A Multidisciplinary and Multi-Scale Approach to Identify Hydrogeochemical Processes Altering Porosity-Permeability Properties of Reservoir Rocks*

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Abstract

Several processes, such as oil degradation, seawater injection, and inflow of external water by seismic pumping, affect reservoir rock matrices which can be considered to be chemically reactive. Thus, complex hydrogeochemical reaction chains are established among minerals, formation water, oil-derived aqueous hydrocarbons, and gases. Such reactions can cause formation of minerals, and especially of expandable clay minerals. These processes may strongly reduce the number of large pore and the permeability, and consequently, are attributed to significant mechanisms of formation damage. However, hydrogeochemical reactions can induce mineral dissolution, and therefore, improve the reservoir properties. The oil-water contact (OWC) is a hot spot of such processes, where porosity-permeability changes obstructing oil production can be triggered. To evaluate such hydrogeochemical processes and their consequences on reservoir properties, it is necessary to consider that slightest decrease in porosity caused by mineral formation can induce massive permeability reduction. Thus, it is substantial for a successful reservoir engineering (1) to specify whether any mineral can form in specific environments, and, if so, which type and which amount of them can form, (2) to identify which mechanisms induce their formation, and (3) to plausibly predict the spatial and temporal distribution of their formation. Our approach combines a series of analytical methods working from mm-scale (XRD and optical microscopy) to nanometer-scale (SEM and HRTEM) to specify the rock alteration in the Siri oilfield (Danish North Sea). To identify the hydrogeochemical processes which triggered the rock matrix alteration and to specify the parameters controlling its intensity, we applied hydrogeochemical batch modeling by using the program PHREEQC. This modeling enables us to numerically reproduce the proven formation of berthierine, quartz and calcite, and, furthermore, to characterize the hydrogeochemical conditions for their precipitation. Berthierine (plus quartz and calcite) formation results from glauconite dissolution under strong reducing and pH-buffered conditions evolving at OWC. Additionally, we bridge the gap from results of such nanometer-scale investigation to their applications on the reservoir scale. Regarding the spatial and temporal distribution of rock matrix alteration, we upscale our approach by applying a 3D reactive mass transport modeling (using the USGS's PHAST program).

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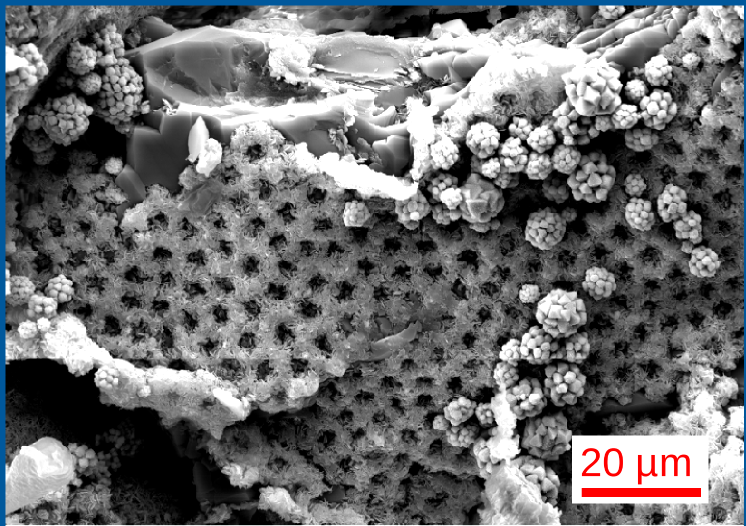
A multidisciplinary and multi-scale approach to identify hydrogeochemical processes altering porosity-permeability properties of reservoir rocks



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- Most reservoir rock matrices: chemically reactive

- Several processes
  e.g., early diagenetic processes, oil degradation, inflow of external fluids, water injection

induce

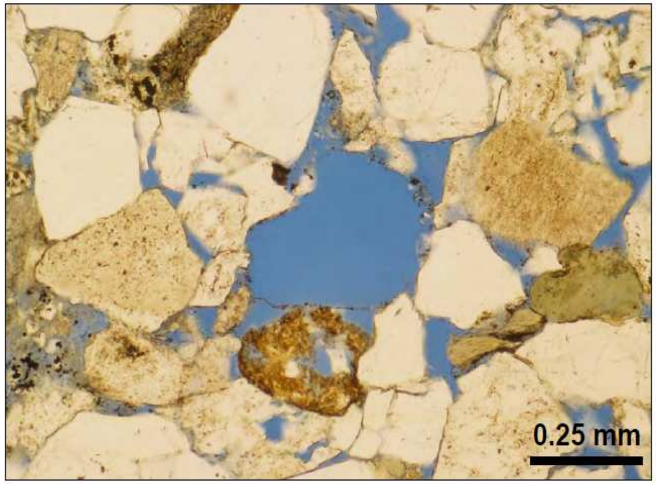
Mineral dissolution → considerable increase

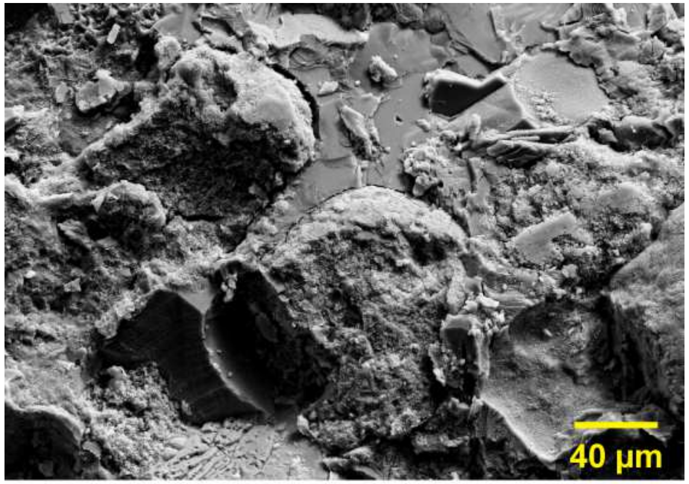
or

Mineral precipitation → significant reduction

in the porosity-permeability properties

(Taylor, 2007)





To assess such hydrogeochemical processes and their consequences

it is necessary to

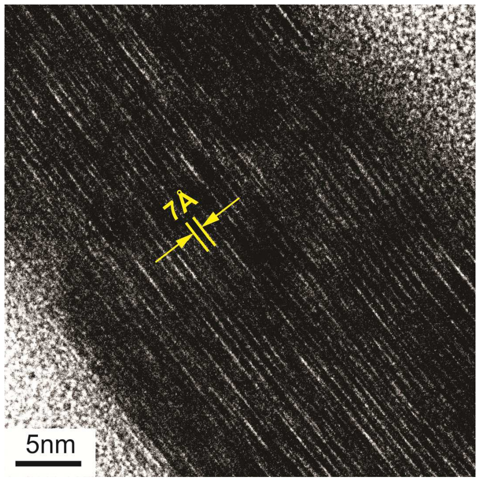
- type and amount of minerals precipitated/dissolved
- mechanisms inducing precipitation/dissolution
- distribution of precipitation/dissolution in time & space

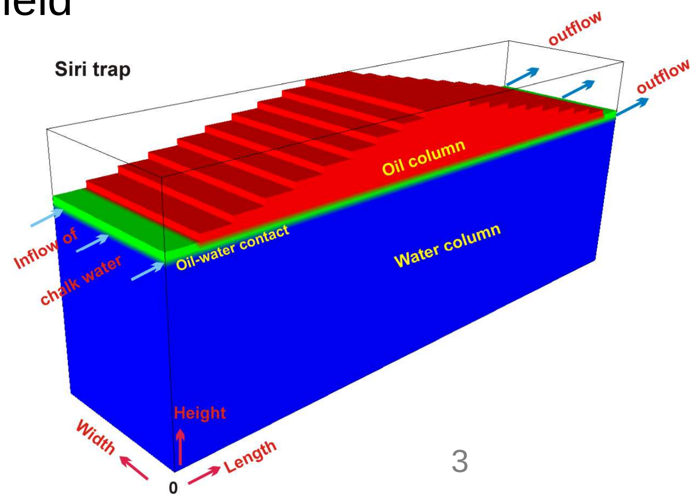
A multidisciplinary and multi-scale approach

Selected analytical methods + Hydrogeochemical modeling

(from nm- to core-scale) (from nm- to reservoir-scale)

