ENERGY GeoHackathon
Society of Petroleum Engineers

SPE International
SPE Europe Region

# 2022 SPE EUROPE ENERGY GEOHACKATHON

## 2. Introduction to Sandstone Diagenesis

**Eva De Boever**

**From sand to stone: processes and products**
**Steps and approaches in quantitative petrography**

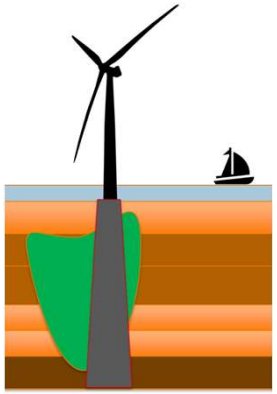
27 September 2022

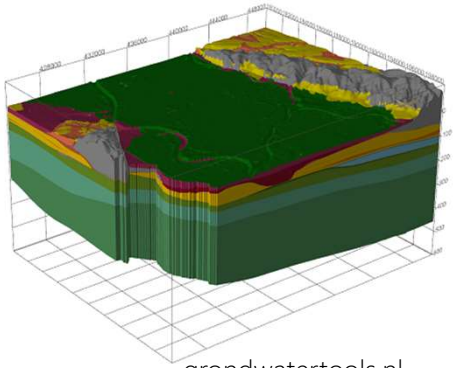
#DatafyingEnergy

# SAND - SANDSTONE

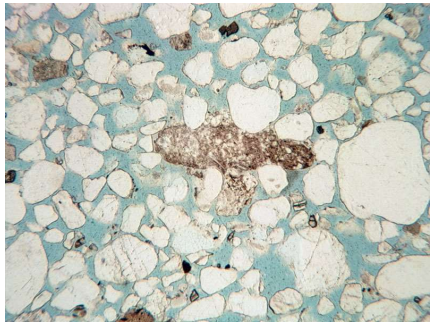
- Widespread in both marine and continental depositional environments

- Important ground water aquifers, relevant to offshore wind park development and as reservoirs (HC, geothermal energy, CCS)





grondwatertools.nl



Bentcliff Gritt (UK)

Geological Survey of the Netherlands

# OUTLINE

- Background
- Sand: deposition and components
- From sand to stone: Diagenetic processes in sandstones
- Diagenesis and effect on pore space
- Can we predict?
- A quantitative approach?
- Sum up

*What is diagenesis? (processes and products)*

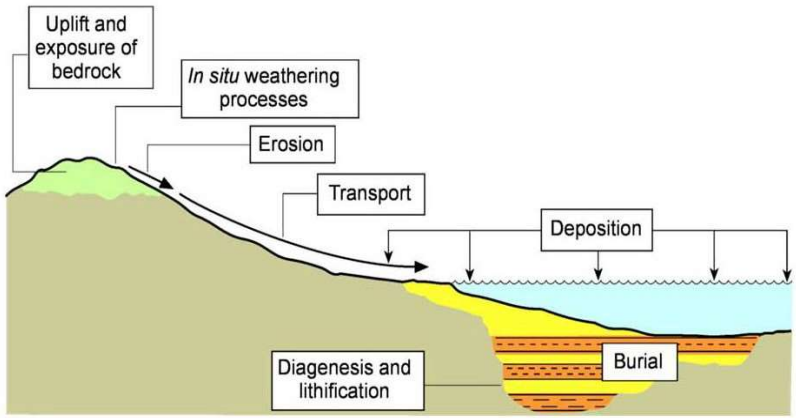
*Why is important and how do you tackle it?*

*Can we quantify the impact of diagenesis back in geological time?*

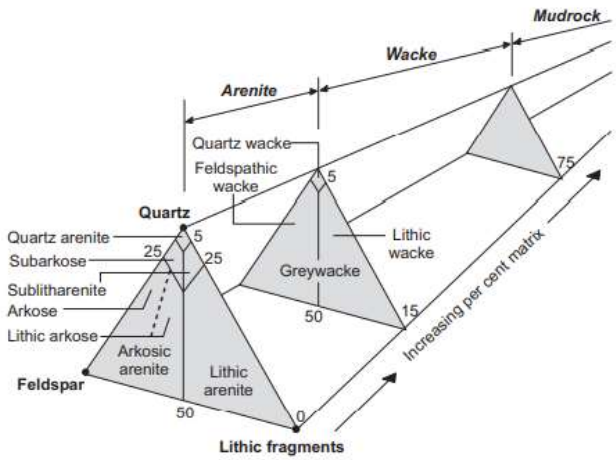
# SAND: DEPOSITION AND COMPONENTS

- Belongs to terrigenous clastic sediments :
  - composed of fragments that result from the weathering and erosion of older rocks.
  - classified according to the sizes of clasts present and the composition of the material.

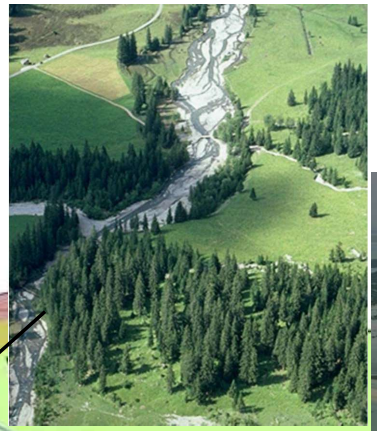
- Depositional environments range from terrestrial to deep marine, including: fluvial; deltaic, aeolian, shoreline , glacial to deep-sea sediments.

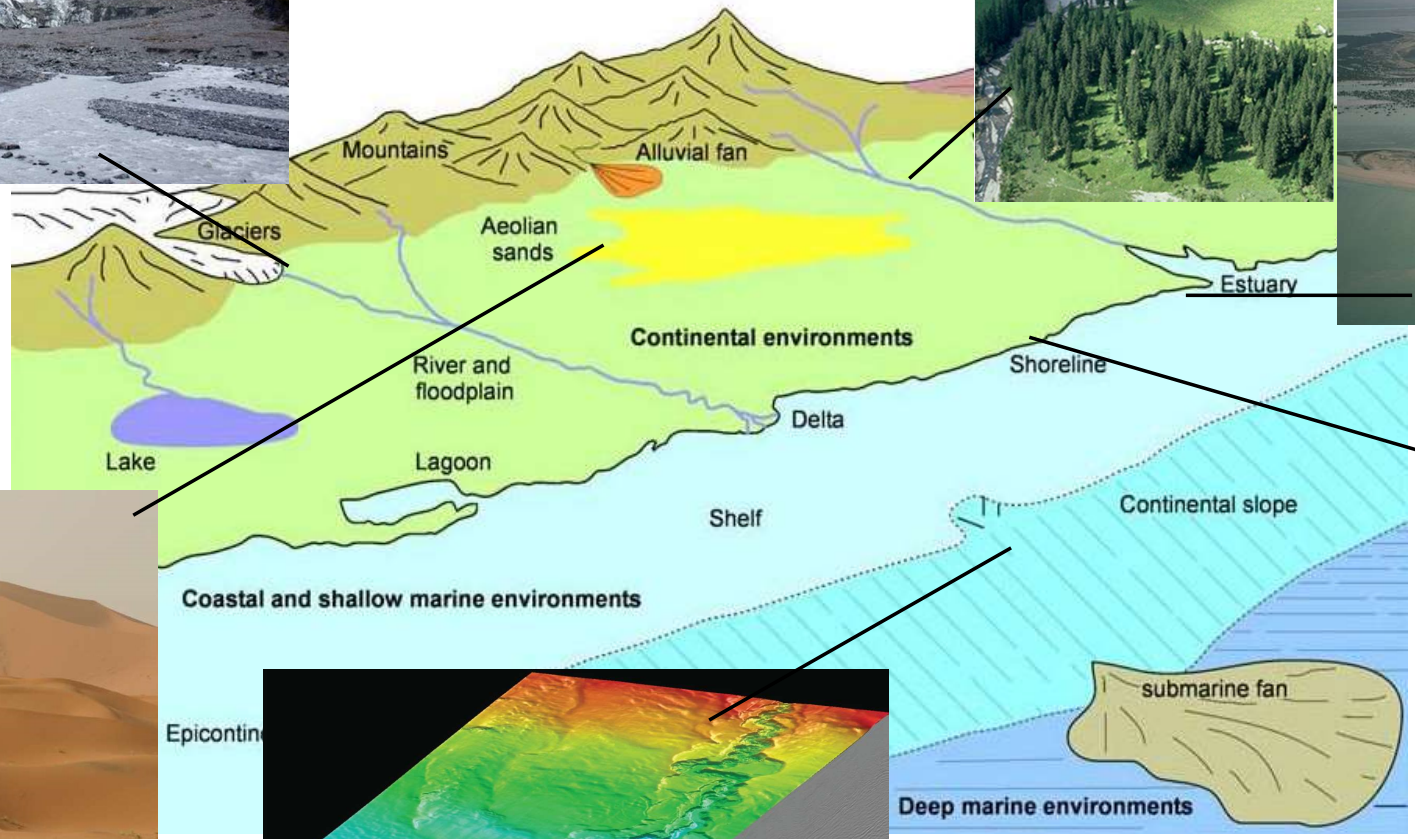



Nichols, 2009

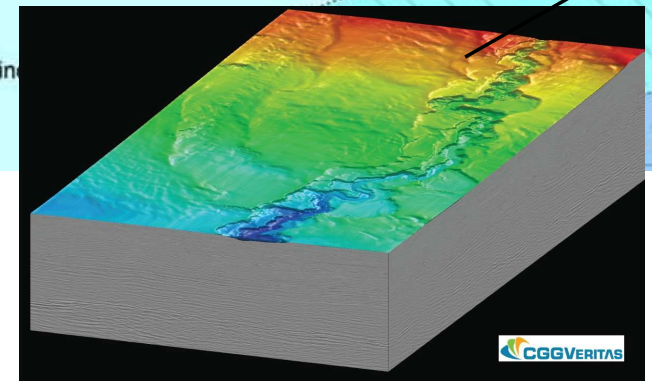



| mm | phi | Name | |
|---|---|---|---|
| 256 | −8 | Boulders | Gravel Conglomerate |
| 128 | −7 | | |
| 64 | −6 | Cobbles | |
| 32 | −5 | | |
| 16 | −4 | | |
| 8 | −3 | Pebbles | |
| 4 | −2 | Granules | |
| 2 | −1 | Very coarse sand | Sand Sandstone |
| 1 | 0 | Coarse sand | |
| 0.5 | 1 | Medium sand | |
| 0.25 | 2 | Fine sand | |
| 0.125 | 3 | Very fine sand | |
| 0.063 | 4 | Coarse silt | Mud Mudrock |
| 0.031 | 5 | Medium silt | |
| 0.0156 | 6 | Fine silt | |
| 0.0078 | 7 | Very fine silt | |
| 0.0039 | 8 | Clay | |



