SPE DISTINGUISHED LECTURER

Primary funding is provided by

The SPE Foundation through member donations and a contribution from Offshore Europe

The Society is grateful to those companies that allow their professionals to serve as lecturers

Additional support provided by AIME

SPE International

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl

Advances and Challenges in Dynamic Characterization of Naturally Fractured Reservoirs

Rodolfo G. Camacho-Velázquez

PEMEX EXPLORACION Y PRODUCCION

SPE International

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl

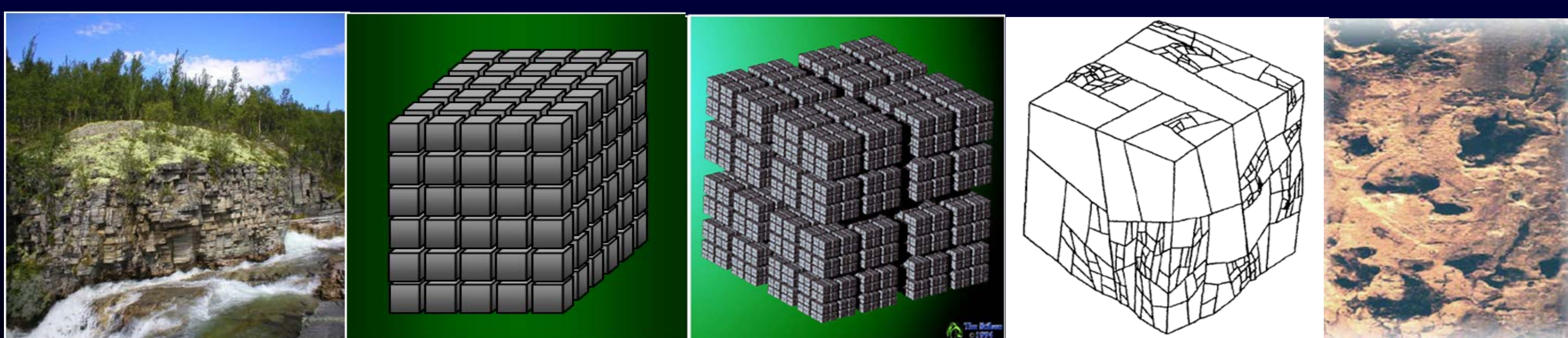
SPE DISTINGUISHED LECTURER

OUTLINE

- Objectives
- Motivation
- Background on fractals and naturally fractured vuggy reservoirs (NFVRs)
- Results with fractal and 3ϕ–$2k$ models
- Conclusions about proposed models
- Current and Future Vision

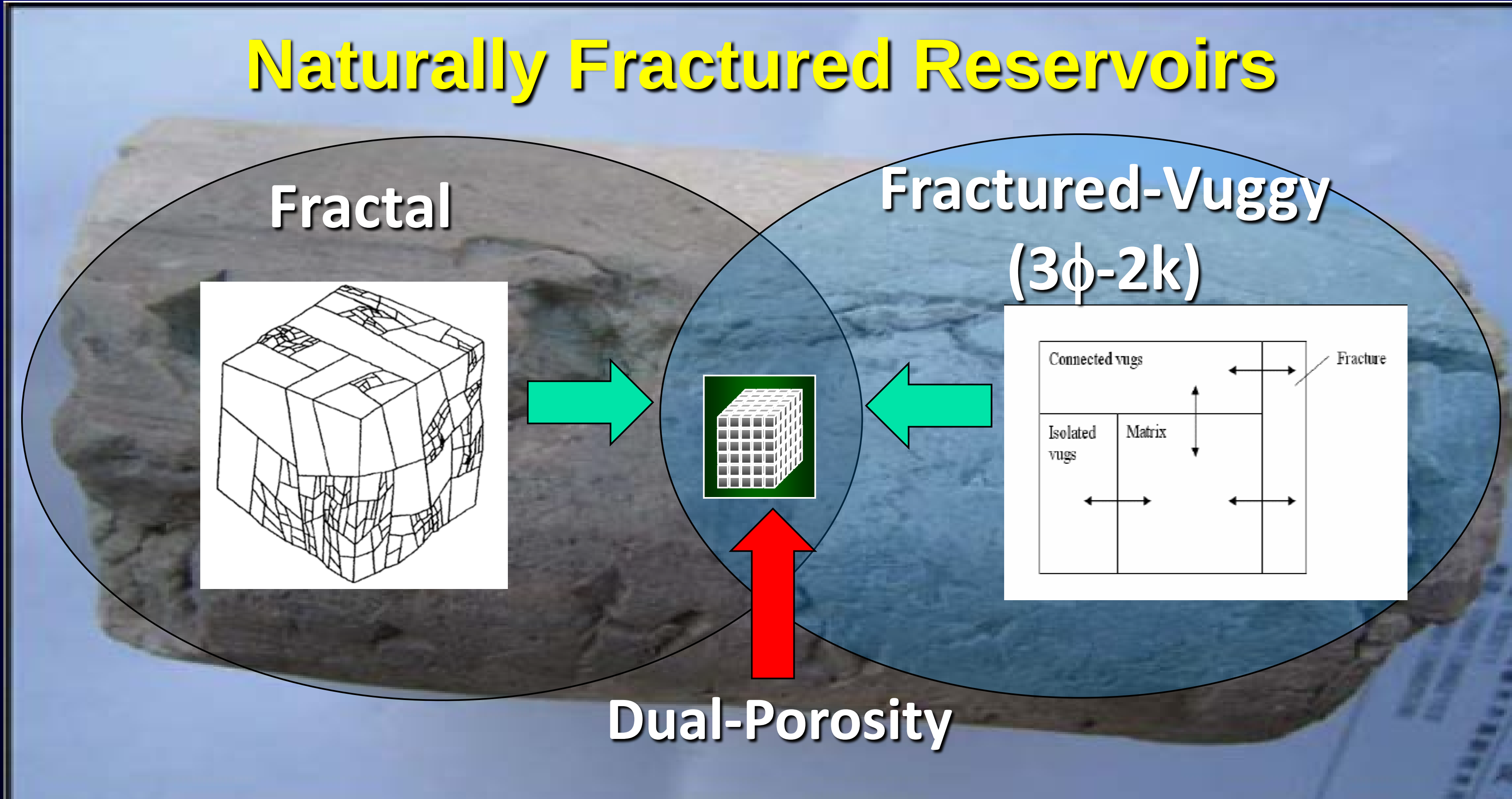
Objectives

- Advances in characterization of Naturally Fractured Vuggy Reservoirs (NFVRs**, 3ϕ–2k**) and NFRs with fractures at multiple scales with non-uniform spatial distribution, poor connectivity (**fractal**).
- Reservoir characterization challenges and current- future vision.



Acuña & Yortsos, SPEFE 1995

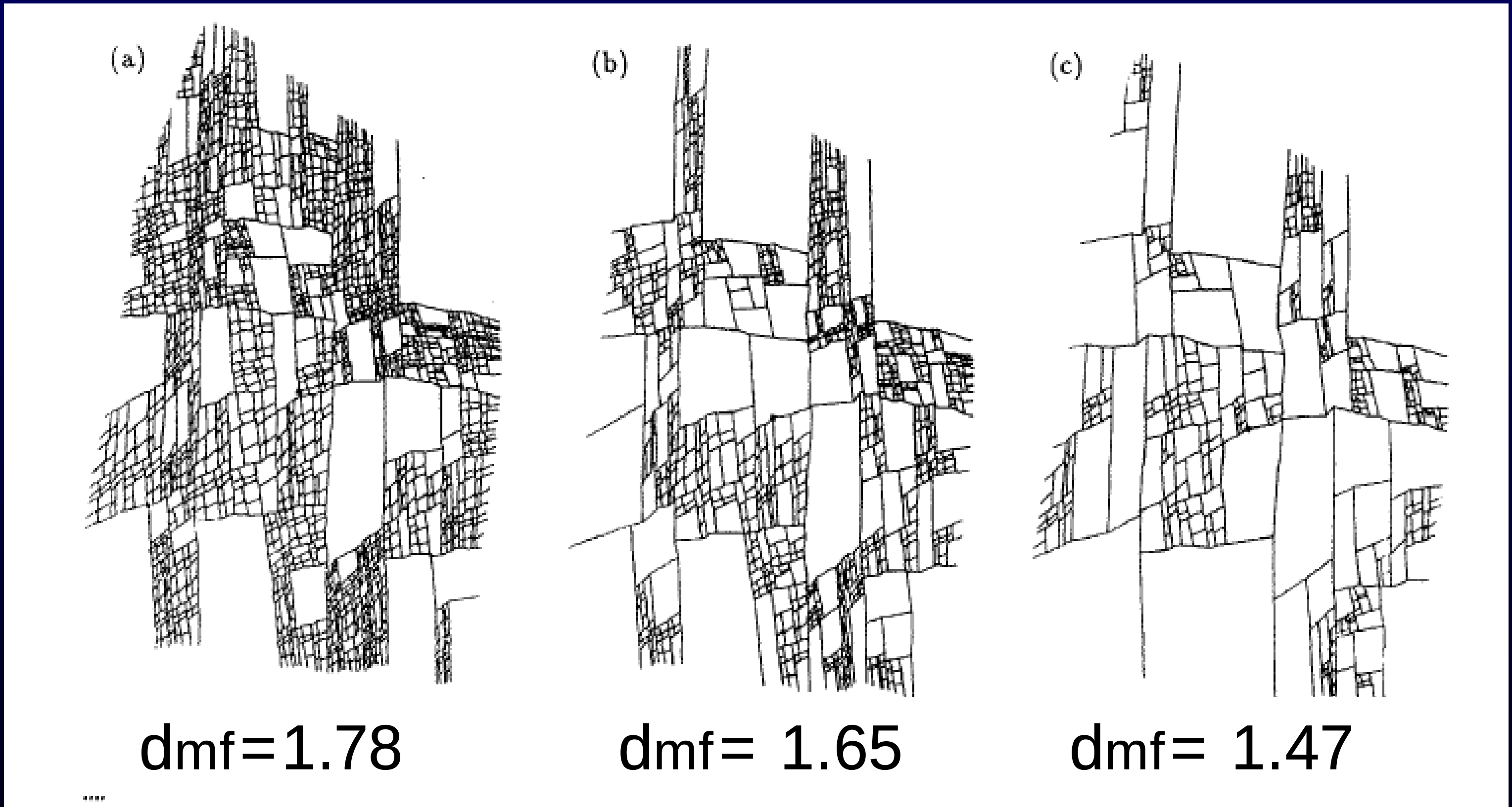
Motivation



More general continuous models

Background on fractals

Fractures are on a wide range of scales. There are zones with clusters of fractures and others where fractures are scarce.



$$d_{mf} = \frac{\log(N)}{\log(L)}$$; N= number of parts from original figure, L= scale of measurement.

Acuña & Yortsos, SPEFE 1995

Background on fractals

- Statistical method to describe structure of a fractured medium and identified by a power law → fractal dimension, dmf.

