

Norwegian Formation Evaluation Society

Monthly Meeting @ Solastranden Gård, Sola

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Reservoir Quality In Deep Sandstone Prospects, What Are The Main Controls?

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Sponsors



What controls reservoir quality, most important factors:

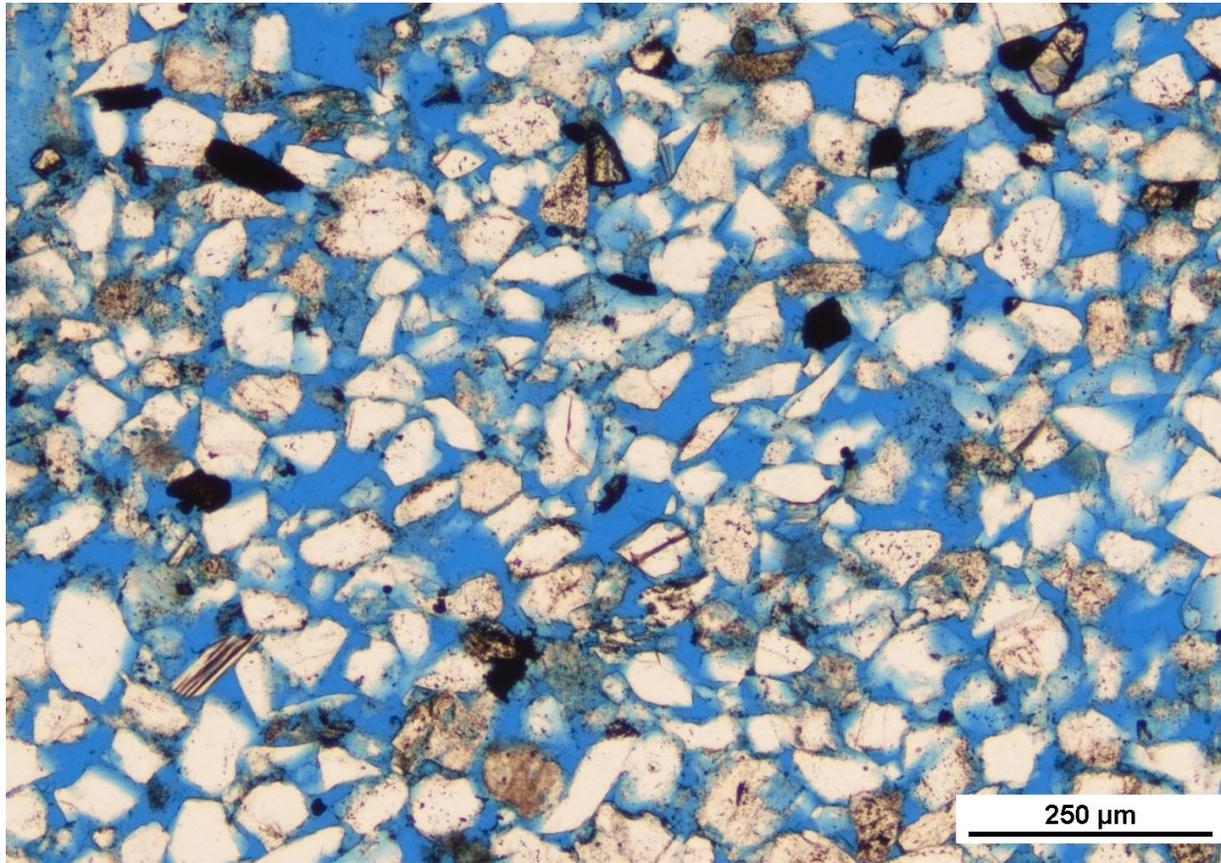
- Presence of enough sandstone

- Composition and texture at deposition:
 - Grain size
 - Sorting and packing
 - Clay matrix content
 - Mineralogy of the grains

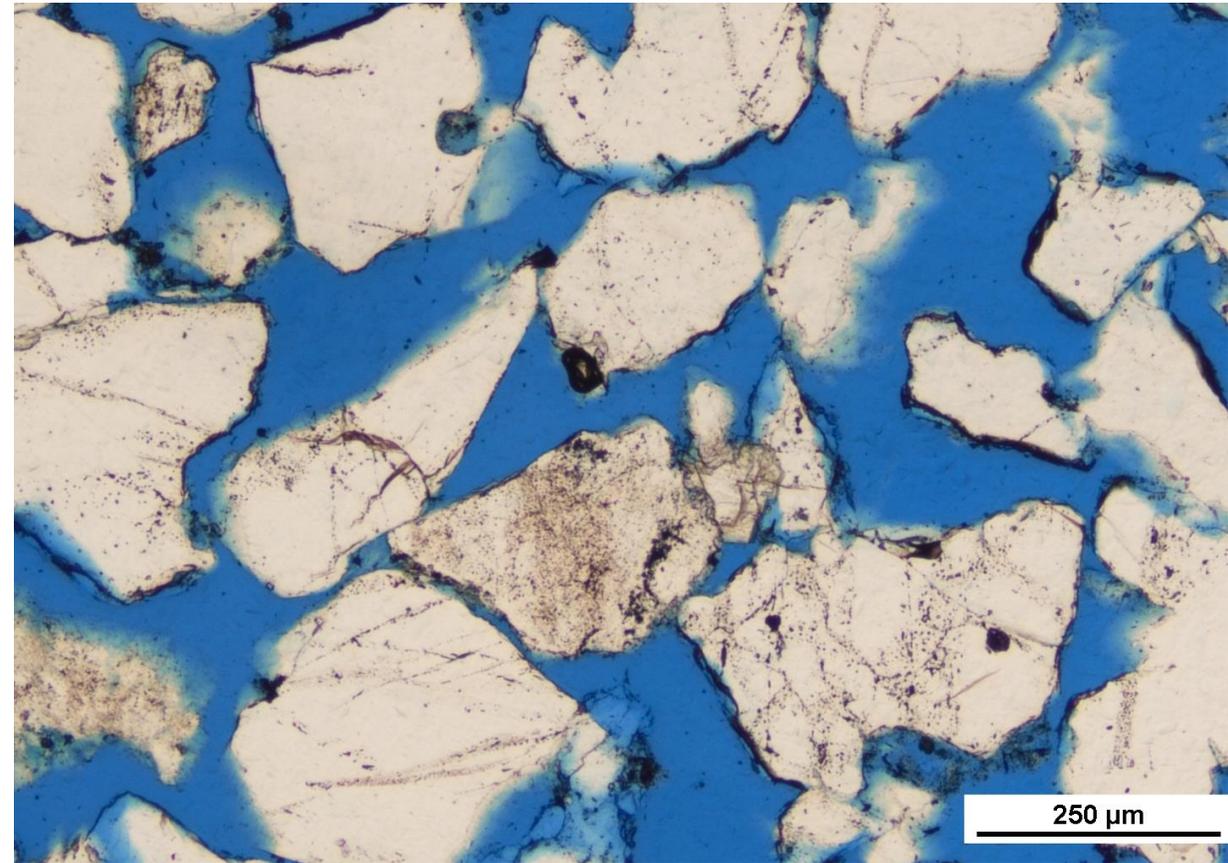
- Compaction (mechanical and chemical)

- Cementation:
 - Clays (kaolin, smectite, illite, chlorite)
 - Carbonate cements (calcite, dolomite)
 - Quartz cement

Grain size greatly affects permeability, proportional to grain size squared for a fixed porosity and type of pore system. Also, slower quartz cementation in coarser sandstones (less quartz surface area where overgrowths can precipitate).

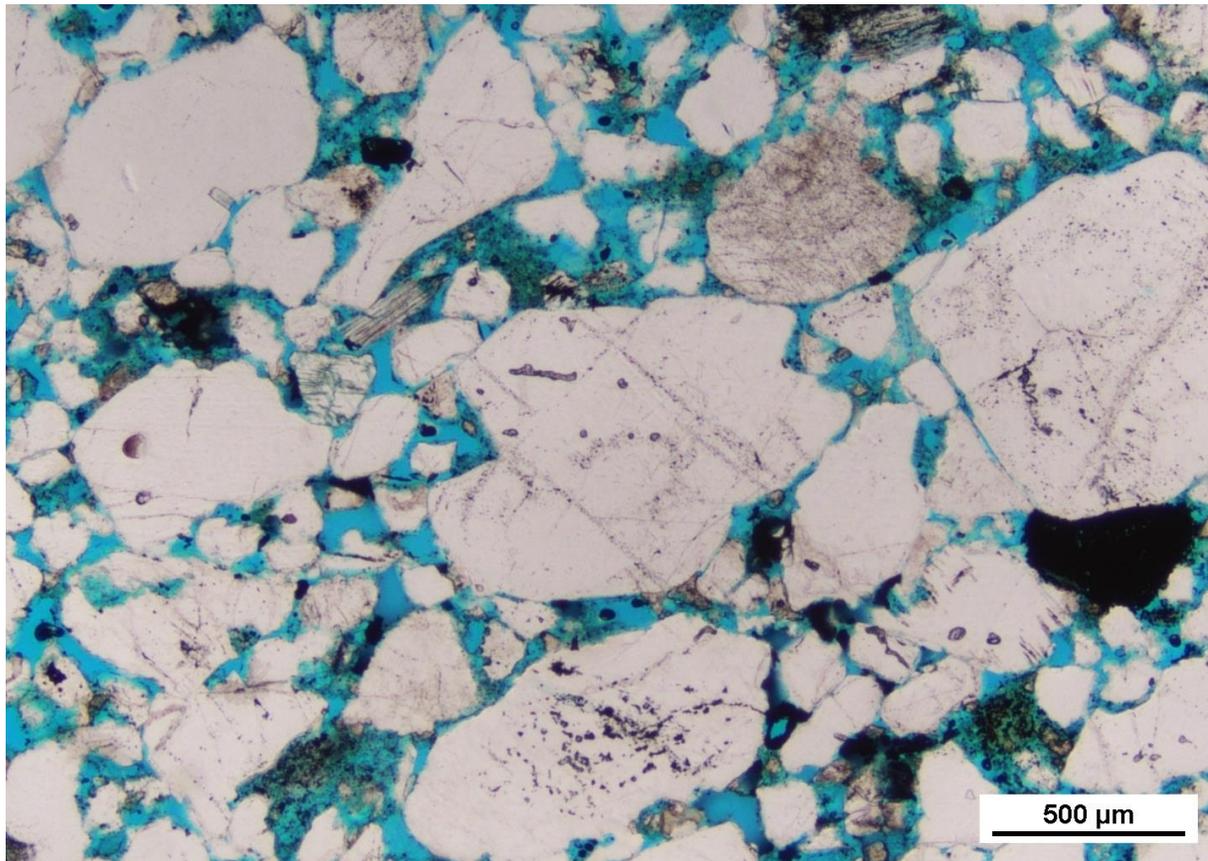


Tilje Fm, 1632 m burial depth, grain size 0.09 mm, porosity 35.0 %, permeability 544.0 md.

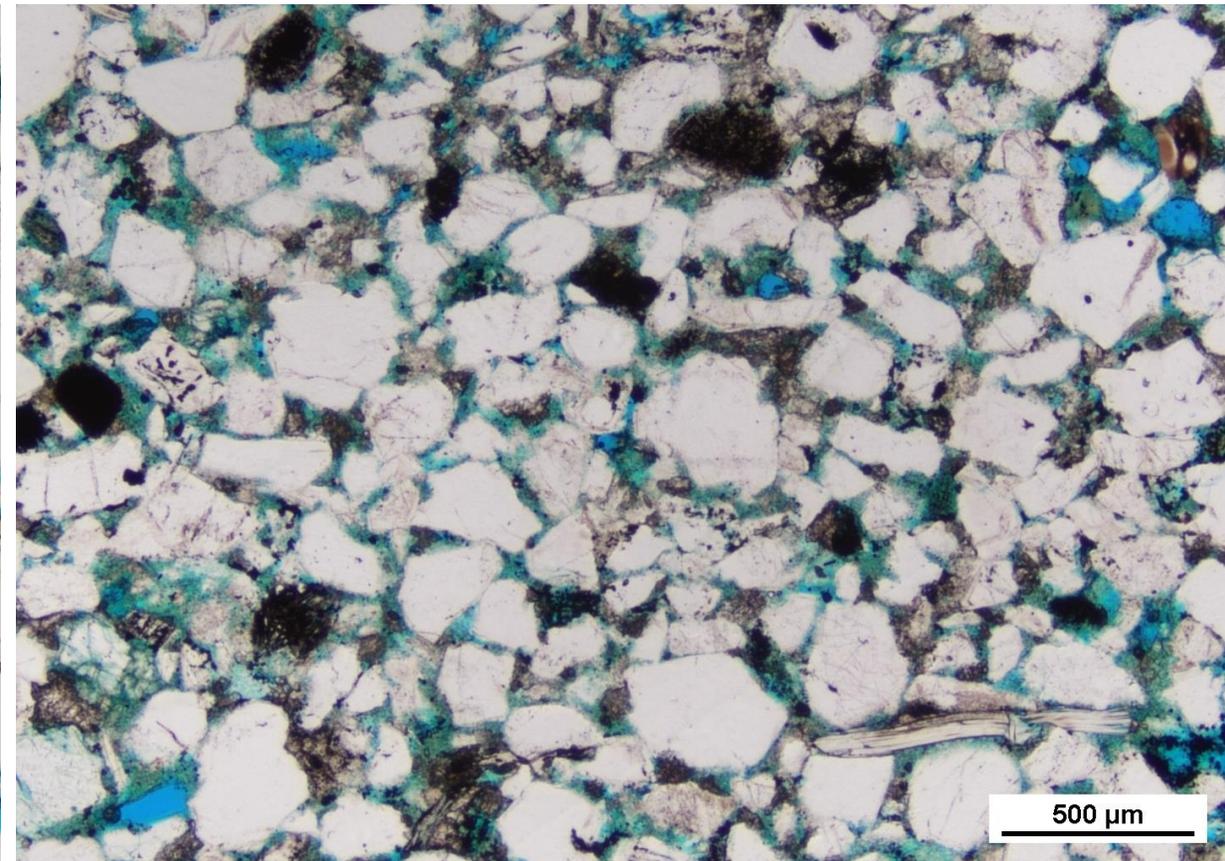


Åre Fm, 1669 m burial depth, grain size 0.33 mm, porosity 33.2 %, permeability 5140.0 md.

Poor sorting (left micrograph) and tight grain packing (right micrograph) lowers porosity which in turn reduces permeability.

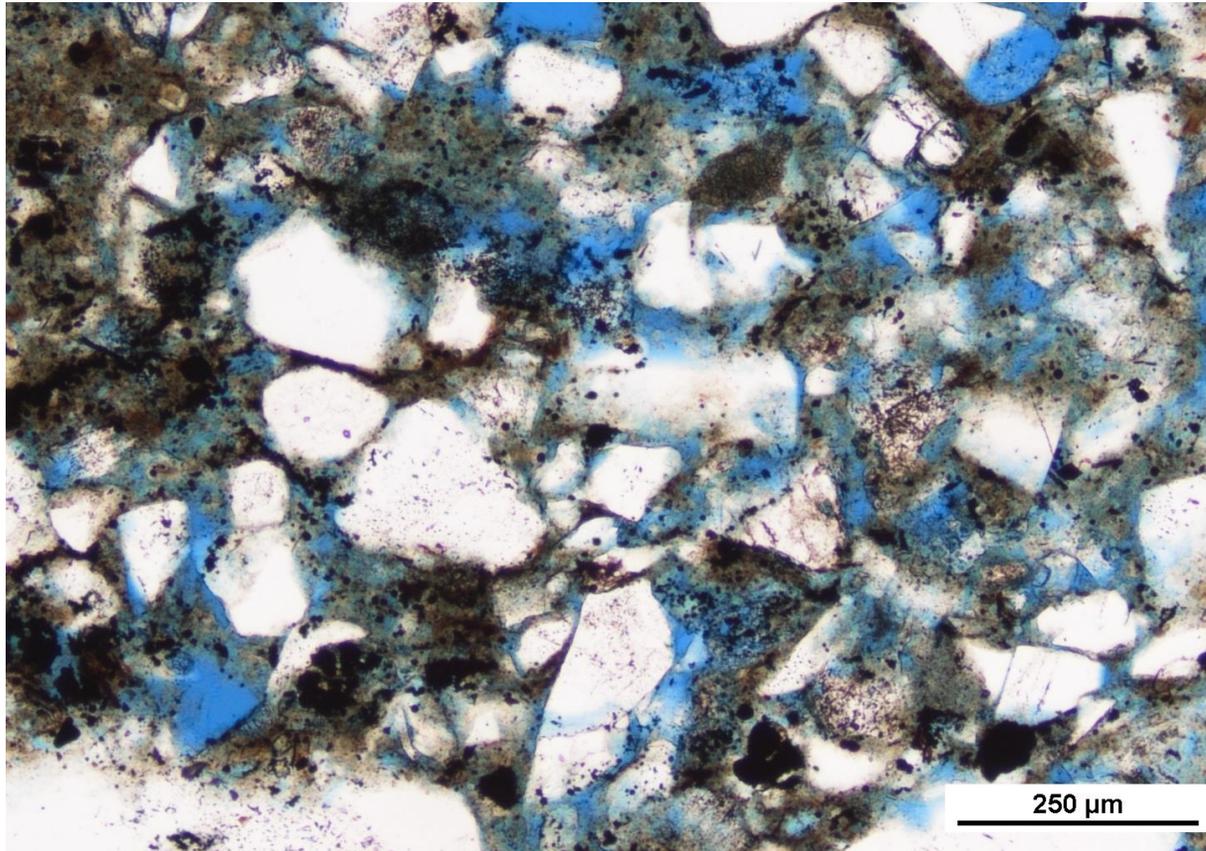


Nise Fm, 1857 m burial depth,
porosity 22.8 %, permeability 128.0 md.