Case study: Siri oilfield

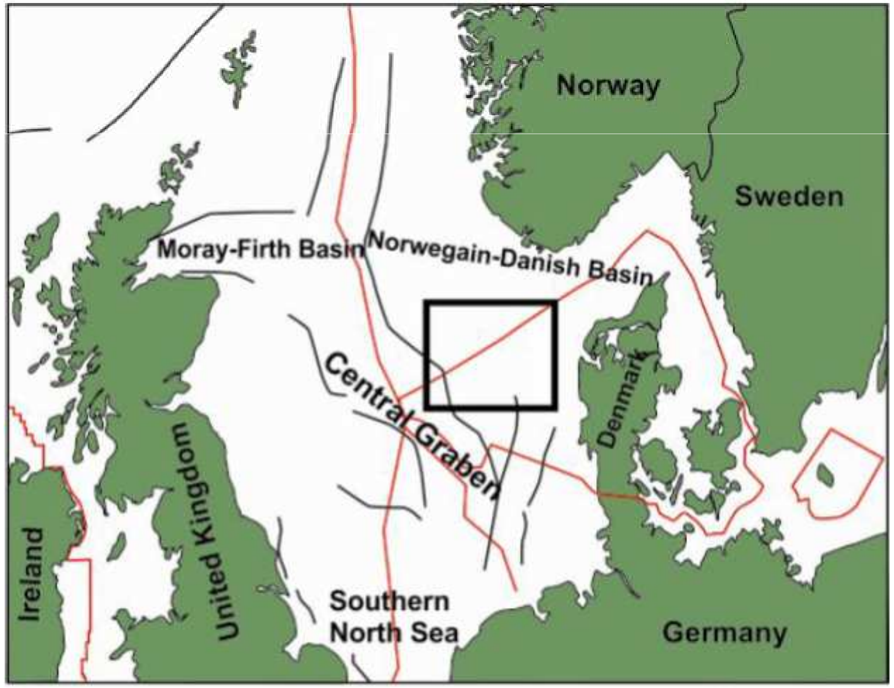




Siri oilfield

- Danish North Sea

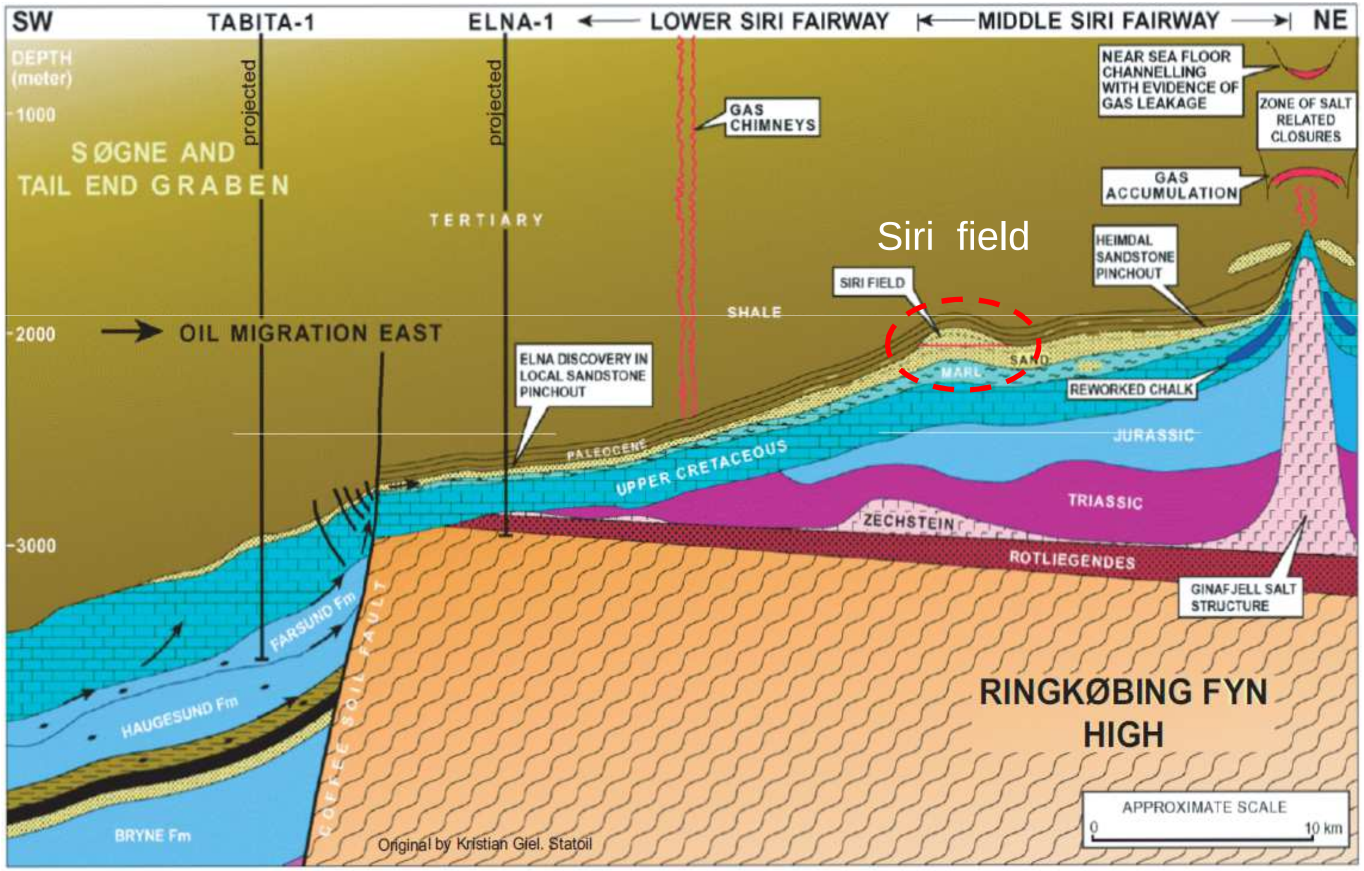
(Hamberg et al., 2005)



Siri oilfield

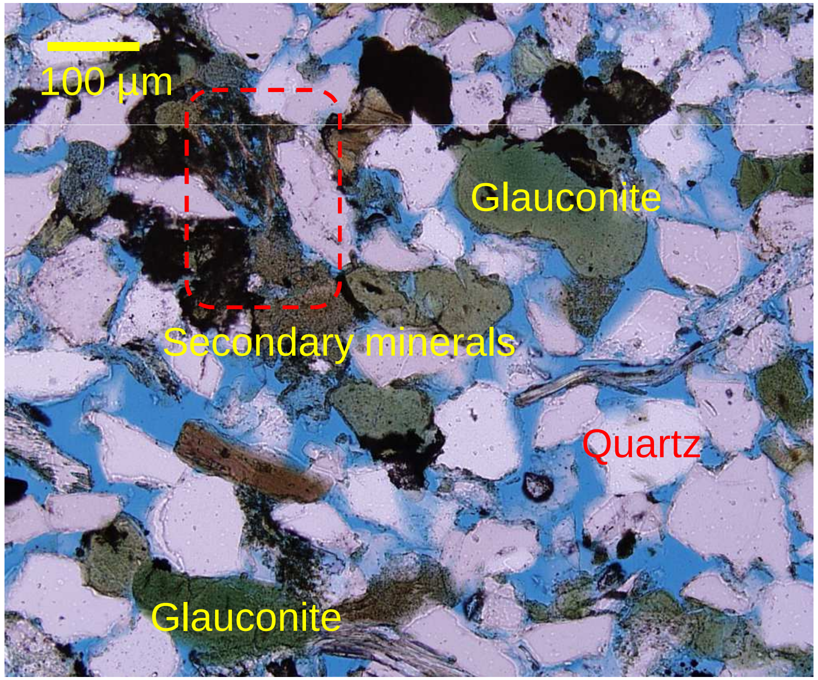
- Danish North Sea
- a part of the Siri Fairway

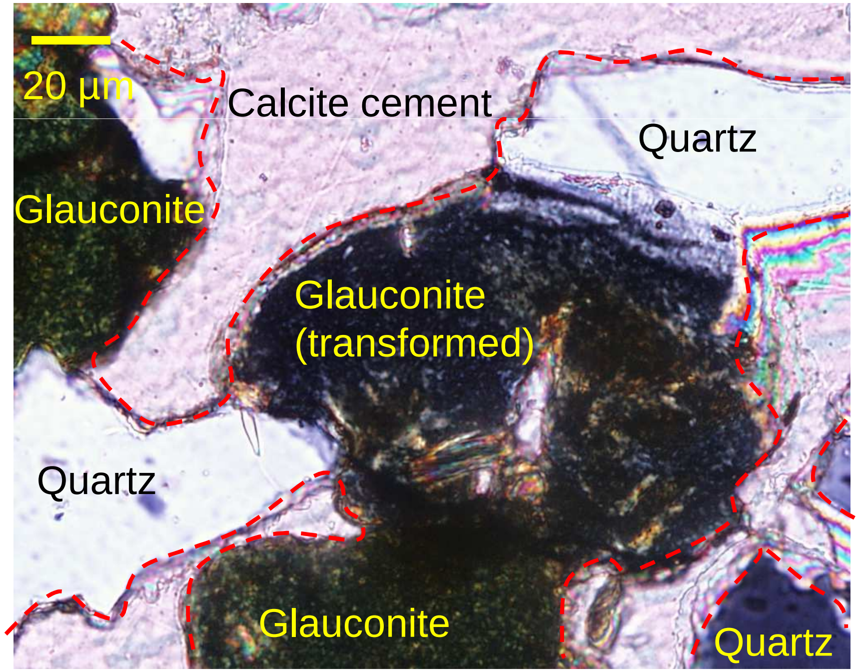
(Ohm et al., 2006)



Siri oilfield

- Danish North Sea
- a part of the Siri Fairway
- observed by strongly diagenetic features





