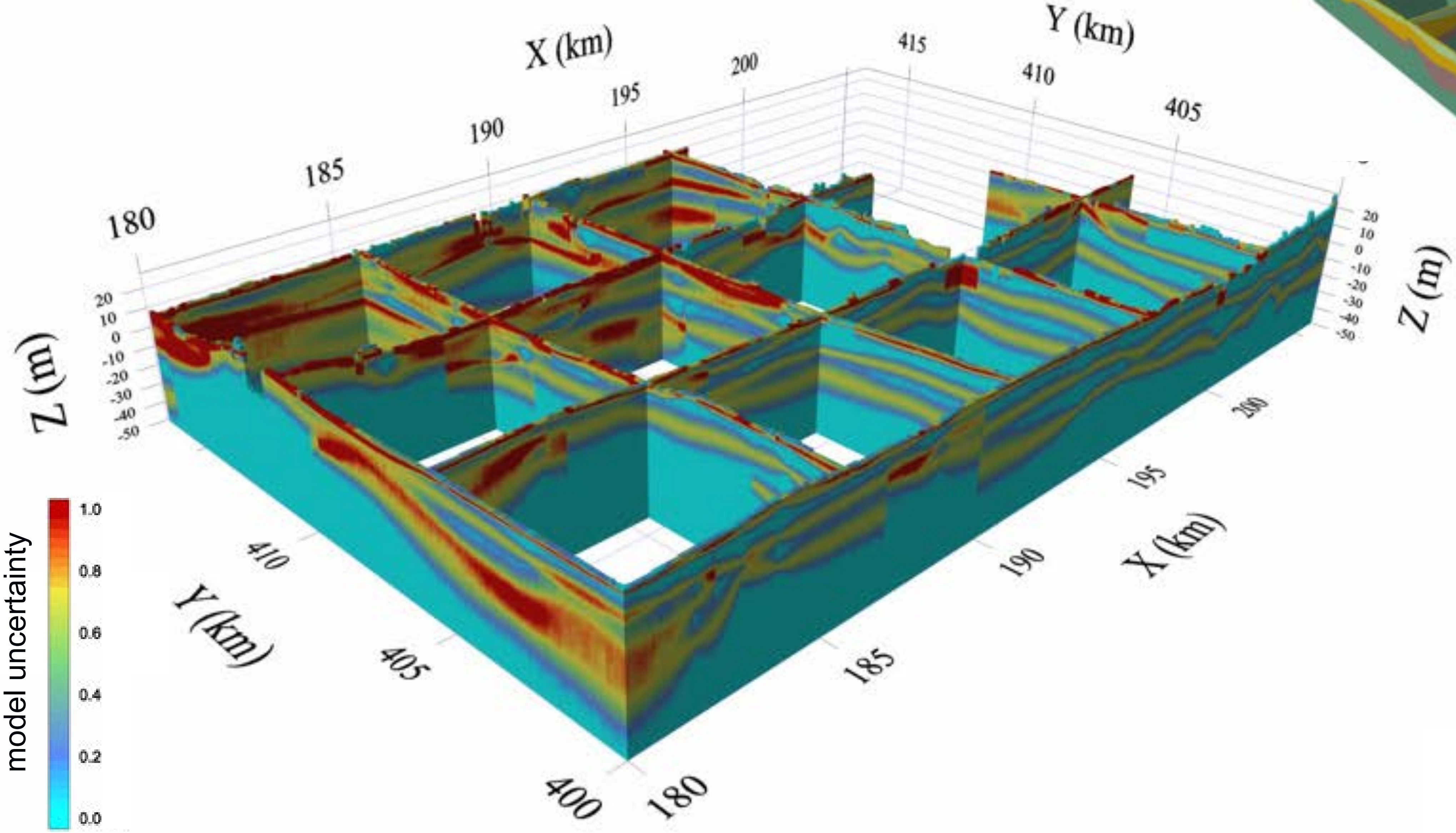
Probability of stratigraphy (per unit)

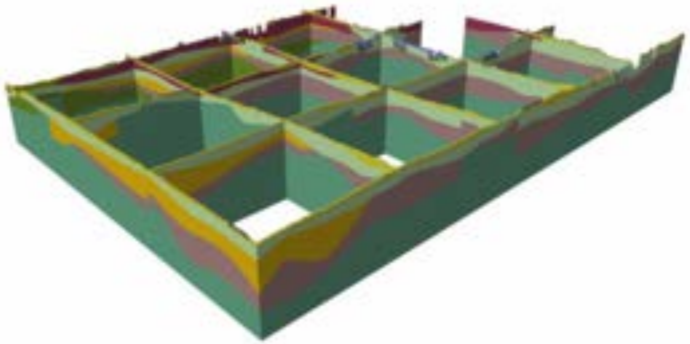




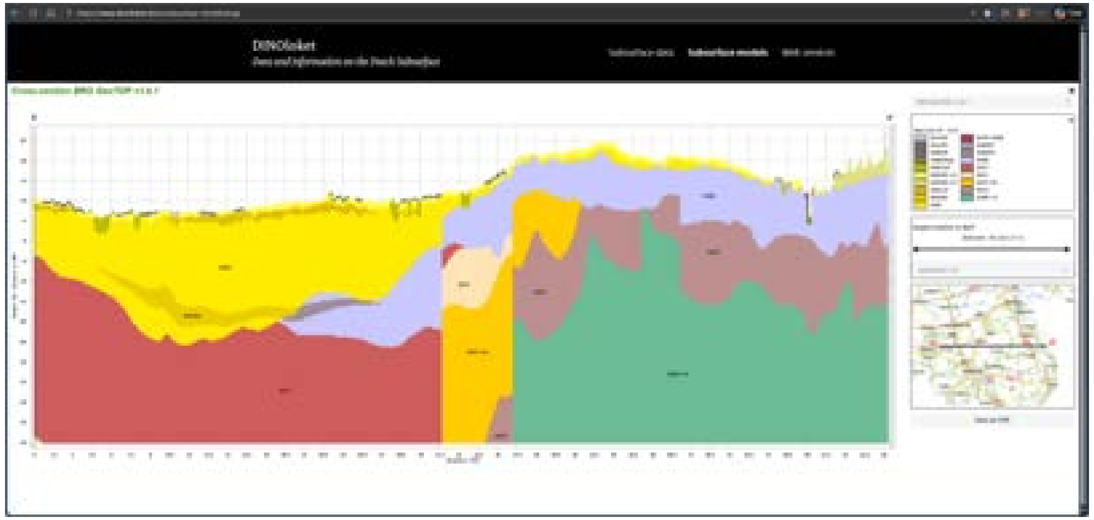


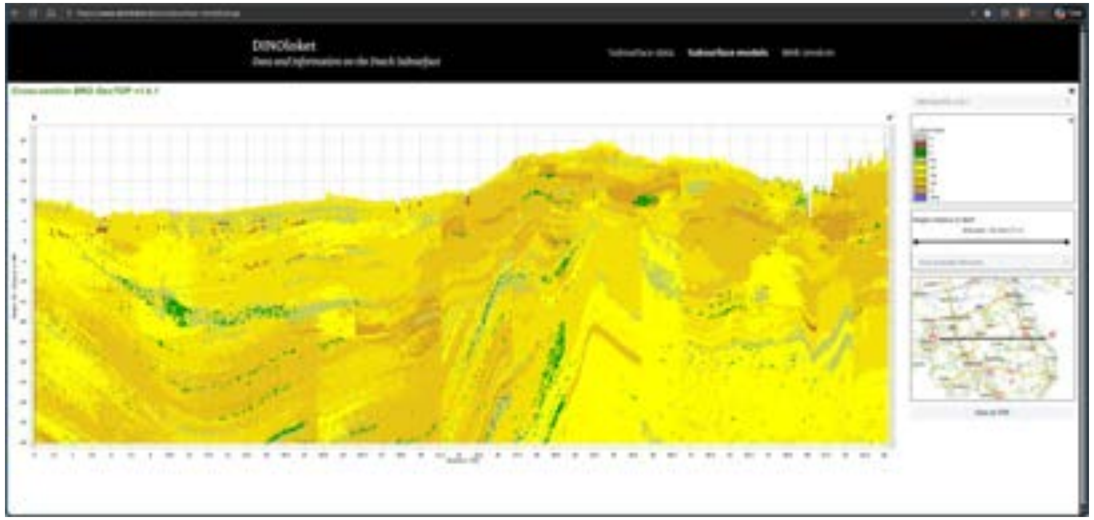
Model uncertainty – stratigraphy

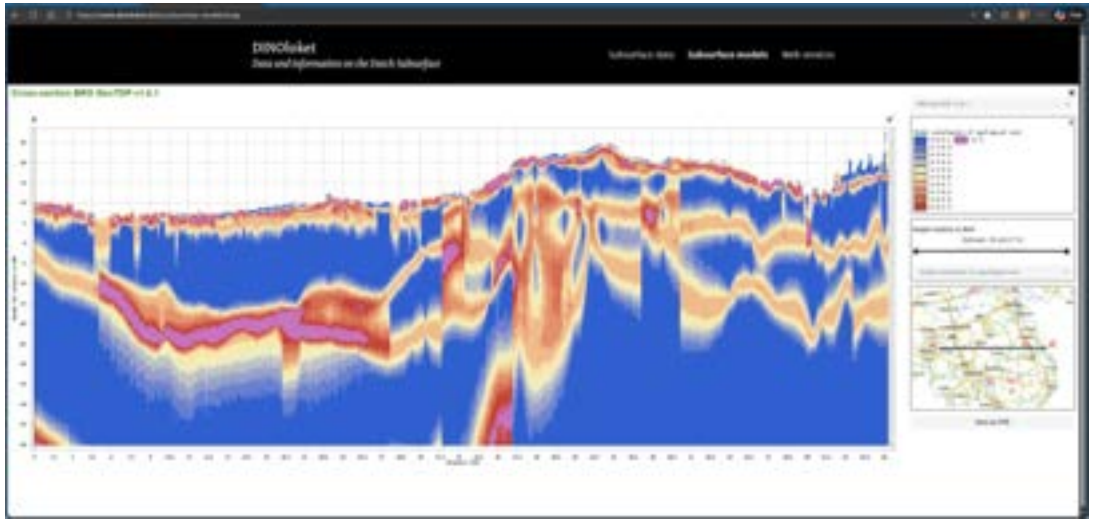




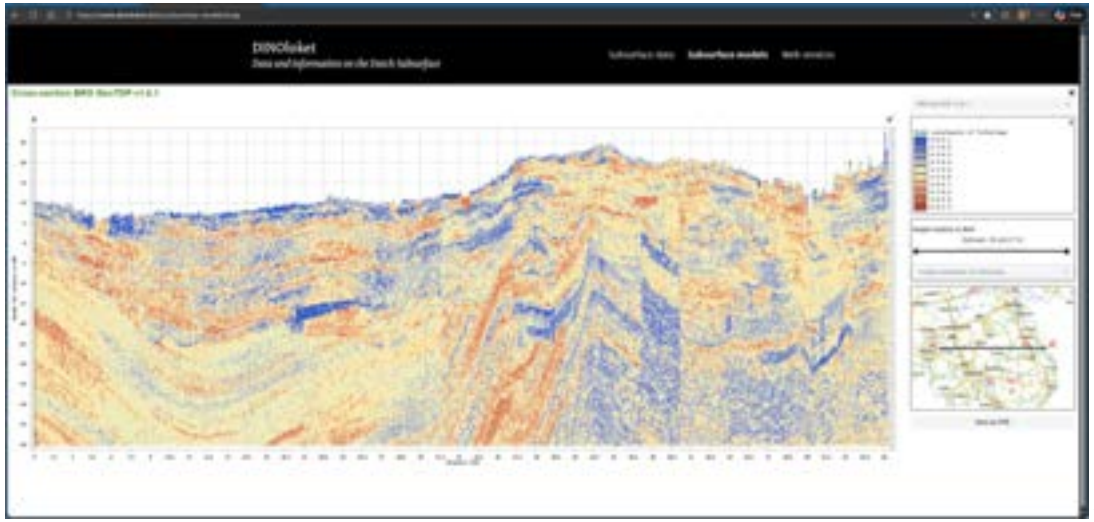
Delivery on the web portal







Model uncertainty – stratigraphy



Model uncertainty – lithological class

Thank you for your attention

Uncertainties in geological modelling – the GEUS perspective

Ingelise Møller, Anne-Sophie Høyer, Rasmus Bødker Madsen and Peter Sandersen

GEUS, Geological Survey of Denmark and Greenland

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Introduction

Uncertainties in 3D geological modelling

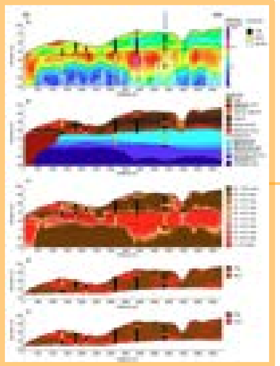
- Experiences gained from c. 25 years of 3D geological modelling in Denmark
- Main target is mapping of groundwater resources
- Shallow depth – 0-300 m

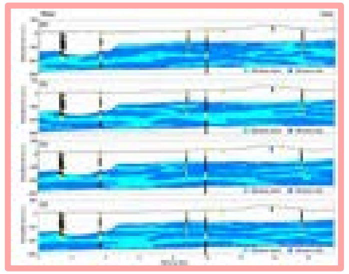
Learnings can be transferred to 3D geological modelling in all kinds of applications

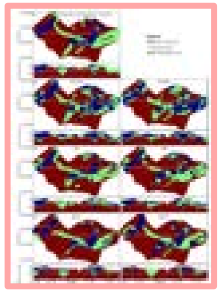
Communicating the model uncertainties to other scientist and authorities have been in focus through the years

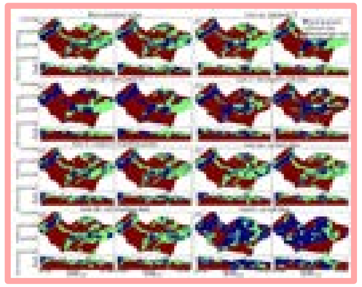
Handling uncertainties in geological modelling in the Danish groundwater mapping

Influence of modelling techniques (Voxel vs. layer modelling)
Enemark et al., 2022. Hydrogeol J 30, 617–635. doi: 10.1007/s10040-021-02442-9

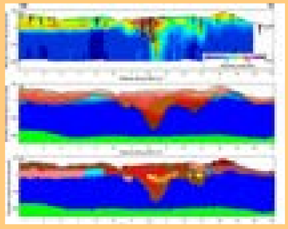


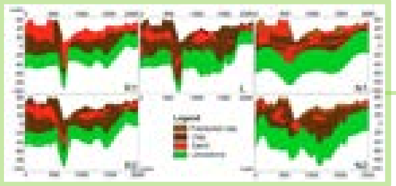




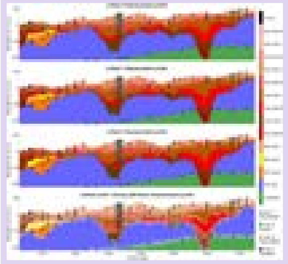


MPS modelling in geological elements
Madsen et al. 2021. Hydrol. Earth Syst. Sci., 25, 2759–2787, doi: 10.5194/hess-25-2759-2021

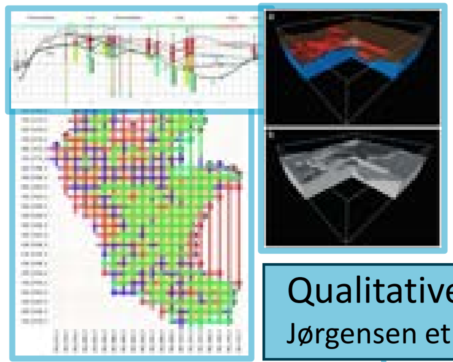




Multiple points statistics (MPS): Influence of choice of Algorithm, Training Image, handling of hard /soft data on ensemble uncertainty
Høyer et al. 2017. Hydrol. Earth Syst. Sci., 21, 6069–6089. doi:10.5194/hess-21-6069-2017
Barfod et al. 2018. Hydrol. Earth Syst. Sci., 22, 3351–3373. doi: 10.5194/hess-22-3351-2018
Barfod et al. 2018. Hydrol. Earth Syst. Sci., 22, 5485-5508. doi: 10.5194/hess-22-5485-2018

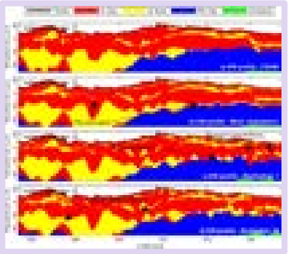


‘GDM’ - Geology-Driven-Modelling simulating layer surfaces within uncertainty of interpretation points
Madsen et al. 2022. Eng. Geol. 309, 106833. doi: 10.1016/j.enggeo.2022.106833



Discussing utilization of data uncertainties in different modelling techniques
Høyer et al. 2015. J. Appl. Geophys 115, 65-78, doi:10.1016/j.jappgeo.2015.02.005

Influence of different conceptual geological models
Seifert et al., 2012. Water Resour. Res. 48, W06503. doi: 10.1029/2011WR011149



Qualitative uncertainty assessment on interpretations, voxel models
Jørgensen et al. 2010. GEUS Bulletin, 20, 27-30. doi:10.34194/geusb.v20.4892

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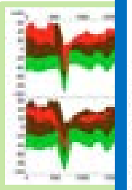
Sandersen 2008, IAHS Publ. 320, 345-349.

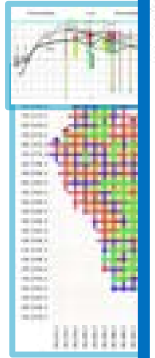
‘GDM’ on national hydro-stratigraphic models
Madsen et al. 2026. Math. Geosci., doi: 10.1007/s11004-025-10263-9

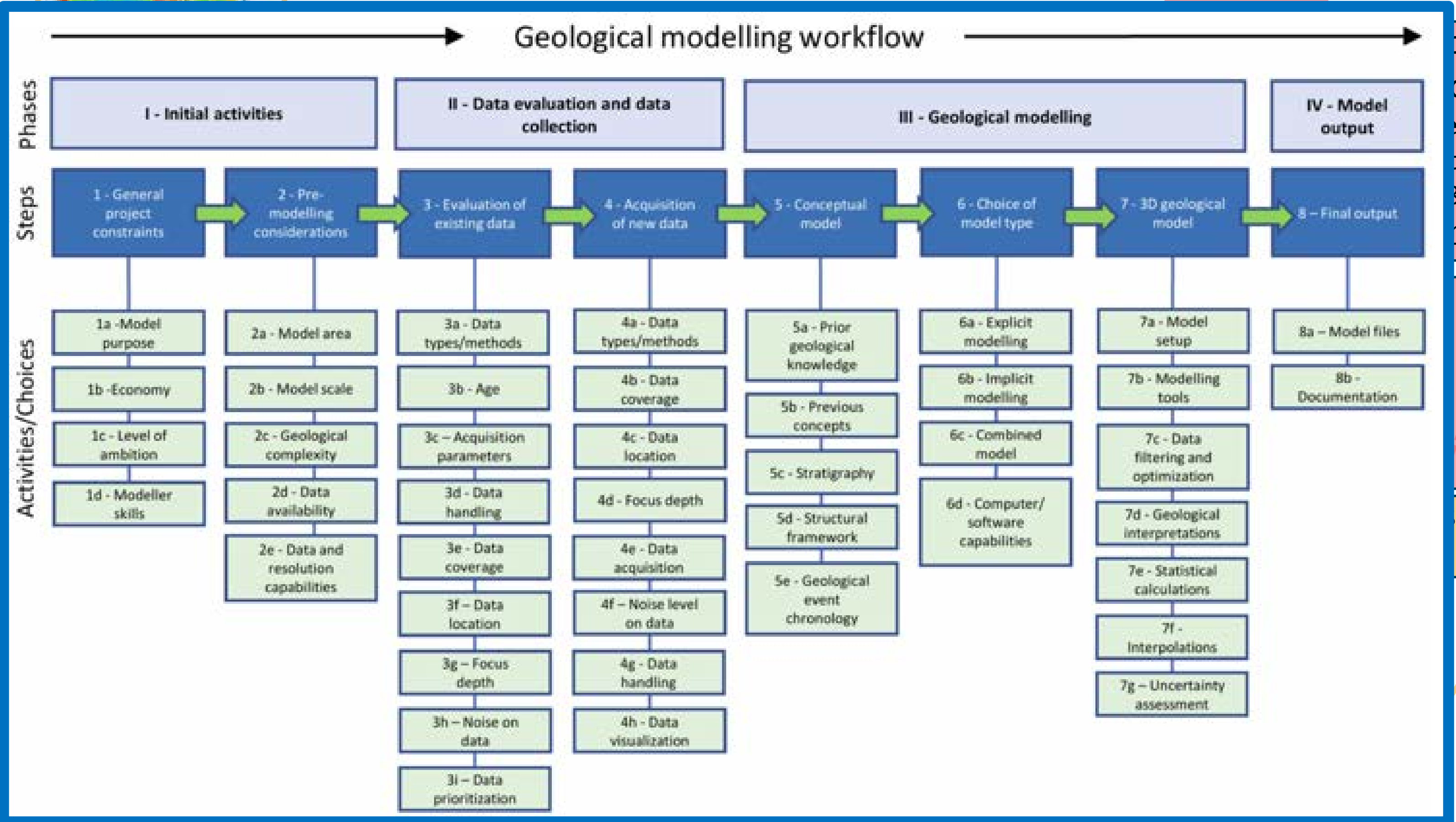
2008

2025

Handling uncertainties in geological modelling in the Danish groundwater mapping

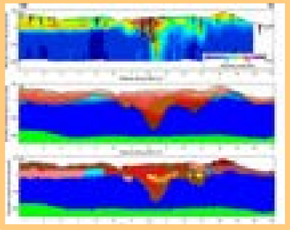


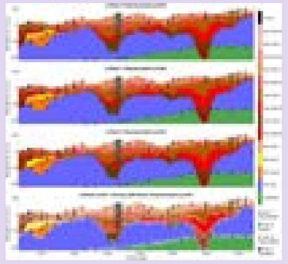


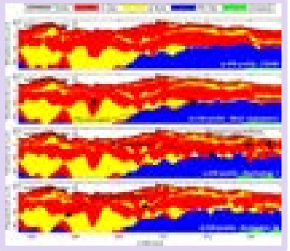


Influence of modelling techniques (Voxel vs. layer modelling)
Enemark et al., 2022. Hydrogeol J 30, 617–635. doi: 10.1007/s10040-021-02442-9

…odelling in …cal elements
…et al. 2021. Hydrol. …. Sci., 25, …37, doi: …hess-25-2759-2021







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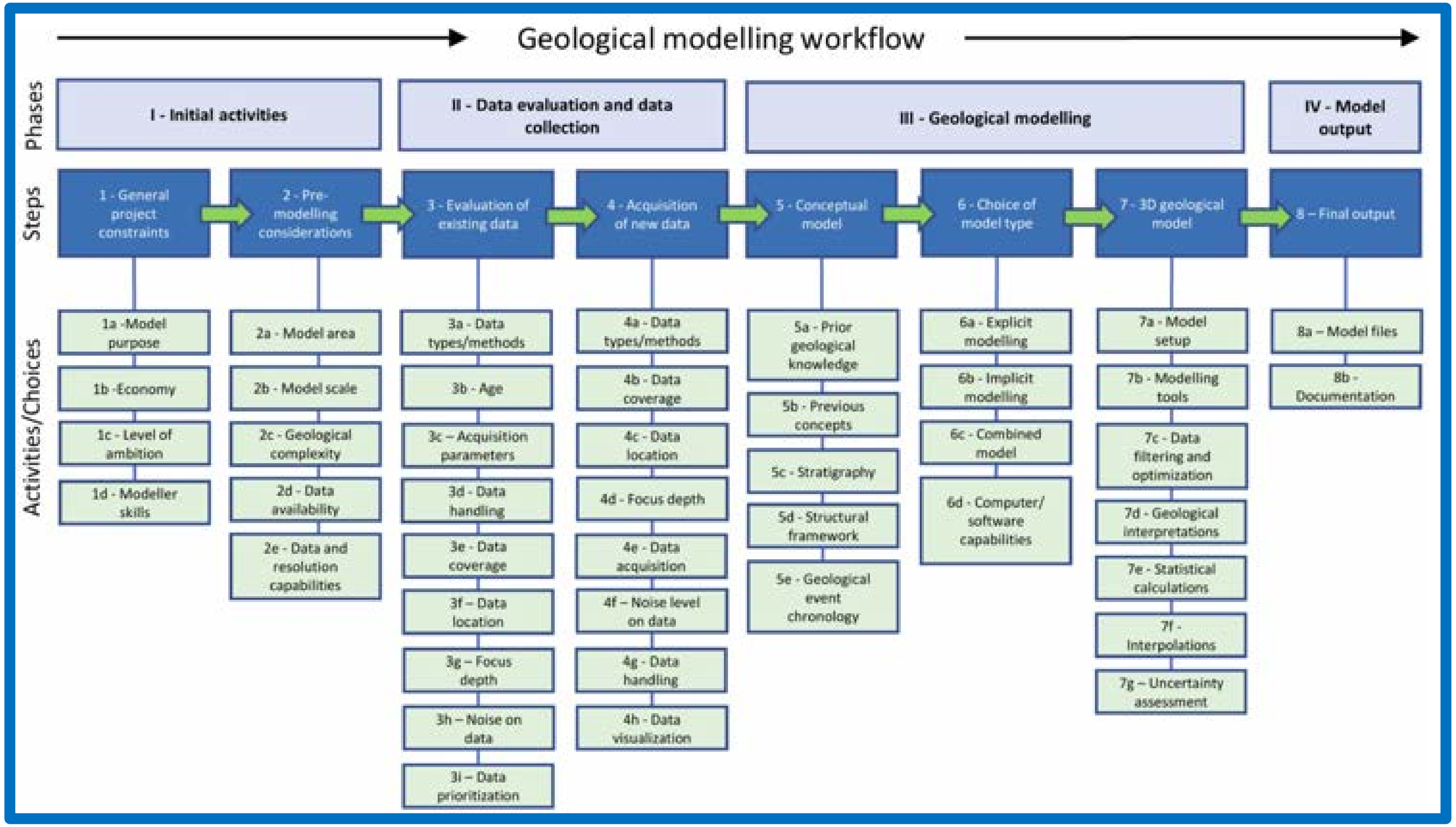
Handling uncertainties in geological modelling
Outline



