Réseau québécois sur les eaux souterraines

Outils d'interprétation des aquifères non-uniformes en essai de pompage : des "diagnostic plots" aux séquences de dimensions d'écoulement

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Séminaire RQES, 12 décembre 2019

Fonds de recherche Nature et technologies Québec

CERM Centre d'études sur les ressources minérales

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Anouck Ferroud *, Silvain Rafini, Romain Chesnaux
Research Group R2Eau, Cen

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Research papers

Insights on pumping well interpretation from flow dimension analysis: The learnings of a multi-context field database

Anouck Ferroud *, Romain Chesnaux, Silvain Rafini
Research Group R2Eau, Centre d'étu

Hydrogeol J (2017) 25:877–894
DOI 10.1007/s10040-017-1560-x

TECHNICAL NOTE

A numerical investigation of pumping-test responses from contiguous aquifers

Silvain Rafini[1] · Romain Chesnaux[1] · Anouck Ferroud[1]

Hydrogeology Journal
https://doi.org/10.1007/s10040-019-01972-7

PAPER

Drawdown log-derived analysis for interpreting constant-rate pumping tests in inclined substratum aquifers

Anouck Ferroud[1] · Romain Chesnaux[1] · Silvain Rafini[1]

GW resources management : current challenges

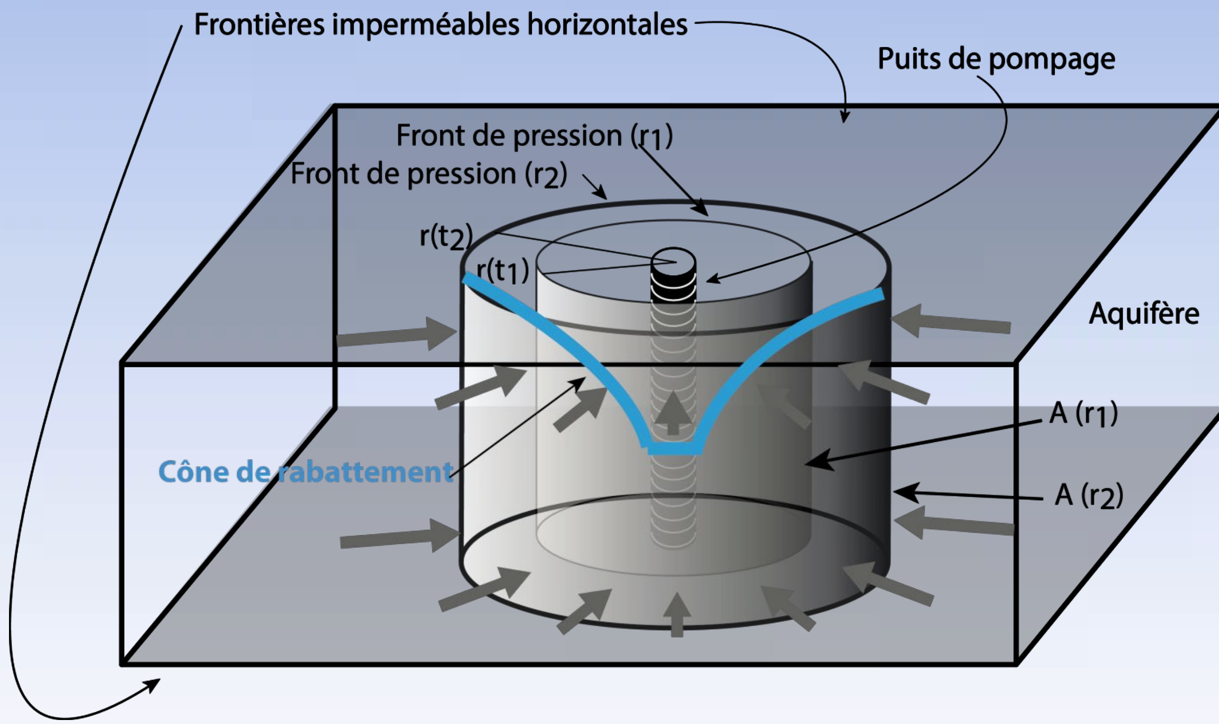
- **Hydrogeology practitioners** must cope with new contexts:
  - **Sustainability management of GW resources systems that are increasingly pressured** (population growth and industrial development)
  - Emerging advanced fields: geothermal energy, radionuclide in situ repositioning, carbon sequestration etc.
  - Stricter legislations for water quality and environmental impacts assessment
- This requires to provide **refined investigation tools in routine applications**
- **Better assessing the complex nature of real aquifers**
- **Conceptual models accounting for heterogeneous flow conditions**

GW resources management : common practices

- Routinely used models are **overly simplified**
  - Curve-matching with **Theis** type-curves (Theis, 1935)
  - Theis-derived models: **Cooper and Jacob** semilog plot (Cooper and Jacob 1946)

- **Theis model (80 years-old…!)**
  - First-order solution to the hyperbolic transient-diffusivity problem,
  - Assumes **perfectly homogeneous and uniform domain**
  - **Radially symetric flow geometry** into an *Infinite Acting Radial Flow* (IARF) domain

Theis-like aquifer *(also refered to as IARF model) :*
radially symetric flow geometry



Unable to render any heterogeneity of flow occurring into real aquifers

Produce gross assessments of the hydraulic properties

Overestimation and underestimation the hydraulic properties of specific hydraulic objects into the aquifer

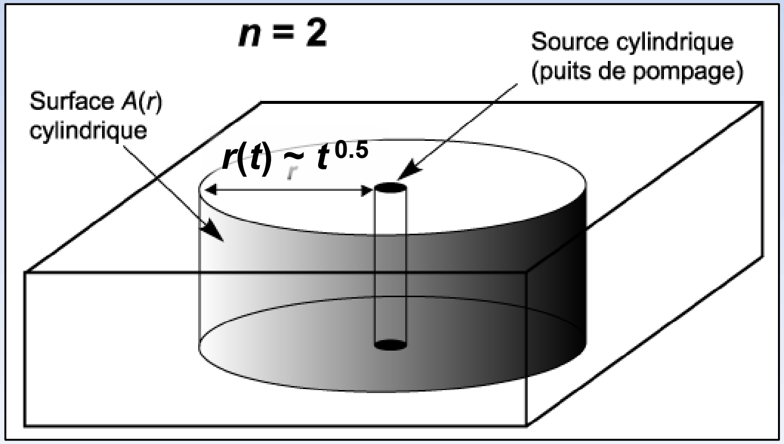
Radially symetric flow geometry vs radial flow regime

Radially symetric flow geometry (Theis-like) is a specific type of radial flow regime
Radial flow regime is refers to the **transient growth of the cross-flow area A(r)**

Theis = IARF

Cylindrical shapes, radially symetric flow
(homogeneous isotropic aquifer)

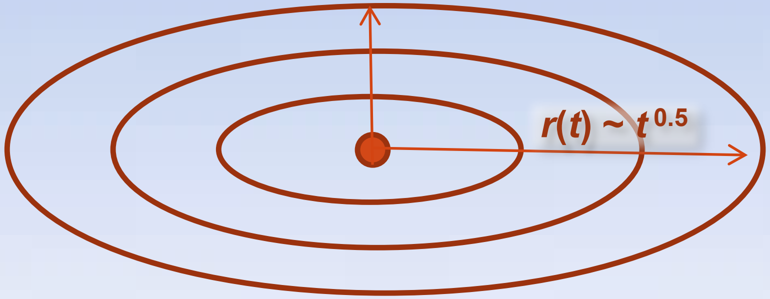
$A(r) \sim r$ → Radial



Non-Theis

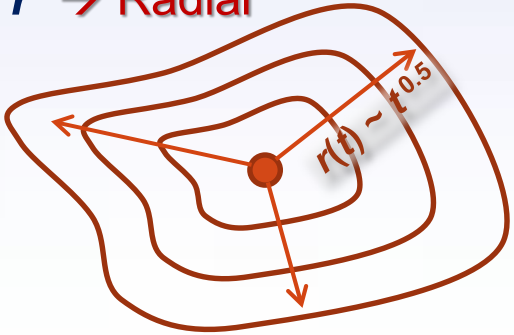
Elliptical
(homogeneous anisotropic aquifer)

$A(r) \sim r$ → Radial



Any shape (heterogeneous aquifer)

$A(r) \sim r$ → Radial



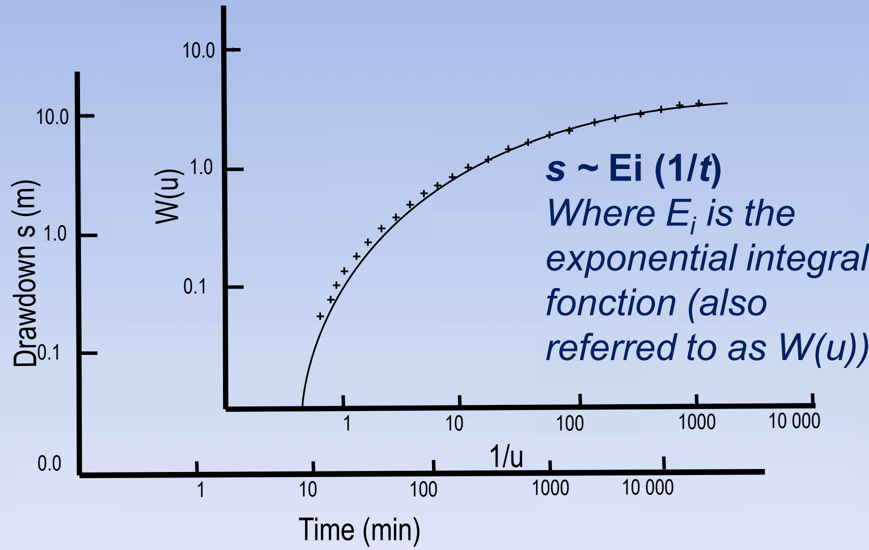
Radial flow strictly means $A(r) \sim r$

It does not refer to any specific symmetry of flow lines, a priori

The diagnostic response of a radial flow regime

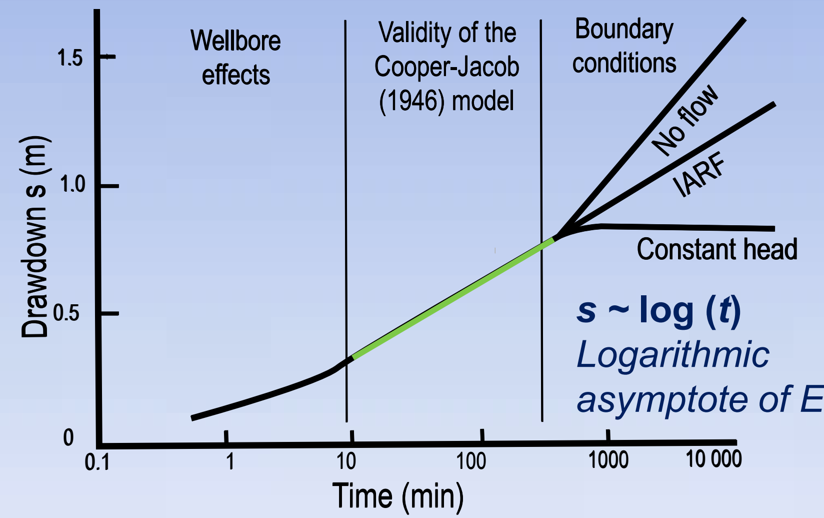
Theis (1935)

Curve-fitting on log-log time-drawdown plots



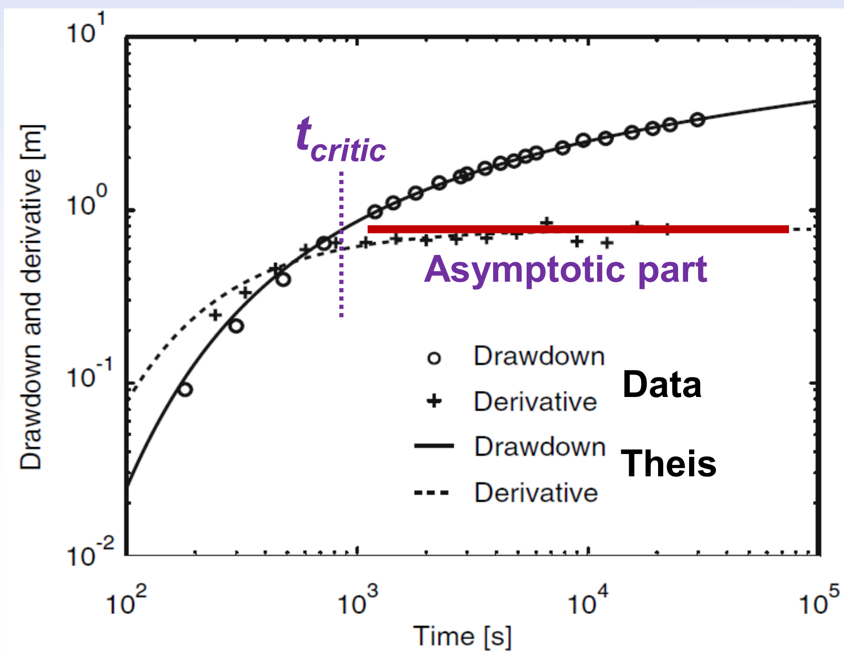
Cooper-Jacob (1946)*

Straight line on semi-log time-drawdown plots



** for large t or small r → at the source, practically from pumping test's beginning*

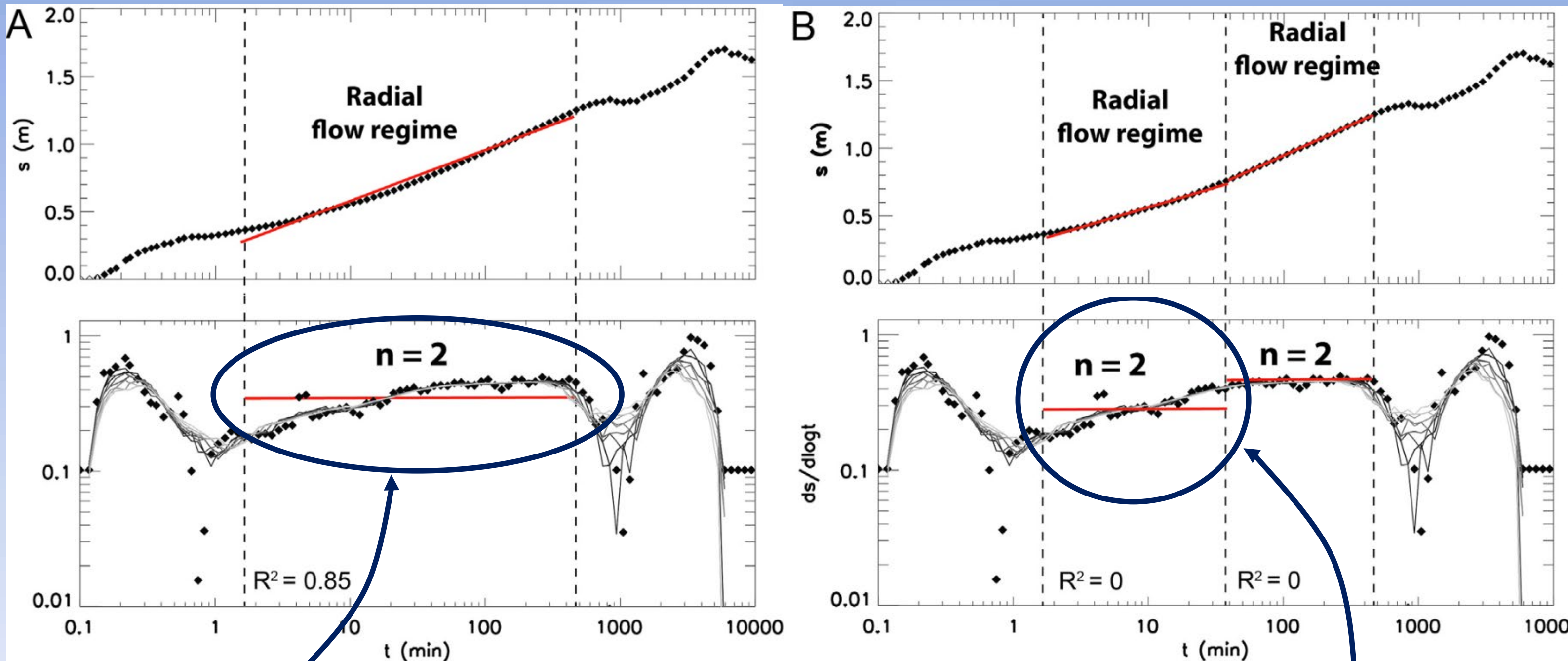
Drawdown log-derivative *ds*/*d*log(*t*)



Plateau elevation = 2.3Q/4π T

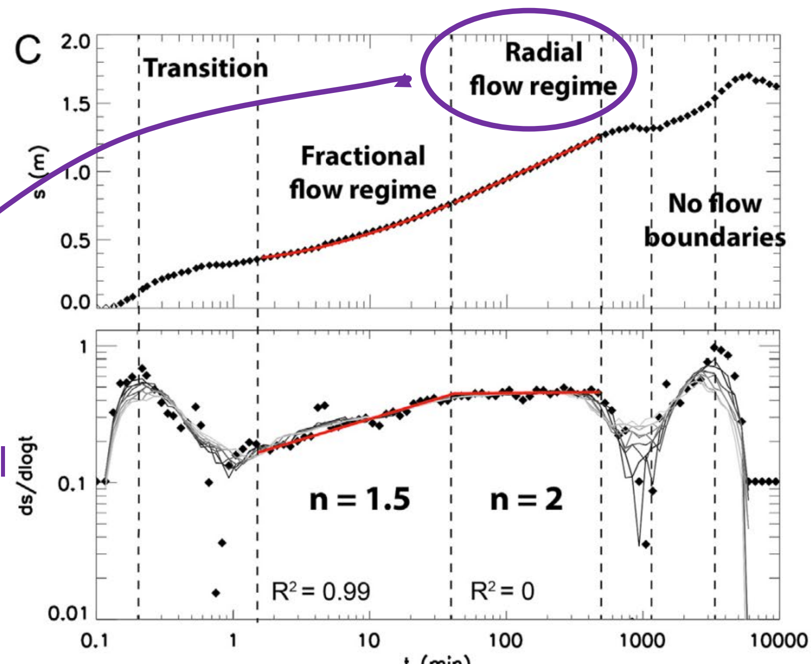
The derivative signature of a radial flow regime is a horizontal plateau (slope = 0)

Verifying the validity of the Theis model with the log-derivative signal



Mis-use of the Theis model
The multistage hydrodynamic response is grossly approximated

Mis-use of the Theis model
The assumption of a radial flow regime *is not* valid



Theis can be used only into this time-window
The assumption of a radial flow regime *is* verified

Diagnostic non-radial flow regime (n = 1.5): the hydrodynamics of the aquifer is governed by a strongly inclined high-conductivity fault

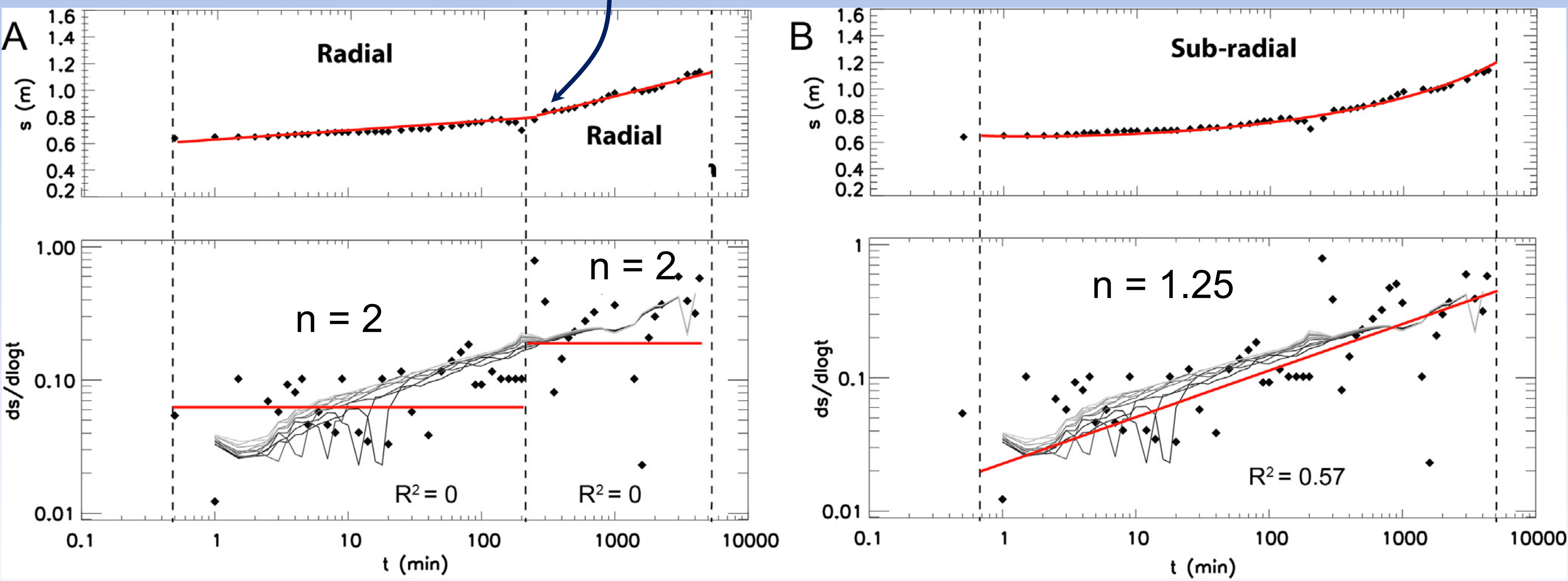
Verifying the validity of the Theis model with the log-derivative signal

Interpretation withTheis-derived model

Interpretation with fractional flow model

Impermeable boundary ?

→ No !



Noisy derivative time serie → Bourdet differentiation

Mis-use of the Theis model

The assumption of a radial flow regime *is not* valid

GW resources management : validity of the common practices

Prior validation of a radial flow regime should be done in routine applications before applying Theis or CJ methods

Poorly assessed by straight lines in CJ semi-log plots → derivative plots

1. How valid is the Theis model in nature? To which degrees does it diverge from reality ?
2. How significant are the qualitative and quantitative errors induced on aquifers characterisation ? Practical implications ?
3. How to assess the validity of the Theis model in routine applications ?
4. If not in a radial flow regime… what are the alternative models ?

