Scientific and technological integration in geothermal exploration:

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Case study: The Den Haag Geothermal District Heating Project - 3-D Models for Temperature Prediction and Reservoir Characterization

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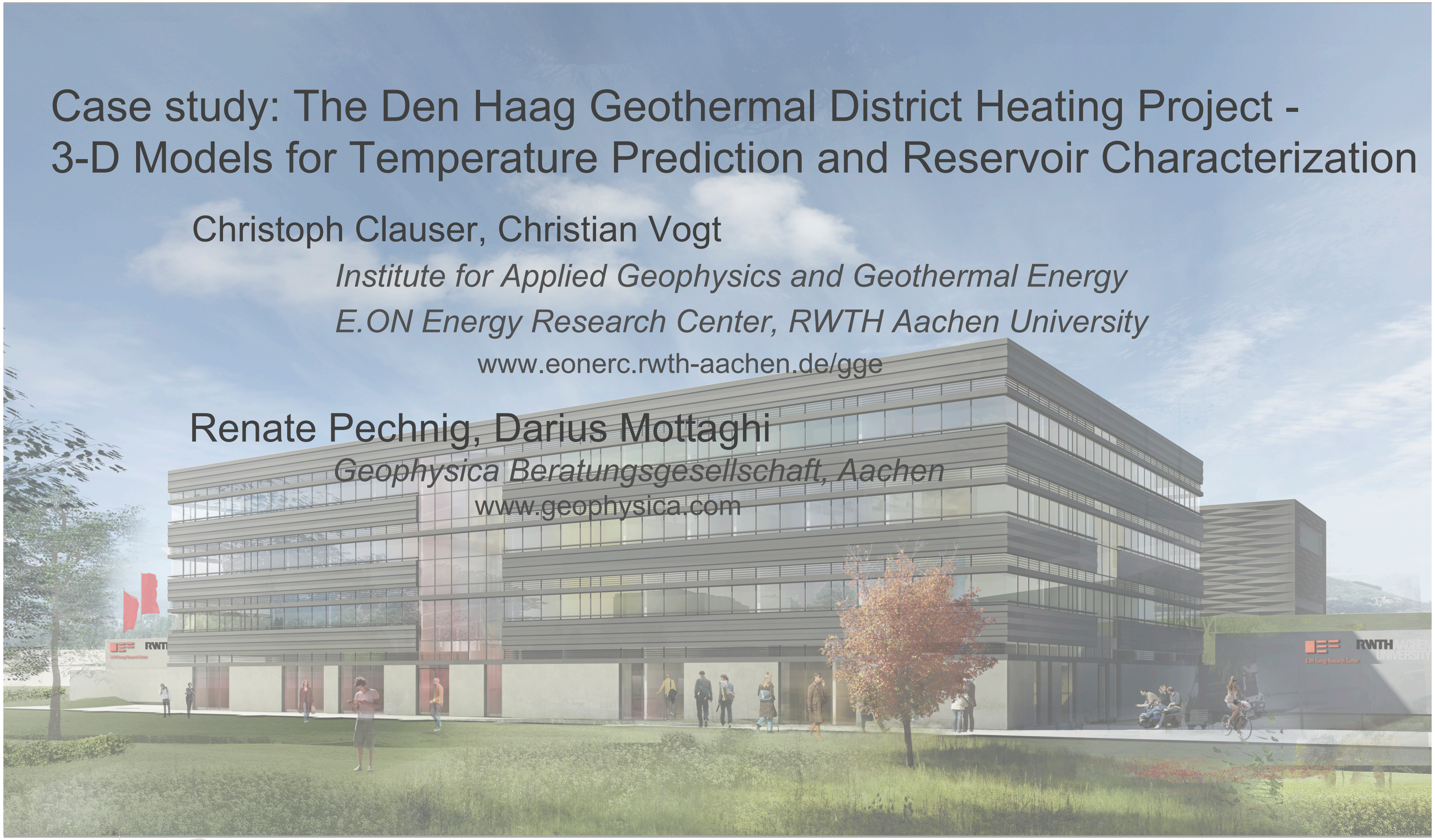

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Background

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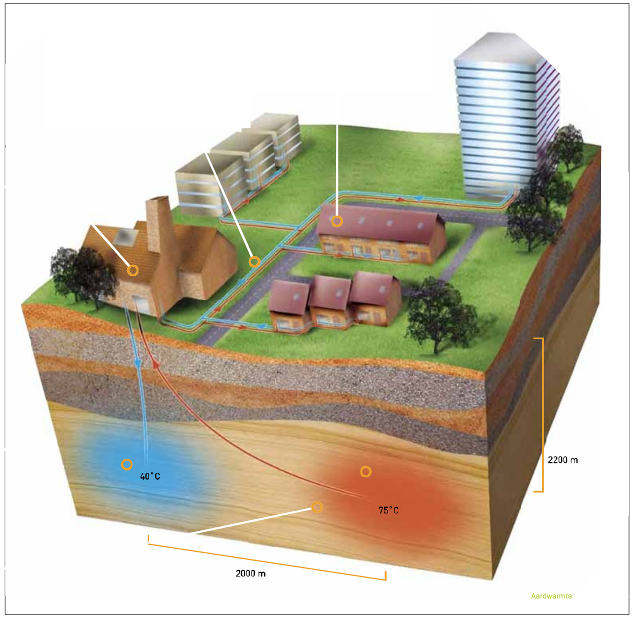
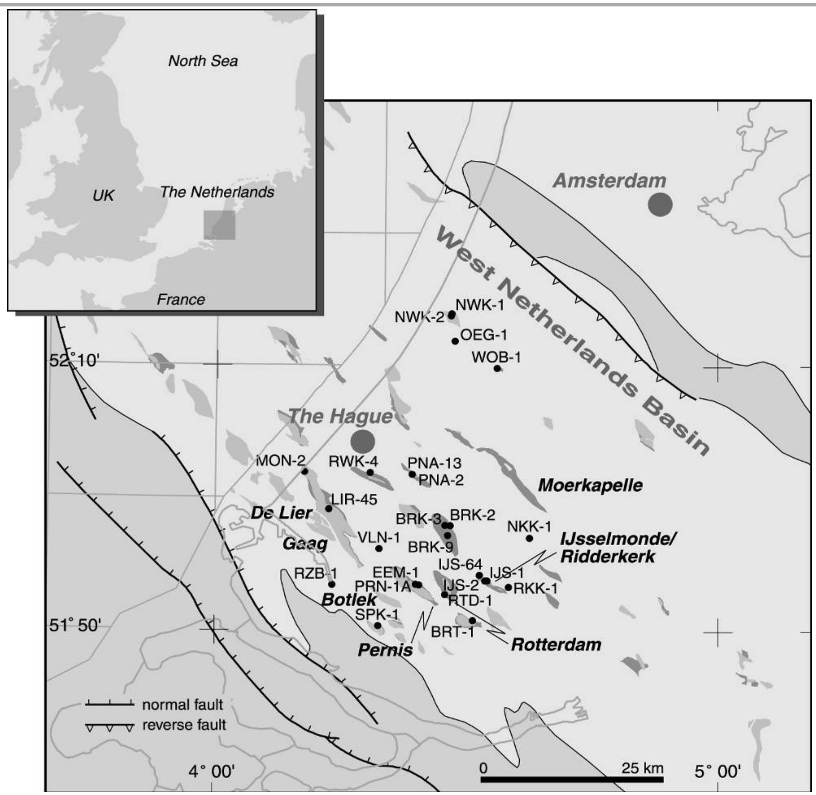
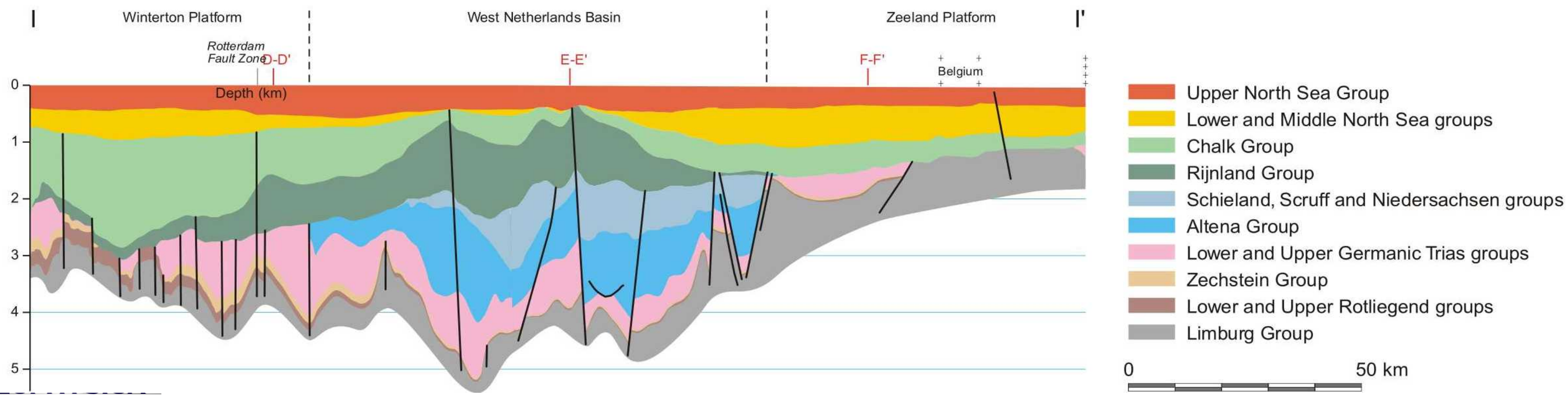
- Deep Geothermal Installation - Doublet System
  - Heating for 6000 houses in the "Den Haag Zuidwest" district
    - Investors: Eneco Energy, E.ON Benelux, City of Den Haag and three housing companies: Vestia, Staedion, Haagwonen
  - Requirements for geothermal doublet:
    - Thermal power: ~ 5MW_{th}
    - Well depth: ~ 2200 m, deep reservoirs: Rijswijk and Delft sands
    - Production temperature: ~ 75°C
    - Flow rate: ~ 150 m³/h



Geological Setting



- West-Netherlands Basin
  - Late Jurassic/Early Cretaceous basin system.
  - Rifting formed half graben systems, filled with fluviatile sediments. Rijswijk, Berkel, & Delft sandstones: prominent reservoir rocks.
  - basin inverted during late Cretaceous, creating horst and graben structures. Accumulation of oil and gas in anticlines.



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Well Locations

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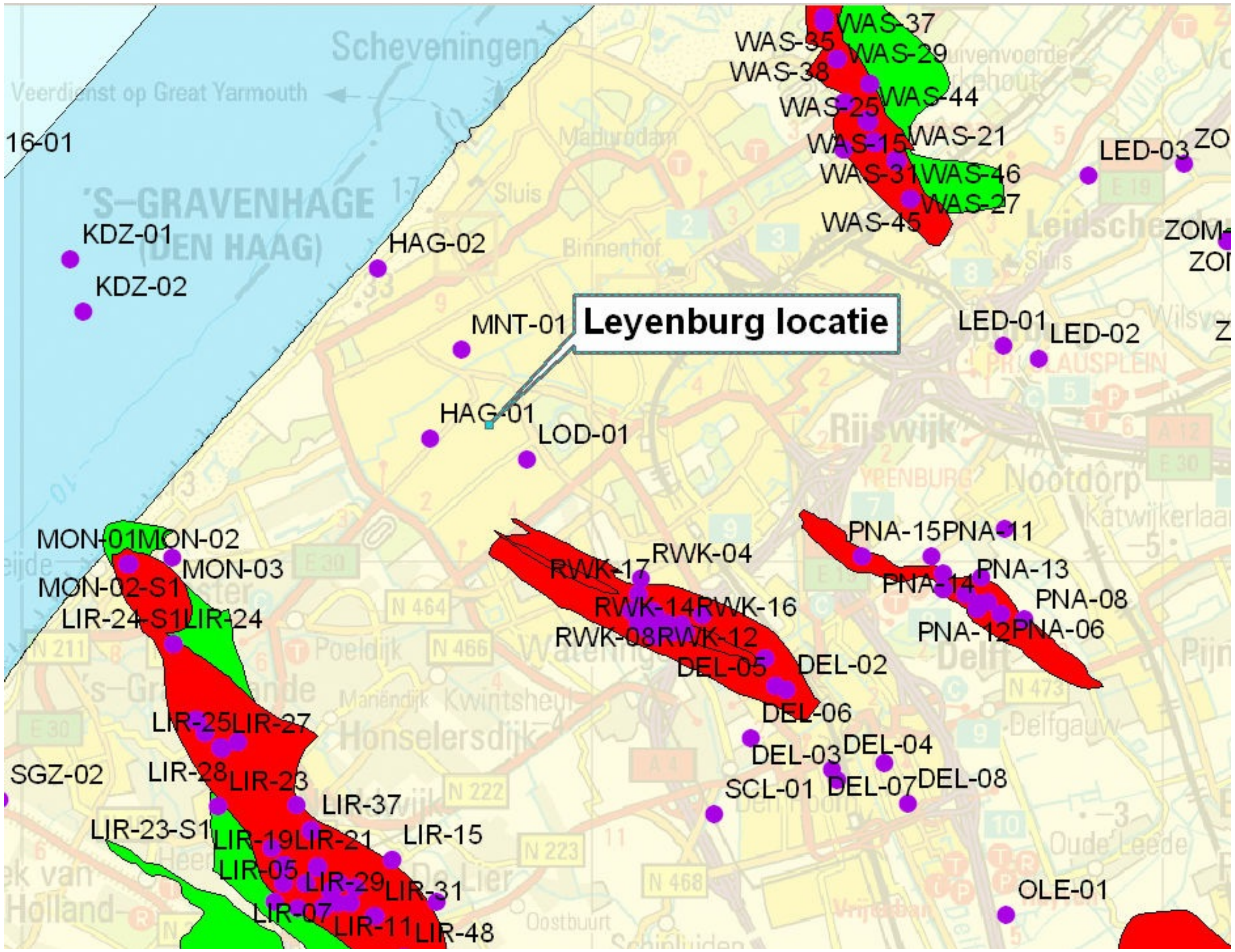
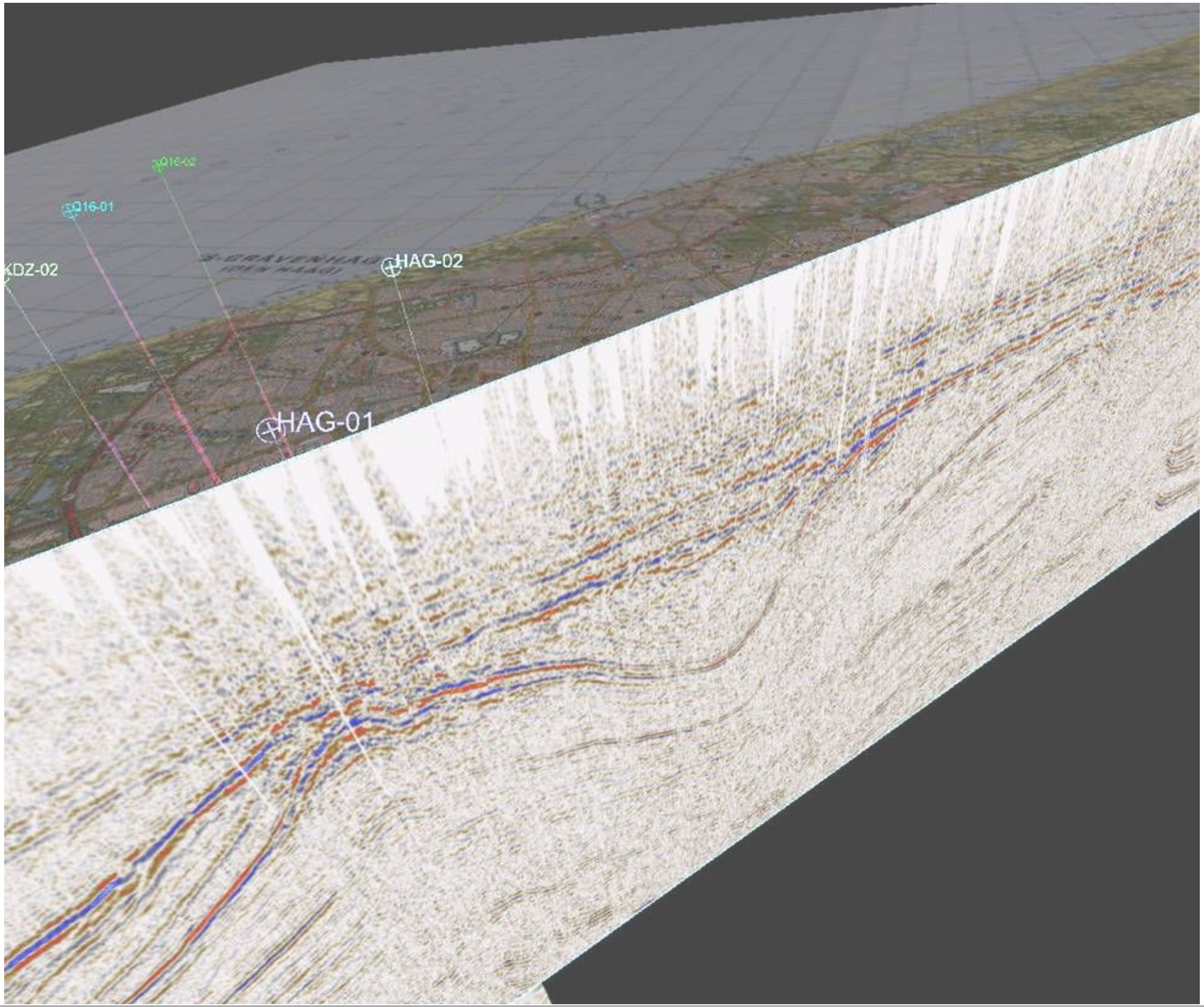
- Exploration wells around target region:
  - oil and gas borholes near anticlines
  - geothermal drill target in syncline, little information.