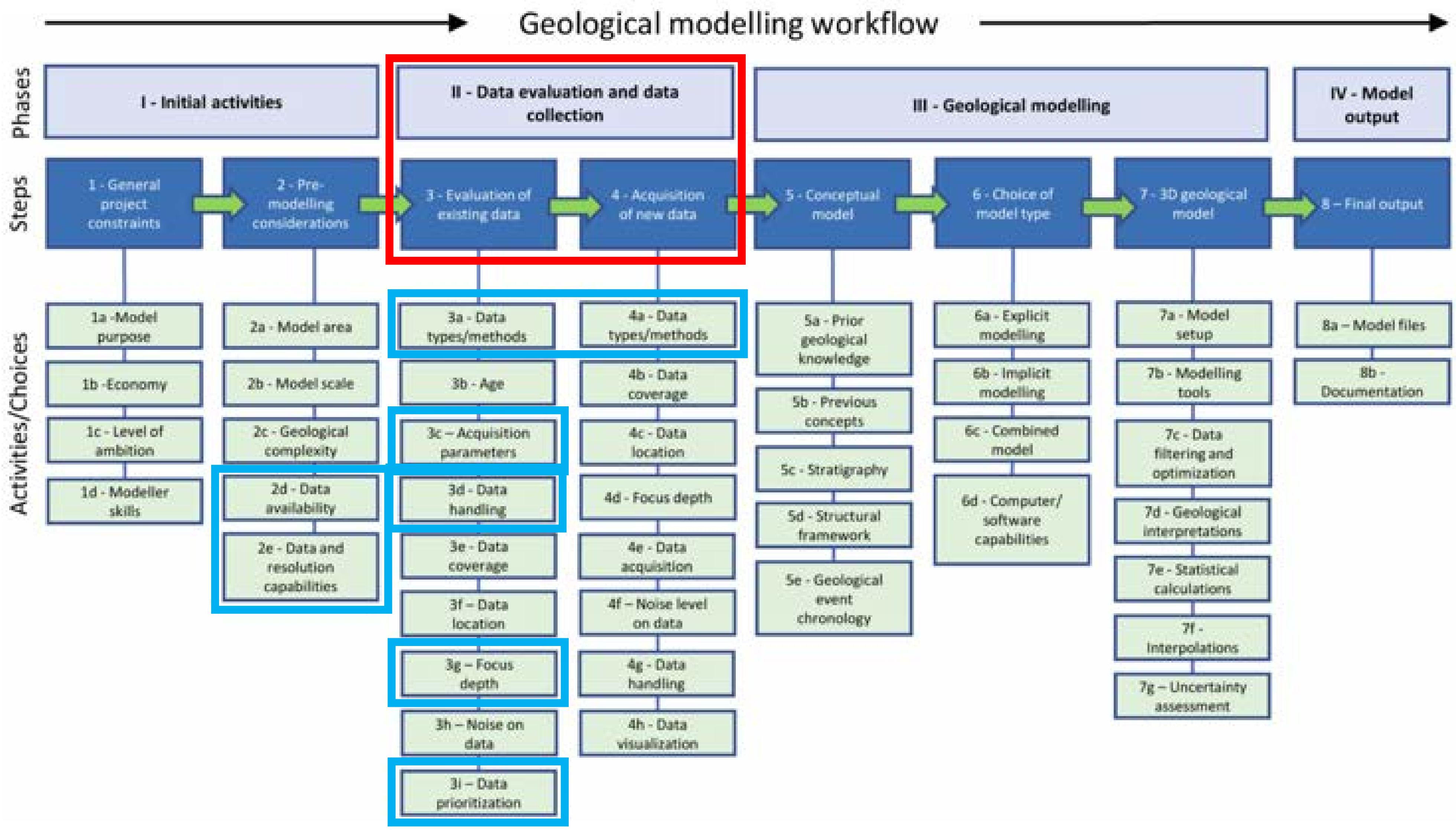
Uncertainties introduced in every step of the workflow

Chain of uncertainties:
linking aspects in all steps of a geological modelling workflow

The most important sources of uncertainties are presented in the forthcoming slides

Examples on how modelling uncertainty assessment are communicated

Uncertainty in geological modelling workflow
Høyer et al., 2024. Eng. Geol. 343, 10779. 10.1016/j.enggeo.2024.107792



Geological modelling workflow
Phases
Steps
Activities/Choices
I - Initial activities
II - Data evaluation and data collection
III - Geological modelling
IV - Model output
1 - General project constraints
2 - Pre-modelling considerations
3 - Evaluation of existing data
4 - Acquisition of new data
5 - Conceptual model
6 - Choice of model type
7 - 3D geological model
8 – Final output
1a -Model purpose
1b -Economy
1c - Level of ambition
1d - Modeller skills
2a - Model area
2b - Model scale
2c - Geological complexity
2d - Data availability
2e - Data and resolution capabilities
3a - Data types/methods
3b - Age
3c – Acquisition parameters
3d - Data handling
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7e - Statistical calculations
7f - Interpolations
7g – Uncertainty assessment
8a – Model files
8b - Documentation

II Data evaluation and data collection

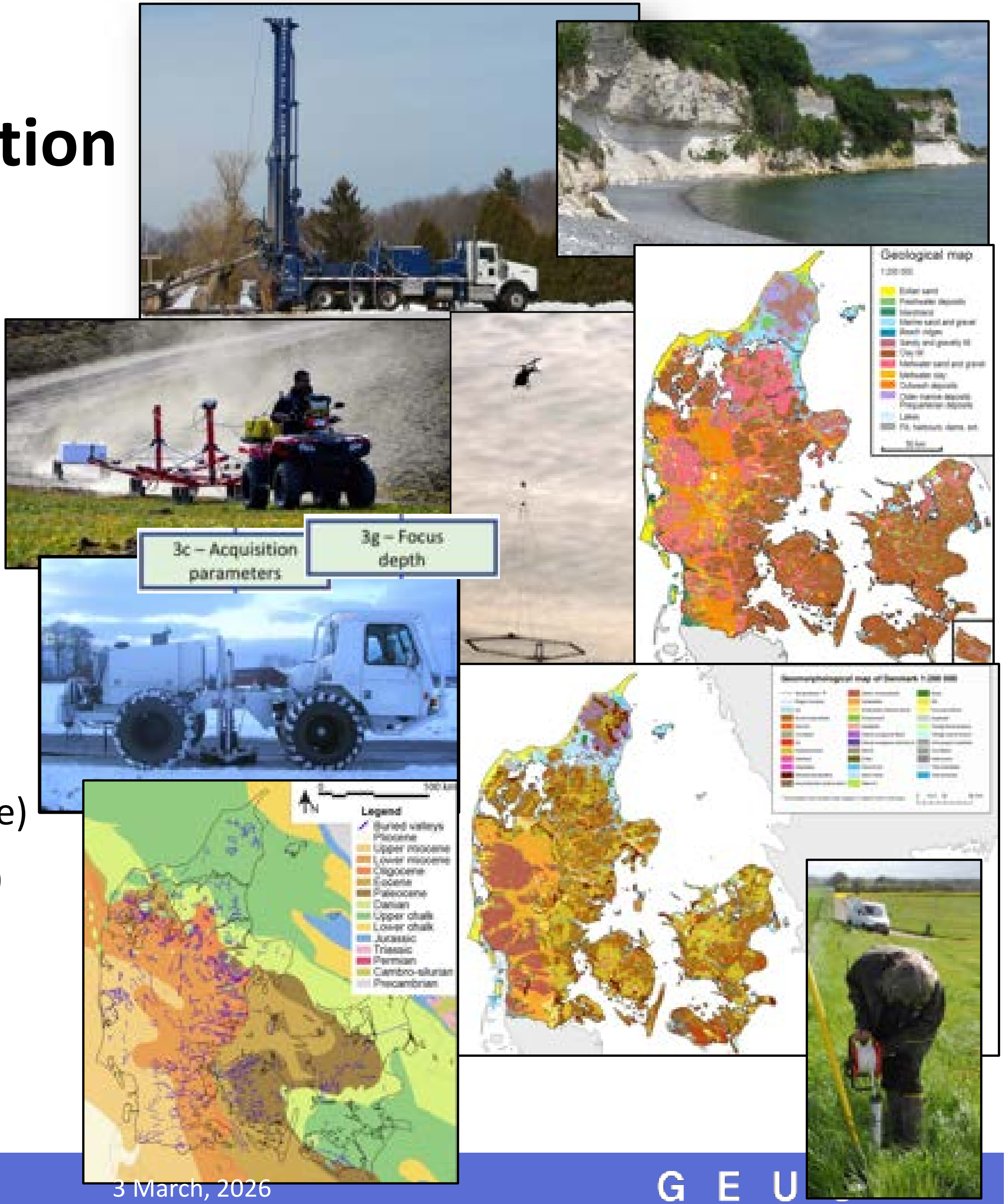
3a/4a data types / methods

‘Direct’ data:

Borehole lithological logs	(1 – 4000 m)
Outcrops	(2 – 40 m)
Surficial geological map	(1 – 2 m)

‘Indirect’ data:

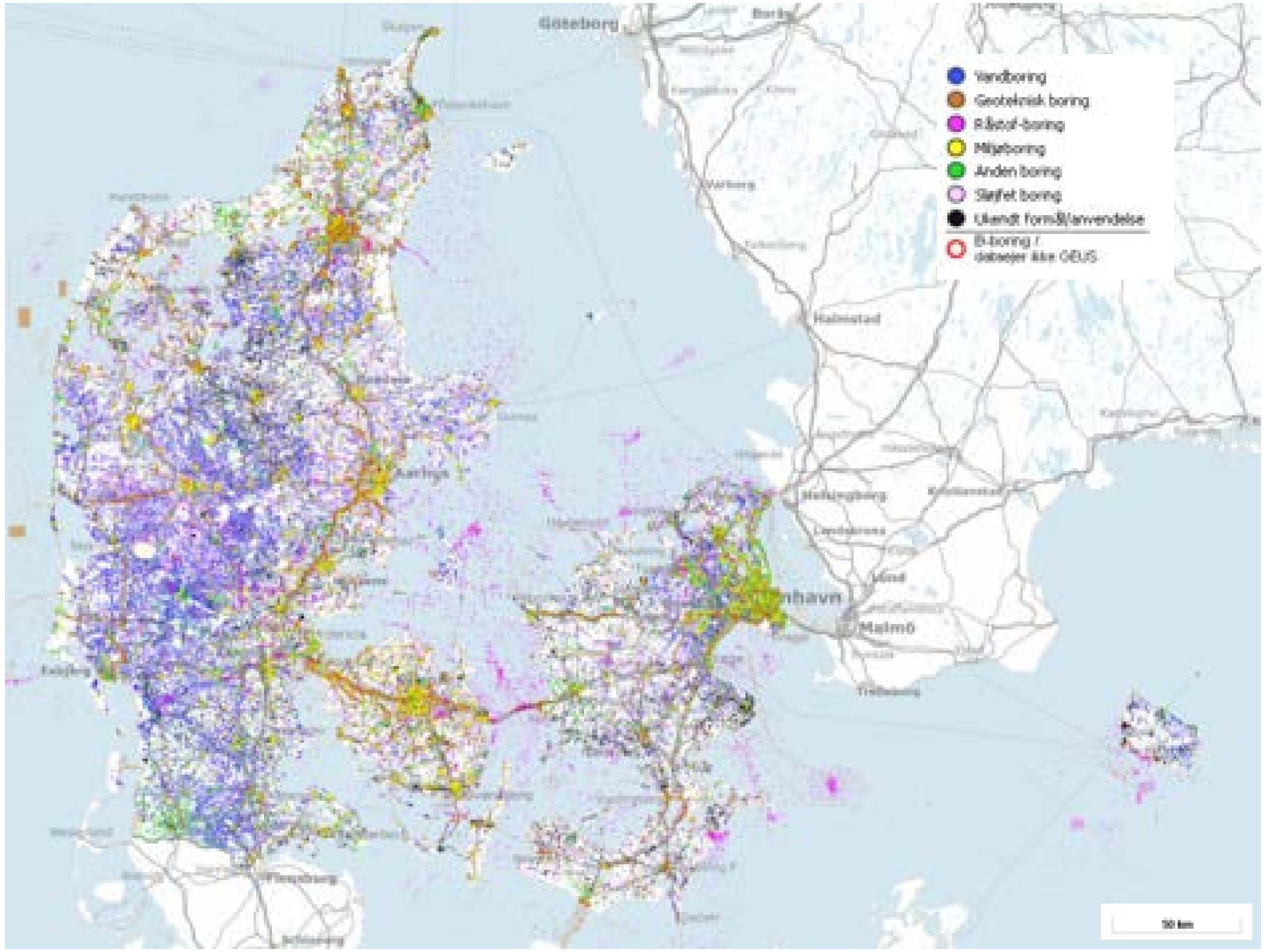
Geophysical (resistivity) information	(3 – 300 m)
High-resolution seismic data	(10 – 5000 m)
Geological maps	(dependent on theme)
Geochemical & hydrological data	(dependent on wells)



II Data evaluation and data collection

Borehole data – sources of uncertainties and limitations related to modelling

- > 450.000 boreholes reported to the Danish national borehole database Jupiter, drilled during a period of >100 years with various purposes
- Ca. 250.000 boreholes with lithology information



https://eng.geus.dk/products-services-facilities/data-and-maps/national-well-database-jupiter

II Data evaluation and data collection

Borehole data – sources of uncertainties and limitations related to modelling

- > 450.000 boreholes reported to the Danish national borehole database Jupiter, drilled during a period of >100 years with various purposes
- Ca. 250.000 boreholes with lithology information
- Different drilling methods results in large variations in the quality of the geological sample
- Large variation in details of sample descriptions

⇒Knowledge about the method is important!

⇒Important to communicate on data uncertainties

Sample collected with auger

Sample cut by a wing bit in reverse circulation rotary drilling

Sample cut by a roller cone bit in reverse circulation rotary drilling

Ditlefsen et al. 2008, (Geovejledningen, 2008) Jordprøver fra grundvandsboringer

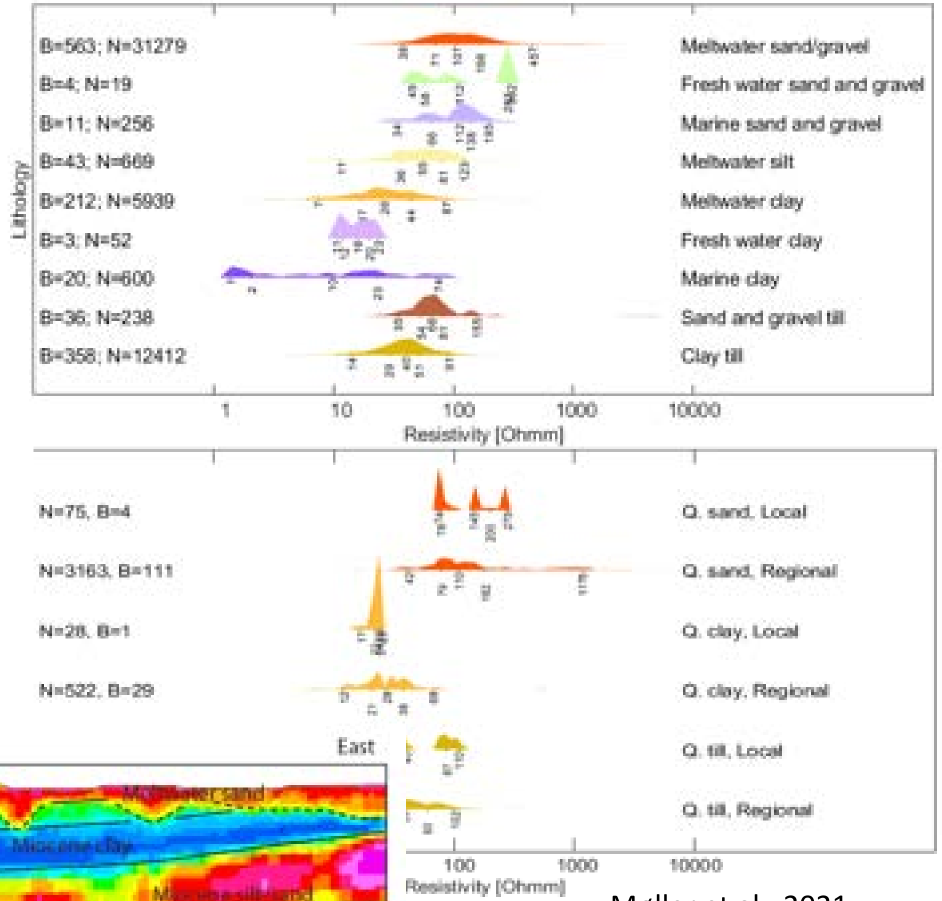
II Data evaluation and data collection

Resistivity data – sources of uncertainties and limitations related to modelling

- Ambiguity – different geophysical models can fit the data!
- Resolution - both vertical and horizontal decrease with depth
- Ambiguity in the resistivity-lithology relationship
- Influence from ion content and concentration in the pore water
- Presence of corrupted or noisy data
- Presence of artefacts in 1D inversion models due to 3D effects

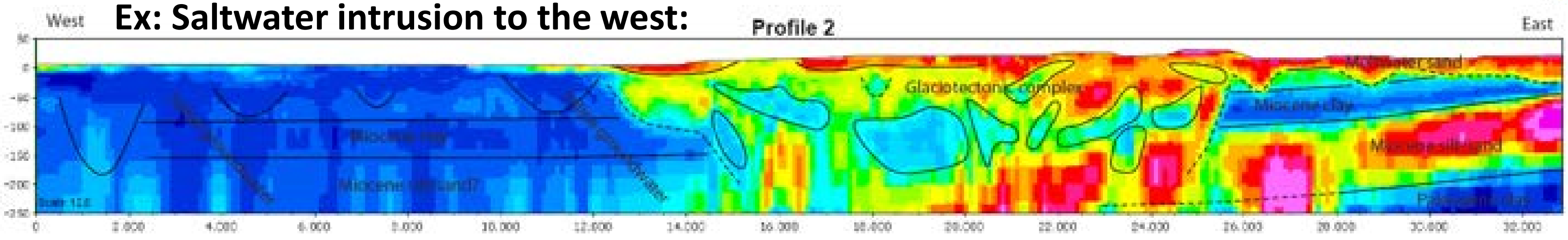
⇒Knowledge about the methods is important!

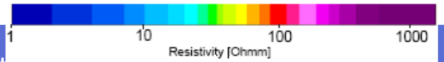
⇒Important to communicate on data uncertainties



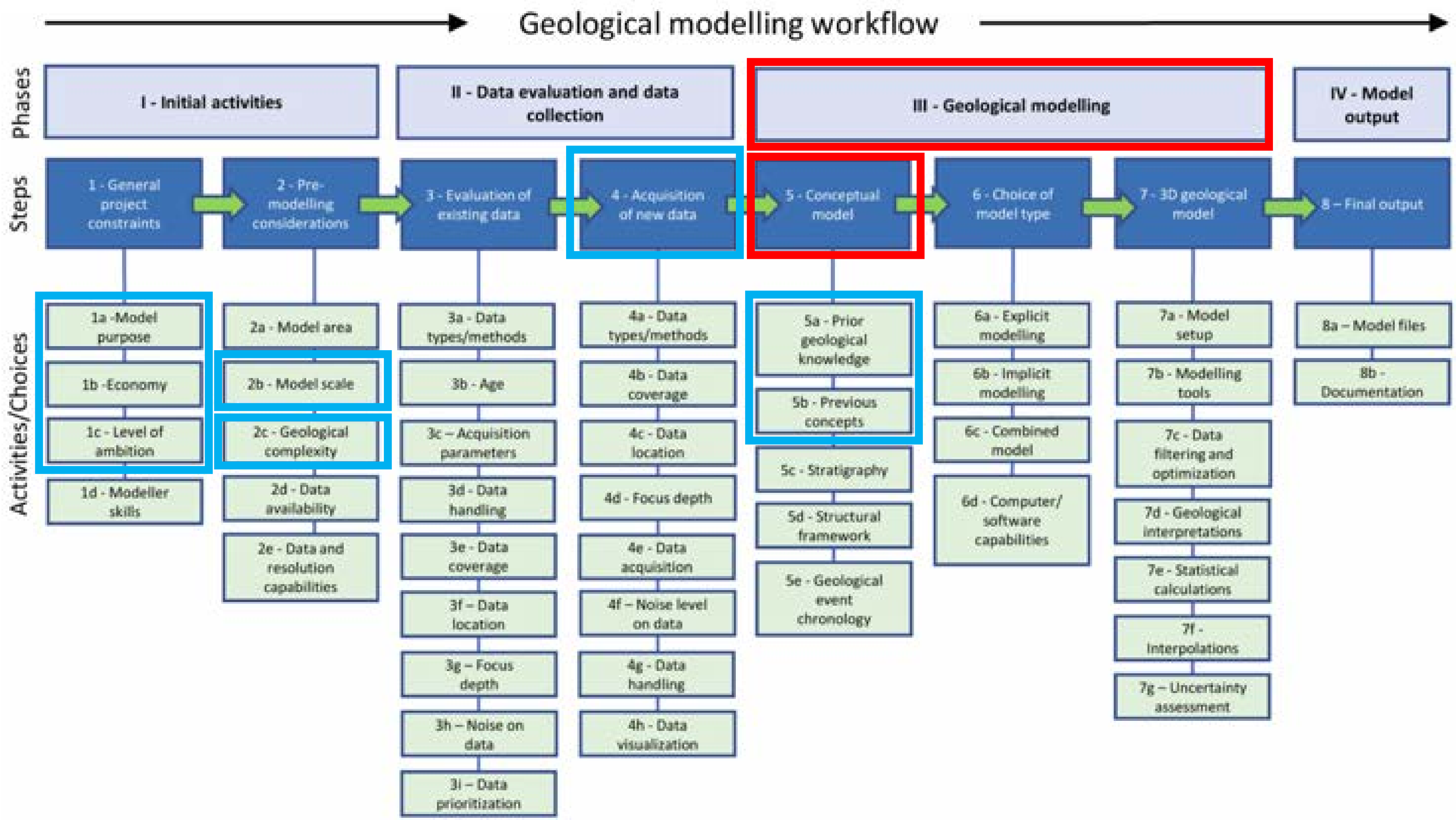
Møller et al., 2021

Ex: Saltwater intrusion to the west:





Jørgensen et al. 2012. HESS. 16, 1845-1862. doi: 10.5194/hess-16-1845-2012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III Geological modelling, conceptual model
1a – Model purpose, 1c – Level of ambition, 2b – Model scale

Model purpose

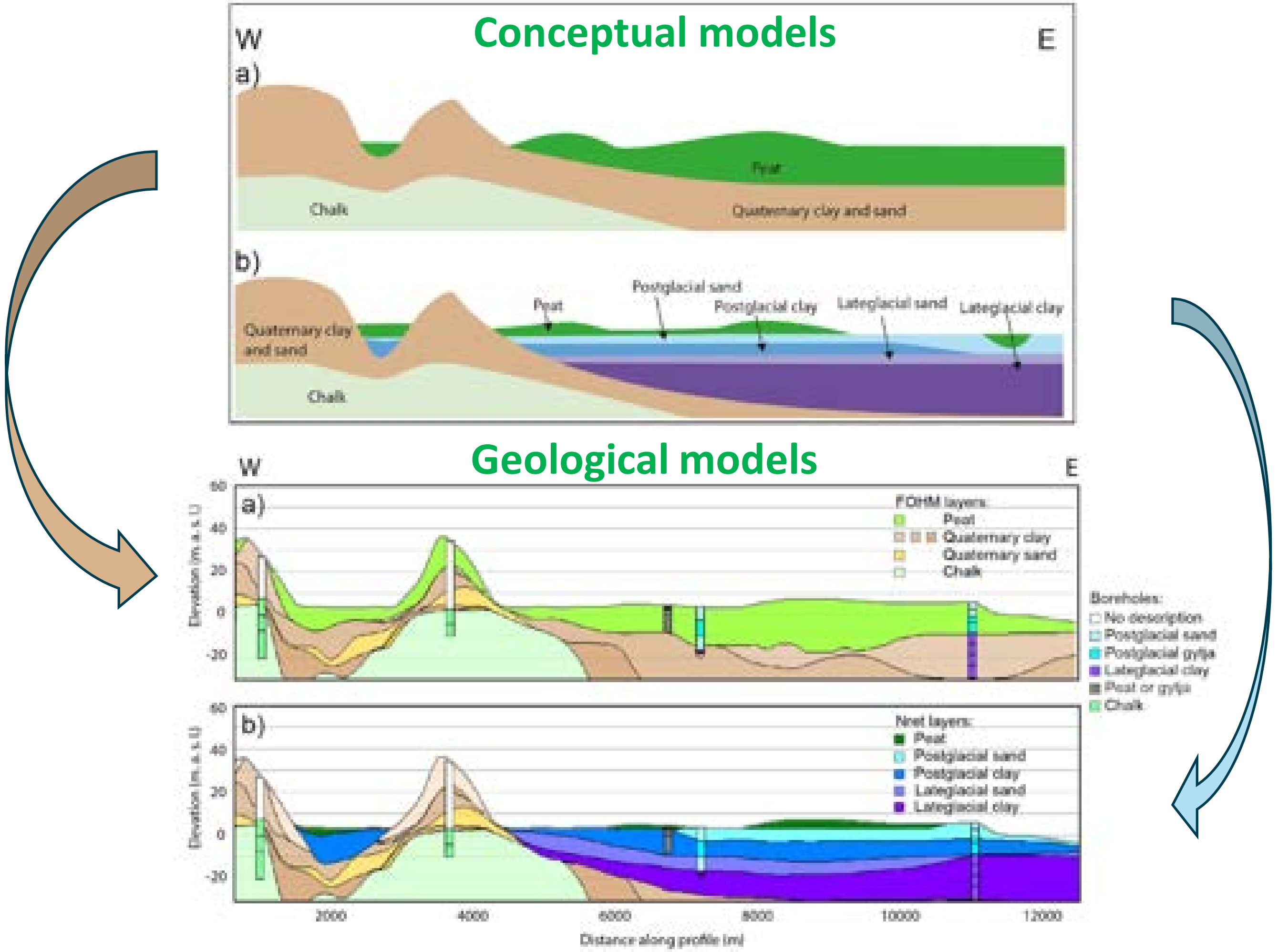
a) Regional hydrostratigraphic model

b) Model for nitrate retention modelling differentiating in layers with varying organic content

