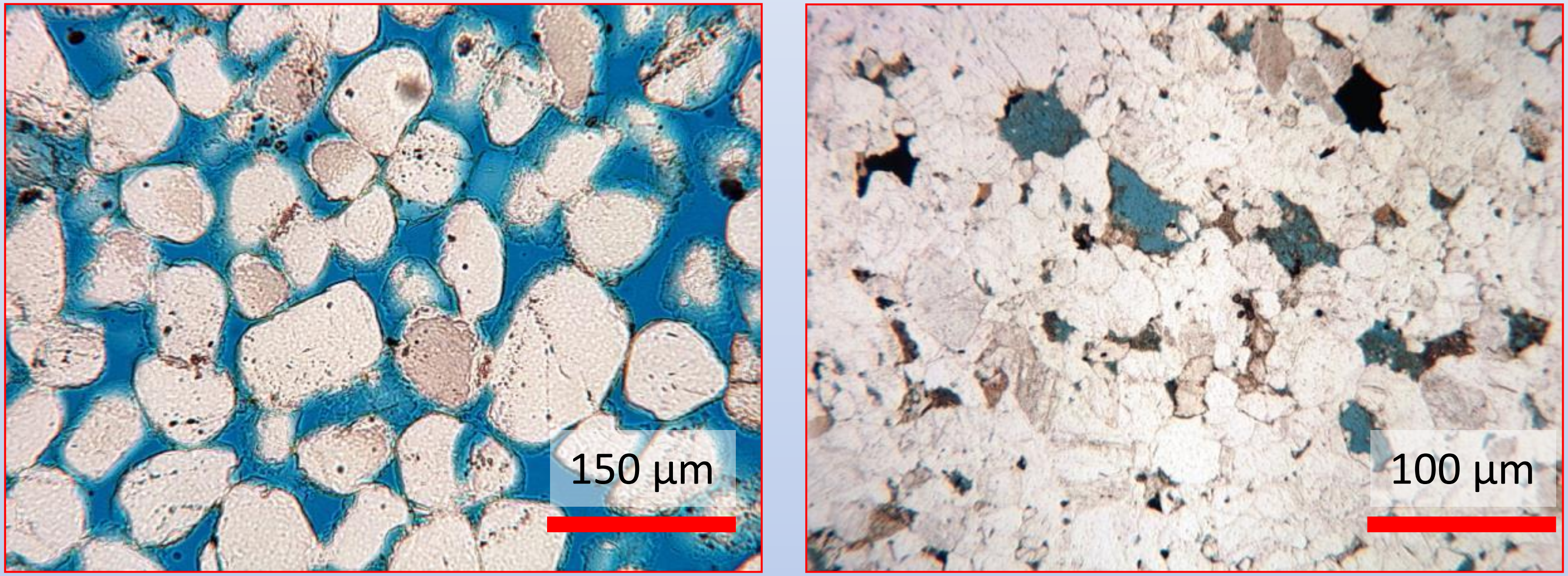
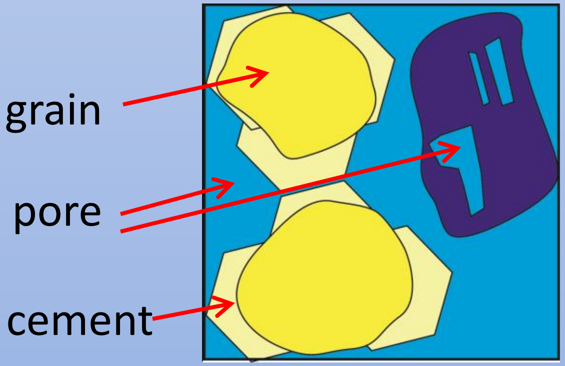
Chemical and Mechanical Controls on Reservoir Quality



Two quartz-rich fine sandstones. Pores are injected with blue-dyed medium. Thin section viewed in transmitted plane-polarized light.

Why is the porosity so different between these two samples? (and, in fact, also permeability, velocity, elastic moduli….)?

- Depositional environment?
- Age?
- Fluid flow?
- Burial depth?

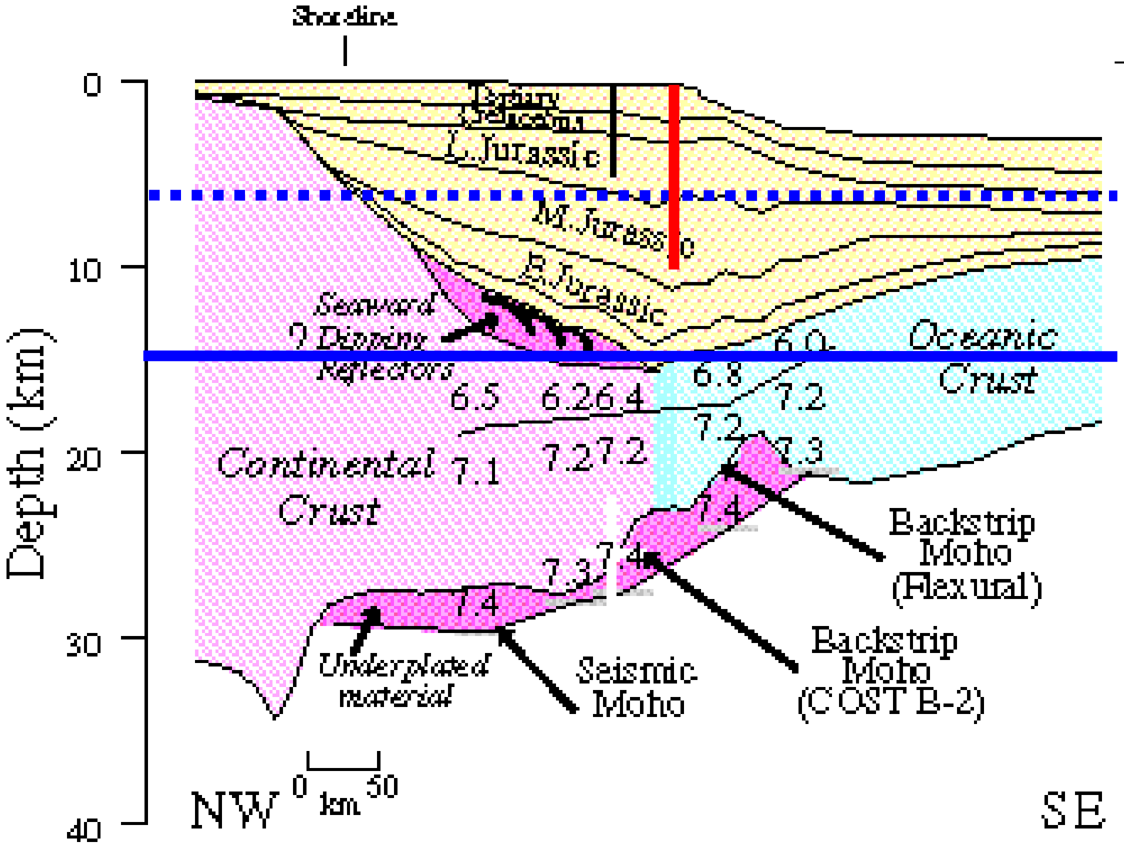


Diagenesis encompasses all of the chemical and mechanical processes that affect sediments and sedimentary rocks between deposition and metamorphism and between metamorphism and weathering. Diagenesis is a major control on reservoir quality.

40% of dry holes may be attributed to inaccurate assessment of reservoir rock properties (Rose, 1987, p. 11).

The Realm of Diagenesis:

Sedimentary basins constitute a significant portion of total crustal thickness.



	°C/km 20	30
6 km	140°	200°
15 km	320°	470°

The boundary between "diagenesis" and "metamorphism" is gradational and within reach of deep drilling.

www.earth.ox.ac.uk/ ~tony/watts/MARGIN/MARGIN.HTM

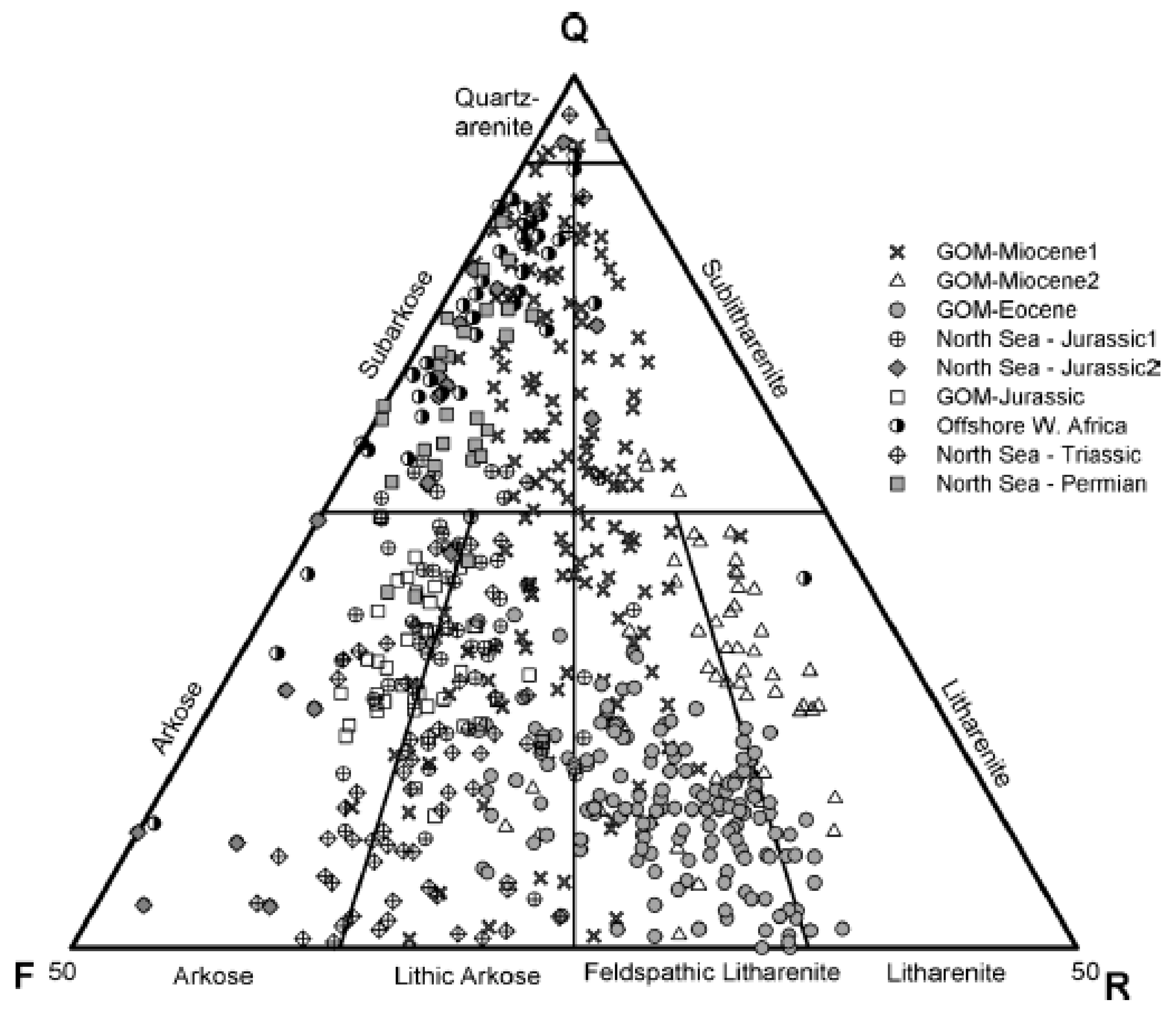
Elements of Diagenesis:

- *Compaction*
- *Cementation*
- Dissolution
- Replacement
- Fracturing (apart from compaction)

Evolution of porosity and other bulk rock properties in sediments is controlled by post-depositional mechanical and chemical processes.