Some consequences of applying overly idealized interpretation model

- Simplifying the behaviour of the system to an extreme degree and disregarding the real geometry of flow;
- Ignoring the presence of several 1D, 2D or 3D hydraulic objects with non-equal properties, which may actually be governing the aquifer's global hydrodynamics at various pumping times;
- In low-conductivity contexts, overestimating by several order of magnitude the hydraulic properties of the pumped domain and missing the presence of distal and/or discrete conductive domains which may be exerting a predominant role in supplying water to the well over some pumping time-windows;
- Missing the presence of boundaries, or erroneously interpret non-existent ones;
- Globally, dismissing most of the diagnostic potential of the time-drawdown signal;
- Poorly assessing the impact of pumping an aquifer :
  - Erroneous sustainable pumping rates
  - Erroneous delineation of WHPA (wellhead protection areas)
  - Misunderstanding of the risk from potential contaminant source inventory,
  - Misunderstanding of the incidence on various objects into the environment, wet zones, etc.

FLOW REGIMES ANALYSIS

Real-world pumping tests databases

Compilations from various geological contexts : hard-rock (magmatic, sandstones, limestones), granular (unconsolidated sediments, fluvial channels)

- Rafini (2008) : compilation of **41 constant-rate pumping tests**
  - 80% exhibited multi-stage responses
  - **Radial regime occurs in 17% of the 41 datasets**

- Ferroud et al. (2018) : compilation of **69 constant-rate pumping tests**
  - 88% exhibited multi-stage responses
  - **Radial regime = 31% (of 121 interpreted flow regimes)**

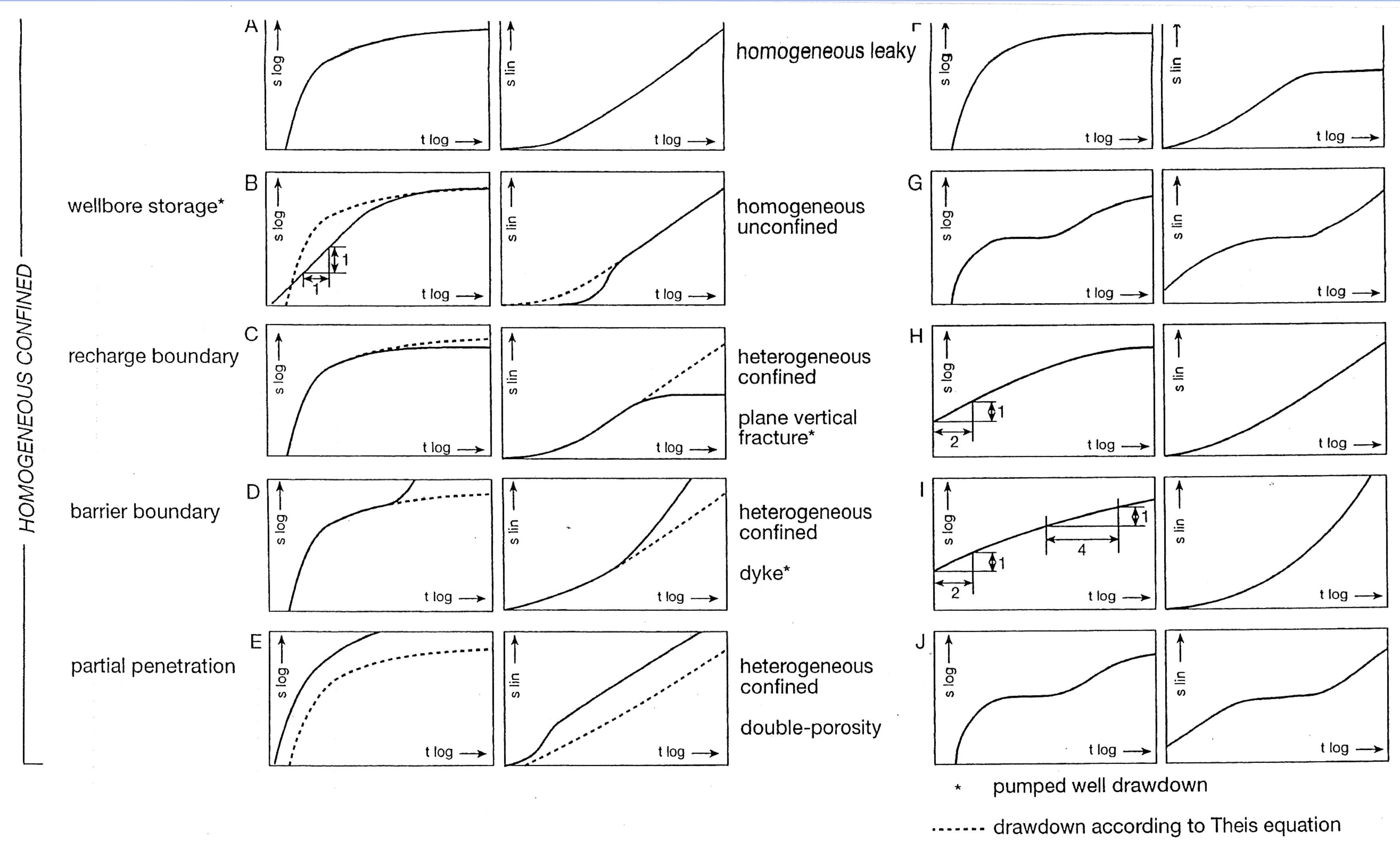
- **Since the early 80's,** numerous authors* have reported
    1. that the **flow regimes occurring in real media are actually much more complex and diversified** than the unique radial flow regime
    2. That **Theis model is unable to accurately reproduce the obtained responses** in many occurrences

- **<u>70's, 80's, 90's</u> :** Oil&Gas + GW researches produced **numerous analytical models** accounting for **heterogeneous flow** into various reservoir configurations

- **Provides numerous diagnostic diagrams : *diagnostic plots approach***

* (Audouin et al., 2008; Ferroud et al., 2018; Kuusela-Lahtinen et al., 2003; Leveinen, 2000; Lods and Gouze, 2004; Maréchal et al., 2004; Odling et al., 2013; Verbovšek, 2011, 2009 ; Bourdet et al, 1983)

Diagnostic plots approach



Verweij, 1995 ; Renard, 2009

Two fundamental historic breakthrough developments

1. The *derivative analysis* (Bourdet et al, 1983)

Use of Pressure Derivative in Well-Test Interpretation

Dominique Bourdet,* SPE, **J.A. Ayoub,** SPE, and **Y.M. Pirard,**** SPE, Flopetrol-Johnston Schlumberger

Summary. A well-test interpretation method based on the analysis of the time rate of pressure change and the actual pressure response is discussed. A differentiation algorithm is proposed, and several field examples illustrate how the method simplifies the analysis process, making interpretation of well tests easier and more accurate.

Introduction

The interpretation of pressure data recorded during a well test has been used for many years to evaluate reservoir characteristics. Static reservoir pressure, measured in shut-in wells, is used to predict

ogeneous formations reveals the good definition obtained with derivative plots, and the distinction between currently used interpretation models is clearly shown.

2. The flow dimension theory (Barker, 1988)

WATER RESOURCES RESEARCH, VOL. 24, NO. 10, PAGES 1796–1804, OCTOBER 1988

A Generalized Radial Flow Model for Hydraulic Tests in Fractured Rock

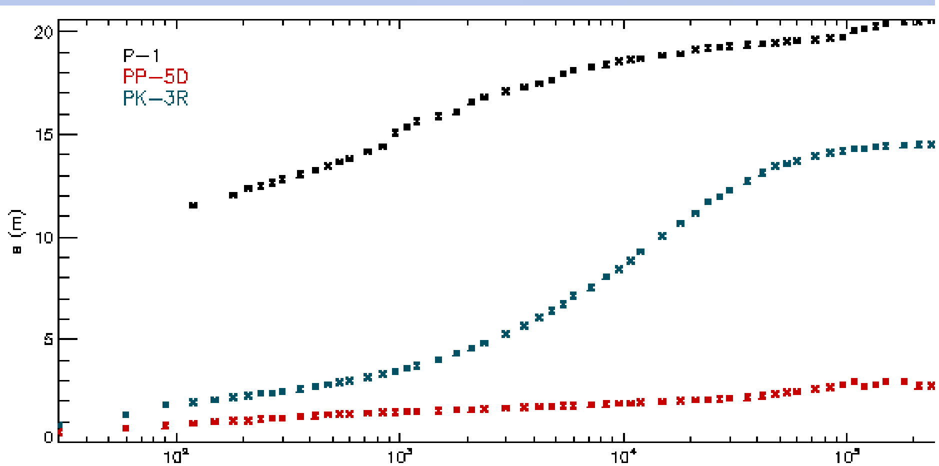
J. A. Barker

British Geological Survey, Wallingford, Oxfordshire, United Kingdom

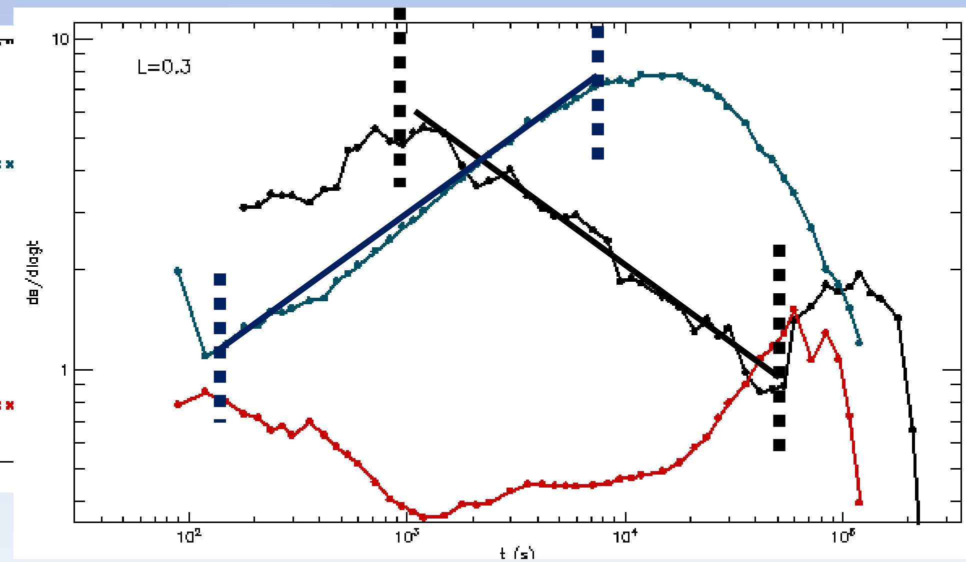
Models commonly used for the analysis of hydraulic test data are generalized by regarding the

1st historic breakthrough development :
the *derivative analysis* (eg. Bourdet et al, 1983)

Drawdown semi-log plot



Log-derivative ds/dlogt bilog plots



The derivative signal provides a drastic gain in sensitivity

Makes it possible to distinguish between changes in flow regime caused by subtle variations in aquifer conditions

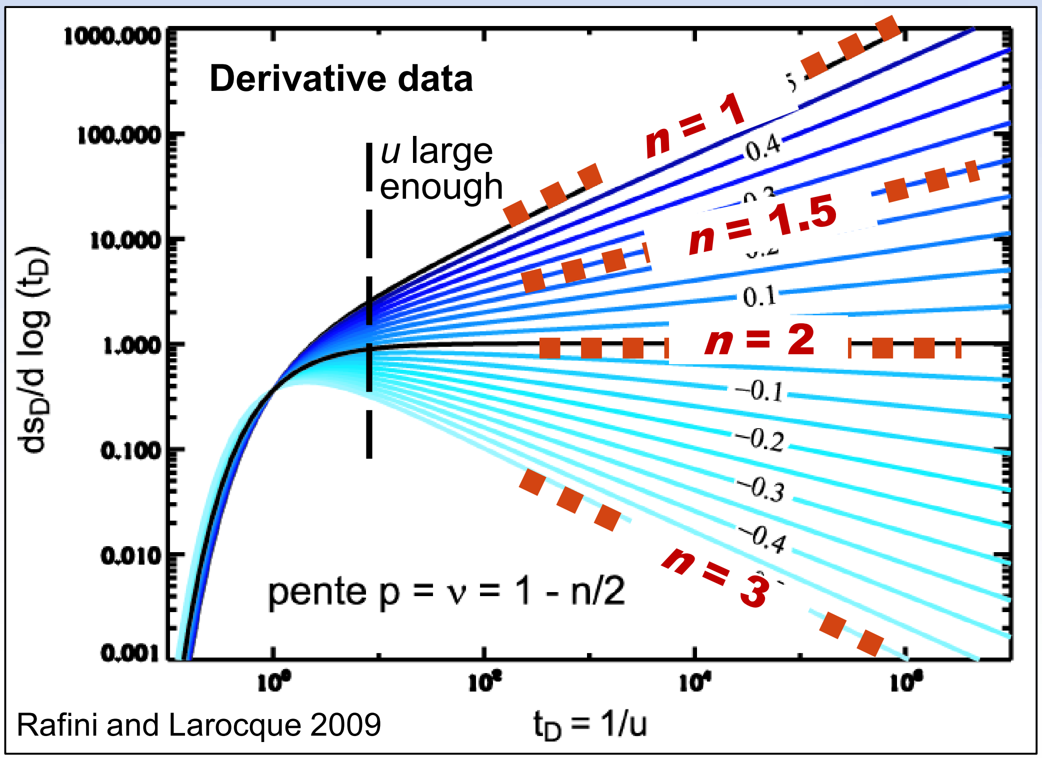
→ **identification of several successive flow regimes**

Constant slope of the derivative signal = **hydrodynamic stable flow regime** (Barker, 1988)

2rd historic breakthrough development :
the *flow dimension theory* (Barker, 1988)

<u>The basics of a new formalism :</u>

1. **The flow regime is defined by a new parameter : the flow dimension *n***
2. Radial flow regime : ***A*(*r*) ~ *r* ; Generalized** Radial Flow (GRF) regimes **: *A*(*r*) ~ *r*** $^{n\text{-}1}$
3. ***n* reflects the transient evolution of the frontal cross-flow area *A*(*r*) at distance *r***
4. *n* is obtained by a **direct reading*** of the log-derivative slope *p* : ***n* = 2 - 2(*p*)**
5. **Stable *n* = hydrodynamically settled flow regime**



***n* = 2, radial flow regime** = drawdown log-rate is constant

***n* < 2 flow regimes**
= drawdown log-rate is increasing
*Aquifers with a **limited potential***

***n* > 2 flow regimes**
= drawdown log-rate is decreasing
***High potential** aquifers*

* *for large u*, i.e., *large t or small r → at the source, practically from pumping test's beginning*

2rd historic breakthrough development : the *flow dimension theory* (Barker, 1988)

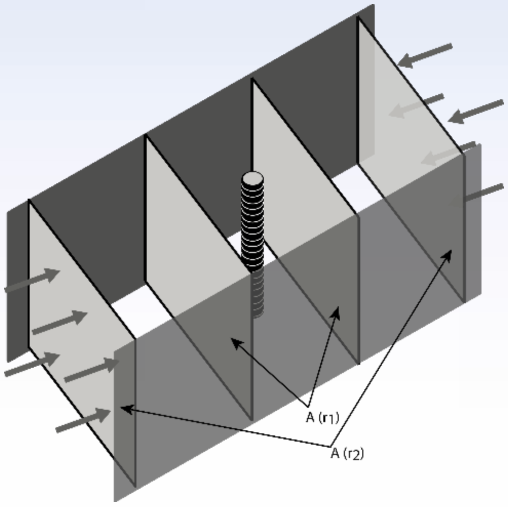
Barker's GRF model and flow dimension theory provide with a universal relationship between :

1. **The drawdown rate,** which is given by the log-derivative signal : $n = 2 - 2p$
2. **The expansion rate of the frontal cross-flow area $A(r)$ (depressurization front pulse),** which is unknown and relates to conceptual models : $A(r) \sim r^{(n-1)}$

Ideal geometrical shapes

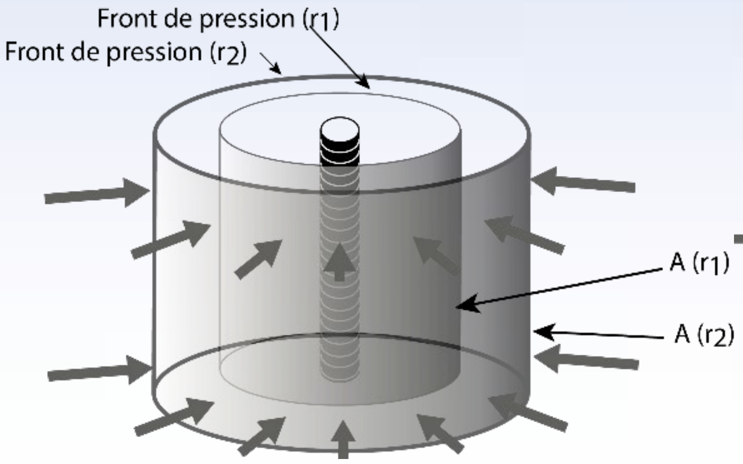
Linear regime: corridor

$n = 1$; A = constant



Radial regime: cylinders

$n = 2$; $A \sim 2\pi r$



Spherical regime: spheres

$n = 3$; $A \sim 4\pi r^2$

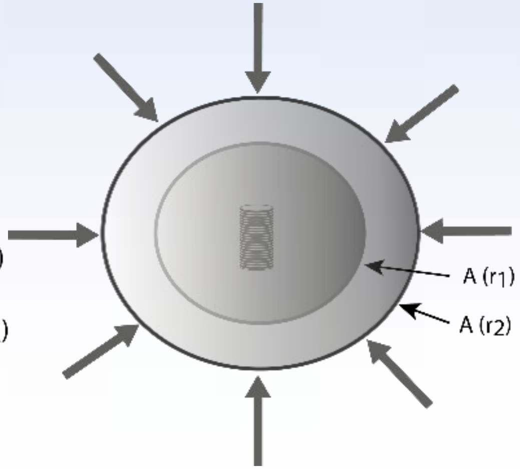
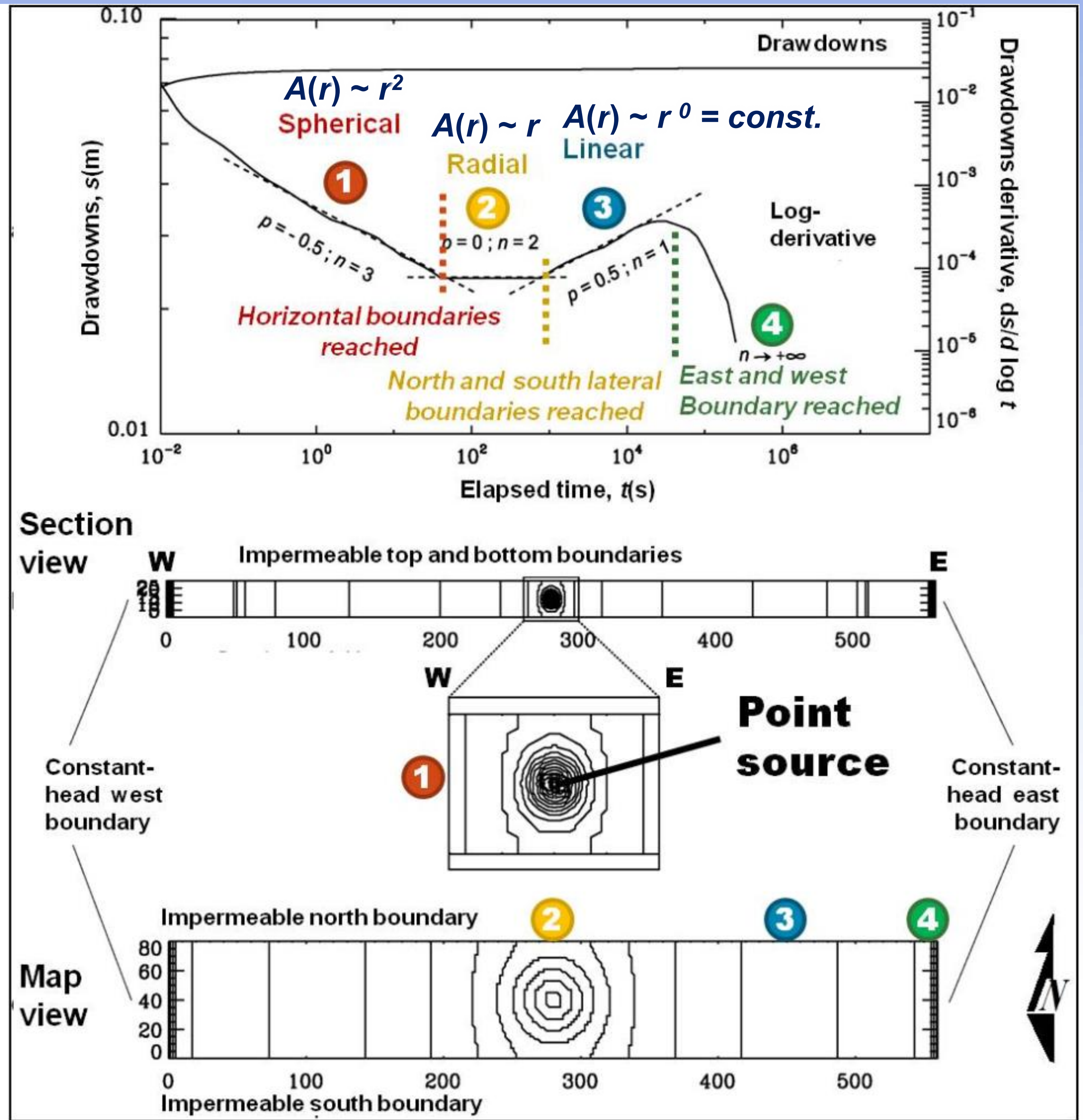


Illustration of the relationships between the propagation of the cross flow frontal area *A* and the flow dimension *n* *(and the drawdown rate)*