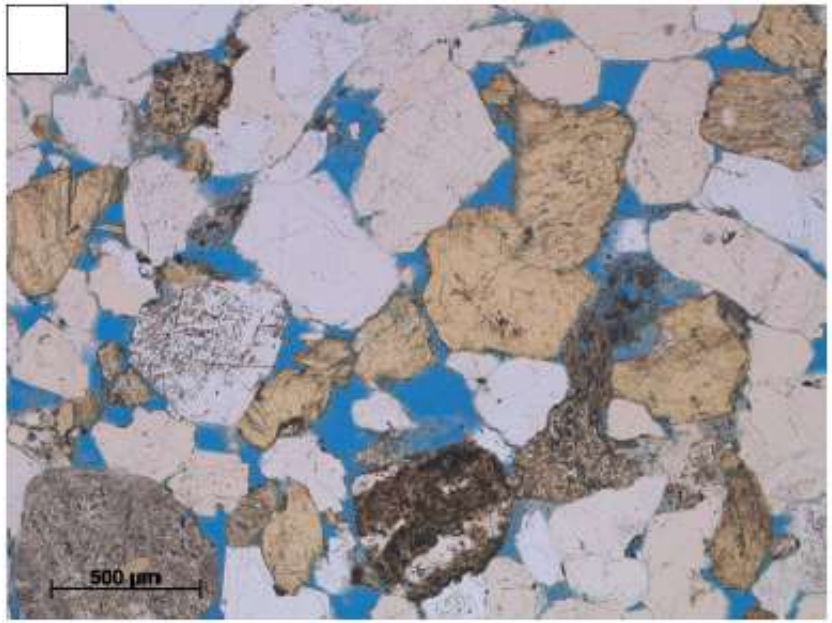


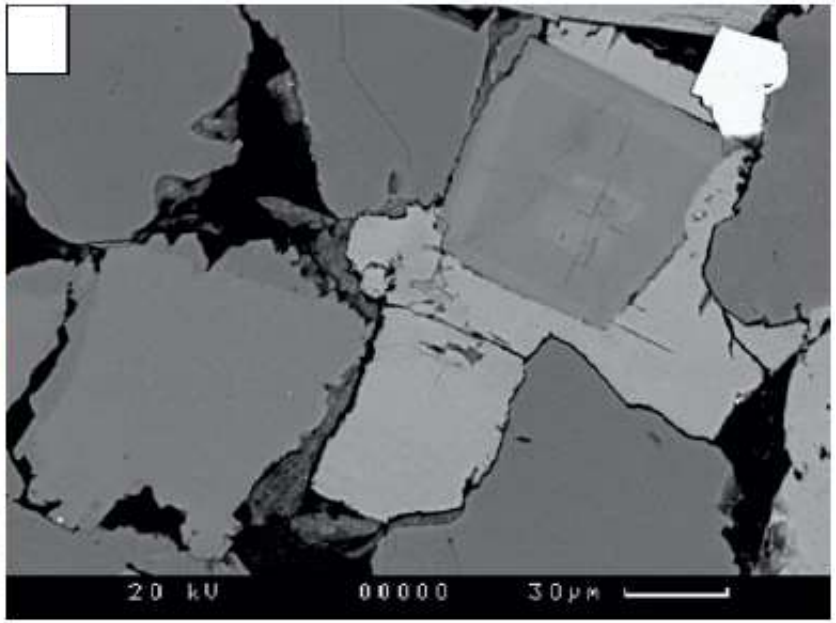

Nichols, 2009

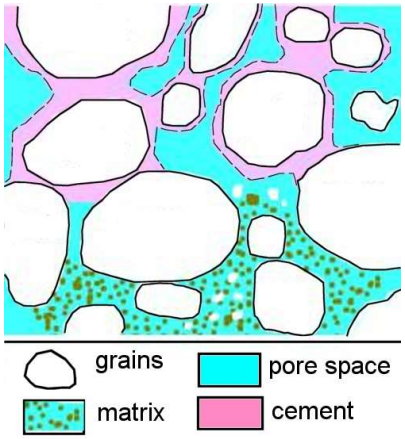


# SAND: DEPOSITION AND COMPONENTS

## COMPONENTS



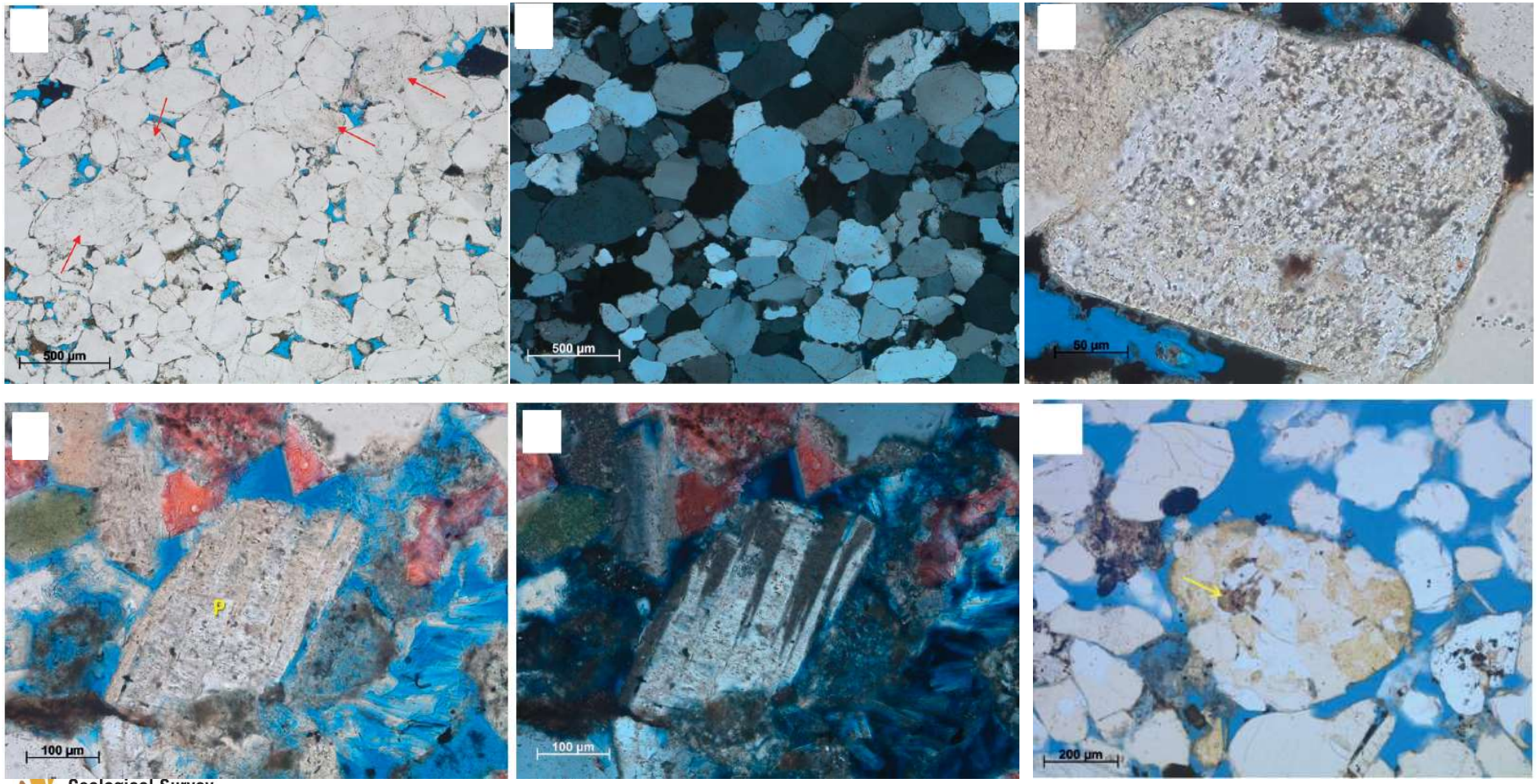




Taylor, Lander and Bonnell, 2022

Grain – Matrix - Pore space - Cement

# SAND: DEPOSITION AND COMPONENTS

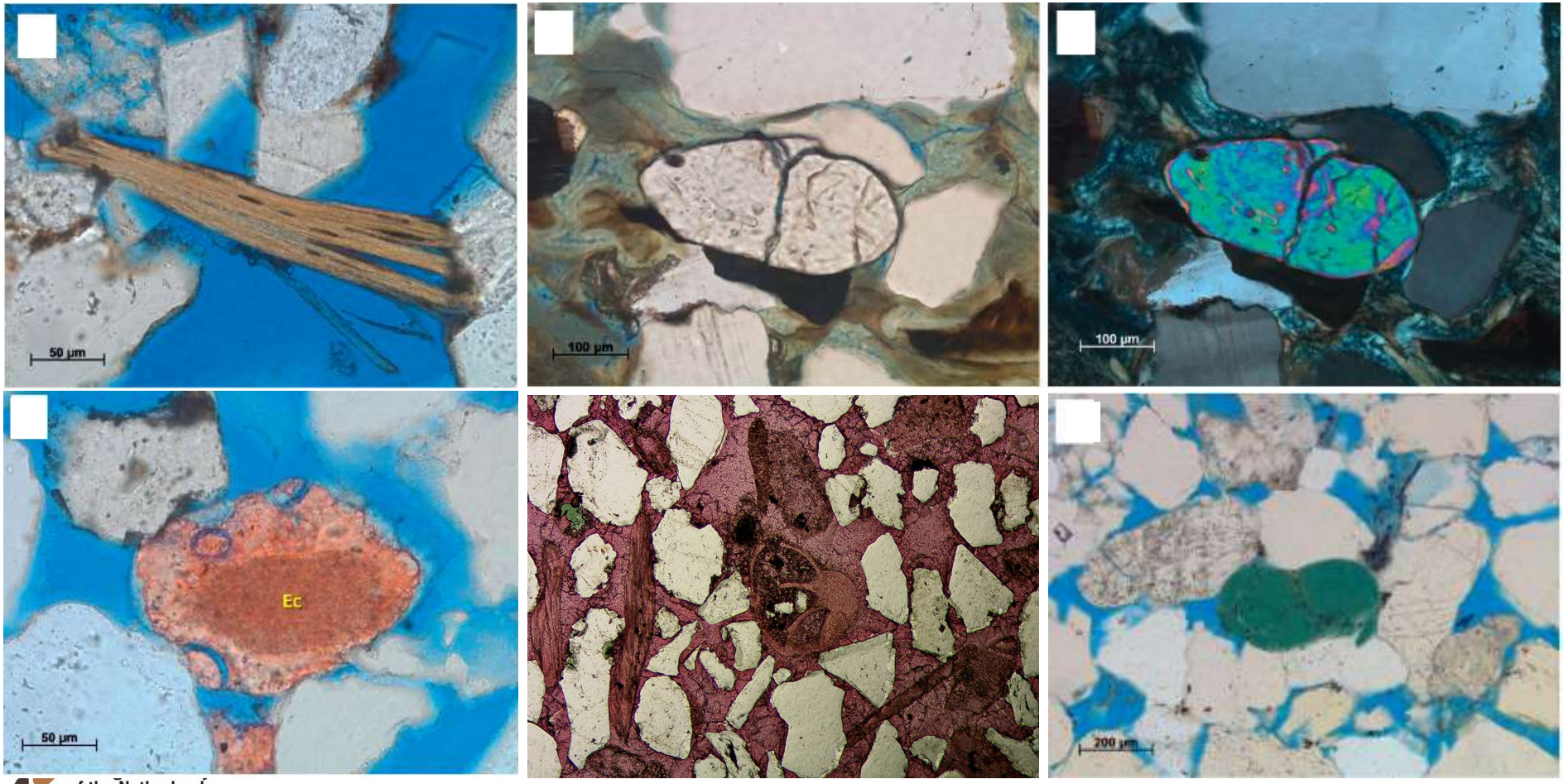
## COMPONENTS: GRAINS




Taylor, Lander and Bonnell, 2022

# SAND: DEPOSITION AND COMPONENTS

## COMPONENTS: GRAINS

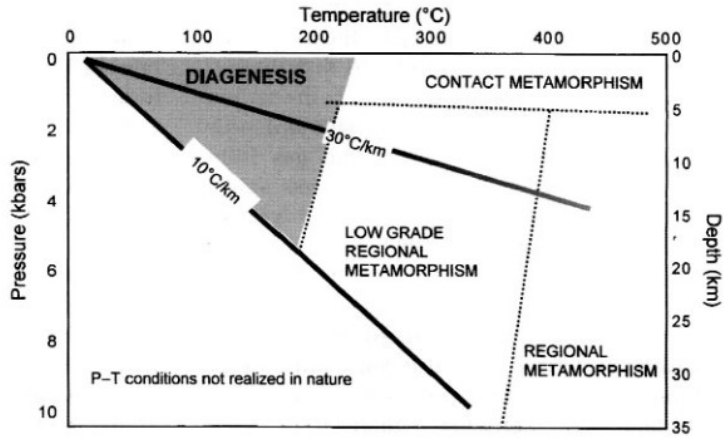



Taylor, Lander and Bonnell, 2022 + TNO study

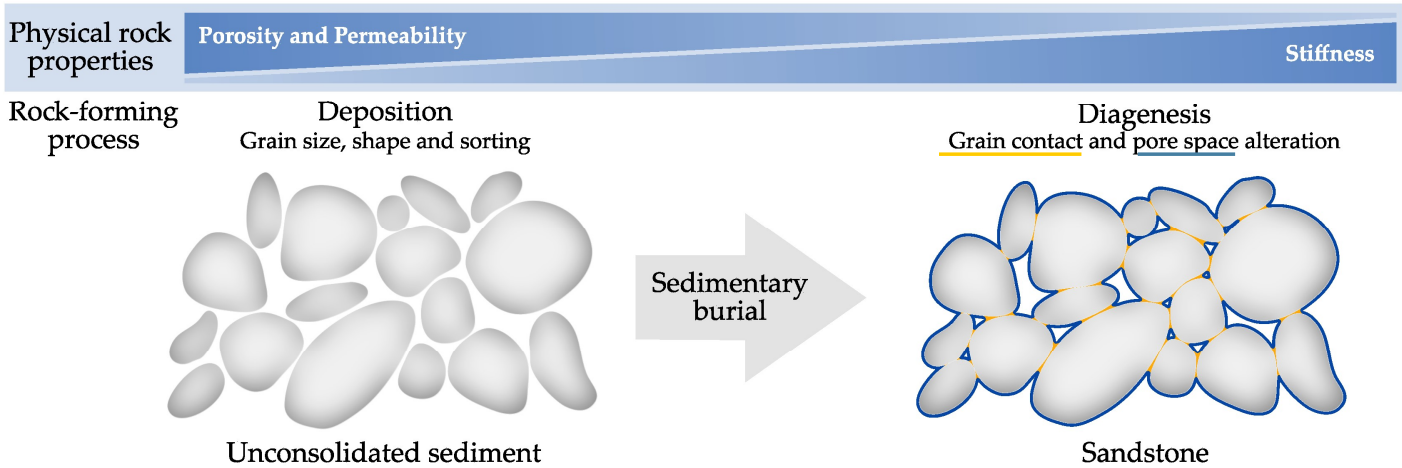
# FROM SAND TO STONE

Diagenesis = All processes (chemical, physical, biological) which affect sediments after deposition during burial untill temperatures and pressures changes reach the domain of metamorphism

Diagenetic research in reservoirs




Worden & Burley, 2003

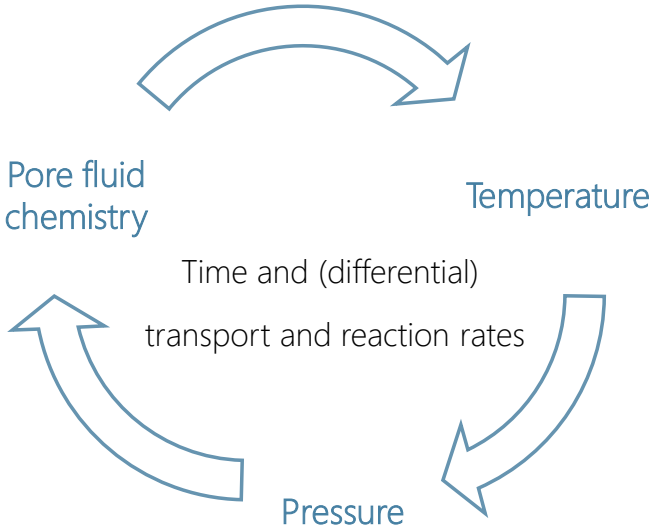



Wetzel et al., 2021

# FROM SAND TO STONE

A **complex and dynamic story** of reestablishing equilibrium states between sediment & post-depositional setting in the subsurface

- Post-depositional environments (realms) & the fluids within them are **seldom uniform through time and space**:
- Changes may be progressive, abrupt or even cyclic
- There exists a variety of timeframes (±10.000 versus ±million years)



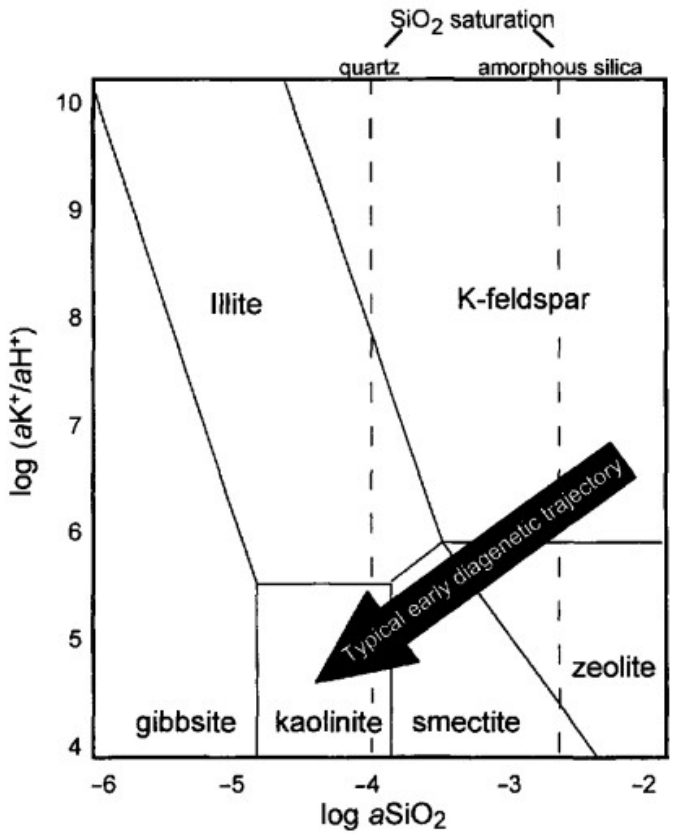



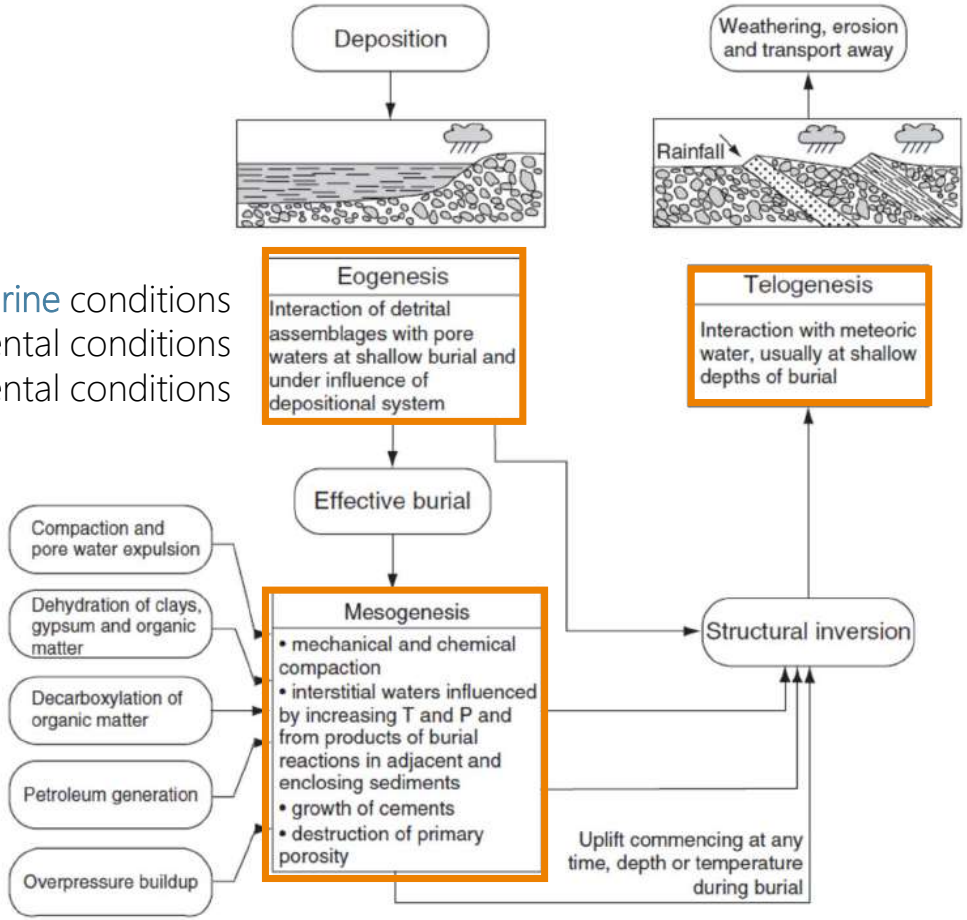

**Fig. 3** Phase diagram for the system $\log(aK^+/aH^+)$–$\log aSiO_2$ (where '$a$' indicates chemical activity of species) illustrating how changing isothermal water geochemistry can lead to diagenetic reactions. For example, if water in contact with feldspathic sandstones is flushed with fresh water (e.g. meteoric water) then the water will progressively evolve to lower aqueous potassium and silica concentrations. This explains why advanced eogenesis (and telogenesis) leads to kaolinite growth at the expense of feldspar minerals.

Worden & Burley, 2003

# FROM SAND TO STONE

## DIAGENETIC REGIMES and PROCESSES

Normal marine conditions
humid and tropical continental conditions
hot arid continental conditions



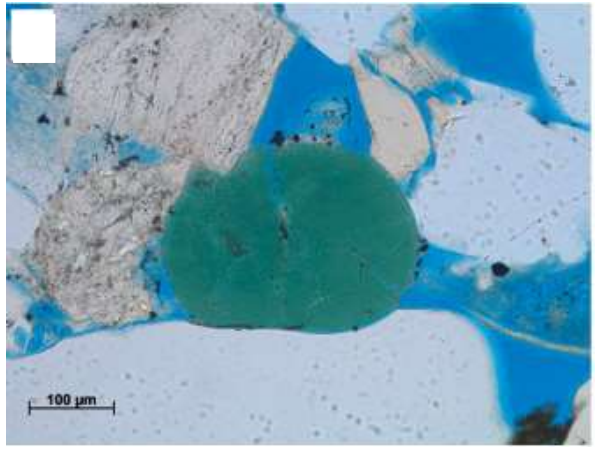

Worden & Burley, 2003

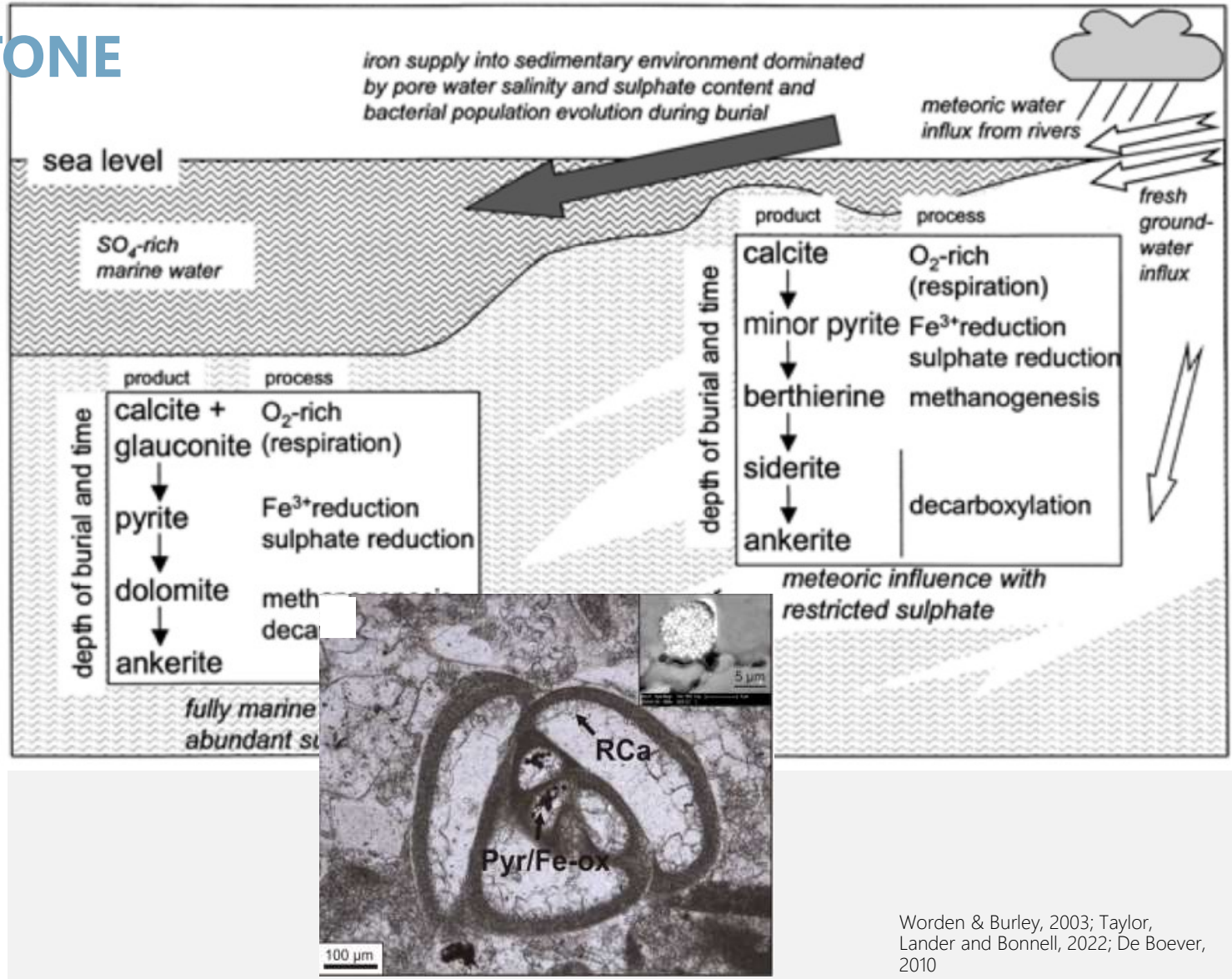
dissolution
neomorphism
Cementation
replacement
dehydration
authigenesis
LITHIFICATION
compaction
precipitation
overgrowth
recrystallization