“Schools” of reservoir quality prediction

- Empirical
- Chemical modeling
- Hybrid empirical-chemical/mechanical modeling

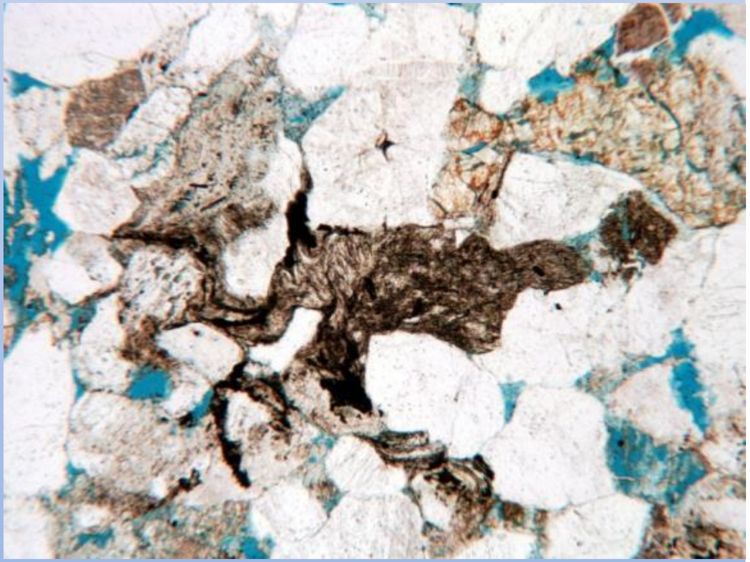


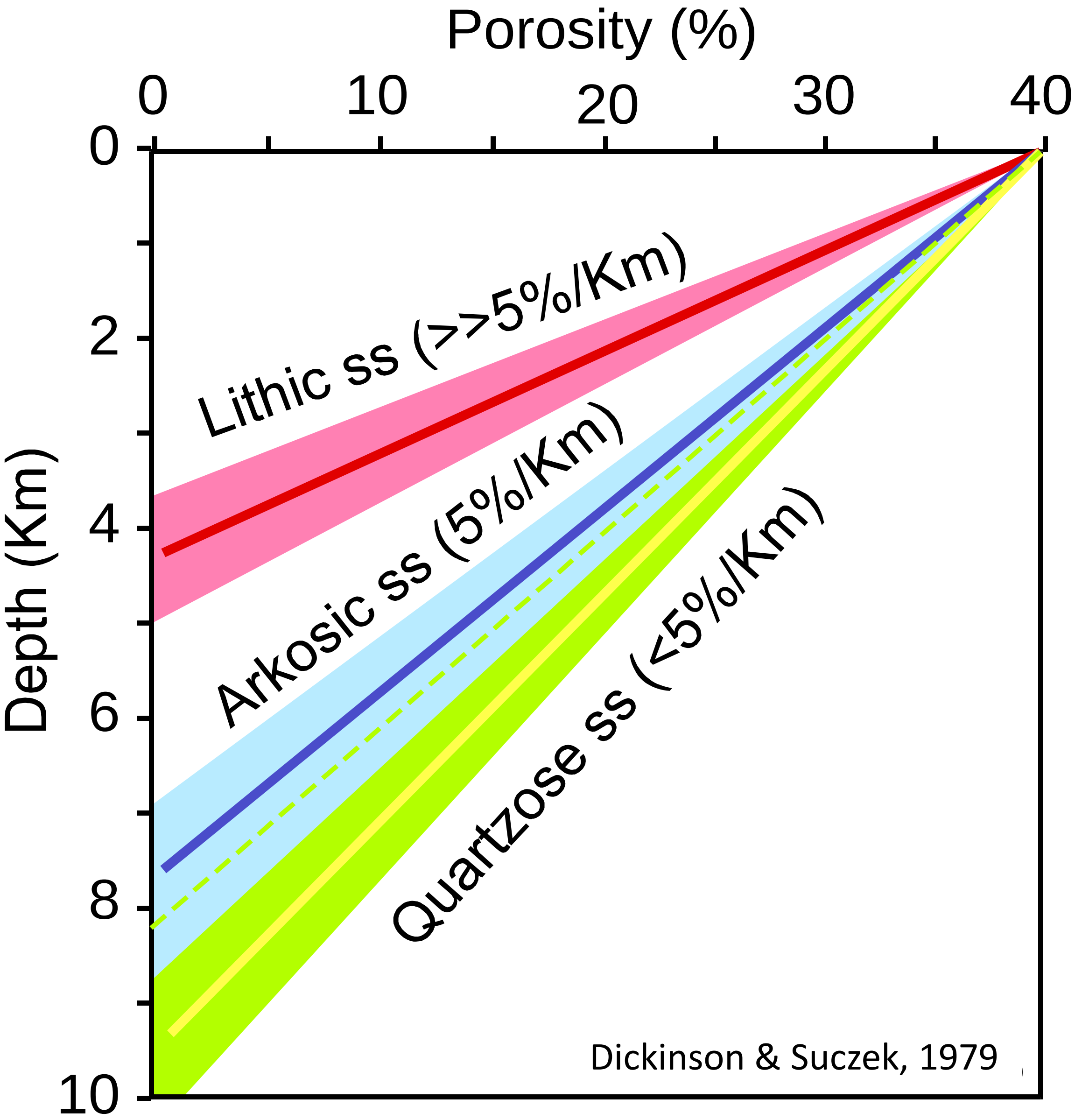
Taylor et al., 2010

Provenance Control on Reservoir Quality Relative to Depth

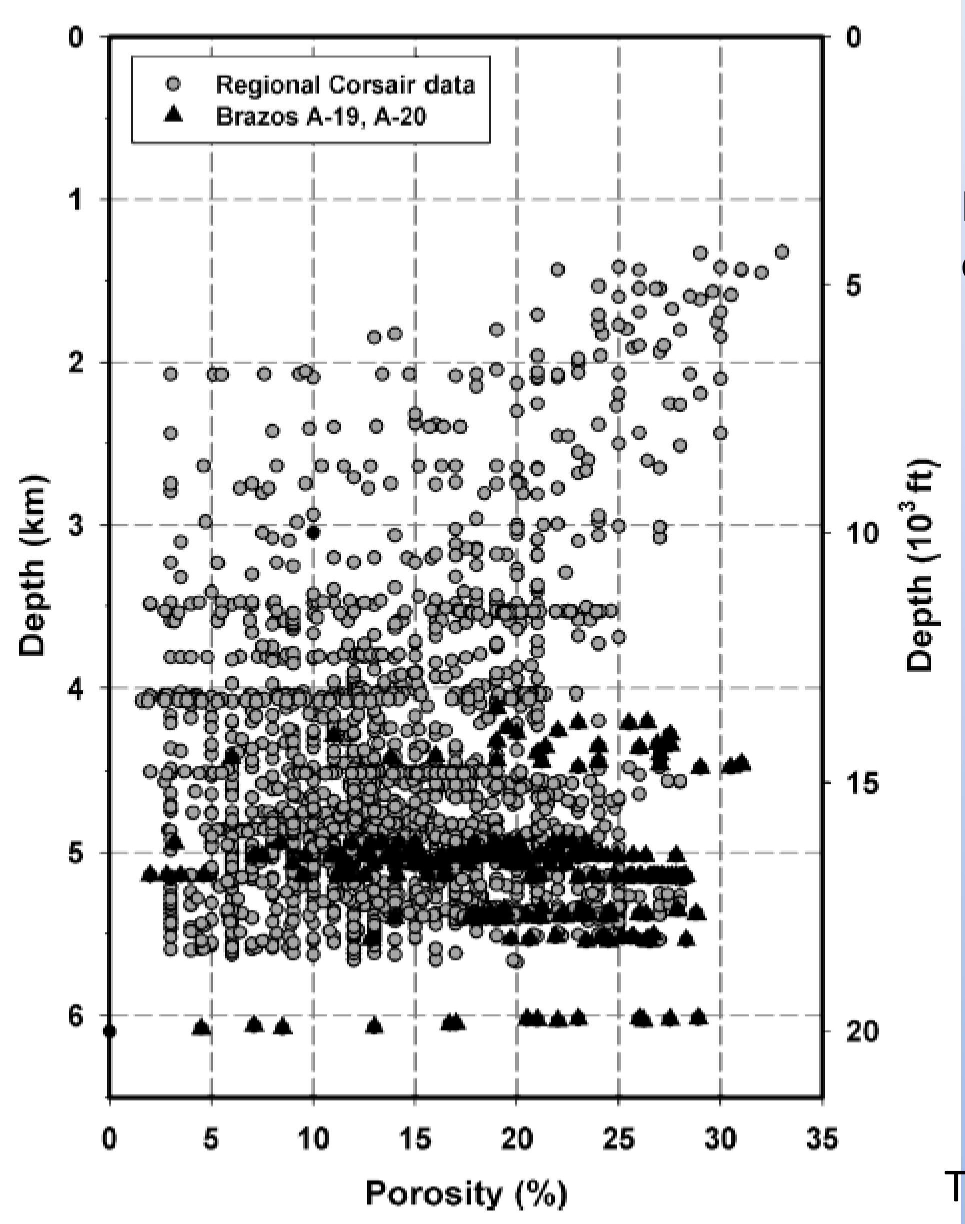
Lithic-rich sandstones, which are chemically and mechanically unstable, lose porosity at a greater rate with depth than do quartz-rich sandstones.

Ductile rock fragments (e.g., shale, phyllite, tuffaceous VRF) accelerate the rate of porosity loss in lithic sandstones