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

Numerical simulation of a point source into an elongated aquifer (homogeneous isotropic medium)

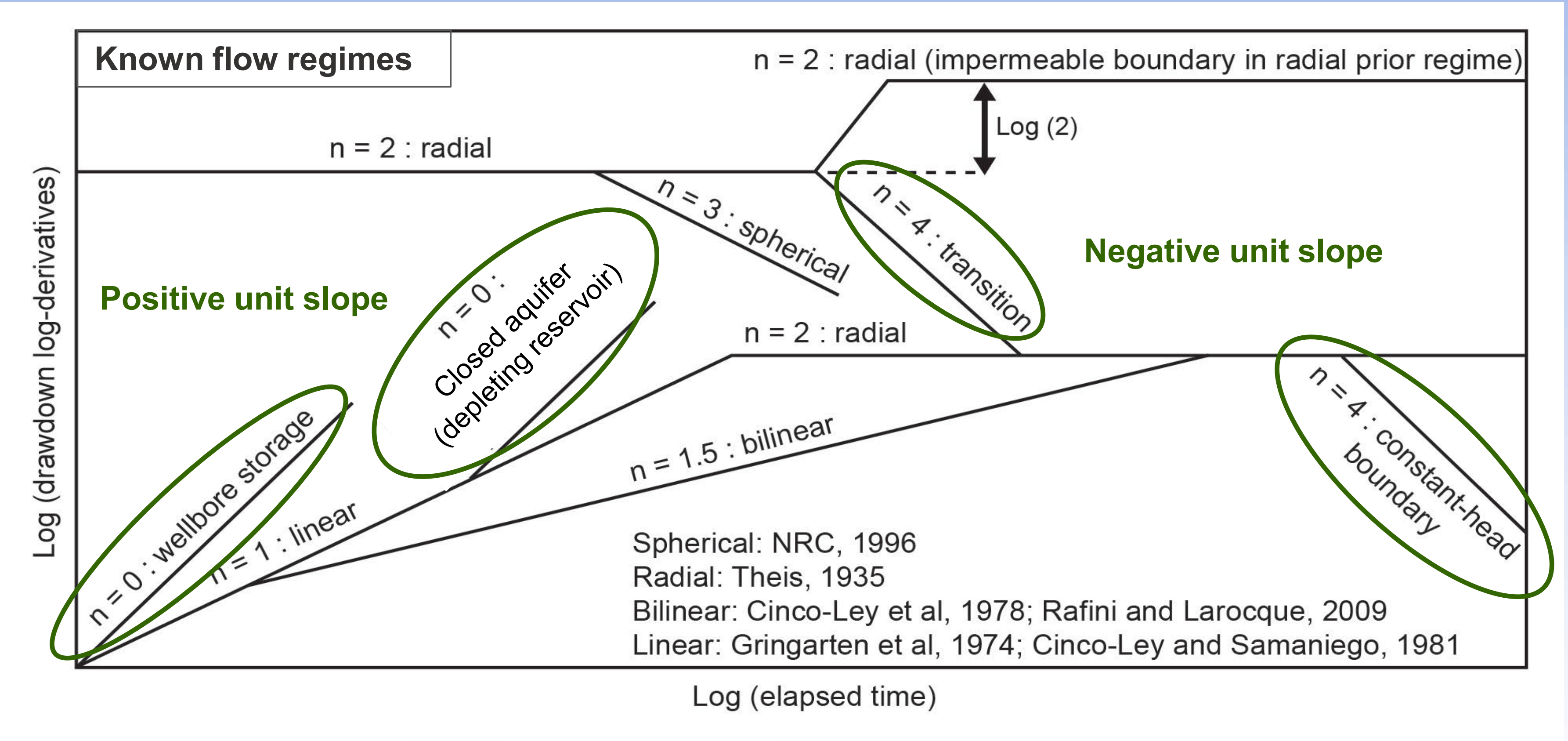


Evolution of n during the pumping test : ***scan*** **of hydraulic conditions in the aquifer**

n **sequence : 3 – 2 – 1 – inf (sperical – radial – linear – inf)**

The interpretable elementary flow regimes

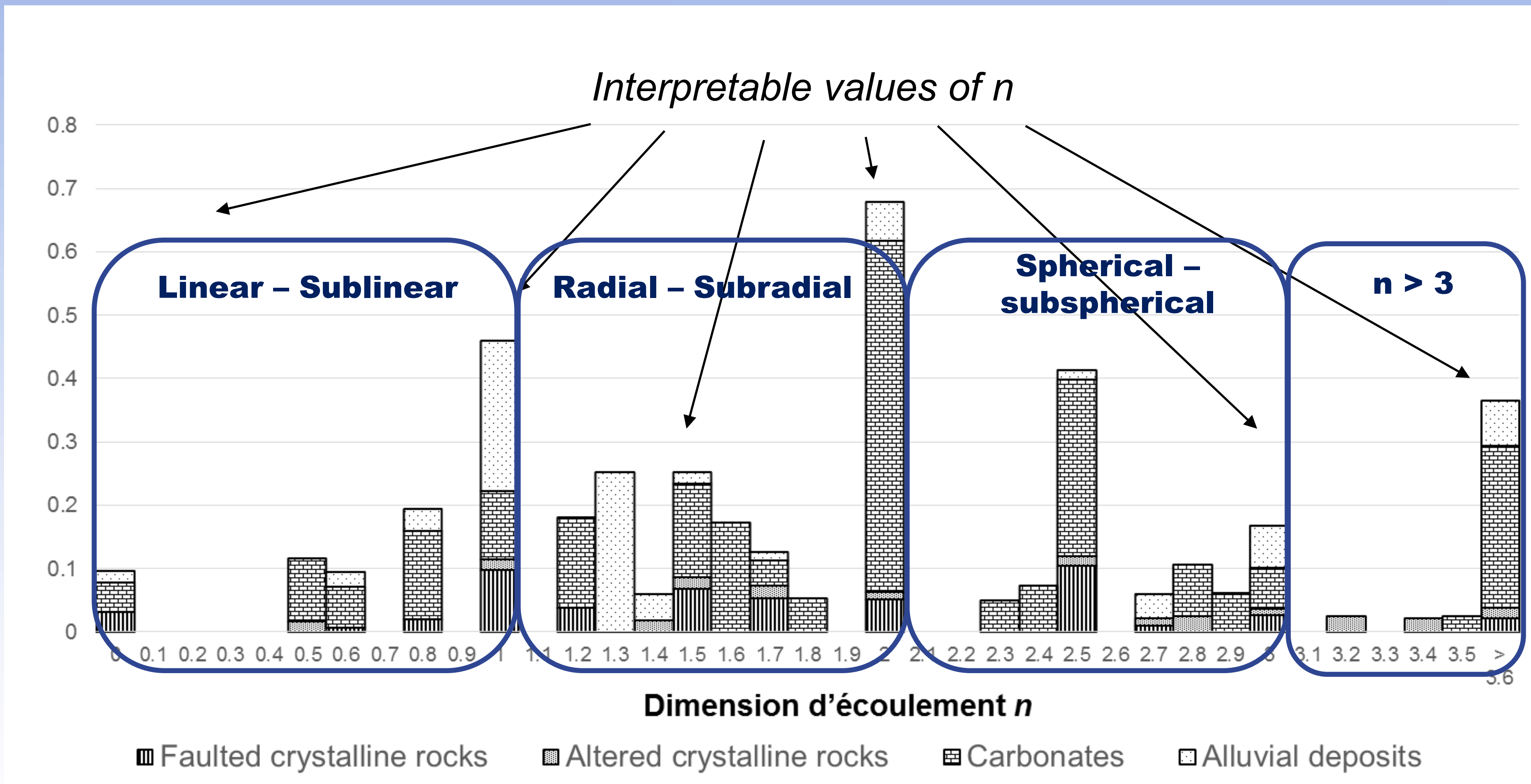
- Several types of flow regimes are recognized, in theory and in nature



- ***n* = 0 and 4 : positive or negative unit slopes**
- ***n* = 1, 1.5, 2, 3 : reflects specific hydrodynamic conditions → conceptual models**
- **Other values of *n* remain non-interpretable since no consensual conceptual flow model is available**

The elementary flow regimes reported in nature

Ferroud ea (2017) database of 69 pumping datasets (121 distinct flow regimes)

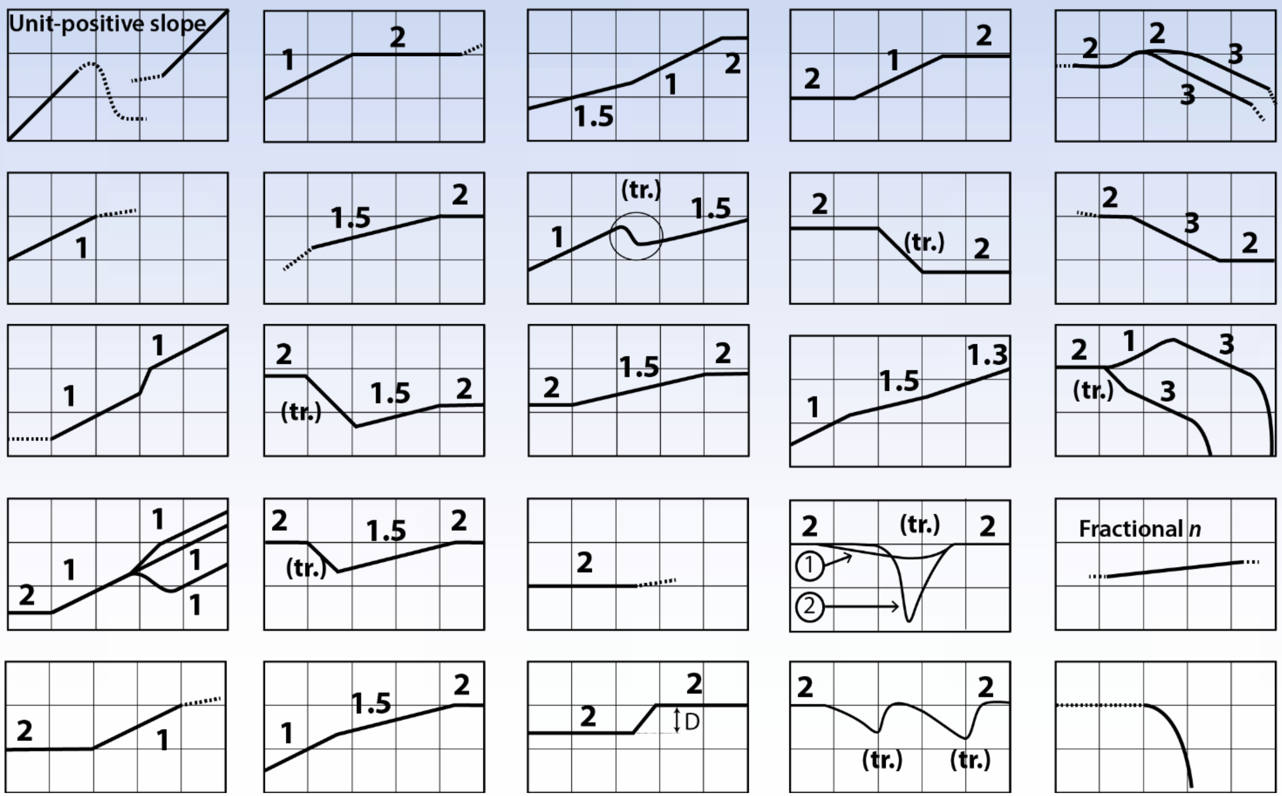


Reminder : n ≠ 2 ➔ Non-Theis aquifer

Theis is valid only to 30% of occurrences, and essentially in carbonate aquifers

Catalog of interpretable flow dimension sequences and associated conceptual models

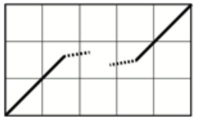
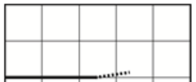
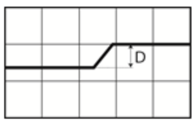
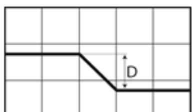
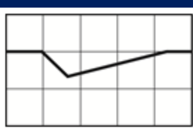
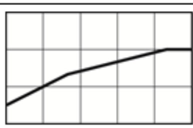
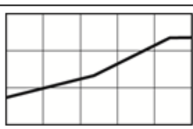
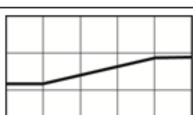
- Comprehensive review of published conceptual flow models from petroleum and hydrogeology literature
- Mostly **analytical models** = various mathematical resolutions of the diffusivity problem with specific assumptions on the flow conditions (hydraulical and geometrical postulates)
- Also **numerical models** = empirical models obtained from experimental simulations, less idealized but criticized for its discutable generalization



Catalog of the interpretable flow dimension sequences, i.e. associated to a conceptual flow model

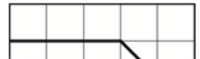
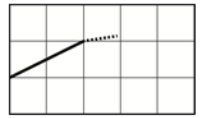
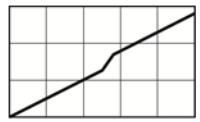
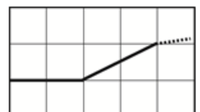
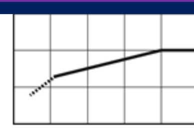
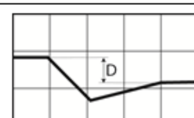
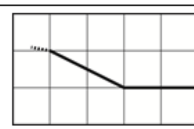
1. Radial, dual radial

3. Bilinear combinations

Flow dimension	Log-derivative response (bilog plots)	Conceptual model
0		Early time: wellbore storage [1] Late time: impermeable boundaries in the four directions [1, 2, 9], referred to as *closed reservoir* and *pseudosteady state*
2		Theis aquifer (IARF), Cooper-Jacob approximation valid[3]
2 – 2		• **Impermeable vertical frontier** D = log(2) → single frontier D > log(2) → dual frontiers [4] • **Aquifer cross-cut by a weakly-inclined finite-conductivity fault** [13] • **Leaky aquifer with depressurization of the non-pumped aquifer** [16]
2 – (4) – 2		(D < 1) Presence of a lateral, blind (non-pumped), more transmissive flow domain [15]
2 – ∞		Leaky aquifer with negligible drawdown into the non-pumped aquifer [18]
2 – 4 – 1.5 – 2		(Early and late plateau elevations are equal) Aquifer cross-cut by a stongly inclined finite-conductivity fault; the fault is *not connected* to the wellbore (not intercepted) [11, 14]
1 – 1.5 – (2)		Aquifer cross-cut by a strongly inclined finite-conductivity fault with occurrence of an early fault-related linear regime [10] possibly caused by fault's skin effects or internal layering
1.5 – 1 – (2)		Aquifer cross-cut by a strongly inclined finite-conductivity fault with occurrence of a matrix-related linear regime (fault acts as a planar source) [1, 10]; barely realistic
2 – 1.5 – (2)		Aquifer cross-cut by a moderately inclined finite-conductivity fault [13]

2. Linear, dual linear

4. Spherical combinations

Flow dimension	Log-derivative response (bilog plots)	Conceptual model
2 – 4		Recharge frontier
1		• **2D structures** Early time: submetric fracture [5] Medium time: infinitely conductive fault[6]; finite-conductivity fault with skin effect • **1D conduits** (Glacio-)fluvial channel [7], elongated reservoir [8], fractures or faults intersection [17]
1 - 1		Dual linear [9]: two opposite impermeable frontiers (elongated reservoir) reaching an impermeable boundary
2 - 1		(Glacio-)fluvial channel, elongated reservoir
1.5 – (2)		Aquifer cross-cut by a stongly inclined finite-conductivity fault [10, 11]
2 – 4 – 1.5 – 2		(D < 1) Presence of a lateral, blind (non-pumped), more transmissive flow domain with a conductive fault at the interface [15]
2 – 3		Aquifer with an inclined substratum or confining layer leading to variable thickness (wedge-like) [9, 17]
3 - 2		**Point source:** Screen length shorter than the aquifer thickness [17], partially penetrating well [17], or pumping between packers
n non-integer		

(1)Tiab, 2005;
(2) Linear no-flow frontier;
(3) Theis (1935), Cooper et Jacob (1949);
(4) Beauheim and Walker (1998);
(5) Cinco-Ley et al (1978)
(6) Gringarten et Ramey (1974, 1975);
(7) Massonat et al 1993;
(8) Miller (1962; Nutakki and Mattar 1982 ; Escobar et al, 2012; Escobar et al, 2007;
(9) Escobar et al (2004), Escobar and Montealegre (2007) ;
(10) Cinco-Ley et Samaniego (1981);
(11) Rafini et Larocque (2009);
(13) Rafini and Larocque (2012);
(14) Abbazsadeh et Cinco-Ley (1995);
(15) Rafini et al (accepted);
(16) Neuman et Witherspoon (1969);
(17) Ferroud et al (2016);
(18) Hantush (1956), Hanush (1960);
(19) Barker (1988).

Radial and dual radial combinations

$n = 2$

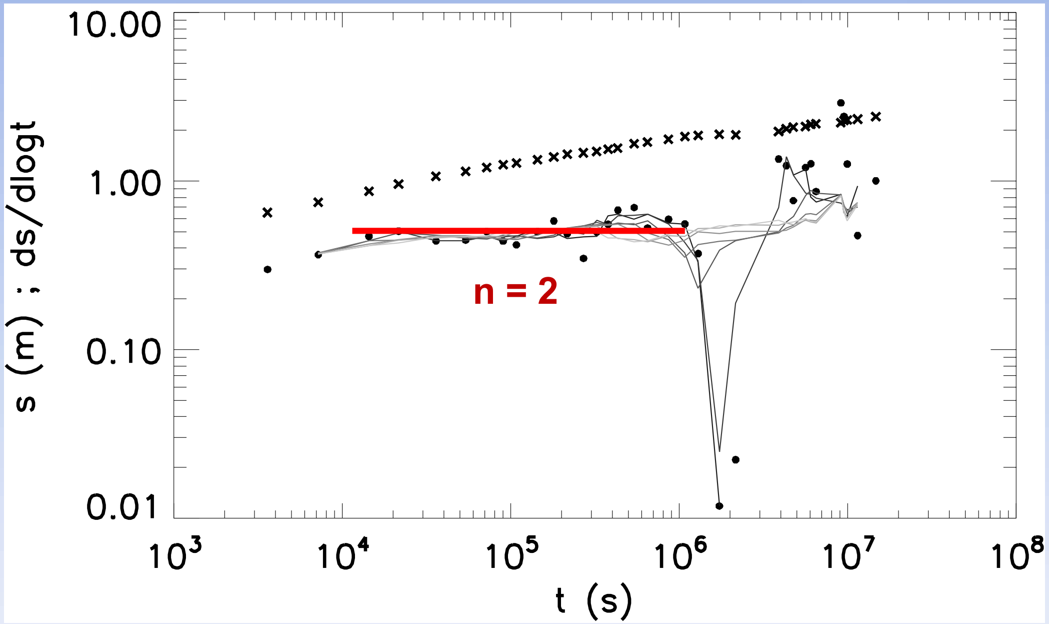
$n = 2 – 2$

$n = 2 – 4 – 2$

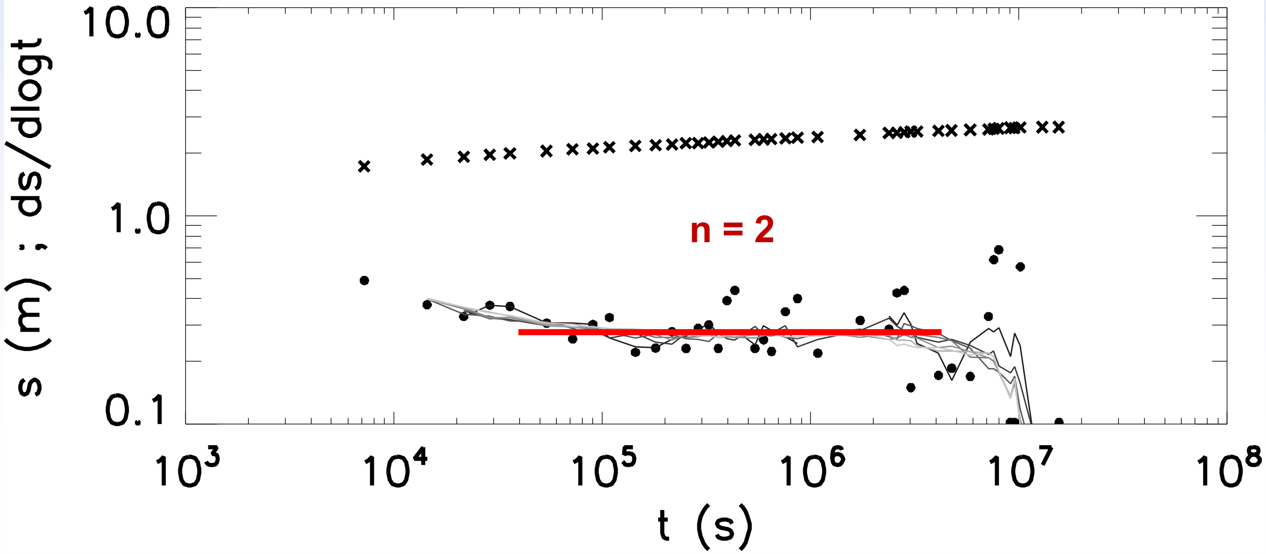
Radial flow regime

- The **most frequently observed** regime in natural media (ca. 20 to 30%)
- Occurs as often in fractured as in granular aquifers
- **3D hydraulic continuum** (e.g., sandstone, dense and conductive fracture network) **or…**
- **Weakly inclined conductive structure**
- In fractured aquifers, occurs **most frequently in carbonateous formations** due to the presence of conductive subhorizontal stratification planes
- Frequently the **last flow regime** (very late pumping time) regardless the aquifer conditions, due to heterogeneities being « diluted » or « averaged » into the high volume of depressurized aquifer → ***bulk***, or ***large-scale, hydraulic properties***

