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

Session 8.03 - Geometrical structure and hydrogeological properties of Hard-Rock aquifers

Characterizing Complex Aquifers Using Flow Dimension Diagnostic Sequences

Silvain Rafini, Romain Chesnaux, Anouck Ferroud

CERM – Groupe R2Eau
Université du Québec à Chicoutimi, Québec, Canada

Fonds de recherche Nature et technologies Québec

CERM Centre d'études sur les ressources minérales

UQAC Université du Québec à Chicoutimi

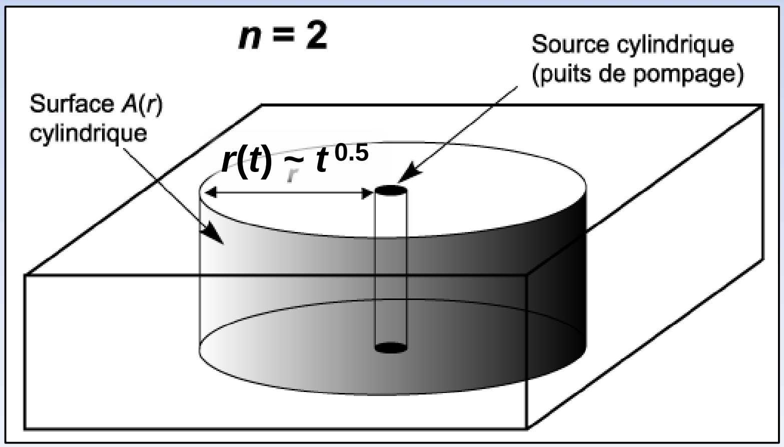
Definitions

Radial flow regime *is defined by the* ***transient growth of the cross-flow area A(r)***

Theis

Cylindrical
(homogeneous isotropic aquifer)

A*(*r*) ~ *r → Radial



Radial flow means *A*(*r*) ~ *r*

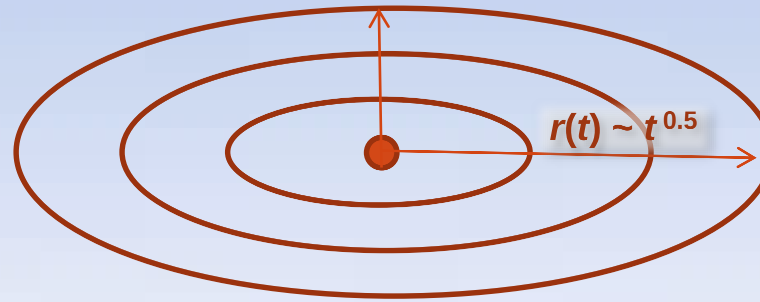
→Occurs in normal diffusion regime *r*(*t*) ~ *t* $^{0.5}$
(see Rafini and Larocque, 2009)

« Complex » aquifer means irregular, non-Theisian, heterogeneous, discontinuous etc.

Non-Theis

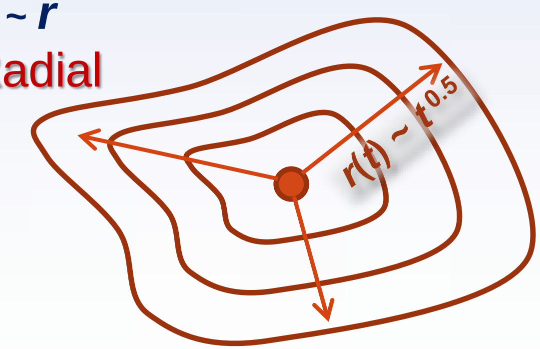
Elliptical
(homogeneous anisotropic aquifer)

A*(*r*) ~ *r → Radial



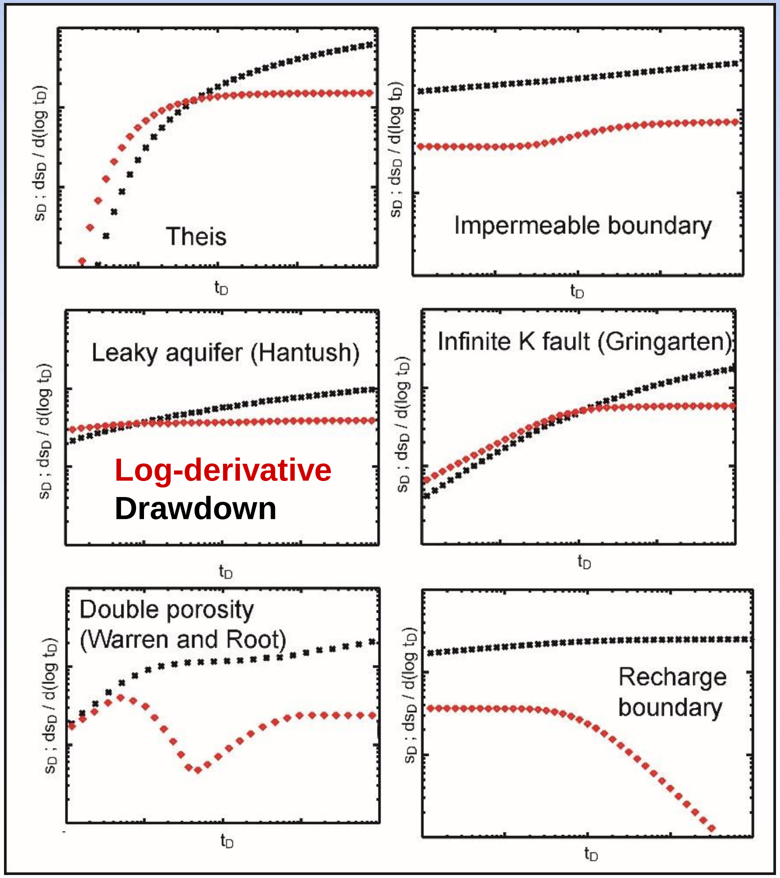
Any shape (heterogeneous aquifer)

