Influence of Climate on the Early Diagenesis of Triassic and Jurassic Sediments*

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Abstract

The Fennoscandian Shield constitutes the major sediment source area for the sediments in the eastern part of the Norwegian-Danish Basin. Different climate, depositional environments, transport distances, and alterations lead to variations in the detrital composition and caused different early diagenetic changes. The proximal Triassic Skagerrak Formation, deposited in the alluvial fans and braided streams, has the highest content of unstable minerals, as heavy minerals, rock fragments, and feldspar grains. Only minor alteration of feldspar grains occurred in the arid climate. The Triassic Bunter Sandstone Formation was deposited farther away from the sediments source, though under similar climatic conditions, and it has a somewhat lower content of these unstable grains. The Upper Triassic - Lower Jurassic Gassum Formation and the Middle Jurassic Haldager Sand Formation were deposited in fluvial, paralic, and shallow-marine environments under a humid, wet climate. Under these climatic conditions detrital mineral alteration probably took place in the hinterland as well as in situ (in the sediment). The Gassum and the Haldager Sand formations, therefore, contain more stable minerals than the Bunter Sandstone and the Skagerrak formations.

The iron-rich minerals that formed in the eogenetic regime vary according to climate and depositional environments, as iron-oxide/hydroxide coatings formed in the arid Triassic alluvial fan, ephemeral fluvial, lacustrinem and aeolian environment, whereas siderite and pyrite, occasionally as concretions, are characteristic for the humid fluvial, paralic and shallow-marine deposits. Concretions in the arid deposits are gypsum/anhydrite or calcite (calcrete), which probably formed by evaporation of groundwater. Kaolinite is the dominating authigenic clay mineral in both the Gassum and the Haldager Sand formations. Illite and mixed-layer illite/smectite are the typical authigenic clays in the Skagerrak and Bunter Sandstone formations. These pore-lining clays and iron-oxide/hydroxide coatings cover all detrital grains in the Skagerrak and Bunter Sandstone formations and inhibit authigenic quartz growth, which, therefore, becomes prismatic or with only few contact points. Pore-filling kaolinite in the Gassum and Haldager Sand formations has less influence on the authigenic quartz growth, which begins on most detrital quartz. Climatic induced early diagenetic variations between the arid and humid deposits thus also affect the burial diagenesis.

References Cited

Coleman, M.L., and R. Raiswell, 1981, Carbon, oxygen and sulphur isotope variations in concretions from the Upper Lias of NE England: Geochim. Cosmochim. Acta, v. 45, p. 329-340.

Mathiesen, A., K. Kristensen, T. Bidstrup, and L.H. Nielsen, 2009, Vurdering af det geotermiske potentiale i Danmark: Danmarks og Gronlands Geologiske Undersogelse Rapport 2009/59, 30 p.