Model scale

- A need for modelling thinner layers

Impact on uncertainty assessment



Høyer et al., 2024. Eng. Geol. 343, 10779. 10.1016/j.enggeo.2024.107792

III Geological modelling, conceptual model

5a – Prior geological knowledge, 5b – Previous concept, 4. – New data

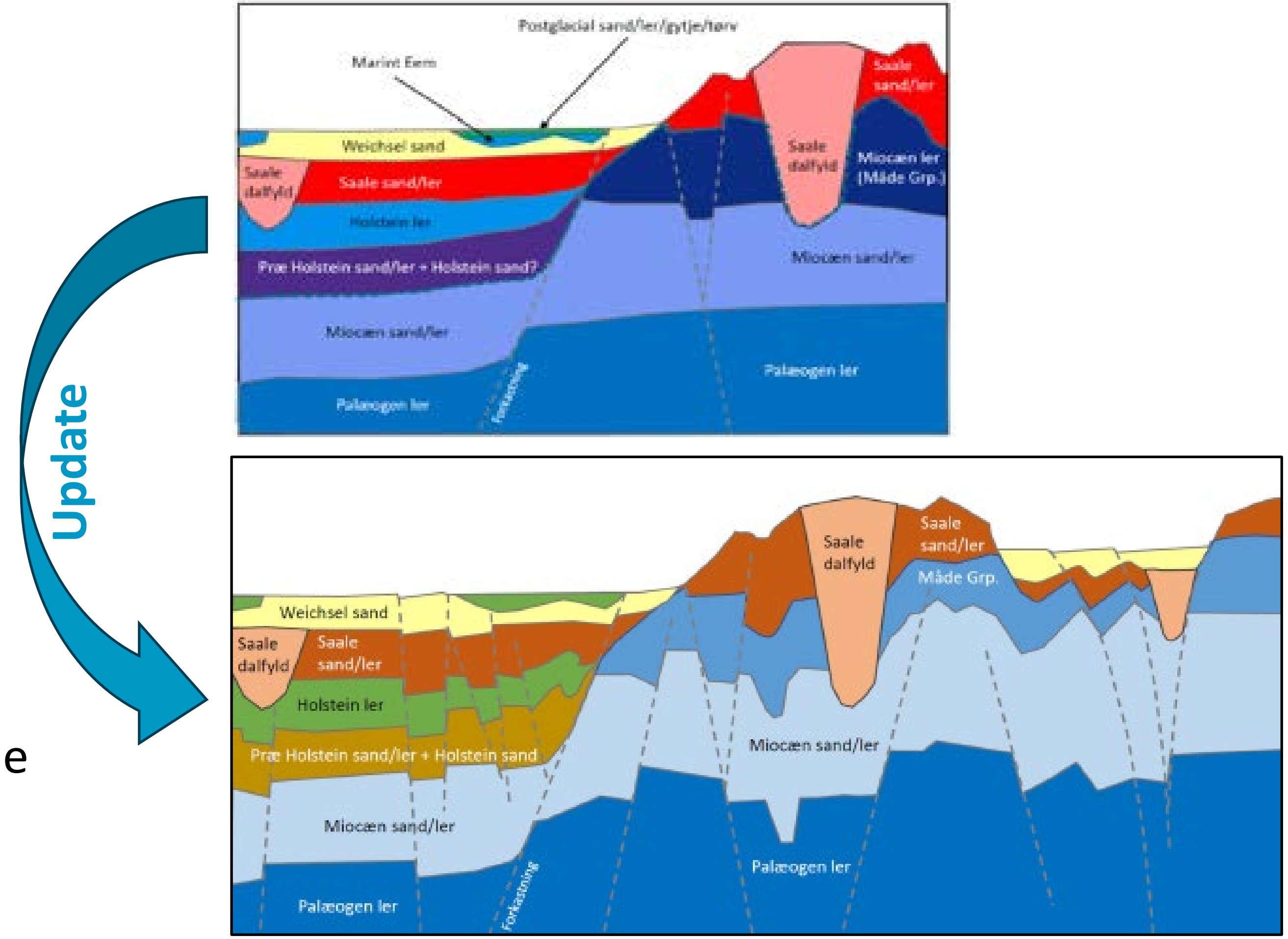
Revised previous concepts

- New data
- Revisiting existing data
- Higher level of geological complexity observed

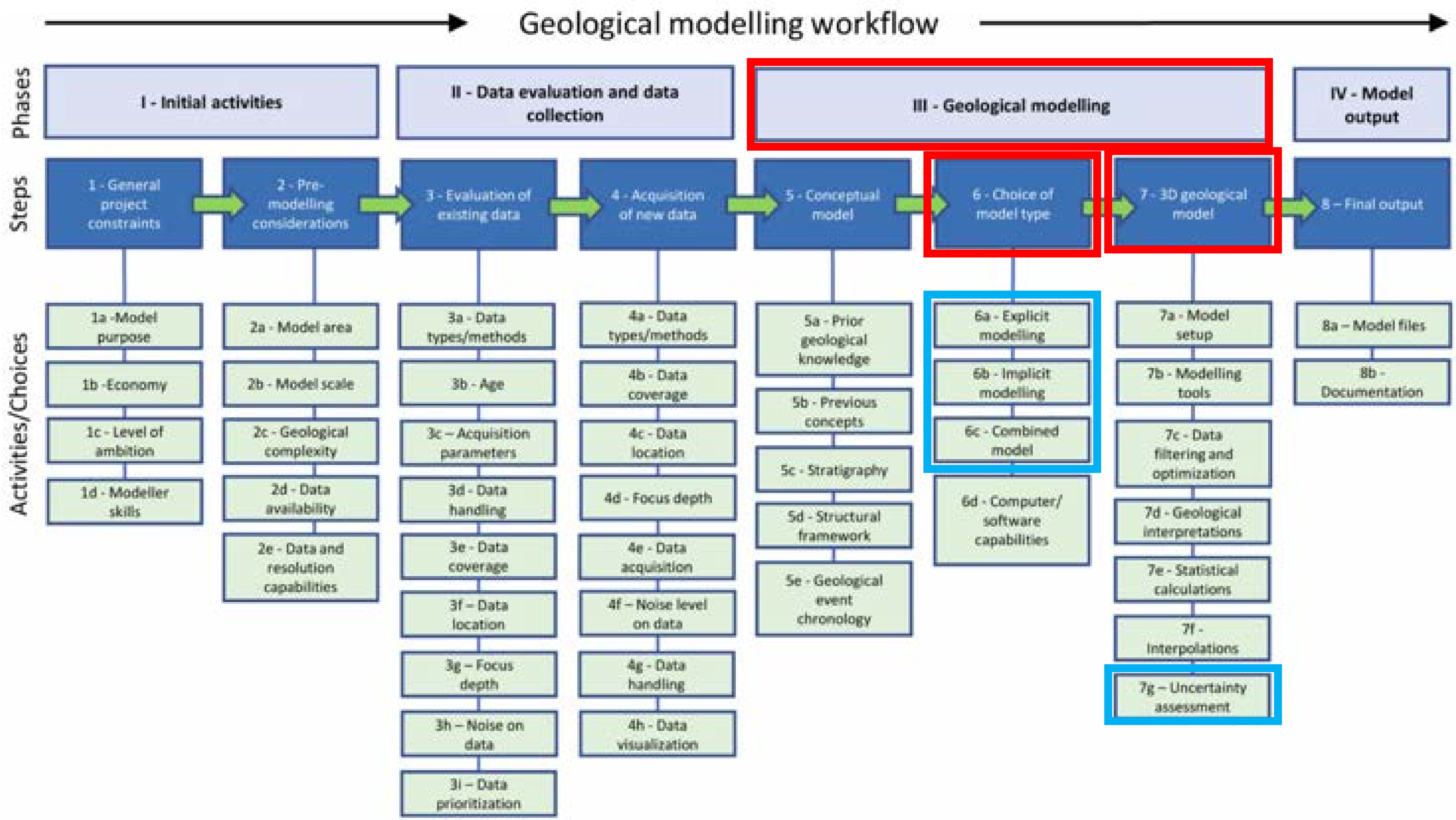
=> Introduce intensive faulting in specific areas

Always under the assumption that the conceptual model is "the best possible"

Important to include conceptual model in the communication of the model uncertainty



Sandersen et al. 2025. GEUS Report 2025/28 doi: 10.22008/gpub/34785



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III Geological modelling, choice of model type

Interpretation-based modelling

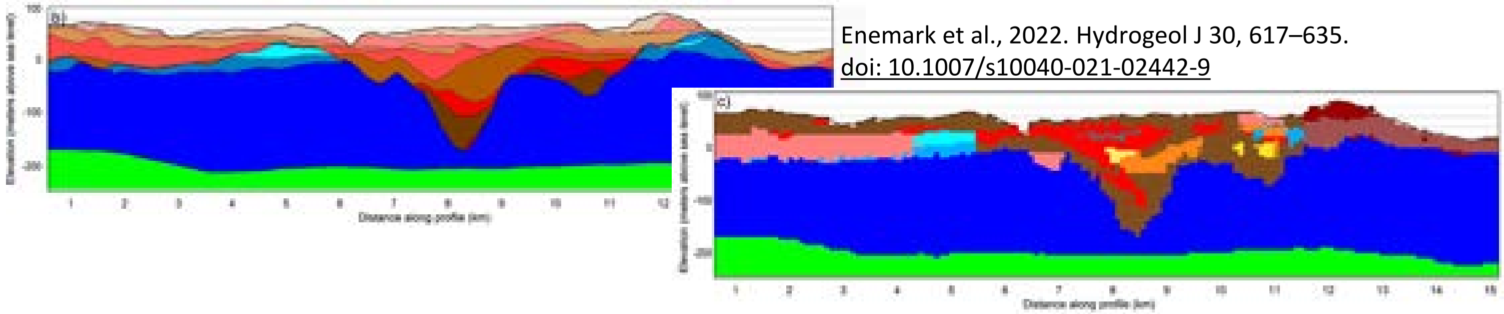
- Explicit
- Driven by prior knowledge and data
- Manuel
- Qualitative uncertainty assessment

Geostatistical modelling

- Implicit
- Mainly data-driven
- Numerical calculations and simulations
- Quantitative uncertainty assessment

Combined modelling

- Different modelling approaches and techniques in individual parts of the model
- Uncertainty assessment dependent on modelling approach



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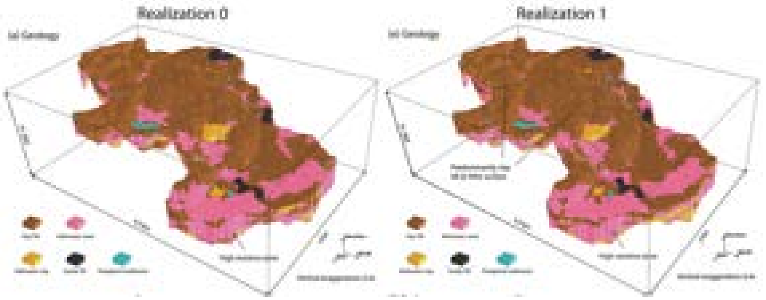

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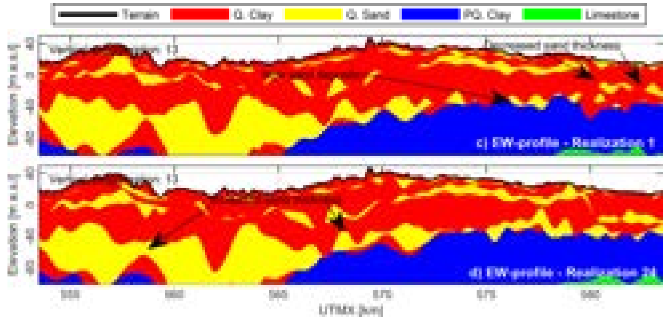

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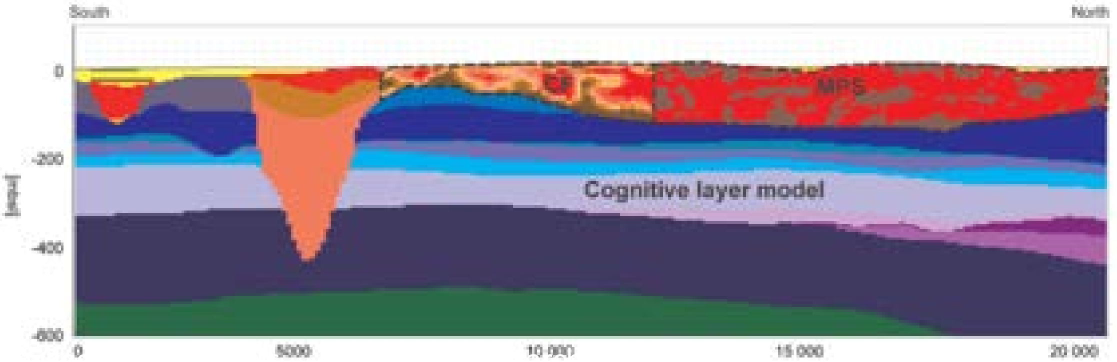


Jørgensen et al. 2015. Comput. Geosci 81, 53-63. doi: 10.1016/j.cageo.2015.04.010

III Geological modelling, 3D geological model

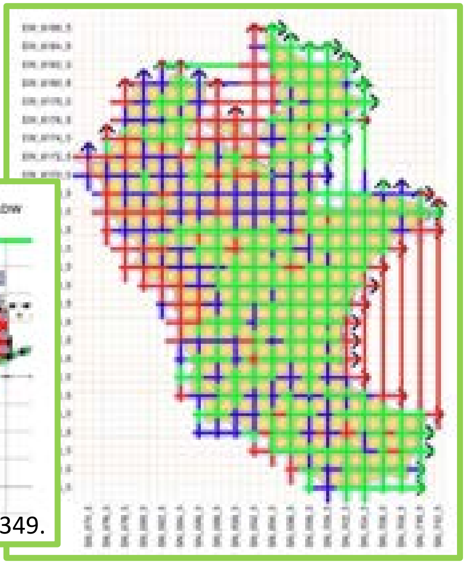
7g - Uncertainty assessment

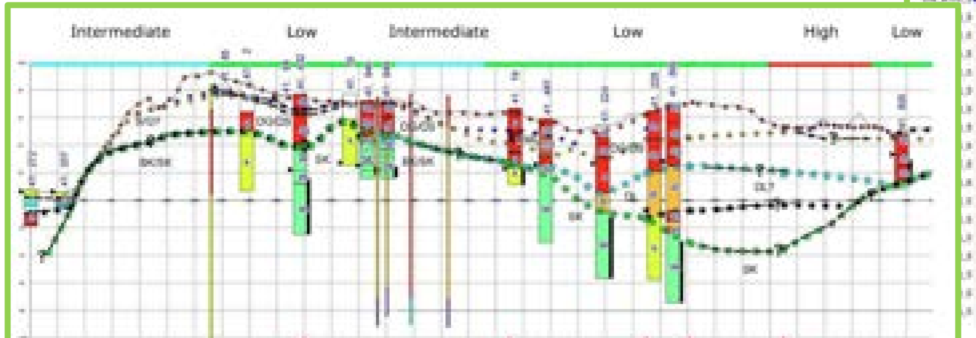
Interpretation-based modelling

- Qualitative uncertainty assessment
- Evaluate on profiles
- Evaluate all individual interpretation points
- Evaluate on voxels
- Divide into uncertainty categories
- Based on amount of data, data type and quality, ambiguous data, complexity of the conceptual geological model

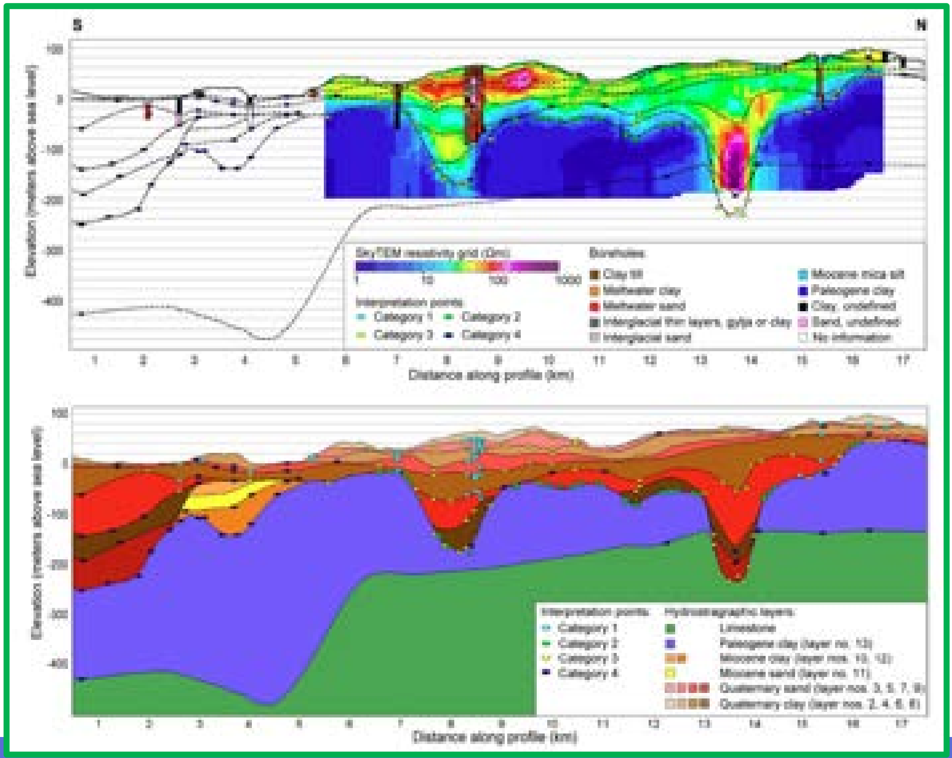
The assessment reflects the geologist's own evaluation of the reliability of the model interpretation along the profile.

The assessment relative to the model area – not directly comparable to other model areas.





Sandersen 2008, IAHS Publ. 320, 345-349.



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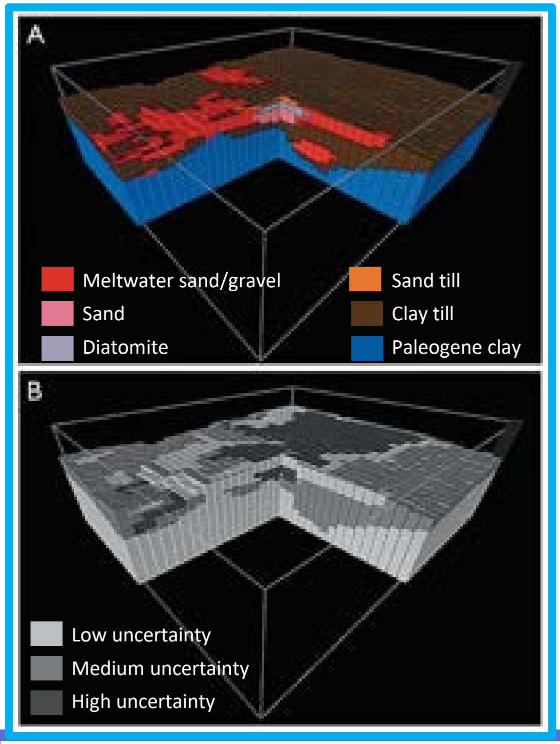

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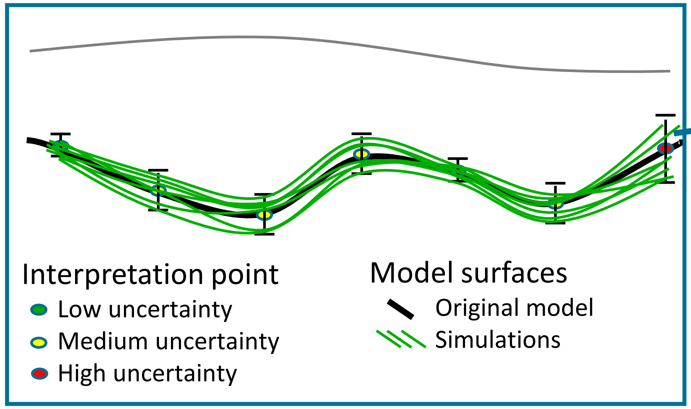
III Geological modelling, 3D geological model

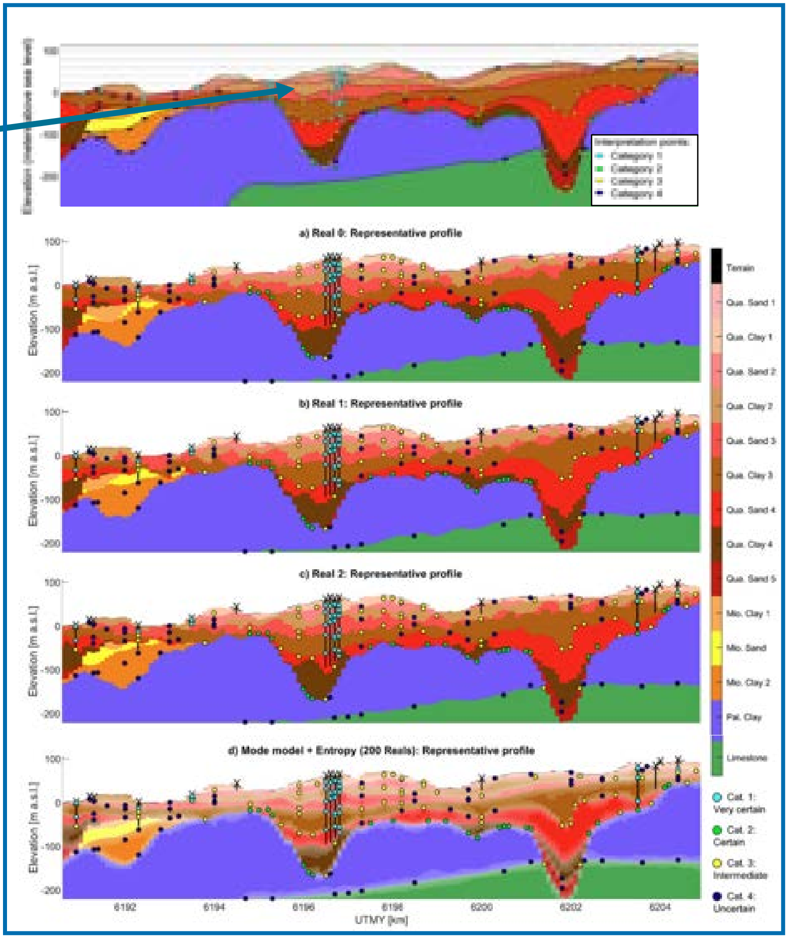
7g - Uncertainty assessment

Geostatistical modelling – layer based

- Calculating or estimating model uncertainties
- Quantitative uncertainties on (geophysical) data directly used
- Need for quantifying subjective elements (geological descriptions)

- Simulating model layers based on quantification of qualitative uncertainties - realisations
- Evaluation of model ensemble – uncertainty.





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III Geological modelling, 3D geological model

7g - Uncertainty assessment

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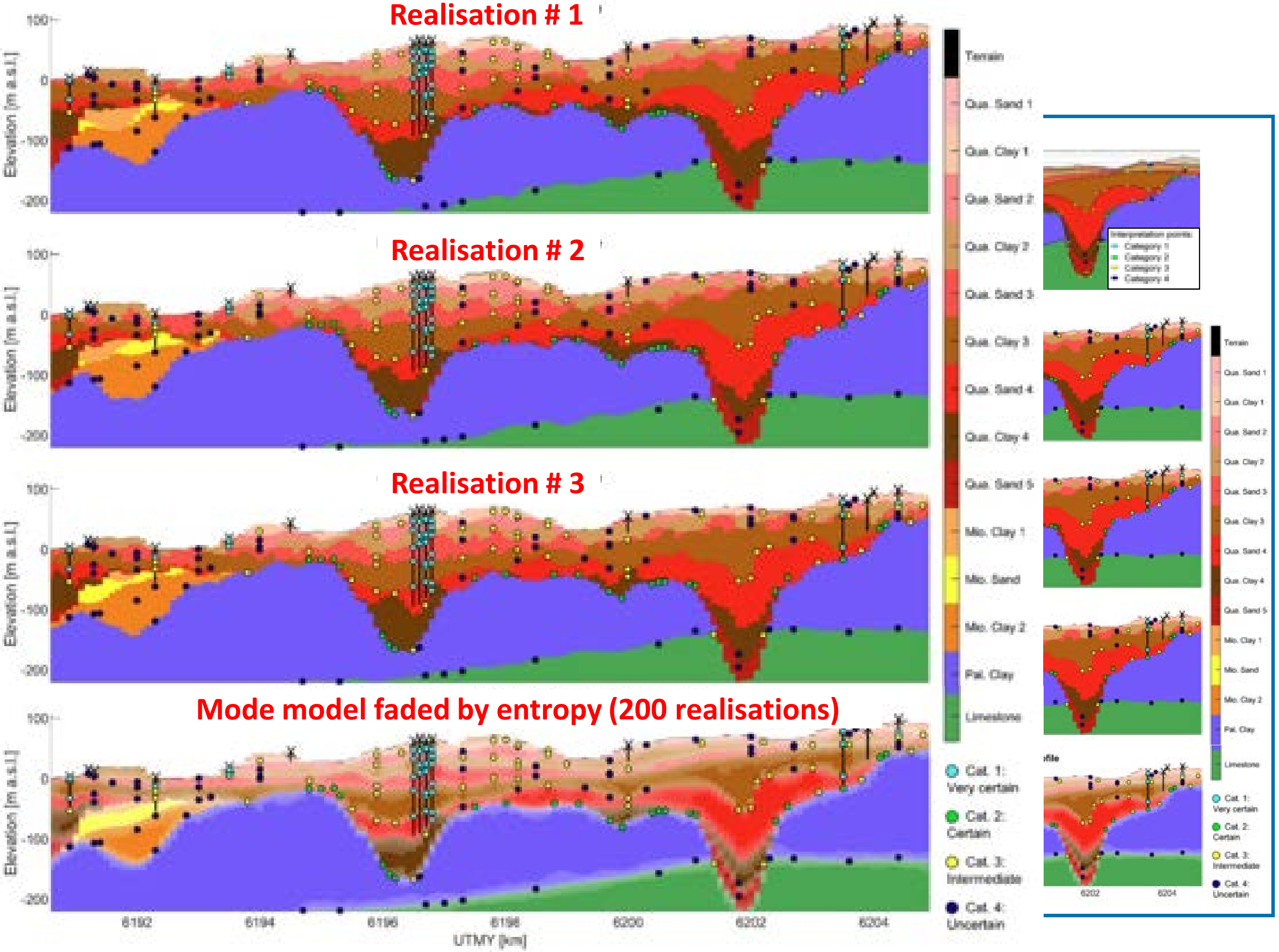
- Calculating or estimating model uncertainties
- Quantitative uncertainties on (geophysical) data directly used
- Need for quantifying subjective elements (geological descriptions)

- Simulating model layers based on quantification of qualitative uncertainties - realisations
- Evaluation of model ensemble – uncertainty.

