UQAC
Université du Québec
à Chicoutimi

CERM
Centre d'études sur
les ressources minérales

Numerical investigations of the spherical flow regimes induced by constant-rate pumping tests

Anouck FERROUD, Romain CHESNAUX, Silvain RAFINI
anouck.ferroud@gmail.com

Abstract n°2120

25-29th September, 2016

25-29th September 2016
43rd IAH congress
Montpellier, France
CORUM CONFERENCE CENTER

1. Introduction

1.1 Terms and concepts

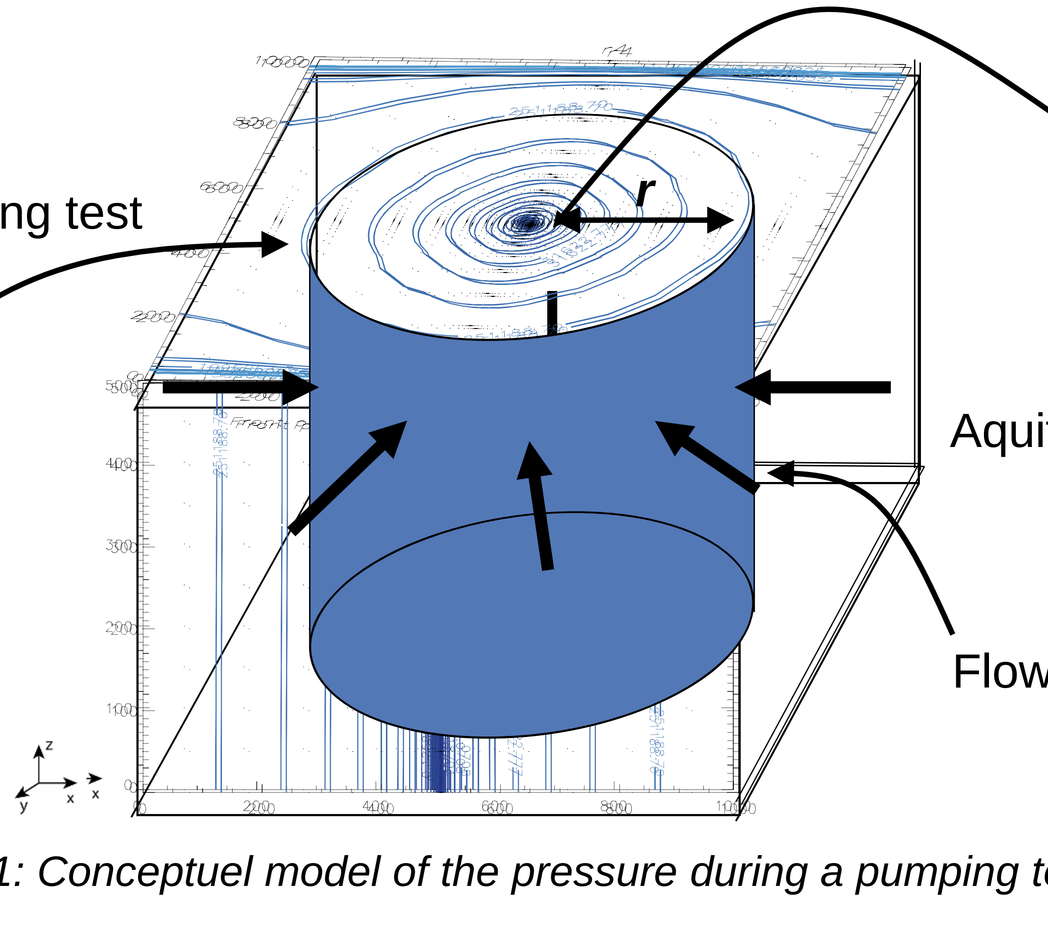


Fig. 1: Conceptuel model of the pressure during a pumping test

Pressure front pulse (or pressure wave)

Radial distance *r*

Cross flow area *A(r)* (equipotential surface)

1.2 Constant rate pumping tests : diagnostic tools

" The old way " *	" The new way " *
Drawdown **s**	Drawdown-log derivative **ds/dlogt**

P–1
PP–5D
PK–3R

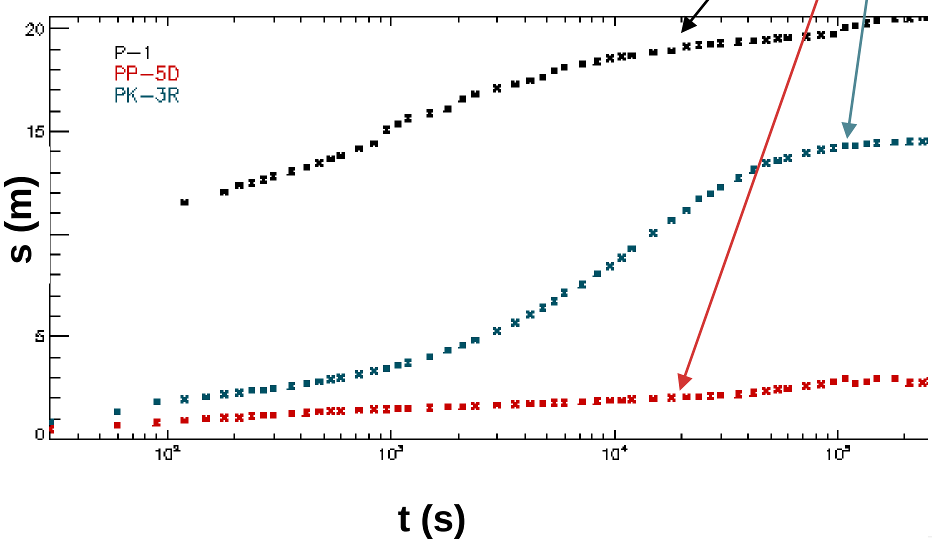


Fig. 2: Semi-log plot of the s.

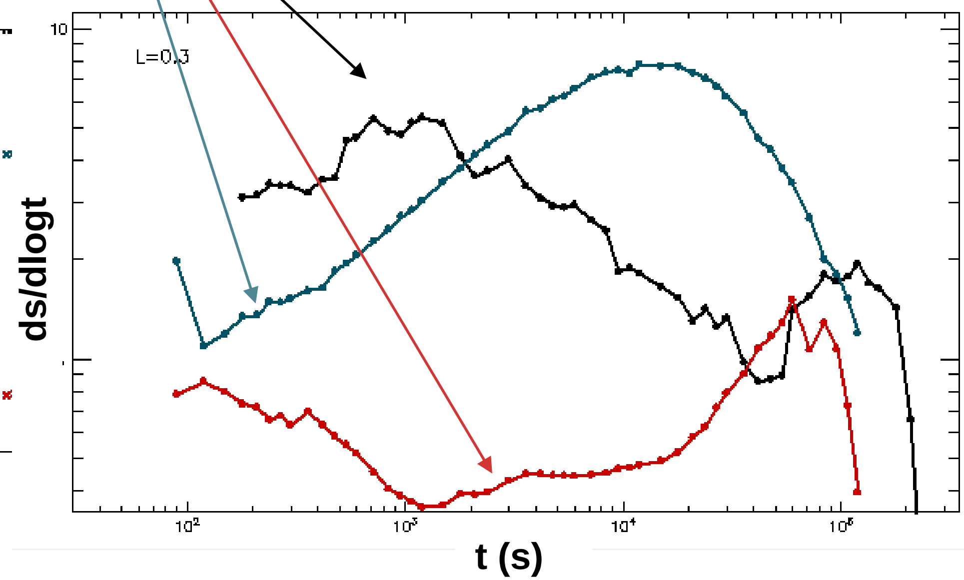


Fig. 3: Log-log plot of ds/dlogt (Bourdet et al., 1989).

Much more sensitive signal

…But the physical interpretation = still enigmatic

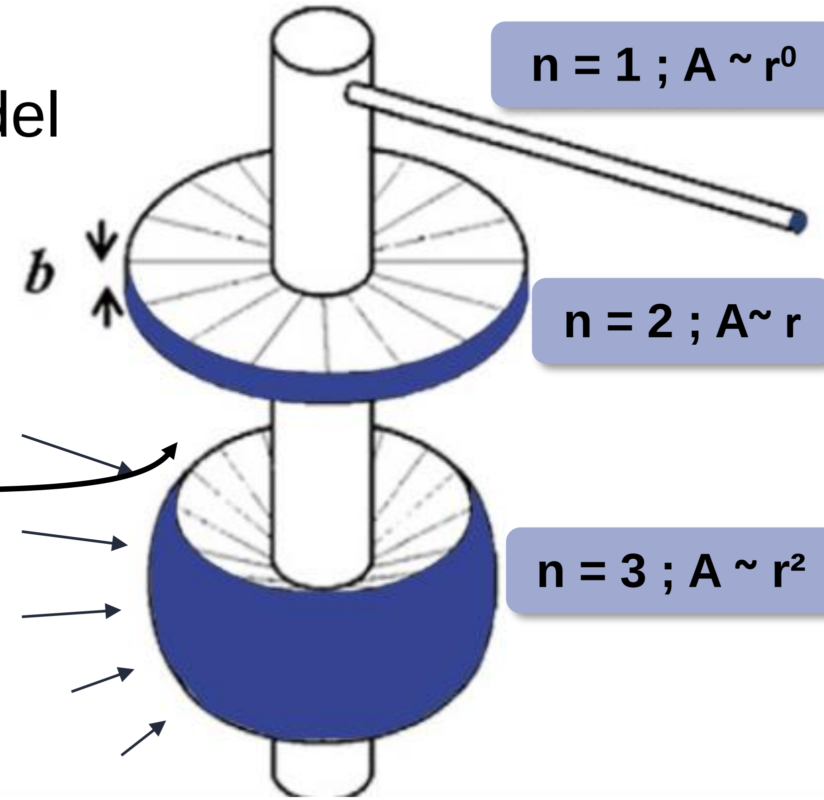
** Mattar (1997)*

43rd IAH congress

1.3 Hydraulic interpretation of *ds/dlogt*

Generalized Radial flow (GRF) Model
(Barker, 1988)

$$A(r) \sim r^{n-1}$$



n reflects the **geometry of the pressure wave** when it diffused through the aquifer

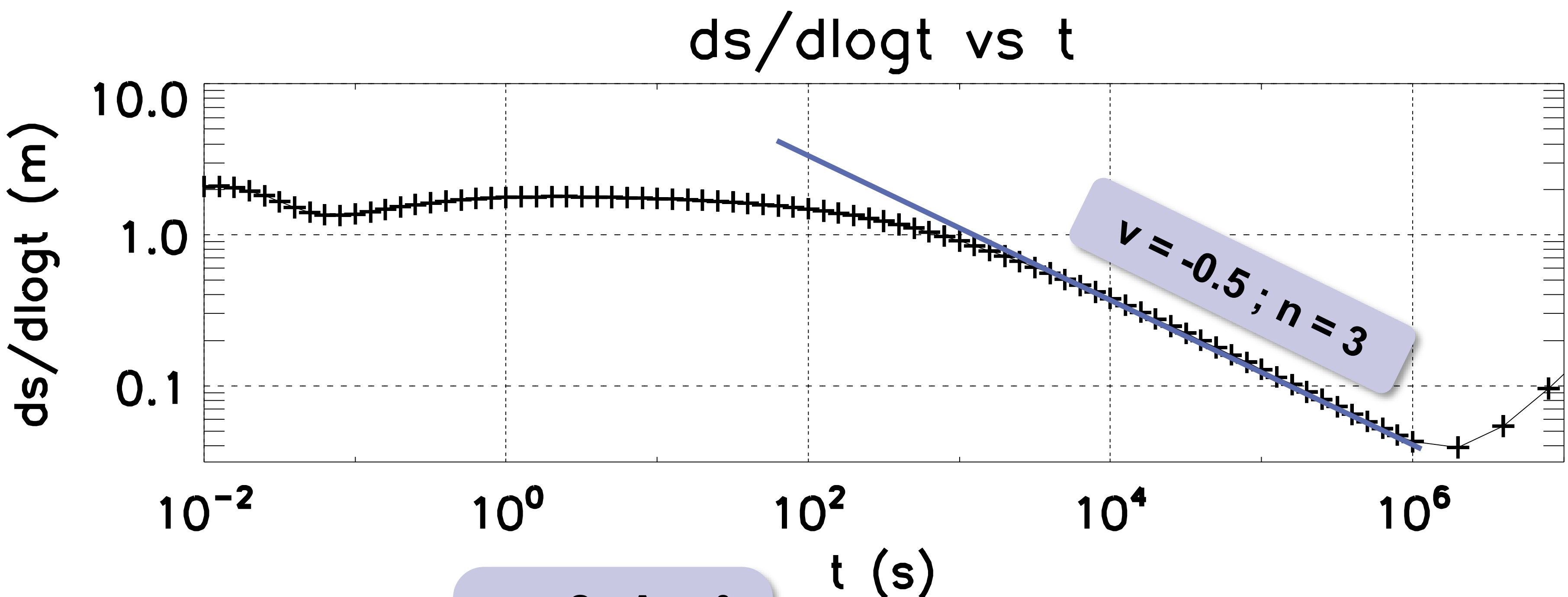
"Flow geometry combined to the hydraulic properties of the aquifer" (Beauheim et Roberts, 1998).

