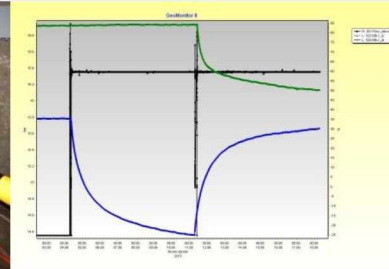
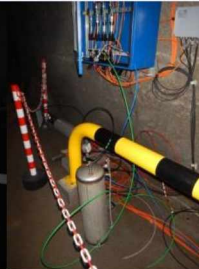
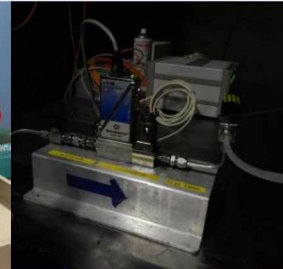
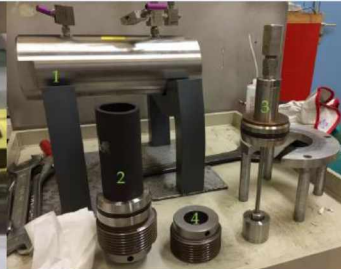


**IRSN**

INSTITUT  
DE RADIOPROTECTION  
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Comparative study of methods for estimating a permeability profile across the Opalinus Clay at the Mont Terri rock laboratory (DB Experiment)

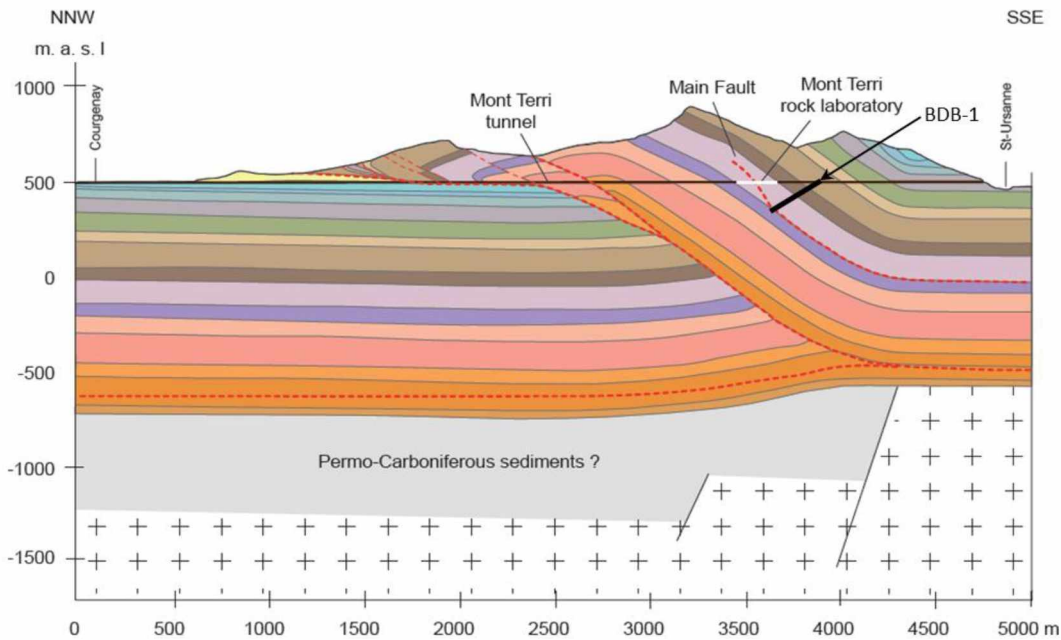
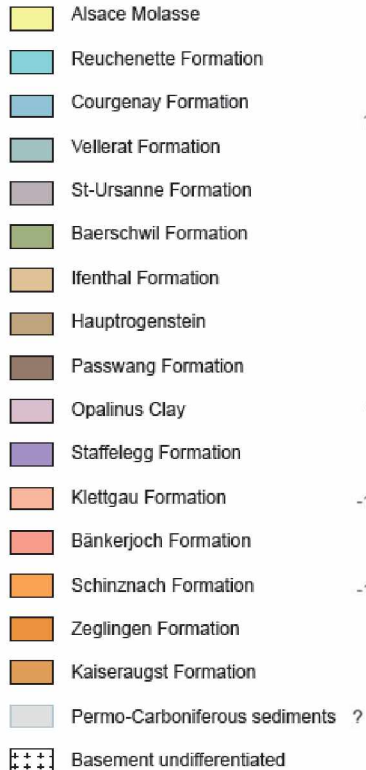


25<sup>th</sup> Earth Science Meeting  
Caen  
October 26<sup>th</sup> 2016

C. Yu, M. Al Reda,  
J.-M. Matray, G. Berthe,  
J. Gonçalves, D. Jaeggi

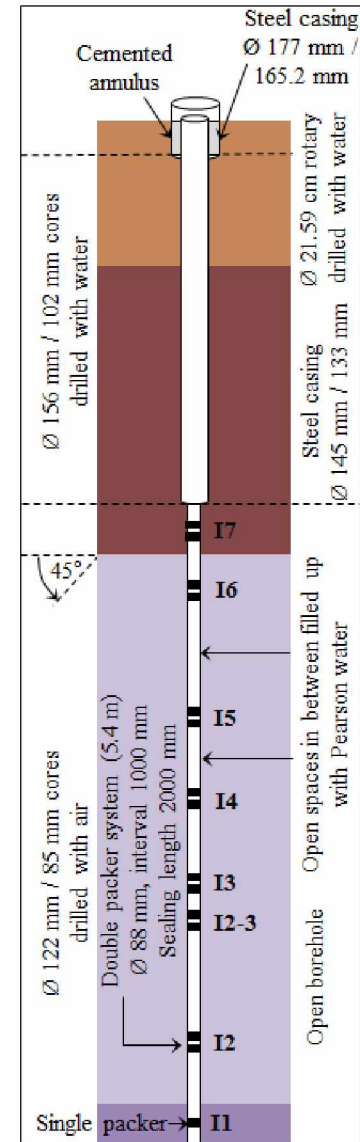
## The Deep Borehole (DB) experiment

- Drilling of a 250 m deep inclined borehole and installation of a multipacker system (7 double packer intervals with P and T sensors)
- Goal: develop and validate a methodology for assessing the containment properties of a thick argillaceous unit using the Opalinus Clay as an example.



