2014 IAH-CNC Annual Meeting – GSA Conference
VANCOUVER, BC

A numerical analysis to illustrate the usefulness of drawdown log-derivative diagnostic plots in characterizing the heterogeneity of non-Theis aquifers

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Presentation summary

- **Definitions**
  - Theis vs non-Theis aquifer
  - Radial vs non-radial behaviour
  - Diagnostic plots
  - Barker’s GRF theory
  - Multistage responses

- **Experimental numerical modeling**
  - Faulted aquifers (with various fault dip)
  - Variable-thickness aquifers

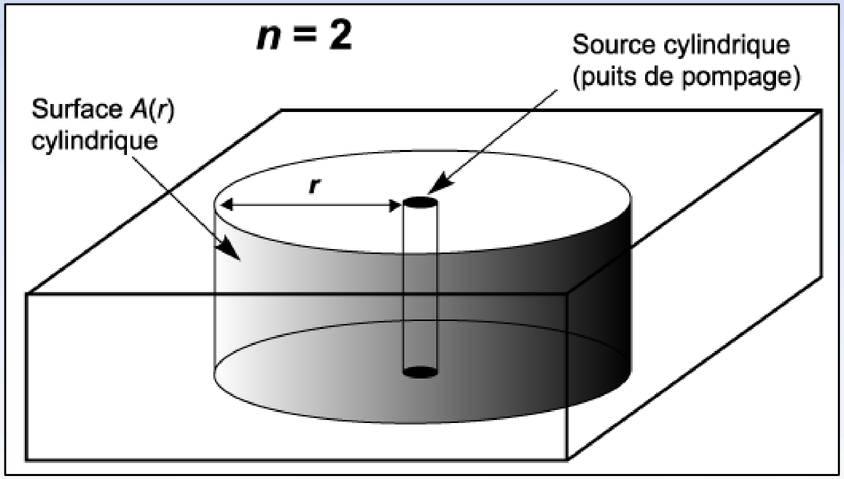
- **Conclusions**

Theis vs non-Theis aquifer

*Defined by the **shape of the cross-flow surface A***

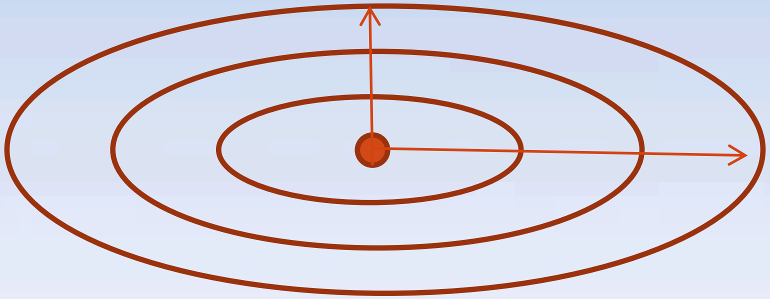
Theis

Cylindrical
(homogeneous isotropic aquifer)

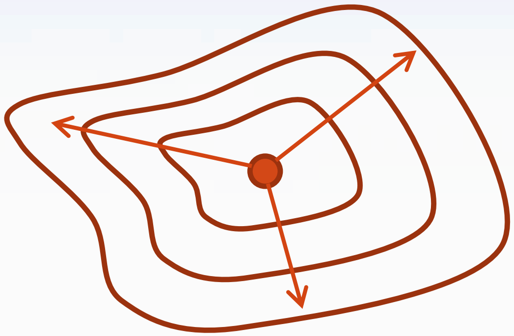


Non-Theis

Elliptical
(homogeneous anisotropic aquifer)



Any shape (heterogeneous aquifer)



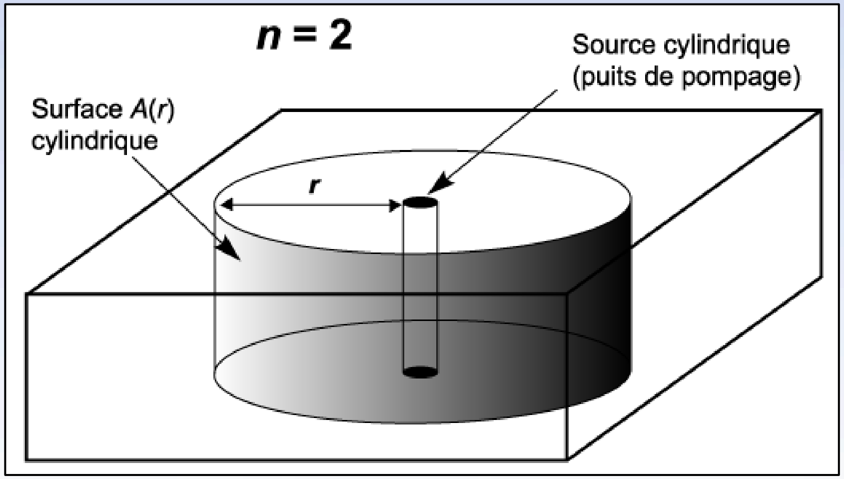
Radial vs non-radial flow regime

Defined by the ***transient growth of the cross-flow area A(r)***
where $r(t)$ is the travelled distance from the source at elapsed time t

Theis

Cylindrical
(homogeneous isotropic aquifer)

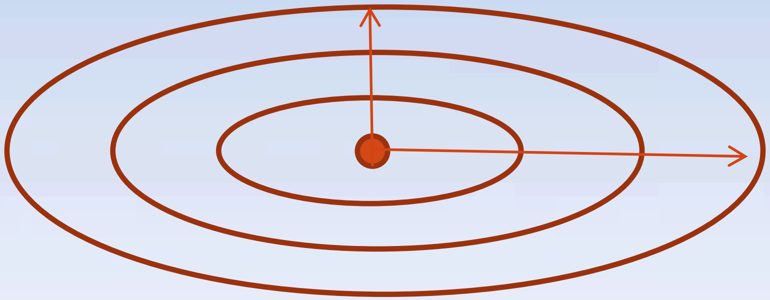
$\boldsymbol{A(r) \sim r}$ → Radial



Non-Theis

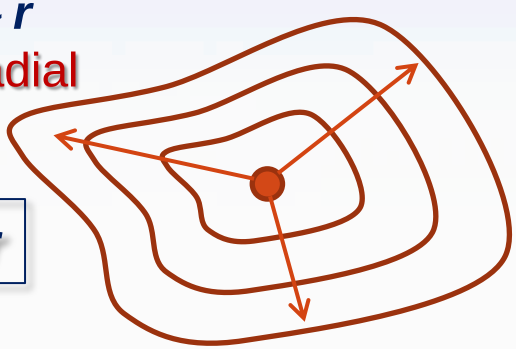
Elliptical
(homogeneous anisotropic aquifer)

$\boldsymbol{A(r) \sim r}$ → Radial



Any shape (heterogeneous aquifer)

