Study of the variation of thermal conductivity with water saturation of different German sandstones

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AND GEOTHERMAL ENERGY

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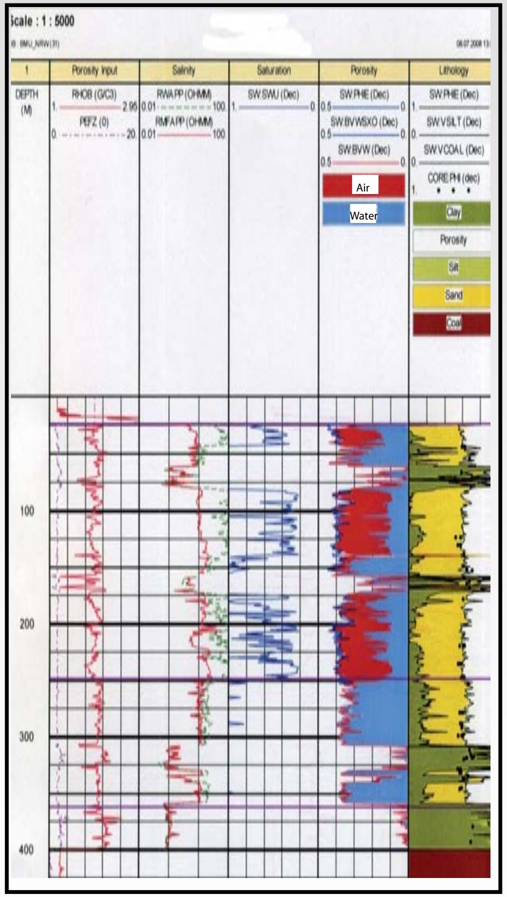
Introduction

Usually in saturated or dry condition **BUT** they cannot be made in unconsolidated sediments or rocks rich in clay minerals



Source: www.Geophysica.de, 2009

3 phases :

air, water, matrix

WATER →

Modification of the microstructure

↓

Destruction of samples

Objective: find a model with a minimum of parameters to correct for the effects of water saturation.

The samples

- 5 German sandstone samples from different stratigraphies with different porosities and mineralogical compositions

✓ Well characterized

✓ Can be resaturated several times without modifying the structure of the rock

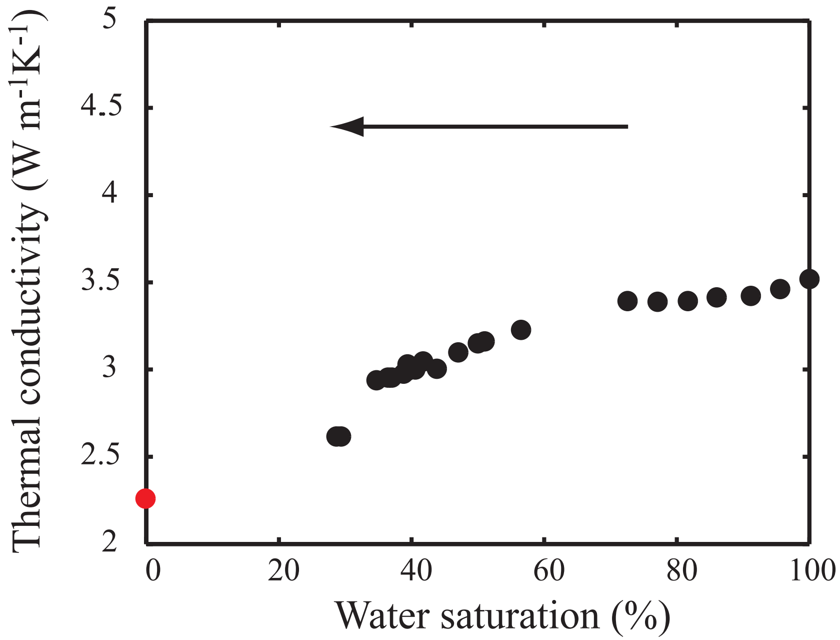
Sample	Porosity (%)	Mineralogical composition (%)				
		Quartz	Carbonates	**Feldspars**	Hematite	Clays
VESF	24	100				
BBSF	22	99		1		
SRSF	14	67	1	17		15
ROWE	6	68		17	2	14
SASF	21	56		32		12