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Introduction

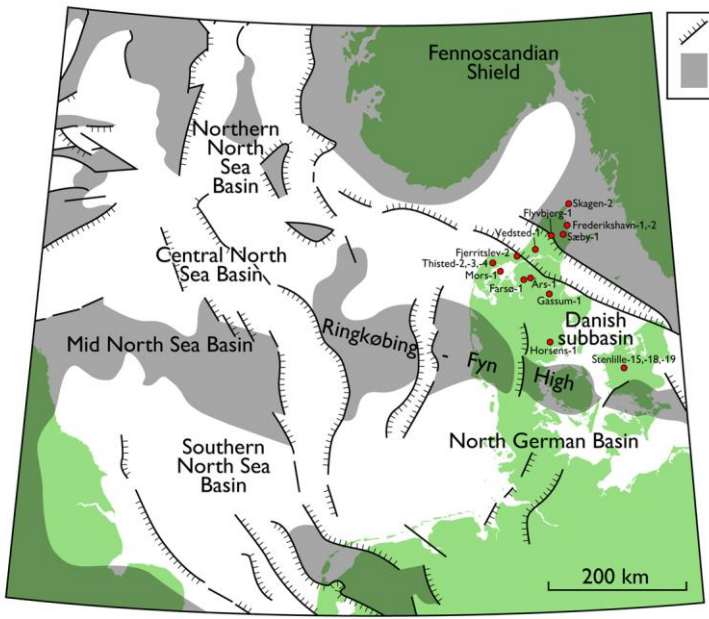
Study area advantages

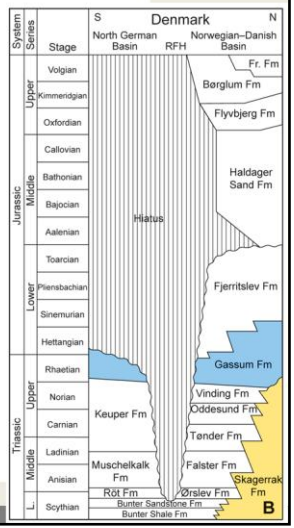
- Similar sediment source
  - Mesozoic sediments in the Danish Subbasin were mainly sourced from the Fennoscandian Shield to the north and east
- Different climate and hence depositional environment
  - Skagerrak Fm: arid to semi-arid climate

    dominated by alluvial fans, braided rivers
  - Gassum Fm: humid climate

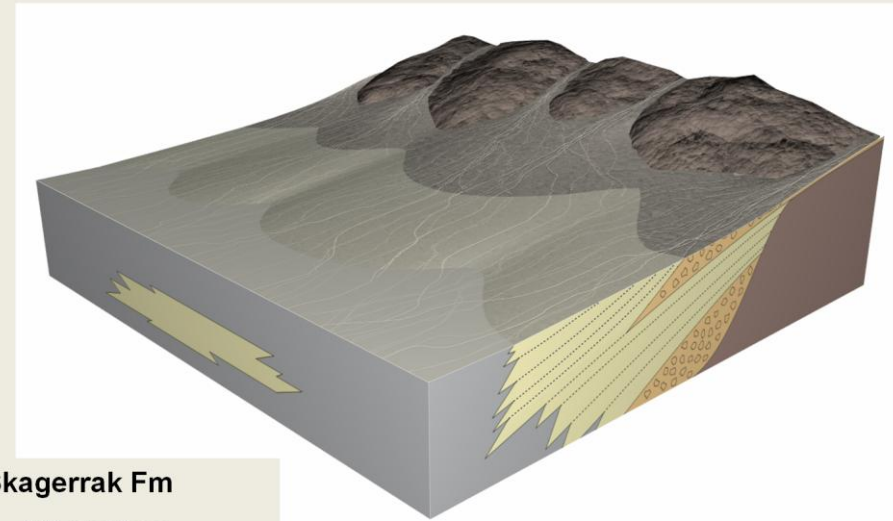
    dominated by fluvial, paralic and shallow marine deposition
- Variation in burial depth
  - Present day burial depths vary from 550–3350 m.
  - Estimated maximum burial depths vary from 1800–5900 m.
- No influence from oil migration!

Geological setting





Semi-arid to arid climate



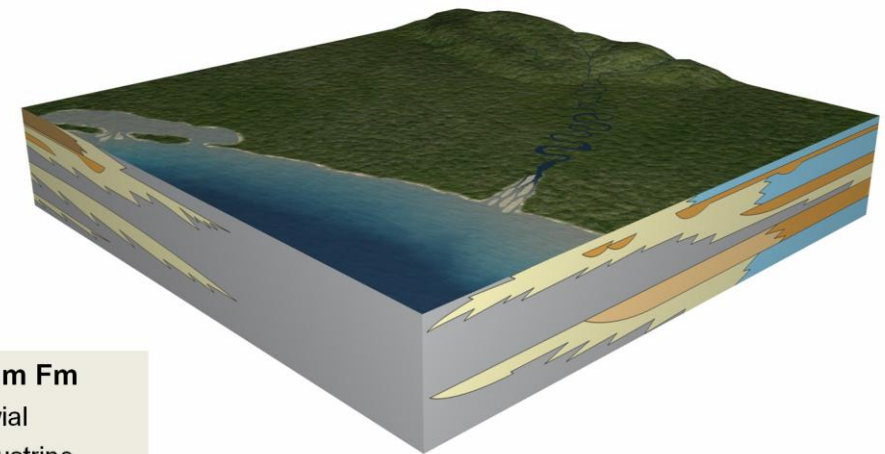
Skagerrak Fm

- Allluvial fans
- Braided streams

Pale reddish fine- to medium-grained sandstones and conglomerates.