A(r): cross-flow area
r: radial distance from the well (m)
n: flow dimension parameter (= **flow regime**)

1.3 Hydraulic interpretation of *ds/dlogt*

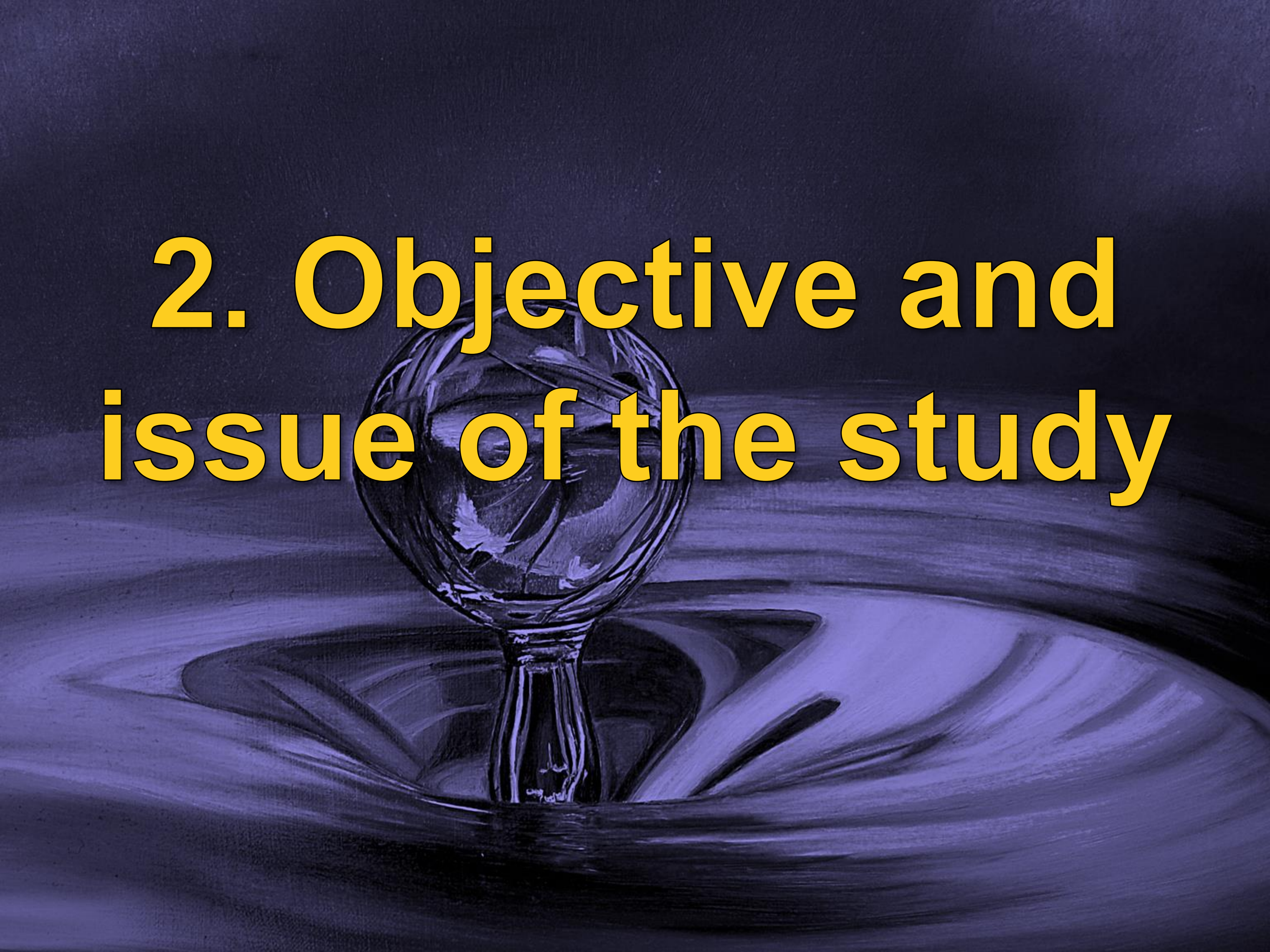
How to estimate *n* from transient well test data?

$n = 2.(1-v)$



n = 3 ; A ~ r²
spherical flow regime

n: flow dimension
v: slope of *ds/dlogt*



2. Objective and issue of the study

Objective

To develop advanced tools of intepretation of pumping tests based on *ds/dlogt* signal and Barker’s theory

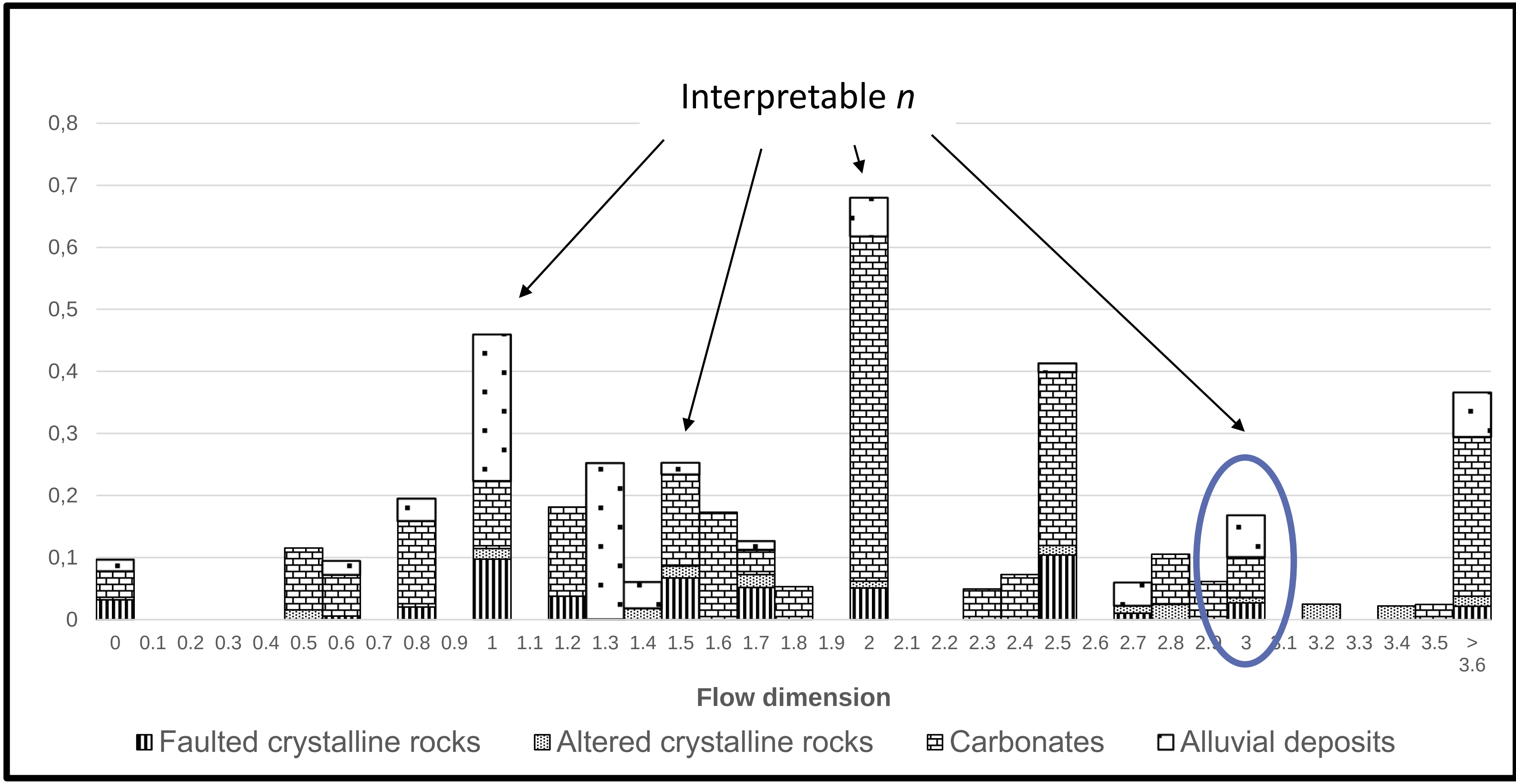
Issue

What are the conceptual models producing a spherical flow regime?

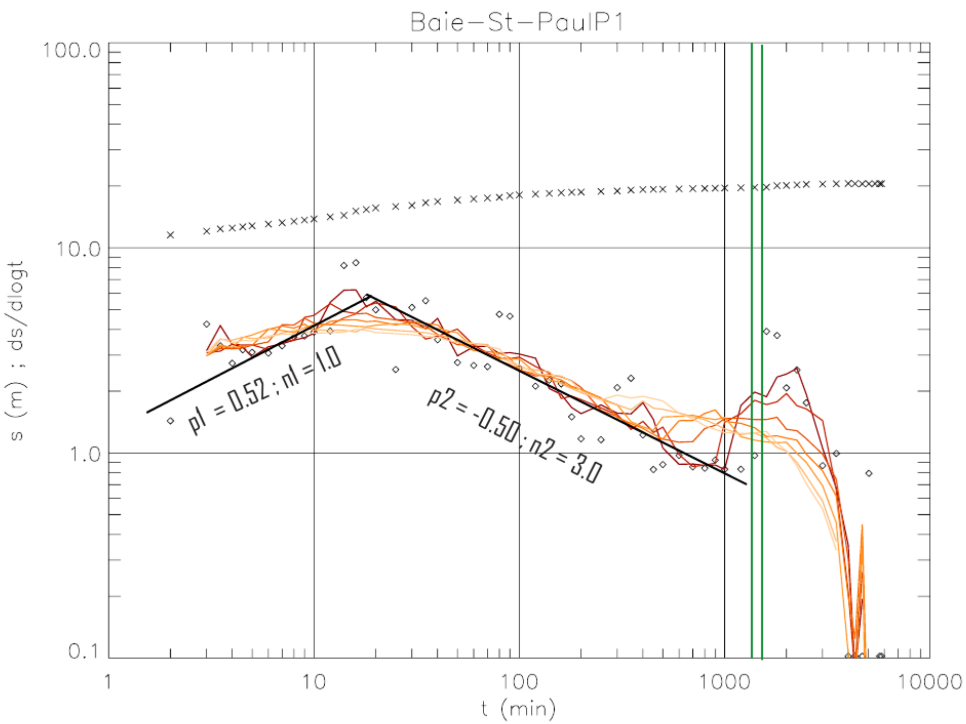
1.4 Field data: observation of *n* in nature