Seismic data

- Cross section of 3-D seismics with exploration wells HAG-01 and HAG-02 near anticline



Scientific and technological integration

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- planning a geothermal doublet requires detailed information on geology and thermal regime
  - *well known*
    - geology and structures from oil and gas exploration - seismics and drilling
  - *less well known*
    - temperature field – only from sparse BHT data

- task: fill in missing and integrate existing information into 3-D static and dynamic reservoir models for predicting
  - steady-state temperature at reservoir depth making allowance for structural and geological heterogeneity of the subsurface
  - transient variation of production temperature during operation period

Work plan

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- Asses steady-state thermal regime
  - acquire and compile basic data sets
  - Measure thermal property on drill cuttings (for lack of core) in the laboratory
  - integrate borehole logs and laboratory data for predicting thermophysical properties of stratigraphic units
  - set up and test static 3-D numerical model (25 km × 25 km × 5 km)
  - perform predictive simulations

Key Well Selection

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Boring	Yr	Analogue		Digital					Coredata
		SP	res	gr	dt	rhob	nphi	Res	
BRK-03	1955								
DEL-08	1994			gr	dt	rhob	nphi	Res	
HAG-01	1954	SP	Res						KNNSR
HAG-02	1955	SP	Res						KNNSR
KDZ-02	1986			gr	dt	rhob	nphi	Res	
LED-01	1956								KNNSR
LIR-45	1982			gr	dt	rhob	nphi	Res	KNNSR
MED-01	1958								KNNSR
MON-01	1956								KNNSR
MON-02	1982			gr	dt	rhob	nphi	Res	KNNSR
MON-03	1990			gr	dt	rhob	nphi	Res	
PNA-02	1955								KNNSR, SLDND
PNA-03	1955								KNNSR
PNA-04-S2	1981			gr		rhob	nphi		
PNA-07	1957								KNNSR
PNA-10	1957								KNNSR
PNA-14	1985			gr	dt	rhob	nphi		
PNA-15	1994			gr		rhob	nphi		
RTD-01	1984								SLDND
RWK-01	1953								KNNSR, SLDND
RWK-02	1953								KNNSR
RWK-03	1953								KNNSR
RWK-04	1954								KNNSR
RWK-05	1954								KNNSR
RWK-06	1954								KNNSR
RWK-07	1954								KNNSR
RWK-08	1955								KNNSR
RWK-09	1955								KNNSR
RWK-11	1956								KNNSR
RWK-14	1956								KNNSR
RWK-18	1954			gr	dt				
Q13-07-S2	1990			gr	dt	rhob	nphi	Res	
Q14-01	1984								KNNSR
Q16-01	1970			gr	dt			Res	KNNSR
Q16-02	1978			gr	dt	rhob	nphi	Res	
WAS-01	1956								KNNSR
WAS-02	1957								KNNSR
WAS-05	1957								KNNSR
WAS-23	1960			gr	dt	rhob	nphi	Res	KNNSR

- lists of wells and availabile logging data and core material.
- cuttings available at repository in Zeist from
  - Q16-01
  - **Q16-02**
  - **KDZ-02**
  - WAS-23
  - MON-02
- little cutting available (< 50 g per bag) from well MON-02

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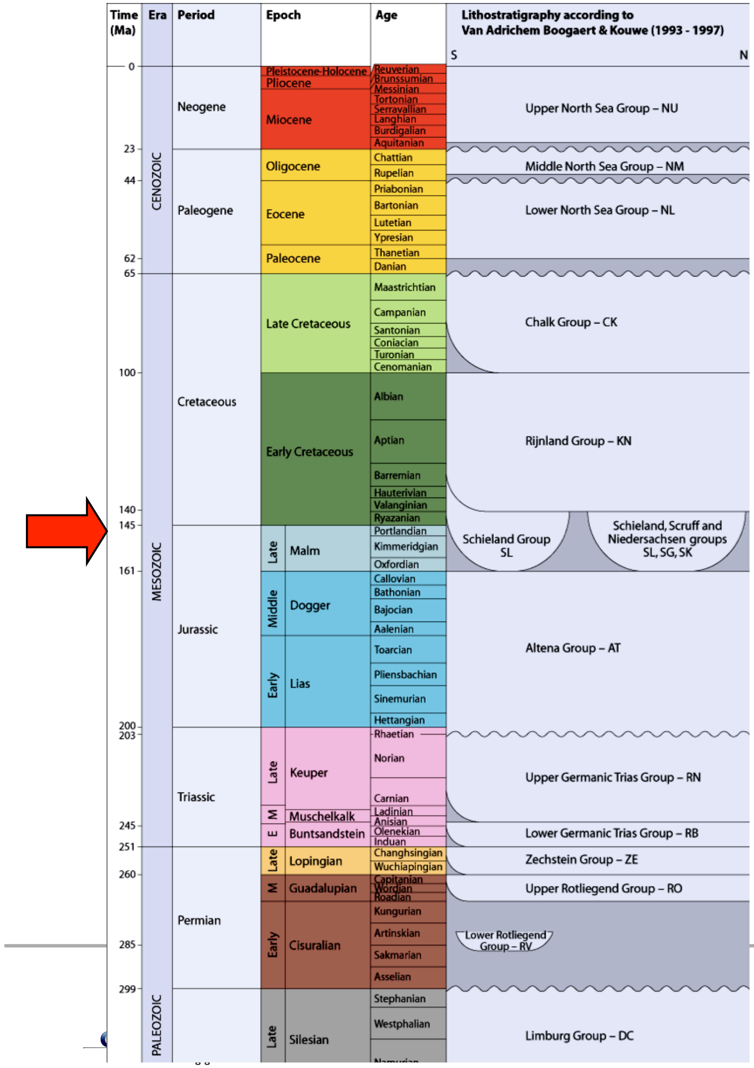
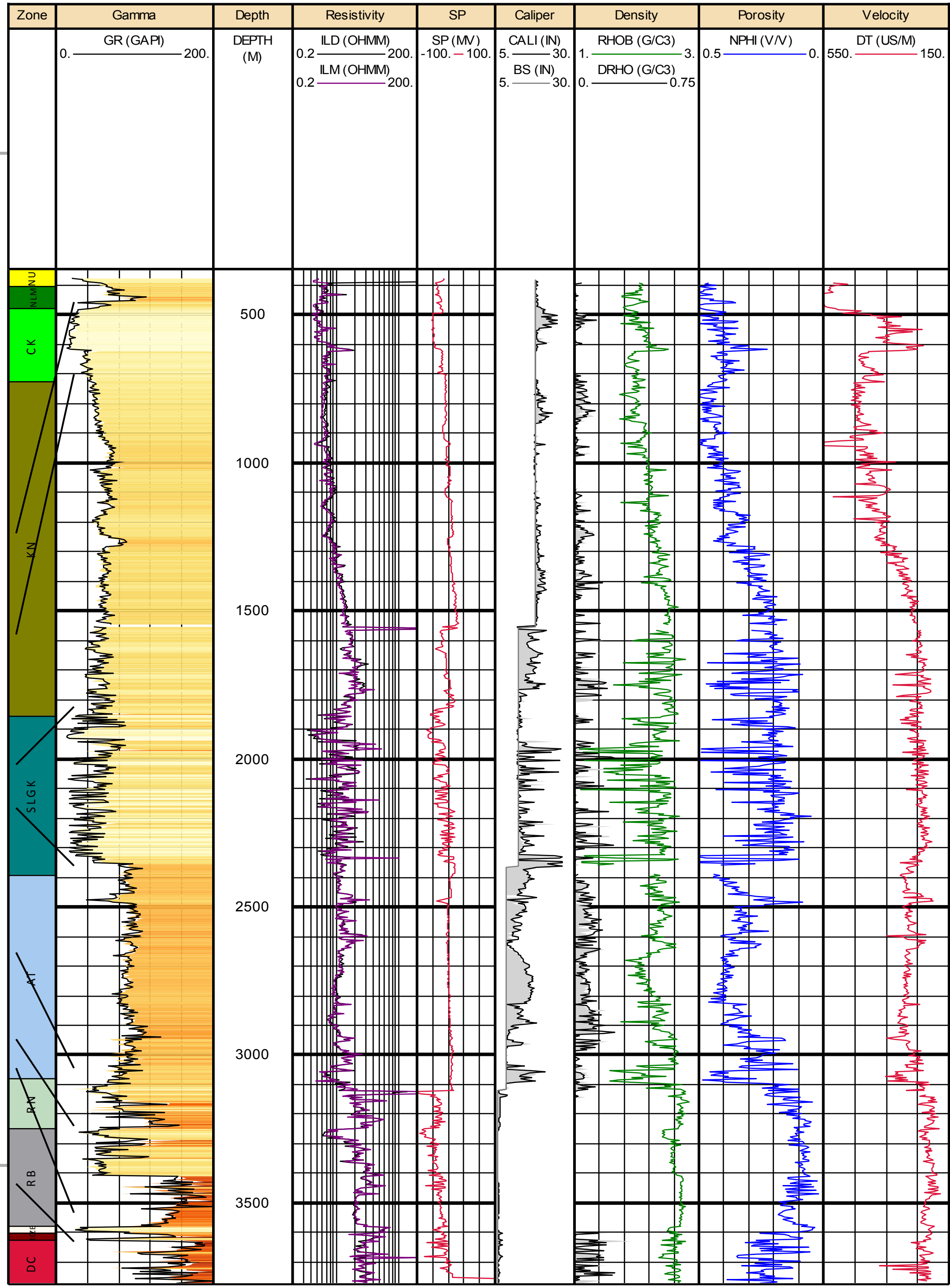
Logs from KDZ-02





Log Quality

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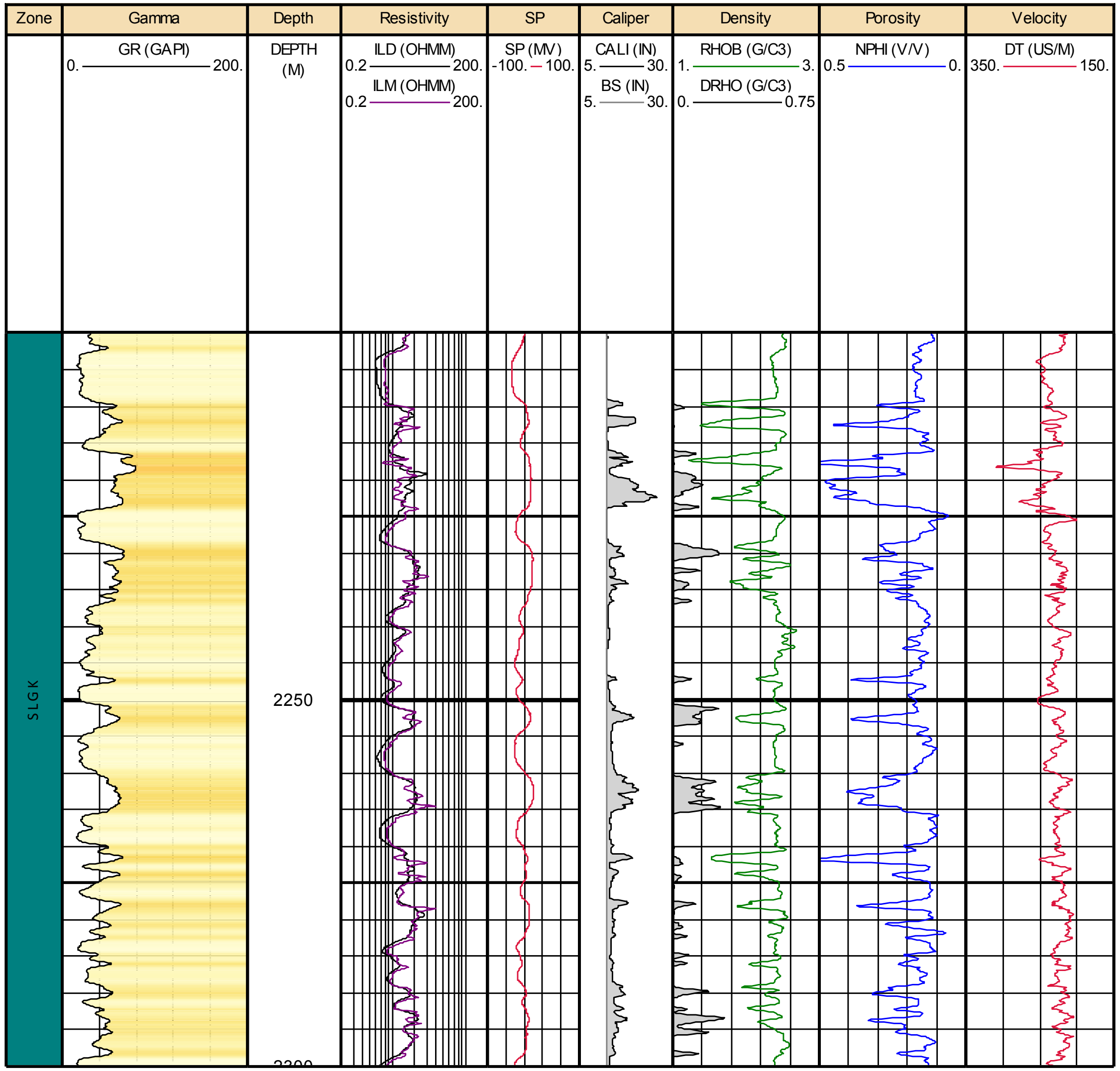

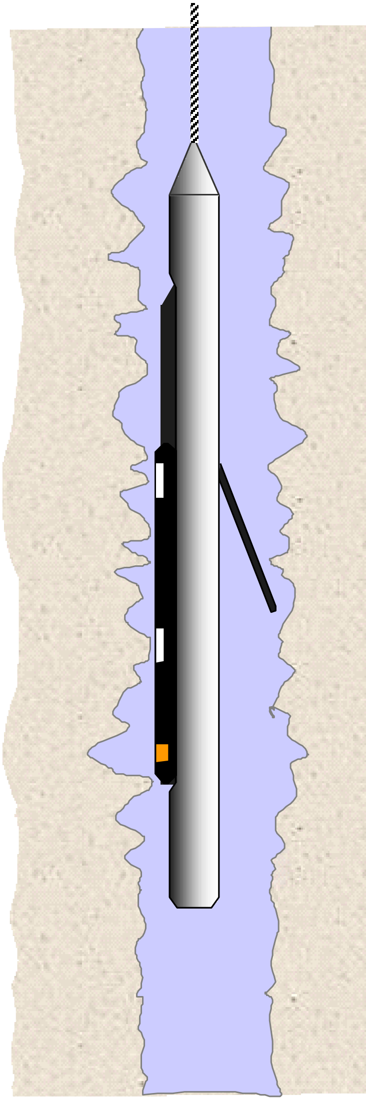

- Density and Neutron tools require good contact to borehole wall
- Sensitive to breakouts and hole enlarge-ments

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Well-to-well correlation

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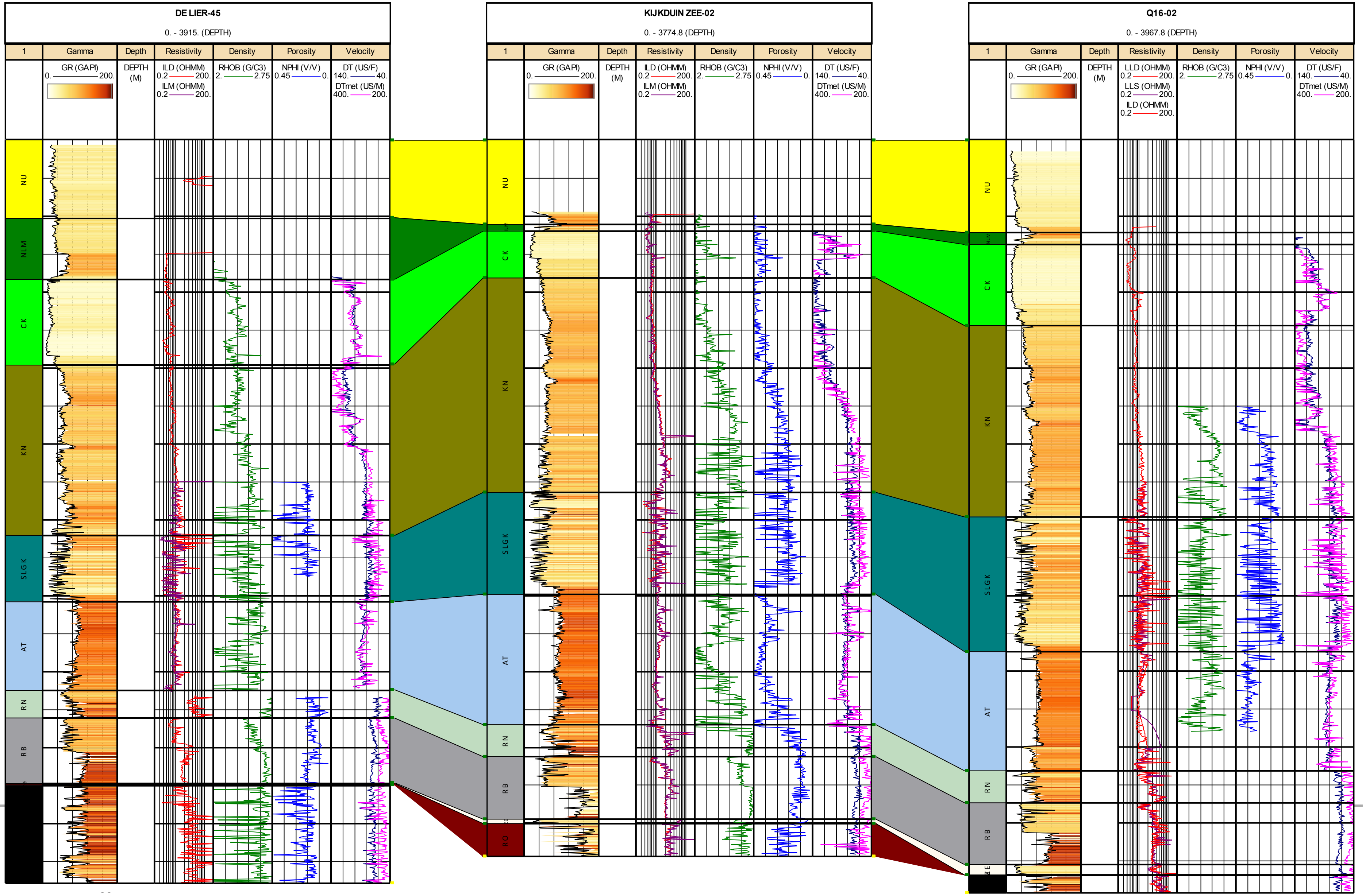
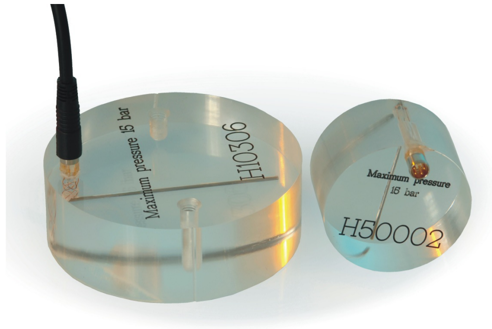