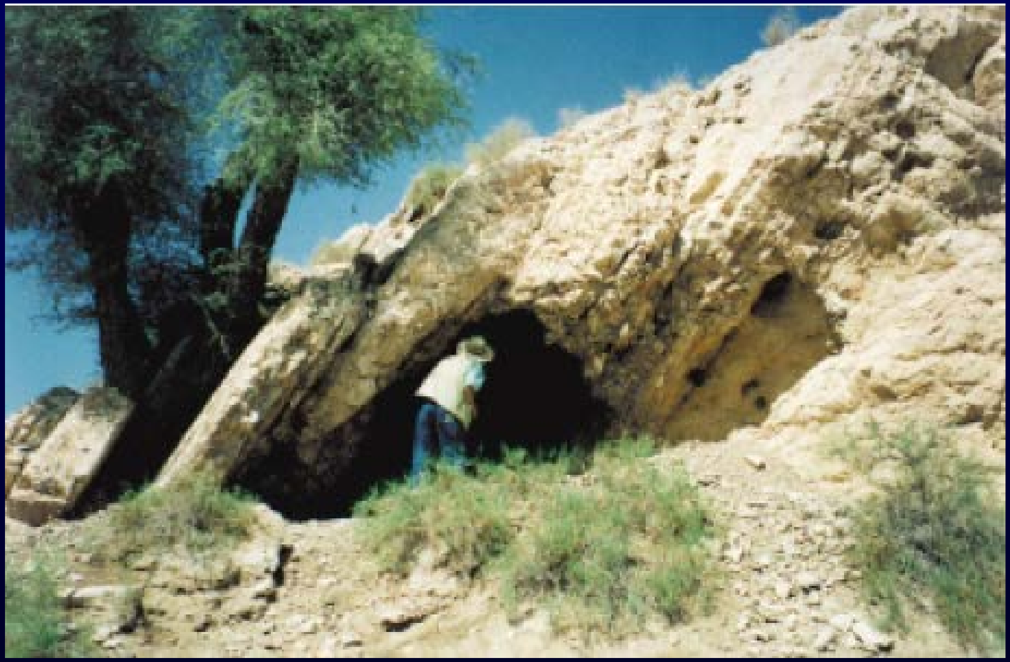
- Fracture networks characterized by: length, orientation, density, aperture, and connectivity. Power laws to quantify these properties.

- Conventional → uniform fracture distribution, fractures at a single scale, and good fracture connectivity. **Fractals → fractures at different scales, poor connectivity and non-uniform distribution** → careful location of wells.

Background on NFVRs

Some of the most prolific fields produce from Naturally Fractured Vuggy Reservoirs (NFVRs).

The effect of vugs on permeability depends on their connectivity.



Fluids are stored in the matrix, fractures and vugs.

Core perm. and ϕ in vuggy zones are likely to be pessimistic.

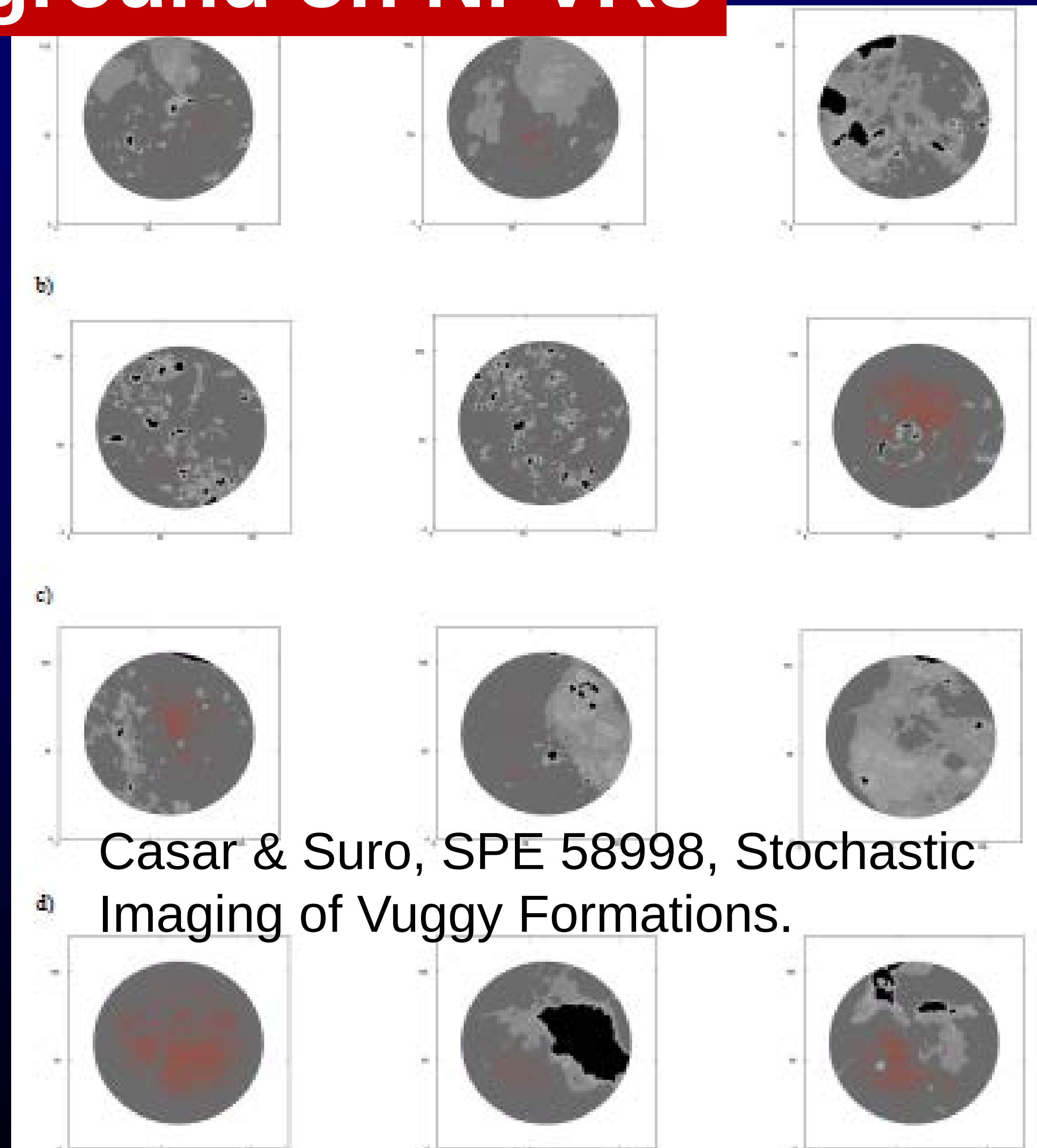
Background on NFVR

- Vugs affect flow & storage. Fractures network generally contributes < 1% of porous volume. Vuggy ϕ can be high.
- Vug network normally has good vertical permeability.
- The degree of fracturing and the presence of vugs are greater at the top of the anticline.
- Vug size, orientation, connectivity, and distribution are caused by deposit environment and diagenetic processes → they are difficult to characterize.

Background on NFVRs

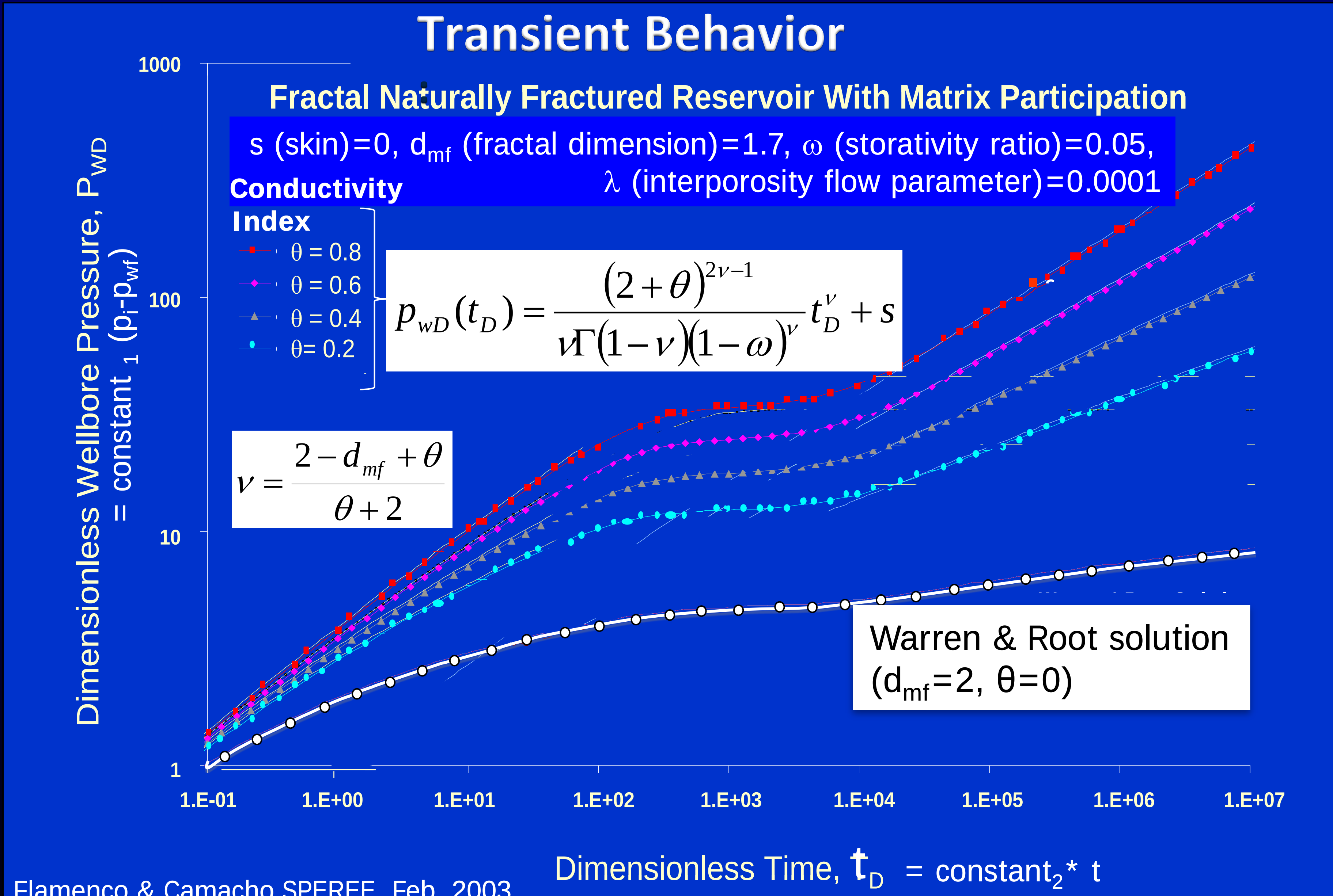
Slides of core segments with halos around vugs.

Increasing ϕ and k may be due to directly connected vugs and vugs connected through their halos. Vuggy kv may be > fracture kf.



Casar & Suro, SPE 58998, Stochastic Imaging of Vuggy Formations.