$\boldsymbol{A(r) \sim r}$
→ Radial



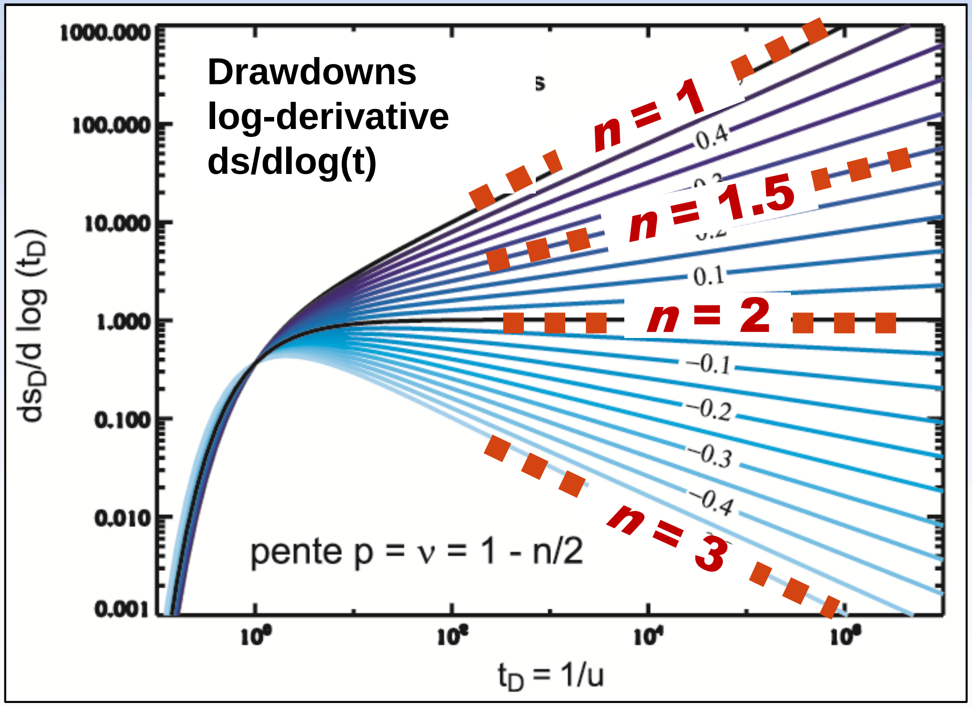
Definition of the radial flow regime : $A(r) \sim r$

Non-radial flow regime

Barker's GRF theory (1988)

- Radial flow regime : ***A*(*r*) ~ *r***
- Generalized Radial Flow (GRF) regimes **: *A*(*r*) ~ r^{n-1}**

where *n* is the **flow dimension**, a **new** – non intrinsic – hydraulic parameter



(for large *u*, i.e., large *t* or small *r* → at the source, from very short *t*))

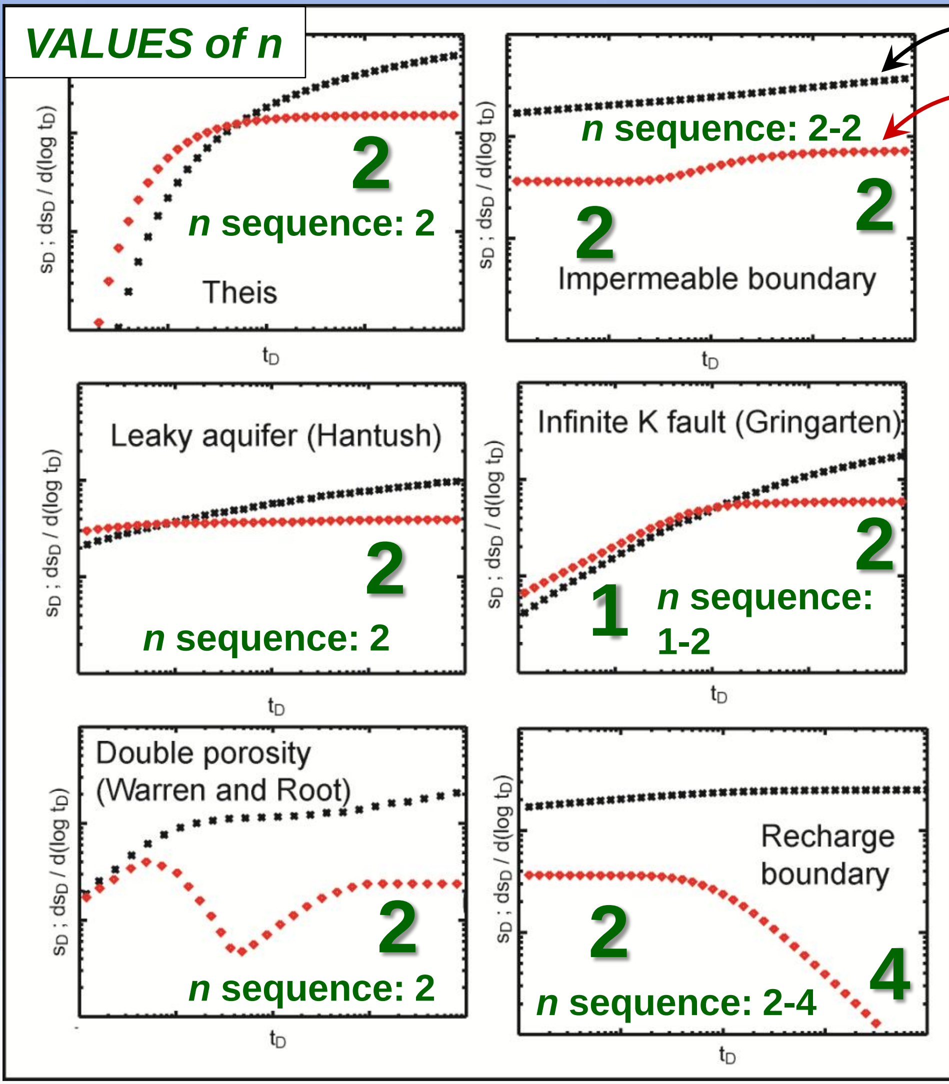
Direct reading : *n* = 2 - 2 *p*
p : slope

***n* = 2 :** radial flow regime (plateau)

***n* ≠ 2 :** non-radial flow regime

- ***n* = 1 :** linear
- ***n* = 3 :** spherical
- ***n non-integer* :** fractional
  - ***n* = 1.5 :** bilinear

Log-derivative diagnostic plots



Adimensional drawdown

Adimensional drawdown log-derivative ***ds/dlog(t)***

Choosing the adequate conceptual model prior to quantitative estimation of hydraulic properties using drawdown log-derivative curves

Diagnostic plots are **commonly used in the petroleum industry** for 3 decades, but still scarcely used in the hydrogeology field

Most classical interpretative models are *radial* (n=2) → poorly univoque

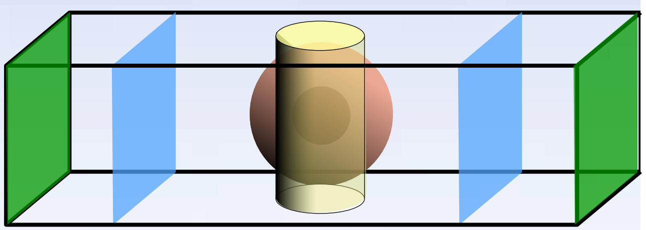
Only univoqueness is provided by their *multistage* character

Multistage reponses

Multistage response :
composed of a sequence of ***n*** marking **successive flow regimes** as the frontal cross-flow surfaces ***A*(*r*)** propagates into the aquifer (front pulse)

