Statistical approach to inferring thermal and hydraulic rock properties

E.ON Energy Research Center

Case study on German tertiary and paleozoic rocks

Christoph Clauser

Institute for Applied Geophysics and Geothermal Energy

E.ON Energy Research Center, RWTH Aachen University

www.eonerc.rwth-aachen.de/gge

Renate Pechnig

Geophysica Beratungsgesellschaft, Aachen

www.geophysica.com

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Motivation

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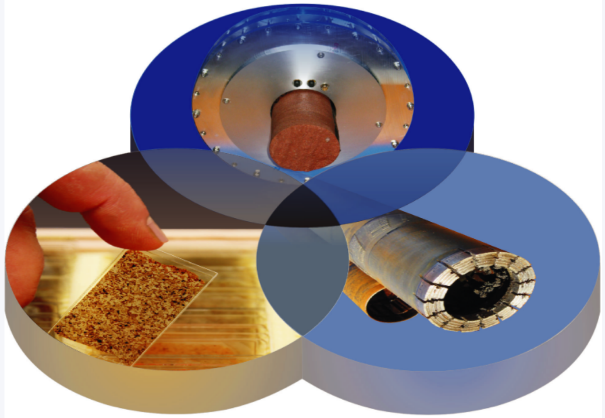
Integrated data analysis

petrophysics

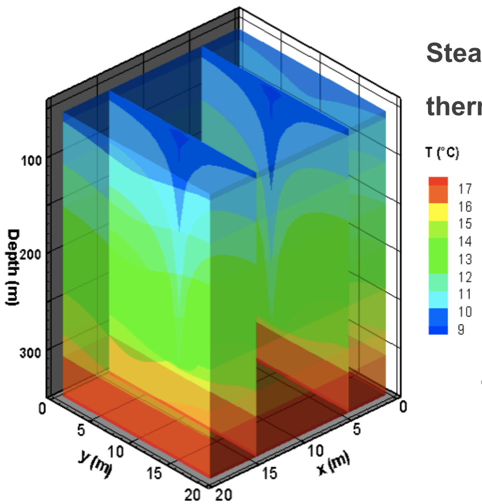


geology

borehole geophysics

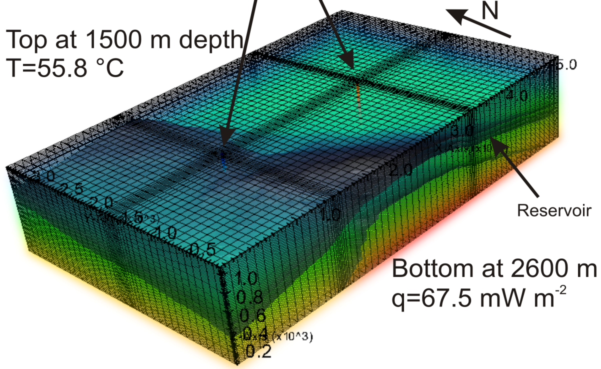
Derivation of statistically representative property values

… as input for numerical models



Steady-state thermal field

Dynamic reservoir model



Data source

Use of available data:

Borehole data and **core samples** from the archives of industry and the state geological surveys,
in particular from exploration wells for:

- hydrocarbons
- lignite
- hard coal
- general research boreholes

Core archive of the State Geological Survey of NRW near Krefeld.

Data source

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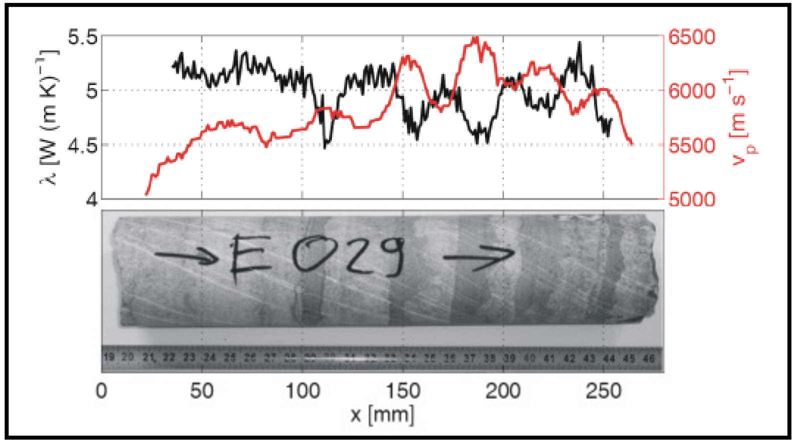
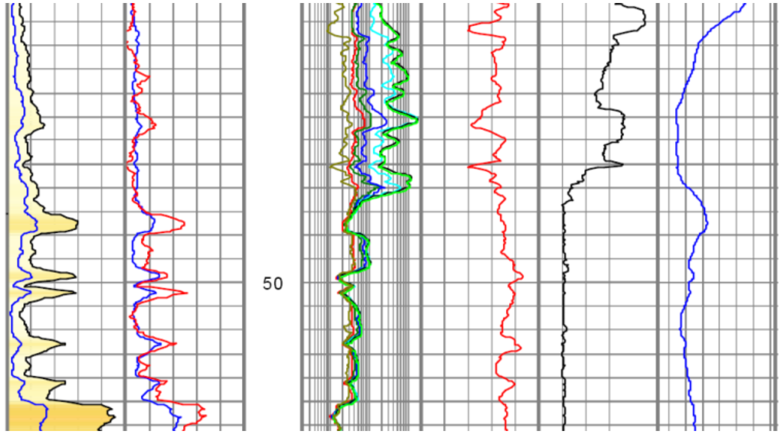
laboratory studies on
core samples

← correlation →

Analysis of
borehole data



Example of scanning measurement of thermal conductivity λ and sonic velocity v_p (interbedded dolomite - anhydrite).

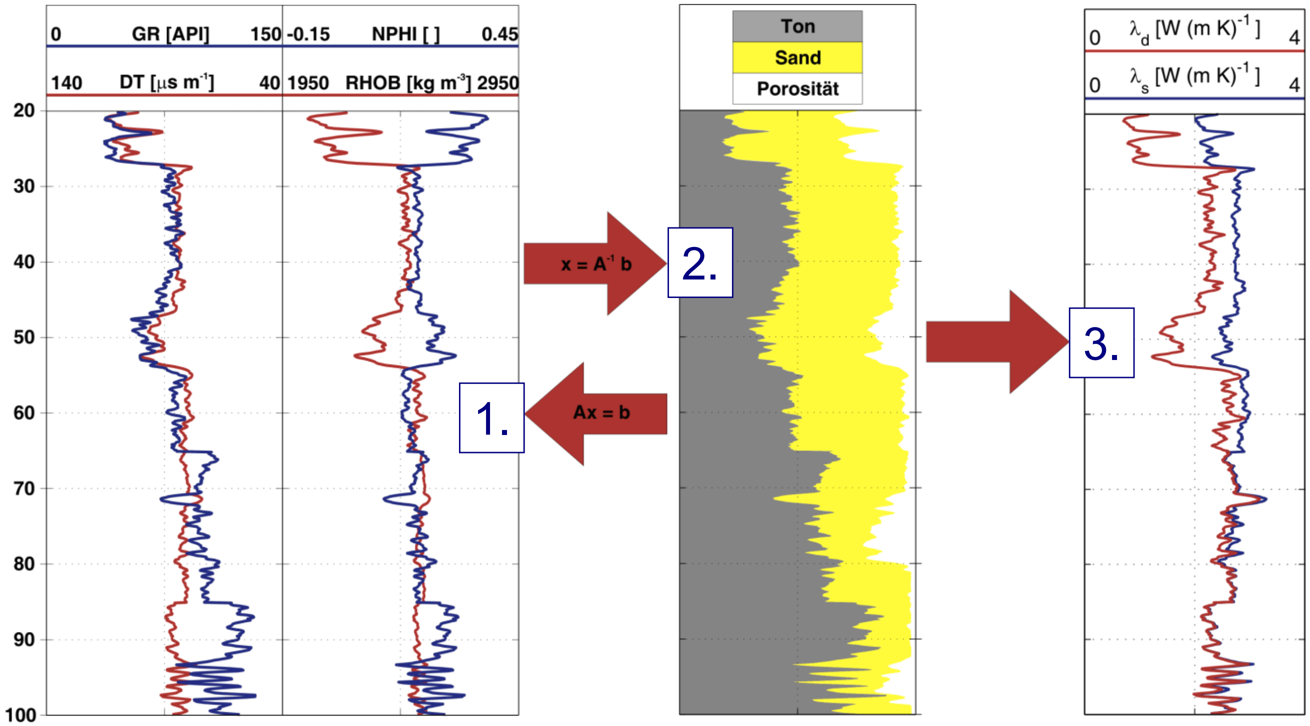


Example borehole data

+ direct measurements
- selective, not representative

+ spatial coverage of geologic units
+ complete vertical profiles

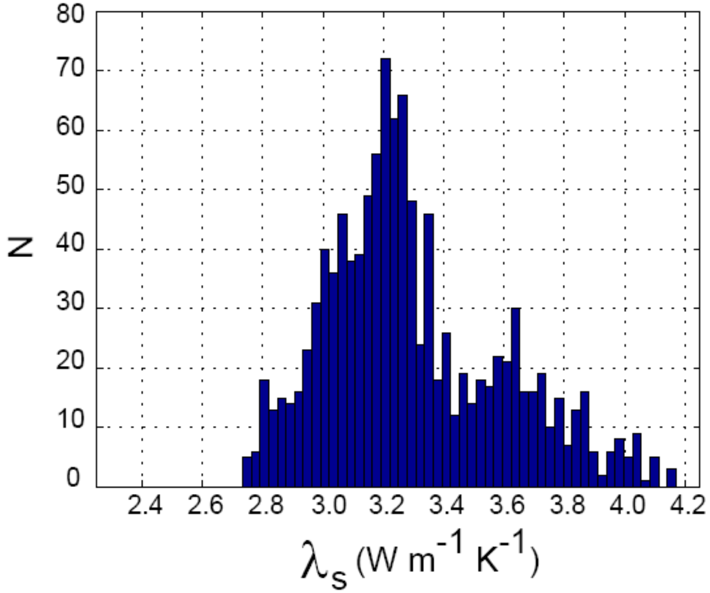
Data base: general approach



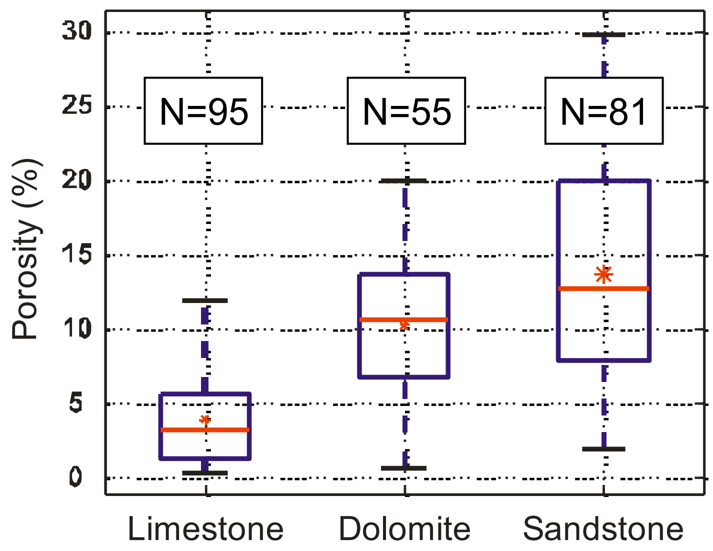
1. Correlate rock components and their specific log responses (provided)
2. Calculate volume fractions of rock components from borehole logs
3. Calculate bulk thermal conductivity from appropriate mixing laws

Data base

Statistical parameters of representative **rock types** and **geologic units**

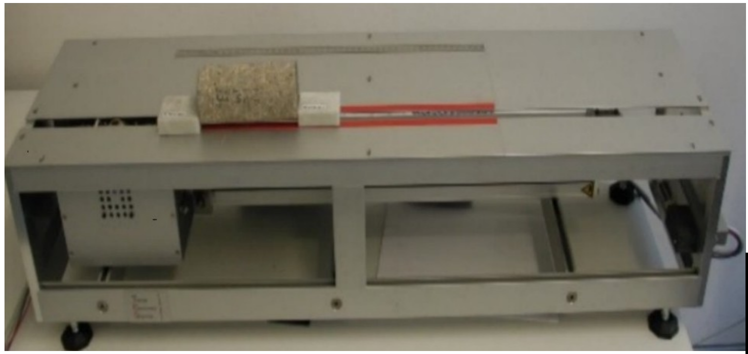


Example : Histogram of water saturated thermal conductivity λ_s of a geologic unit (Upper Devonian Limestone in the Lower Rhine Basin)



*Example : Box-Whisker-diagrams of porosity of main rock types in South-Western Germany (Molasse Basin). *: mean; _: median; box: 25 and 75 percentile; |-----|: min-max range.*

Core scanning (thermal Conductivity)



Optical scanning:
range: 0.2 W m^{-1} K^{-1} – 25 W m^{-1} K^{-1}
accuracy: ± 3 %

up to 60 samples per hour

Data base: thermal conductivity scanning

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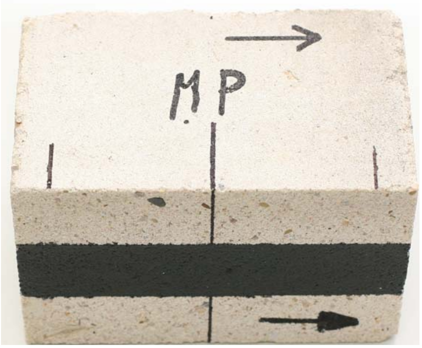
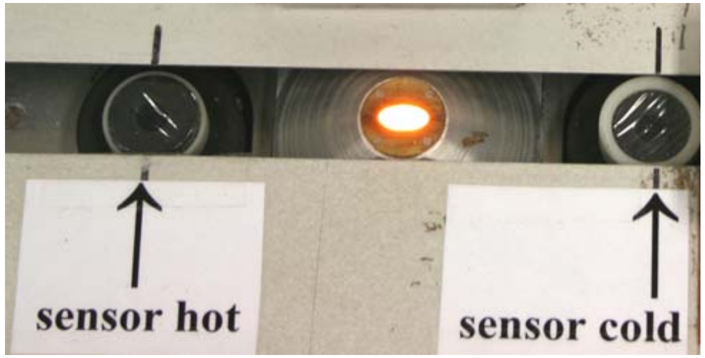
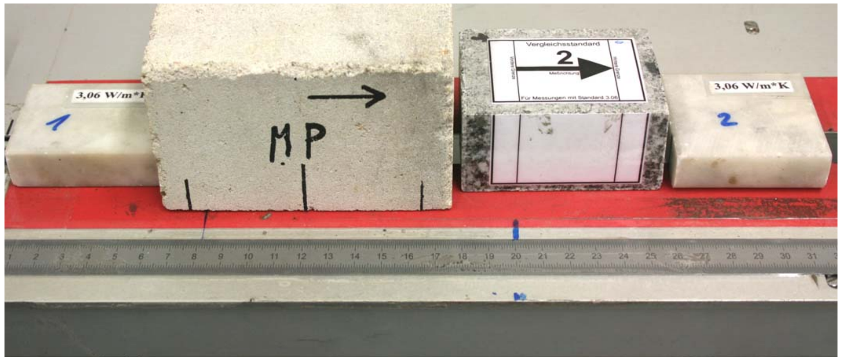
- Thermal conductivity scanner (TCS)



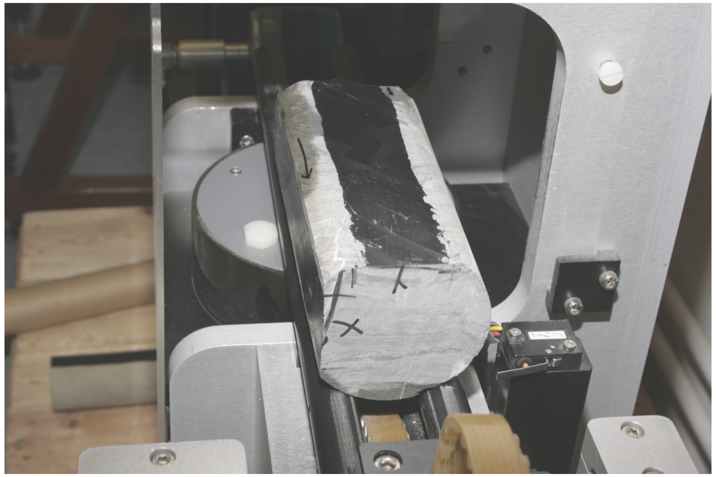
Sample with paint and markings



Sensors with heat source



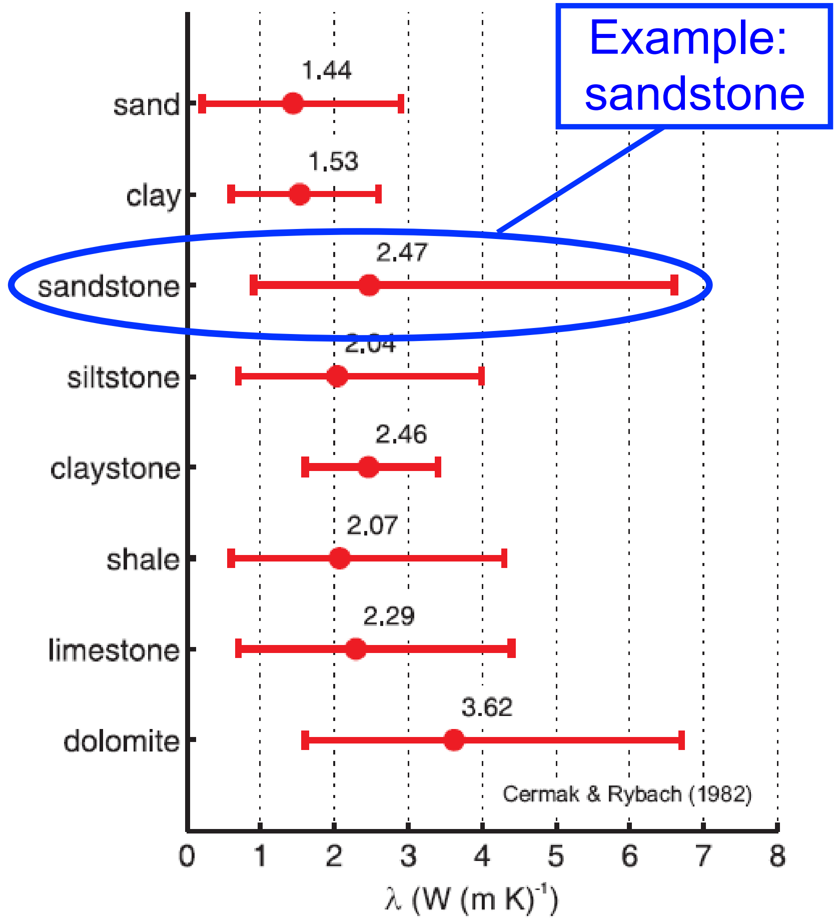
Measuring arrangement on TCS:
standard – sample – standard of comparison - standard