Radial flow regime : real examples

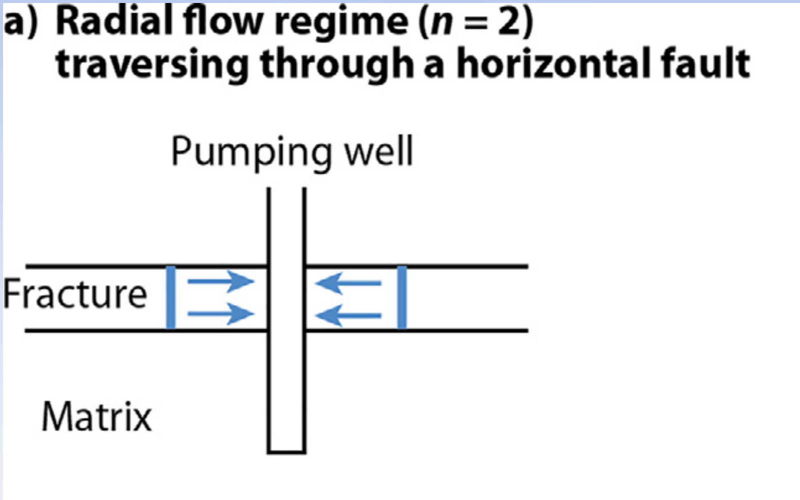


Carbonateous rocks aquifers



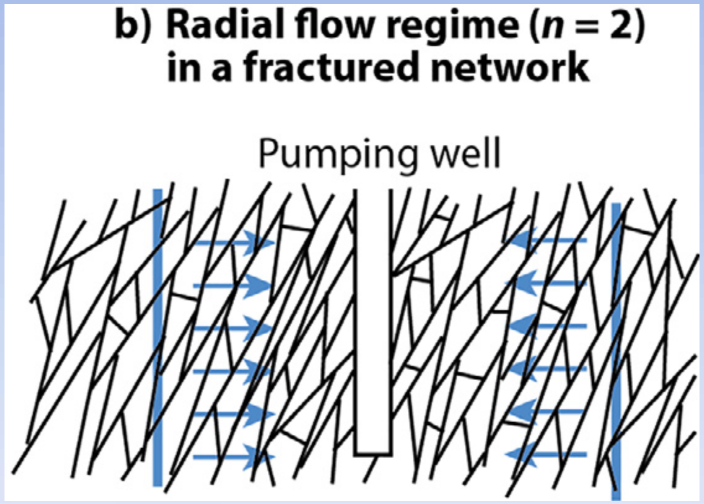
Radial flow regime : subhorizontal flow structures

- In stratified carbonateous rocks
- Hard rocks with weakly inclined conductive faults



e.g., stratification in carbonateous rocks

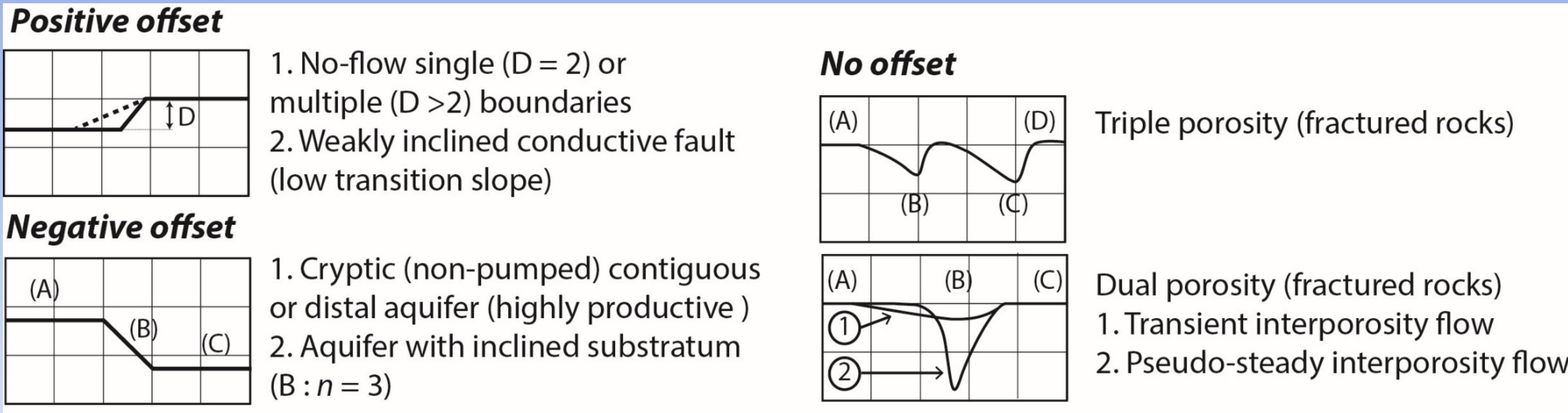
Radial flow regime : dense fractured network (continuum-like)



e.g., fractured hard rock aquifer **when the fractures network is dense and connected**

The cross-flow area is large compared to the size of the individual fractures
➔The fractures network behaves like a continuum

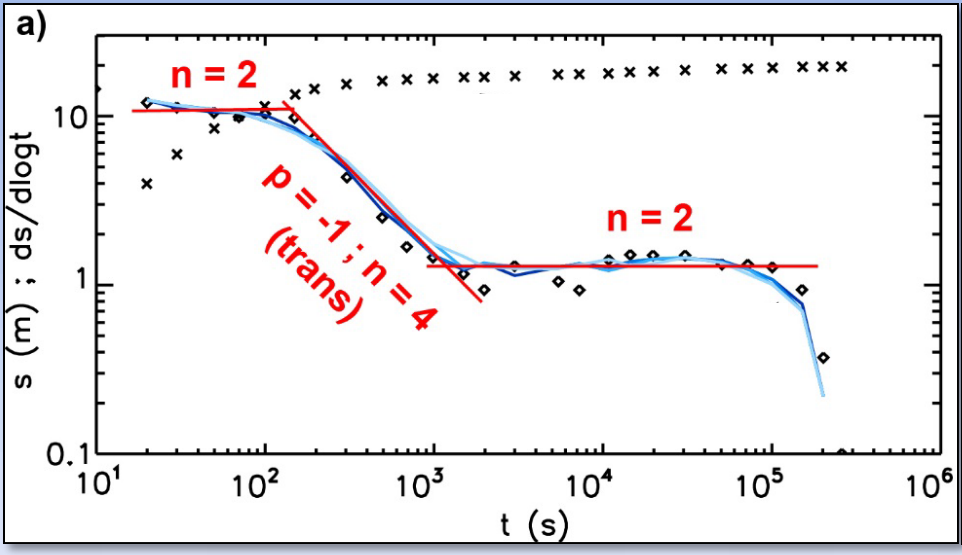
Dual radial sequences: overview



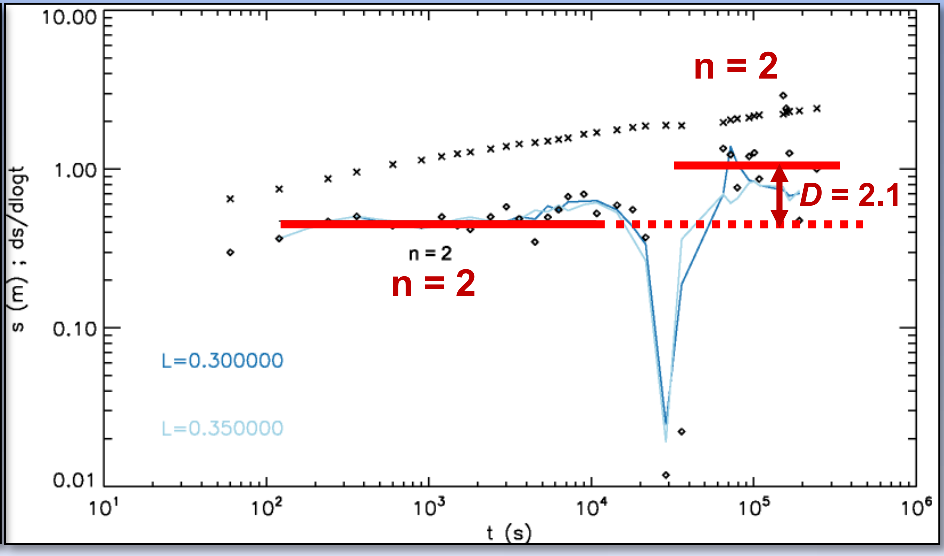
- Indicates the coexistence of several domains, either **juxtaposed** (frontier, contiguous aquifer) or **superposed** (multiple porosity)
- Critical features for interpreting the proper conceptual flow model are :
  1) whether the offset is null, negative or positive,
  2) the magnitude of the offset (whether it is greater or lower than 2)
  3) the shape of the transitional regime

Dual radial sequences: real examples

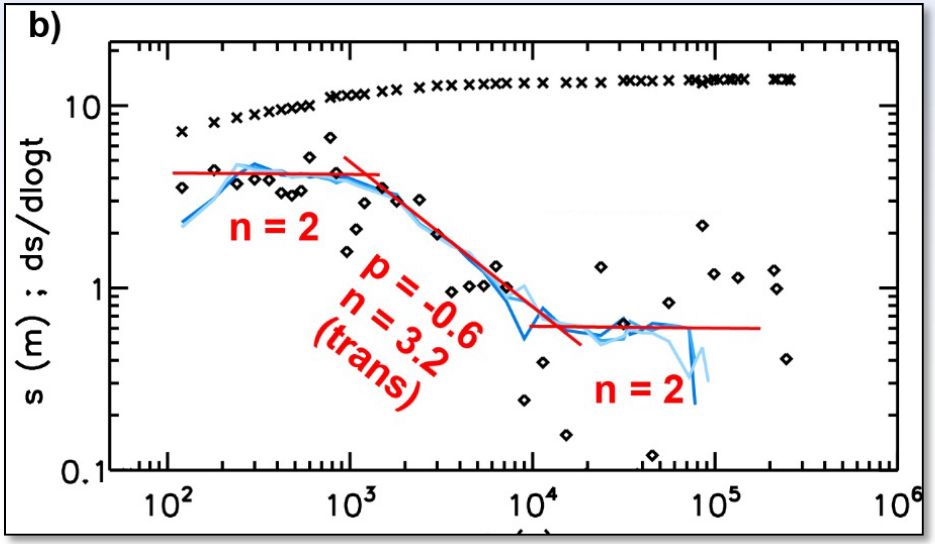
Negative offset



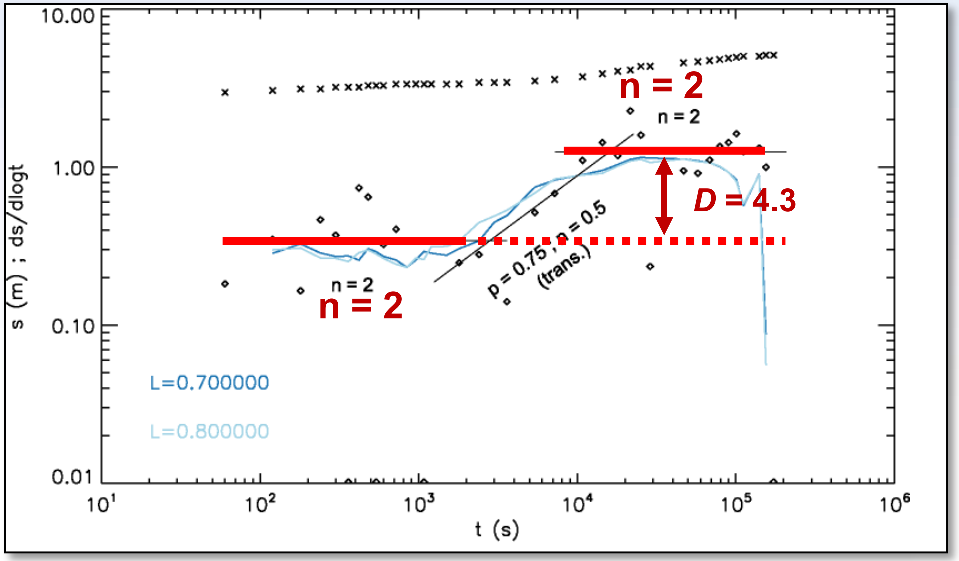
Postitive offset ; *D* ≈ 2



Negative offset

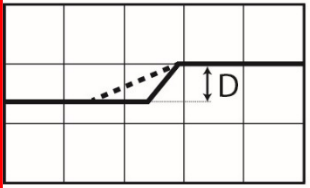


Postitive offset ; *D* > 2



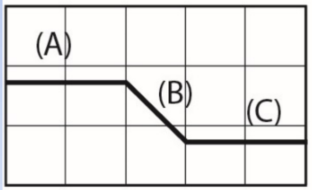
Dual radial sequences: impermeable frontiers

Positive offset



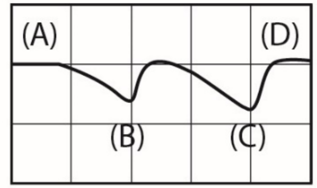
1. No-flow single (D = 2) or multiple (D >2) boundaries
2. Weakly inclined conductive fault (low transition slope)

Negative offset

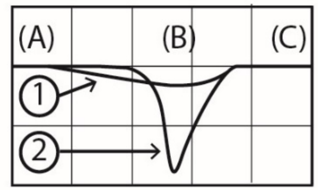


1. Cryptic (non-pumped) contiguous or distal aquifer (highly productive)
2. Aquifer with inclined substratum (B : $n = 3$)

No offset

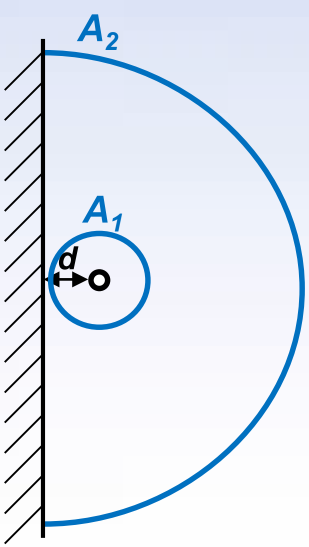


Triple porosity (fractured rocks)



Dual porosity (fractured rocks)
1. Transient interporosity flow
2. Pseudo-steady interporosity flow

CONCEPTUAL MODEL: single impermeable frontier



$r < d : A_1(r) = 2\pi rb$

$r > d : A_2(r) = ½\ 2\pi rb = ½\ A_1(r)$

The transmissive surface is halved → Drawdown log-rate is doubled

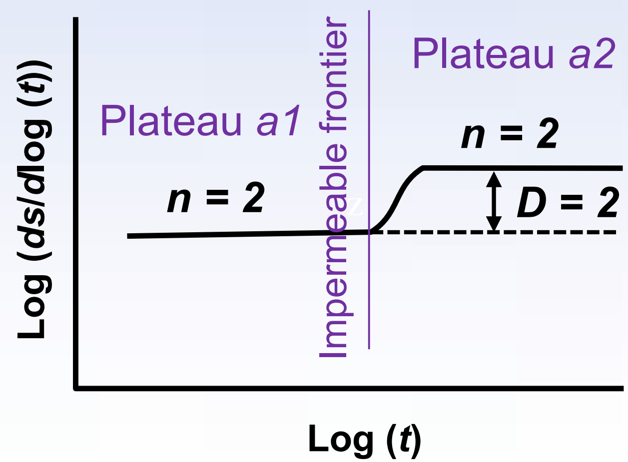
$p = a = 2.3Q/4\pi T$

$a2 = 2\ a1$

(or $p2 = 2\ p1$)

Log-derivative response

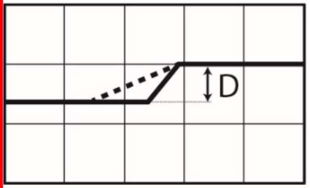
Sequence of *n* : 2 – 2 with *D* = 2



The slope (inversely proportional to transmissivity) is doubled after the no-flow boundary is reached

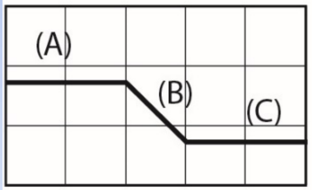
Dual radial sequences: multiple impermeable frontiers

Positive offset



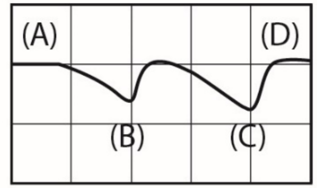
1. No-flow single (D = 2) or multiple (D >2) boundaries
2. Weakly inclined conductive fault (low transition slope)

Negative offset

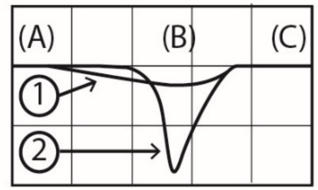


1. Cryptic (non-pumped) contiguous or distal aquifer (highly productive)
2. Aquifer with inclined substratum (B : $n = 3$)

No offset

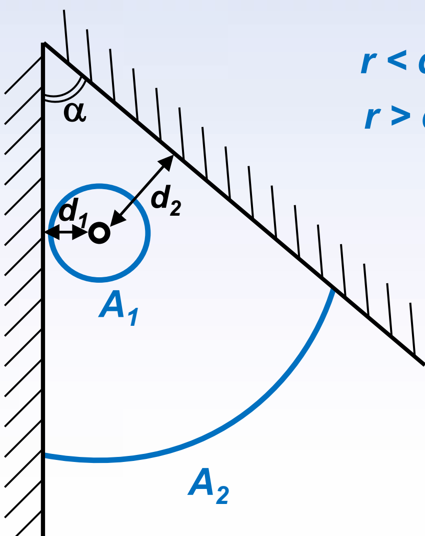


Triple porosity (fractured rocks)



Dual porosity (fractured rocks)
1. Transient interporosity flow
2. Pseudo-steady interporosity flow

CONCEPTUAL MODEL: generalized multiple impermeable frontiers model

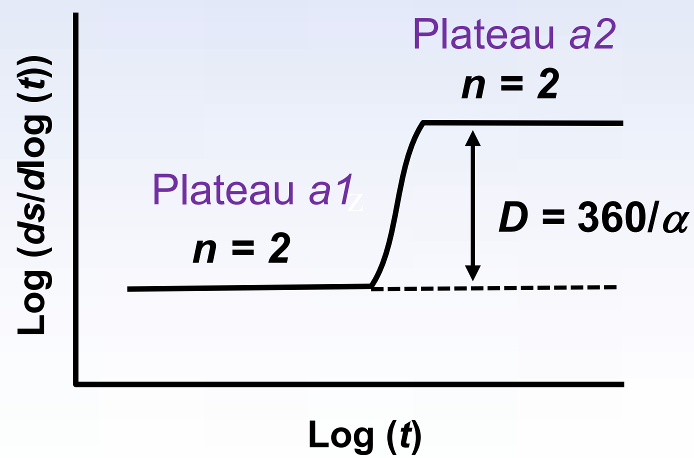


$r < d_1 : A_1(r) = 2\pi rb$

$r > d_2 : A_2(r) = (\alpha/360)\, A_1(r)$

The transmissive surface A_2 is decreased by a factor $\alpha/360$ → Drawdown rate increases by an equal inverse factor

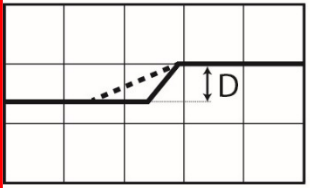
Log-derivative response
Sequence of *n* : 2 – 2 with *D* > 2



$T = 2.3Q/4\pi\, a_1 \,;\; T_{app} = 2.3Q/4\pi\, a_2 \rightarrow \alpha = 360\; T_{app} / T = 360\; a_1 / a_2$

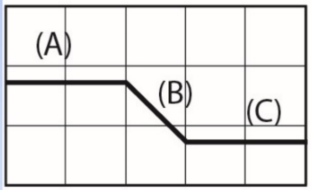
Dual radial sequences: multiple impermeable frontiers

Positive offset



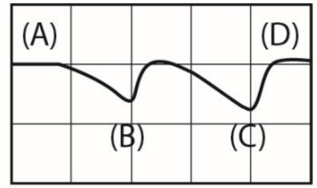
1. No-flow single (D = 2) or multiple (D >2) boundaries
2. Weakly inclined conductive fault (low transition slope)

Negative offset

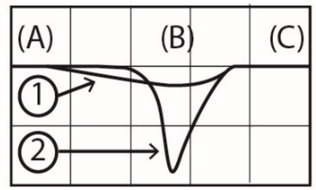


1. Cryptic (non-pumped) contiguous or distal aquifer (highly productive)
2. Aquifer with inclined substratum (B : $n = 3$)

No offset



Triple porosity (fractured rocks)



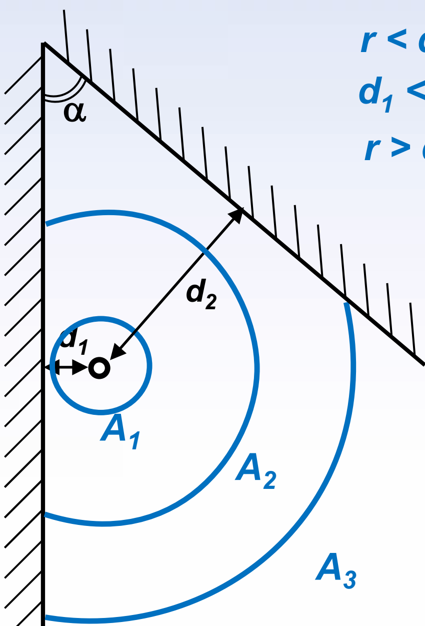
Dual porosity (fractured rocks)
1. Transient interporosity flow
2. Pseudo-steady interporosity flow

CONCEPTUAL MODEL: generalized multiple impermeable frontiers model ; with intermediate stage ($d_2 >> d_1$)