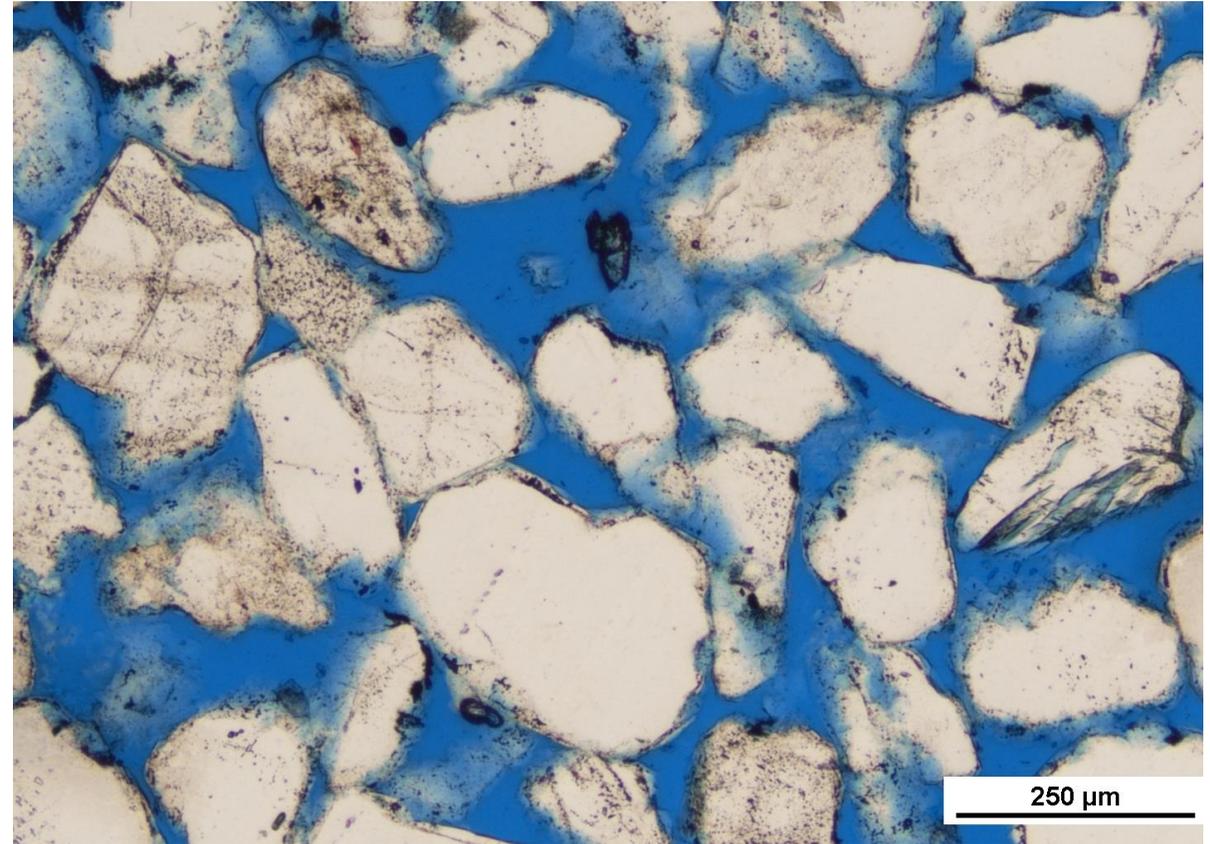


Nise Fm, 1851 m burial depth,
porosity 8.6 %, permeability 0.078 md.

Clay matrix fills pore space and also enhances compaction, but difficult to distinguish from clay-free sandstone if you only have seismic data.

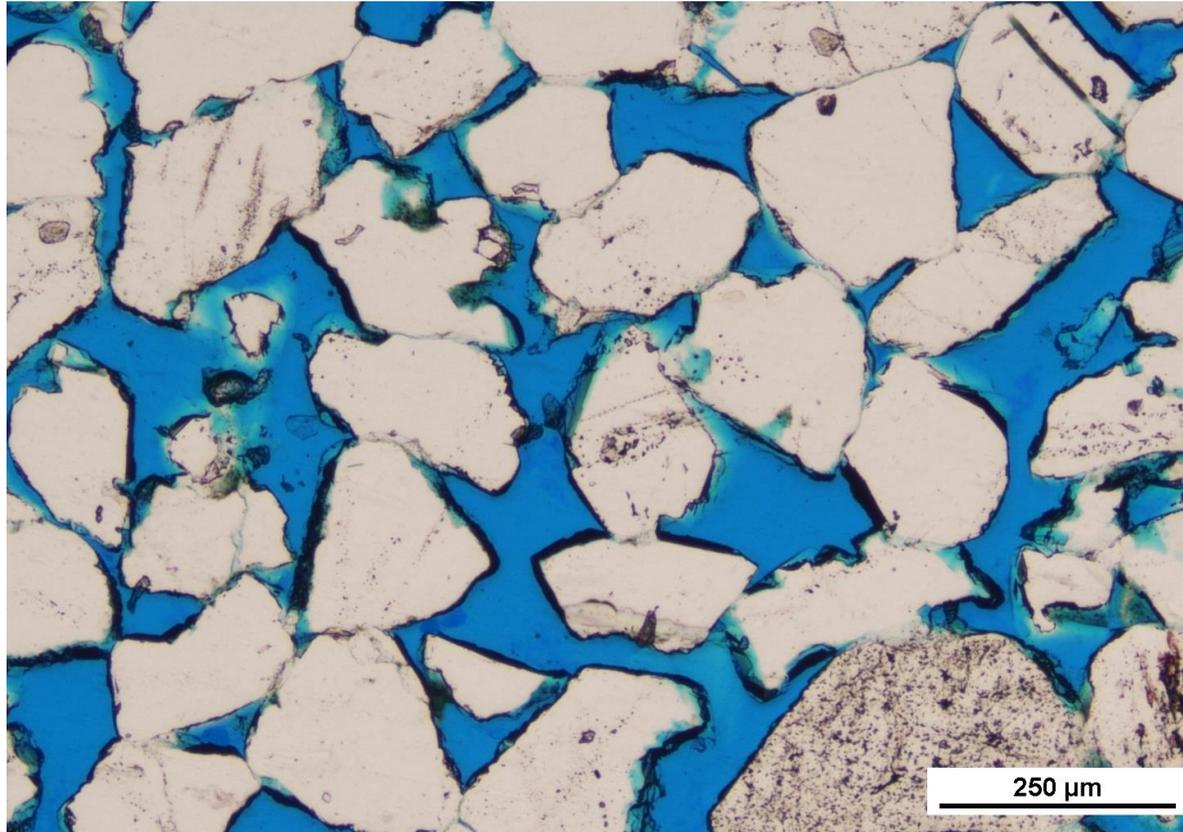


Heather Fm, 1907 m burial depth.
Clay matrix is brown, white grains are mainly quartz.
Porosity 29.4 %, permeability 227.0 md.

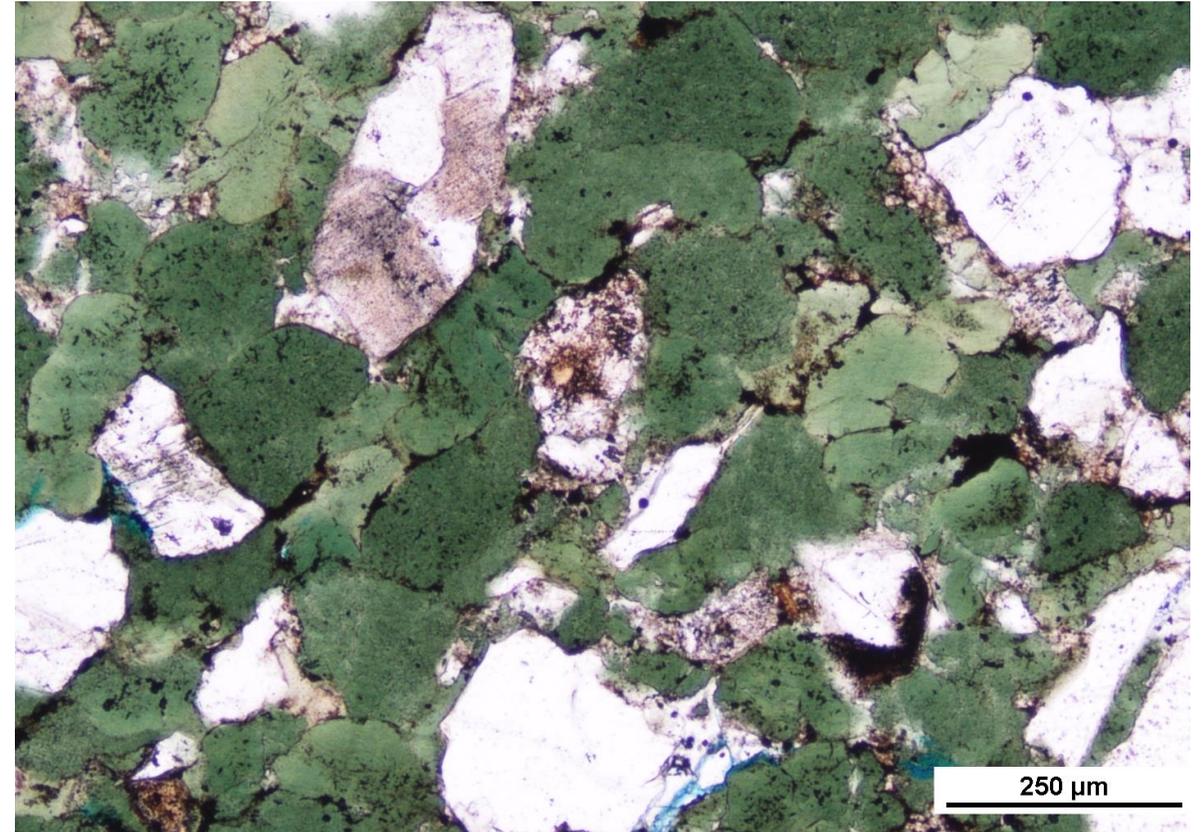


Heather Fm, 1885 m burial depth.
White grains are quartz and in a few cases feldspar.
Porosity 29.1 %, permeability 3640.0 md.

Strong grains such as quartz and feldspar resist mechanical compaction, soft grains deform and reservoir quality is lost at shallow depth.

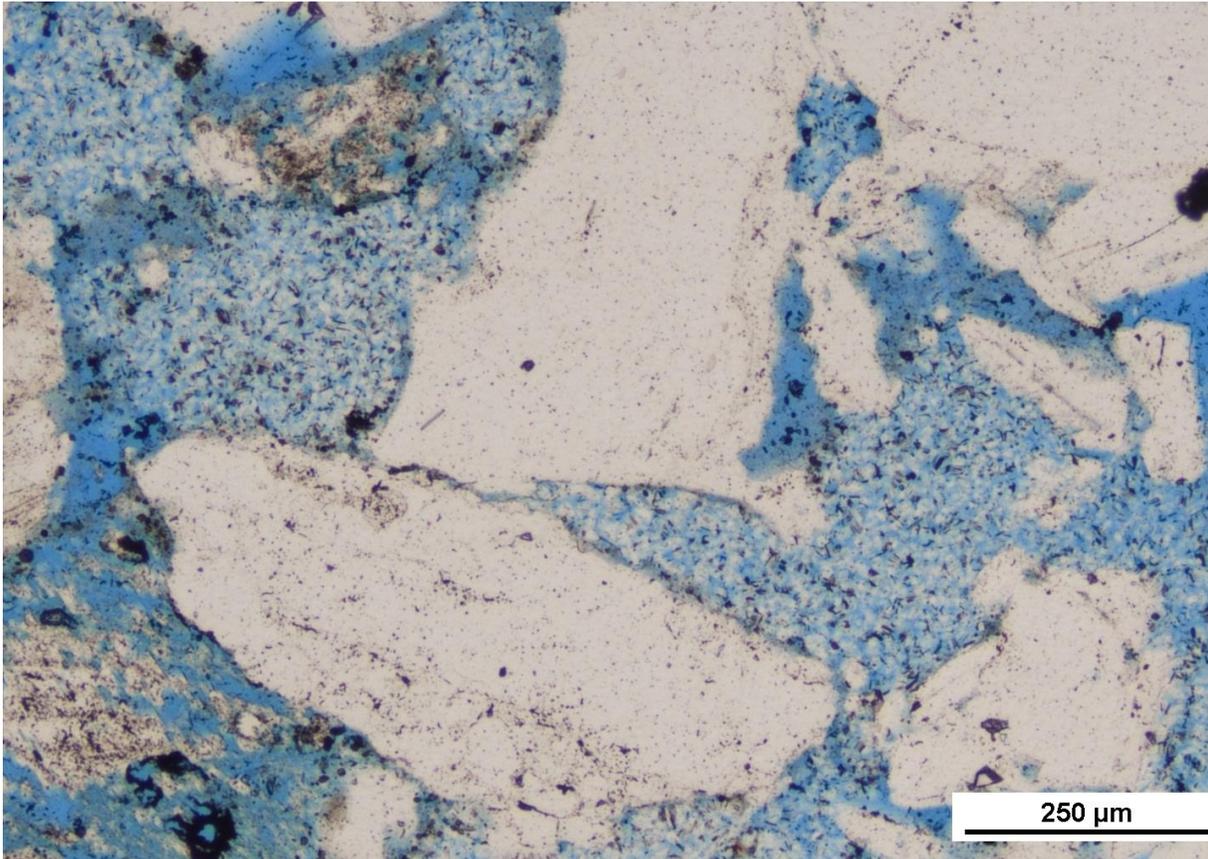


Bryne Fm, 2181 m burial depth.
 White grains are quartz, pores are blue.
 Porosity 26.2 %, permeability 3315.0 md.