The quantitative model uncertainty is convoyed by an ensemble of models.



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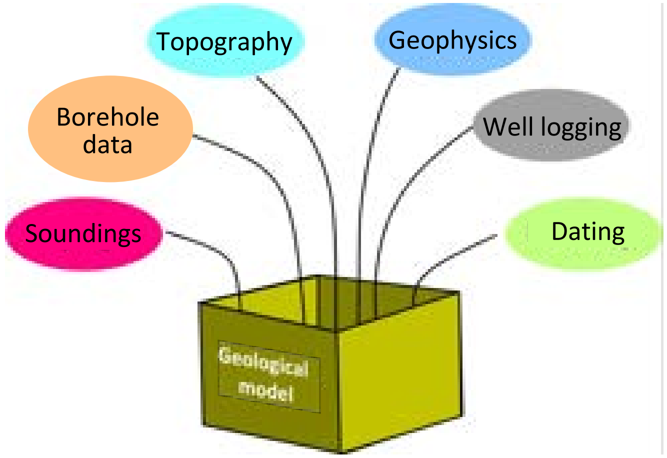
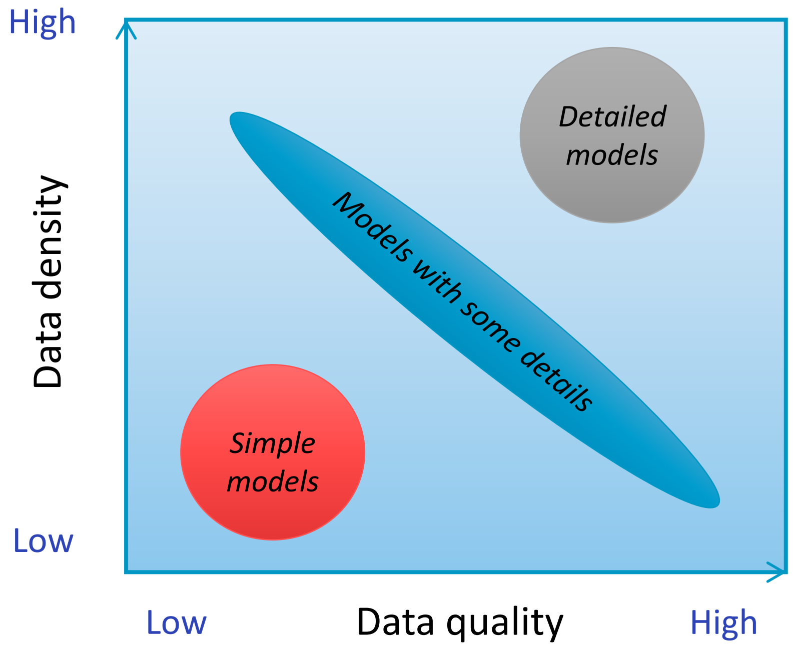
Summary

- The uncertainty of a geological model adds up from a large number of choices in the geological modelling workflow
- It is important to identify and prioritise the uncertainties in the workflow
- It is impossible to make a complete quantification of the uncertainties in a geological model
- Geological uncertainty can be evaluated and conveyed to subsequent modelling like hydrological flow modelling through geostatistical methods
- The uncertainty is related to a concrete type of uncertainty, e.g. the uncertainty of the location of layer surfaces in a layer model based on a specific conceptual model
- All these aspects are important when communicating uncertainties in geological modelling





ALBANIAN GEOLOGICAL SURVEY

"CHALLENGES IN GEOLOGICAL MODELLING AND HANDLING UNCERTAINTIES IN GEOLOGICAL MODELS AND MAPS"

Phd Sirelda Bele

Albanian Geological Survey

- It operates in the Geosciences field according to the *law No. 111/2015 dated 15. 10. 2015,* that defines that the AGS is a ***technical-scientific advisor of the state in the Geosciences field.***

- ***It depends from the Ministry of Infrasturcture and Energy.***

- It has ***its beginnings in 1922***, when the Geological Office was created by the Czech-Austrian chief geologist **Dr. Ernest Nowack.**

- In **100 years** of its existence, AGS is ***the oldest institution in our country, in the Geosciences field.***

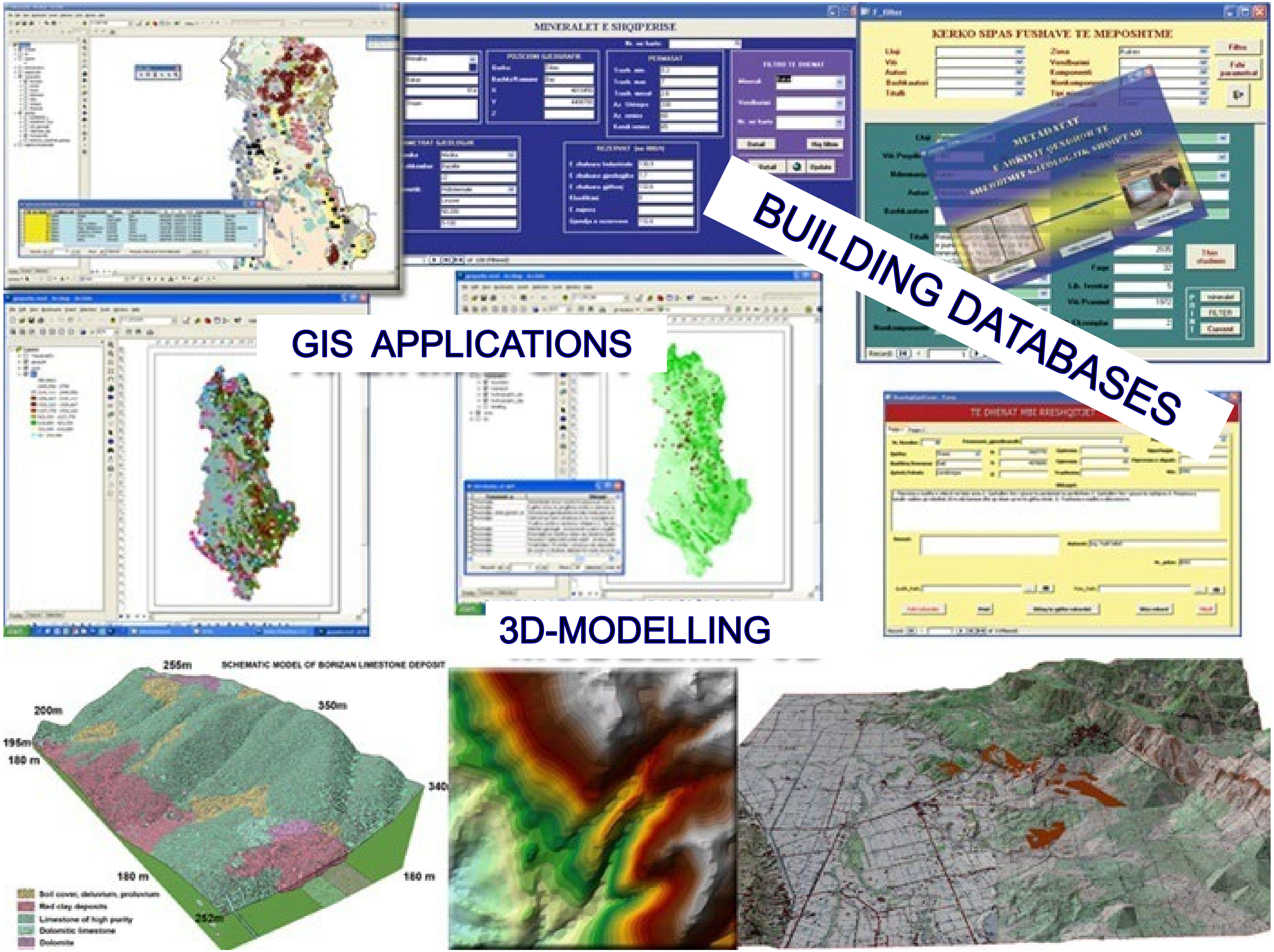
The Directorate of Geo-informatization performs the following main tasks:

- Produces the maps of any scale and the digital documentation for all the units of the Albanian Geological Survey.

- It creates, complements and updates the database for all activity that AGS carries; makes the computerized data processing of the studies.

- Georeferences, digitalises, elaborates all the types of maps for the projects in process and archived ones.

- Builds structures for the databases, presents in the form of catalogs the types of data to be recorded, provides data connection with maps in Arc-GIS program.



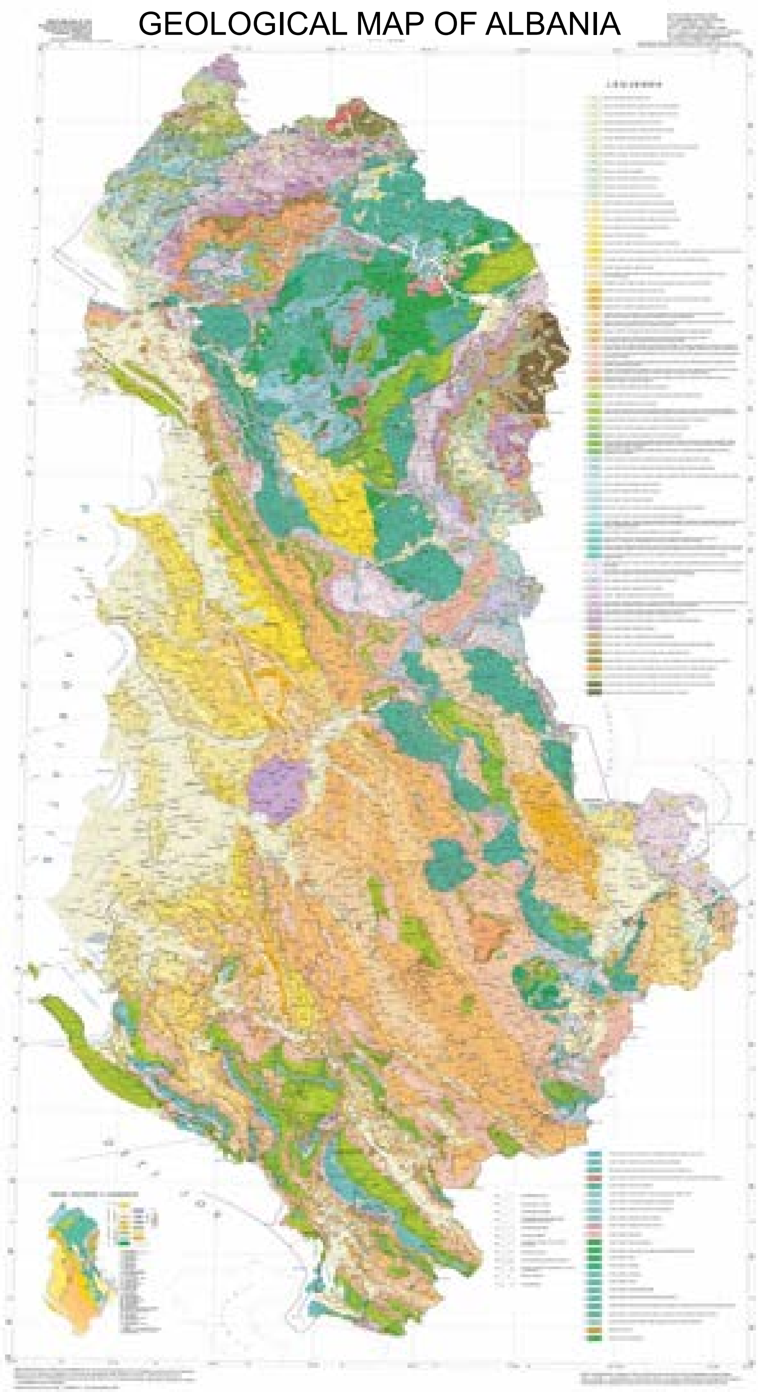
MINERALET E SHQIPERISE
KERKO SIPAS FUSHAVE TE MEPOSHTME
BUILDING DATABASES
GIS APPLICATIONS
3D-MODELLING
SCHEMATIC MODEL OF BORIZAN LIMESTONE DEPOSIT
255m
200m
350m
195m
180 m
340
180 m
180 m
252m
Soil cover, deluvium, proluvium
Red clay deposits
Limestone of high purity
Dolomitic limestone
Dolomite

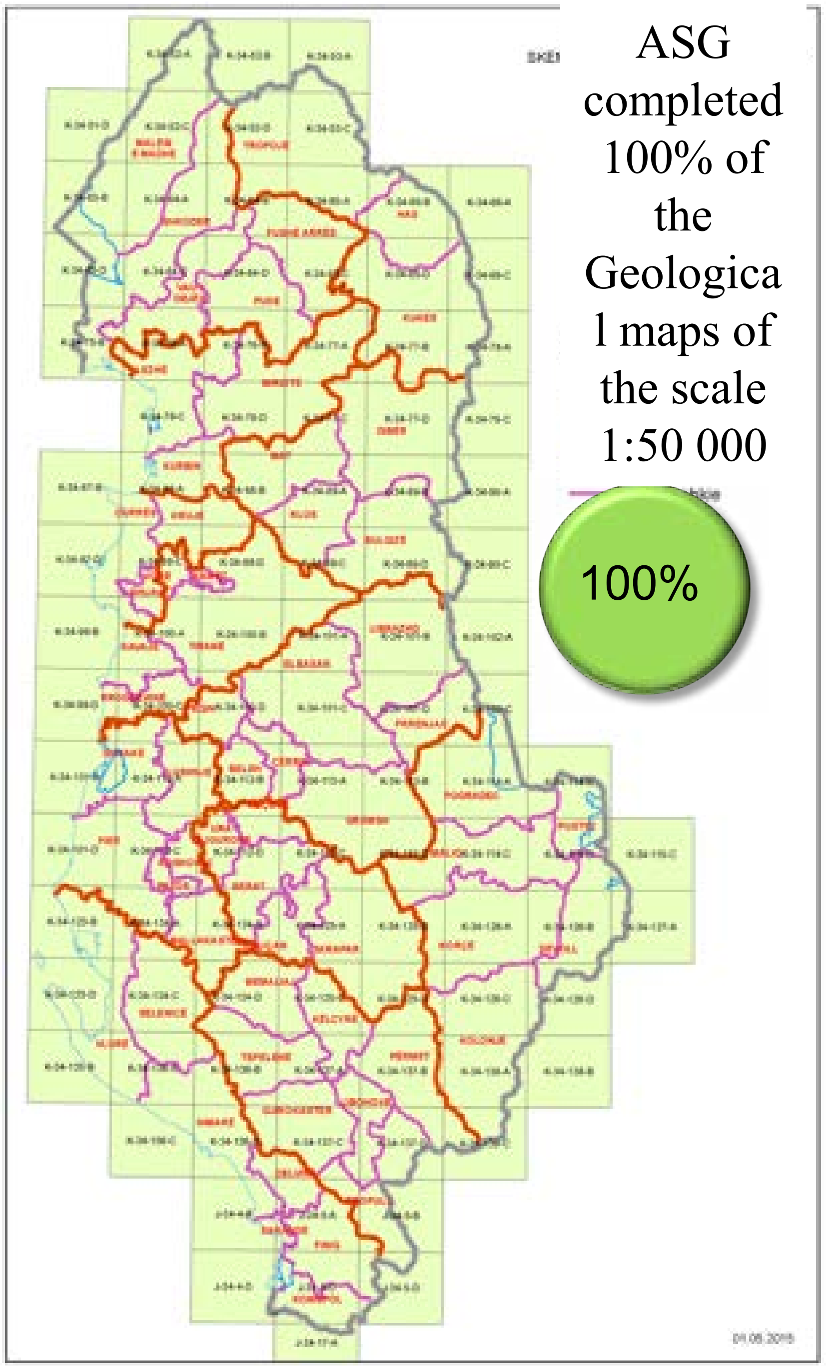
Geological Maps Overview

Geological Maps and Models in Geological Survey of Albania have been significantly developed in recent years.. Our achievements to date:

Name	Scale	Scale	Scale
Geological Maps	1 : 200 000	1 : 50 000	1 : 25 000
Hydrogeological Maps	1 : 200 000	1 : 50 000	1 : 25 000
Mineral Recourse Maps	1 : 200 000	1 : 50 000	1 : 25 000
Geological Maps	1 : 200 000	1 : 50 000	1 : 25 000

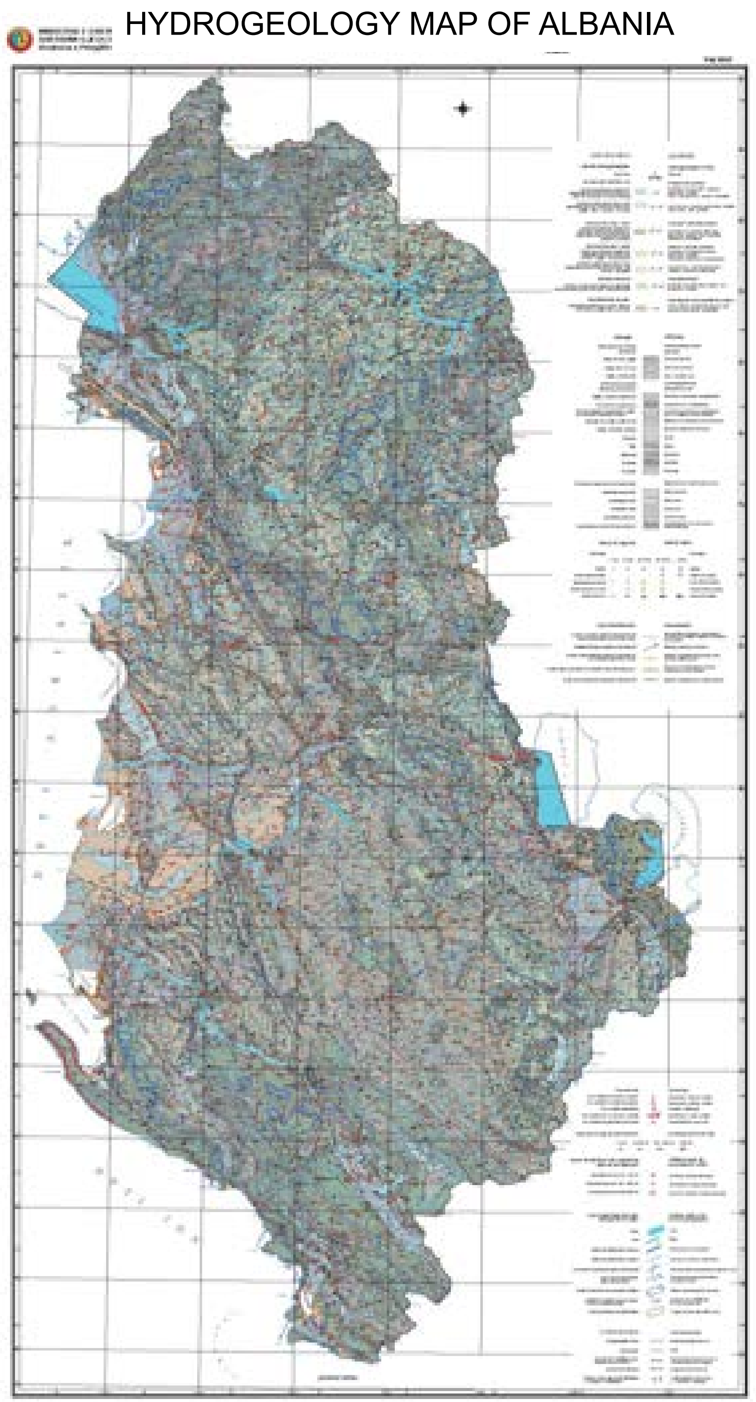
Our Department has just started on geomodelling of ore body deposit
We have taken some ore deposit of chromite to approached a methodology on 3D modelling .



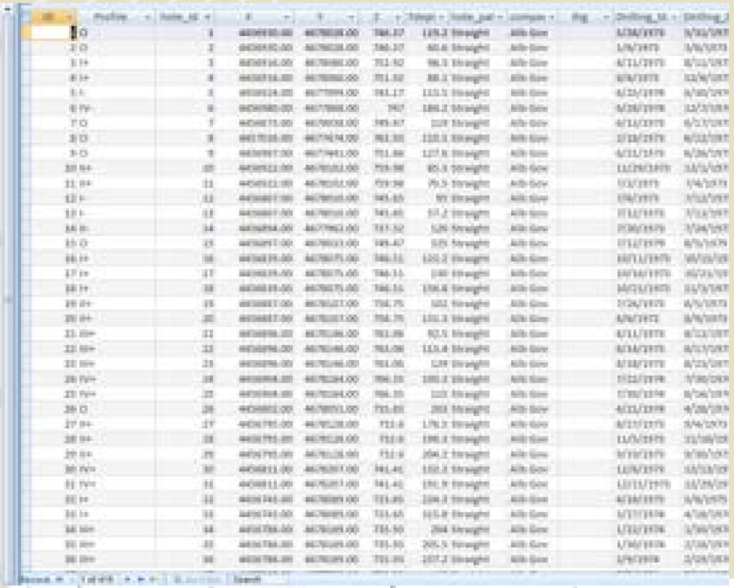


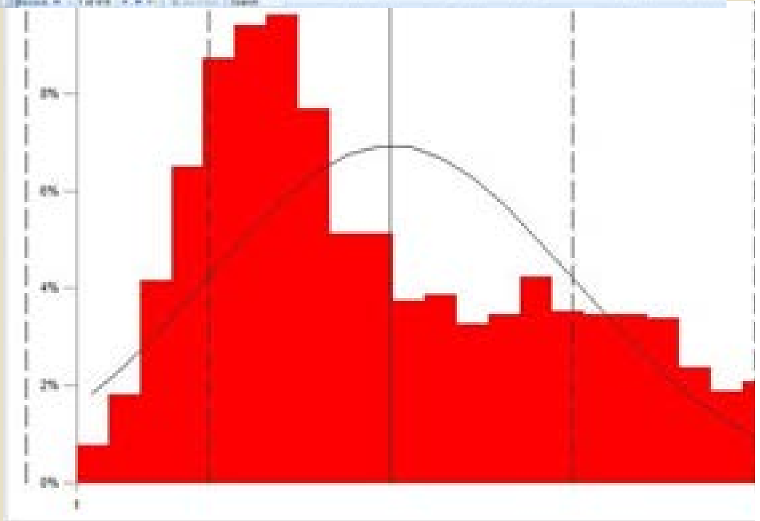
ASG completed 100% of the Geologica l maps of the scale 1:50 000