$r < d_1 : A_1(r) = 2\pi rb$

$d_1 < r < d_2 : A_2(r) = ½\, A_1(r)$

$r > d_2 : A_3(r) = (\alpha/360)\, A_1(r)$

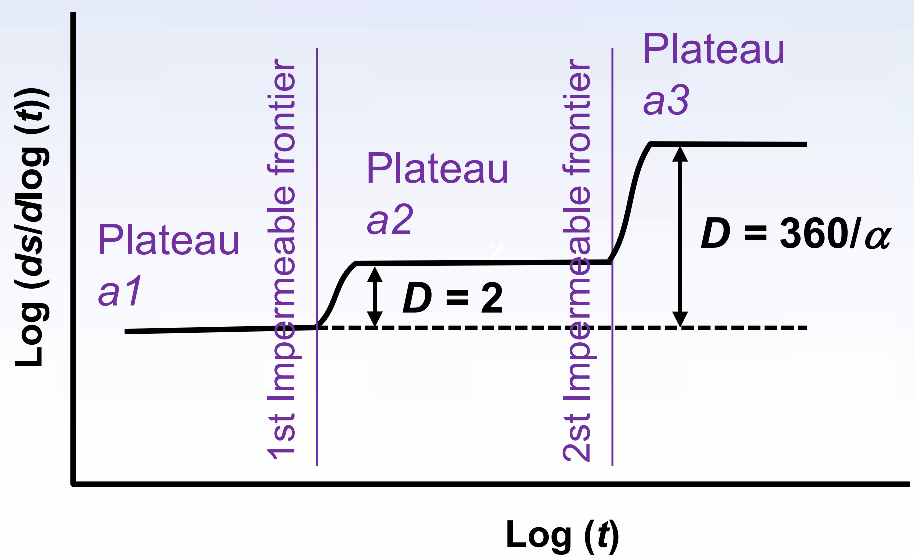


The transmissive surface A_3 is decreased by a factor $360/\alpha$ → Drawdown rate increases by an equal factor

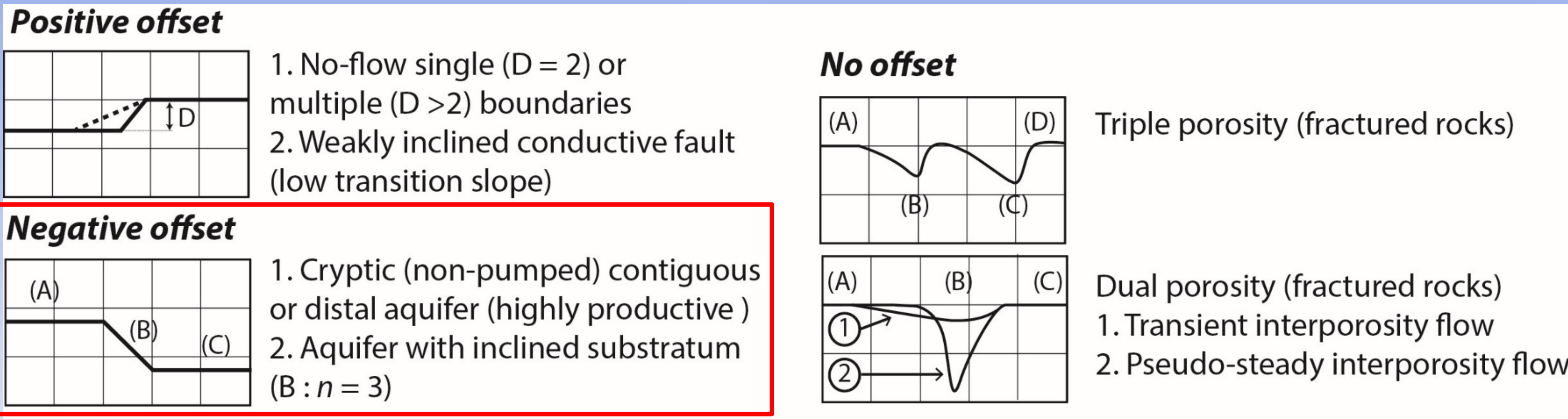
Log-derivative response

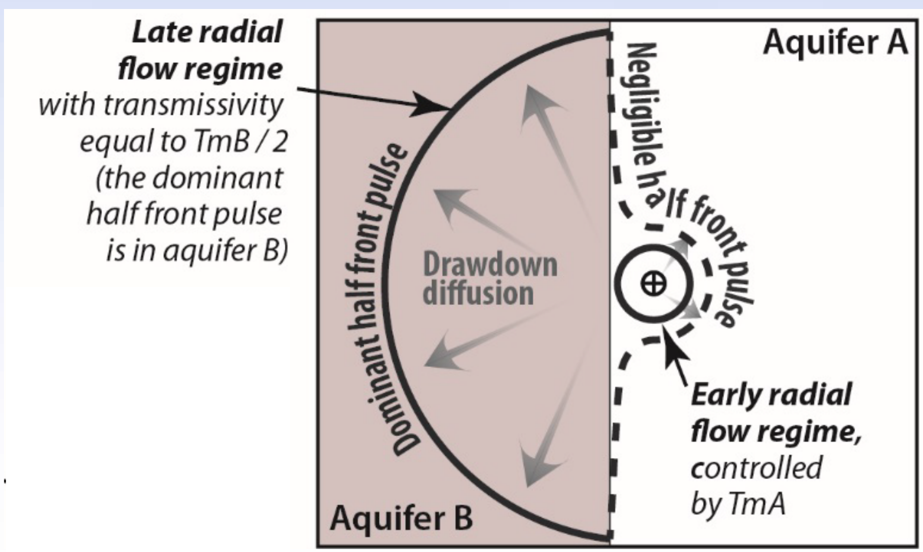
Sequence of *n* : 2 – 2 – 2

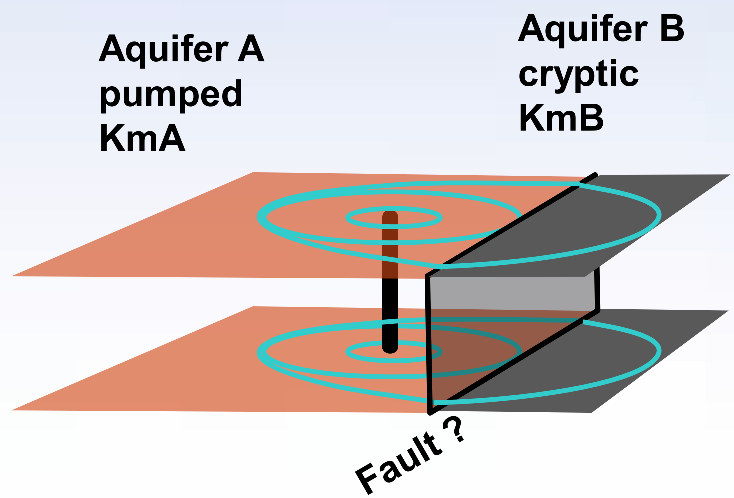
with successively *D* = 2 and D > 2



Dual radial sequences: contiguous aquifers



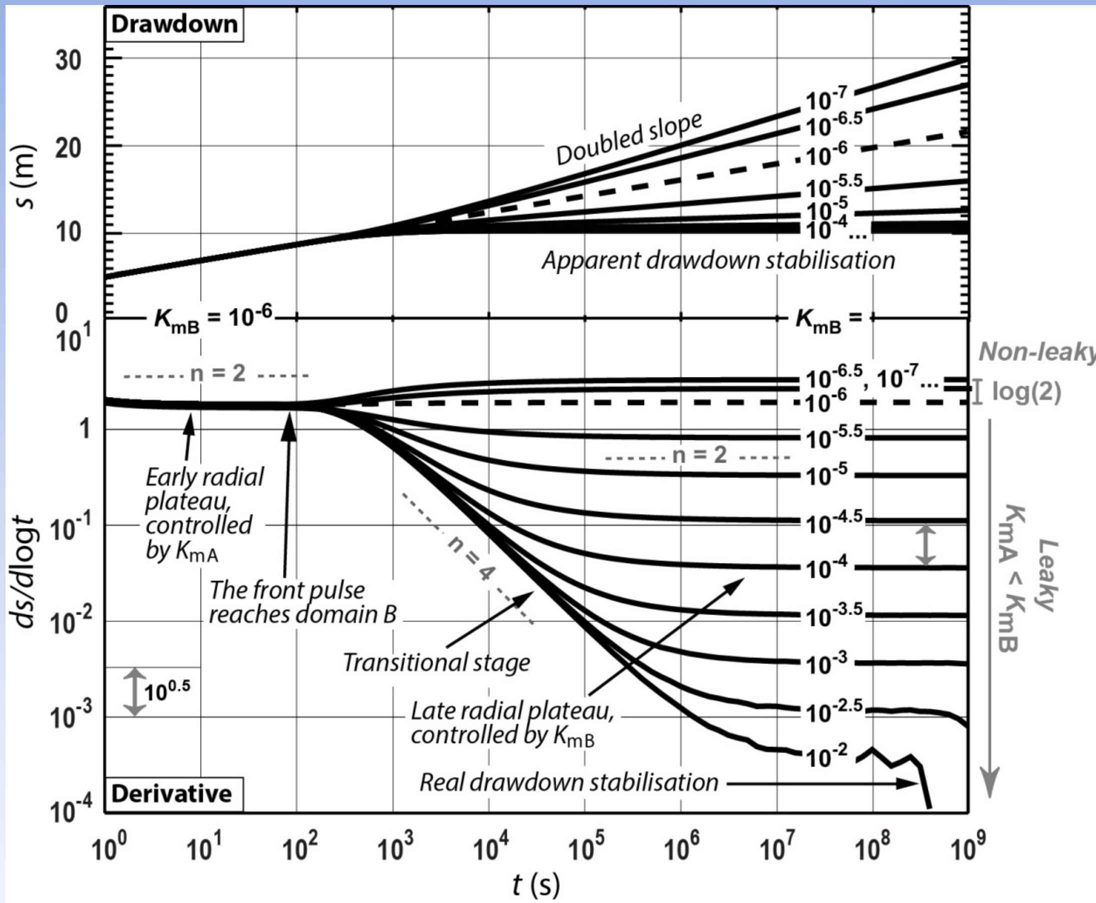


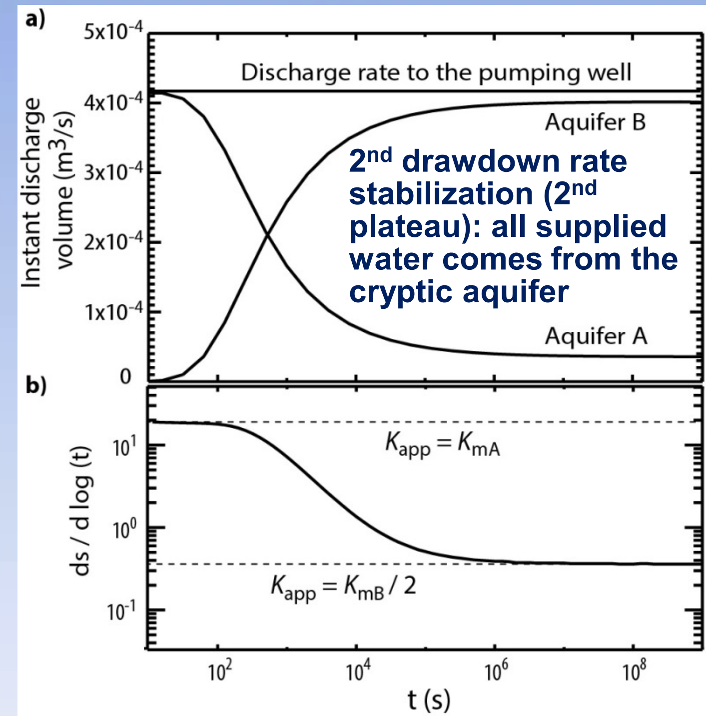


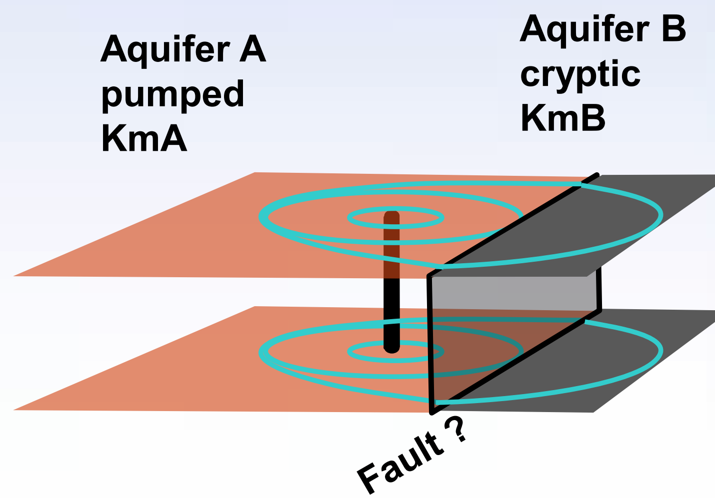
Non-pumped domain is <u>more</u> transmissive:

cryptic aquifer model → $K_{app} = K_{mB} / 2$

Dual radial sequences: contiguous aquifers





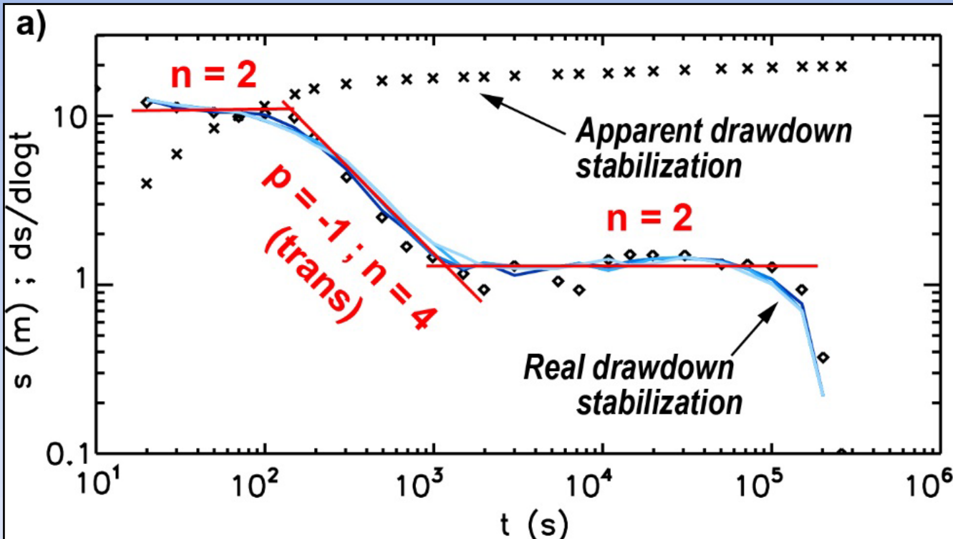


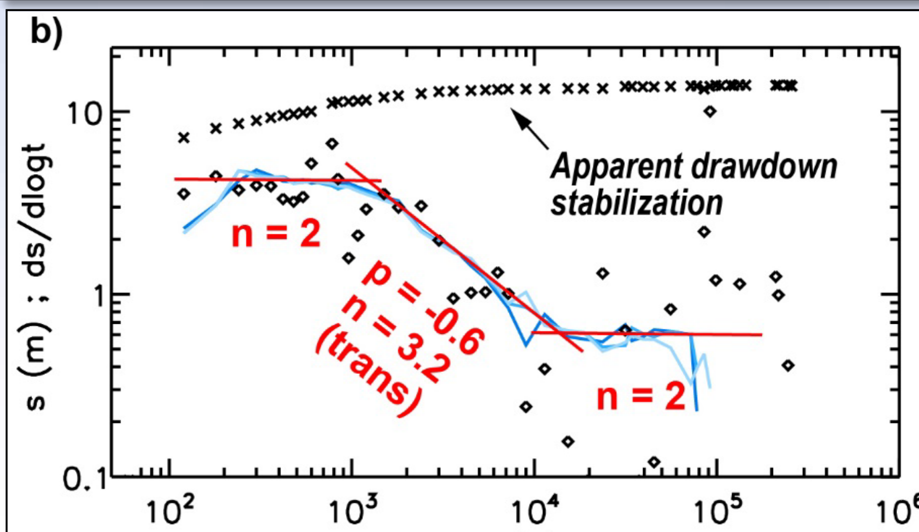
- The 2nd plateau is lower than the 1st one because the cryptic aquifer is more transmissive ($a = 2.3Q/4\pi T$)
- 2nd plateau: $T_{app} = T_{mB} / 2$; offset is proportional to T_{mB} / T_{mA}
- Transitional stage is a negative unit slope : *n* = 4
- Sequence *n* : 2 – 4 – 2

Dual radial sequences: real examples

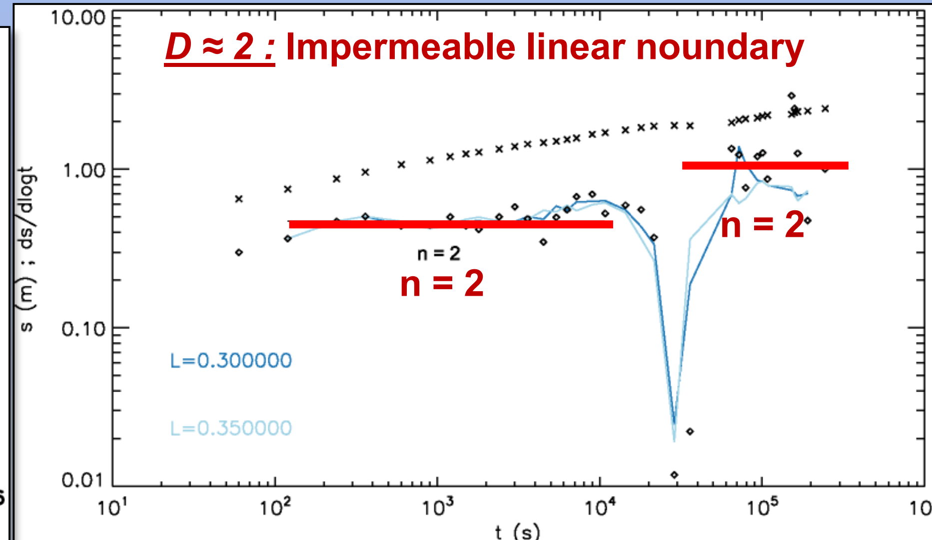
Negative offset :

Cryptic (non-pumped) highly conductive aquifer

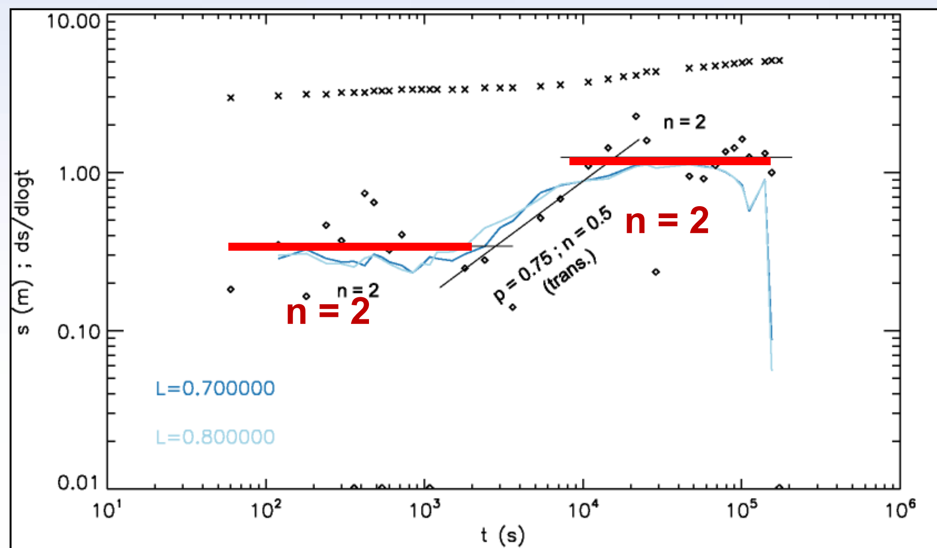




Positive offset



D > 2 : **Multiple linear boundaries or a horizontal conductive fault**

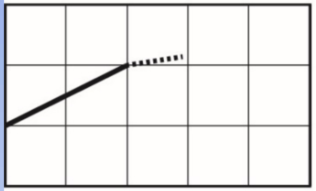


Linear, dual linear combinations

$$n = 2 - 1$$

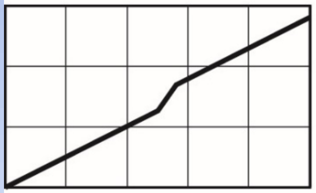
$$n = 1 - 1$$

Linear combinations: overview



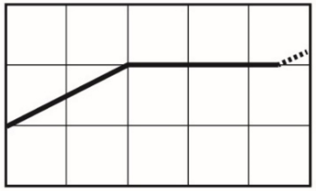
1

1. Fluvial channels (delta fans, glacial deposits, etc.)
2. Conductive fault in an aquitard
3. Infinitely conductive fault
4. Elongated aquifer



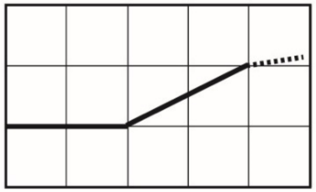
1 - 1

1. T shaped fluvial channels
2. Impermeable boundary in an elongated aquifer



1 - 2

Dense and connective fractured network (continuum-like)



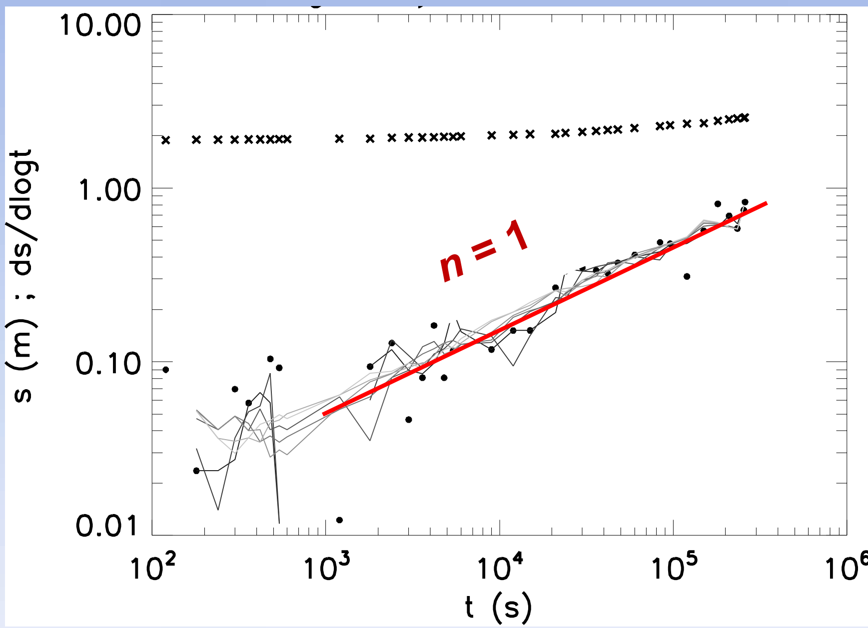
2 - 1

Elongated aquifer (large channel)