Presenter's notes: The proximal deposits: more coarse-grained (up to conglomeratic).
The distal deposits: more well sorted; yet still fine-grained sandstones up to medium- or coarse-grained.

Humid climate



Gassum Fm

- Fluvial
- Lacustrine
- Lagoonal
- Estuarine
- Shoreface
- Offshore

Light greyish fine- to medium-grained sandstones and heterolithic bedded sandstone/claystones,

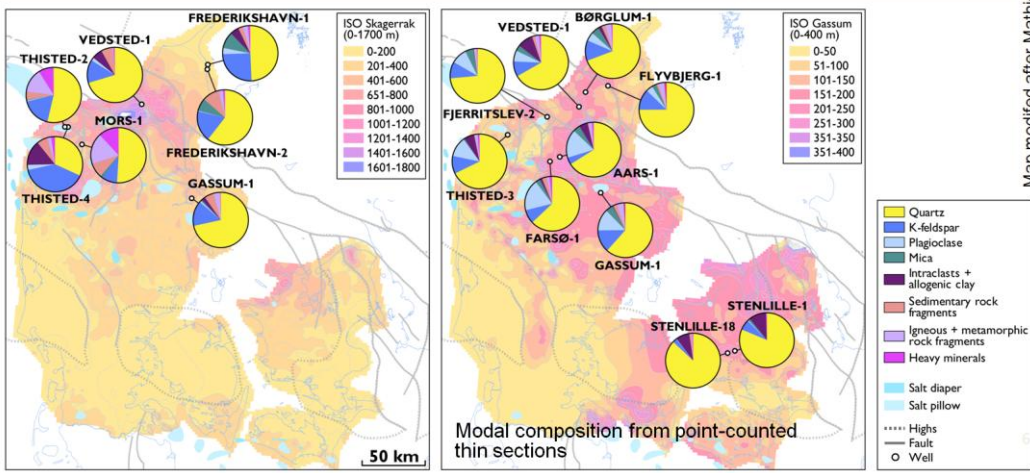
Detrital mineralogy

Skagerrak Fm

- Quartz dominates
- K-feldspar is common
- Rock fragments are common
- Heavy minerals are fairly common

Gassum Fm

- Quartz dominates
- Feldspar content varies
- Rock fragments are rare
- Intraclast and allogenic clay content vary



Map modifed after Mathiesen et al. 2009

Presenter's notes: Arid conditions: Relative immature mineralogical composition: high content of rock fragments and feldspar.
Humid conditions: Mineralogically more mature composition, relatively lower content of rock fragments and feldspar. Part of the allogenic clay content may be due to drilling mud infiltration.

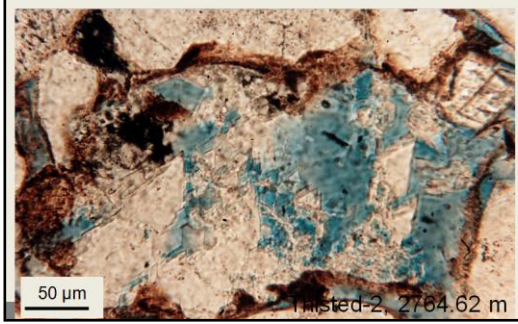
Early diagenesis – Fe-rich phases

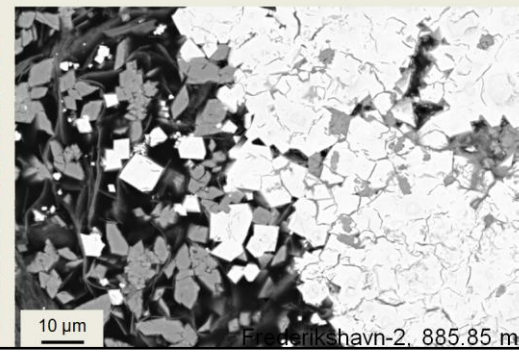
Skagerrak Fm (arid to semi-arid)

- Fe^{3+} is insoluble promoting iron-oxide/hydroxides precipitation close to altered unstable heavy minerals
- Hematisation of Fe-rich minerals also occur under these oxidising conditions

Gassum Fm (humid climate)

- Fe^{2+} is highly soluble under the redu-cing conditions caused by degradation of organic matter
- Pyrite precipitation is promoted by sulphate-reducing bacteria
- Siderite can be promoted by sulphate-reducing bacteria when occurring in a consortium of microbial fermenters (Coleman & Raiswell 1981)





Presenter's notes: Oxidising conditions: Iron-oxide/hydroxides precipitated close to to its source, i.e., altered heavy minerals.
Reducing conditions: Reduced iron can be transported for longer distances; the result may be concretionary precipitation or more dispersed precipitation. Organic matter creates reducing condition. Sulphate-reducing bacteria may promote precipitation of pyrite, and may, in a consortium of fermenters, also promote siderite formation.