Laboratory measurements

- Thermal conductivity on cuttings: TK04 half-space line source



Laboratory measurements

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- Thermal conductivity measured on 50 cutting samples
  - saturated rock-water mixture
  - result: rock matrix conductivity from appropriate mixing law:

$$(a)\ \lambda_{max} = \lambda_{ari} = \lambda_{\parallel} = \sum_{i=1}^{N} n_i \lambda_i \ ;$$

$$(b)\ \lambda_{min} = \lambda_{har} = \lambda_{\perp} = \left(\sum_{i=1}^{N} \frac{n_i}{\lambda_i} \right)^{-1} ;$$

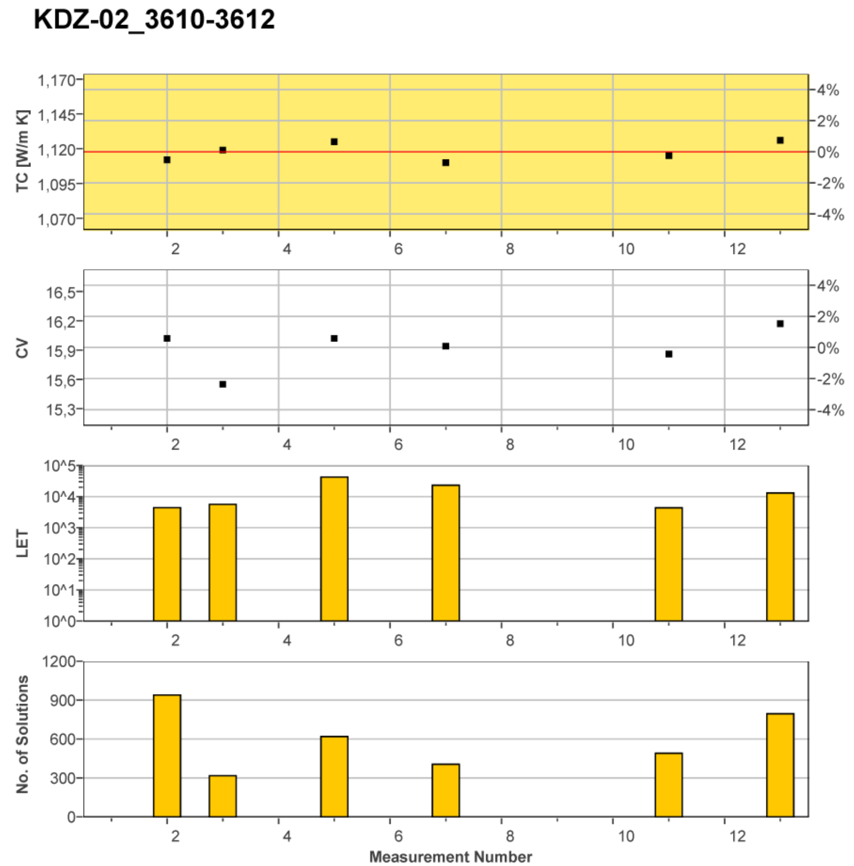
$$(c)\ \lambda_{mean} = \frac{1}{2}\left(\lambda_{\parallel} + \lambda_{\perp}\right);$$

$$(d)\ \lambda_{geo} = \prod_{i=1}^{N} \lambda_i^{n_i} \ ;$$

$$(e)\ \sqrt{\lambda_{sqr}} = \sum_{i=1}^{N} n_i \sqrt{\lambda_i};$$

$$(f)\ \left(\frac{1}{\lambda}\right)_{eff} = \sum_{i=1}^{N} \frac{3 n_i}{2\lambda + \lambda_i} \ ;$$

$$(g)\ \lambda_{HS} = \frac{1}{2}\left(\lambda_{HS}^{U} + \lambda_{HS}^{L}\right);$$



TC_{mean} : 1,118 W m^{-1}K^{-1}
TC_{min} : 1,110 W m^{-1}K^{-1}
TC_{max} : 1,126 W m^{-1}K^{-1}
Number of Measurements : 13
Measurement Date : 21.02.2008

Std. Deviation : 0,007 W m^{-1}K^{-1}
Std. Error : 0,003 W m^{-1}K^{-1}
Variation : ± 0,7%

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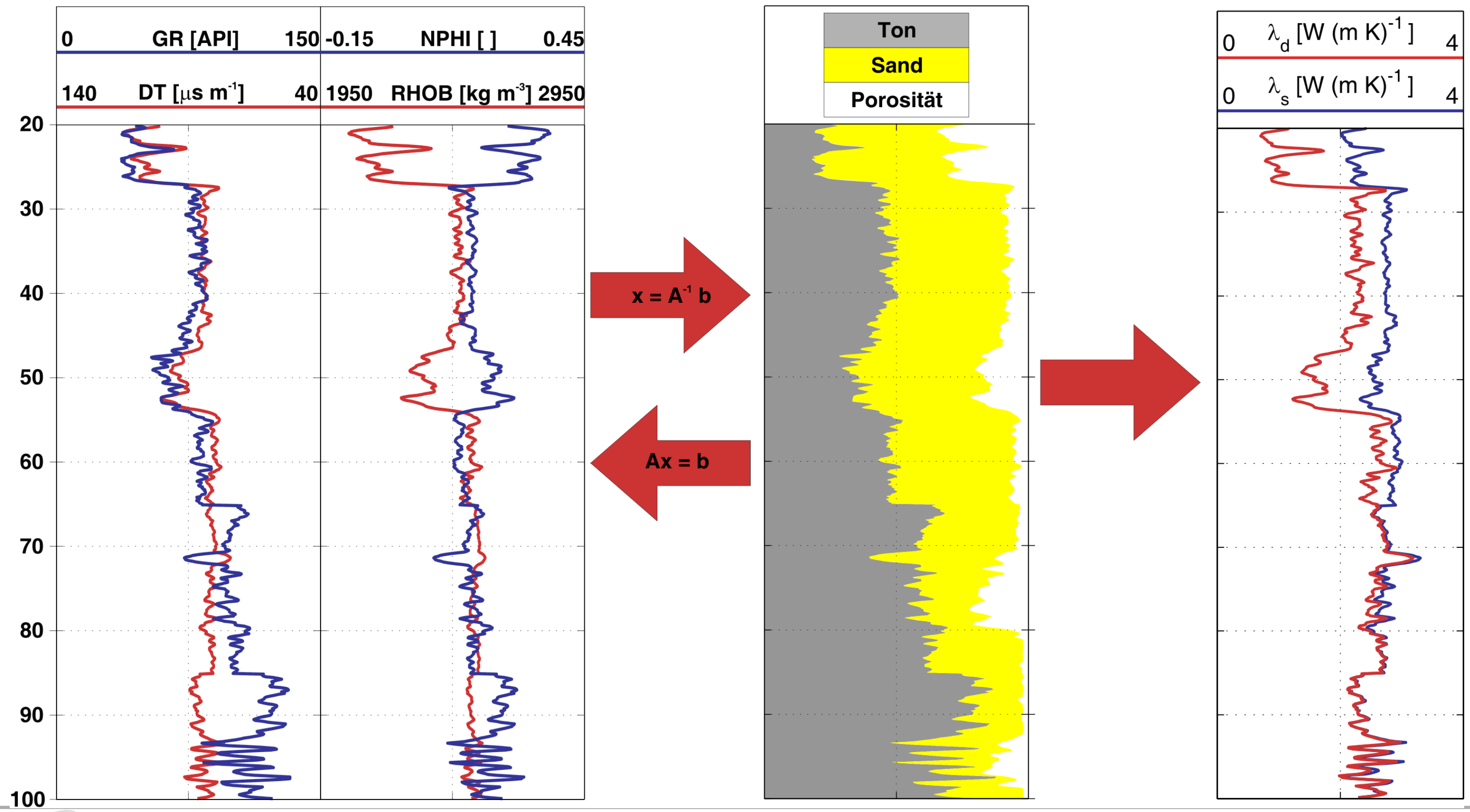
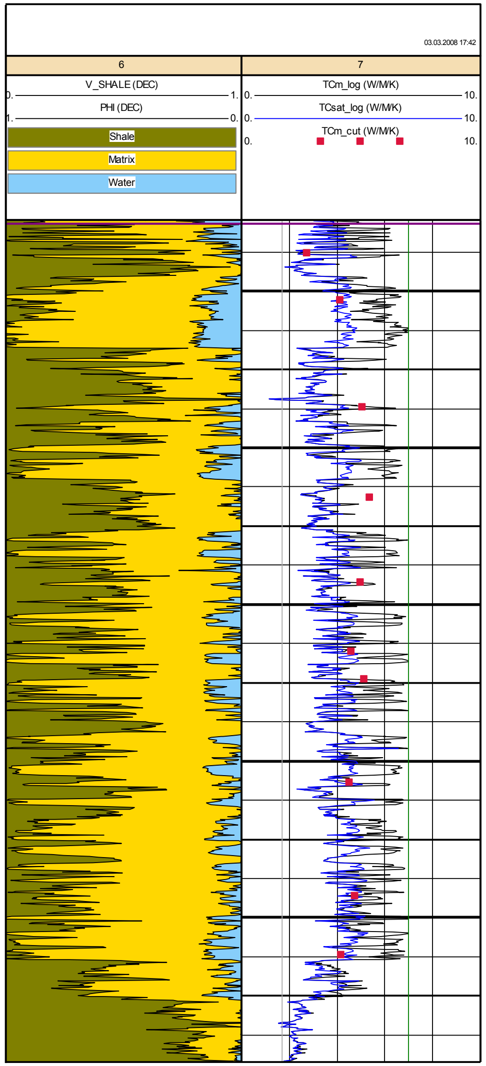
Log Analysis

- Determine thermophysical properties for stratigraphic units:
  - Invert volume percentage of rock type from suitable borehole logs
  - Assign representative values for rock and fluid thermal conductivity and porosity
  - Apply suitable mixing law for deriving thermal conductivity log
  - Calibrate with laboratory measurements



Formation thermal conductivity



- Calculating effective thermal conductivity of saturated rock by accounting for porosity ϕ:

$$\lambda_{sat} = \lambda_{fluid}^{\phi} \, \lambda_{matrix}^{(1-\phi)}$$

- Effective thermal conductivity logs allow calculating statistical moments for characterising the different geological model units

Rock matrix thermal conductivity

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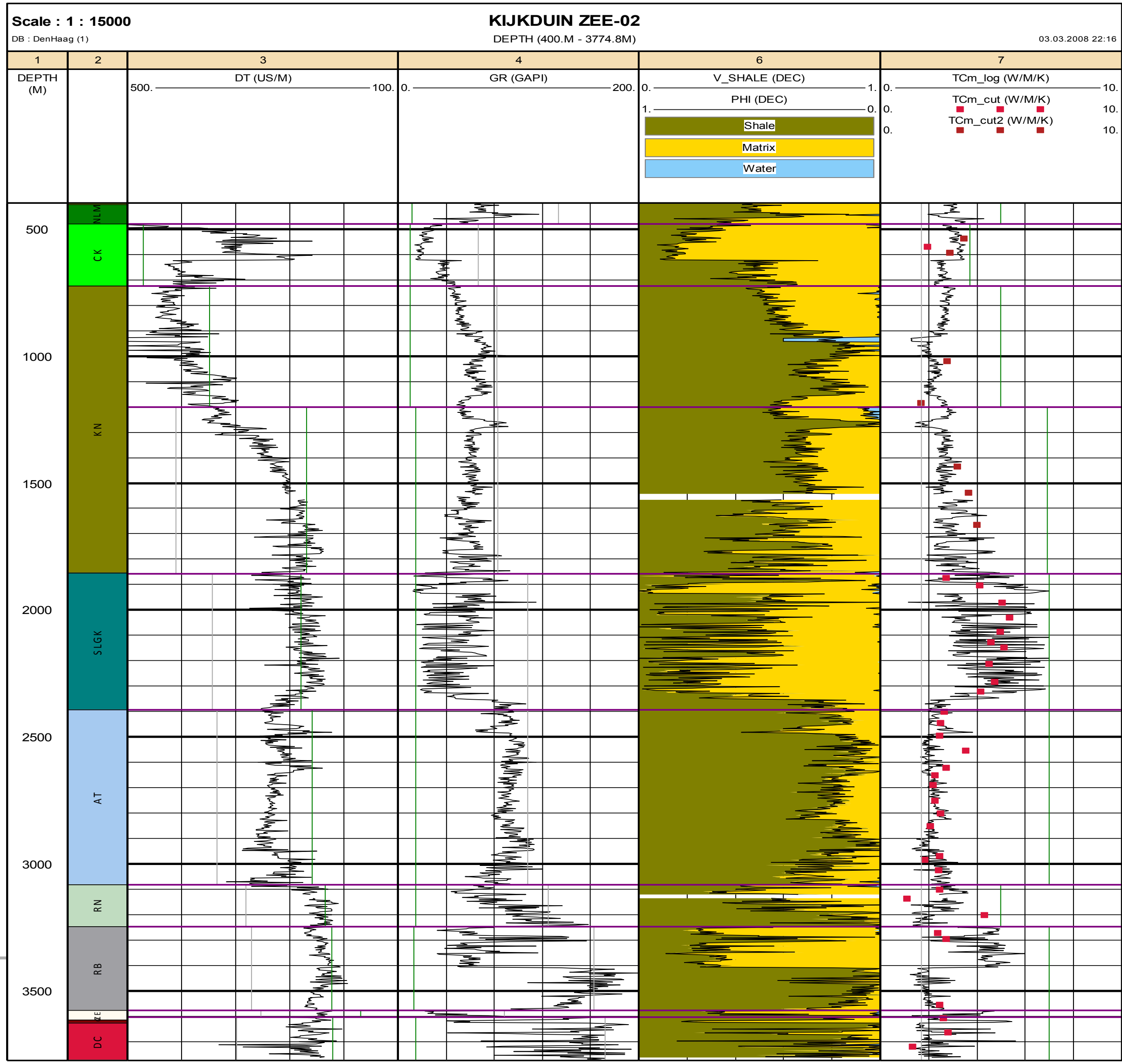
- Comparison of thermal conductivity predicted (from logs) vs. measured (in the lab)



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Rock matrix thermal conductivity

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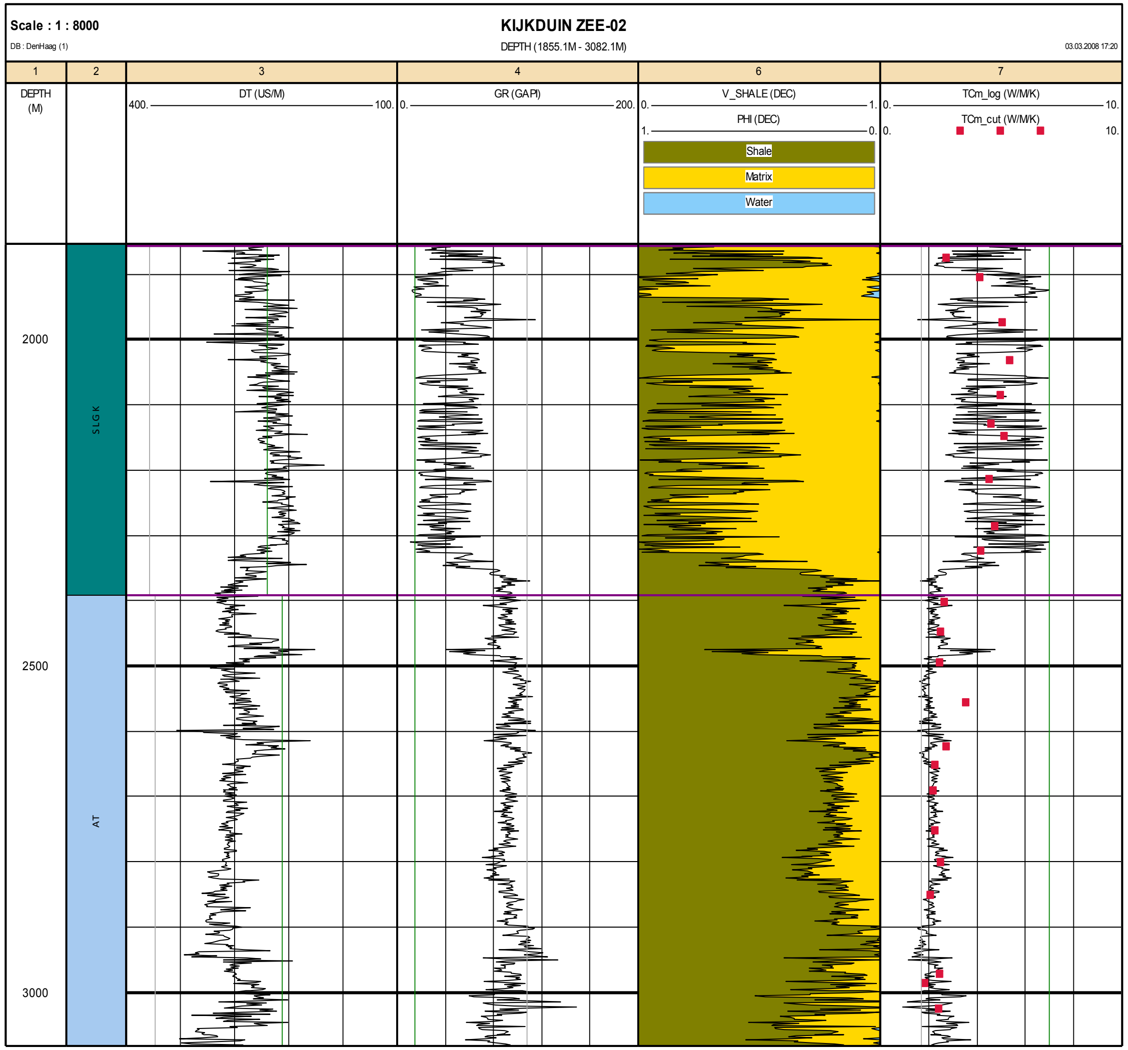

- Siliciclastic sediments of the „SLGK - Jurassic Group“ and the „AT-Altena Formation“.