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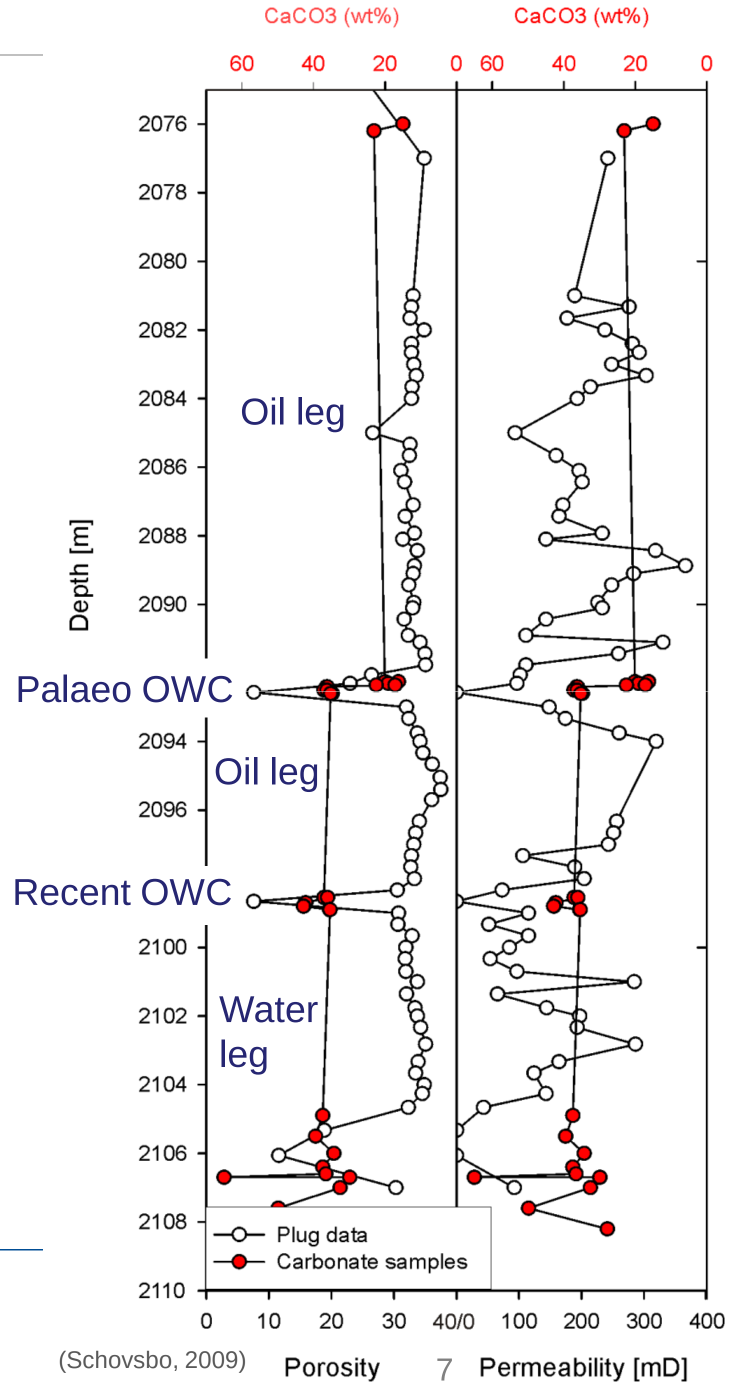
Siri oilfield

- Danish North Sea
- a part of the Siri Fairway
- observed by strongly diagenetic features
- inhomogeneous distribution
  diagenetic features and permeability



(Schovsbo, 2009)

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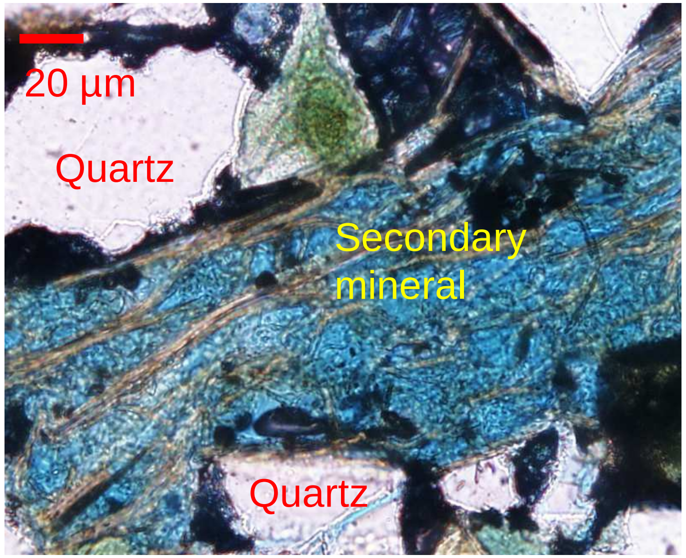
Diagenetic processes & practical significance

- precipitation of secondary minerals
  - negative impacts on permeability

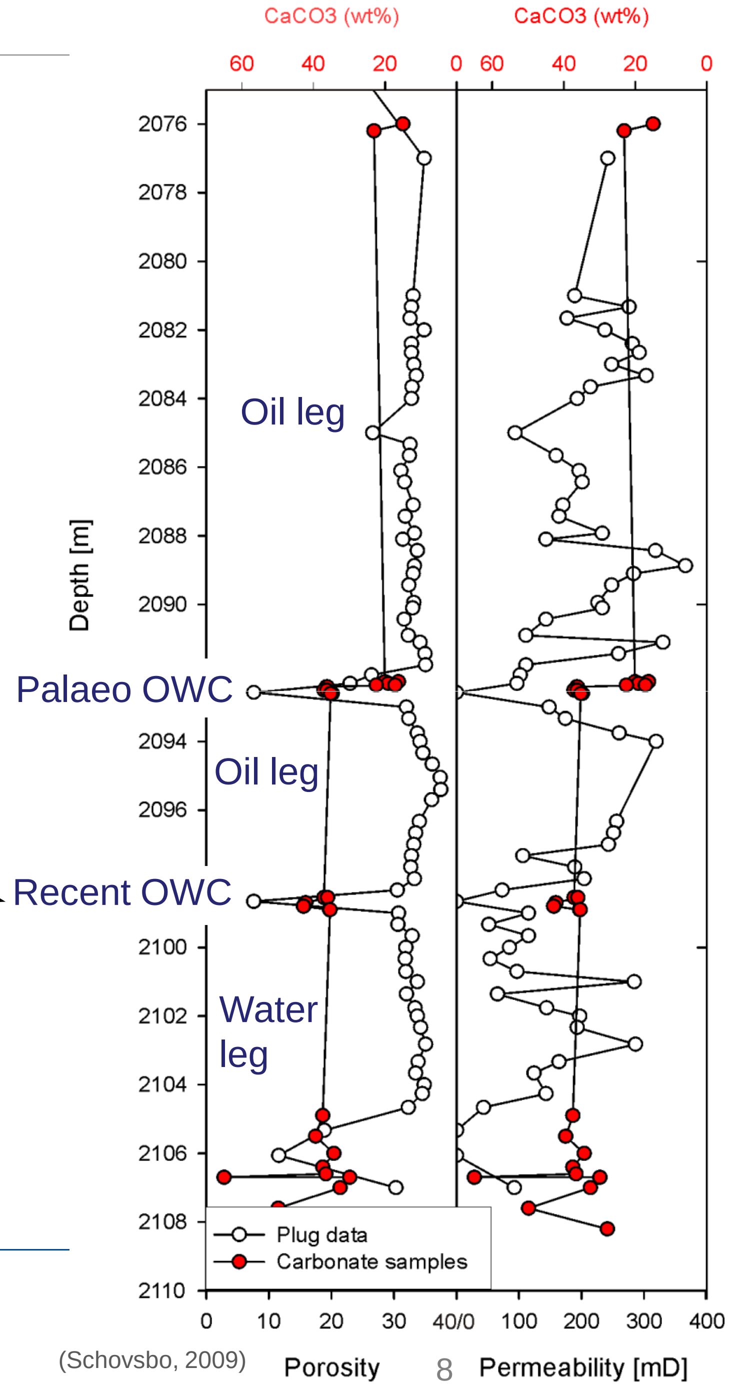
- calcite cement: laterally continuous or discontinuous

Which processes
- where
- when
- under which conditions
- how intensive



laterally continuous

or discontinuous ?



(Schovsbo, 2009)

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Investigating the reservoir rocks on various scales

Selected analytical methods

(from nm- to core-scale)

- Chemical composition (on core-scale)
  XRF and TIC (total inorganic carbon)
- Mineralogical composition (down to µm-scale)
  XRD, thin section, and SEM
- Diagenetic features (down to nm-scale)
  Thin section, SEM, and HR-TEM

+

Hydrogeochemical modeling

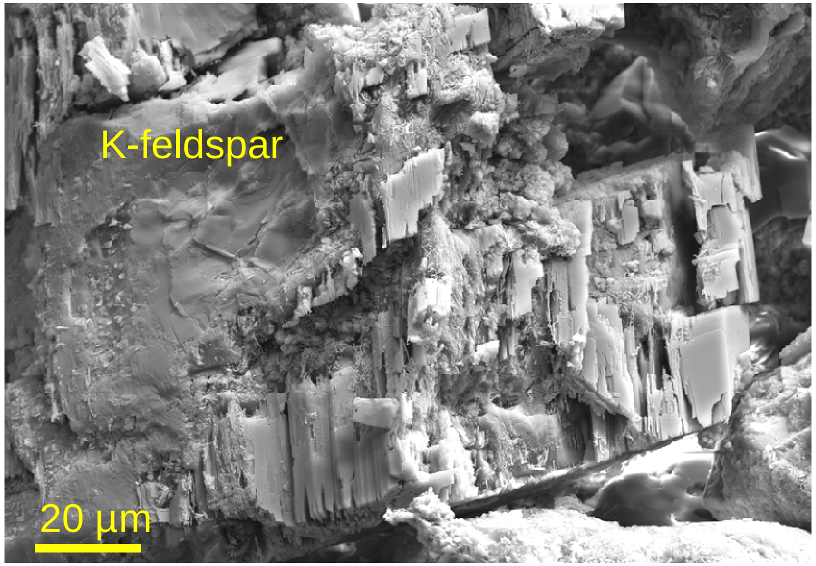
(from nm- to reservoir-scale)

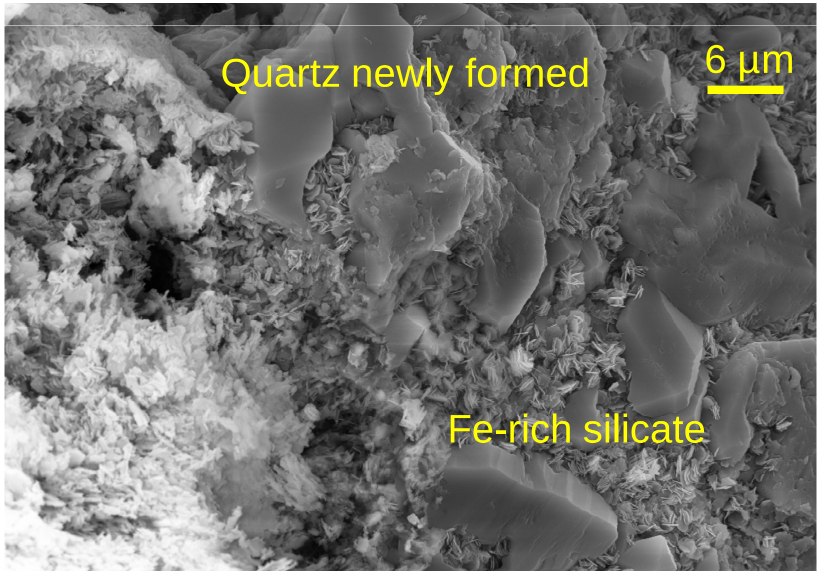
Batch	down to nm-scale	Phreeqc
1D	from core- to reservoir-scale	PhreeqcI
3D	on reservoir-scale	PHAST & Model Viewer