Finished core sample with two scan lines

Conventional input data

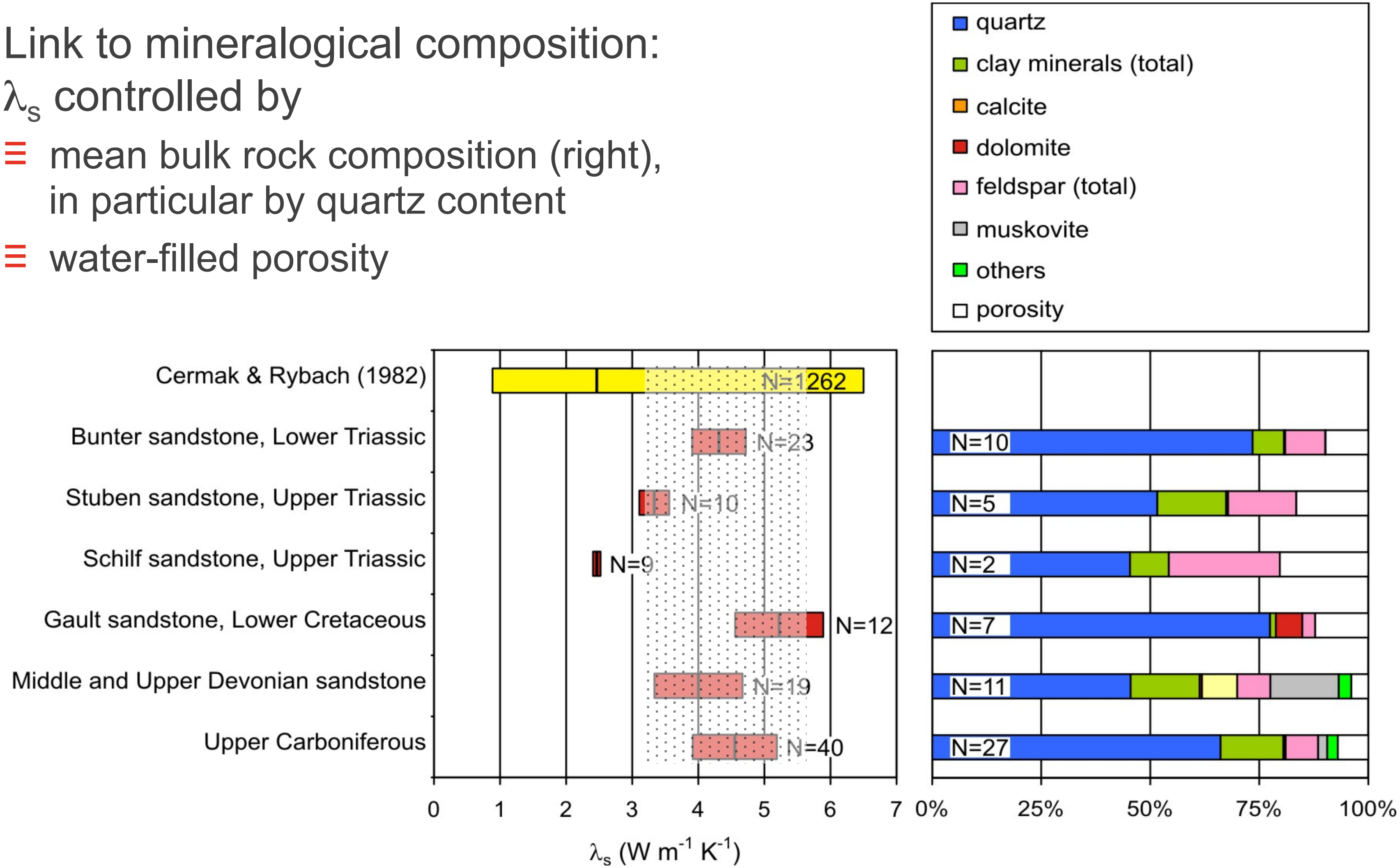
- Wide range of tabulated data values: large uncertainty for predicted energy production
- Conservative estimates of rock properties: deeper boreholes than necessary
- ⇨ Cost reduction possible if rock properties were known more accurately and with specified precision



Range of thermal conductivity (min-max) for various rock types (Čermak & Rybach, 1982).

Data base: thermal conductivity of sandstones

- Link to mineralogical composition: λ_s controlled by
  - mean bulk rock composition (right), in particular by quartz content
  - water-filled porosity

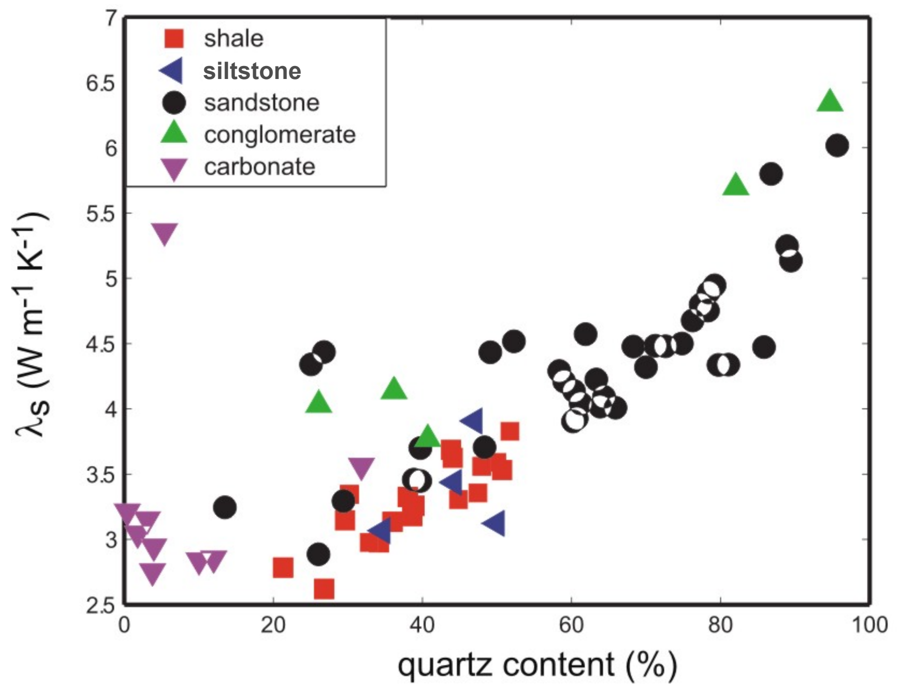


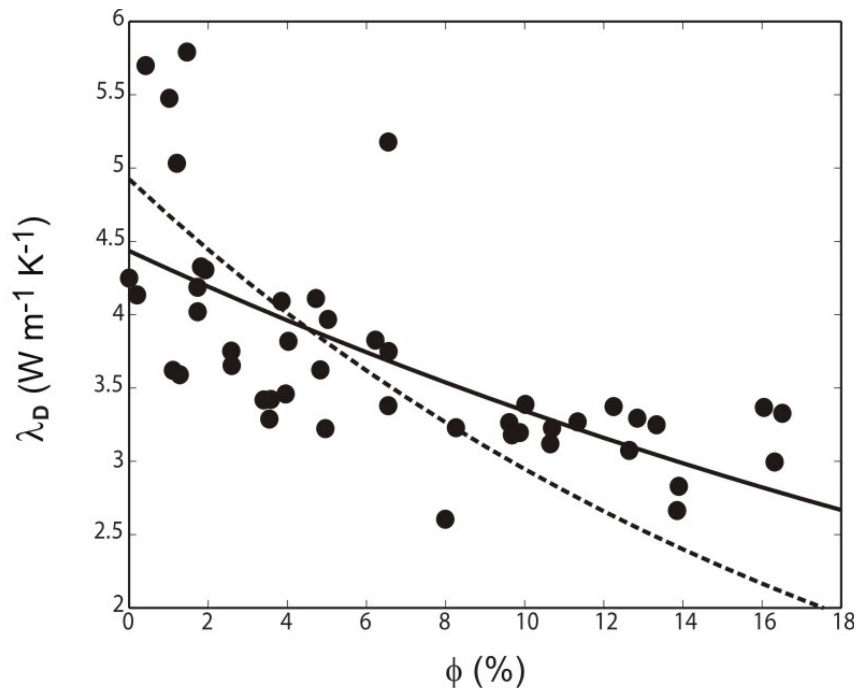
Data base: thermal conductivity of sandstones

- Saturated thermal conductivity vs. quartz content (left)
- Dry thermal conductivity vs. porosity (right)

$$\lambda_{geo}(\phi) = \lambda_{matrix}^{(1-\phi)} \cdot \lambda_{air}^{\phi}$$

$$\lambda_{Asaad}(\phi) = \lambda_{matrix}^{(1-f\phi)} \cdot \lambda_{air}^{f\phi}$$





Data base: variation of thermal conductivity with pressure and temperature

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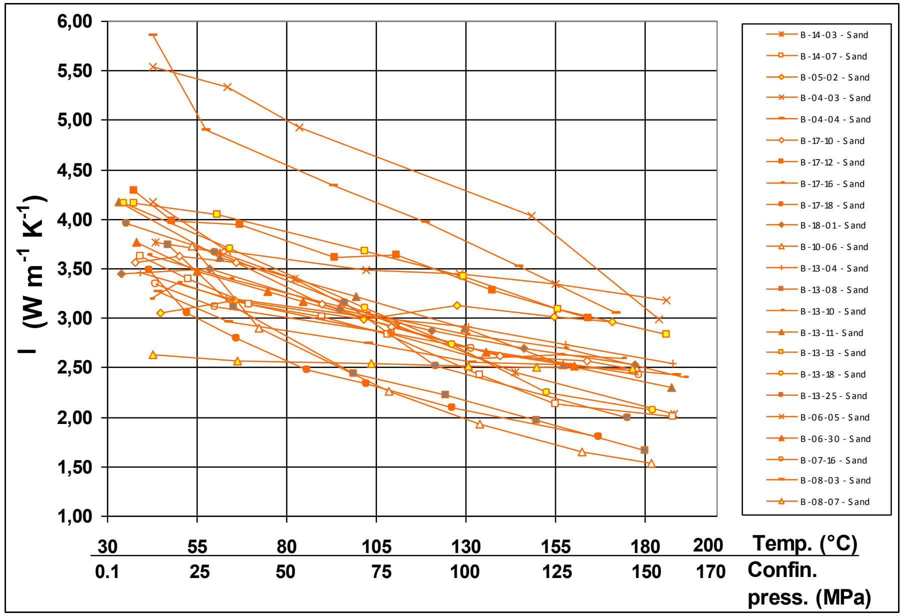
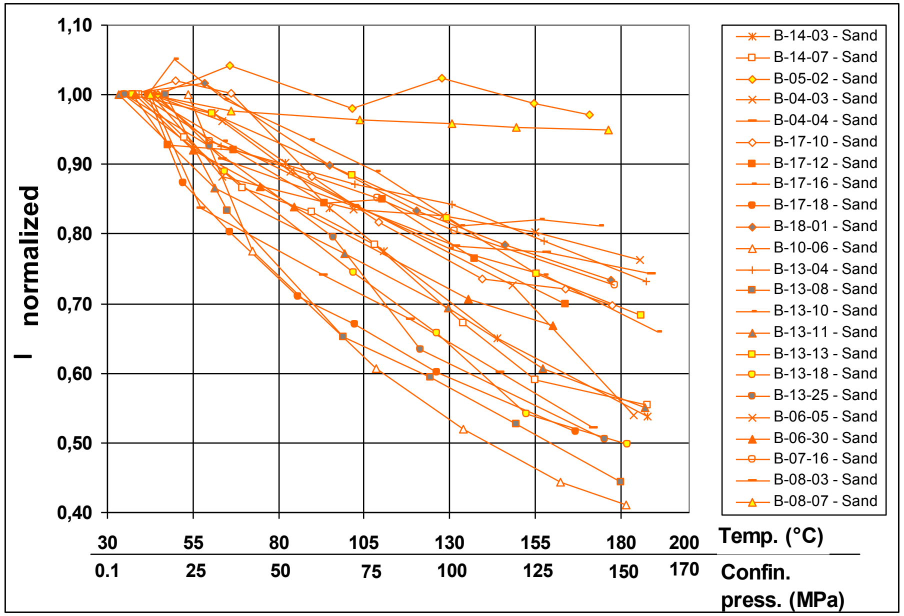
- λ as a function of burial depth (pressure and temperature)





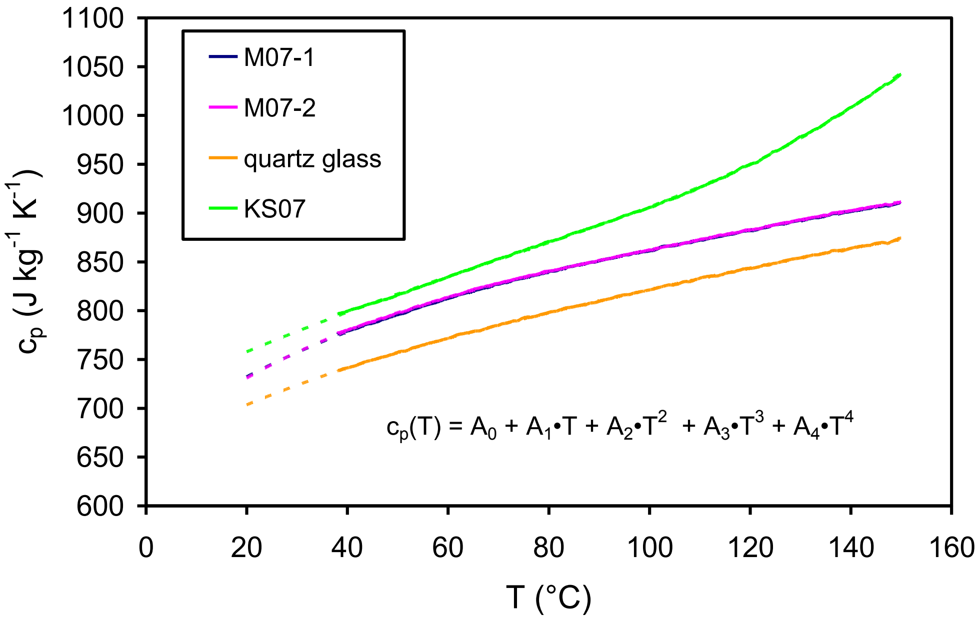
Variation of sandstone thermal conductivity with p and T (left)

and normalized to ambient p-T conditions (right)

Data base: specific heat capacity testing

- Device: differential heat flow calorimeter

- Example of c_p-measurements



Data base: specific heat capacity

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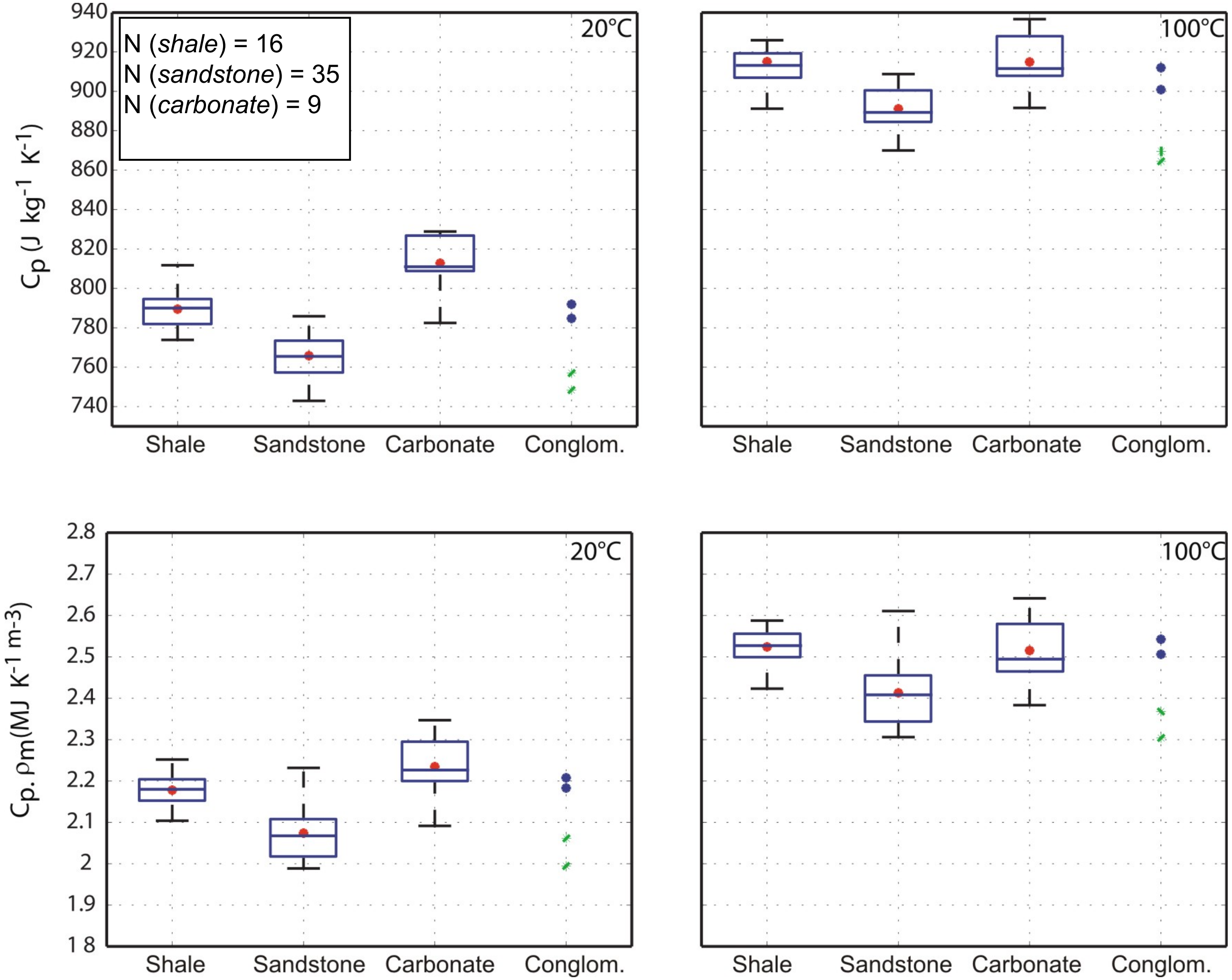
- specific heat capacity of main rock types
- volumetric heat capacity of main rock types