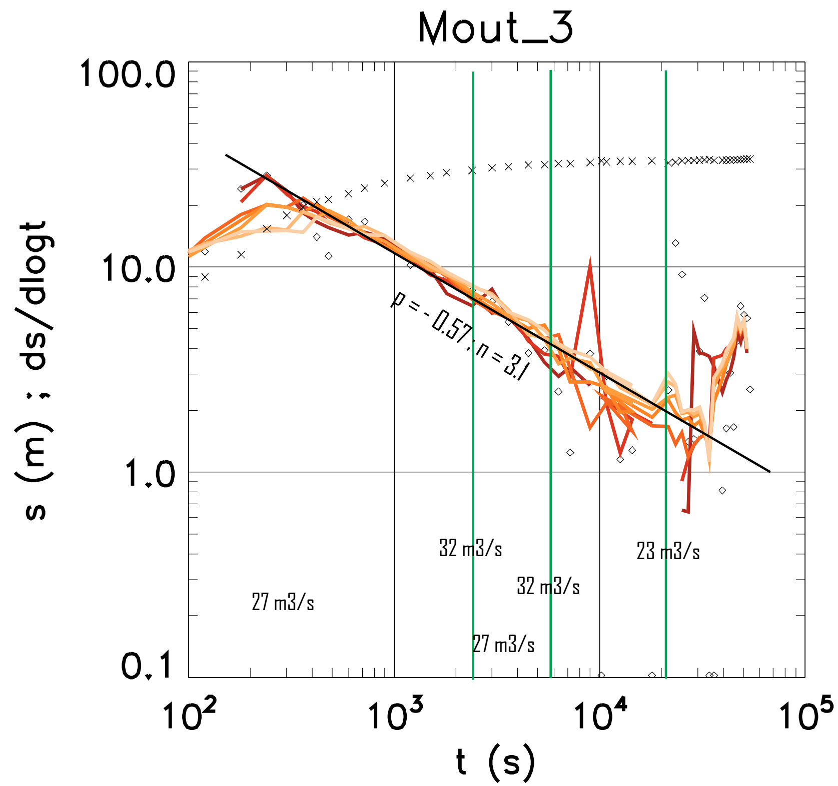
Previous study:

Statistical occurrence of flow dimension in various geological environments→ *n* distribution in nature.



1.4 Field data: spherical flow regime





3. Methodology

3.1 The model: HydroGeoSphere (HGS)

HydroGeoSphere *(Therrien et al., 2010, Aquanty, 2015)*

HGS = Spatially distributed and physically-based 3D modelling software.

Numerical implementation:

For sub-surface and saturated flow:

Diffusivity equation

$$\vec{\nabla}\left(\overline{\overline{\mathrm{K}}}(\mathrm{x},\mathrm{t})\overrightarrow{\nabla \mathrm{h}}\right) = S_s(x,t)\frac{\partial h}{\partial t} \pm \mathrm{f}(\mathrm{x},\mathrm{t})$$

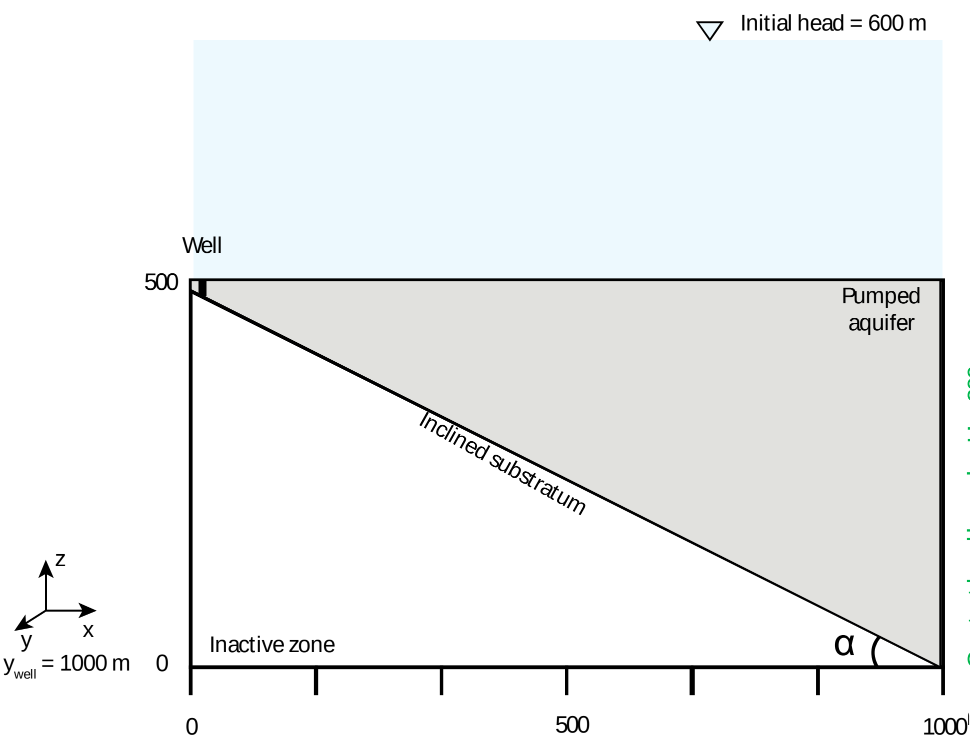
Discretization :

- Finite element method,
- Control-volume finite element method.

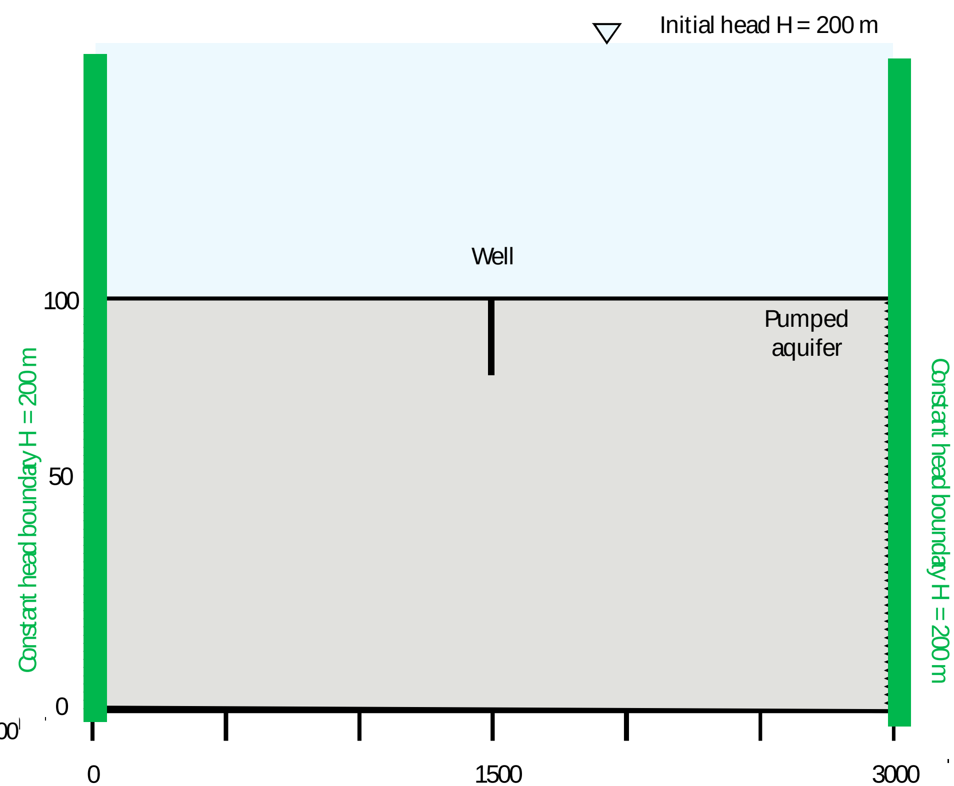
K: Hydraulic conductivity (m/s)
S_s: Specific storage
h: hydraulic head (m)