(all provided by USGS)

Investigation results

- independent on depth
  - dissolution: glauconite, feldspars
  - precipitation: quartz, muscovite, Fe-rich silicate (unidentified)





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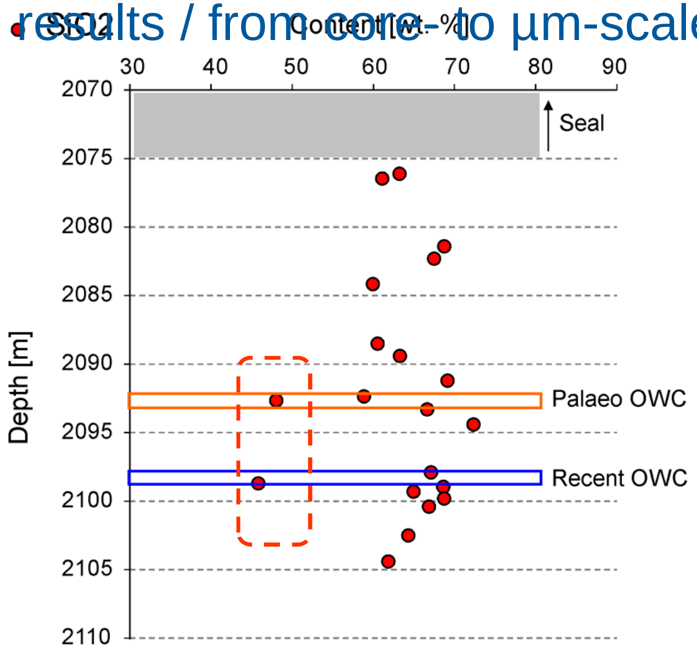
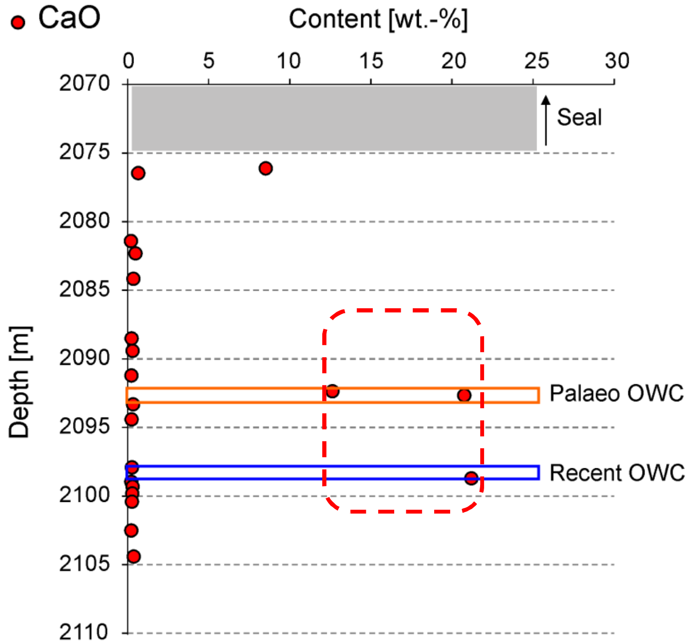
- dependent on depth (only at OWCs)
  - variation of the chemical composition
    impoverishment: Si, Al, Fe, Na, K, Mg
    enrichment: Ca, TIC, Mn, Sr
  - calcite formation





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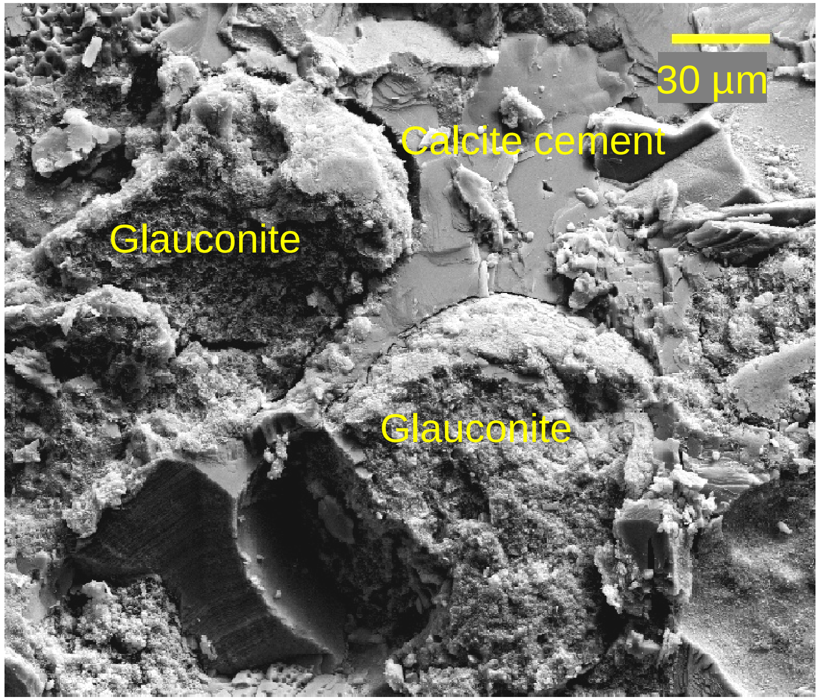
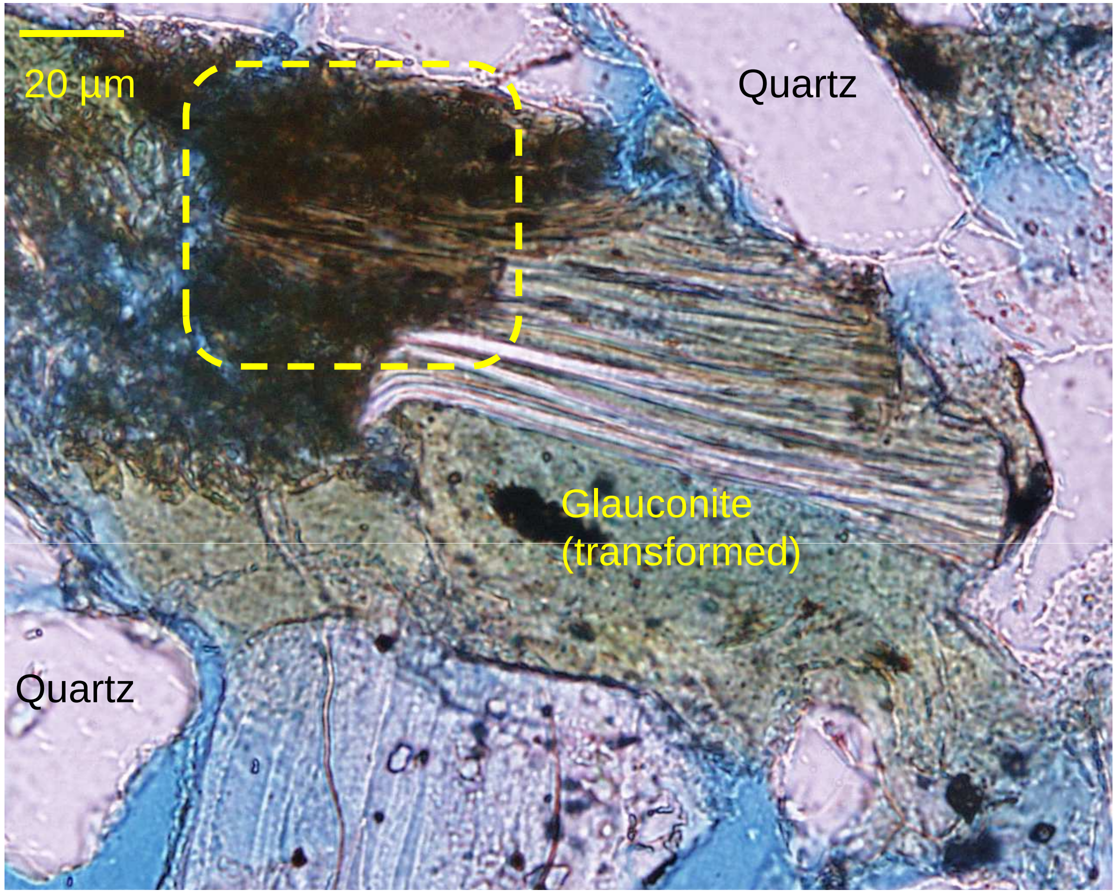