Geological Survey of the Netherlands

# FROM SAND TO STONE

- Eogenetic reactions in shallow-marine sediments

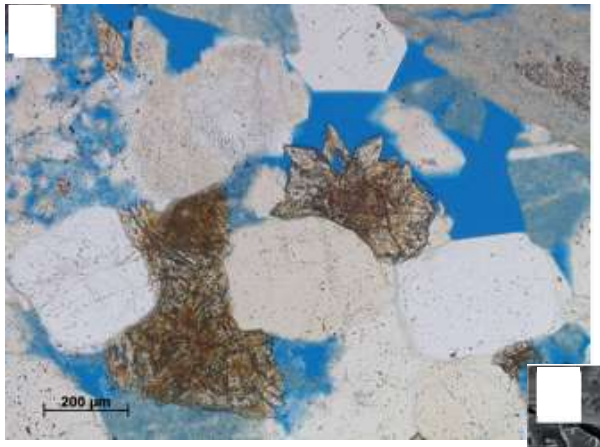


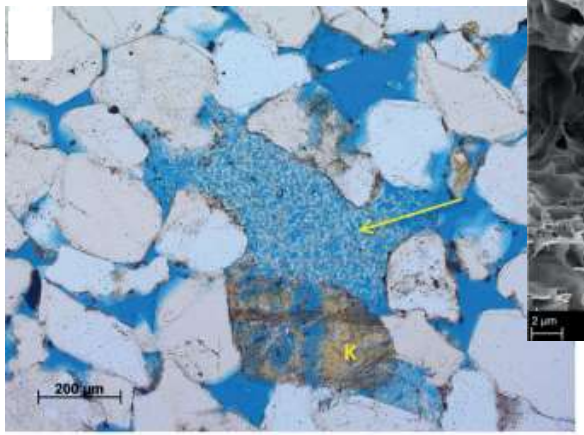



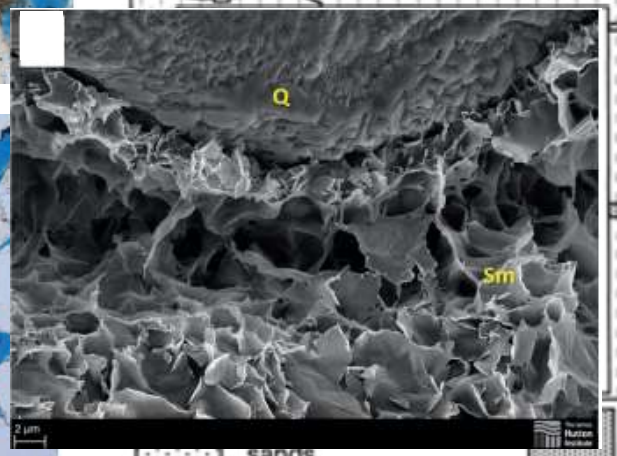

Worden & Burley, 2003; Taylor, Lander and Bonnell, 2022; De Boever, 2010

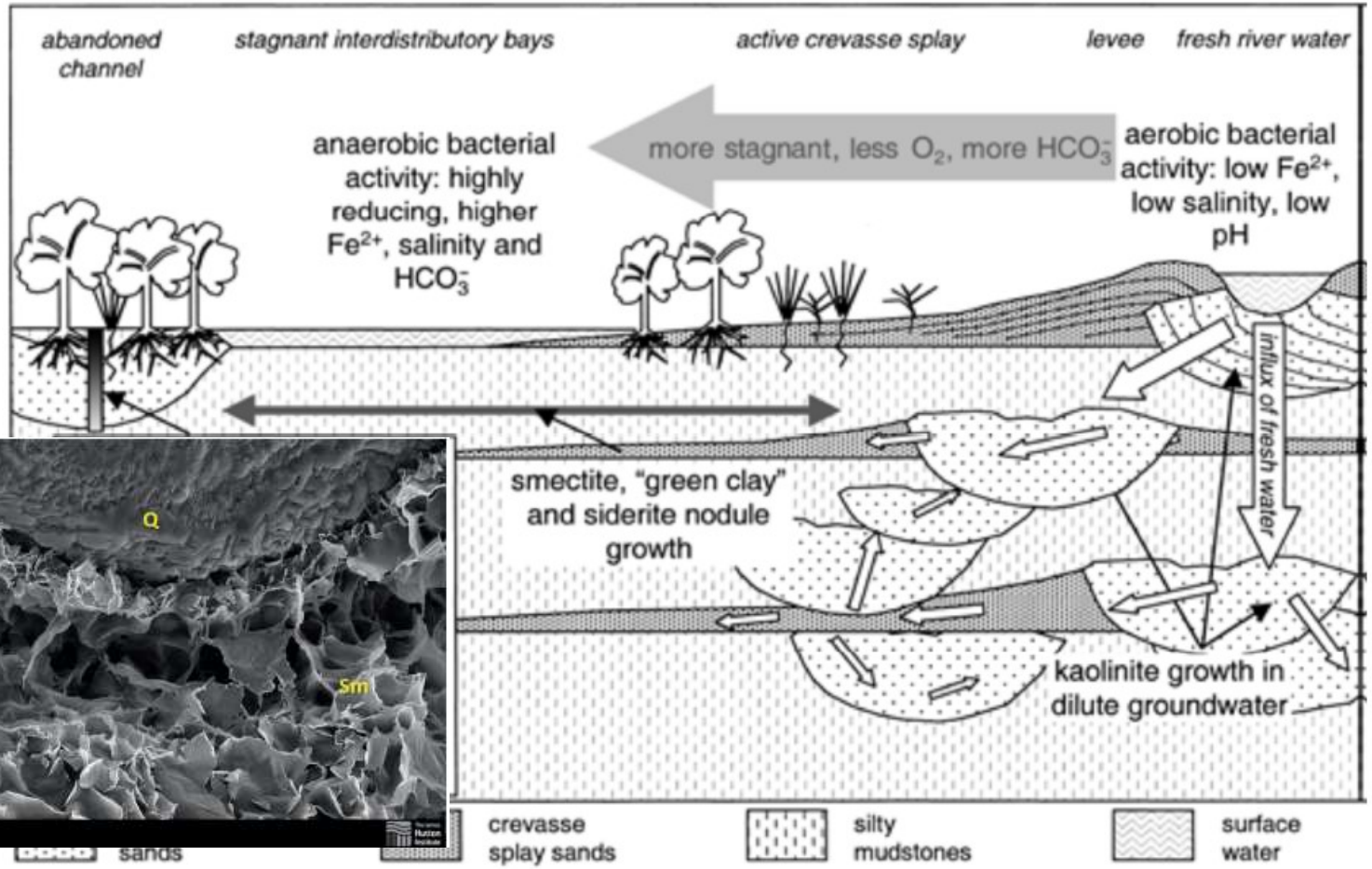
# FROM SAND TO STONE

- Eogeneis under humid-tropical climate



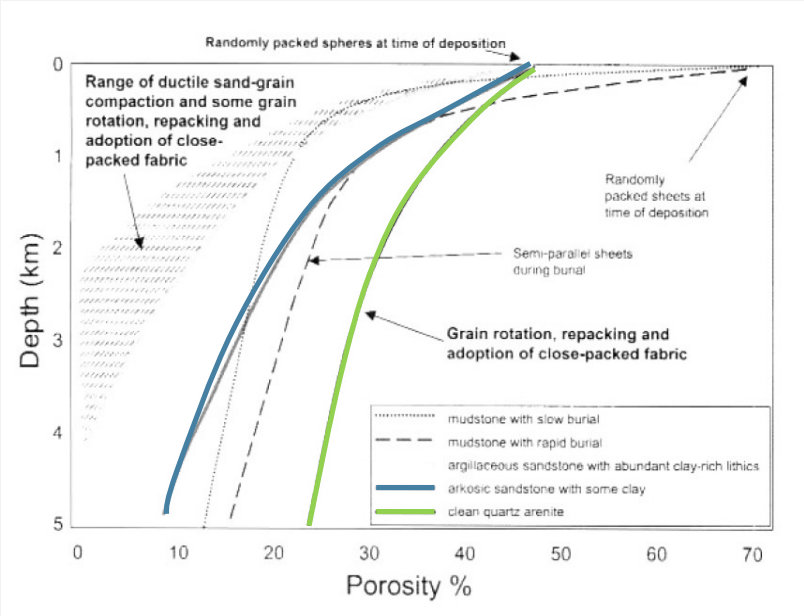



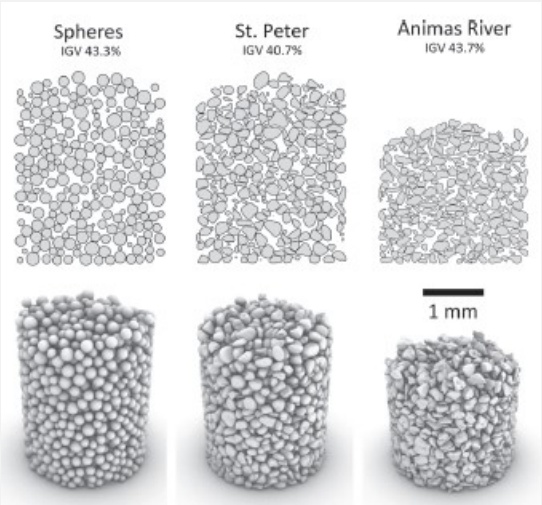

Worden & Burley, 2003;Taylor, Lander and Bonnell, 2022

# FROM SAND TO STONE

- Change in pore fluids
  - THERMAL MATURATION of OM: Generation of $CO_2$ with light $\delta^{13}C$; Generation of oil and gas
  - Maturation of plant material (peat -> anthracite)
  - ADVECTIVE transport of pore-water
  - Infiltration of meteoric surface water into subsurface
- Increase of temperature T
  - Increase of reaction rates
  - Change of equilibrium constants for minerals
  - Rock/water interactions at elevated T and P
- Increase of pressure P (lithostatic + hydrostatic p)
  - Compaction
  - Pressure-solution

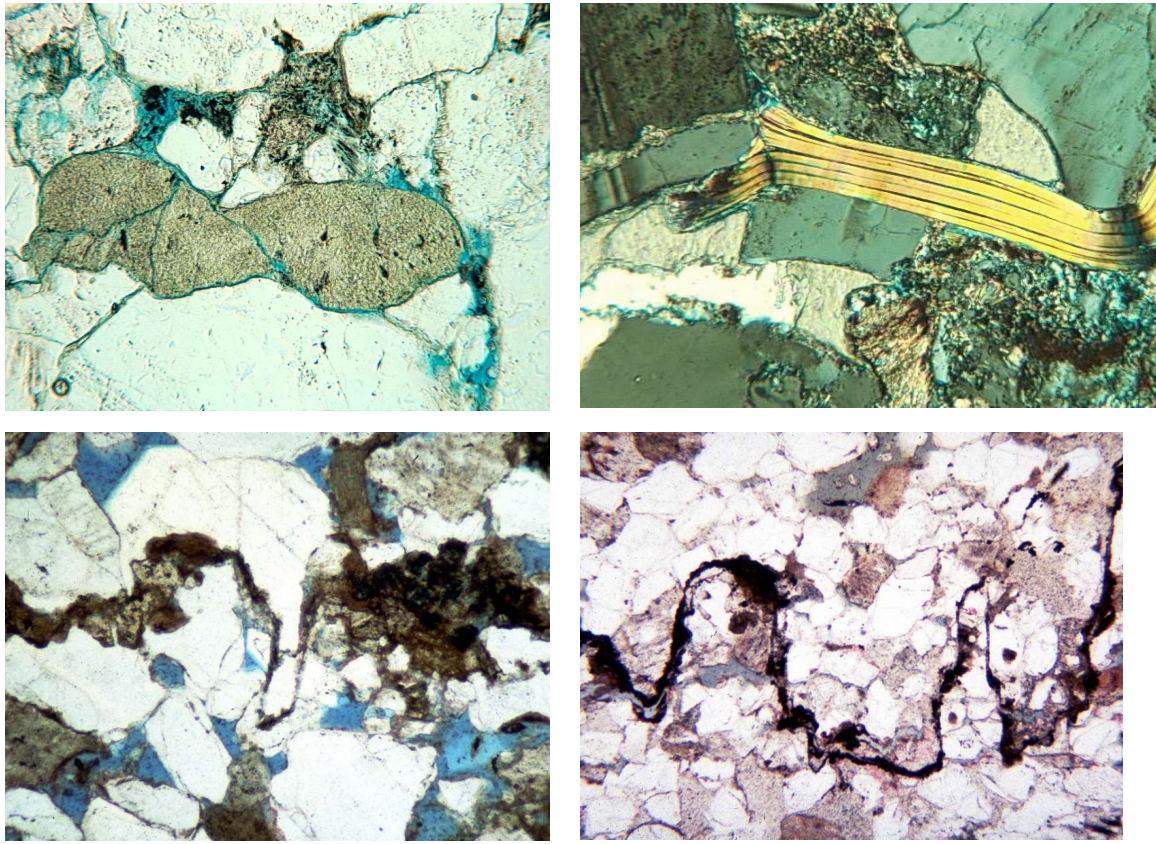



Worden & Burley, 2003

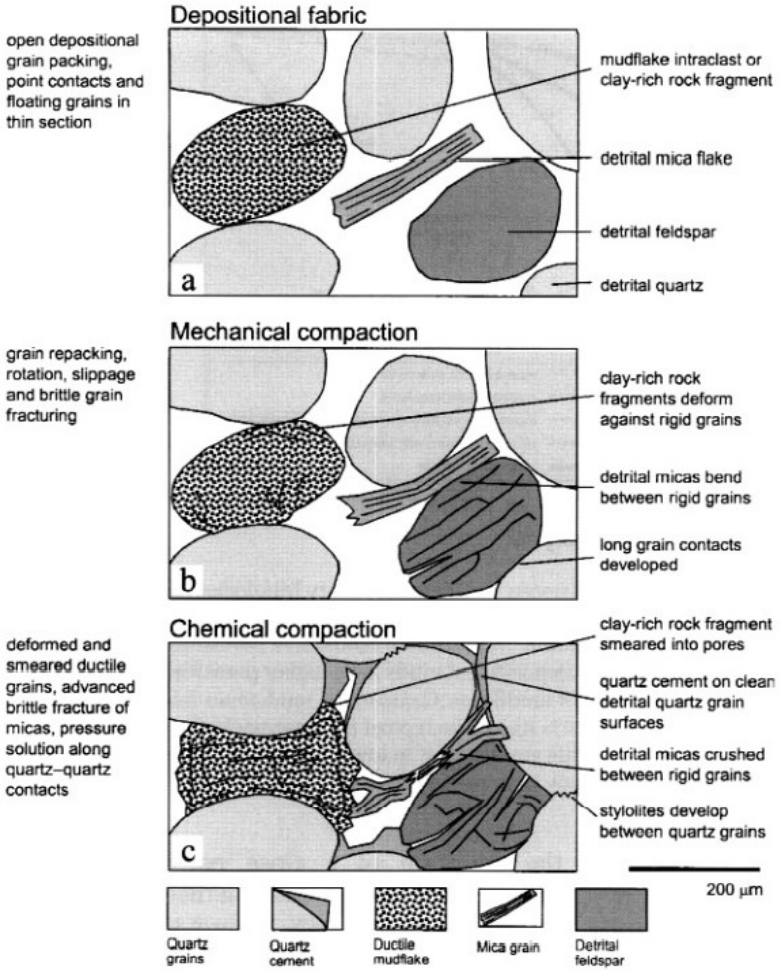


# FROM SAND TO STONE

## COMPACTION



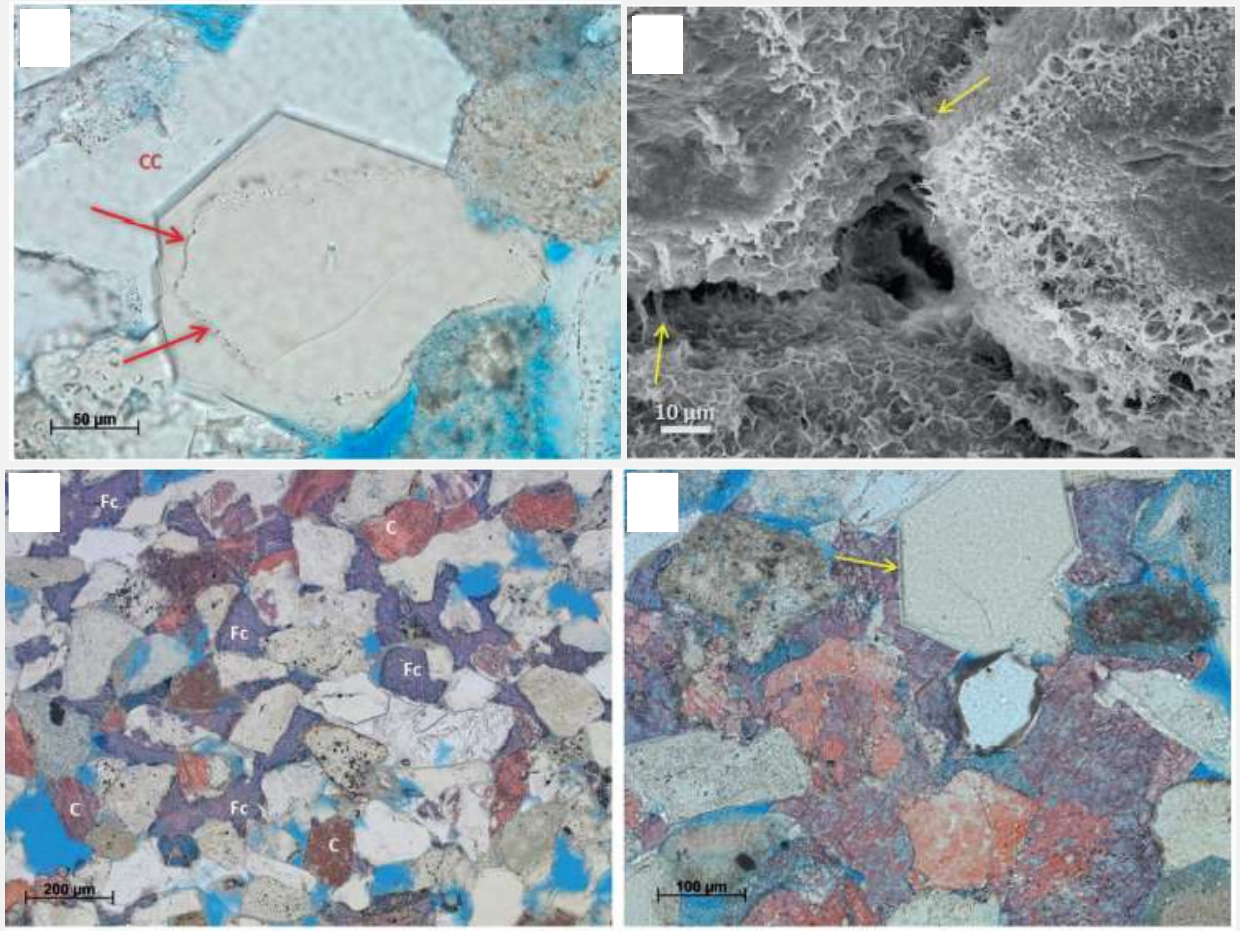
Taylor, Lander and Bonnell, 2022




Worden & Burley, 2003

# FROM SAND TO STONE

## CEMENTATION

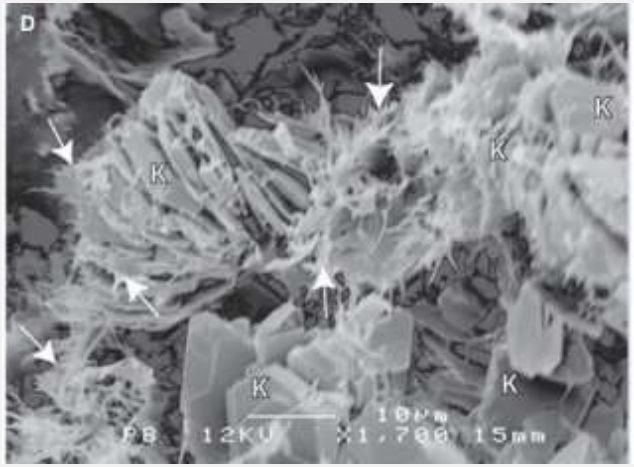



$$2KAlSi_3O_8 + 2H^+ + H_2O = Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2K^+ \quad (1)$$

K-feldspar → Kaolinite

$$KAlSi_3O_8 + Al_2Si_2O_5(OH)_4 = KAl_3Si_3O_{10}(OH)_2 + 2SiO_2 + H_2O$$

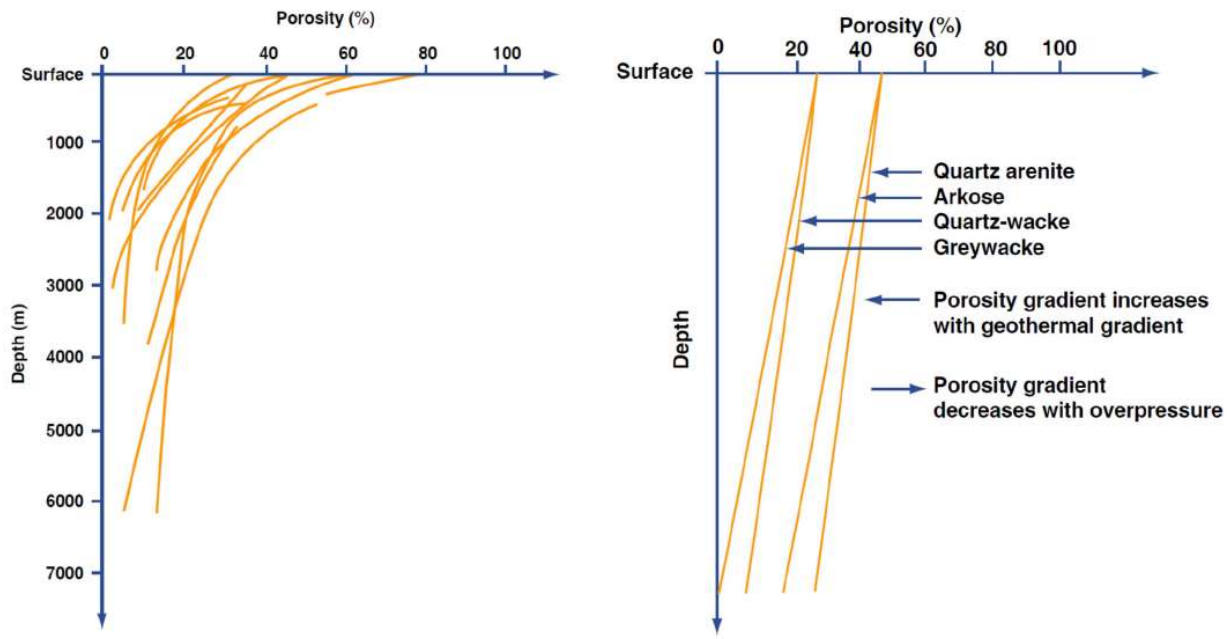
K-feldspar, Kaolinite → Illite




Origin of cement phases/replacements: stable and radiogenic isotopes, fluid inclusion microthermometry, elemental composition & mineral assemblage