100%

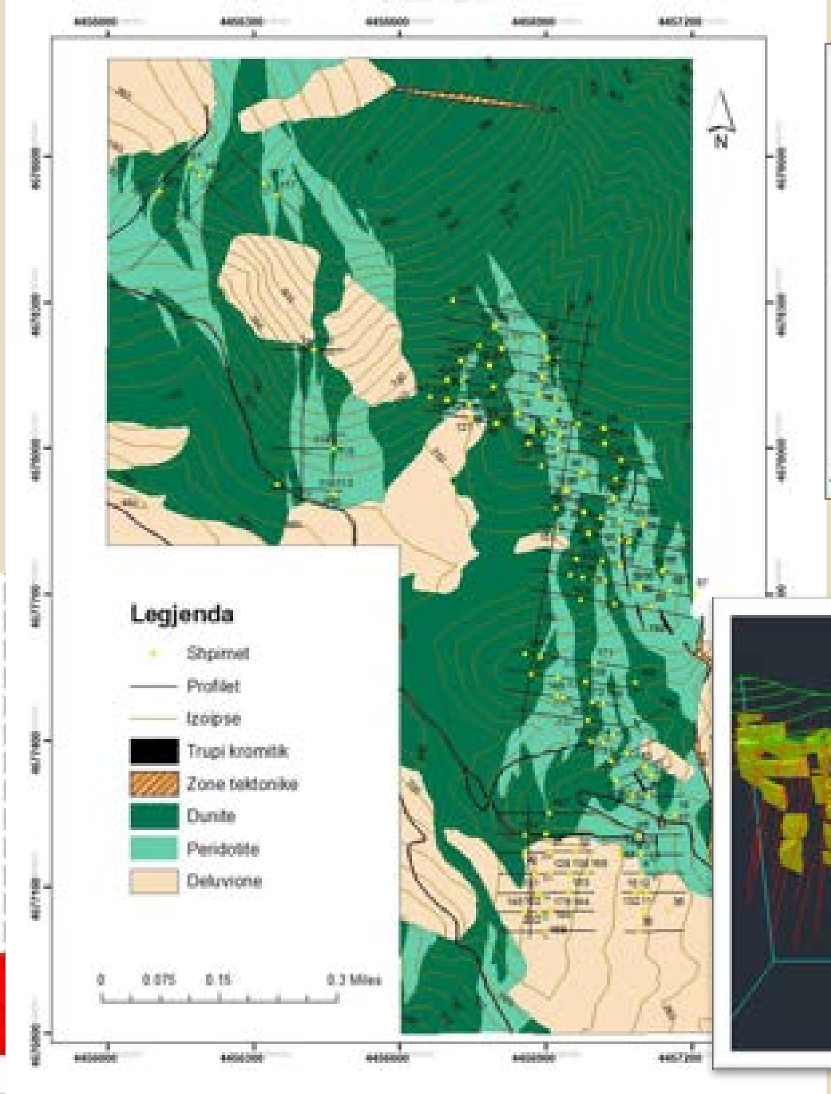


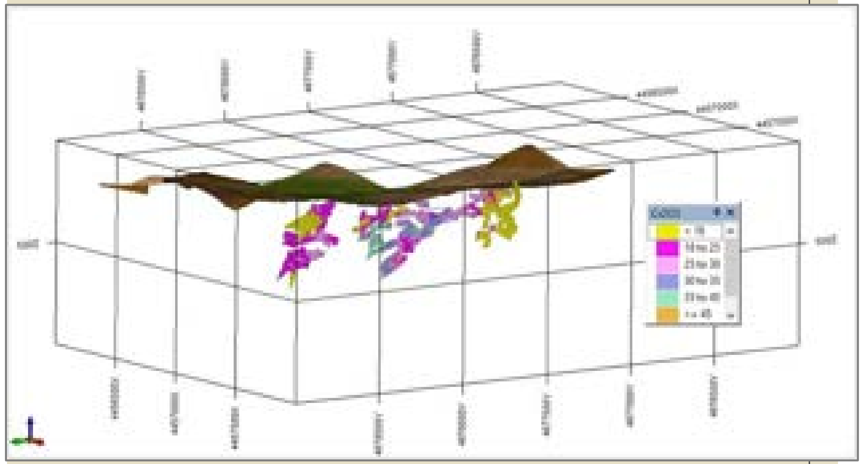
3D MODELING EXAMPLE

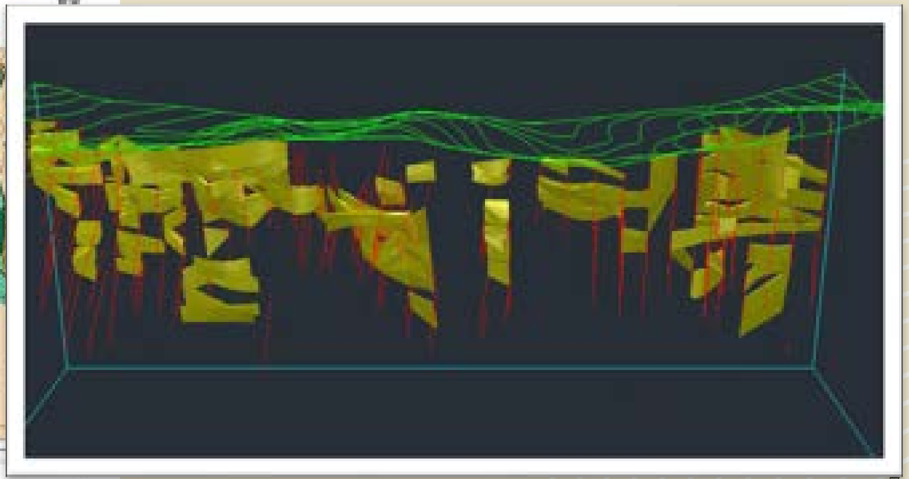




GEOLOGICAL MAP OF VLAHEN ORE DEPOSIT







Handling uncertainties in map data and interpretations

1. The main concern remains to gather new data
2. We use mostly historical data
3. Uncertainties are handled in collaboration with field experts for specific themes, by analyzing and comparing historical data.

- We don't have new data from boreholes that previous studies have drilled
- Since 1990 we haven't collected any new data on mineral resources
- We don't have sufficient borehole data to create 3D models of stratigraphy, geology or karst aquifers

The main reason for this is the lack of funding
Additionally, we are limited to using outdated software or open -source tools, which restricts our ability to adopt new technological approaches.

Stakeholder Communication & Interaction

Communication Barriers:

- Communicating uncertainties to stakeholders is a challenge in itself.
- Decision-makers often prefer clear and simple messages, even if this oversimplifies the underlying complexity

Effective : visual representations (maps and graphs, which help make the uncertainty understandable).
*Ineffective :*Technical terminology lengthy explanation

Current Situation:

- No direct stakeholder communication

Independent operations : stakeholders purchase finished product

- No collaborative service requests

Opportunity:

- Collaborative services would enhance value, but stakeholders currently prefer ready made outputs processed by their own technical staff.
- **Our focus** :Producing high quality maps and data for their use.

Institutional Limitations

- **The institution** currently lacks sufficient funding to carry out all necessary work, such as new drilling or extensive data collection.
- **There is** a strong need for staff training and specialization in new methods for using software and developing innovative approaches.

Conclusions & Key recommendations

- **Uncertainties** in geological models and maps stem from limited data, complex geology, and outdated tools.
- **Main challenges**, Recommendations and Future directions at AGS: insufficient funding for new data collection, need for staff training in advanced GIS/3D modeling software, and difficulty communicating uncertainties to non-technical stakeholders
- **Recommendations**: Prioritize investment in modern geological survey technologies, develop visual communication methods (simplified maps/graphs), and foster collaboration with stakeholders for data sharing
- **Future direction**: Transition to open-source tools and establish uncertainty quantification protocols for all published maps and models.

THANK YOU!

Sirelda Bele

Albanian Geological Survey

Sirelda.Bele@gsa.gov.al

sireldabele@gmail.com

Causes of uncertainty in geomodelling inputs

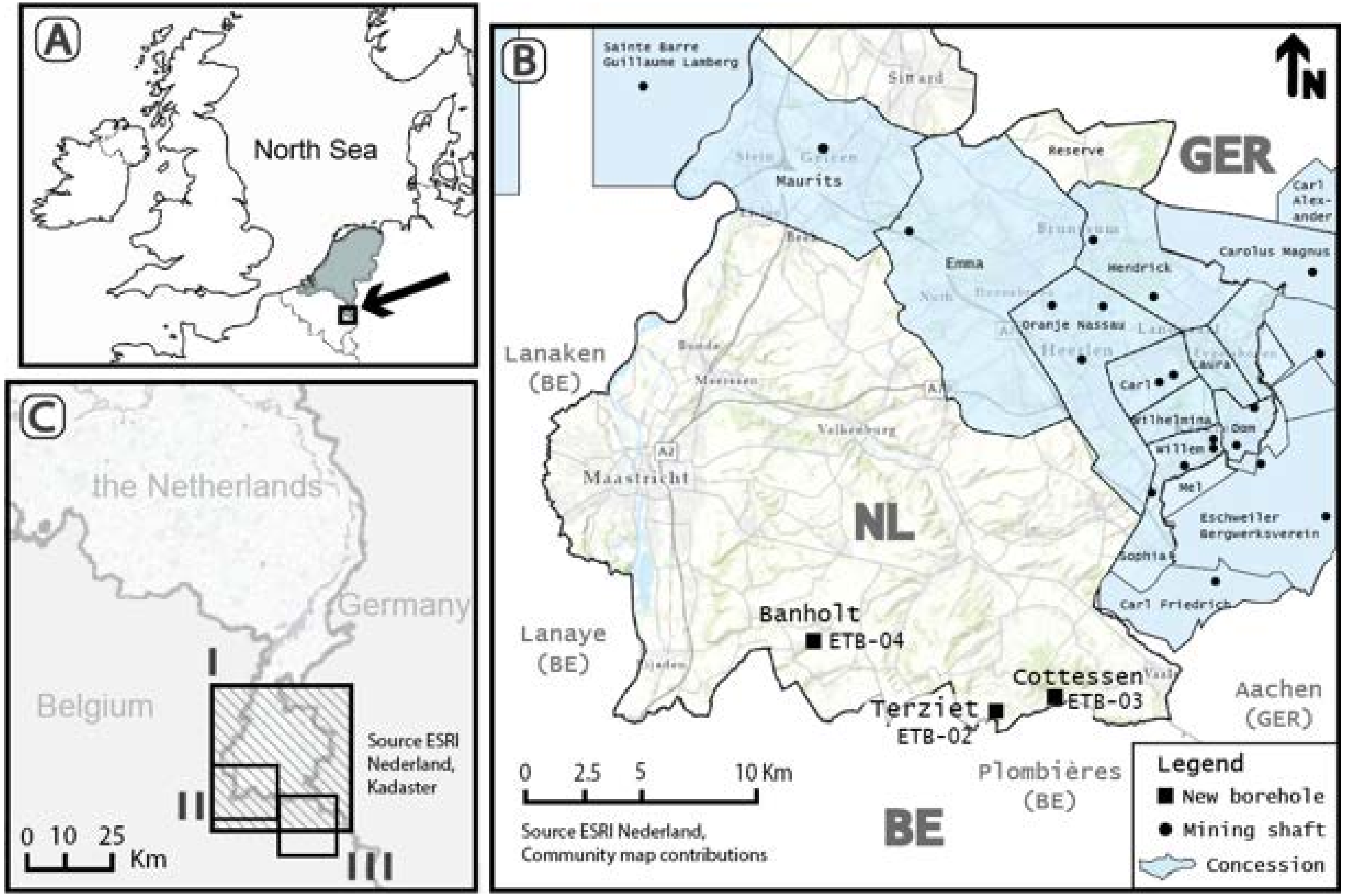
Data review of Paleozoic geology in the Euregion Meuse-Rhine

Jasper Maars[1-2], Jasper Hupkes[1], Alexander J.P. Houben[2], Geert-Jan Vis[2], Allard W. Martinius[1-3], Cornelis, R. Geel[4], Marleen de Ceukelaire[5], Hemmo A. Abels[1]

1. *Department of Geoscience and Engineering, Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands*
2. *Subsurface modelling, TNO, Princetonlaan 6, 3584 CB Utrecht, The Netherlands*
3. *Equinor ASA, Arkitekt Ebbellsvei 10, Trondheim, Norway*
4. *Applied Geosciences, TNO, Princetonlaan 6, 3584 CB Utrecht, The Netherlands*
5. *Department of Geology, Royal Belgian Institute of Natural Sciences—Geological Survey of Belgium, Jennerstraat 13, 1000 Brussels, Belgium*

TU Delft

TNO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Guillaume Lamberg
Sittard
Maurits
Reserve
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Carl
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Emma
Hendrick
Carolus Magnus
Oranje Nassau
Heerlen
Carl
Laura
Wilhelmina
Dom
Willem
Mel
Eschweiler
Bergwerksverein
Sophia
Carl Friedrich
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Maastricht
Valkenburg
NL
Lanaye
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(BE)
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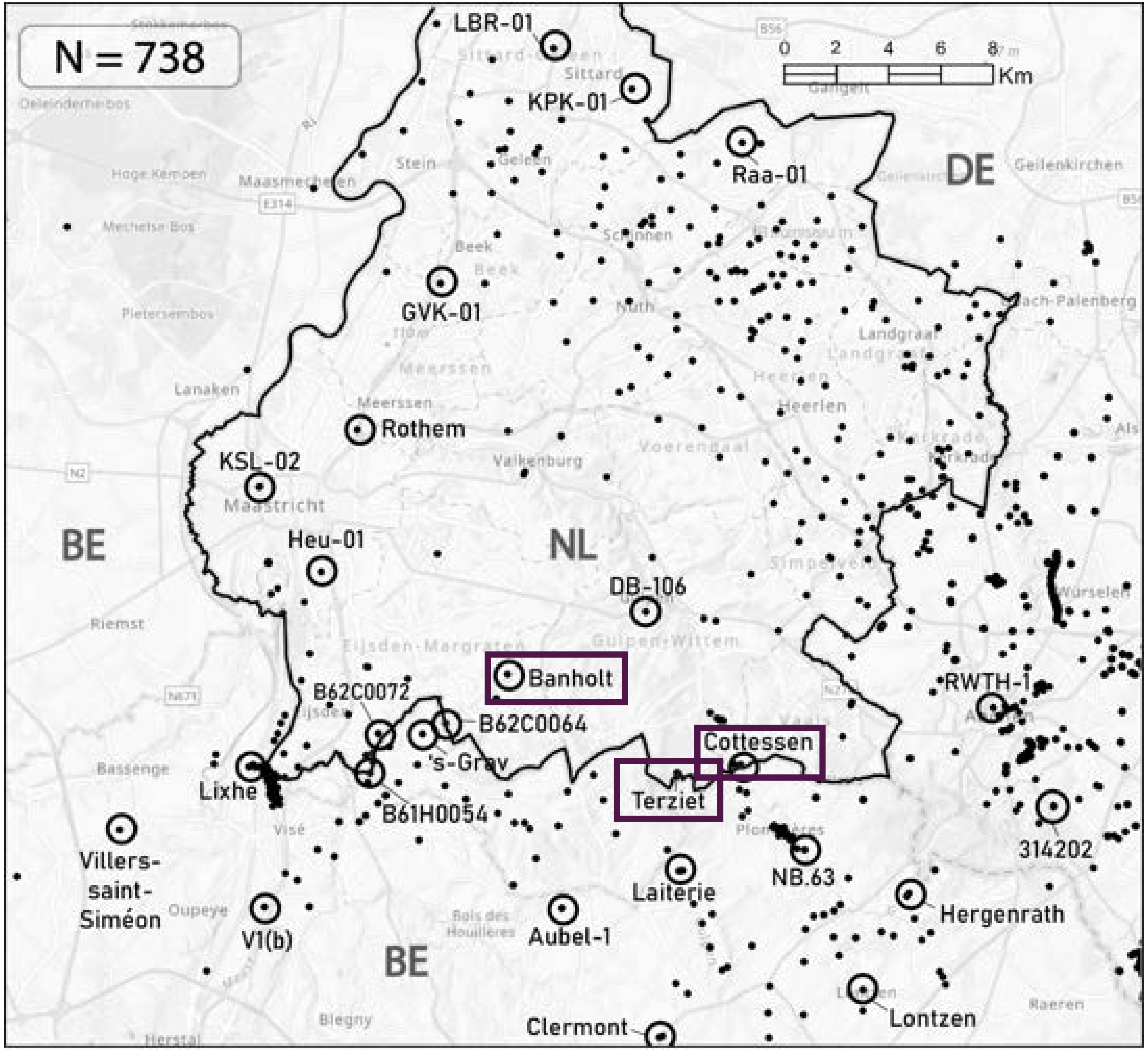
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Lixhe
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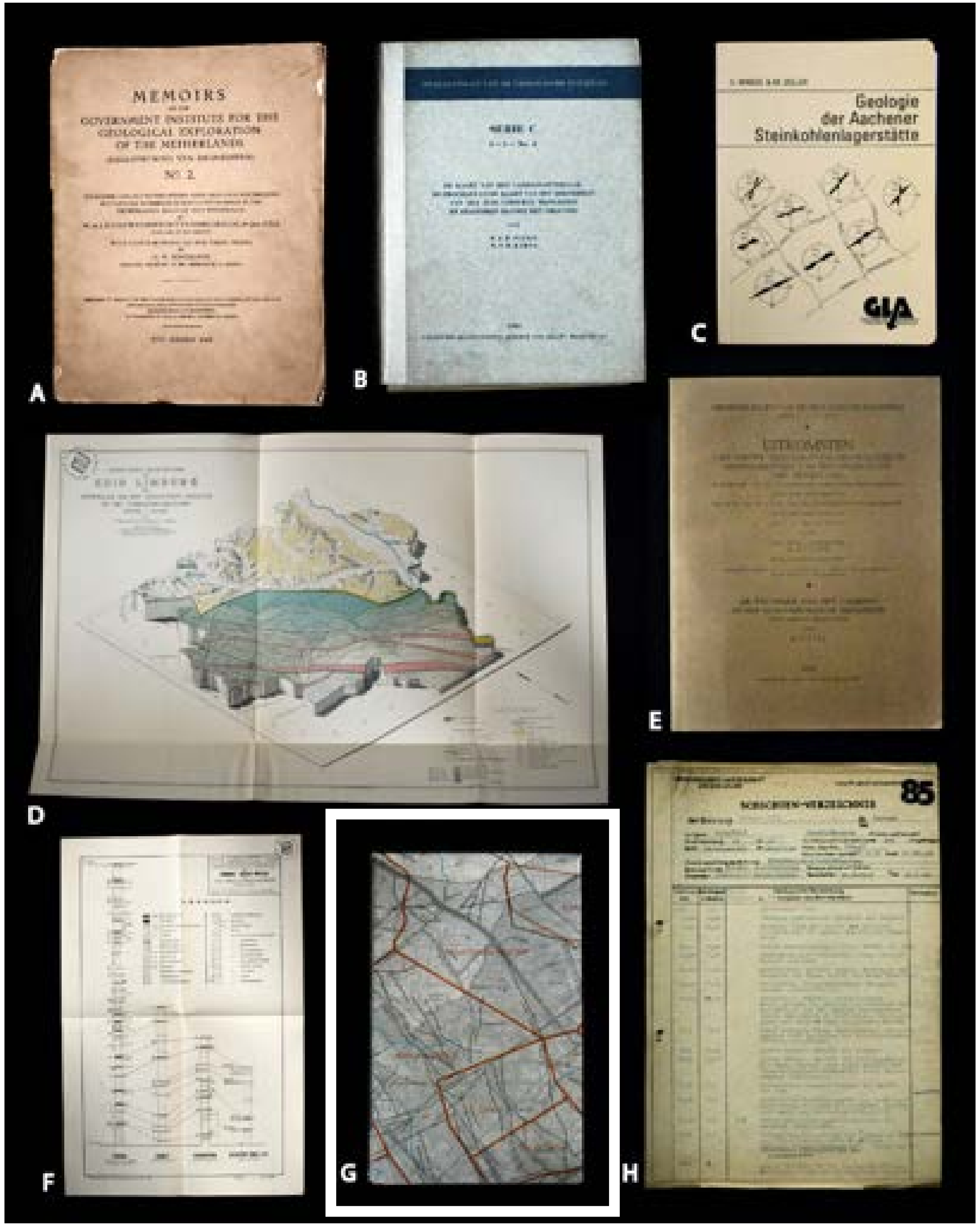
BE
Clermont
Lontzen


MEMOIRS
GOVERNMENT INSTITUTE FOR THE
GEOLOGICAL EXPLORATION
OF THE NETHERLANDS
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A
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Geologie
der Aachener
Steinkohlenlagerstätte
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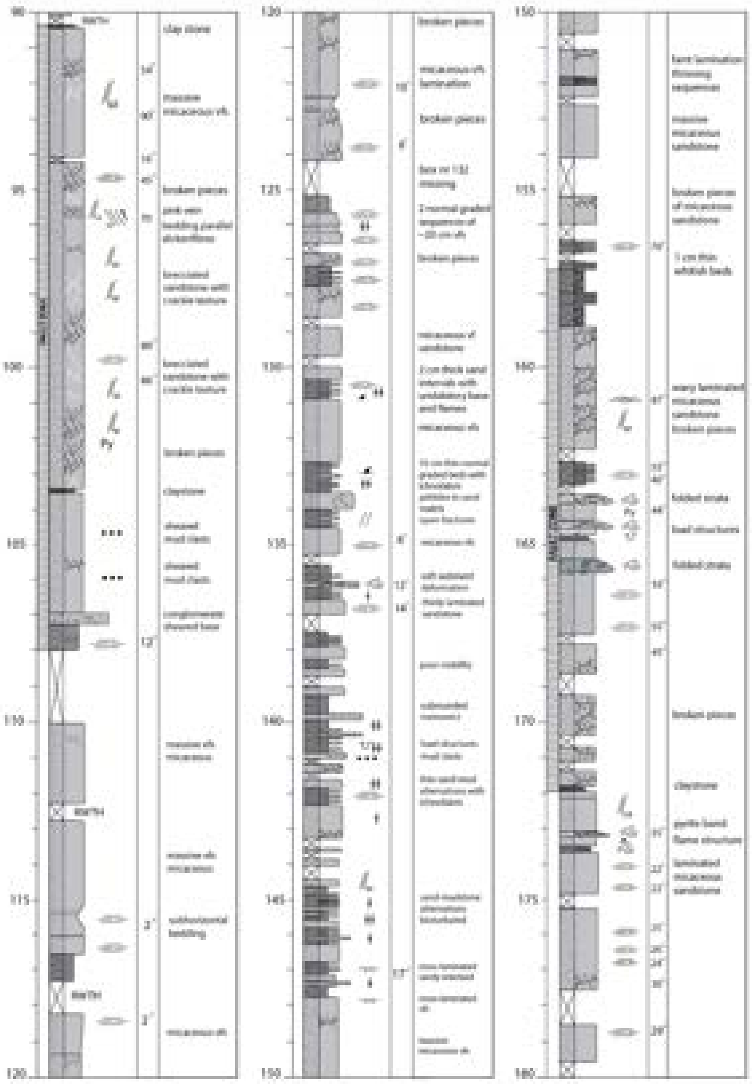
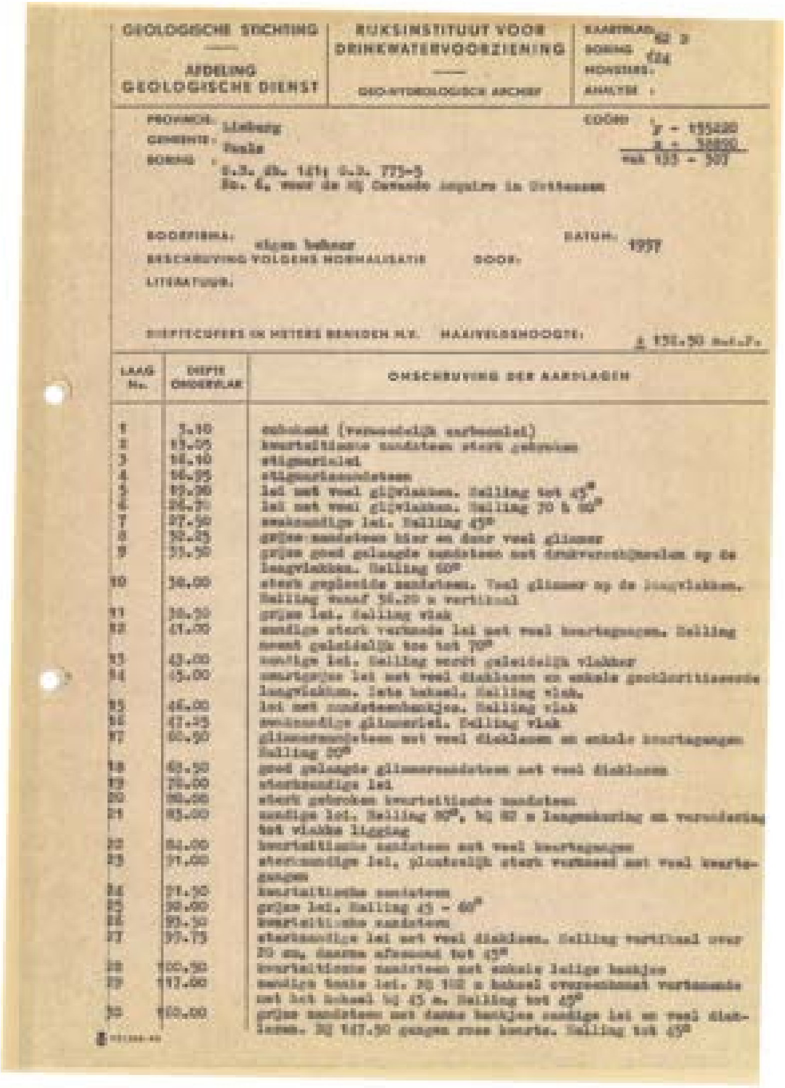
New borehole



ETB-03

Legacy borehole


GEOLOGISCHE STICHTING — AFDELING GEOLOGISCHE DIENST

RIJKSINSTITUUT VOOR DRINKWATERVOORZIENING — GEO-HYDROLOGISCH ARCHIEF

KAARTBLAD:

BORING:

MONSTERS:

ANALYSE:

PROVINCIE: Limburg

GEMEENTE:

BORING:

COÖRD:

BOORFIRMA:

DATUM: 1937

BESCHRIJVING VOLGENS NORMALISATIE DOOR:

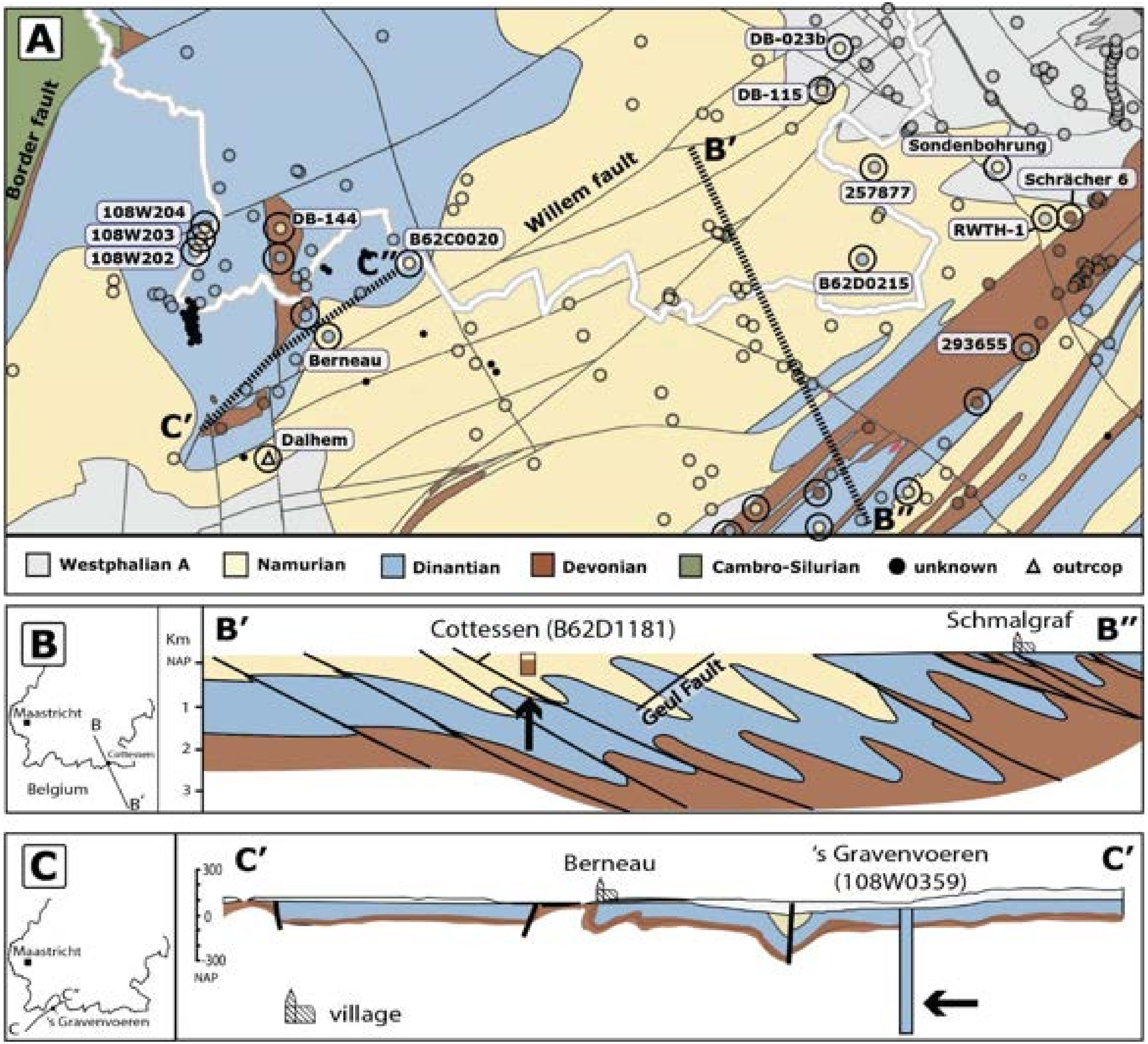
LITERATUUR:

DIEPTECIJFERS IN METERS BENEDEN M.V. MAAIVELDSHOOGTE:

LAAG No.	DIEPTE ONDERVLAK	OMSCHRIJVING DER AARDLAGEN

DB-141

~250 m


A
Border fault
Willem fault
DB-023b
DB-115
B′
Sondenbohrung
Schrächer 6
257877
RWTH-1
108W204
108W203
108W202
DB-144
B62C0020
C″
B62D0215
Berneau
293655
C′
Dalhem
B″
Westphalian A
Namurian
Dinantian
Devonian
Cambro-Silurian
unknown
outrcop
B
Maastricht
Belgium
Km
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3
B′
Cottessen (B62D1181)
Geul Fault
Schmalgraf
B″
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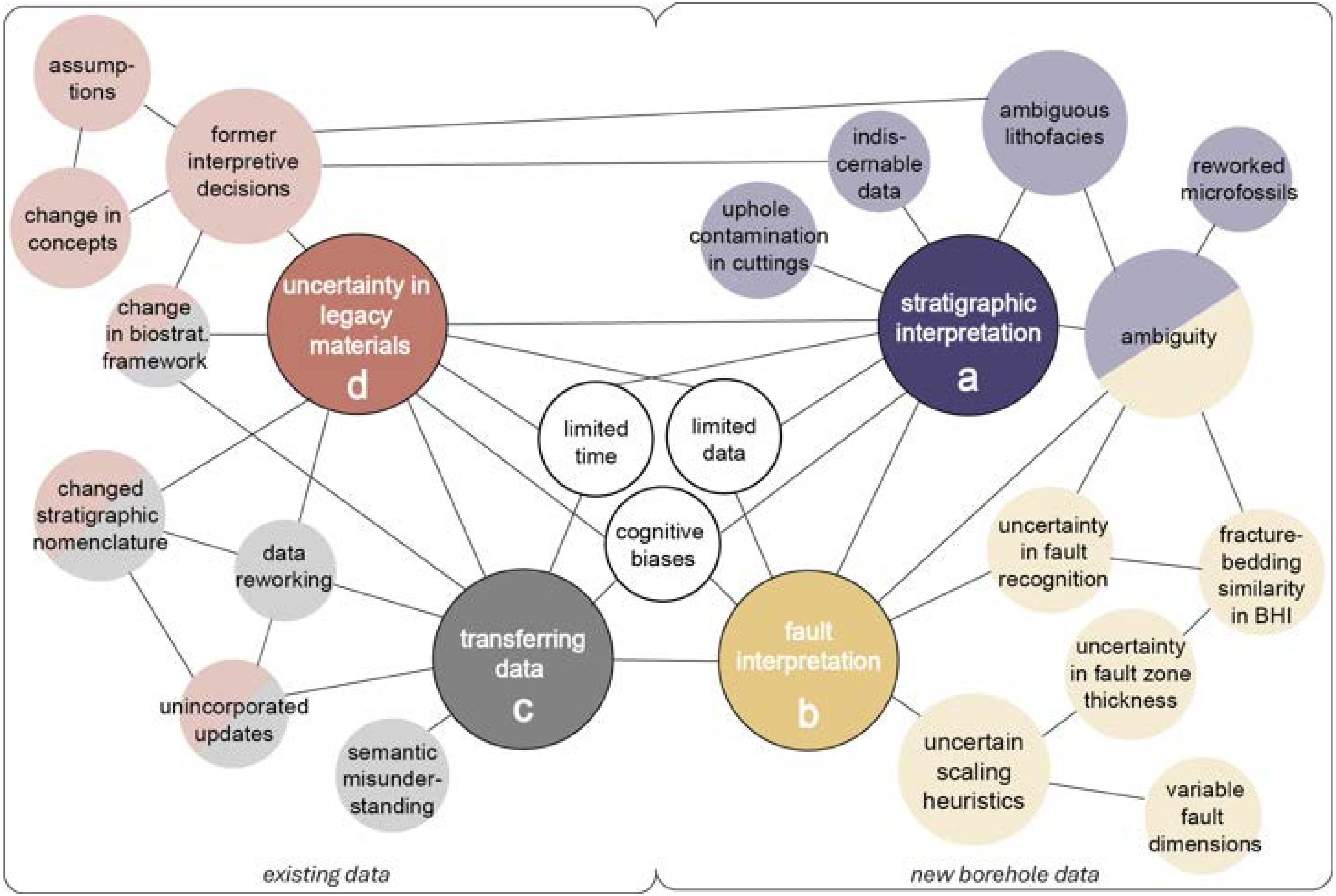
NAP
C′
Berneau
's Gravenvoeren
(108W0359)
C′
village


assump-tions
former interpretive decisions
change in concepts
change in biostrat. framework
uncertainty in legacy materials d
changed stratigraphic nomenclature
data reworking
unincorporated updates
semantic misunder-standing
transferring data c
limited time
limited data
cognitive biases
fault interpretation b
stratigraphic interpretation a
uphole contamination in cuttings
indis-cernable data
ambiguous lithofacies
reworked microfossils
ambiguity
uncertainty in fault recognition
fracture-bedding similarity in BHI
uncertainty in fault zone thickness
uncertain scaling heuristics
variable fault dimensions
existing data
new borehole data

‘Namurian’ shale

Silicified ‘Dinantian’ Limestone

There are several sources of uncertainty; what now?

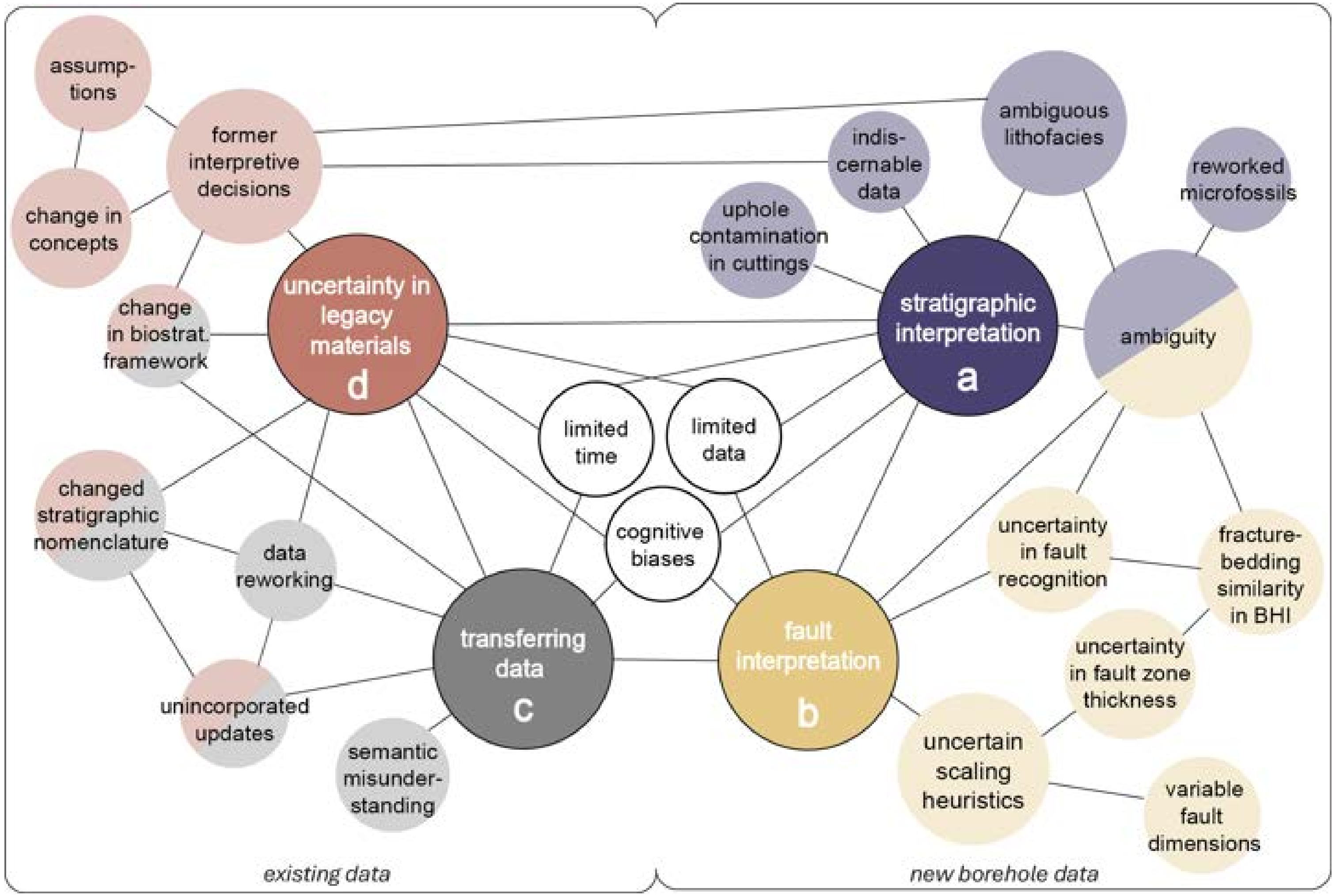
Necessity of validating legacy materials

Input uncertainty = Freq. of inconsistency x degree of inconsistency

How frequent do these causes occur?

Which type of uncertainty matters most?

What is their impact on geomodel design?



assump-tions
former interpretive decisions
change in concepts
change in biostrat. framework
uncertainty in legacy materials
d
changed stratigraphic nomenclature
data reworking
unincorporated updates
semantic misunder-standing
transferring data
c
limited time
limited data
cognitive biases
ambiguous lithofacies
indis-cernable data
uphole contamination in cuttings
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a
ambiguity
uncertainty in fault recognition
fracture-bedding similarity in BHI
uncertainty in fault zone thickness
fault interpretation
b
uncertain scaling heuristics
variable fault dimensions
existing data
new borehole data

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

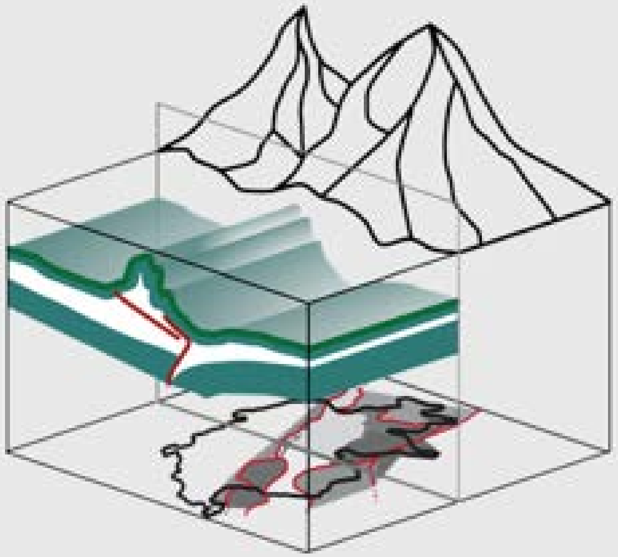
Bundesamt für Landestopografie swisstopo
Office fédéral de topographie swisstopo
Ufficio federale di topografia swisstopo
Uffizi federal da topografia swisstopo

Identifying uncertainties in 3D geological modelling in Alpine regions: challenges and open questions

Ferdinando Musso Piantelli[1], Sofia Brisson[2], and Eva Kurmann[1]

[1] *Federal Office of Topography swisstopo, Seftigenstrasse 264, 3084 Bern, Switzerland*

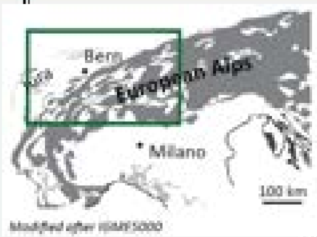
[2] *University of Lausanne, Institute of Earth Sciences (ISTE), Géopolis, 1022 Chavannes-près-Renens*



Exploring, Quantifying and Communicating Uncertainties in Geological Models

03.03.2026

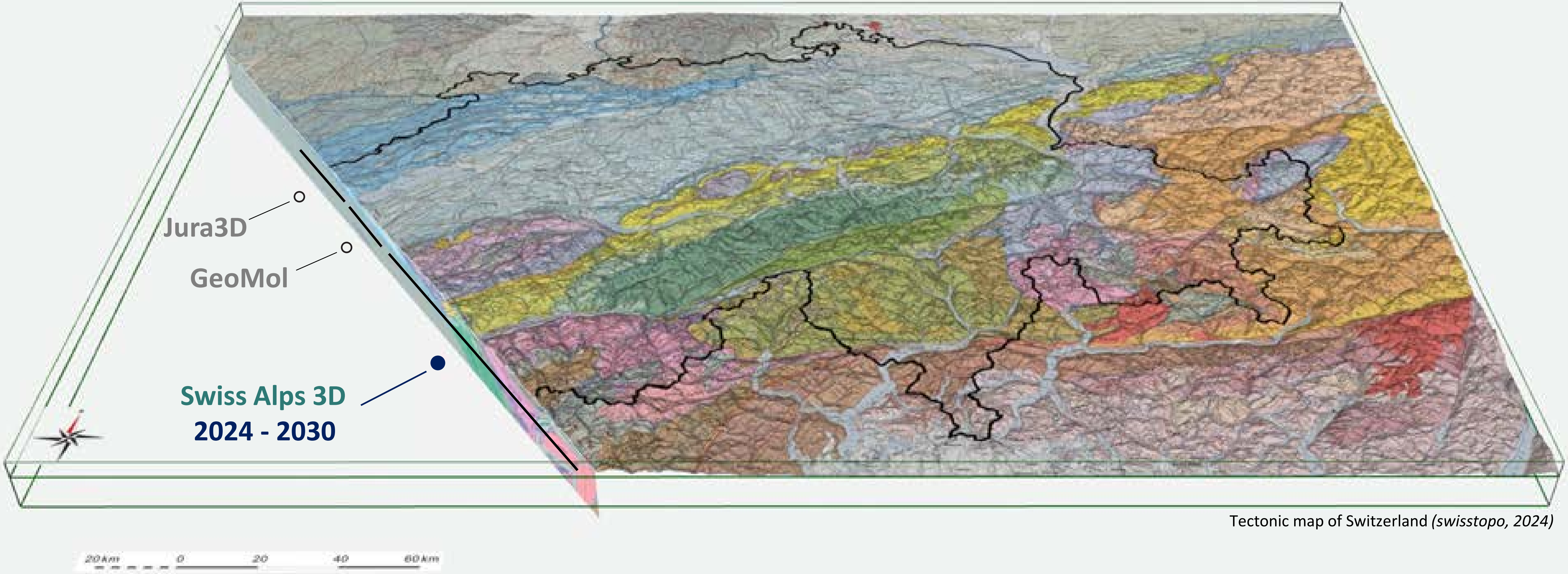
The NGM Program



Tectonic map of Switzerland *(swisstopo, 2024)*

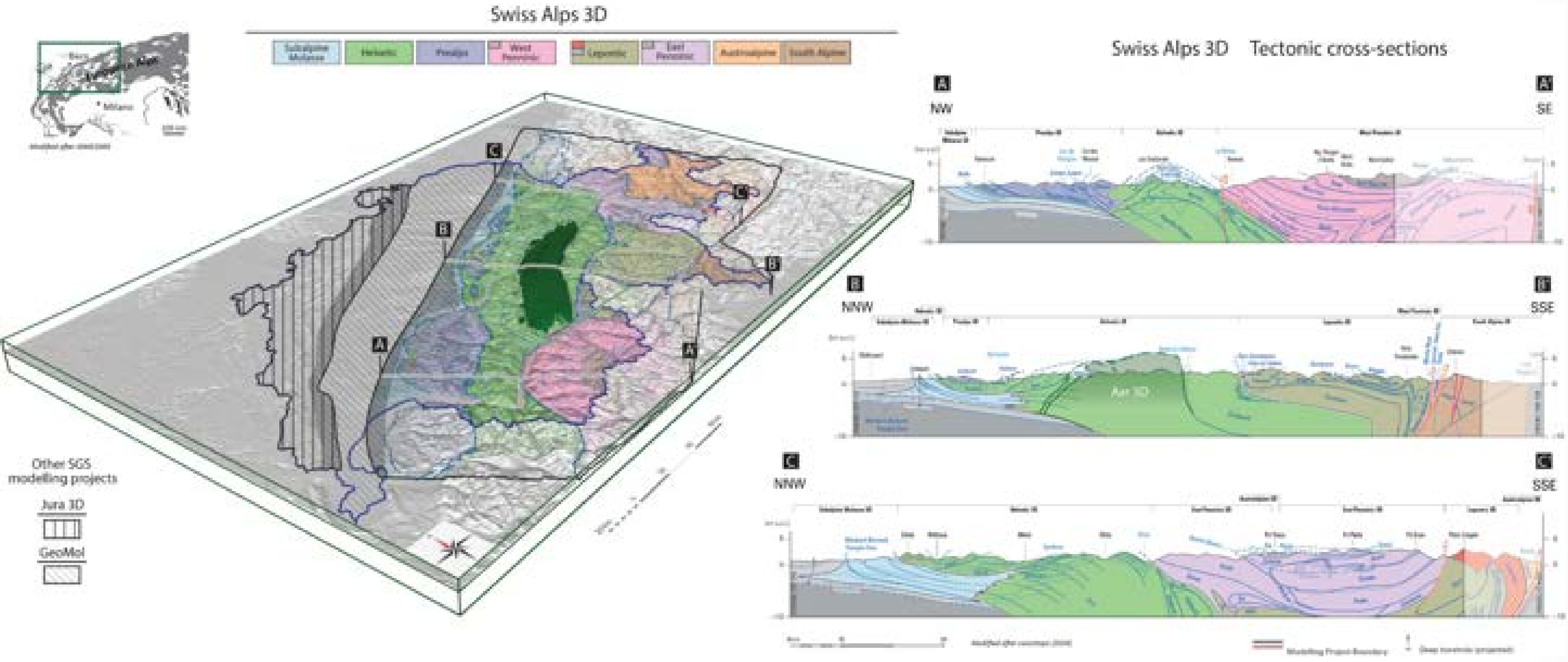
With the National Geological Models program, swisstopo has the objective to build harmonised geological models of Switzerland's surface and subsurface by 2030

Swiss Alps 3D (SA3D)



Tectonic map of Switzerland *(swisstopo, 2024)*

Swiss Alps 3D: 2024 - 2030



Key results

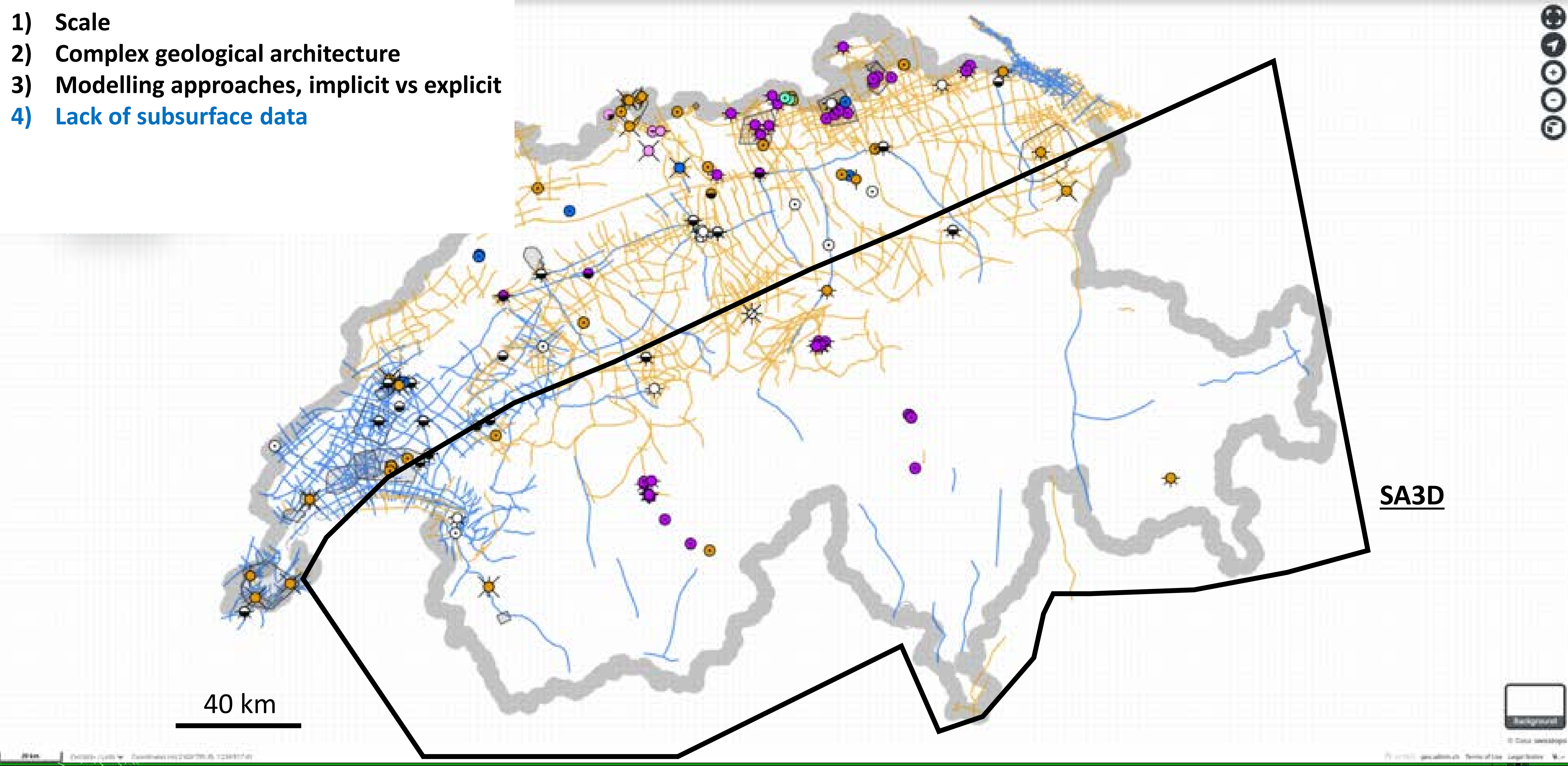
Development of:

- A consistent large-scale 3D geological model of the Swiss Alpine nappe stack subsurface.
- Key knowledge and digital visualization of the main lithostratigraphic and structural systems of the Alpine subsurface.
- A diverse community of experts in 3D modelling of deformed Alpine regions.