Identifying the authigenic, unknown Fe-rich clay mineral



- olive brown
- pleochroitic

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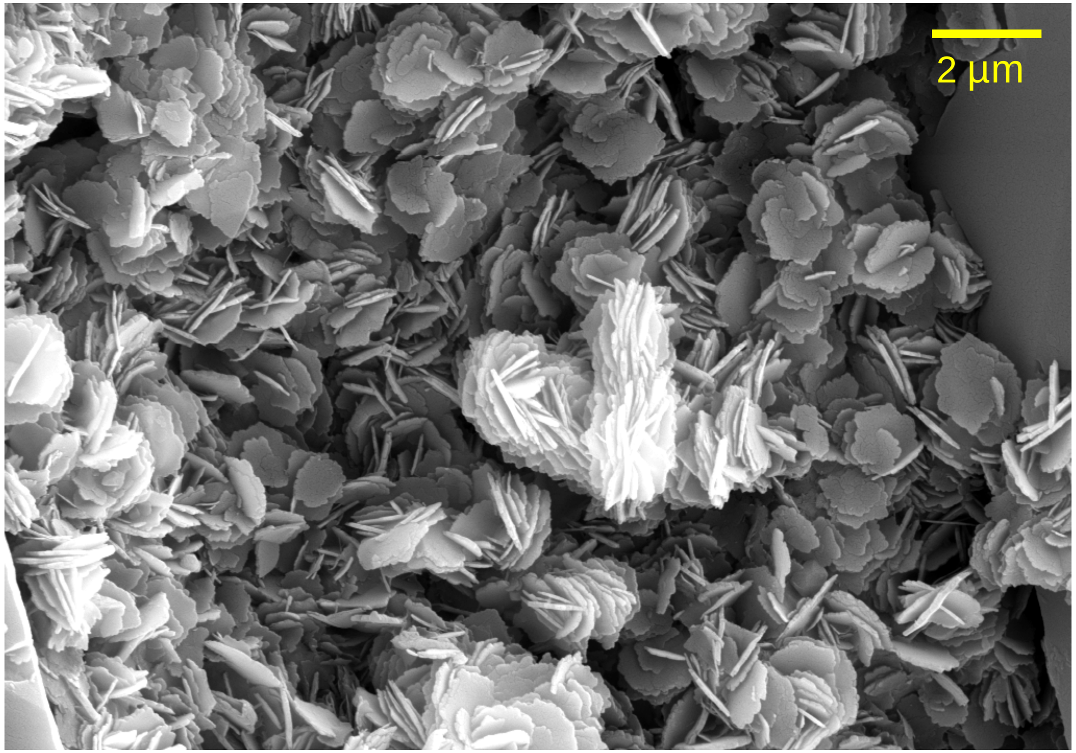
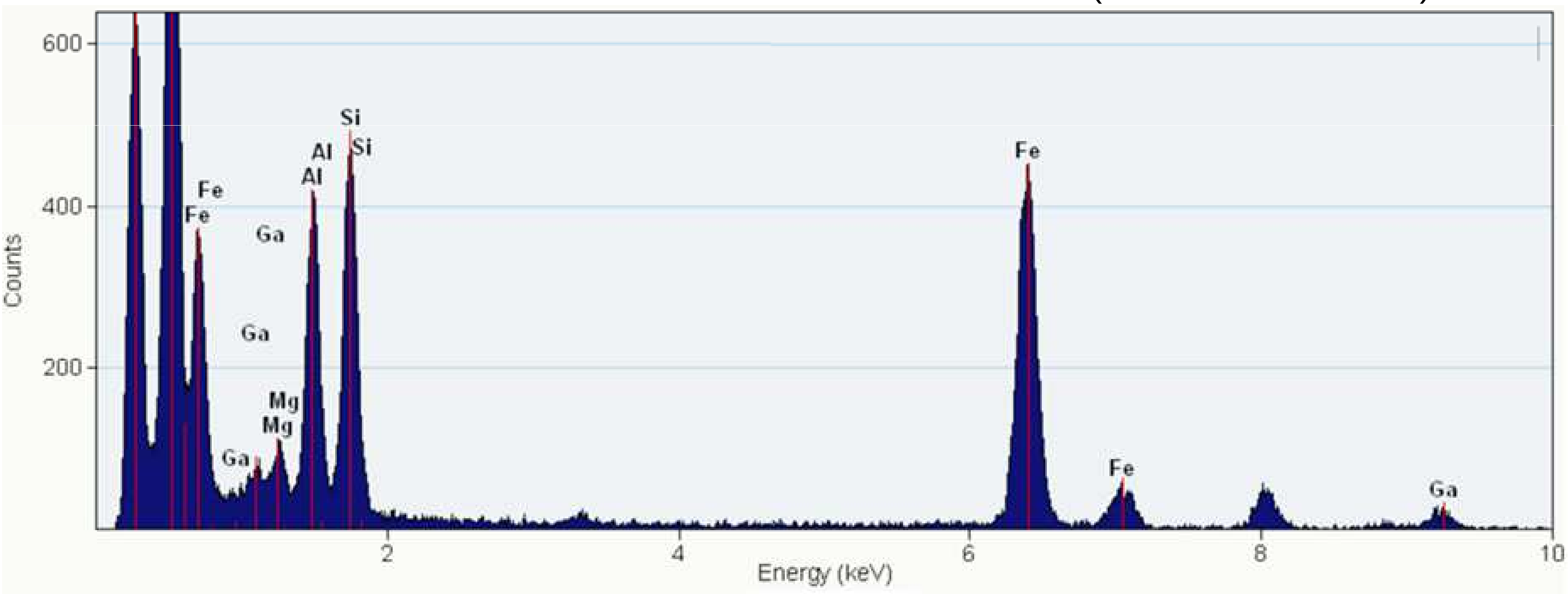


- olive brown
- pleochroitic
- formed in expense of glauconite
- similar to chlorite under SEM

Identifying the authigenic, unknown Fe-rich clay mineral

- olive brown
- pleochroitic
- formed in expense of glauconite
- similar to chlorite under SEM
- Fe-rich, containing Mg (EDX under HR-TEM)



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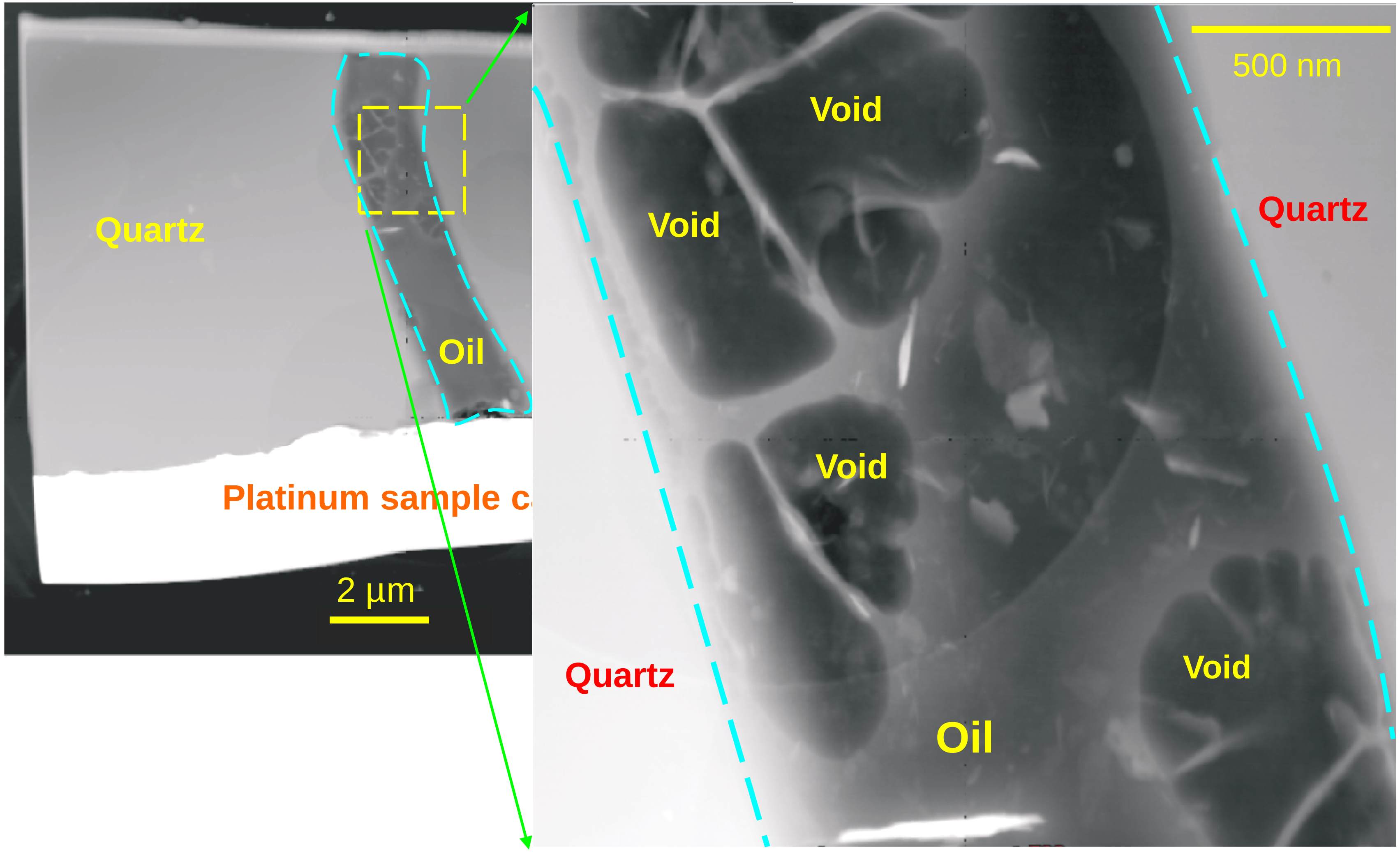
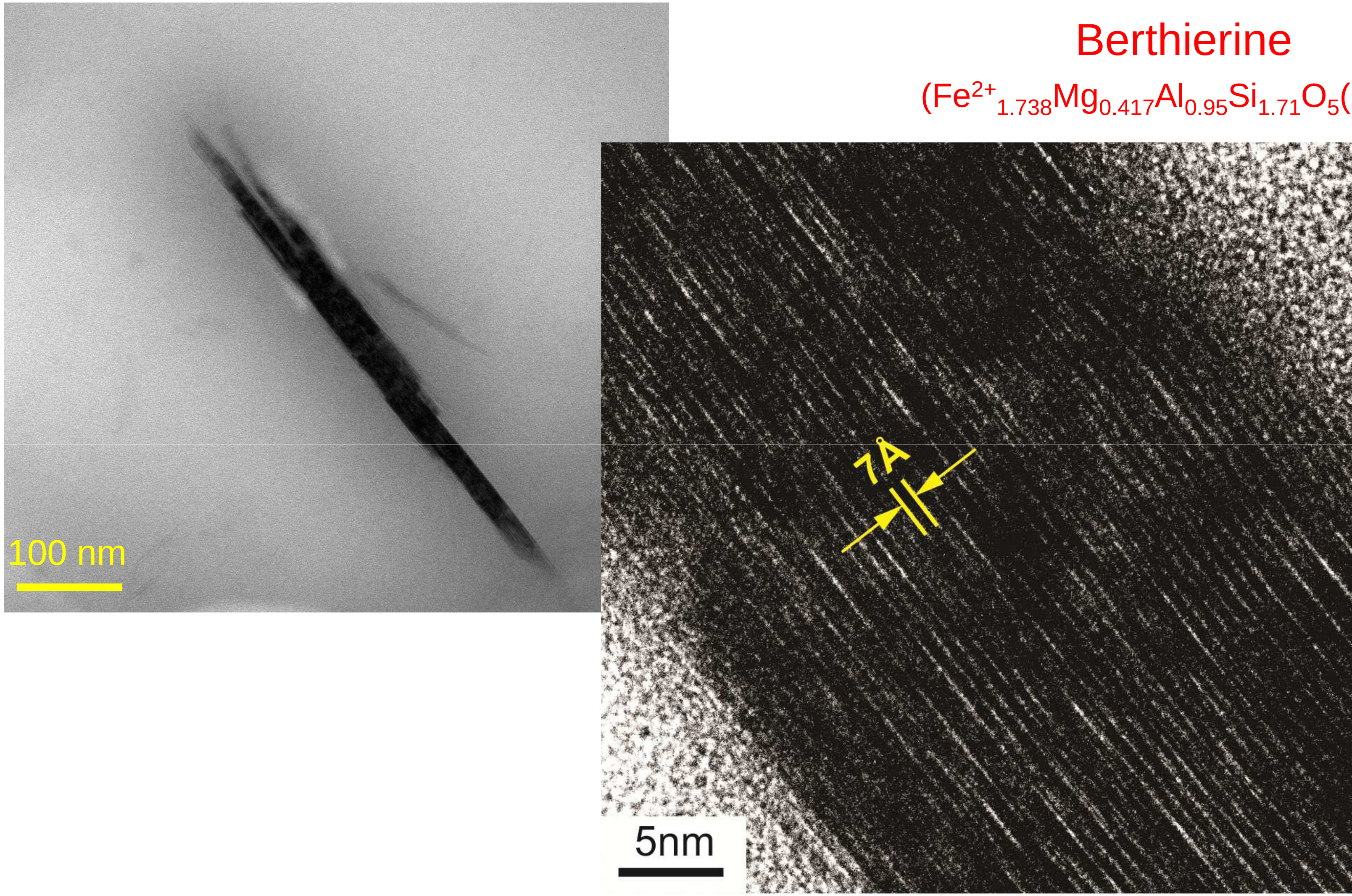