3.2 The conceptual models

Inclined substratum

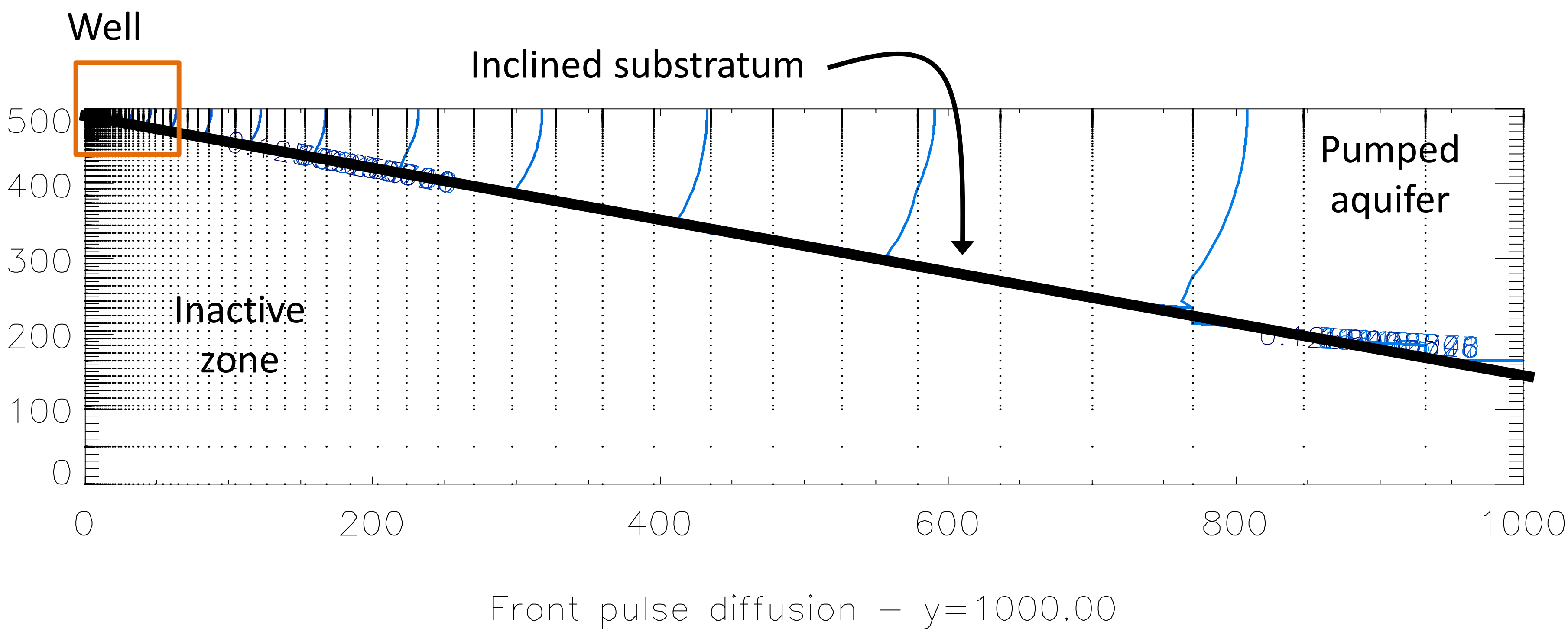


Partially penetrated aquifer



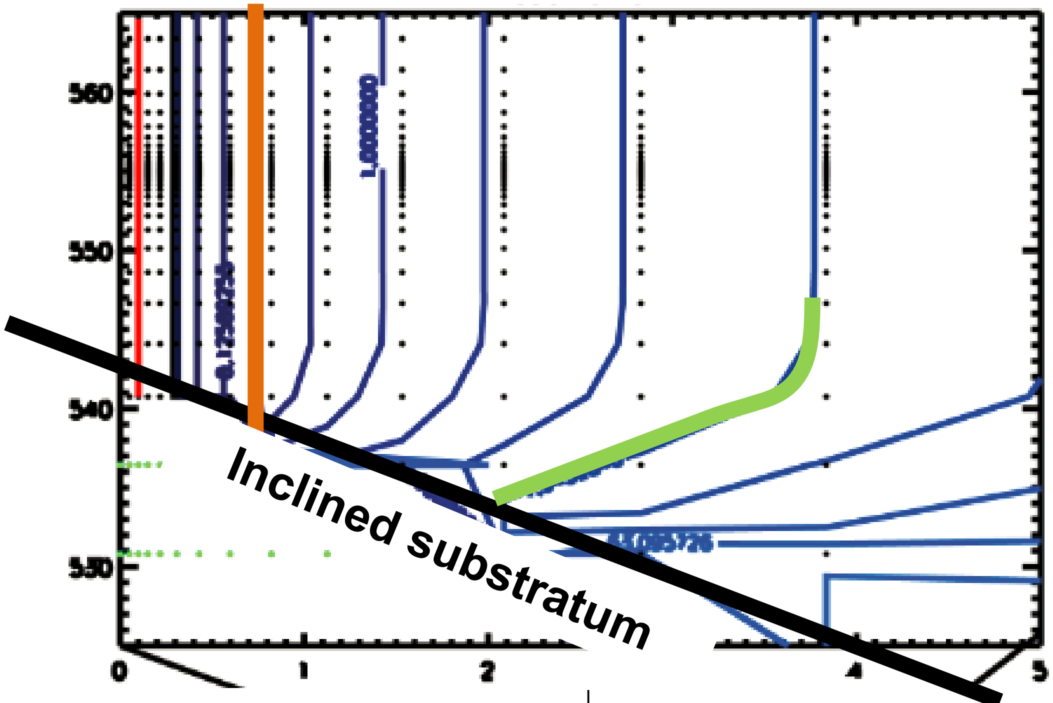
4. Results

4.1 Propagation of frontal the equipotential surface



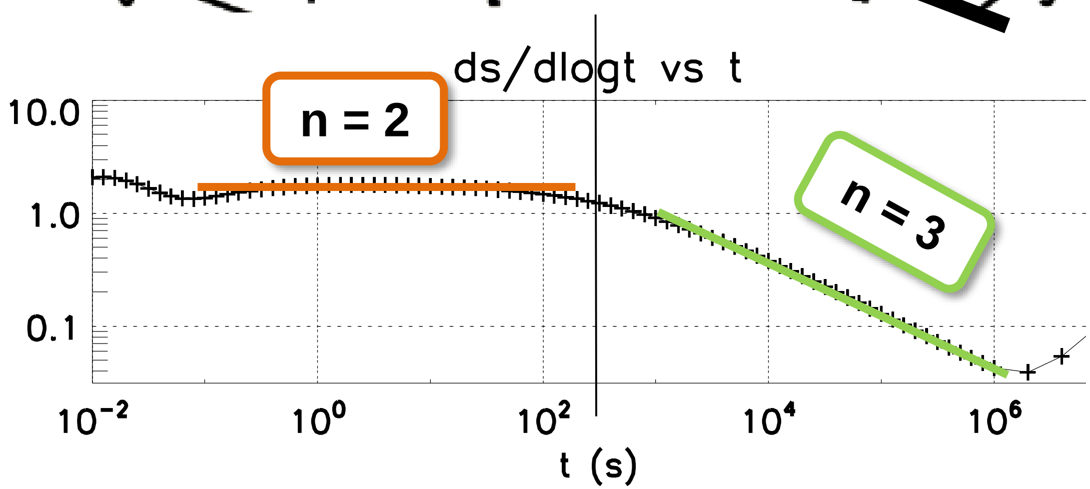
4.1 Propagation of frontal the equipotential surface

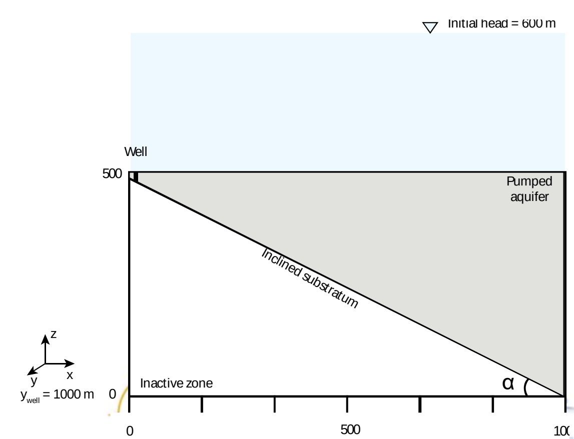
Well



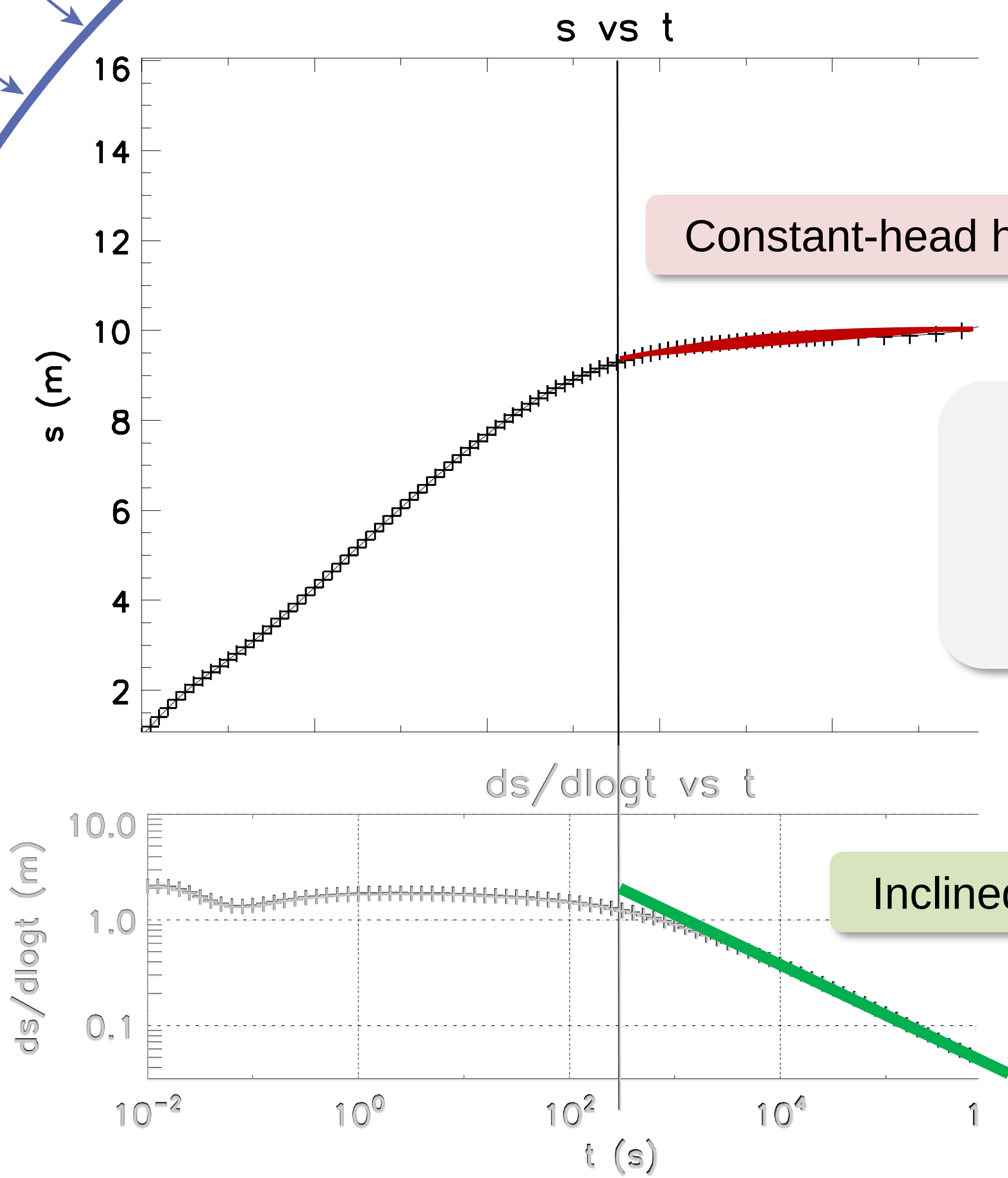
A ~ r
Early cylindrical-radial flow regime

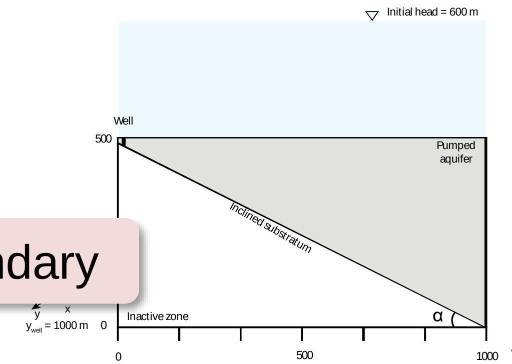
A ~ r²
Spherical flow regime





4.2 The *ds/dlogt* signal: inclined substratum





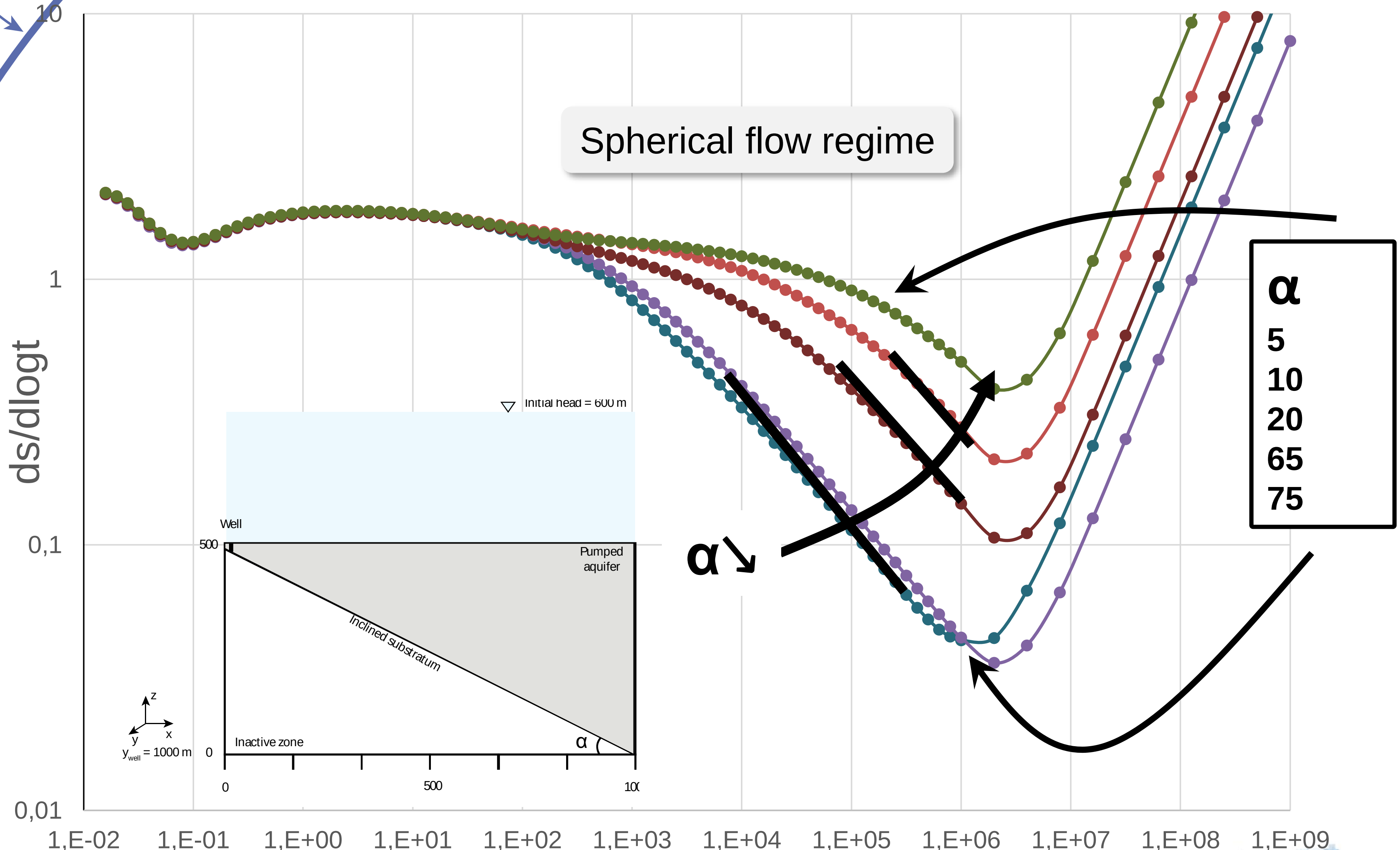
Constant-head hydraulic boundary

Interpretation of the hydraulic signal and detection of the boundary conditions = more reliable