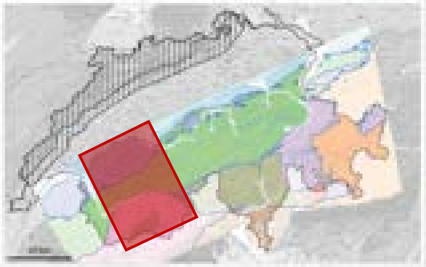
UNIL | Université de Lausanne · Universität Bern · SUPSI · ETH zürich · CY Cergy Paris Université · Université de Strasbourg

Challenges in Regional-Scale Modelling Projects in the Alps

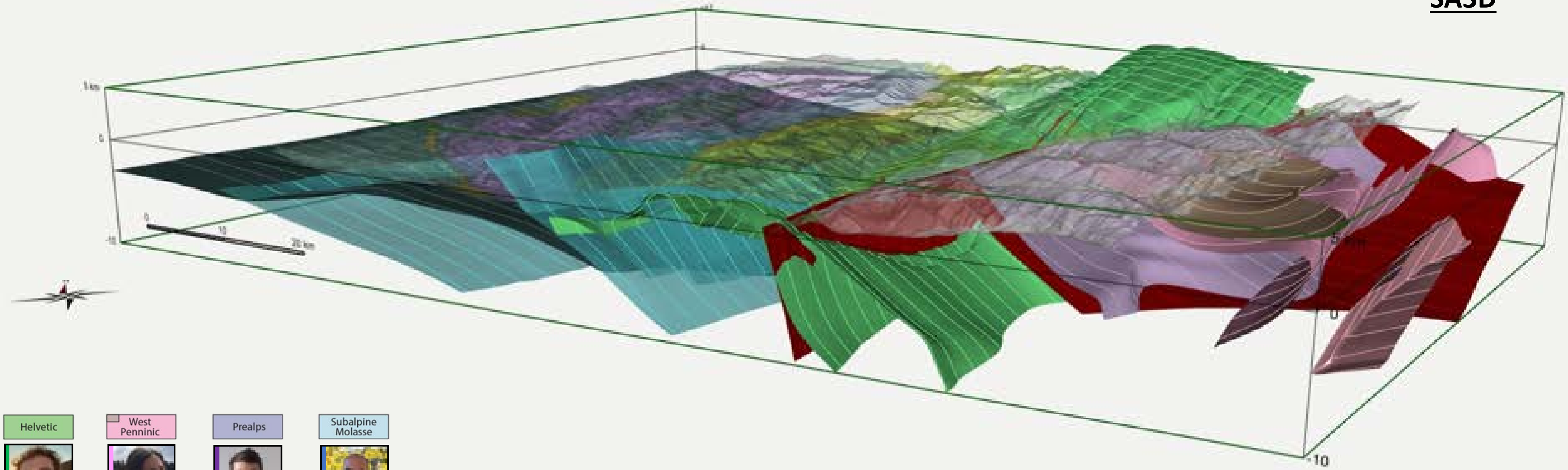
1) **Scale**
2) **Complex geological architecture**
3) **Modelling approaches, implicit vs explicit**
4) **Lack of subsurface data**

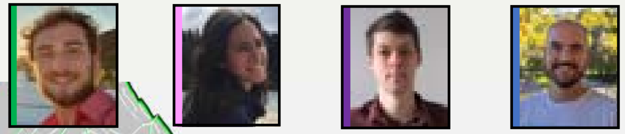


SA3D Models: First results



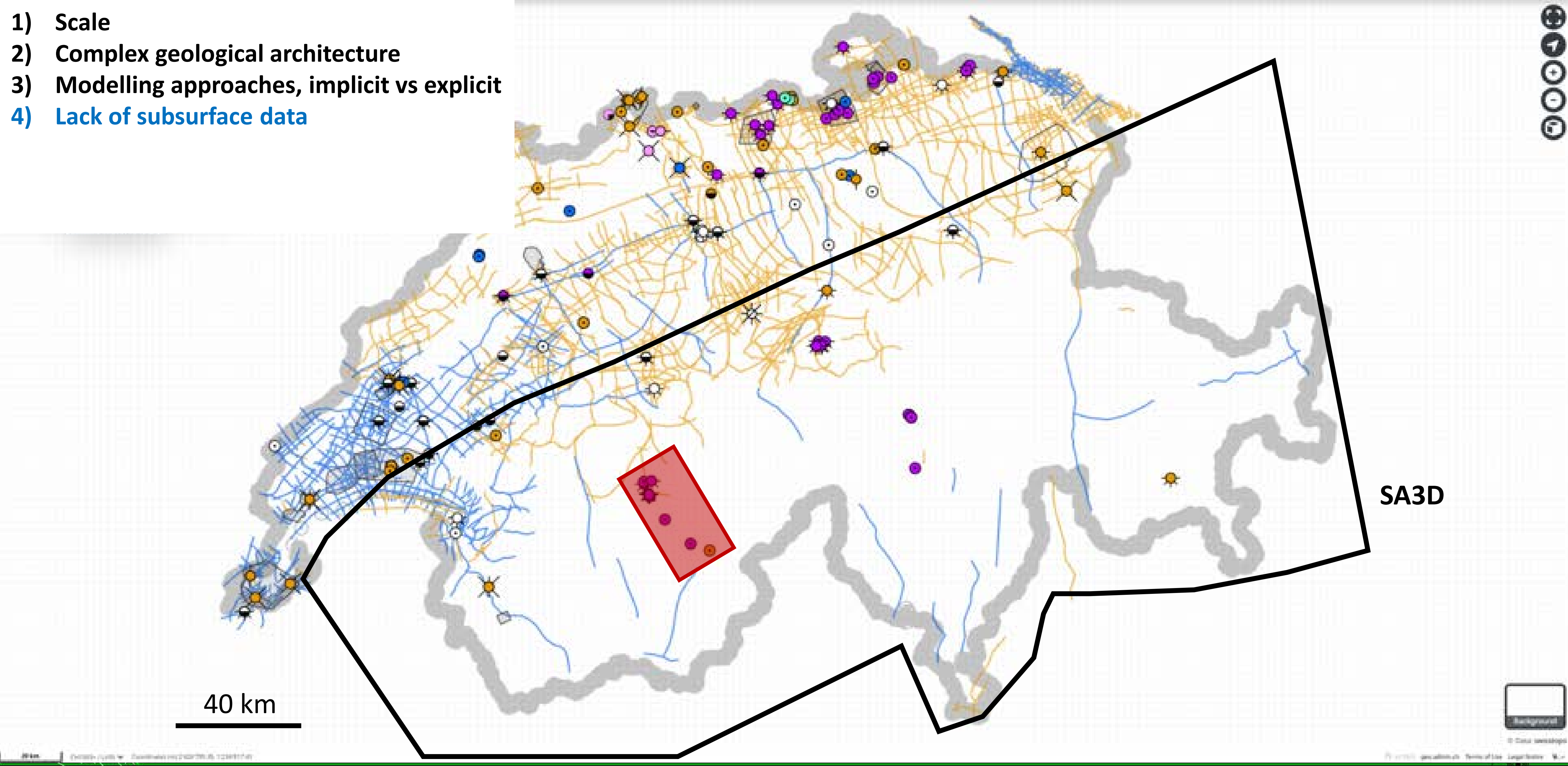
SA3D



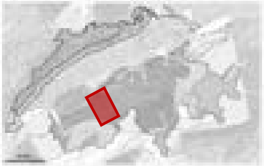


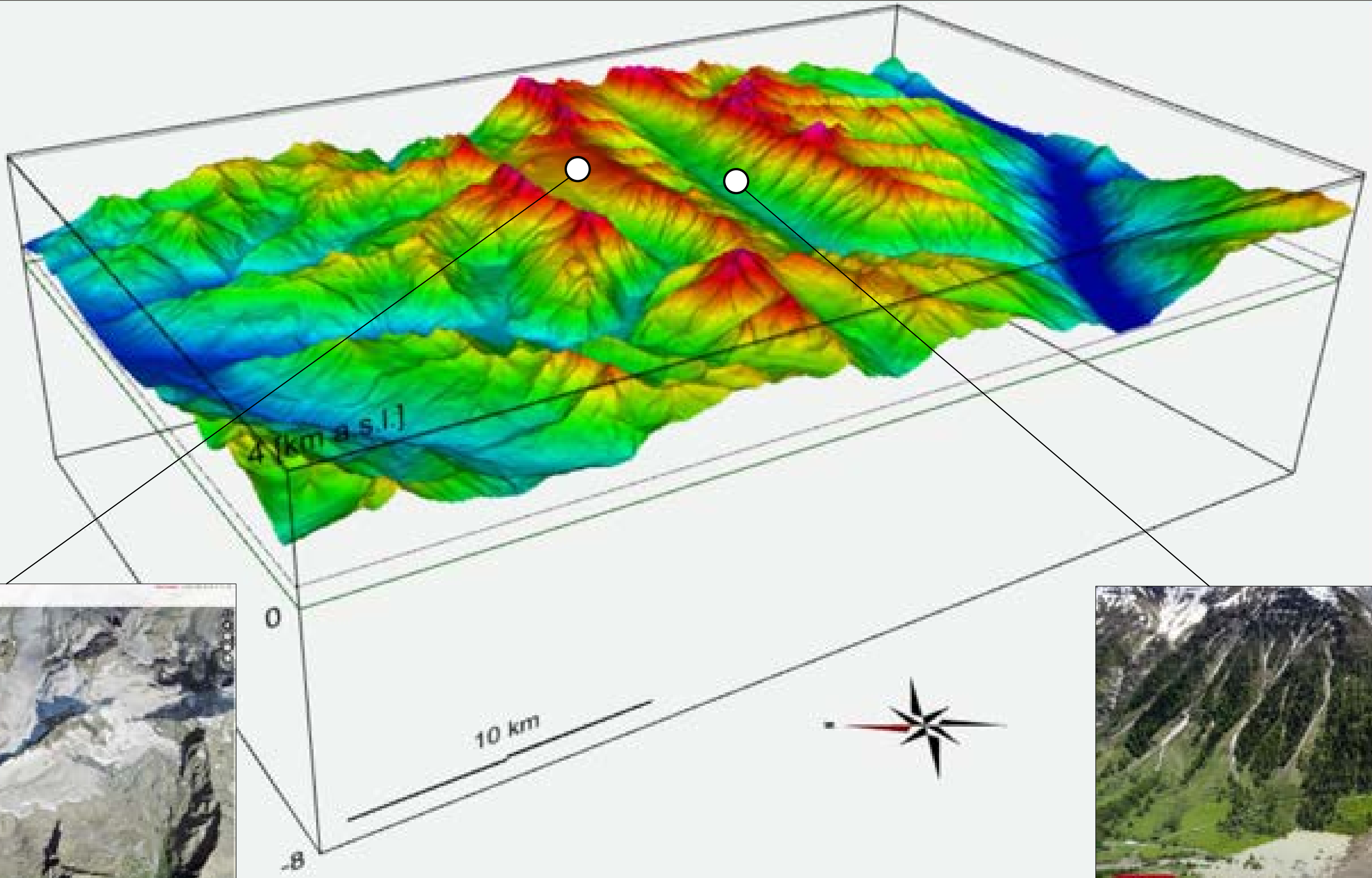
Matteo Furlan | Dr. Sofia Brisson | Sebastian Drvorderic | Dr. Philippos Garefalakis

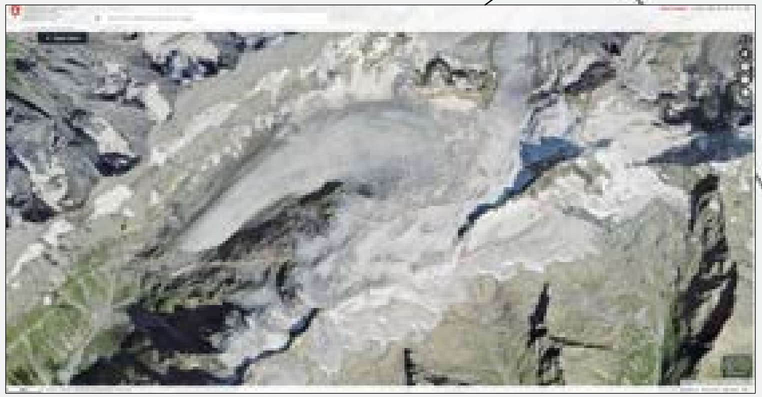
1) Scale
2) Complex geological architecture
3) Modelling approaches, implicit vs explicit
4) Lack of subsurface data



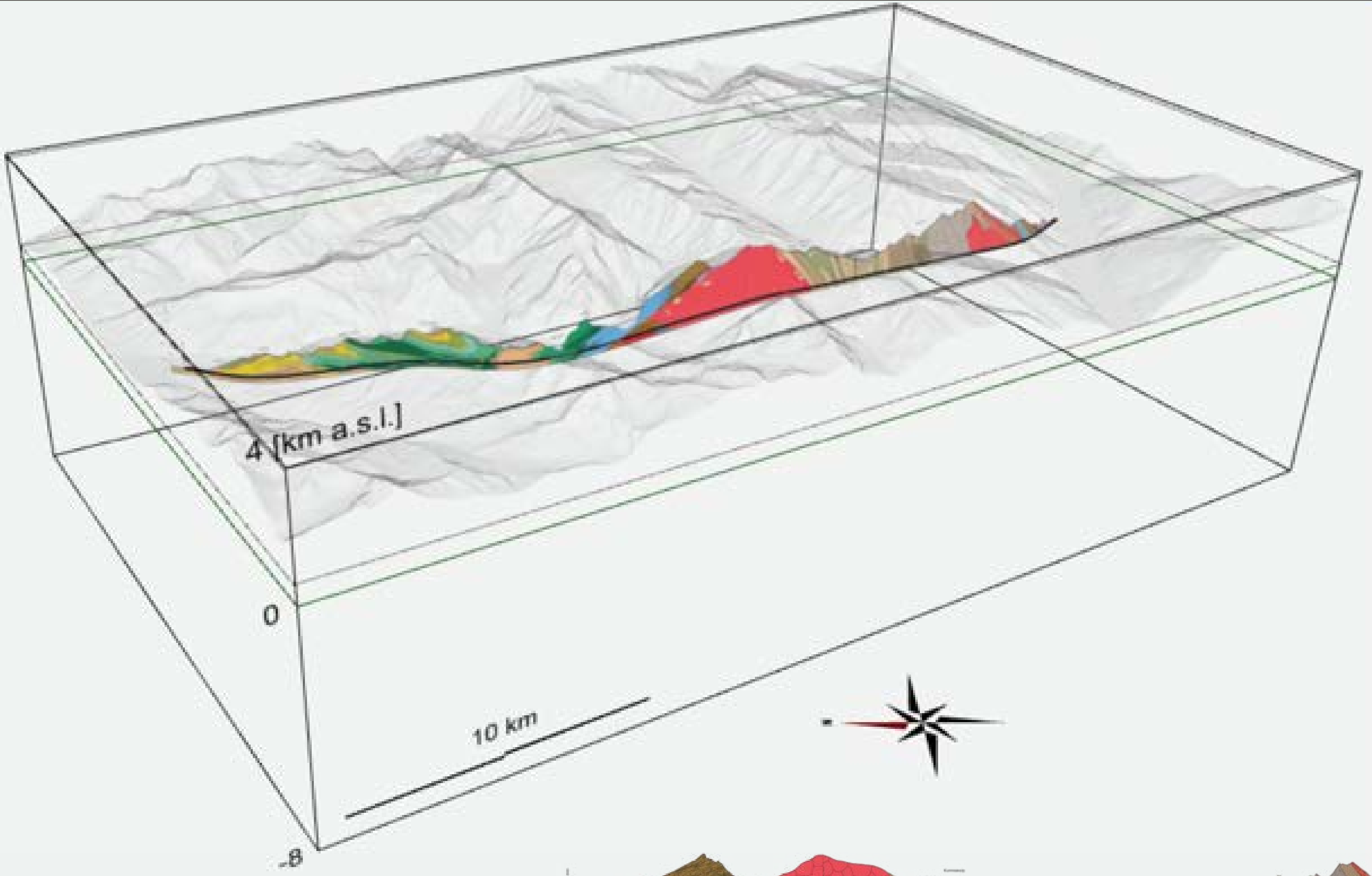
SA3D Models

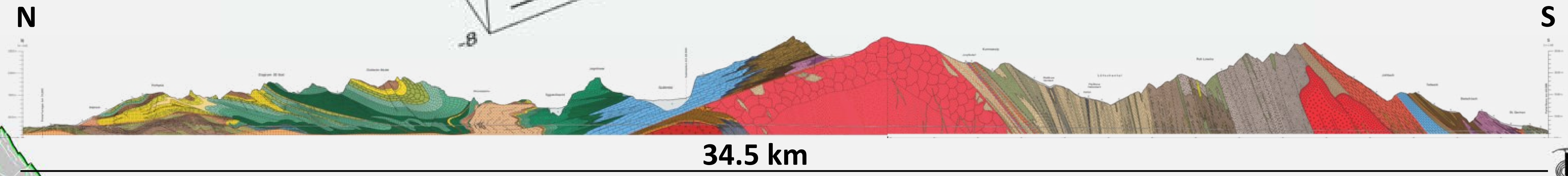




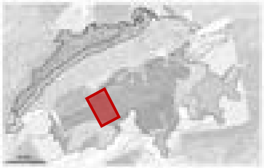


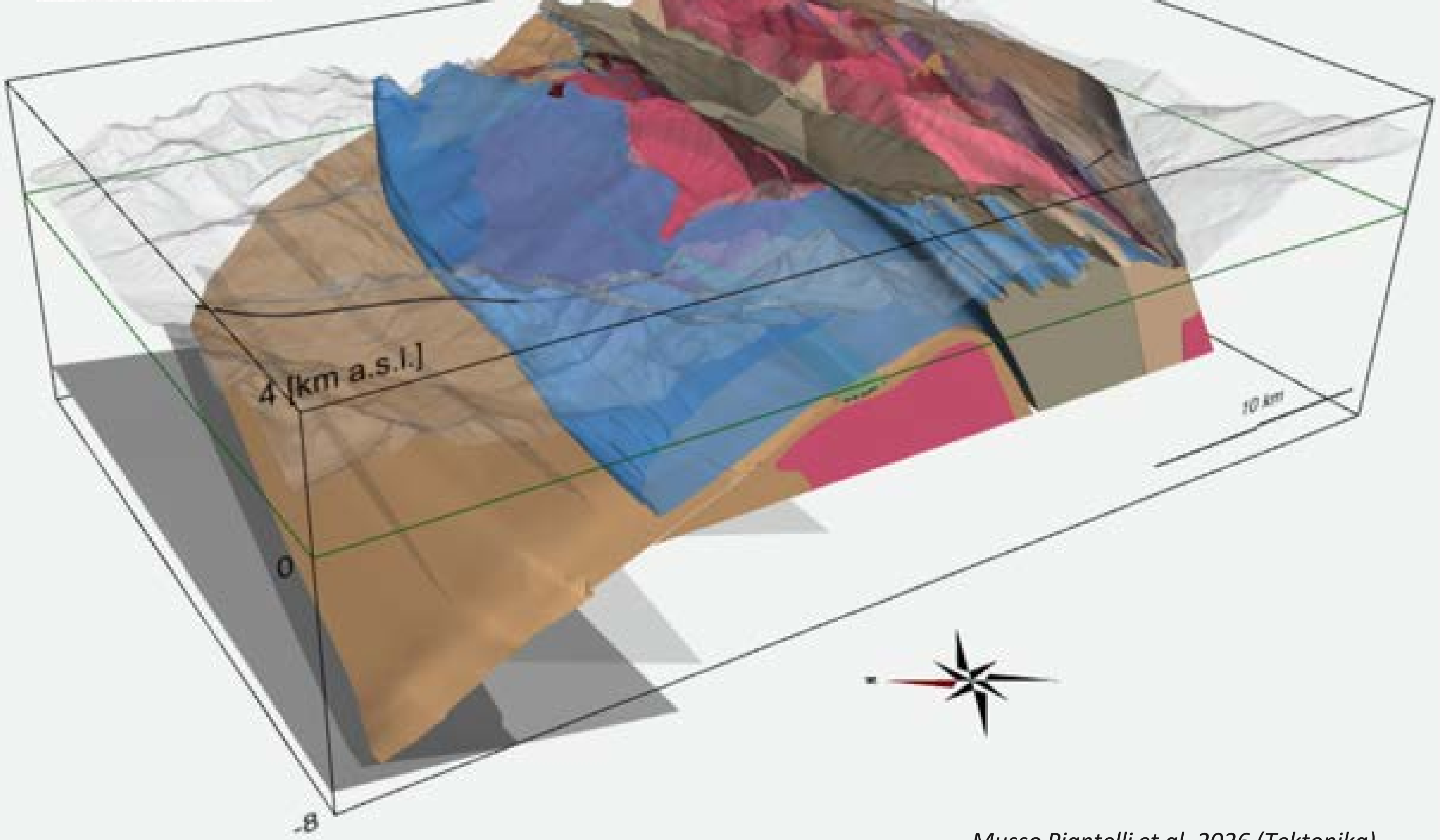
SA3D Models





SA3D Models





Musso Piantelli et al. 2026 (Tektonika)

Aar Massif

- Doldenhorn nappe
- Molasse top-basement
- Aar massif basal thrust

Plutonic rocks

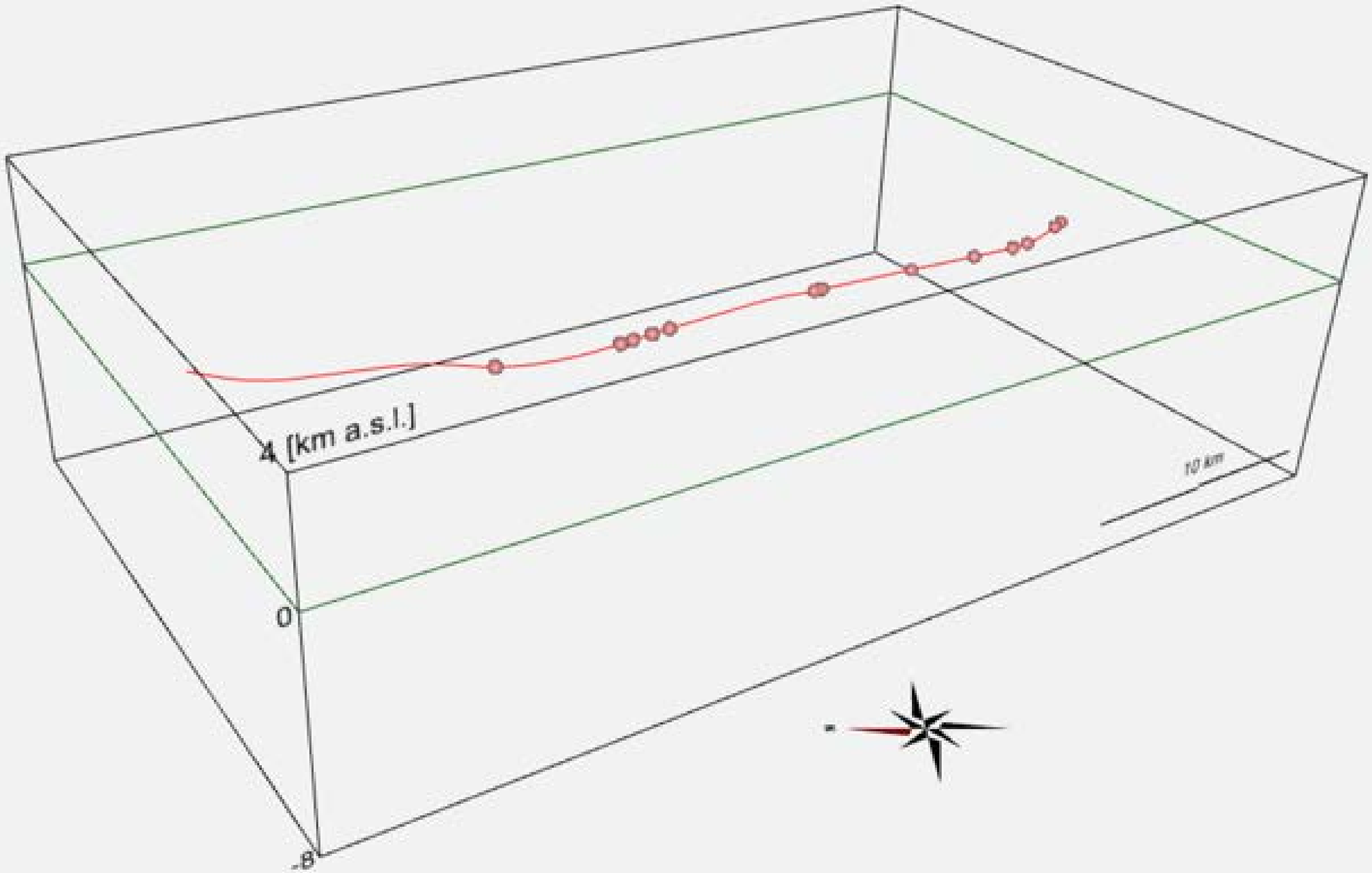
- Haslital Group
- Fruttstock Group
- Rötfirn Group

Permo-Carboniferous rocks

- Wenden- Lötschental-Maderanertal Zone

Pre-Variscan basement (northern units)

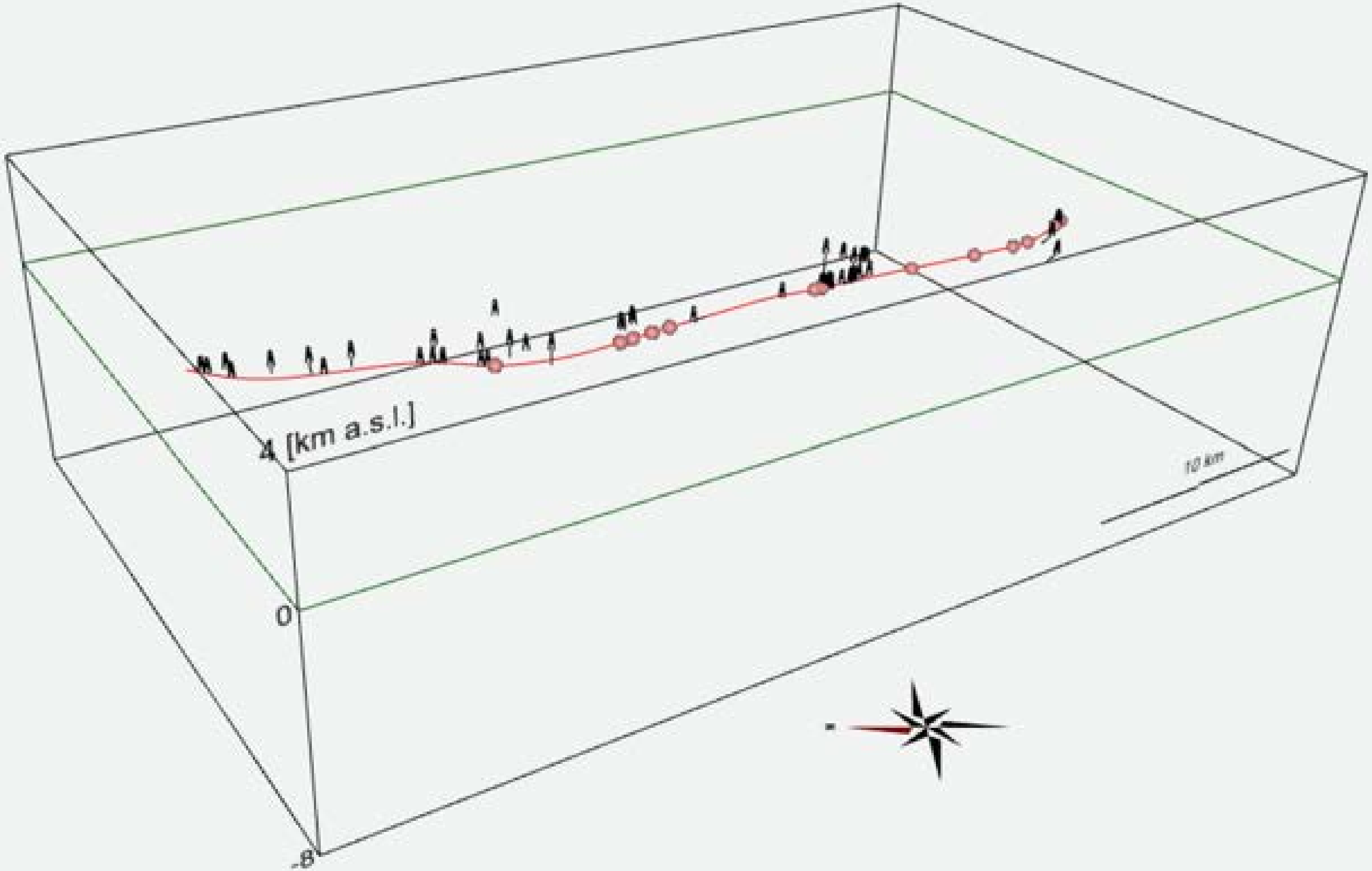
- Innertkirchen-Lauterbrunnen Zone
- Erstfeld Zone
- Ferden-Guttannen Zone