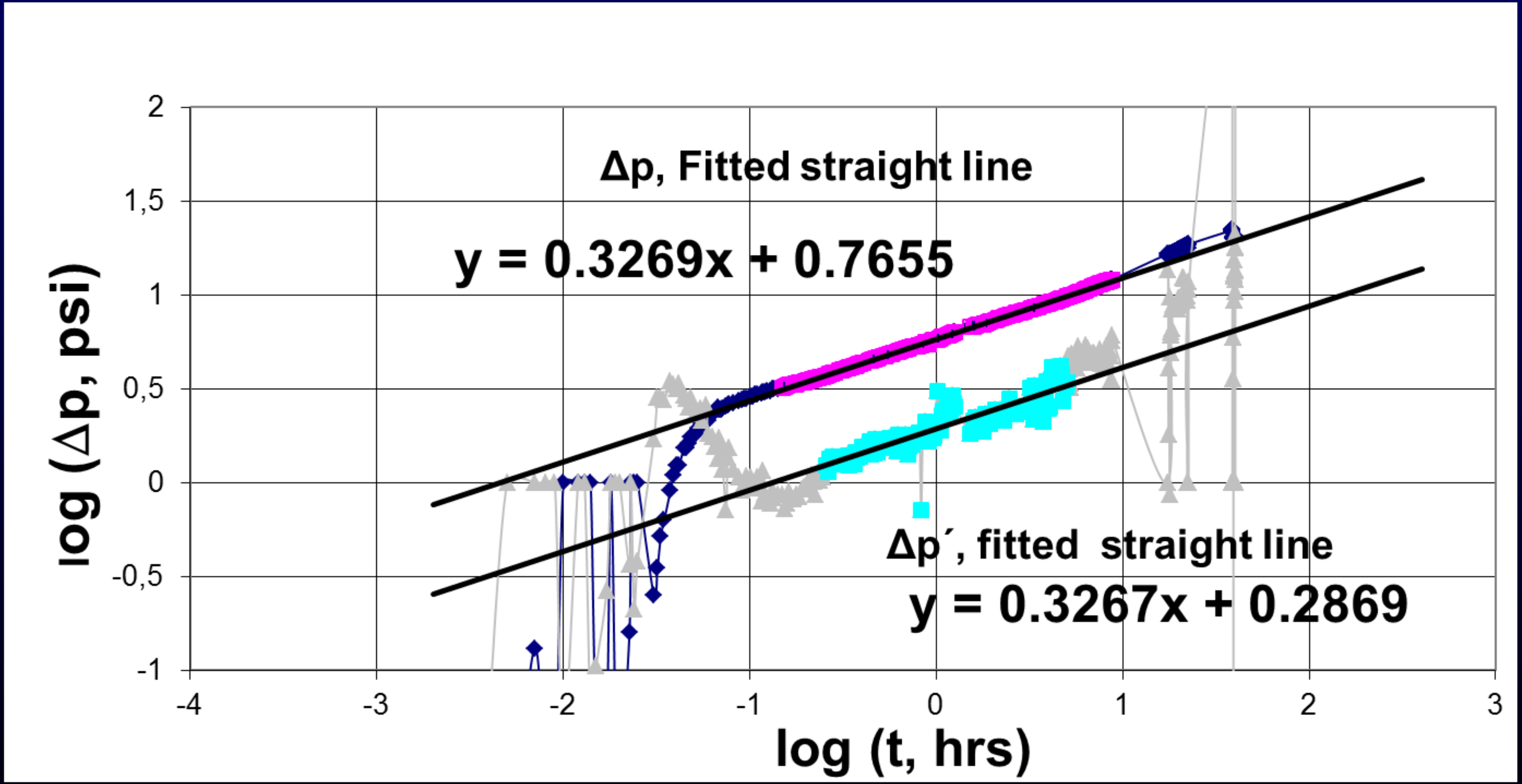
Results with Fractal Modeling



Flamenco & Camacho, SPEREE, Feb, 2003

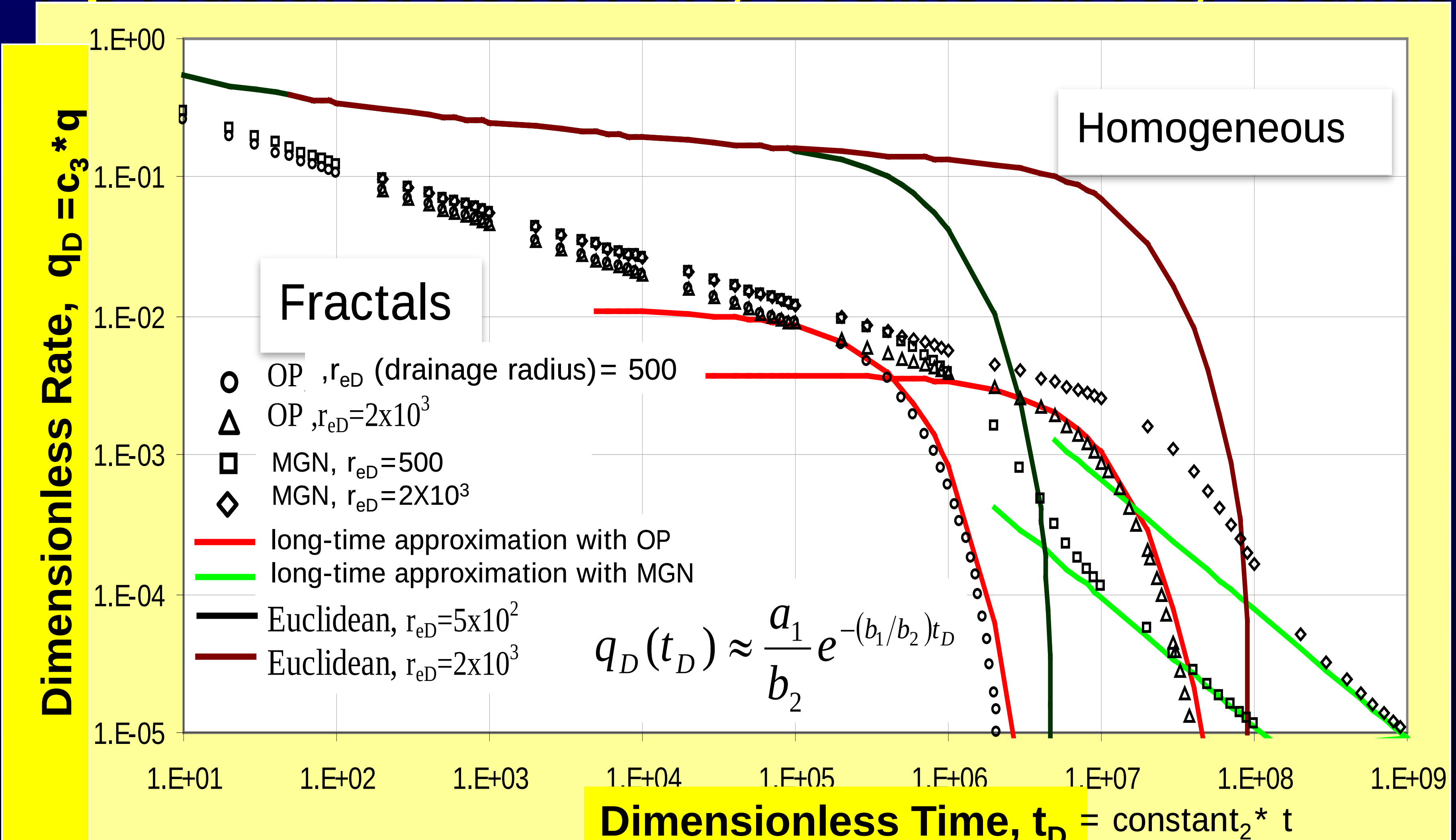
Results with fractal modeling

Slope = υ = 0.326, difference between coordinates to the origin is 0.4786, wich yields υ = 0.3322 ~ slope. This is another indication of fractal behavior.



Results with fractal modeling

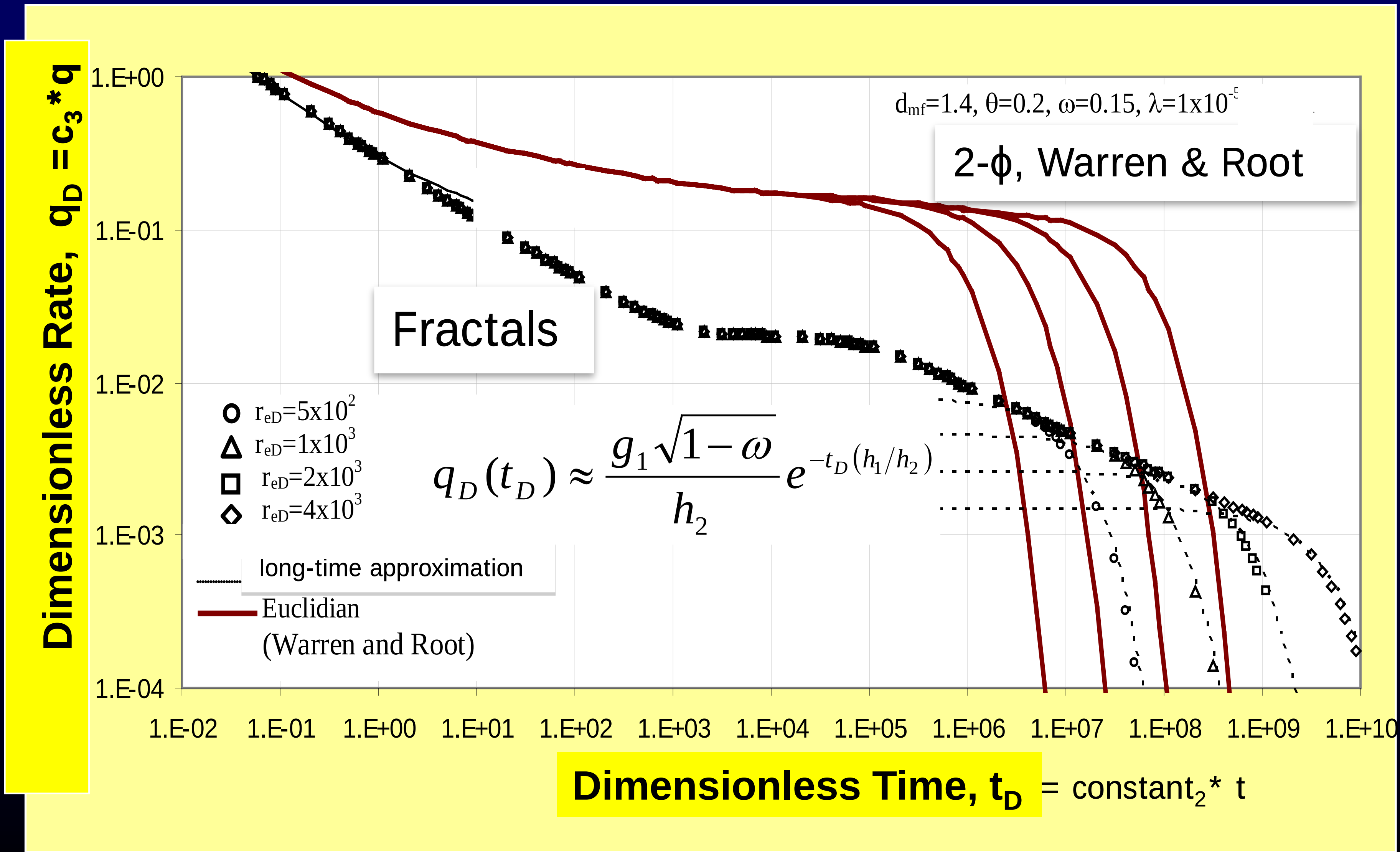
1-ϕ Fractured Reservoirs, Decline Curves, Bounded