Inclined substratum

25-29th September 2016
Montpellier, France
CORUM CONFERENCE CENTER
43rd IAH congress

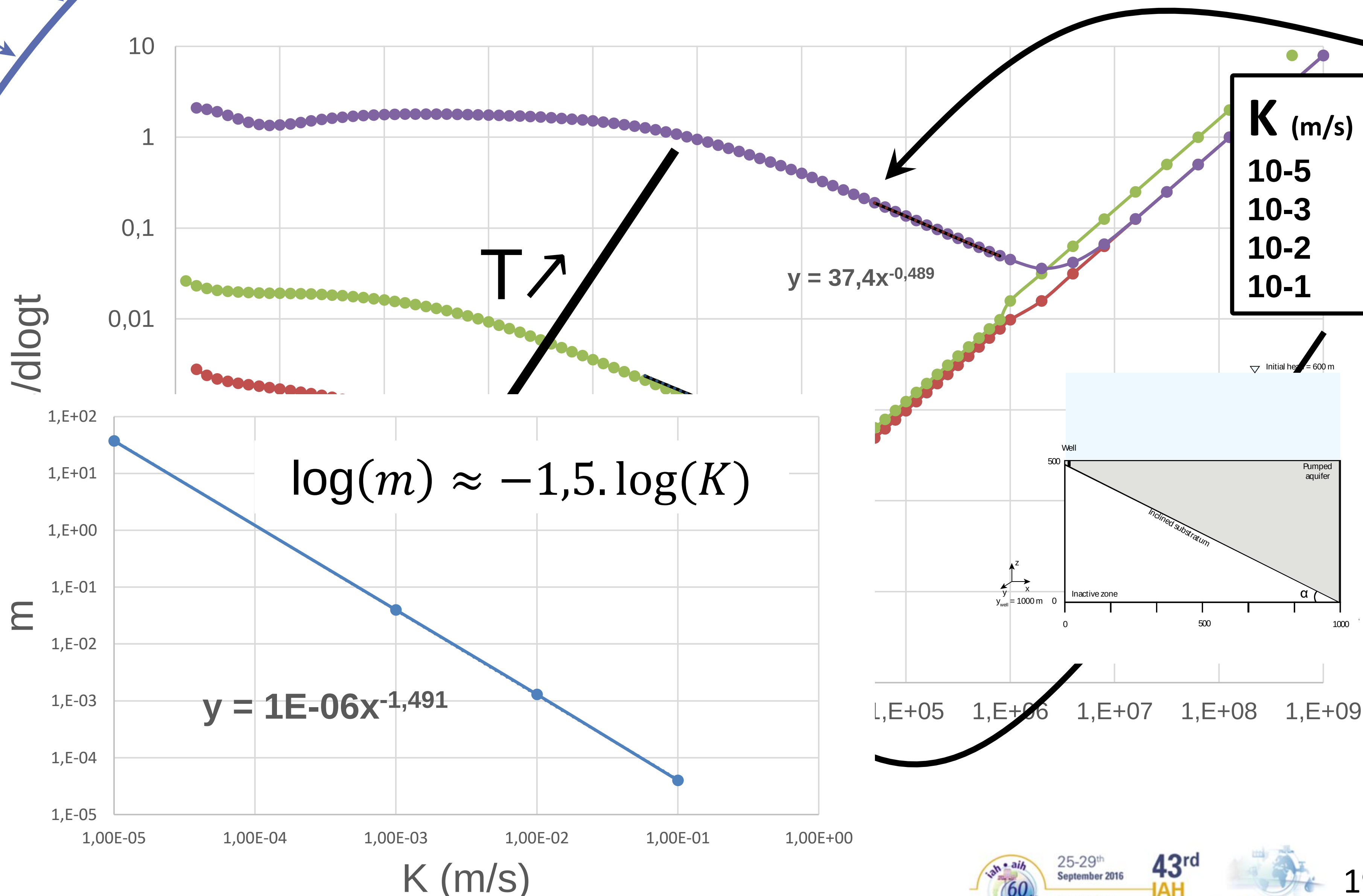
4.2 The *ds/dlogt* signal: inclined substratum

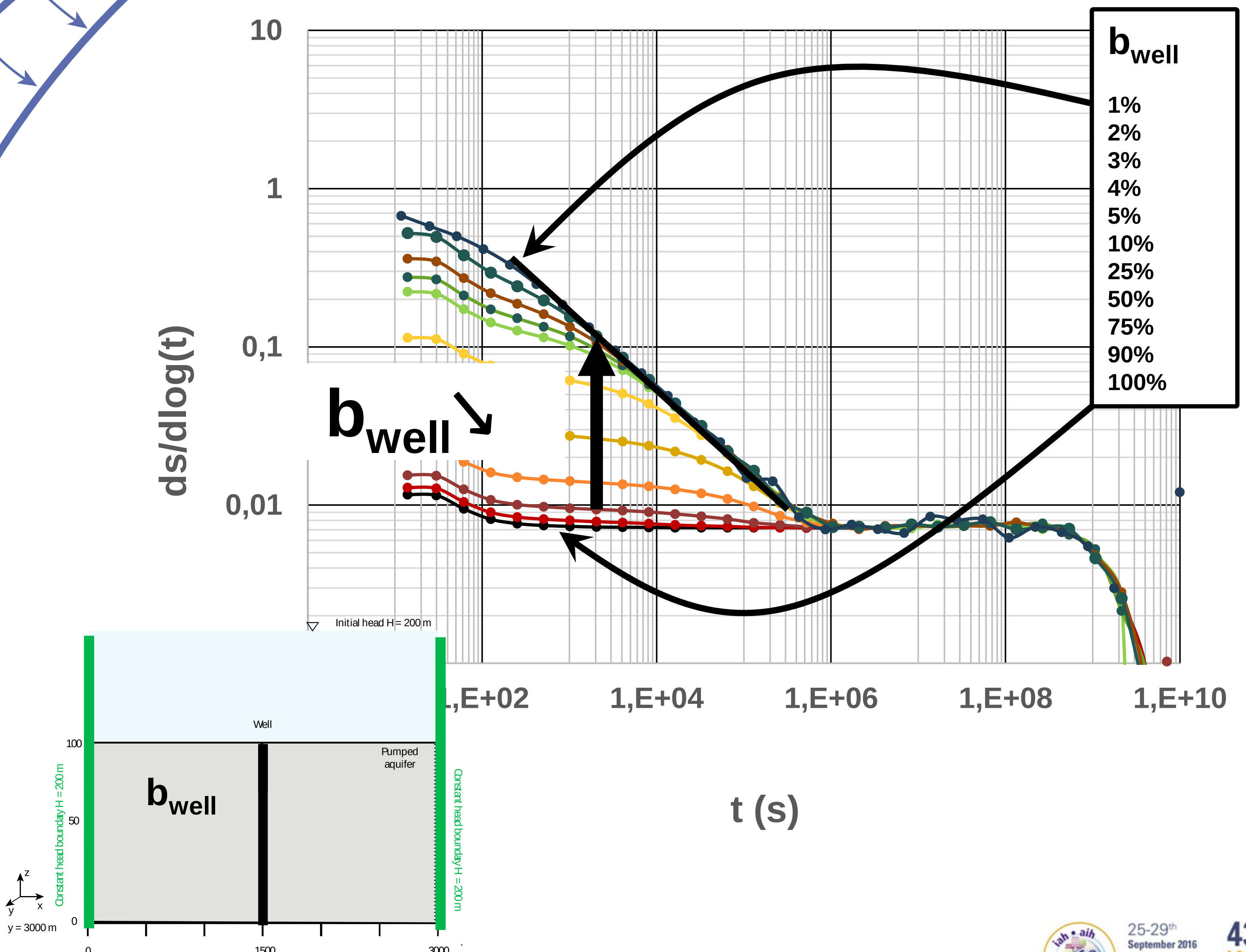


α: slope of the inclined substratum

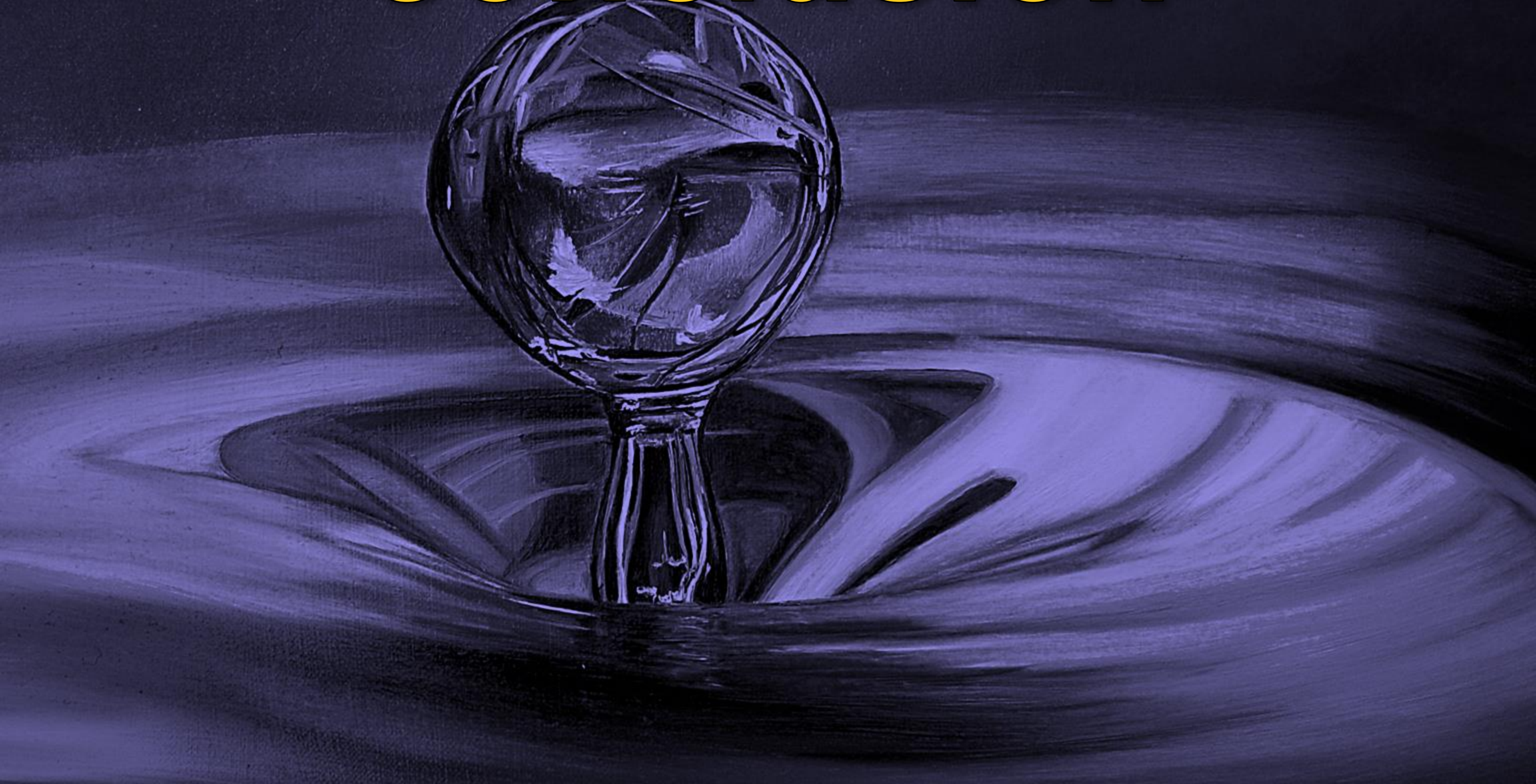
25-29th September 2016 Montpellier, France 43rd IAH congress

4.2 The *ds/dlogt* signal: inclined susbtratum




10
1
0,1
0,01
ds/dlog(t)
1,E+02
1,E+04
1,E+06
1,E+08
1,E+10
t (s)
b_well
1%
2%
3%
4%
5%
10%
25%
50%
75%
90%
100%
b_well ↘
Initial head H = 200 m
Well
Pumped aquifer
b_well
Constant head boundary H = 200 m
Constant head boundary H = 200 m
100
50
0
0
1500
3000
y = 3000 m
z
x
y

5. Discussion and conclusion



The derivative approach doesn't need more data, but it gives much more information!
- qualititative: analysis of flow geometry
- quantitative: estimation of hydraulic properties with more reliability

Sensistivity analysis → empirical equation → estimation of *K* from a *ds/dlogt* curve fitting

Non-uniqueness of the flow regimes!!!
Partially penetrated aquifer → $n = 3$
An inclined substratum → $n = 3$

Geological settings = essential to inteprret a pumping test!
Sequences of n = help to reduce the non uniqueness!