Input Data Sources

Tunnel data

- Contact / Structure (m accuracy)

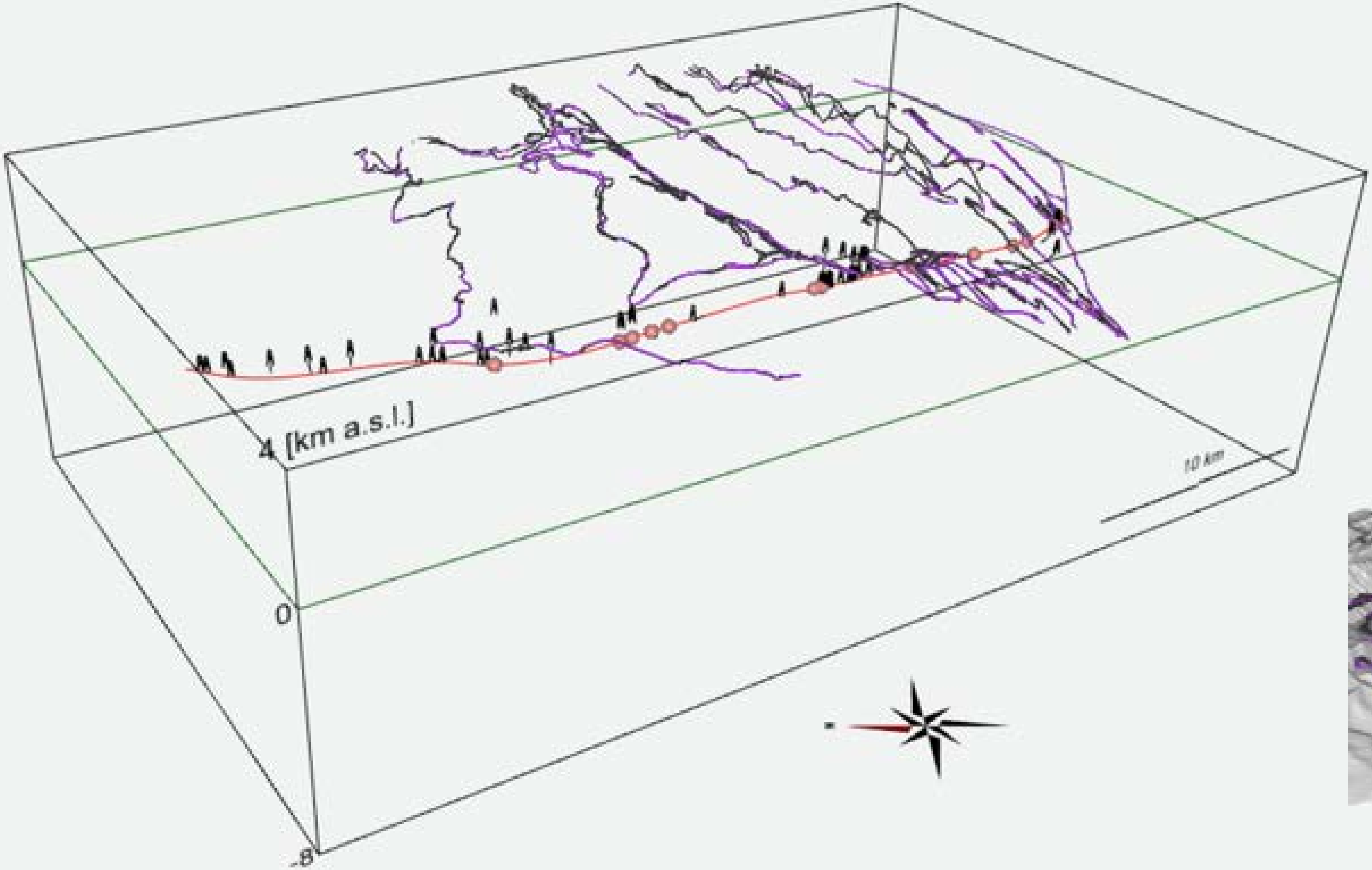


Input Data Sources

Tunnel data

Boreholes

Contact / Structure (m accuracy)



Input Data Sources

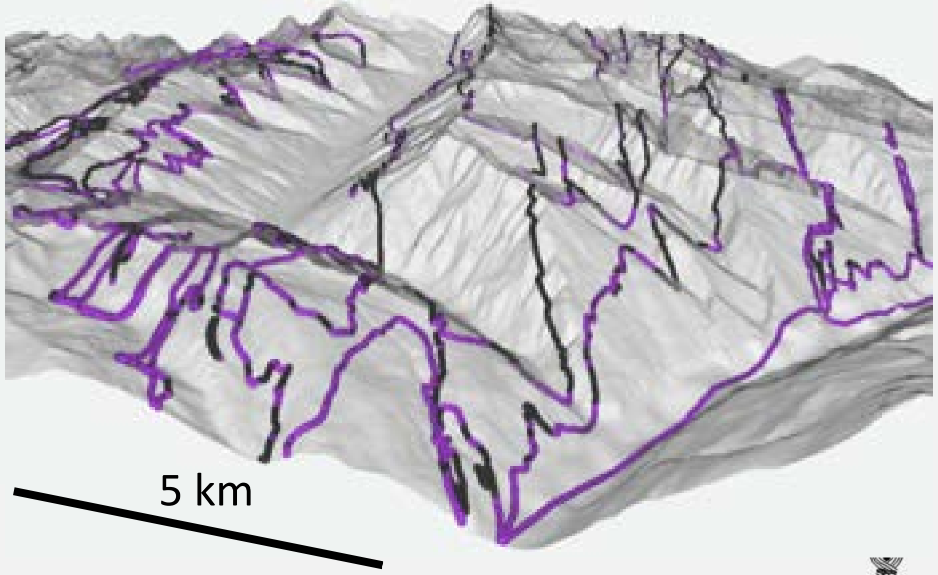
Tunnel data

Boreholes

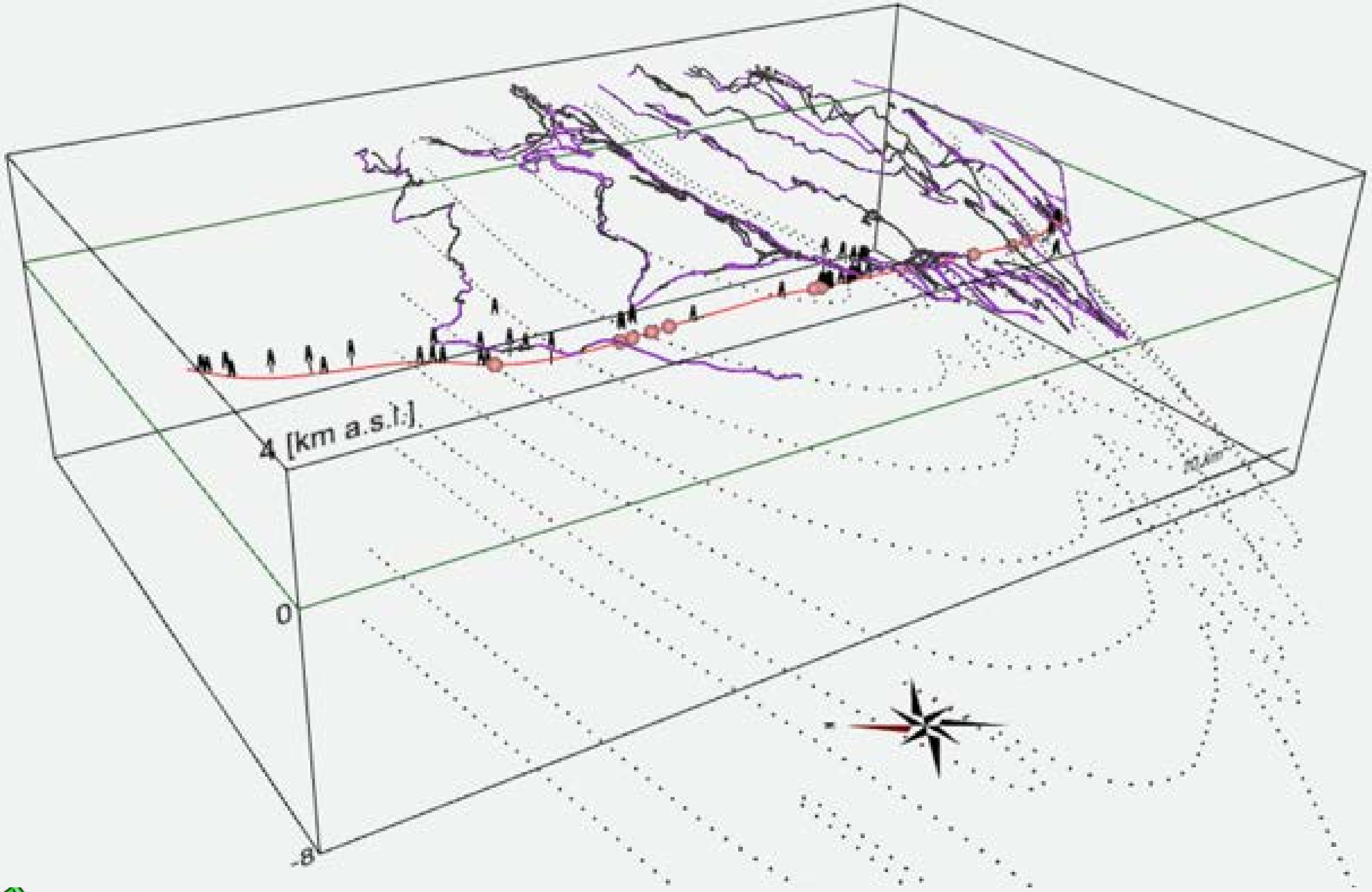
Geological map

Structural measurements

- Outcropping (<25 m accuracy)
- Below Quat.- Glaciers (>25 m accuracy)



Input Data



Input Data Sources

Tunnel data

Boreholes

Geological map

Structural measurements

Seismic data

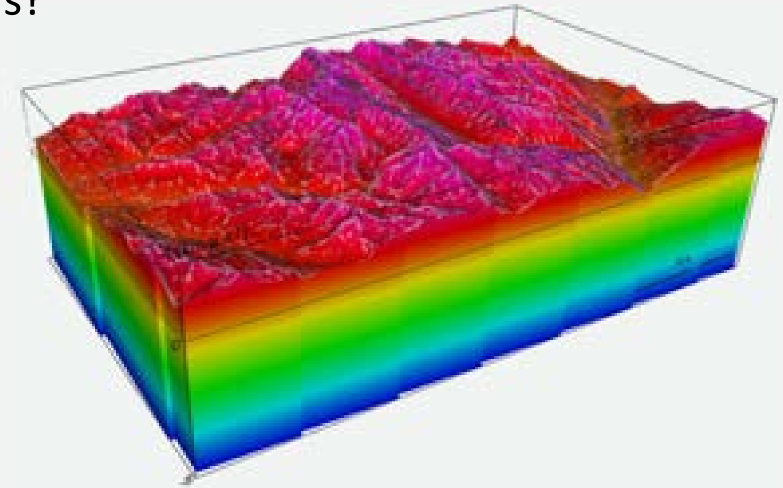
- Low accuracy >500m

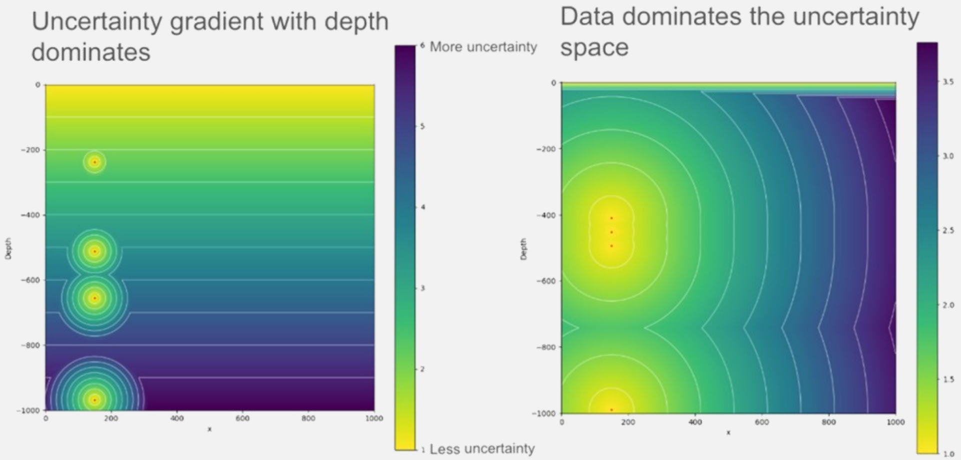
Key Questions

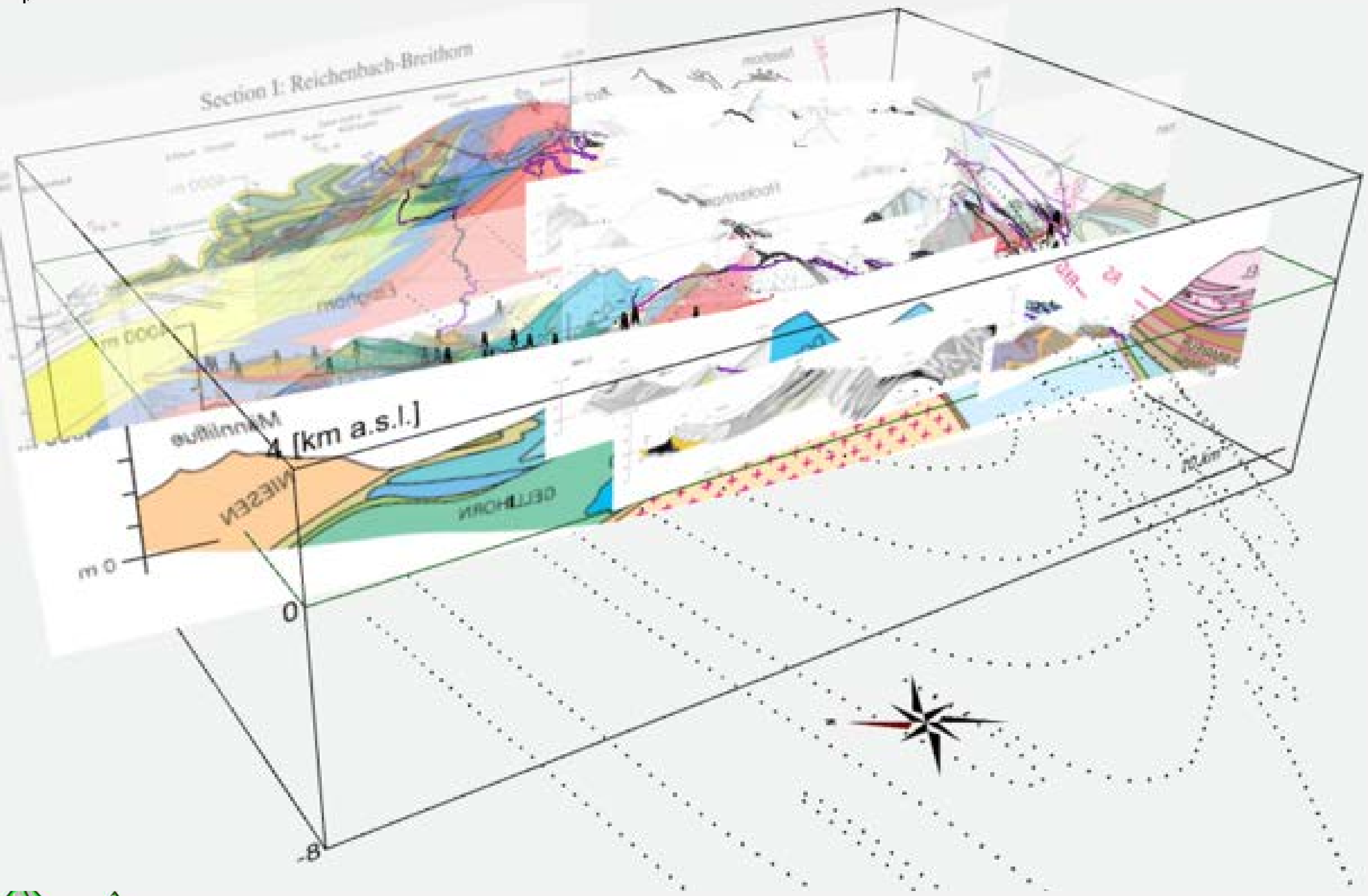
1. Applicability of Uncertainty Quantification Methods
How applicable are existing uncertainty quantification methods to this type of models?
(large scale – geological setting – sparse data)

2. Uncertainty Propagation
How does uncertainty in individual data points (x, y, z) propagate into the full 3D model?

3. Distance–Uncertainty Relationship
Is there a universal relationship between distance and uncertainty?







Input Data Sources

Tunnel data

Boreholes

Geological map

Structural measurements

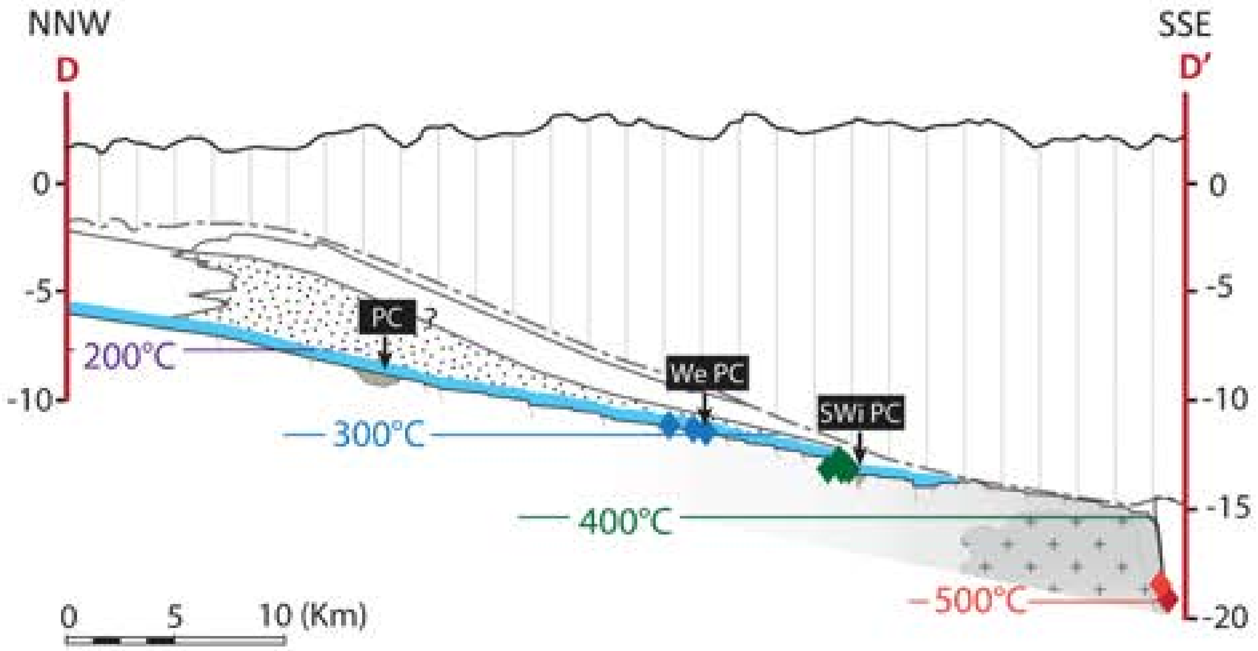
Seismic data

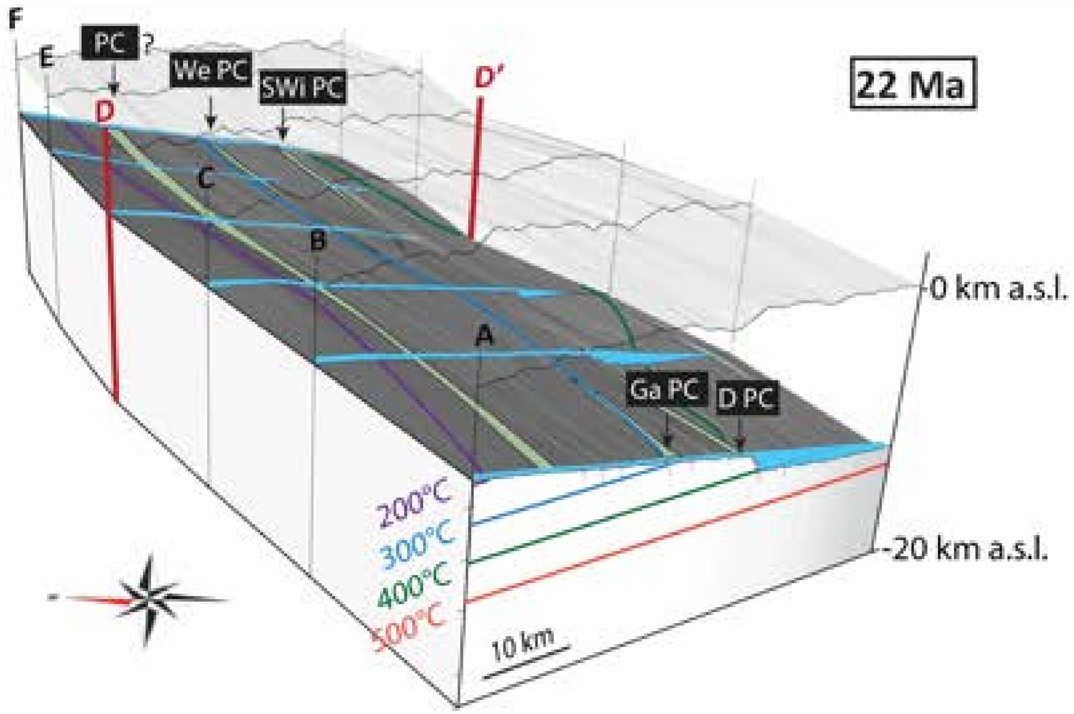
Geological cross-sections

Published literature

Model validation: e.g. 4D Reconstruction

Cross section view | **3D view**





Musso Piantelli et al. 2026 (Tektonika)

Penninic/Austroalpine
Undifferenciated

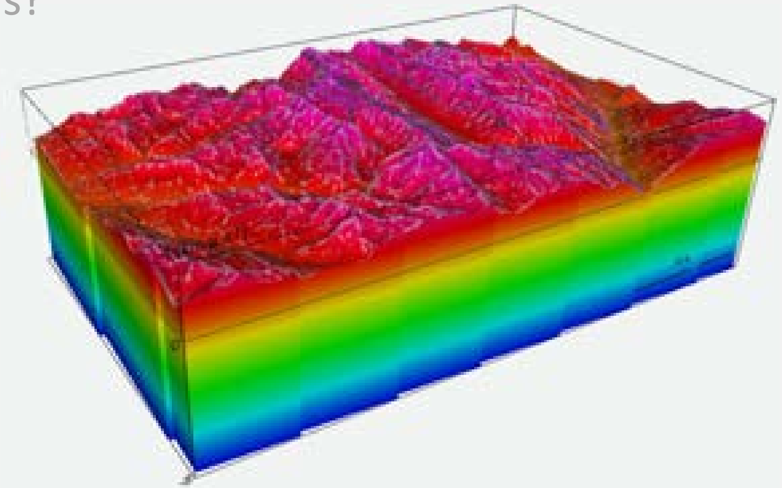
Helvetic
Cover nappes

Aar Massif
Paleogene sediments
Para-/Autochtonous cover
Permo-Carb. Zones (PC)
Basement Units

Structural elements
Strike-slip faults
Thrust faults
Reverse faults
Rhone-Simplon fault sys.

Key Questions

1. Applicability of Uncertainty Quantification Methods
How applicable are existing uncertainty quantification methods to this type of models?
(large scale – geological setting – sparse data)



2. Uncertainty Propagation
How does uncertainty in individual data points (x, y, z) propagate into the full 3D model?

3. Distance–Uncertainty Relationship
Is there a universal relationship between distance and uncertainty?

4. Integrating Prior Geological Knowledge
How can geological cross-sections and existing literature be embedded into uncertainty quantification?

5. Quantifying model Validation
How can model-specific validation (e.g., restoration) be incorporated and weighted in uncertainty quantification?