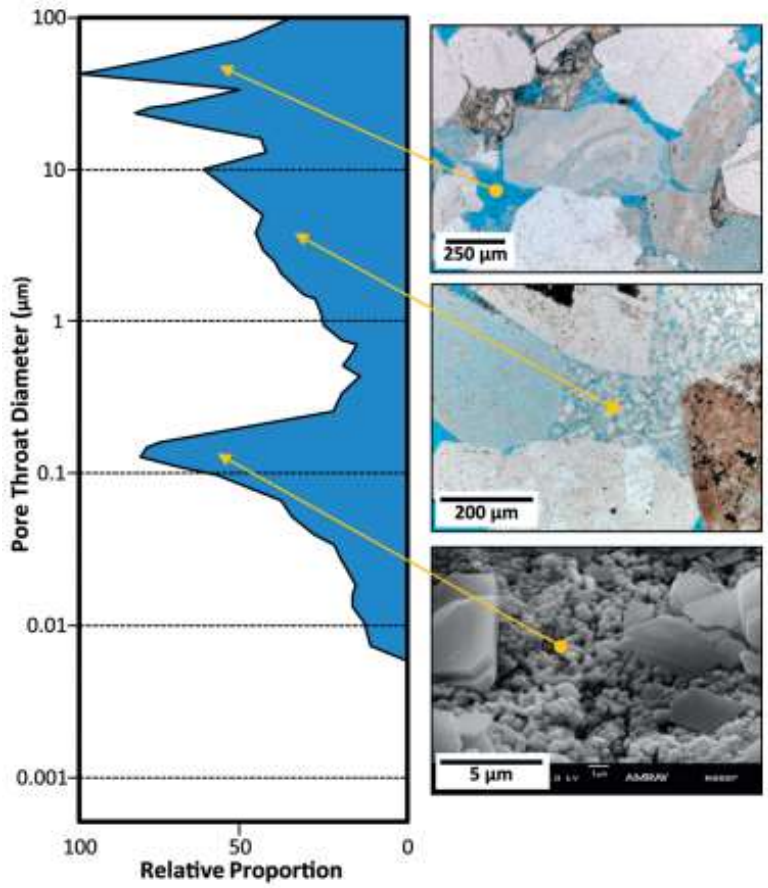
Taylor, Lander and Bonnell, 2022; Bertier et al., 2008

# DIAGENESIS AND EFFECTS ON PORE SPACE




$$\varphi = \frac{V_V}{V_T} = \frac{V_T - V_S}{V_T}$$

Total porosity – primary / secondary porosity – 'pore system'



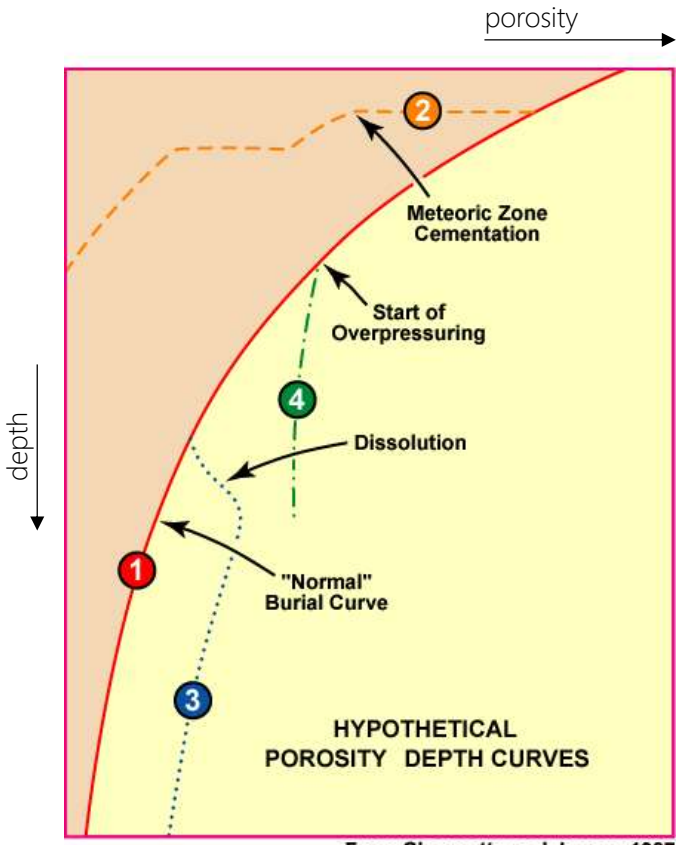

Taylor, Lander and Bonnell, 2022

# DIAGENESIS AND EFFECTS ON PORE SPACE

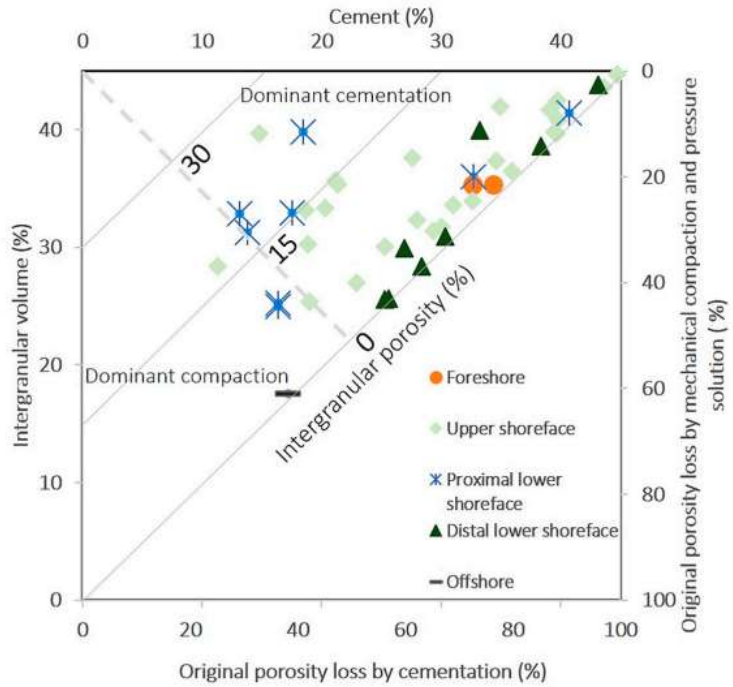
- Relevance of diagenesis and paragenetic analysis?

Diagenesis often overprints the sedimentary fabric = change in φ/k

Timing of diagenetic events in relation to the migration of e.g. HC's is of vital importance ('race against time')



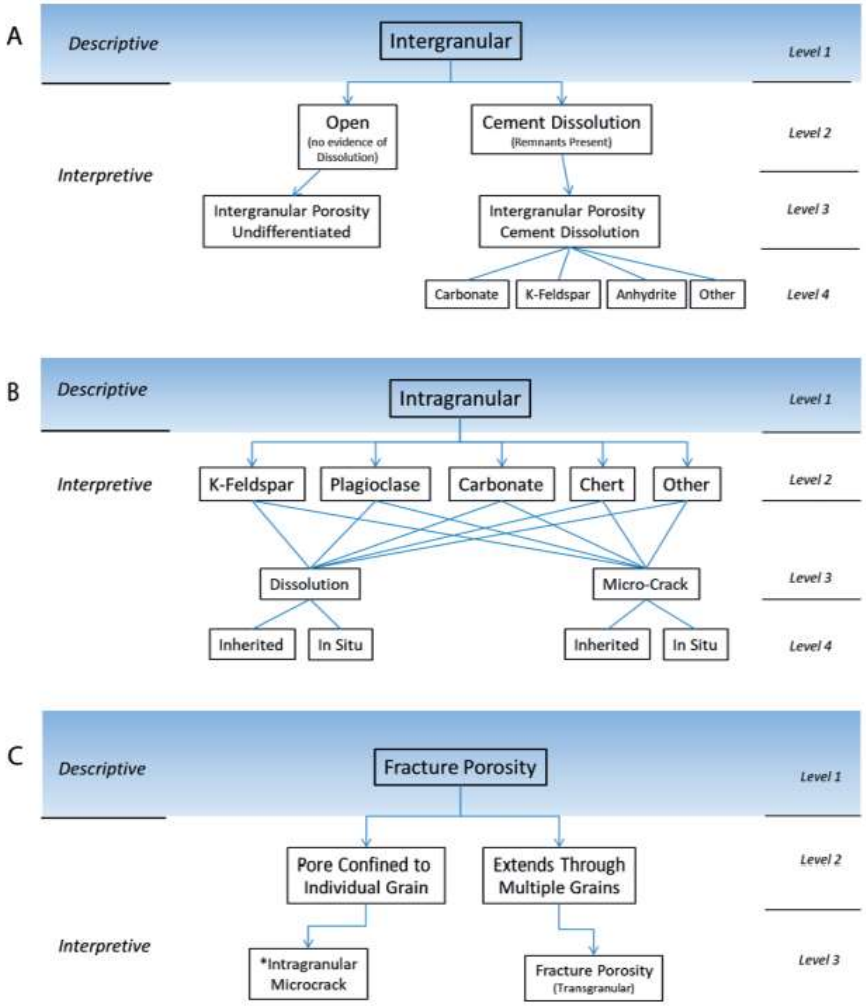

From Choquette and James, 1987

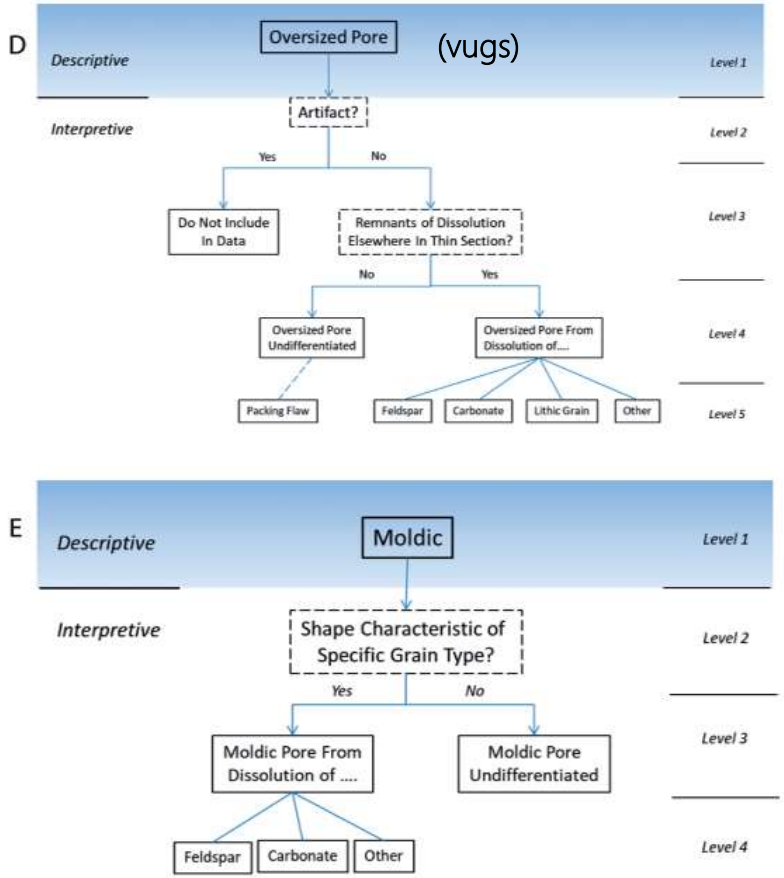



Barshep and Worden, 2021 - Upper Jurassic Corallian sandstone reservoirs in the Weald Basin, UK

IGV = ∑(pore filling cement + porosity + primary matrix)