Marie-Claire Houmeau painting

Ano AFINI

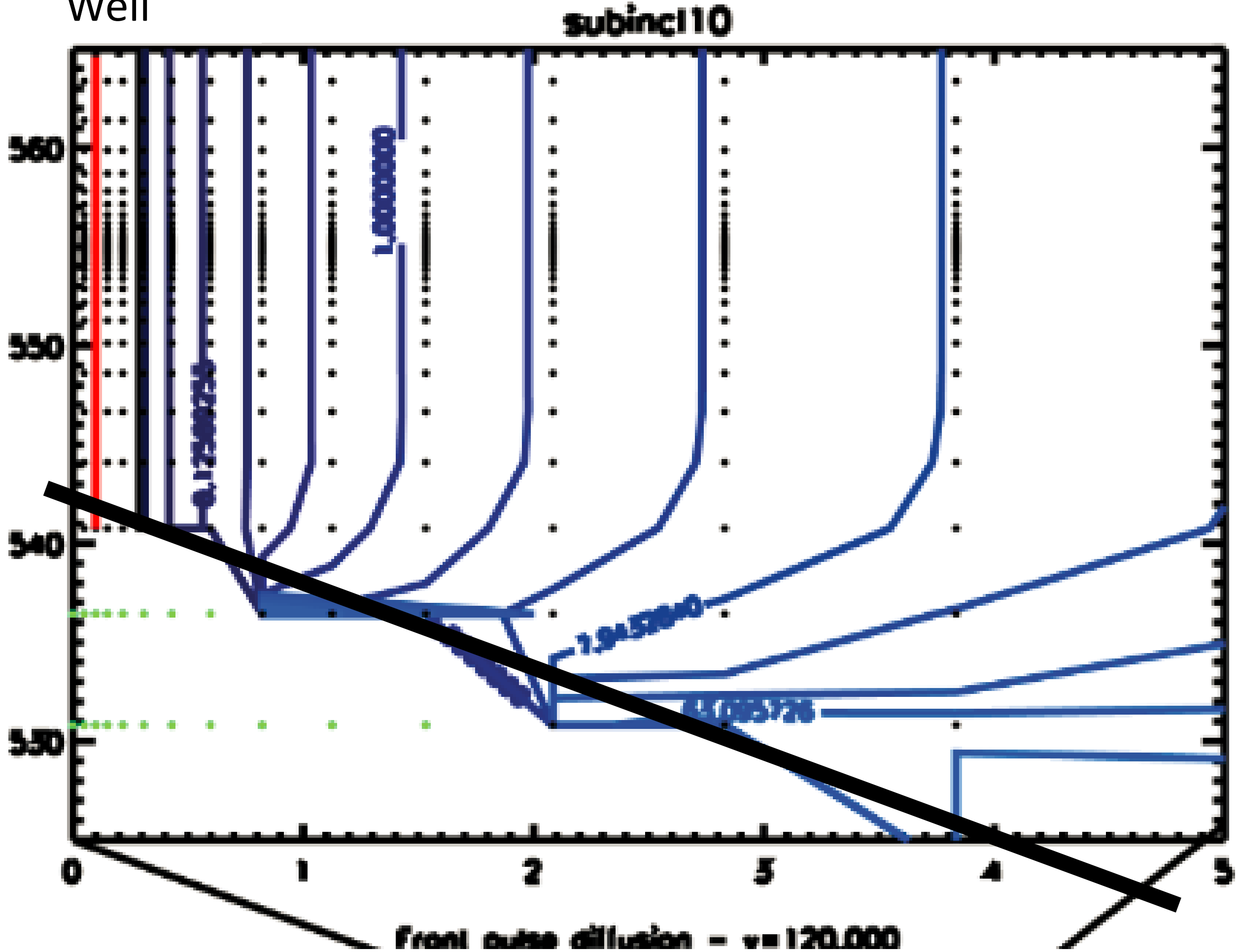
anouc

QAC

é du Québec
coutimi

Th tion.

Well


subincl10
560
550
540
530
0
1
2
3
4
5
1.00000000
Front pulse dillusion - y=120.000

Algorithm of Bourdet *et al.* (1989)

$$\frac{dS_i}{dX_i} = \left(\frac{\Delta s_1}{\Delta X_1} \Delta X_2 + \frac{\Delta s_2}{\Delta X_2} \Delta X_1 \right) / \left(\Delta X_1 + \Delta X_2 \right)$$

$$X = \log\,(t)$$

$$\Delta X_1 = X_i - X_1$$

$$\Delta X_2 = X_i - X_2$$

$$\Delta s_1 = s_i - s_1$$

$$\Delta s_2 = s_i - s_2$$

Estimation de n

Generalized difffusivity equation

$$\frac{K}{r^{n-1}}\frac{\partial}{\partial r}\left(r^{n-1}\frac{\partial h}{\partial r}\right)=S_s\frac{\partial h}{\partial t}$$

Laplace transformation

Hyp:

Constant head head at the boundaries

Initial head = 0 m at the begining

General solution

$$h(r,t)=\frac{Qr^{2v}}{4\pi^{1-v}Kb^{3-n}}\Gamma(-v,u)\quad v\neq 0$$

avec, $u=\frac{S_s r^2}{4Kt}$ et, $v=1-\frac{n}{2}$

$$\Gamma(a,x)=\int_x^{\infty}t^{a-1}e^{-t}dt$$

Estimation de n

For a little u,

$$h(r,t) = \frac{Q}{4\pi^{1-\nu} K b^{3-n} \nu} \left(\left(\frac{4Kt}{S_s} \right)^{\nu} - \Gamma(1-\nu) r^{2\nu} \right) \qquad \nu \neq 0$$

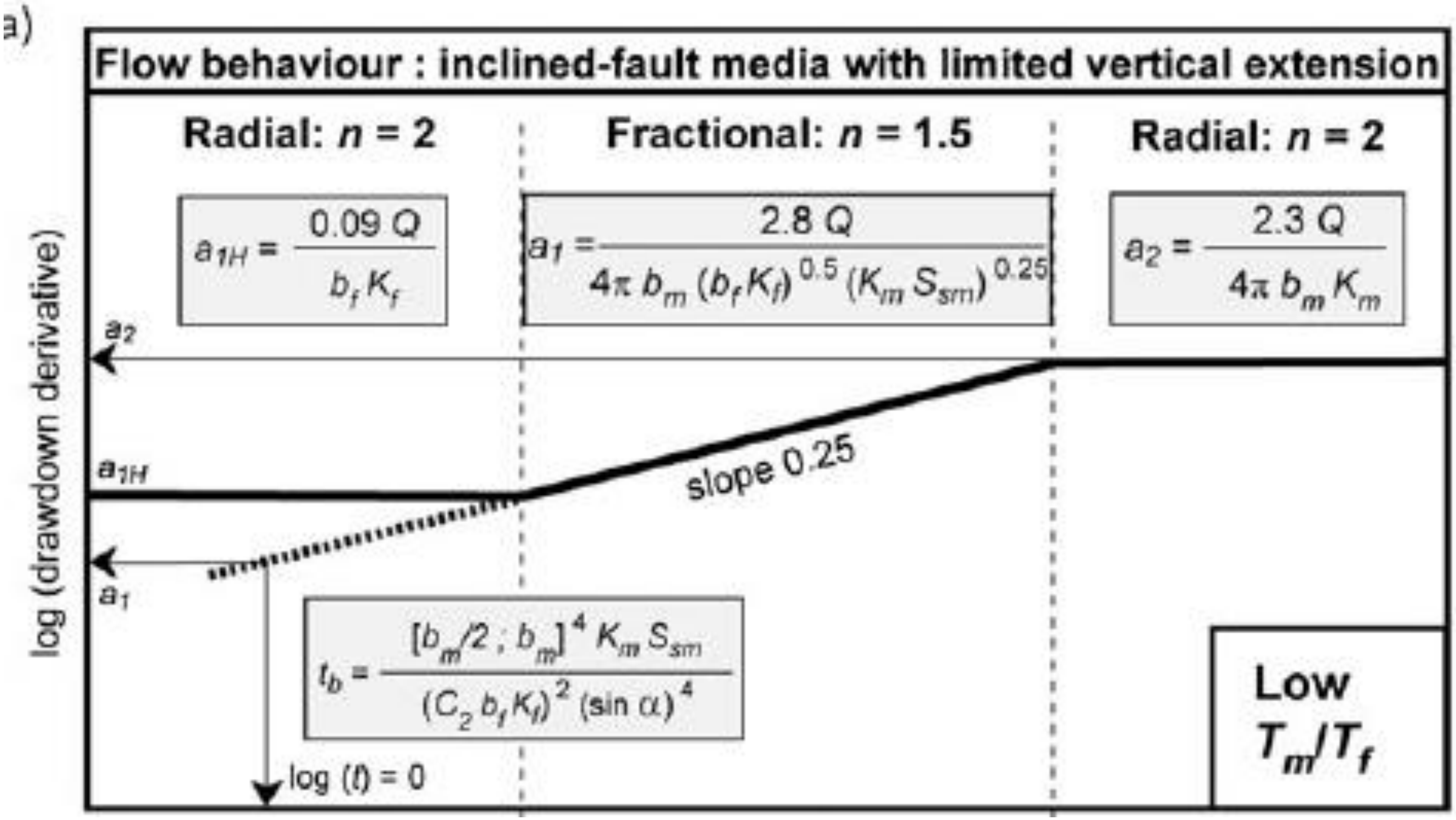
$$h(t) = Ct^{\nu} + C'$$

$$\frac{dh}{dlogt} = t\frac{dh}{dt} = 2{,}3.\, C.\, v\, t^{v}$$

$$n = 2(1-p)$$

Slope of ds/dlogt

Rafini, S., & Larocque, M. (2012). Numerical modeling of the hydraulic signatures of horizontal and inclined faults. Hydrogeology Journal, *20*(2), 337-350