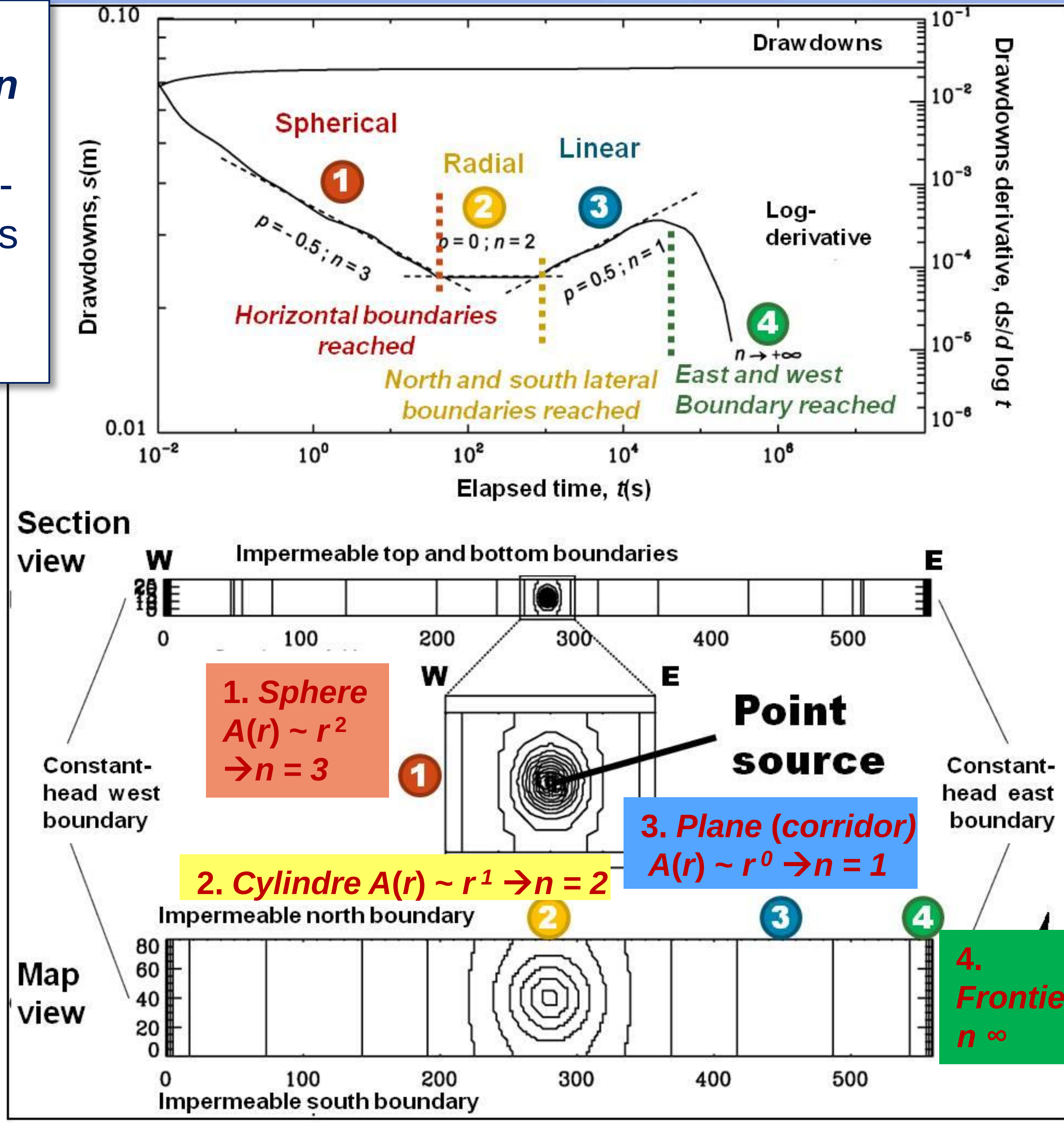
$$A(r) \sim r^{(n-1)}$$

Example from a numerical simulation of a pumping test from a point source
(homogeneous isotropic medium)



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

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

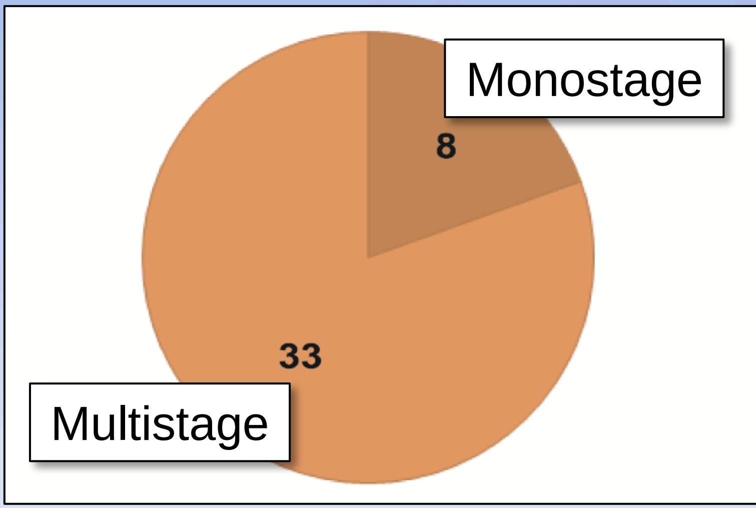


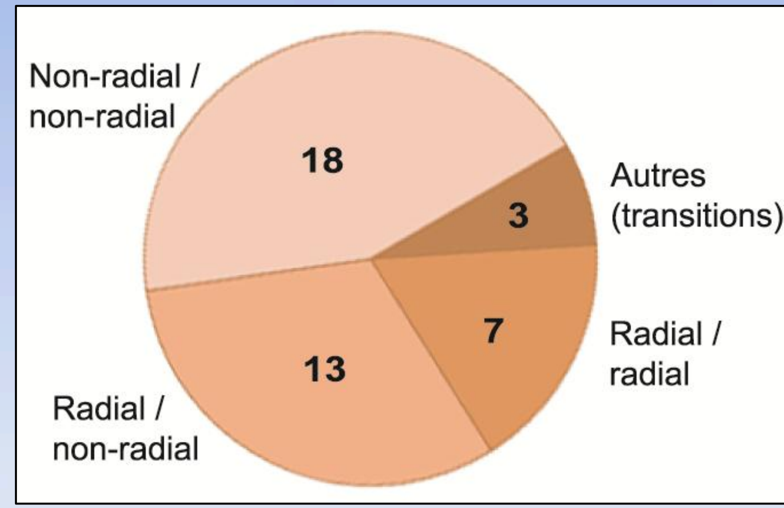
3D numerical flow simulation performed with Hydrogeosphere (Therrien and Sudicky, 1996)

Occurrence of non-radial and multistage responses in nature

Pumping test database from GSC-Québec (Nastev et al, 2004) in the region of Mirabel, Qc

Out of 41 pumping tests…

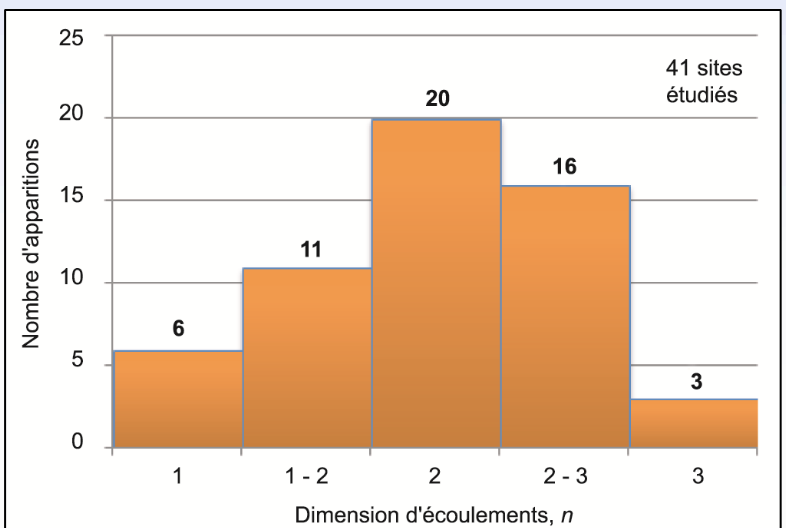




➢ **Multistage responses** are largely dominant (radial/non-radial, non-radial/non-radial) **: 80 %**