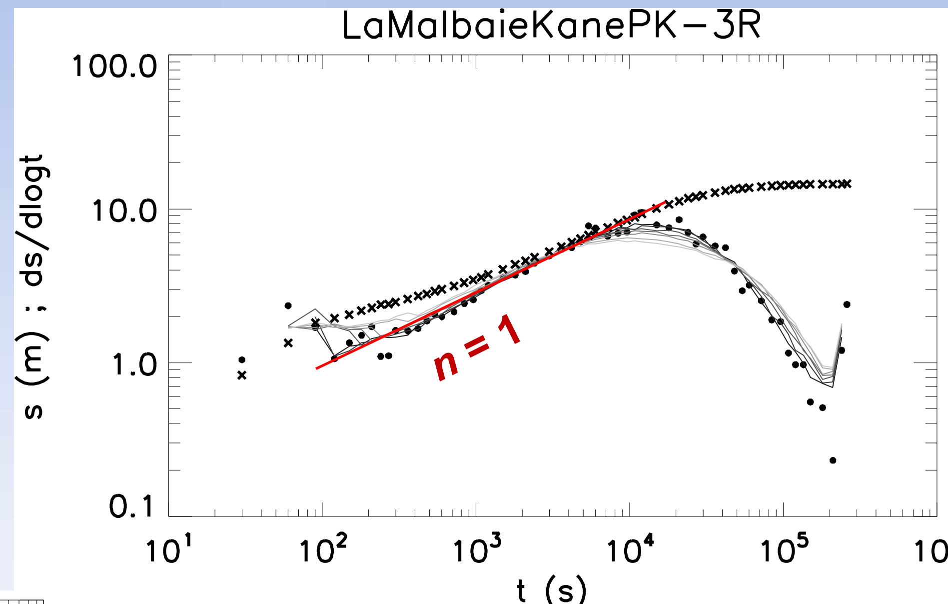
- Linear response = **laterally restricted flow**
- Lateral restriction may be caused by
  - Impermeable boundaries: **fluvial channel**, **elongated aquifer** models
  - Hardrocks aquifers :
    - **High diffusivity ratios** between a conductive fracture or fault and the **surrounding aquifer or aquitard**
    - **Delayed pressure transfers** to the matrix due to either skin effects on the fractures walls or impermeable material in a layered fault's core zone
- Features allowing to decipher between these various models are**: the time of occurrence** (early, medium or late time pumping time) and the **associations to prior or late radial stage**

Linear combinations: real examples

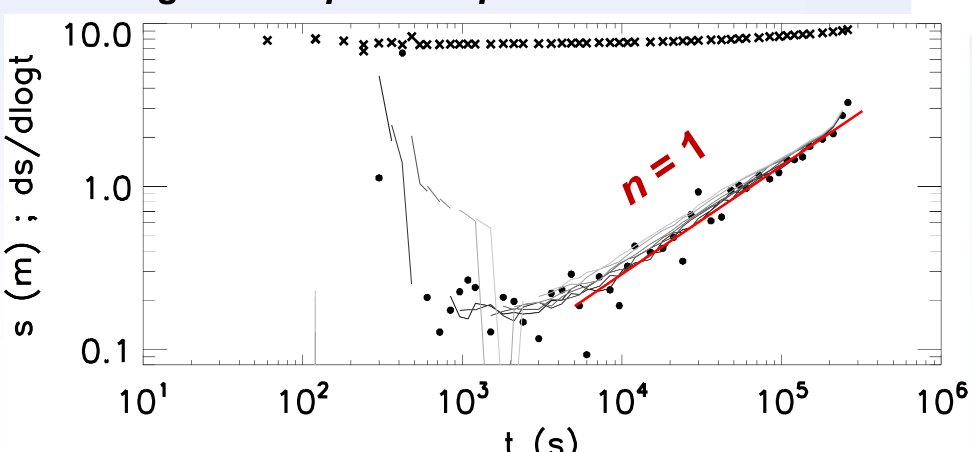
Deltaic deposits aquifer



Faulted hardrock aquifer

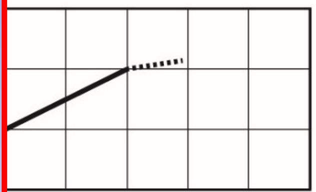


Fluvio-glacial deposits aquifer



- **Occurs in short or long time ?**
- **Infinite-acting ?**
- **Association to other regimes (n = 2, n = 1.5) ?**

Linear regime: elongated (channel) aquifer



1

1. Fluvial channels (delta fans, glacial deposits, etc.)
2. Conductive fault in an aquitard
3. Infinitely conductive fault
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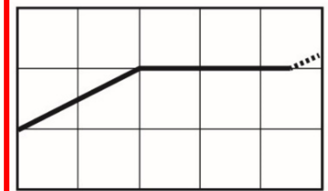
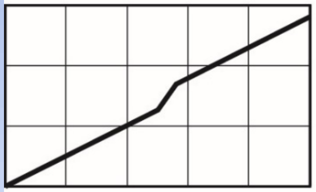


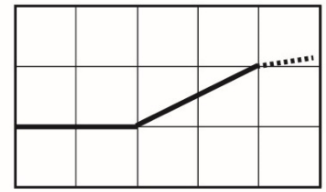
1 - 2

Dense and connective fractured network (continuum-like)



1 - 1

1. T shaped fluvial channels
2. Impermeable boundary in an elongated aquifer



2 - 1

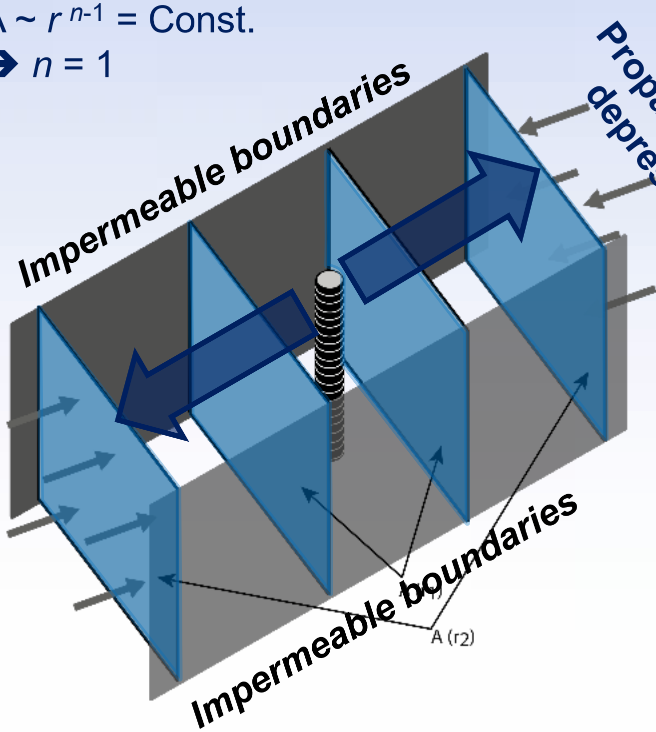
Elongated aquifer (large channel)

Lateral flow restriction due to two impermeable opposite boundaries

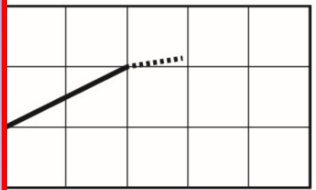
Constant cross flow surface

$A \sim r^{n-1}$ = Const.

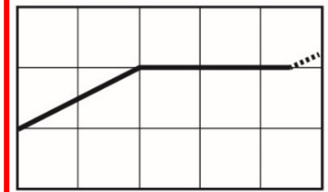
➔ $n = 1$



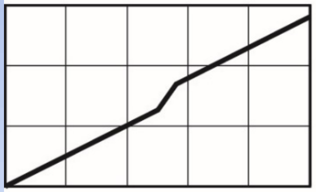
Linear regime: faulted/fractured aquifers



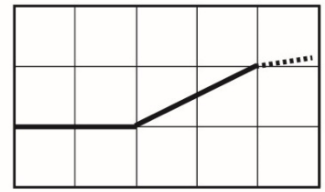
1
1. Fluvial channels (delta fans, glacial deposits, etc.)
2. Conductive fault in an aquitard
3. Infinitely conductive fault
4. Elongated aquifer



1 - 2
Dense and connective fractured network (continuum-like)



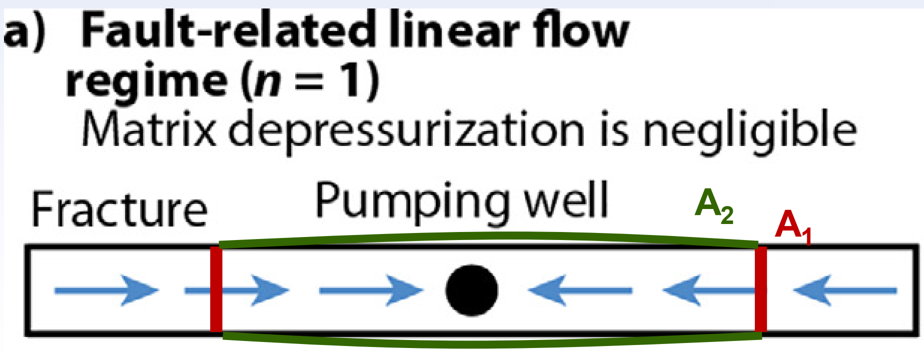
1 - 1
1. T shaped fluvial channels
2. Impermeable boundary in an elongated aquifer



2 - 1
Elongated aquifer (large channel)

Lateral flow restriction due to **high fracture/matrix diffusivity constrast or delayed pressure transfers (skin)** (or confinement into a fault's internal impermeable core zone)

Fault-related linear flow regime
Introduced in Cinco-Ley and Samaniego (1981)
finite conductivity fracture model



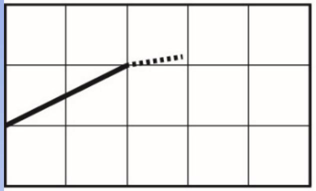
The constant cross flow surface = the fracture's section A_1
➔ Linear stage remains as long as $A_1 > A_2$

The highest diffusivity contrasts, the longest the linear regime

➔ In hard rocks aquifers, the linear regime is typically a **short-duration, early stage regime**

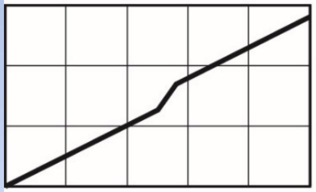
➔ After A2 > A1 : radial flow regime ; sequence 1 – 2 for densely fractured bedrock aquifers

Linear regime: faulted/fractured aquifers



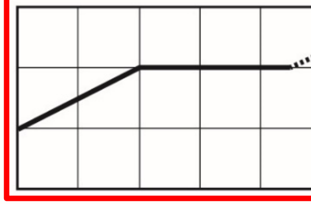
1

1. Fluvial channels (delta fans, glacial deposits, etc.)
2. Conductive fault in an aquitard
3. Infinitely conductive fault
4. Elongated aquifer



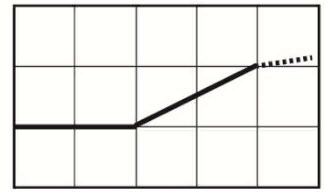
1 - 1

1. T shaped fluvial channels
2. Impermeable boundary in an elongated aquifer



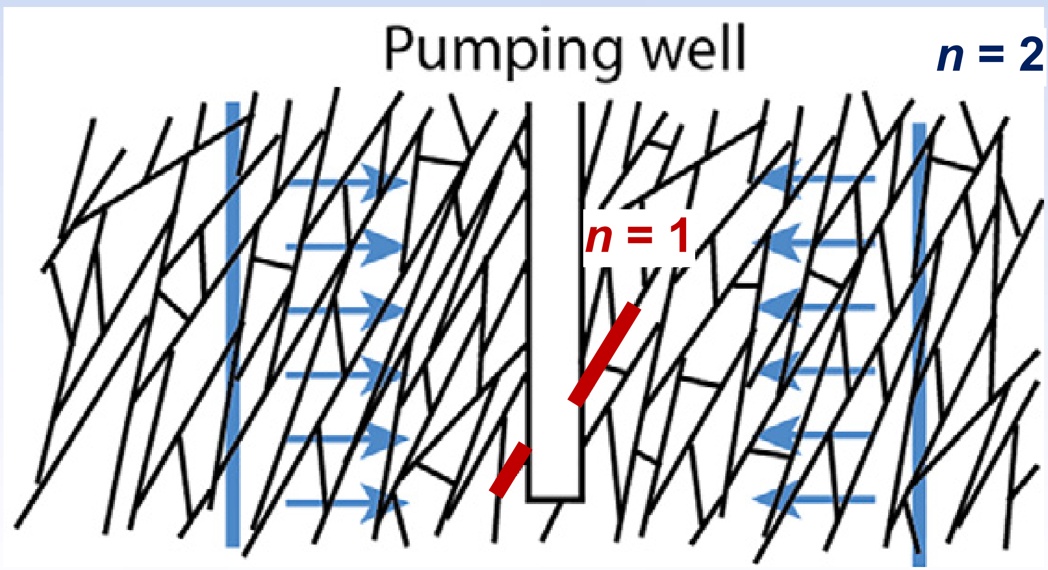
1 - 2

Dense and connective fractured network (continuum-like)



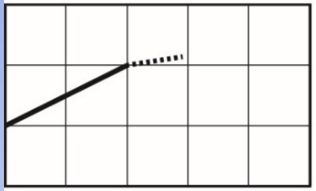
2 - 1

Elongated aquifer (large channel)



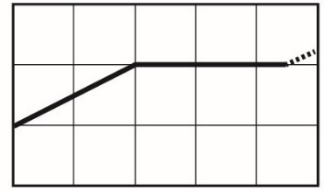
Sequence 1 – 2 with increasing observation scale (front pulse diffusion)

Dual linear regime: fluvial channel



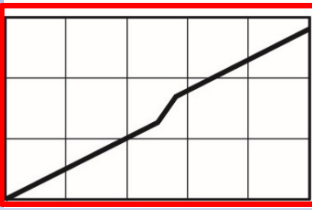
1

1. Fluvial channels (delta fans, glacial deposits, etc.)
2. Conductive fault in an aquitard
3. Infinitely conductive fault
4. Elongated aquifer



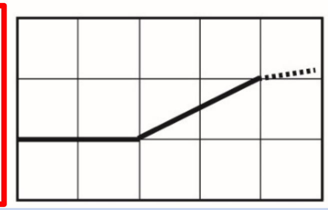
1 - 2

Dense and connective fractured network (continuum-like)



1 - 1

1. T shaped fluvial channels
2. Impermeable boundary in an elongated aquifer



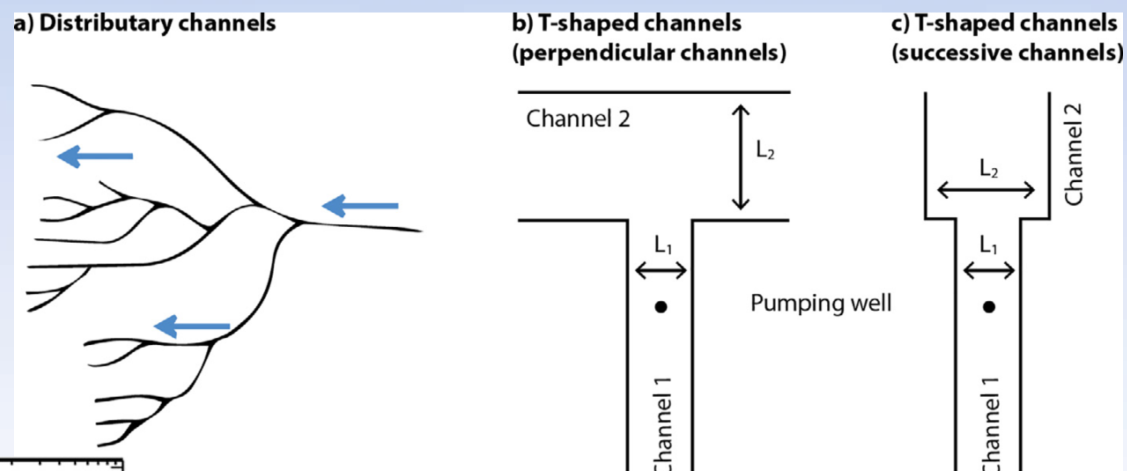
2 - 1

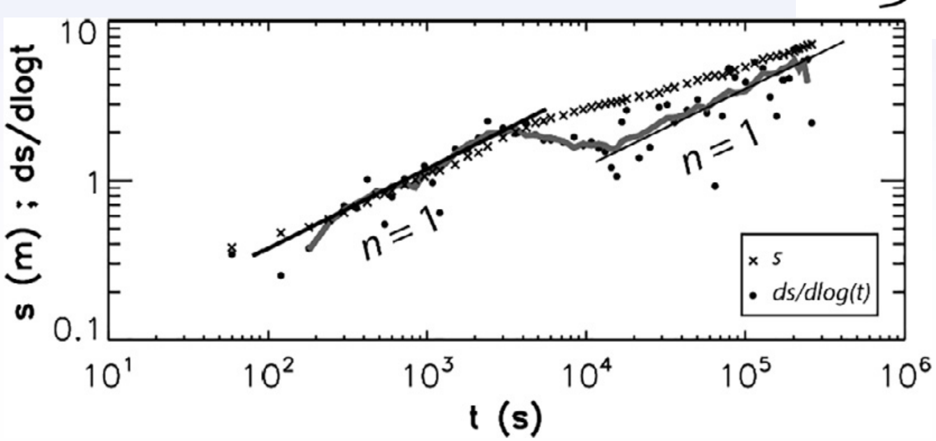
Elongated aquifer (large channel)

Two successive linear regimes

T shaped channel model:
channel enlargment or junction of two channels

Channel network in deltaic fans





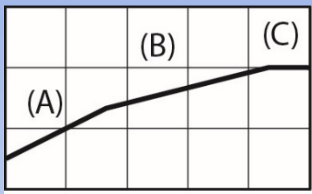
n = 1.5 « bilinear » combinations

n = 1 – 1.5 – 2

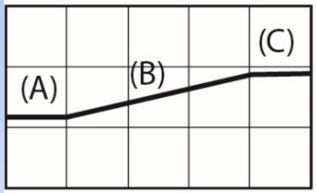
n = 2 – 1.5

n = 2 – 4 – 1.5 – 2

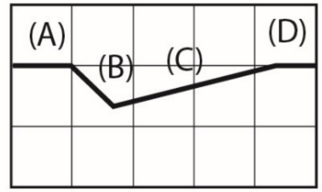
n = 1.5 « bilinear » combinations: overview



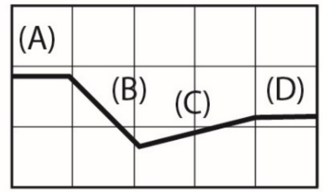
(1) - 1.5 - 2
Strongly inclined conductive fault connected to the well



2 - 1.5 - 2
Weakly inclined conductive fault



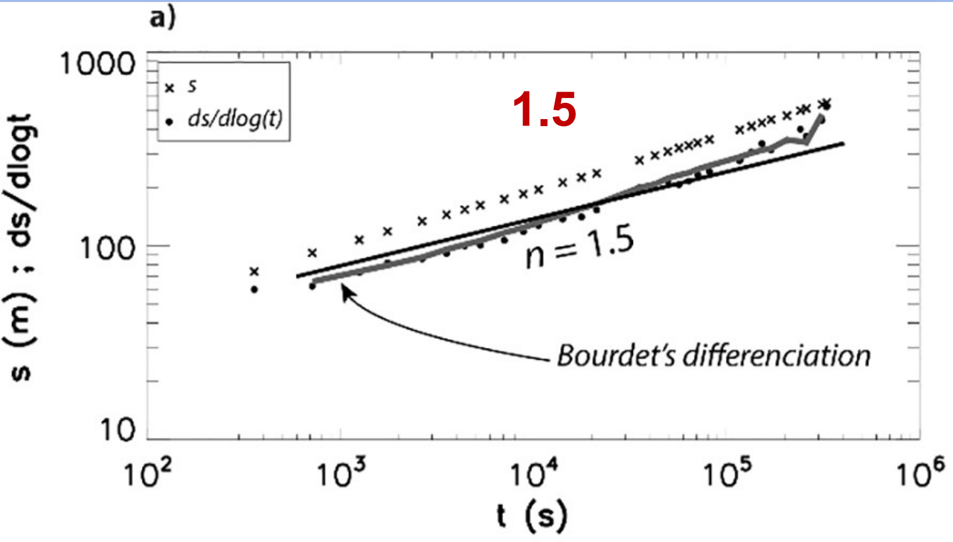
2 - 4 - 1.5 - 2
Strongly inclined conductive fault non-connected to the well

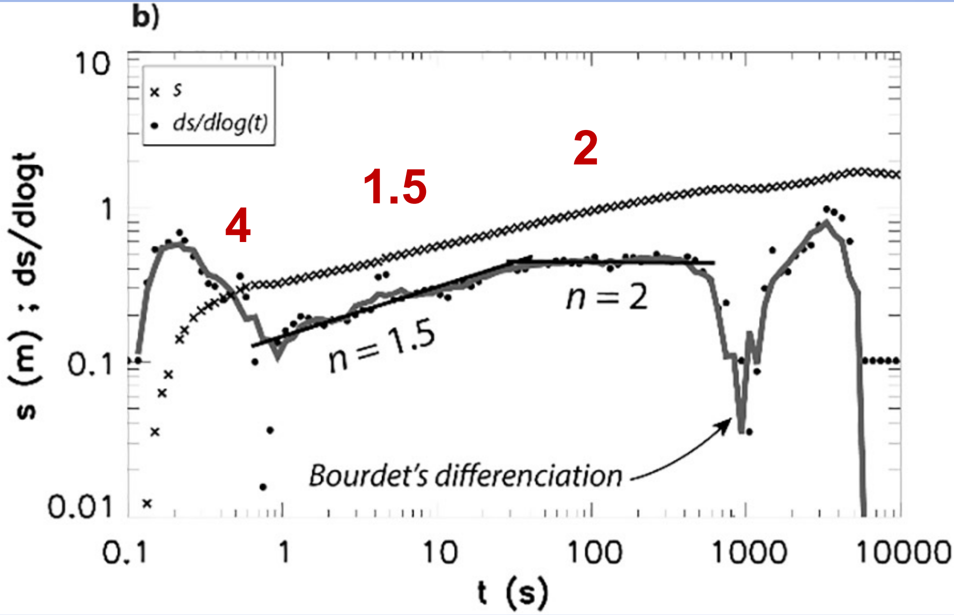


2 - 4 - 1.5 - 2 with offset between the two radial plateaus :
Strongly inclined conductive fault non-connected to the well separating two aquifers with distinct properties