Identifying the authigenic, unknown Fe-rich clay mineral

Berthierine

$(Fe^{2+}_{1.738}Mg_{0.417}Al_{0.95}Si_{1.71}O_5(OH)_4)$



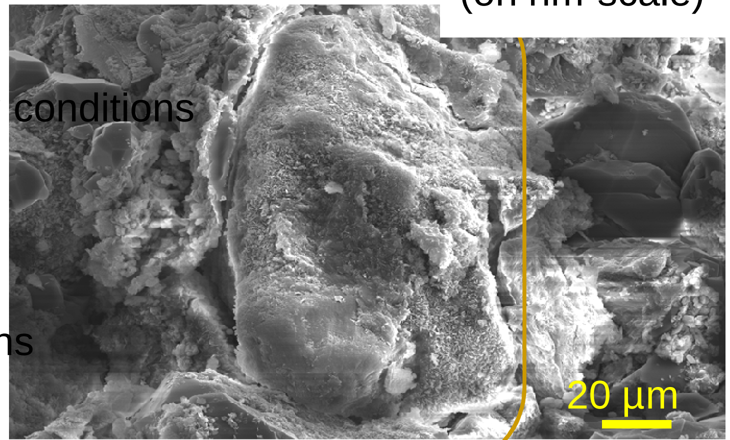
Glauconite

$K_{0.489}Na_{0.045}Mg_{0.281}Al_{0.634}Fe^{3+}_{0.869}Fe^{2+}_{0.176}Si_{3.793}O_{10}(OH)_2$

Batch

(on nm-scale)

- organic-inorganic interactions
- glauconite dissolution: only under reducing conditions
- dissolution: feldspars, glauconite
- formation: berthierine, quartz, muscovite
- berthierine: stable under reducing conditions
- no secondary siderite, little calcite



Glauconite ⟷ [Na^+, K^+, Mg^{2+}, Fe^{2+}, Fe^{3+} → Fe^{2+}, Al^{3+}, H_4SiO_4]

Driving force

$+ Al^{3+} + H_4SiO_4$ → Muscovite $KAl_3Si_3O_{10}(OH)_2$

→ Berthierine $Fe^{2+}_{1.738}Mg_{0.417}Al_{0.95}Si_{1.71}O_5(OH)_4$

→ $SiO_{2(s)}$ (secondary)

Dissolution of feldspars
Na^+, K^+, Ca^{2+}, Al^{3+}, H_4SiO_4

$$R\text{-}CH_2\text{-}CH_2\text{-}CH_3 + 4H_2O \rightarrow R + \mathbf{2CO_2 + CH_4 + 5H_2}$$

(Seewald, 2003)

Batch

(on nm-scale)

anorthite ($Ca_2Al_2Si_2O_8$) dissolution at OWC:

not the reason for calcite cementation

3D

(on reservoir scale)

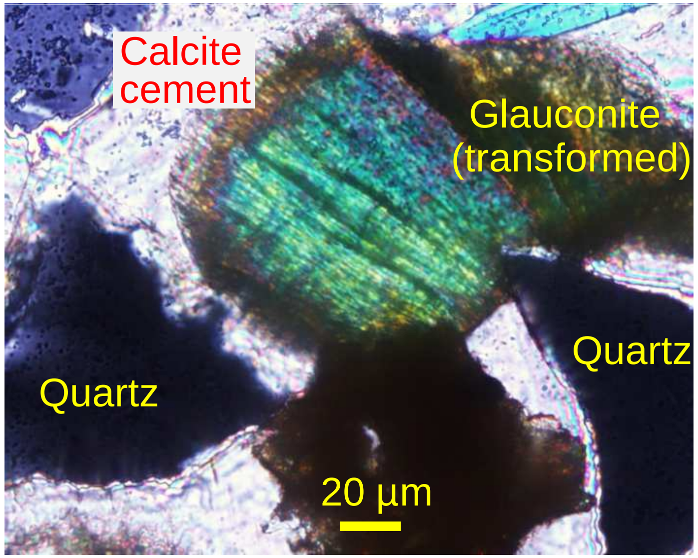
External Ca^{2+}-Source

+

Advective mass transport

for the calcite cementation

at OWC



External Ca^{2+}-Source?

"Siri Fairway":

3D

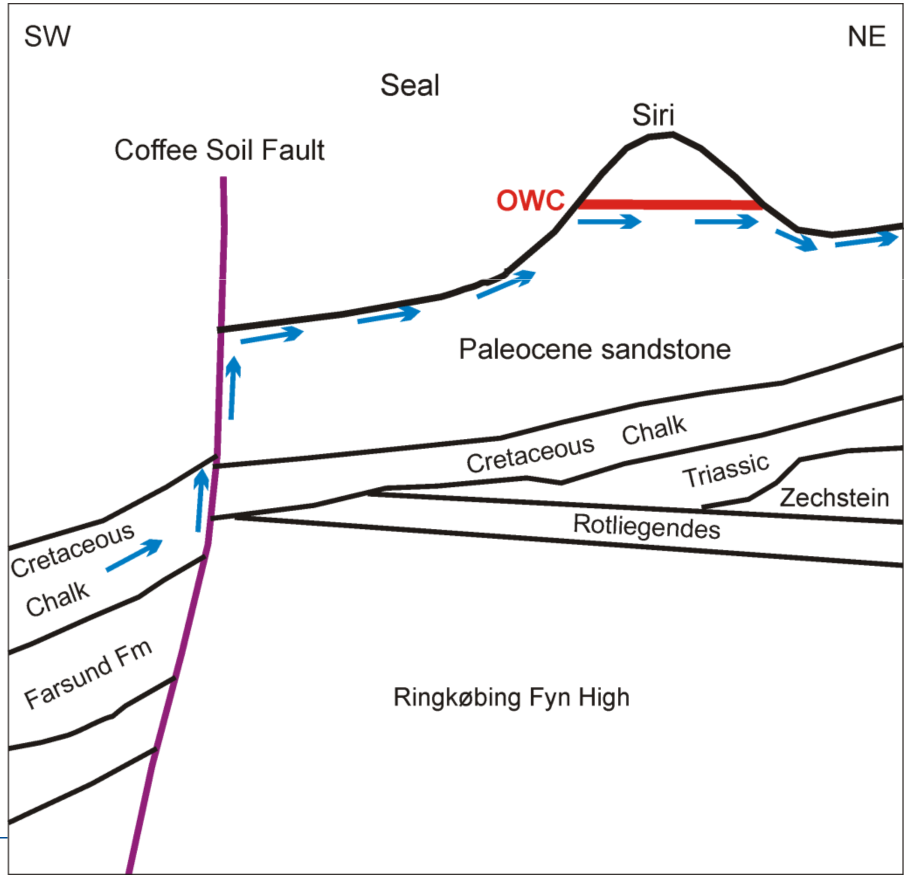
(on reservoir scale)