➢ **Non-radial responses occur in 83 % (34/41)**

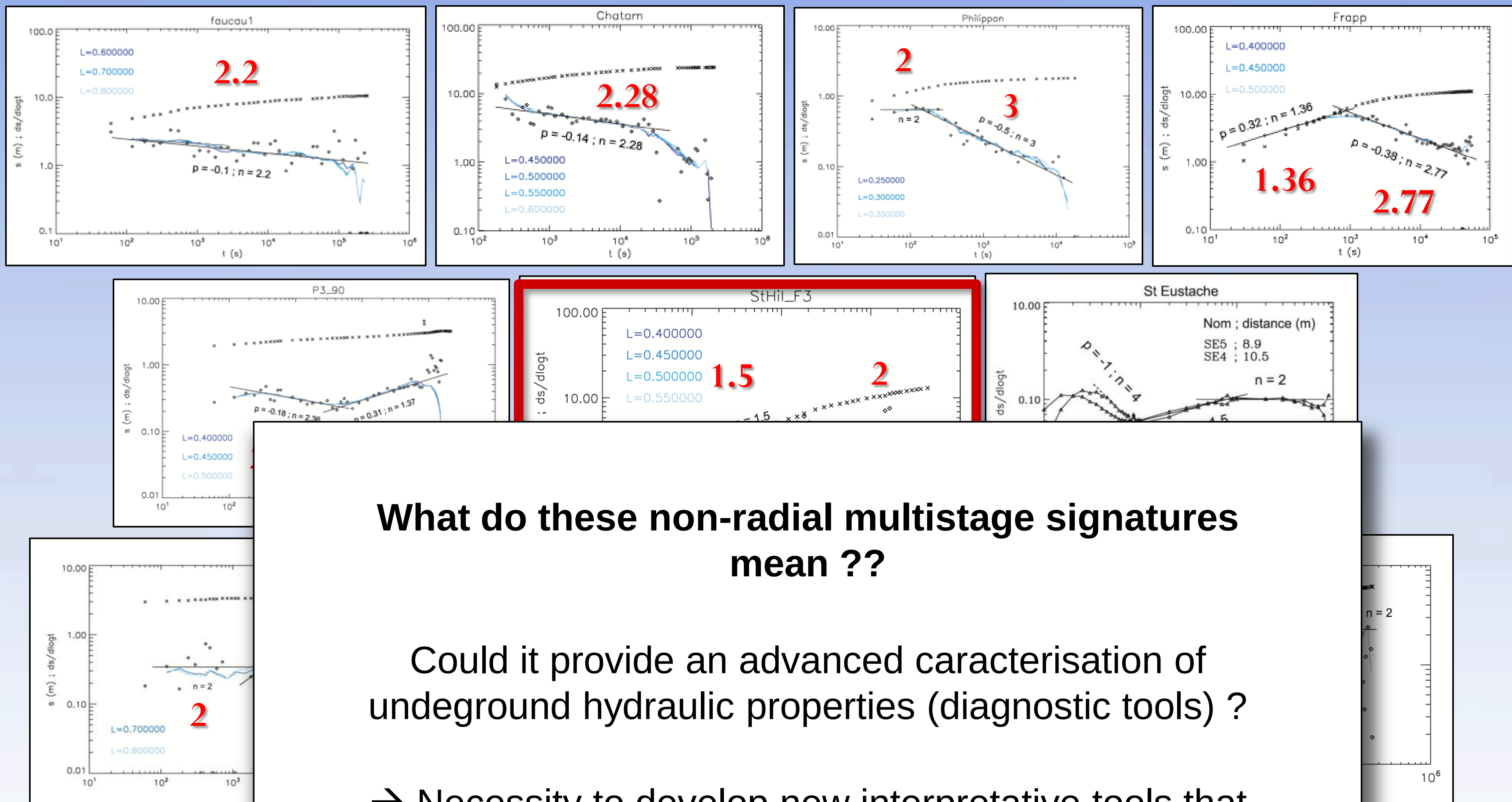
Less than 17% of cases (7/41) actually validate Theis postulates



➢ **Specific values** of $n = 2$, $n = 1$, $n = 1.5$ and $n = 3$ are **more frequent** than *any* values

See Rafini (2009) for details

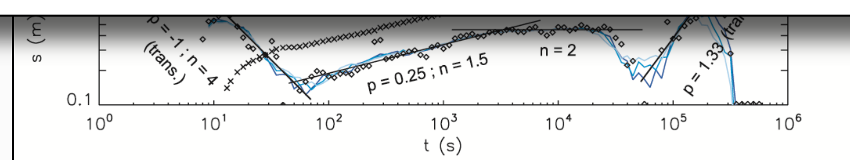
Occurrence of non-radial and multistage responses in nature



What do these non-radial multistage signatures mean ??

Could it provide an advanced caracterisation of undeground hydraulic properties (diagnostic tools) ?

→ Necessity to develop new interpretative tools that can handle the complexity of real signatures



...el, Qc
...Québec
(Nastev et al, 2004)

Numerical flow modelling into idealized systems

Experimental approach in the aim of

- Constraining the hydraulic conditions in which non-radial and multistage responses occur
- Develloping advanced diagnostic tools for pumping test interpretation

Configurations presented

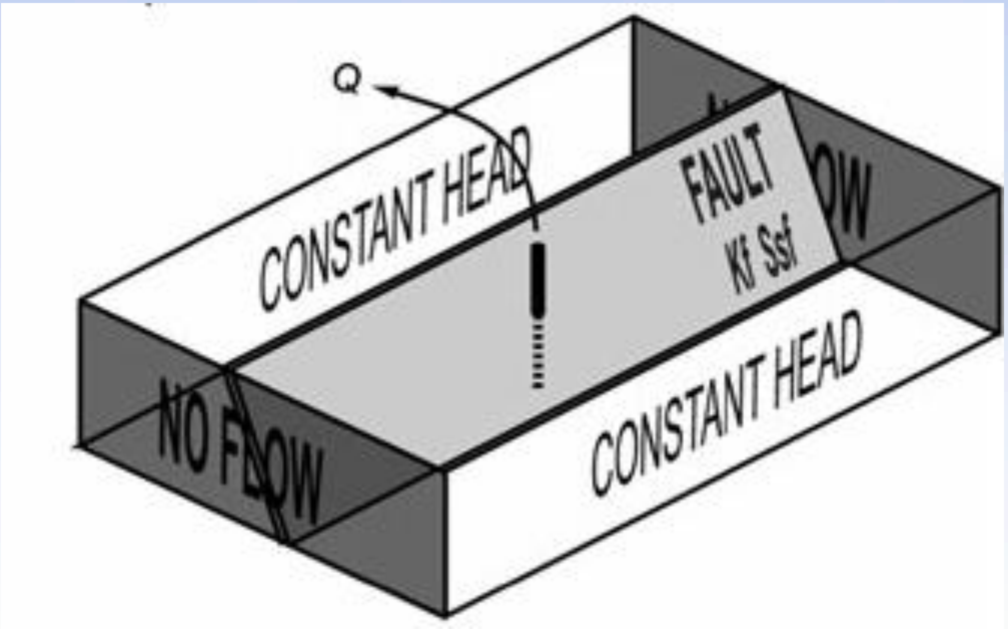
- Faulted aquifers (with various fault dip)
- Variable-thickness aquifers

Finite element codes : Geo-Slope and Hydrogeosphere

Faulted aquifer

Hydrogeosphere 3D flow modelling

Determining the **transient hydrodynamic interactions** between a non-impermeable matrix and a fault of any attitude, during a pumping test