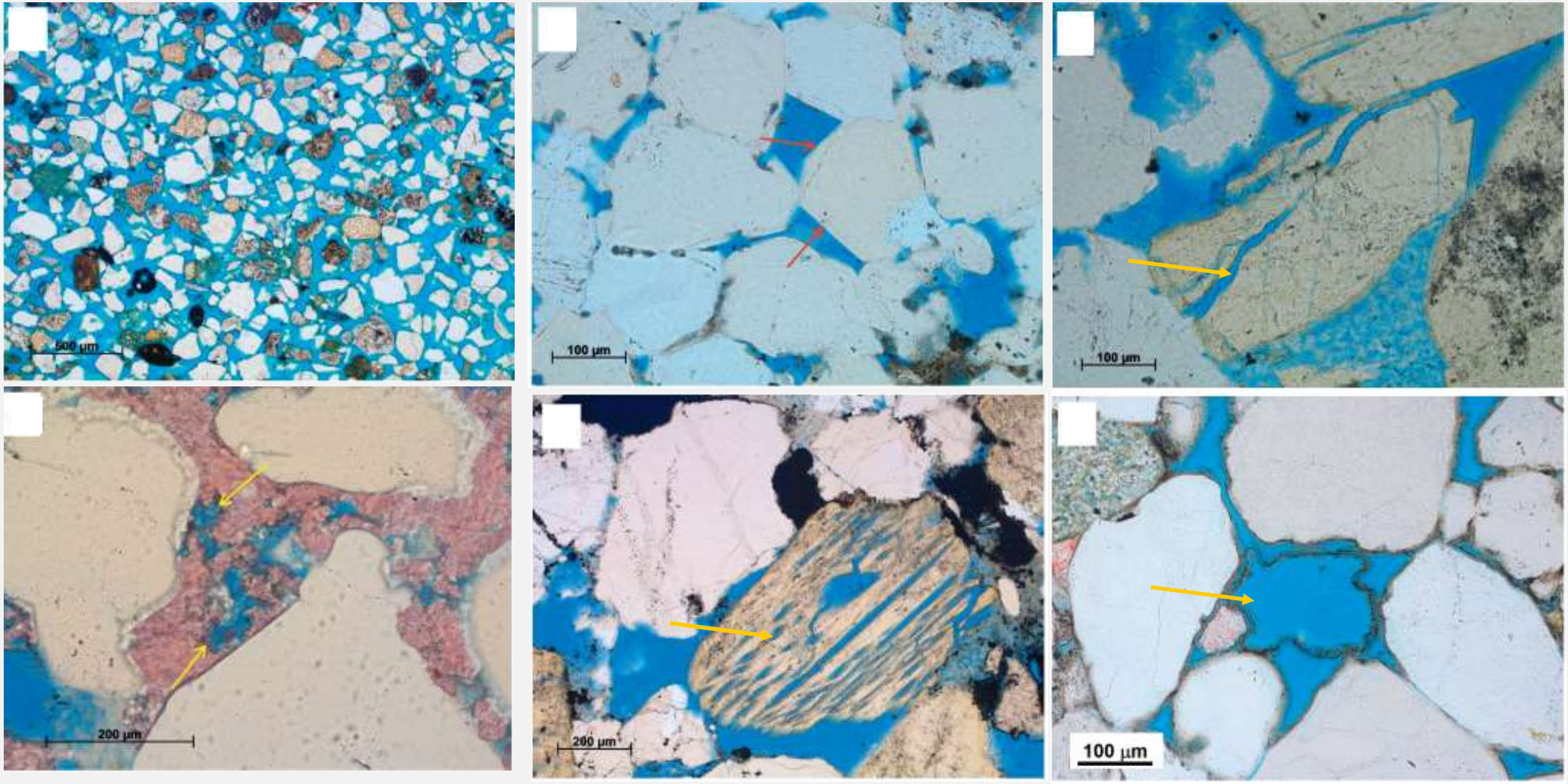
# DIAGENESIS AND EFFECTS ON PORE SPACE




Common porosity types - nomenclature

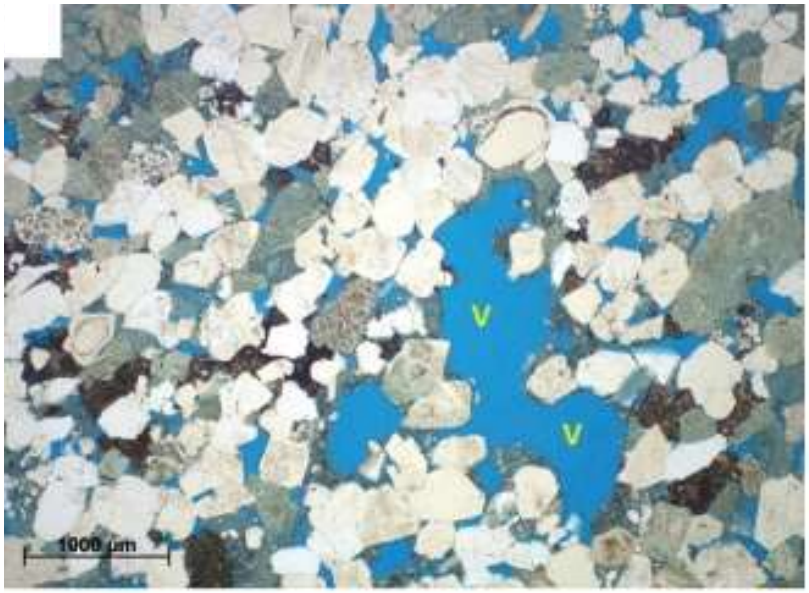
Taylor, Lander and Bonnell, 2022

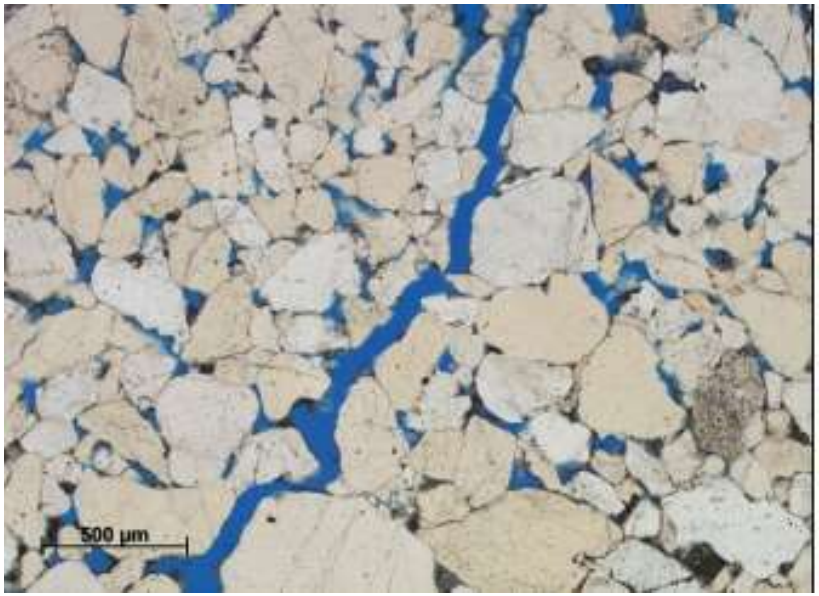



Porosity enhancement

Taylor, Lander and Bonnell, 2022

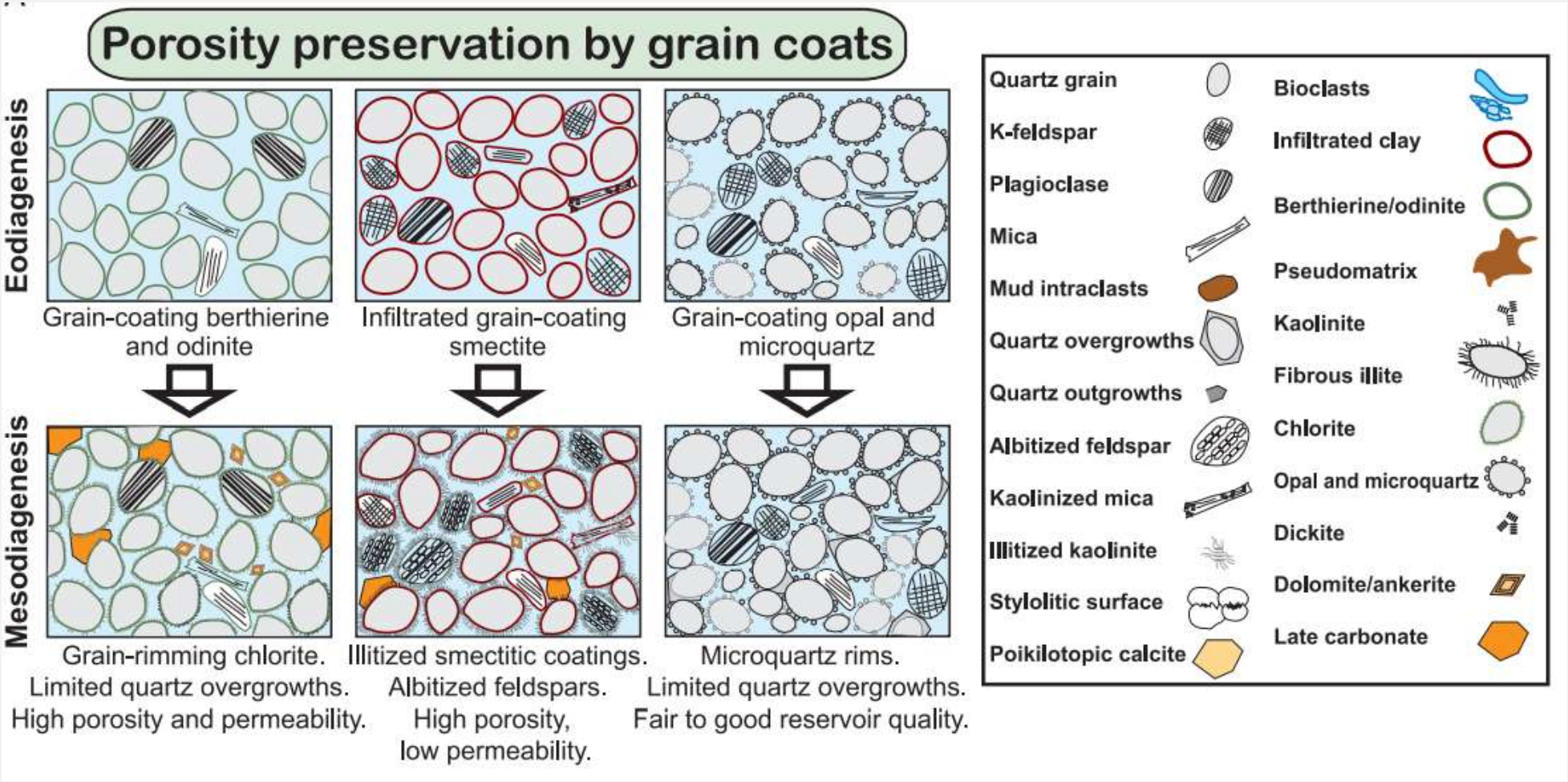
# DIAGENESIS AND EFFECTS ON PORE SPACE



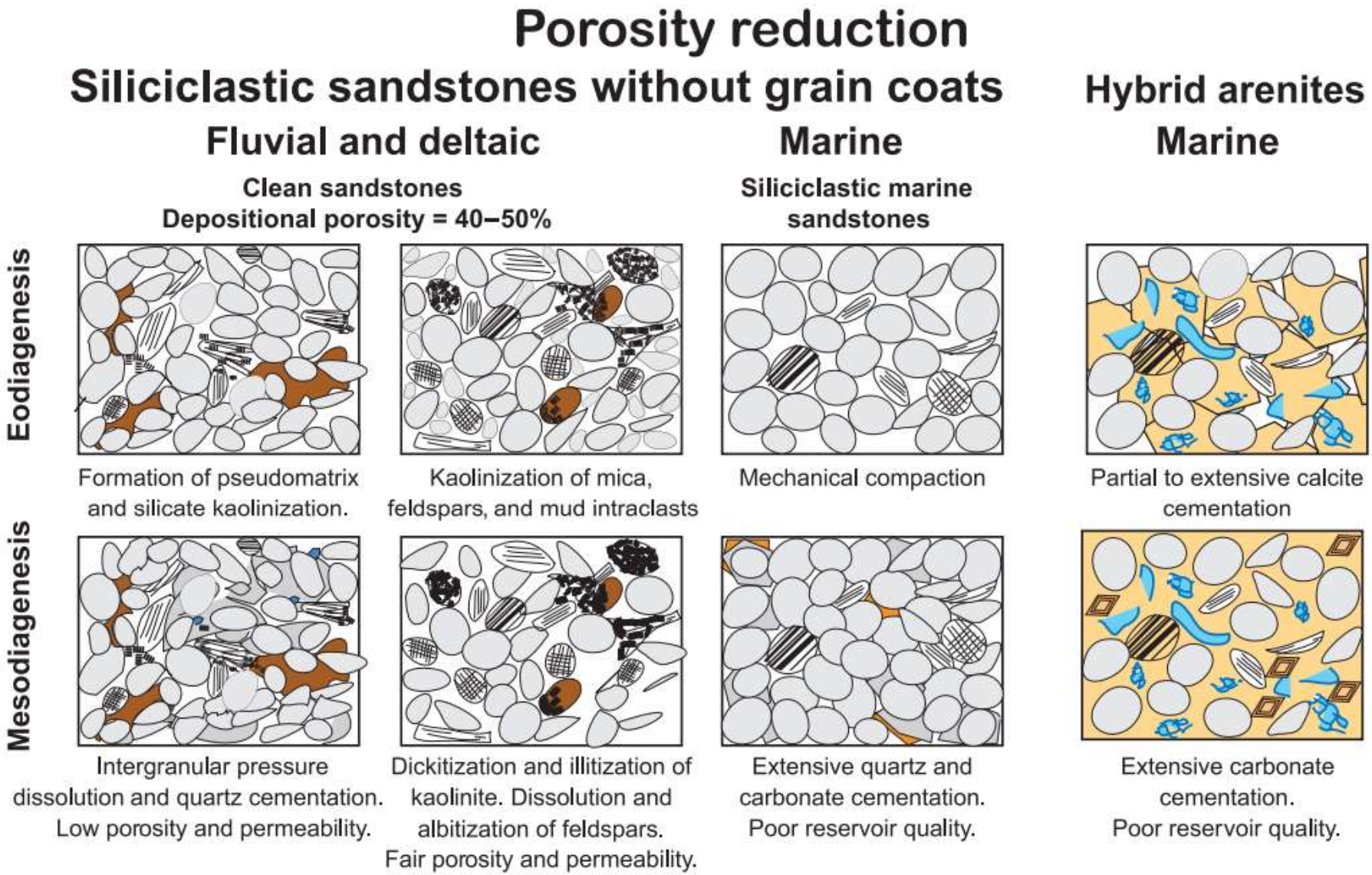

Taylor, Lander and Bonnell, 2022; TNO Study

# DIAGENESIS AND EFFECTS ON PORE SPACE




Morad et al. (2010)

Common diagenetic and related reservoir evolution pathways



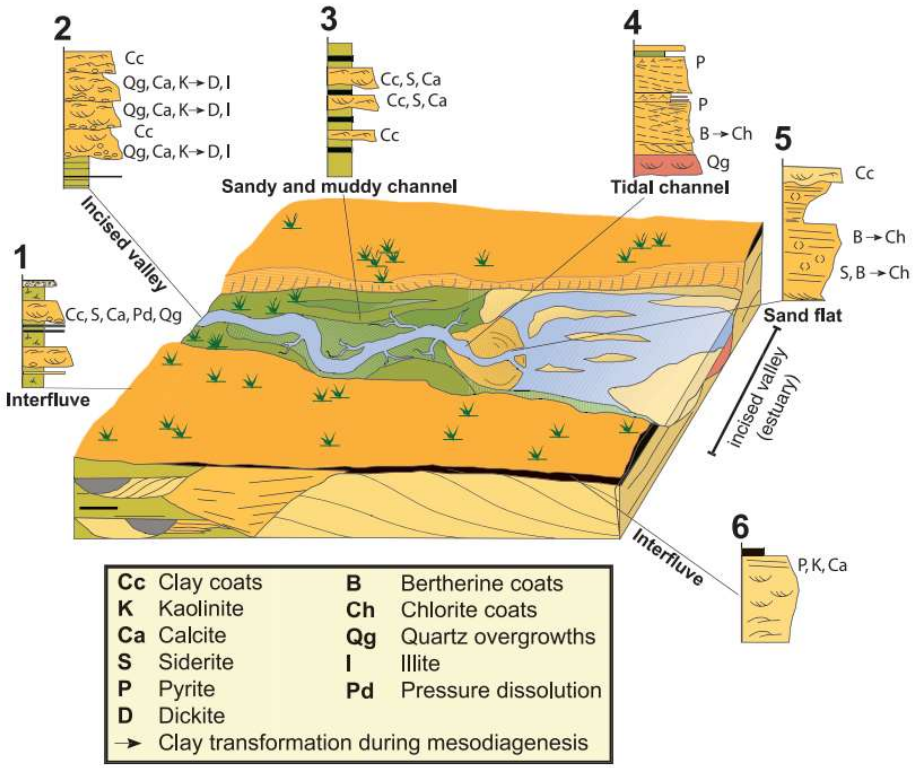

Common diagenetic and related reservoir evolution pathways.

Morad et al. (2010l)

# CAN WE PREDICT

- Sequences of diagenetic events depend on :
  - detrital grain composition: grain size, sorting, bioturbation, mineralogy
  - the depositional facies and climate
  - the rate of deposition (near-surface residence time)
  - evolution of pore fluids: salinity, organic matter, saturation in, K, Si, Al, $CaCO_3$
  - the basin history: P, T evolution (burial – and uplift – curve)

- Common sequences permit models and prediction … but closely associated deposits may have different styles of diagenesis.

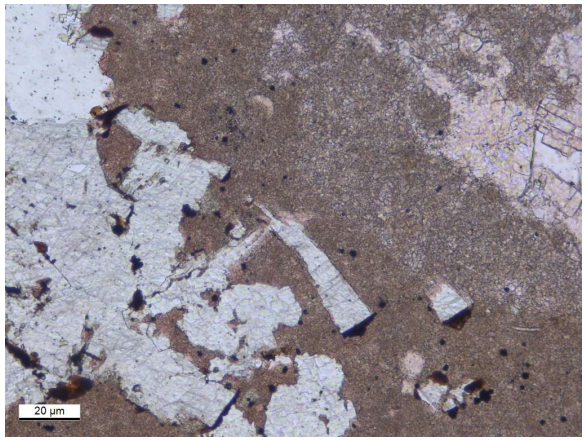


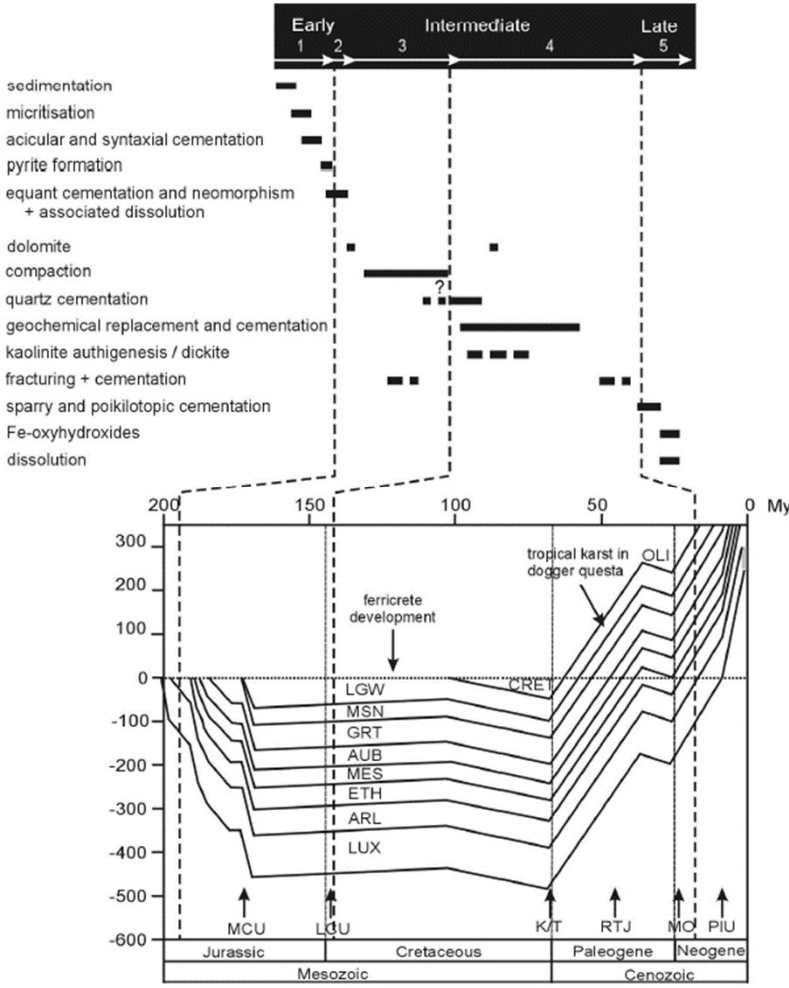

LINKING THE IMPACT OF DIAGENETIC ALTERATIONS ON RESERVOIR HETEROGENEITY TO SEQUENCE STRATIGRAPHY

Morad et al. (2010)

# CAN WE PREDICT
## PARAGENESIS

- Paragenetic analysis = relative time history of mineral precipitation, dissolution, and replacement.
- Paragenetic information, supported by geochemical data;
  - Allows placing the diagenetic phases precisely on a burial curve and integrate them with regional tectonic and fluid migration history
  - Provides important evidence for **controls on diagenesis that** ultimately **influence rock properties** (e.g. reservoir, mechanical)
  - Timing of secondary porosity development



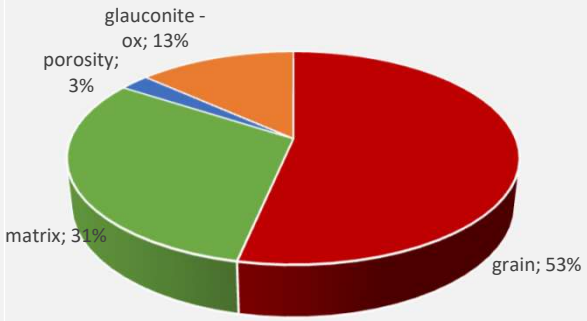



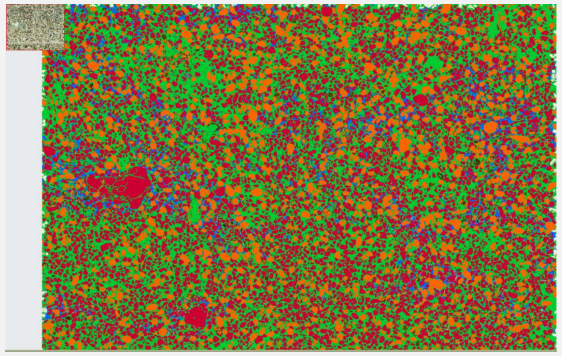

Van den Bril, 2008

# CAN WE PREDICT
## PARAGENESIS

- Accurate **paragenesis analyses are fundamental inputs or benchmarks for numerical forward models** used in predicting sandstone reservoir quality (e.g. in places where samples are absent)

- Quantitative assessment of the diagenetic phases



# A QUANTITATIVE APPROACH

## GSD

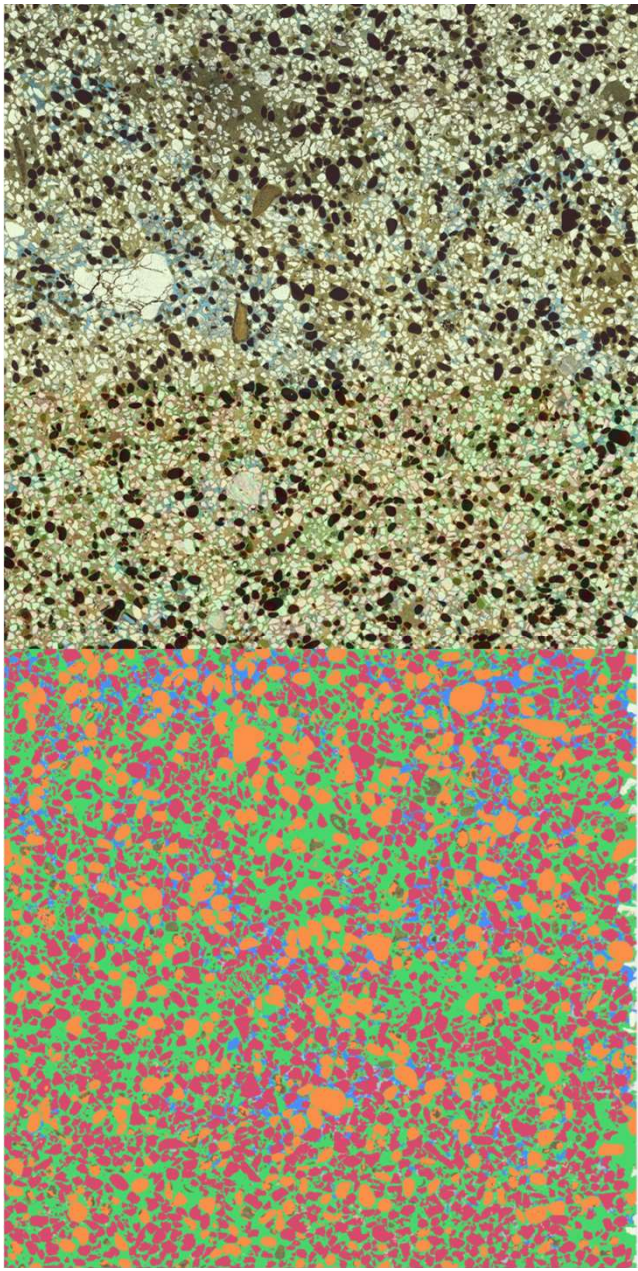
- Necessity to quantify essential parameters of **clastic rocks** for numerical models
- Important textural characteristics include
  - the grain size distributions (GSD)
  - (shapes of grains)
  - composition

$$\varphi = -\log2(mm)$$

(Krumbein, 1934)

| | | Phi (Φ) | mm | µm |
|---|---|---|---|---|
| ↑ *Gravel* | | -1 | 2 | 2000 |
| *Sand* | Very coarse | 0 | 1 | 1000 |
| | Coarse | 1 | 0.5 | 500 |
| | Medium | 2 | 0.25 | 250 |
| | Fine | 3 | 0.125 | 125 |
| | Very fine | 4 | 0.0625 | 62.5 |
| ↓ *Silt* | | | | |

Wenthworth grade scale



# A QUANTITATIVE APPROACH

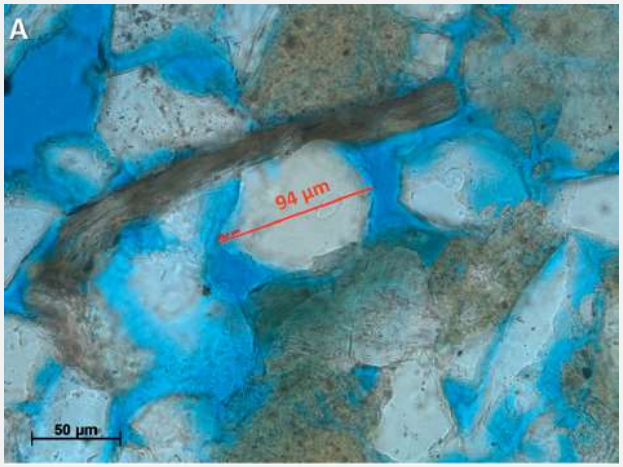
## GSD

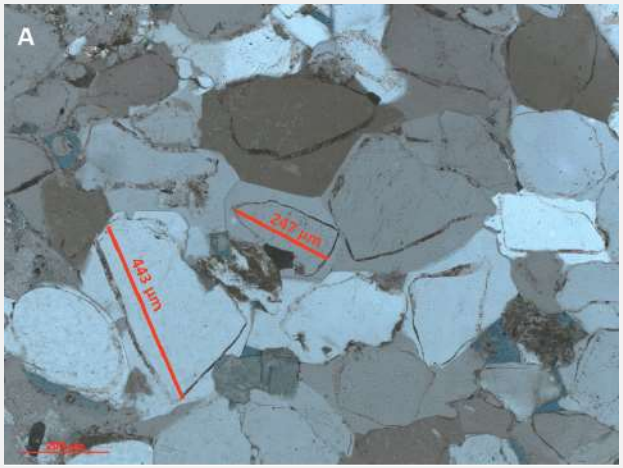
- The grain size distributions (GSD)

*Manual or digital image analysis of apparent long and short axis of large number of individual (rigid) grains*