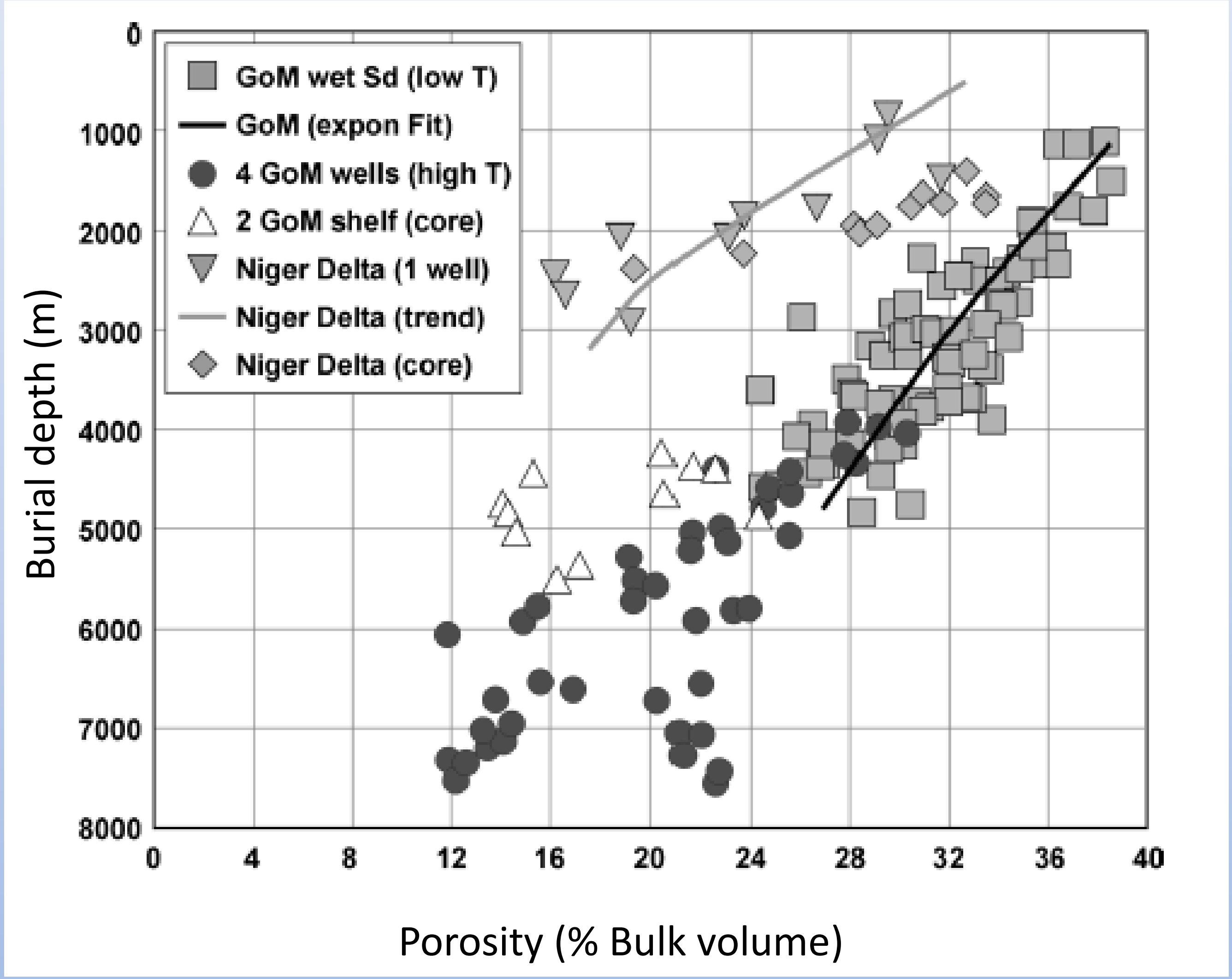


Dickinson & Suczek, 1979



Miocene sandstones,
offshore Gulf of Mexico

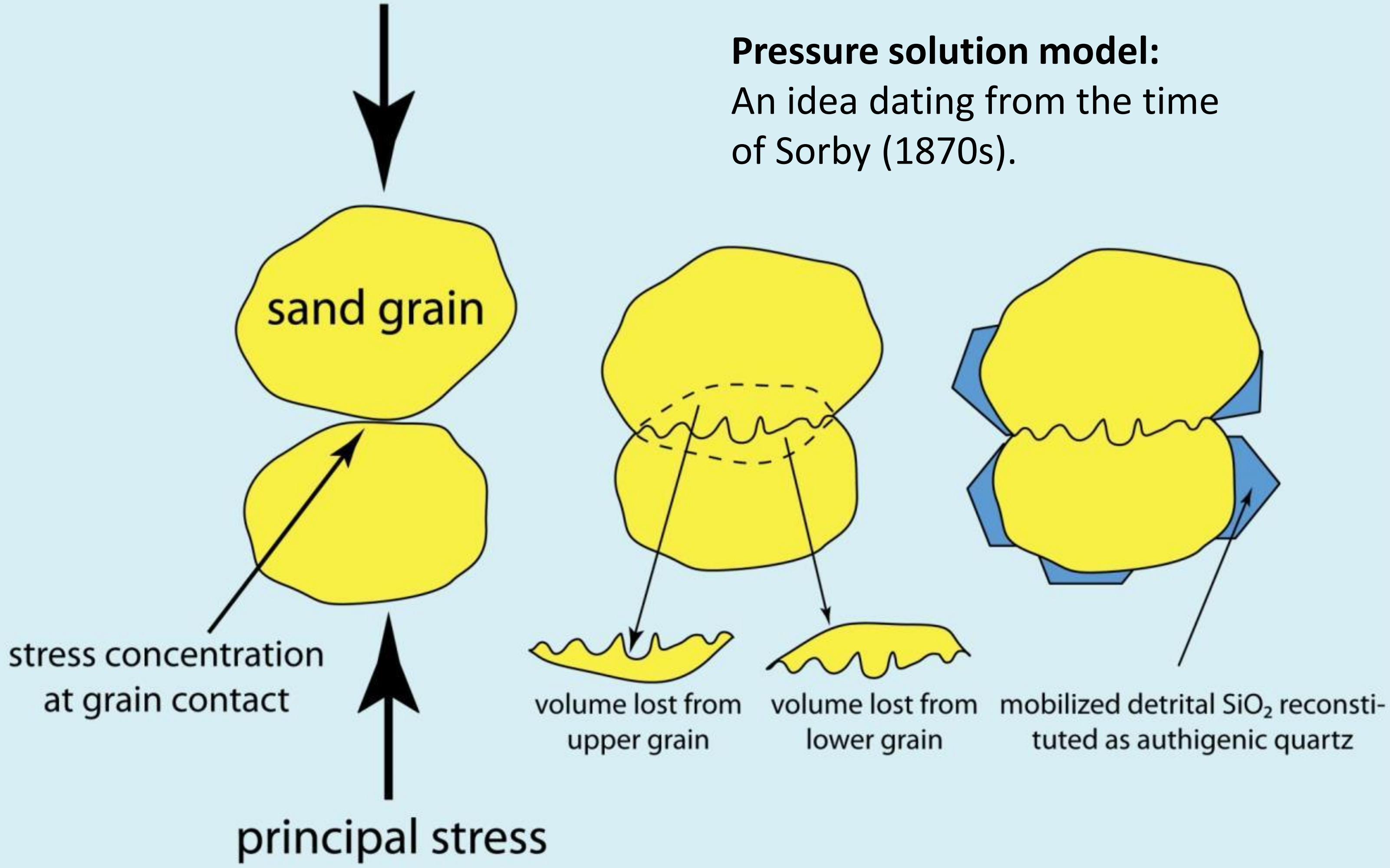
Taylor et al., 2010

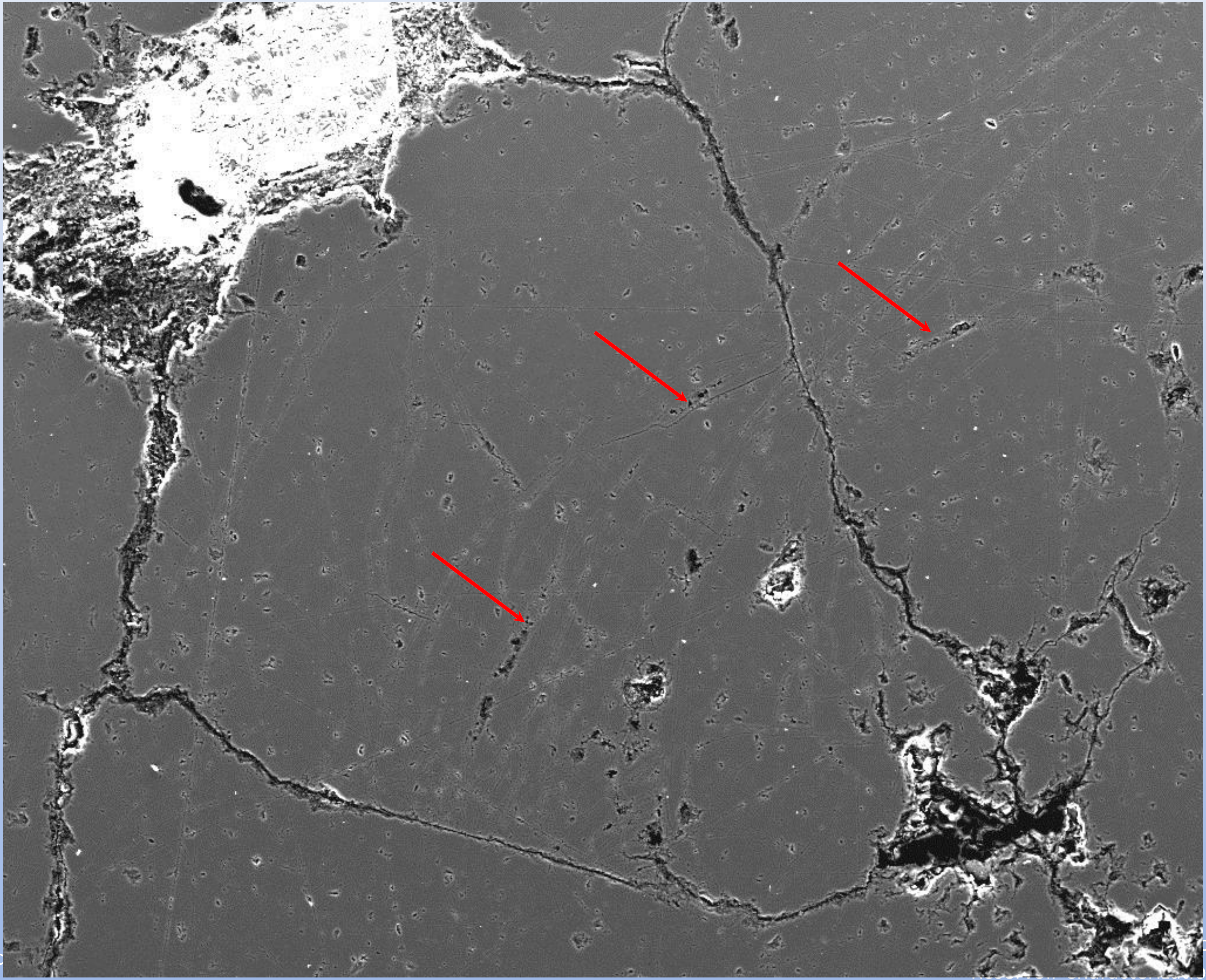


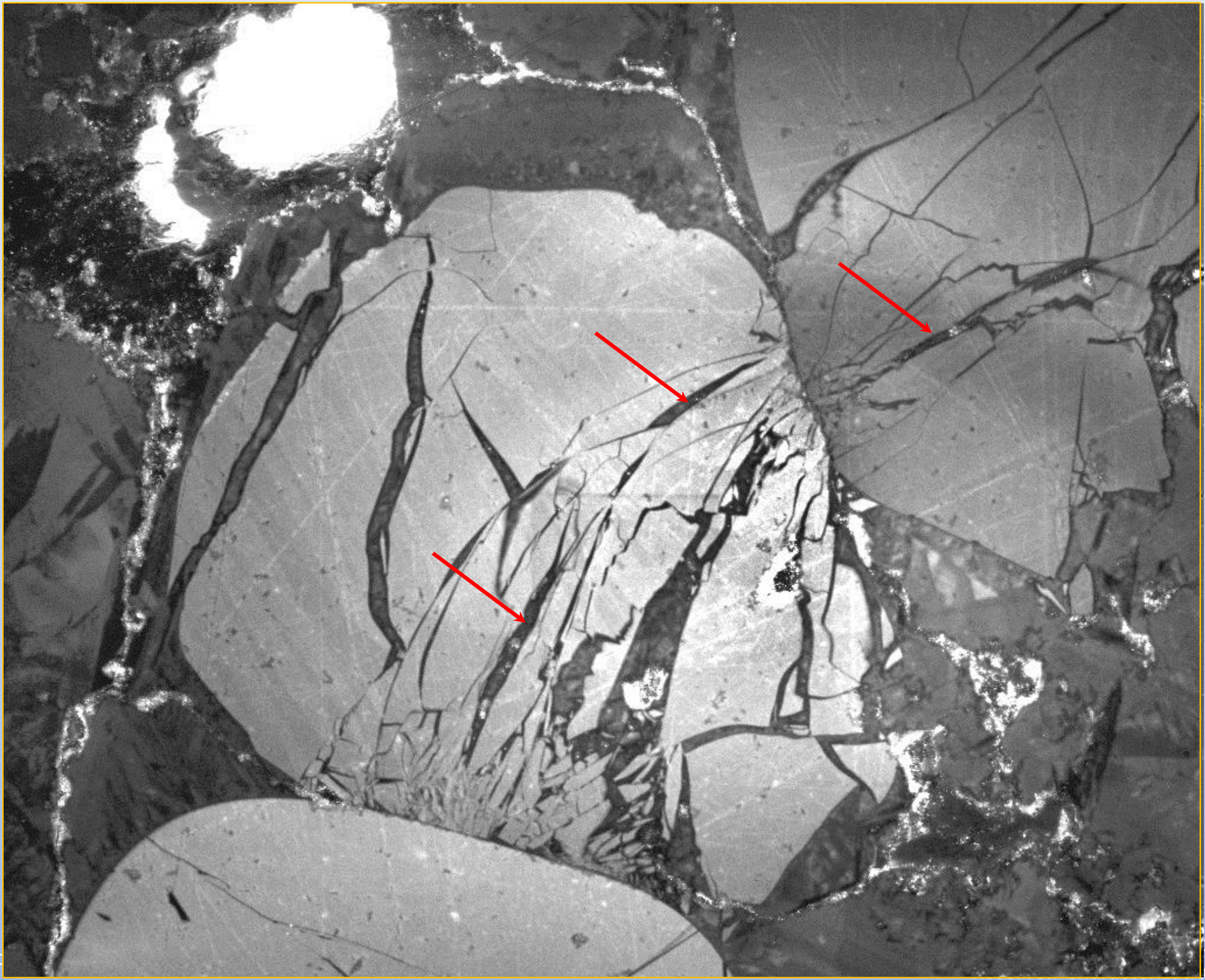
Taylor et al., 2010

Why does porosity progressively decline in the subsurface?

Pressure solution model:
An idea dating from the time of Sorby (1870s).