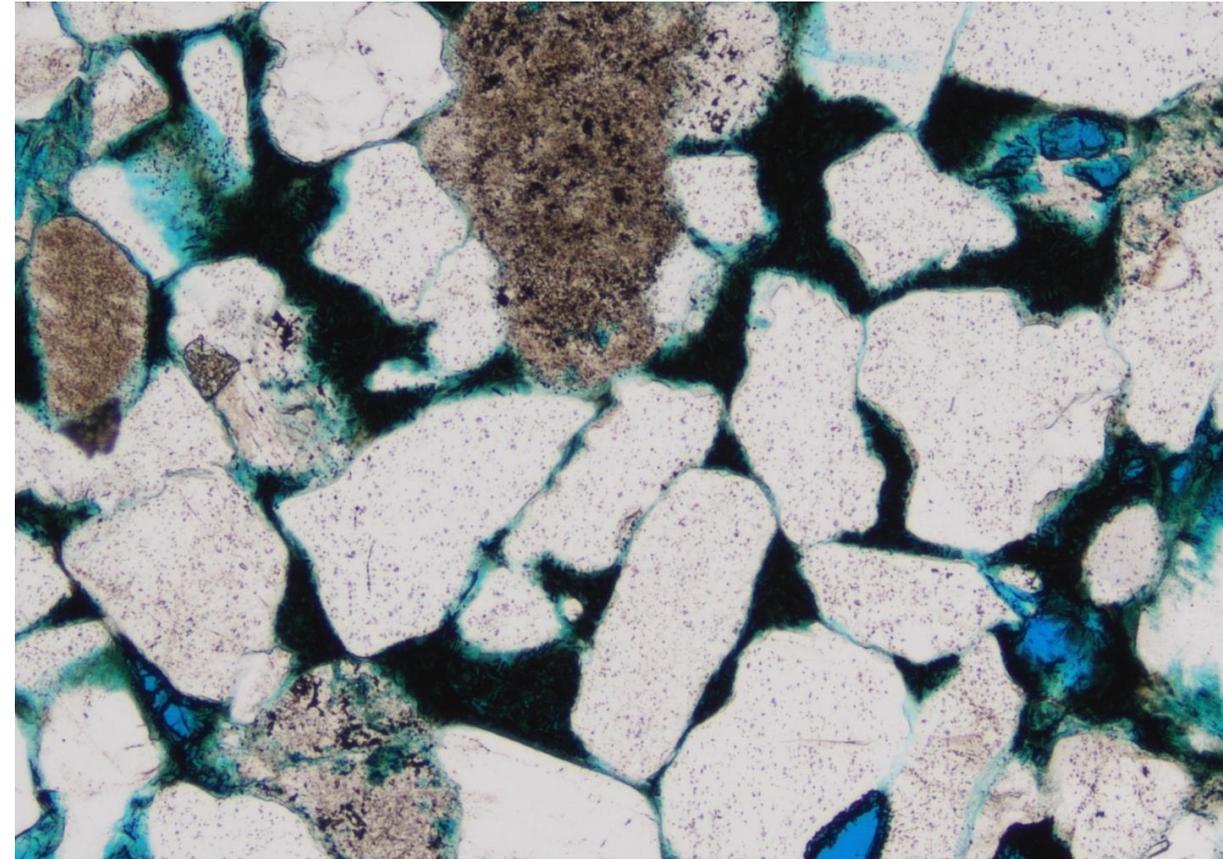


Draupne Fm, 1862 m burial depth.
 Green grains are glauconite. Porosity ca. 15 % (micropores in glauconite grains), permeability <0.1 md.

Various diagenetic clays precipitated at shallow to intermediate burial depths will typically be found in deeply buried sandstones.



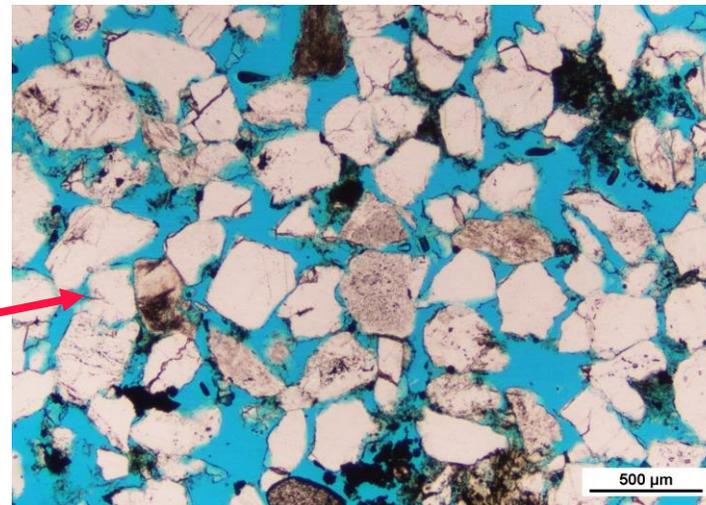
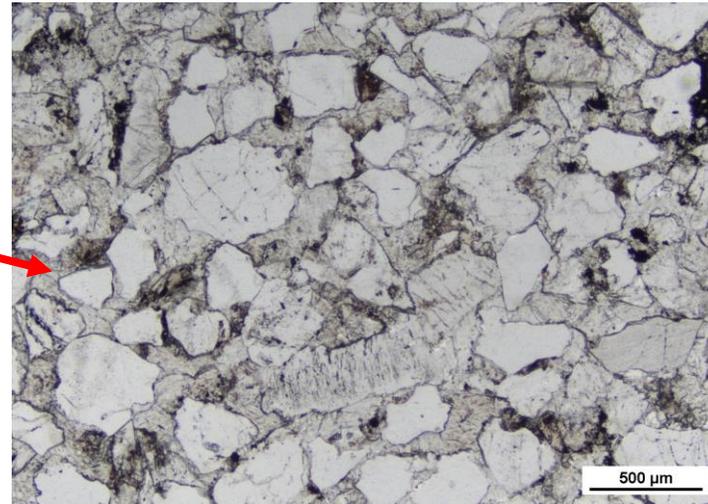
Pore-filling kaolin, Cook Fm, 2803 m burial depth. Transforms to illite when temperature exceeds 130°C and K-feldspar (potassium source) is present.



Pore-filling dark green chlorite, Lomvi Fm, 3597 m burial depth. There can be too much chlorite in some sandstones.

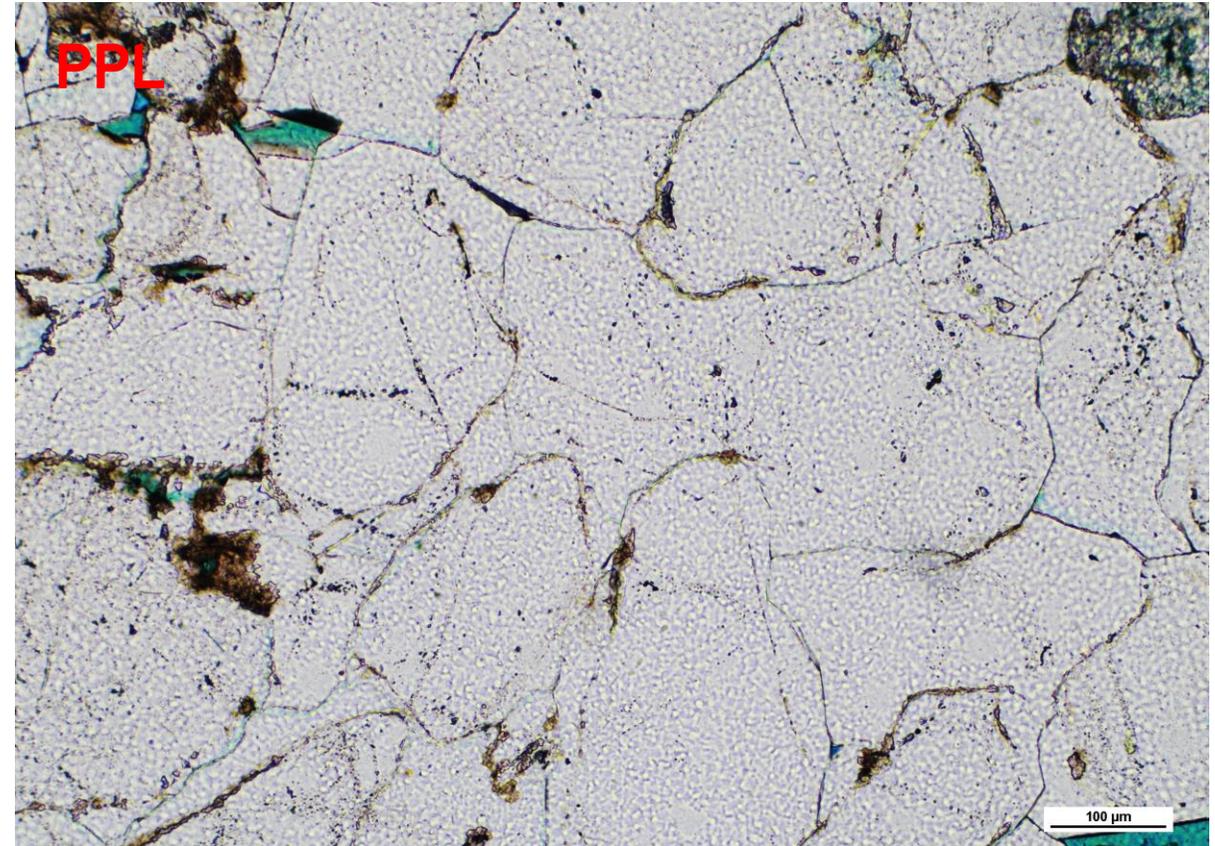
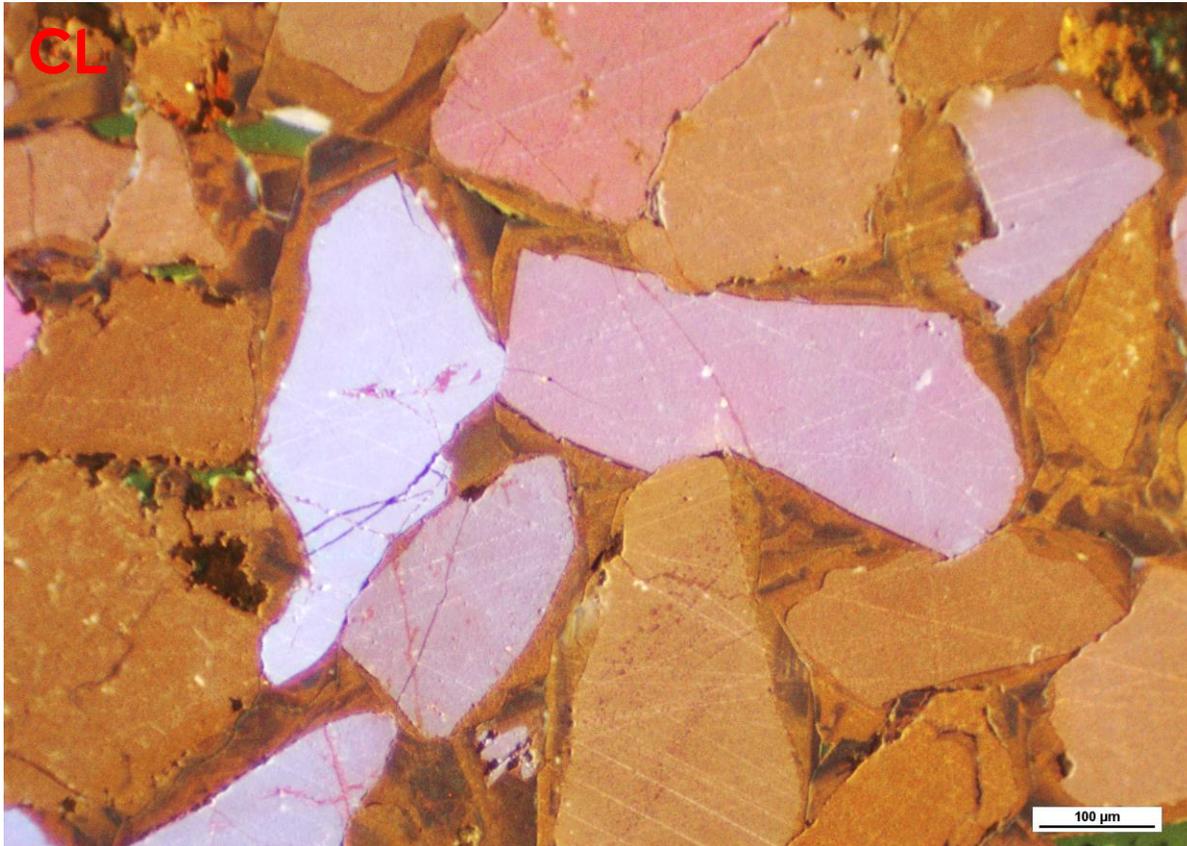
Early carbonate cements, mainly calcite, will often occur as cemented layers and concretions. In marine sandstones the source is normally carbonate fossils.

Calcite-cemented interval (light grey) at 1.6 km burial in otherwise very porous Sognefjord Fm shoreface sandstone.



Shells (white) on the beach at Lista, southern Norway. Typical source of calcite cement.

The greatest cause of porosity loss at depth is quartz cementation. Forms overgrowths on detrital quartz grains, sourced from stylolites within the sandstones.

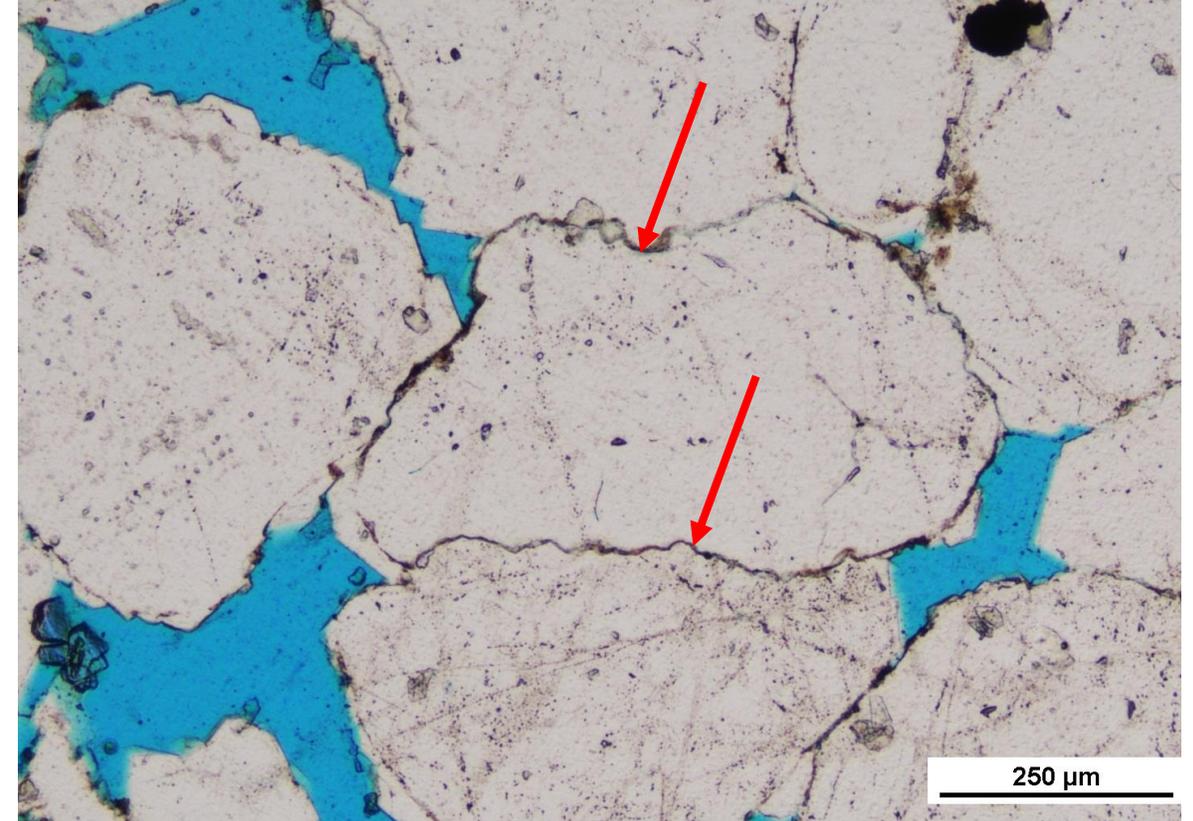


Heather Fm, 4039 m burial depth, 133°C, almost complete quartz cementation. All grains and overgrowths are quartz, pores are green...

Clay-catalyzed stylolitic dissolution of detrital quartz is the dominant source of quartz cement. Stylolites vary in size from macroscopically visible to microscopic.

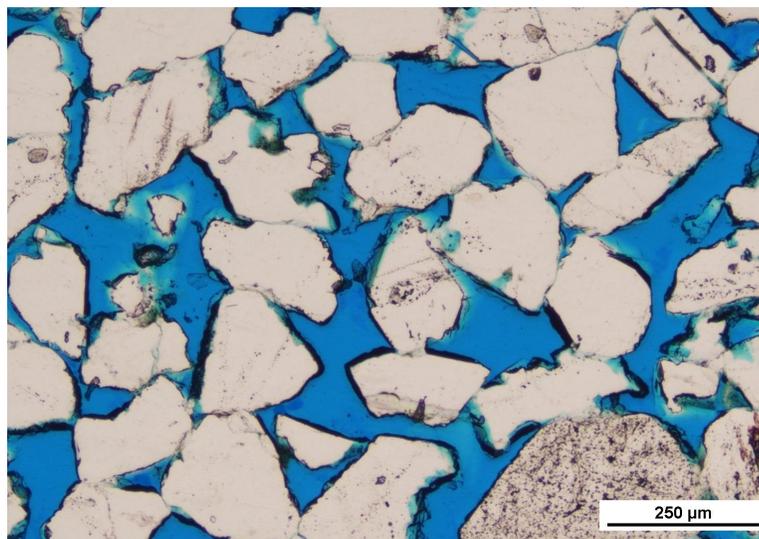


Draupne Fm, 4486 m burial depth, 157°C, large stylolite.