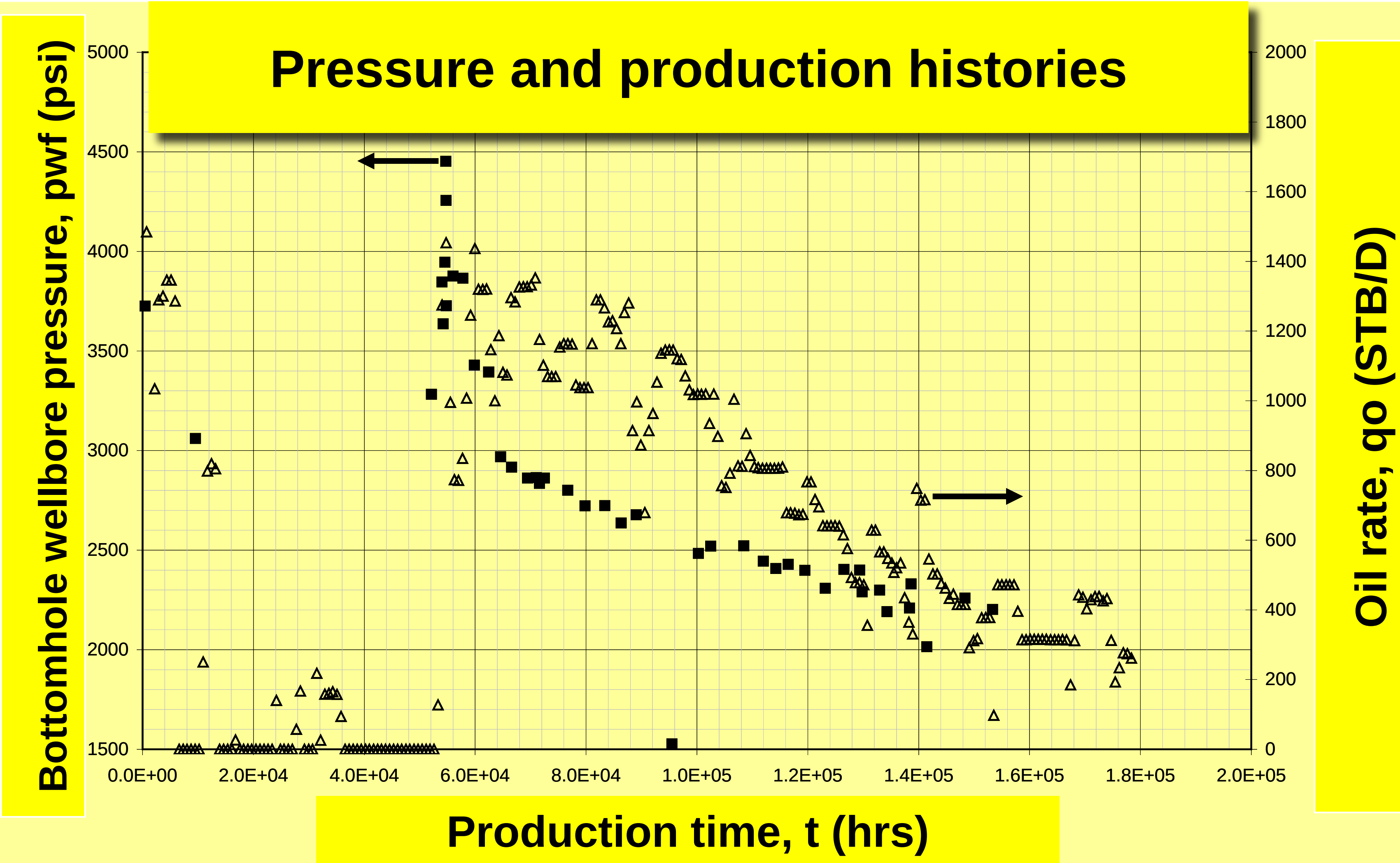
OP-- O' Shaughnessy & Procaccia. 1985. Physical Review; **MGN**--Metzler et. al. 1994. Physica
Camacho-V., R.G., et al., SPE REE, June 2008

Results with fractal modeling

2- ϕ, Influence of r_{eD}, closed reservoir



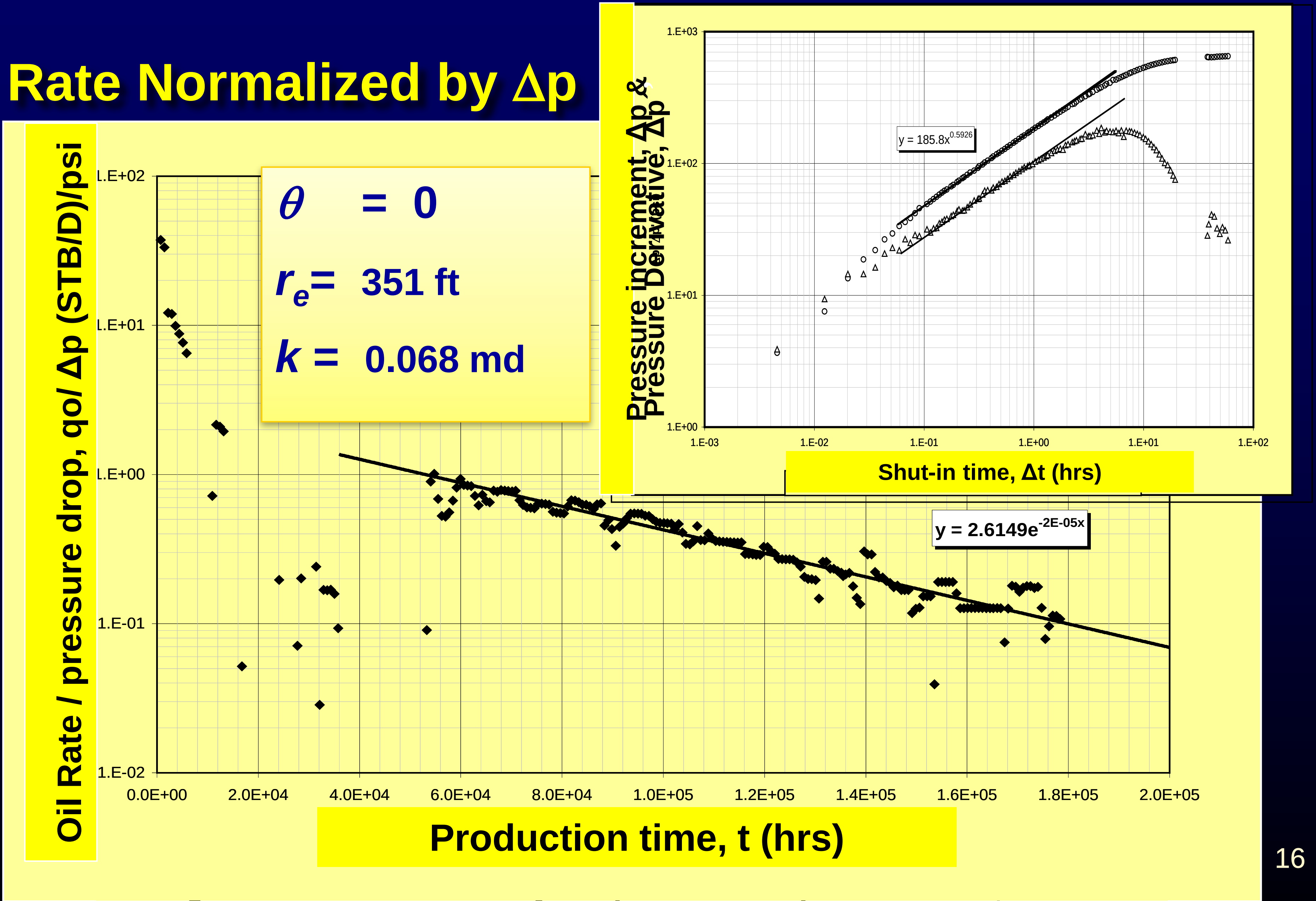
Results with fractal modeling



Camacho et. al.: "Decline Curve Analysis of Fractured Reservoirs with Fractal Geometry," SPEREE, 2008

Results with fractal modeling

Rate Normalized by Δp



θ = 0

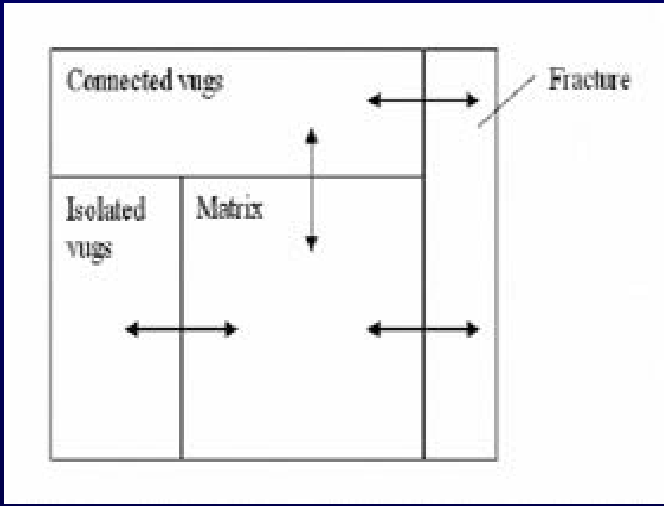
r_e = 351 ft

k = 0.068 md

Results with fractal modeling

- 1-ϕ and 2-ϕ, show power-law transient behavior ⇒ **fractal dimension** (fracture density).
- PSS, both 1-ϕ and 2-ϕ, show a Cartesian straight line for pressure response ⇒ porous volume evaluation.
- Rate during boundary-dominated flow presents typical semilog behavior ⇒ porous volume eval.
- Transient and boundary-dominated flow data should be used to fully characterize fractal NFRs, obtaining better estimates of permeability and drainage area.