End member values:

- Quartz: 7.0 W m^{-1} K^{-1}
- Clay minerals: 1.7 W m^{-1} K^{-1}

Average Values Tc_{matrix} (W m^{-1} K^{-1}):

	SLGK	AT
TC_{m_log}	*4.42*	*2.16*
TC_{m_cut}	*4.54*	*2.46*

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Gamma ray: well-to-well comparison

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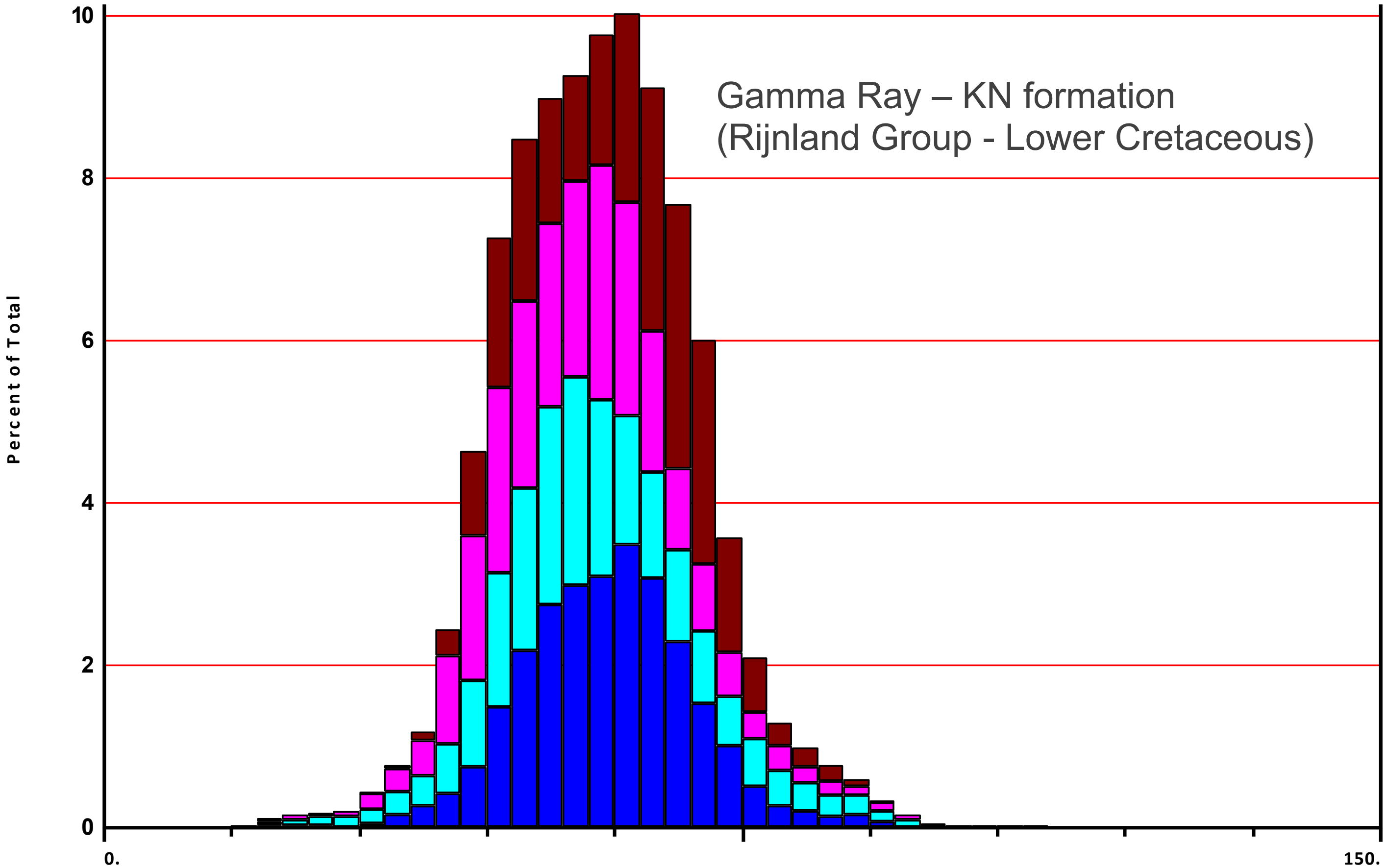
- How well do data from single boreholes represent formations?



40481 points plotted out of 40575

	Curve	Well	Zone	Depths	Mean	Std Dev
■ (blue)	GR	KIJKDUIN ZEE-02	(4) KN	725.M - 1855.1M	59.174	9.912
■ (cyan)	GR	DE LIER-45	(4) KN	1183.M - 2084.M	57.606	13.27
■ (magenta)	GR	MONSTER-02	(4) KN	1163.M - 2178.M	55.686	11.41
■ (dark red)	GR	Q16-02	(4) KN	976.M - 1987.M	61.162	10.41
	All Zones				58.448	11.41

Gamma ray: well-to-well comparison

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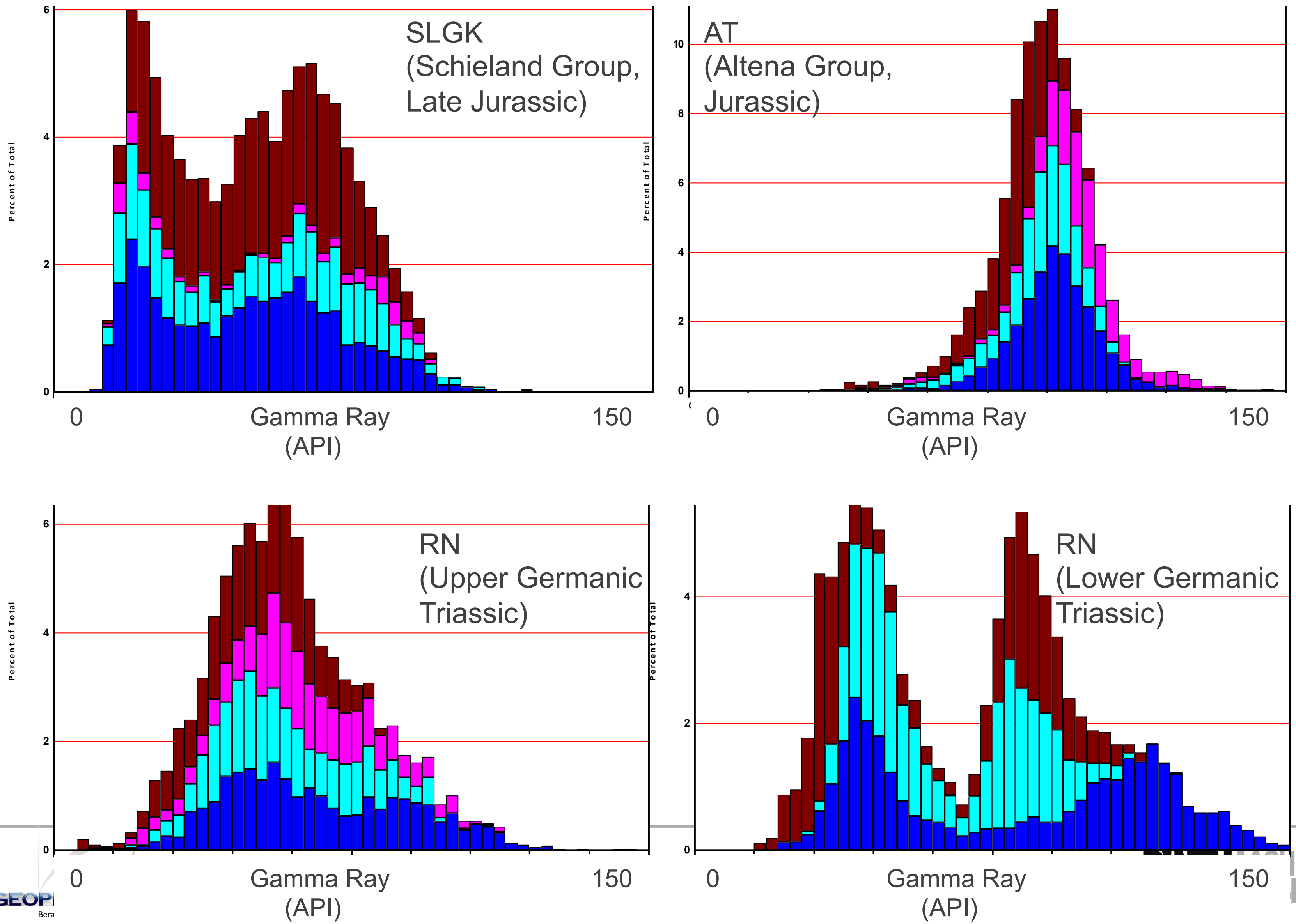

3-D model: thermal properties

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Unit	Bulk Thermal Conductivity ($W\ m^{-1}\ K^{-1}$) Mean–Stdv. **Mean** Mean+Stdv.	Heat production ($\mu W\ m^{-3}$)
North Sea super-group (N)	**2.3**	1.05
Upper Cretaceous super-group (CK)	1.80 – **2.20** – 2.60	0.46
Lower Cretaceous super-group (KN)	1.94 – **2.51** – 3.08	0.92
Jurassic super-group (S)	2.75 - **3.75** – 4.57	0.75
Altena Group (AT)	1.81 – **2.17** – 2.53	1.44
Lower Germanic Triassic Group (RB)	1.93 – **2.80** – 3.67	1.61
Permian Zechstein Group (ZE)	1.90 – **3.14** – 4.35	1.33
Rotliegend (RO)	**4.0**	0.75
Basement (DC)	**2.3**	2.30

3-D model set up

- Static model: 3-D steady-state heat transport
  - dimensions: 22.5 km × 24.3 km × 5 km
  - Finite Difference grid with ~ 2.4 million nodes
  - 9 Geological units, layer interfaces according to seismic survey (TNO)
  - Physical properties vary with temperature
  - boundary conditions
    - No lateral inflow or outflow
    - Temperature at surface: 11 °C
    - Specific heat flow at bottom: 65 mW m^{-2}
- Model used to
  - predict temperature at bottom of production well
  - asses sensitivity of prediction

Location of 3-D model

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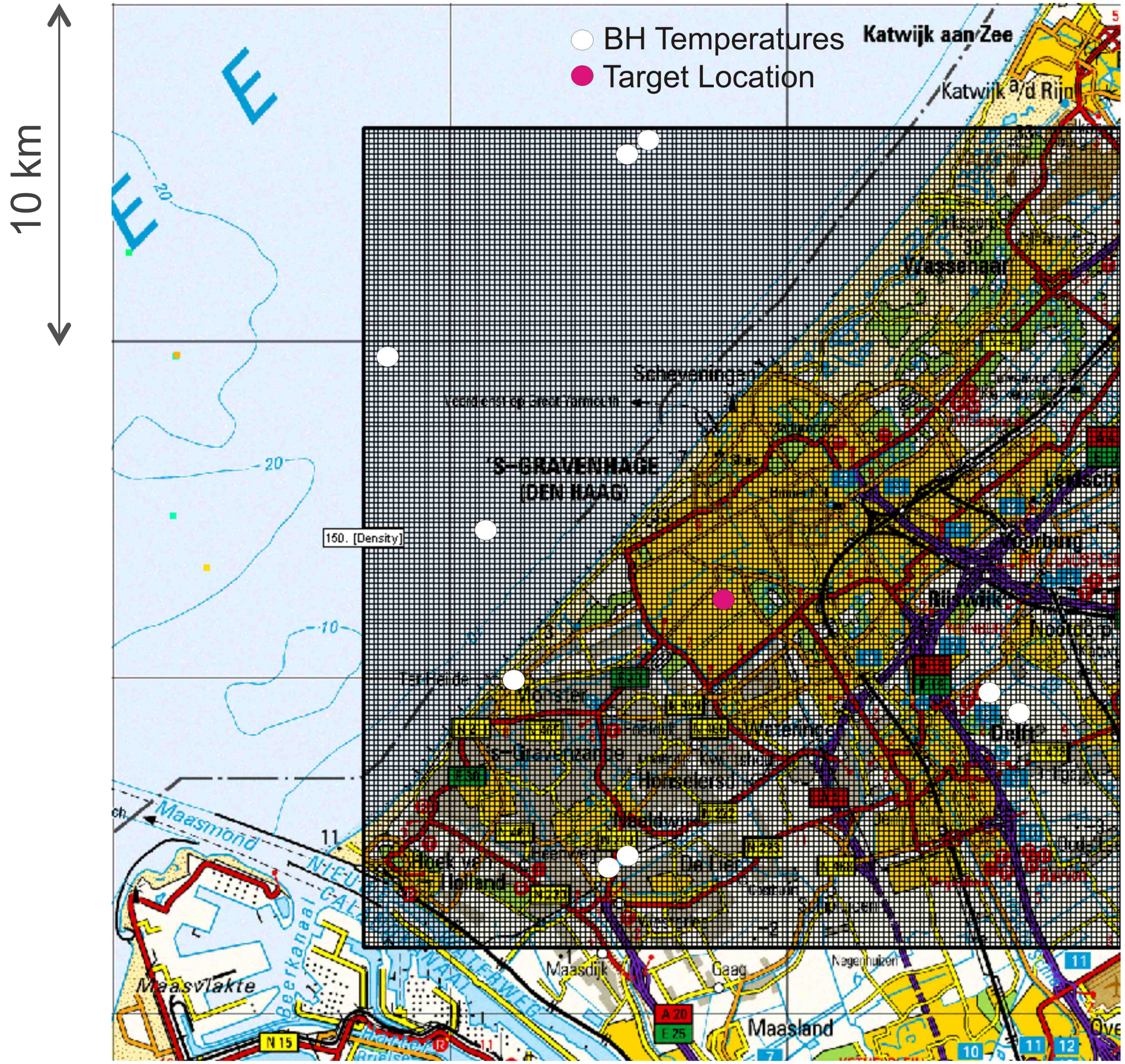

Layers in 3-D model

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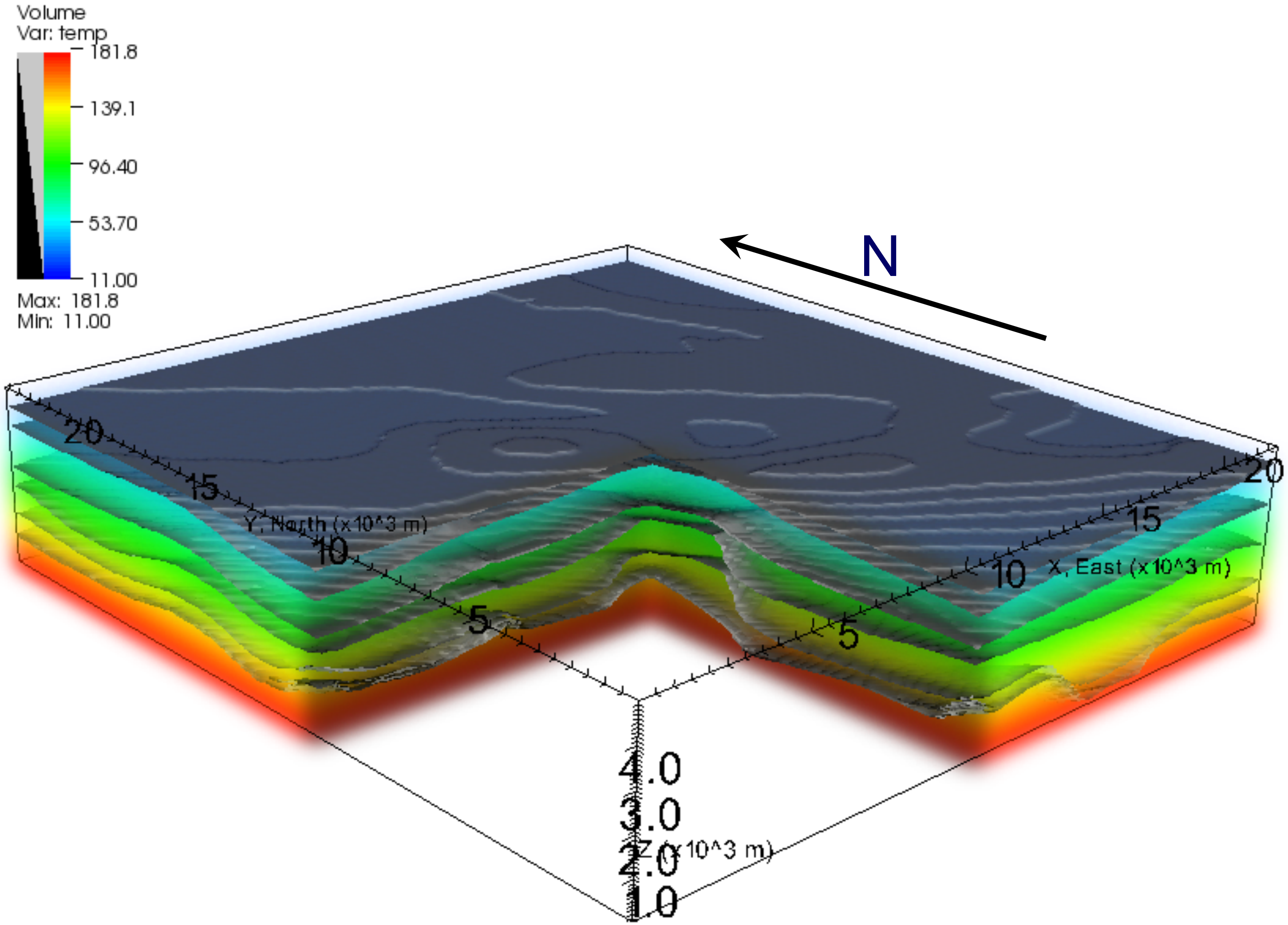

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Comparison predicted geotherms vs. regional BHT

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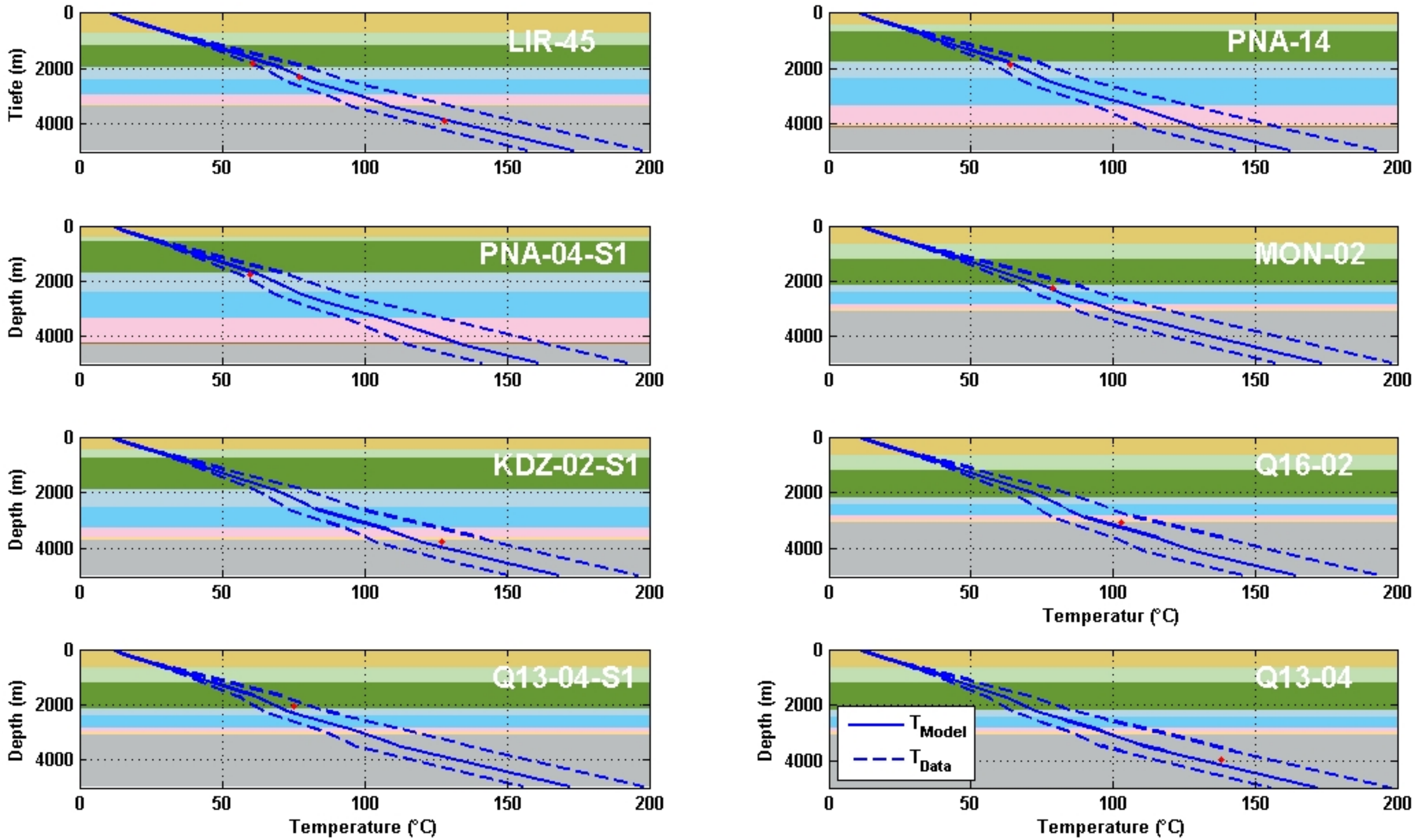