Conoc

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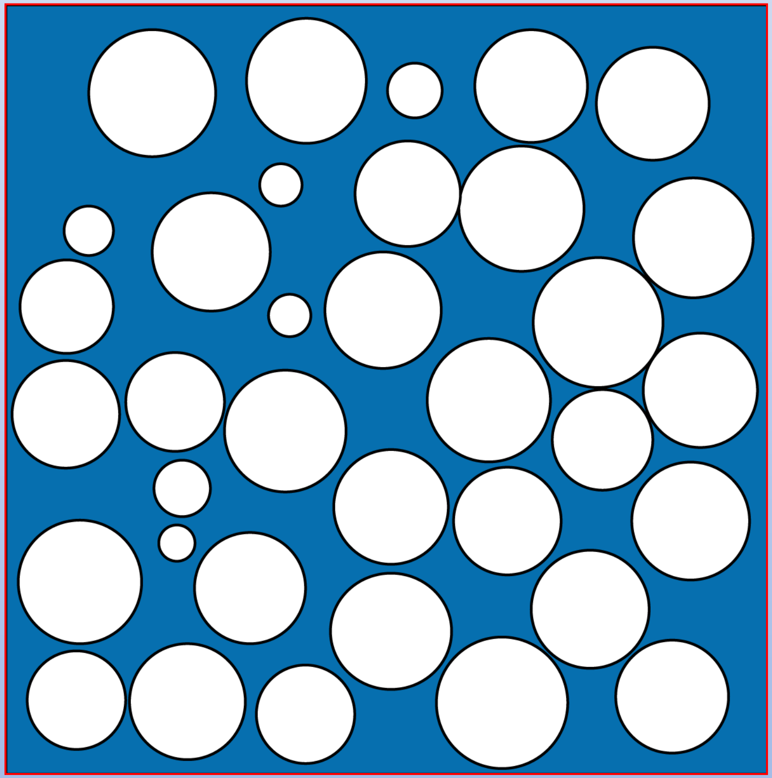
Compaction: IGV concept

The Intergranular Volume (IGV) Concept in Sandstones:
At deposition, in well-sorted sand, the intergranular space makes up 40-45% by volume. Grains make up 55-60%.

Marbles in blue epoxy;
pore space = 43%



Compaction: IGV concept

Compaction is the most important cause of porosity decline in the subsurface.

Four principal mechanisms of IGV decline in well-sorted sand:

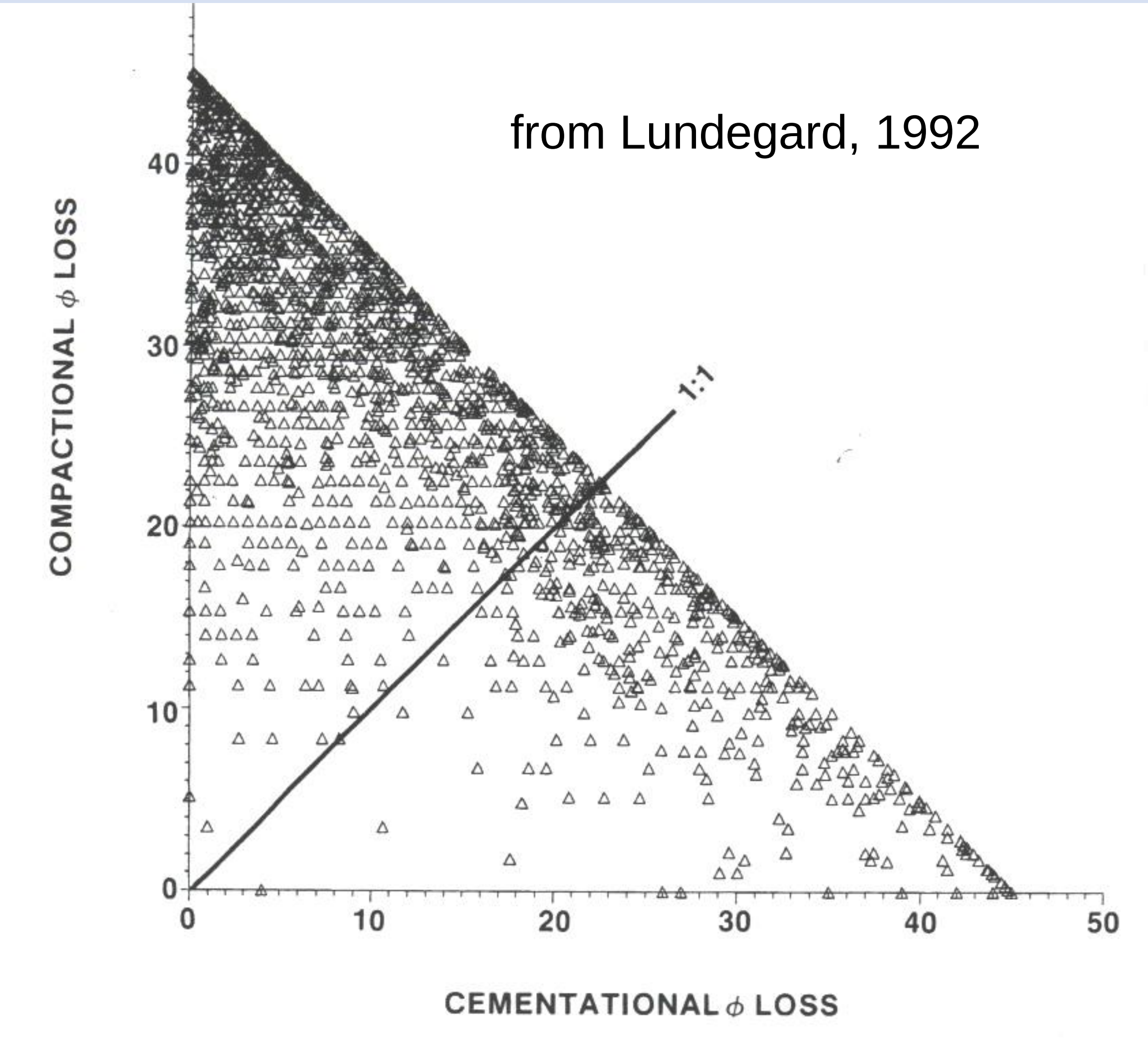
grain rearrangement
ductile deformation
pressure solution:
  grain-to-grain
  stylolites
brittle fracture

Compactional porosity loss:

$$COPL = P_i - \frac{(100 - P_i) * IGV}{100 - IGV}$$

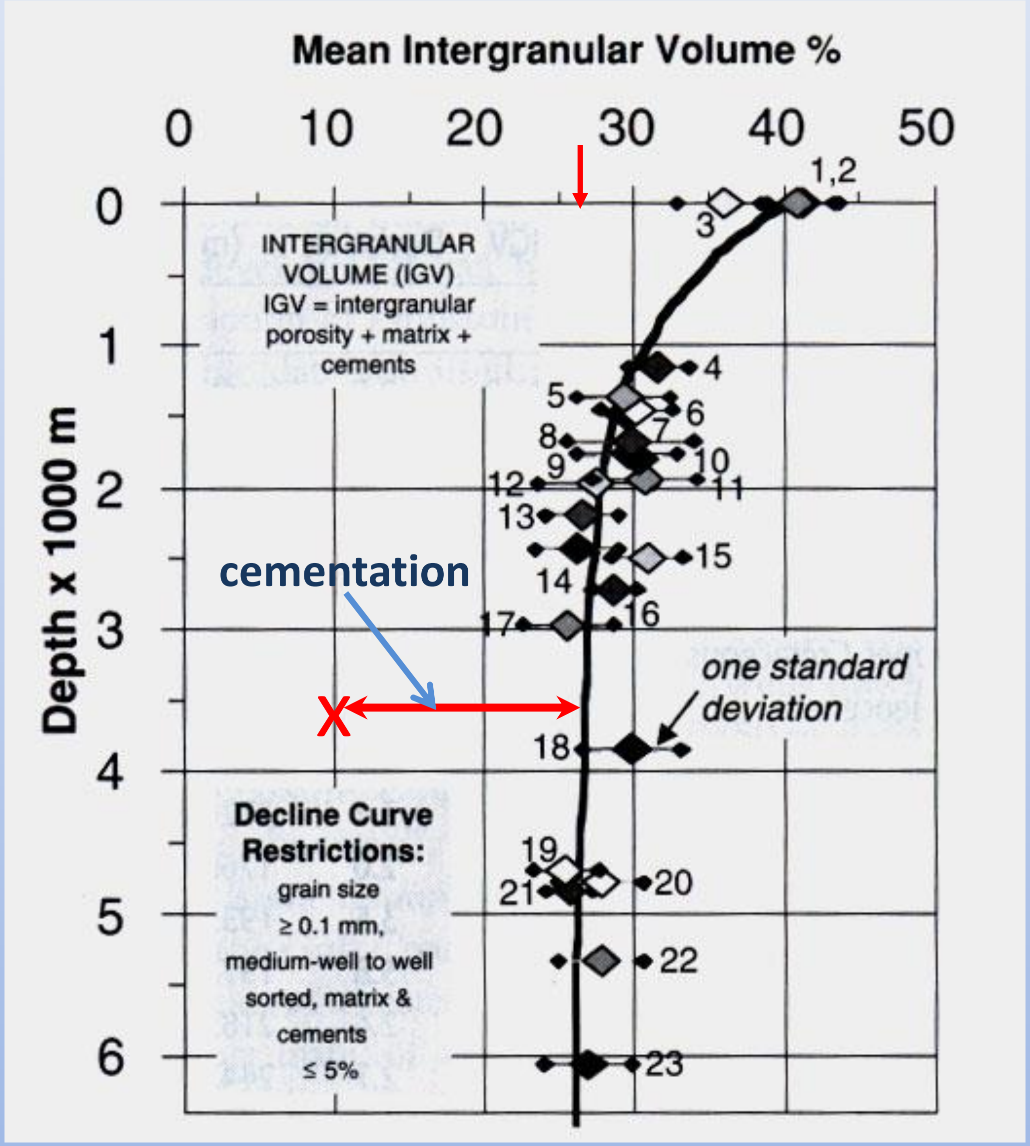
Cementational porosity loss:

$$CEPL = (P_i - COPL) * \left(\frac{C}{IGV}\right)$$



from Lundegard, 1992

Compaction: IGV concept



"The EXXON Compaction Curve"

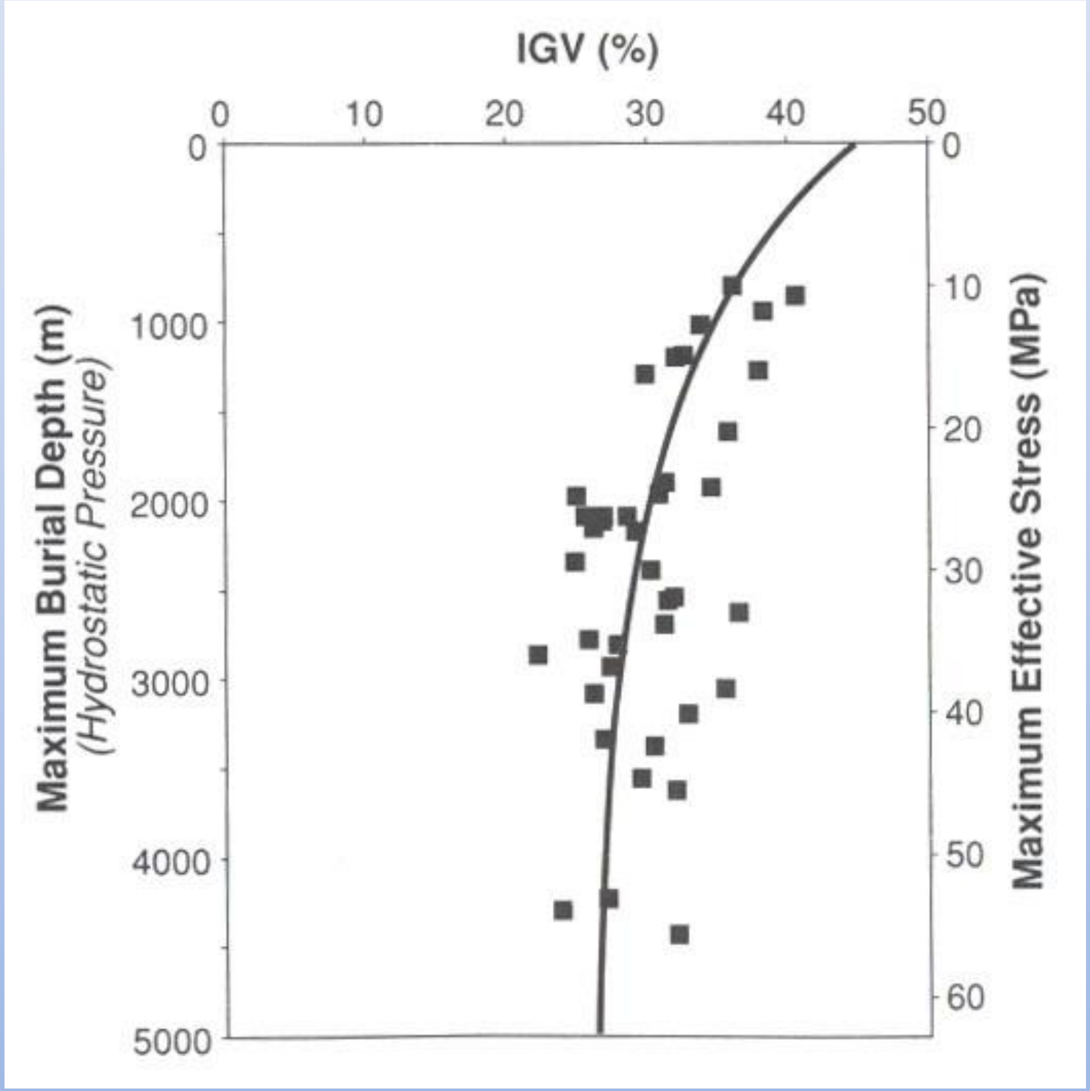
Paxton, et al., 2002

Based on 368 samples from 23 units: all quartzo-feldspathic sandstones:

<5% cement

<5% detrital matrix

$$IGV = IGV_f + (\text{Ø}_0 + m_0 - IGV_f)\, e^{-\beta\sigma es}$$



From Lander & Walderhaug, 1999

IGV = measured IGV

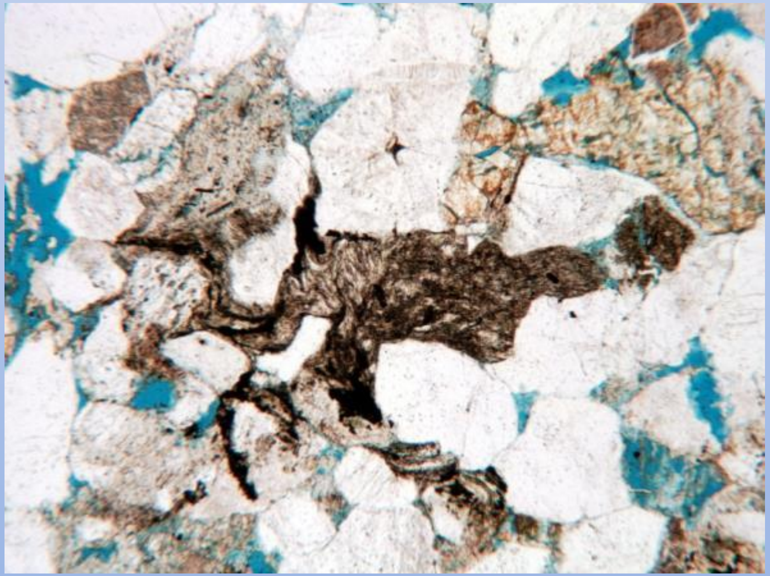
IGV_f= final IGV

Ø_0 = depositional porosity

m_0 = matrix content at deposition

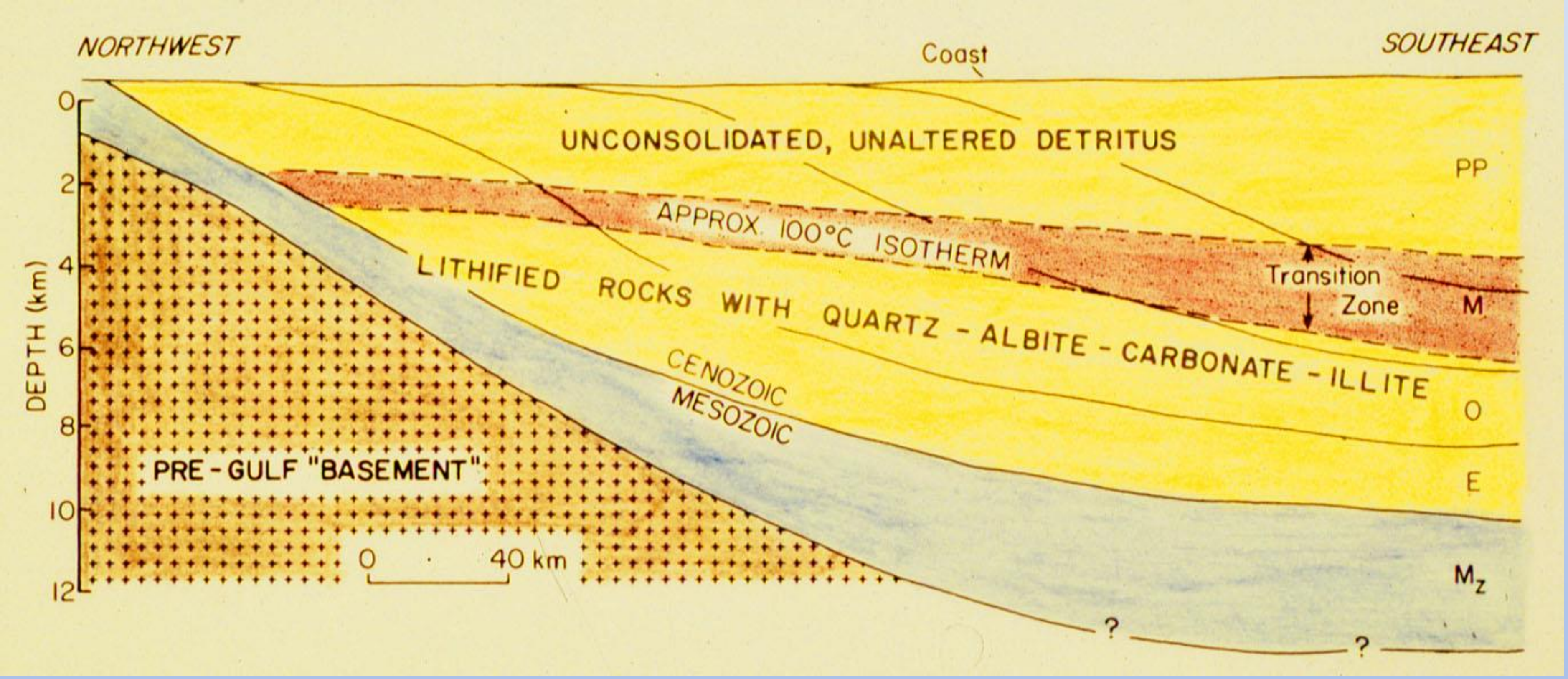
ß = exponential rate of IGV decline with effective stress (MPa^{-1}); rate can be adjusted to reality in analog data set: this parameter allows empiricism into model)

σ_{es}=maximum effective stress



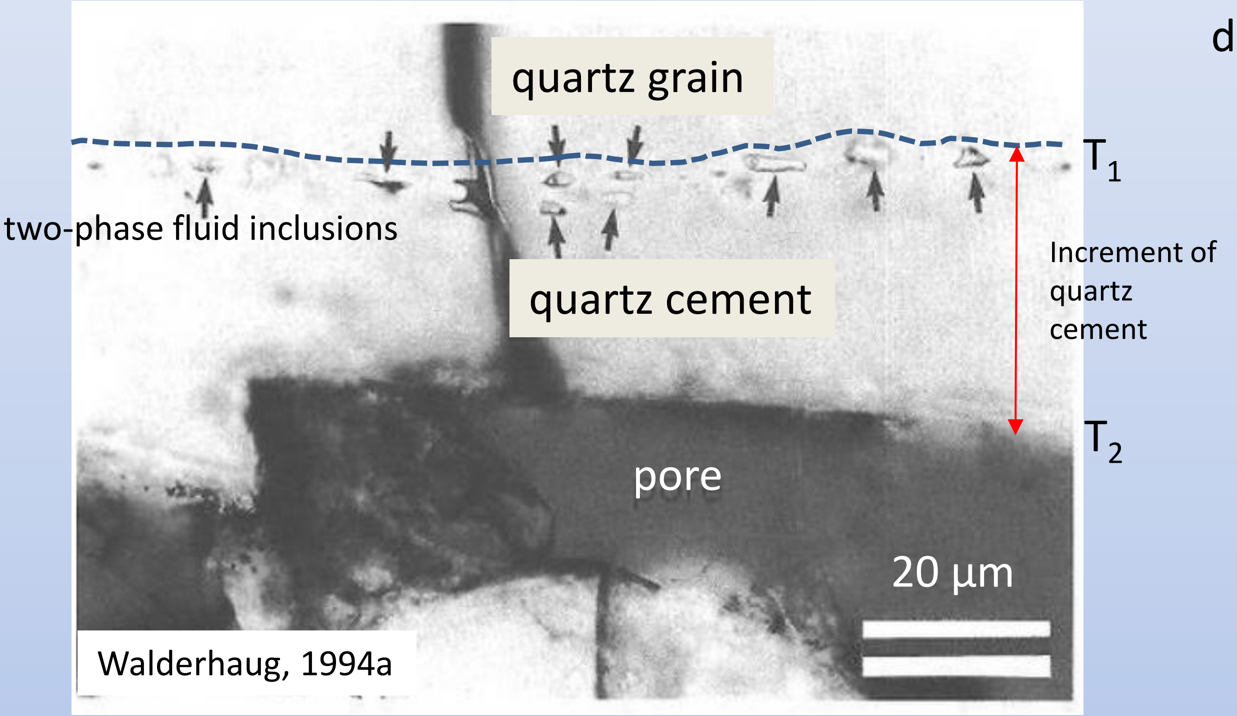
Diagenetic Evolution of the GOM

40°/km 30°/km 20°/km



From Land et al., 1987

Walderhaug's great contribution:



Walderhaug, 1994a

Fluid inclusions at the grain/overgrowth boundary, Garn Formation, North Sea.

Arrhenius Equation:

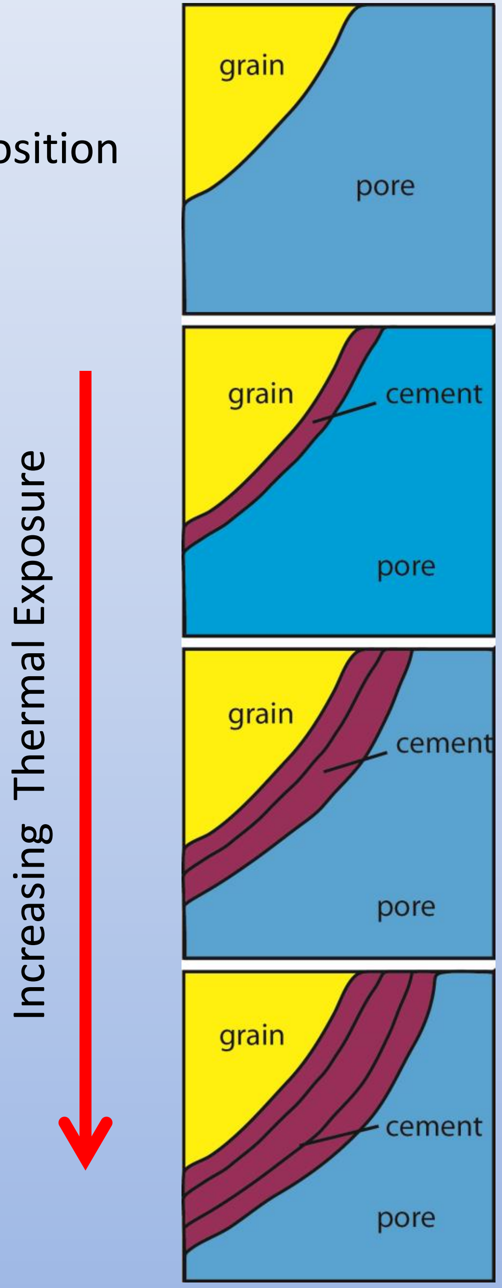
$$k = Ae^{-Ea/RT}$$

$$r = a10^{(bT)}$$

a = pre-exponential constant, (mole/cm^2/sec)
b = precipitation rate exponential constant (C$°^{-1}$)
T = temperature (C°)