Clays: chlorite and illite

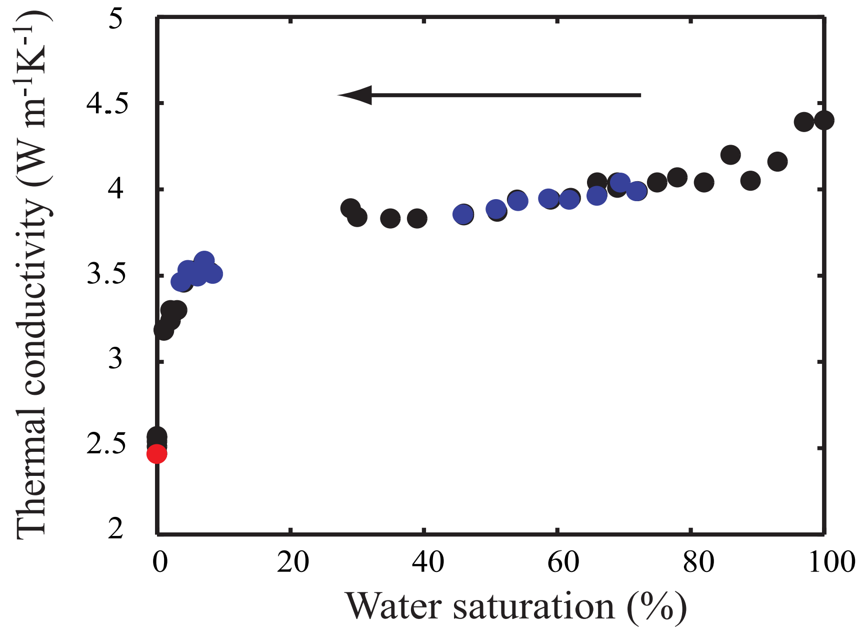
λ = f (saturation)

- ✓ Open samples
- ✓ Optical Thermal Conductivity Scanning (Popov et al., 1999)
- ✓ 1 measurement per hour at different degrees of saturation
- ✓ 2 initial water saturations to cover the entire range of saturation