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Data base: specific heat capacity

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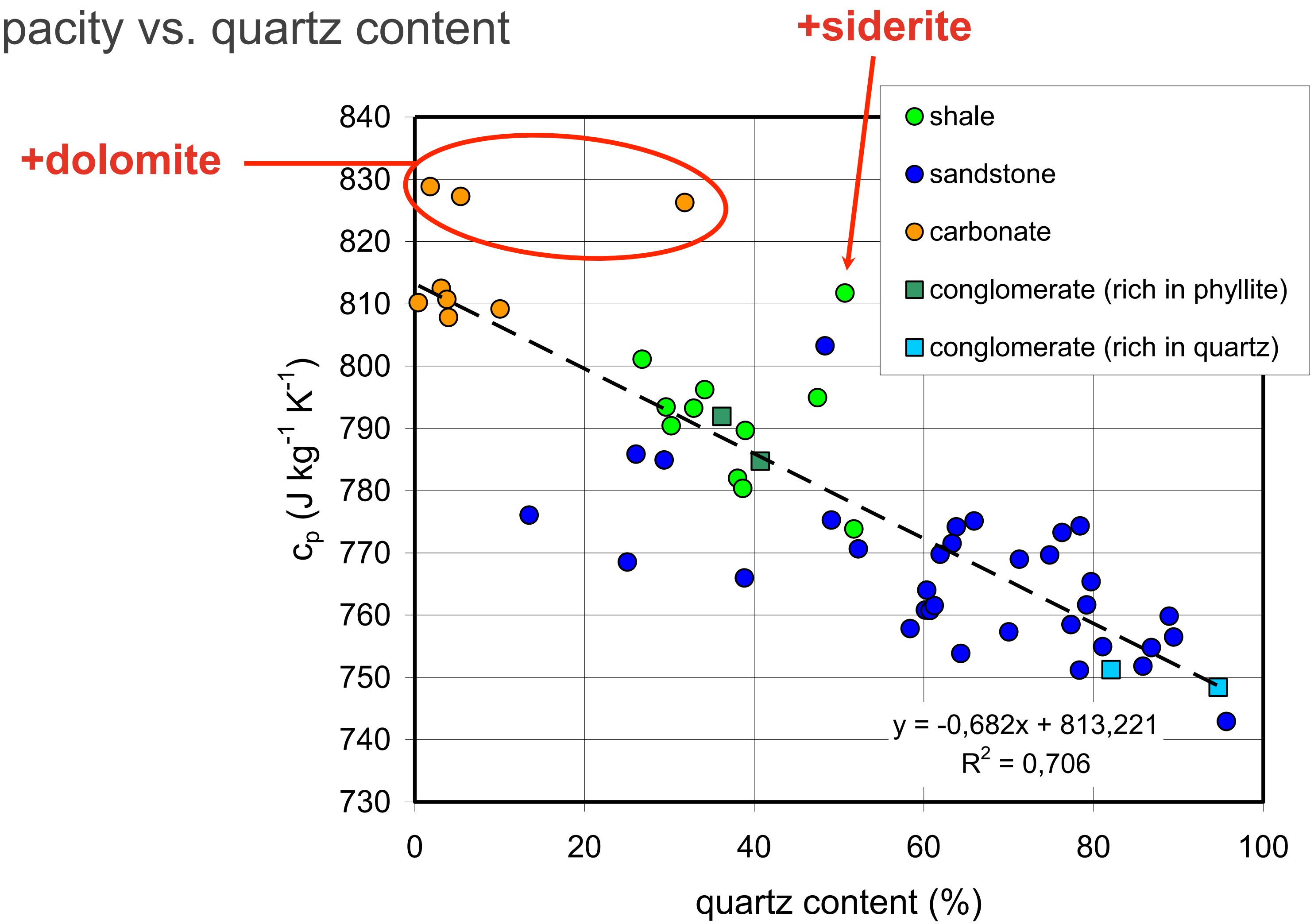
heat capacity vs. quartz content



Case study on tertiary and paleozoic rocks

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APPLIED GEOPHYSICS AND GEOTHERMAL ENERGY

- Measurements on core samples:
  - Thermal Conductivity
  - Specific Heat Capacity
  - P-Wave Velocity
  - Bulk and Matrix Density
  - Gamma Density
  - Porosity by different methods
  - NMR for Porosity/Permeability
- By third party:
  - He-Permeability
  - XRF and XRD
  - Mercury Injection

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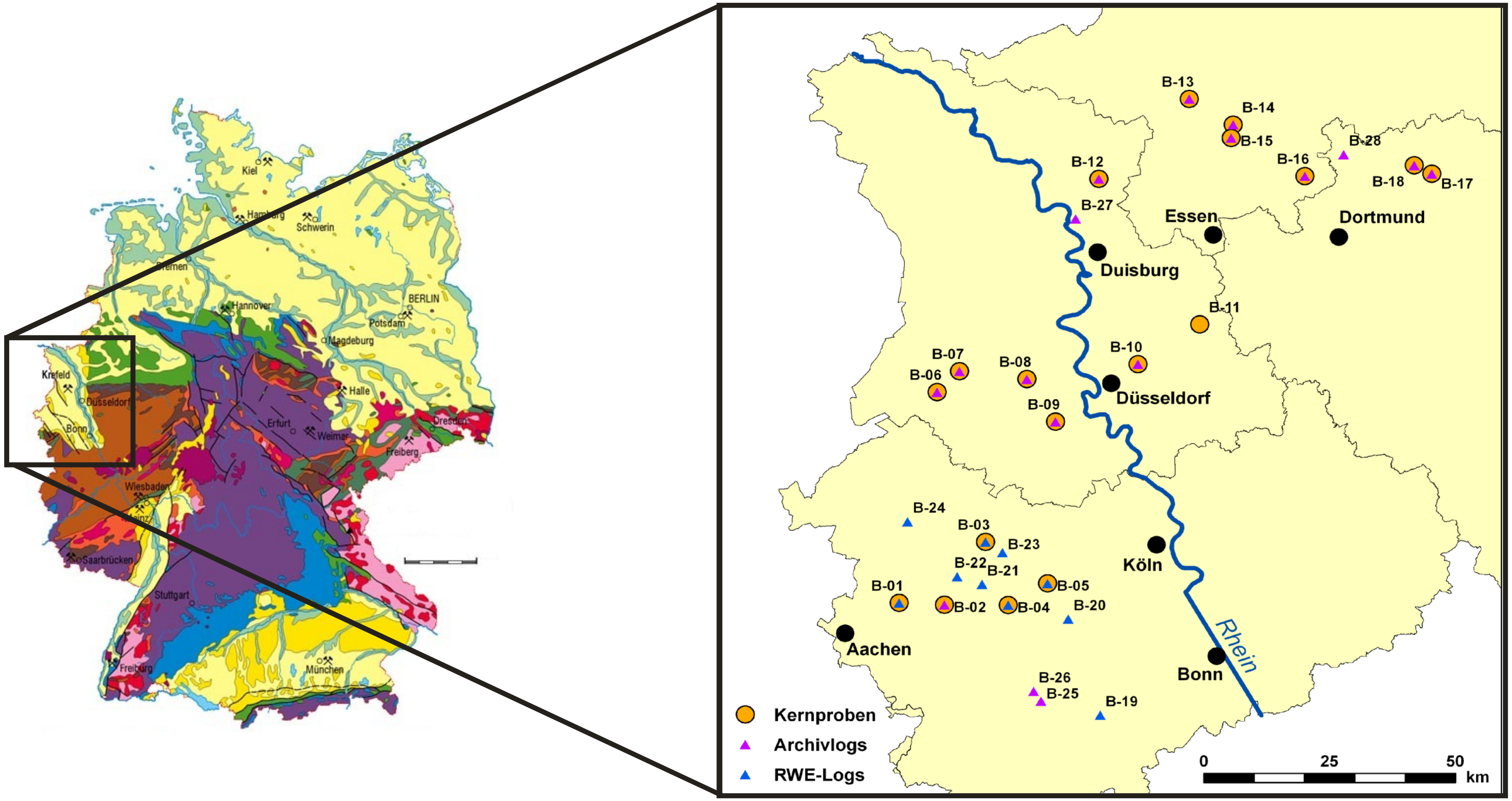
- Log Analysis:
  - Formation Evaluation
  - Lithology, Clay Volume
  - Porosity
  - Core-Log Integration
  - Thermal Conductivity Profiles
- Measurements on core samples
  - Spectral Gamma (K, Th, U)
- By third party (Prof. Popov, Moscow)
  - P-T dependend thermal conductivity and diffusivity

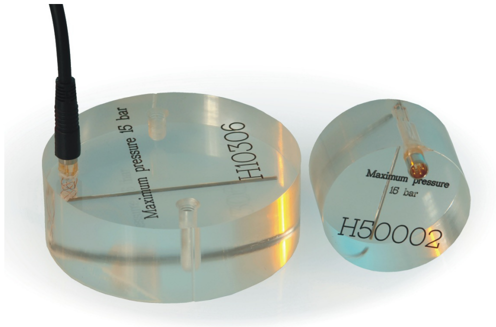
Study area and boreholes



Exploration and research wells:
Tertiary sediments and paleozoic basement

Thermal conductivity on cottings

- 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:

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

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

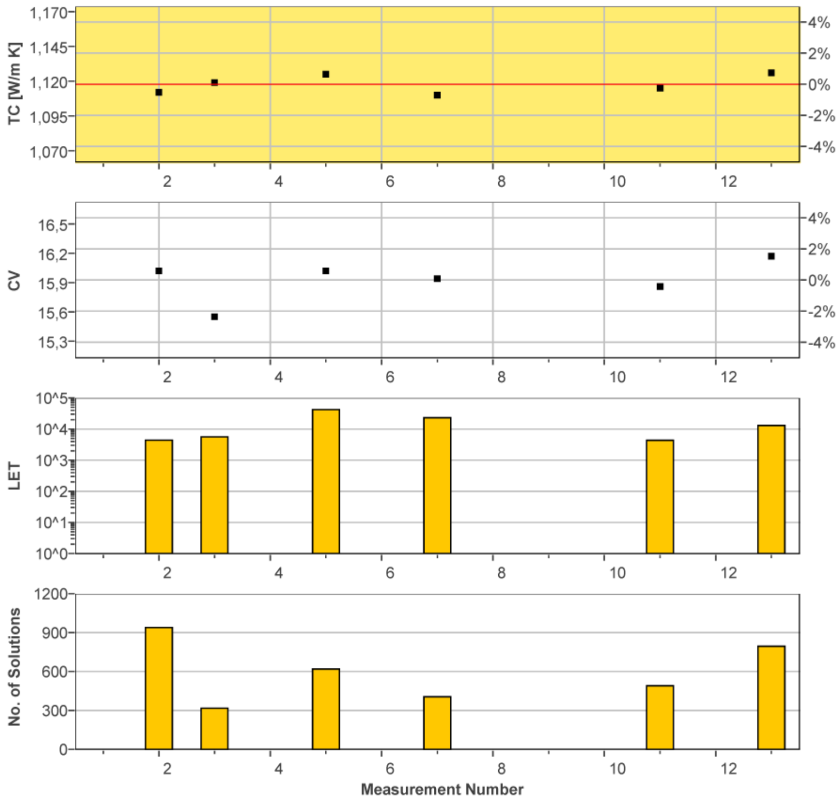
$$\text{(c)}\ \lambda_{mean} = \frac{1}{2}\left(\lambda_{\parallel} + \lambda_{\perp}\right);$$

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

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

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

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



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%

Lower Rhine Embayment (Tertiary)

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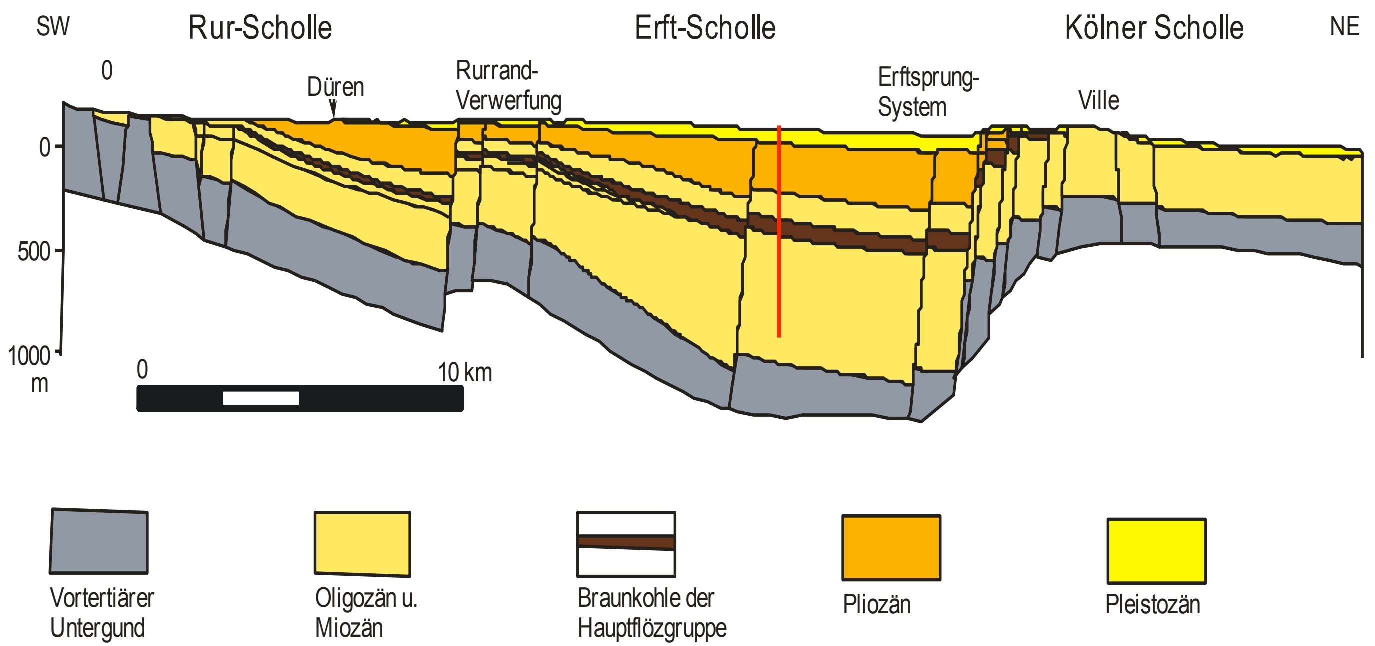
- 740 m borehole penetrating the complete sequence of unconsolidated tertiary sediments
- Samples: Sands snd clays



nach Geol. Landesamt NRW (1988)

Petrophysics - Tertiary sediments

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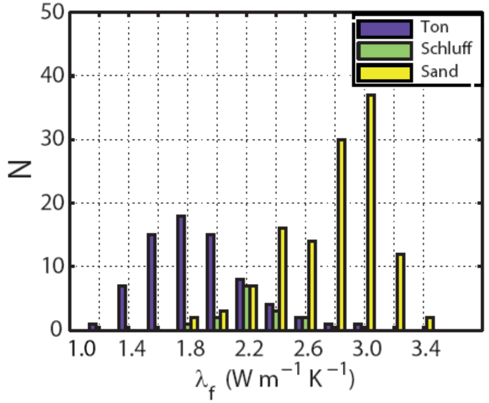
Statistical moments