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Horizontal cross section at 1900 m

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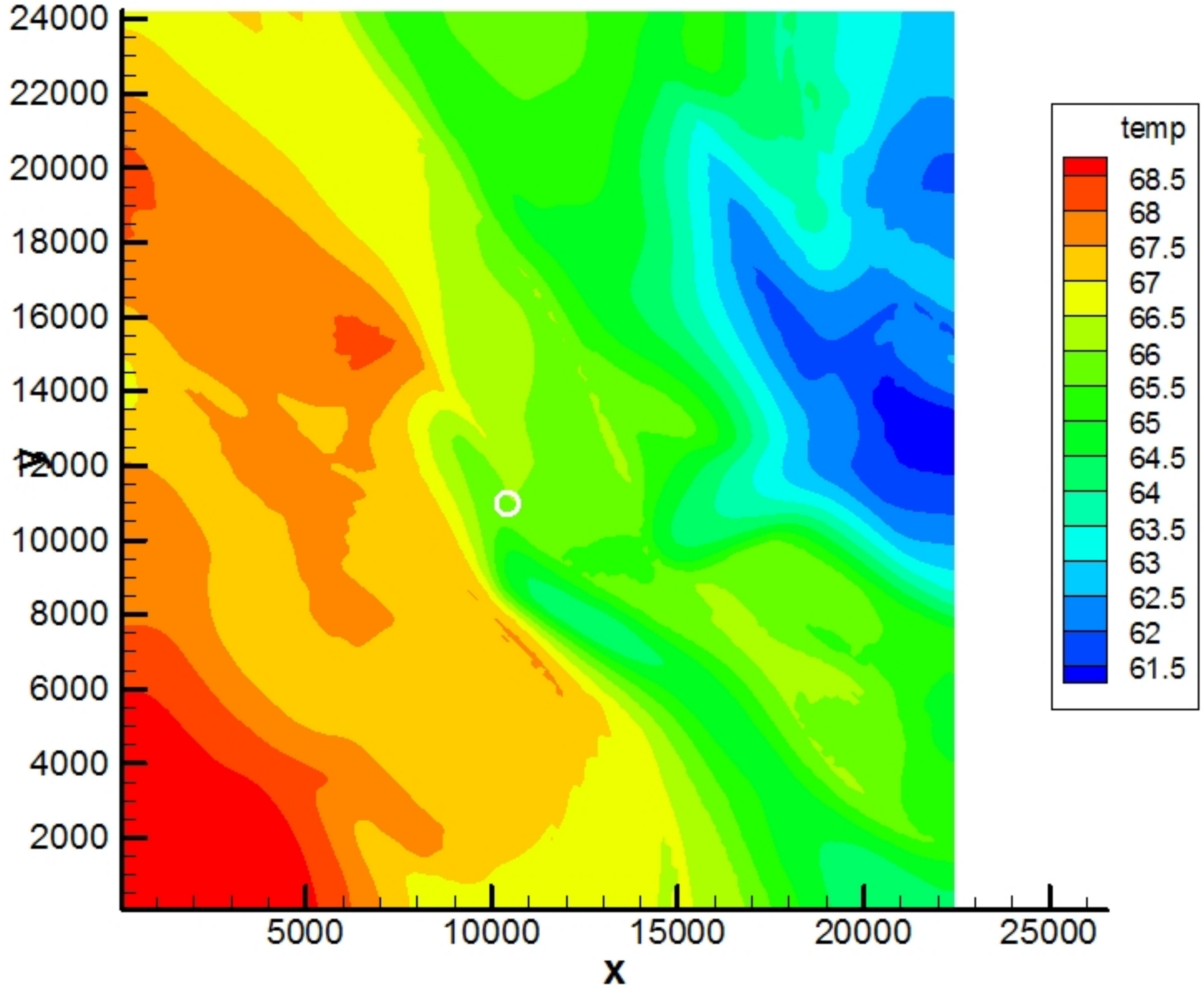

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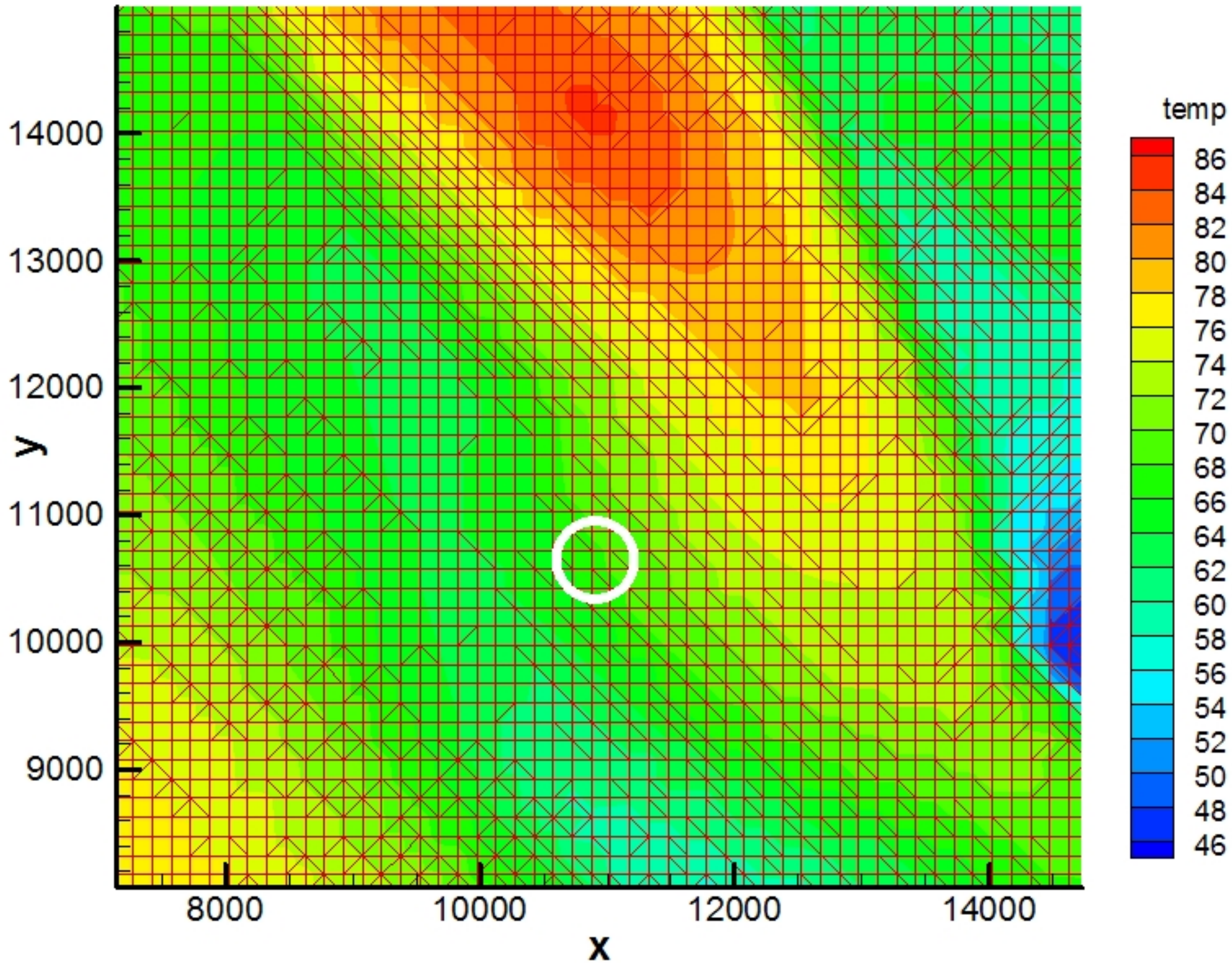
Temperature at top of reservoir (unit 4)



Static thermal model - summary

- Combining laboratory and logging data allows
  - proper assignment of thermal properties for geological units
  - characterization in terms of statistical moments, such as mean, median, standard deviation, etc.
  - Quantifying the uncertainty in model input parameters caused by the variability of rock properties within a geological unit
- In contrast, thermal models based on estimated thermal properties will often result in largely over- or underestimated, unreliable temperature predictions with unspecified uncertainty
- 3-D thermal models may support decision making in drilling design with respect to well path, deviation, drilling length, and target depth
- Result of Den Haag case study:
  - **Predicted** bottom-hole temperature: **76.0 °C**
  - **Measured** bottom-hole temperature: **76.5 °C**

Dynamic reservoir model

- **Set up and test transient 3-D reservoir model**
- **Perform simulations for**
  - the operating doublet system
  - predicting the transient variation of production temperature
  - inferring radius of cooling around injector
  - identifying a potential thermal breakthrough

Location of 3-D model

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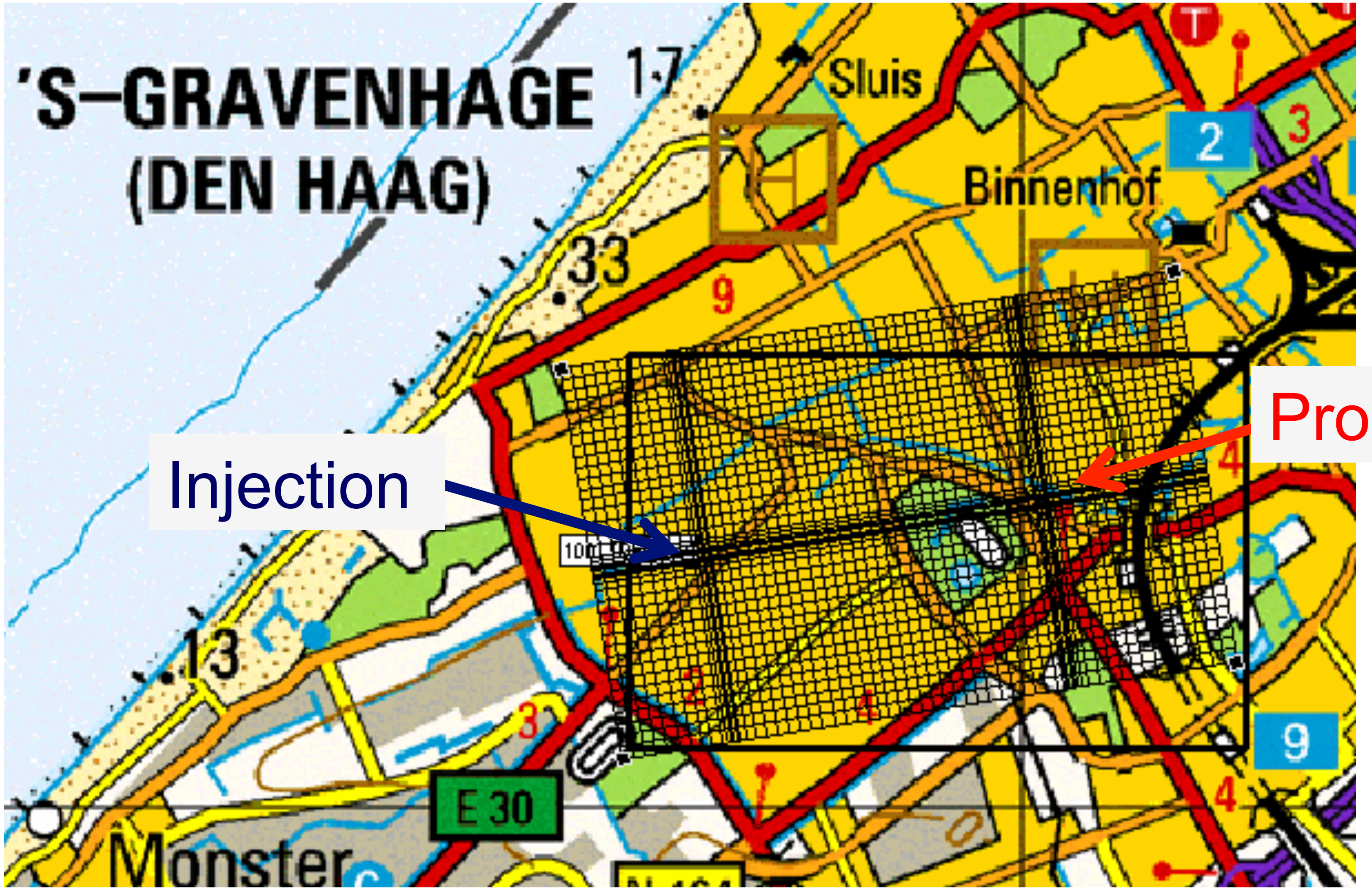

Comparison with regional model

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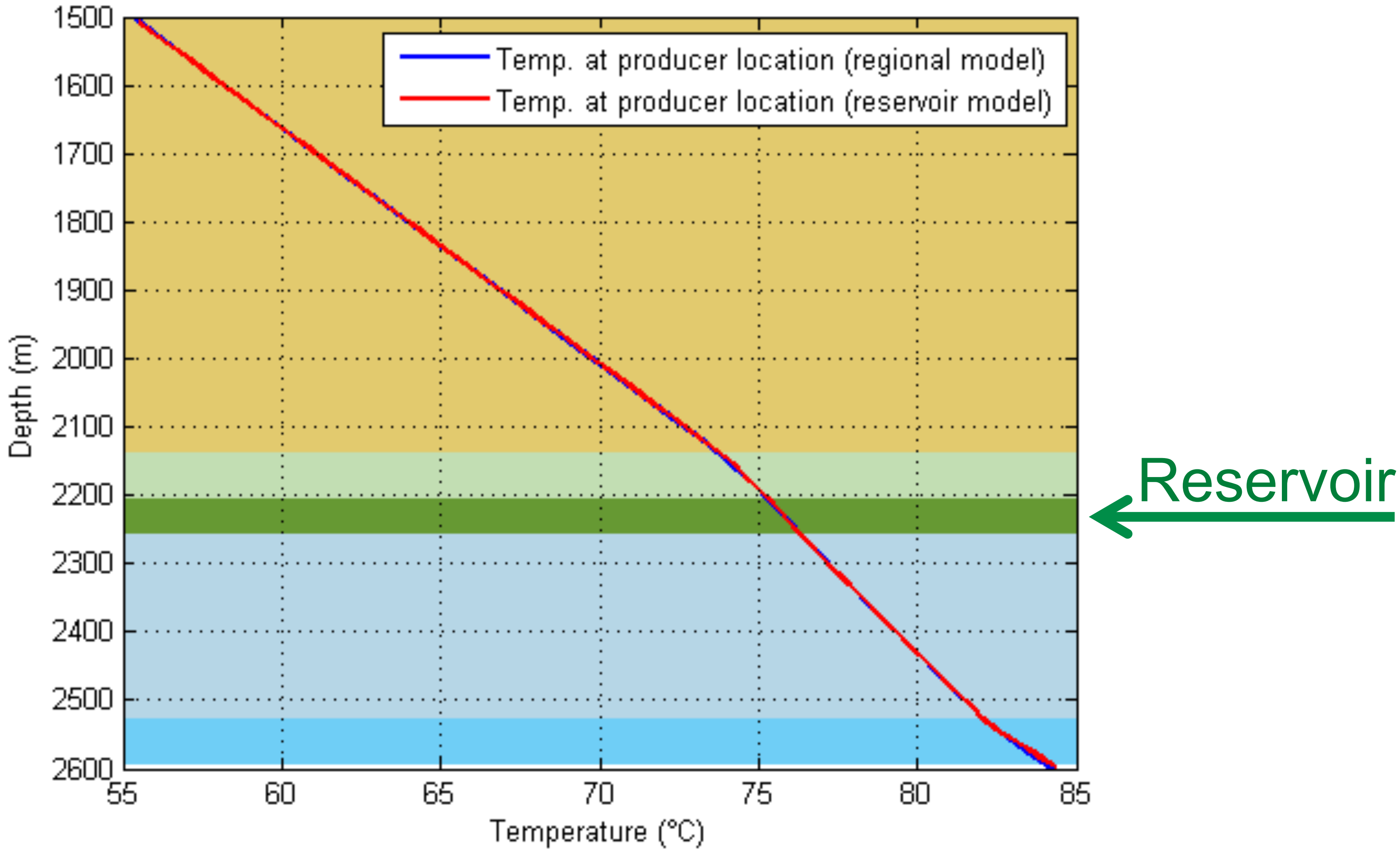