A*(*r*) ~ *r
→ Radial



Background: diagnostic plots approach

- Developed by petroleum researchers to model **complex reservoirs behavior**
- Based on the ***log-derivative analysis***
- Fundamental publications: Chow (1952); Tiab and Kumar (1980); Bourdet et al. (1983); Mattar and Zaoral (1992)



Review papers: *Kruseman and* de Ridder *(1994); Verweij (1995); Bourdet (2002); Gringarten (2008); Renard (2009)*

Many other models: *Neuman's leaky aquifer, unconfined aquifer, partially penetrating well, large diameter well, wedge-shaped aquifers, finite-conductivity vertical fracture (dyke) etc.*

Two stages interpetation:

1. **Qualitative diagnostic**: selecting the adequat theoretical model based on the resemblance of real data with theoretical type-curves
2. **Quantitative diagnostic:** calculating the specific hydraulic properties using the equations of the selected model

- Very common in **petroleum works**
- **In hydrogeology: still resticted to theoretical works**, should be used in routine applications

➔ ***Questionable uniqueness of interpretations***

In many cases, several theoretical models may fit on a single real dataset…

Straight lines analysis: an alternative to the type-curves method

- Flow regimes form successive **straight segments** of the log-derivative signal

Tiab (1989, 1993 a, b, c, d) ***Society of Petroleum Engineers***

SPE International
Society of Petroleum Engineers

SPE 26138

Analysis of Pressure and Pressure Derivative without Type-Curve Matching - III. Vertically Fractured Wells in Closed Systems

Djebbar Tiab, U. of Oklahoma
SPE Member

Tiab (1995) ***Petroleum Science & Engineering***

ELSEVIER

Journal of Petroleum Science and Engineering 12 (1995) 171–181

PETROLEUM SCIENCE & ENGINEERING

Analysis of pressure and pressure derivative without type-curve matching — Skin and wellbore storage

Djebbar Tiab

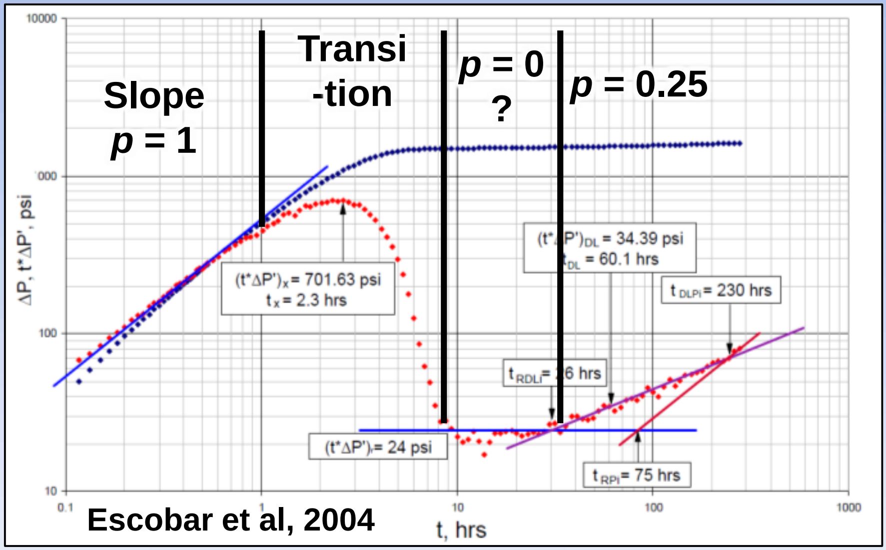
School of Petroleum and Geological Engineering, The University of Oklahoma, 100 East Boyd Street, T301 SEC, Norman, OK 73019-0628, USA

Mattar (1999) ***J. of Canadian Petroleum Technology***

JCPT

Derivative Analysis Without Type Curves

L. MATTAR
Fekete Associates Inc.



- More robust segmentation. Yet the recognition of a straight segment, and the distinction of a **settled flow regime** from a **transitional stage** between two flow regimes, **remains critical**

→ Practical guideline: slope p should be stable over at least one log-cycle (Beauheim and Walker, 1998), not consensual…

Other papers: Tiab (2005); Escobar et al (2004, 2007, 2010, 2012); Escobar and Montealegre (2007); Gringarten (2008)