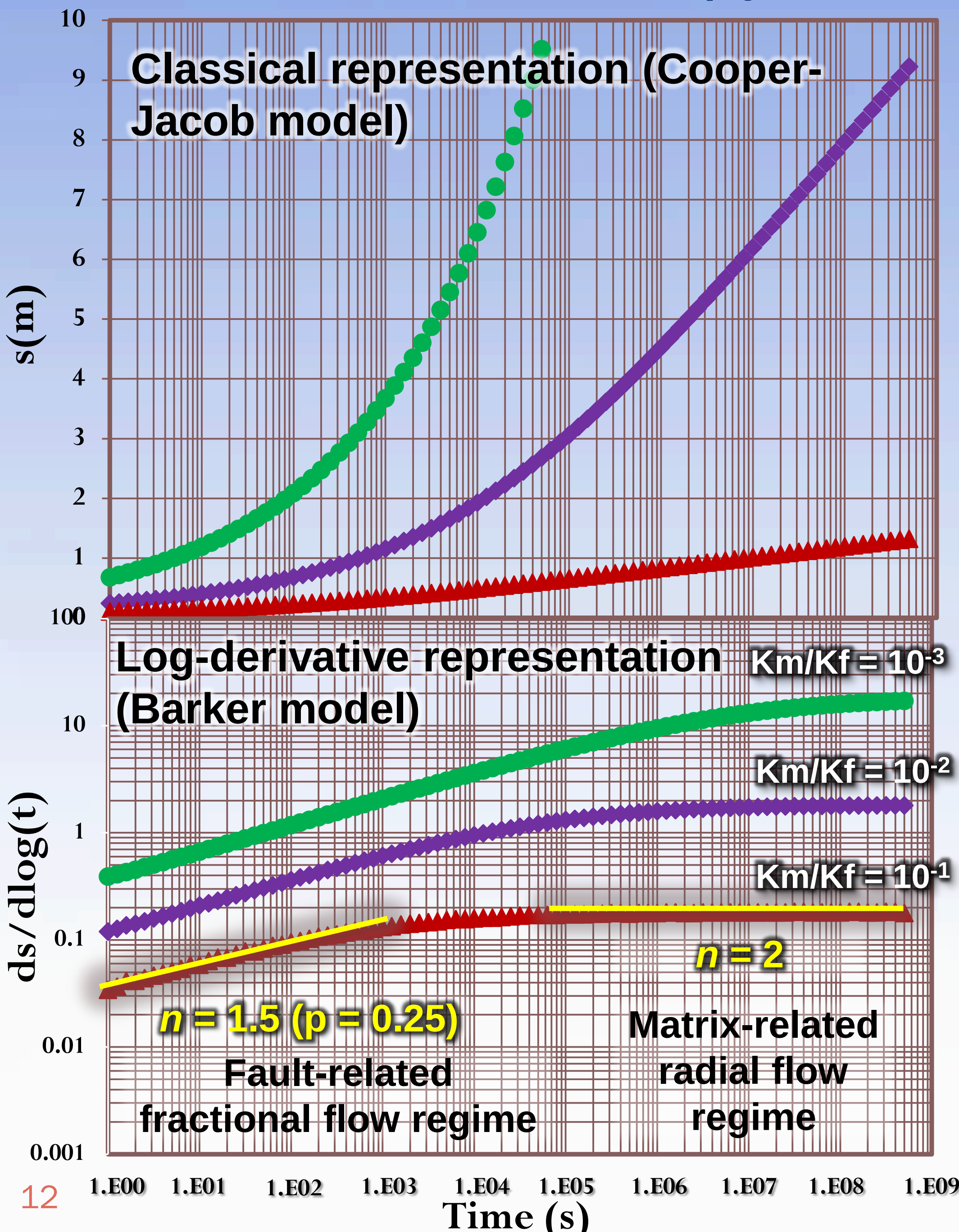
Rafini et Larocque (2012)

Steeply faulted aquifer

Matrix: K_m ; S_{sm}
Fault: K_f ; S_{sf}

Top and bottom borders : no flow

Steeply faulted aquifer



Serial simulations with variable matrix conductivity and storativity

Early fractional flow regime

The aquifer response is governed by fault and matrix transient hydraulic interactions

Slope $p = 0.25$ → $\boldsymbol{n = 2 - 2p = 1.5}$

→ *Estimation of the fault transmissivity*

Late matrix-related radial flow regime

Cylindrical Theis-like conditions, the aquifer response is not governed by the fault properties anymore

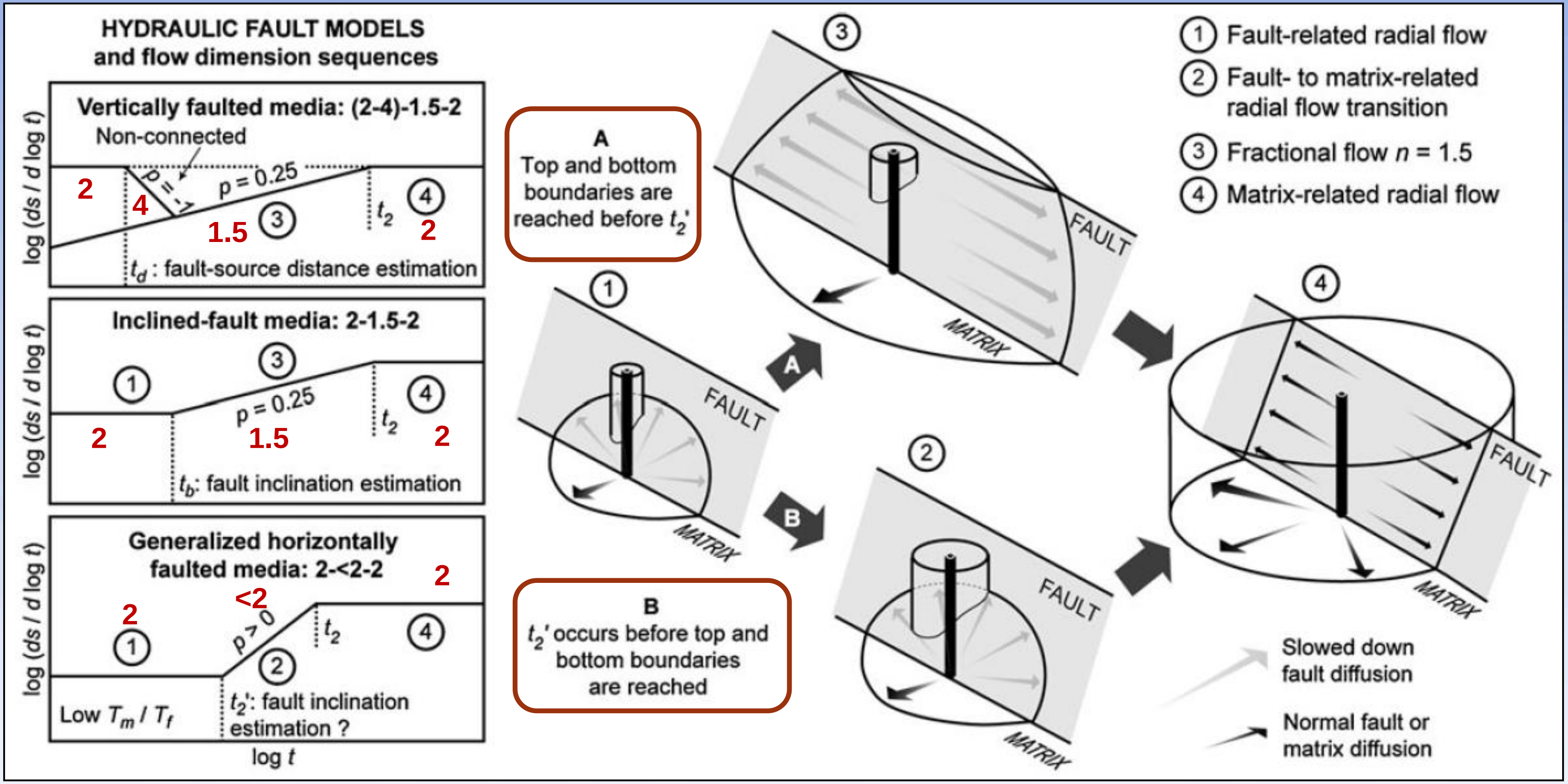
→ *Estimation of the matrix transmissivity*

Log-derivative plot allows

- A confident diagnostic of the presence of a conductive fault : caracteristic flow dimension sequence 1.5 – 2
- Estimating **distinctly** the fault and the matrix hydraulic properties (K, S) rather than bulk aquifer properties