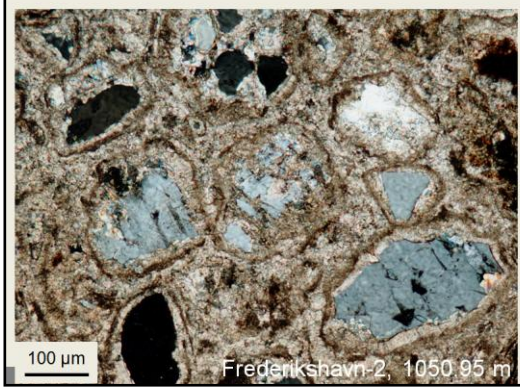
Early diagenesis – Ca-rich phases

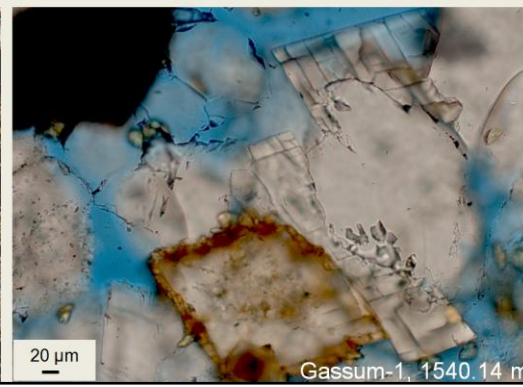
Skagerrak Fm (arid to semi-arid)

- Calcrete, formed by pedogenetic processes only in the proximal and shallowest buried sandstones. Or recrystallisation of calcrete may have occurred during burial.
- Gypsum (now anhydrite) formed by evaporation of groundwater

Gassum Fm (humid climate)

- Calcite cement may be associated with shell deposits in the marine-influenced environment





Presenter's notes: Arid conditions: Concretions are of calcite or gypsum/anhydrite formed by evaporation of groundwater/water. Humid conditions: Besides siderite, early calcite cement formed.

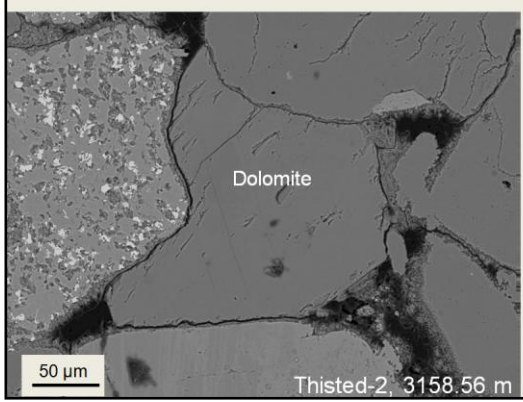
Burial diagenesis – carbonate cement

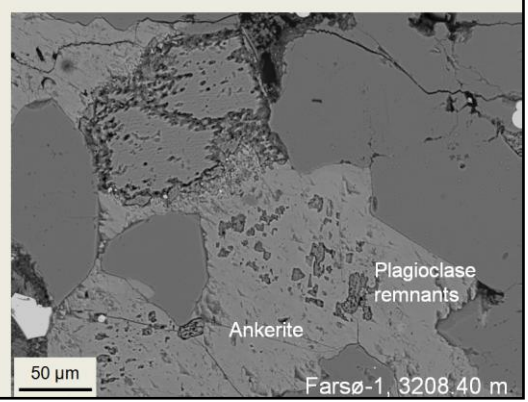
Skagerrak Fm
(arid to semi-arid climate)

- Dolomite probably sourced by unstable heavy minerals, clay minerals and rarely carbonate clasts (Ankerite)

Gassum Fm
(humid climate)