--- Thrust planes  
 / Extensional faults

(adapted from Nussbaum et al., 2017)



(Yu et al., 2017)

# Permeability evaluation at different scales of investigation

- Methods based on pore structure model, Darcy's law combined to Poiseuille law, poro-elastic deformation due to tidal load, interpretation of the pressure response to an hydraulic load (in situ test or laboratory scale permeameter)
- Different sample volumes => interrogation on the results comparability

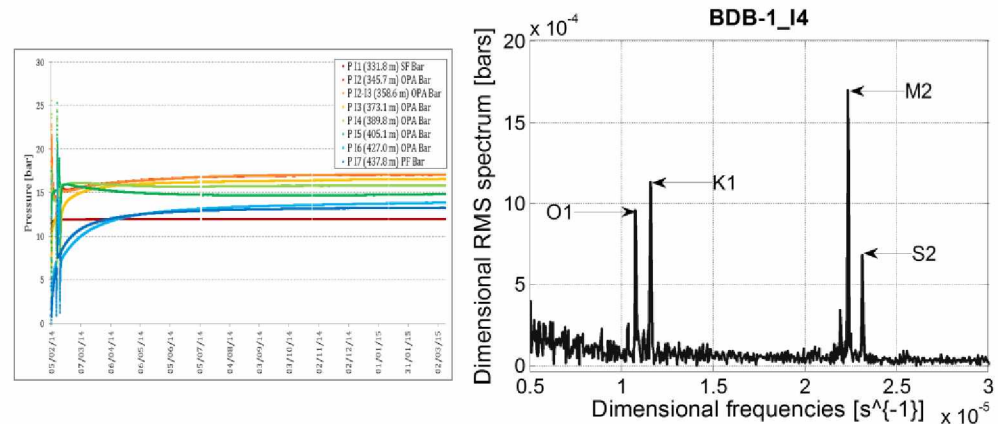
## *In situ hydraulic tests and permeameter tests*



## *Petrophysical measurements*



## *Pressure time series and tidal identification*



# Petrophysical model

## Density

$\rho$

Deduced from  
chlorinity data  
(Unesco, 1980)

## Dynamic viscosity

$\mu$

Deduced from T and P  
measurements  
(Mercer et al. 1975)

## Hydraulic conductivity

$$K = \frac{\rho k g}{\mu}$$

## Intrinsic permeability

$$k = \frac{b^2}{3F}$$

(Kostek et al.,  
1992; Pape et al.,  
1999)

## Grain density

$\rho_s$

He pycnometry  
and XRD

## Half pore size

$\omega$

$$b = \frac{\omega}{\rho_s A_s (1 - \omega)}$$

(Neuzil and  
Provost; 2009)

## Formation factor

$$F = \omega^{-m}$$

(Archie, 1942; Revil  
and Leroy, 2004)