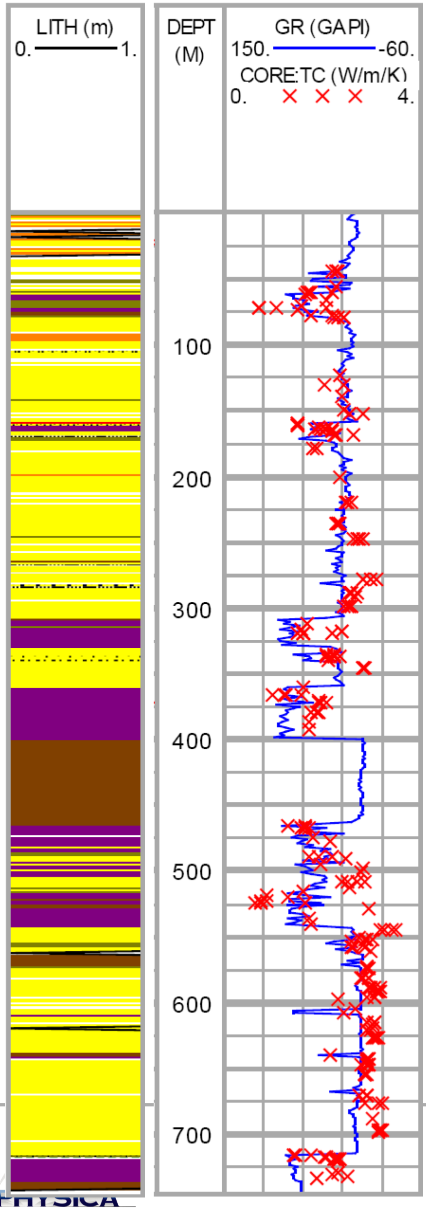
Listed in tables and histrograms

For the main rock types

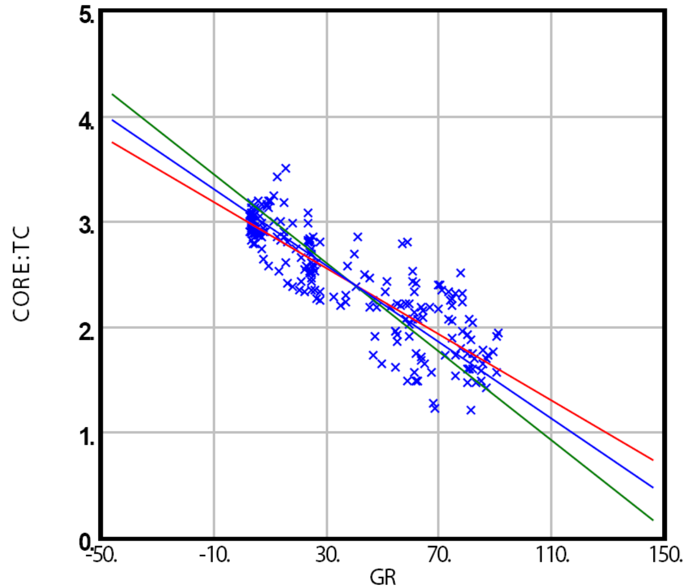


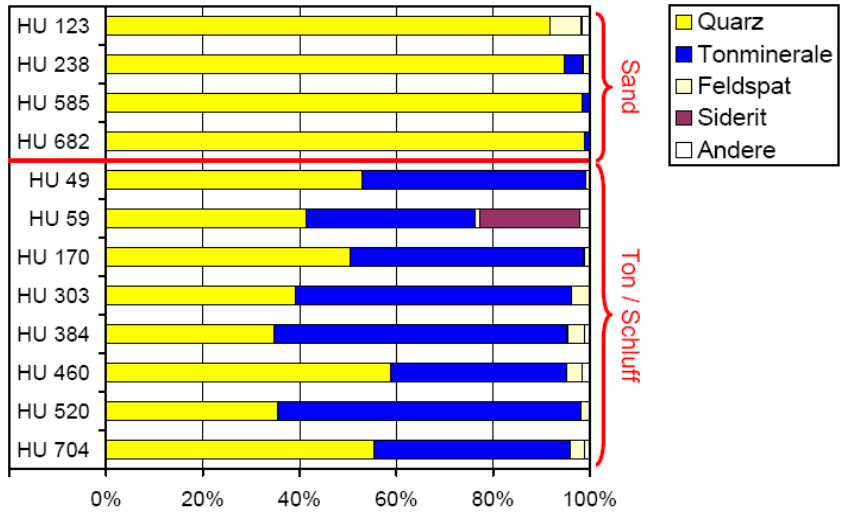
			N	Mittel-wert	Stabw.	Min.	25%-Quart.	Median	75%-Quart.	Max.
λ_f (W m^{-1} K^{-1})	Ton		72	1,88	0,33	1,28	1,64	1,81	2,06	2,96
	Schluff		15	2,25	0,20	1,86	2,19	2,24	2,41	2,61
	Sand	Gesamt:	123	2,76	0,33	1,82	2,53	2,86	2,99	3,50
		<245 m:	27	2,39	0,24	1,82	2,30	2,36	2,52	2,82
		>245 m:	96	2,86	0,27	2,07	2,80	2,90	3,02	3,50
	Braunkohle		3	0,70	0,05	0,66				0,75
ρ_m (kg m^{-3})	Ton	RWTH:	25	2668	122	2360	2642	2655	2682	3092
		RWE:	28	2613	61	2420	2590	2620	2640	2750
		Gesamt:	53	2639	98	2360	2610	2640	2663	3092
	Schluff		19	2666	49	2547	2645	2680	2697	2759
	Ton/Schluff		72	2646	88	2360	2620	2645	2682	3092
	Sand		139	2640	29	2368	2634	2645	2650	2694
	Braunkohle		4	1428	16	1412				1451
Φ (-)	Ton		49	0,337	0,054	0,219	0,300	0,330	0,378	0,430
	Schluff		19	0,331	0,048	0,270	0,300	0,316	0,353	0,430
	Ton/Schluff		68	0,335	0,052	0,219	0,300	0,322	0,372	0,430
	Sand	RWTH:	117	0,409	0,027	0,285	0,393	0,412	0,425	0,467
		RWE:	19	0,361	0,049	0,250	0,340	0,360	0,395	0,430
		Gesamt:	136	0,403	0,035	0,250	0,390	0,406	0,425	0,467
	Braunkohle		n.b.							

Core-Log Integration



- Correlation of Gamma Ray, thermal conductivity and quartz content.





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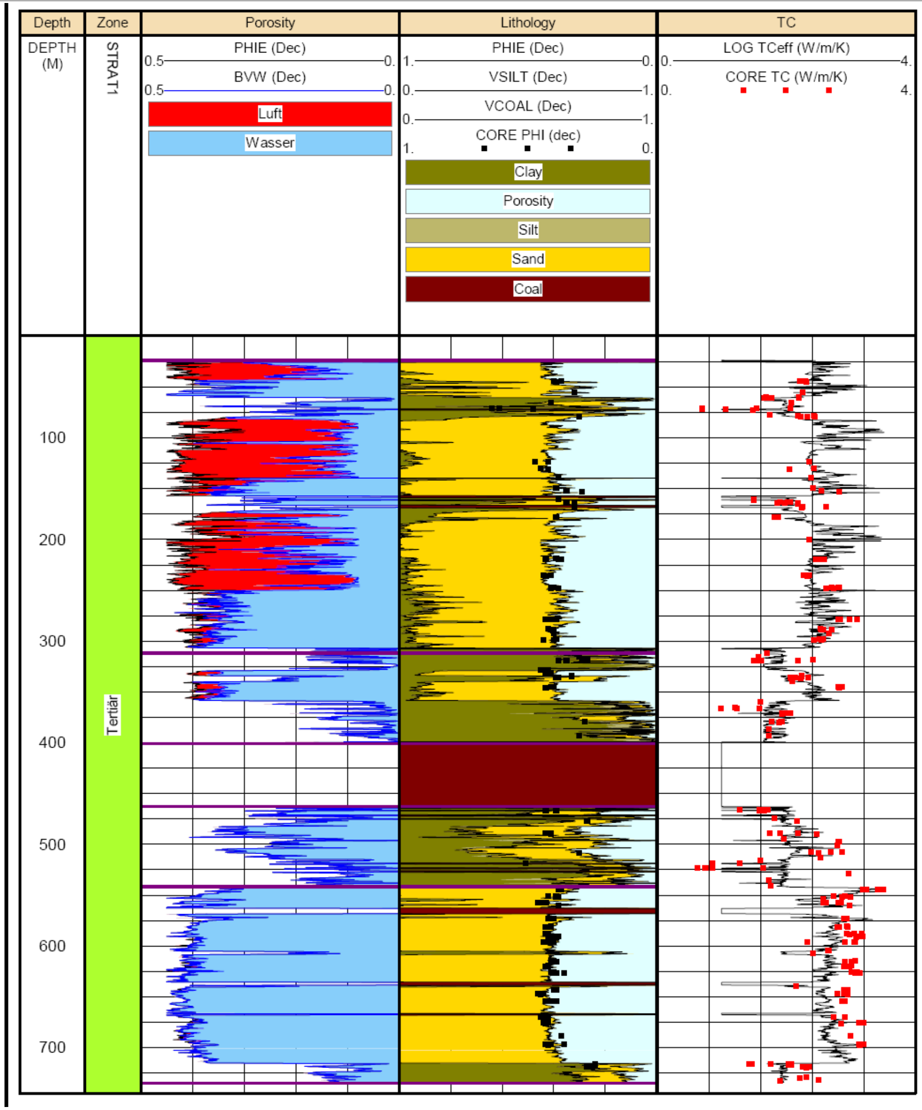
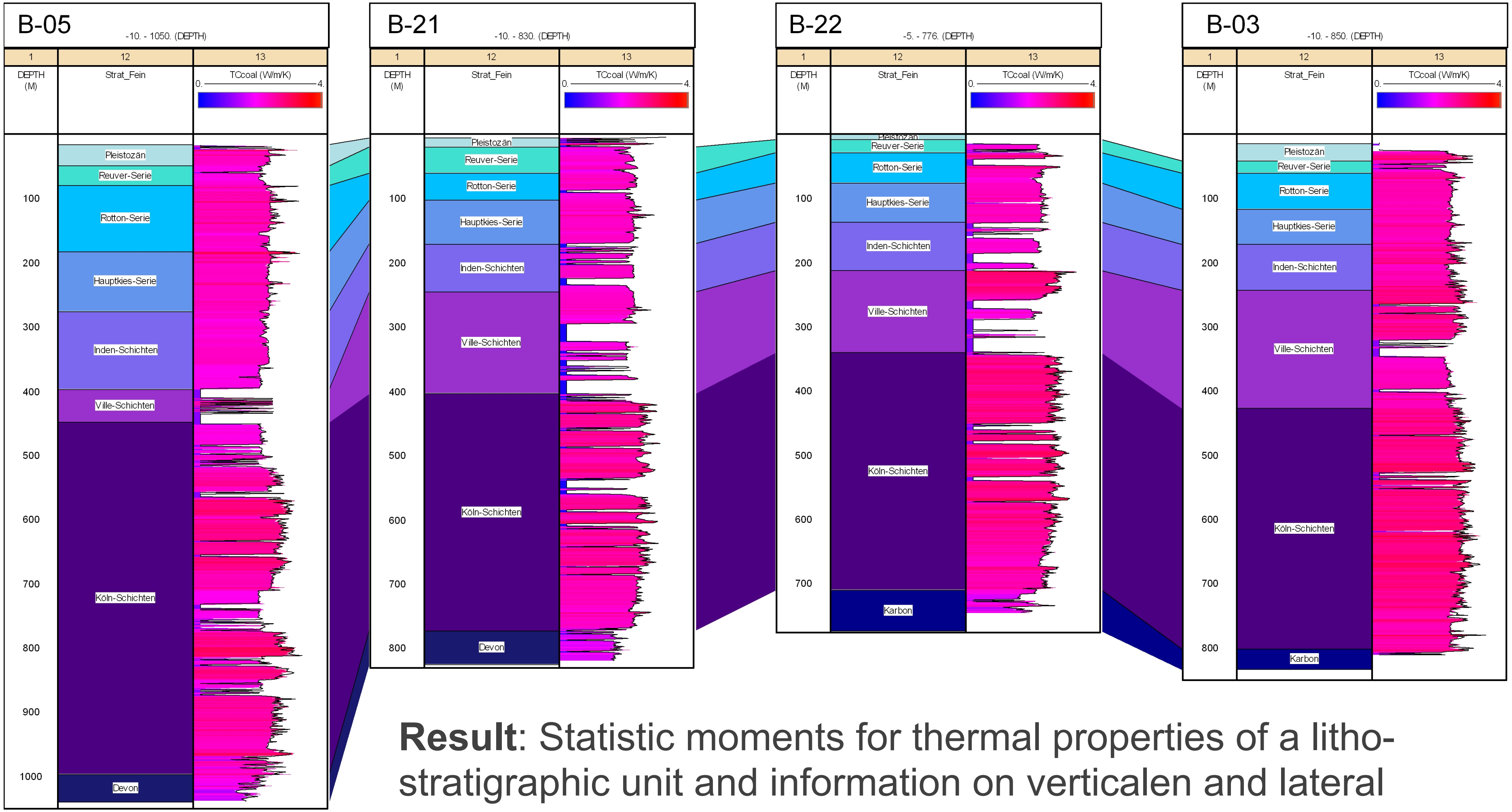
Logs - Tertiary

- Result of log interpretation
  - Porosity from density log
  - Saturation from resistivity logs
  - Lithology from GR
  - Effective thermal conductivity from geometric average: $\lambda_{geo}(\phi) = \lambda_m^{(1-\phi)} \cdot \lambda_{a,w}^{\phi}$
  - Matrix values from laboratory testing



Correlation



Result: Statistic moments for thermal properties of a litho-stratigraphic unit and information on verticalen and lateral variation.

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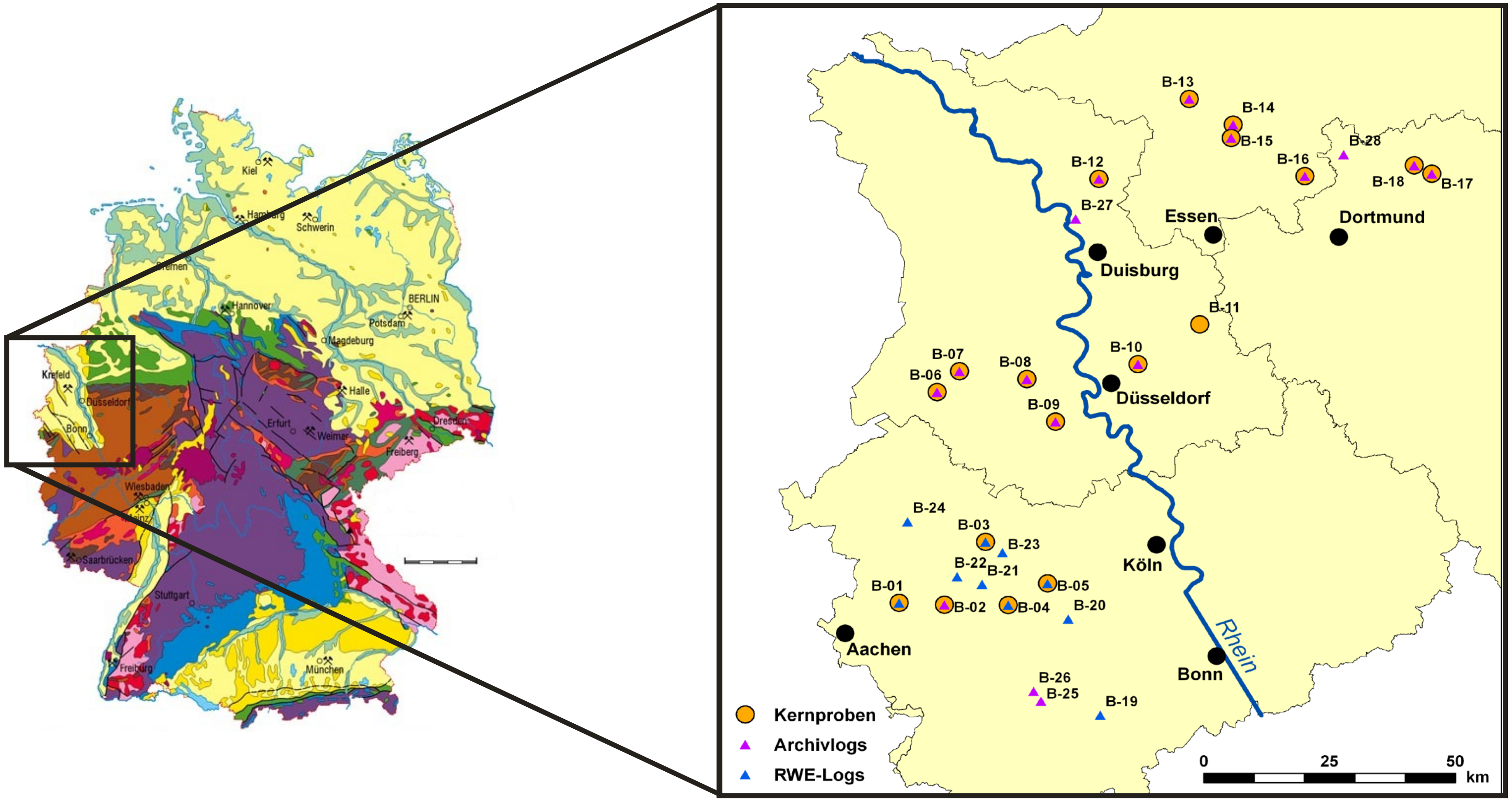
Drilling Locations, Paleozoic rocks



Exploration wells: Tertiary sediments and paleozoic basement rocks

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Examples from RWTH-1

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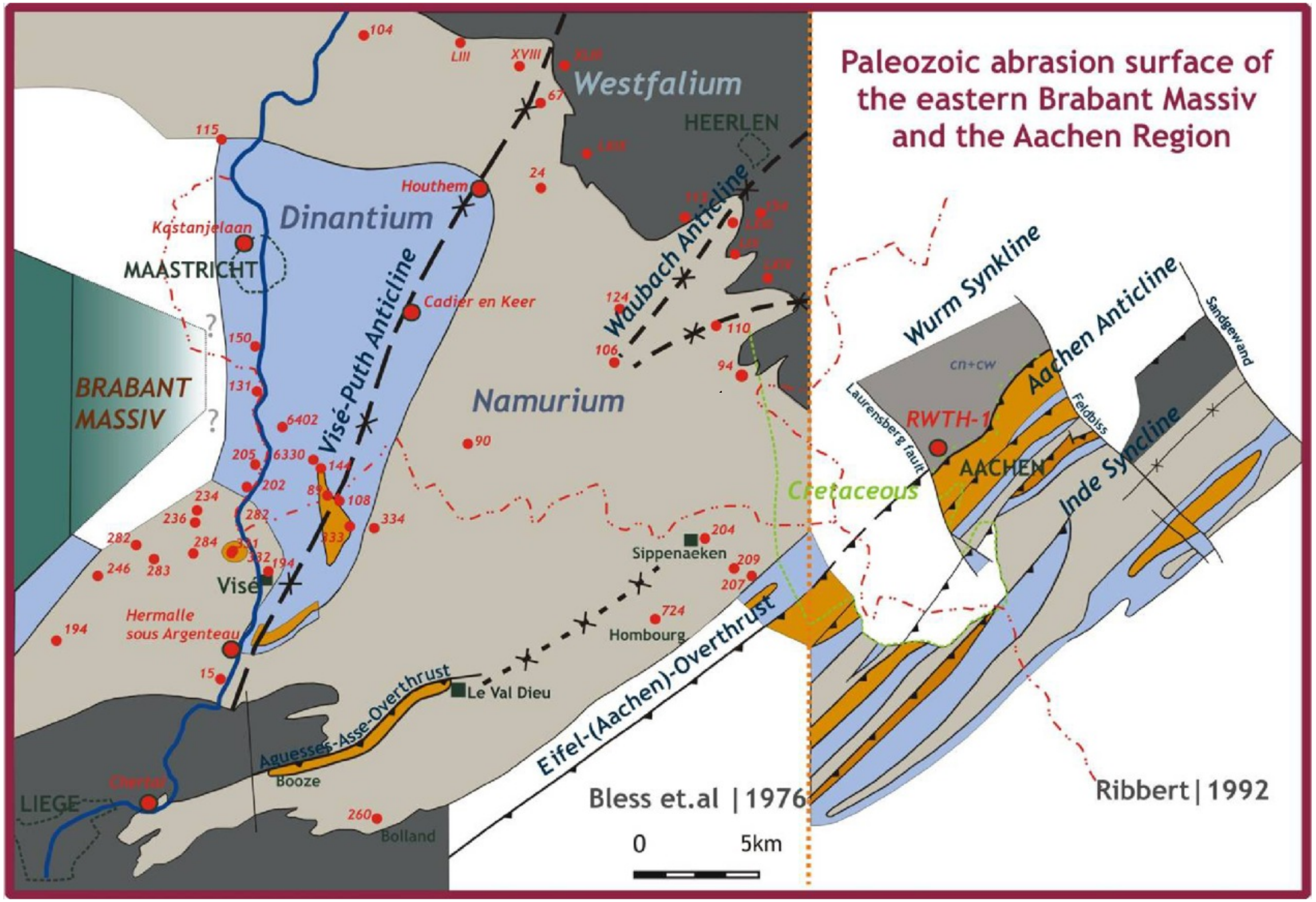
… a 2.5 km deep well in the front of the Aachen overthrust