- Ankerite / Fe-rich dolomite probably sourced by fossil fragments, clay minerals and plagioclase



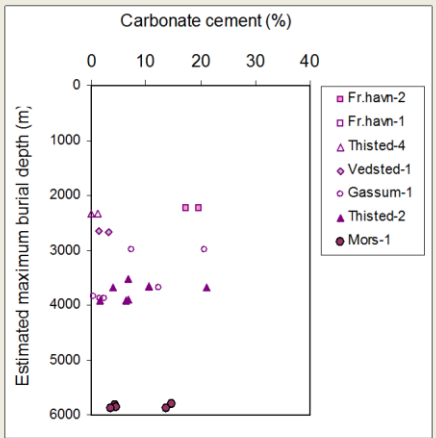


Presenter's notes: Arid conditions: Dolomite occurs in clay clasts; so clay minerals seem to have been a likely internal source. Dolomite cement is likely to have been sourced also from alteration of unstable heavy minerals. Calcite may have been promoted by pressure-solution of ooids in the Bunter Sandstone Fm; carboante clasts less common in the Skagerrak Fm. Humid conditions: Ankerite formed around remnants of intensively altered plagioclase. Fossil fragements may have been present in the some of the sandstones (shoreface).

Burial diagenesis – carbonate cement

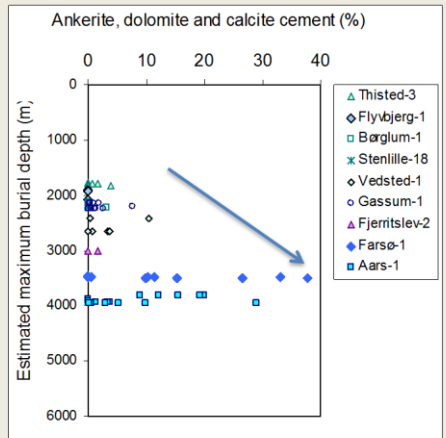
Skagerrak Fm
(arid to semi-arid climate)

- Dolomite
- (Ankerite)
- Calcite



Gassum Fm
(humid climate)

- Ankerite
- Fe-rich dolomite
- Calcite



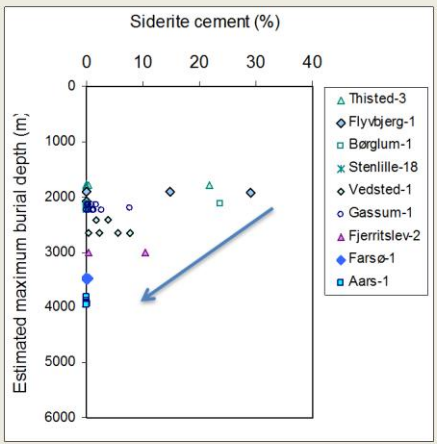
Presenter's notes: Arid conditions: Pore-filling dolomite dominates, sourced by alteration of detrtial plagioclase, biotite, amphibole and pyroxene. Humid conditions: Pore-filling ankerite and Fe-rich dolomite, occasionally calcite, sourced by fossils in the shoreface, but not in the fluvial. Plagioclase clearly a source in some cases. Is siderite a source? At shallow burial, siderite is abundant in some samples Why never in the deeply buried sandstones? Siderite may not be stable at deeper burial and is dissolved/replaced by ankerite and Fe-rich dolomite.

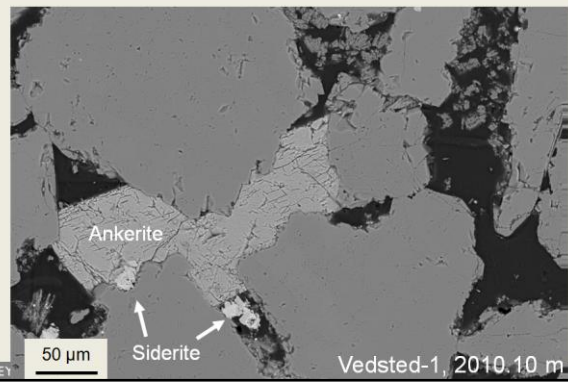
Burial diagenesis – carbonate cement

Gassum Fm (humid climate)

Changes in siderite/ankerite abundance:

- Changes during burial?
- Depositional environments?
  - Siderite: shoreface, lagoonal, fluvial-estuarine
  - Ankerite: shoreface, lagoonal, offshore





Presenter's notes: Arid conditions: Dolomite ???? Humid conditions: Ankerite formed around remnants of intensively altered plagioclase.