- highly tectonic activity (especially during the mid-Miocene)
- widespread fluid expulsion (driven by seismic pumping)

(Andresen et al., 2009)

Inflow of the "chalk water" into the Siri oilfield

(modified according to Ohm et al., 2006)



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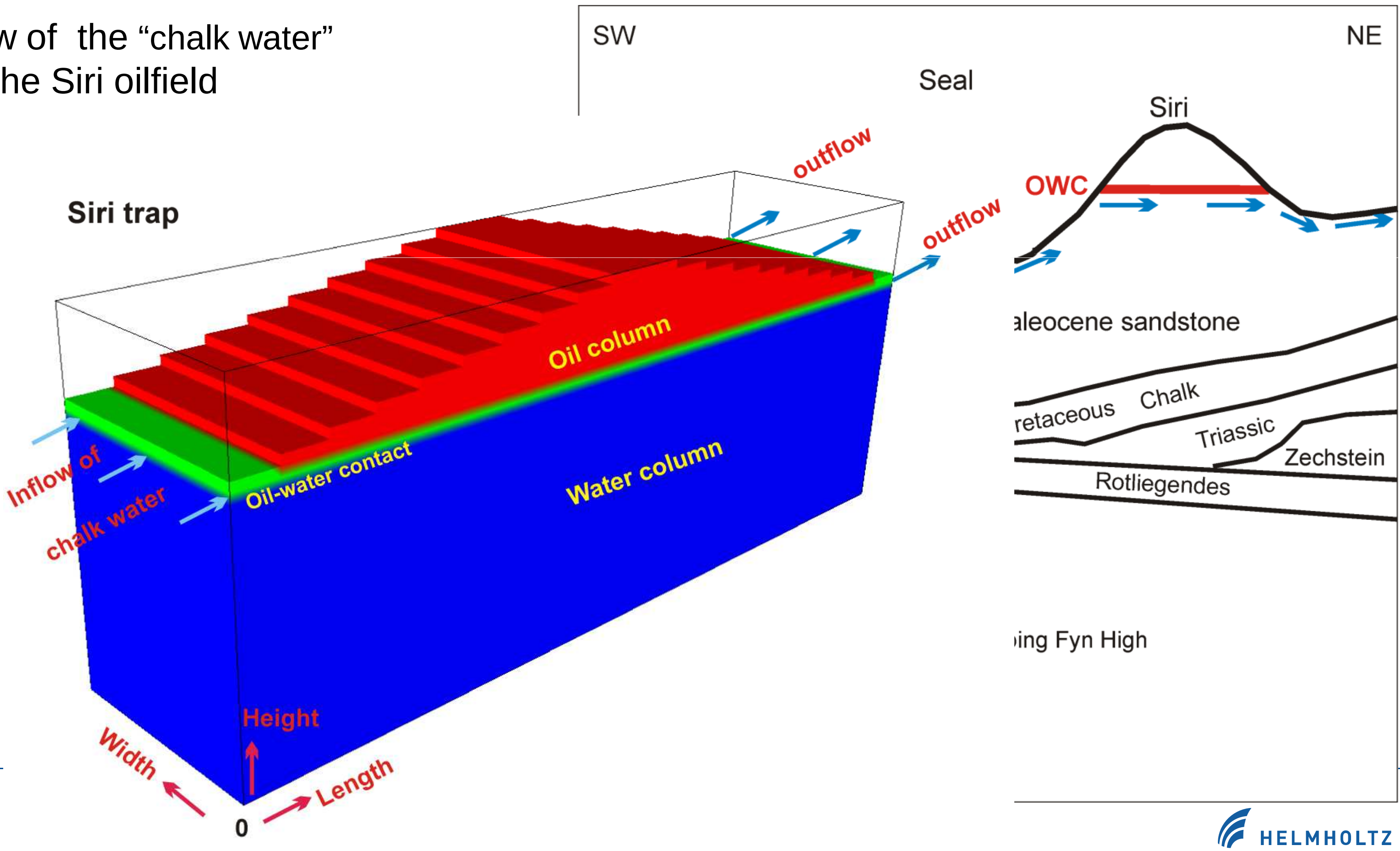

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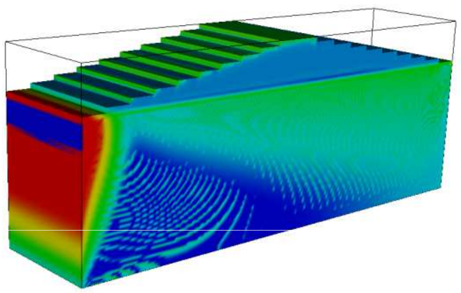
3D

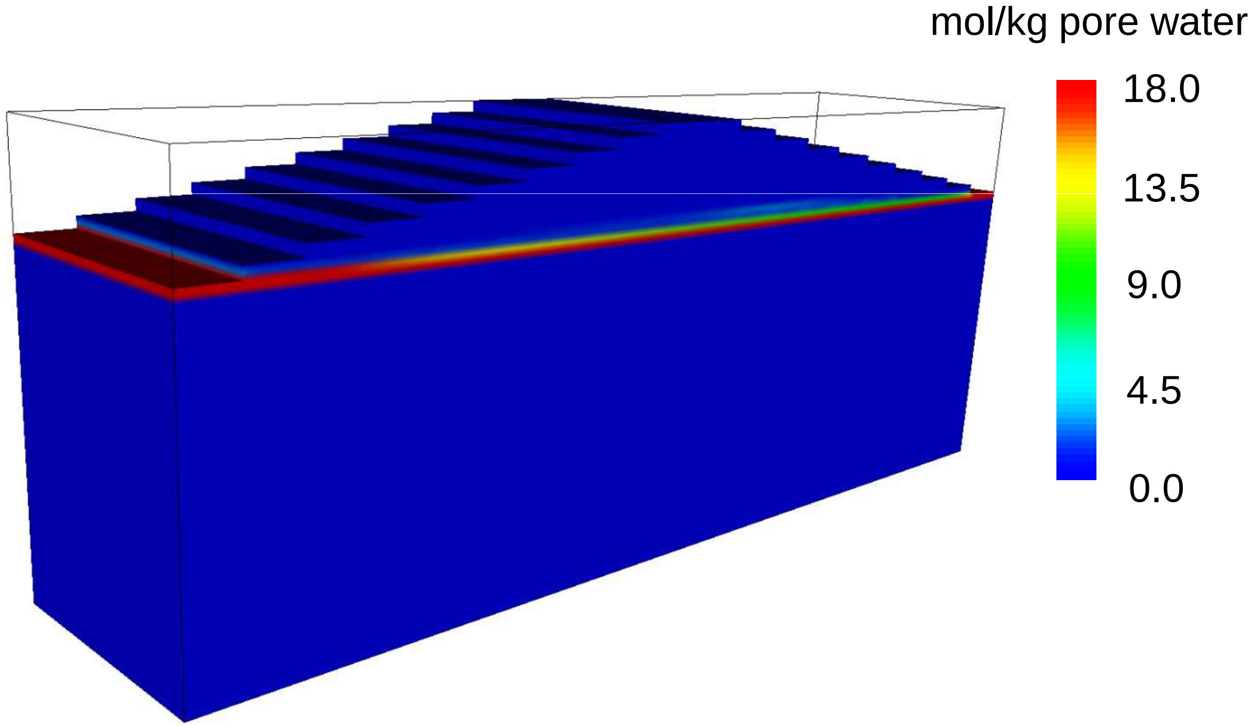
(on reservoir scale)

inflow of the “chalk water”: reason for the cementation at OWC

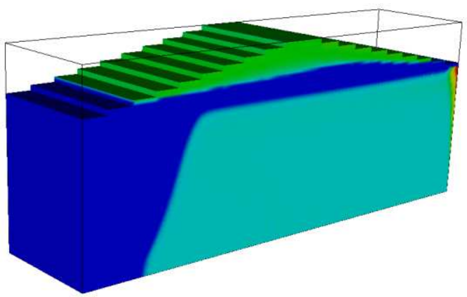
Berthierine (after 1.3 Ma)



Calcite precipitation at OWC (during 1.3 Ma)



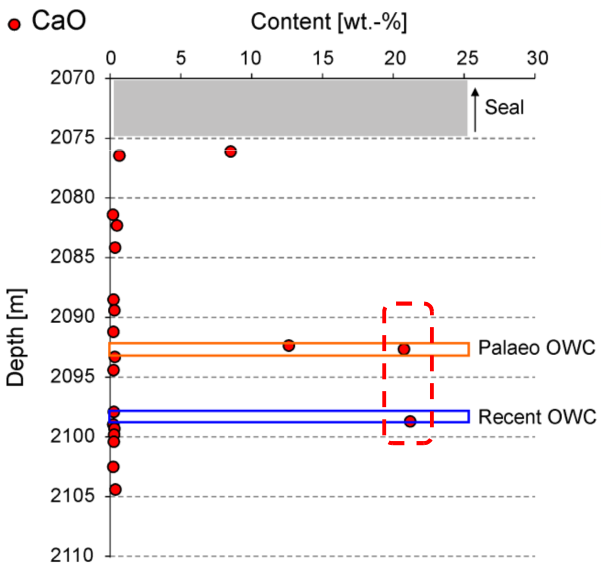
Anorthite (after 1.3 Ma)