Rock samples from RWTH-1

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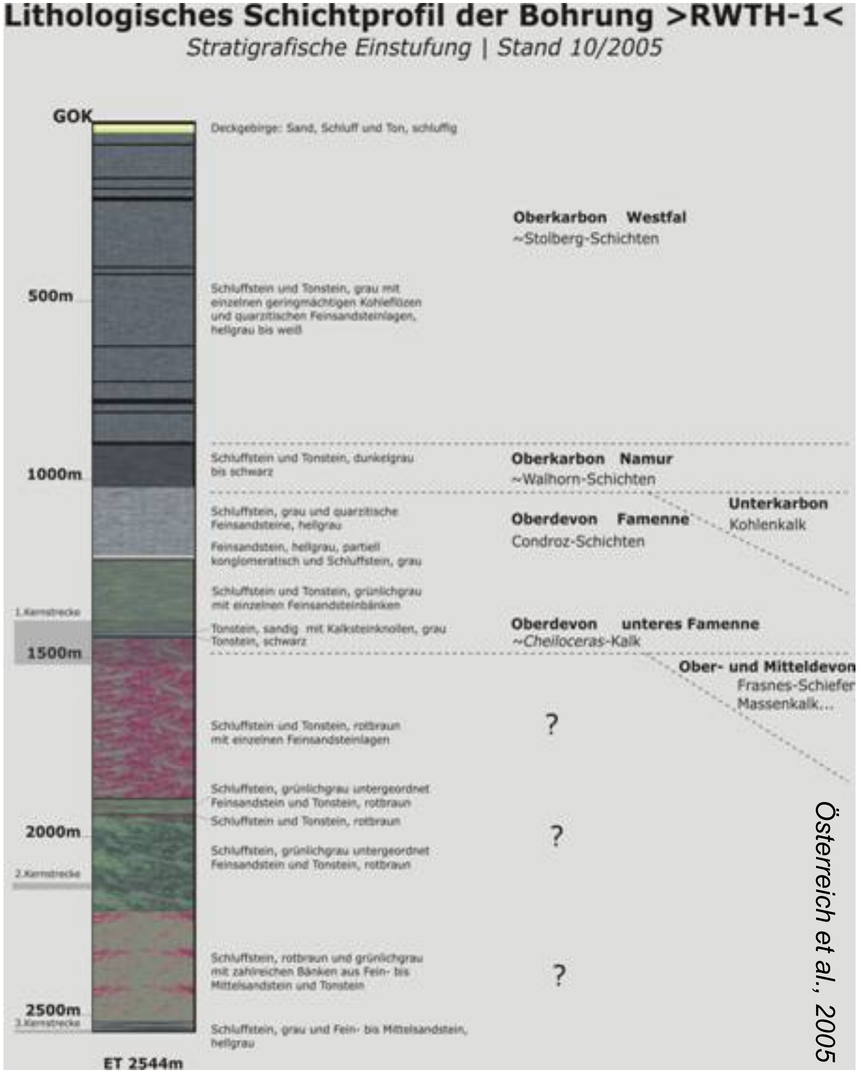

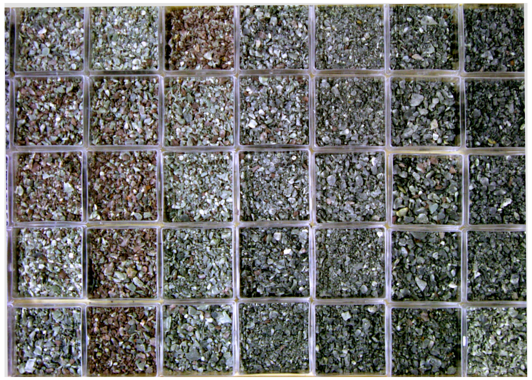

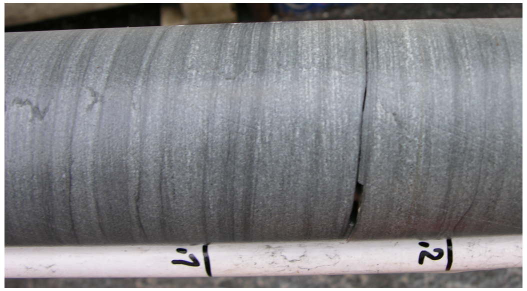

Thermal conductivity – density

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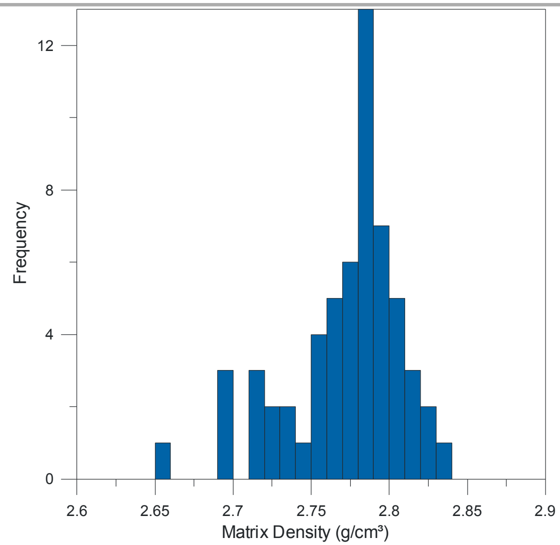

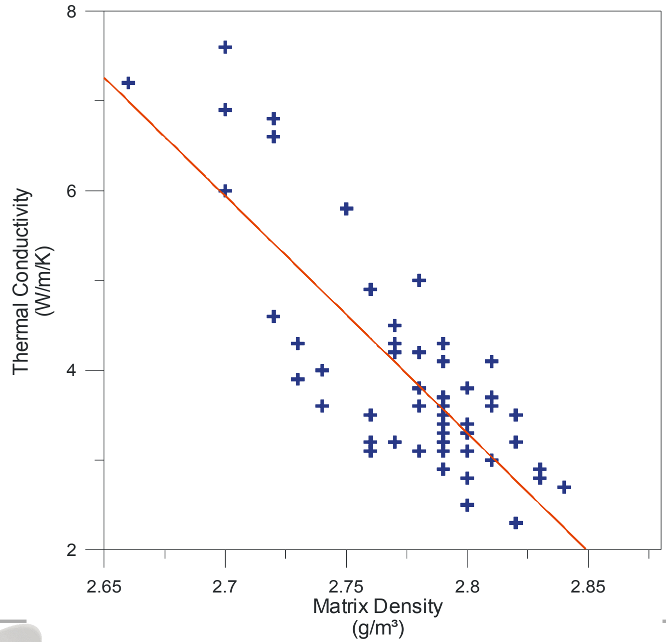

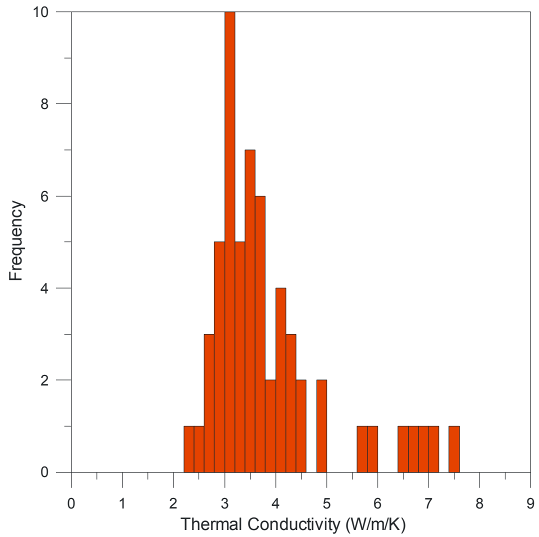

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Dijkshoorn and Pechnig, 2007

Variation of thermal conductivity with depth

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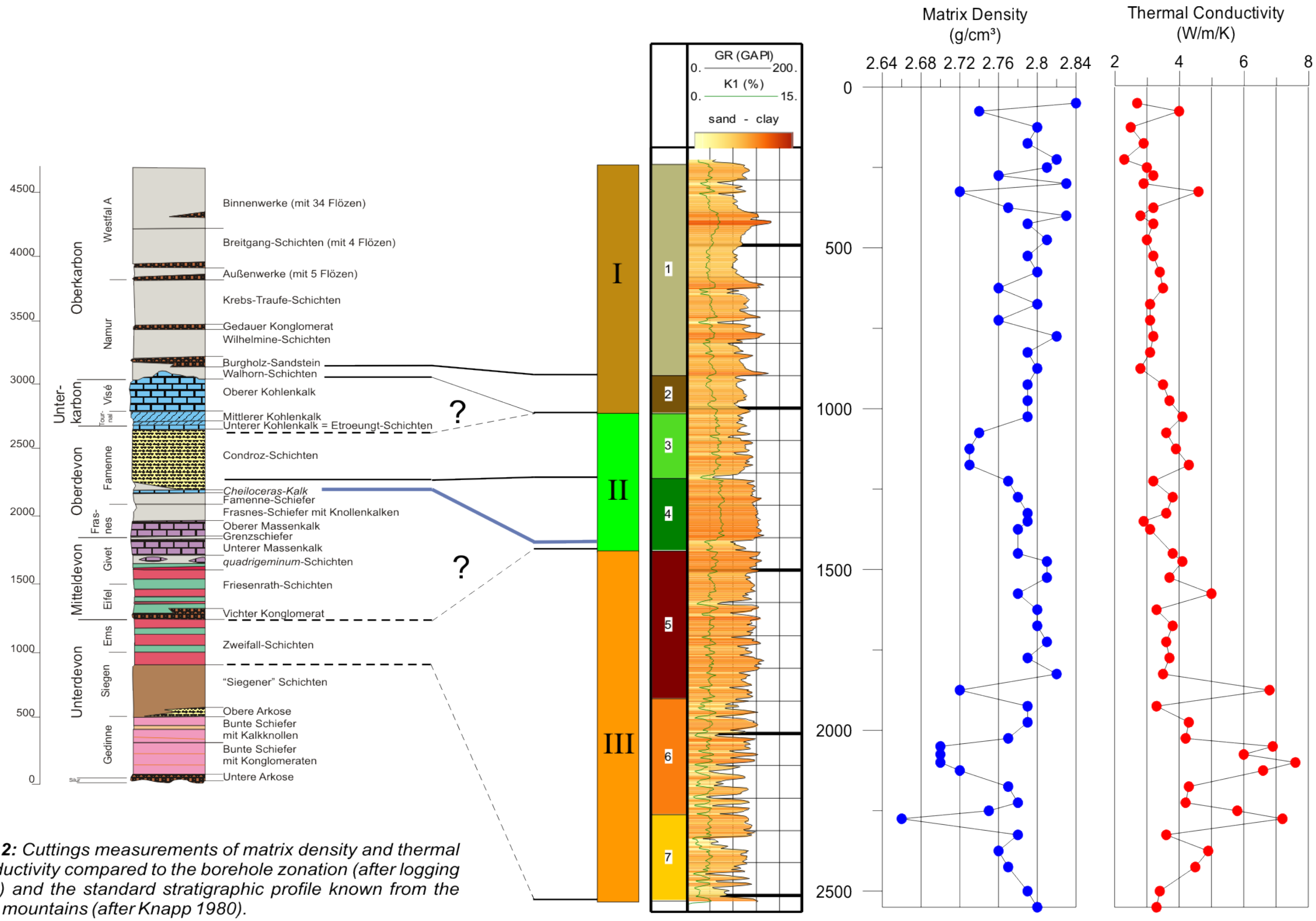

Fig. 2: Cuttings measurements of matrix density and thermal conductivity compared to the borehole zonation (after logging data) and the standard stratigraphic profile known from the Eifel mountains (after Knapp 1980).

Dijkshoorn and Pechnig, 2007

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Variation of pysical properties with depth

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Pechnig and Trautwein-Bruns, 2007

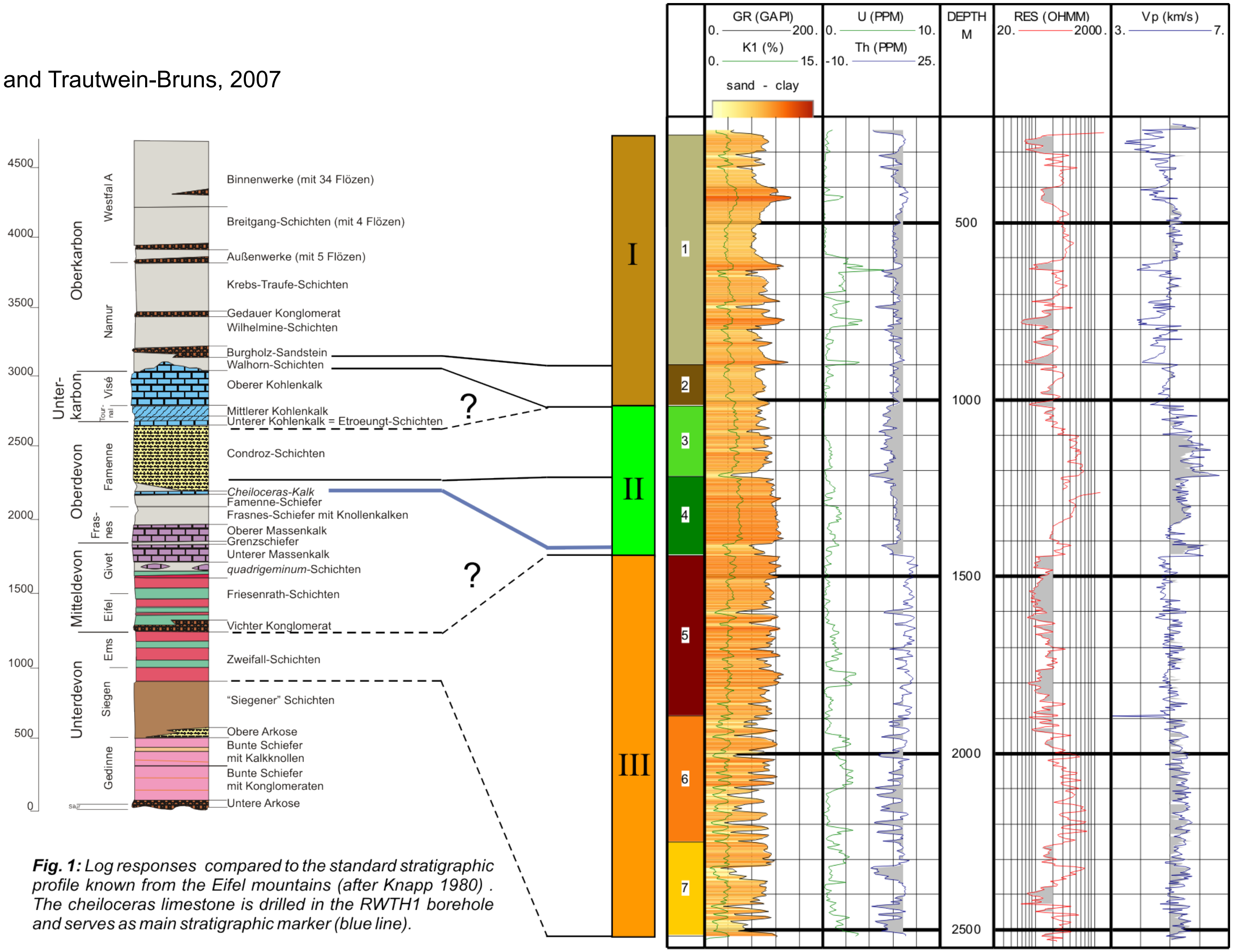

Fig. 1: *Log responses compared to the standard stratigraphic profile known from the Eifel mountains (after Knapp 1980). The cheiloceras limestone is drilled in the RWTH1 borehole and serves as main stratigraphic marker (blue line).*

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Rock Matrix Properties

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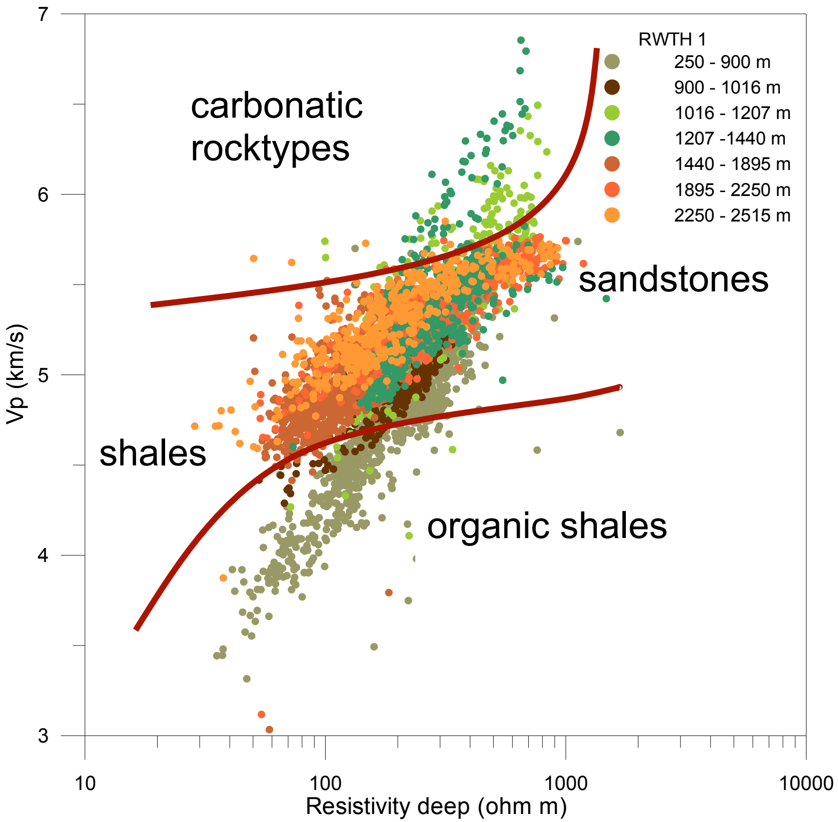

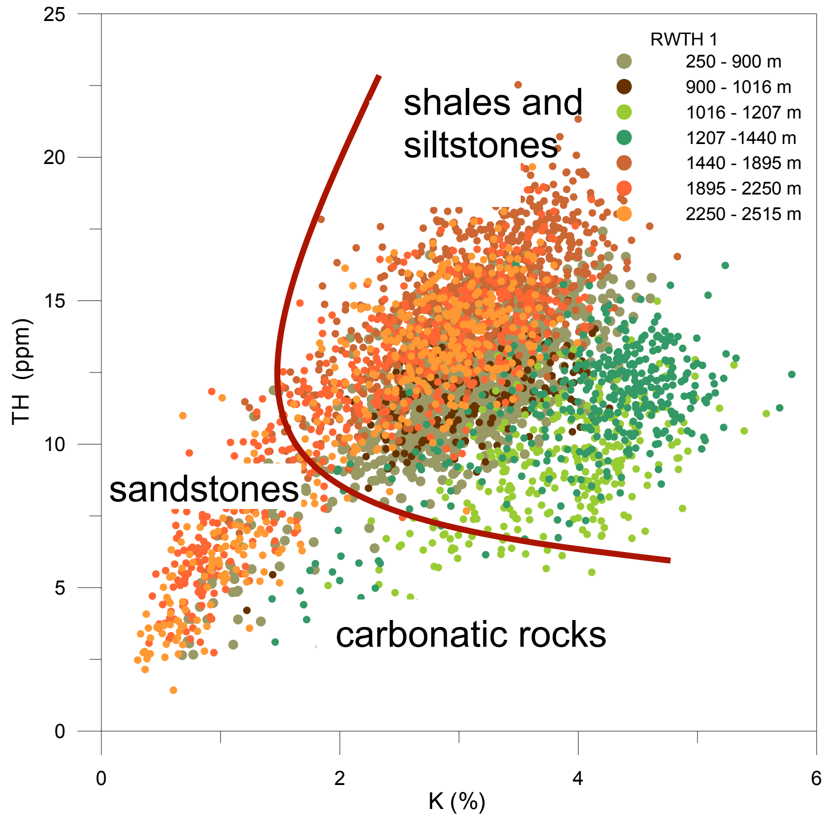

- **v_p and resistivity trends are controlled by rock composition**
- **entire rock column is massive**
- **rock porosity is low**