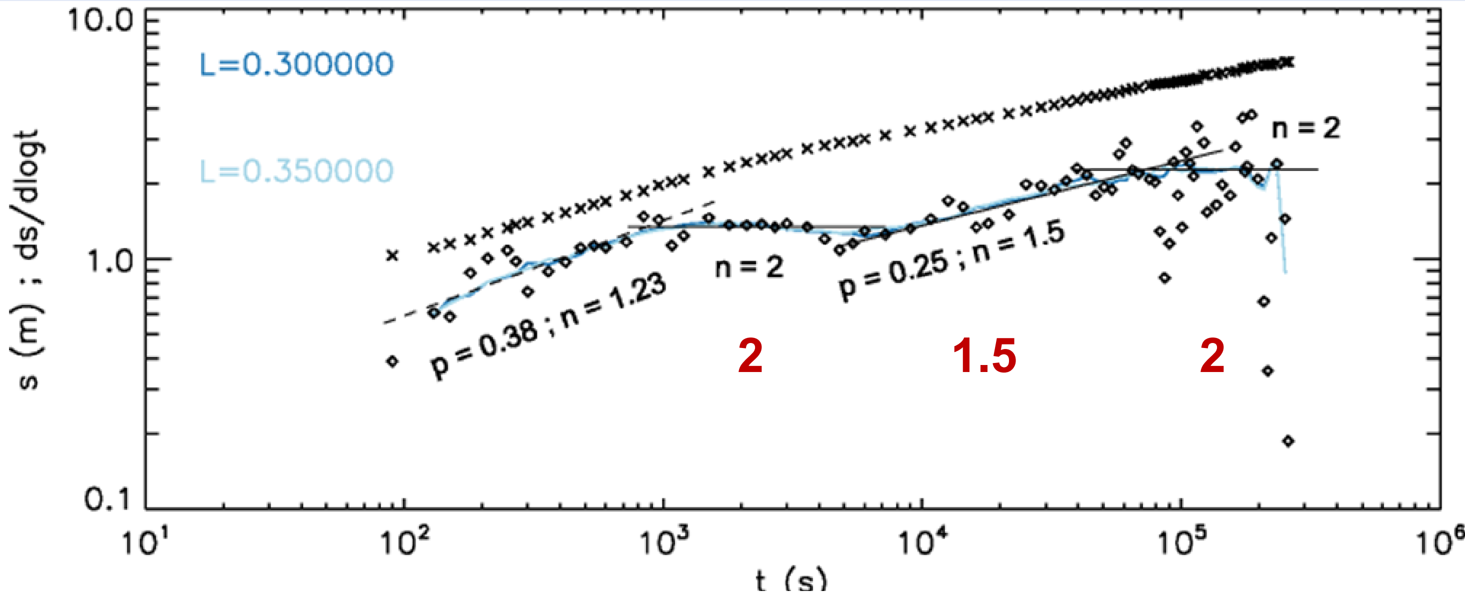
- The *n* = 1.5 flow regime, early referred to as bilinear flow regime, has been long recognized as produced by a **vertical conductive fault embedded into a non-impermeable aquifer** (Cinco-Ley and Samaniego, 1981; Rafini and Larocque, 2009, 2012)
- The associated flow regimes with *n* = 1, 2, or 4 indicate whether the fault is distal or directly connected to the pumping well and, in a lower extent, the attitude of the fault into the aquifer

n = 1.5 « bilinear » combinations: real examples

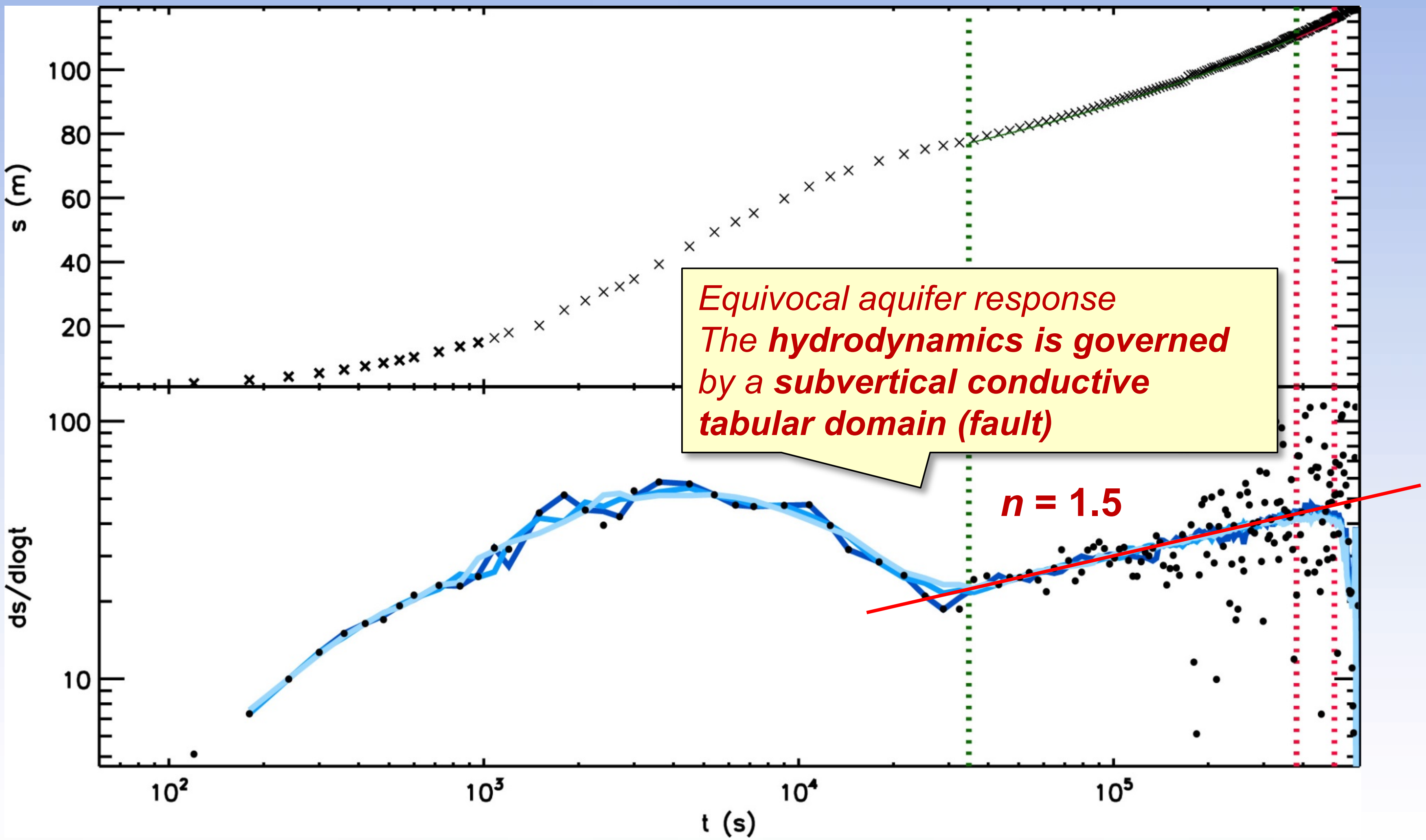




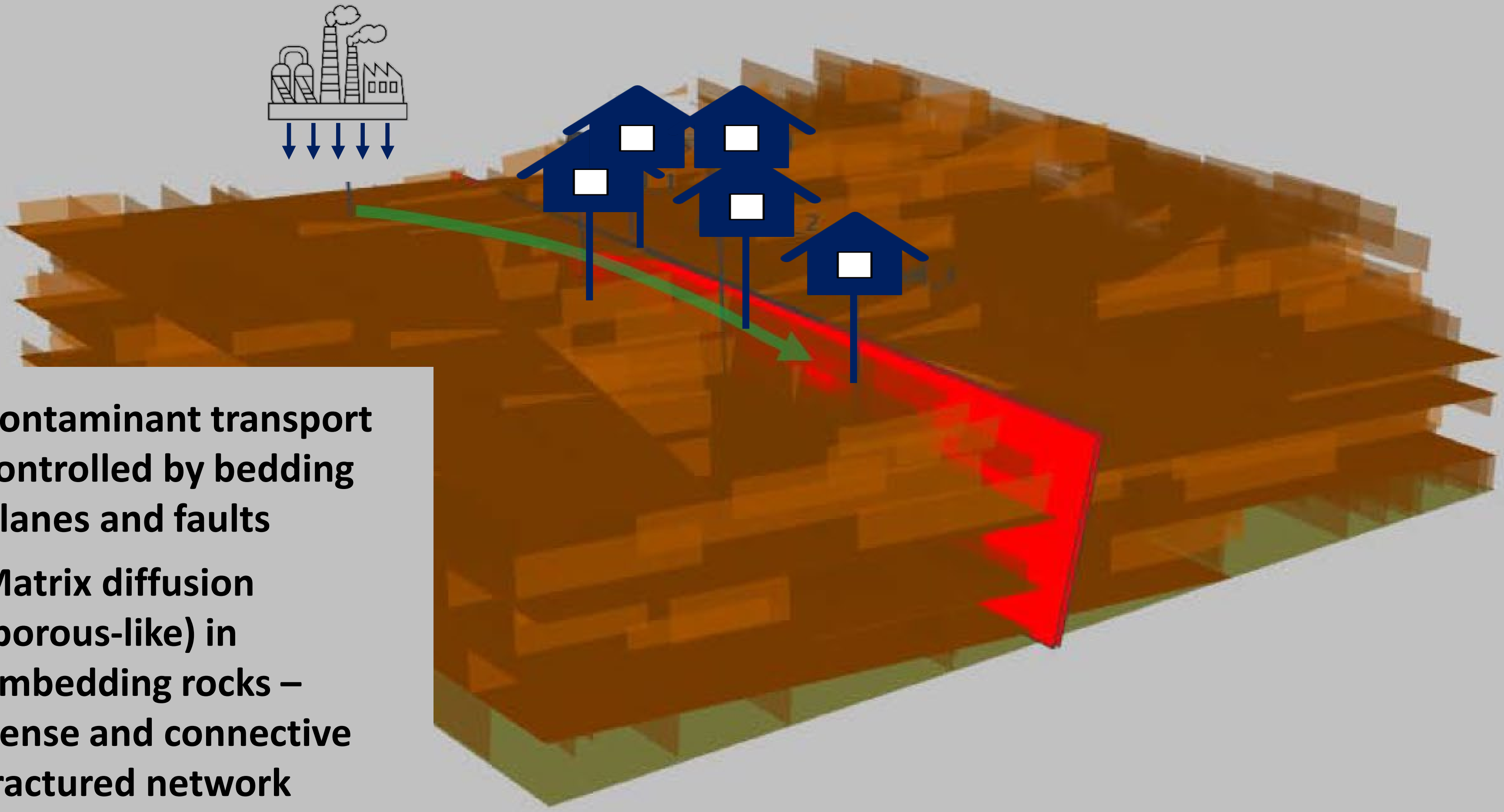
Hard rocks aquifers



n = 1.5 « bilinear » combinations: real examples

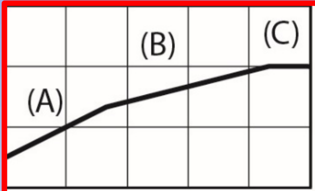


Differenciation (Bourdet, 1983) of dataset measured with levelloger

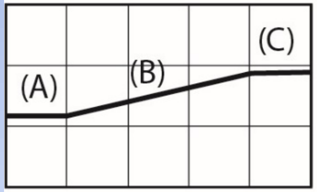


- **Contaminant transport controlled by bedding planes and faults**
- **Matrix diffusion (porous-like) in embedding rocks – dense and connective fractured network**

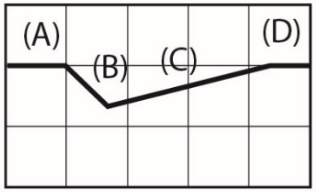
n = 1.5 « bilinear » combinations



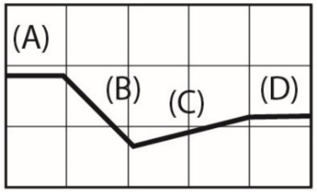
(1) - 1.5 - 2
Strongly inclined conductive fault connected to the well



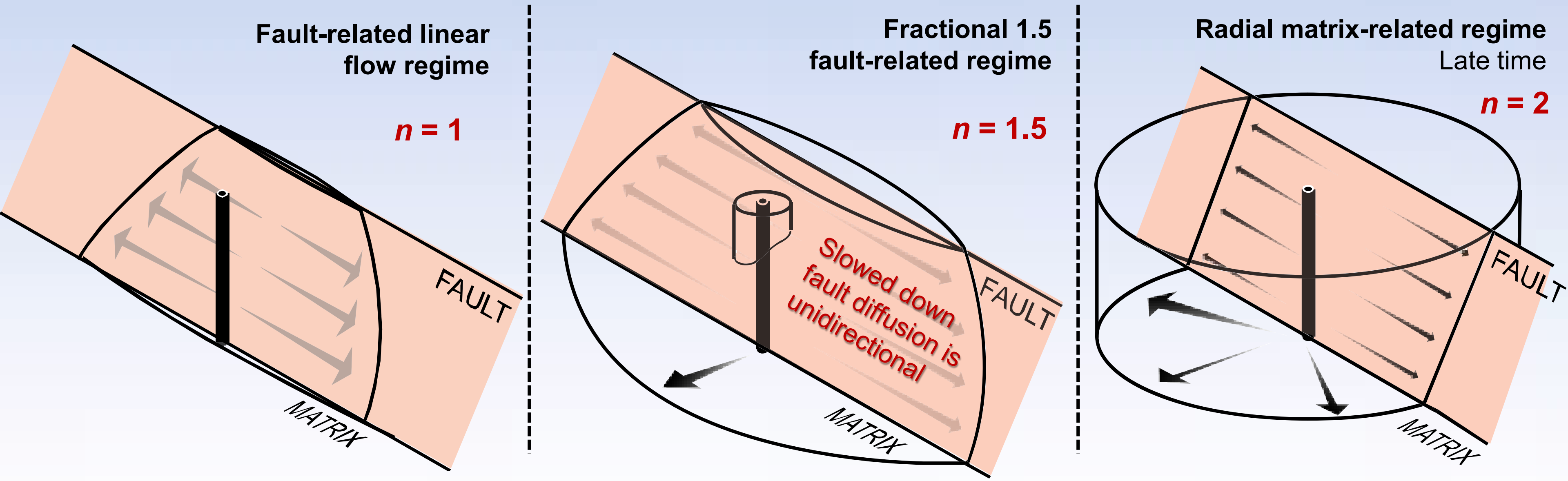
2 - 1.5 - 2
Weakly inclined conductive fault



2 - 4 - 1.5 - 2
Strongly inclined conductive fault non-connected to the well



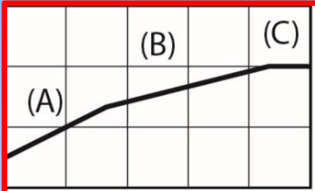
2 - 4 - 1.5 - 2 with offset between the two radial plateaus :
Strongly inclined conductive fault non-connected to the well separating two aquifers with distinct properties



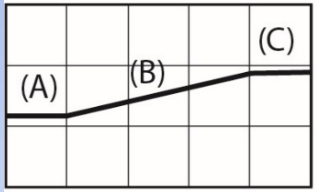
Rafini and Larocque, 2009, 2012

- **Early stage n = 1** : matrix depressurization is negligible
- **Mid-stage n = 1.5 :** the response of the system is governed by fault properties, fault diffusion slow-down
- **Late stage n = 2 :** the fault does not extert any influence on the hydrodynamics, the response is governed by matrix properties

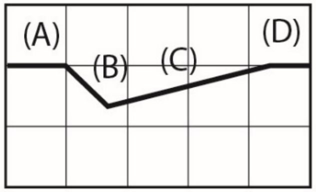
n = 1.5 « bilinear » combinations



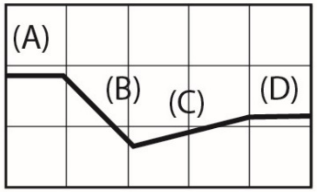
(1) - 1.5 - 2
Strongly inclined conductive fault connected to the well



2 - 1.5 - 2
Weakly inclined conductive fault



2 - 4 - 1.5 - 2
Strongly inclined conductive fault non-connected to the well



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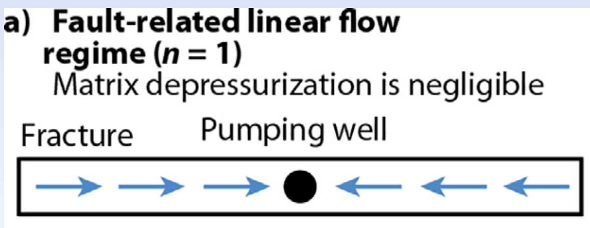
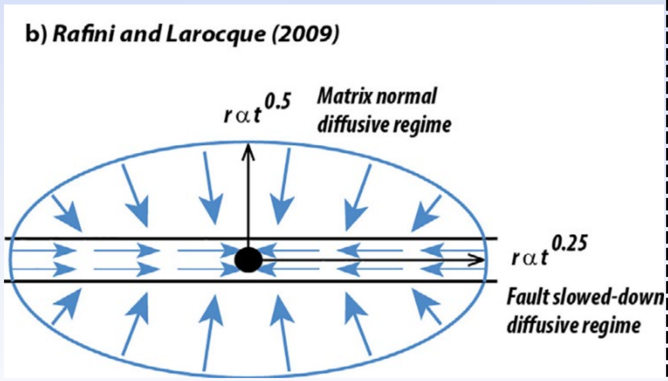
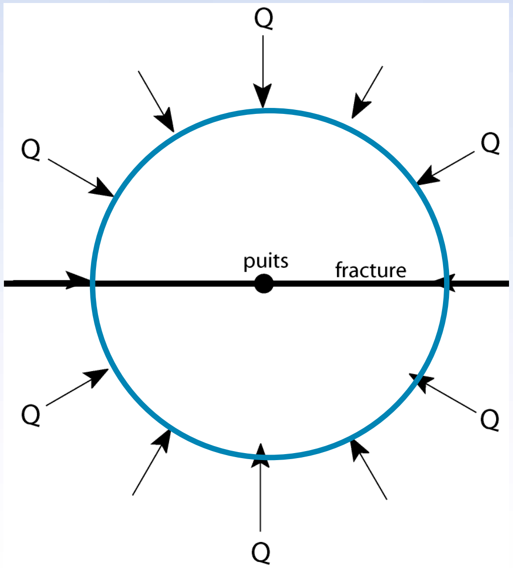




Large investigation scale: the fault is invisible



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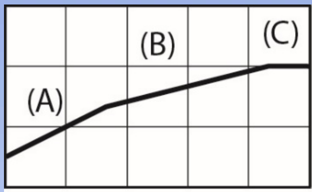
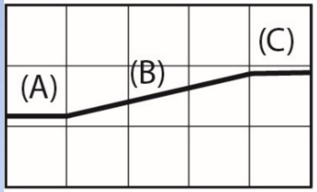
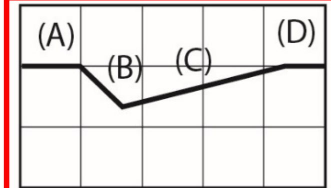
n = 1.5 « bilinear » combinations



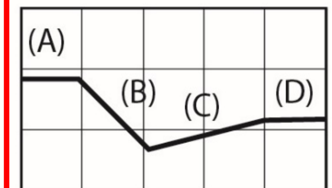
(1) - 1.5 - 2
Strongly inclined conductive fault connected to the well



2 - 1.5 - 2
Weakly inclined conductive fault



2 - 4 - 1.5 - 2
Strongly inclined conductive fault non-connected to the well



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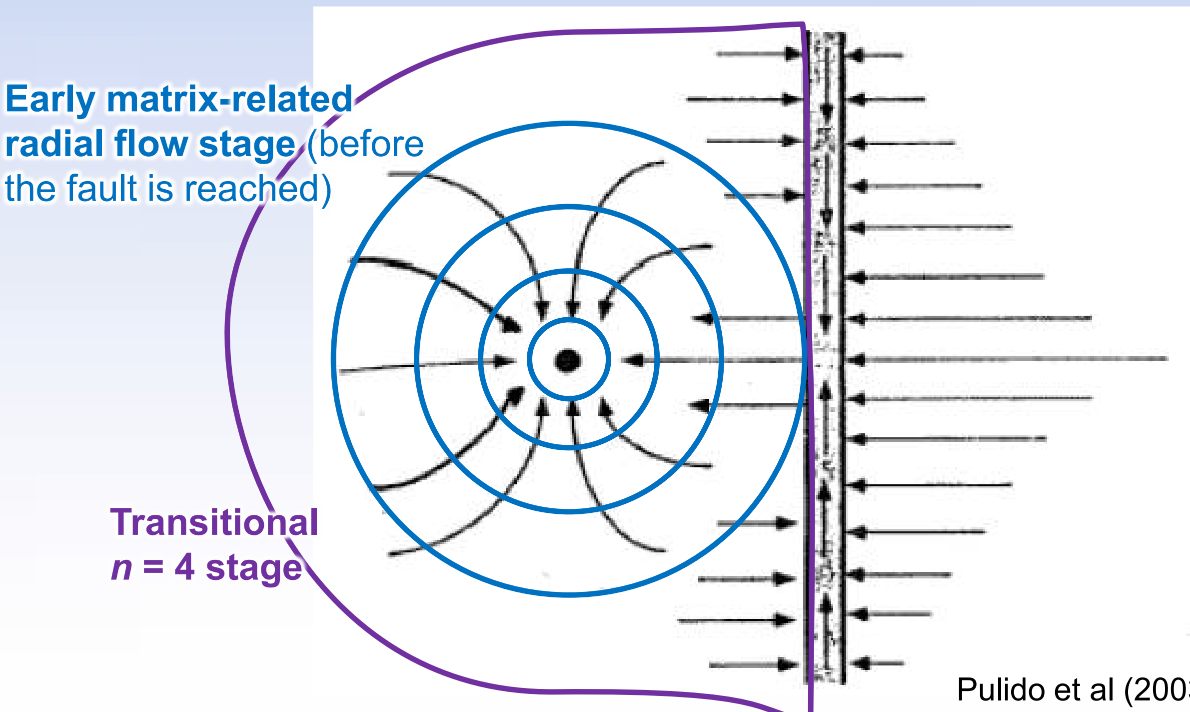