*Longest visible (2D–apparent) dimension of the original detrital grain*

*BUT: authigenic rims, coatings, pressure solution, grain fracturing*

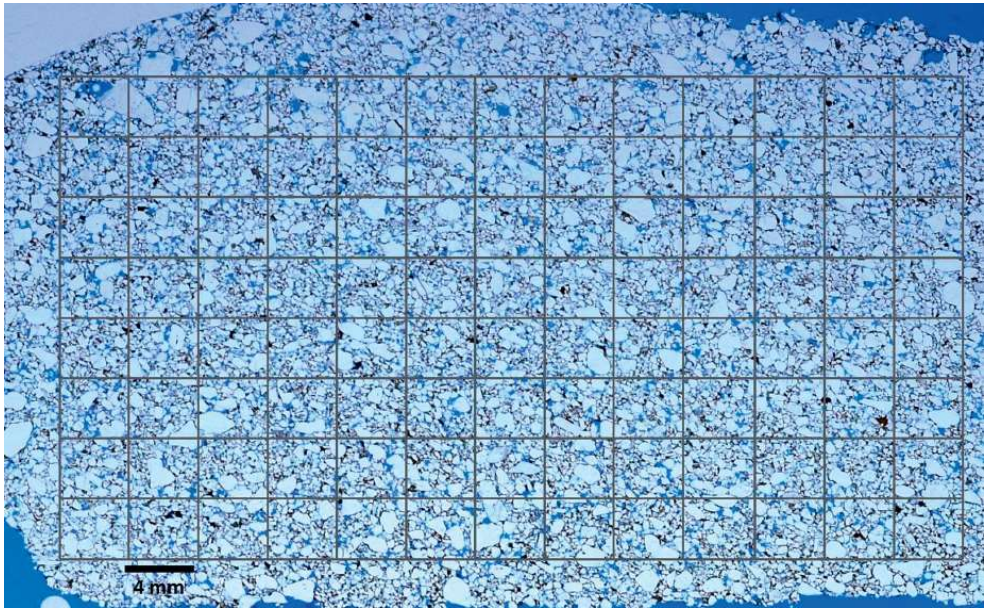


# A QUANTITATIVE APPROACH

## GSD

- High frequency of grains
- Random sampling




(automated) grid and grain picking

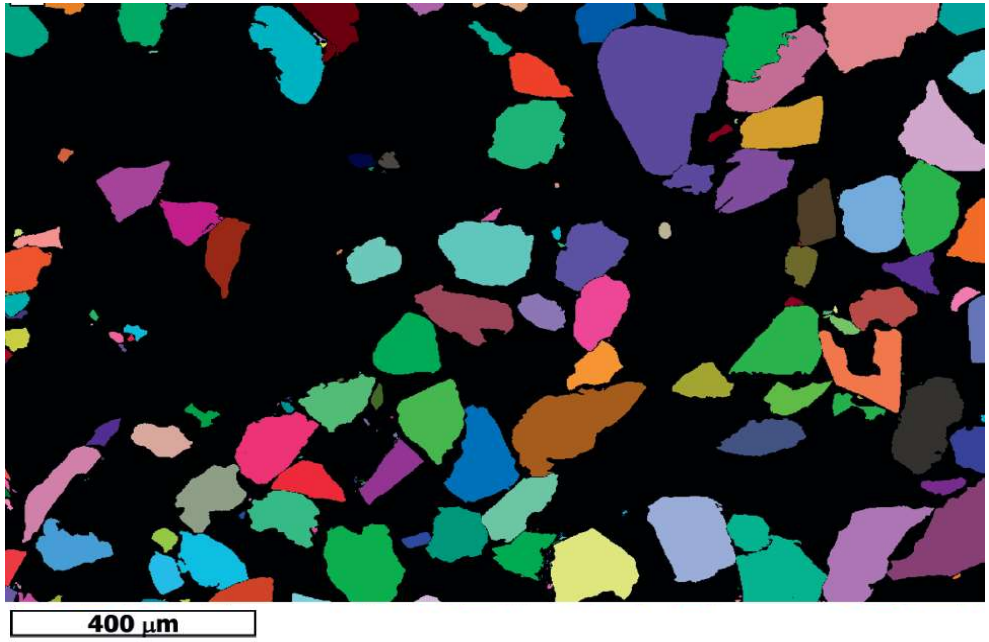
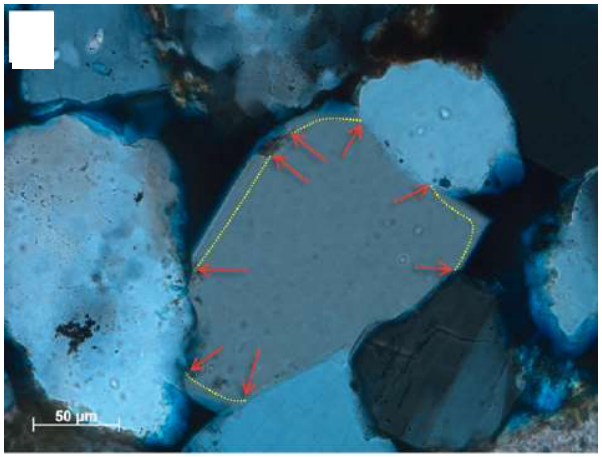



Image analysis of all grains captured

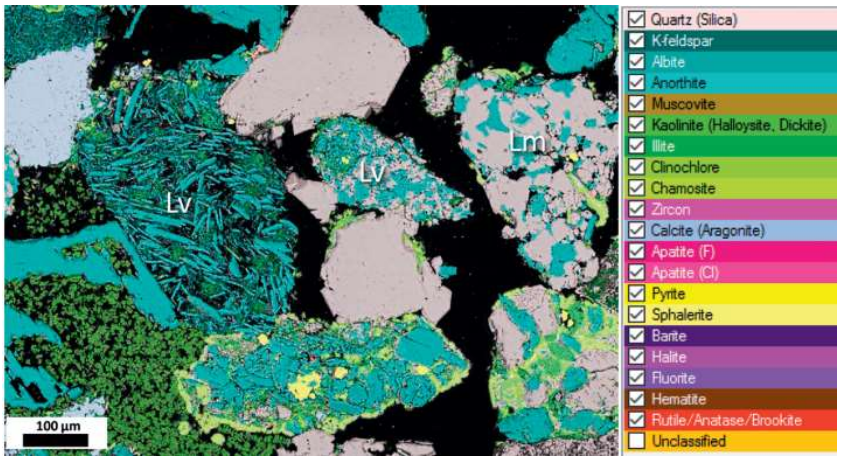
Sorting, mean grain size, (assymetry of) GSD, lineament analysis

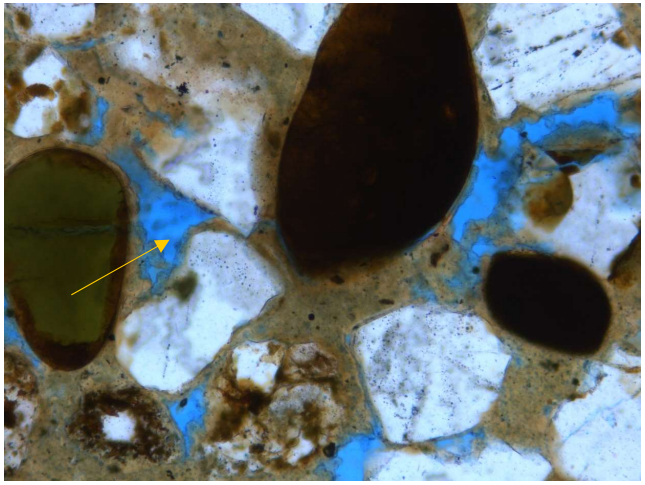
# A QUANTITATIVE APPROACH
## MODAL COMPOSITION

- Modal analysis : the quantitative assessment of the volume abundances of rock constituents and pore space
- Choose most useful image type for your goal and consider representativity of area
- Choose relevant approach: Point counting, digital image analysis (color or gray-scale images and/or mineral maps)
  - Challenge to recognize overgrowths -> SEM-BSE/-CL
  - Identification and quantification of lithic grains, polycrystalline qz, glauconite may be problematic



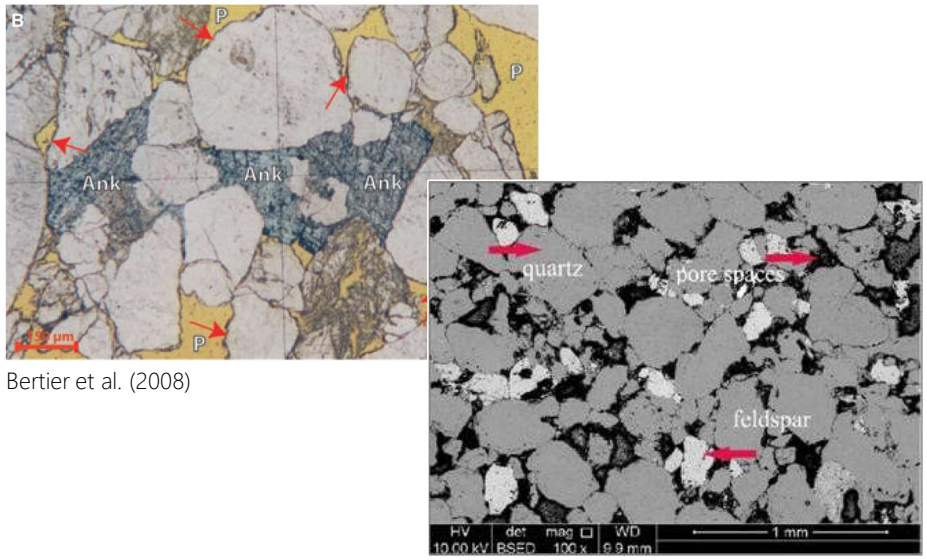

Taylor, Lander and Bonnell, 2022



SEM-BSE-EDS based mineral maps

# A QUANTITATIVE APPROACH

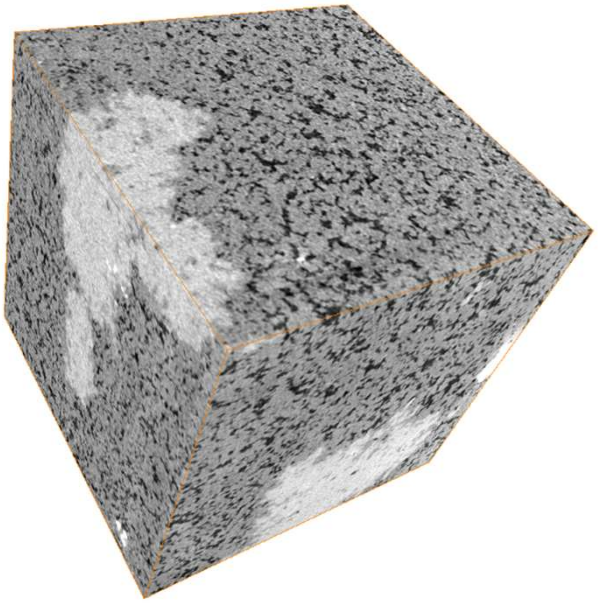



Bertier et al. (2008)

Classical petrographic tools

+ detailed paragenetic history can be reconstructed

− Quantification, shape analysis approximative 2D

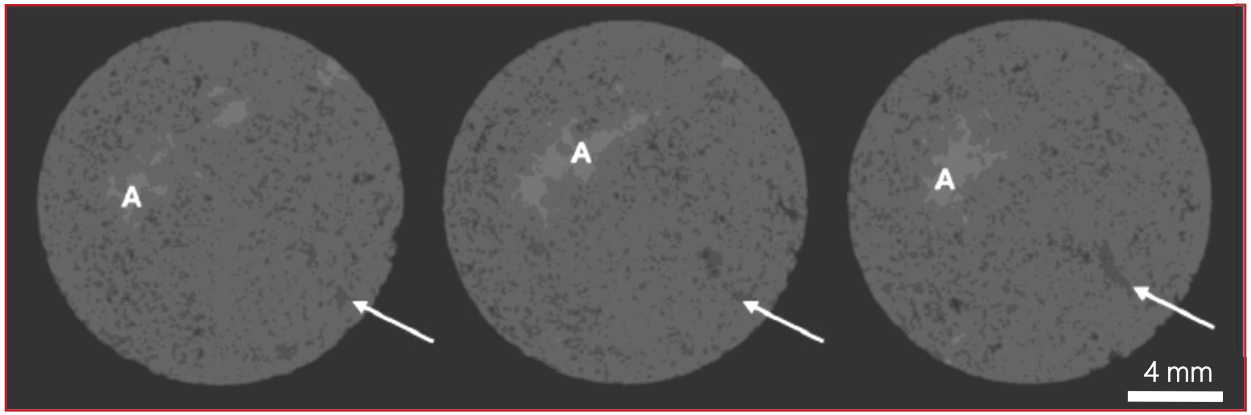


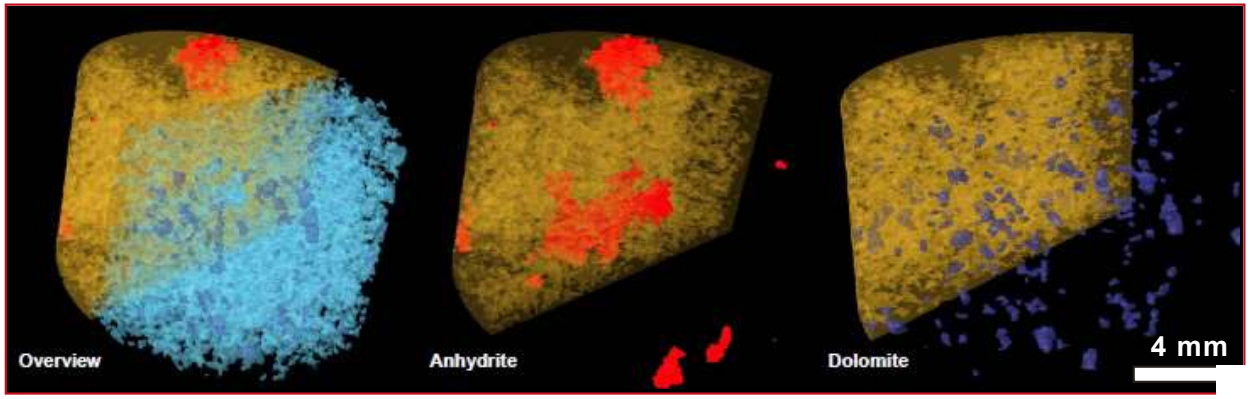
X-ray (µ-)CT

+ 3D petrography
More reliable quantification and shape studies
Pore network studies

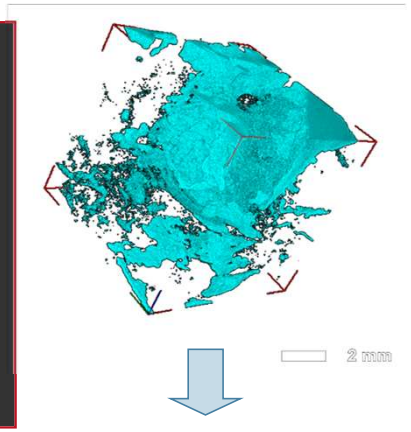
− No distinction between different cement phases with same mineralogy

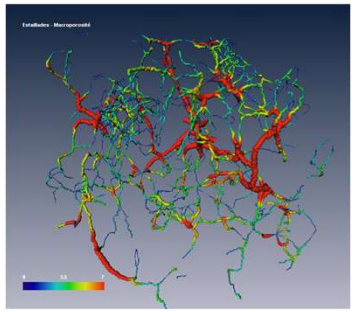
# A QUANTITATIVE APPROACH




3D rock typing through time



(R-)PNM

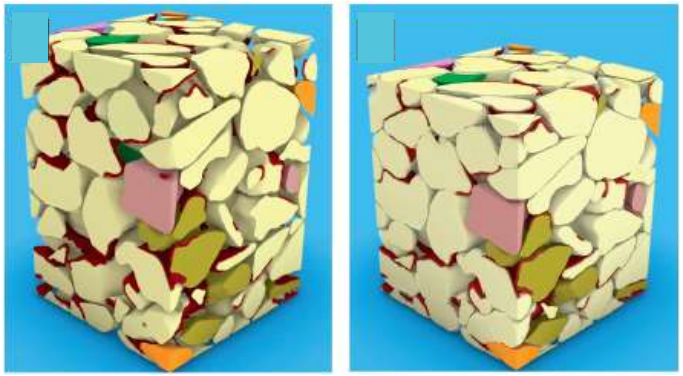
Numerical tool to simulate/predict petrophysical rock properties

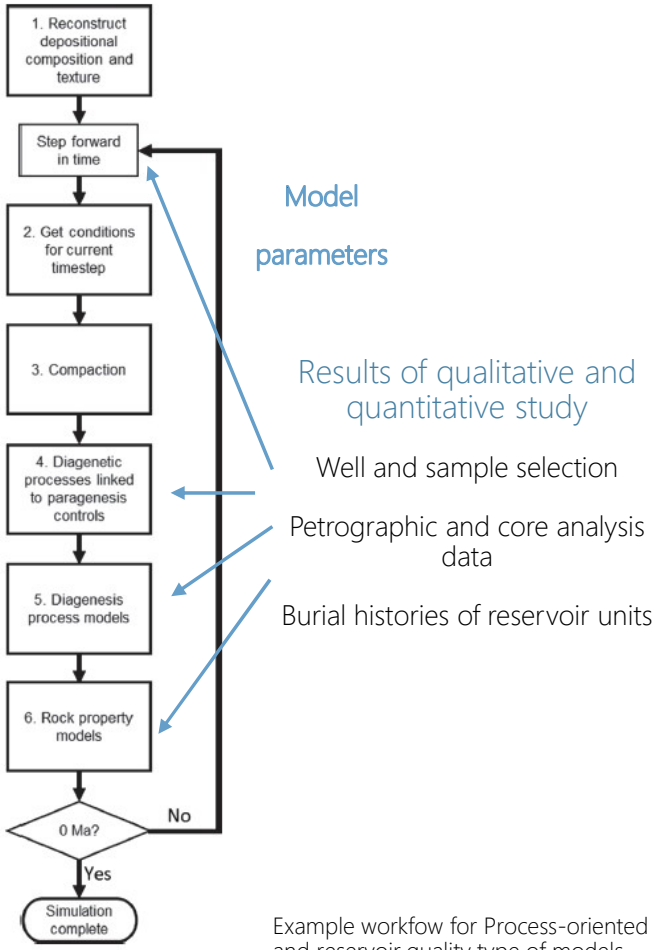
# A QUANTITATIVE APPROACH

- Depositional state of the sample
  - Remove cement modal categories (formed after deposition)
  - Restore original modal category abundances
  - Mass balance calculations to reconstrct depositional composition (e.g. mica and feldspar from kaolinite and illite)
  - Determine depositional IGV (mean grain size, sorting can help)
  - Reset grain coating to coatings present during deposition

Quantitative composition, texture and IGV

*If feasible repeat this for other geologic time steps / snap shots during diagenetic evolution of reservoir rock.*





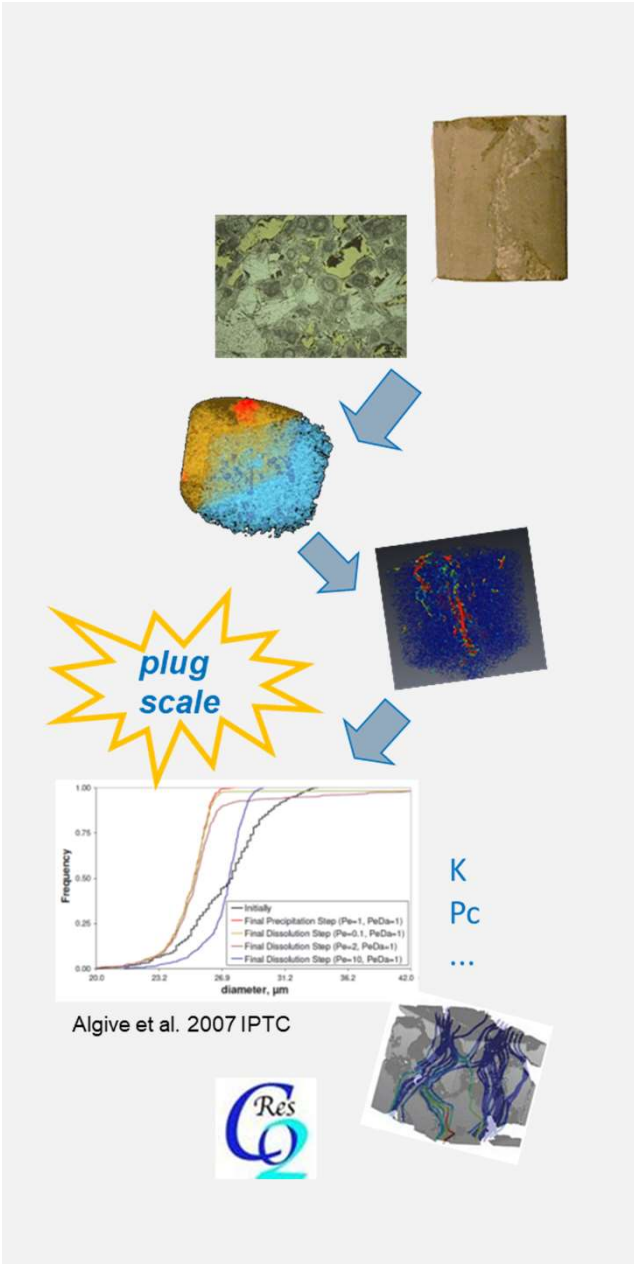

Example workfow for Process-oriented and reservoir quality type of models

Taylor, Lander and Bonnell, 2022

# A QUANTITATIVE APPROACH

## CASE STUDY EXAMPLE

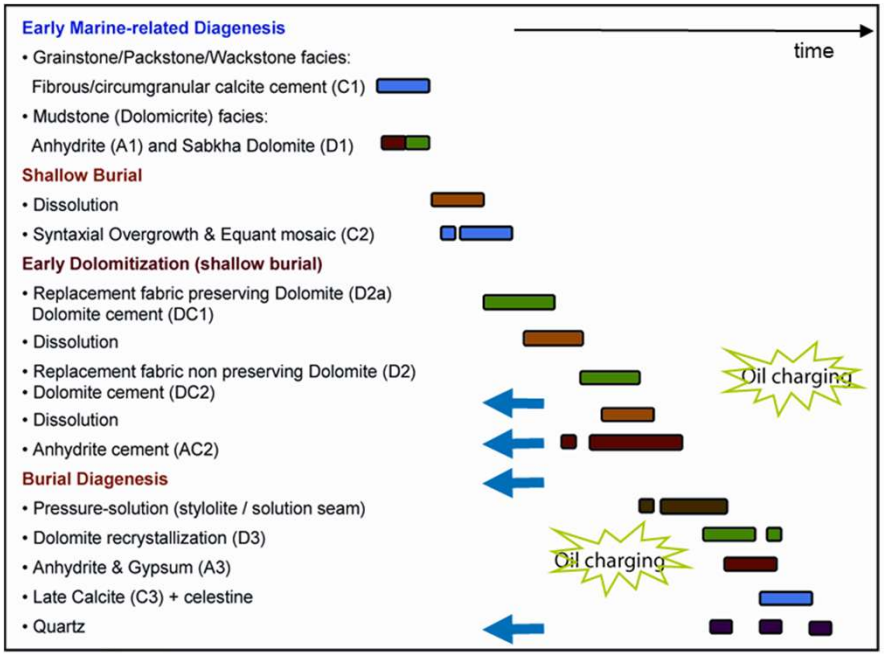
- Case study (carbonate reservoir)
  - Quantification of the pore structure evolution in reservoir rocks during 2 important diagenetic events
  - Numerical simulation of petrophysical property changes during diagenetic processes
- To show common problems related to 'reconstructing the depositional state of the sample'
- Some practical challenges we encountered in the modelling step