Lander & Walderhaug, 1999

deposition

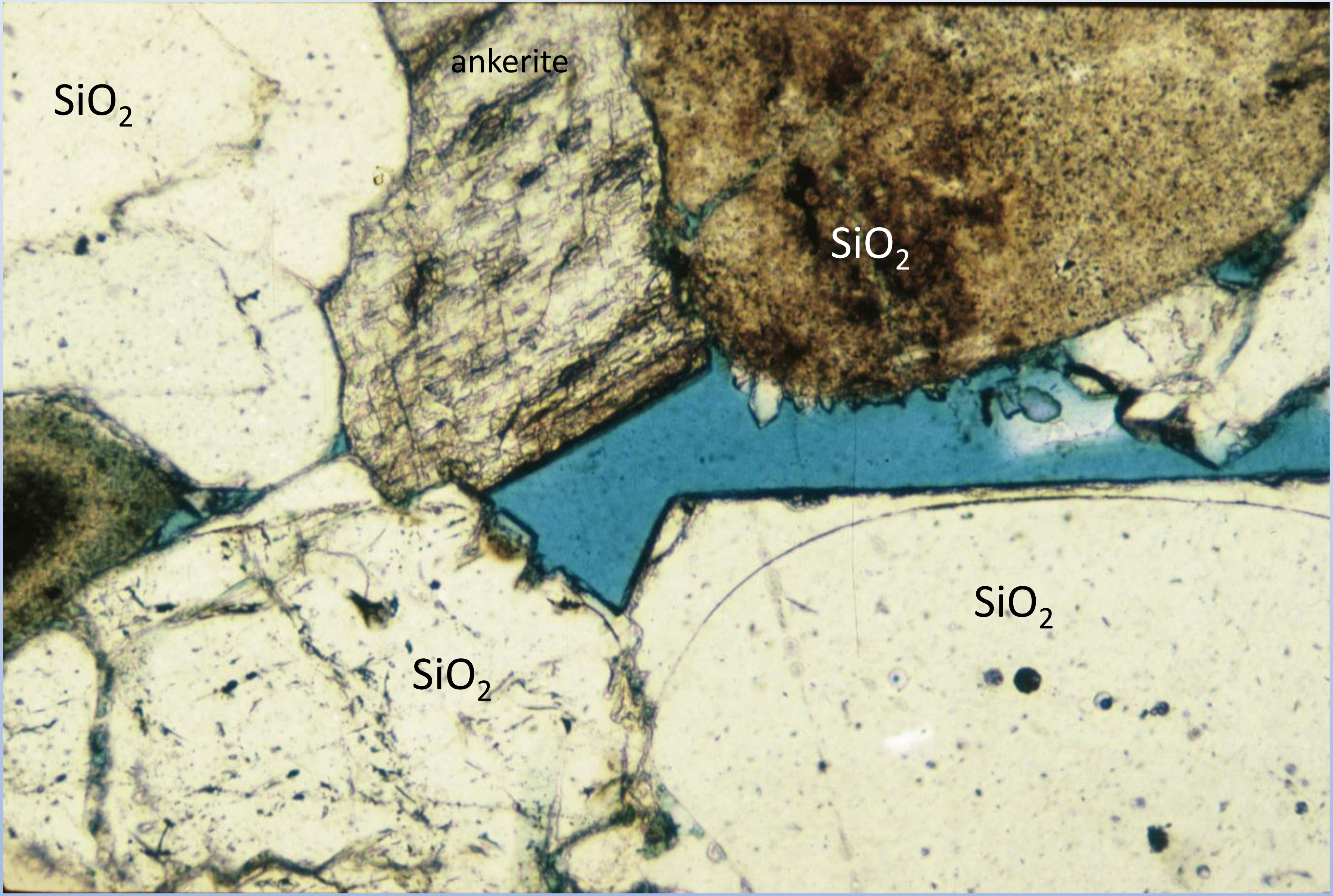


Calculating quartz cement volume:

$$qcv = m/\rho \; Aa \int 10^{b(c_n t + d_n)} \, dt$$

qcv = quartz cement volume
m = molar weight of quartz (60.08 g/mole)
ρ = density of quartz (2.65 g/cm^3)
A = quartz surface area (cm^2)
a = quartz ppt pre-exponential rate constant (mole/cm^2/sec)
b = quartz ppt rate exponential constant (1/°C)
t = duration of time step (sec)
cn = constant for time step, based on thermal history
dn = constant for time step, based on thermal history

From Lander & Walderhaug, 1999


ankerite
SiO₂
SiO₂
SiO₂
SiO₂
SiO₂

Calculating Quartz Surface Area

Assumes that quartz grains are spherical and of uniform size (and coated to some extent):

$$A = (1-\text{coat})\left[\frac{6\,qgf_0\,\nu_0}{D}\right]\frac{(\text{Ø})}{(\text{Ø}_0)}$$

qgf_0 = initial quartz grain fraction

D = average grain diameter

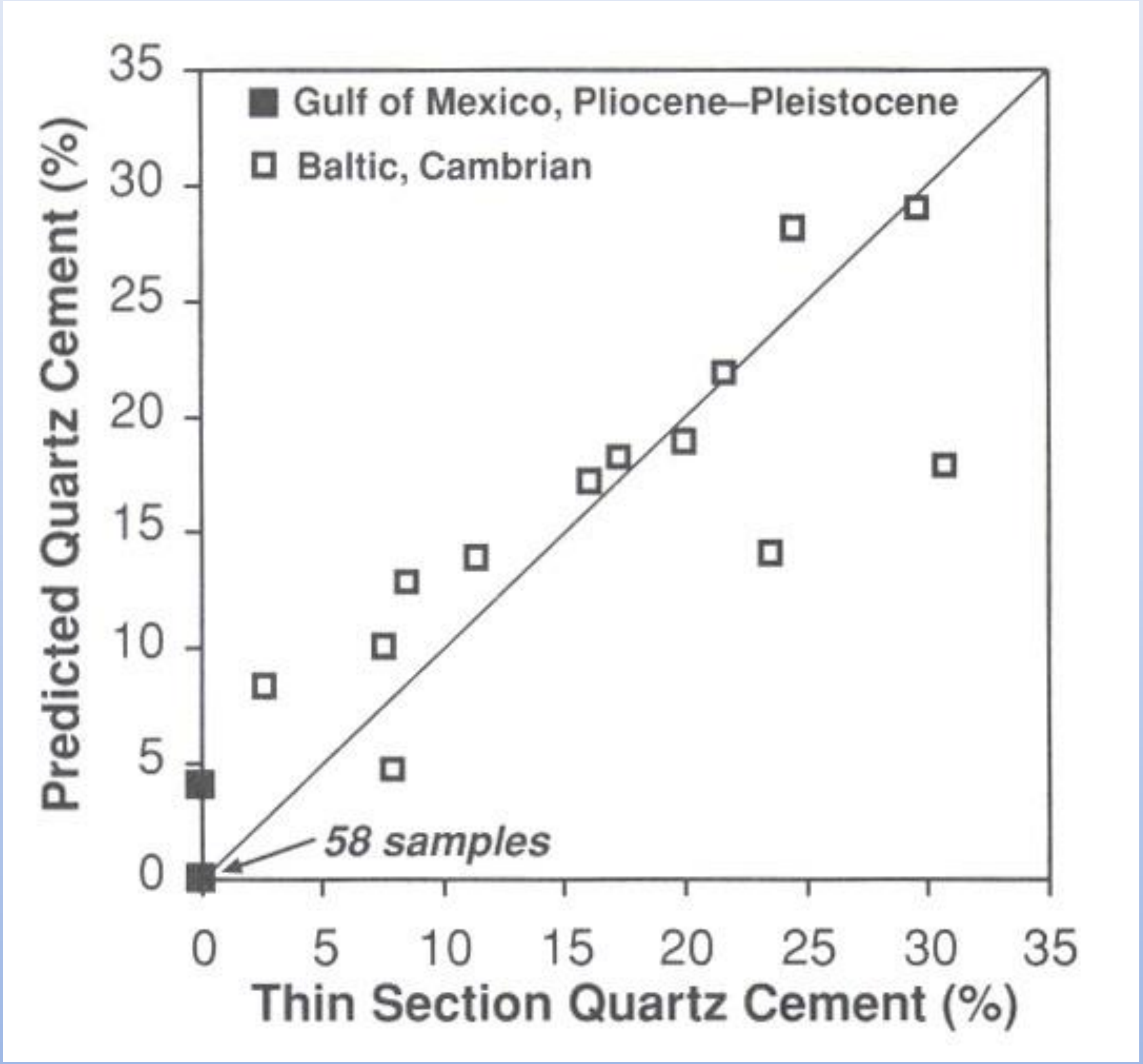
Ø = porosity at given time step

Ø_0 = initial porosity

coat = fraction of surface that is coated and not available for quartz nucleation

Empirical quantities (red) are determined from point counts of calibration samples.