Pulido et al (2003)

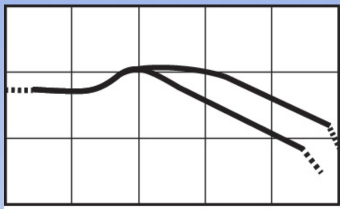
Theoretical model of a not-connected vertical finite-conductivity fault:
Abbaszadeh and Cinco-Ley (1995); Rafini and Larocque (2009)

Spherical combinations

$n = 3 – 2$

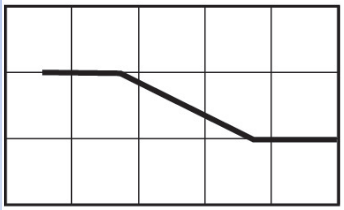
$n = 2 – 3 – 2$

Spherical combinations: overview and real examples



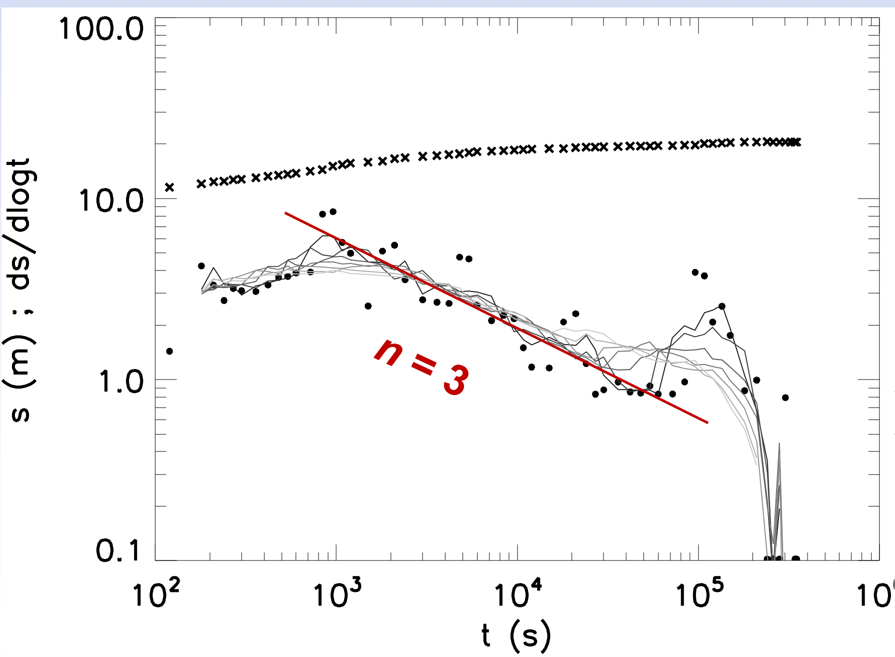
2 - (2) - 3

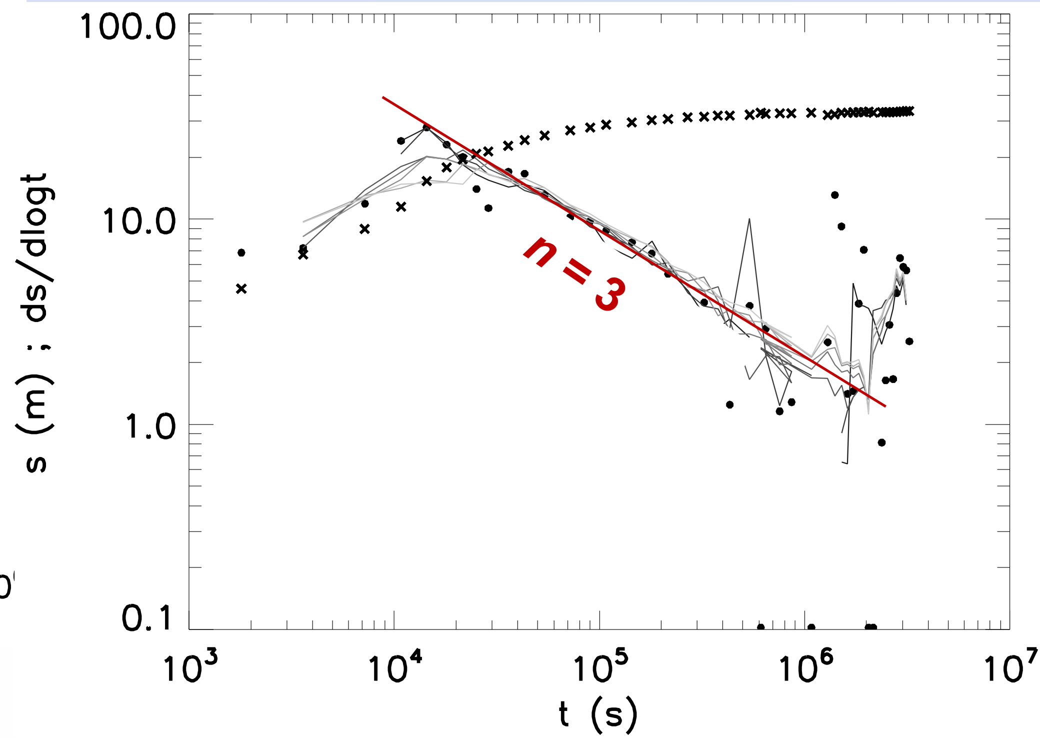
1. Inclined substratum aquifer with wedge



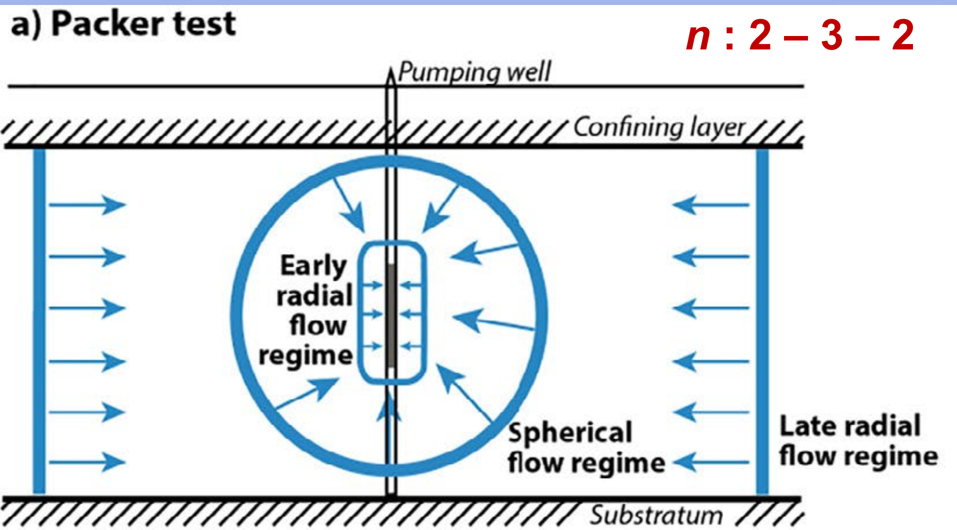
(2) - 3 - 2

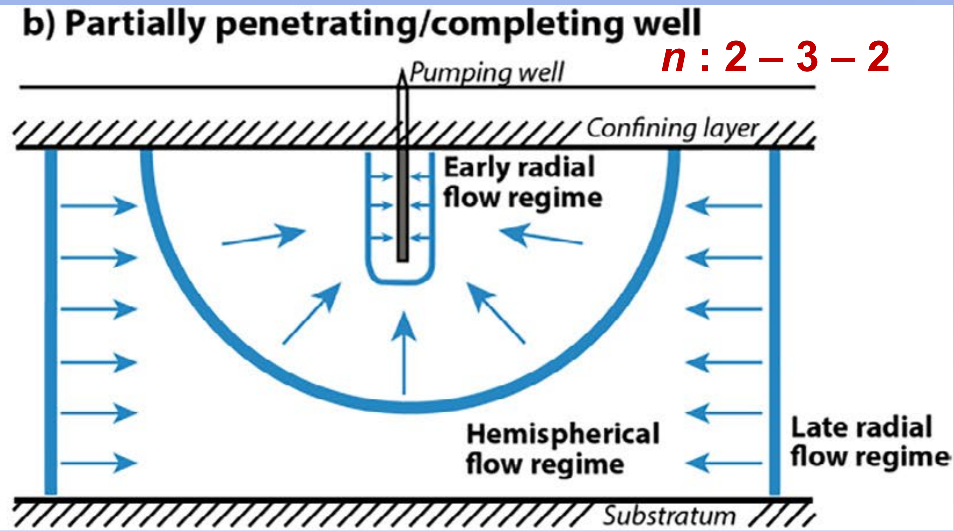
1. (Early radial stage is absent or very short-duration) partially penetrated aquifer or screen length very shorter that the aquifer thickness (or packer tests)
2. Punctual connection to an outer homogeneous aquifer (confinement gap)

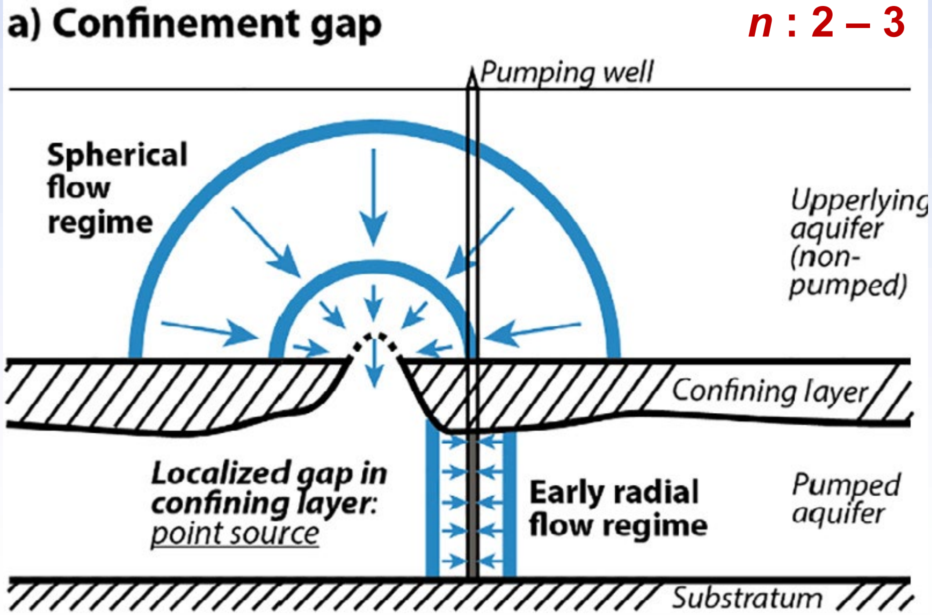


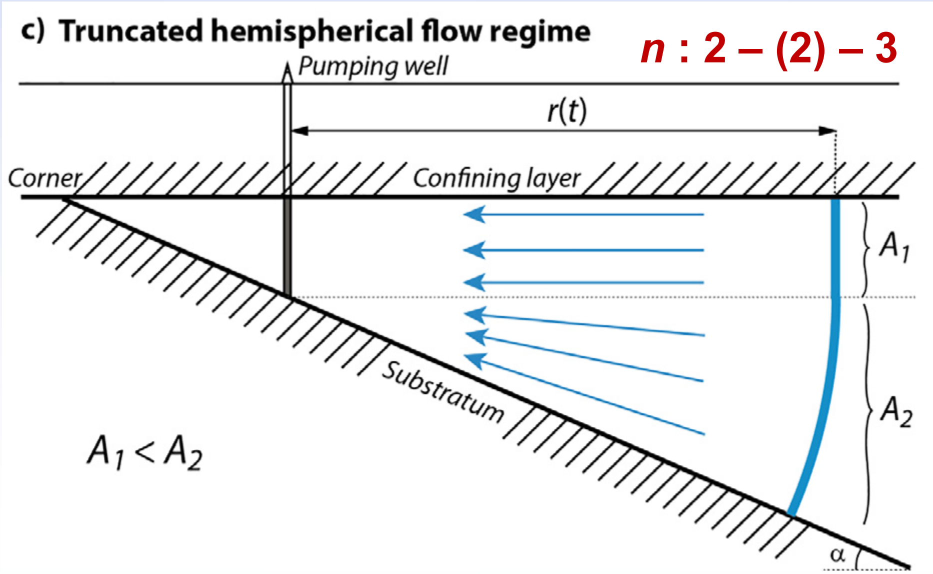


Spherical combinations: conceptual models









Discussions

- Global methodology
- Limitations of the approach

Limitations of the submitted methodology

- Non-unique interpretion of the conceptual flow model: different conceptual models predict similar flow regime sequences

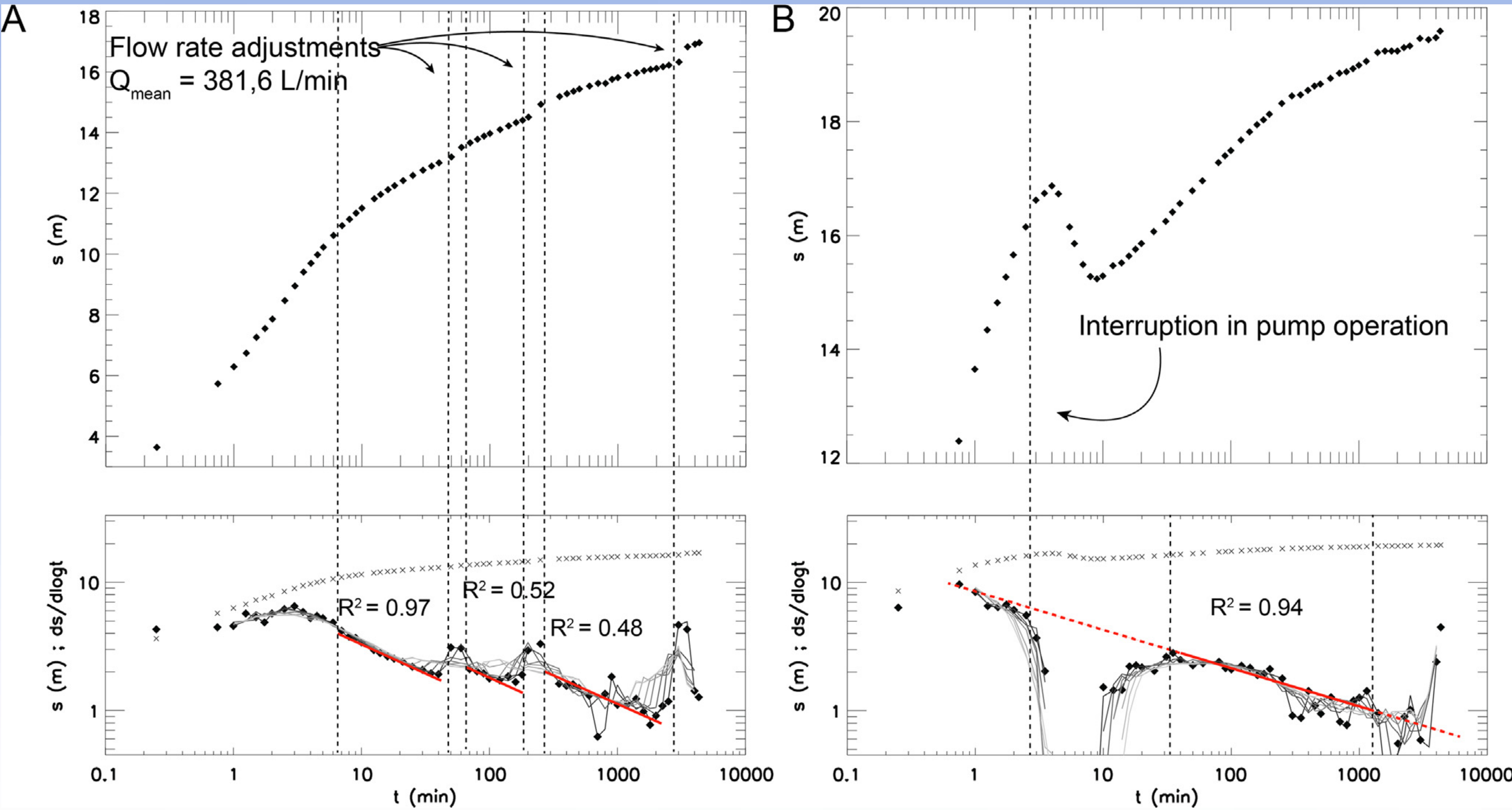
  → Look for other data: geological environment, probes data

- Noisy derivative datasets lead to uncertained graphical interpretations

  → Data preprocessing helps…

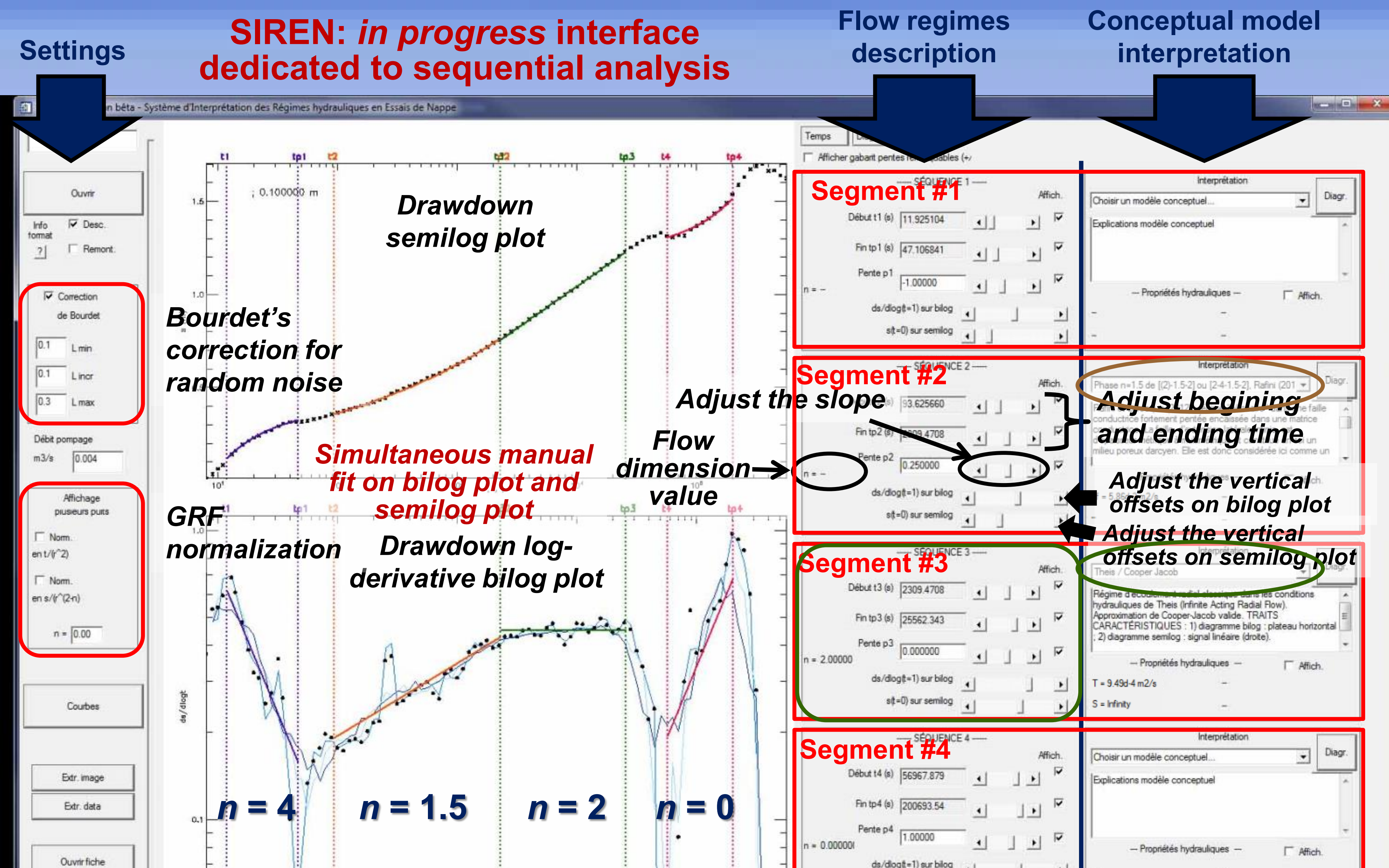
- Truncated sequences = partial diagnostic

Flow rate unstabilities



- Only qualitative diagnostic were presented in this talk
- Every conceptual model provides with sets of equations for the estimation of specific hydraulic parameters (oil & gas, hydrogeoloy)
- Integration of observation wells drawdowns series: higher complexity, spatial interpertation of the hydraulic objects
- Ongoing PhD - Daouda Meite

SIREN: *in progress* interface dedicated to sequential analysis



Interpretation: this aquifer is governed by a transmissive steep fault *Tf* = 5.86x10^{-3} m^2/s in the vicinity of the wellbore (not intercepted), embedded into a transmissive matrix *Tm* = 9.49x10^{-4}m^2/s

+

Late time: closed reservoir = impermeable barriers… (in all directions?)

Thank you

Provide pump test dataset for our compilation

silvain.rafini@gmail.com

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Natural Sciences and Engineering Research Council of Canada

Conseil de recherches en sciences naturelles et en génie du Canada

Fonds de recherche Nature et technologies

Québec