- **Strong scatter of thorium and potassium in shales and siltstone**
- **Calculation of shale volume separatly for each zone**

Calculated thermal conductivity

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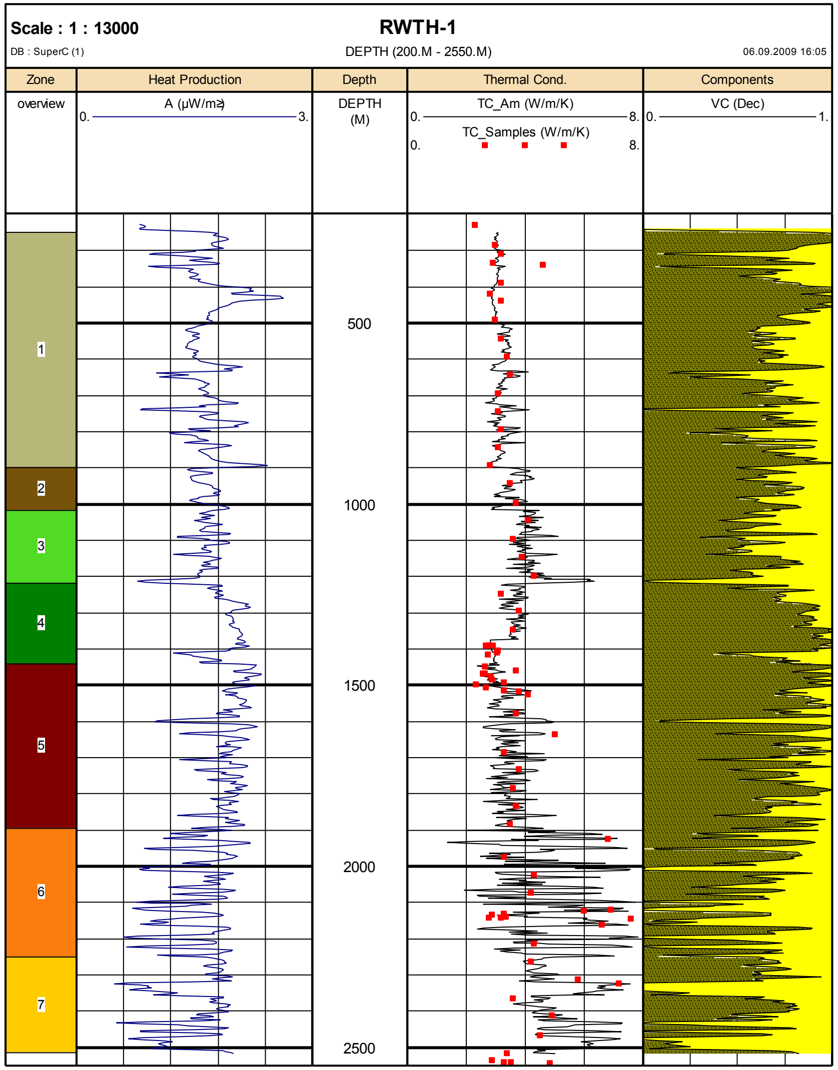
- Thermal Conductivity from shale and matrix values.
- of shale volume calculated separately for each zone
- Due to rock composition (carbonaceous, siliciclastic) matrix values for thermal conductivity differ from zone to zone.



Borehole Locations, Paleozoic rocks

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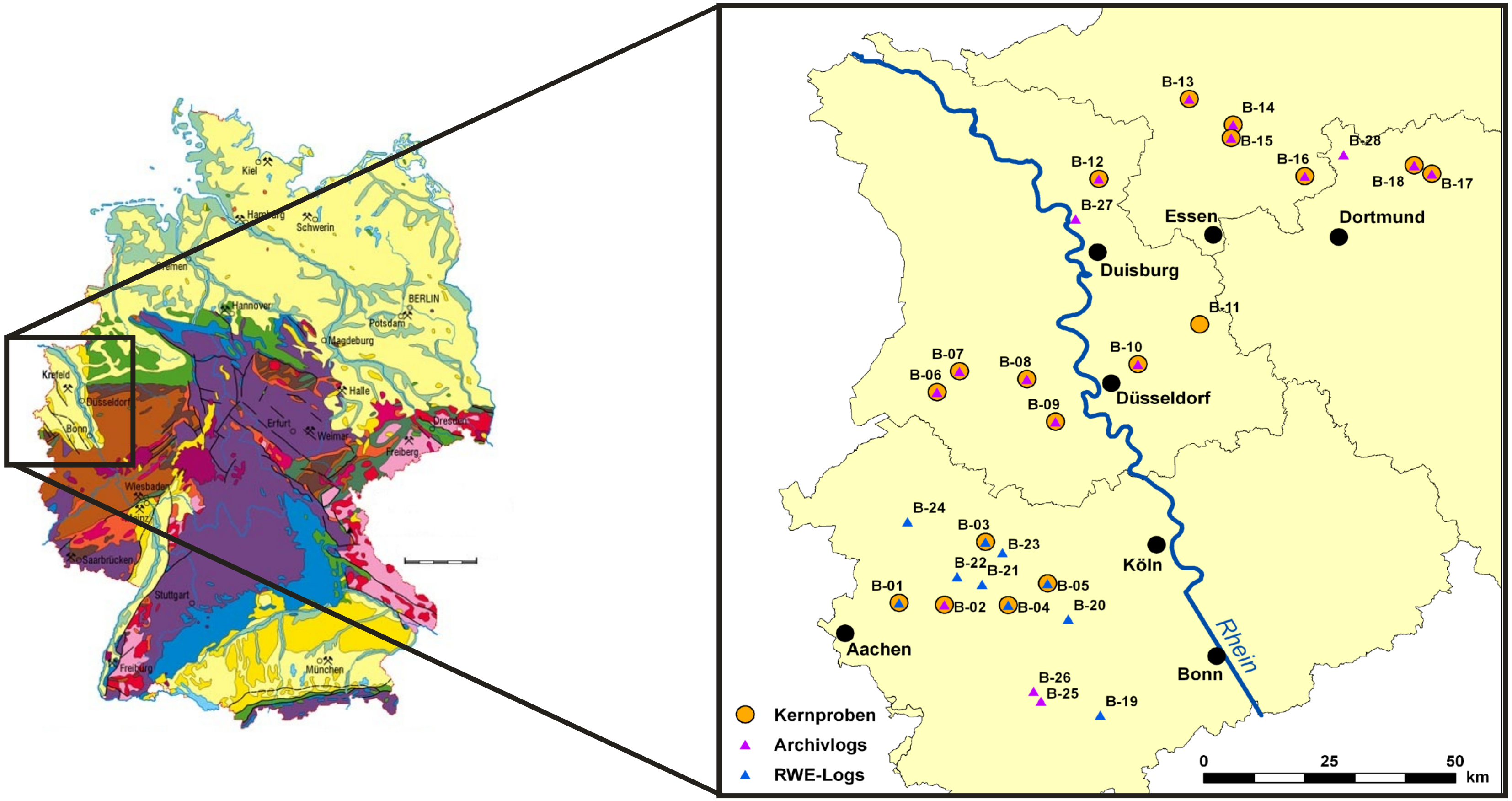

Exploration wells: Tertiary sediments and paleozoic basement rocks

Rock Samples - Stratigraphy

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Series	Stage	Substage	B-01	B-02	B-03	B-04	B-05	B-06	B-07	B-08	B-09	B-10	B-11	B-12	B-13	B-14	B-15	B-16	B-17	B-18	Total
Upper Carboniferous	Stefanian	Stefanian C																			
		Stefanian B																			0
		Stefanian A																			
	Westfalian	Westfalian D																			
		Westfalian C													7, 20	7					
		Westfalian B		14	3											1	3			8	85
		Westfalian A																	21	1	
	Namurian	Namurian C																11			
		Namurian B						28													39
		Namurian A																			
Lower Carboni-ferous	Visean		3					11					2								16
	Tournaisian																				
Upper Devonian	Famennian	Dasberg																			
		Hemberg								9			3								34
		Nehden							7												
	Frasnian	Adorf							6		9										
Middle Devonian	Givetian						3		20		1	15									44
	Eifelian					5															
Lower Devonian	Emsian																				
	Pragian																				0
	Lochkovian																				

231 samples from 18 wells, covering different stratigraphic units of Devonian and Carboniferous age

Rock Samples – Examples

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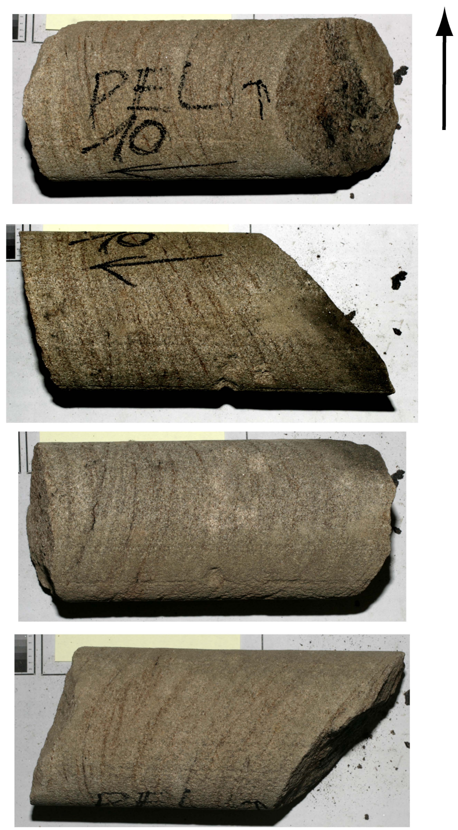
SHALE

0°
45°
90°
135°

SANDSTONE

0°
45°
90°
135°



Upper Carbonifereous (sampling supported by NRW Geological Survey, Krefeld)

Thermal conductivity vs. porosity

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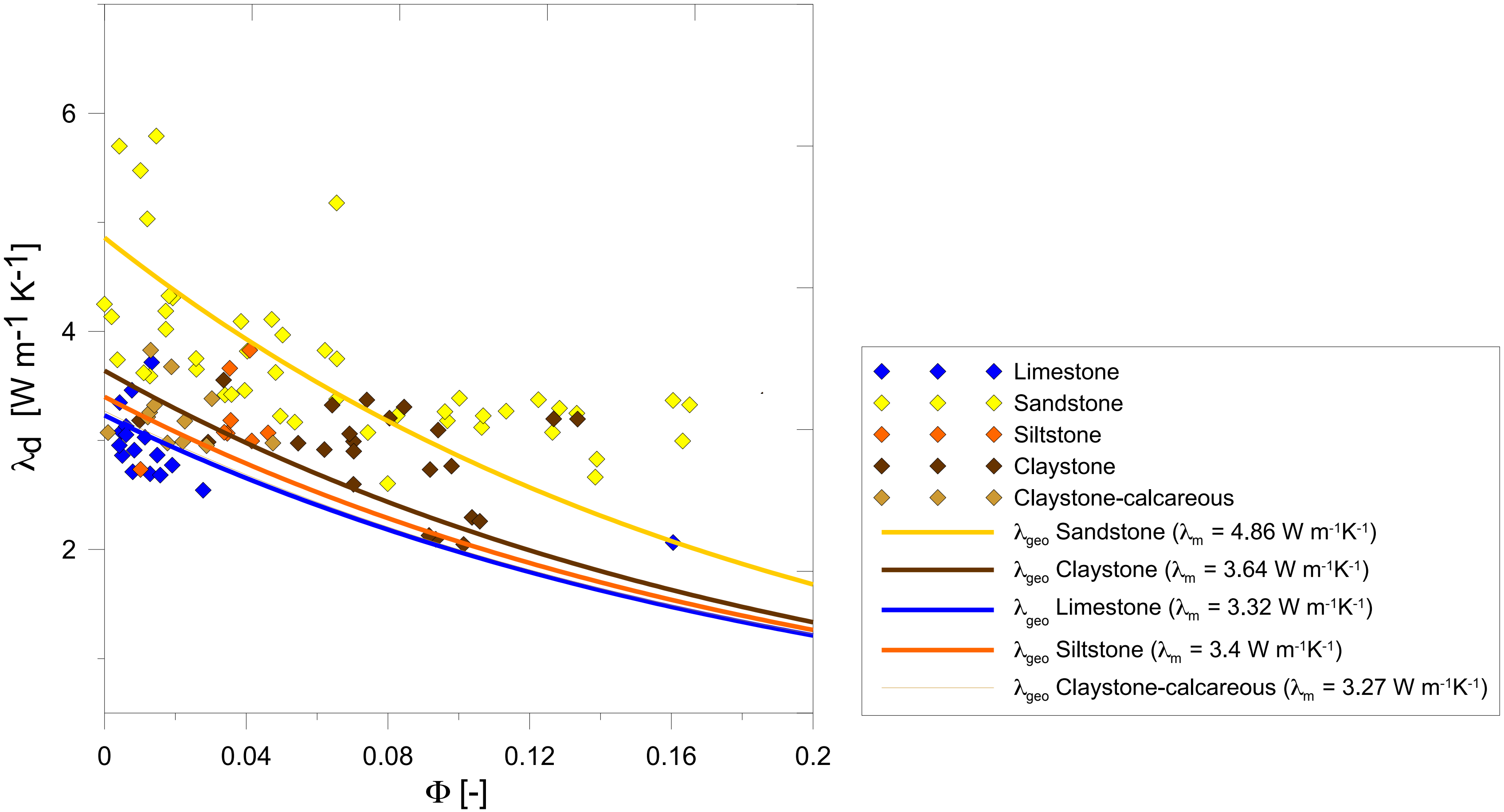

Cross-plot of thermal conductivity (dry samples) and rock porosity shows large scatter, in particular for the paleozoic sandstones

Thermal conductivity vs. porosity

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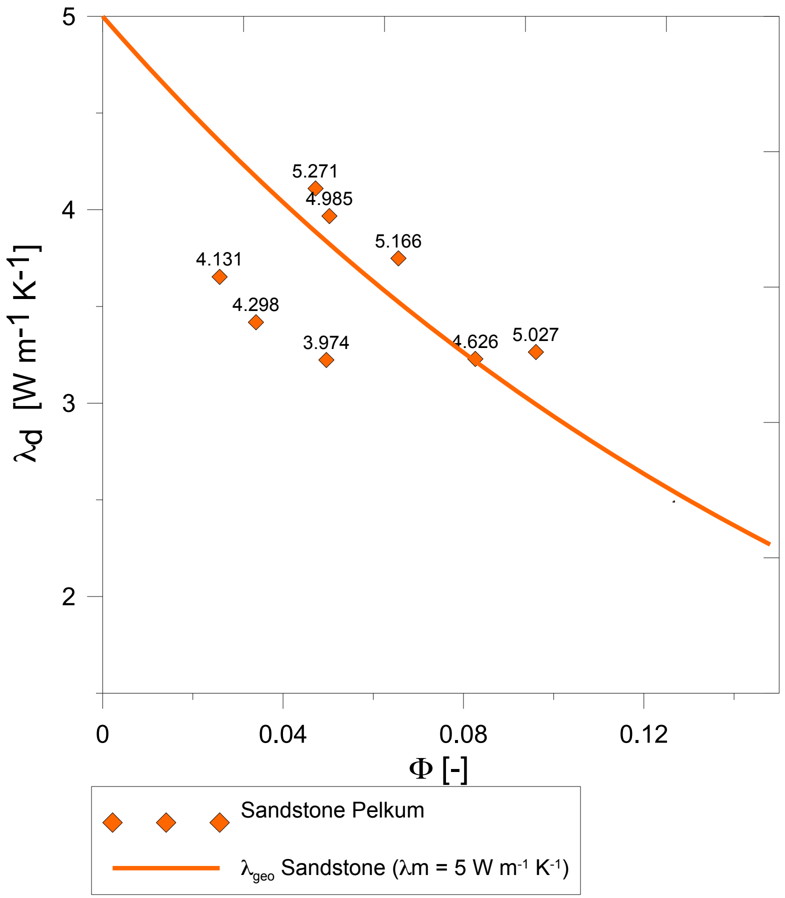
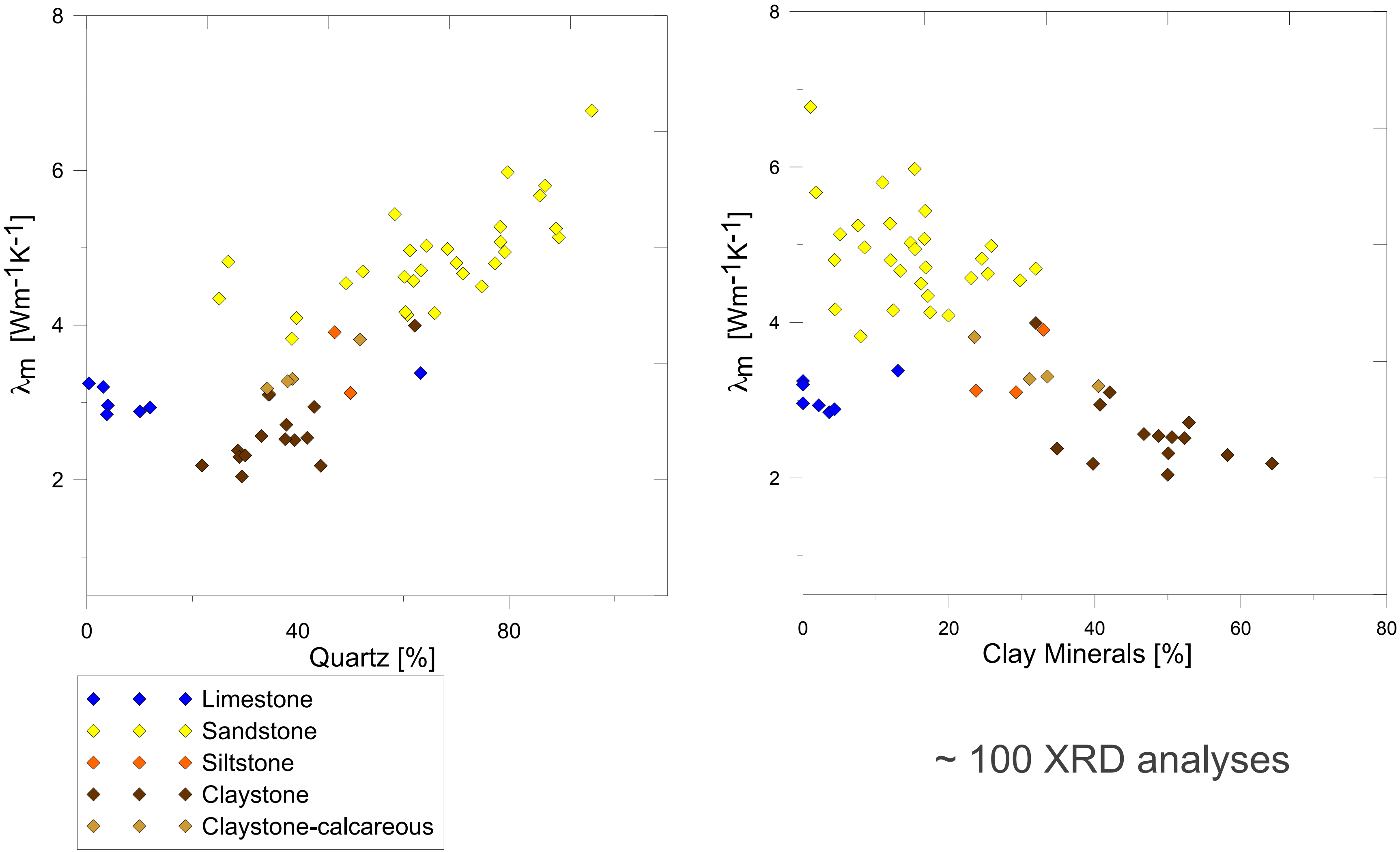


- Relationship depends strongly on rock matrix conductivity (numbers)
- sandstones with similar rock matrix are well described by the geometric law.