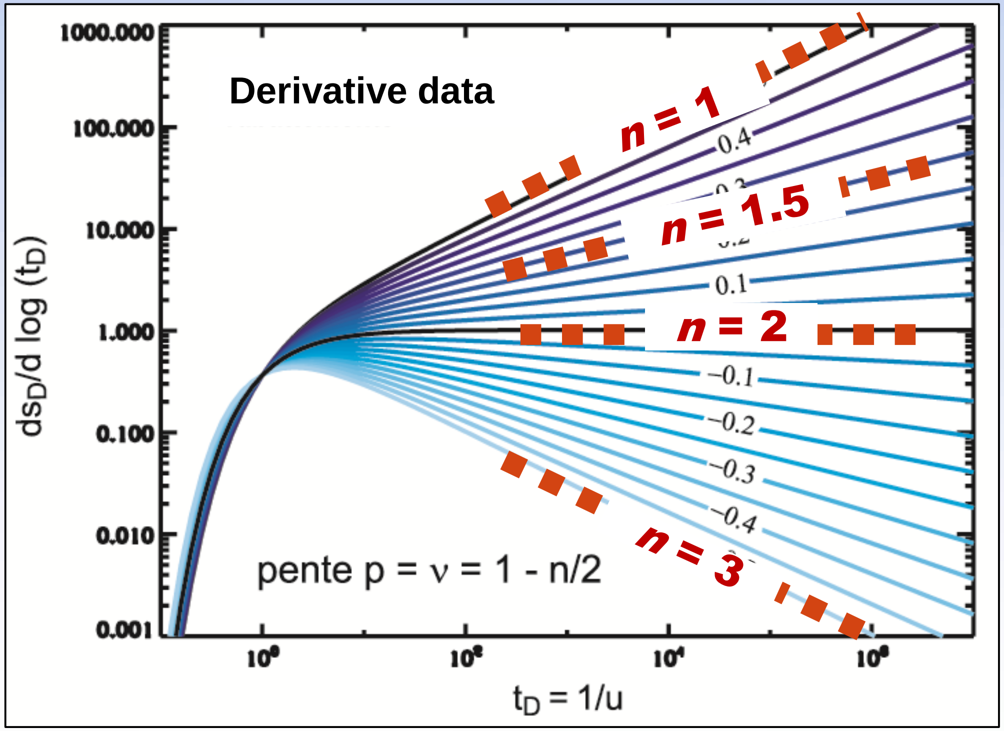
Flow dimension theory

Barker (1988):

stable log-derivative slope *p* = hydrodynamically settled flow regime

This flow regime is governed by the **fundamental relationship $A(r) \sim r^{n-1}$**

where $A(r)$ is the cross-flow area and n *is* the flow dimension



n is obtained by a **direct reading** of the log-derivative slope *p* :

$n = 2 - 2(p)$

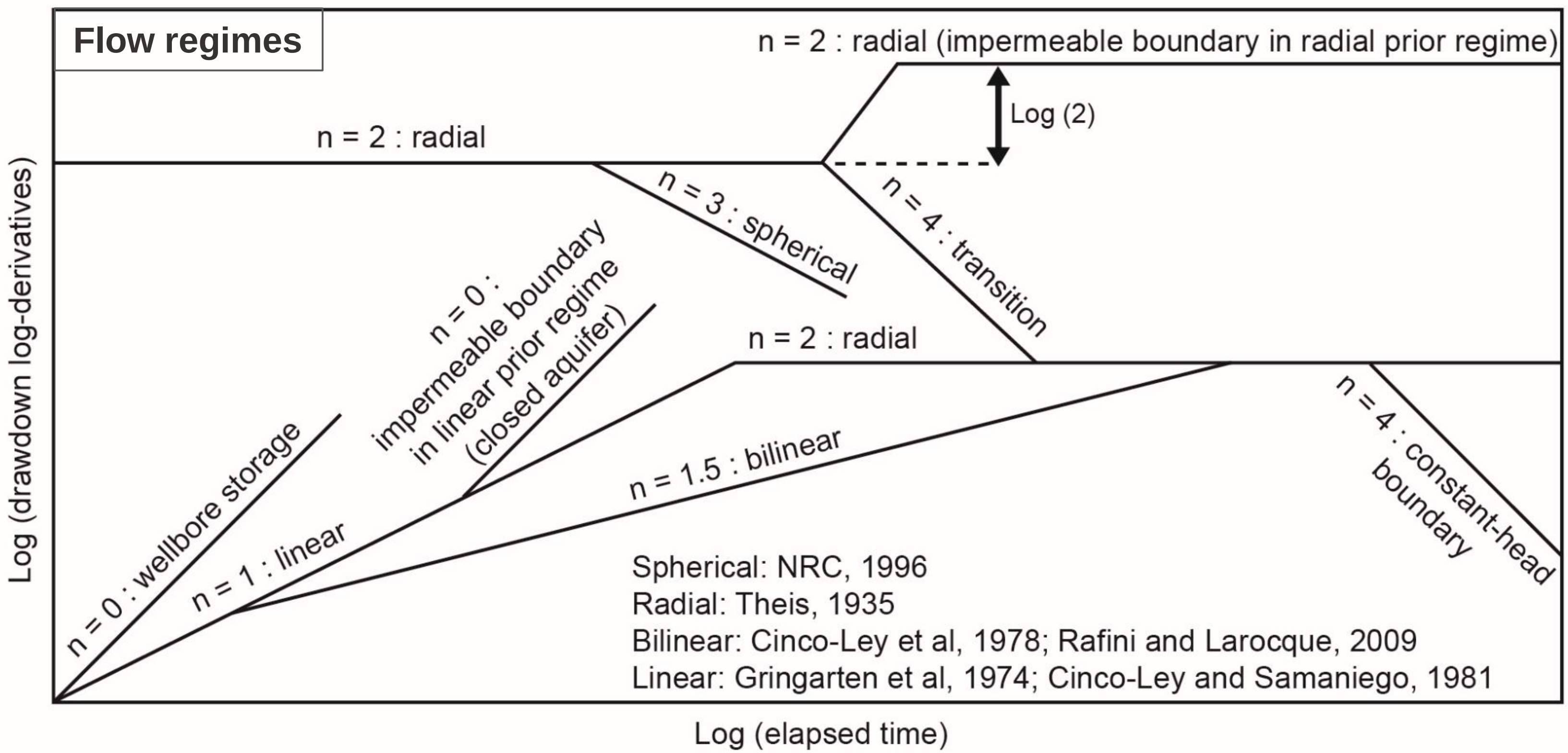
(for large u, i.e., *large t or small r → at the source, practically from pumping test's beginning)*