Results with 3 ϕ – 2 k modeling



$$\omega_f = \phi_f c_f / \left[\phi_f c_f + \phi_m c_m + \phi_v c_v\right]$$

$$\omega_v = \phi_v c_v / \left[\phi_f c_f + \phi_m c_m + \phi_v c_v\right]$$

ω (storativity ratio), λ (interporosity flow parameter), c (compressibility), ϕ (porosity), κ (permeability ratio), k (permeability), l (flow direction), σ (interporosity-flow shape factor), rw (wellbore radius)

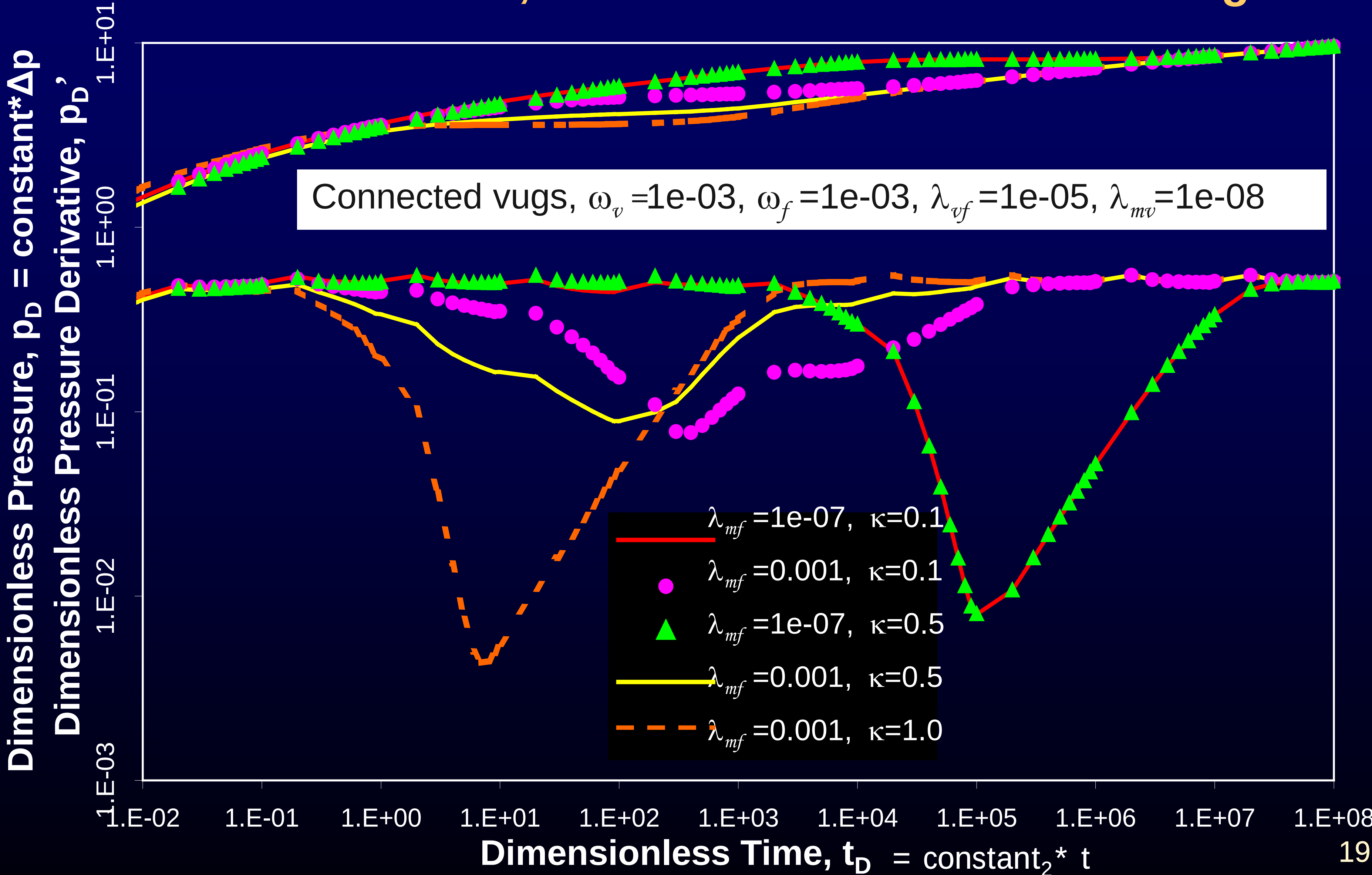
$$K_l = k_{fl} / \left[k_f + k_v\right]_l \qquad \lambda_{mf} = \sigma_{mf} k_m r_w^2 / \left[k_f + k_v\right]$$

$$\lambda_{mv} = \sigma_{mv} k_m r_w^2 / \left[k_f + k_v\right] \qquad \lambda_{vf} = \sigma_{vf} k_{vf} r_w^2 / \left[k_f + k_v\right]$$

Camacho-V., R., et. al.: "Pressure-Transient and Decline-Curve Behavior in Naturally Fractured Vuggy Carbonate Reservoirs," SPEREE, 2005.

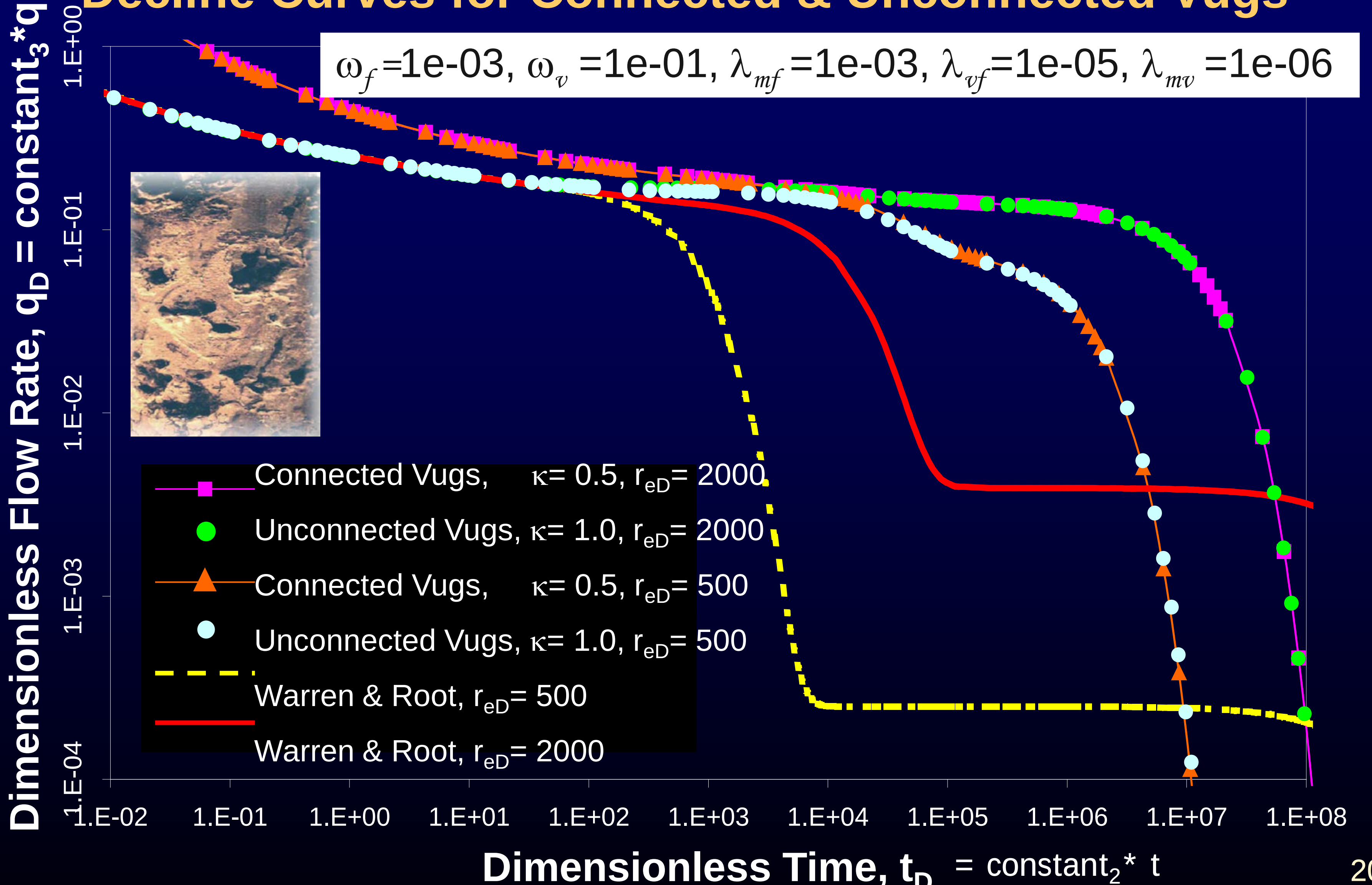
Results with 3 φ – 2 k modeling

Transient Behavior, Connected & Unconnected Vugs



Results with 3 φ – 2 k modeling

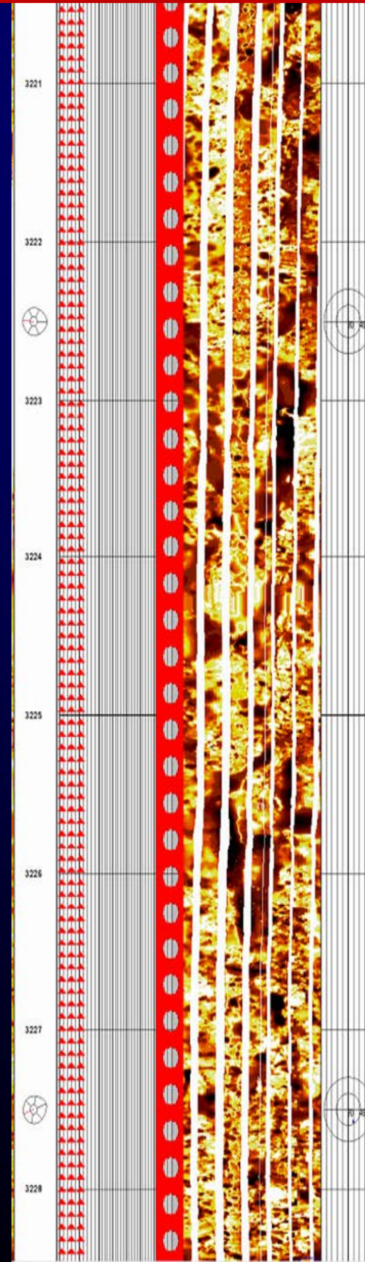
Decline Curves for Connected & Unconnected Vugs

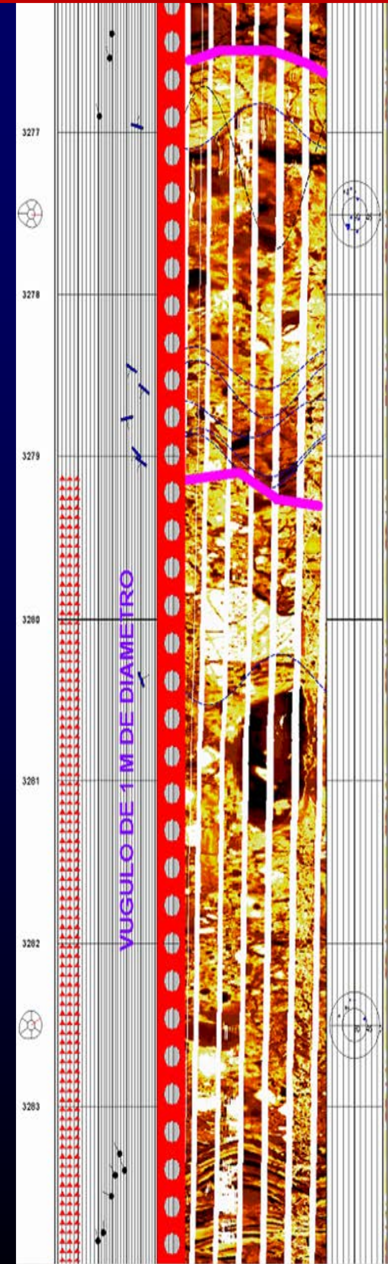


Results with 3 ϕ – 2 k model

Breccioid zone showing connected vugular porosity.