With clays



Without clays



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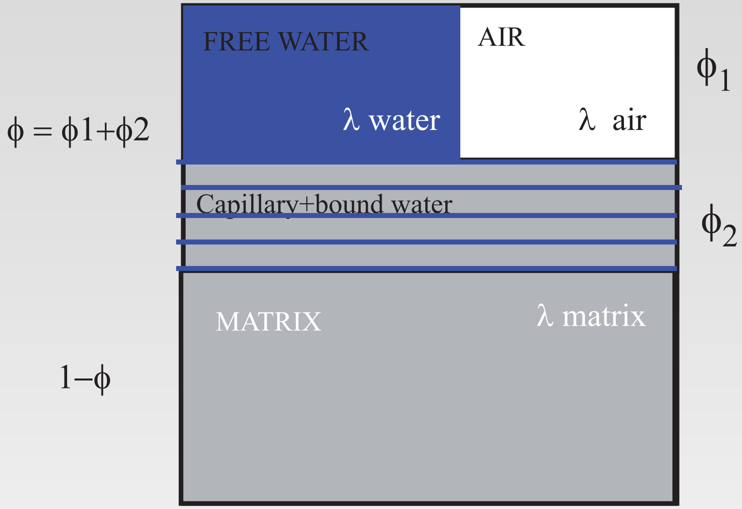
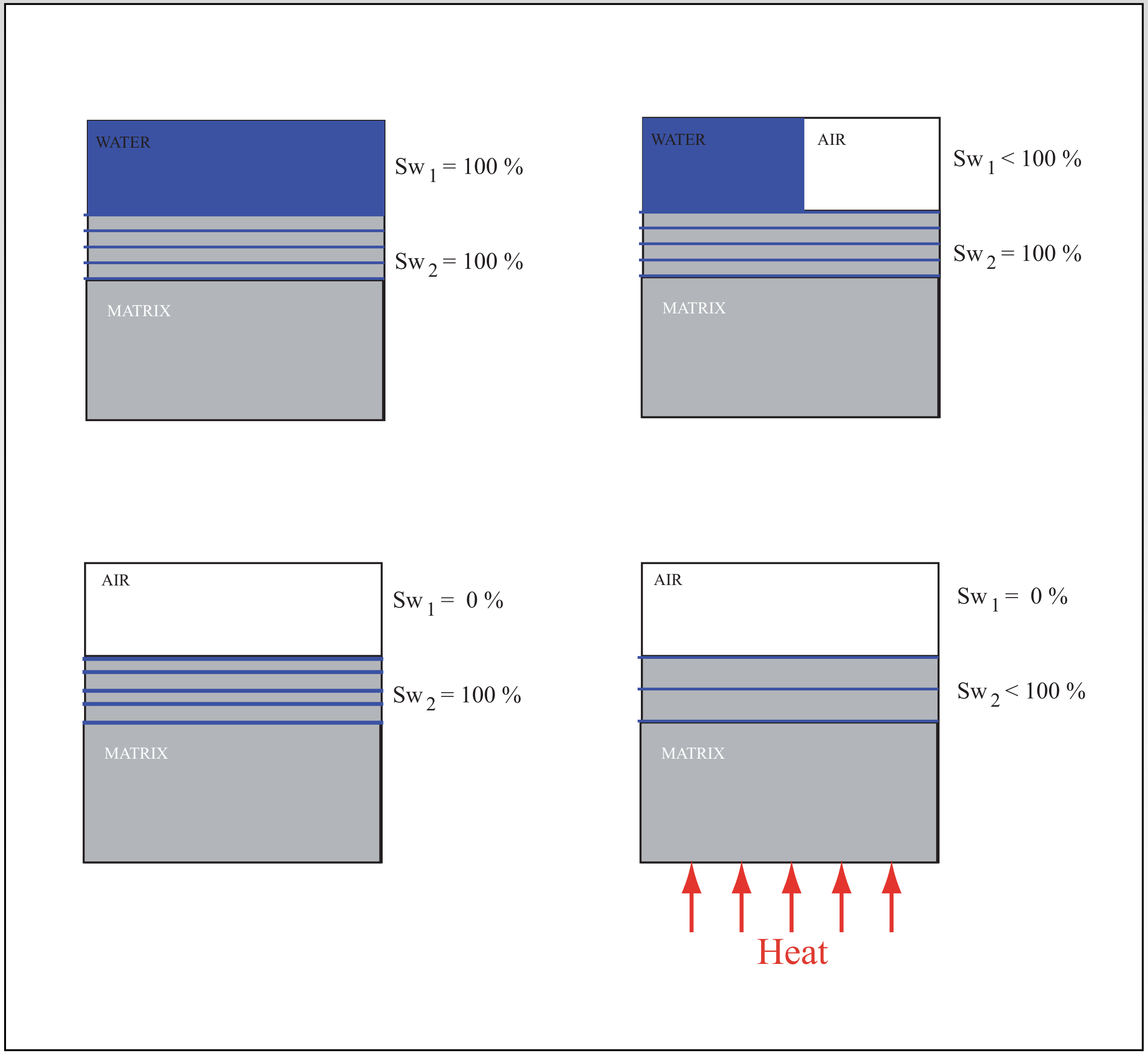
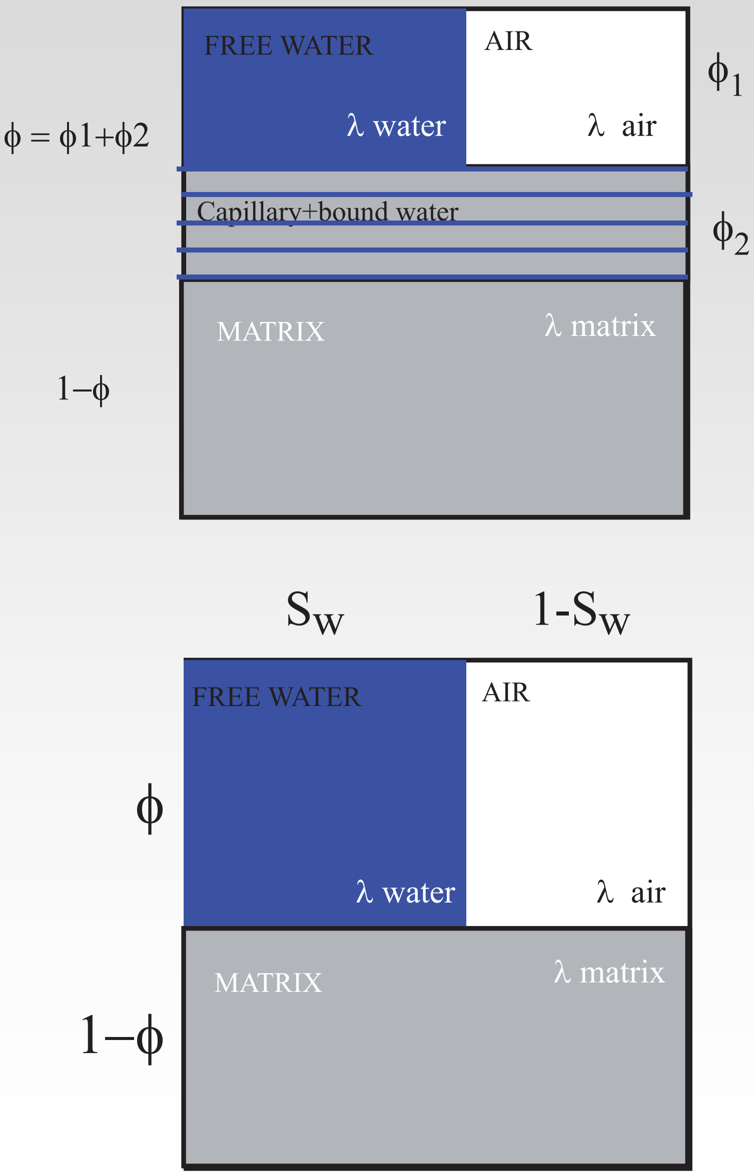
Models