Reservoir model and boundary conditions

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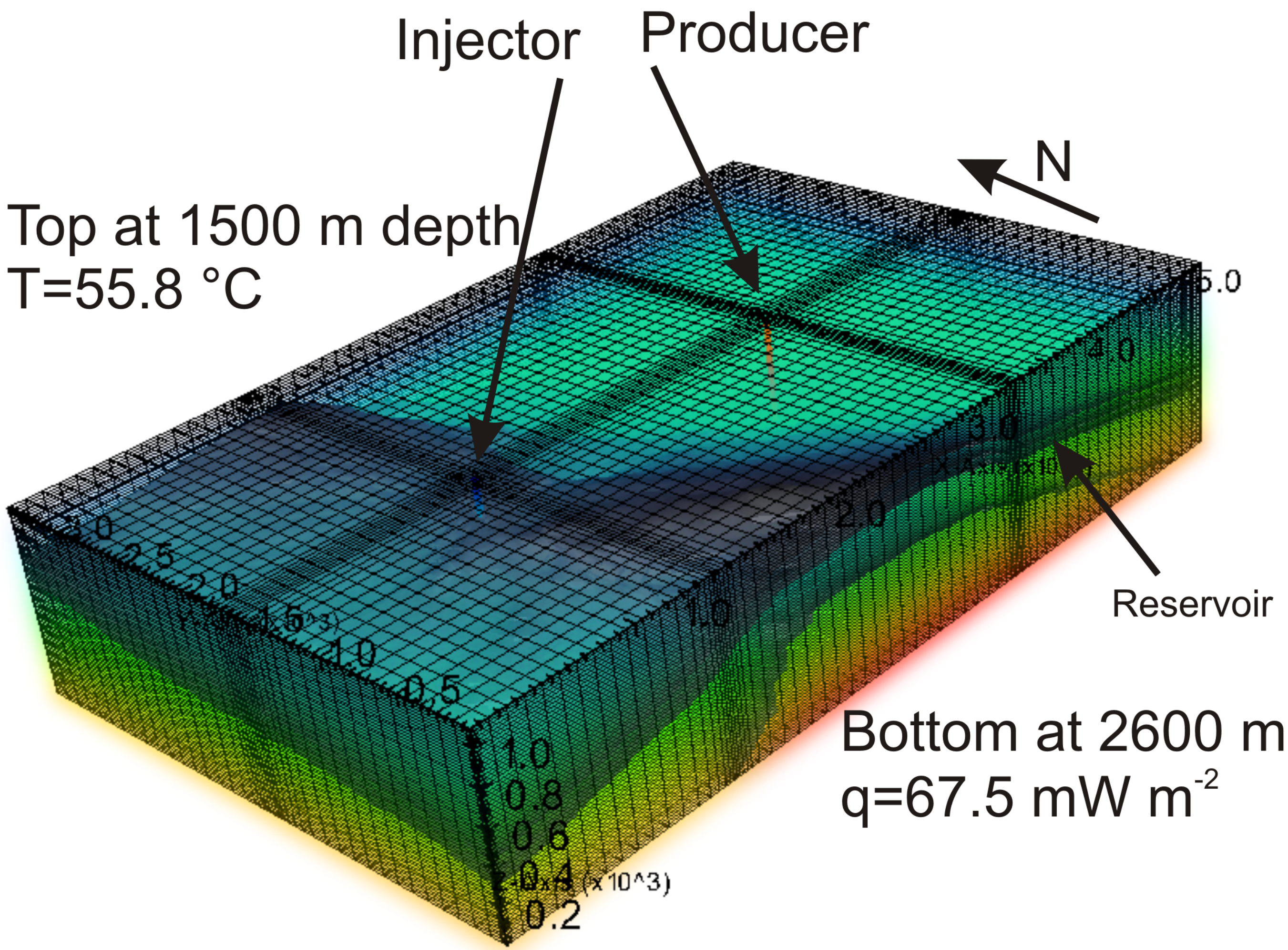

Reservoir thickness

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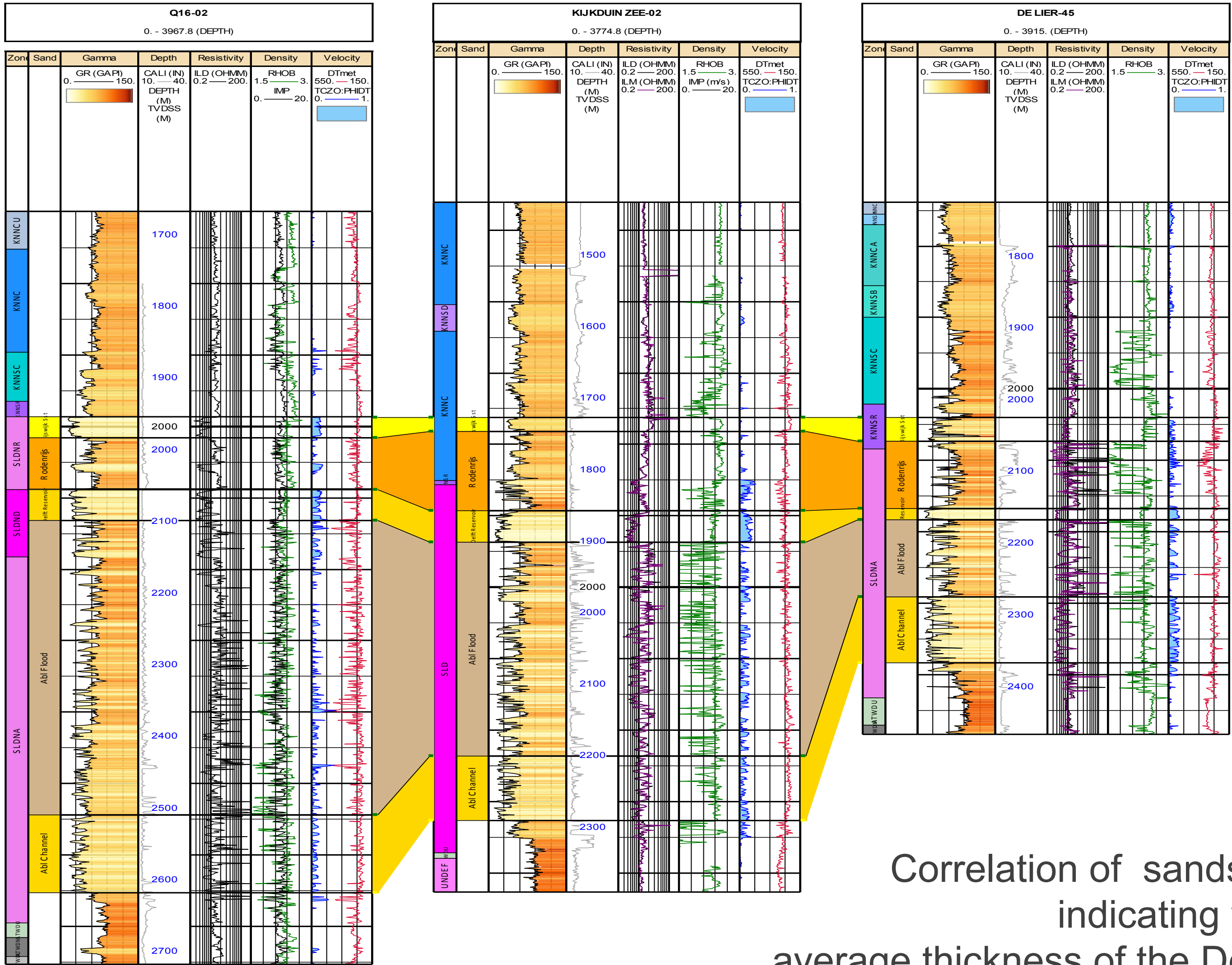

Correlation of sandstone layers (yellow);
indicating variable thickness;
average thickness of the Delft-sandstone: 55 m.

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Model properties

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Parameter	Value
Number of nodes	170 560
Extension	5.5 km × 3.5 km × 1.105 km
Porosity	17 %
Permeability	500 mD
Reservoir thickness	55 m
Transmissivity	2.75×10^{-4} m^2 s^{-1}
Injection and production rate	150 m^3 h^{-1}
Temperature of injected water	40 °C
Thermal conductivity matrix Delft	5.6 W m^{-1} K^{-1} = f(temperature)

Variation	Value
Permeability	100 mD – 1000 mD
Transmissivity	5.5×10^{-5} m^2 s^{-1} - 5.5×10^{-4} m^2 s^{-1}

Delft Sandstone petrophysical properties

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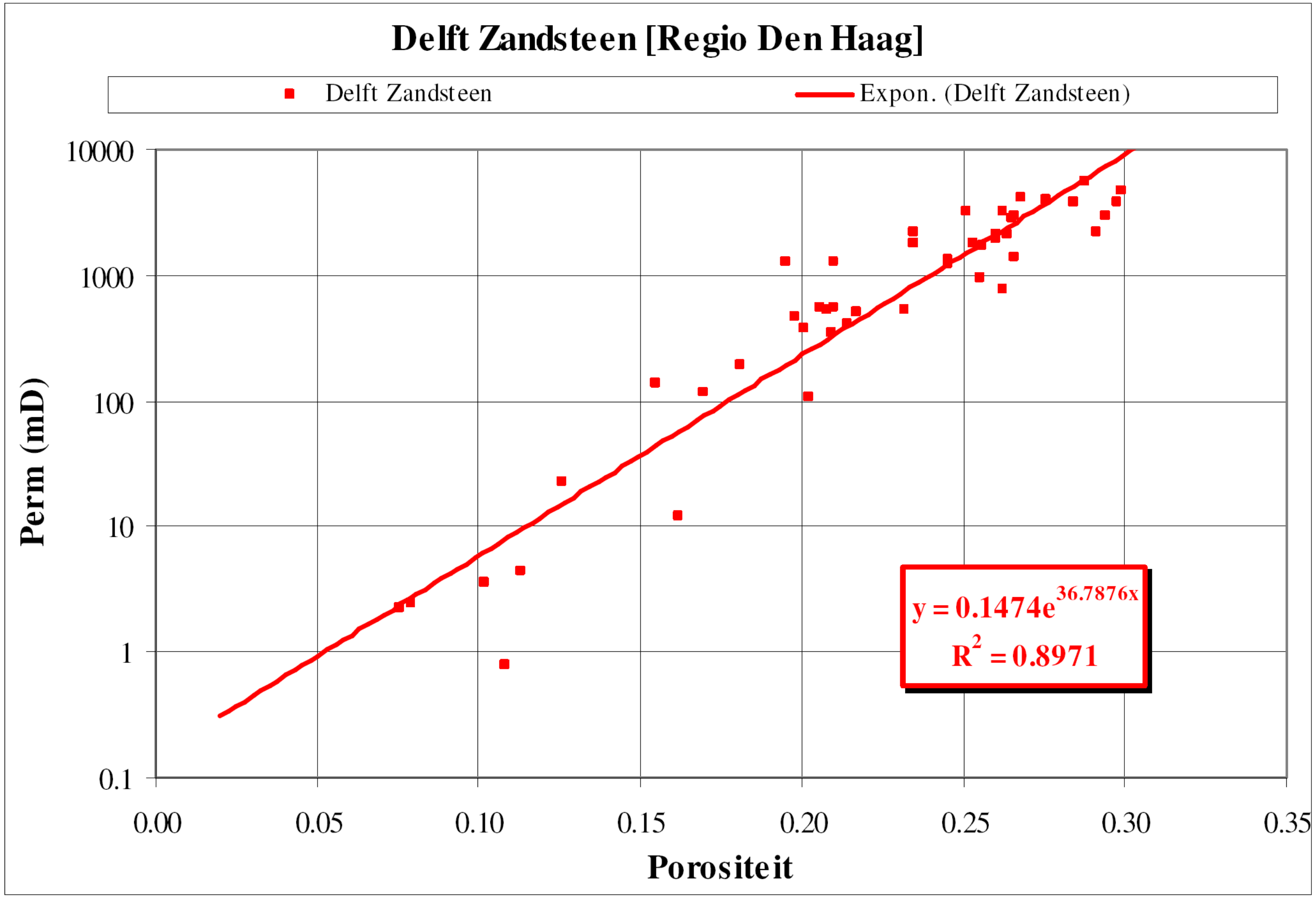

Porosity – permeability relationship from measurements on core in the laboratory

Temperature (°C) after 100 years

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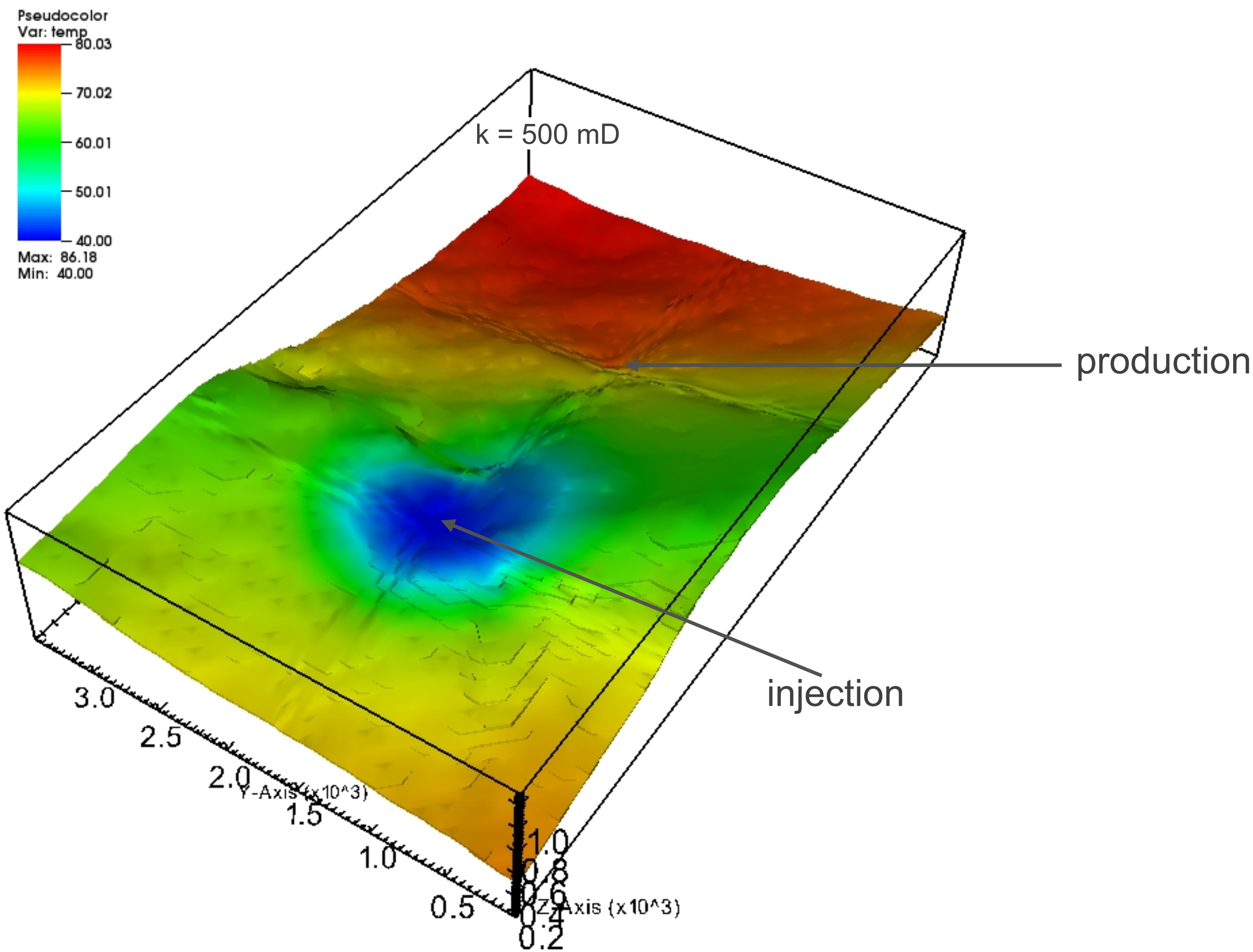

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Transient variation of production temperature

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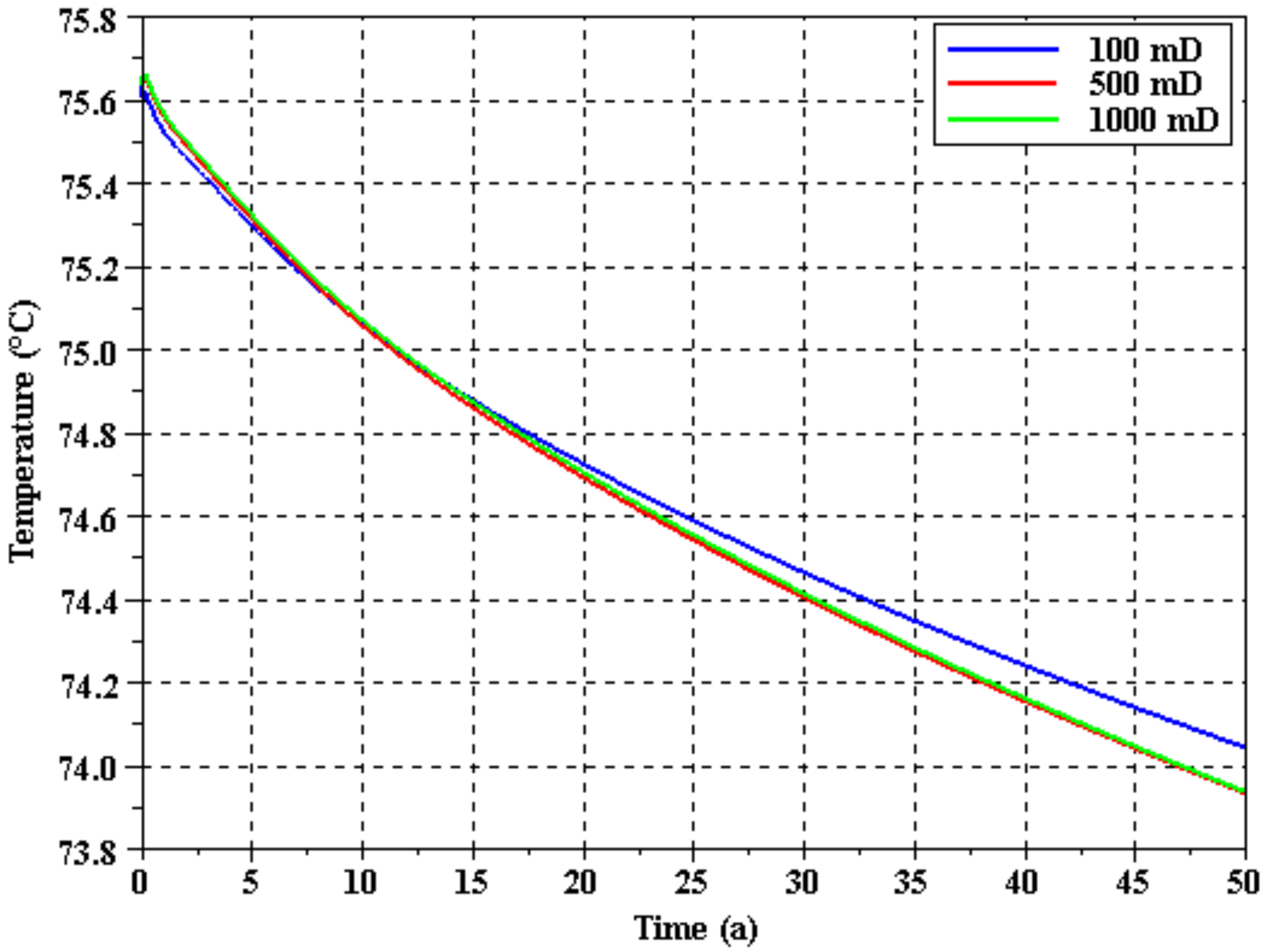