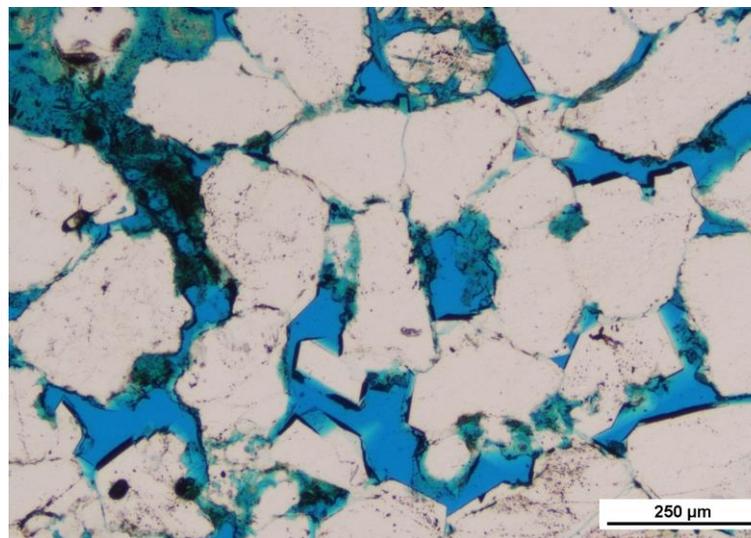
Heather Fm, 4044 m burial depth, 134°C.
Red arrows mark stylolites.

Quartz cementation starts slowly at 70 - 80°C and increases with depth and thermal exposure. A long time at high temperatures gives large volumes of quartz cement.

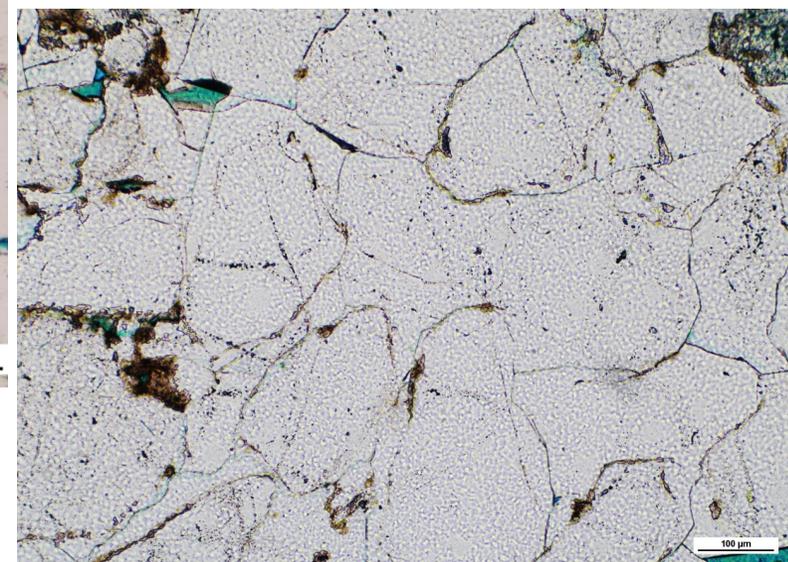


2181 m burial depth, 89°C,
traces of quartz cement

Porosity is blue, white grains are quartz and in a few cases feldspar, quartz overgrowths are white.

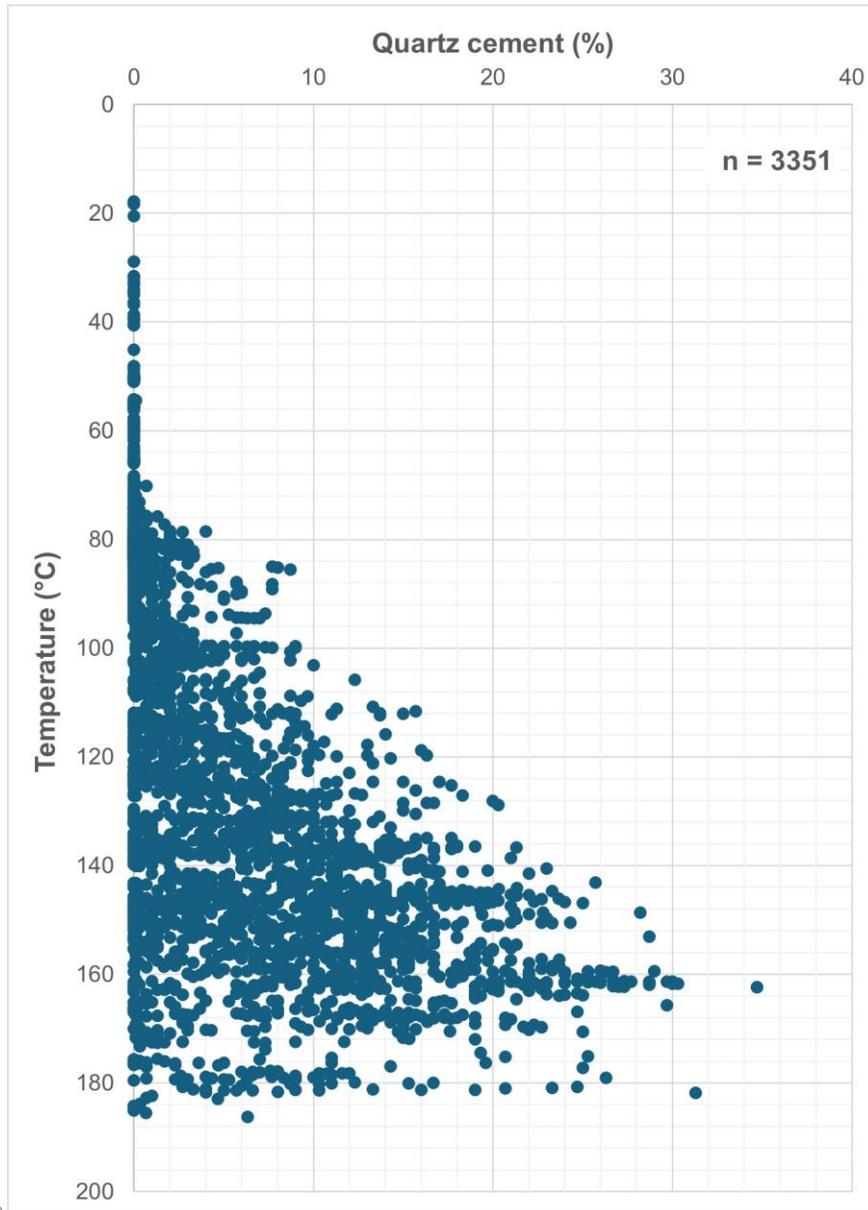


3299 m burial depth, 124°C
moderate quartz cement

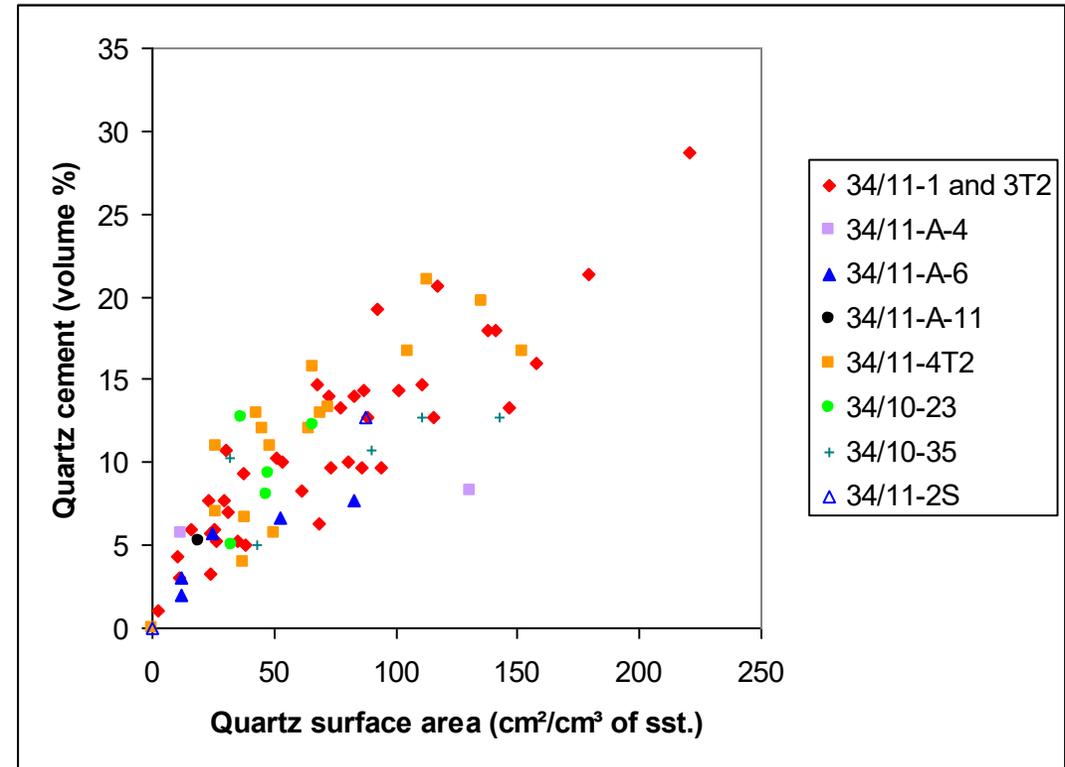


4039 m burial depth, 133°C,
large volumes of quartz cement

Point-counted quartz cement versus temperature NCS (no uplifted samples).

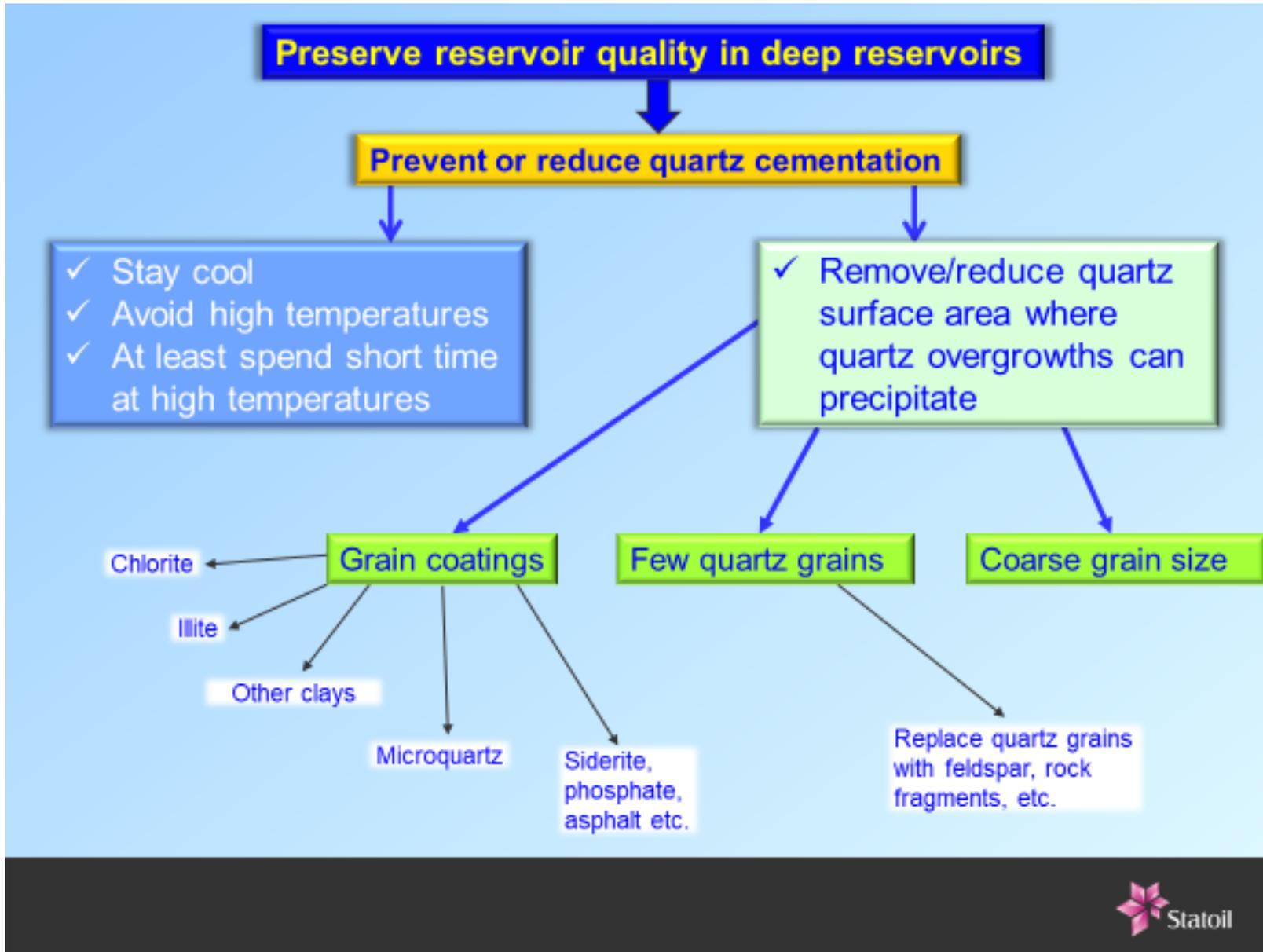


Quartz cement increases with depth and temperature, but variable volume at a specific depth due to different temperature *histories* and amount of quartz surface area for precipitation.

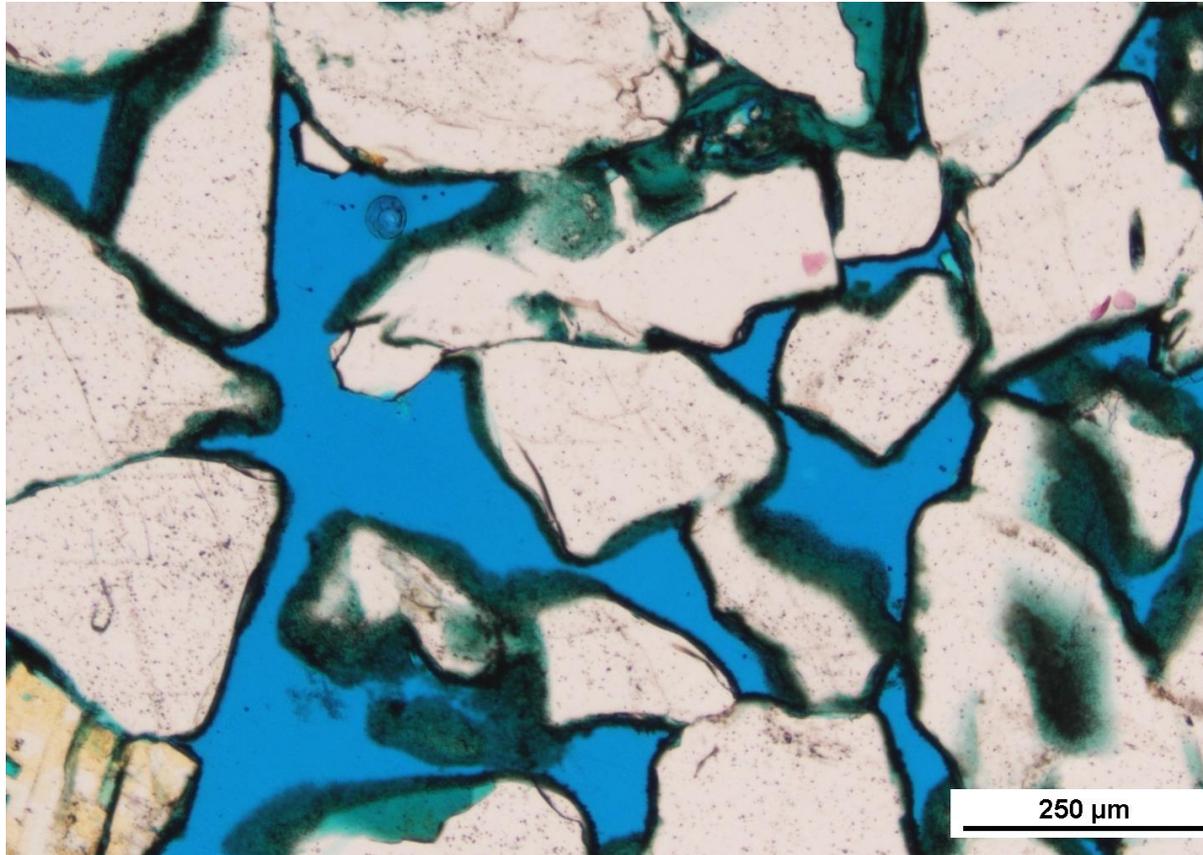


Effect of quartz surface area on quartz cementation for Kvitebjørn area samples with similar temperature histories.