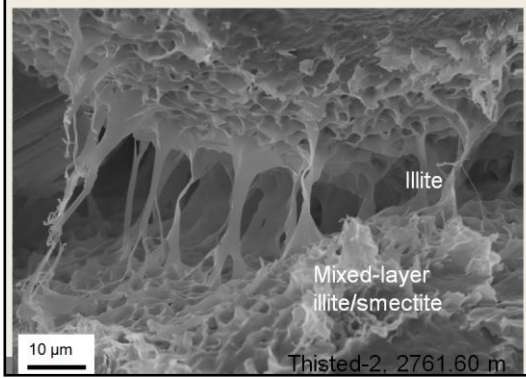
Clay mineral diagenesis

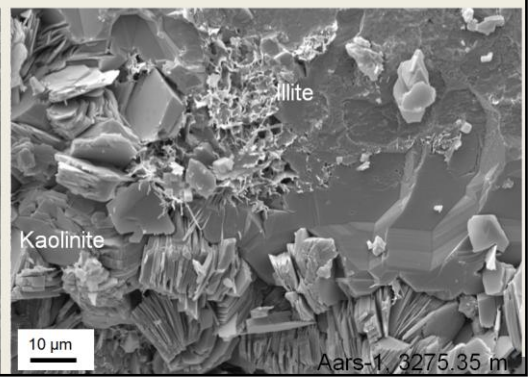
Skagerrak Fm (arid to semi-arid)

- Smectitic infiltration clays occur the shallow buried parts
- Illitisation and illite preciptation dominates the deeper buried parts
- Late Mg-rich chlorite is rare
- Kaolinite occurs in reduction spots

Gassum Fm (humid climate)

- Fe-rich chlorite (and smectite) occur as allogenic clays and early pore-lining clays
- Illitisation and/or illite precipitation is common in the deeper buried parts
- Kaolinite occurs extensively, probably associated with alteration of feldspar grains, due to meteoric water flushing?





Presenter's notes: Arid to semi-arid conditions: Rare rainfall results in limited weathering of detrital grains in the hinterland. Low leaching of elements and hence both the detrital clays and the early authigenic clays obtain a smectitic composition and form ubiquitous grain coatings, which therefore inhibit quartz overgrowths or leads to limited quartz overgrowths/outgrowths.

Humid conditions: Humid conditions results more stable detrital composition, intense leaching af elements and hence the clays formed are kaolin. Bioturbation may influence the clay distriibution and small-scale heterogeneity, hence chlorite/illite may by less evenly distributed and therefore not inhibit quartz overgrowth!

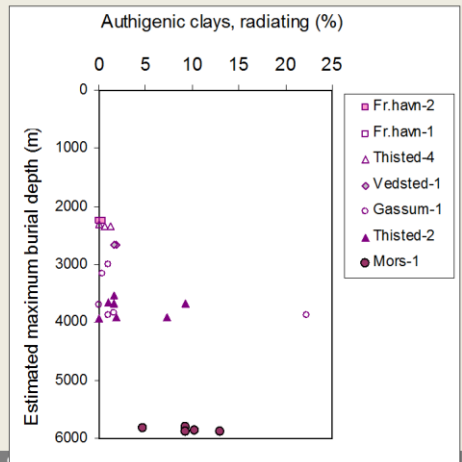
Clay mineral diagenesis

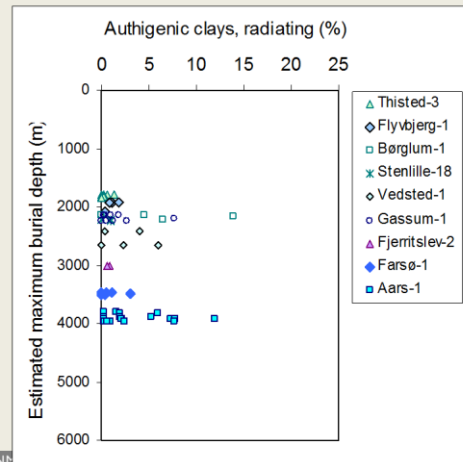
Skagerrak Fm (arid to semi-arid)

- Smectitic infiltration clays occur in the shallow buried parts
- Illitisation and illite precipitation dominates the deeper buried parts

Gassum Fm (humid climate)

- Fe-rich chlorite (and smectitic) pore-lining
- Illitisation and/or illite precipitation is common in the deeper buried parts





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Presenter's notes: There is not a large variation in the abundance of pore-lining clays. Skagerrak Fm: mainly smectitic replaced by illite. Gassum Fm: mainly chlorite replaced by illite? AND KAOLINITE.