- Depth: 2320 m
- Initial temperatures from conductive model, calibrated to static regional model

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Conclusions

- No thermal breakthrough during 100 years of operation
- Cooling around the injection extends roughly 1 km
- Temperature decrease of ~1.5 K after 50 years of production

- *To be kept in mind, however:*
  - thickness of reservoir layer only estimated
  - reservoir permeability and porosity assumed homogeneous

Stochastic thermal simulation

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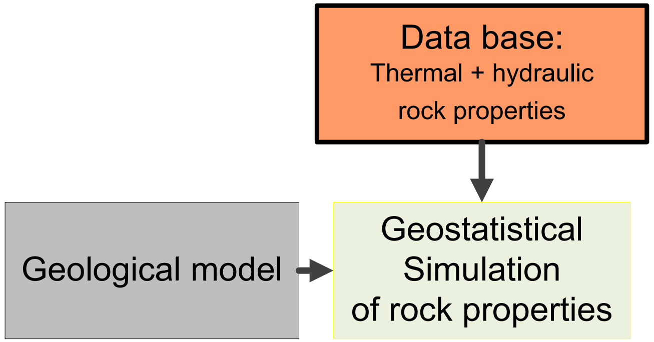
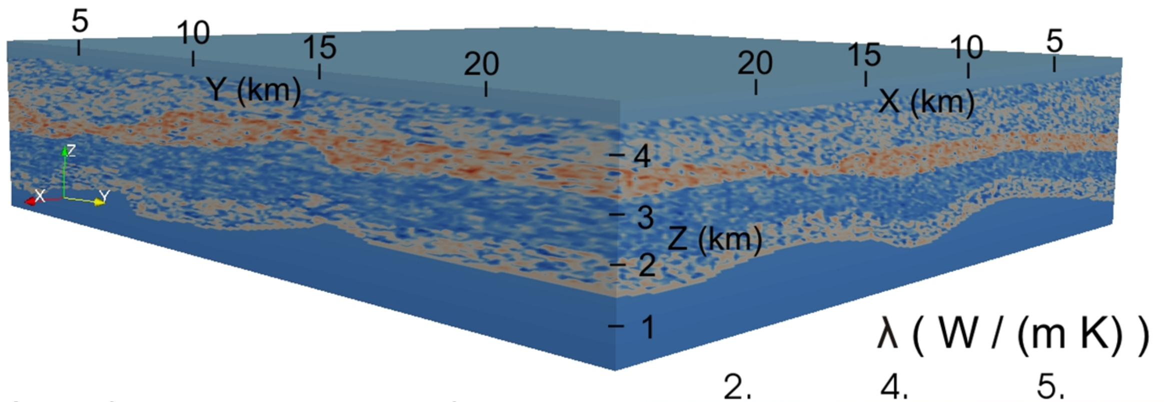


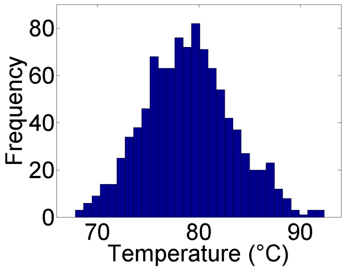


One of many realizations of thermal conductivity distribution in model.

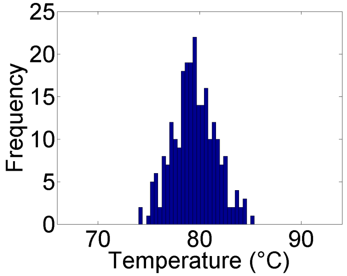
- Modeling approach:
  - traditionally, each model unit characterized by one constant value (here: thermal conductivity)
  - Stochastic simulation takes into account
    - the probability distribution of physical rock properties (input parameter from data base)
    - its spatial correlation
    - **and** generates a set of realizations, equally likely with respect to the data

Constraining post-processing

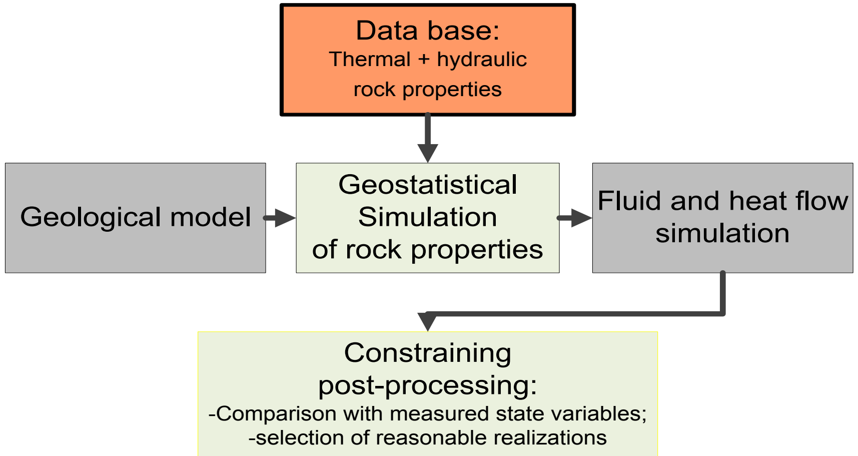
- Further uncertainty reduction:
  - Perform fluid and heat flow simulations for obtaining state variables (here: temperature)



  - Discard all realizations incompatible with available temperature data and uncertainty



Smaller set of realizations, smaller variance



Result: ~50 % reduction of initial uncertainty!

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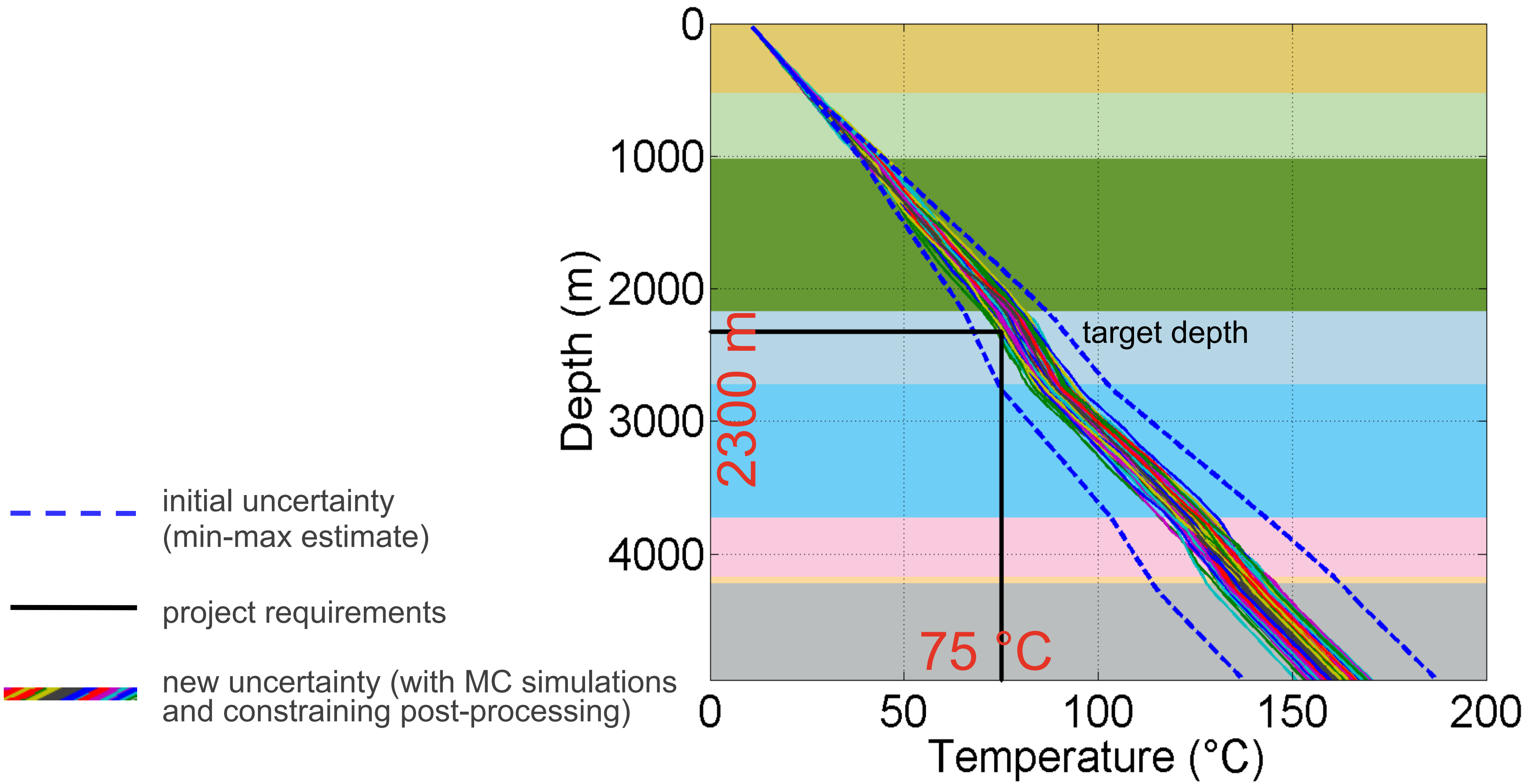

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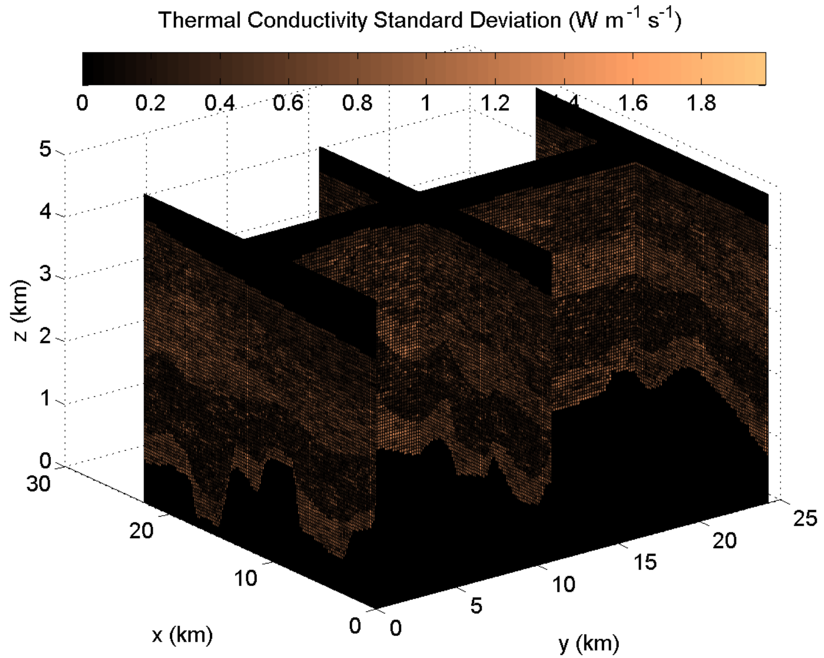
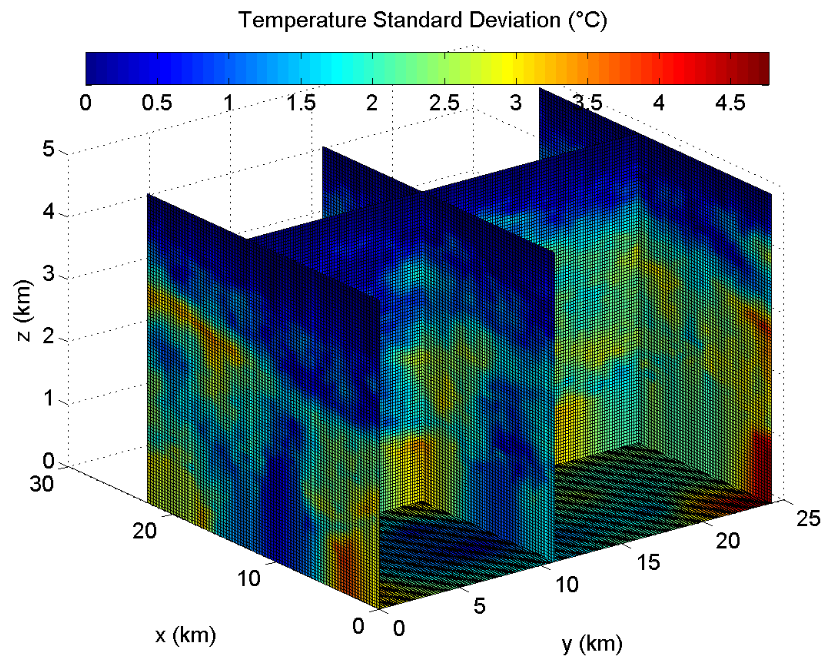
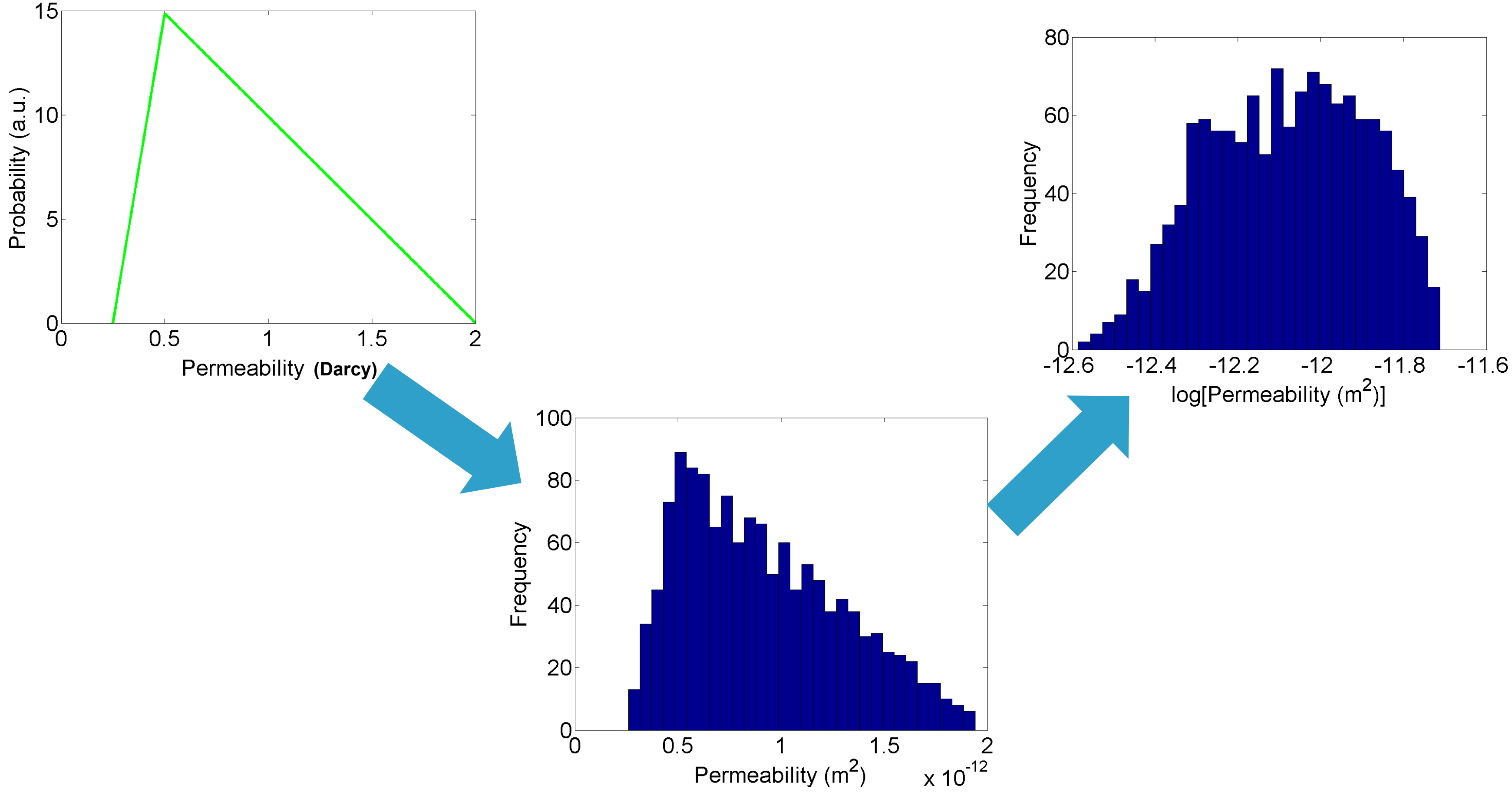
Visualising uncertainty





Stochastic reservoir simulation

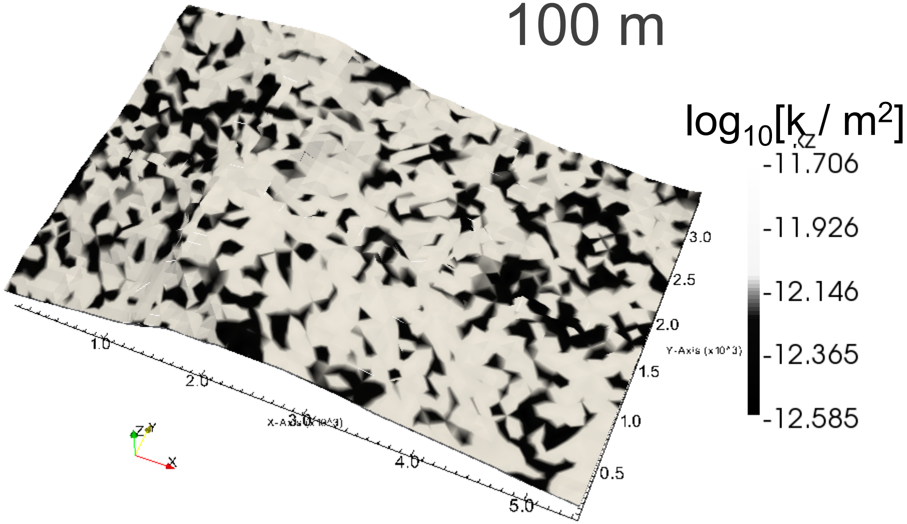
- Problem: Permeability histogram known, but no information on spatial distribution (i.e. correlation length)