3D

(on reservoir scale)

inflow of the “chalk water”: reason for the cementation at OWC



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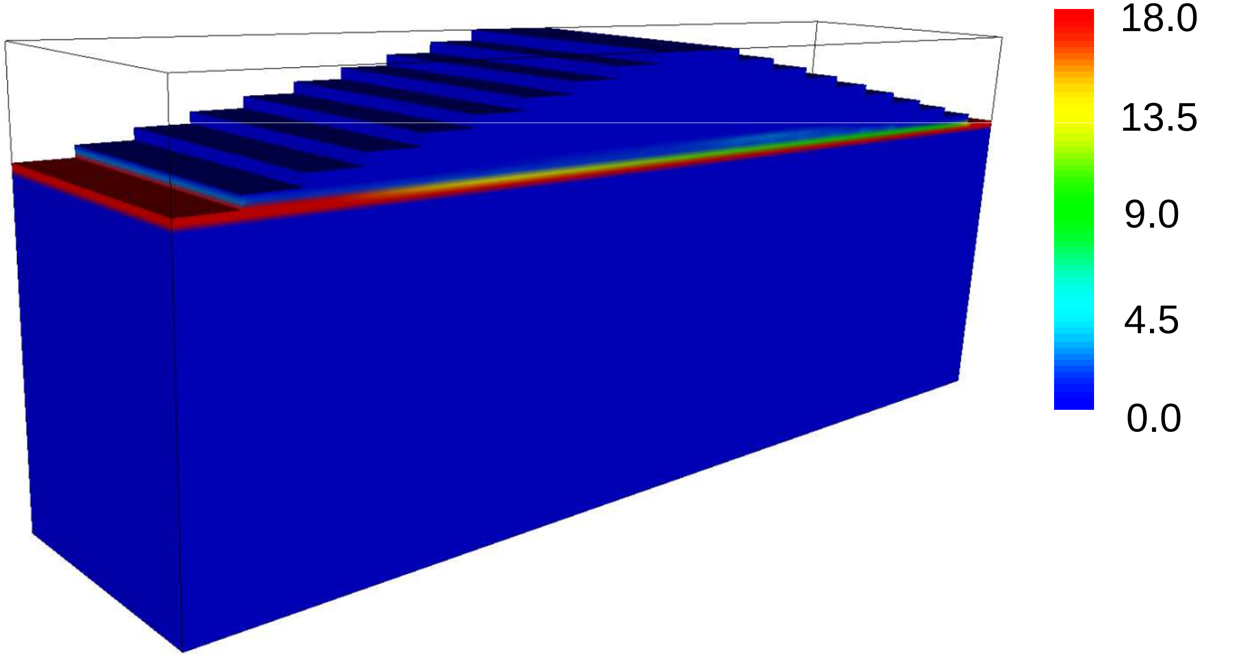
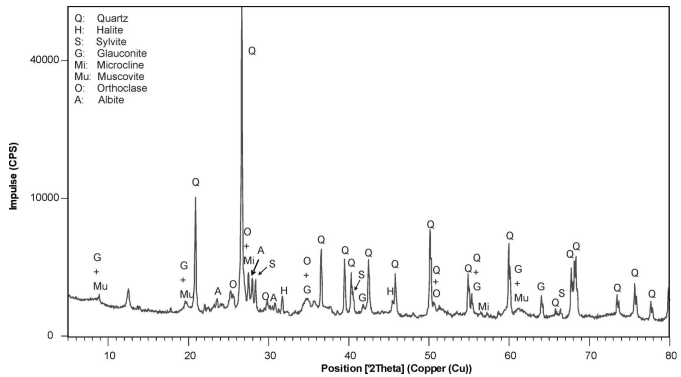
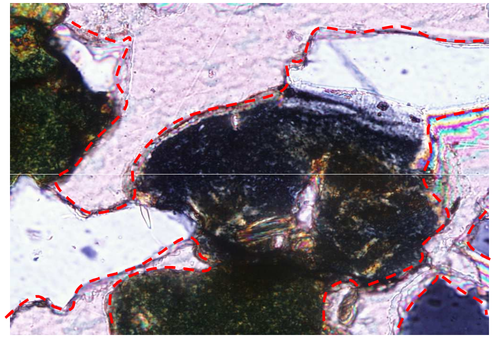
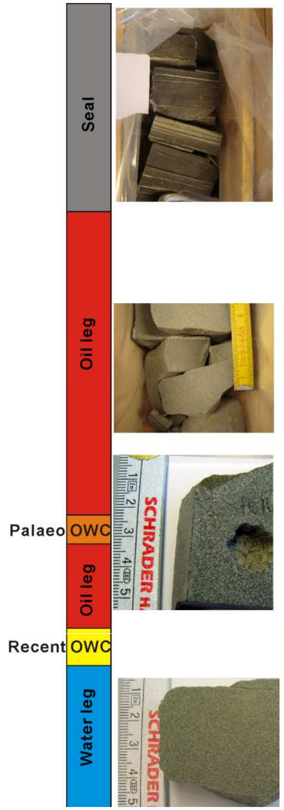


Conclusions



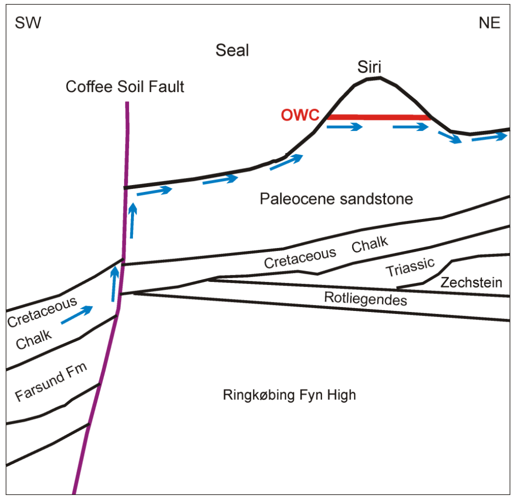


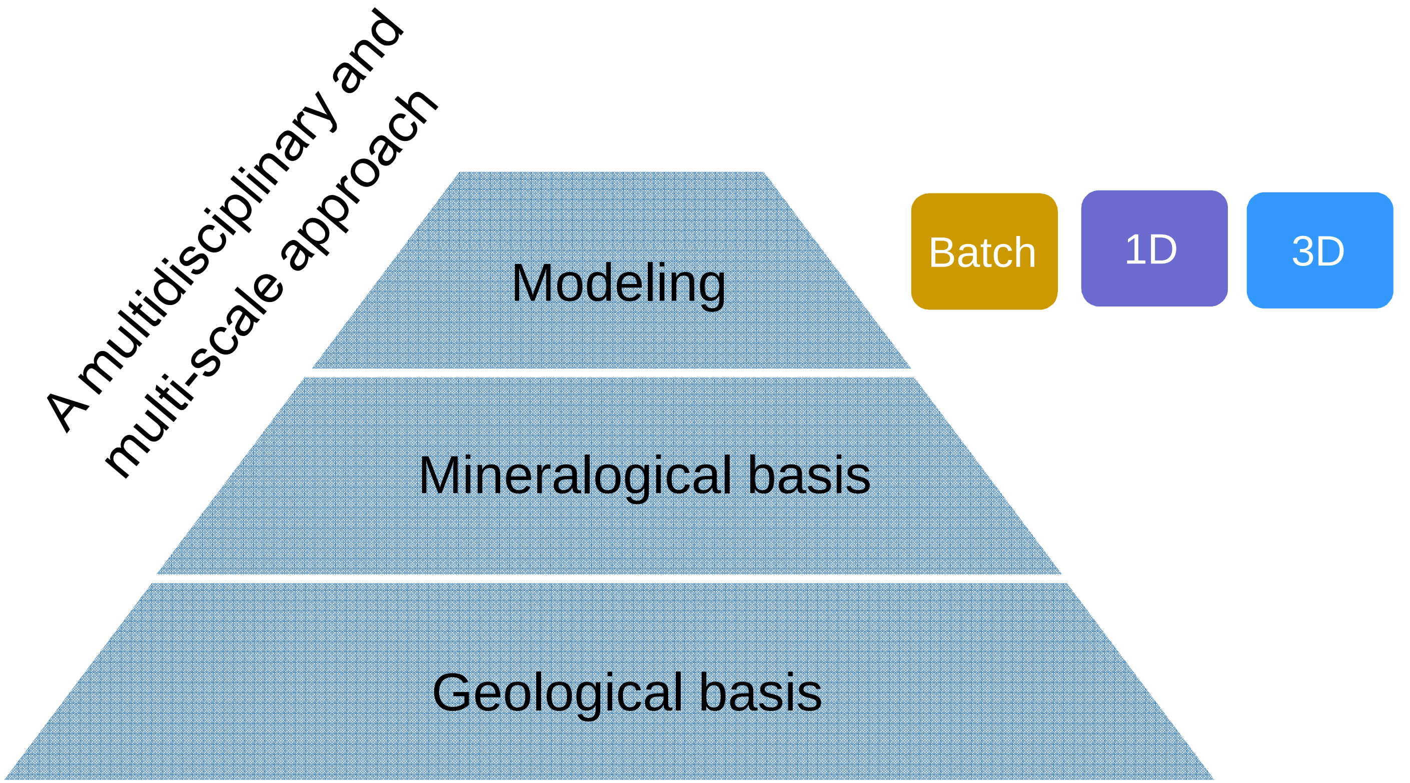


A multidisciplinary and multi-scale approach

Mineralogical basis

Geological basis




A multidisciplinary and
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Modeling
Batch
1D
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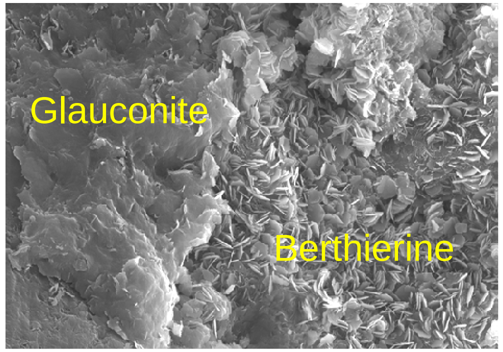

- berthierine formation: organic-inorganic interactions due to glauconite dissolution
- calcite cementation: inflow of chalk water organic-interaction interactions