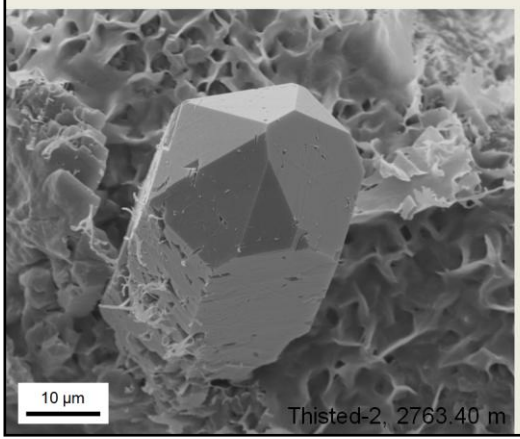
Burial diagenesis – quartz

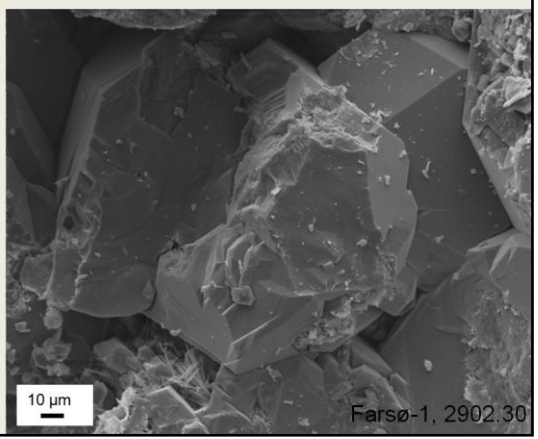
Skagerrak Fm
(arid to semi-arid climate)

- Quartz overgrowth
- Quartz outgrowths

Gassum Fm
(humid climate)

- Quartz overgrowths
- Pressure-solution
- Stylolites

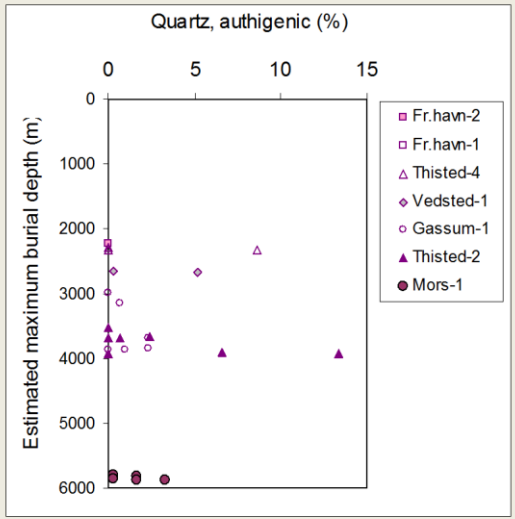




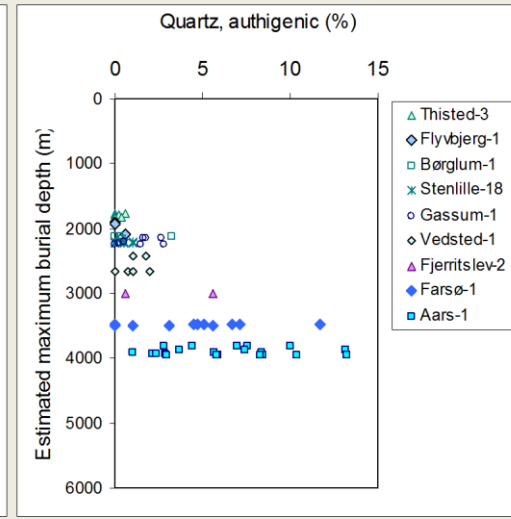
Presenter's notes: Arid conditions: Concretions are of calcite or gypsum/anhydrite formed by evaporation of groundwater/water. Humid conditions: Early cement formed.