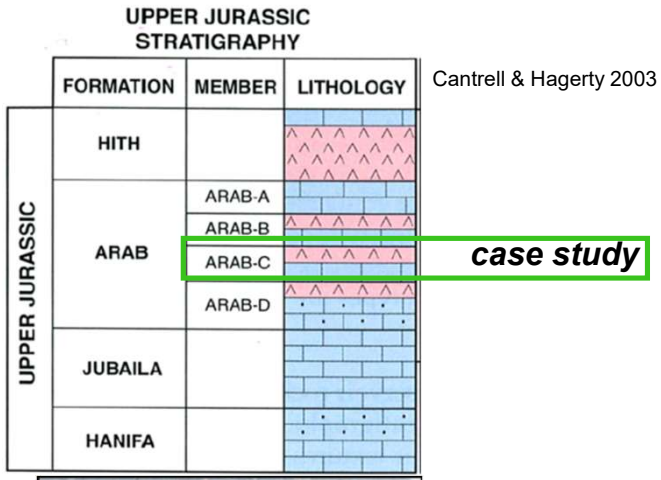
# A QUANTITATIVE APPROACH

## Case study: Arab Formation

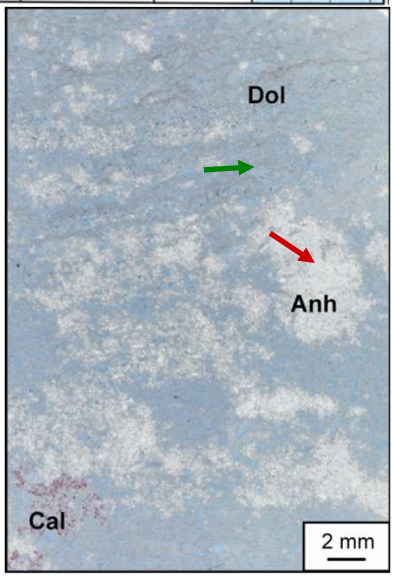
- subsurface well core material
- important oil reservoir in the Arabian Gulf
- different pore types/sizes
- pluri-mineralogical




De Boever et al., 2012; Nader et al., 2013

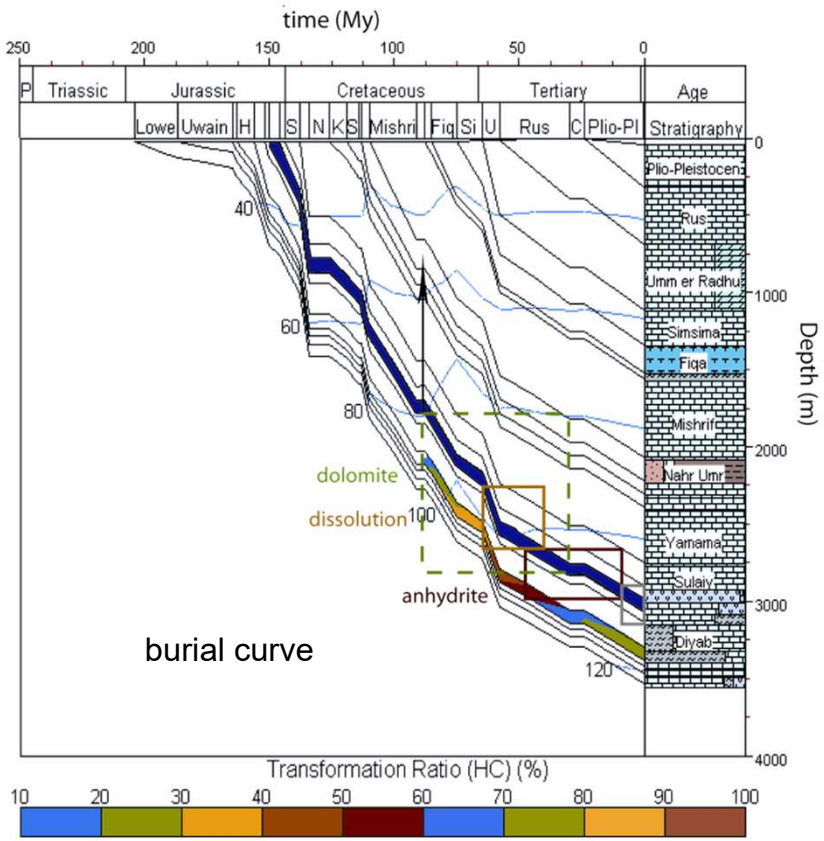



Cantrell & Hagerty 2003



# A QUANTITATIVE APPROACH

## Case study: Arab Formation

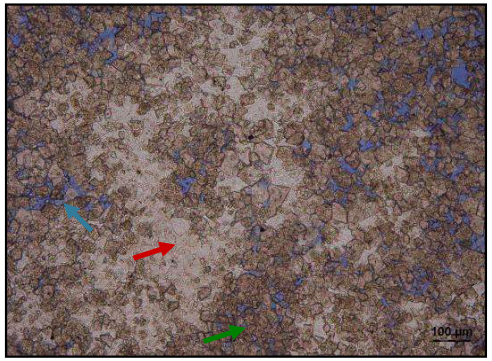


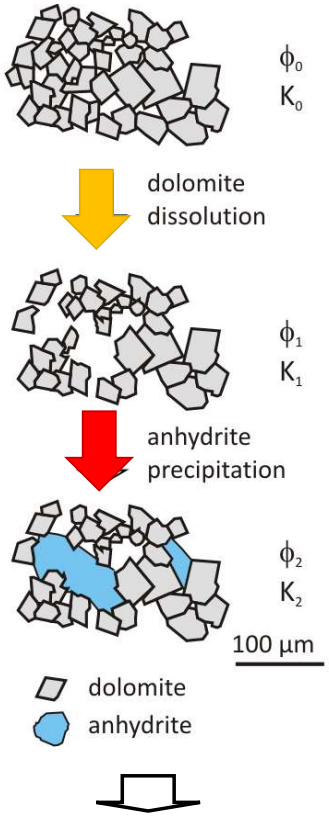

36°C/km

**Dolomite dissolution**: 85° - 95°C

**Anhydrite precipitation:** 95° - 105°C

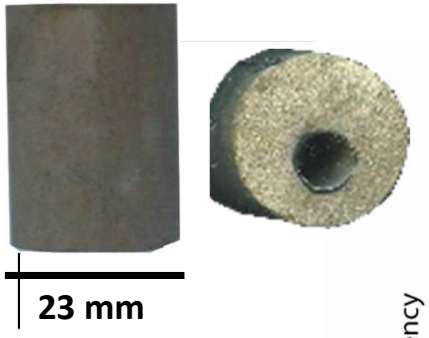
diagenetic steps in studied sample



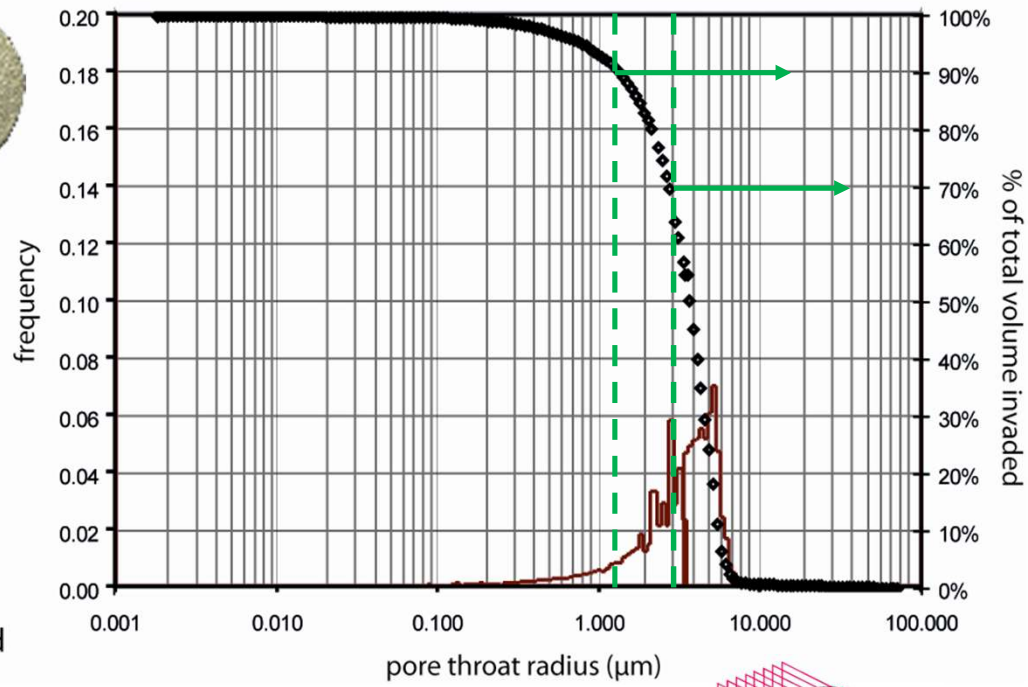

***QUANTITATIVE STEP***

# A QUANTITATIVE APPROACH

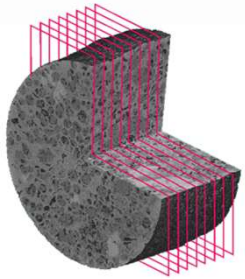



Arab Formation
dolostone

| | |
|---|---|
| dolomite wt% | 96.3 |
| anhydrite wt% | 3.7 |
| celestine wt% | 1.0 |
| porosity | 18.5% |
| permeability | 31.0 md |

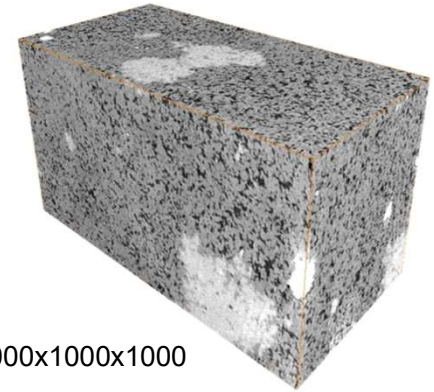



Quantitative XRD (Rietveld refinement method)
Petrophysical measurements
Micro-CT



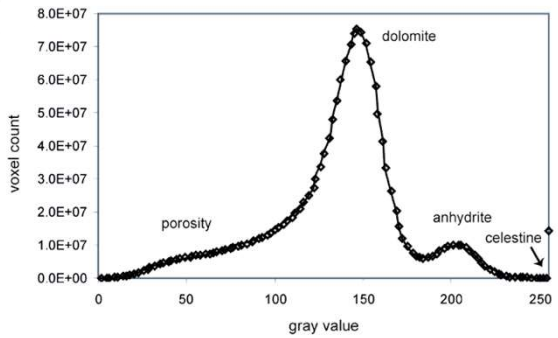
# A QUANTITATIVE APPROACH

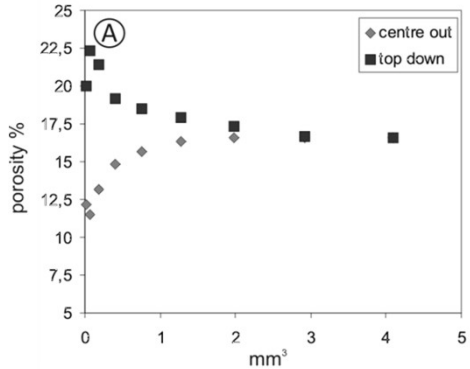
## 3D quantification of present pore space



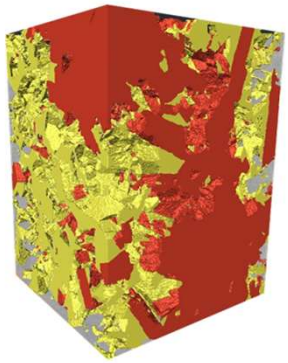
2000x1000x1000

6.7 mm³




⟹ Improve gray level histogram
⟹ Segmentation (image binarisation) + quantification of components

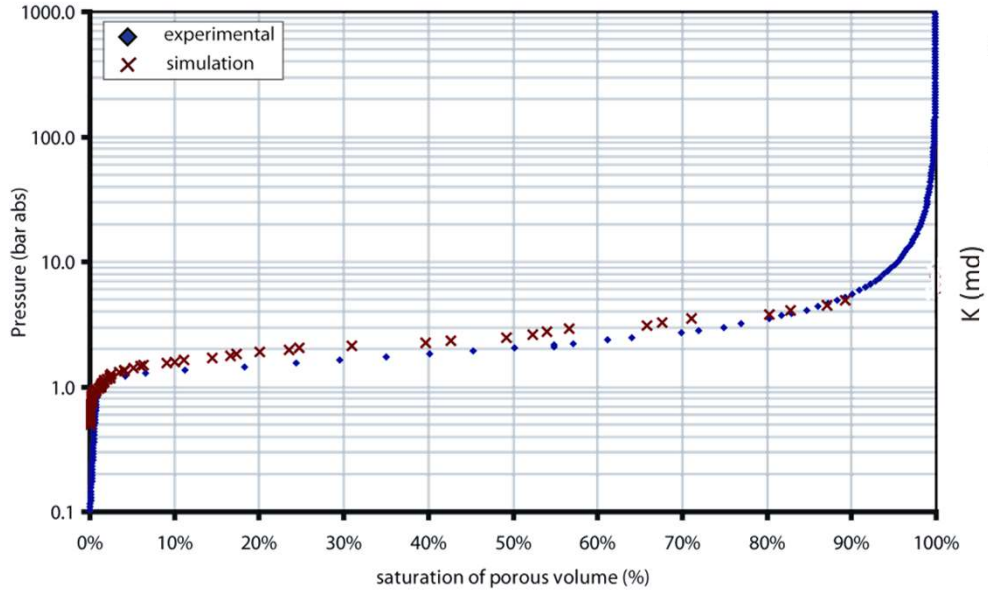


| | dolomite | anhydrite | celestine | total porosity | volume perco-lating cluster |
|---|---|---|---|---|---|
| vol% | 74.8 | 8.1 | 1.1 | 16.0% | 15.3 % |
| wt% | 88.2 | 10.0 | 1.8 | | |
| XRD wt% | 95.4 | 3.6 | 1.0 | | |

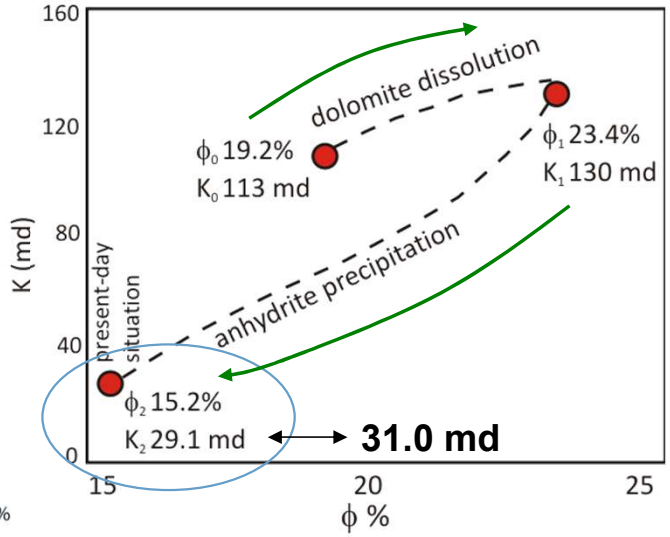
He-porosimetry: 18.5%

# A QUANTITATIVE APPROACH

## Validation of equivalent pore network




MICP



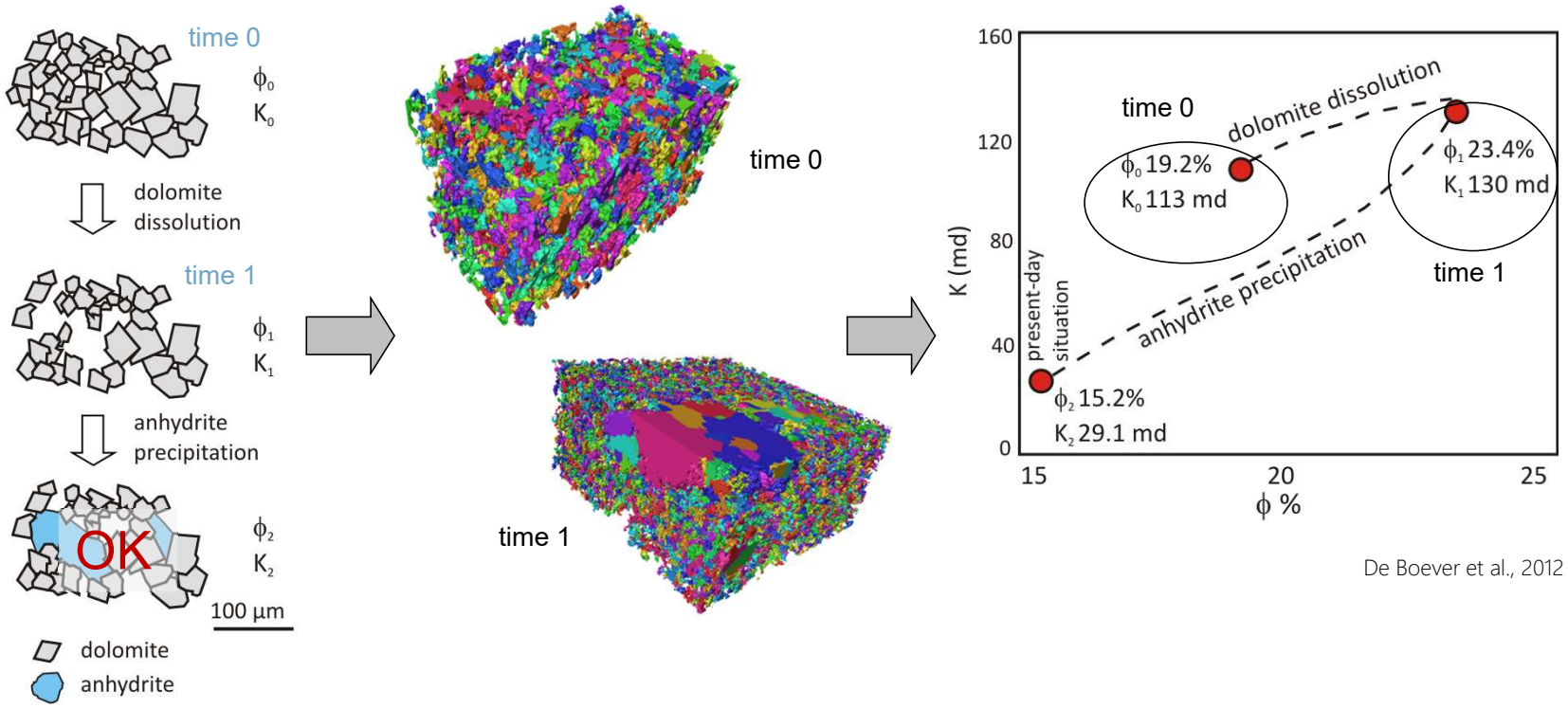

Permeability (mD)