There is good vertical communication through the vugs.



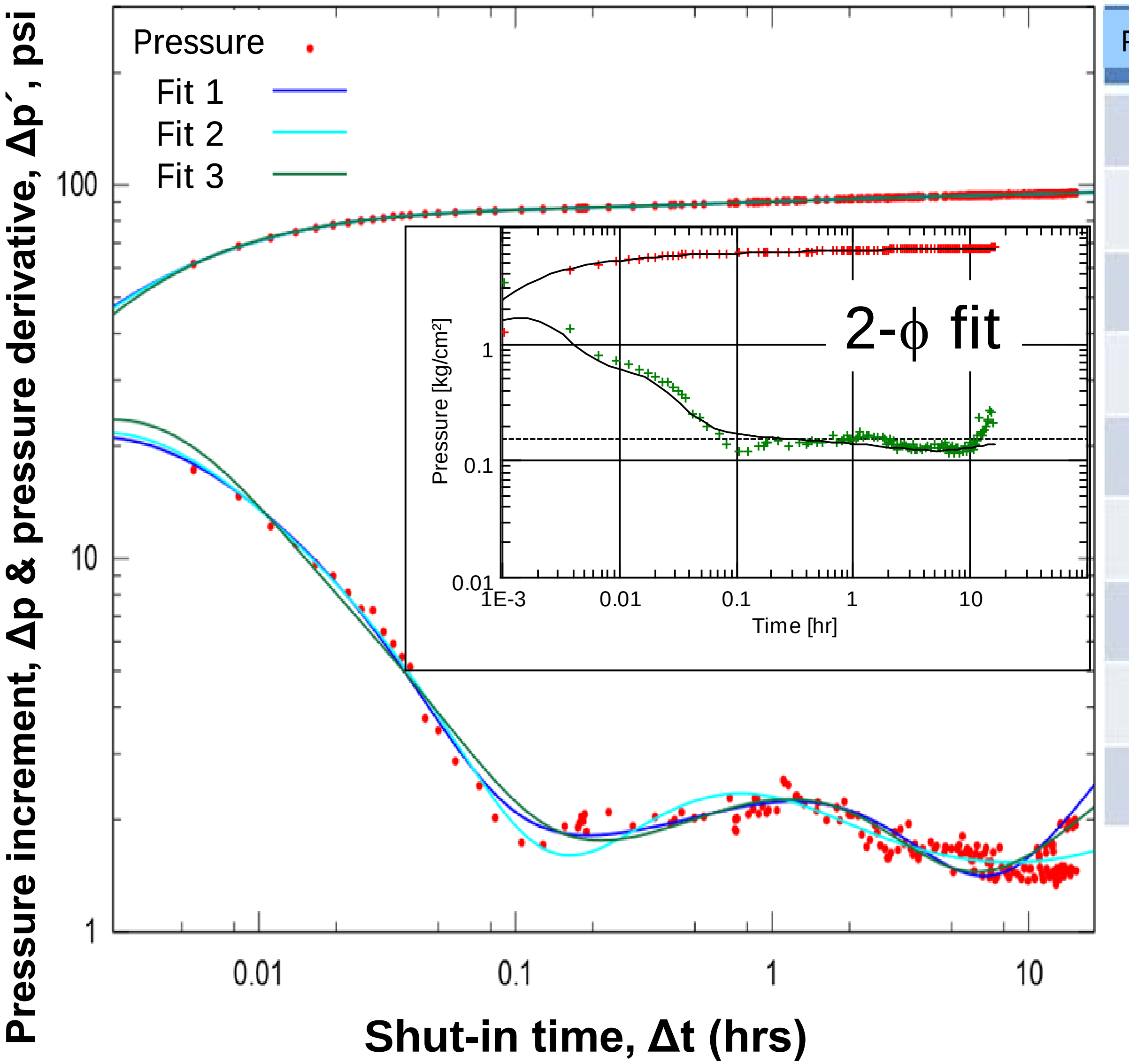


At 3280 – 3281 m depth there is a cavern with a vertical length of 1 - 1.5 m.

Camacho-V., R., et. al., **SPE 171078, 2014**

Results with 3 ϕ – 2 k modeling

Well 1-KS, multiple fittings, total penetration

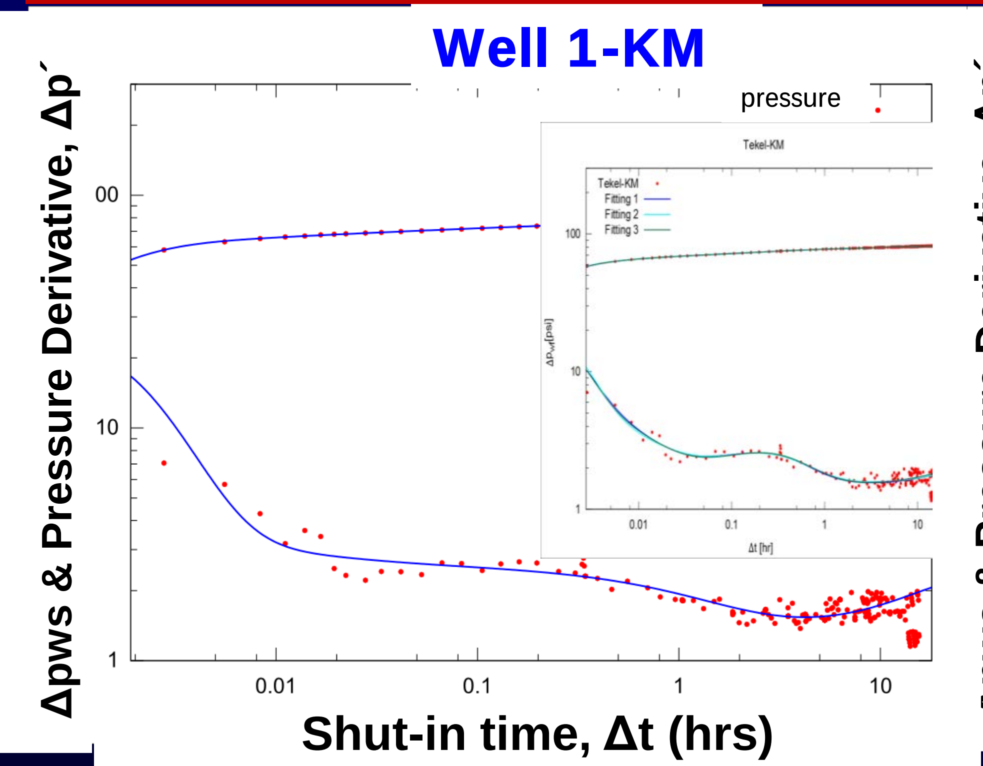


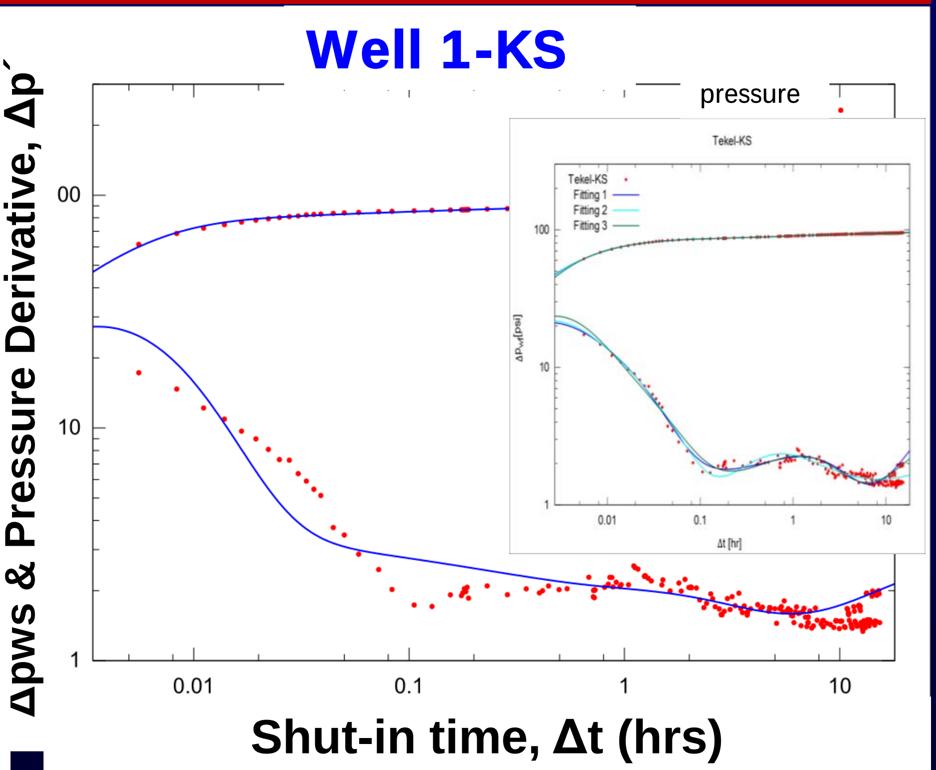
Parameter	Fit 1	Fit 2	Fit 3
ω_v	4.2E-4	1.9E-1	0.98
ω_f	1.1E-2	8.2E-5	8.4E-4
λ_{mf}	1E-9	1.1E-9	7.9E-4
λ_{vf}	7.7E-9	1.2E-9	8.9E-8
λ_{mv}	1.5E-7	1.8E-6	1E-9
κ	0.03	0.94	0.96
k_T	8286 mD	11990 mD	13950 mD
C_D	41	455	59
s	-3.5	-3.6	-1