Flow regimes

Focus is on values of *n* we do understand

Radial n = 2

Non-radial n = 0, 1, 1.5, 3, 4

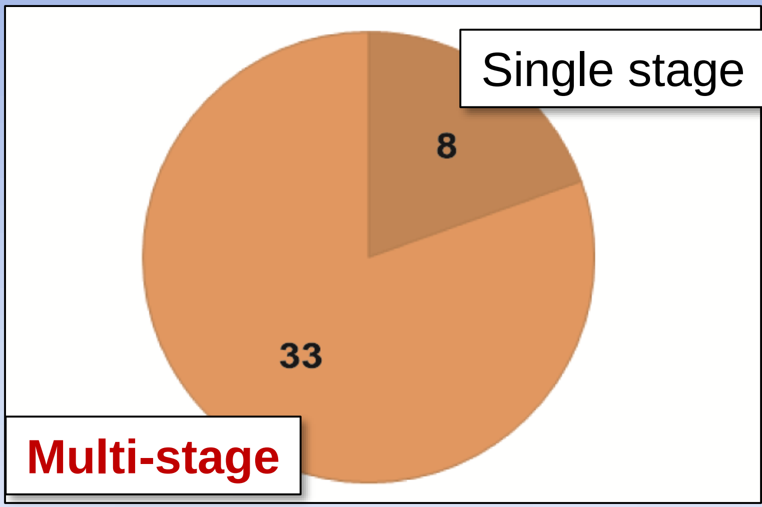


Rafini et al (in prep.)
modified from Ehlig-Economides et al (1994)

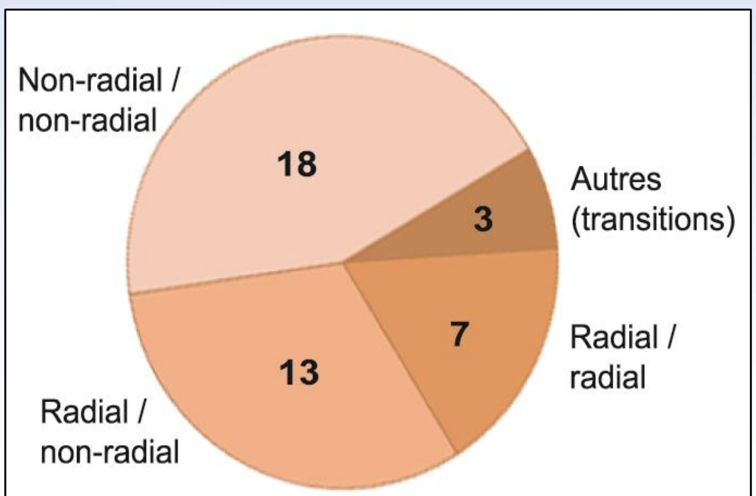
In the real world…

Database : region of Mirabel (Québec)
CGC-Québec (Nastev et al, 2004)

Out of 41 pumping test…



Rafini (2009)



- **The flow dimension time-variant** in 80 % of real aquifer responses to pump tests
- **Specific values** of *n* = *2*, *n* = 1, *n* = 1.5 and *n* = 3 are the **most frequently reported**

→Complex signatures combining elementary behaviours (linear, bilinear, radial, spherical)

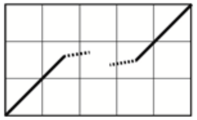
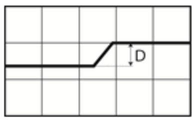
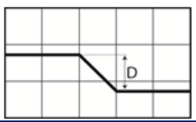
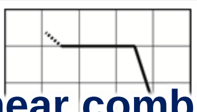
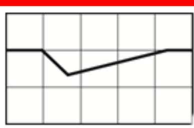
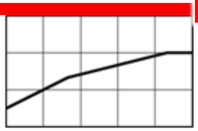
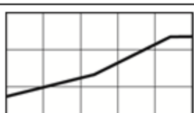
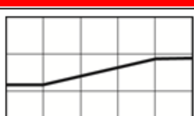
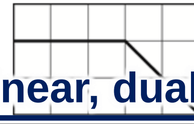
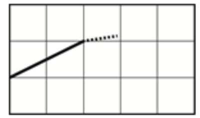
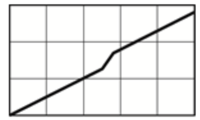
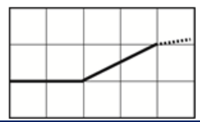
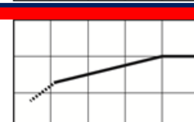
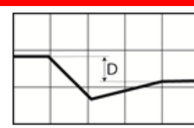
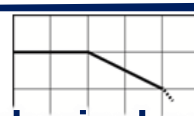
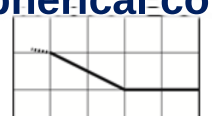
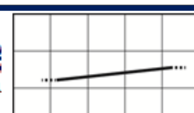
→ Non-trivial interpretation

