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).
References Cited

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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

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

Case study: Siri oilfield
Siri oilfield

- Danish North Sea
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
Siri oilfield

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

(Schovsbo, 2009)
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)
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
  - Phreeqcl

- 3D on reservoir-scale
  - PHAST & Model Viewer
  - (all provided by USGS)
Investigation results / from core- to µm-scale

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

- K-feldspar
- Quartz newly formed
- Fe-rich silicate

20 µm
6 µm
Investigation results

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

- 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
Investigation results / from core- to µm-scale

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  - calcite formation

30 µm
Calcite cement
Glauconite
Glauconite
Identifying the authigenic, unknown Fe-rich clay mineral

- olive brown
- pleochroitic
Identifying the authigenic, unknown Fe-rich clay mineral

- 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)
Identifying the authigenic, unknown Fe-rich clay mineral
Identifying the authigenic, unknown Fe-rich clay mineral

Berthierine

\( \text{Fe}^{2+}_{1.738}\text{Mg}_{0.417}\text{Al}_{0.95}\text{Si}_{1.74}\text{O}_5(\text{OH})_4 \)
Glaucnite

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

- 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

Modeling results / on nm-scale

Batch (on nm-scale)

\[
\text{Driving force: } \ \text{SiO}_2(s) \rightarrow \text{Fe}^{2+} \text{Berthierine} \quad \text{Fe}^{2+}_{1.738} \text{Mg}_{0.417} \text{Al}_{0.95} \text{Si}_{1.71} \text{O}_5(\text{OH})_4
\]

\[ R\cdot\text{CH}_2\cdot\text{CH}_2\cdot\text{CH}_3 + 4\text{H}_2\text{O} \rightarrow R + 2\text{CO}_2 + \text{CH}_4 + 5\text{H}_2 \quad (\text{Seewald, 2003}) \]
anorthite ($\text{Ca}_2\text{Al}_2\text{Si}_2\text{O}_8$) dissolution at OWC:

not the reason for calcite cementation

External $\text{Ca}^{2+}$-Source

+ Advective mass transport

for the calcite cementation

at OWC
External Ca\(^{2+}\)-Source?

“Siri Fairway”:

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

Inflow of the “chalk water” into the Siri oilfield

(modified according to Ohm et al., 2006)
External Ca\(^{2+}\)-Source?
“Siri Fairway”:
- highly tectonic activity (especially during the mid-Miocene)
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Inflow of the “chalk water” into the Siri oilfield

(modified according to Ohm et al., 2006)
Modeling results / on reservoir-scale

- Inflow of the "chalk water": reason for the cementation at OWC

- Berthierine (after 1.3 Ma)

- Anorthite (after 1.3 Ma)

- Calcite precipitation at OWC (during 1.3 Ma)

3D representation with mol/kg pore water values:

- Berthierine: 18.0 mol/kg pore water
- Anorthite: 13.5 mol/kg pore water
Modeling results / on reservoir-scale

Calcite precipitation at OWC (during 1.3 Ma)

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

3D

(on reservoir scale)
Conclusions

A multidisciplinary and multi-scale approach

Mineralogical basis

Geological basis
Conclusions

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

A multidisciplinary and multi-scale approach

Modeling

Mineralogical basis

Geological basis