⇨ **Realistic description of the geometry and topology of the pore network.**

De Boever et al., 2012

# A QUANTITATIVE APPROACH

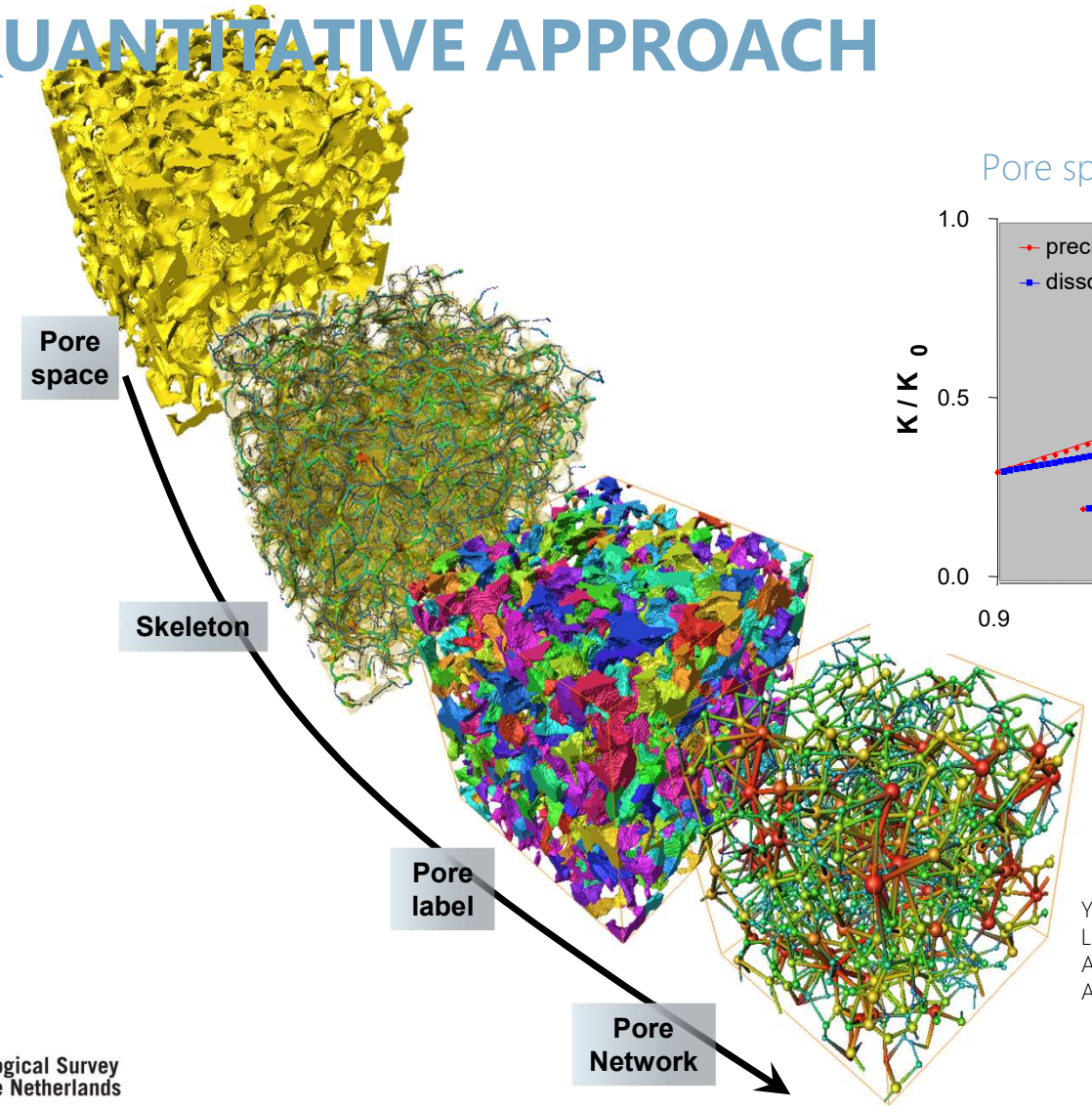
## Back in time: Pore networks at ancient diagenetic steps



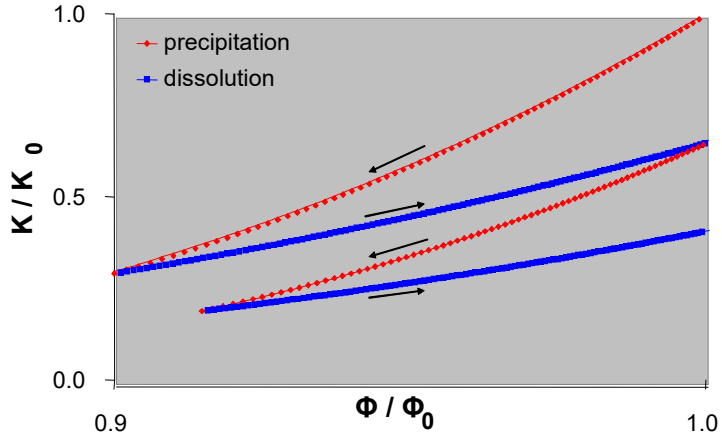

De Boever et al., 2012

3D pore structure reconstructed (approximation !!) at key diagenetic steps
Approach for quantitative rock-types throughout diagenetic history, BUT:
different cements of same mineralogy not distinguished, replacement reactions difficult to quantify…

# A QUANTITATIVE APPROACH



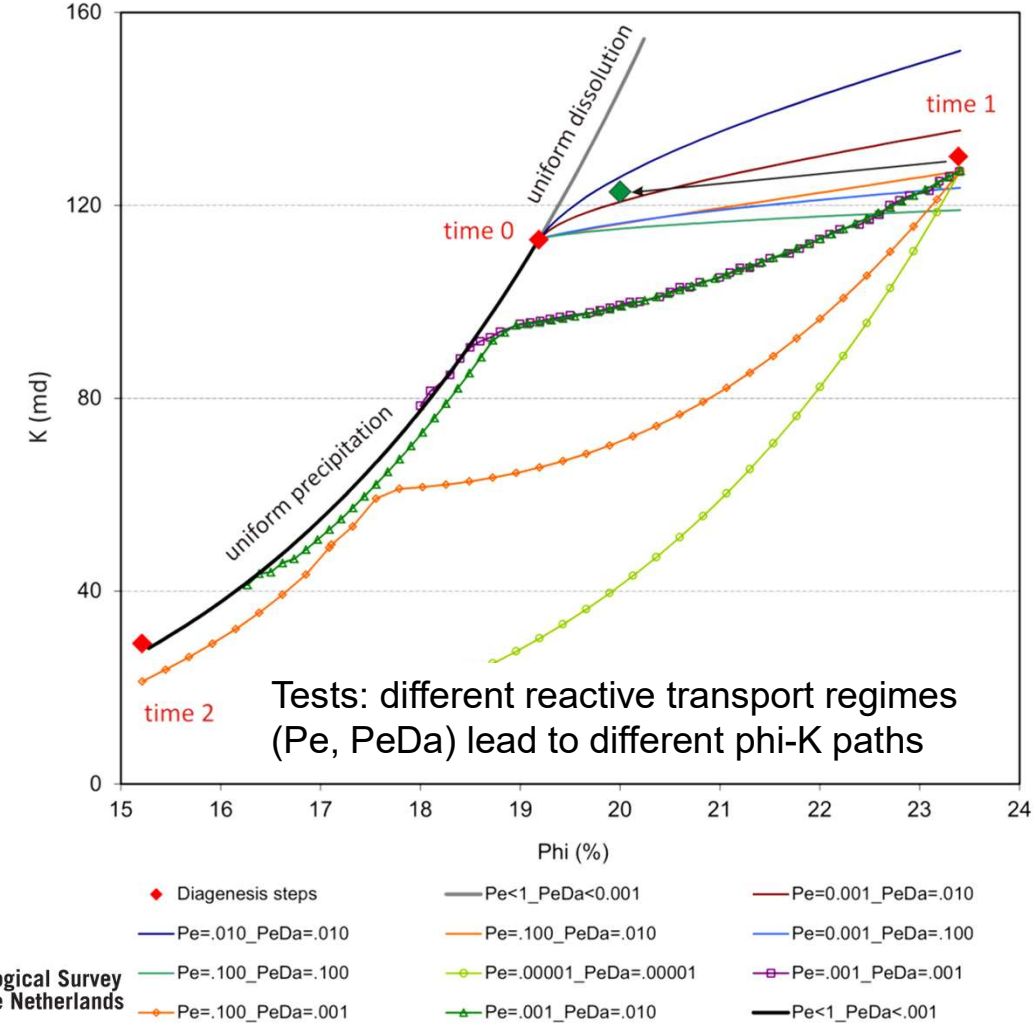

Pore space description to PNM-R modeling




Youssef et al SPE2007
Laroche & Vizika 2005
Algive et al. 2009 IPTC
Algive et al. 2009SPE

Geological Survey of the Netherlands

# A QUANTITATIVE APPROACH




PNM-R versus geochemical modeling

Microscopic reactive transport parameters

$$Pe = \frac{\bar{v} l}{D} \qquad PeDa = \frac{\kappa l}{D}$$

**Geochemical reaction-path modeling**

**v** : fluid flow velocity,
**κ**: intrinsic reaction rate constant

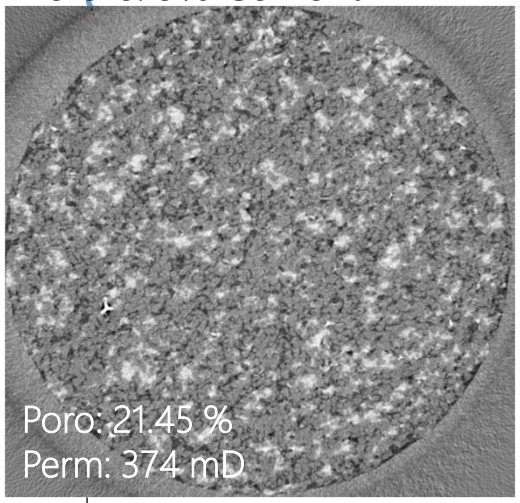
**Conflict between κ values of geochemical modeling and PNM-R**

Geological Survey of the Netherlands

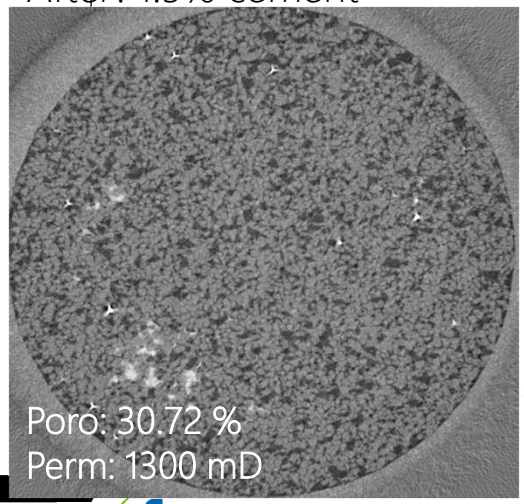
De Boever et al., 2012

# DISSOLUTION EXPERIMENT - RESULTS

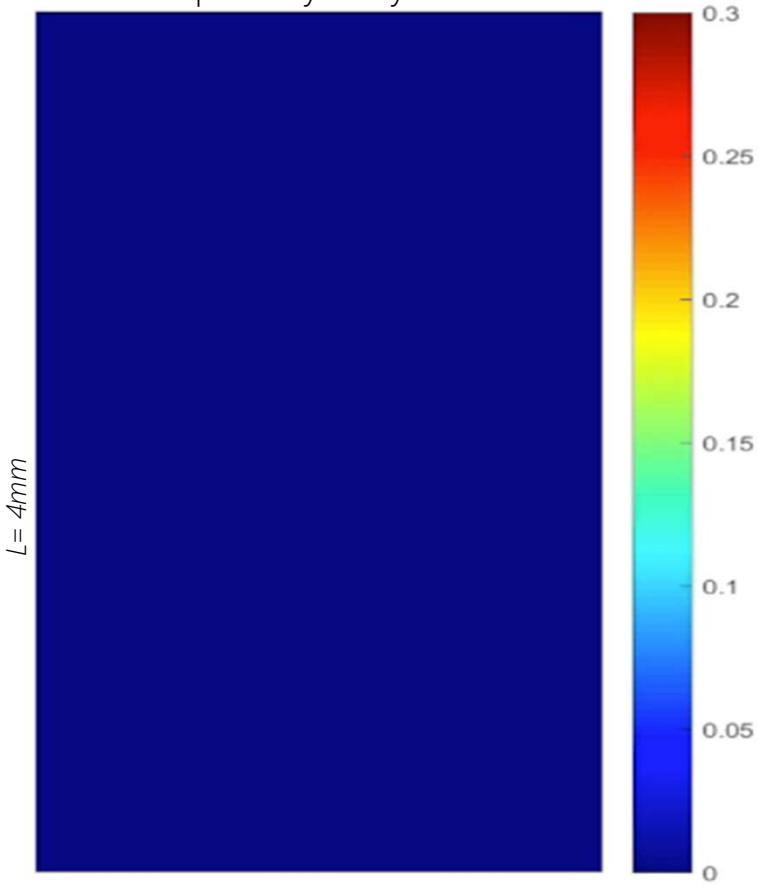
Before: 9% Cement



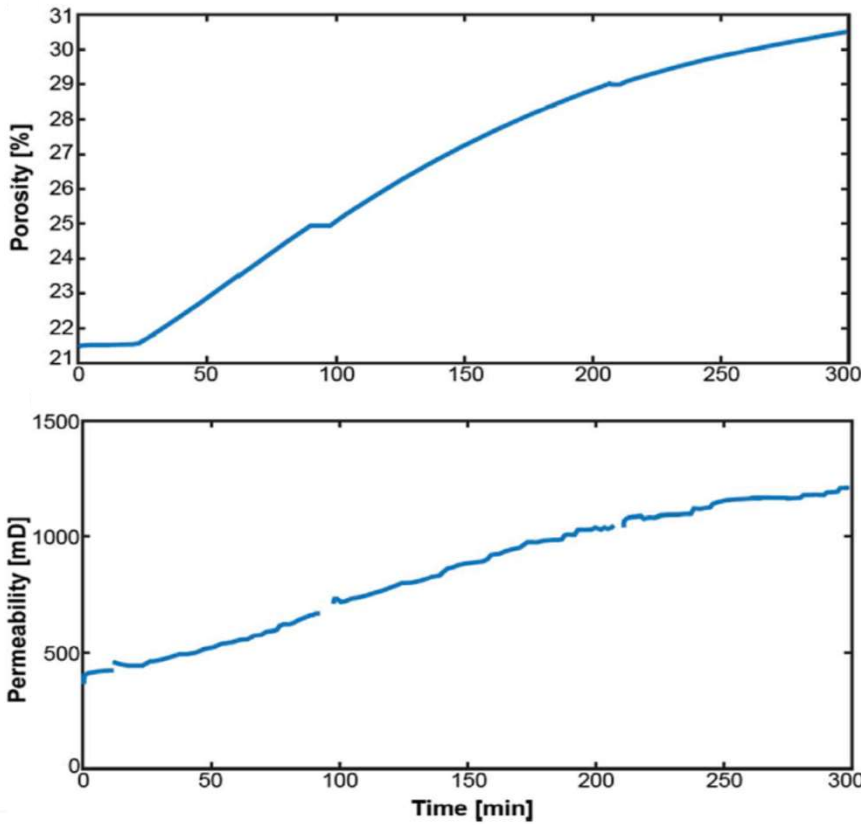

After: 1.5% cement




Created porosity % by dissolution



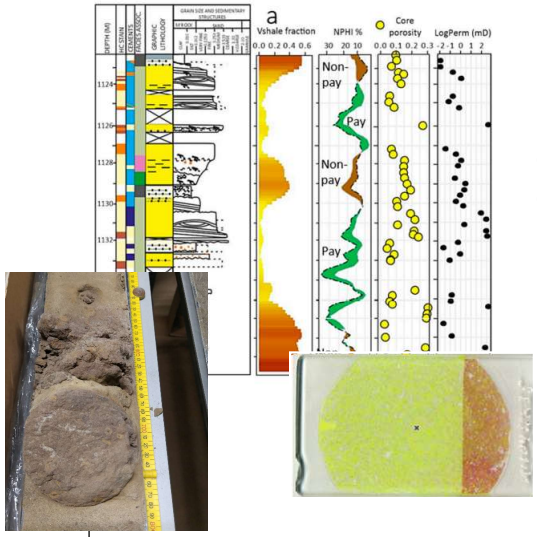

Simulated Porosity & Permeability during dissolution




Claes, Nader et al., 2018

# A QUANTITATIVE APPROACH

TOWARDS DYNAMIC 3D PETROGRAPHY




## 1. QUALITATIVE STEP

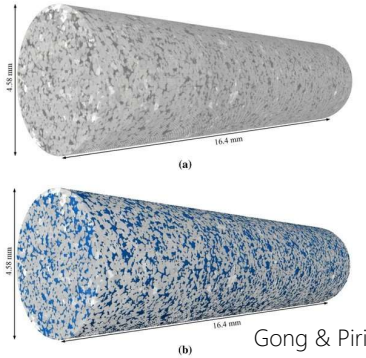
From outcrop – well – core – sample
Classical petrographic techniques
Geochemistry
Fluid inclusions study

- Paragenesis
- Burial curve (P, T, duration)
- Fluid types

## 2. QUANTITATIVE STEP

Petrophysical measurements
Quantitative XRD
Computer tomography

- Volume and/or wt% of mineral phases & porosity
- spatial distribution of rock components
- equivalent pore network
- pore statistics

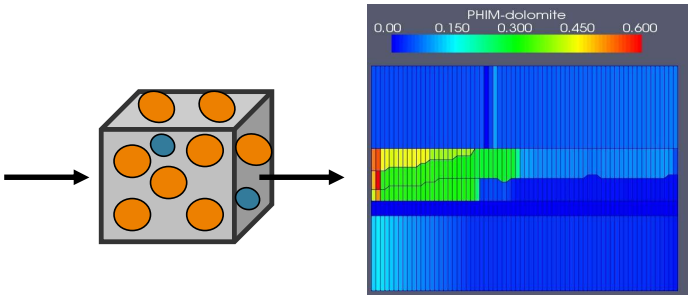



Gong & Piri, 2020

## 3. NUMERICAL SIMULATION STEP

R(T)M'S or
LAB EXPERIMENTS

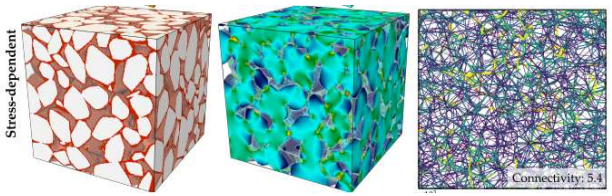
- reaction rates ($m^3/s$), duration of diagenetic step
- V(fluid)



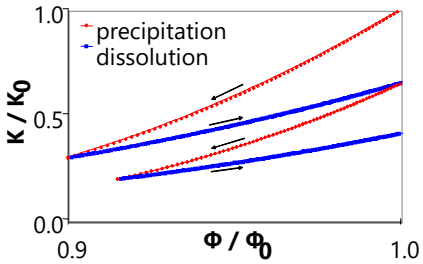

R-PNM / DIGITAL ROCK PHYSICS (DRP)

compaction and diagenetic phenomena

spatial & temporal evolution of reservoir/
elastic/geomechanical properties

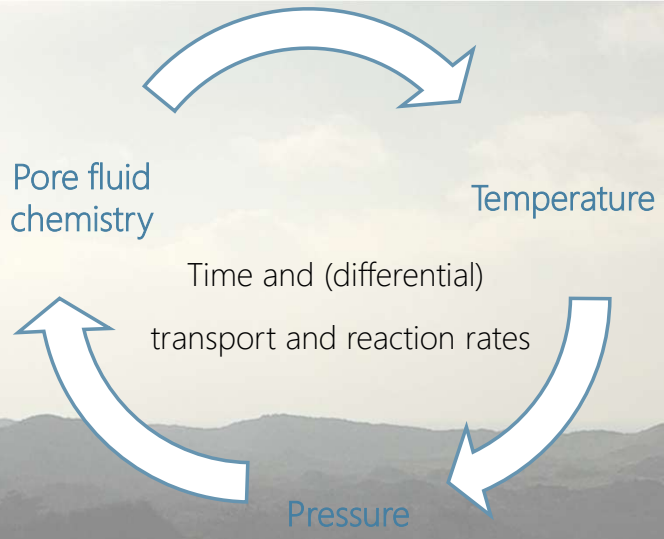



Wetzel et al. 2021




**PHI-K = f(DIAGENESIS)**

# SUM UP AND RELEVANCE




Diagenesis still relevant in the Energy Transition?

Diagenesis upon geothermal energy production (induced flow, T-P changes)

Predict diagenesis when decommissioning fields

When reservoirs are used for new purposes (potential for carbon capture and storage and hydrogen storage)

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- And input from course material, studies and colleagues at University of Fribourg, TNO, IFP Energies Nouvelles


- Contact: eva.deboever@tno.nl
- Linkedin: https://www.linkedin.com/in/evadeboever/

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# Q&A

**Please, type your Question in the Zoom Chat**

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