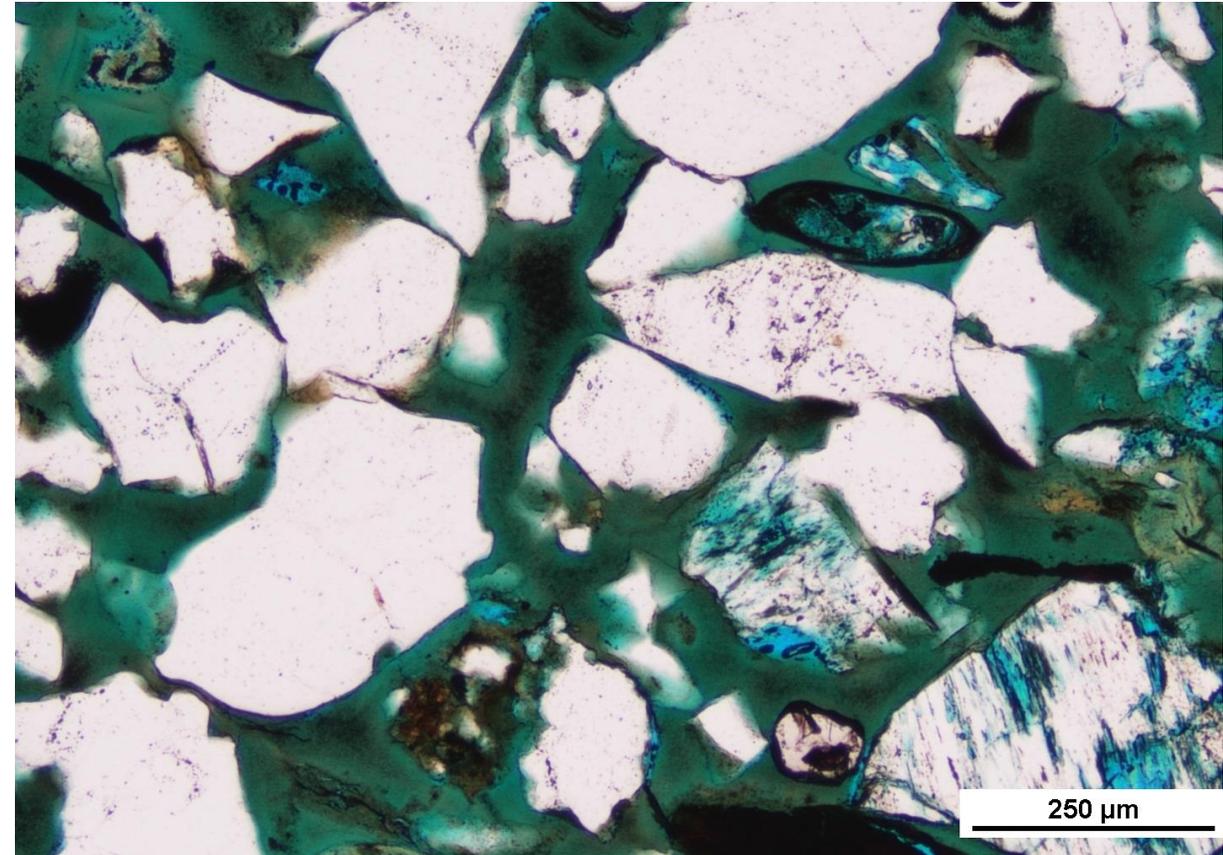
Ways to reduce or avoid quartz cementation and preserve reservoir quality.



Chlorite grain coats almost totally prevent quartz cementation in some sandstones (although sometimes there is too much chlorite). Sourced from weathering material deposited/flocculated out with the sand grains, precipitates close to the surface.

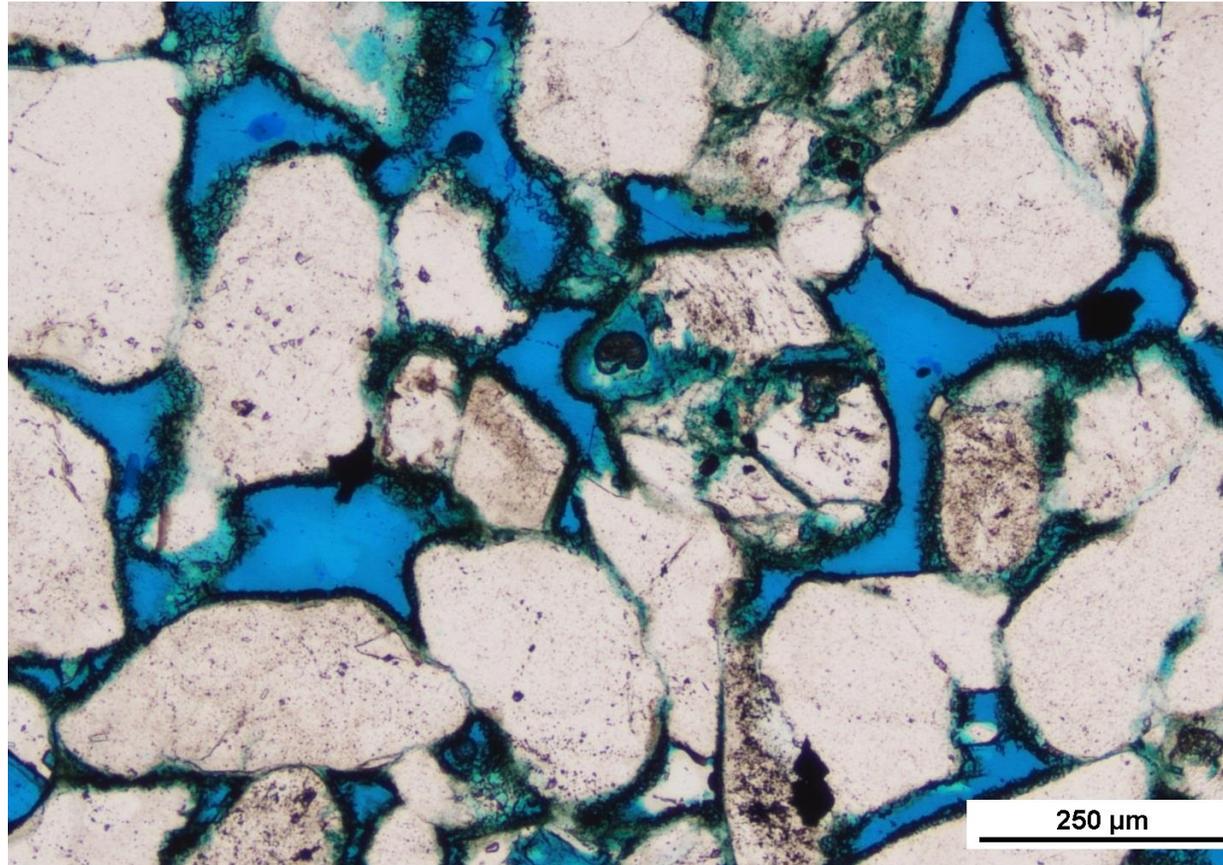


Tilje Fm, 4341 m burial depth, 173°C,
porosity 23.6 %, permeability 1165.0 md.

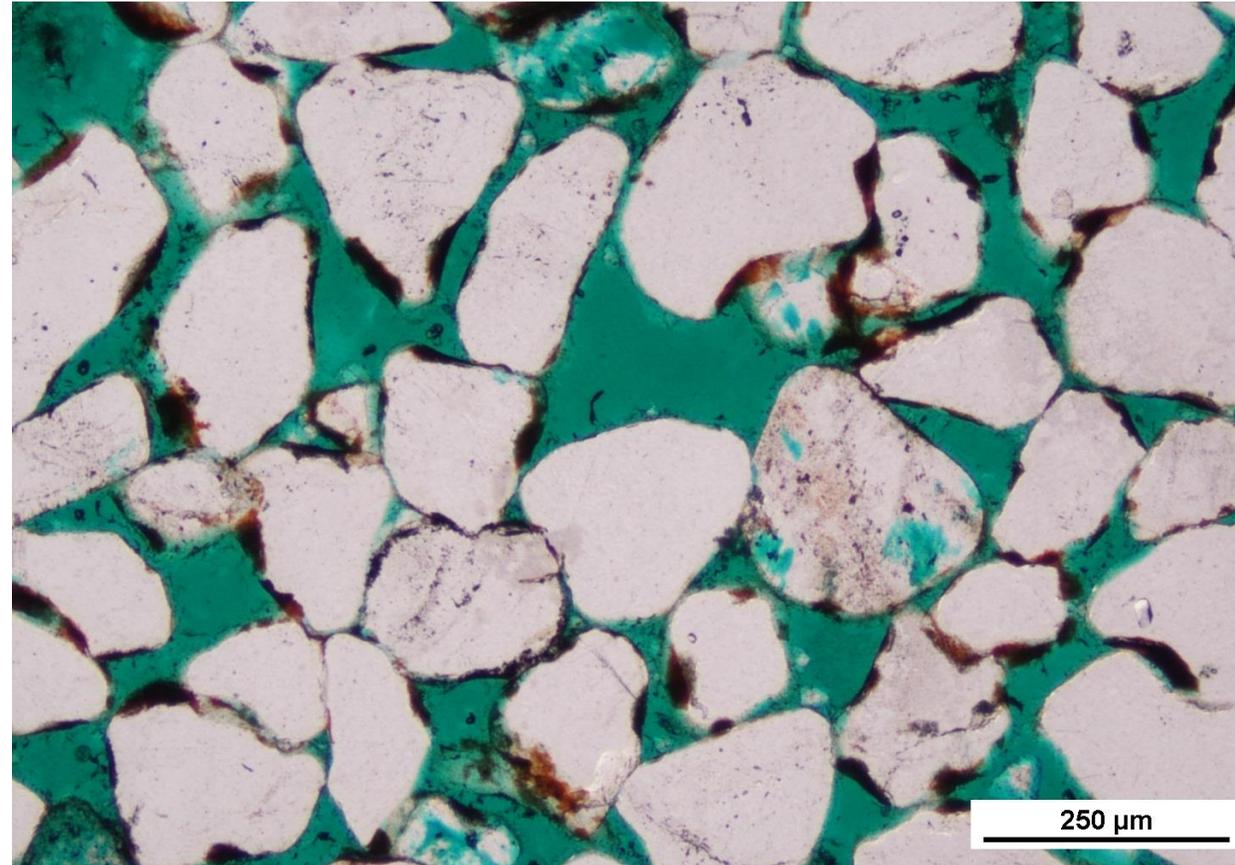


Heather Fm, 1788 m burial depth, 88°C,
porosity 28.0 %, permeability 0.2 md.

Illite grain coats are quite common in eolian sandstones and can also occur in other facies, but illite fibres may extend outward from the coats and reduce permeability.

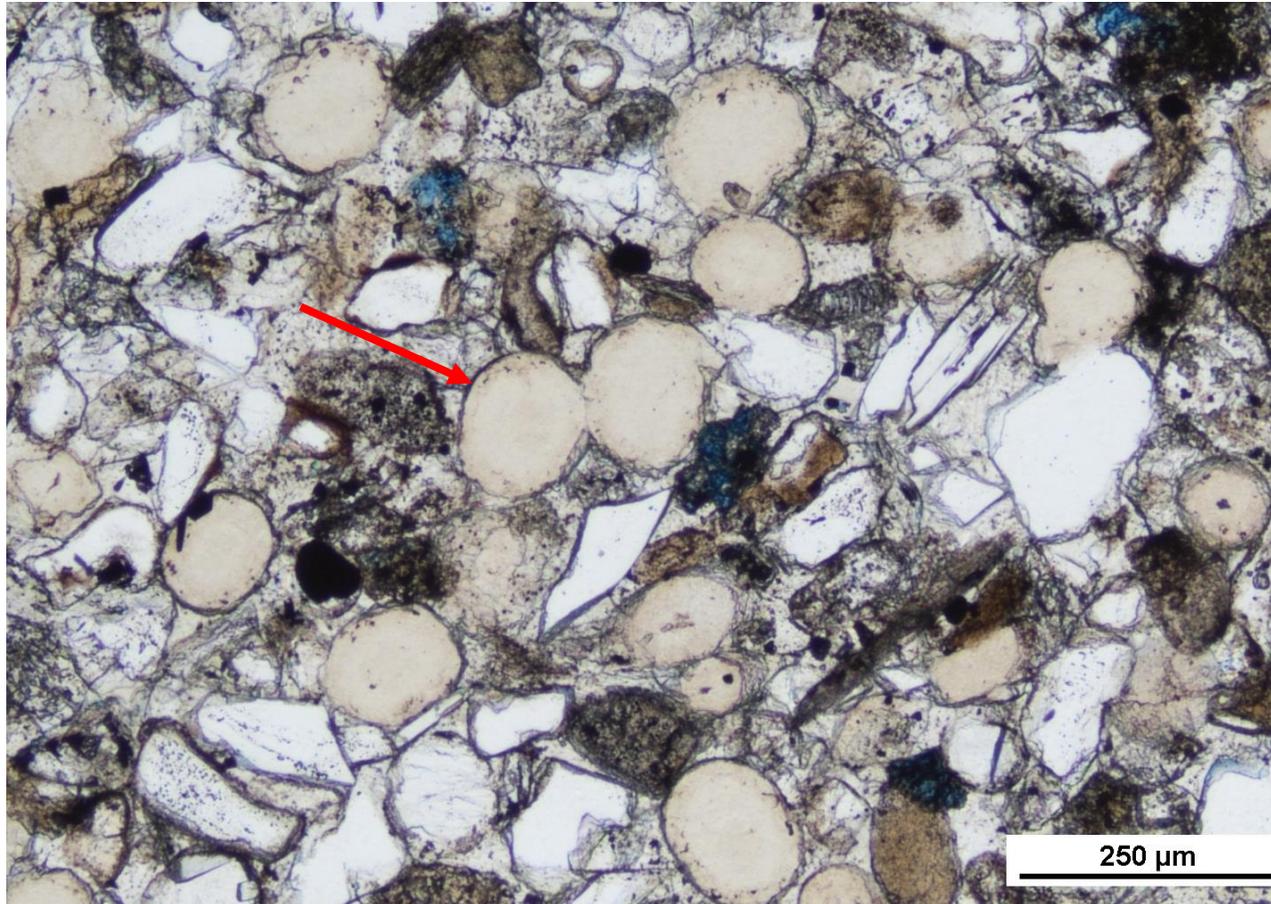


Lomvi Fm, 3596 m burial depth, 146°C, the coats may originally have consisted of smectite.
Porosity 14.4 %, permeability 25.0 md.



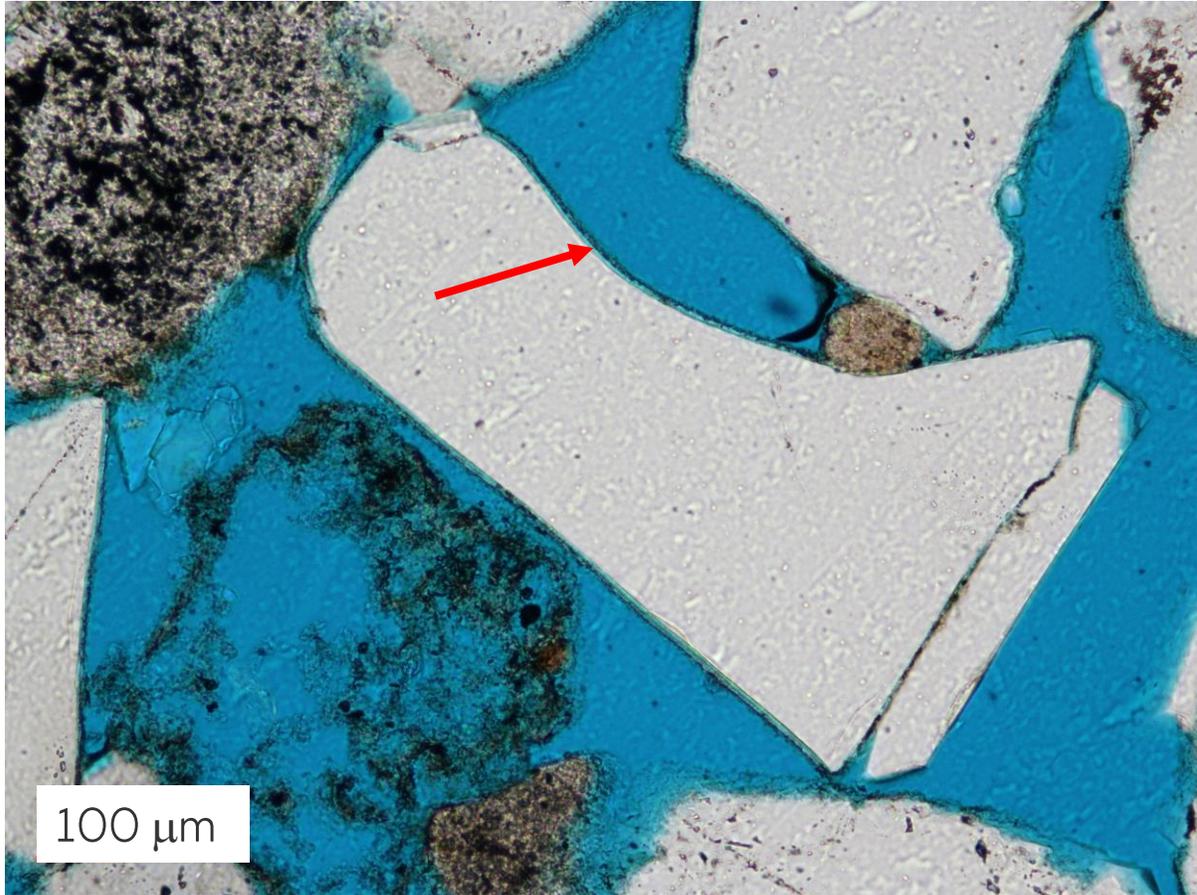
Rotliegend Gp, eolian sandstone, 4706 m burial depth, 171°C, illitic coats, reddish colour due to hematite staining.
Porosity 23.8 %, permeability 10.5 md.