These changes express changes in the hydrodynamic conditions as the front pulse propagates

1. Flow regimes **independently** relate to **successive hydraulic objects**
   → Segments are interpreted independently

2. …or reflect **transient interactions** between hydraulic objects with contrasting properties (K, Ss, topological dimension)
   → Combinations are meaningful

Review of flow dimension sequences associated to known conceptual models

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
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 – 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 ≠ 1.5		??? [19]

Linear, dual linear, radial + linear

Double-radial with positive or negative offset

Bilinear combinations

Following slides

Spherical combinations

Rafini et al (in prep.)

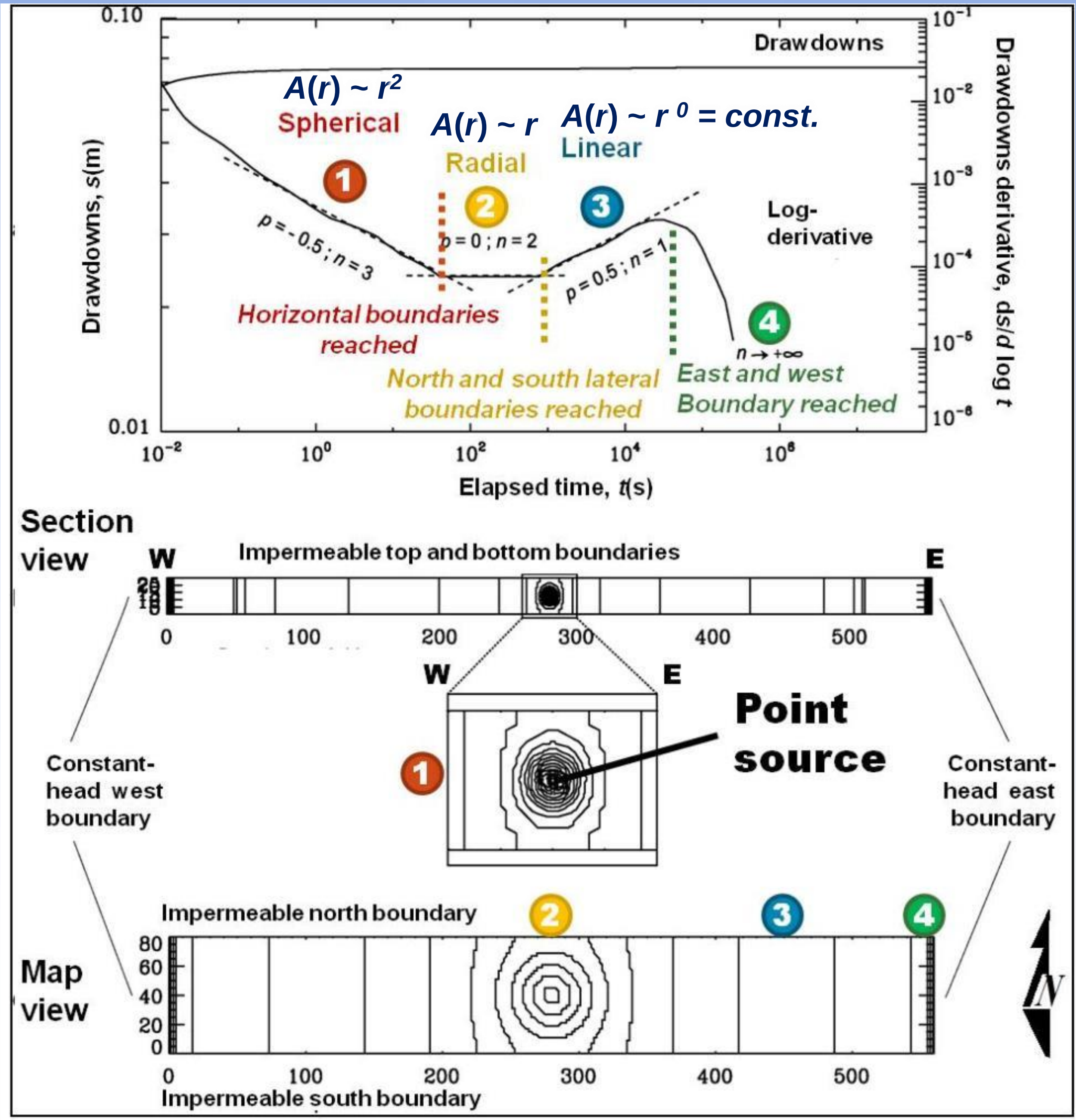
(1)Tiab, 2005;
(2) Linear no-flow frontier;
(3) Theis (1935), Cooper et Jacob (1949);
(4) Beauheim and Walker (1998);
(5) Cinco-Ley et al (1978)
(6) Gringarten et Ramey (1974, 1975);
(7) Massonat et al 1993;
(8) Miller (1962; Nutakki and Mattar 1982 ; Escobar et al, 2012; Escobar et al, 2007;
(9) Escobar 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).