→ **Much more accurate knowledge of the aquifer behaviour**

Several flow dimension sequences in faulted aquifers

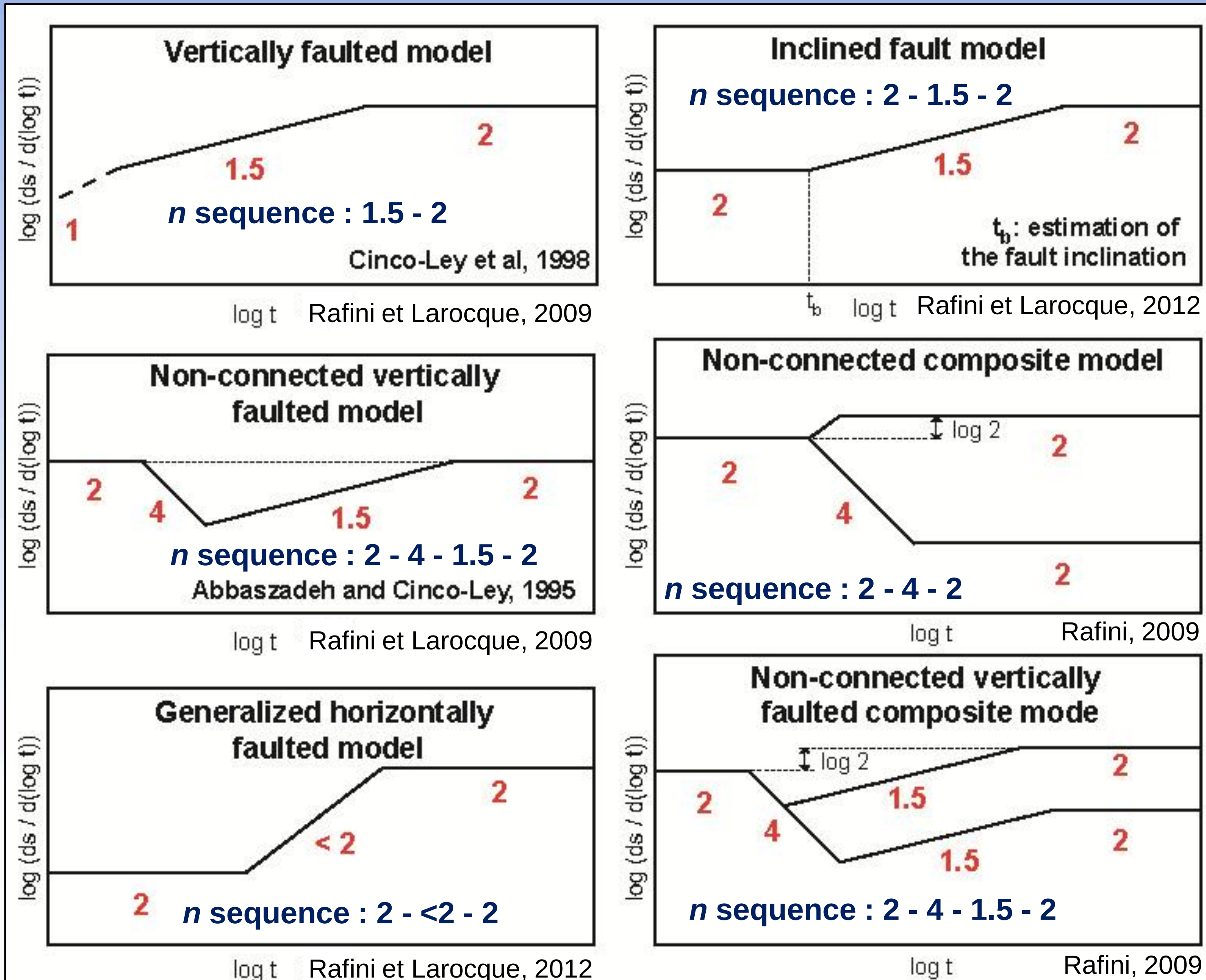


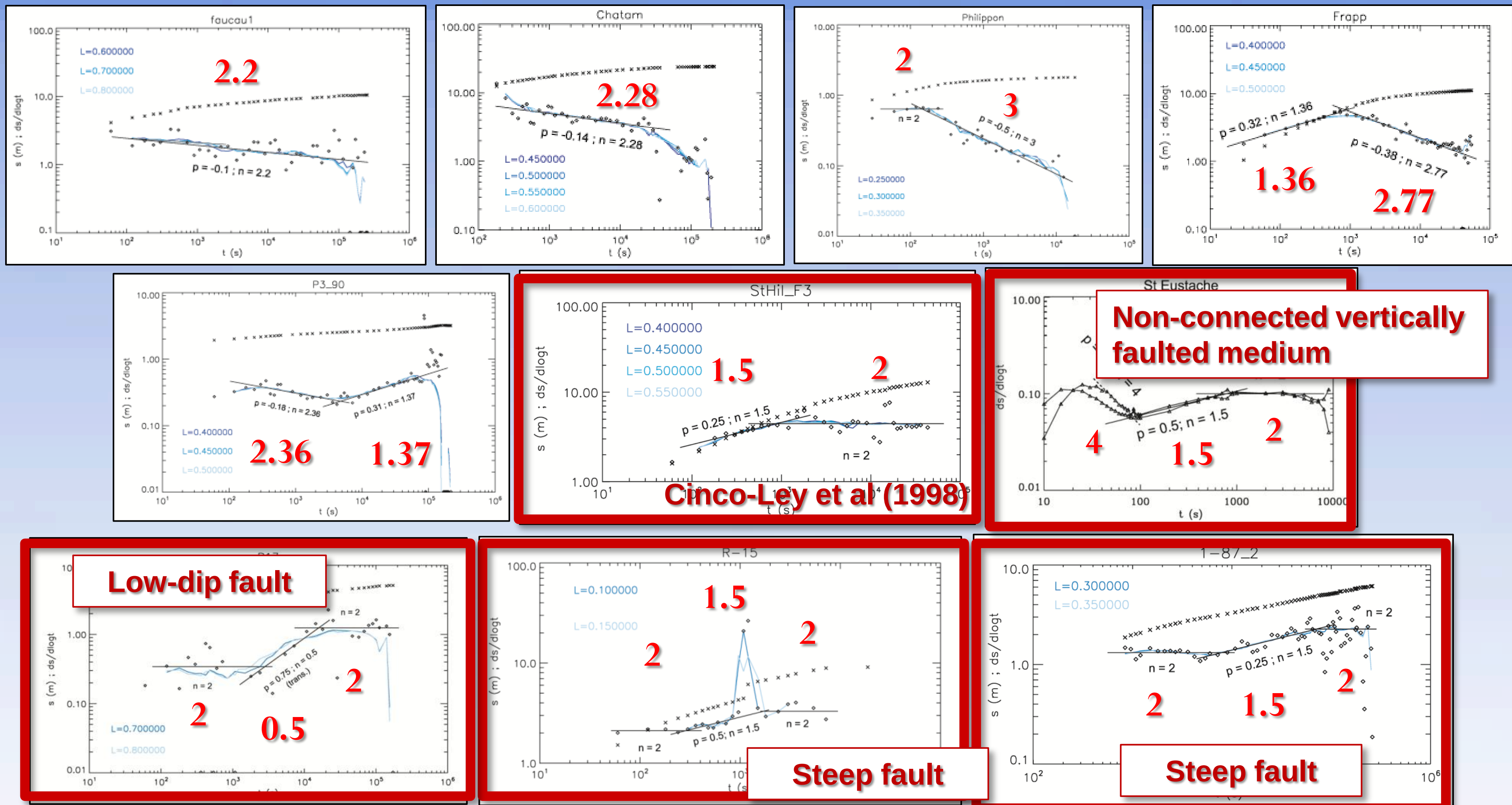
Rafini et Larocque, 2012

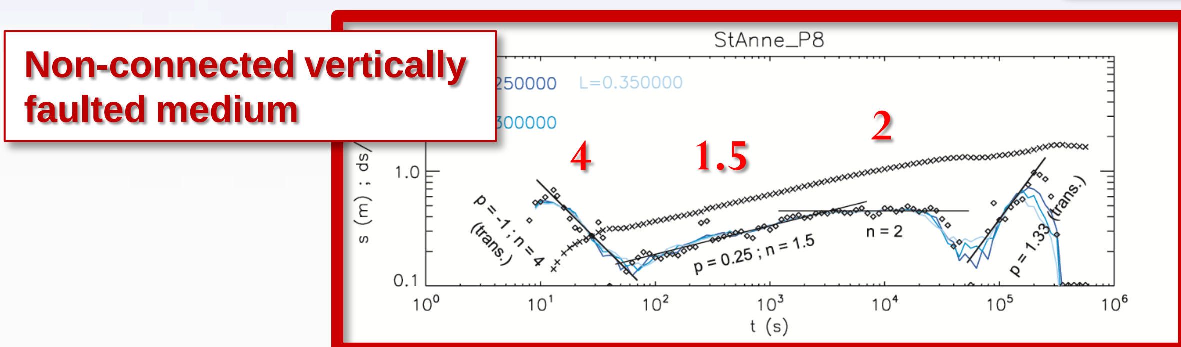
Each flow dimension time period corresponds to a specific flow regime as the front pulse propagates into the fault-matrix system