## Specific surface area

$A_s$

BET and BJH

## Connected porosity

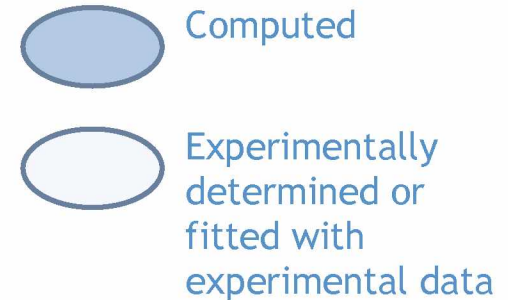
$\omega$

Water loss at 105°C  
and density  
measurements

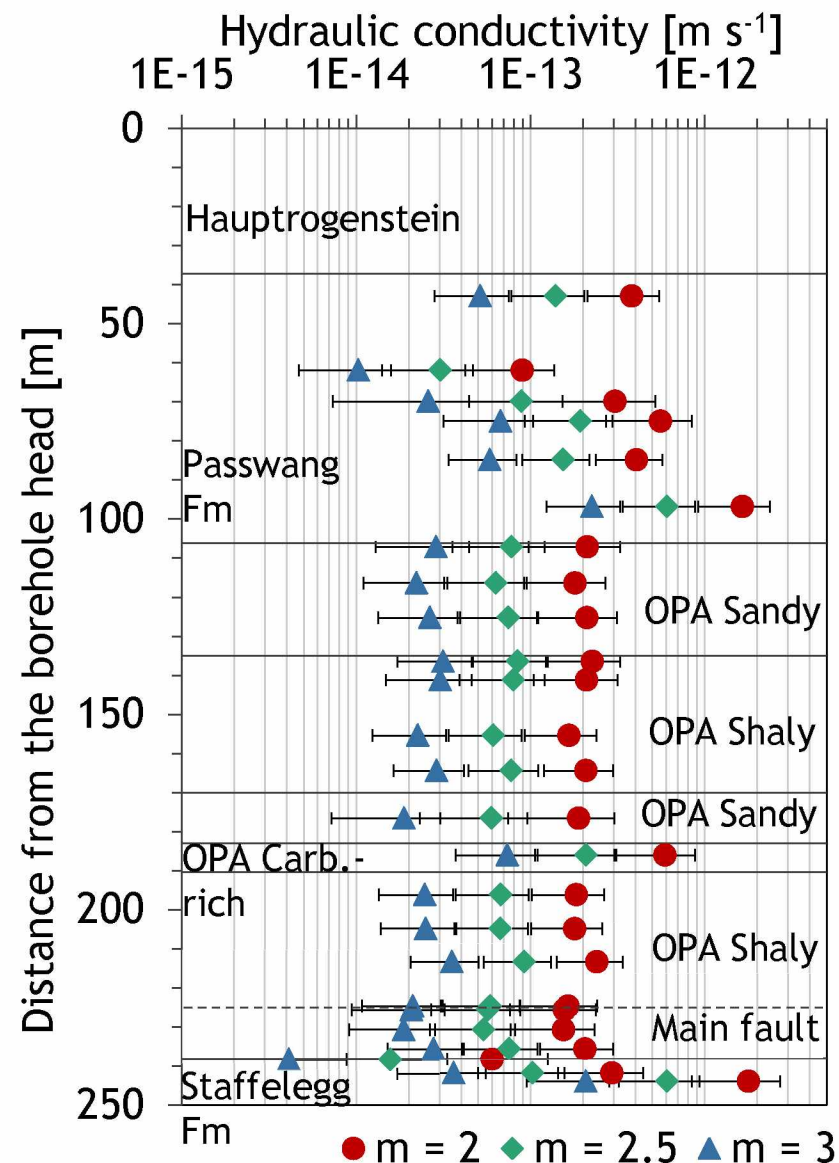
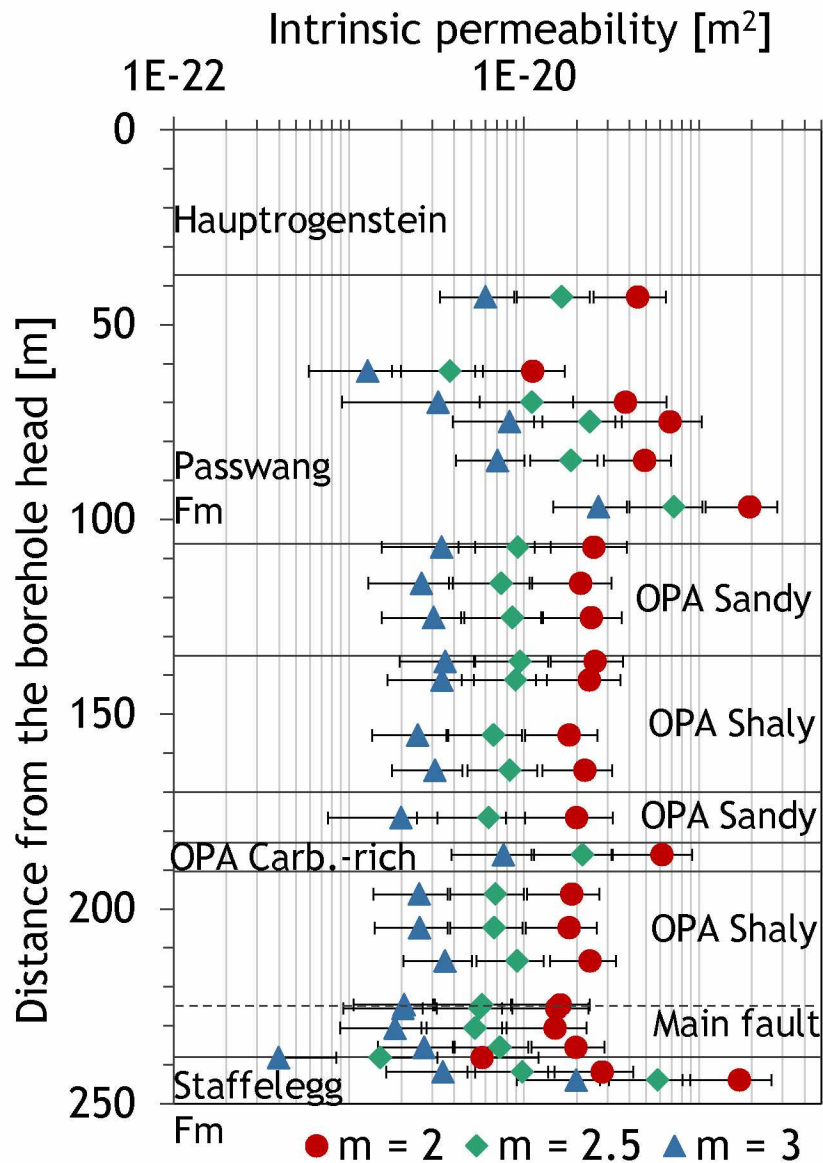
## Cementation factor