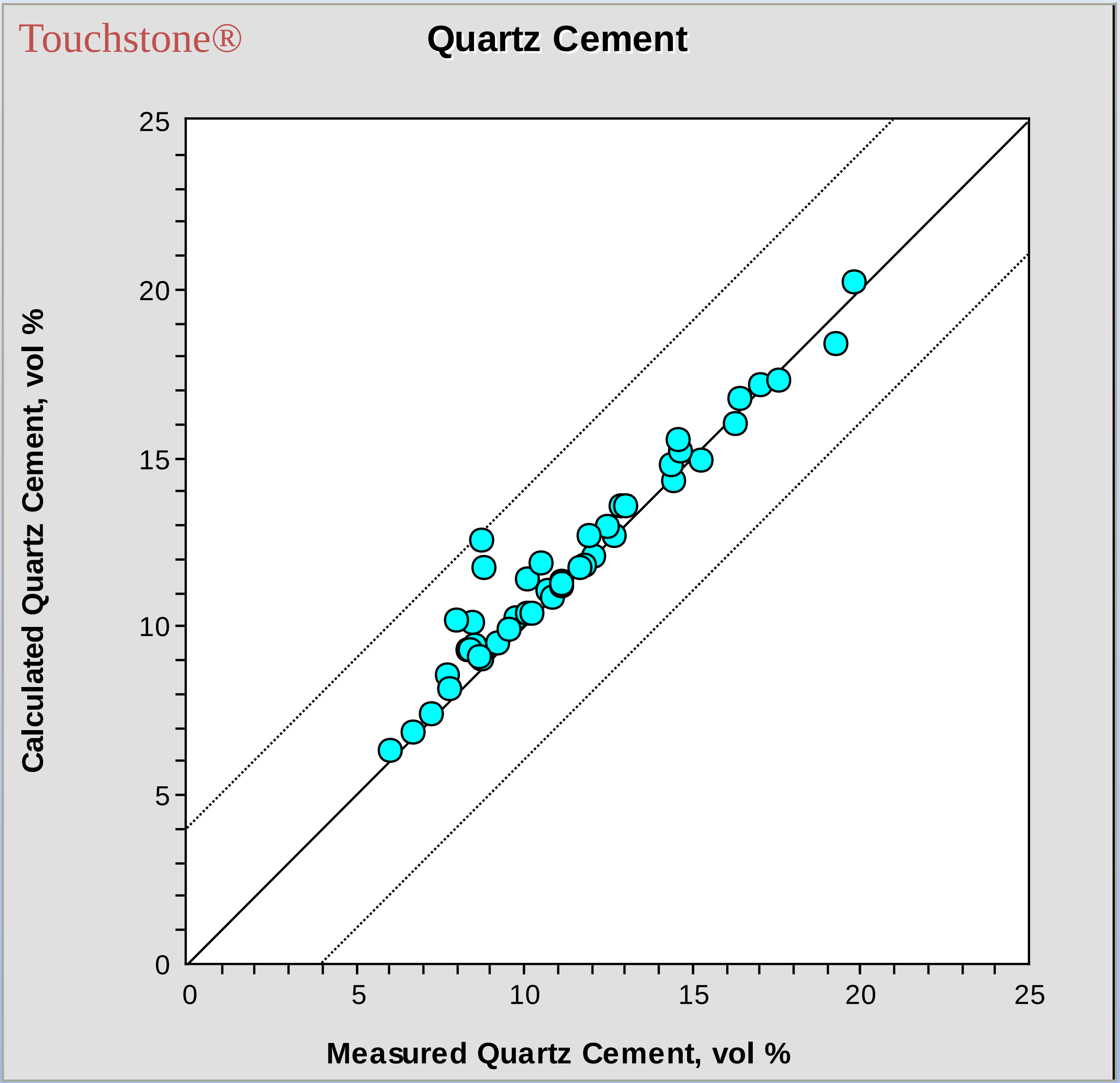
From Lander & Walderhaug, 1999



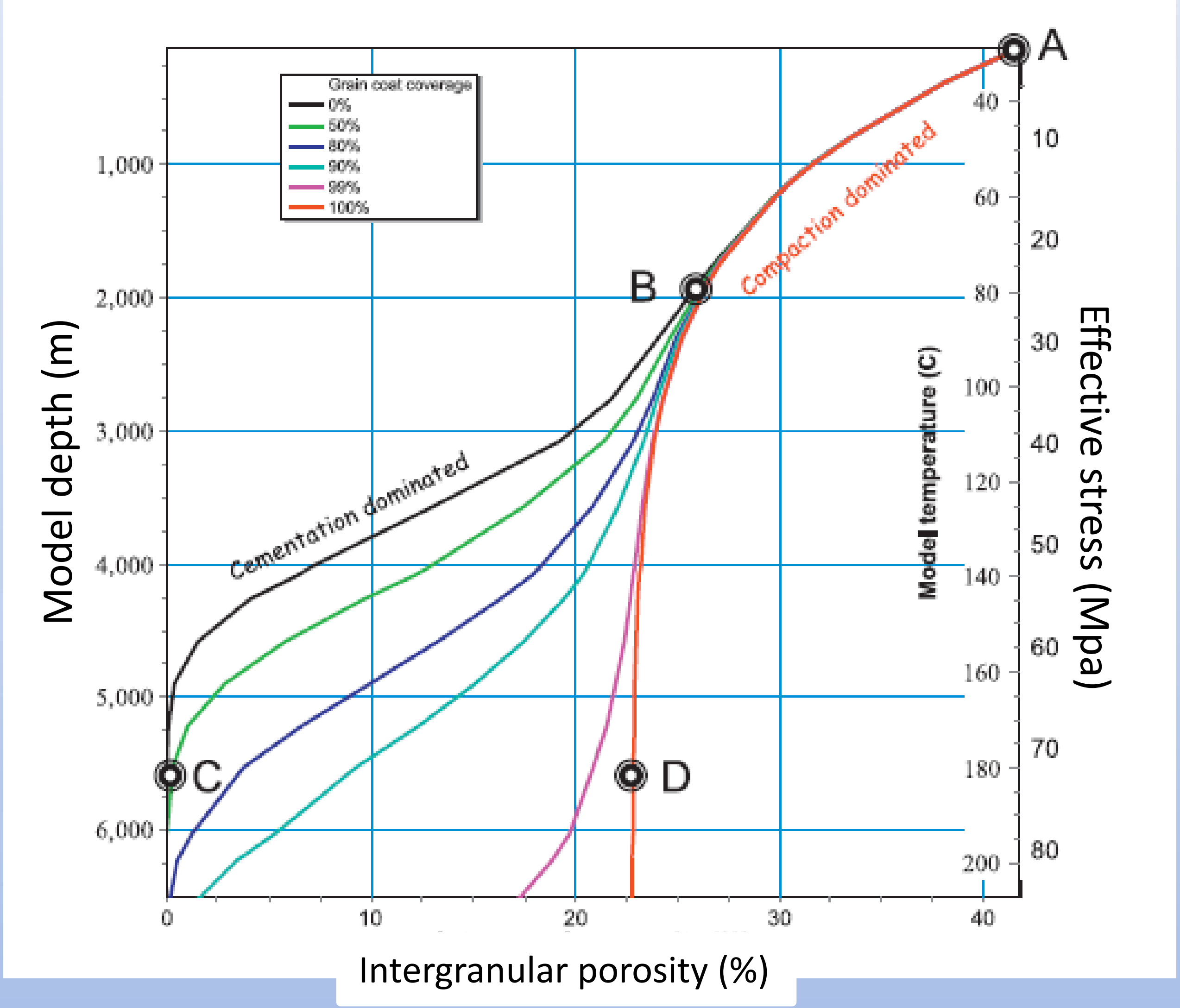
Calibrated to data from Jurassic of North Sea

(Walderhaug, 1994)

Lander and Walderhaug, 1999



Thermal history from apatite fission track study of Boettcher & Milliken, 1994.



Ajdukiewicz & Lander, 2010

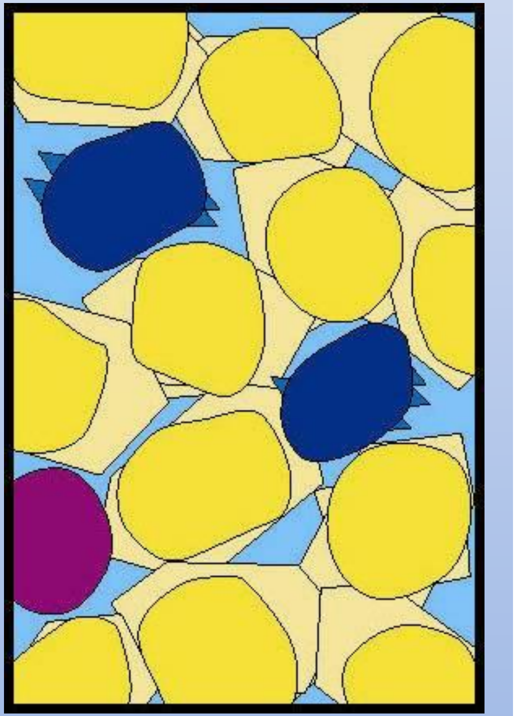
A hybrid empirical-chemical/mechanical model for porosity prediction.

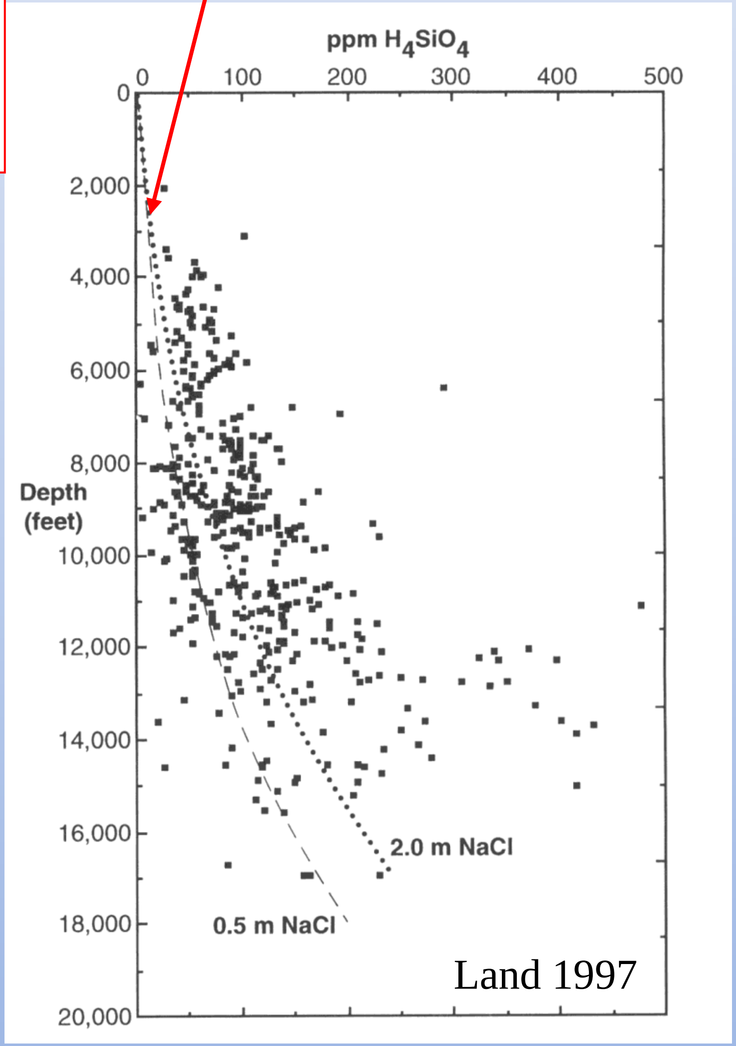
Authigenic minerals with strong thermal controls:

Minerals that behave “like quartz”

- albite
- ankerite
- illite

Minerals that exhibit strong thermal controls on their distribution typically manifest evidence of particularly sluggish reaction kinetics, for example, the need for very special nucleation surfaces and supersaturation in pore fluids.





Quartz saturation

Land 1997

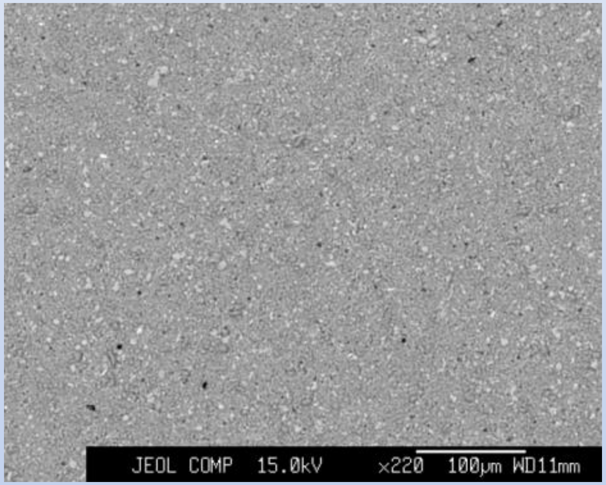
Cementation minerals that do not behave like quartz: “wild cards”

- Carbonate minerals
- Kaolinite
- Chlorite
- Iron oxides

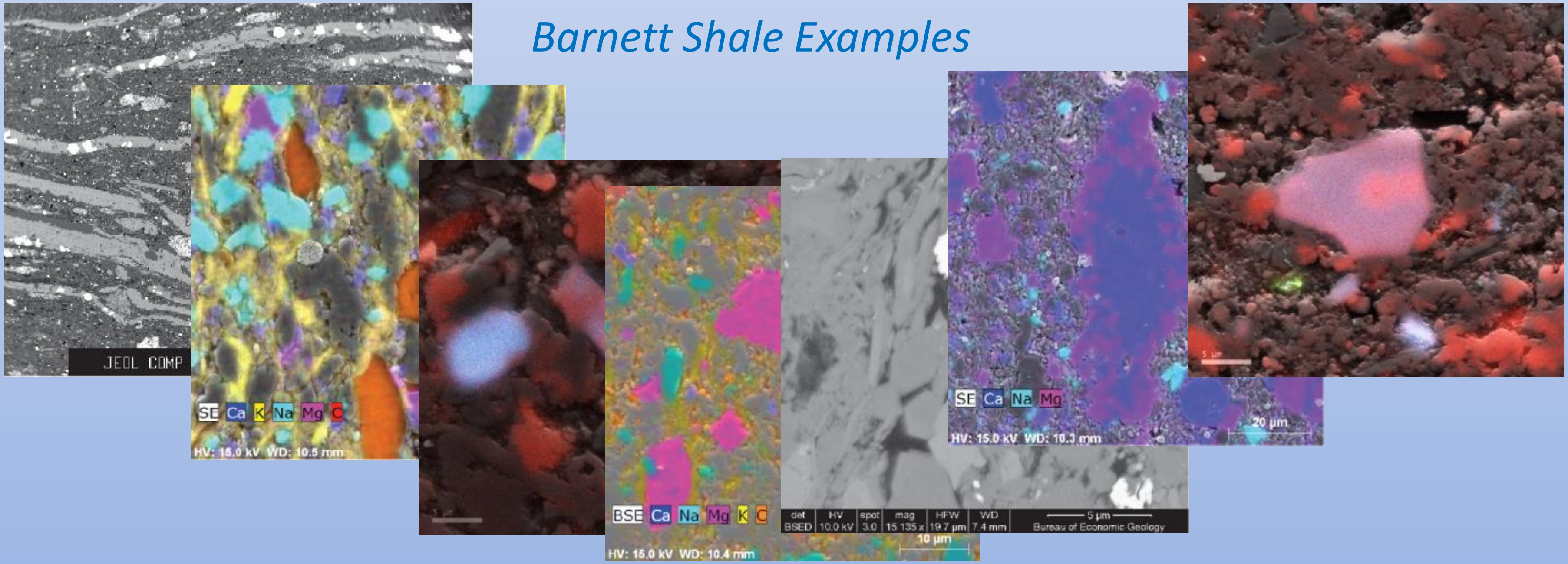
Highly localized precipitation (concretions, bands); much evidence of microbial controls

Apparent homogeneity of shales (mudrocks, mudstones) as seen by visual inspection is misleading……

At high magnifications, we learn that most shales don’t look like this:

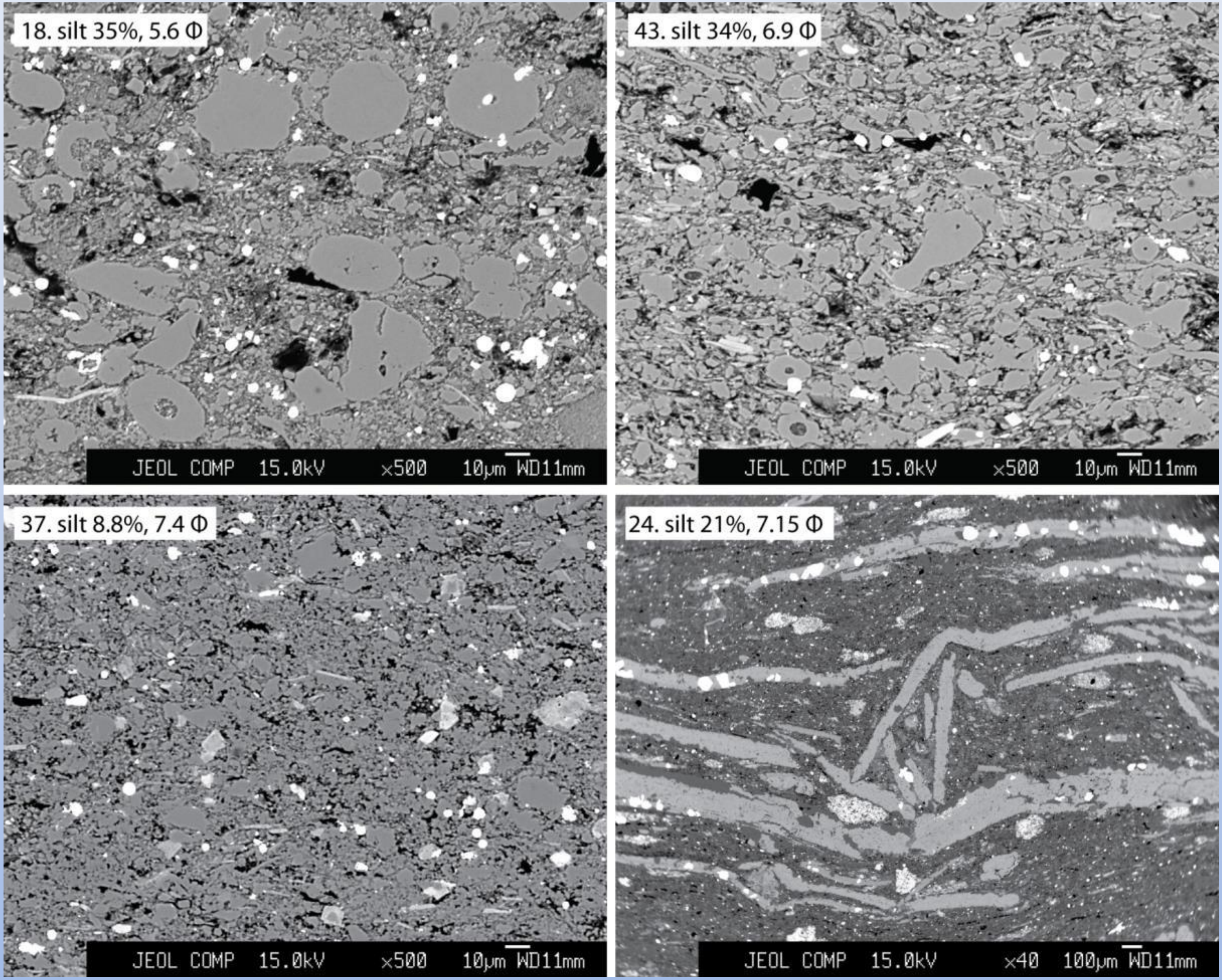


But rather, like:



Barnett Shale Examples

Back-scattered electron images.

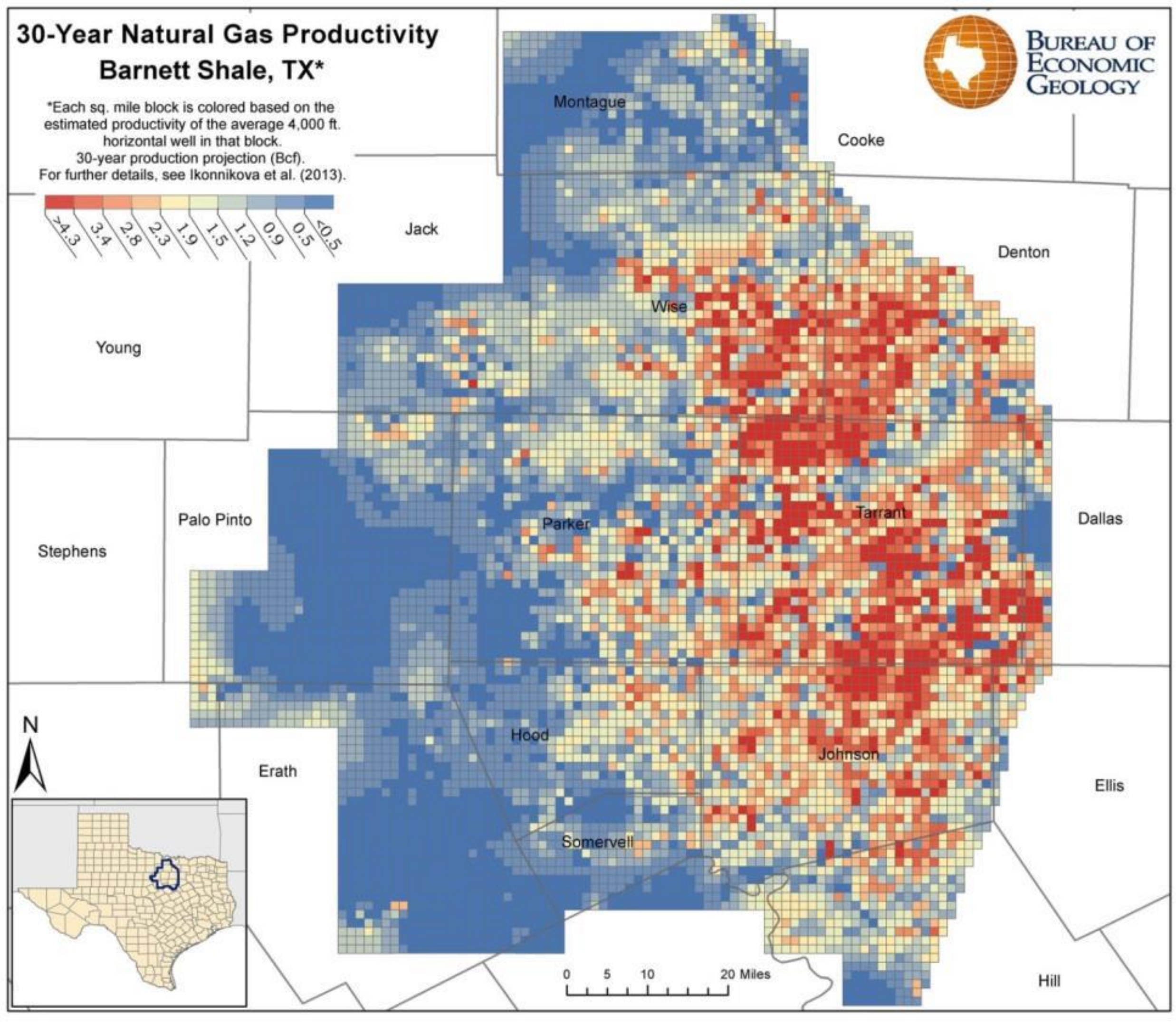


Textural heterogeneity: silt content, silt size

Barnett Shale, Ellis County, Texas, USA

To guess is cheap;
to guess wrongly is expensive.

Chinese proverb

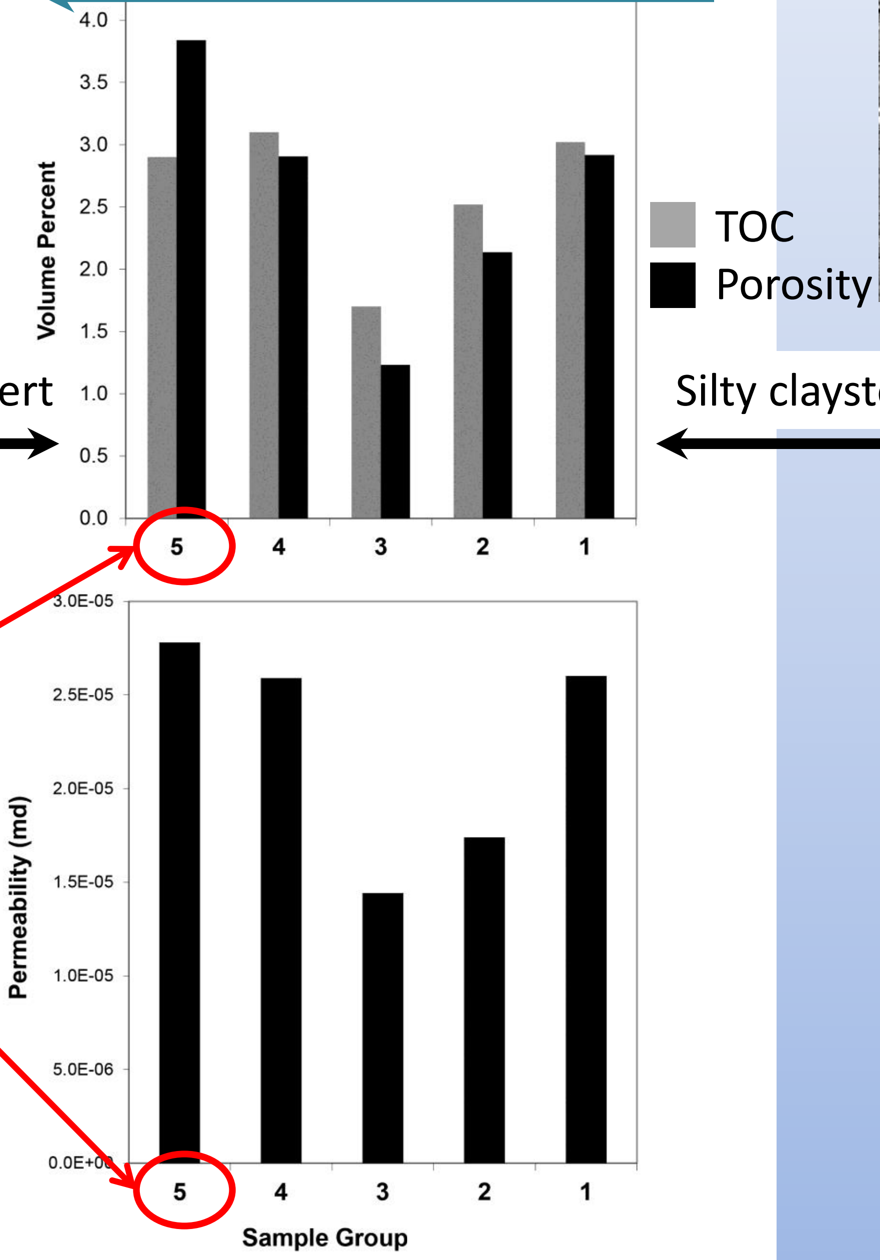


http://www.beg.utexas.edu/info/sloan_barnett.php

Productivity tiers of the Barnett Shale; Ikonnikova et al., in review.

"Sweet spots" : suggest potential for significant gains in efficiency by application of exploration models that address depositional environments, grain source mixing, and other basic causes of shale heterogeneity.

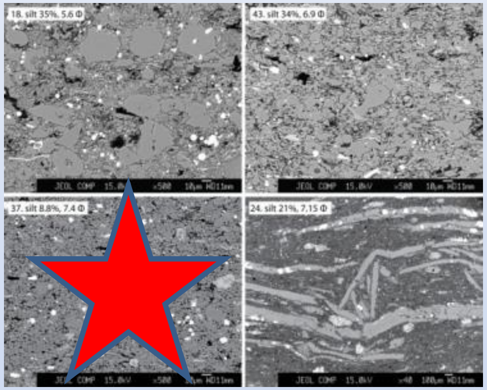
Declining siliciclastic content



Clayey chert

Silty claystone

Porous
Permeable
Brittle
Oil-prone



MODEL

best reservoir quality where:

- extrabasinal influx is minimal
- marine OM is highest
- siliceous fossils react to form brittle chert.

Milliken et al., 2012

Svalbard Outcrops for Understanding Subsurface Offshore Units

Valuable insights into:

- Depositional environments & sediment geometries
- Primary detrital composition (including TOC)
- Basinal trends in lithology and composition.

Indirect analogues for:

- Chemical and mechanical history
- Bulk rock properties:
  - Porosity
  - Permeability
  - Velocity
  - Elastic moduli

Primary composition and burial history are key variables for predicting bulk rock properties.