These *n* sequences are strictly controlled by fault and matrix geometrical and hydraulic properties → **diagnostic tool**

Multistage diagnostic plots for faulted aquifers



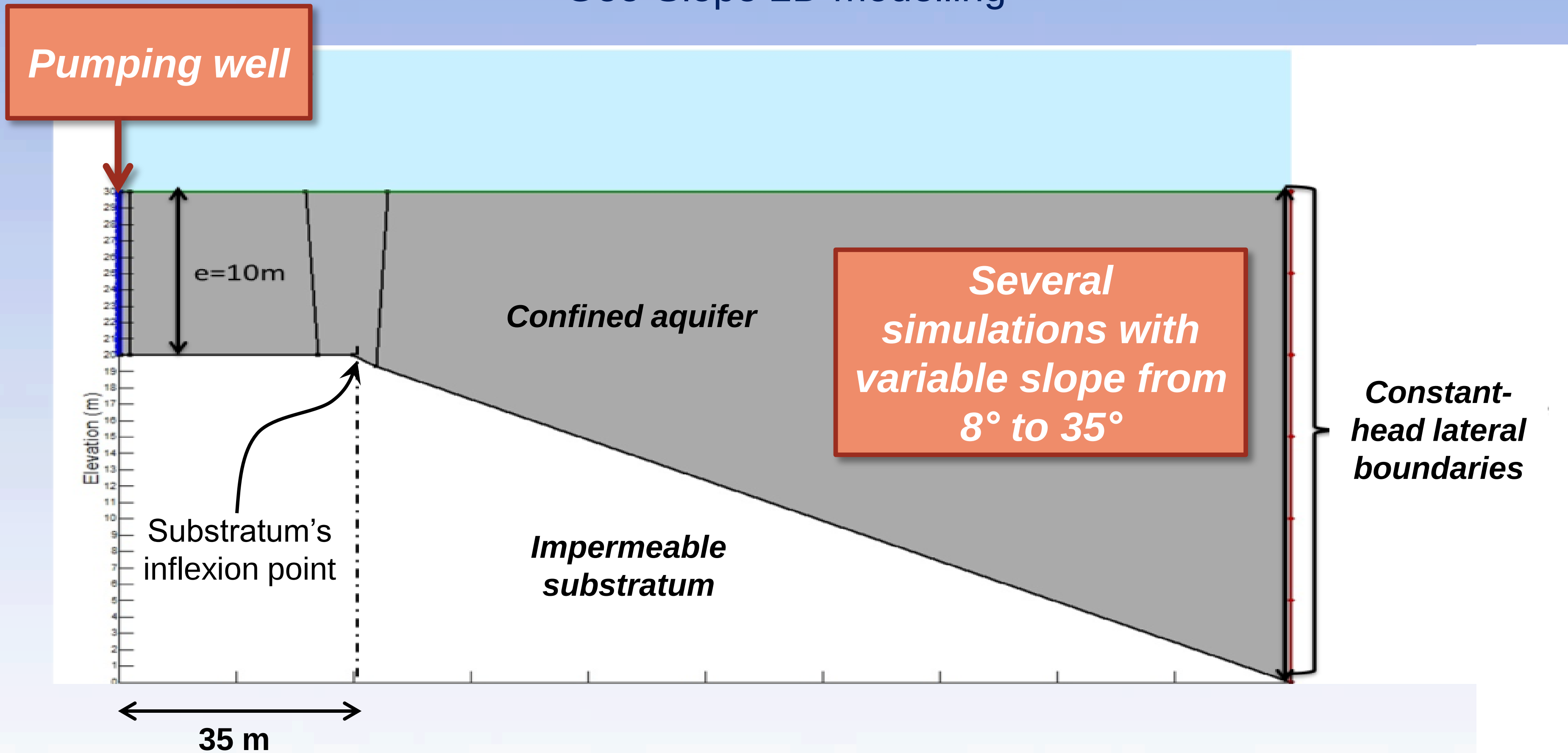




Region of Mirabel, Qc
Data from CGC-Québec
(Nastev et al, 2004)

Variable thickness aquifer

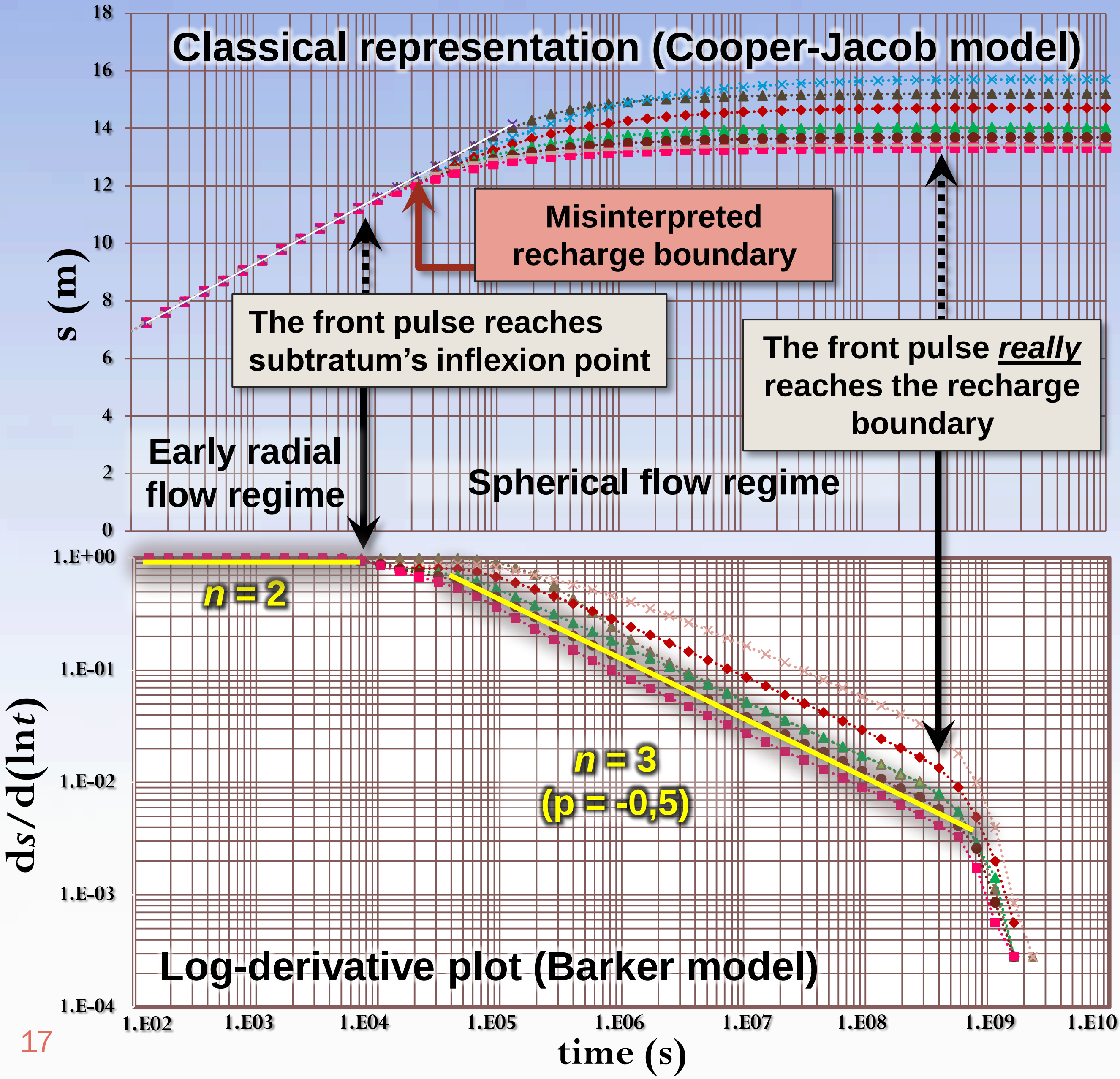
Geo-Slope 2D modelling



$K = 5.10^{-5}$ m/s
$Ss = 1,6.10^{-3}$ m^{-1}
$Q = 6,28.10^{-3}$ $m^3.s^{-1}$

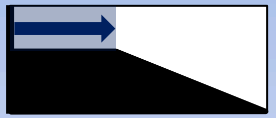
Variable thickness aquifer

Serial simulations with variable substratum inclination from 5° to 39 °



Early radial flow regime

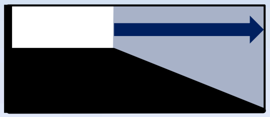
Theis-like regime before the front pulse reaches the substratum's inflexion point



Spherical flow regime

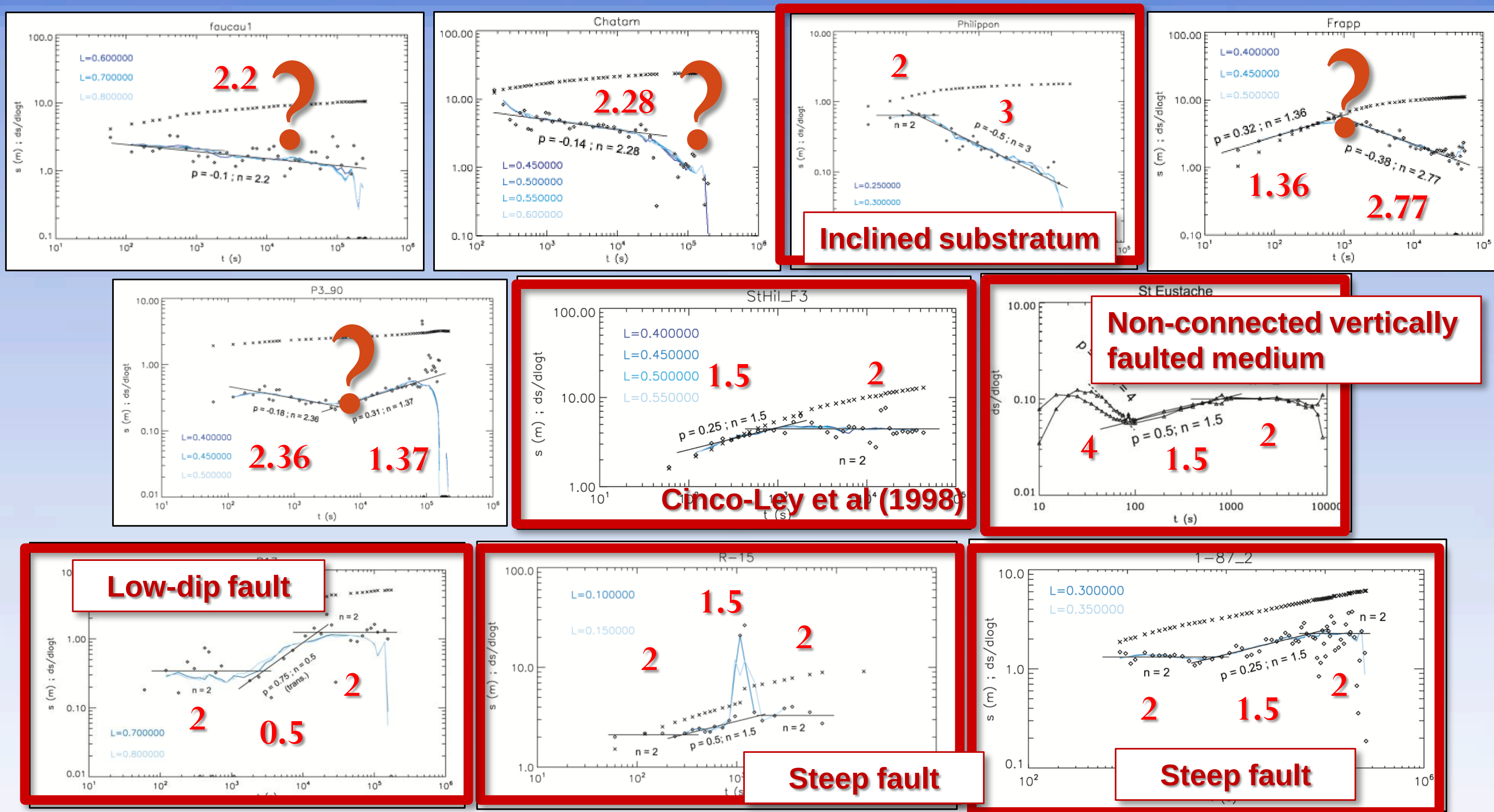
Variable thickness aquifer signature on derivative-log plot : slope p = -0,5

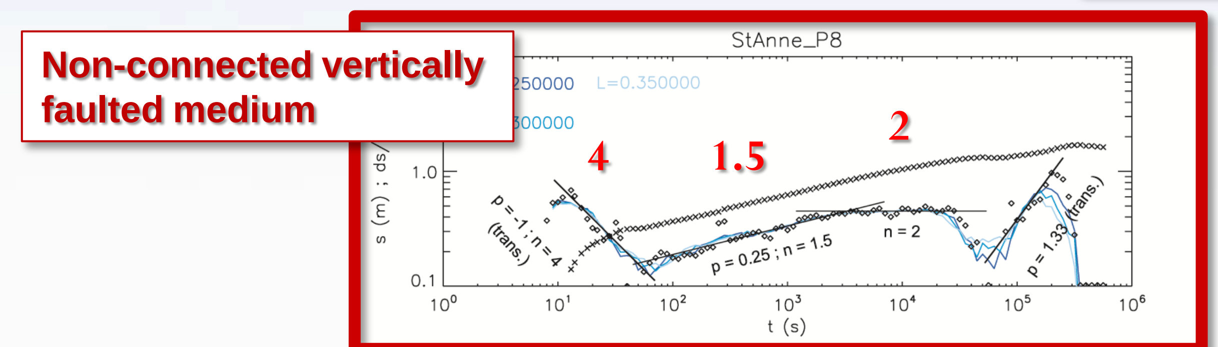
$\boldsymbol{n = 2 - 2p = 3}$



Classical Cooper-Jacob representation:

- **No distinction** between a **recharge boundary** (river) and the **inclined substratum** (that produces an increasing of the cross-flow area). **Low sensitivity** to fine variations of the drawdown regime.
- True recharge boundary is *<u>not visible</u>*





Region of Mirabel, Qc

Data from CGC-Québec

(Nastev et al, 2004)

Synthesis - Conclusions

- Most pump test conventional interpretative models **only account for (monostage) radial flow regime**, which is actually of **very limited occurrence** in nature

- This rough approximation produces **erroneous interpretations** of heterogeneities like the substratum inclination as a recharge boundary

- *Diagnostic plot* approach along with Barker's flow dimension interpretations provide **more accurate qualitative and quantitative diagnostic of hydraulic conditions** as they account for finer drawdown variations in non-radial flow regimes

- <u>Ongoing works at the University of Québec at Chicoutimi (UQAC) :</u>

  - Anouck Ferroud's Ph.D. (in progress)
    - *Numerical modelling for understanding physical conditions related to various flow dimensions sequences (non-radial and multistage) obtained in the nature*
    - *Field verification for constraining numerically-derived theoretical models : packers tests, tracer tests, geophysics (TDEM), structural survey, well-logging*

  - Programming a software for pumping tests interpretation with these tools : SIREEN 1.0 (in progress)

Thank you

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