Example 1: flow regimes **independently relating to successive hydraulic objects (boundaries)**

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)



3D numerical flow simulation performed with Hydrogeosphere (Therrien and Sudicky, 1996)

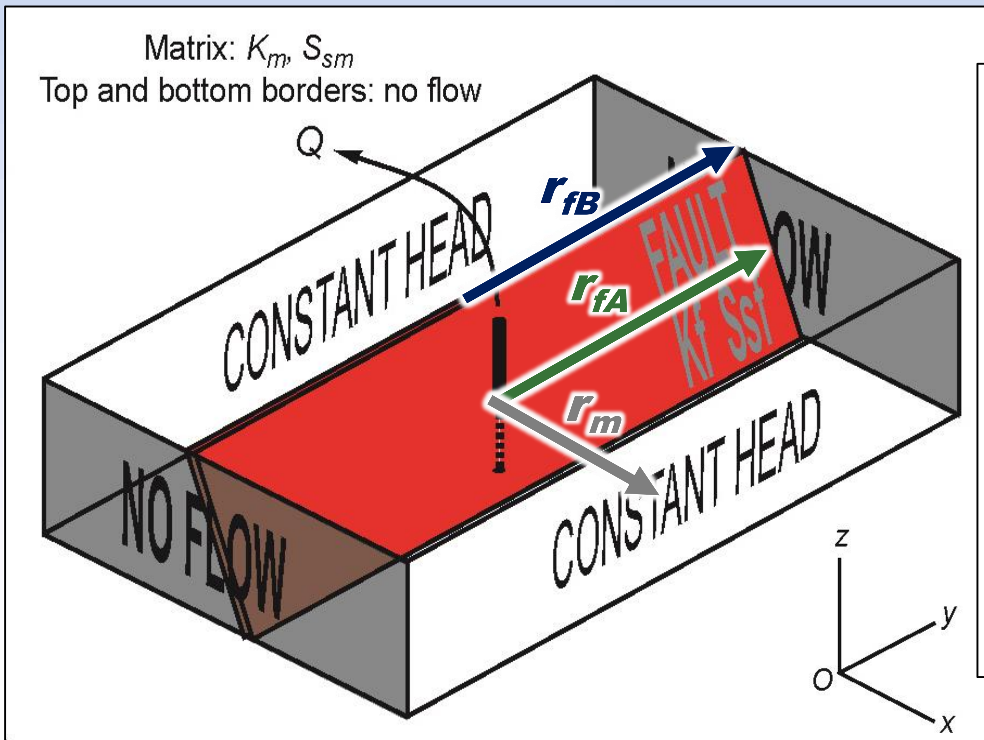
Example 2: flow regimes sequences reflecting **transient interactions between hydraulic** objects with contrasting properties (K, Ss, topological dimension)

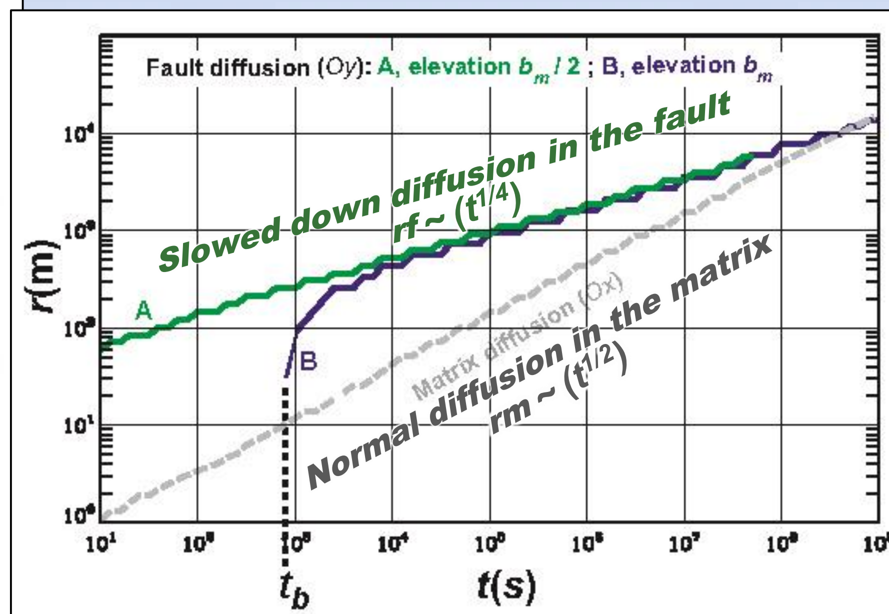
***n* = 1.5 is produced by a conductive fault into an aquifer** (Cinco-Ley et al, 1981; Rafini and Larocque, 2009); **fault**: tabular (2D), high K, low Ss; **matrix**: 3D, low K, high Ss

1.5 – (2) → the fault is **practically vertical**

2 – 1.5 – (2) → the fault is **inclined**

(2) – 4 – 1.5 – 2 → the fault is **not connected to the wellbore (not intercepted)**