Sponge spicules (red arrow) are the dominant source of microquartz grain coats in Upper Jurassic sandstones in the North Sea. Spicules are normally not preserved, but if they are encased in early calcite cement they may avoid dissolution.

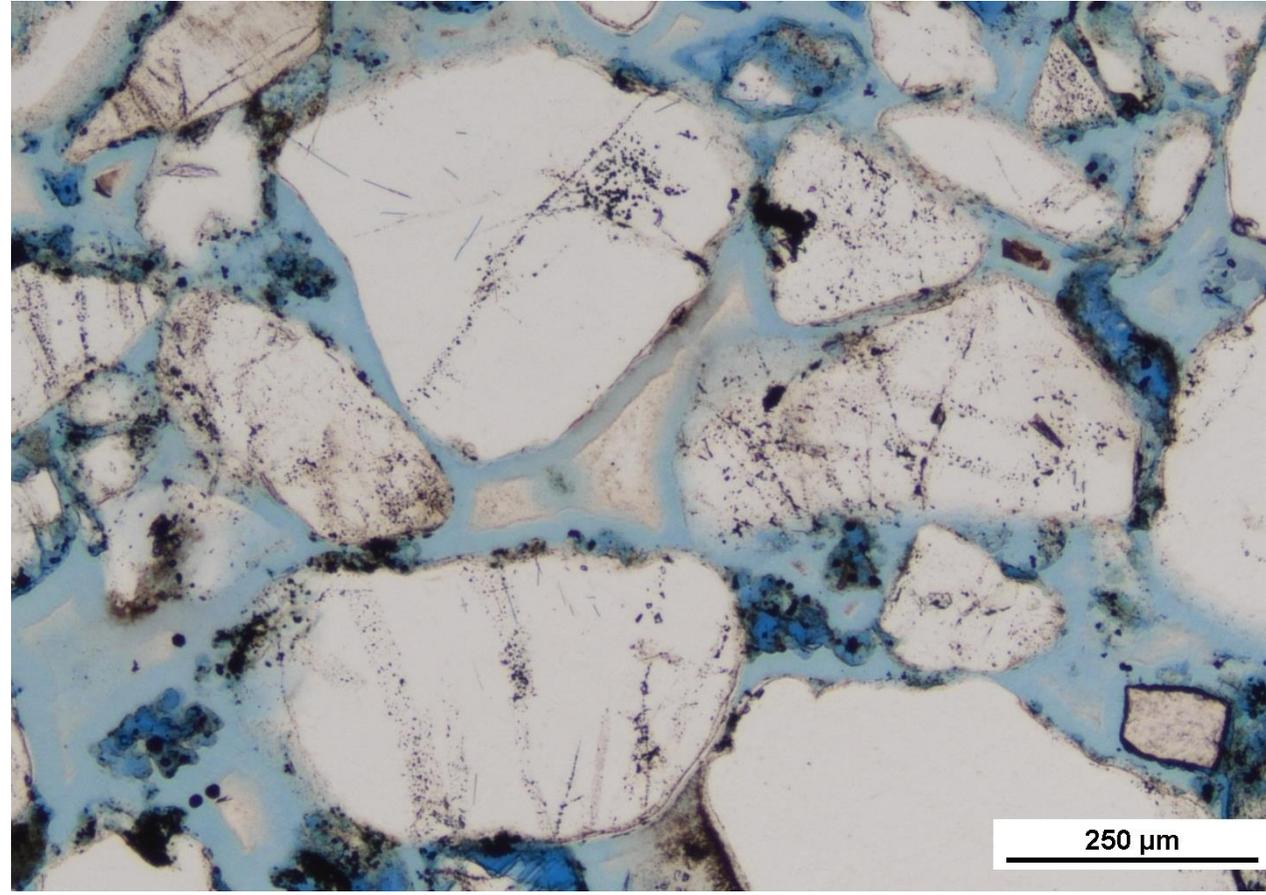


Draupne Fm, 4028 m burial, 133°C, pervasively calcite-cemented.

Grain coats of tiny quartz cement crystals (microquartz) prevent quartz overgrowths forming (not time to explain the mechanism here).



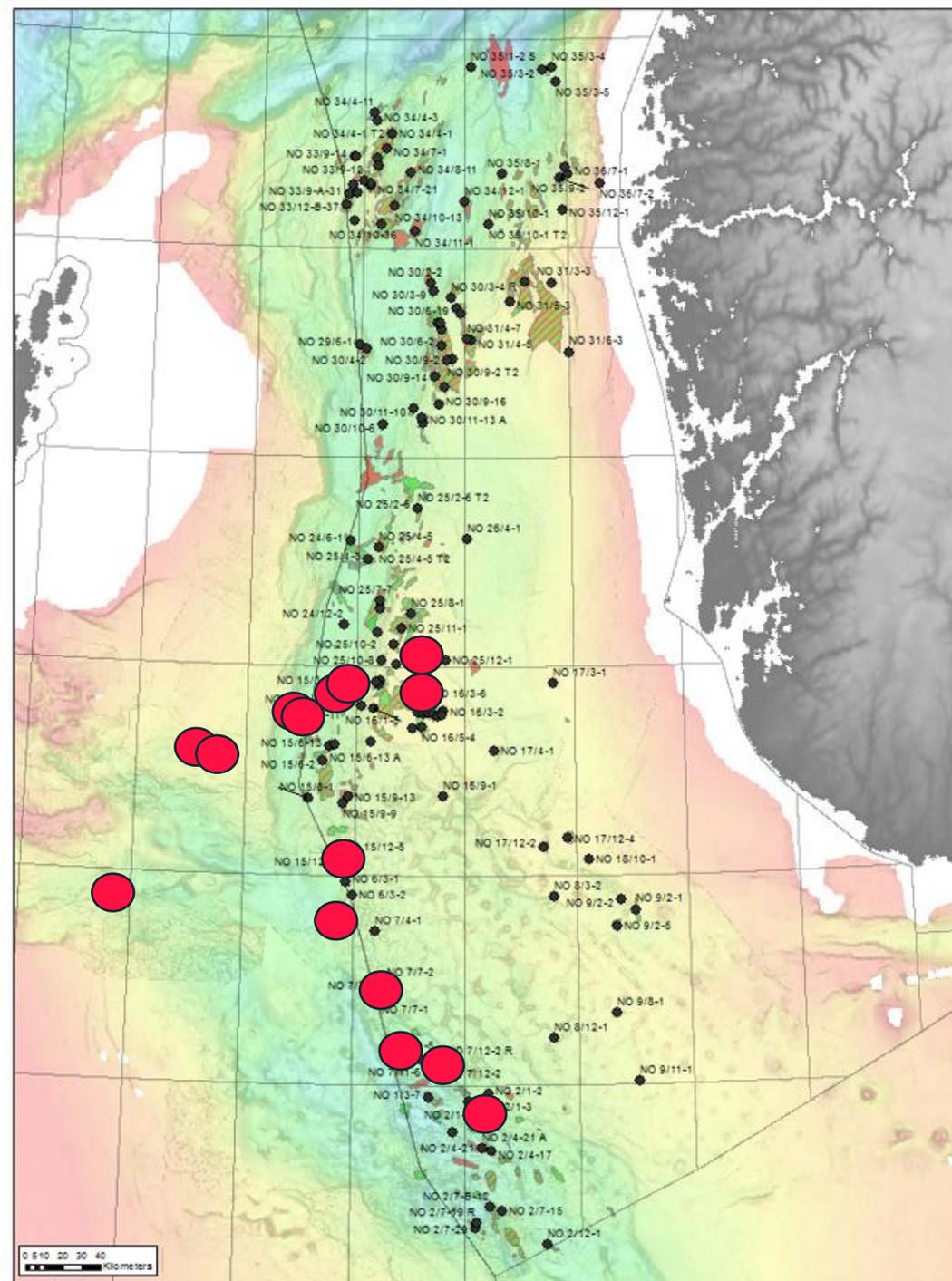
Draupne Fm, 4006 m burial depth, 132°C. Coats of microquartz (red arrow) prevent quartz cementation. Porosity 27.3 %, permeability 1104.0 md.



Draupne? Fm, 1902 m burial depth, 71°C. Too much early quartz cement from sponge spicules. Porosity 17.2 %, permeability 11.1 md.

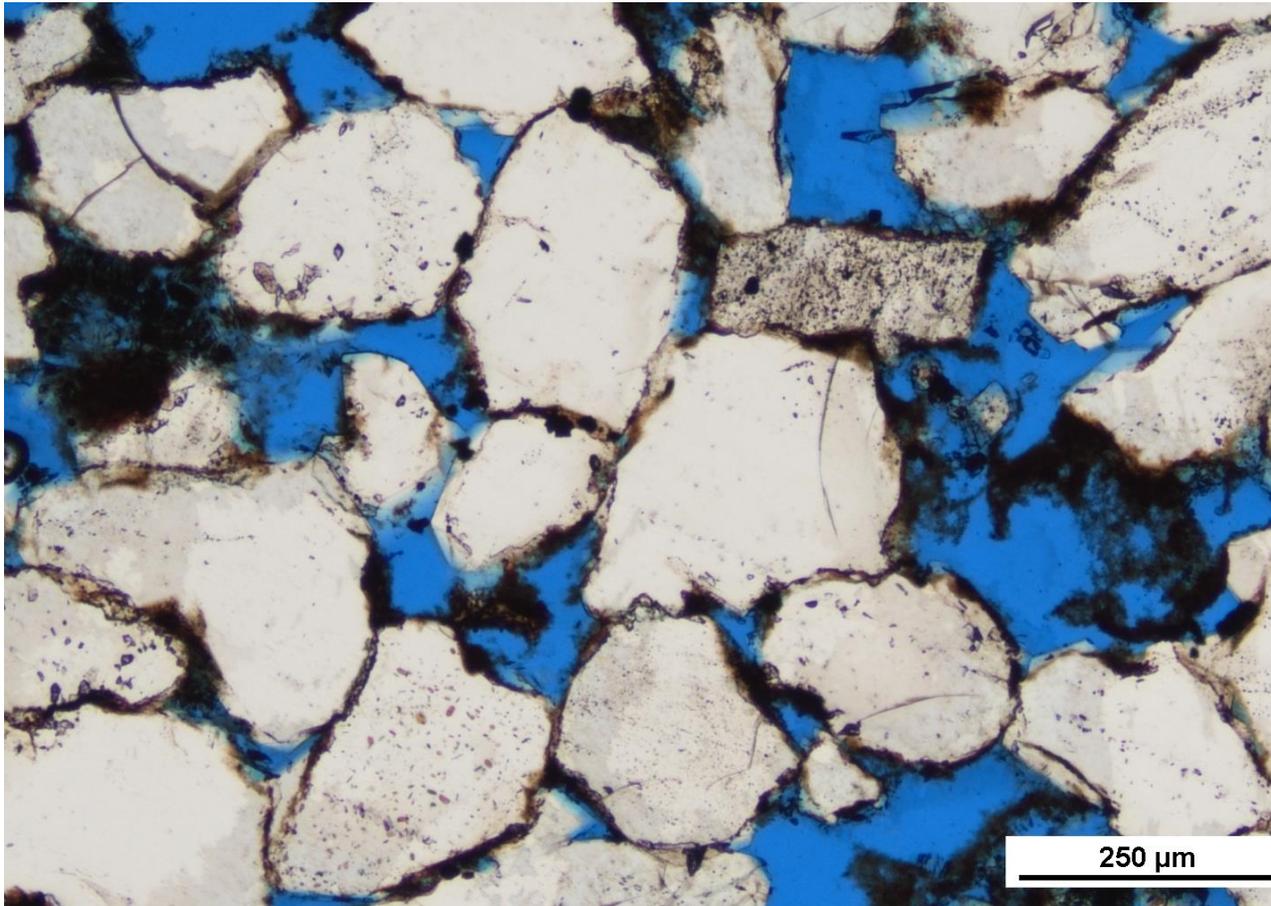
Red dots: wells with microquartz grain coats present in Upper Jurassic sandstones.

The source of the microquartz coats is dominantly sponge spicules. The coats are therefore found in marine sandstones from certain time periods.



Examples of zones where microquartz coats have reduced quartz cementation occur in the Gudrun Field, in the Ula Field, and in the Miller Field in the UK sector.

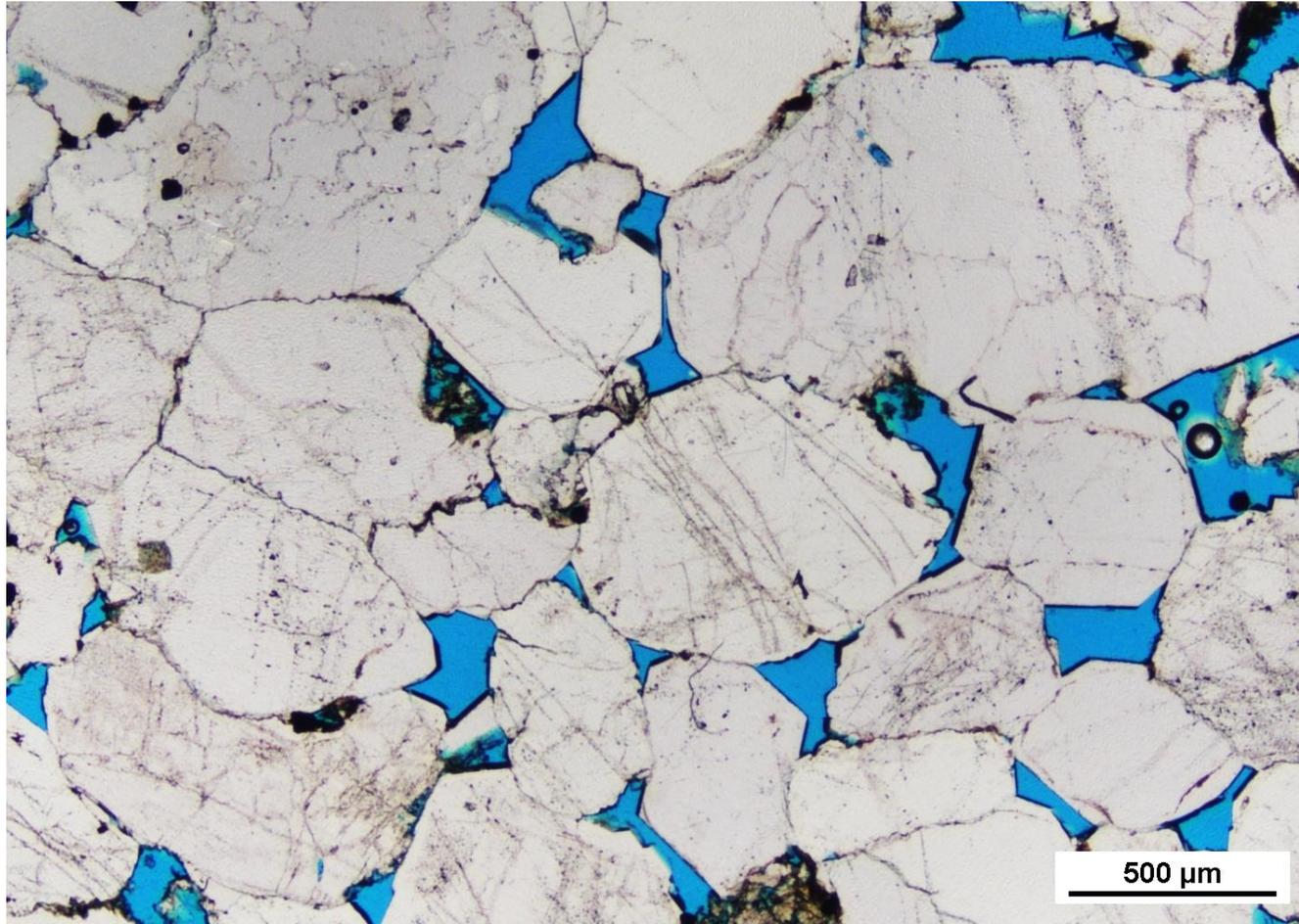
Grain coats of detrital clay are probably more common than coats of chlorite and microquartz, but detrital clay coats receive less attention (less photogenic...).