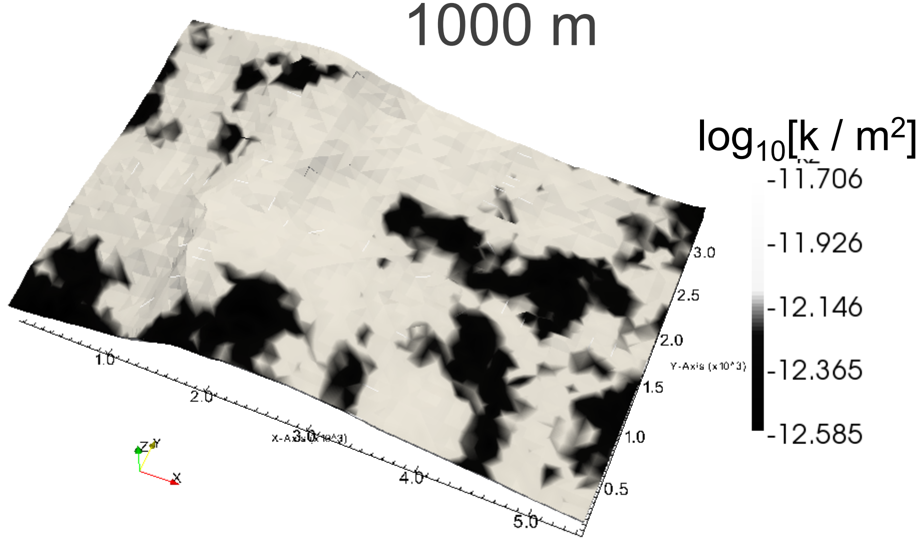
Correlation length study with SGSIM*

*Sequential Gaussian Simulation

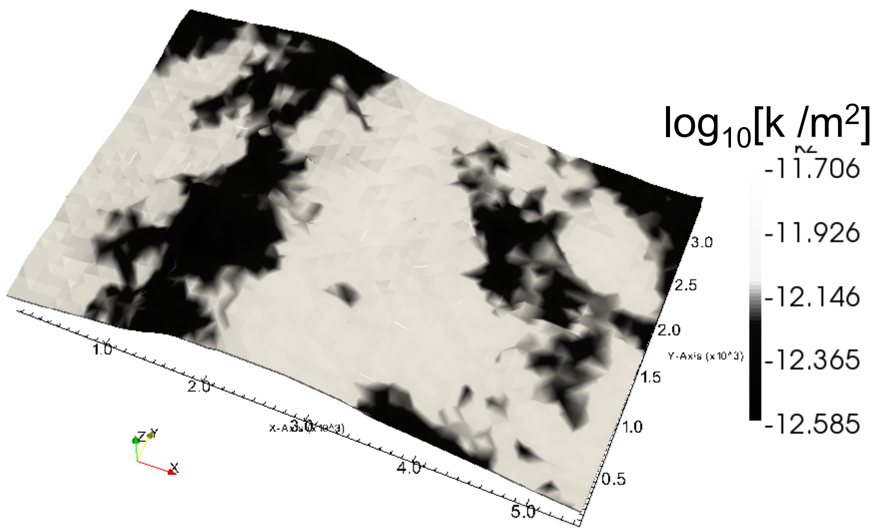
100 m



1000 m

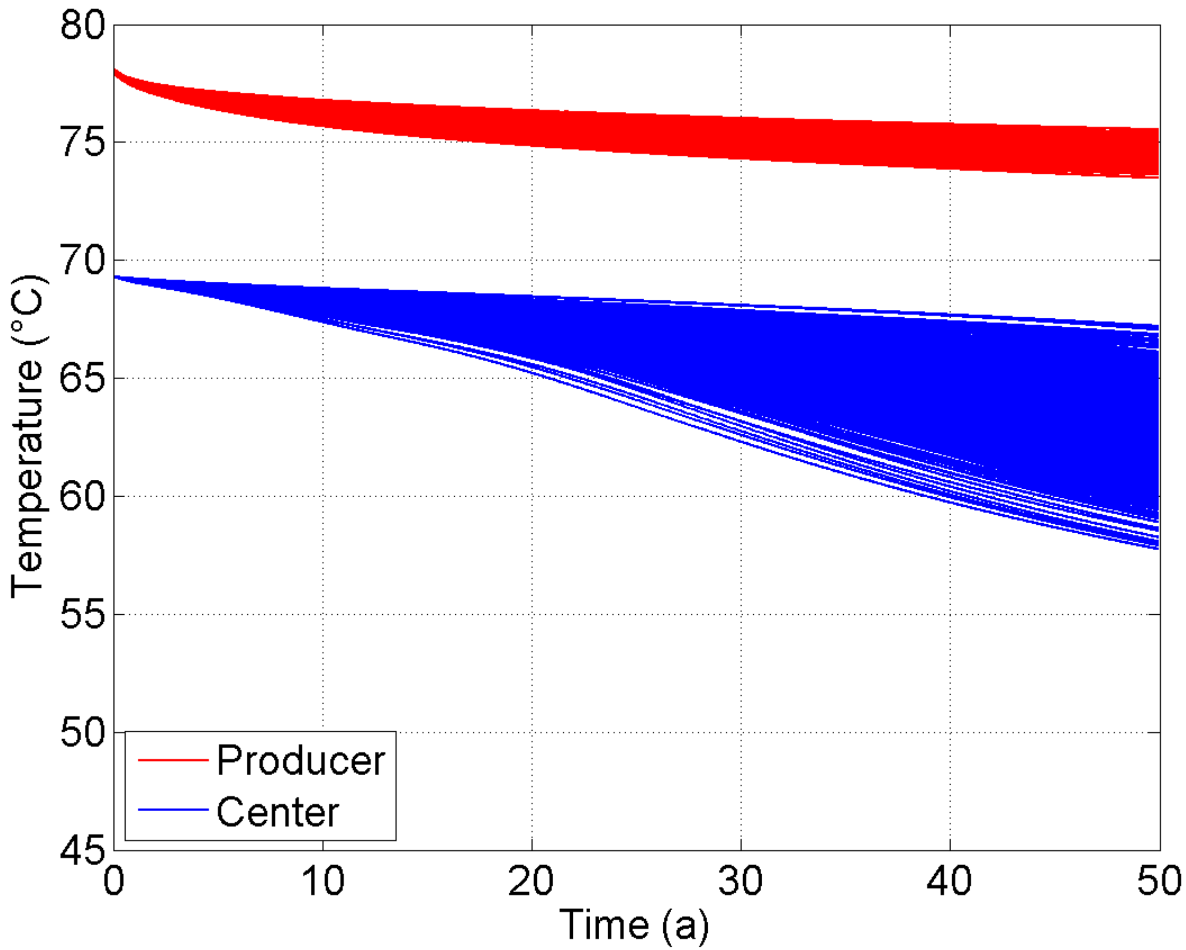


2000 m



Visualization support provided by Irene Tedjo-Palczynski

Transient temperature variation



- Correlation length: 1000 m
- 500 Realizations

Production temperature after 50 a

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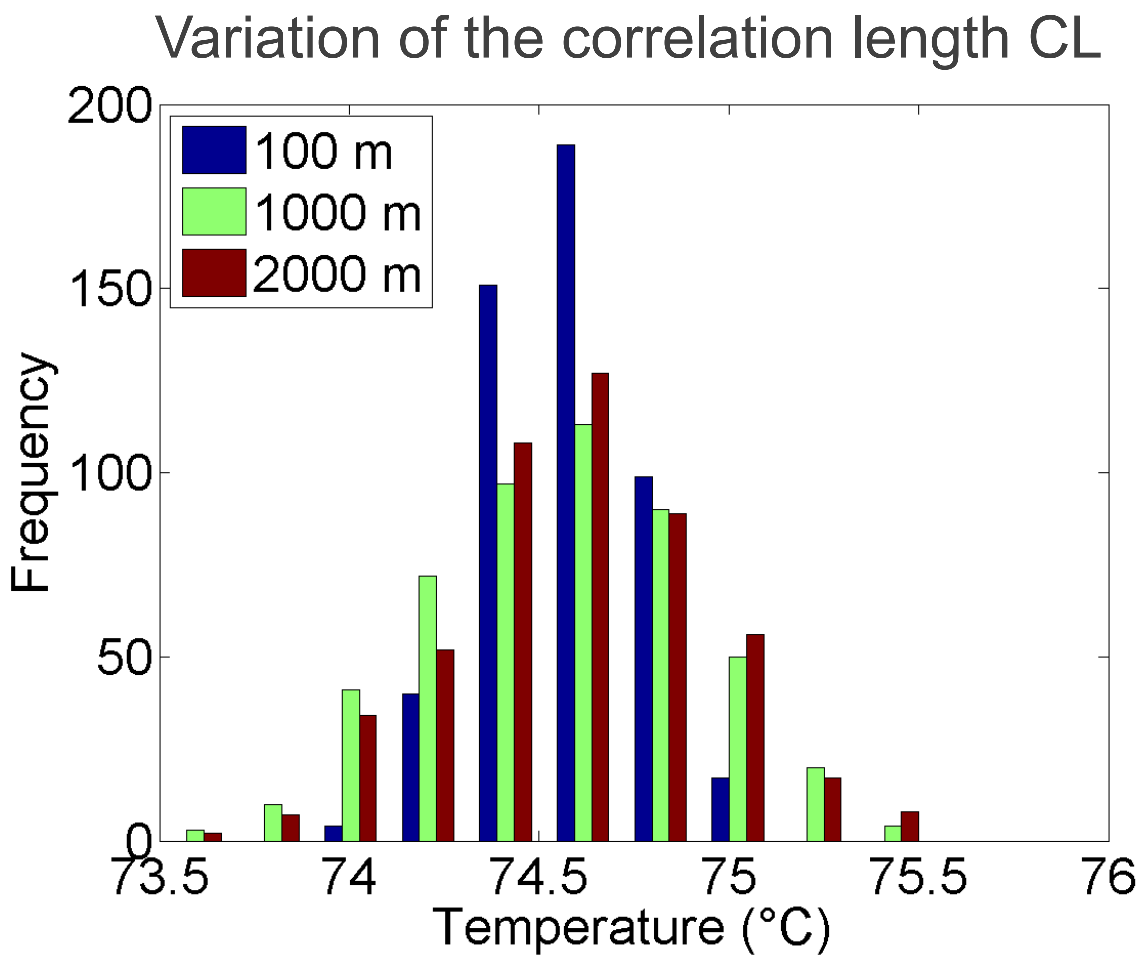

CL	T_{Mean}	σ(T)
100 m	74.6 °C	0.19 °C
1000 m	74.6 °C	0.35 °C
2000 m	74.6 °C	0.34 °C

σ (i.e. uncertainty) generally increases with correlation length

Thermal conductivity variation

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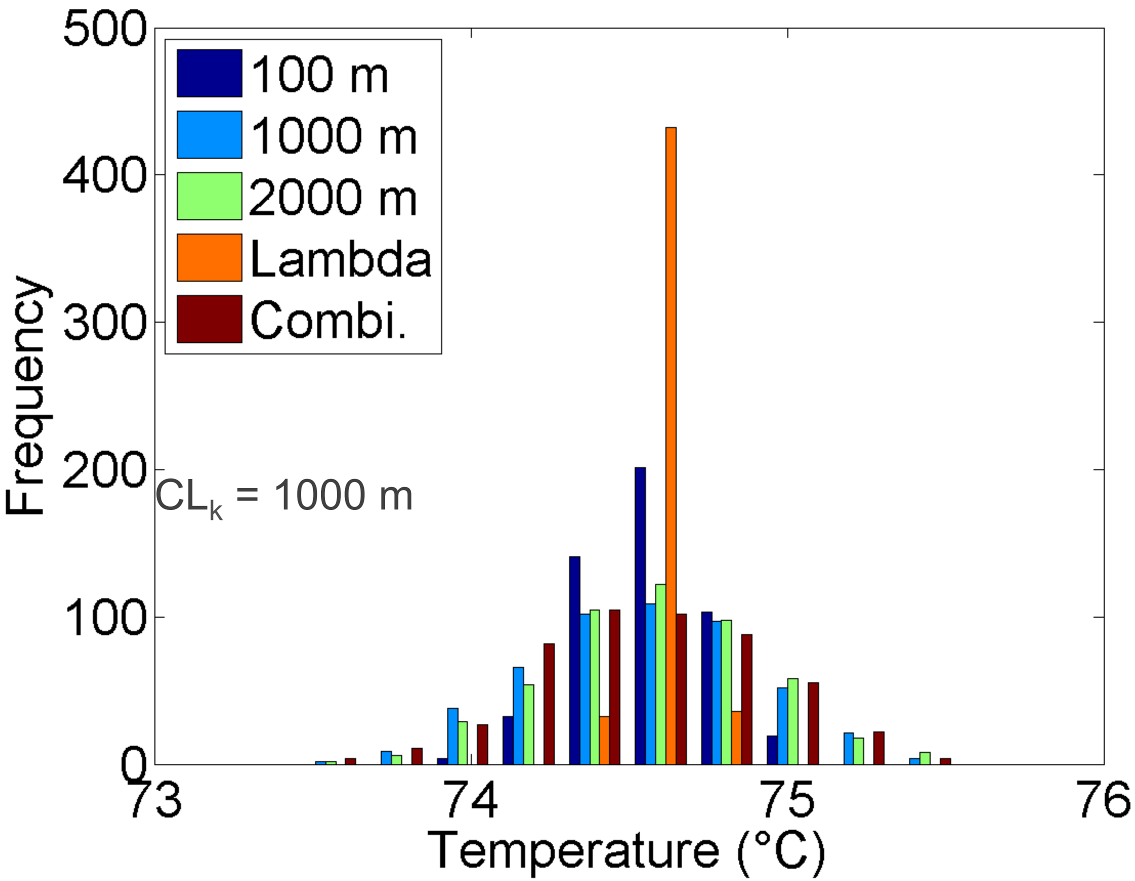

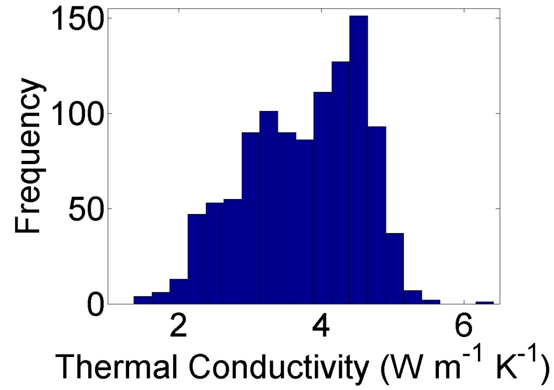

	T_{Mean}	σ(T)
λ	74.6 °C	0.07 °C
k	74.6 °C	0.35 °C
Combined	74.5 °C	0.36 °C

➔ Very little influence!

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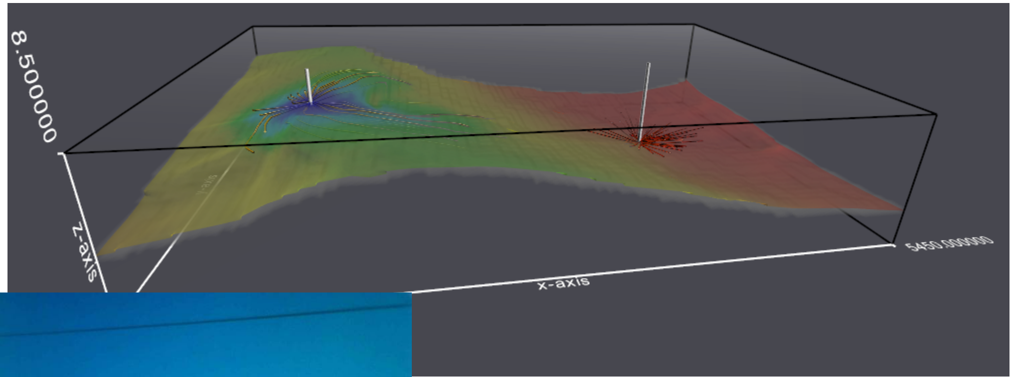
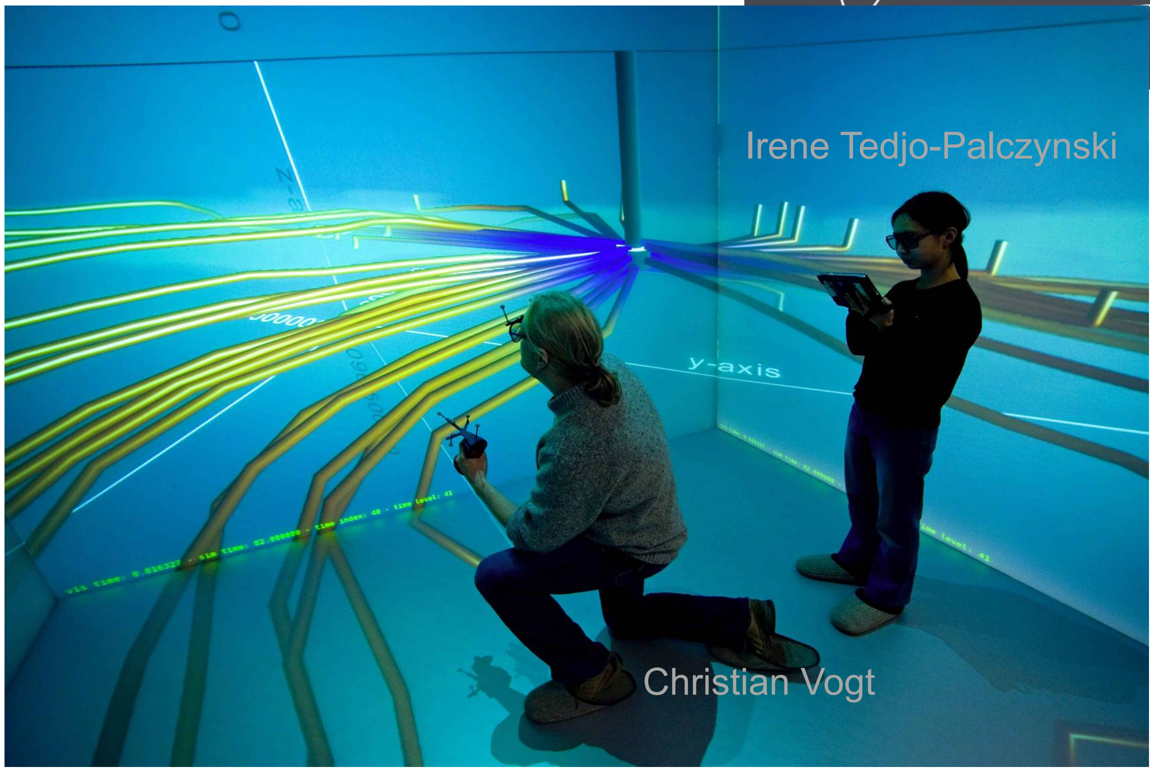
3D visualisation for optimizing interpretation





Thank you for your attention!