Thermal conductivity vs. rock type and mineral content



~ 100 XRD analyses

Thermal conductivity vs. rock type

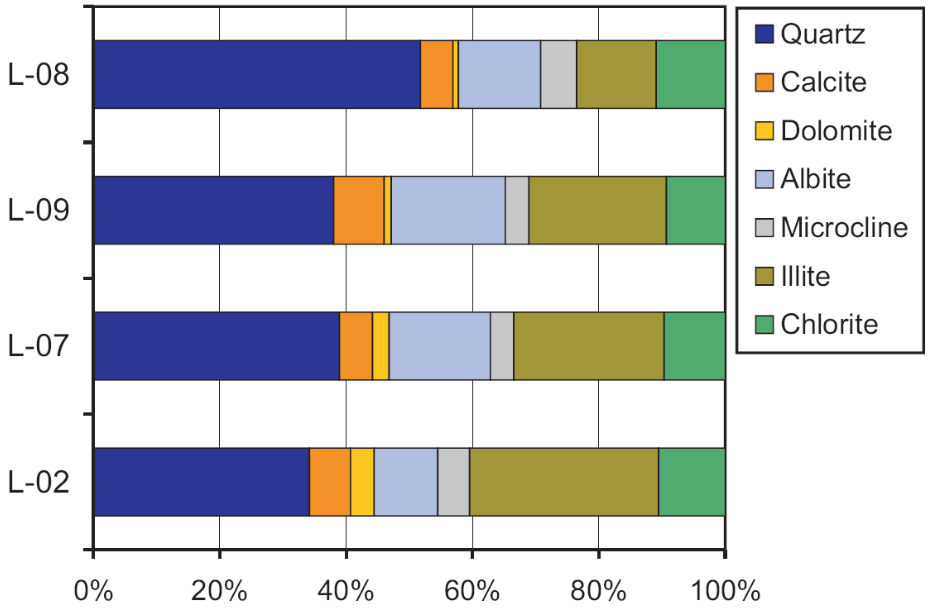


Figure 5: *Mineralogical composition of four samples from borehole B-09 (Frasnian shale with varying lime and silt content).*

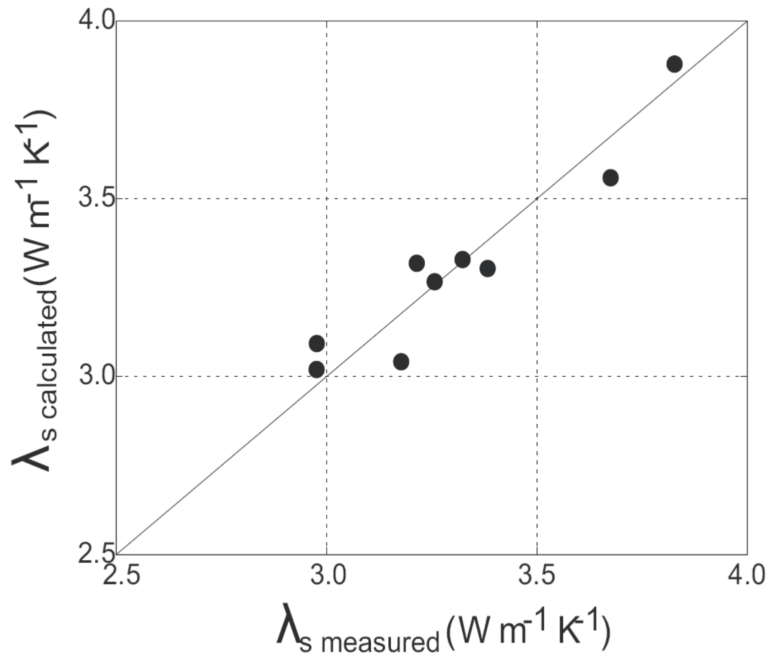


Figure 6: *Comparison between calculated and measured thermal conductivity of nine water saturated samples from borehole B-09.*

Koch et al. 2009

Logs of Upper Carboniferous Strata

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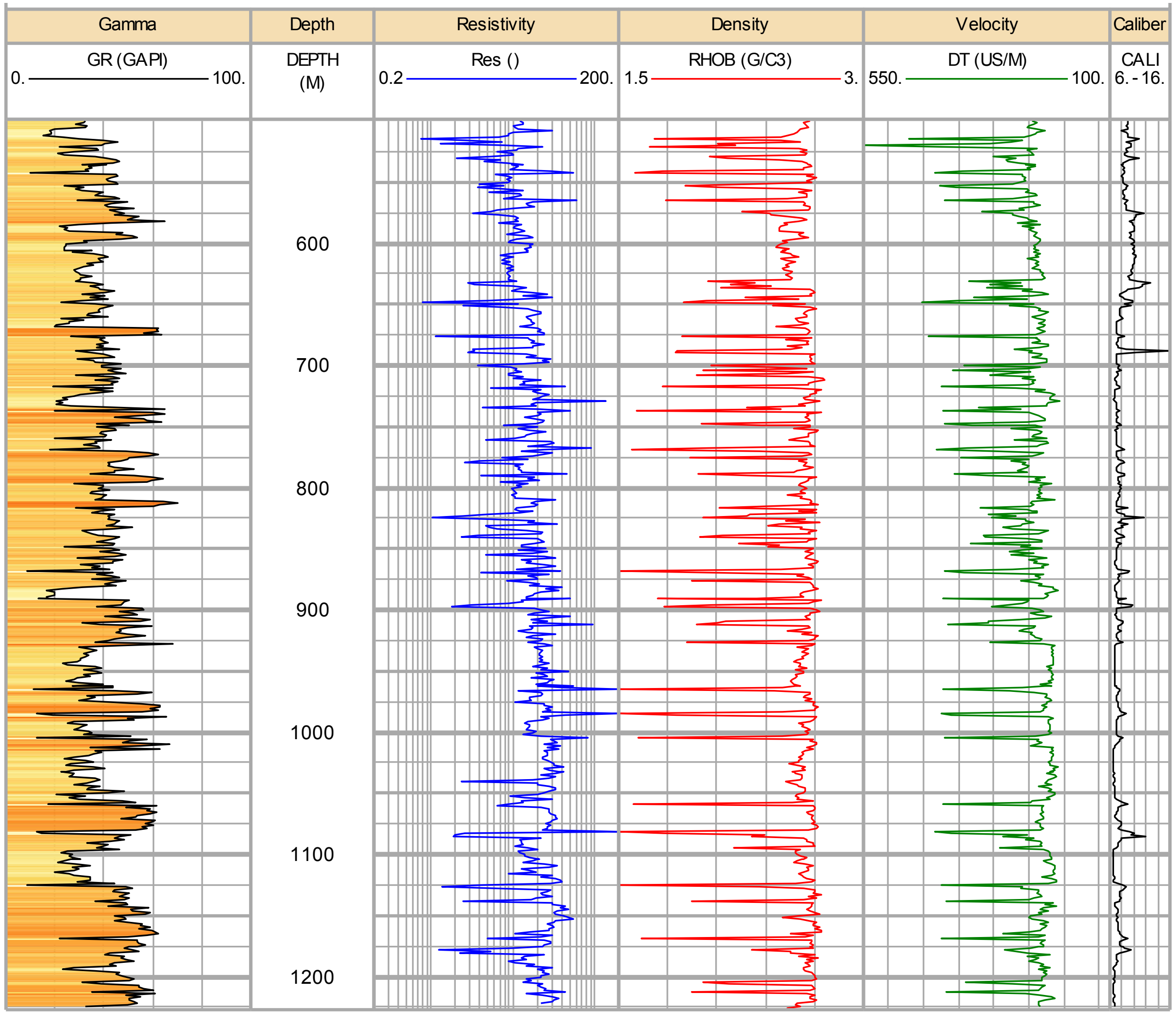

Composite log of a coal mining exploration well

Westfalian (Bochum formation)

Coal beds:
low density, low velocity and high resisitiviy

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Coal Bed Responses

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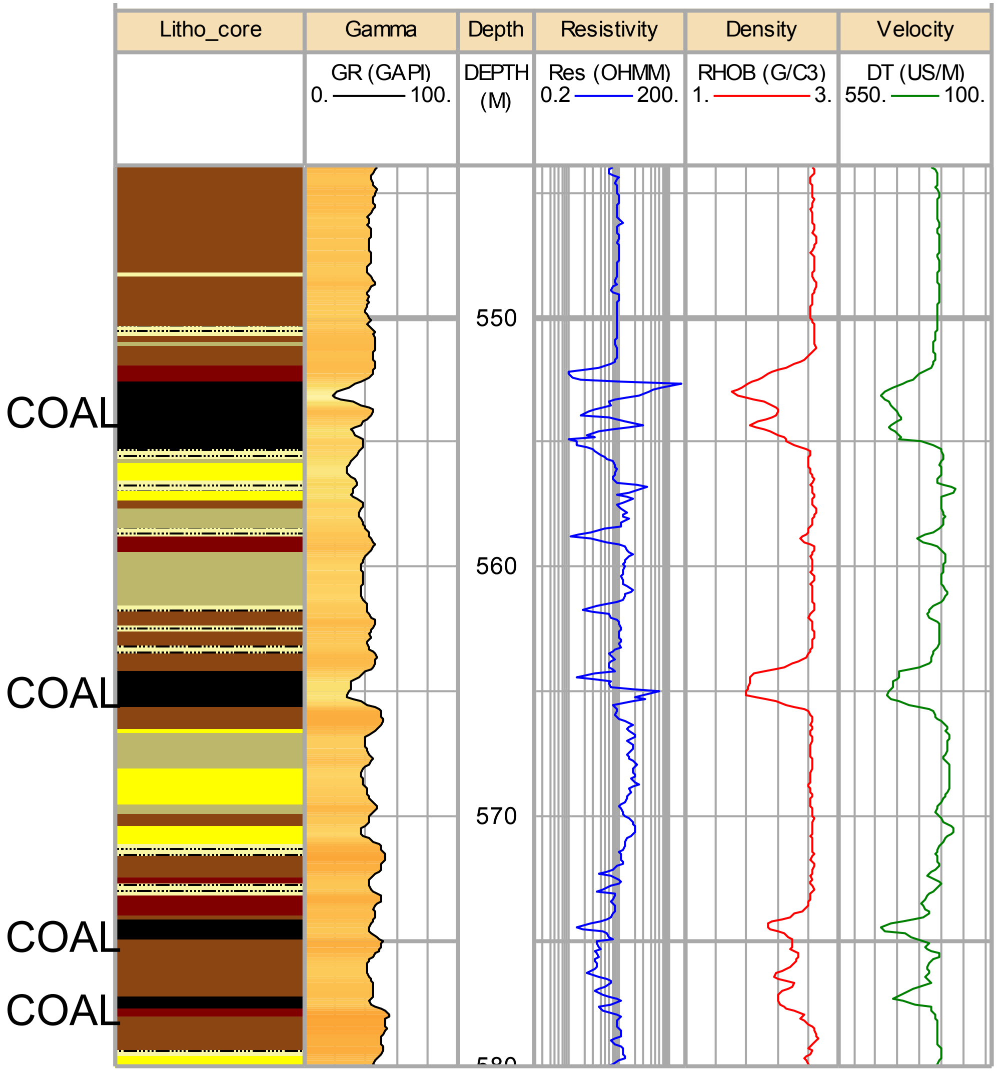

Typical log responses of coal beds (black) interlayered with sandstones (yellow), siltstones (greyish) and claystones (brown).

Log Analysis - Lithology

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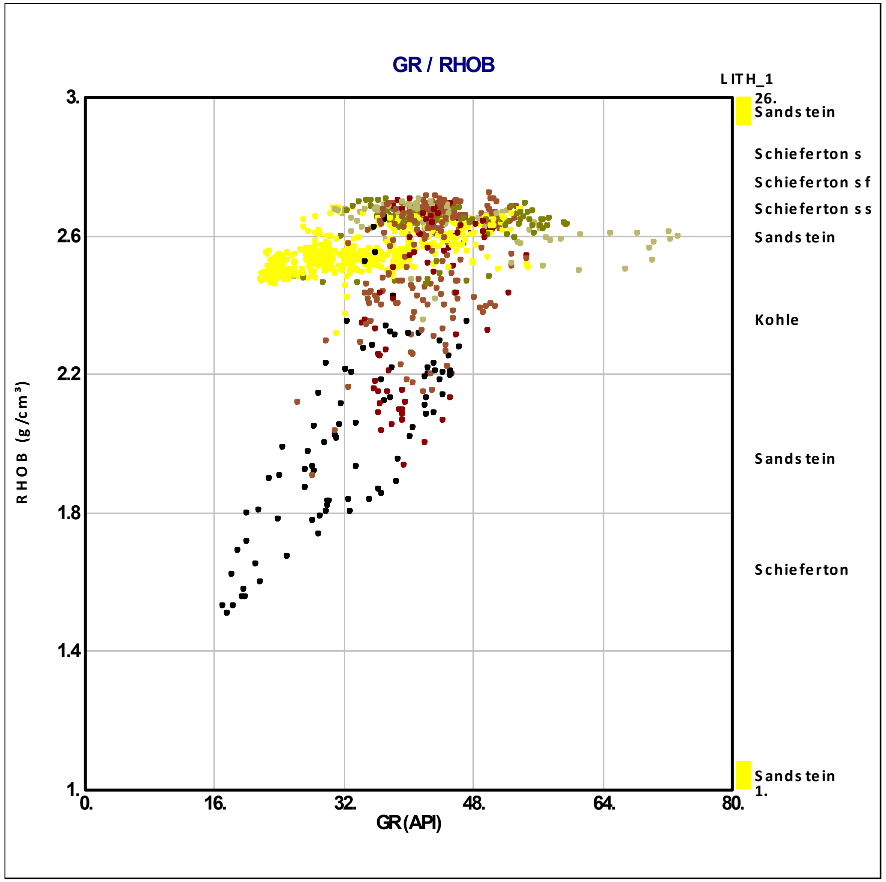