FREE WATER
AIR
λ water
λ air
ϕ_1
$\phi = \phi 1 + \phi 2$
Capillary+bound water
ϕ_2
MATRIX
λ matrix
$1-\phi$


WATER
$Sw_1 = 100$ %
$Sw_2 = 100$ %
MATRIX
WATER
AIR
$Sw_1 < 100$ %
$Sw_2 = 100$ %
MATRIX
AIR
$Sw_1 = 0$ %
$Sw_2 = 100$ %
MATRIX
AIR
$Sw_1 = 0$ %
$Sw_2 < 100$ %
MATRIX
Heat

Models



Known properties

- $\lambda_{water}, \lambda_{air}$

Measured properties

- S_w: water saturation
- ϕ: total porosity
- ϕ_2: bound and capillary water
- $\phi_1 = \phi - \phi_2$: "free water"

by NMR relaxation

Calculated properties

λ_{matrix}

Models

Fluid distribution: Arithmetic model

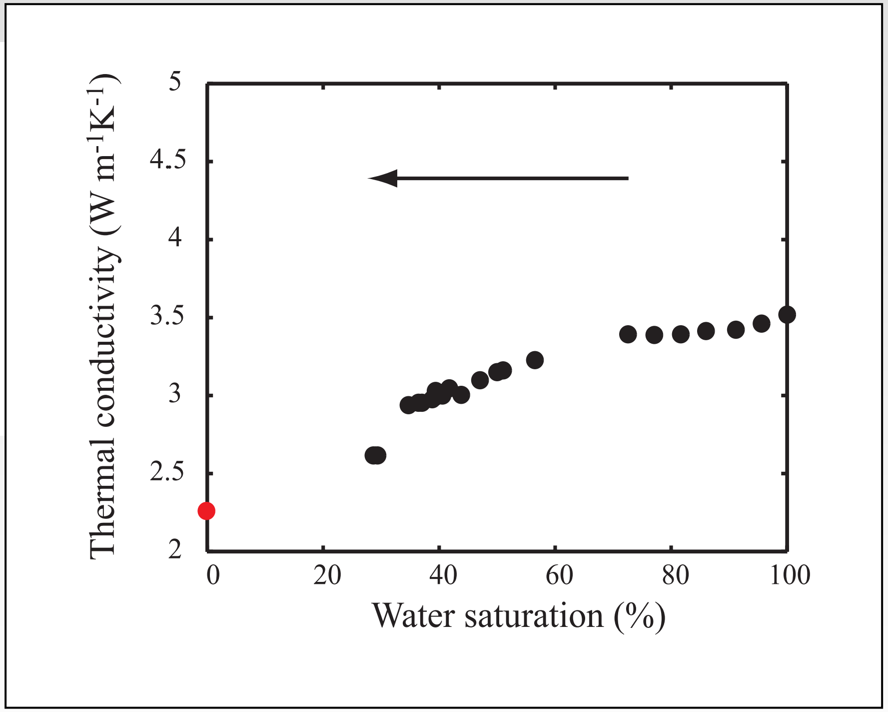
$$\lambda_{fluid} = (1 - S')\lambda_{air} + S'\lambda_{water}$$

With clays

$S' = S_w - S_e$

a) $S_e = \frac{\phi_2}{\phi} = \frac{\phi_2}{\phi_1 + \phi_2}$

b) S_e determined from measurements



Models

Fluid distribution: Arithmetic model

$$\lambda_{fluid} = (1 - S')\lambda_{air} + S'\lambda_{water}$$

With clays

$S' = S_w - S_e$

a) $S_e = \frac{\phi_2}{\phi} = \frac{\phi_2}{\phi_1 + \phi_2}$

b) S_e determined from measurements

Without clays

$S' = S_w$

Model 1

$$\lambda_{ari} = \frac{1}{2}(\lambda_{par} + \lambda_{ser})$$

With $\lambda_{par} = (1-\phi)\lambda_{matrix} + \phi_1\lambda_{fluid} + \phi_2\lambda_{water},$

$$\lambda_{ser} = \left(\frac{1-\phi}{\lambda_{matrix}} + \frac{\phi_1}{\lambda_{fluid}} + \frac{\phi_2}{\lambda_{water}}\right)^{-1}.$$

Model 2

$$\lambda_{geo} = \lambda_{matrix}^{(1-k\phi)}\,\lambda_{fluid}^{k\phi_1}\,\lambda_{water}^{k\phi_2}$$