Burial diagenesis – quartz

Skagerrak Fm
(arid to semi-arid climate)



Gassum Fm
(humid climate)



Presenter's notes: Arid conditions: Concretions are of calcite or gypsum/anhydrite formed by evaporation of groundwater/water. Humid conditions: Early cement formed.

Burial diagenesis – quartz

Quartz diagenesis depends on:

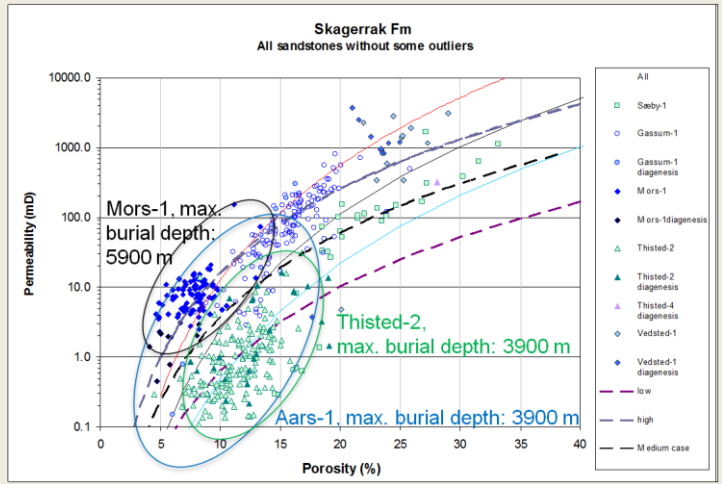
- Abundance of detrital quartz
  - Skagerrak Fm: Lower abundance of quartz
  - Gassum Fm: Higher detrital quartz abundance
- Abundance of ductile grains
  - Skagerrak Fm: High abundance of ductile grains (several types)
  - Gassum Fm: Low abundance of ductile grains, which are mainly mica and therefore promotes stylolite formation.
- Type and abundance of grain coatings
  - Skagerrak Fm:
    - Iron-oxide/hydroxide coatings – little influence on the successive diagenesis
    - Pore lining smectite/illite coatings– major influence on the successive diagenesis
  - Gassum Fm (Farsø-1 well):
    - Irregular distributed chlorite and ilite coatings – little or no influence on the successive diagenesis

Porosity and permeability

Different diagenesis

Similar porosity and permeability trend

Higher porosity-permeability reduction with burial depth in the humid Gassum Fm than in the arid to semi-arid Skagerrak Fm



Conclusion (1 of 2)

Diagenetic changes in relation to climatic conditions:

- Detrital composition
  - Similar sediment source area for the Skagerrak and Gassum formations
  - Different degrees of the alteration during humid and arid to semi-arid climatic conditions, which define the detrital composition of the deposit
- Evaporation
  - Early cements (calcrete and gypsum) are formed due to evaporation
- Clay minerals
  - Skagerrak Fm: Smectitic infiltration clays covering all grains
  - Gassum Fm: Irregular occurrence of chlorite (and smectite) clays, and abundant kaolinite
- Presence of organic matter
  - Skagerrak Fm: Oxidising conditions, though with local reduction spots
  - Gassum Fm: Reducing conditions due to abundant organic matter

Oxidising / reducing conditions have major influence on the diagenesis of Fe-rich phases!

Conclusion (2 of 2)

Successive burial diagenesis:

- Carbonate cement
  - More abundant in the formation deposited under humid conditions and different cement types
  - Skagerrak Fm: Typically dolomite and calcite cement
  - Gassum Fm: Siderite dominates at shallow burial depth, whereas ankerite and Fe-dolomite cement are characteristic of the deeper buried samples.
- Clay minerals
  - Illitisation occurs in both formations
- Quartz cement
  - Skagerrak Fm: Limited quartz overgrowths due to clay mineral coatings and limited internal silica sources.
  - Gassum Fm: Extensive authigenic quartz cement due to higher abundance of detrital quartz, irregular distributed clays and fewer unstable minerals, typically mica, which promote stylolite formation and acts as an internal silica source.


Thank you for your attention