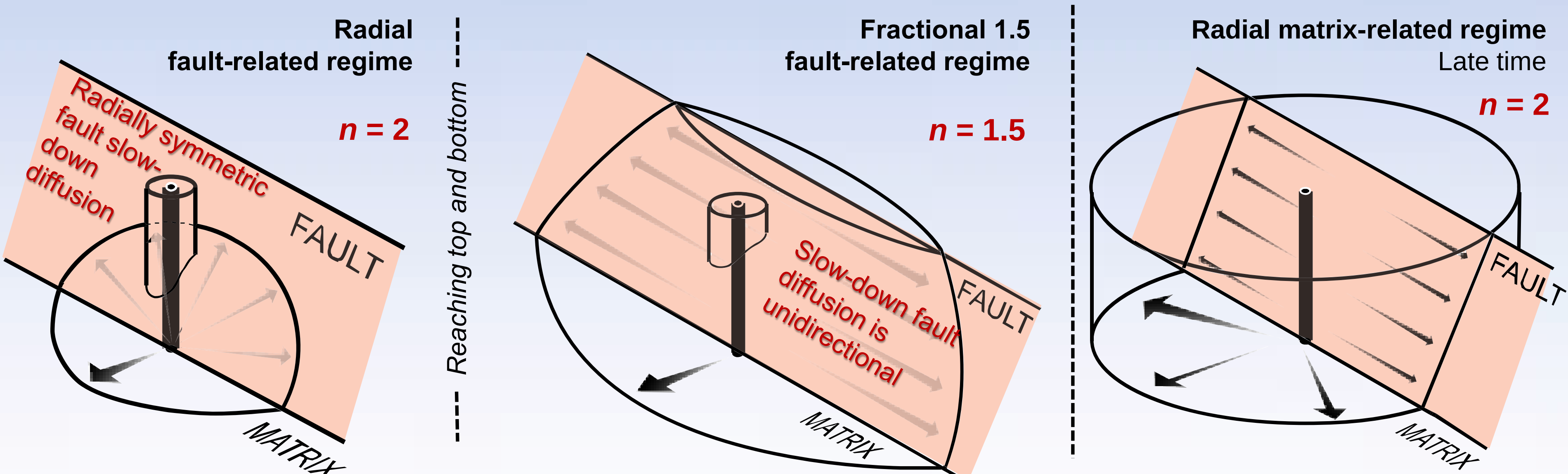
3D numerical simulation (Rafini and Larocque, 2009)

→ ***n* = 1.5: diffusion slow-down in the fault, due to water supply from the matrix**

Example 2: flow regimes sequences reflecting **transient interactions between hydraulic** objects with contrasting properties (K, Ss, topological dimension)

***n* = 1.5 is produced by a conductive fault into an aquifer** (Cinco-Ley et al, 1981; Rafini and Larocque, 2009); **fault**: tabular (2D), high K, low Ss; **matrix**: 3D, low K, high Ss

1.5 – (2) → **the fault is practically vertical**
2 – 1.5 – (2) → **the fault is inclined**
(2) – 4 – 1.5 – 2 → the fault is not connected to the wellbore (not intercepted)



Rafini and Larocque (2012)

- **Radially symmetric** slow-down diffusion in the fault DOES NOT generate fractional 1.5 flow but a **radial fault-related flow**
- **Unidirectional** slow-down diffusion in the fault DOES generate **fractional 1.5 fault-related flow**

→ **Only faults with significant <u>inclination</u> are prone to produce an early radial fault-related regime**

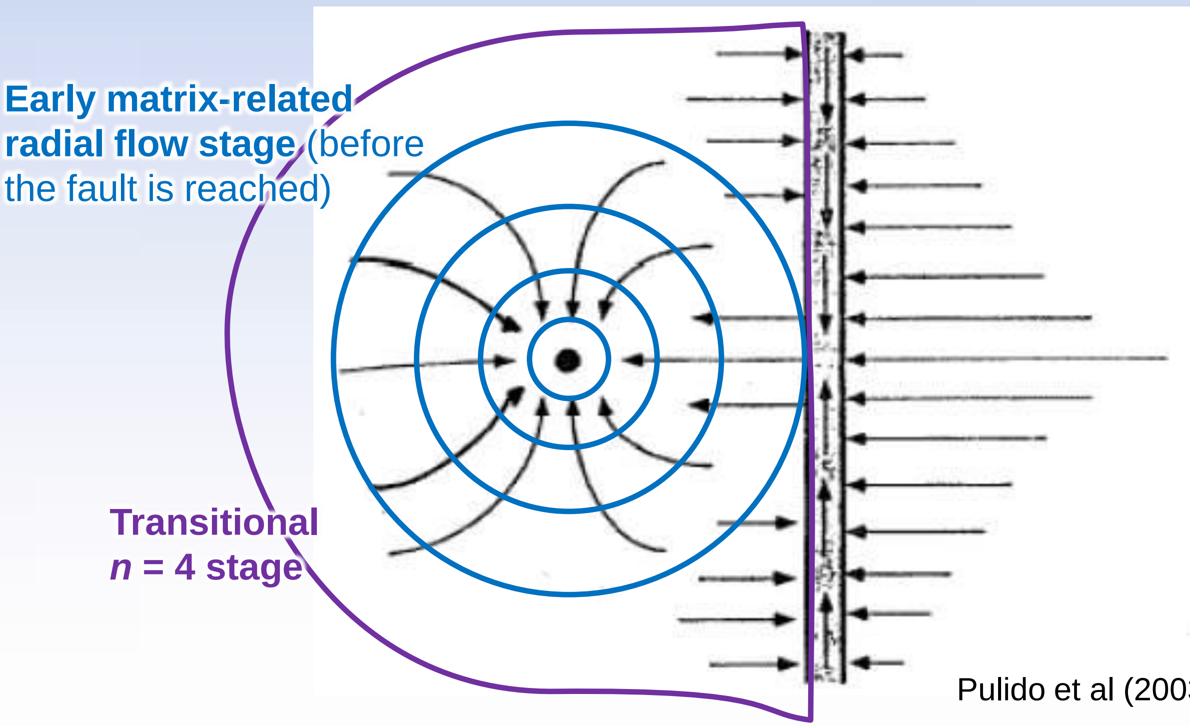
Example 2: flow regimes sequences reflecting **transient interactions between hydraulic** objects with contrasting properties (K, Ss, topological dimension)