This type of coat probably often forms in weathering zones in the source area. Erosion of the weathering zones leads to deposition of grains with coats. The coats originally consist of a mix of clays, dominated by illite at depth.

Ness Fm, ca. 3750 m burial depth, 140°C, Kvitebjørn Field.
Porosity 24.5 %, permeability 438.0 md.

Coarse grains and lack of clay result in higher permeability for a given porosity, also less quartz cement due to reduced quartz surface area.



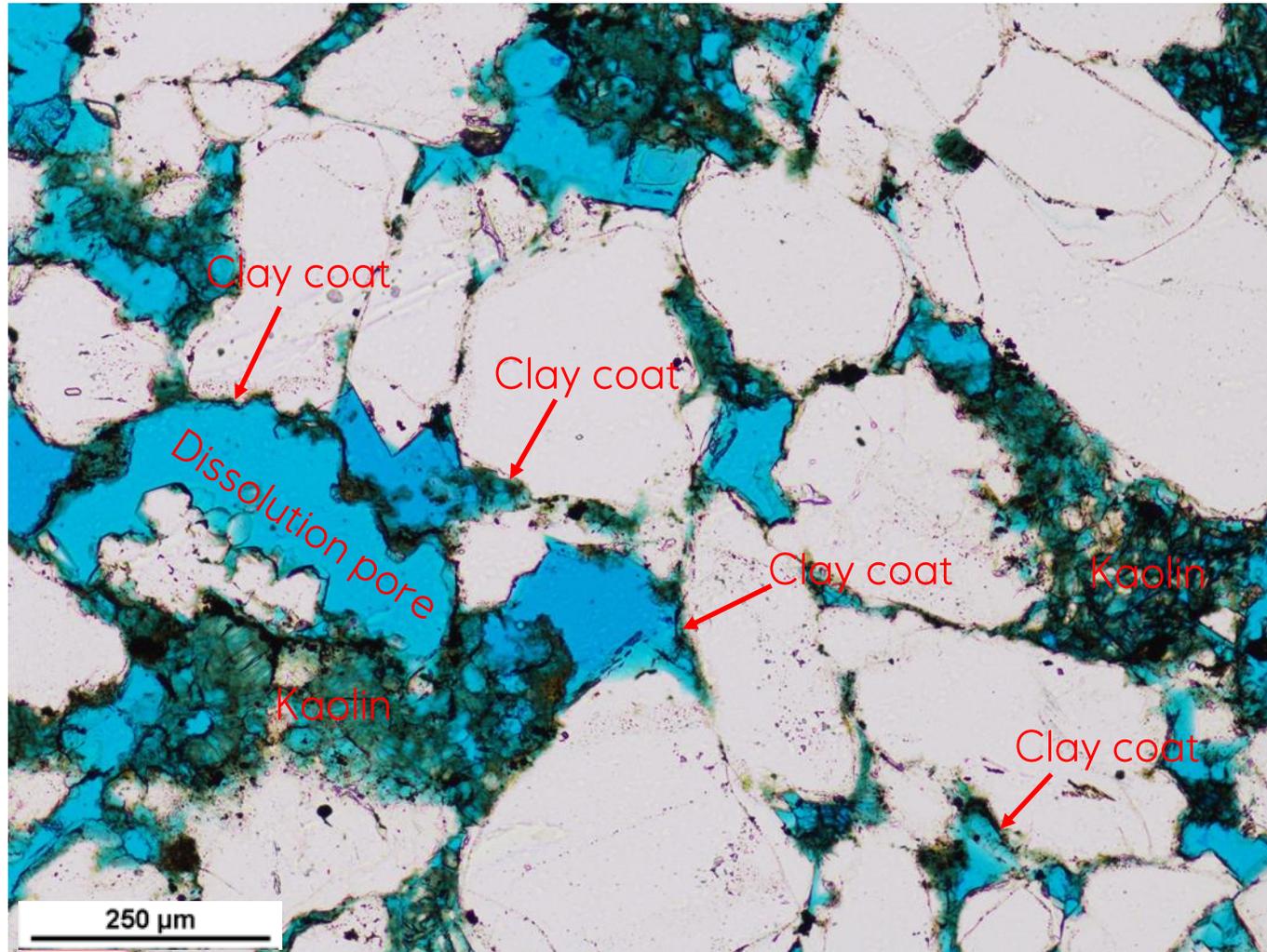
Kozeny equation (1927):

$$k = \frac{C P^3 D^2}{(100 - P)^2}$$

k is permeability (md)
P is porosity (%)
D is grain size (mm)
C is a constant for each type of sandstone

Heather Fm, 4044 m burial depth, 134°C, porosity 10.9 %, permeability 282.0 md, grain size 0.75 mm.

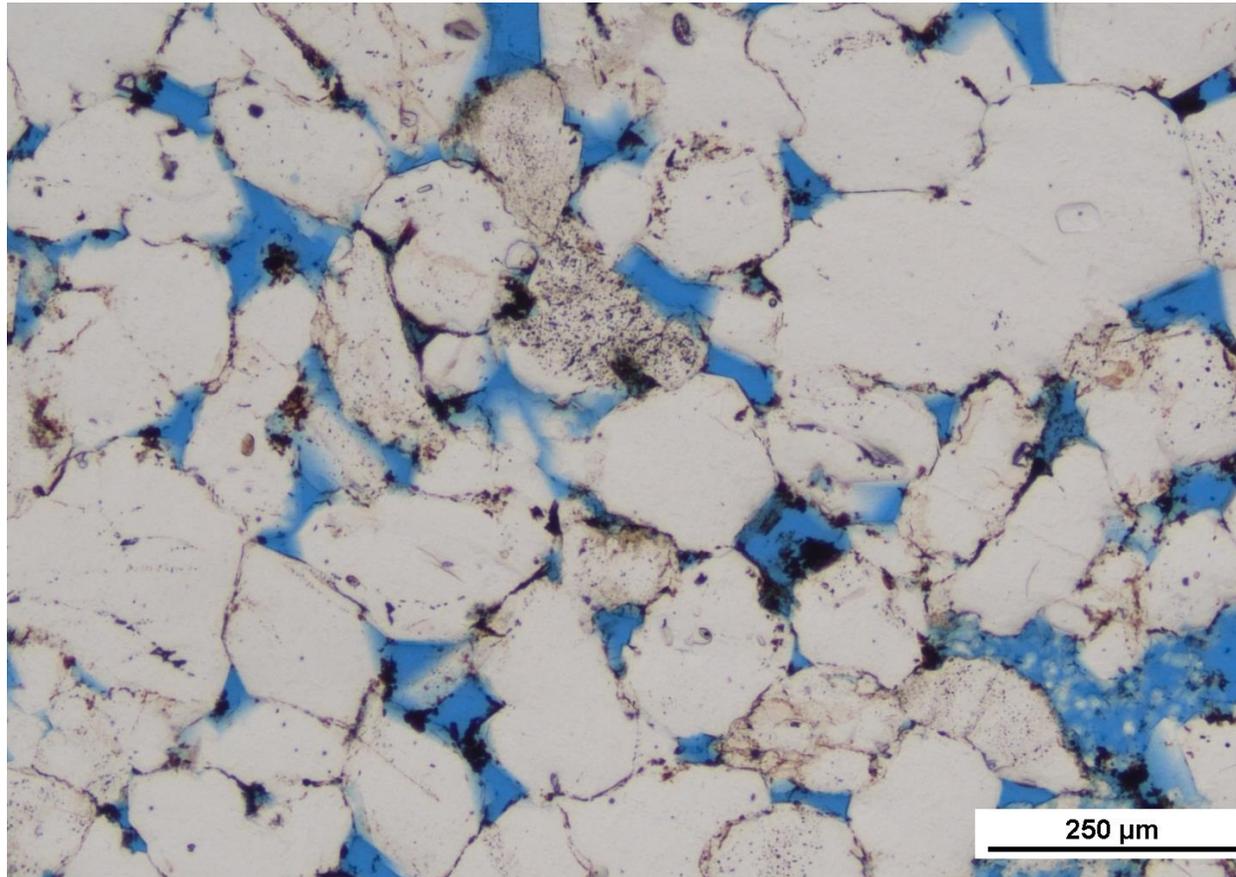
Some deeply buried Draupne Fm sandstones contain coats of detrital clay on some of the quartz grains.



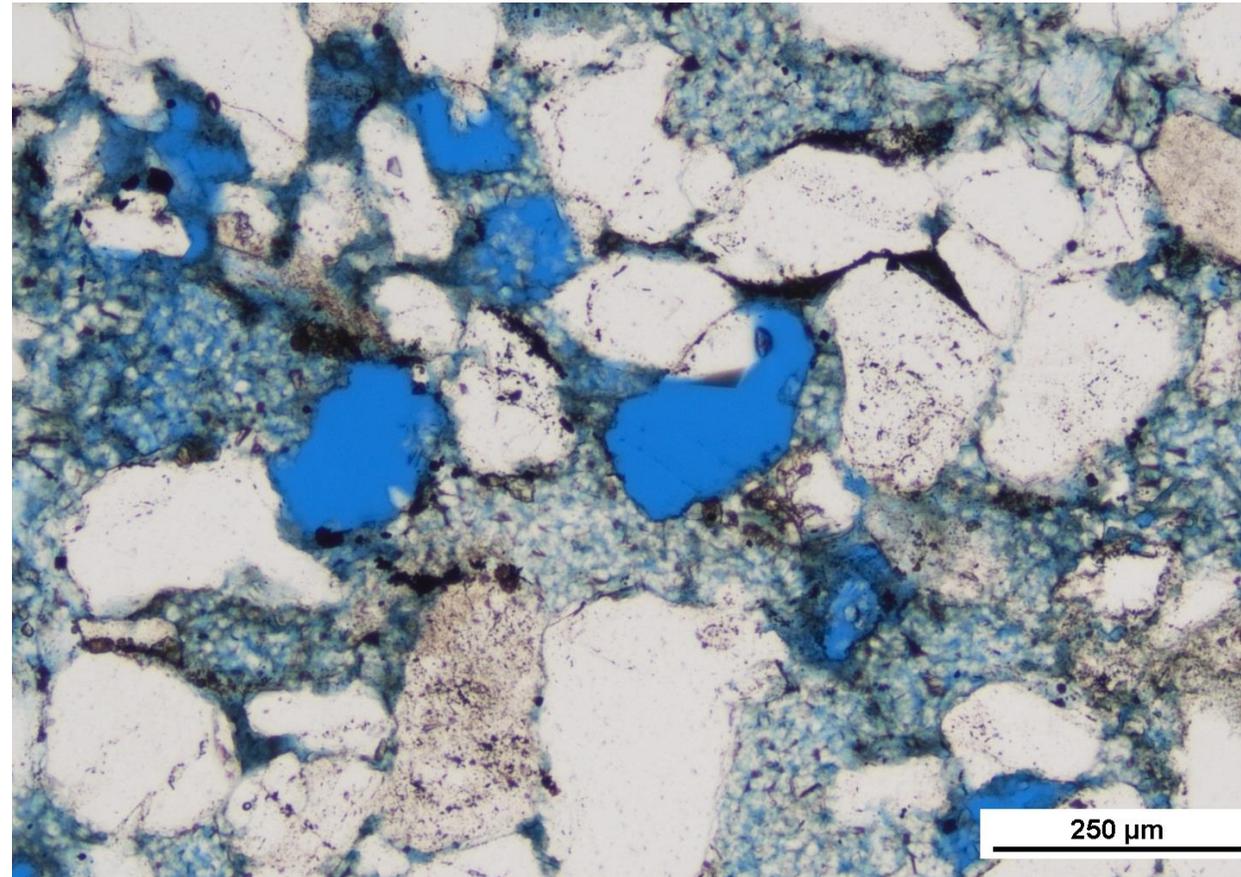
No illitization of kaolin here due to absence of K-feldspar.

Draupne Fm, 4348 m burial depth, 135°C.
Porosity 18.7 %, permeability 10.2 md.

The type of porosity, not just volume of porosity, is very important for permeability (macro/micropores, well-connected or isolated pores).

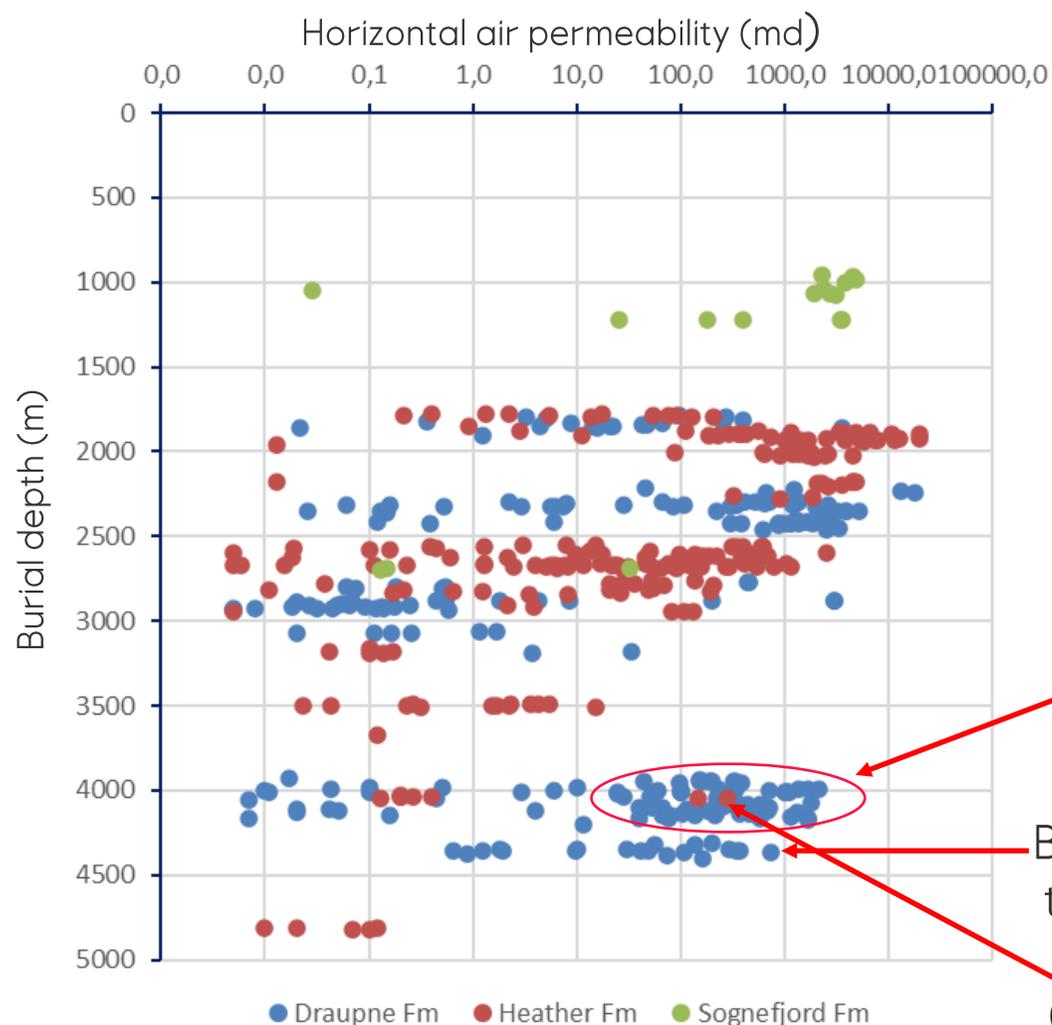


Tubåen Fm, grain size 0.22 mm.
Porosity 15.4 % , permeability 225.0 md.



Tarbert Fm, grain size 0.23 mm.
Porosity 18.4 % , permeability 1.2 md.

Horizontal air permeability versus burial depth, Upper Jurassic marine sandstones.



Study from 2021, North Sea from Gudrun (15/3) and northward. Plug measurements, thin-sections made from all plugs.

Gudrun area, block 15/3. Microquartz grain coats and coarse sand sweet spot.

Block 25/7, detrital clay coats and medium to coarse grain size sweet spot.

0.5 m of Heather Fm sandstone in Block 24/12, clay-free and coarse-grained (0.75 mm), porosity 11 %.