Camacho-V., R., et. al.:
SPE171078, 2014

Results with 3 φ – 2 k modeling

Fixing ωv & ωf from well logs, Total Penetration



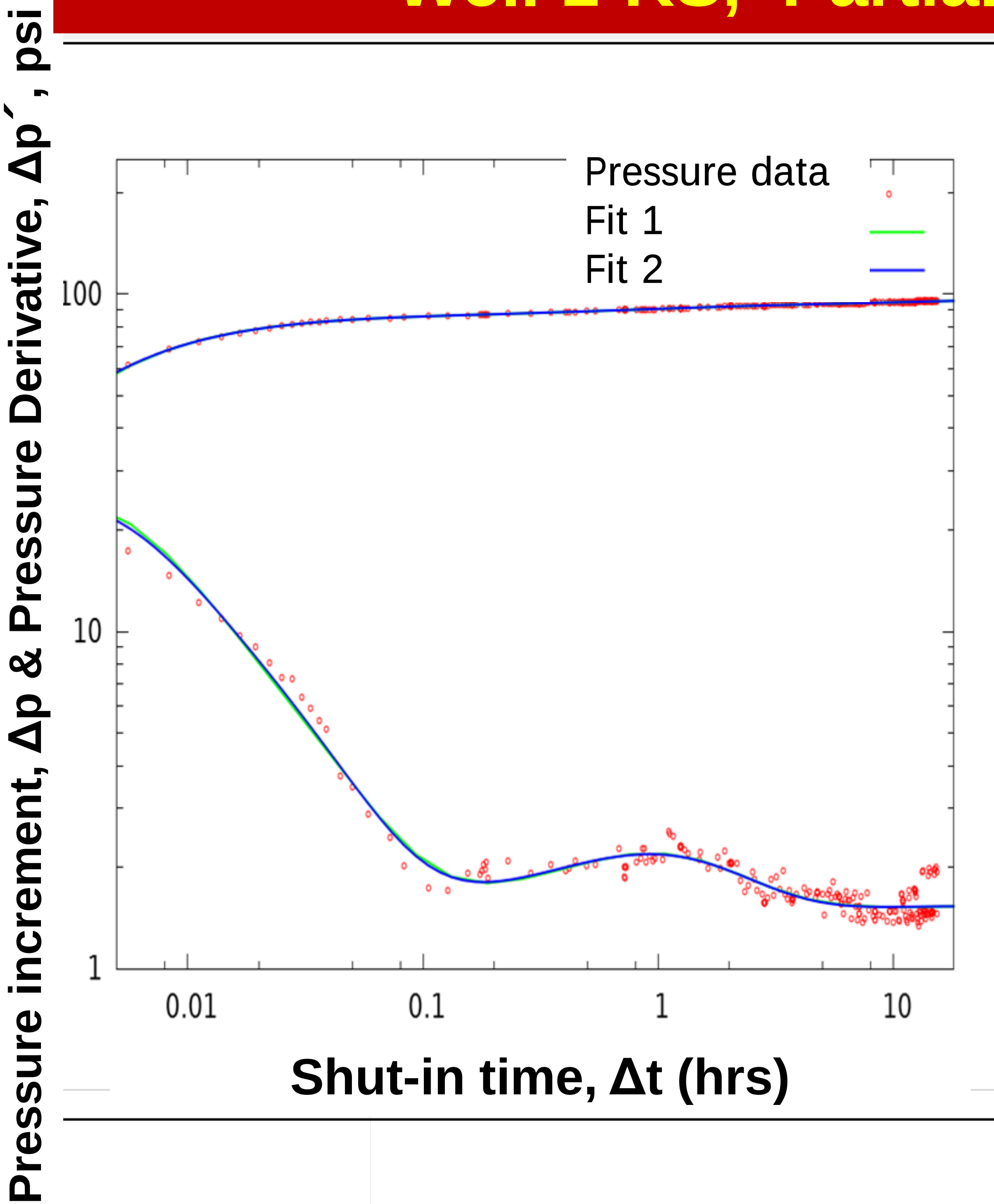


ω_v	ω_f	K	S
0.63	0.013	1.0	7.91
λ_{mf}	λ_{mv}	λ_{vf}	k_T
1.03E-07	1.76E-07	1.00E-09	2.11E+04

ω_v	ω_f	K	S
0.64	0.041	1.0	7.92
λ_{mf}	λ_{mv}	λ_{vf}	k_T
3.61E-08	1.00E-09	1.44E-08	3.37E+04

Results with 3 ϕ – 2 k modeling

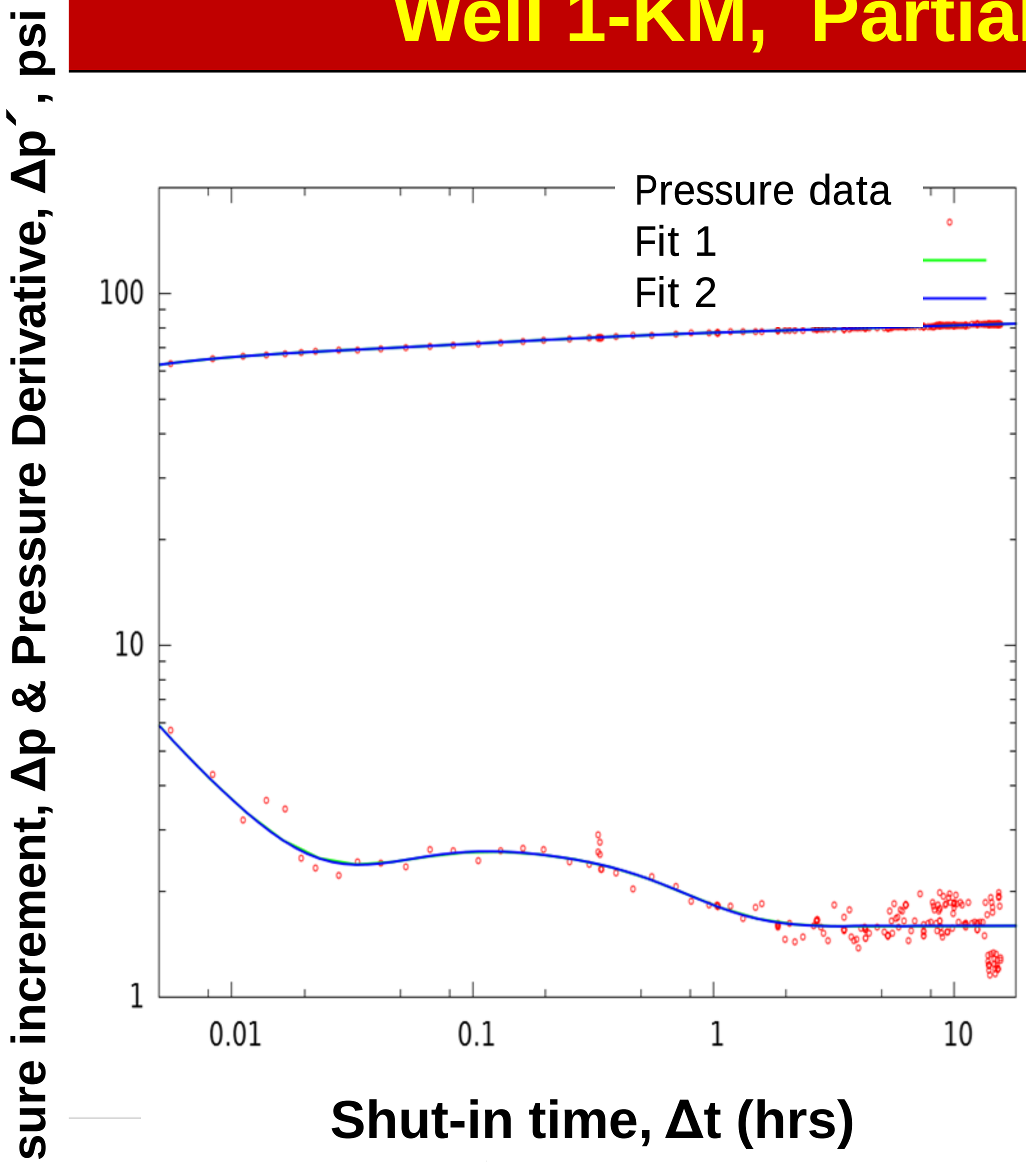
Well 1-KS, Partial Penetration



Parameter	Fit 1	Fit 2
ω_v	3.53E-02	7.00E-01
ω_f	5.24E-01	2.26E-02
λ_{mf}	1.04E-05	2.34E-05
λ_{vf}	2.49E-05	3.95E-05
λ_{mv}	2.56E-05	1.17E-05
κ_r	3.30E-01	8.08E-01
κ_z	9.99E-01	1.00E-03
C_D	2.21E+00	1.24E+00
S_f	8.20E-01	3.90E-01
S_v	5.92E-01	6.52E-01
h_D	3.86E+02	3.43E+02
h_{1D}	1.83E-01	1.01E-01
h_{pD}	1.71E-01	1.67E-01

Results with 3 ϕ – 2 k modeling

Well 1-KM, Partial Penetration



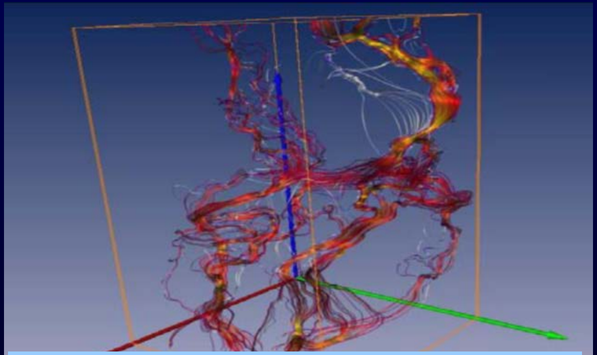
Parameter	Fit 1	**Fit 2**
ω_v	1.08E-01	5.07E-01
ω_f	5.18E-01	1.15E-01
λ_{mf}	5.52E-06	1.79E-05
λ_{vf}	7.88E-05	8.16E-05
λ_{mv}	1.78E-05	5.53E-06
κ_r	7.96E-02	9.31E-01
κ_z	6.29E-02	9.33E-01
C_D	2.82E+00	2.82E+00
S_f	1.09E+00	1.07E+00
S_v	1.08E+00	1.08E+00
h_D	1.04E+03	1.05E+03
h_{1D}	3.74E-01	3.75E-01
h_{pD}	2.51E-01	2.51E-01

Results with 3 ϕ – 2 k modeling
Overview of dynamic characterization– Well 1

- **2 ϕ – 1 k, total penetration (Warren-Root)**
  KS: $\omega = 0.62$, KM: $\omega = 0.40$

  Values from well logs:
  - KS: $\omega_v = 0.64$, $\omega_f = 0.04$ KM: $\omega_v = 0.63$, $\omega_f = 0.01$

- **3 ϕ – 2 k, total penetration**
  - KS: $\omega_v = 0.98$, $\omega_f = 8X10\text{-}4$, $\kappa_r = 0.96$
  - KM: $\omega_v = 0.99$, $\omega_f = 1X10\text{-}4$, $\kappa_r = 0.75$



Ausbrooks, R. et al, SPE 56506

- **3 ϕ – 2 k, partial penetration**
  - KS: ω_v **= 0.7,** ω_f **= 0.023,** **$\kappa_r = 0.8$, $\kappa_z = 0.001$**
  - KM: ω_v **= 0.51,** ω_f **= 0.12,** **$\kappa_r = 0.9$, $\kappa_z = 0.9$**