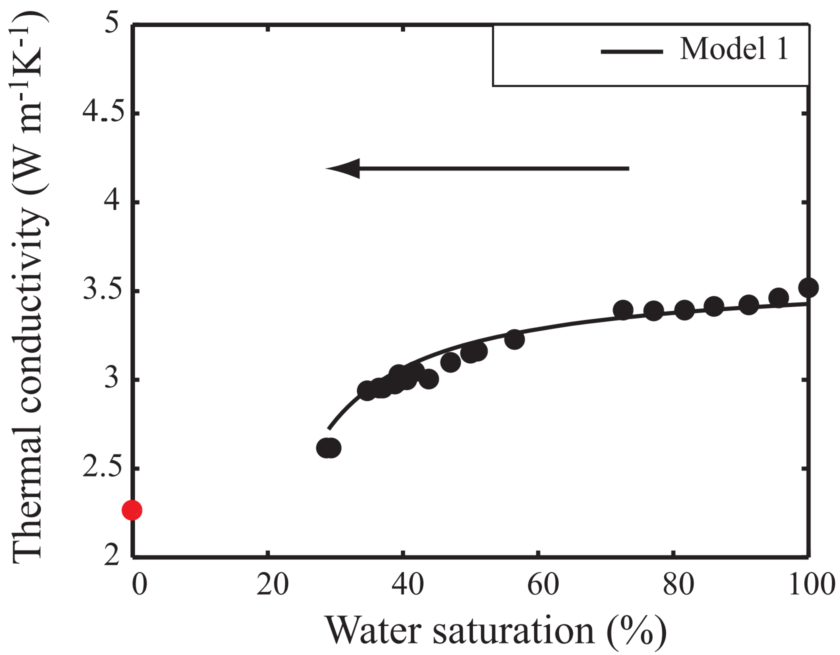
With $0.9 \le k \le 2.3$

Results

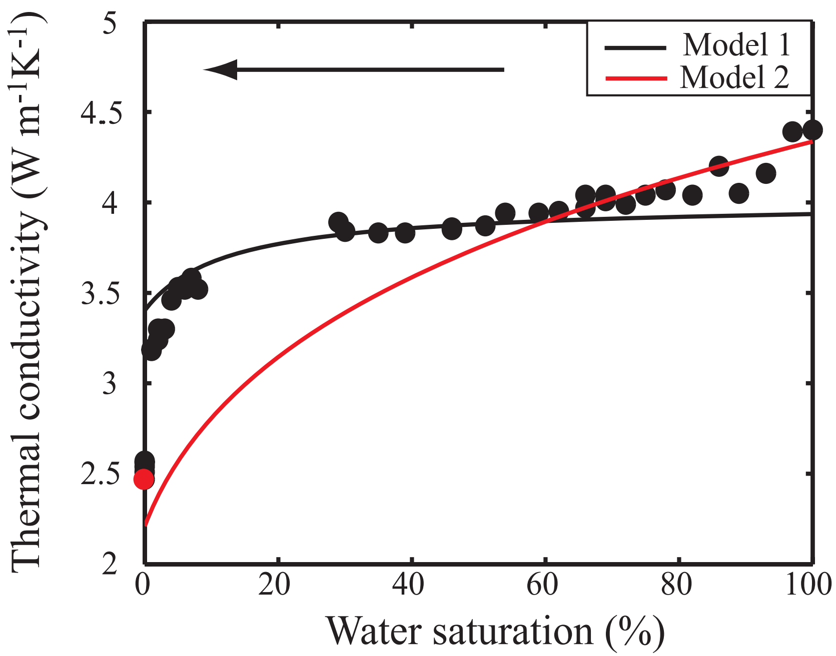
Parameters

Parameters	SRSF	VESF
Se measured (%)	29	
Se calculated (%)	22	
ϕ_1 (%)	14	25
ϕ_2 (%)	3	2
λ_{matrix} (W m^{-1} K^{-1})	5.45	7.7

With clays



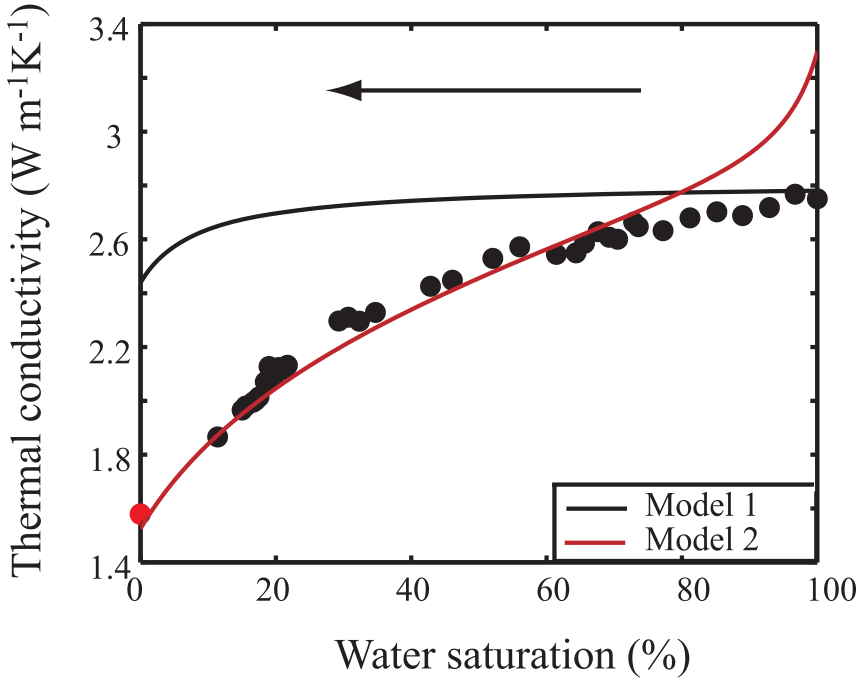
Without clays



An exception…

Parameters

Parameters	SASF
S_e measured (%)	0
S_e calculated (%)	0.02
ϕ_1 (%)	21.5
ϕ_2 (%)	0.5
λ_{matrix} ($W\,m^{-1}\,K^{-1}$)	4.62



- ✓ Model 1 does not fit the measurements.
- ✓ Model 2 fits the measurements for small saturations up to 70%.

At high saturation, it is necessary to find another model.

Conclusions and perspectives

1- Variable saturation of studied samples

Requires combination of two models for inferring matrix thermal conductivity depending on mineral content

2- Samples with and without clays

Combination of two identified models can be applied for all degrees of saturation

3- Sample with complex mineralog (here: rich in feldspars)

One model fits data up to a water saturation of 70 %, but not above

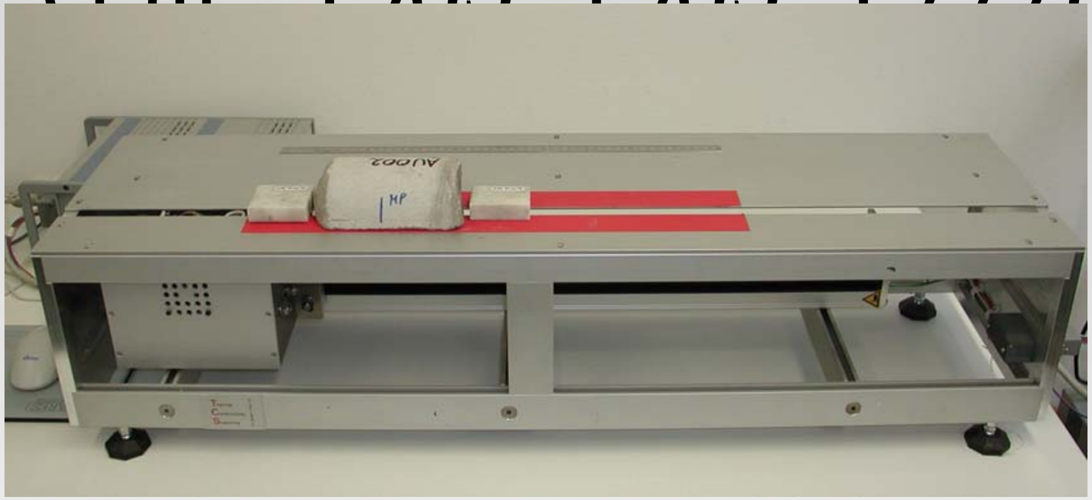
4- In the future,

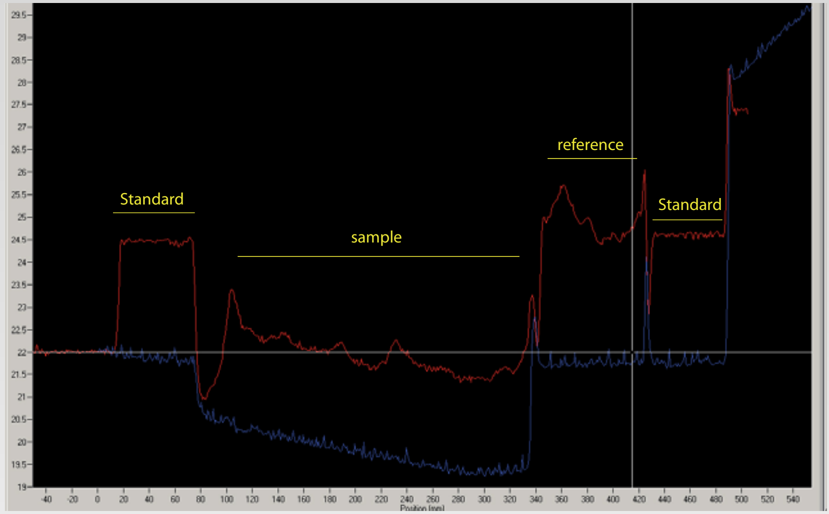
✓ New measurements in controlled atmosphere

✓ Other lithologies like carbonates

- Thank you

Thermal Conductivity Scanner (Popov et al. 1983, 1985, 1999)





For this geometry:

$$\theta(x) = \frac{q}{2\pi l \lambda}$$

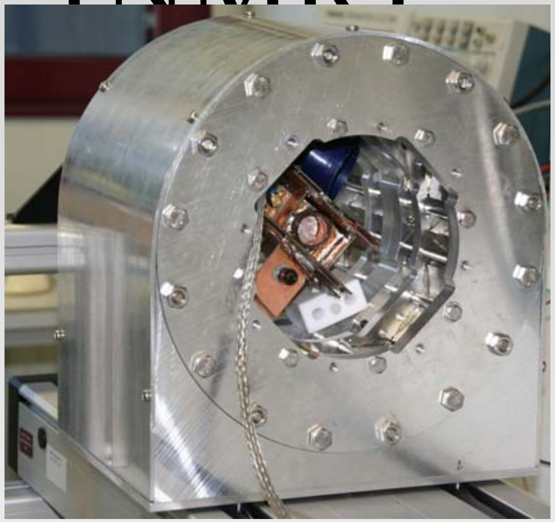
With Θ (x) the maximum temperature rise at point x, q source power (constant), l distance between the source and thermal sensor (constant) and λ thermal conductivity of sample.

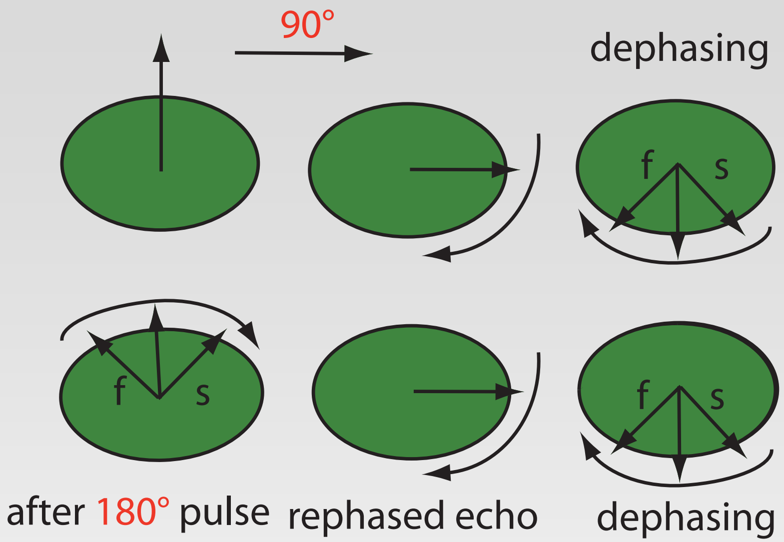
By comparison with a standard:

$$\lambda(x) = \lambda_{std} \frac{\theta_{std}}{\theta(x)}$$

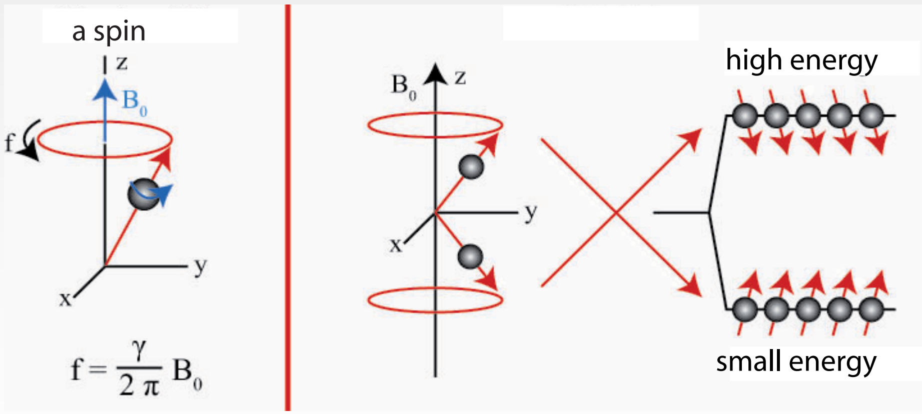
λ_{Std} thermal conductivity of standard, U_{std} and U electrical signals proportional to Θ_{std} and Θ.

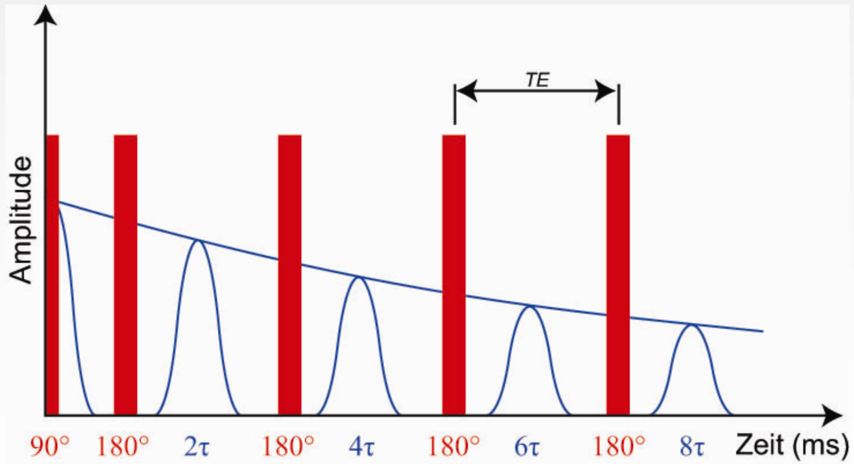
Nuclear Magnetism Resonance (NMR)





- A 90° pulse allow to detect magnetic moment and the 180° pulses refocus the spins and to form a spin echo.

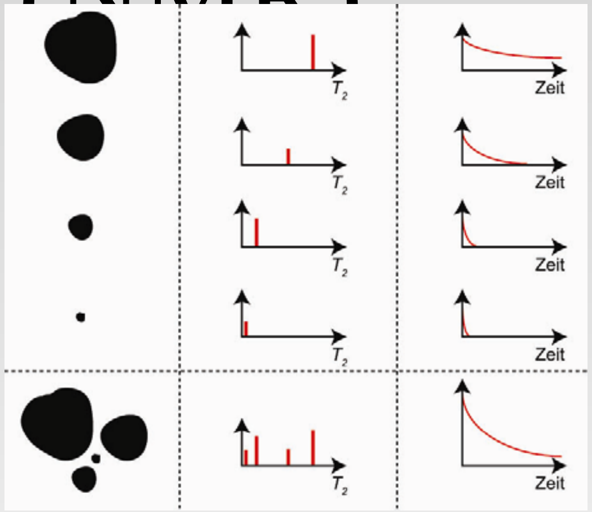


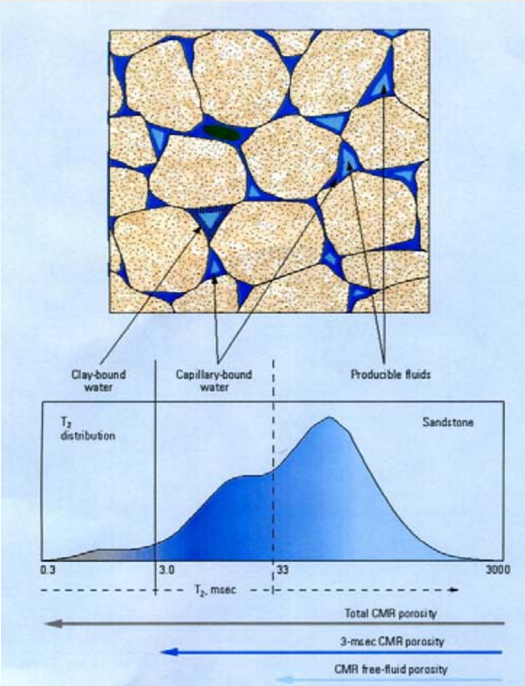


CPMG Sequence

-In the presence of an externally applied magnetic field, B_0, The spins processing around B_0.

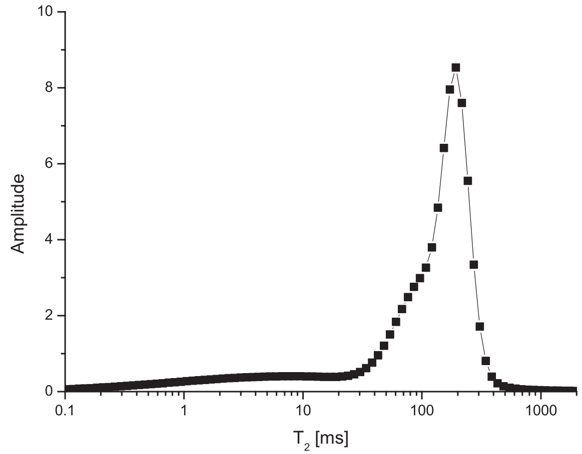
Nuclear Magnetism Resonance (NMR)



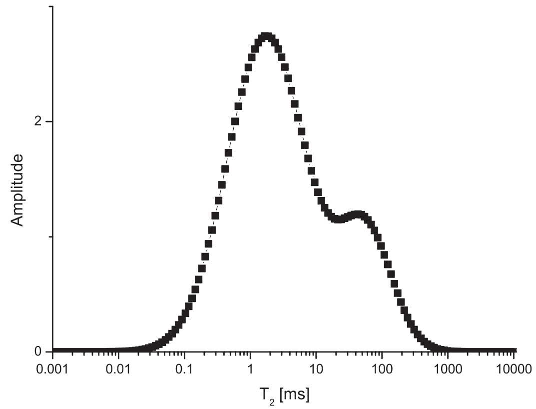


Allen et al., 2000

Without clays



With clays



Separation of : a) clay-bound water and capillary bound water

b) „free“ water