Distribution of factors preserving reservoir quality in an area west of the Utsira High:

Formation	Chlorite coats	Microquartz coats	Detrital clay coats	Coarse and low matrix
Draupne	-	X	x	x
Heather	-	-	-	x
Hugin	-	-	x	X
Skagerrak	x	-	?	-

Dark green: proven and important

Light green: proven, uncertain importance

?: possibly present

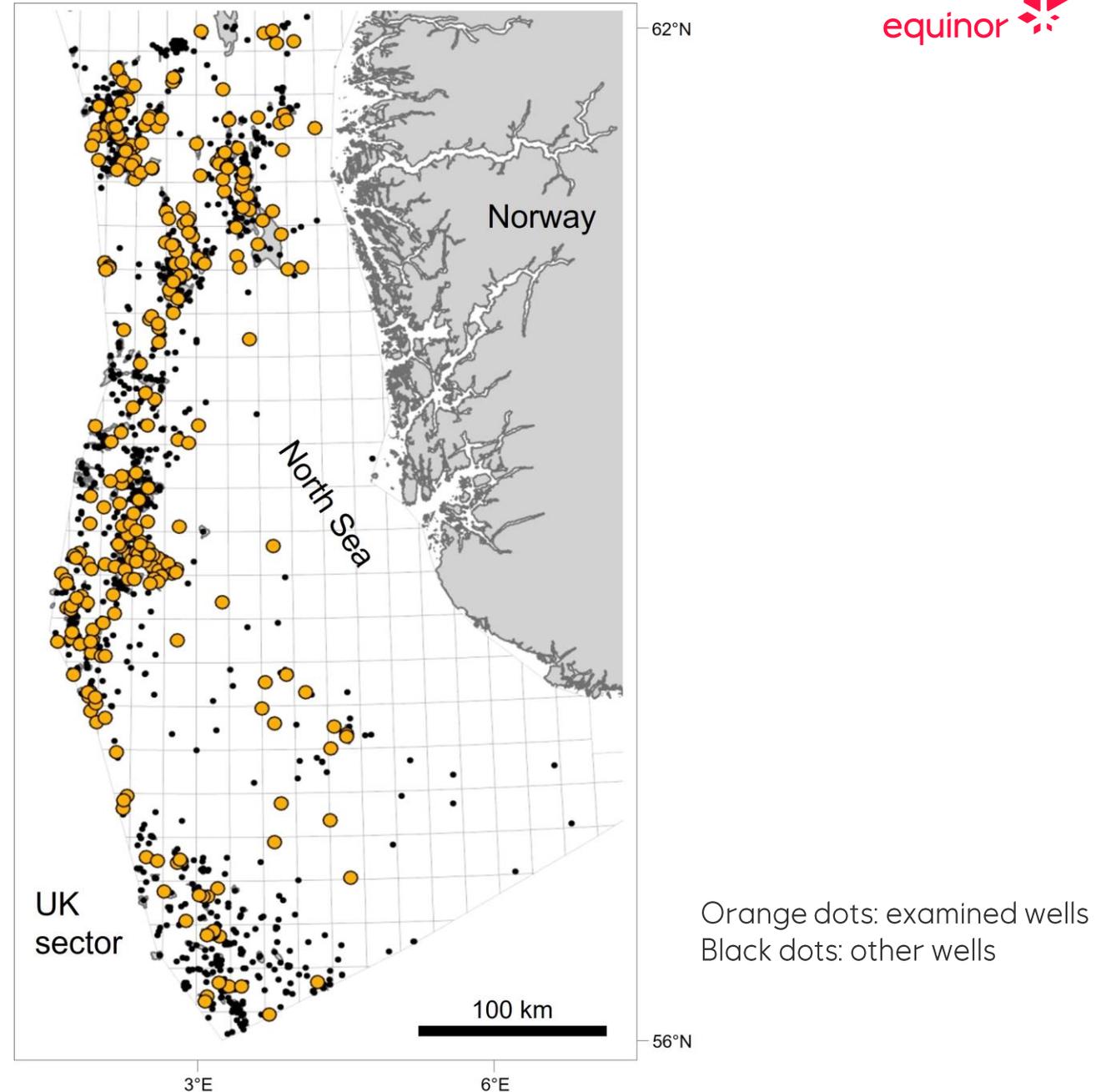
Red: not proven

Oil and gas do not stop nor significantly slow down quartz cementation.

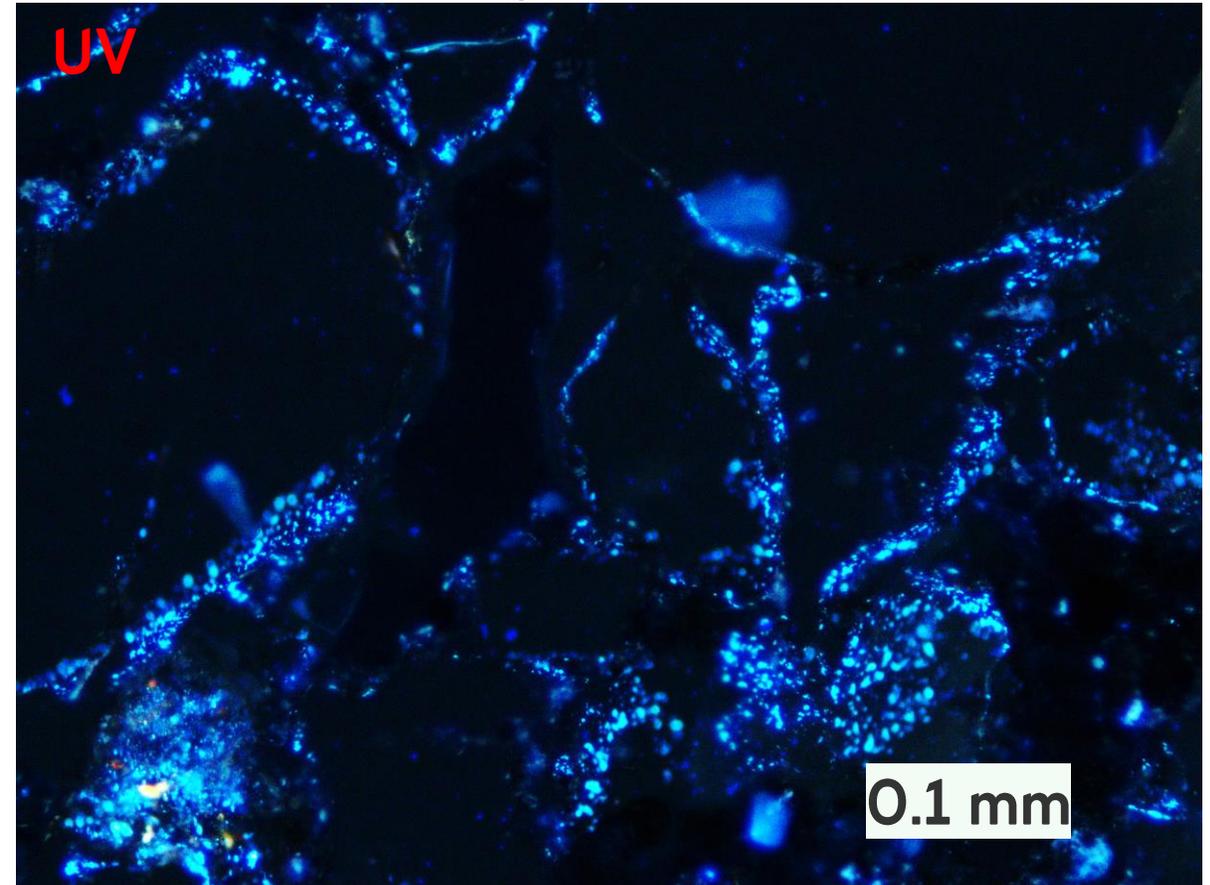
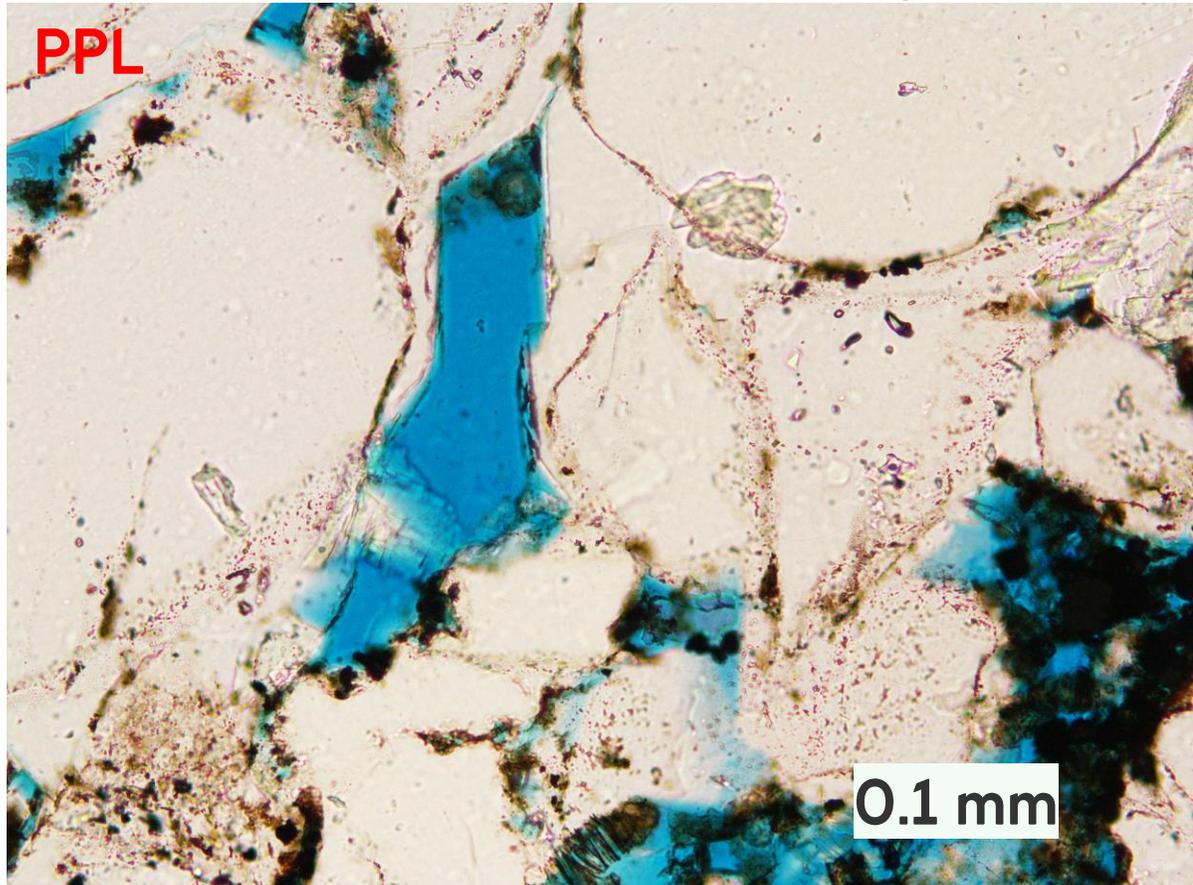
- Oil and gas-filled sandstones are not systematically less quartz-cemented than the same type of water-filled sandstones with the same temperature history.
- Oil and gas-filled sandstones remain water-wet.
- The rate of quartz cementation is controlled by quartz precipitation, not by diffusion of silica through the pore water.
- Oil typically enters reservoirs at temperatures less than 80 - 100°C, so if oil had stopped cementation reservoir quality in deeply buried sandstones wouldn't be a problem, and I wouldn't be giving this talk.

The content of oil inclusions in diagenetic cements has been mapped in 4023 thin-sections from 291 wells in the Norwegian sector of the North Sea using a fluorescence microscope.

Because the temperature of formation for several of the diagenetic cements containing oil inclusions is known, the temperatures of oil emplacement in the examined reservoirs can be constrained.

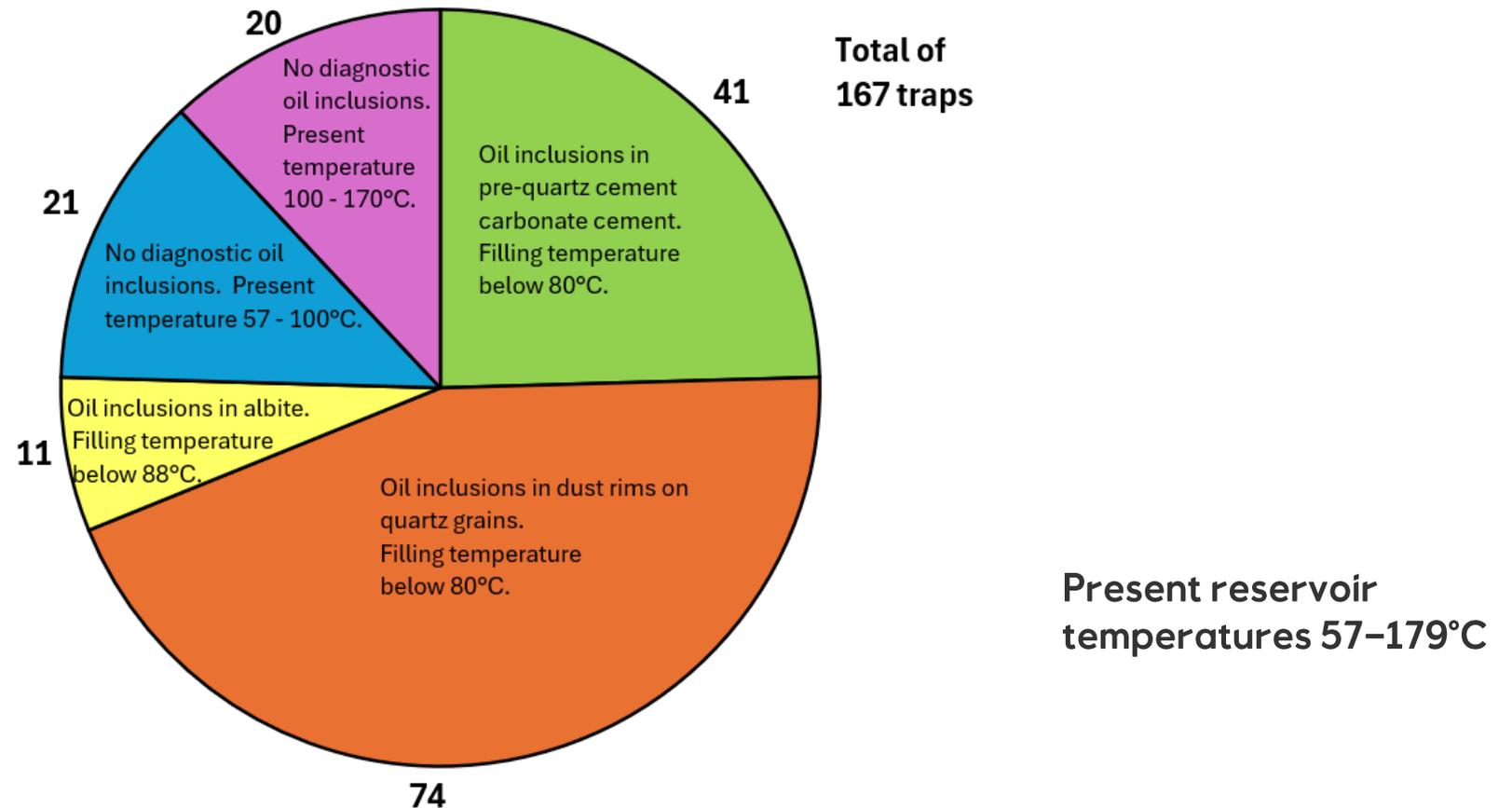


Oil inclusions in dust rims on quartz grains show that an oil column was present at $<80^{\circ}\text{C}$ before the quartz overgrowths covered the detrital grains.



Draupne Fm, 4316 m burial depth. The very high abundance of oil inclusions (blue) points to the presence of a very large oil column when the oil drops attached to the grain surfaces.

Oil-filling of Norwegian North Sea fields dominantly took place at 60–100°C or less. If oil stopped quartz cementation, there should not be much quartz cement in deep North Sea sandstones, but there is. Case closed, oil does not stop cementation.



Conclusions:

Preservation of acceptable reservoir quality in deeply buried sandstones is favoured by:

- coarse grain size
- good sorting and loose packing
- low contents of clay matrix and soft clay clasts
- grain coats (detrital clay, chlorite, illite, microquartz...)
- short time at great depth and high temperatures

Some good zones exist deeper than 4 km burial, but not so easy to find, perhaps better to focus on shallower prospects.

Forget about hydrocarbons stopping cementation, it's just a myth.