***n* = 1.5 is produced by a conductive fault into an aquifer** (Cinco-Ley et al, 1981; Rafini and Larocque, 2009); **fault**: tabular (2D), high K, low Ss; **matrix**: 3D, low K, high Ss

1.5 – (2) → the fault is practically vertical

2 – 1.5 – (2) → the fault is inclined

(2) – 4 – 1.5 – 2 → the fault is not connected to the wellbore (not intercepted)



Pulido et al (2003)

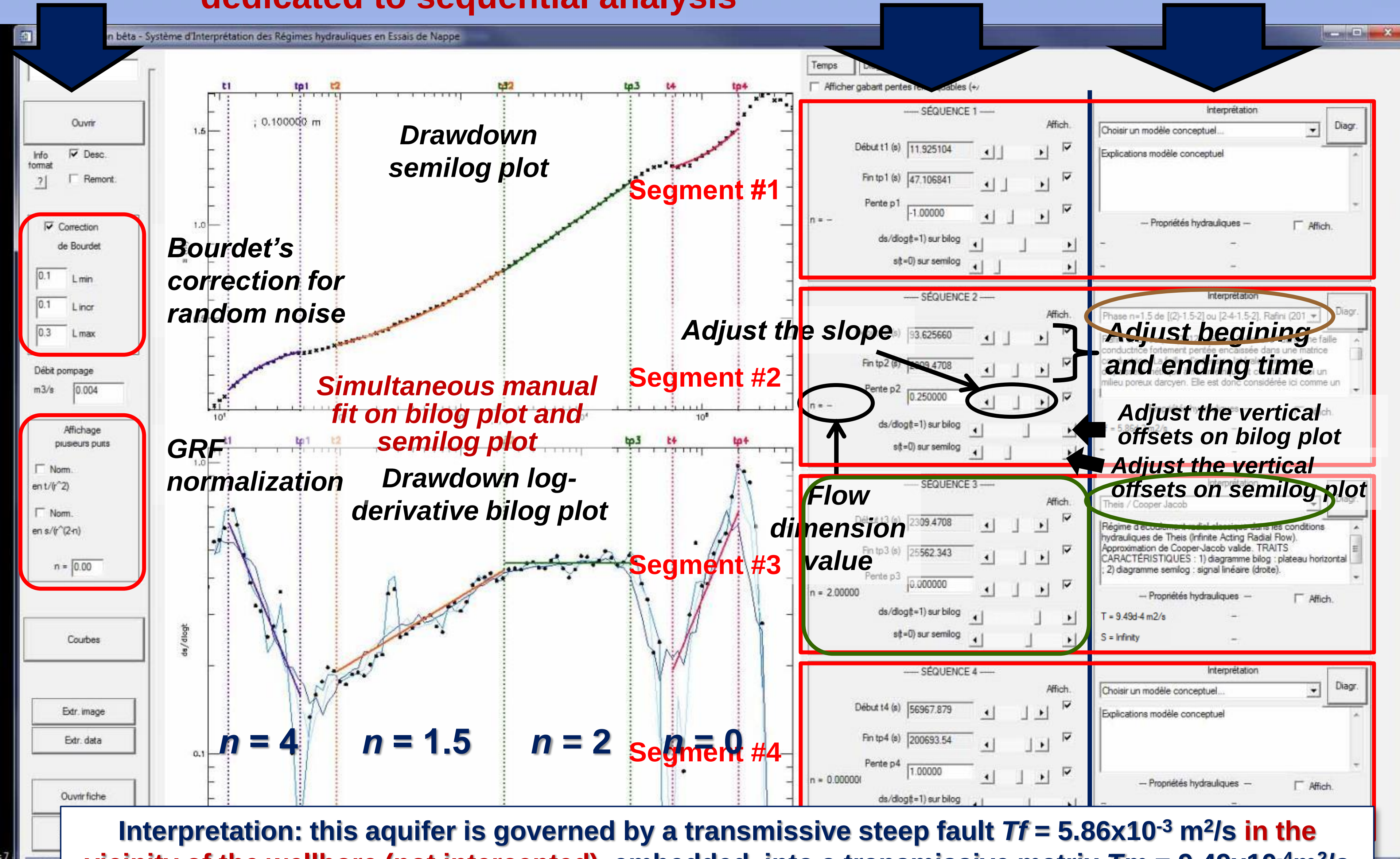
Theoretical model of a not-connected vertical finite-conductivity fault: Abbaszadeh and Cinco-Ley (1995); Rafini and Larocque (2009)

SIREN: *in progress* interface dedicated to sequential analysis

Settings

Flow regimes description

Conceptual model interpretation



Interpretation: this aquifer is governed by a transmissive steep fault $T_f = 5.86 \times 10^{-3}$ m²/s in the vicinity of the wellbore (not intercepted), embedded into a transmissive matrix $T_m = 9.49 \times 10^{-4}$ m²/s

+

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

Thank you

Financial support partners

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