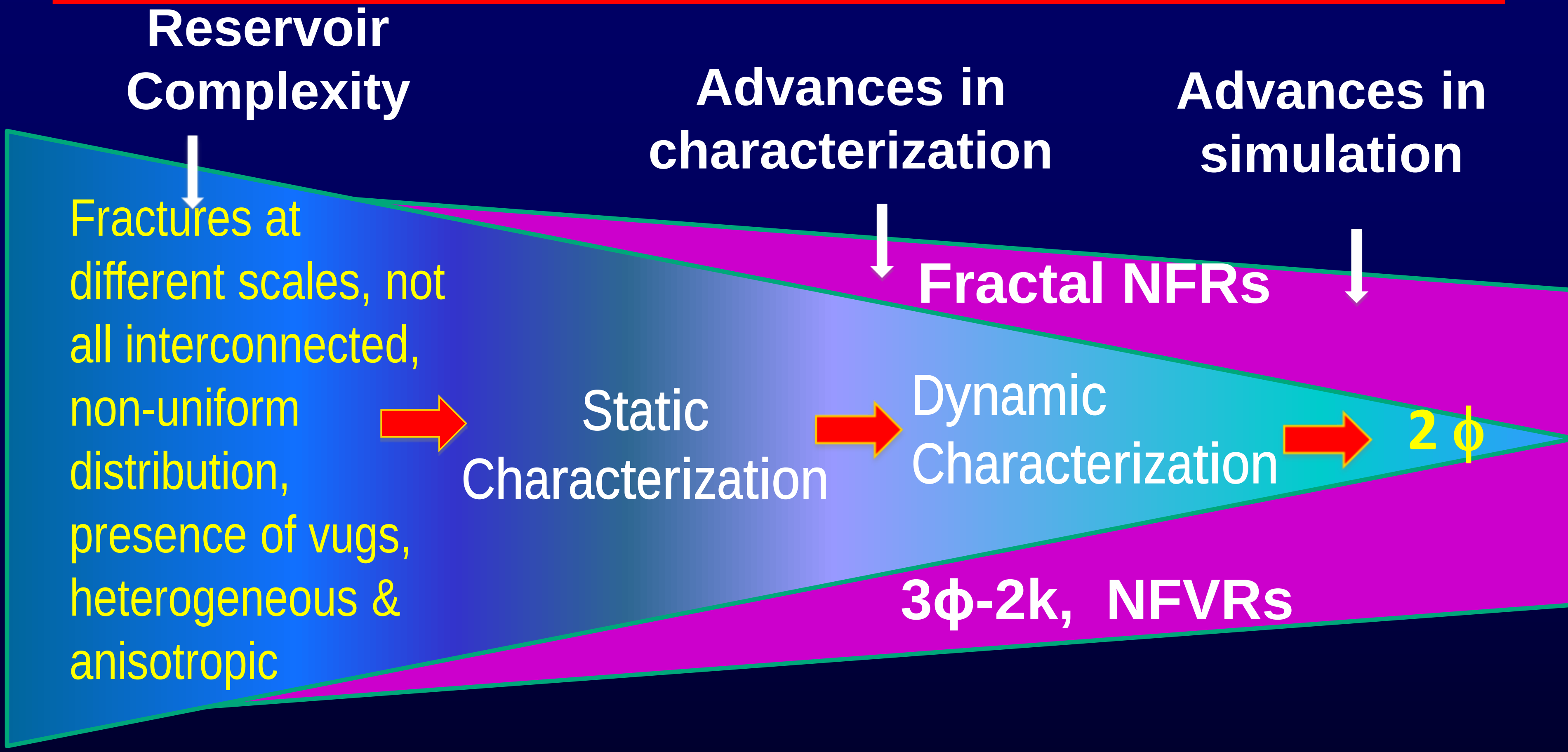
Results with 3 ϕ – 2 k modeling

- **3 ϕ - 2 k** ⟹ better match of pressure tests than 2 ϕ model, obtaining more information about 3 media (matrix- fractures - vugs).
- ($\omega_v + \omega_f$) $\neq \omega$ (2 ϕ, Warren-Root) ⟶ use of traditional 2 ϕ simulators for NFVRs is not justified.
- Partial penetration effects ⟹ information about vertical communication of vugs and fractures.
- Confirmed that vugs' vertical communication can be significant, which is relevant for reservoirs with an active aquifer.

Conclusions about proposed models

- **Fractal** & **3 ϕ - 2 k** models → better characterization → key driver for maximizing production and recovery.
- Proposed models → explanations for production performance that can not be obtained with traditional 2 ϕ simulators.
- Additional information from these models useful to:
  - prevent / anticipate mud losses during drilling
  - evaluate vertical communication for NFVRs
  - evaluate productive potential of NFRs
  - anticipate efficiency of secondary and EOR
  - determine better distribution of wells

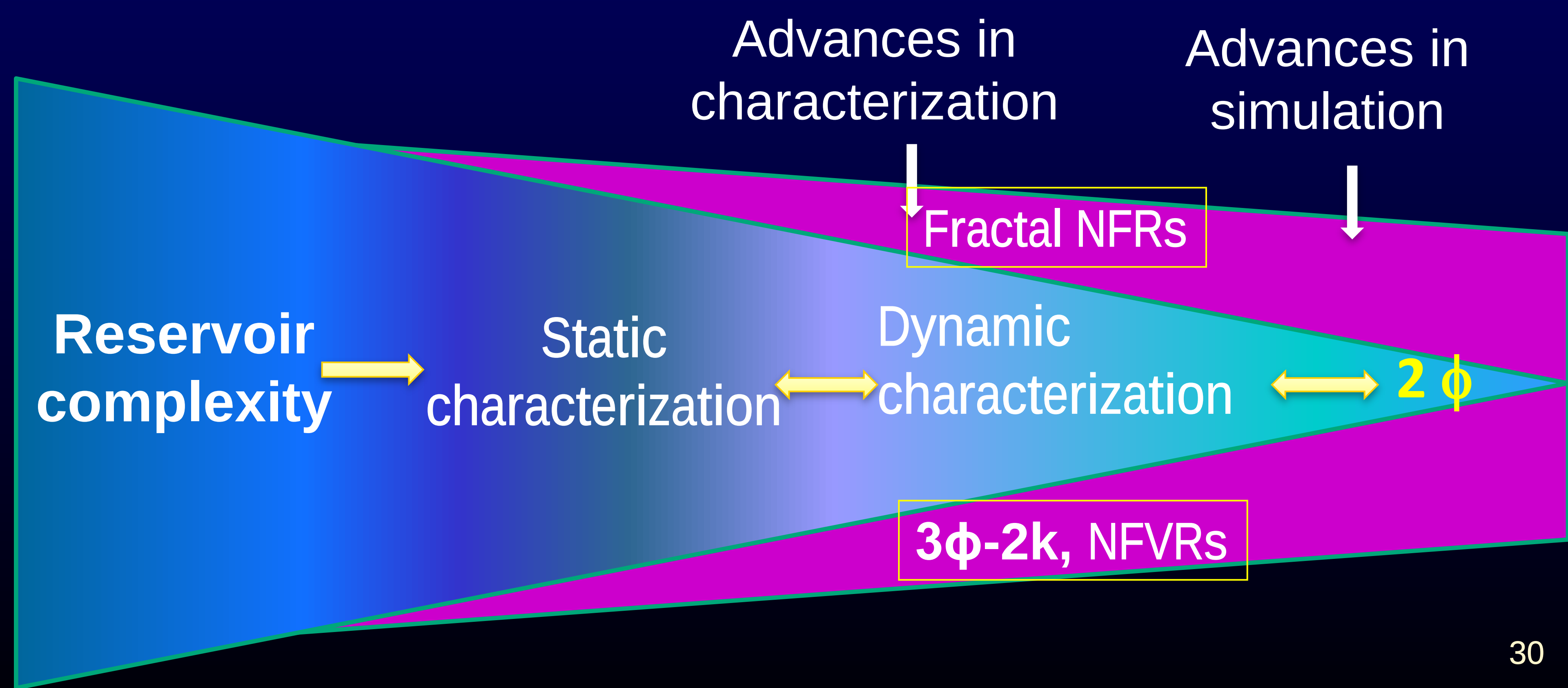
Current and Future Vision



It is important to consider other alternatives that best describe heterogeneities, such as the 3ϕ – 2k models for NFVRs and fractal models

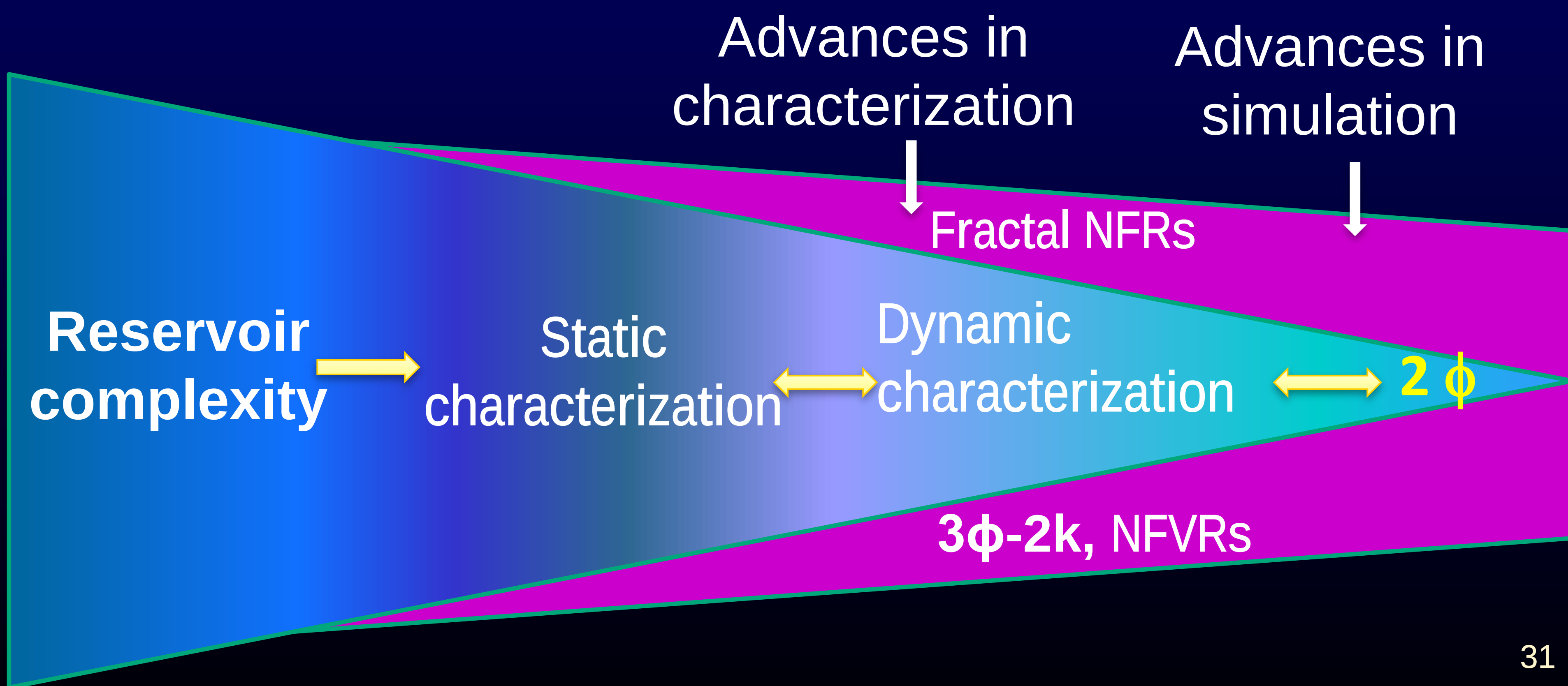
Main message

There are two new models that provide more reservoir information with the same input data



Thank you

Are there any questions?



SPE DISTINGUISHED LECTURER

Your Feedback is Important

Enter your section in the DL Evaluation Contest by completing the evaluation form for this presentation

Visit SPE.org/dl

SPE International

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl