The Role of Faults in Modeling Long Term CO_2 Storage:
The Up-scaling Dilemma

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SOUTH EAST CARB PHASE II PARTNERSHIP
STACKED SINK PROJECT

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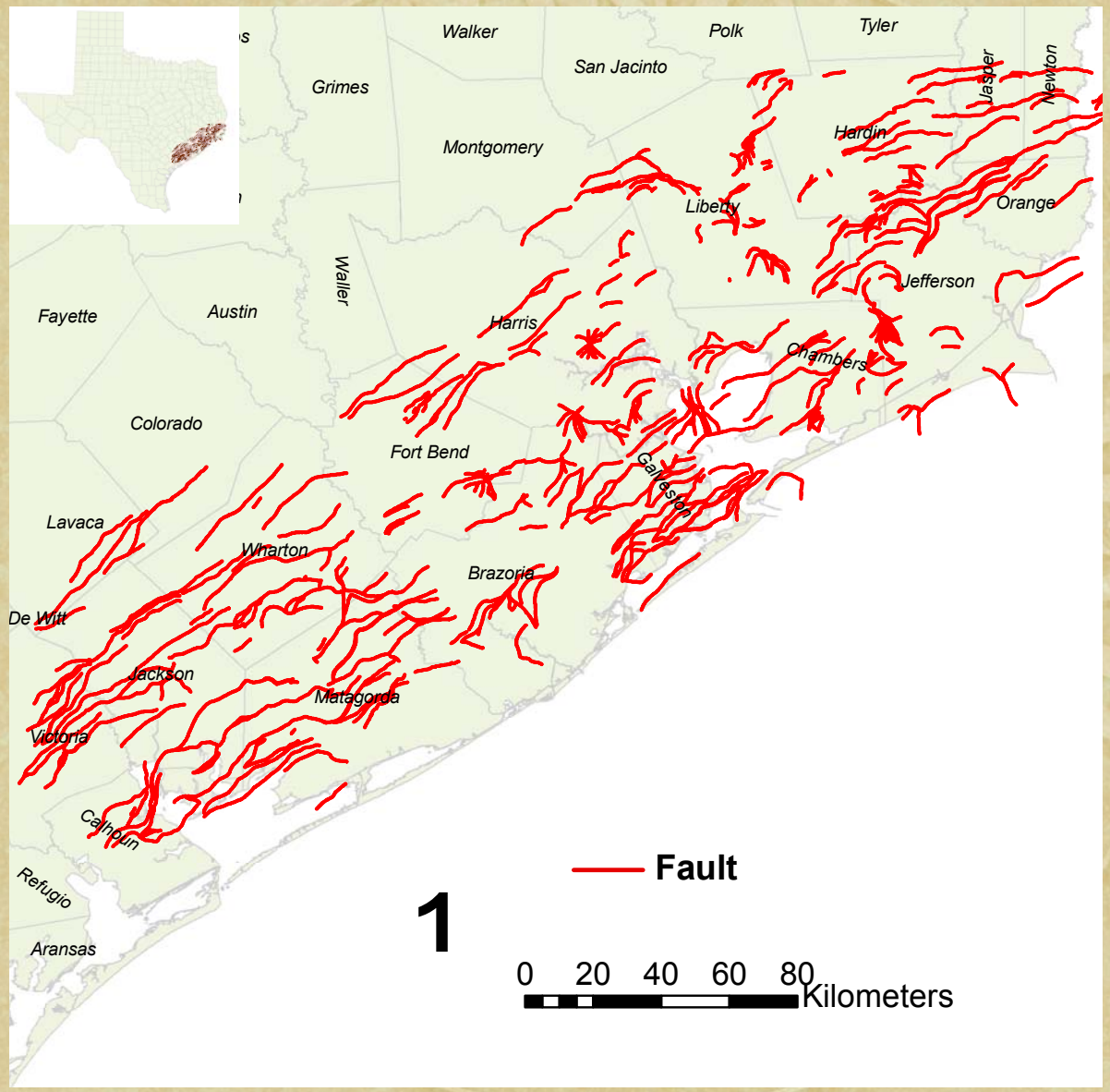
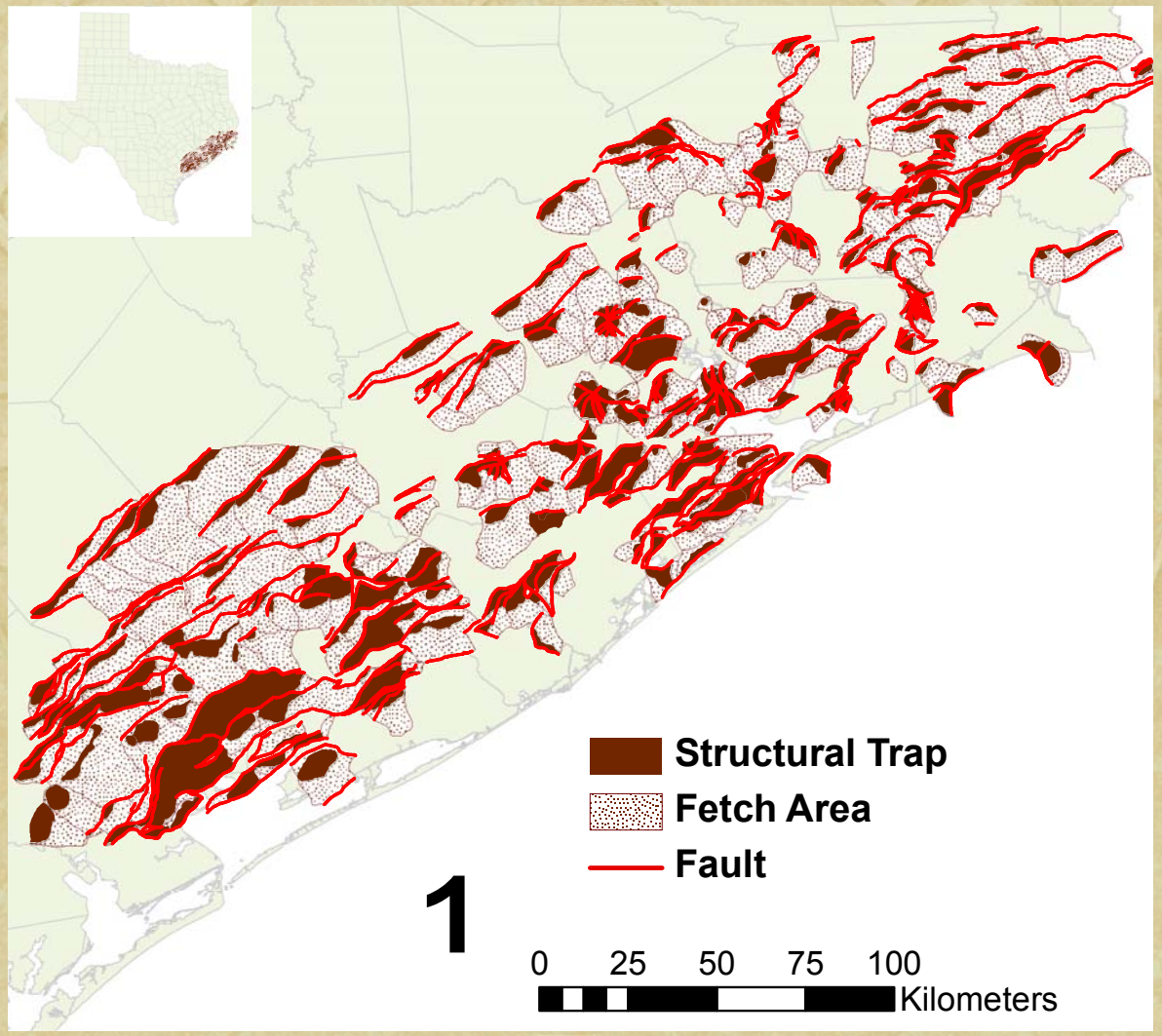
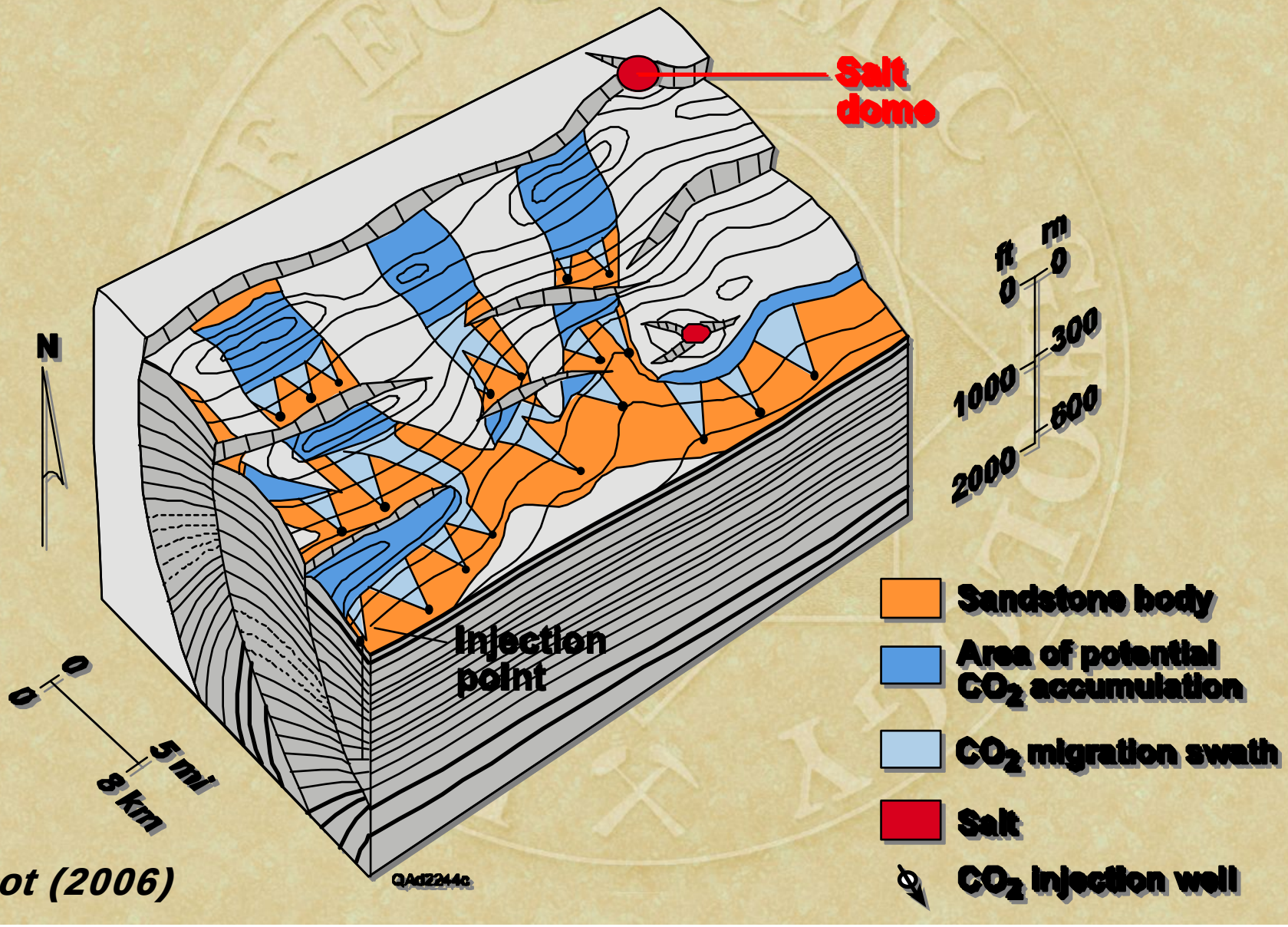

Walker
Polk
Tyler
San Jacinto
Grimes
Jasper
Newton
Hardin
Montgomery
Liberty
Orange
Waller
Jefferson
Fayette
Austin
Harris
Chambers
Colorado
Fort Bend
Galveston
Lavaca
Wharton
Brazoria
De Witt
Jackson
Matagorda
Victoria
Calhoun
Refugio
Aransas
Fault
1
0 20 40 60 80
Kilometers

Closure and Fetch Areas (Top Frio)



Gulf Coast Model for CO_2 Migration

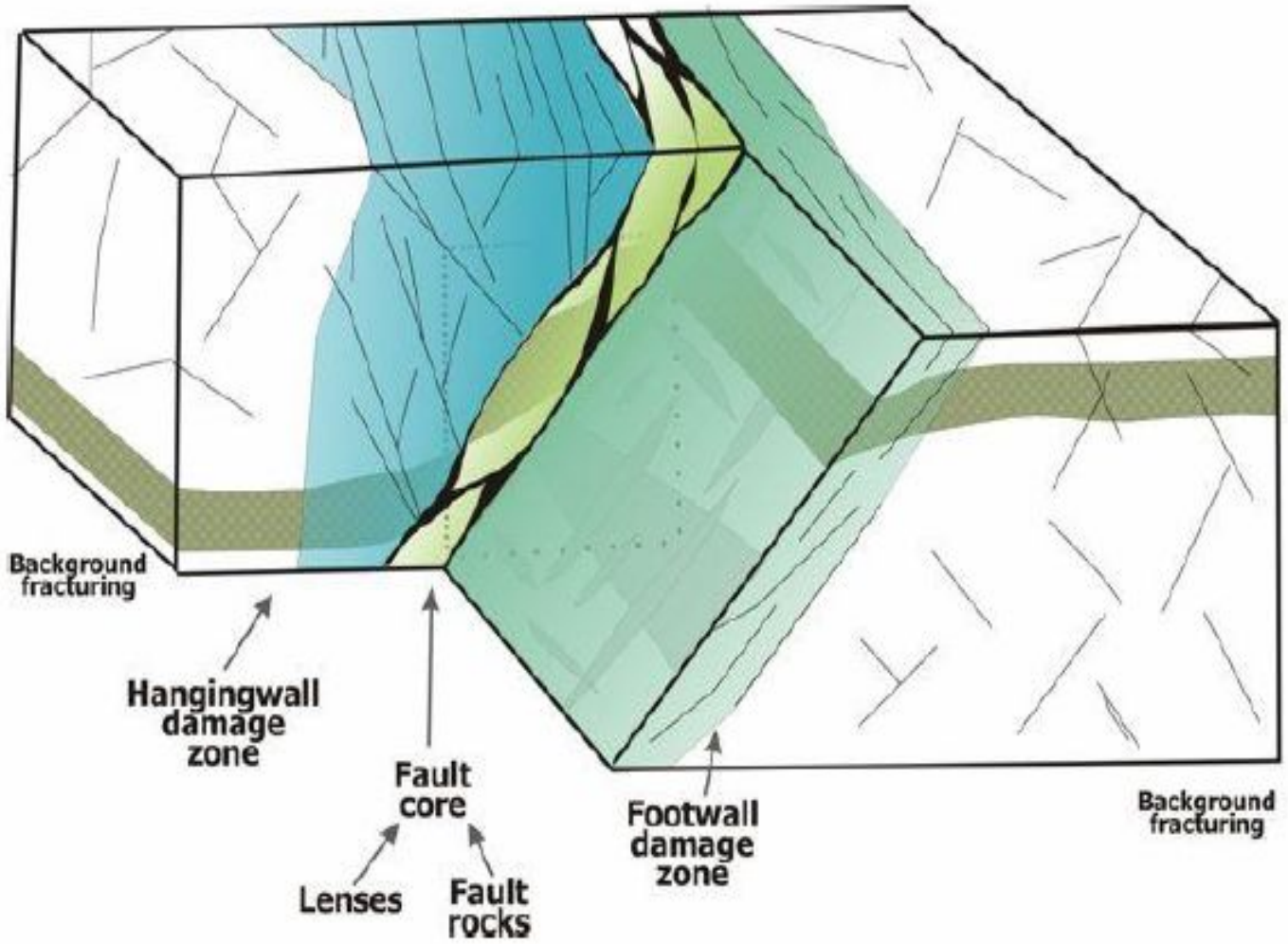


Nicot (2006)

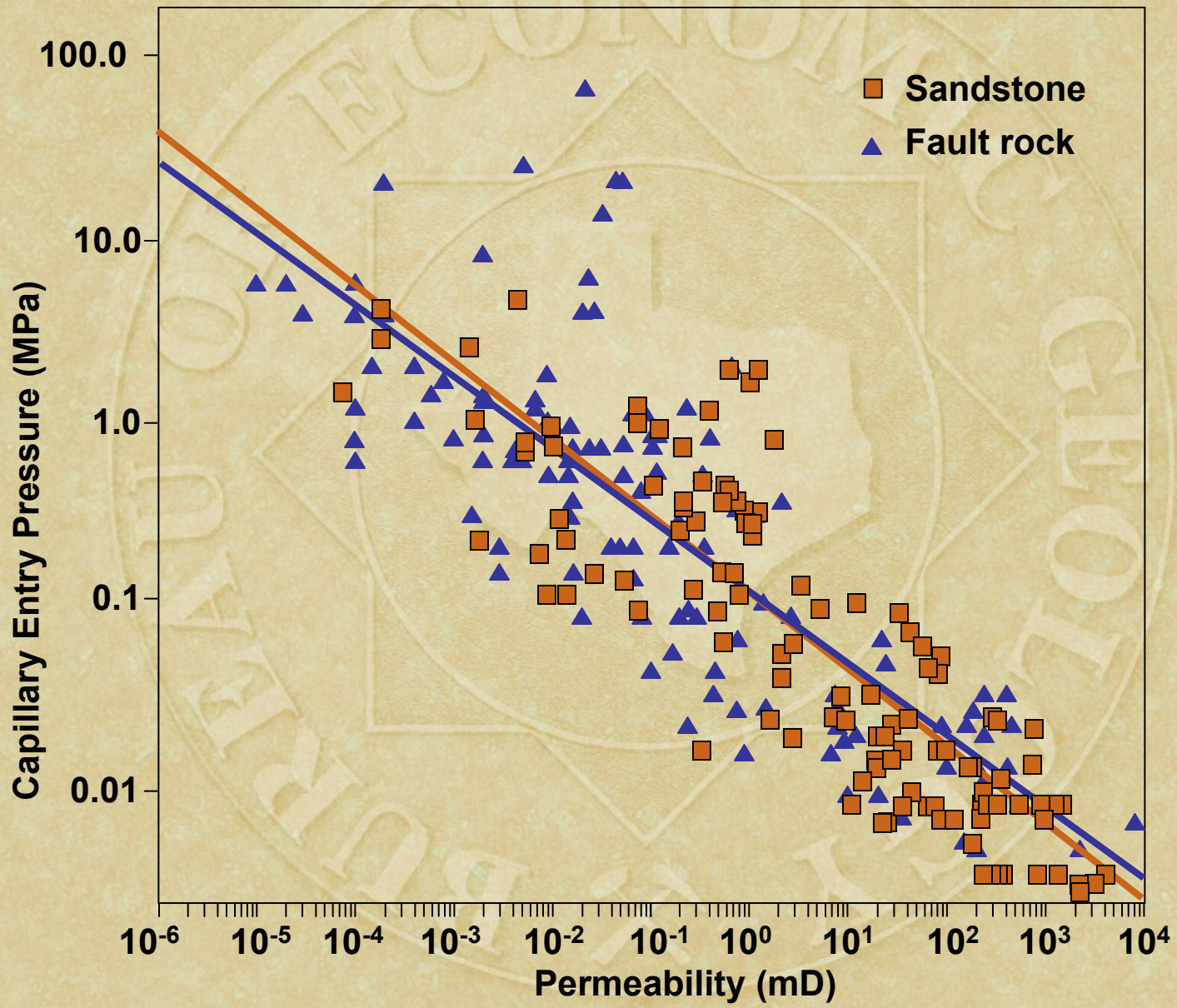
PROBLEM STATEMENT:

- Data from hydrocarbon exploration and production demonstrates faults can act as seals or conduits for fluid flow
- Faults have permeabilties that range over 10 orders of magnitude
- Fault rocks have Capillary Entry Pressures that range over 4 orders of magnitude

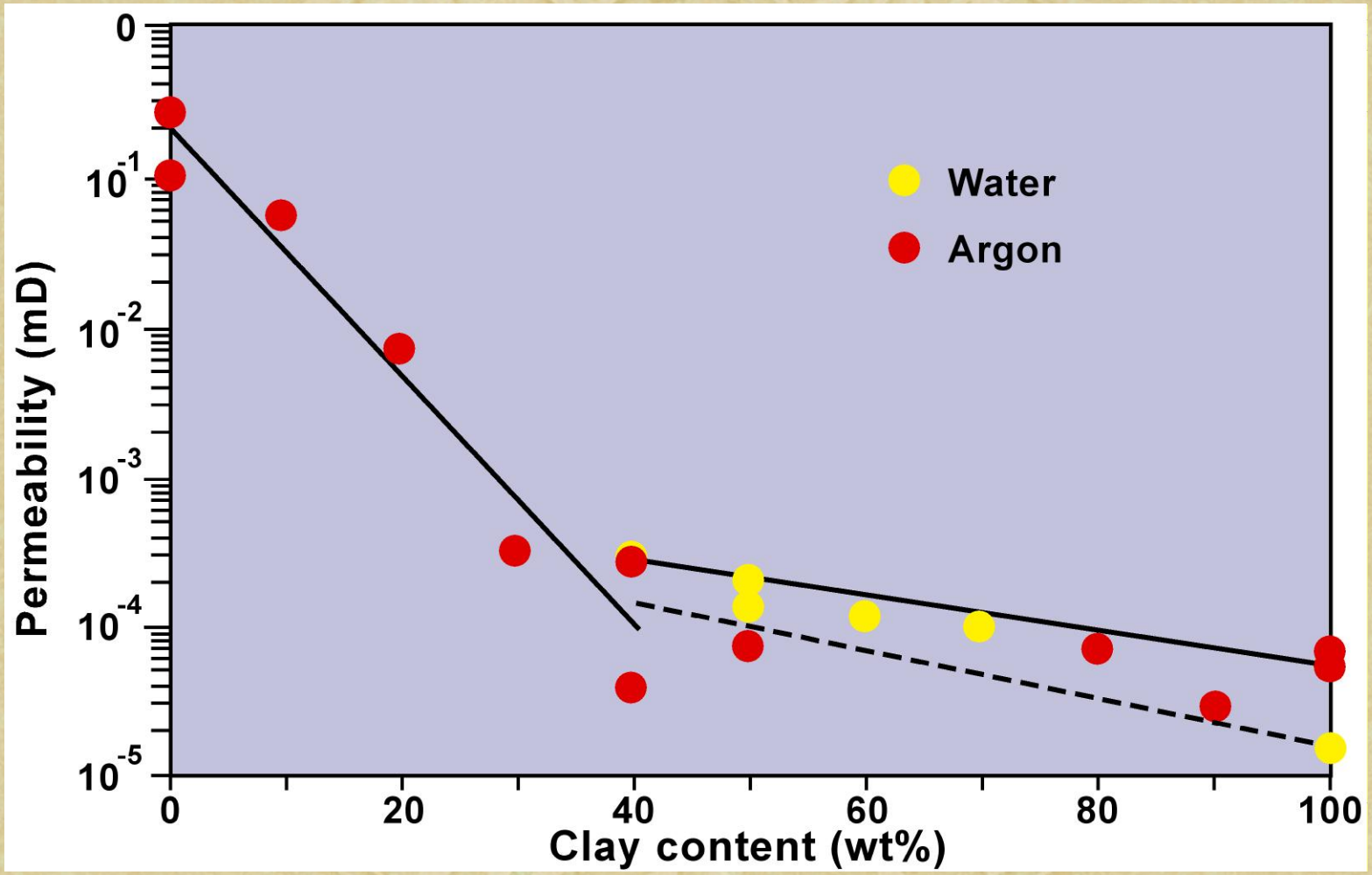
Fault Damage Zones



Capillary Entry Pressure V. Permeability



Compiled by Sorkhabi and Tsuji (2004)


Permeability (mD)
0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
20
40
60
80
100
Clay content (wt%)
Water
Argon

PROBLEM STATEMENT:

- **Multiple order of magnitude variations in permeability and capillary entry pressures in fault zones occur on spatial scales of centimeters to meters**

- **Reservoir to basin scale numerical flow models typically have grid elements on a scale of 10's of meters to hundreds of meters**

- **Up-scaling of these values is required to run numerical flow models**

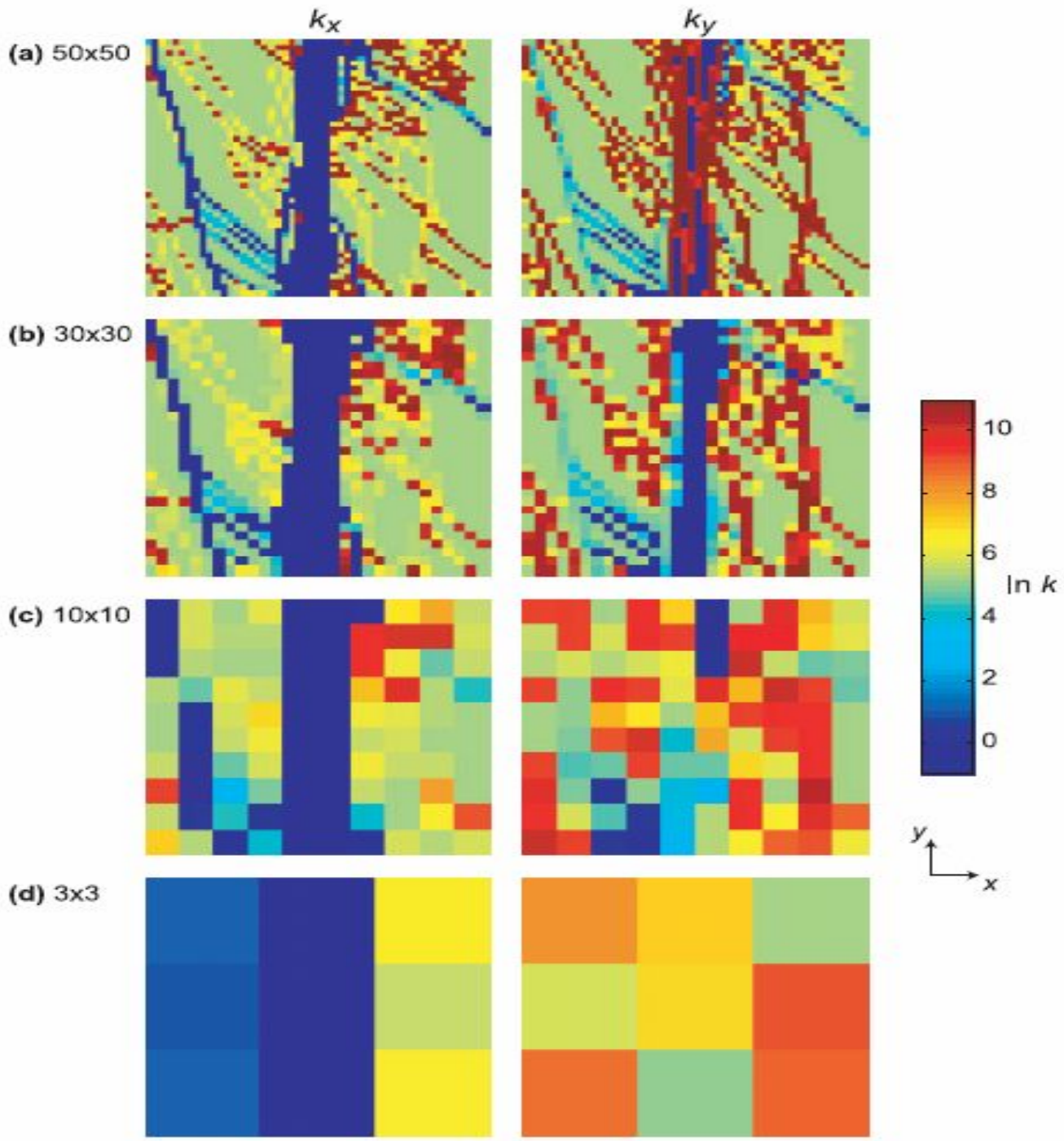
MATHEMATICAL VIEWPOINT

UPSCALING—the approximation of a system of partial differential equations by another, often of the same form, with known coefficients that can be solved with fewer computing resources.

Farmer, 2002

GEOLOGICAL VIEWPOINT

UPSCALING— taking limited petro-physical data from core plugs, and using well log data creating representative values for porosities and permeabilities for specific micro-facies within the aquifer.



From: Flodin et al, 2004

Modeling Solutions to Up-scaling

- Multi-scale grid building

- Wavelet grid building

But are these really SOLUTIONS?

UPSCALING POROSITIES

Porosities are a scalar.

- Arithmetic averages give a valid estimate of the porosity of a grid block if sufficient data are available

- Stochastic realizations based on 3D seismic or well log data can be used in absence of sufficient core measurements

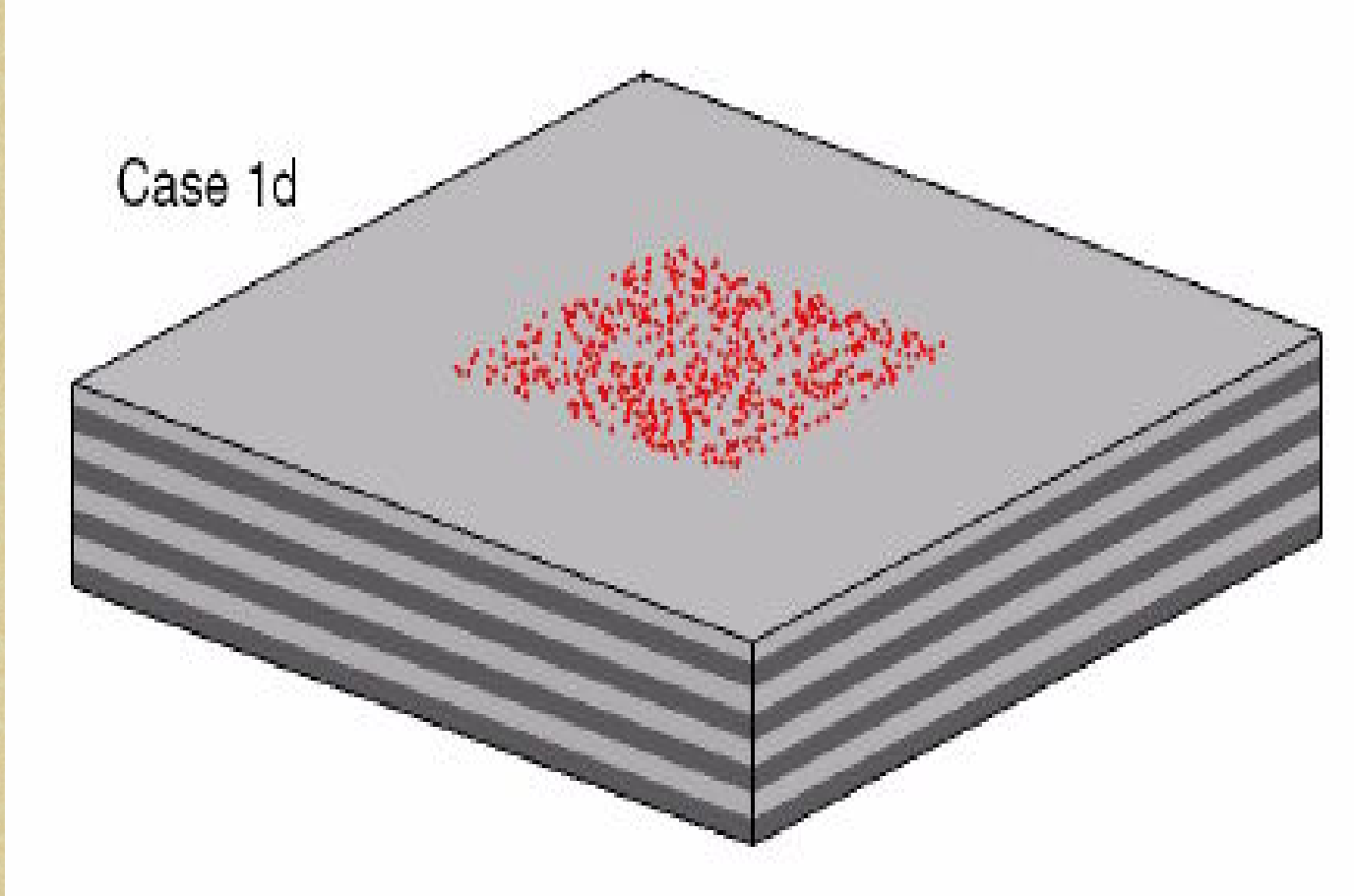
UPSCALING PERMEABILITIES

Permeabilities are a tensor.

- Arithmetic averages don't give a valid estimate of the permeability of a grid block
- The effective permeability of a grid block depends on the direction of flow through the block as well as the material properties
- In modeling flow effective permeability of a grid block depends on boundary conditions imposed on the model

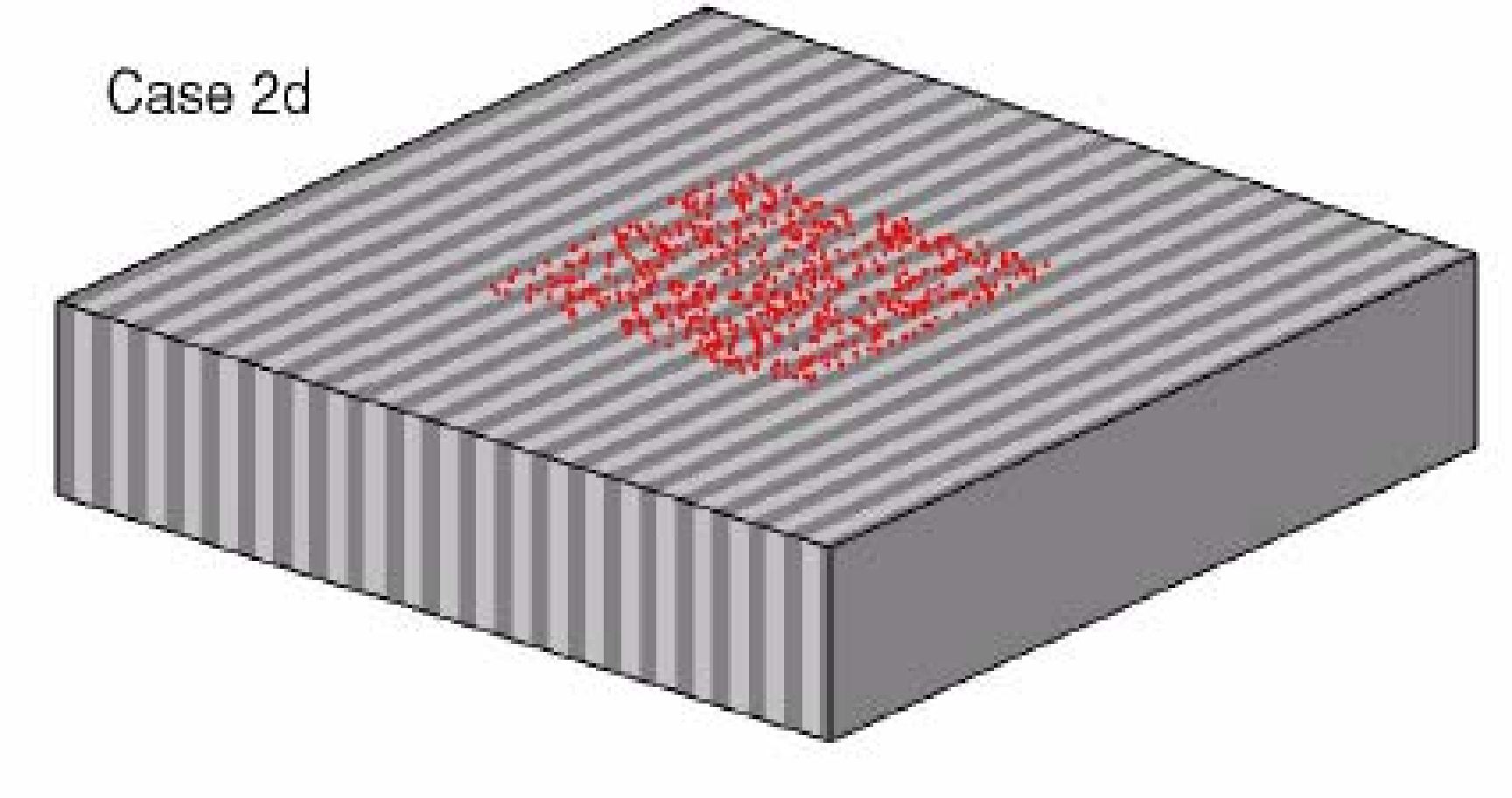
Harmonic Mean

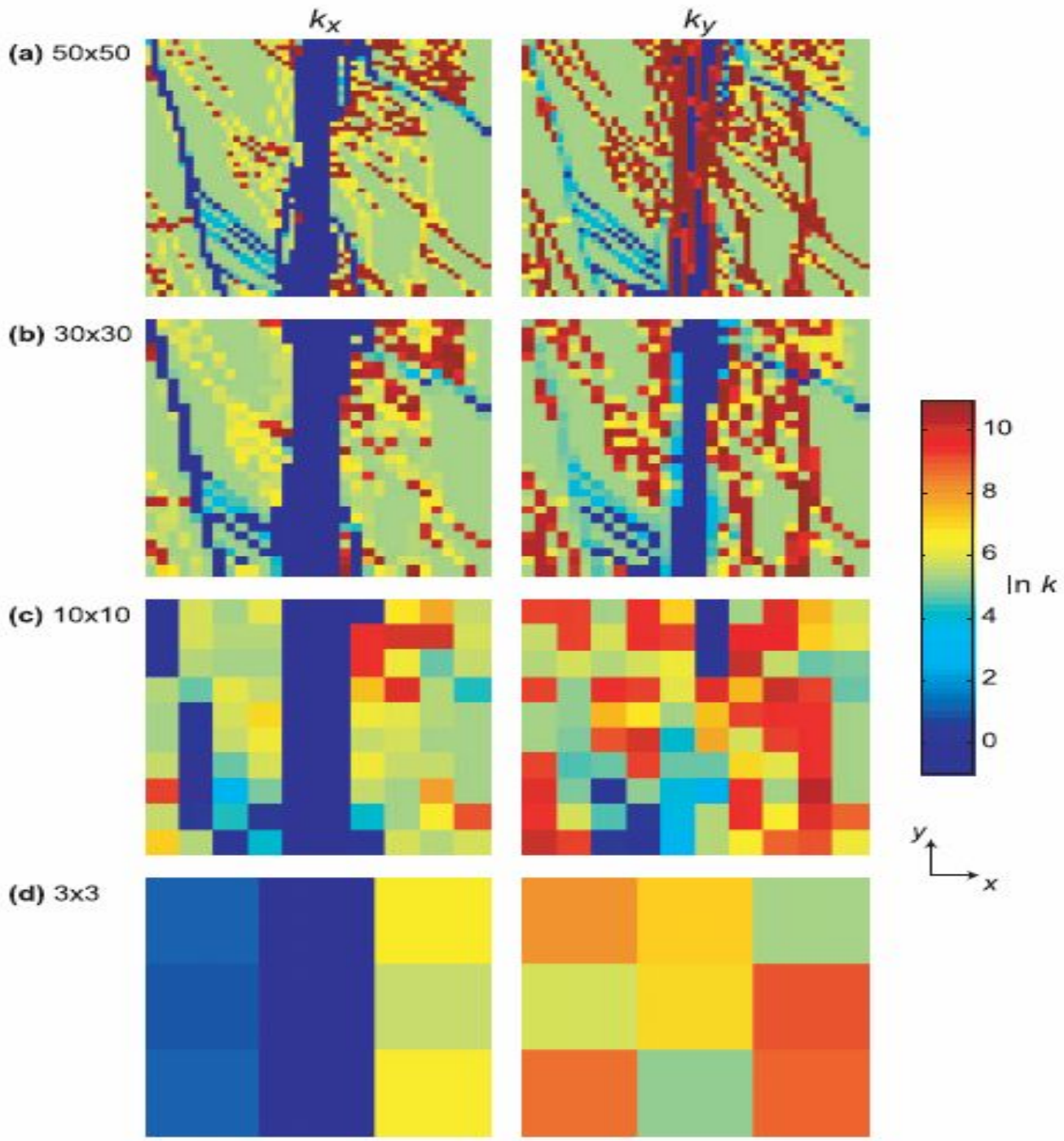
$$k_{eff} = \frac{\Delta z}{\frac{d_1}{k_1} + \frac{d_2}{k_2}}$$



Geometric Mean

$$k_{eff} = \frac{k_1 d_1 + k_2 d_2}{\Delta x \Delta y}$$





From: Flodin et al, 2004

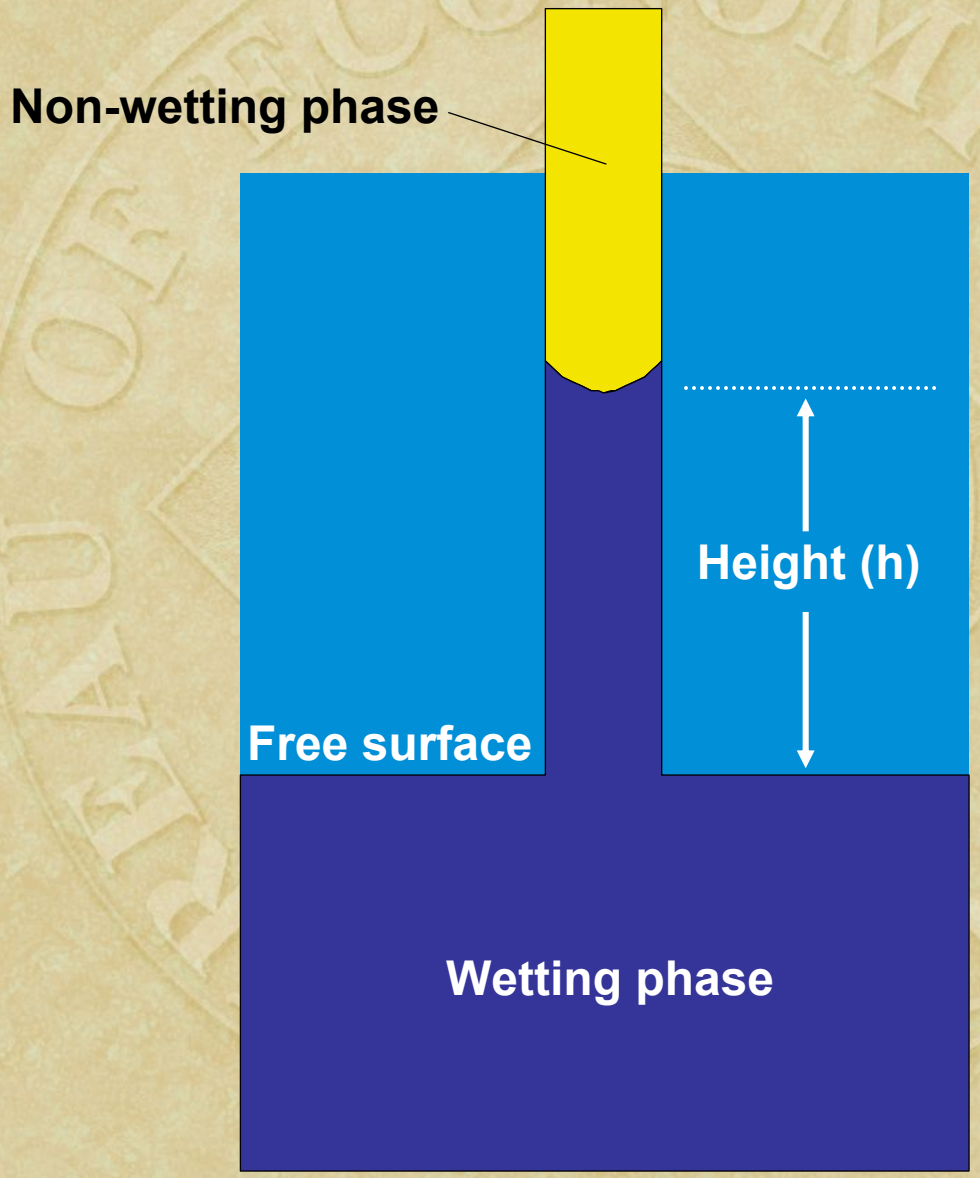
Up-scaling Capillary Entry Pressures

Capillary entry pressures are a scalar.

- Arithmetic averages give a valid estimate of the porosity of a grid block if sufficient data are available

- Stochastic realizations based on 3D seismic or well log data can be used in absence of sufficient core measurements

Capillary Effects at interface between two fluid phases

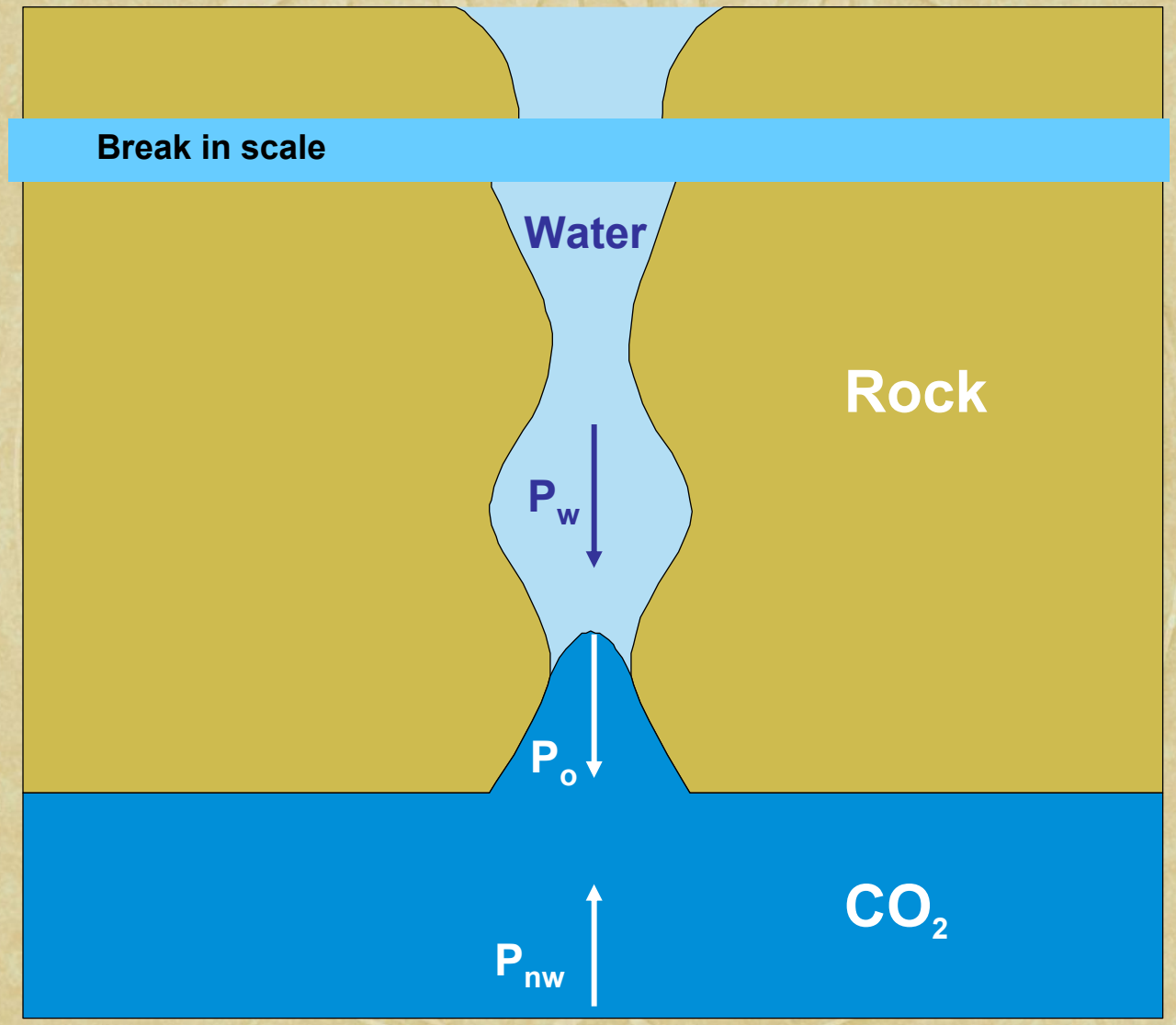


QAd5021(b)x

Scaling Capillary Entry Pressures

$$P_c = \frac{2\sigma}{r_p} \cos \theta,$$

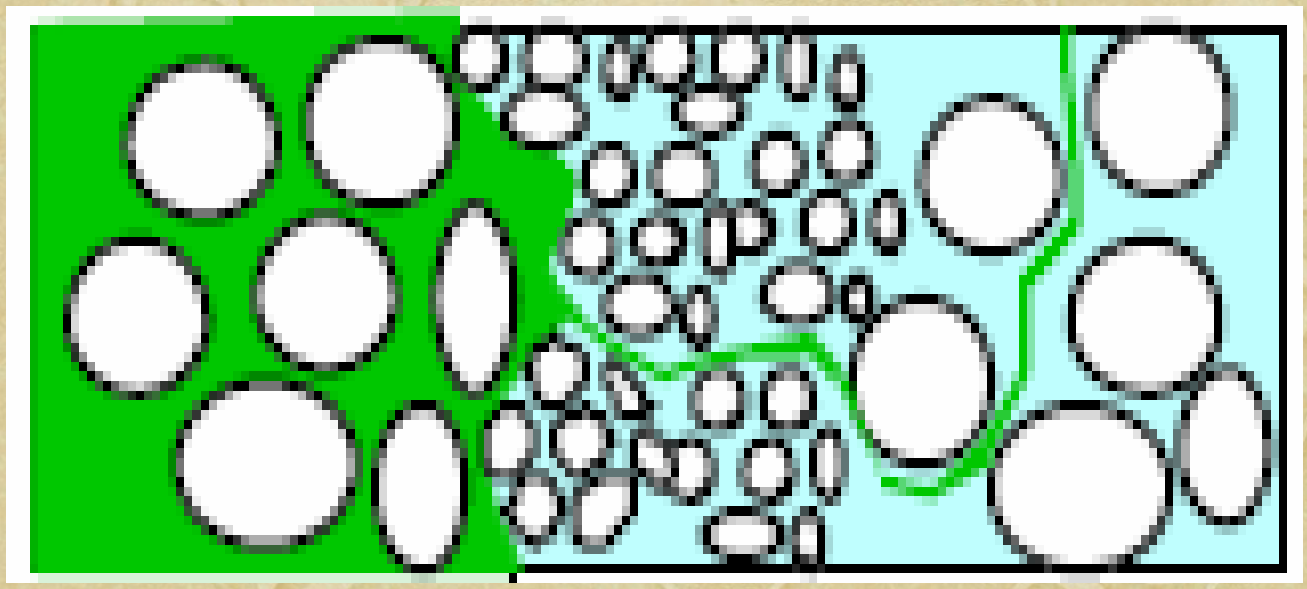
CAPILLARY ENTRY PRESSURE ACROSS A SEAL



$$P_c = P_{nw} - P_w$$

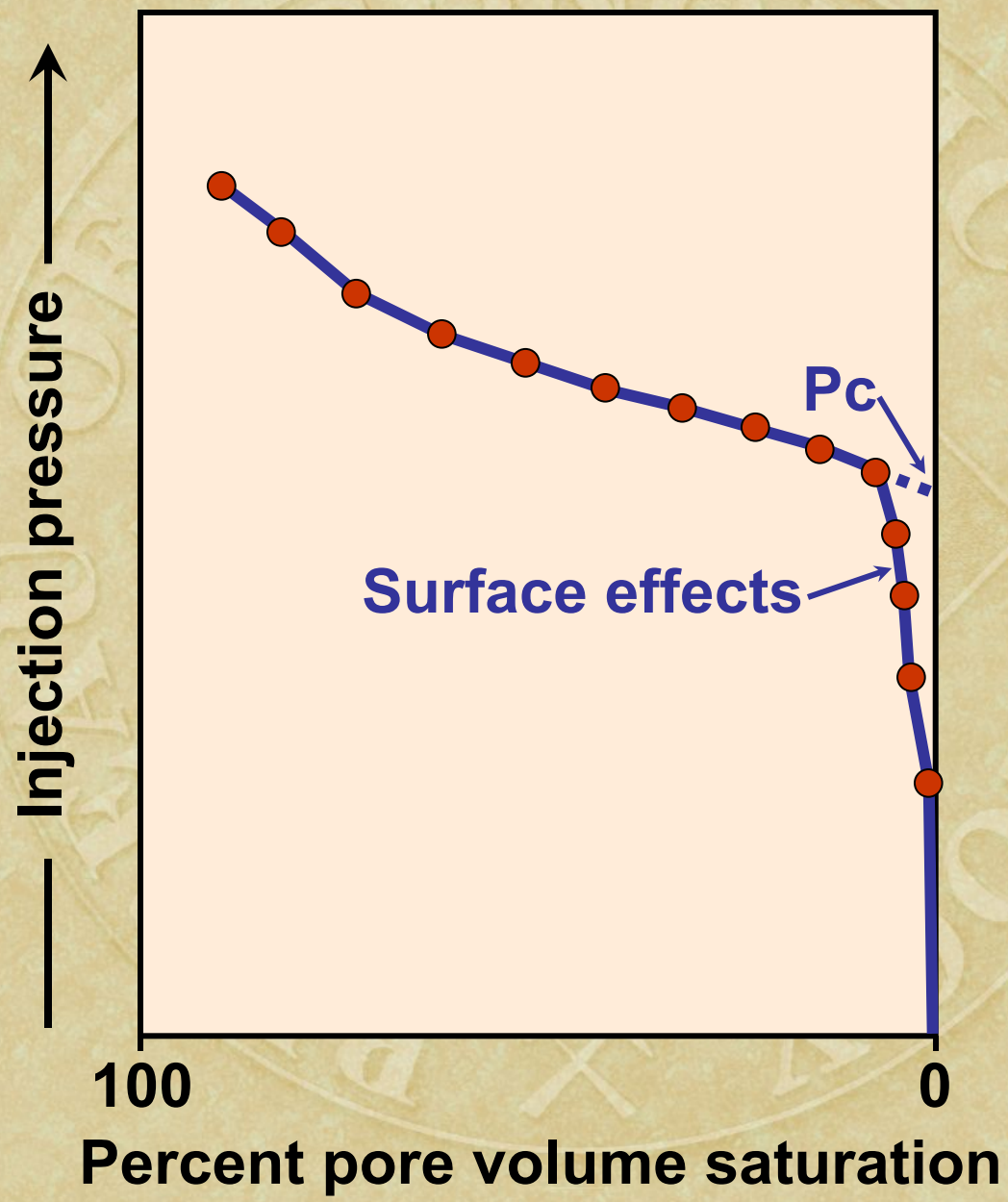
QAd5021(c)x

Capillary threshold pressure



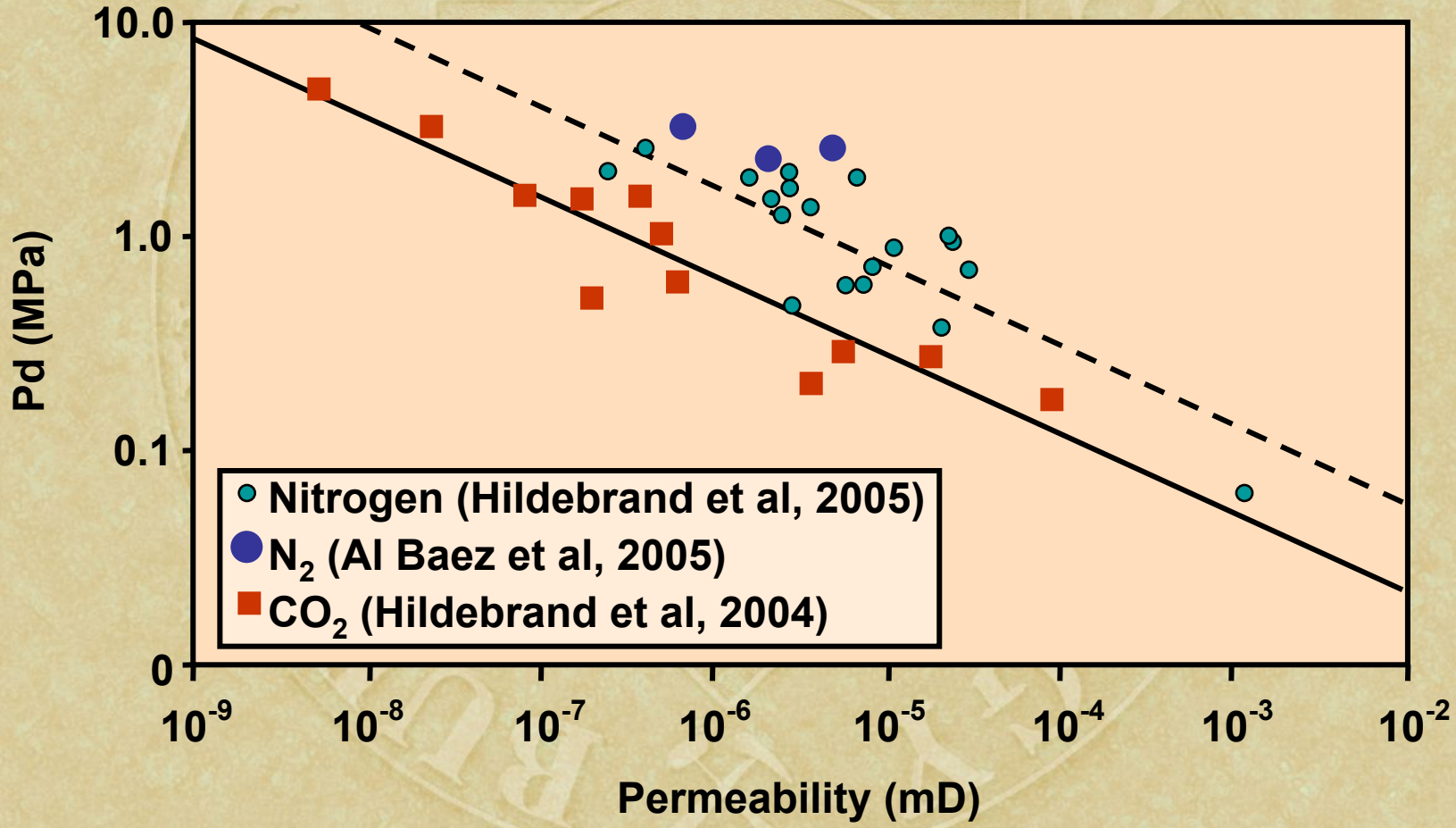
Differential water and CO_2 pressure

Capillary Injection Experiments



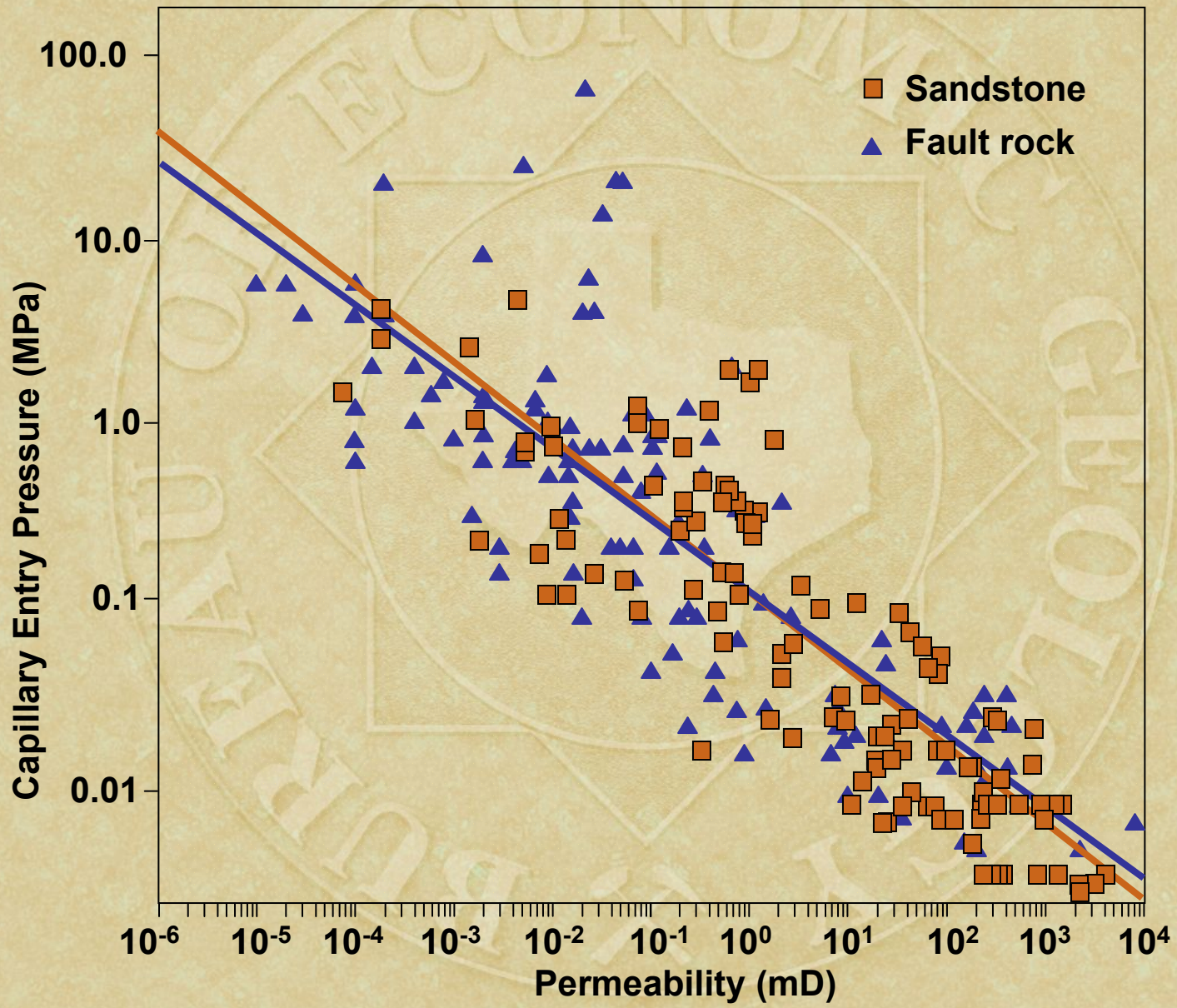
QAd5021(d)x

CAPILLARY ENTRY PRESSURE

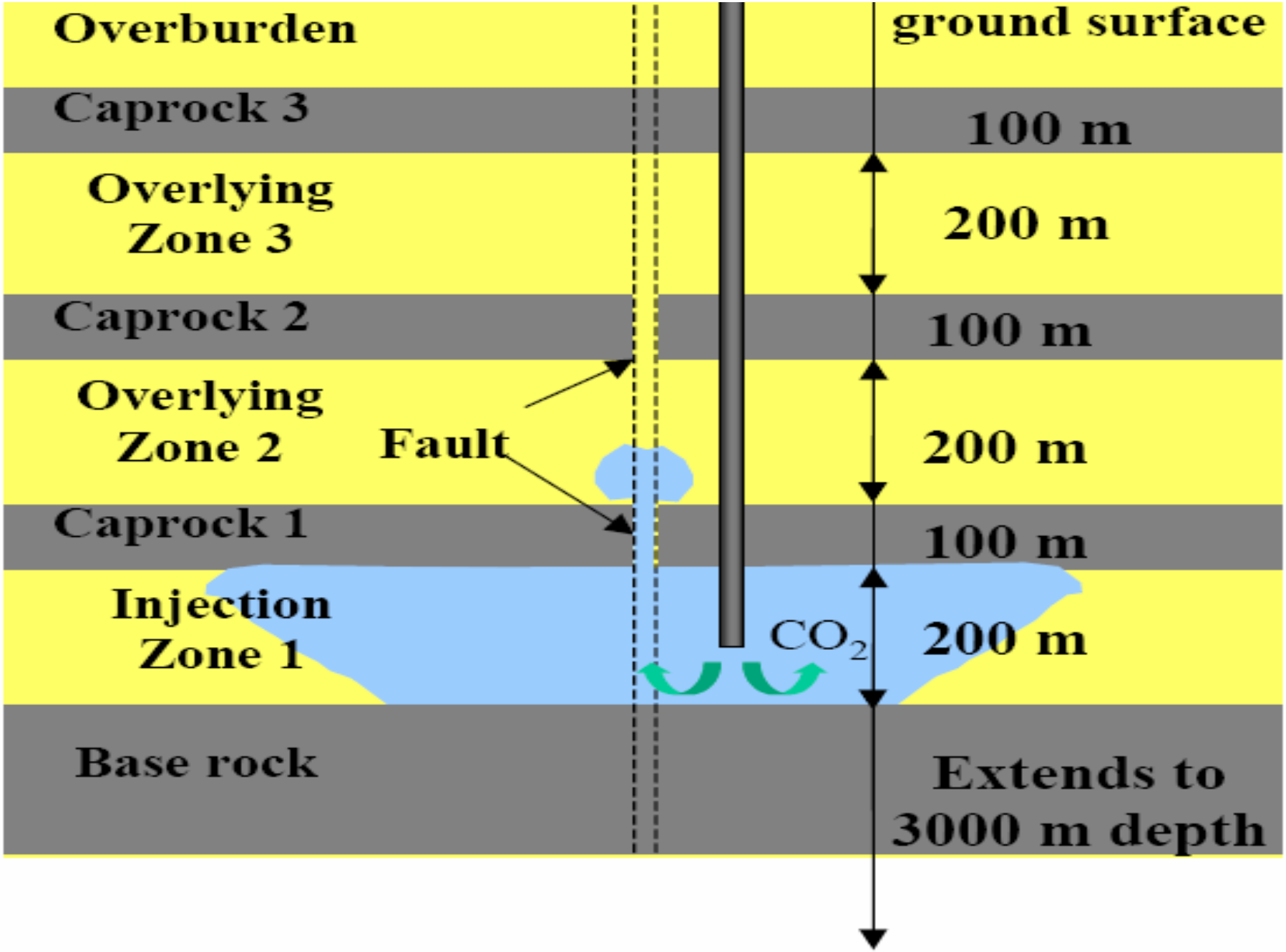


QAd5021(a)x

Capillary Entry Pressure V. Permeability



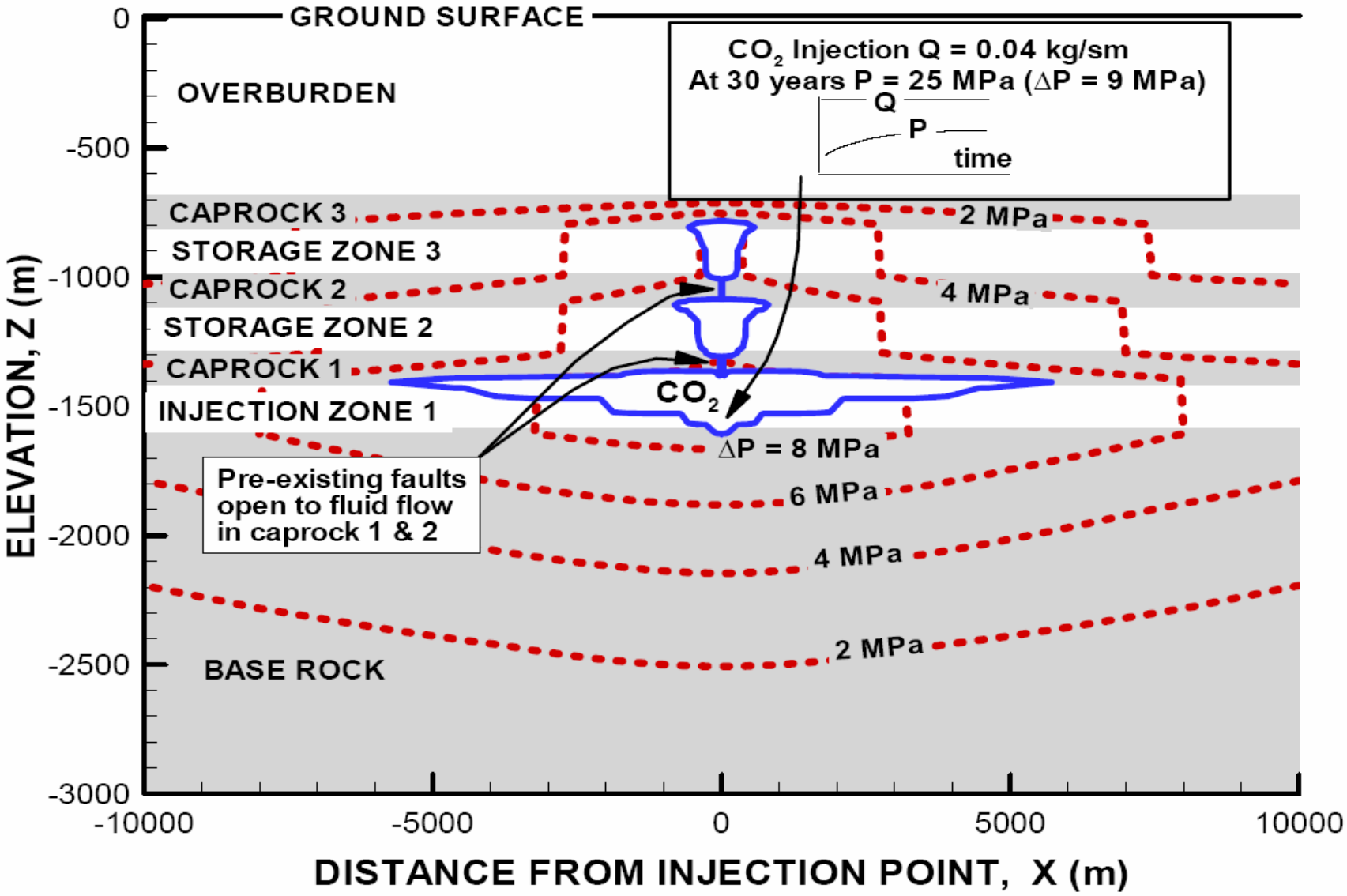
Compiled by Sorkhabi and Tsuji (2004)



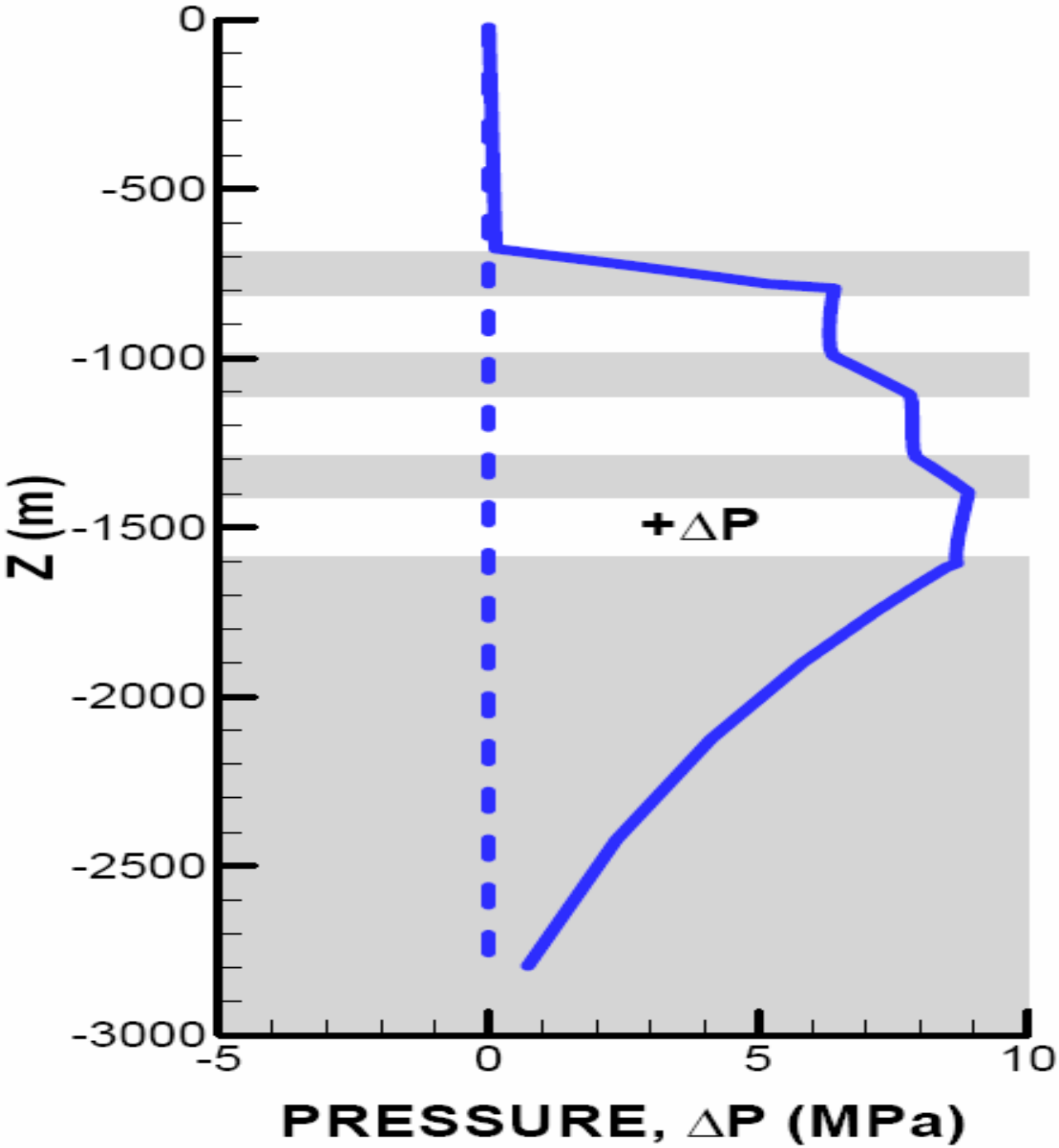
From Rutqvist et al

CO_2 PLUME AND CHANGES IN FLUID PRESSURE

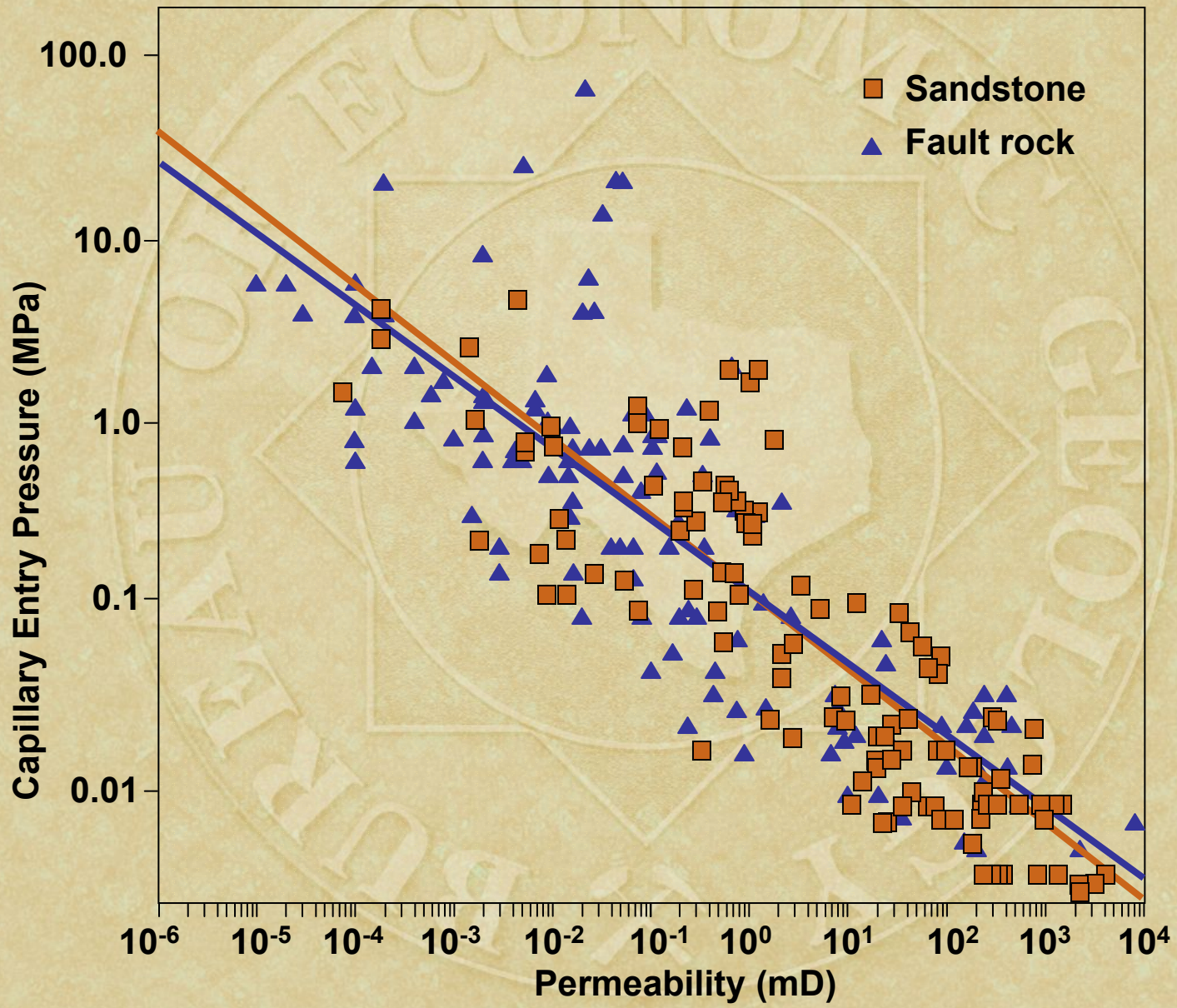
(At the end of the 30-year injection period)



- Injection pressure 70% of lithostatic stress (about 1.5 times hydrostatic pressure)


0
-500
-1000
-1500
-2000
-2500
-3000
Z (m)
+ΔP
-5
0
5
10
PRESSURE, ΔP (MPa)

Capillary Entry Pressure V. Permeability



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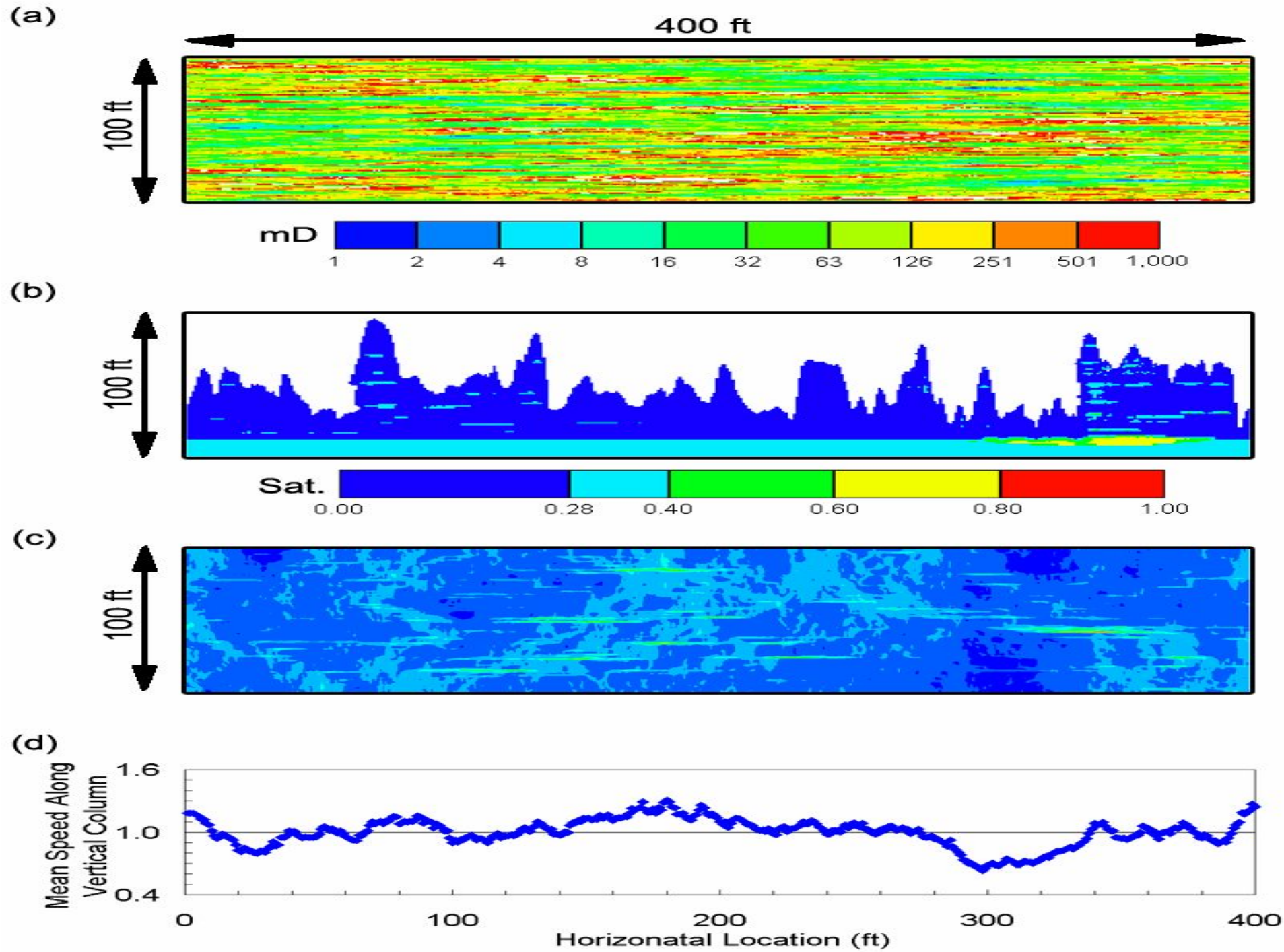
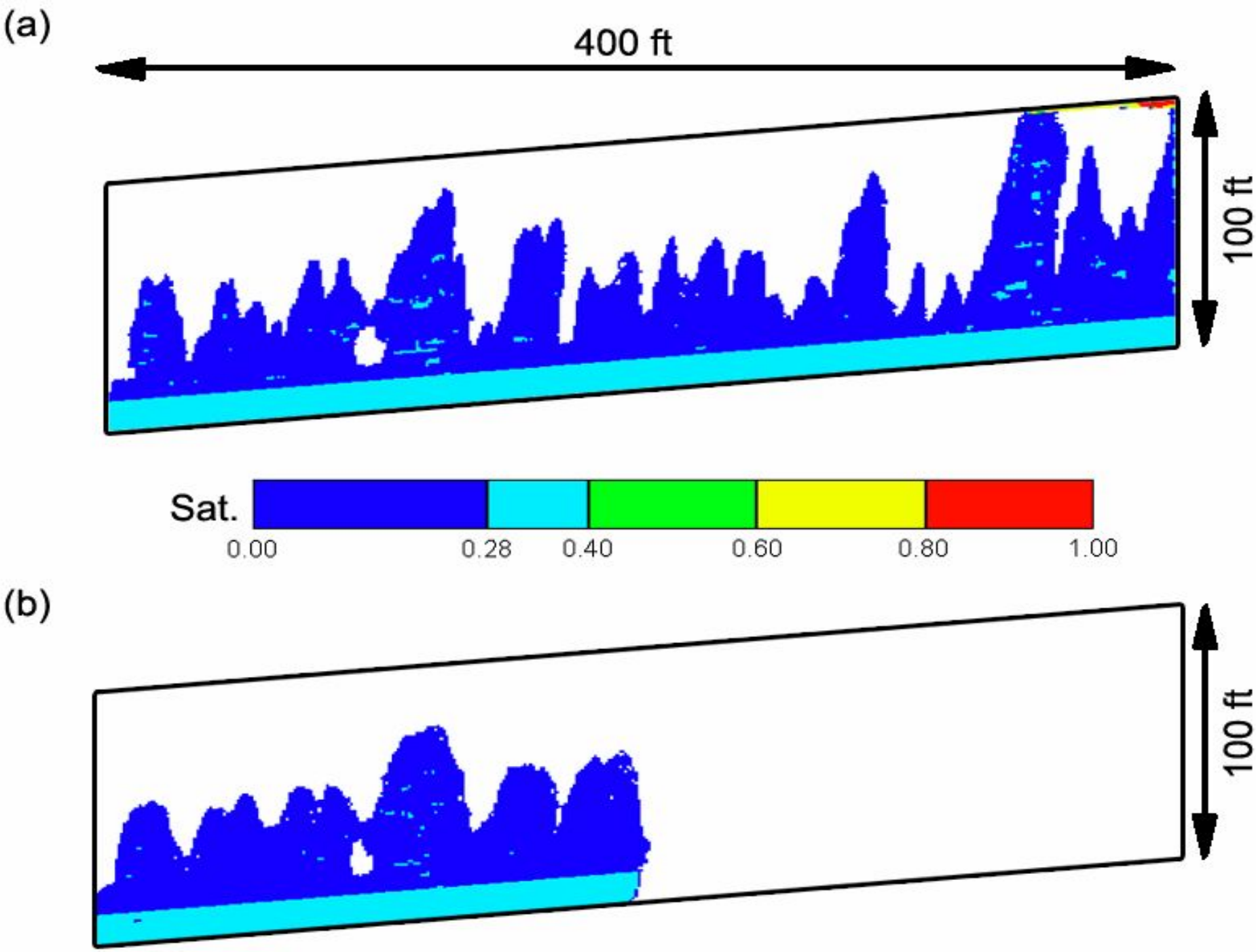
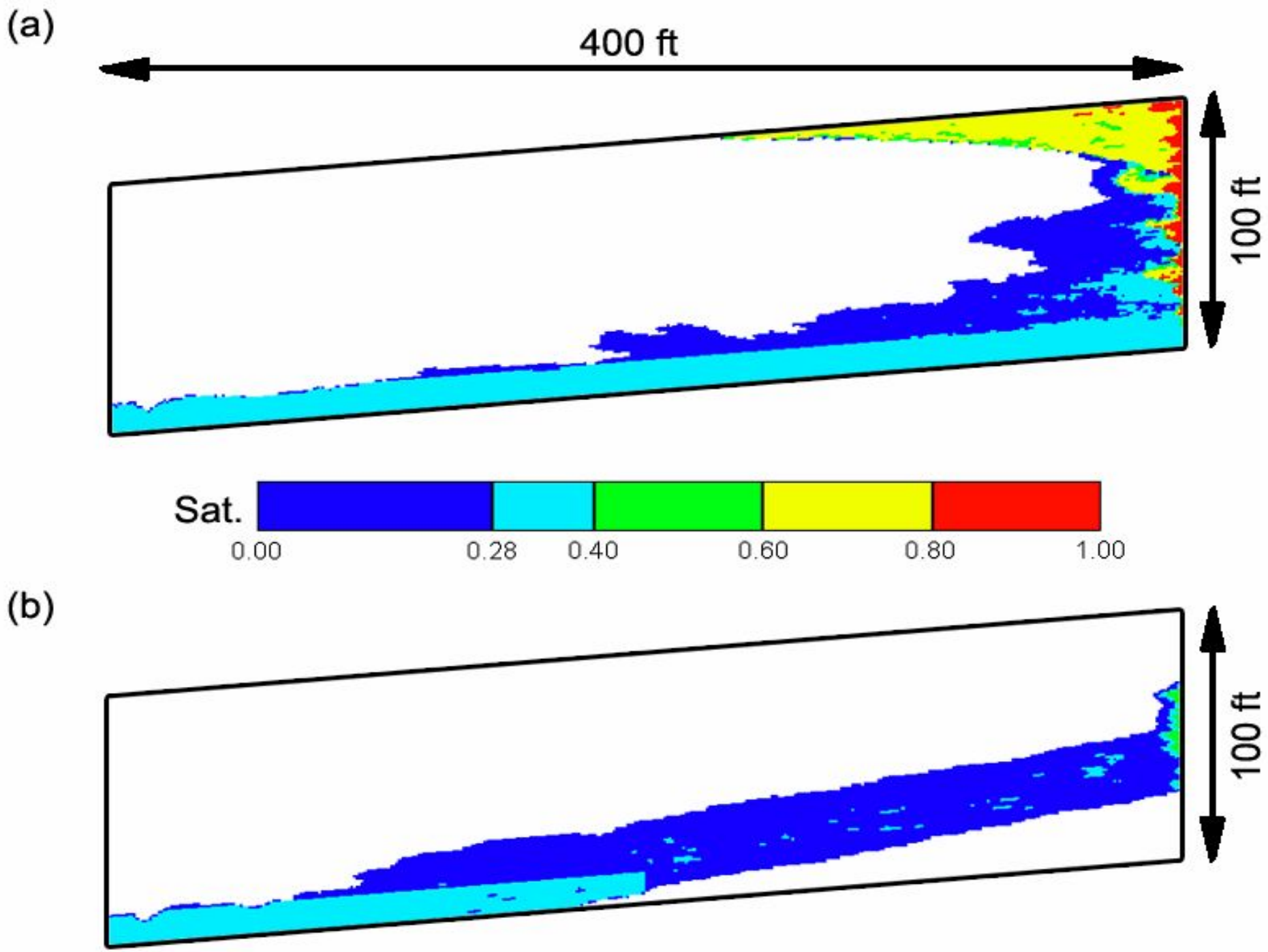

(a)
400 ft
100 ft
mD
1
2
4
8
16
32
63
126
251
501
1,000
(b)
100 ft
Sat.
0.00
0.28
0.40
0.60
0.80
1.00
(c)
100 ft
(d)
Mean Speed Along Vertical Column
1.6
1.0
0.4
0
100
200
300
400
Horizonatal Location (ft)


(a)
400 ft
100 ft
Sat.
0.00
0.28
0.40
0.60
0.80
1.00
(b)
100 ft


(a)
400 ft
100 ft
Sat.
0.00
0.28
0.40
0.60
0.80
1.00
(b)
100 ft

CONCLUSIONS

Up-scaling Permeabilties in Faults:

- Problem of effective permeabilities not resolved

Up-scaling Capillary Entry Pressures:

- Capillary entry pressures are key parameters to model CO2 flow in faulted reservoirs
- Capillary entry pressure can’t be upgraded