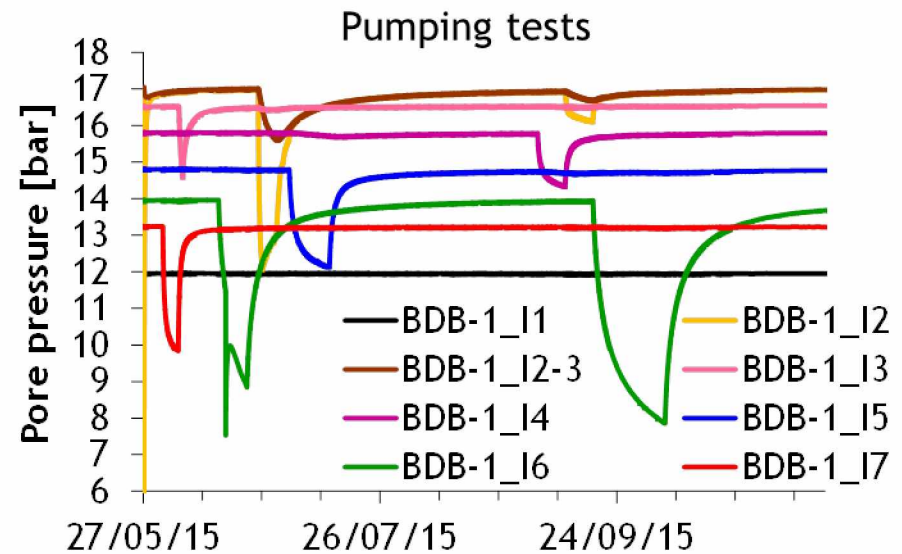
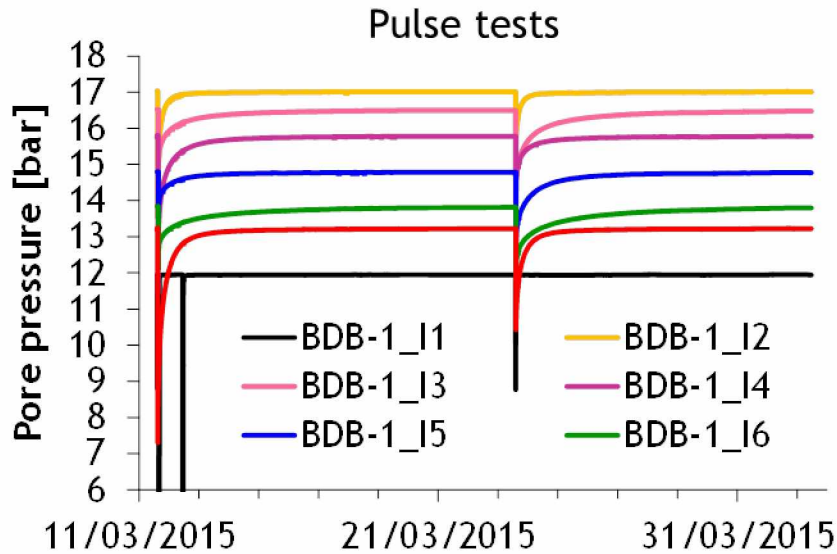
$m$

Between 2 and 3 for  
clayrocks (Mazurek  
et al., 2009)

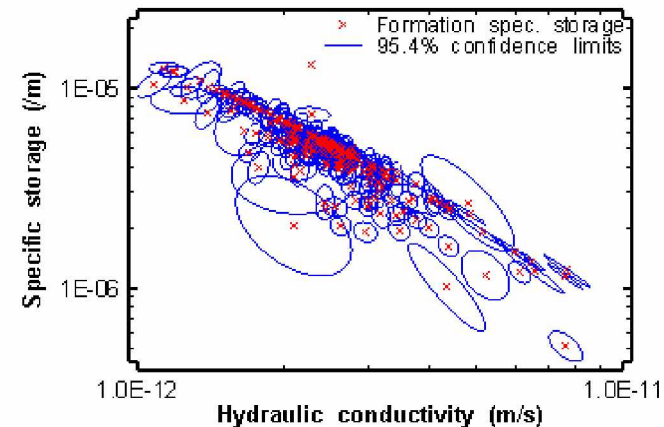
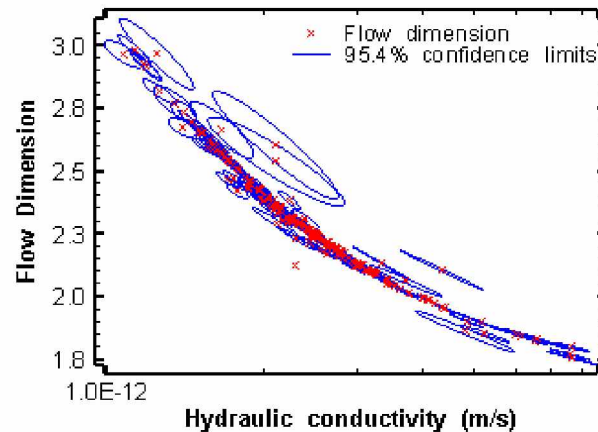
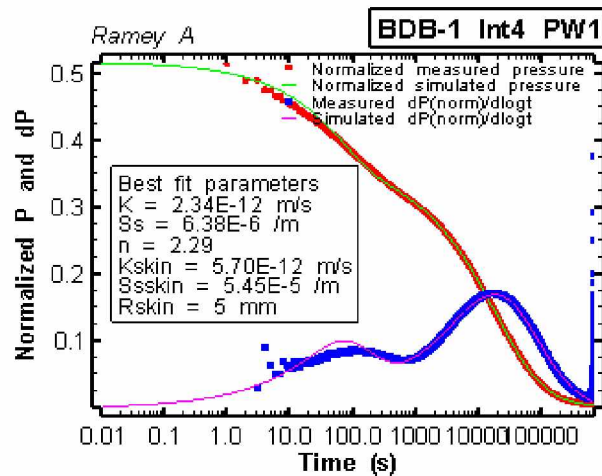


# Intrinsic permeability and hydraulic conductivity

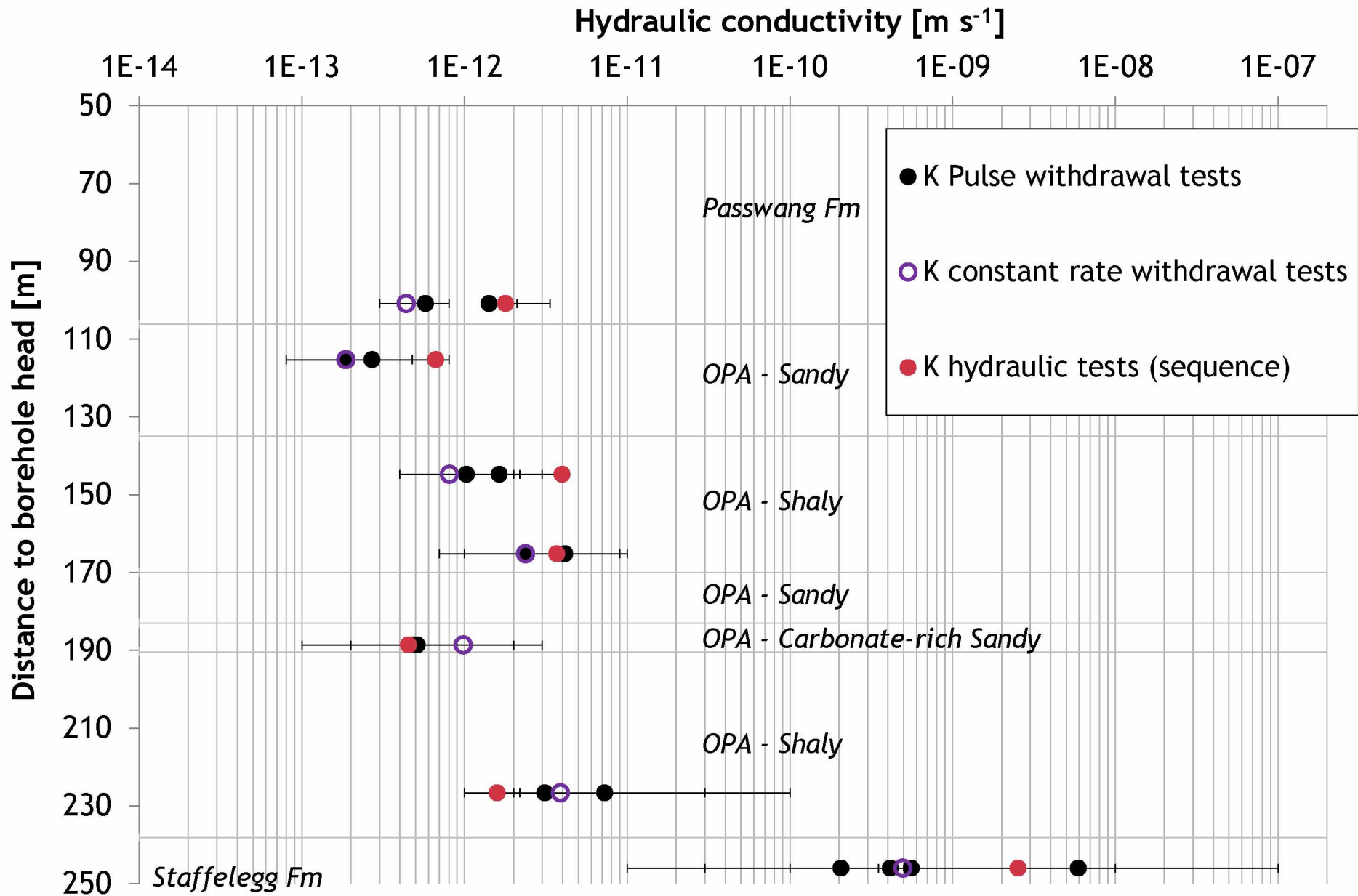




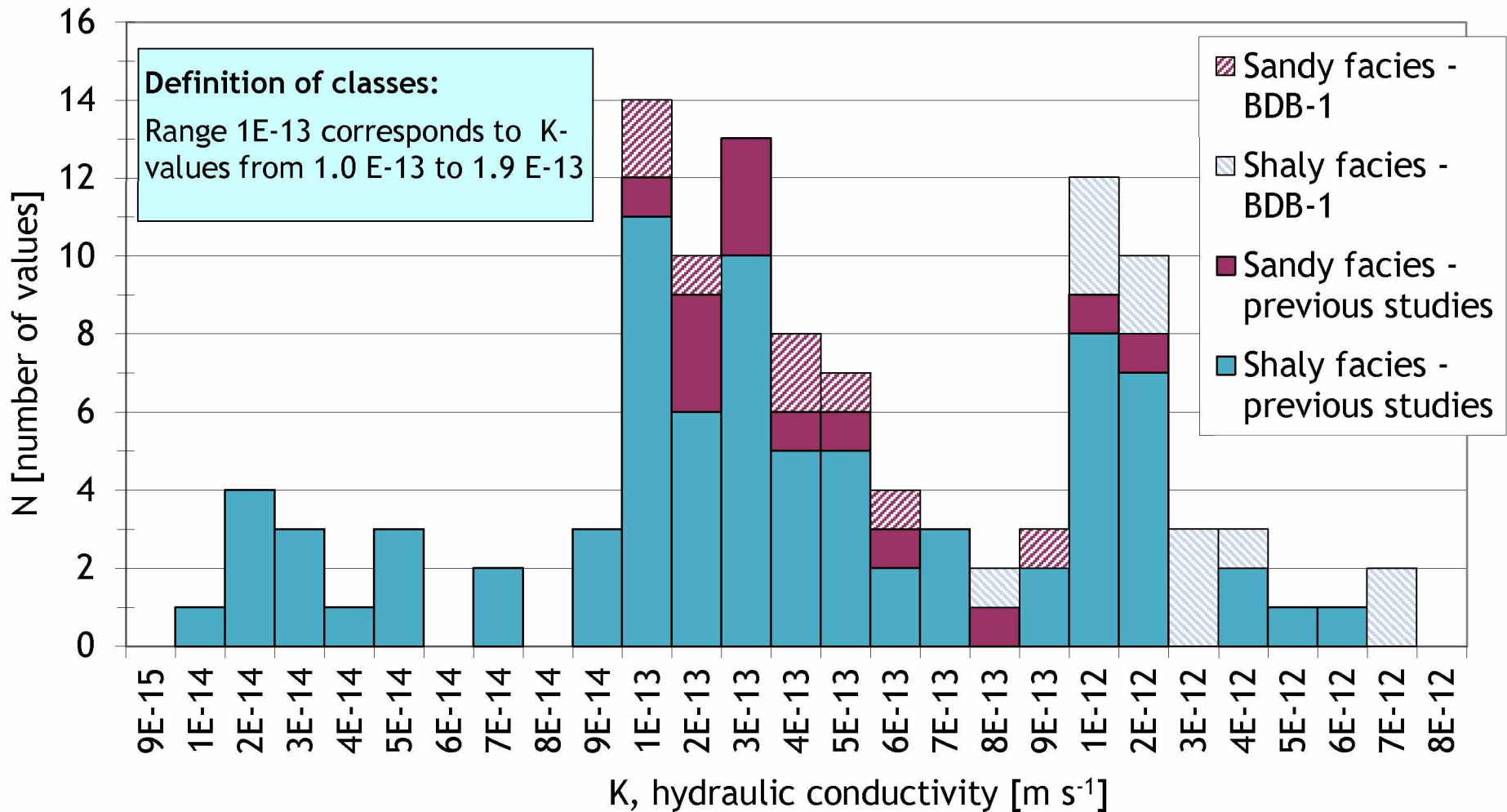
## Numerical interpretation using nSIGHTS and MultiSIM



# In situ hydraulic test results



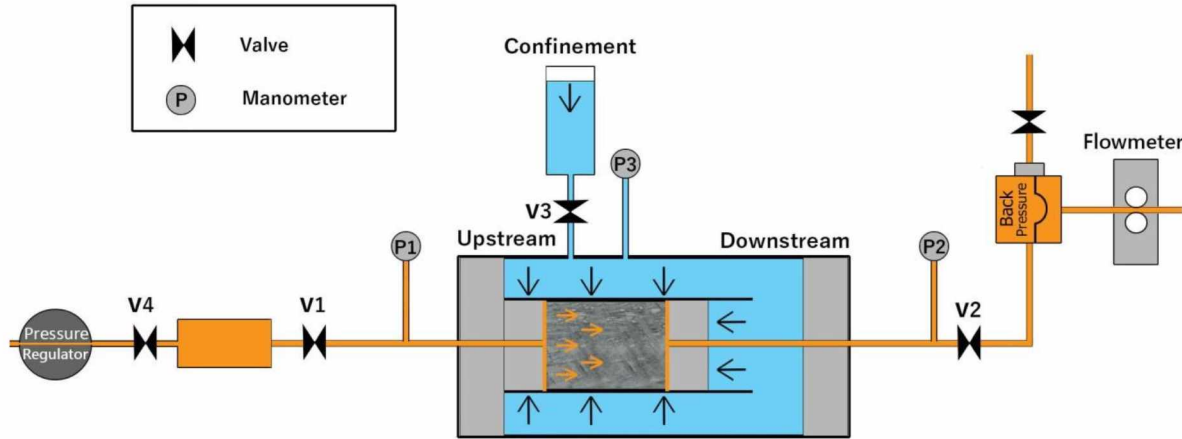
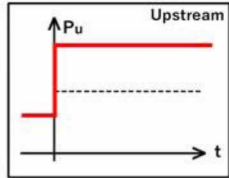
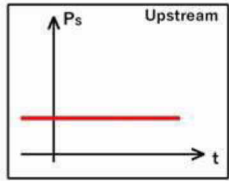
Compilation of K-values obtained by in situ hydraulic tests  
Shaly facies versus sandy facies (not affected by the EDZ)



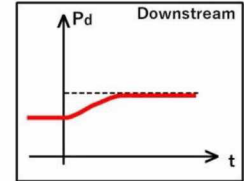
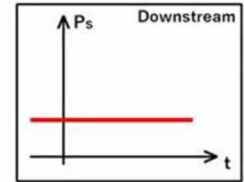


## Steady state method

At  $t=0$ ,  $v_4$  opened,  $v_1$  and  $v_2$  closed



At  $t=x$ ,  $v_4$ ,  $v_1$  and  $v_2$  opened.



(IFPEN)

## Darcy's law-based formula

$$k_{app} = 2 \frac{\mu L Q P}{s (P_u^2 - P_d^2)}$$

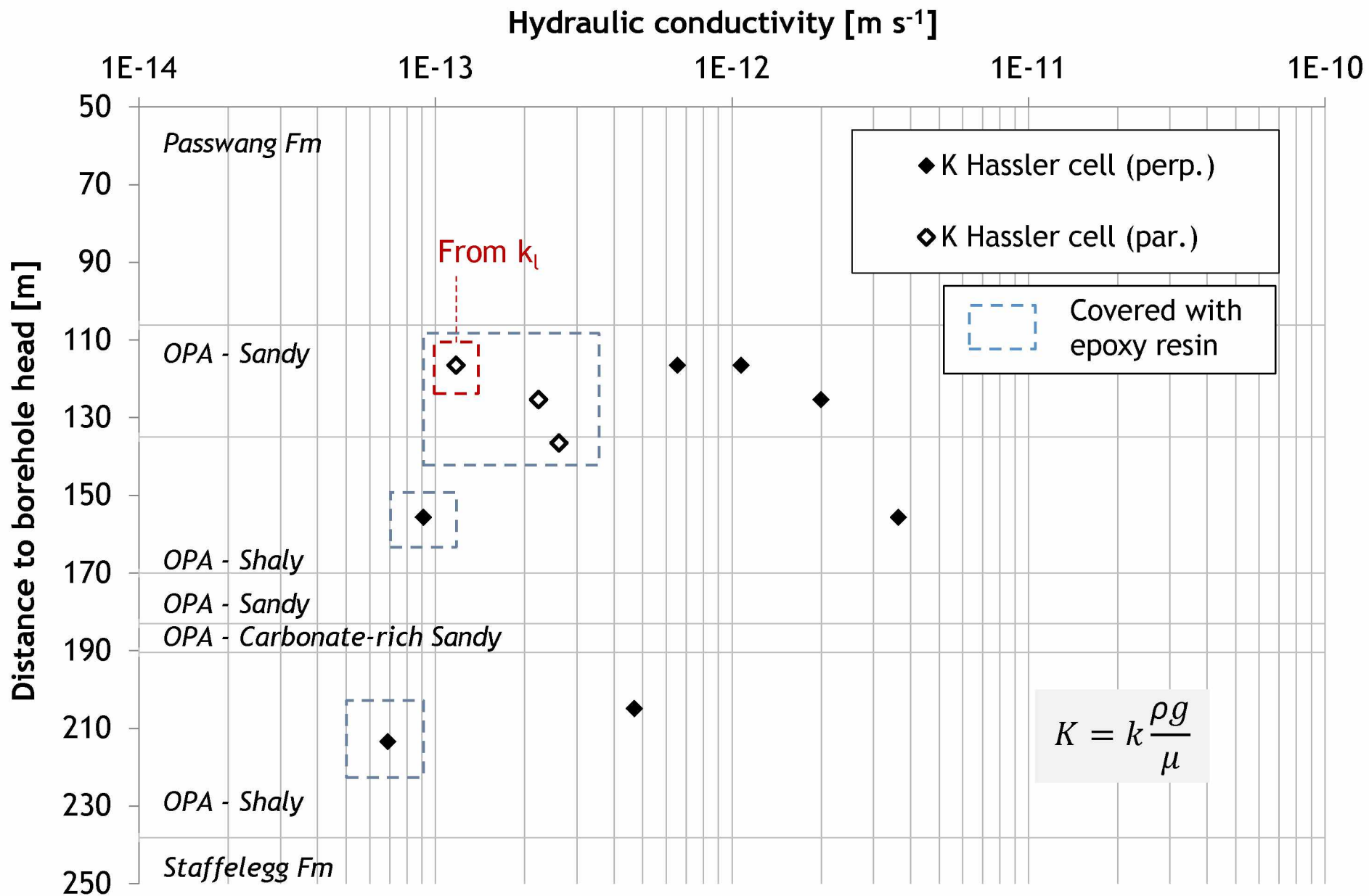


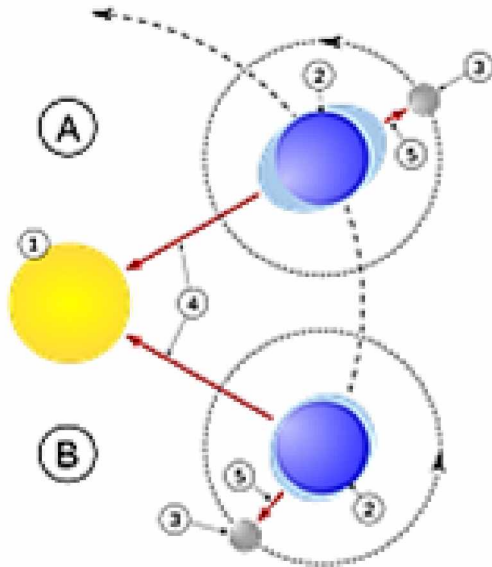
$$k_g = \beta \cdot k_{app} \cdot \frac{1}{P_m} + k_{app}$$

Klinkenberg correction for gas slippage

(no correction for liquid permeability)

# Results of permeameter tests





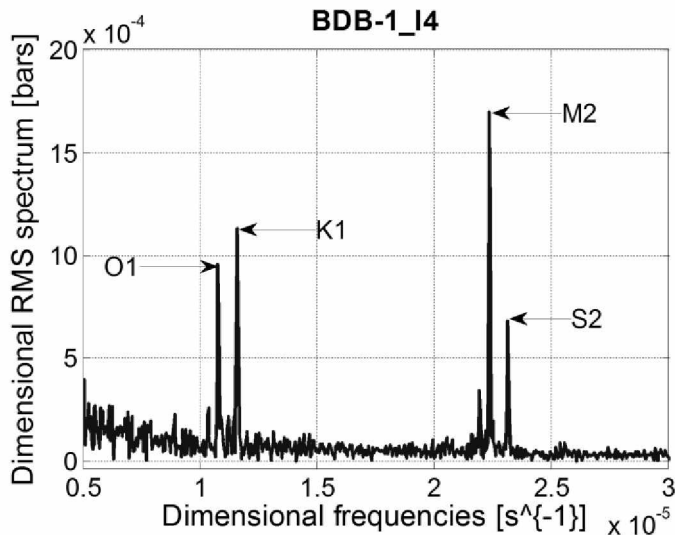
Models based on the bulk deformation effects due to earth tides in the poroelastic water-filled porous medium

**Specific storage** (Bredehoeft, 1967):

$$S_s = \frac{|\Delta\varepsilon|}{|\Delta h|}$$

$|\Delta\varepsilon| = 2 \cdot 10^{-8} \text{ m}^3/\text{m}^3$  Amplitude of the volumetric strain fluctuations related to the  $M_2$  semi-diurnal earth tide (Melchior, 1978)

**Effective dynamic porosity** (Jacob, 1940):  $\tilde{\omega}_{dyna} = \frac{E_W \tilde{S}_s B}{\rho g}$



**Vertical effective hydraulic conductivity** (Boldt-Leppin et al., 2003)

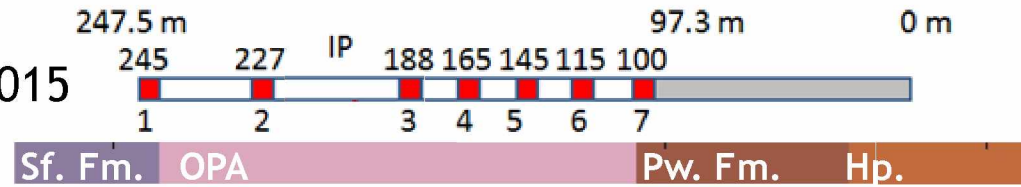
$$\tilde{K}_v^{Ampl.}(f_{M_2}) = \tilde{S}_s(f_{M_2}) \frac{\pi (z_1 - z_2)^2}{(f_{M_2})^{-1}} \left[ \ln \left( \frac{A_{z_1}(f_{M_2})}{A_{z_2}(f_{M_2})} \right) \right]^{-2}$$

$$\tilde{K}_v^{\Delta\varphi}(f_{M_2}) = \tilde{S}_s(f_{M_2}) \frac{\pi}{(f_{M_2})^{-1}} \left[ \frac{(z_1 - z_2)}{\Delta\varphi(f_{M_2})} \right]^2$$

Computed using MUSTAT (Bailly et al., 2014)

# Spectral analysis results

Data from 01/09/2014 to 10/03/2015

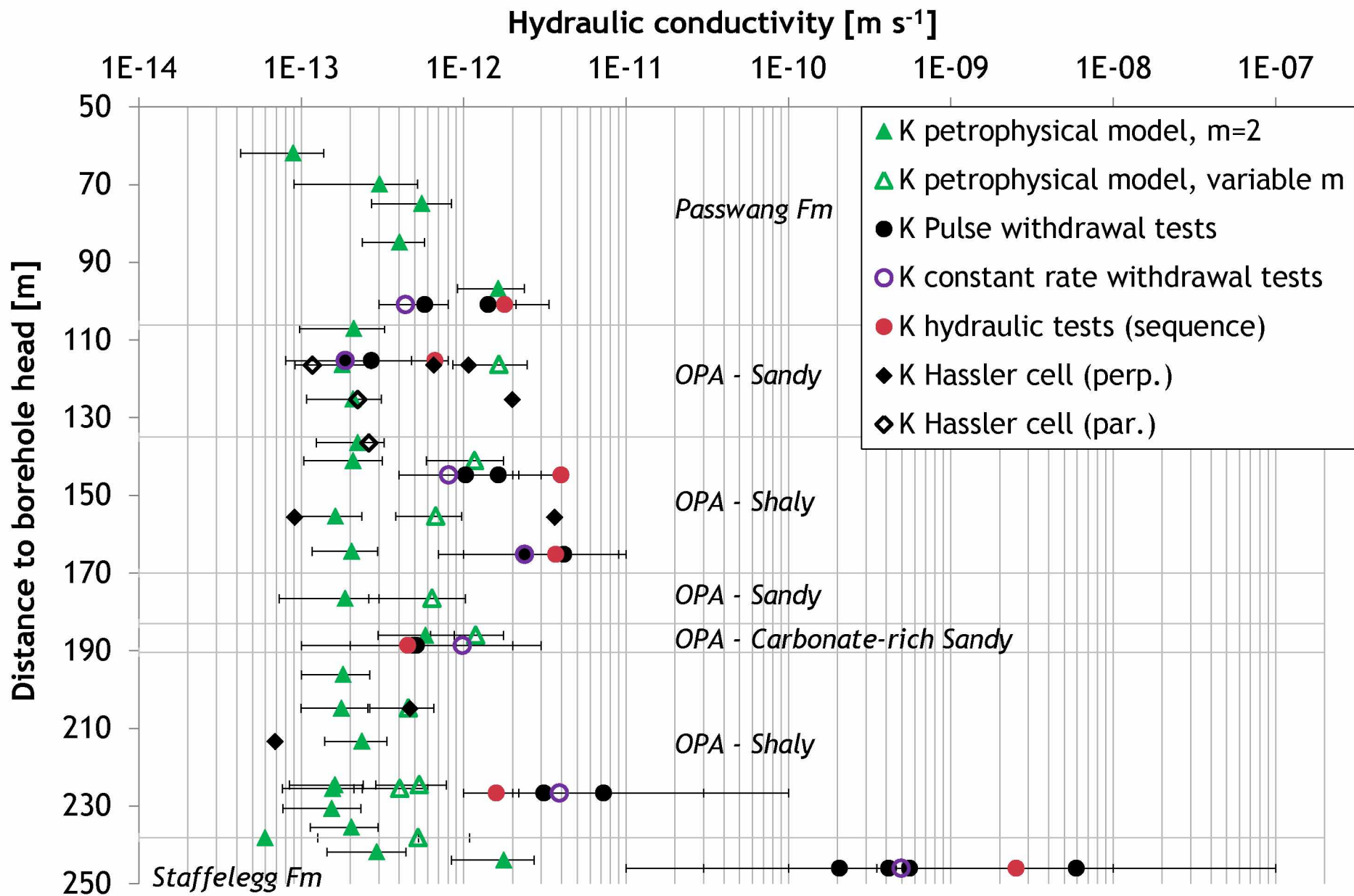


	I1	I2	I2-3	I3	I4	I5	I6	I7
$\Delta h$ (cm)	0.852	1.73	1.86	1.28	1.73	1.70	1.32	0.649
$S_s$ (m <sup>-1</sup> )	2.35·E-06	1.16E-06	1.08E-06	1.28E-06	1.73E-06	1.70E-06	1.53E-06	3.08E-06

	I1 vs I2	I2 vs I2-3	I2-3 vs I3	I3 vs I4	I4 vs I5	I5 vs I6	I6 vs I7
$\tilde{\omega}_{dyna}$	0.09	0.24	0.11	<del>1.33</del>	0.12	0.08	<del>0.79</del>
$\omega_{water\ loss}$	0.14	0.15	0.14	0.10	0.14	0.12	0.14
$\tilde{K}_v^{Ampl.}$	4.78·E-08	2.50E-06	1.40E-07	2.88E-07	5.66E-05	6.38E-07	3.89E-08
$\tilde{K}_v^{\Delta\phi}$	7.17·E-07	1.02E-05	3.32E-06	5.81E-06	4.11E-06	1.80E-05	7.33E-08

- Consistent values for specific storage and effective porosity
- Method unappropriate to estimate hydraulic conductivity (overestimation of several orders of magnitude)

# K measurements comparison



- Global consistency between the results obtained from BDB-1 borehole and data acquired at the rock laboratory level.
- Order of magnitude for OPA permeability  $\sim 10^{-13}$  -  $10^{-12}$  m s<sup>-1</sup>, with higher values in the shaly facies compared to the sandy facies. No clear difference is highlighted by numerical interpretation of hydraulic tests in the fault zone.
- Tidal analysis is unappropriate to compute hydraulic conductivity in this study but gives consistent values for specific storage and effective porosity.
- The acquisition of advective transport parameters will enable a future fluid flow modelling accounting for coupled transport processes.