1.4 Field data: spherical flow regime

Geology: Granitic sand

Hyp 1 : Partial penetration

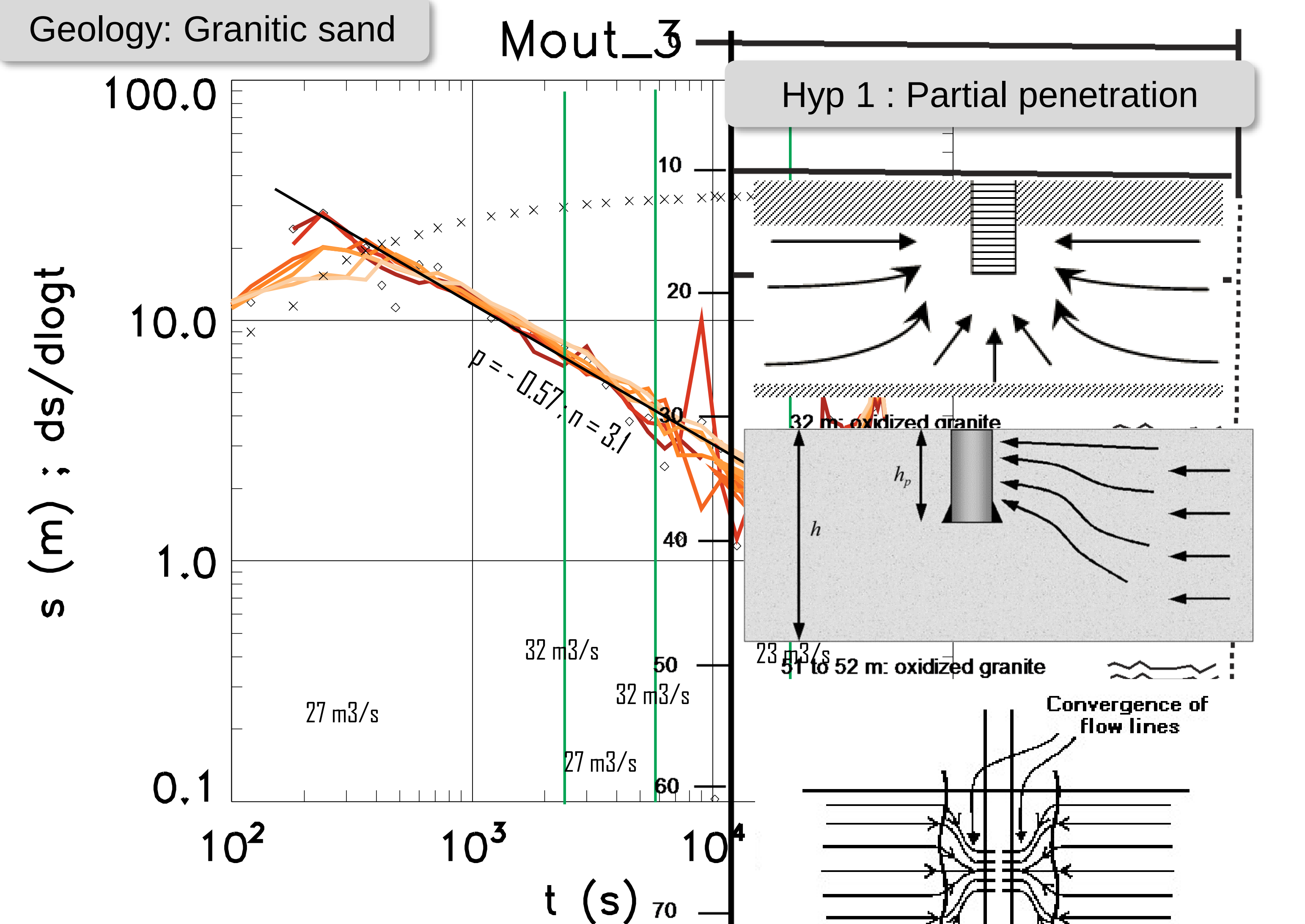


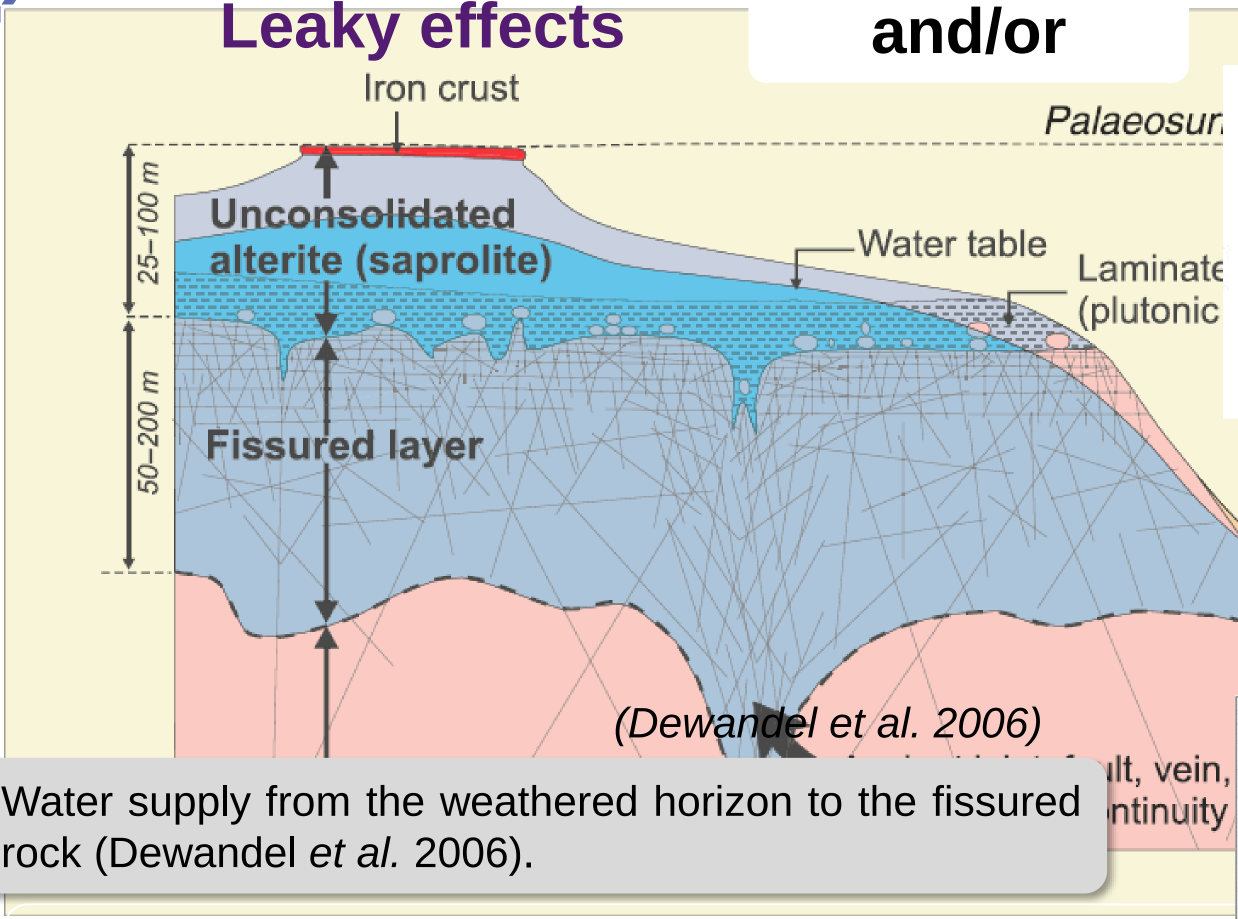
Fig.: Hydraulic signal of s and ds/dlog
Vendée, Pays-de-la-Loire, France.

Altered granitic aquifer

Spherical flow

Hydrogeological interpretation

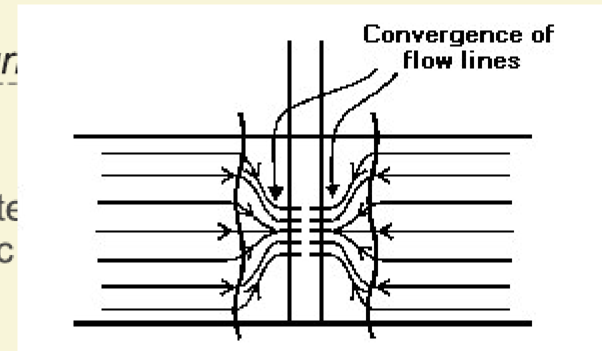
Leaky effects and/or Wellbore effects

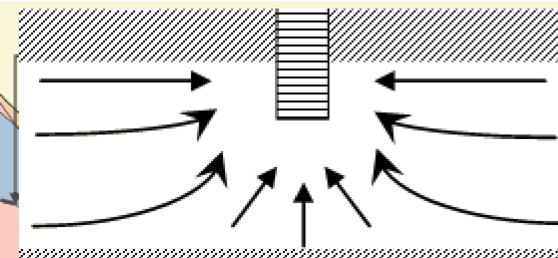


(Dewandel et al. 2006)

Water supply from the weathered horizon to the fissured rock (Dewandel *et al.* 2006).

Fig. 13: Conceptual model of a partly eroded palaeo-weathering profile on hard rock (Dewandel et al. 2006).





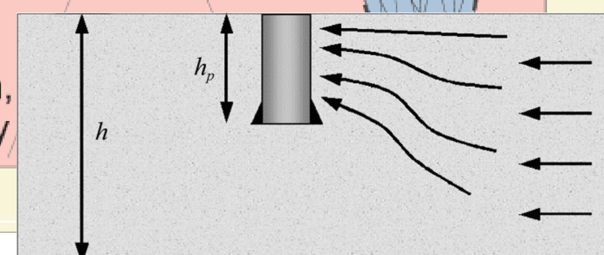


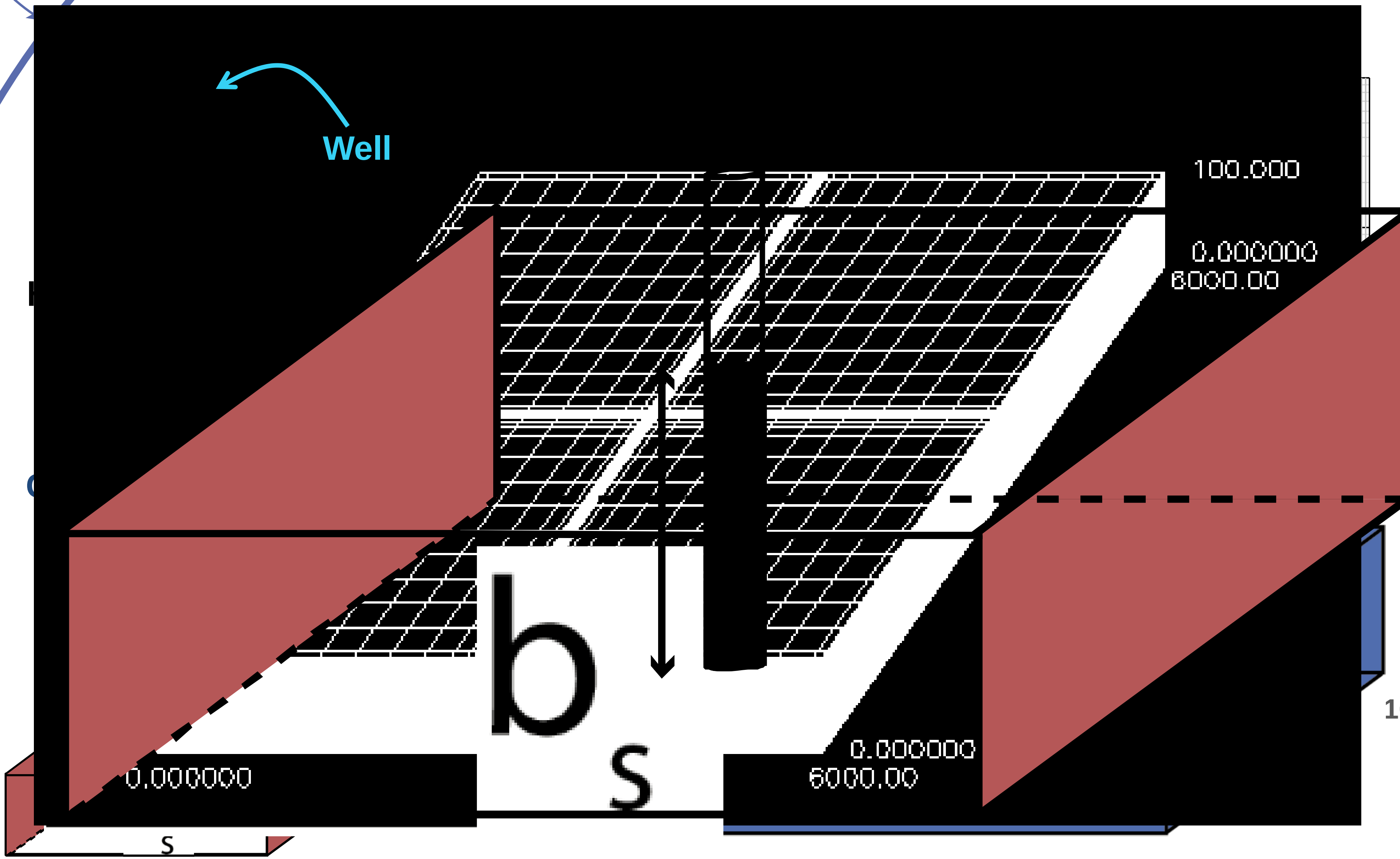
Fig. 14: Illustrations of a partial penetration /completion.