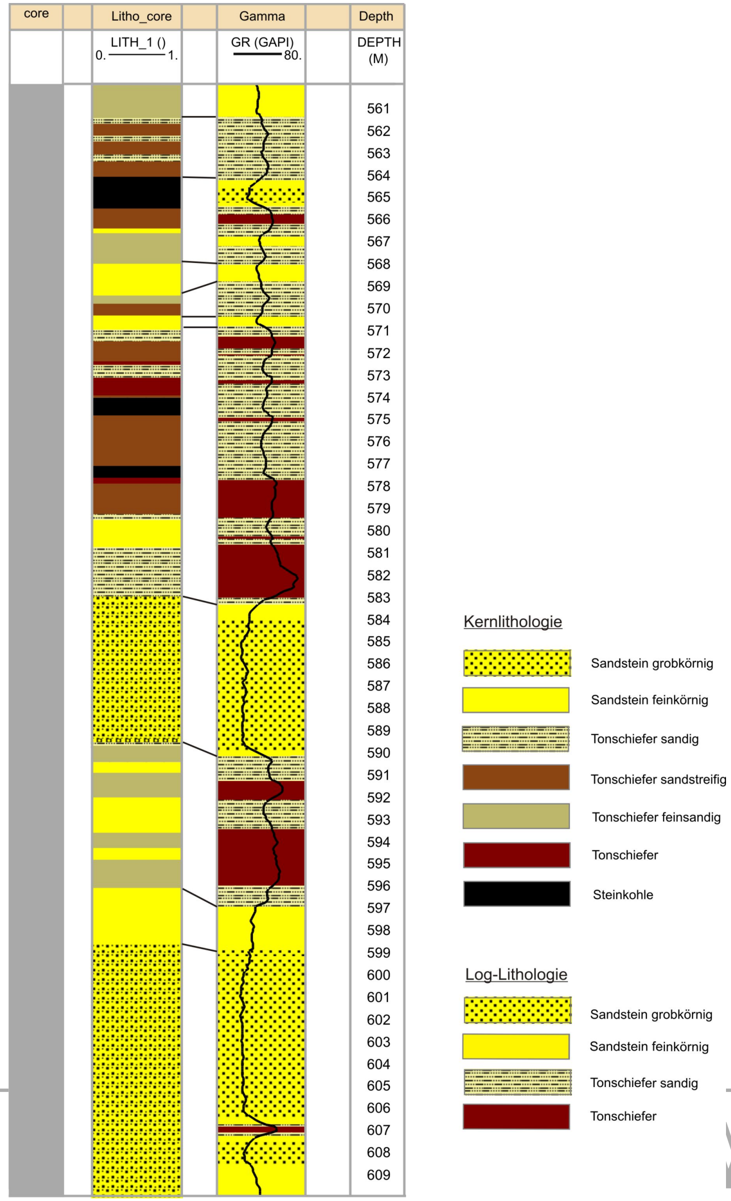

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Core and Log Data

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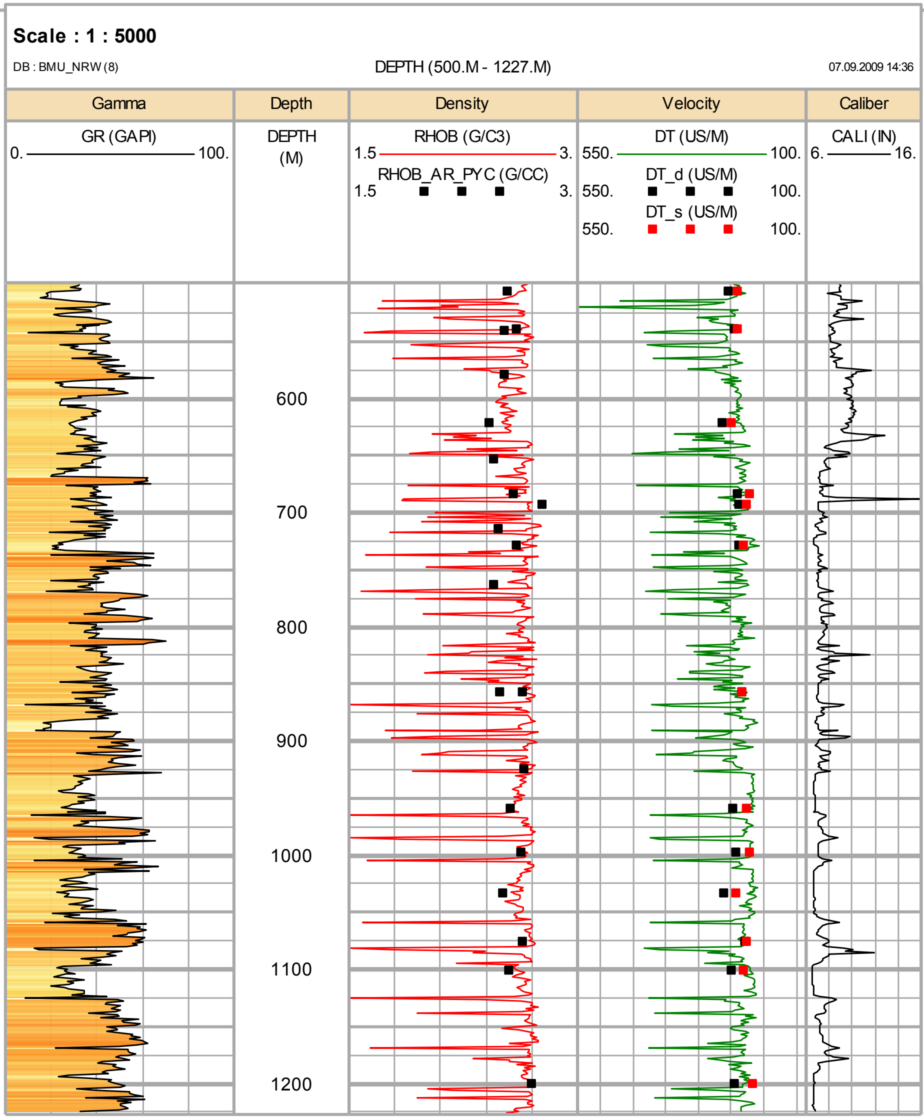

Comparison of core and log bulk density and core and log v_p velocity.

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Porosity Log

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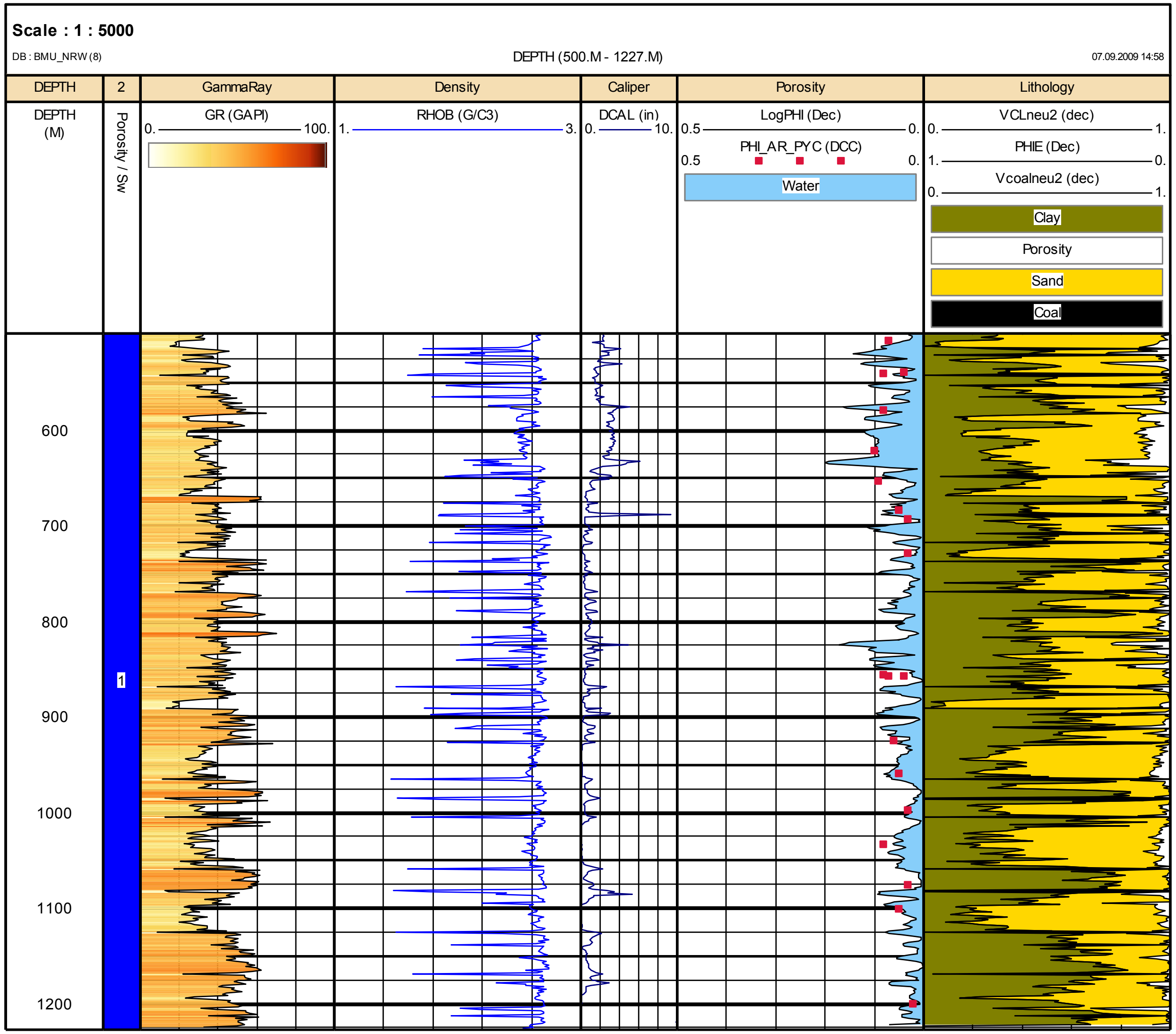

Porosity from density log

Matrix Density Sandstone:

2700 kg/m³

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Thermal conductivity profiles

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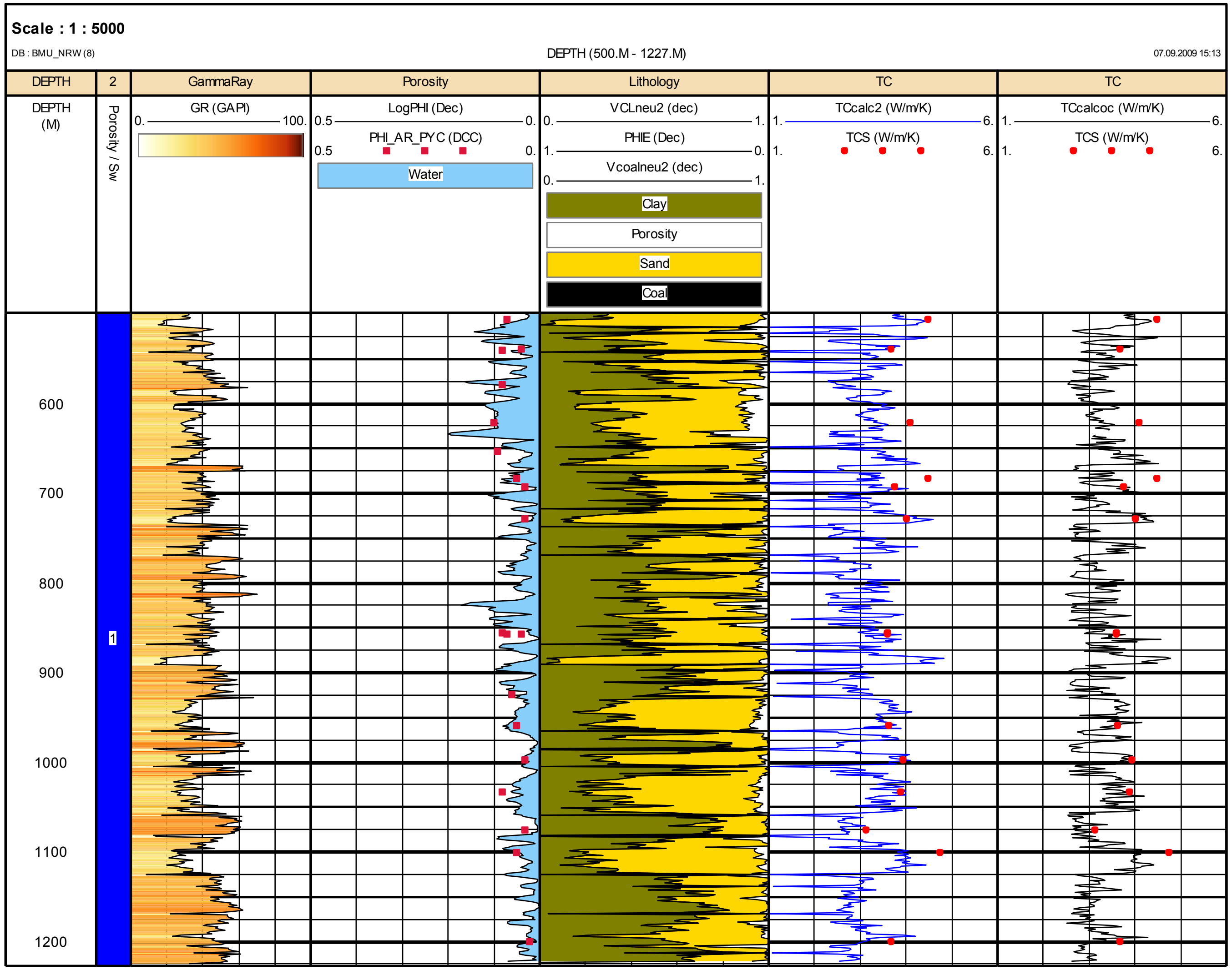

λ_m **Sandstone**
4.86 W/(m K)

λ_m **Shale**
2.4 W/(m K)

λ_m **Coal**
0.7 W/(m K)

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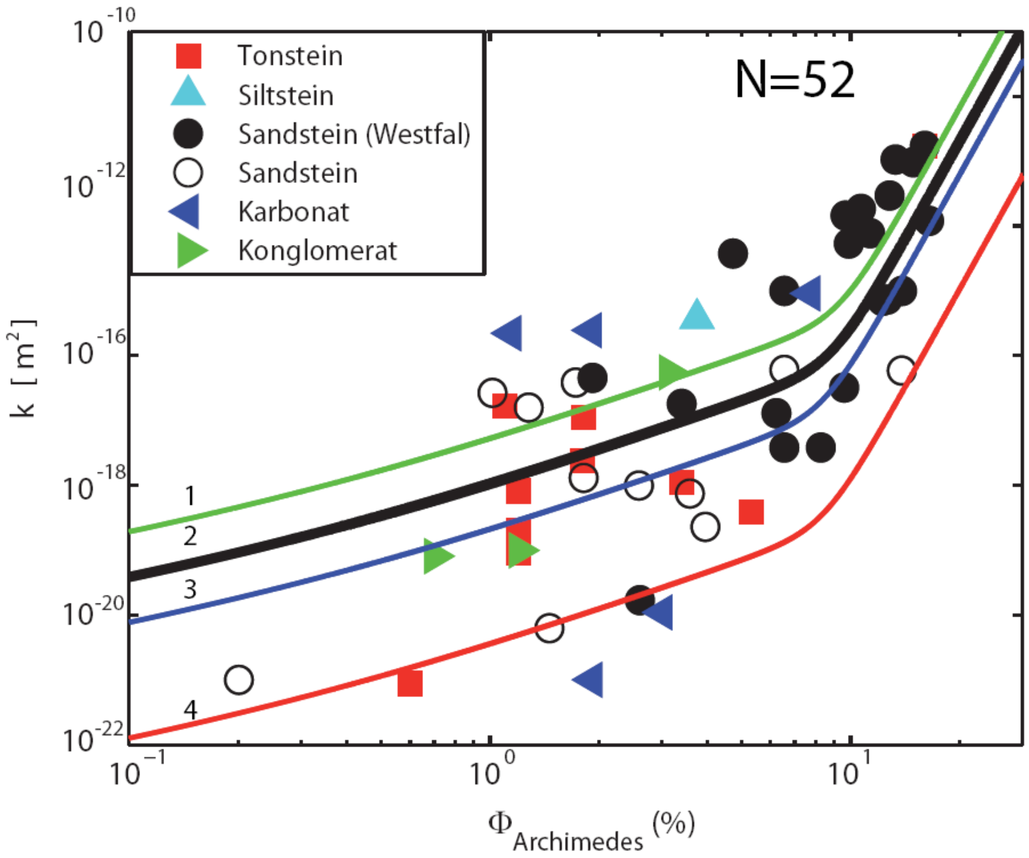
Poro - perm relationships



1 $k = 155\,\phi + 37315\,\phi^2 + 630\,(10\,\phi)^{10}$ Rotliegend-Sandstein (Norddeutschland)
2 $k = 31\,\phi + 7463\,\phi^2 + 191\,(10\,\phi)^{10}$ Durchschnittlicher Sandsteintyp
3 $k = 6{,}2\,\phi + 1493\,\phi^2 + 630\,(10\,\phi)^{10}$ Toniger Sandstein
4 $k = 0{,}1\,\phi + 26\,\phi^2 + (10\,\phi)^{10}$ Tonstein
(k in $10^{-9}\,m^2$)

Thank you for your attention!

Thermal conductivity - dependence on p and T

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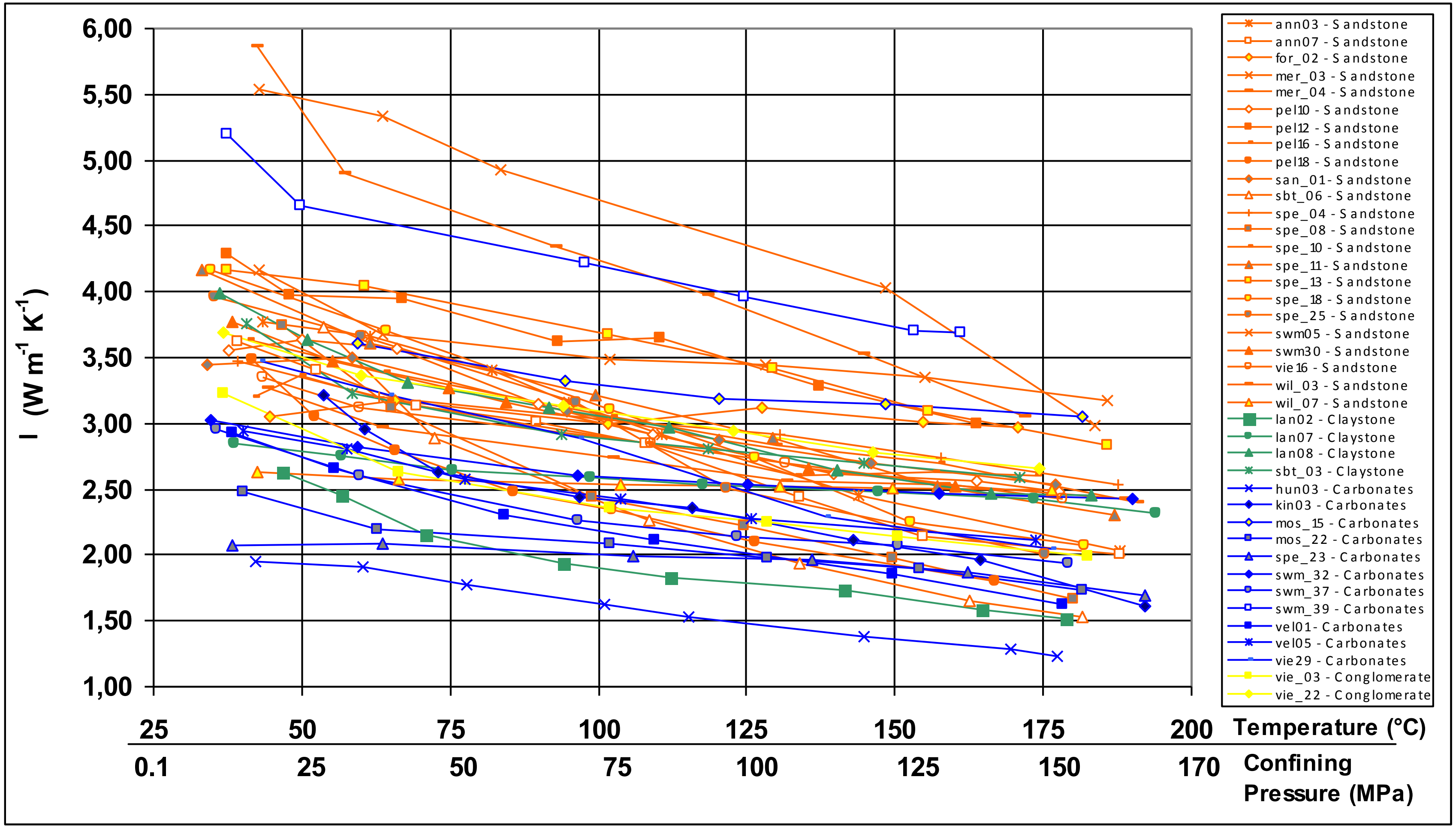

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