http://www.fekete.com/
http://nptel.ac.in/courses/105103026/20
http://petrowiki.org/

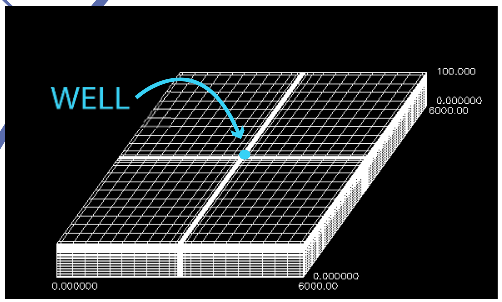
Partial penetration or Partial completion

3.2 The conceptual model 1: inclined substratum

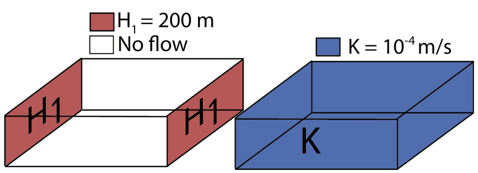
3D grid



3D grid

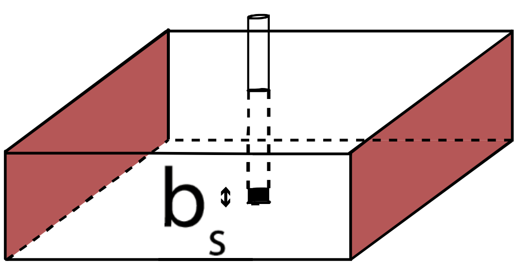


Boundaries and hydraulic properties

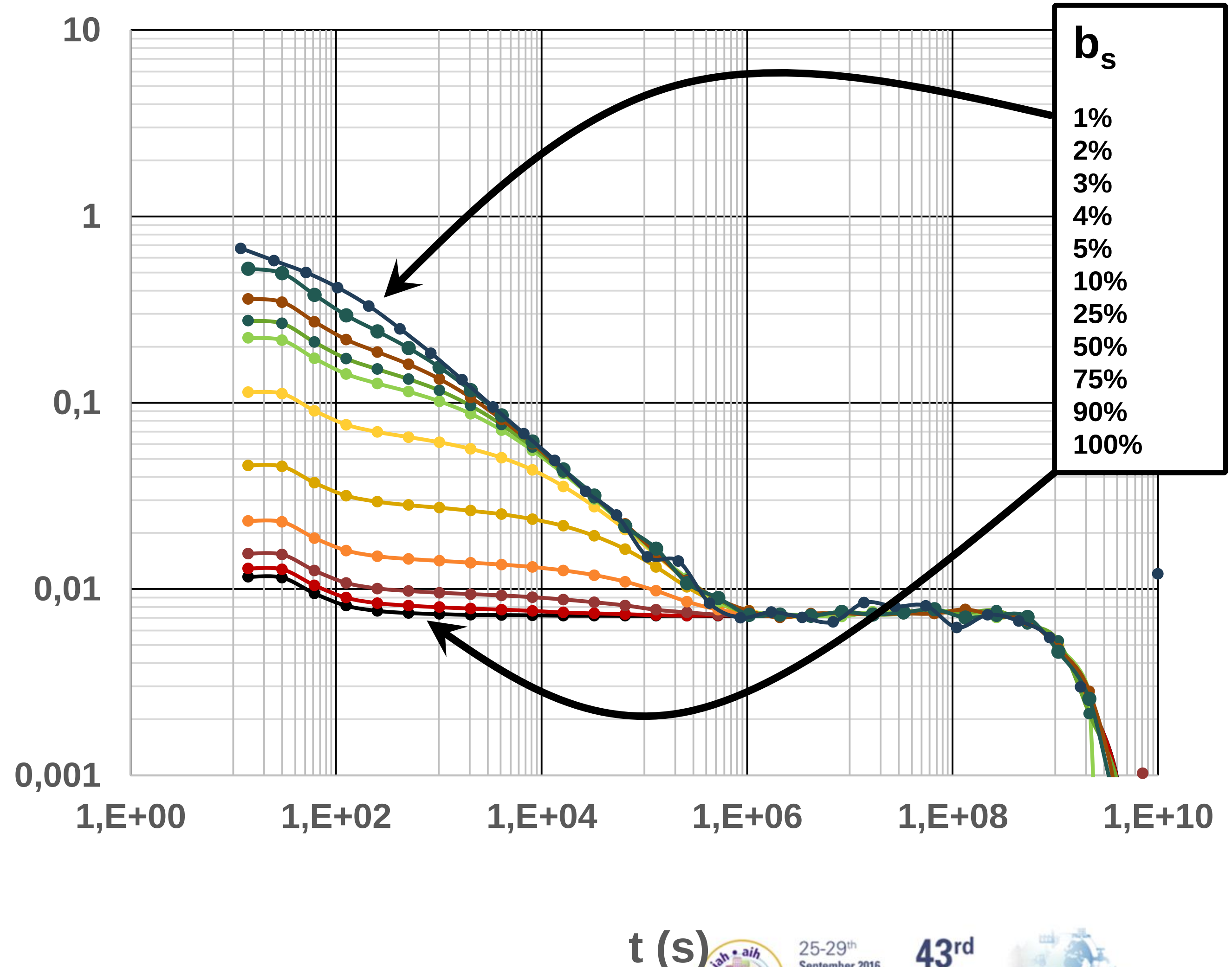


Confined aquifer

Tested parameter

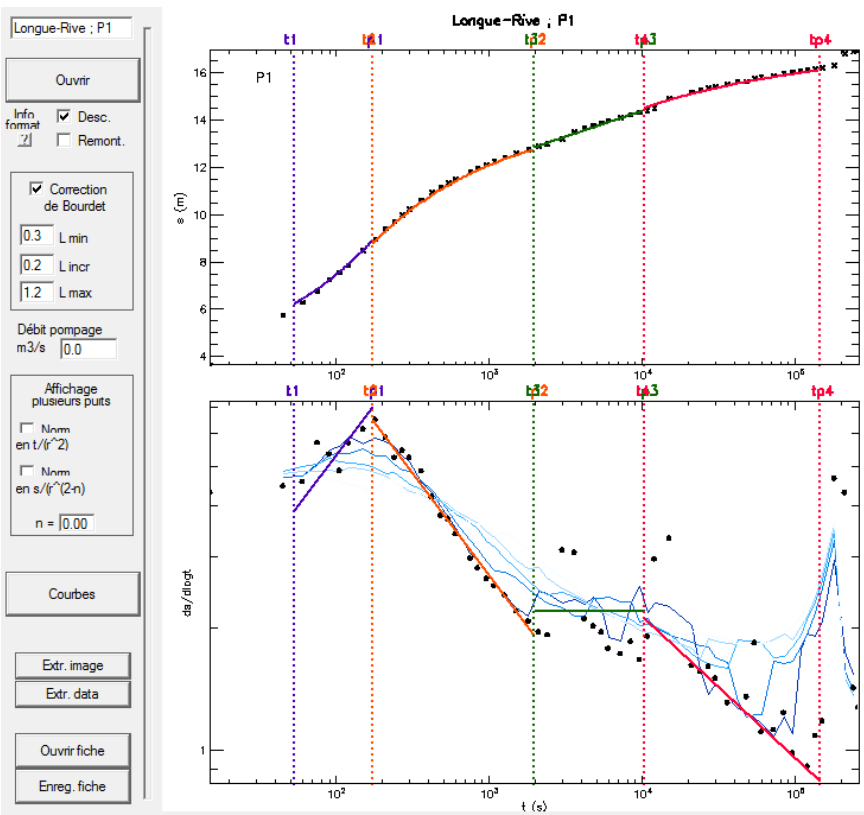


Screen thickness b_s (m)



1.4 Field data: spherical flow regime

Geology: clay; sand; rock



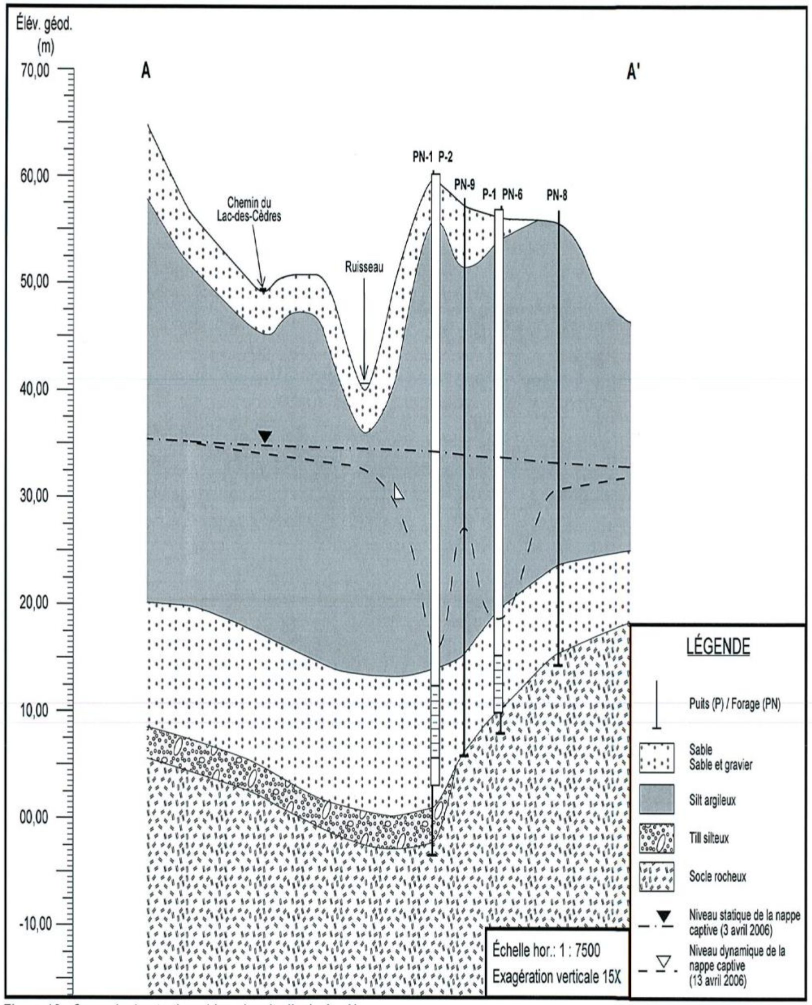


Figure 16. Coupe hydrostratigraphique longitudinale A - A'