2022 SPE EUROPE ENERGY GEOHACKATHON

#1. Introduction to geothermal reservoirs – why mineralogy matters (focus on sandstone reservoirs)

26 September 2022

#DatafyingEnergy

ENERGY GeO Hackathon
Society of Petroleum Engineers

SPE International — Italian Section
SPE International — London Section
SPE International — Netherlands Section
SPE International — Romanian Section
SPE International — Copenhagen Section
SPE International — Geothermal Technical Section

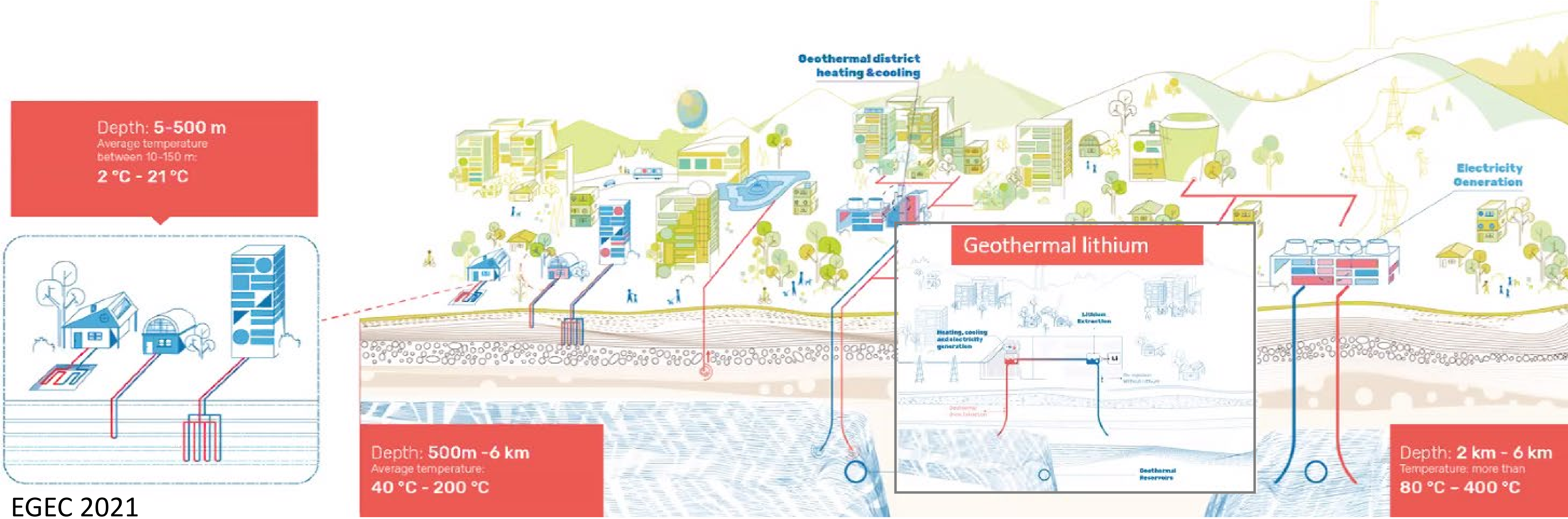
METTE OLIVARIUS

Senior Scientist, GEUS

Nynke Keulen
GEUS

Nikolai Andrianov
GEUS

Geothermal energy technologies



EGEC 2021

Geothermal energy used for district heating

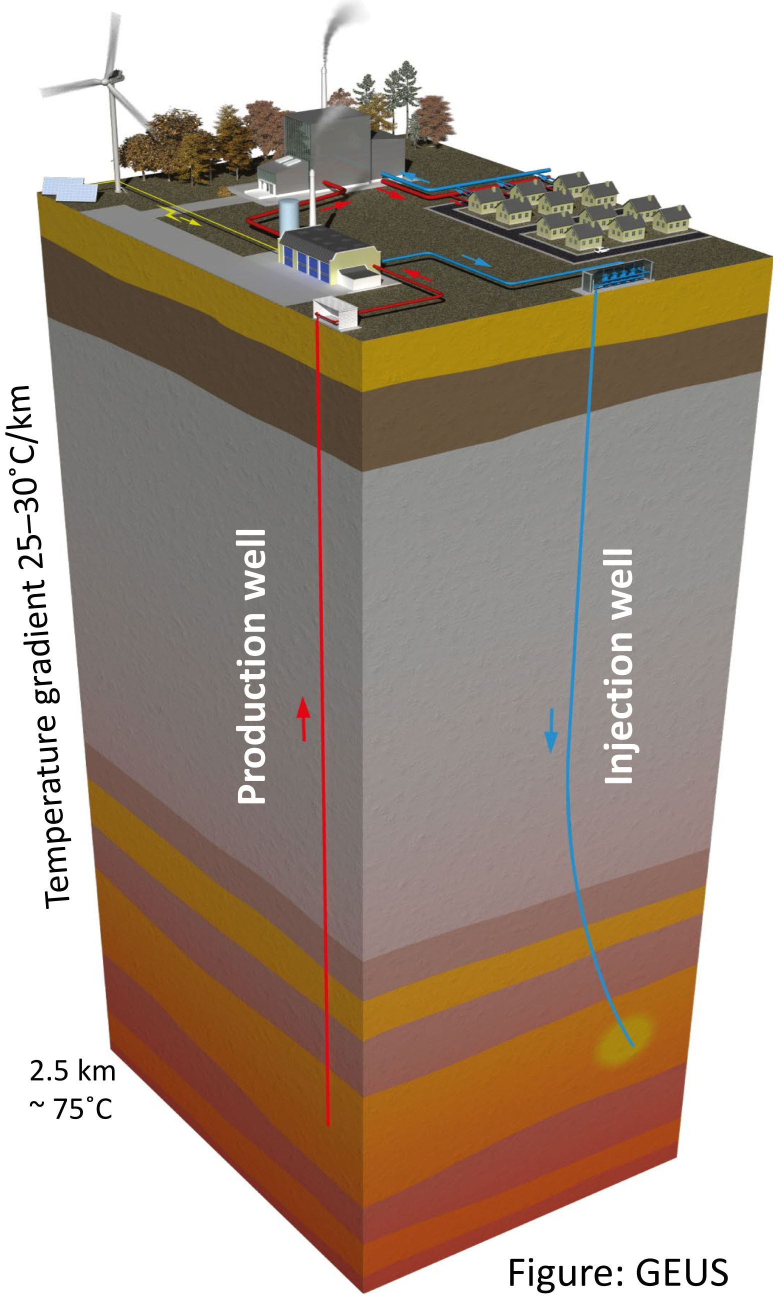


Figure: GEUS

- The formation water is pumped up in a production well
- The heat is transferred to the district heating network by heat exchangers
- The cooled formation water is returned to the reservoir in an injection well at a certain distance
- Extraction of geothermal energy during winter can be combined with heat storage in the summer so that surplus from sun and wind are not wasted

Geothermal heat pumps

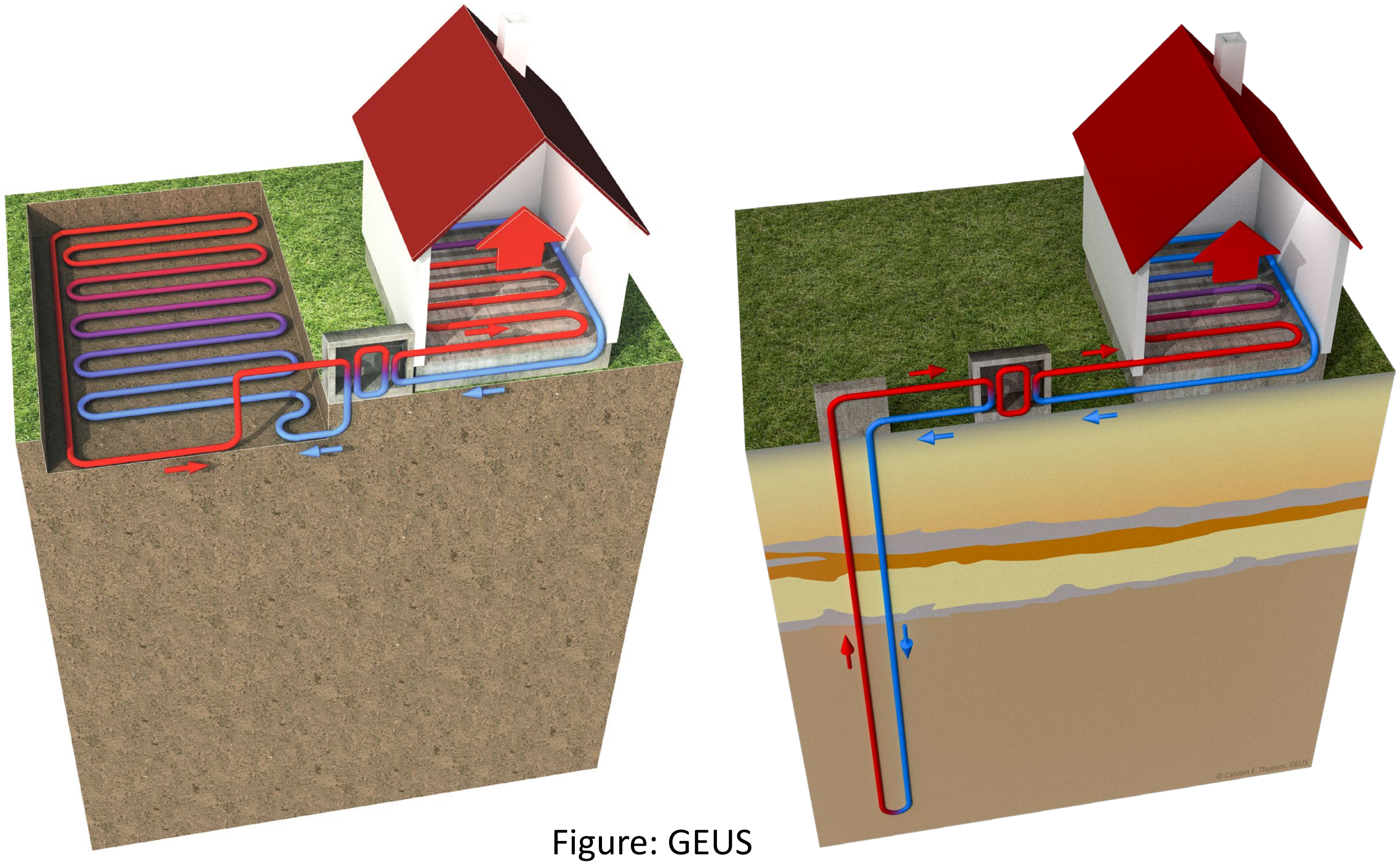
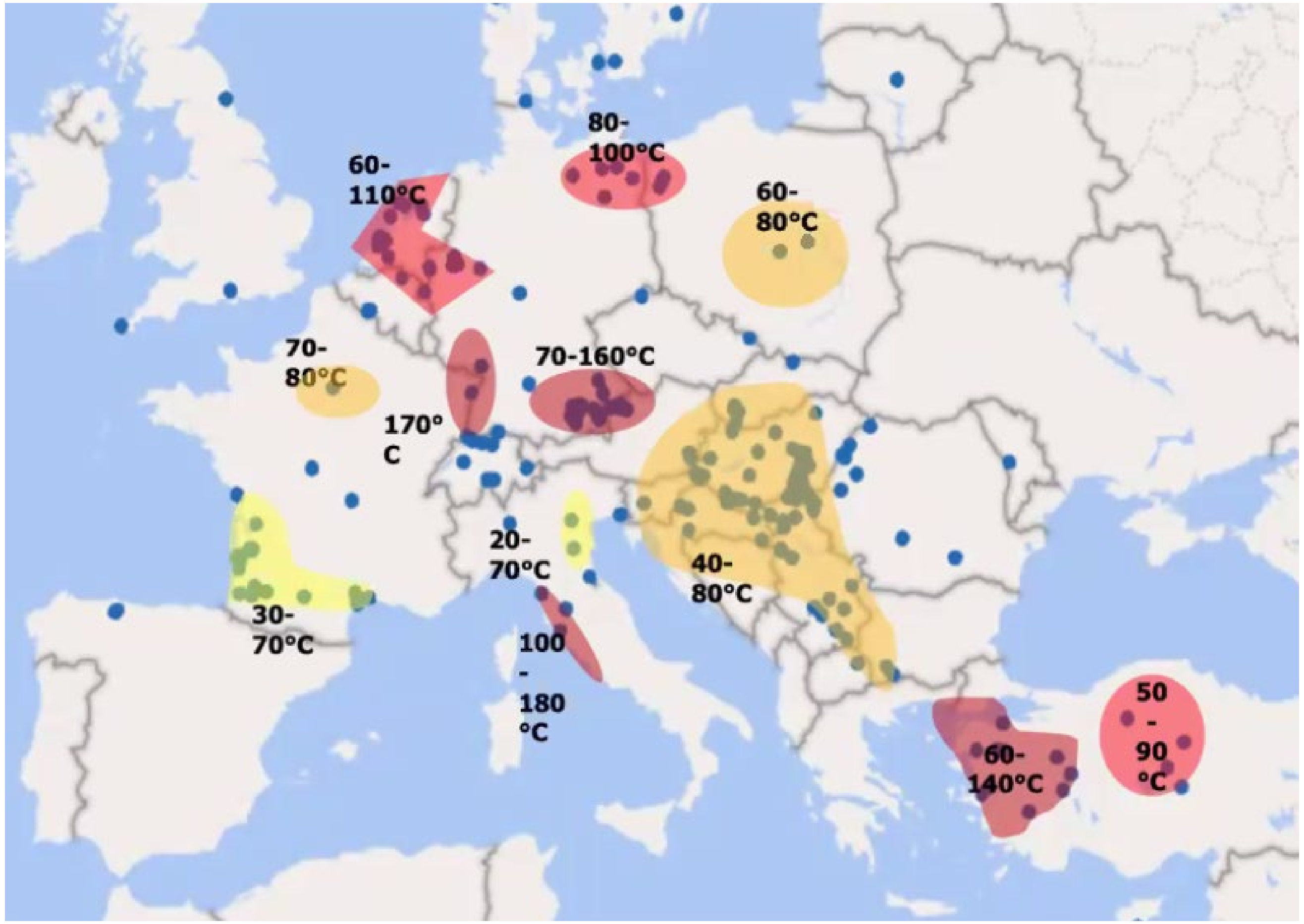


Figure: GEUS

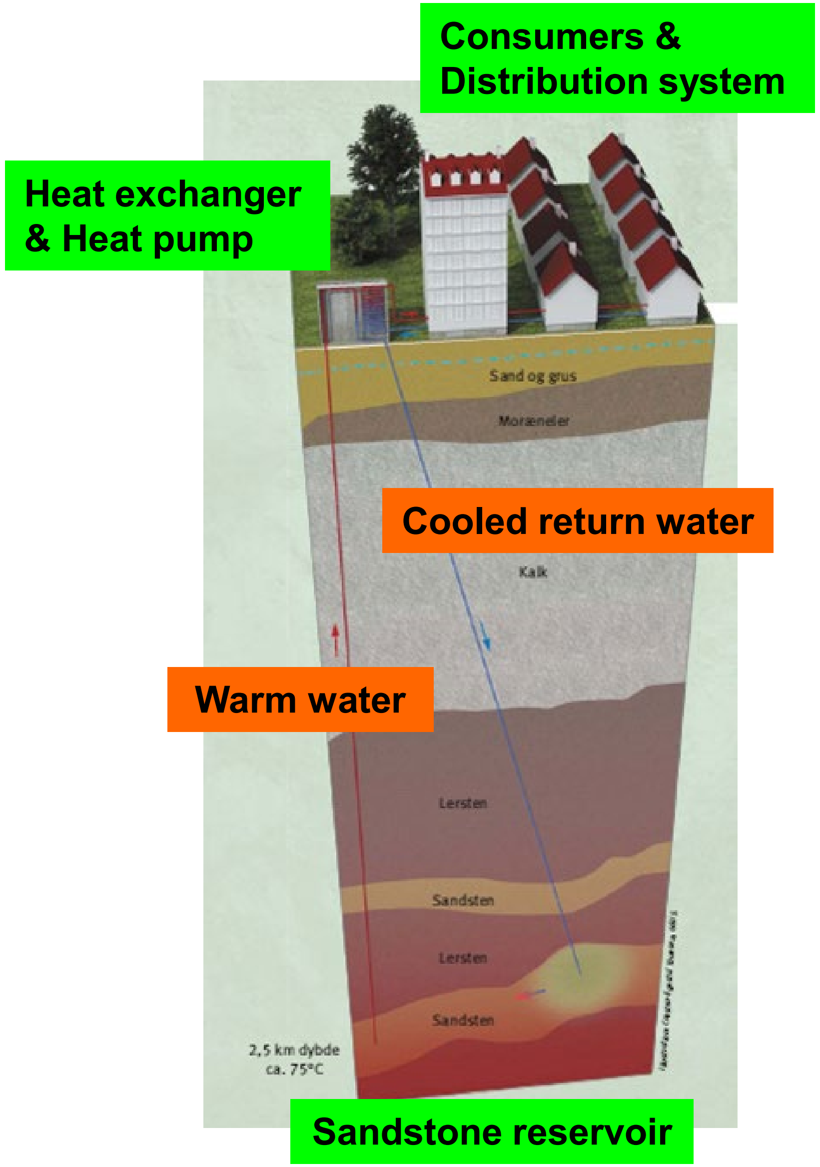
- Heating of individual buildings can be made by a geothermal heat pump that circulates a liquid in a closed circuit
- This can be either hoses placed 1 m below ground or closed wells of up to a few hundred meters depth
- The heat originates primarily from the solar radiation

Geothermal resources for heating

- Most projects use reservoirs with temperatures of 60-80°C
- Used primarily for residential and commercial buildings and for horticulture (greenhouses)
- New attention on applying it for process heating (food drying, beer production etc.)
- Many countries are working on legislative changes to better enable geothermal exploitation



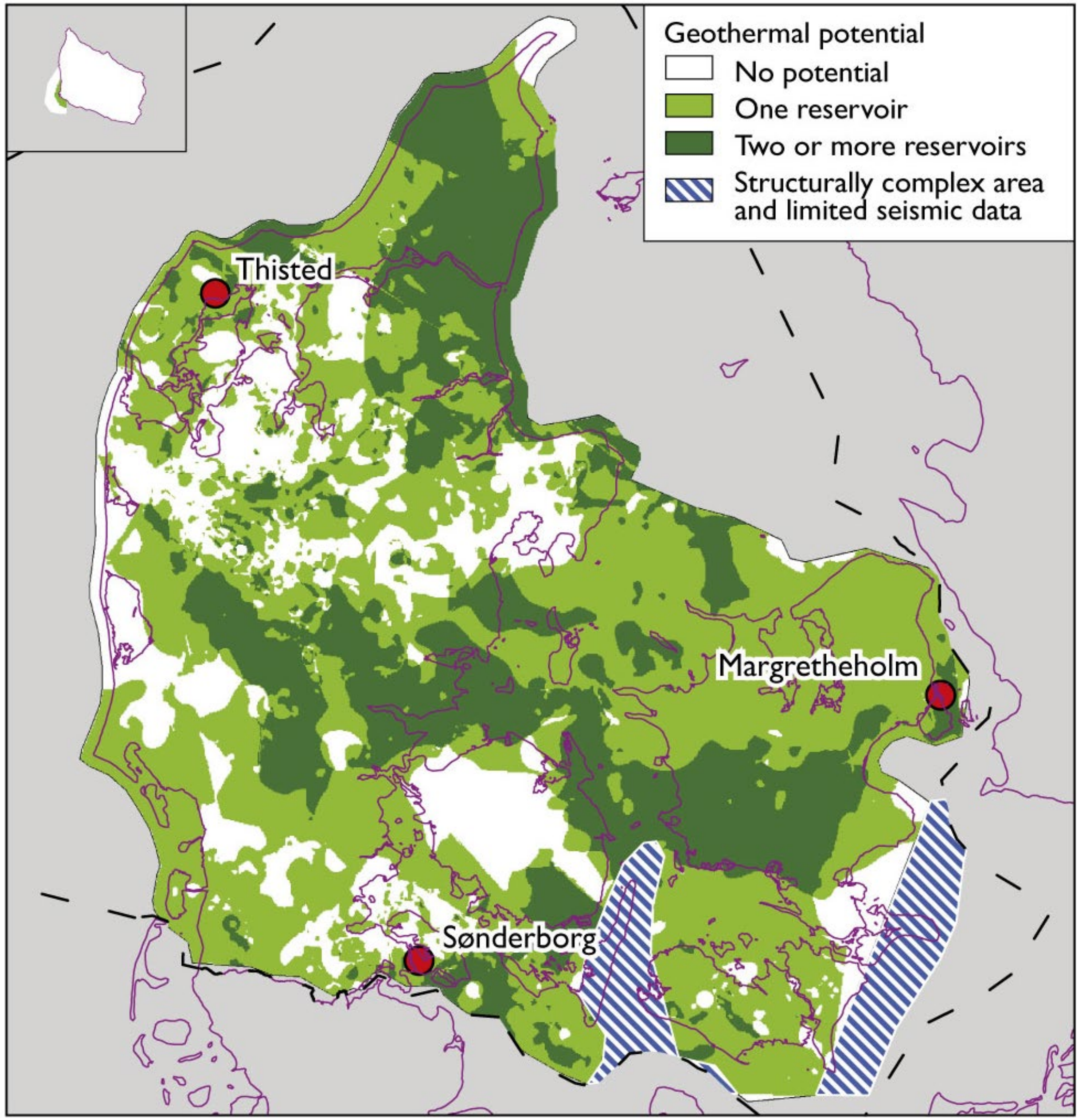
EGEC 2021



Geothermal energy potential in Denmark

- District heating networks exist in many cities and an alternative is needed to replace coal as heat source
- Geothermal energy can be exploited from sandstone reservoirs from c. 1–3 km depth and used for heating
- The temperature increased with 25-30^{o}C/km + 8^{o}C at the surface
- The ressource is huge and geothermal energy can potentially cover 20-50% of the Danish district heating in hundreds of years
- We know largely where the resource is present in the subsurface thanks to several publicly funded research projects

Geothermal reservoirs

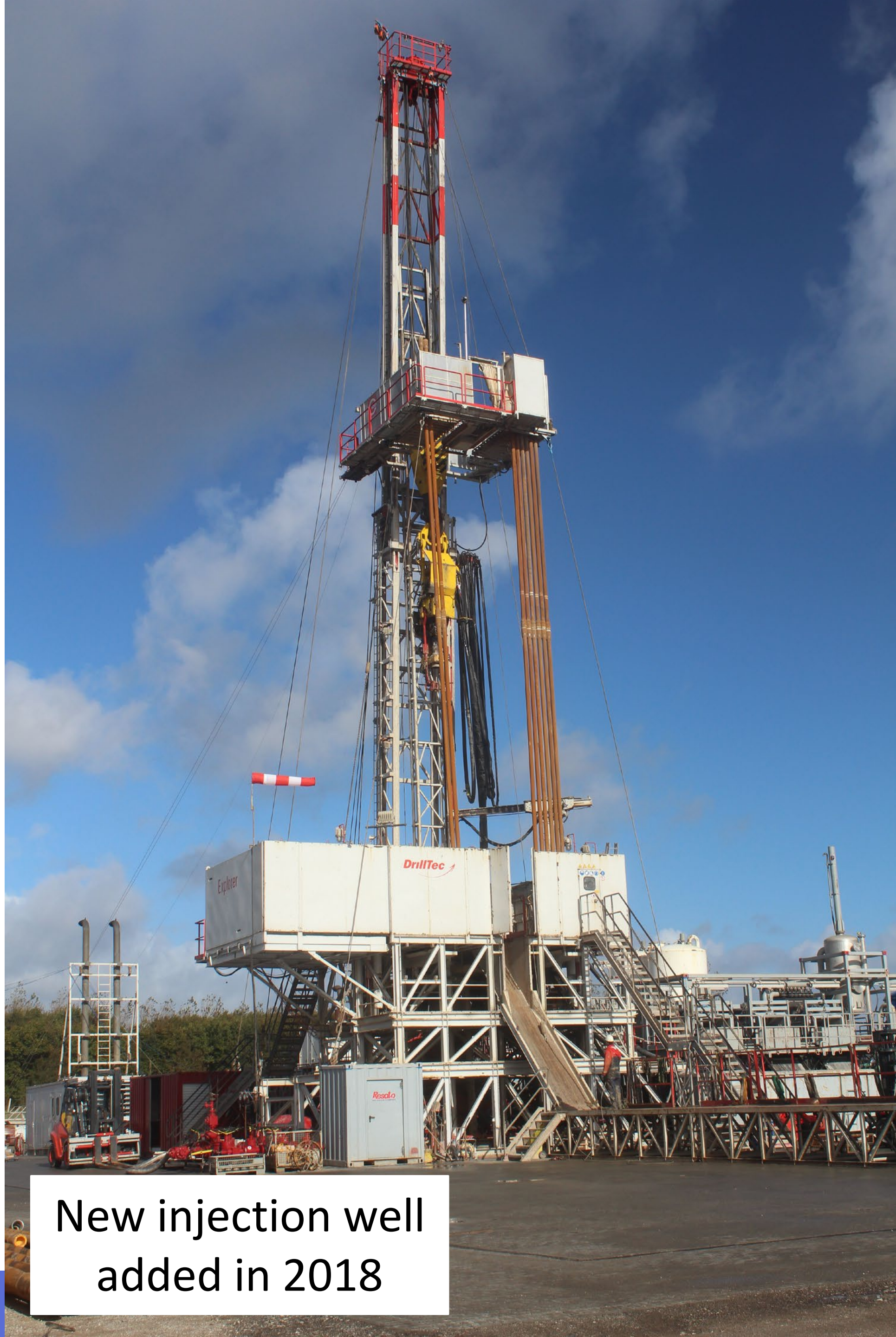


Geothermal plants in Denmark

- Suitable sandstone reservoirs are present across most of Denmark including several in some areas
- However, the porosity and permeability of the reservoirs vary much due to differential burial depths
- Many geological and geophysical disciplines and methods are combined to map the distribution and properties of the reservoirs
- These include e.g. seismics, wireline logs, sedimentology, sequence stratigraphy, biostratigraphy, burial history, core analysis, pore fluid composition, petrography, diagenesis and provenance

Thisted plant

Build in 1984 as the first in Denmark



New injection well added in 2018

Margretheholm plant

Geothermal district heating plants take up limited space

Heat exchangers and filters

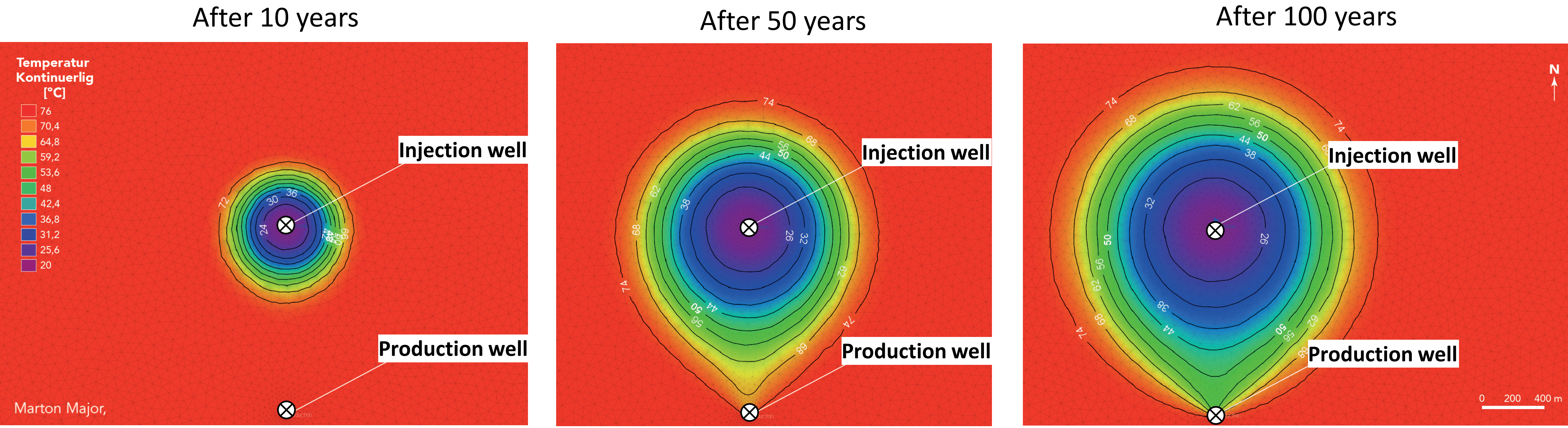
Injection well

Production well

The wells are deviated so there is >1 km between them in the reservoir

Injection in a reservoir

- Cooling of the reservoir by injection of the cooled water is very slow
- A distance of 1 km between the wells in the reservoir is in general sufficient
- The injection and production wells can be drilled deviated from the same place

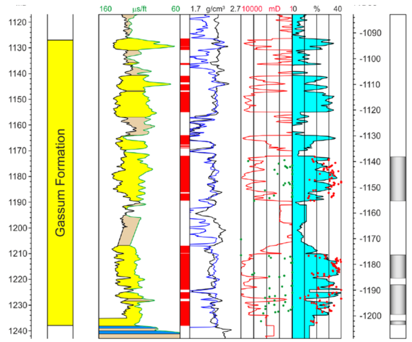


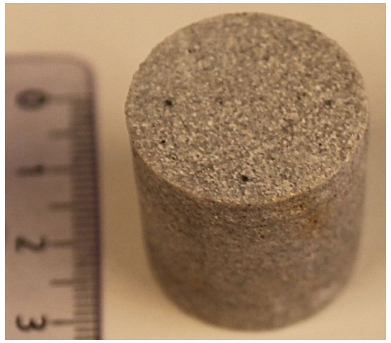
Database

Most wells were drilled for oil and gas exploration

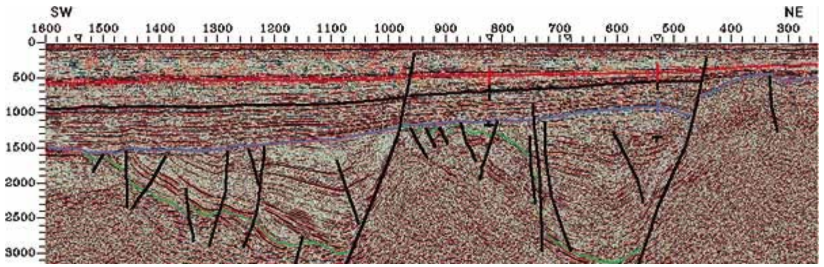
The seismic data are scattered in some areas

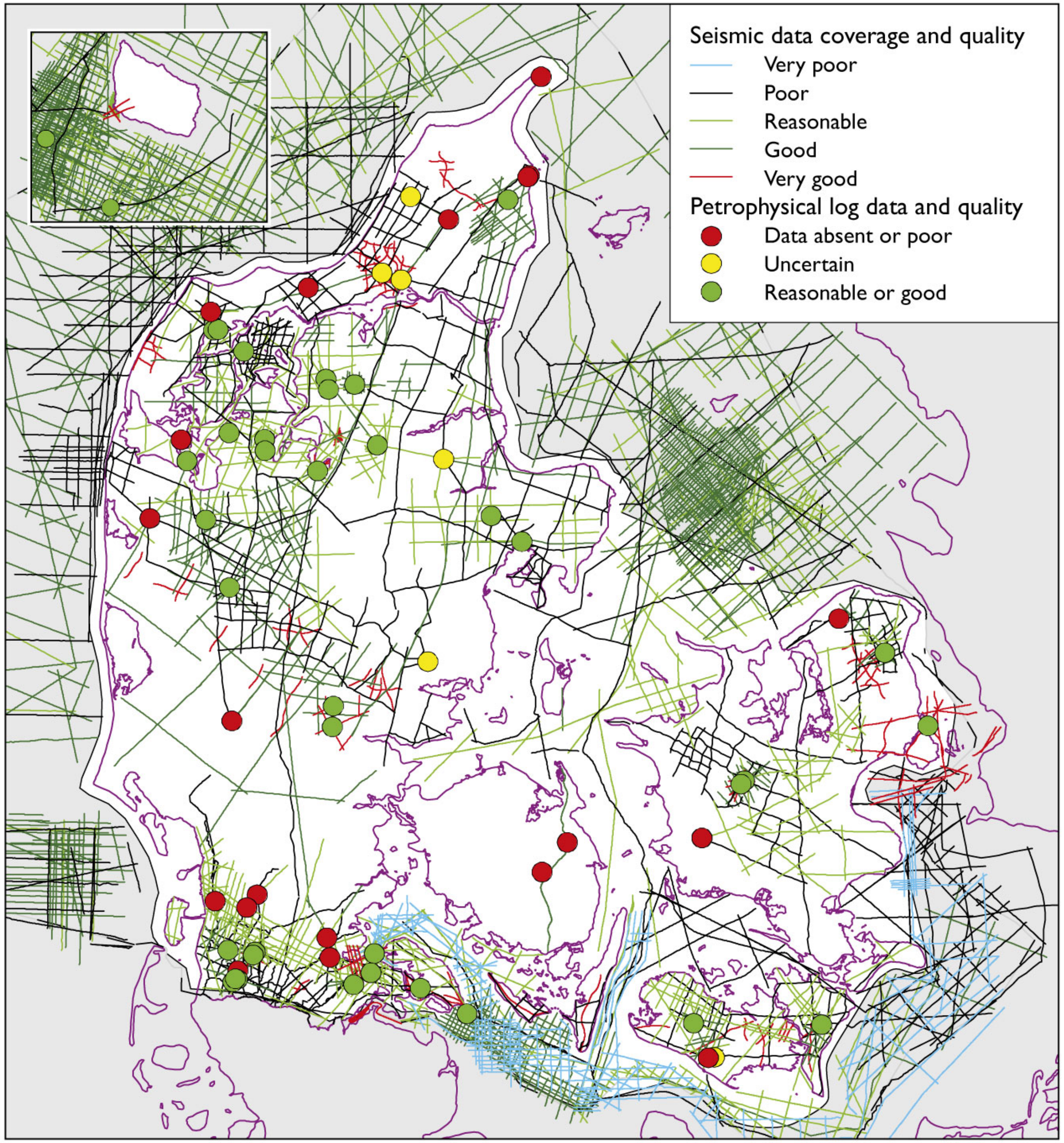
Well data





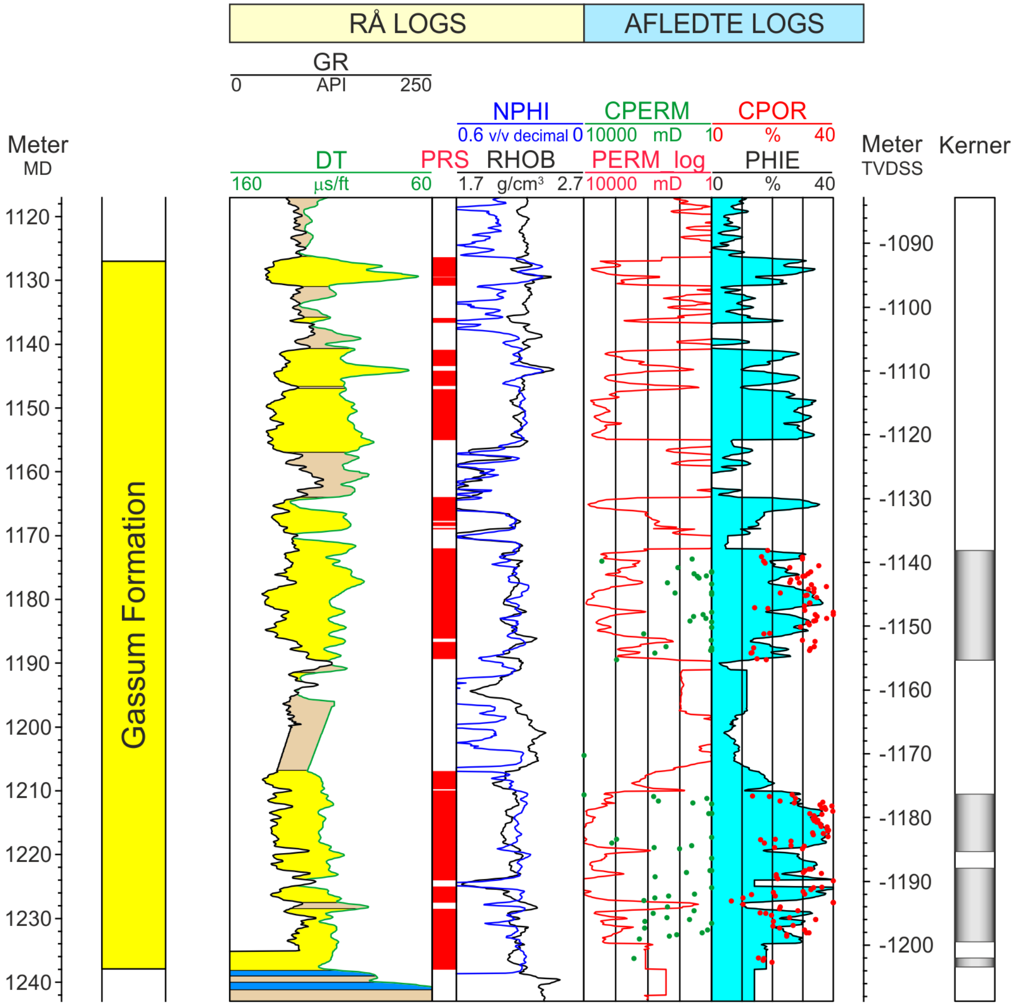
Seismic data





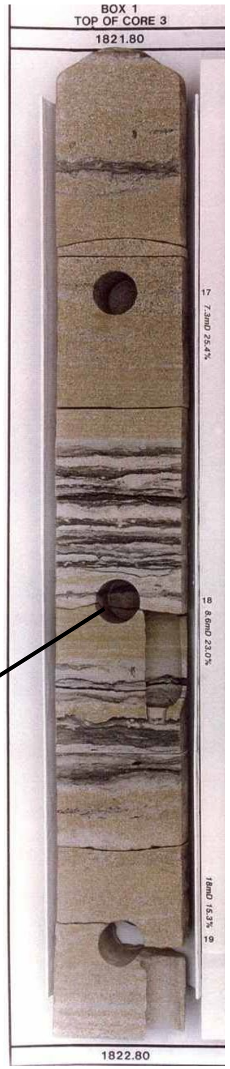
Data from wells

Petrophysical log interpretations

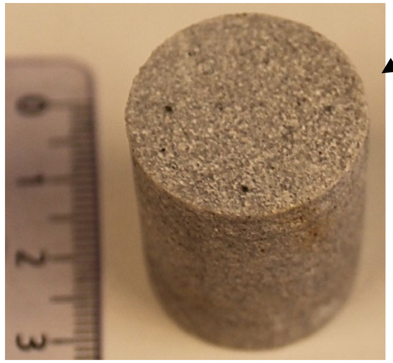


Cuttings

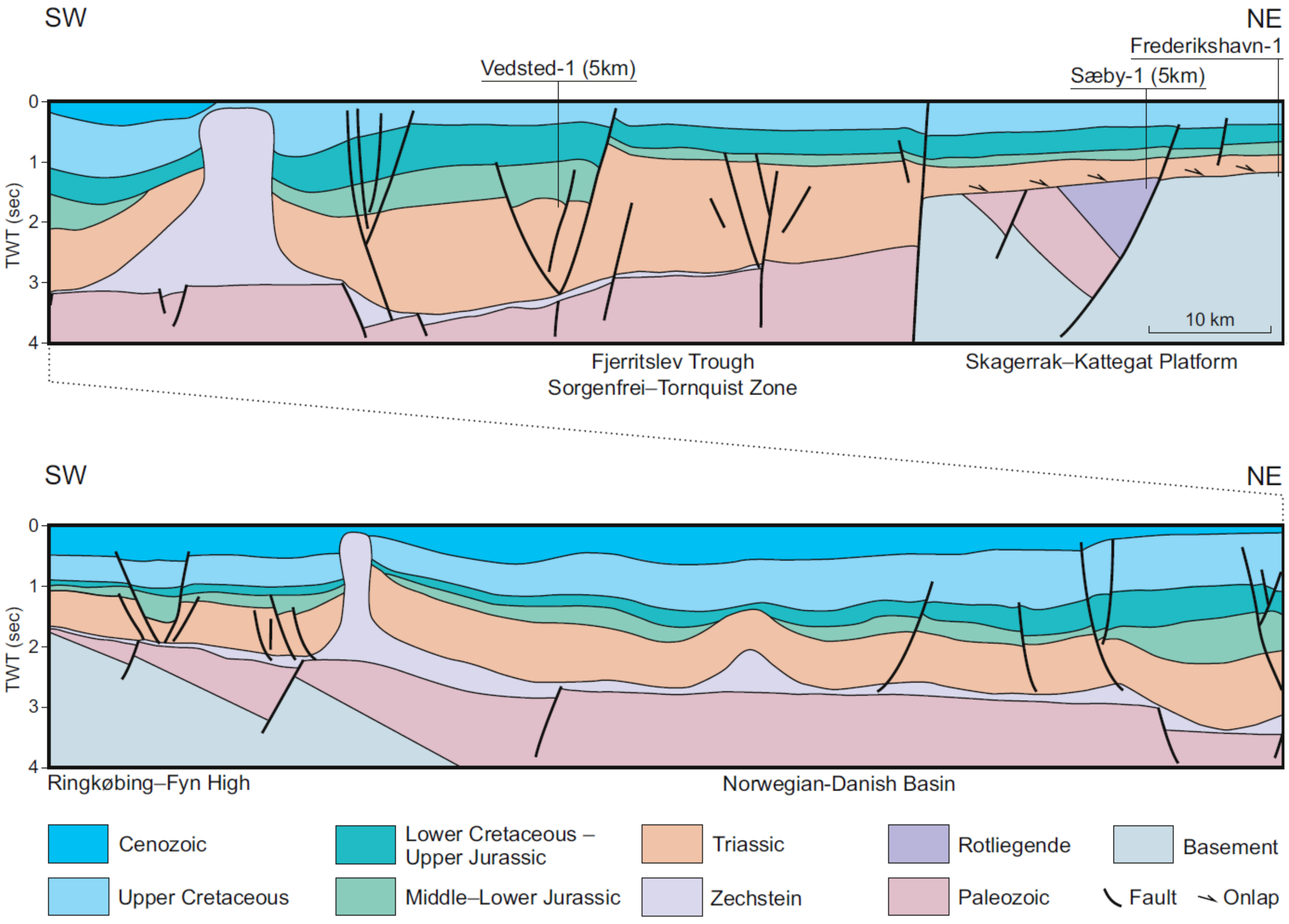
Cores

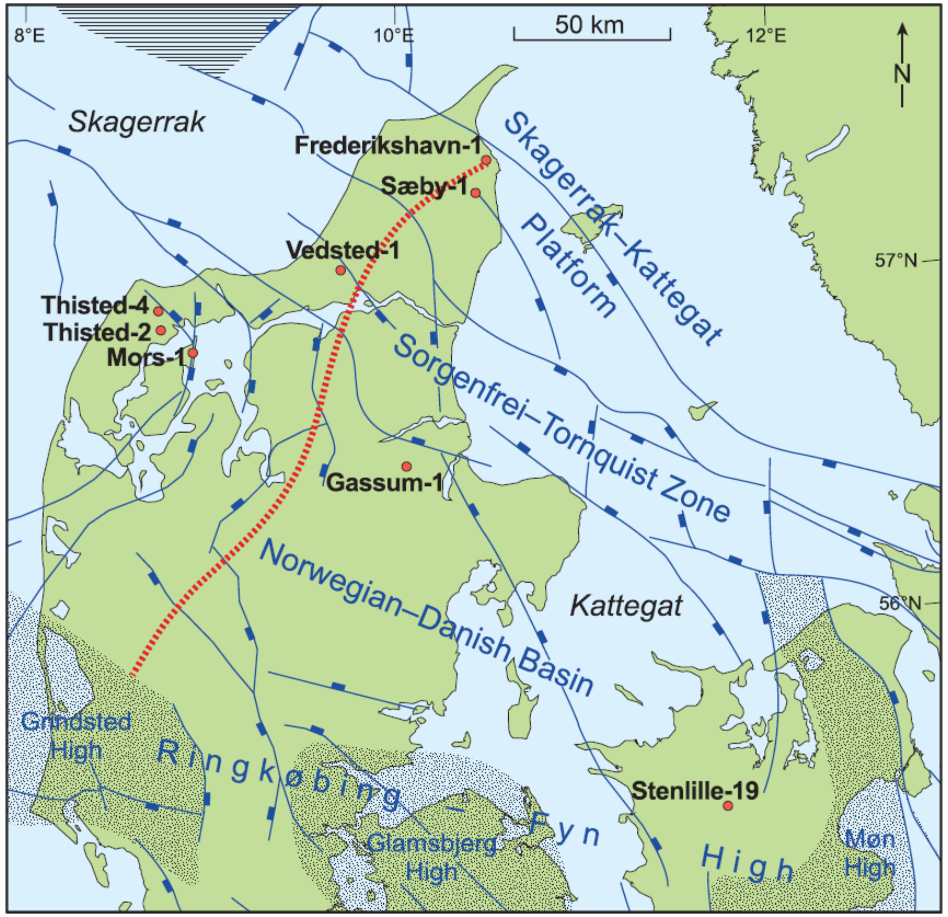


Porosity and permeability are measured on core plugs of the sandstones



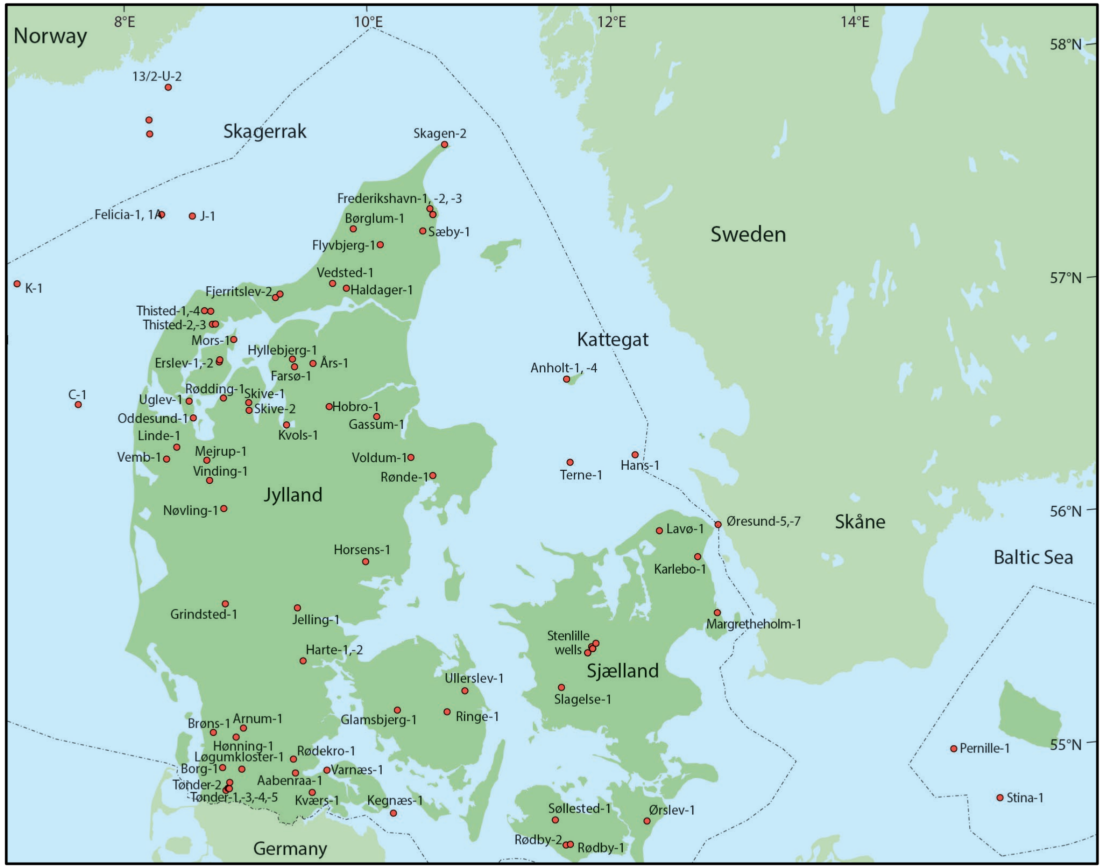
Seismic interpretations





Burial histories

- The burial depths vary greatly and the sandstones have in some places been too deeply buried for geothermal exploitation due to permeability reduction by diagenesis



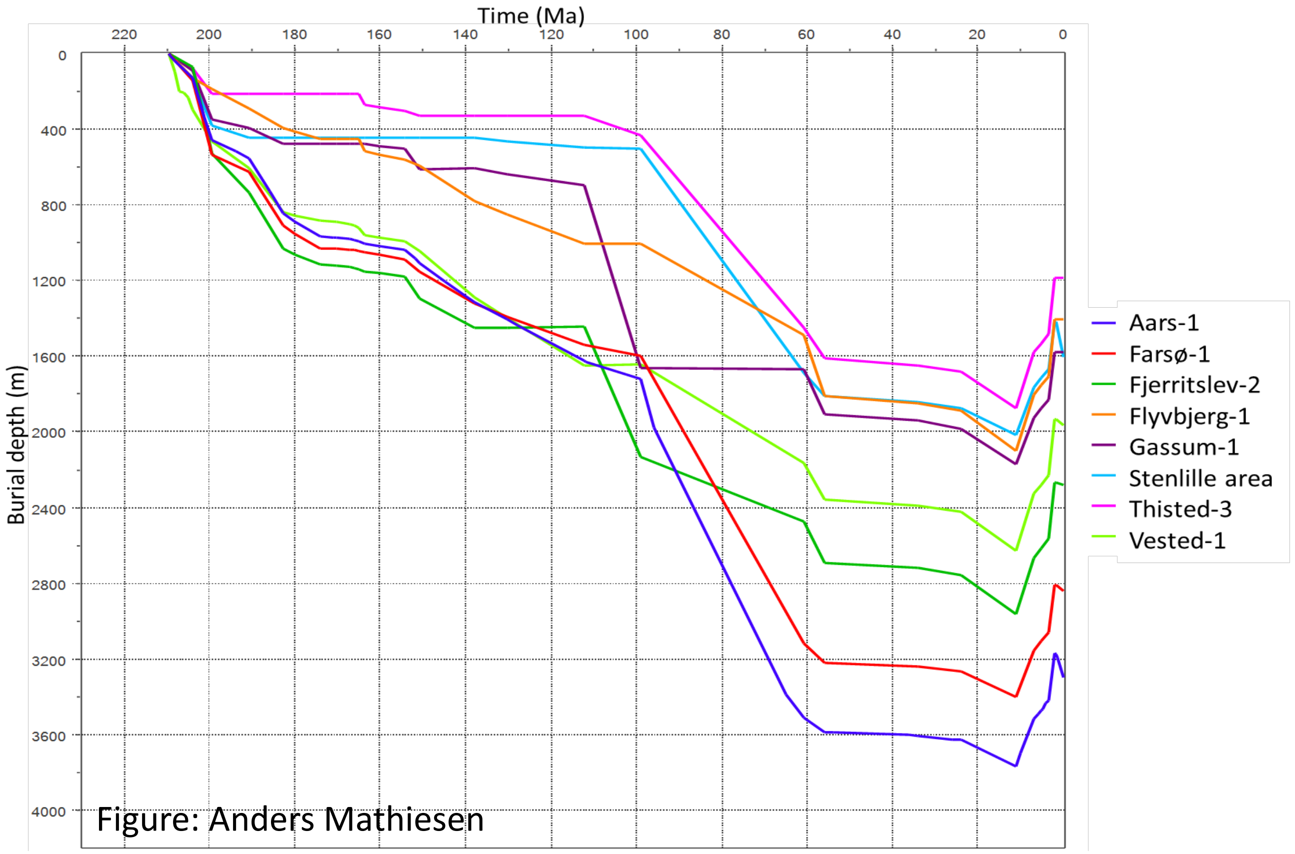
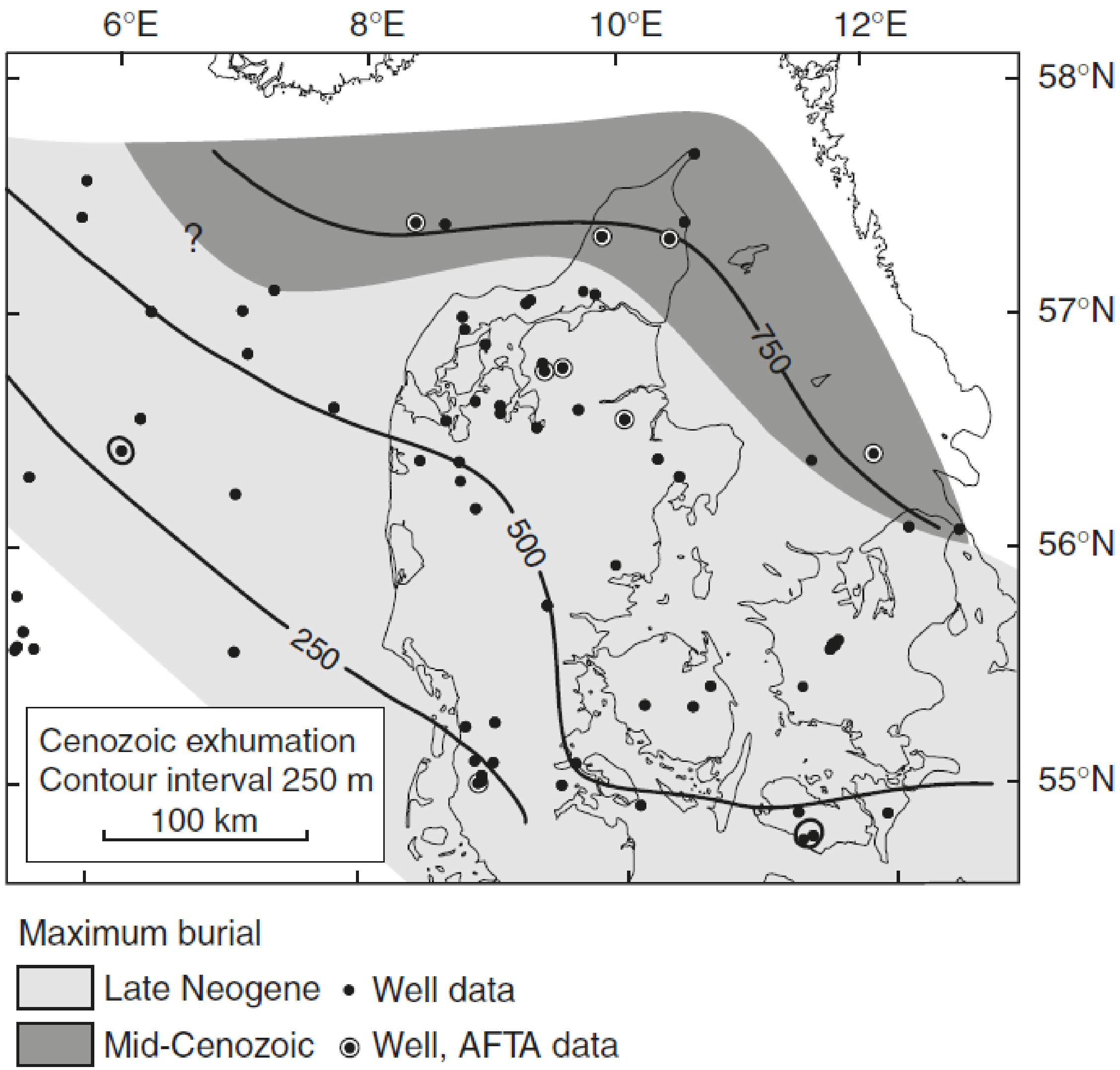


Figure: Anders Mathiesen

Burial anomaly

- The burial anomaly expresses how much the overbruden thickness has been reduced since maximum burial depth
- The burial anomaly changes across Denmark due to differential amount of Neogene uplift and erosion
- Based on vitrinite reflectance, apatite fission-track analyses, sonic velocities, stratigraphic and seismic data



Japsen et al. 2007

Reservoir quality

- The reservoir quality depends on the thickness of the sandstone layer and on how fast fluid can flow through it
- The flow speed (permeability) depends on size of the pores (porosity) and whether the pores are connected
- The type of cement that precipitates between the sand grains greatly affect how much the permeability is reduced

Illite (clay) cement:
Much reduction in permeability

Quartz cement:
Some reduction in permeability

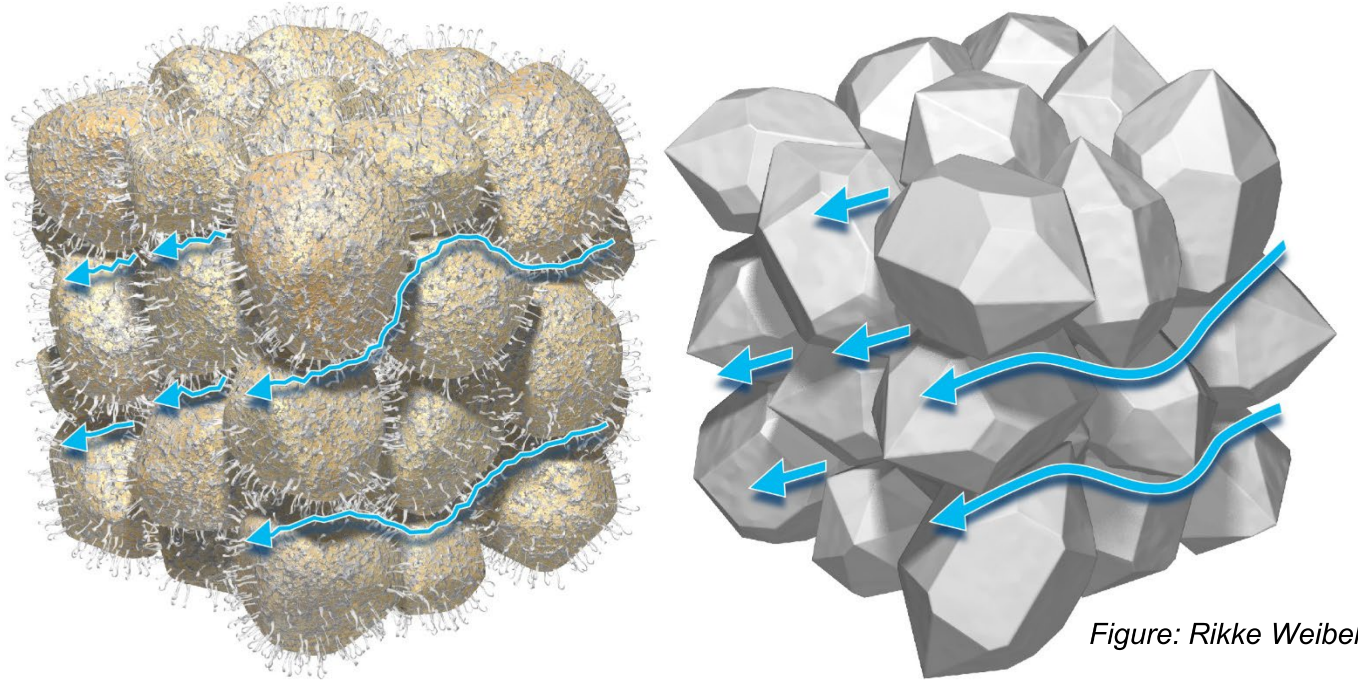
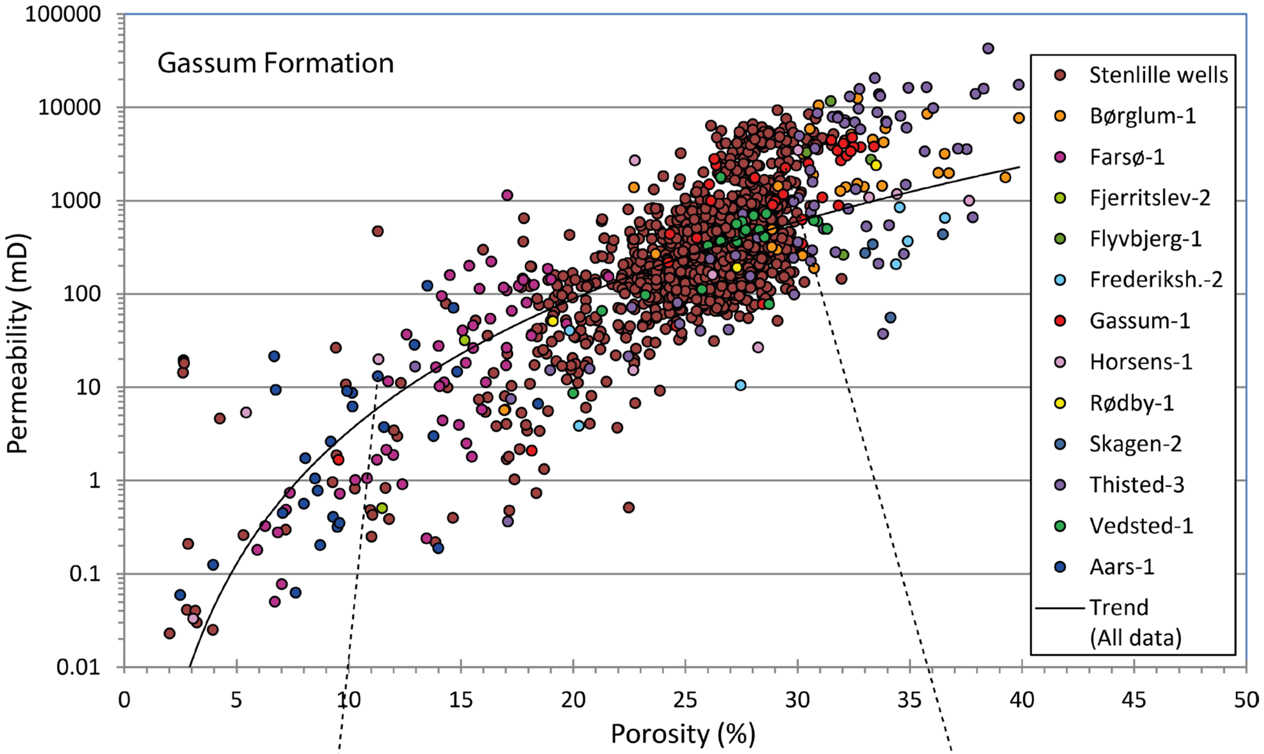
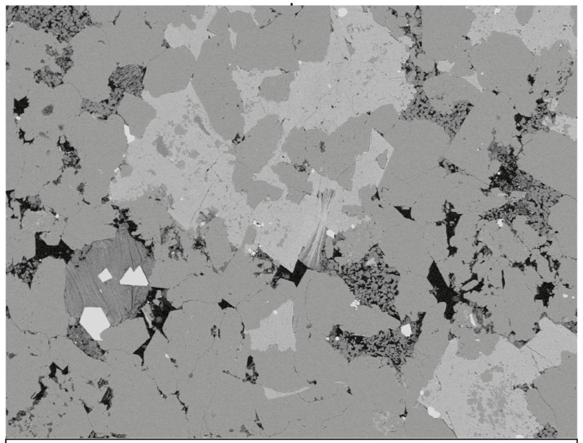


Figure: Rikke Weibel

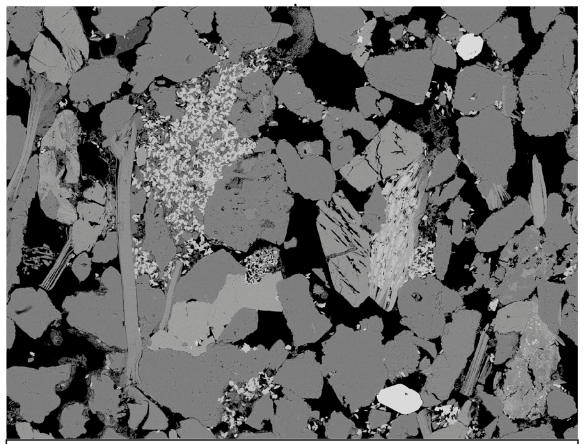
Example:
Gassum Formation

- High porosities and permeabilities are present in most of the formation
- Although there is an overall increase in diagenesis with increasing depth, much variation occurs
- This is due to a combination of factors including provenance, depositional environment, texture, mineralogy, burial history
- The combined effect of these factors can be estimated by diagenesis modelling to enable better pre-drill predictions of reservoir properties





Aars-1 well, 3208.40 m 200 µm



Gassum-1 well, 1540.14 m 200 µm

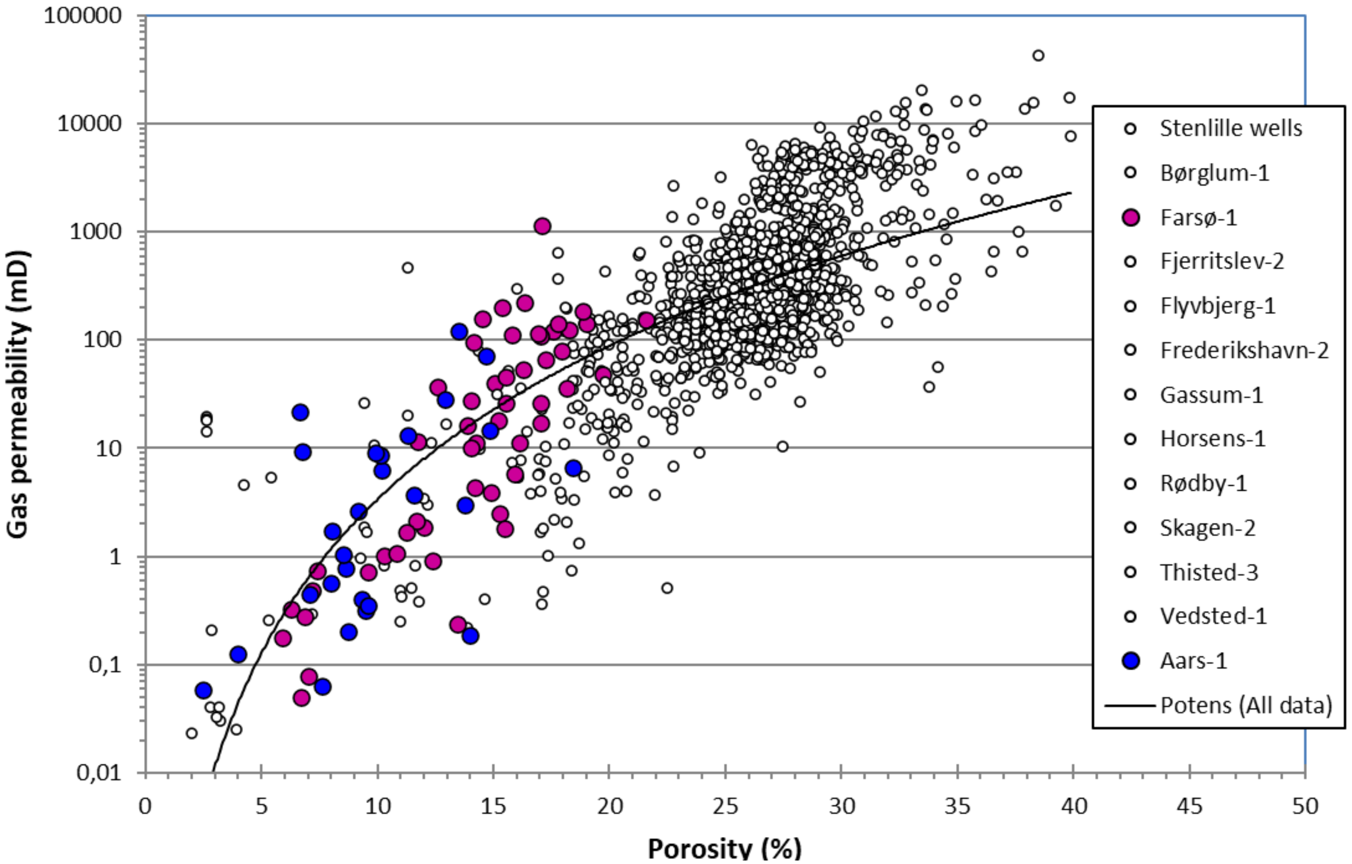
Some unsuccessful wells:

Before maximum burial effects on diagenesis were considered

The deepest wells in Gassum Formation were drilled before the effect of burial history on diagenesis was considered:

- *Aars-1 well*
  - *drilled in 1979*
  - *Gassum Fm in c. 3.3 km*
  - *has been buried 500-700 m deeper*
- *Farsø-1 well*
  - *drilled in 1982*
  - *Gassum Fm in c. 2.9 km*
  - *has been buried 600-800 m deeper*

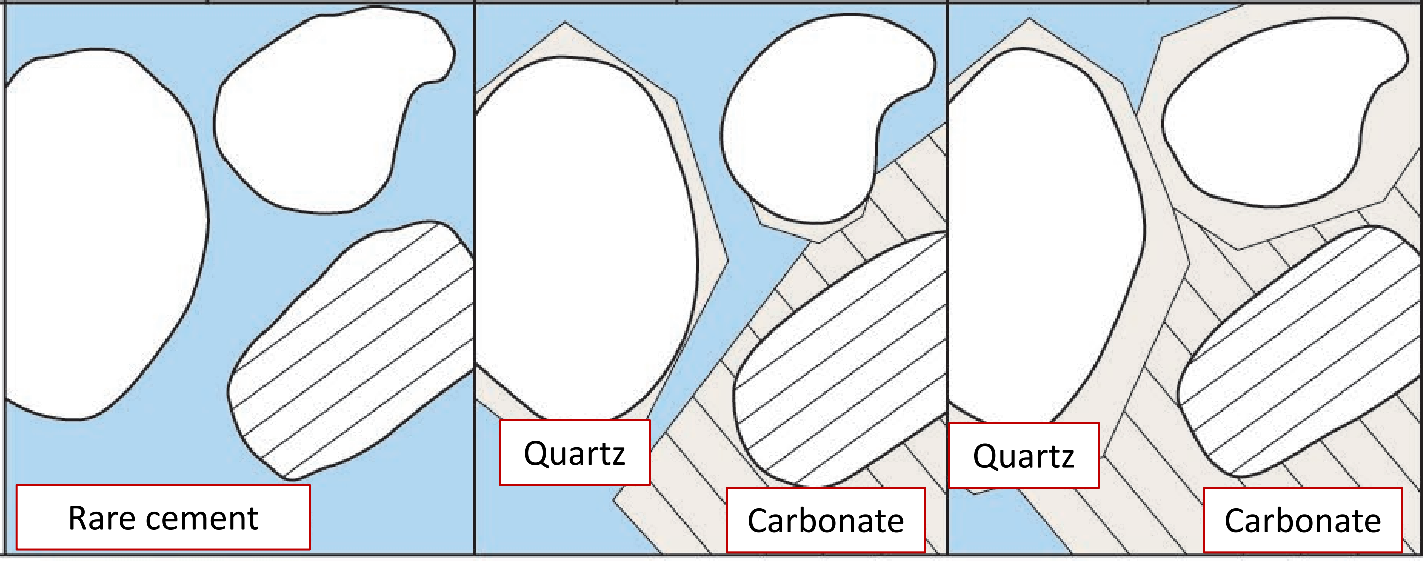
Poor reservoir quality was found due to pervasive cementation with quartz, illite and ankerite



Influence of depositonal environment on diagenesis

Lagoonal sandstones	Depth: 1–2 km		Depth: 2–3 km		Depth: 3–4 km	
	Porosity (%)	Permeability (mD)	Porosity (%)	Permeability (mD)	Porosity (%)	Permeability (mD)
Fine sandstone	30	325	22	99	6	0,2
Medium sandstone	32	2097	23	211	9	2,5

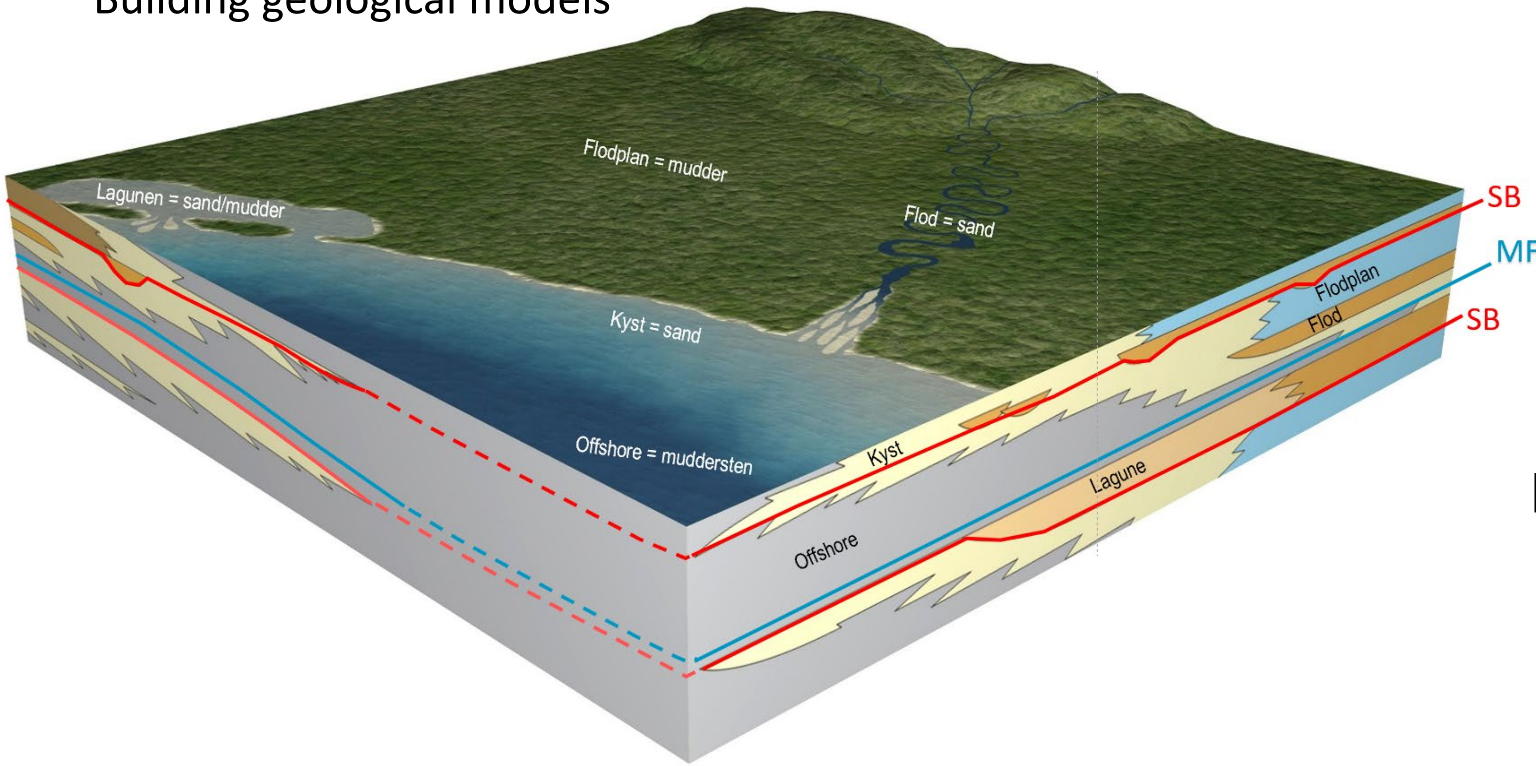
Primary cement types



Increasing temperature →

Depositional environments

Building geological models



Facies map for a selected time slice

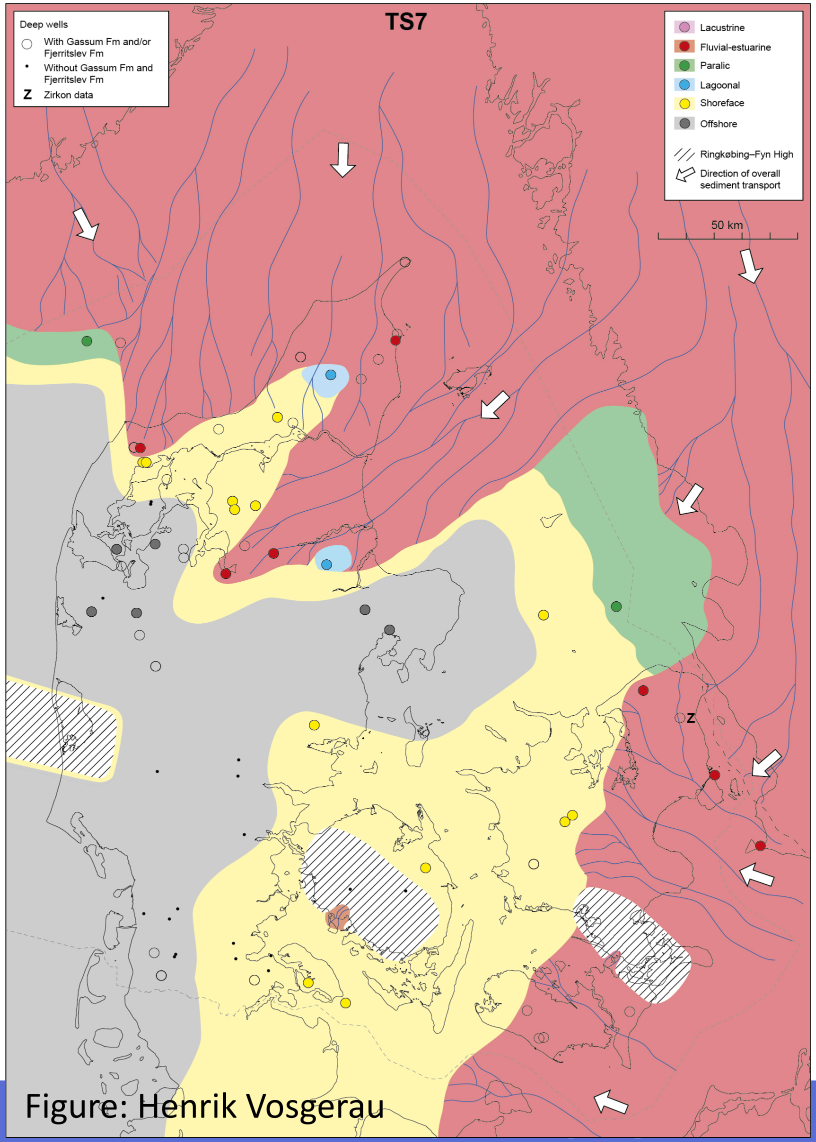


Figure: Henrik Vosgerau

Correlation of sandstone and mudstone layers between wells based on:

- Interpretation of facies and sediment transport directions
- Relative ages of sediments from biostratigraphic data
- Within a sequence stratigraphic framework

Facies maps

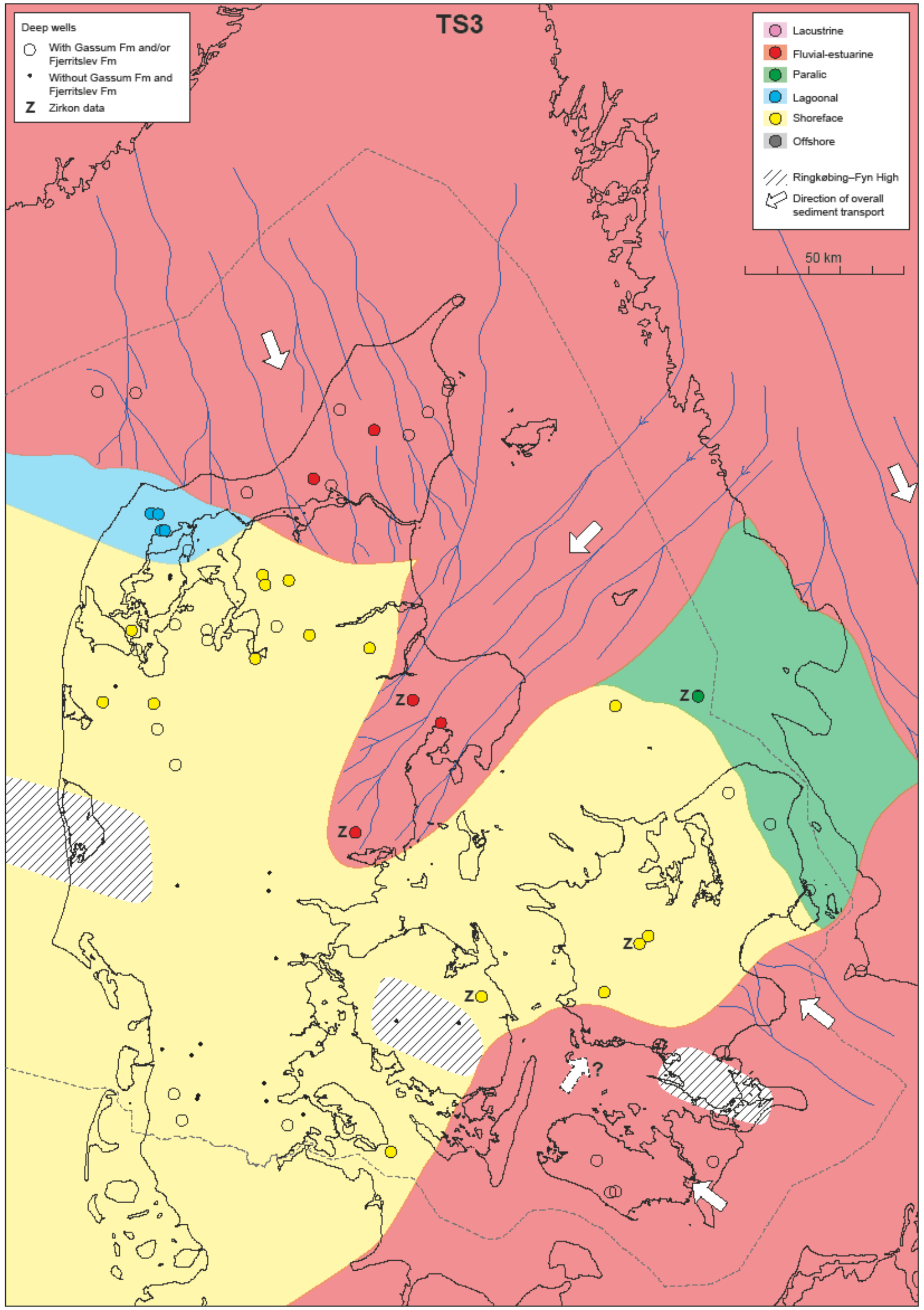


Figure: Henrik Vosgerau

The depositional environments affect the resulting reservoirs in several ways:

- *Distribution*
- *Thickness*
- *Grain size*
- *Clay content*
- *Mineralogy*

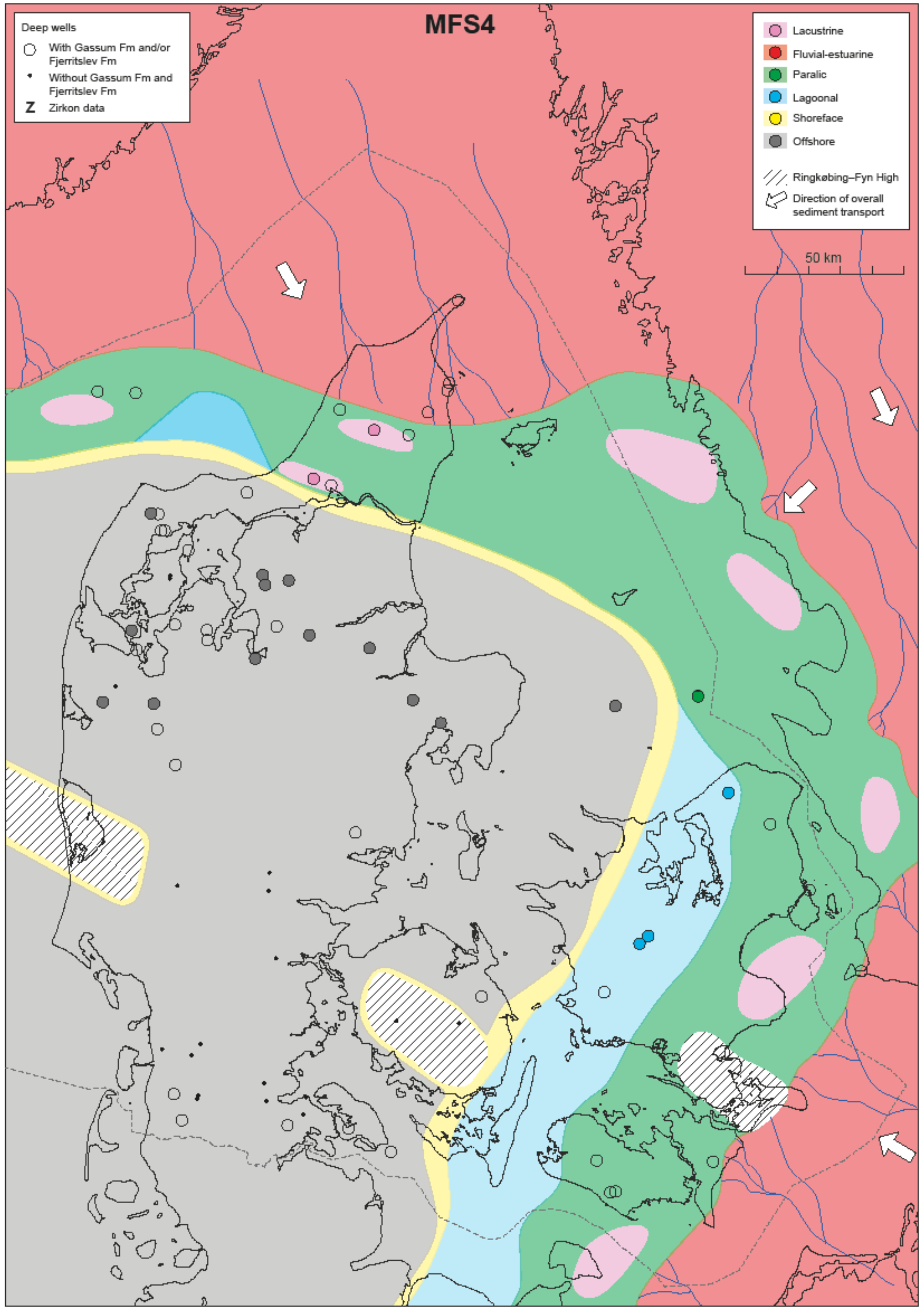
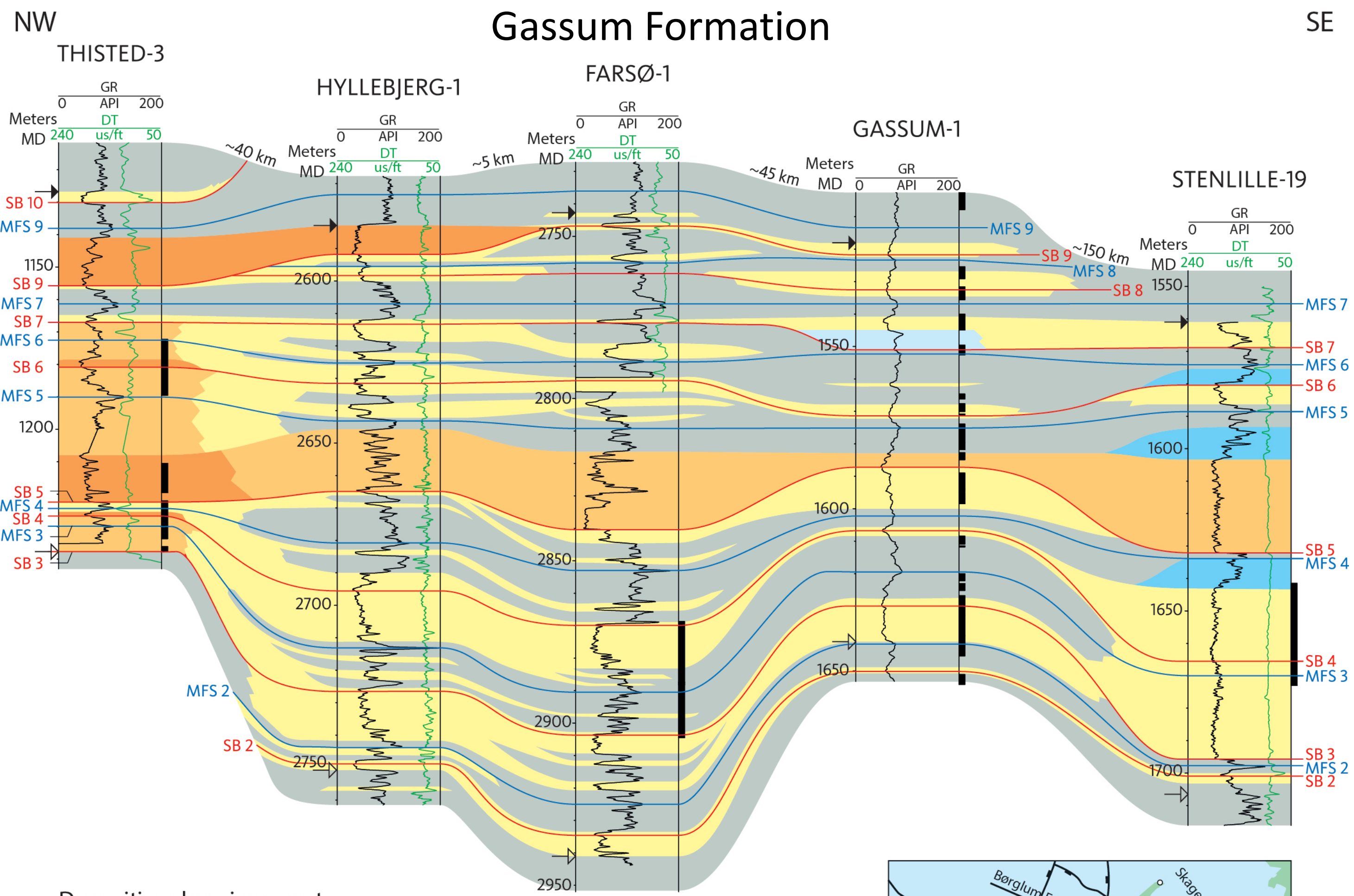


Figure: Henrik Vosgerau



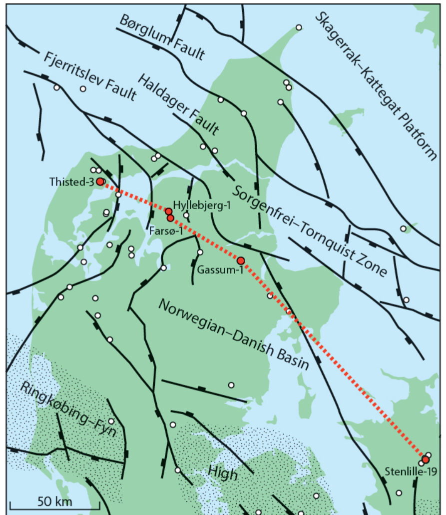
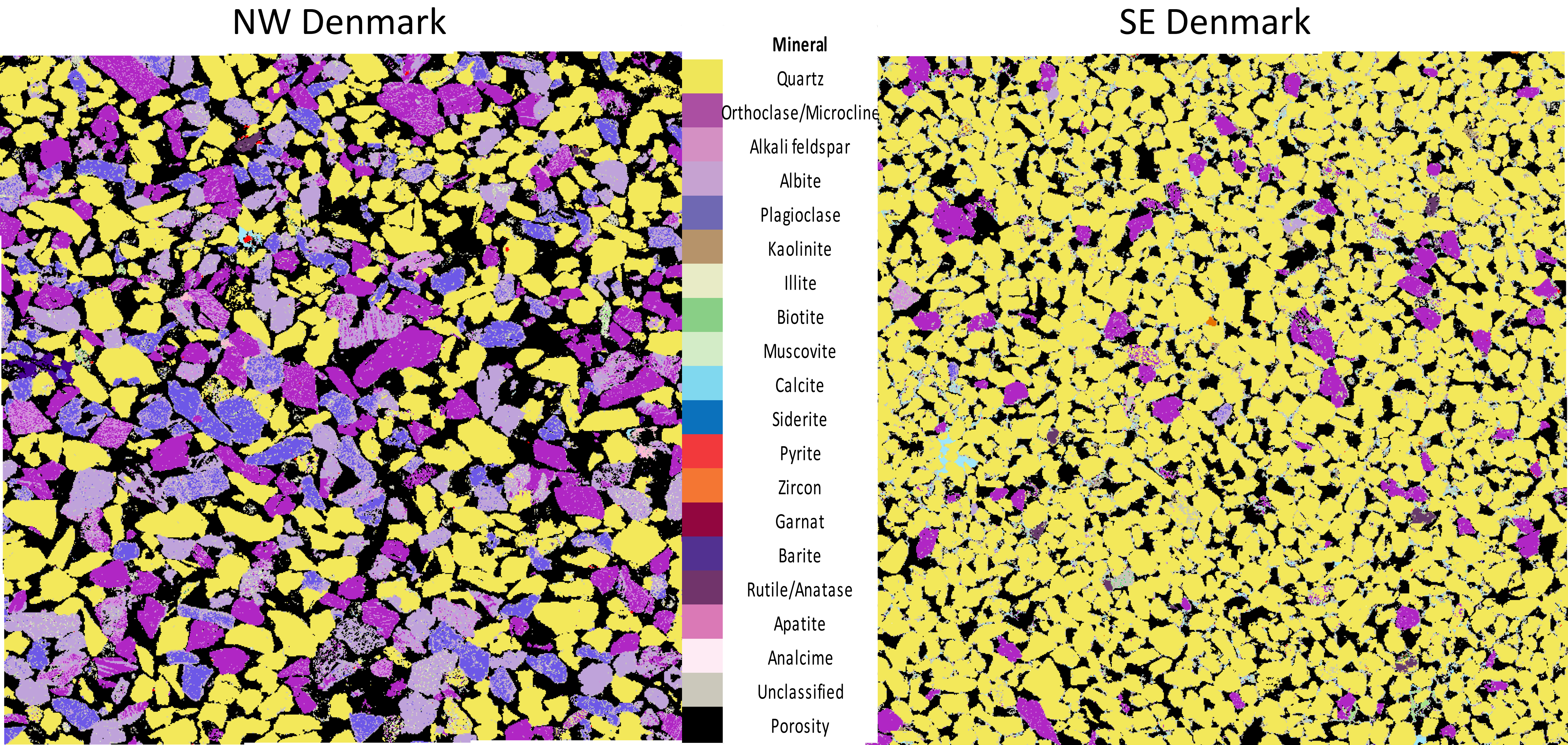


Figure: Henrik Vosgerau

Sequence stratigraphy

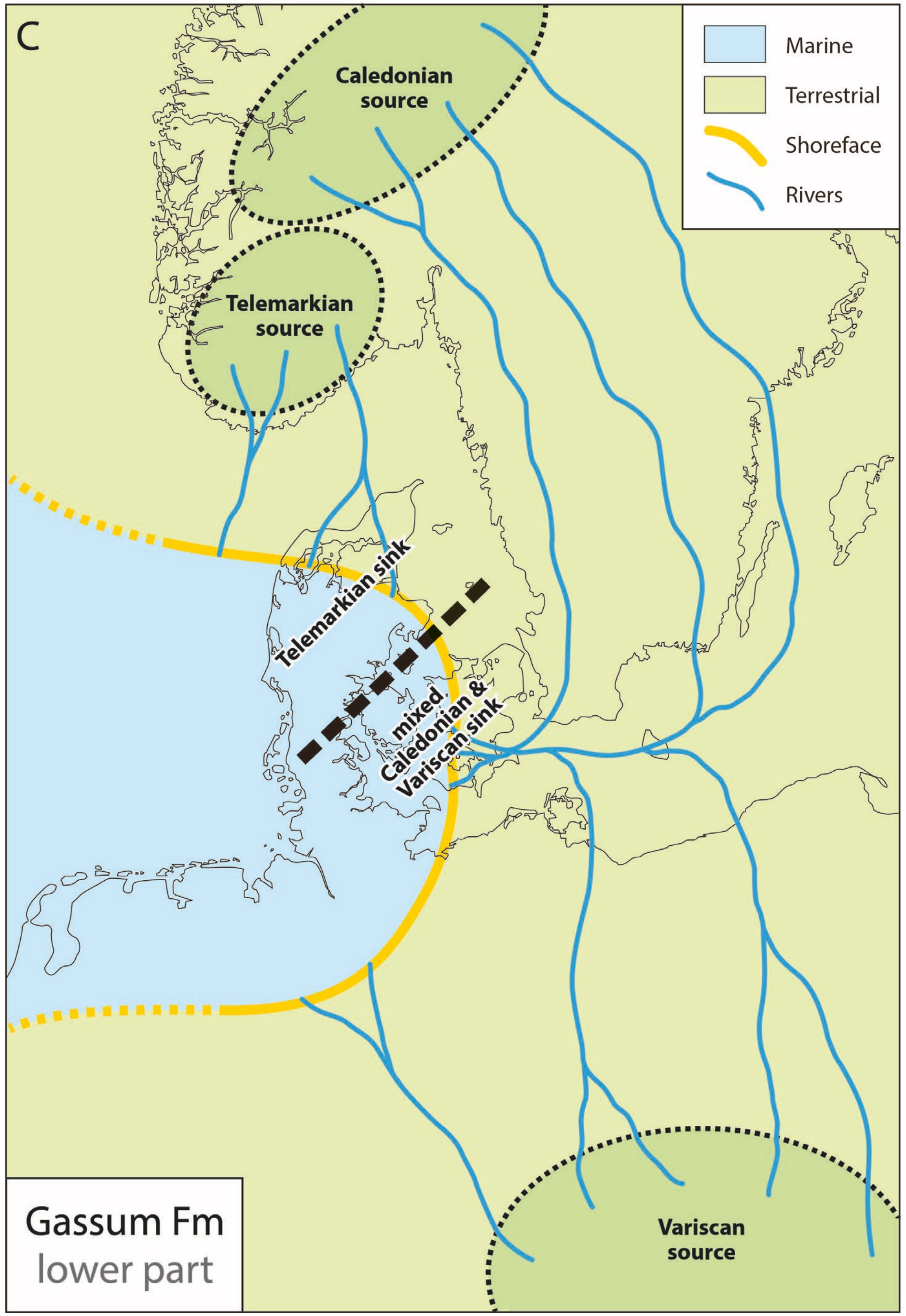
- The cross-basinal profile shows several sediment entry points to the basin
- These correspond to different provenance areas as shown by zircon U-Pb age dating
- The resulting mineralogical maturity is much higher in eastern than western part of Gassum Fm

SEM mineral maps



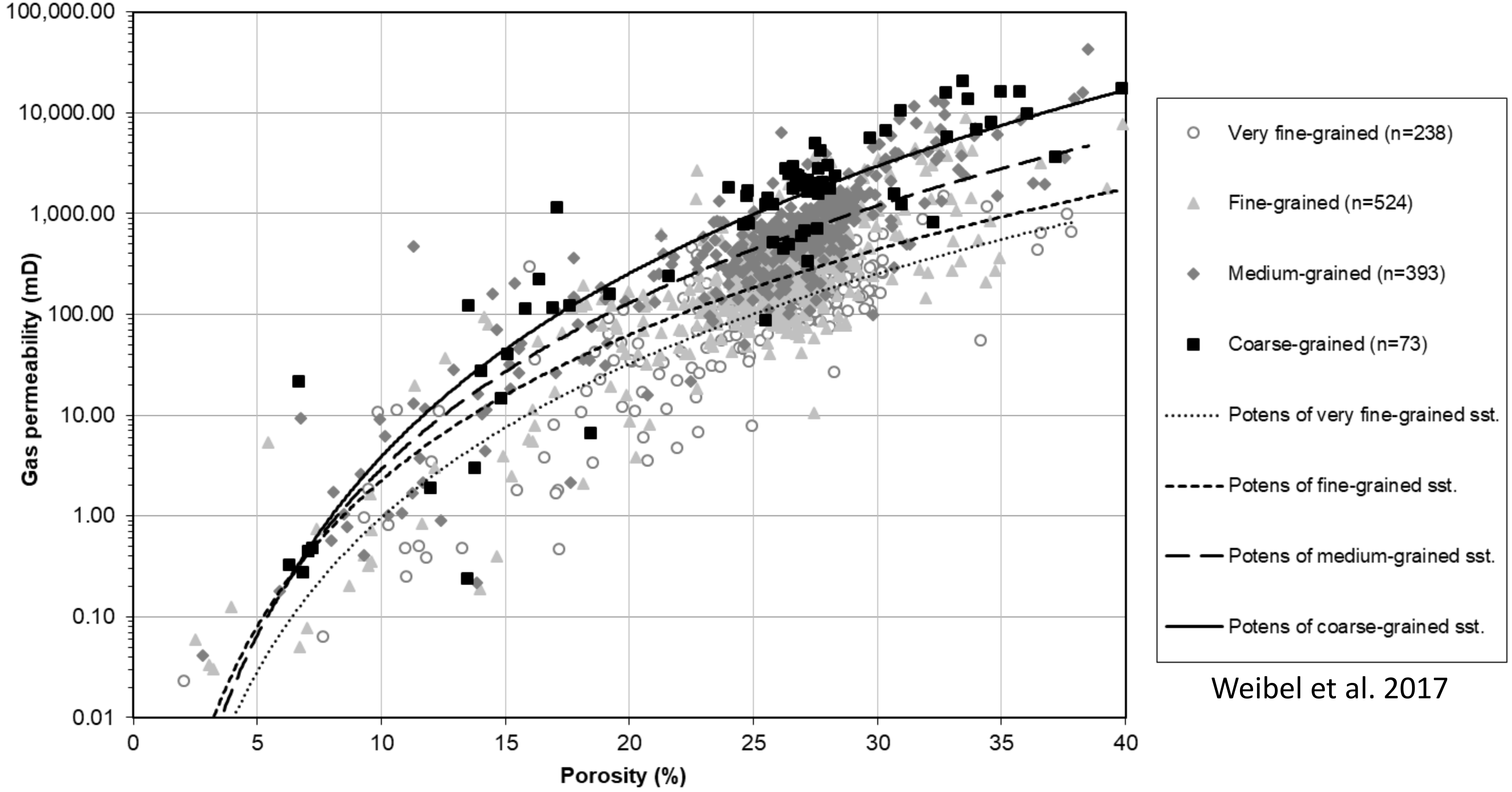
Provenance analysis

- Paleogeographic reconstruction for the lower part of the Gassum Formation
- The location of the primary source areas are shown (Caledonian, Telemarkian, and Variscan)
- It represents a snapshot since the coastline moved back and forth due repeated transgressions and regressions



Olivarius et al. 2022

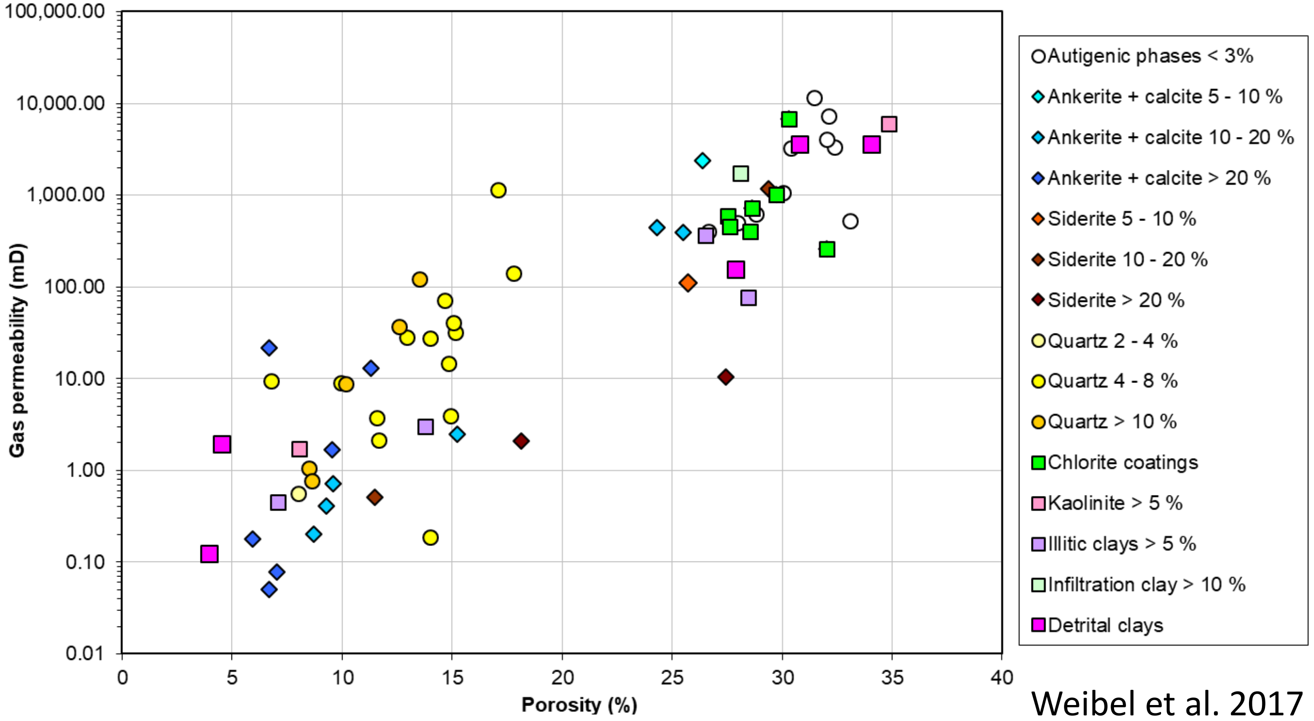
Influence of grain size on reservoir properties



Weibel et al. 2017

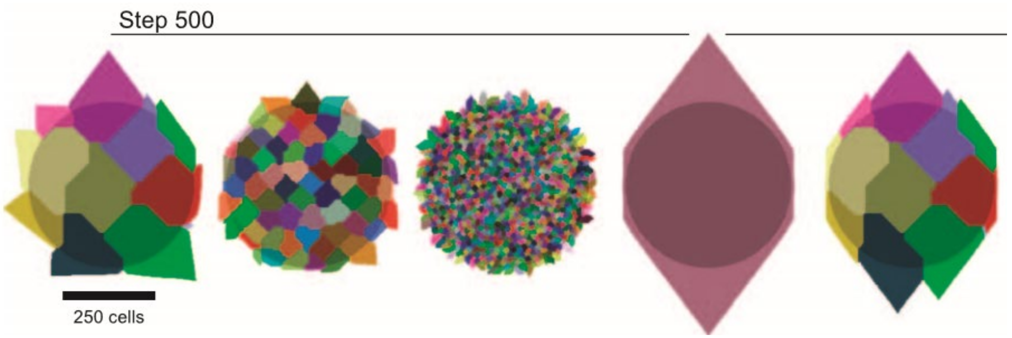
Porosity-permeability data from Gassum Fm divided into grain-size classes of very fine, fine, medium and coarse-grained sandstones

Influence of diagenesis on reservoir properties



Weibel et al. 2017

- Porosity-permeability plot where the samples are shown by the primary cement types that affect the reservoir properties
- Detailed petrographic studies are necessary to model the amount and type of cements in undrilled areas



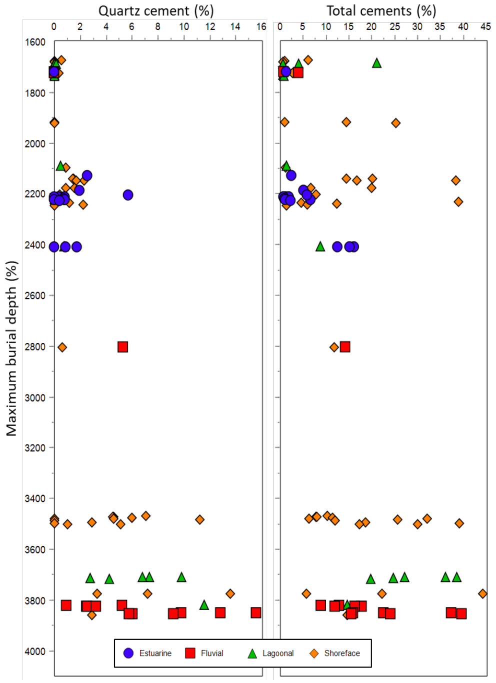
Touchstone quartz cementation model – Lander et al. 2008

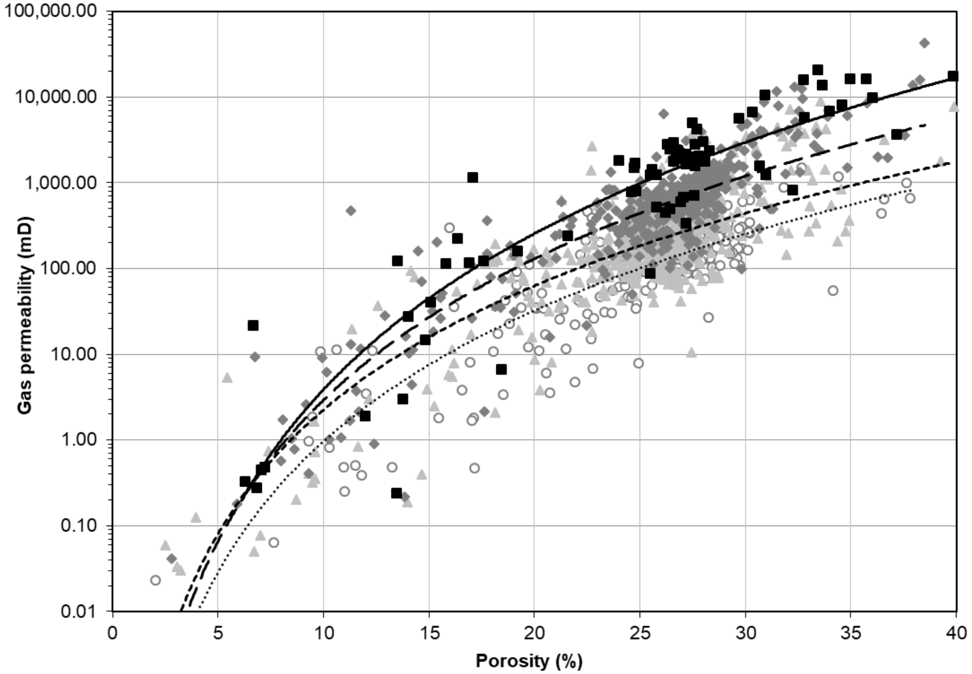
Diagenesis modelling

- Petrography, core analysis and burial history data were analyzed by Touchstone software to make **forward diagenesis modelling** of the evolution in reservoir quality

- For each sample with petrographical data, the **diagenetic development** and **reservoir properties** are simulated in relation to the temperature and effective stress histories

- When an acceptable match is obtained by sensitivity testing and optimization, then the model can be used to **estimate the reservoir properties** in areas without well control

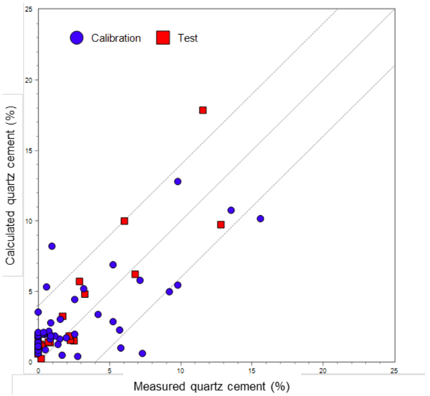


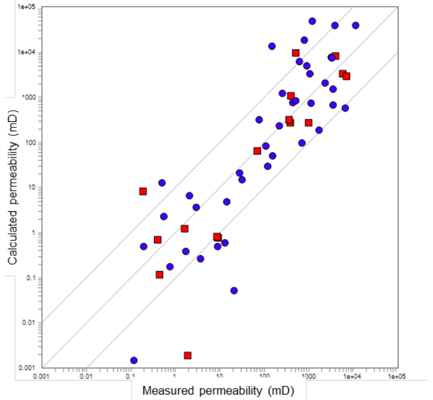


Simulation results

- A diagenesis model is established for each depositional environment
- These can be used to make pre-drill estimates of reservoir properties in prospect areas
- The models are extended on maps by T>Map software using 3D basin modelling by PetroMod software
- Reservoir properties are simulated for multiple timesteps corresponding to the facies maps
- This can be used to make pre-drill estimates of reservoir properties in prospect areas

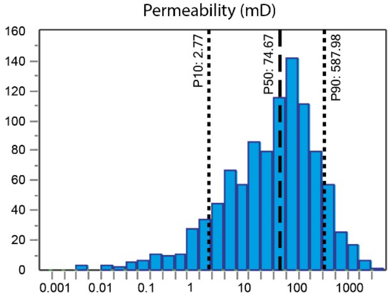
Testing and optimization of models



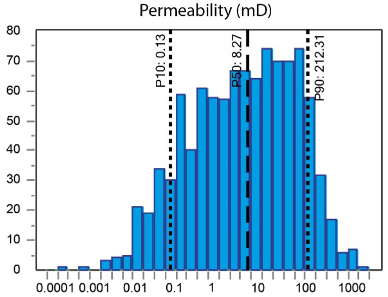


Simulation results for a considered drill site

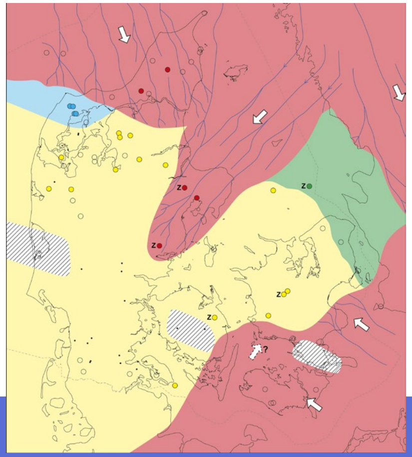
Fluvial depositional environment

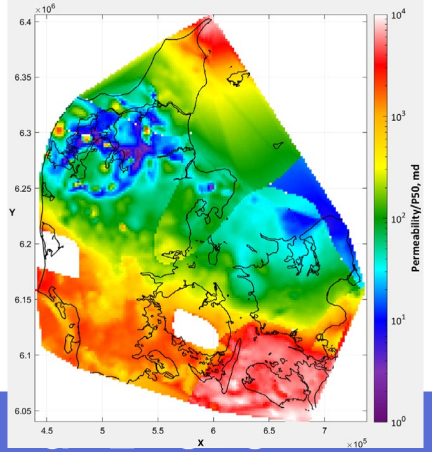


Shoreface depositional environment

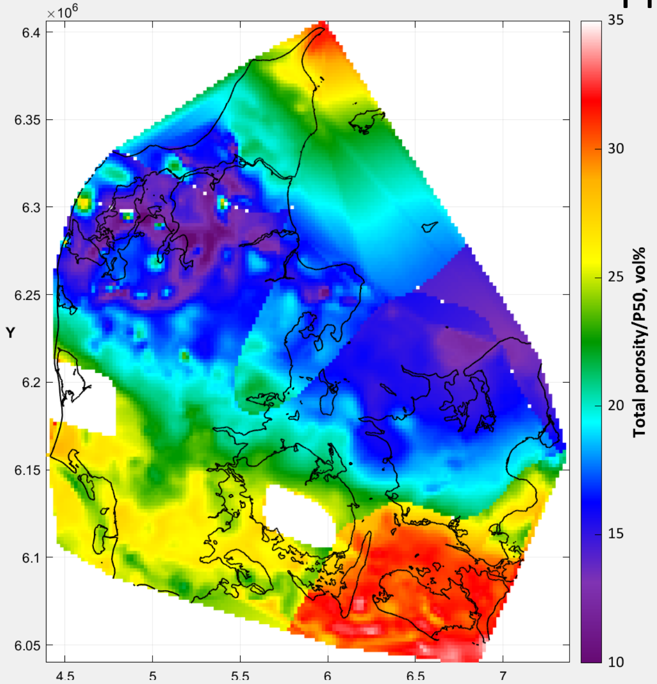


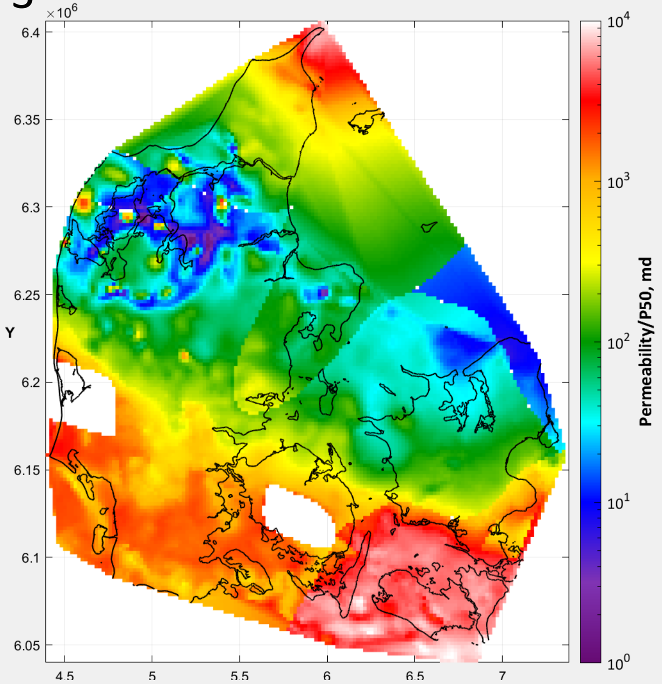
Models extended onto maps for multiple timesteps

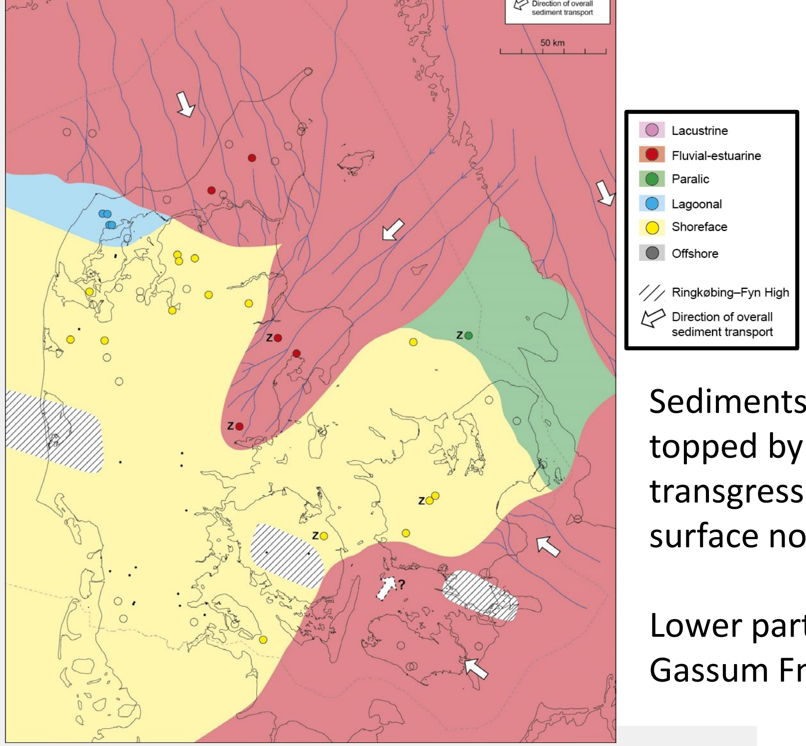




Pre-TS 3

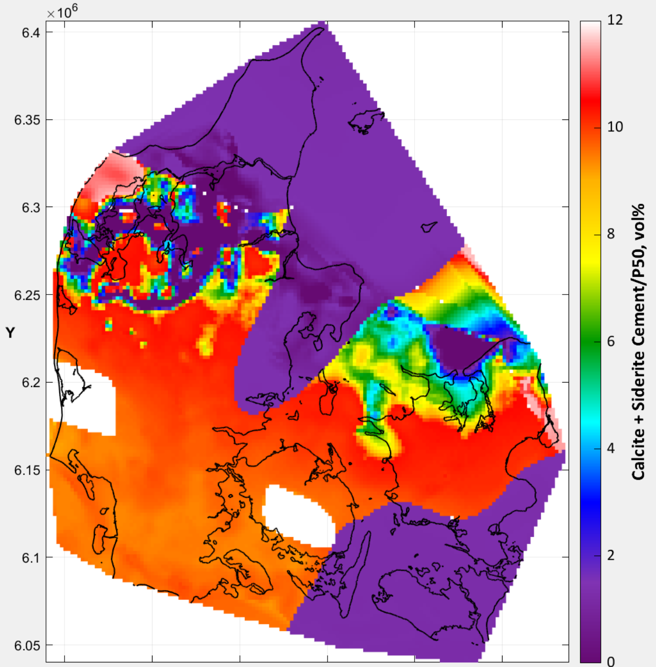


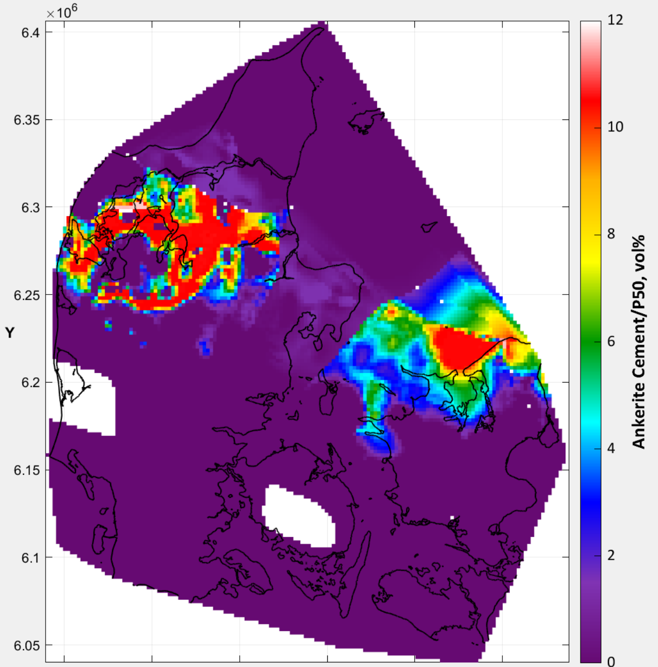


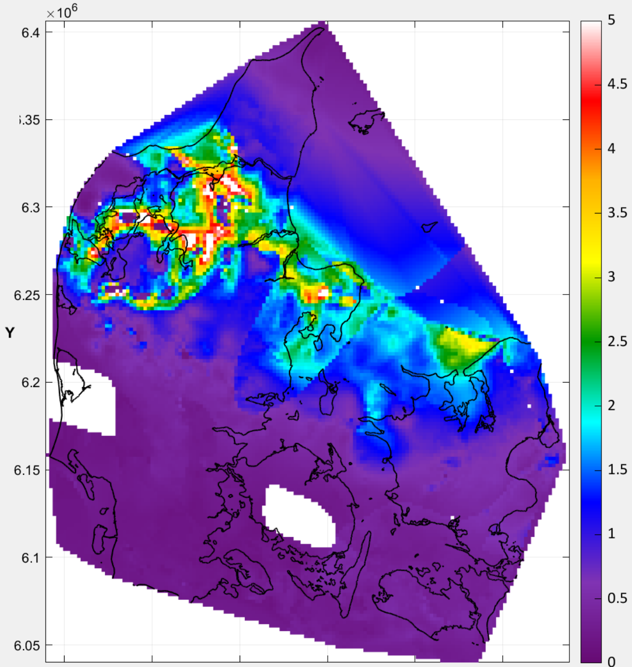


Sediments topped by transgressive surface no. 3

Lower part of Gassum Fm

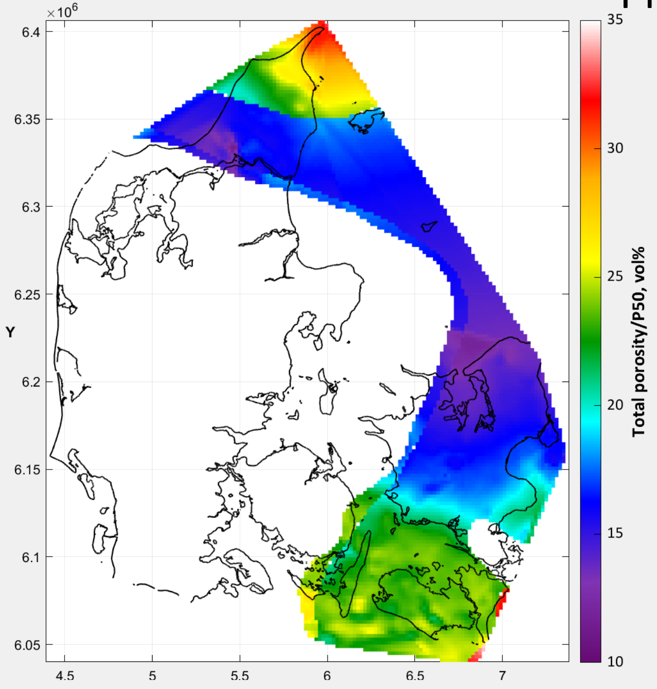


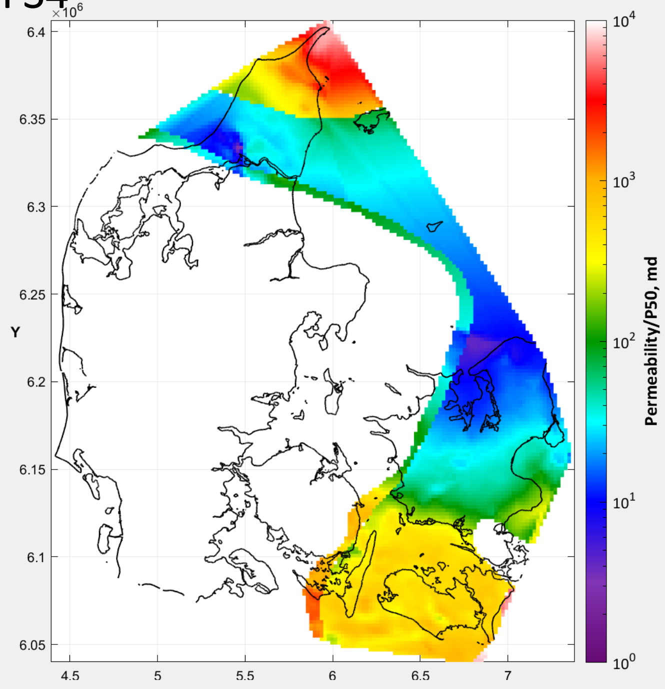


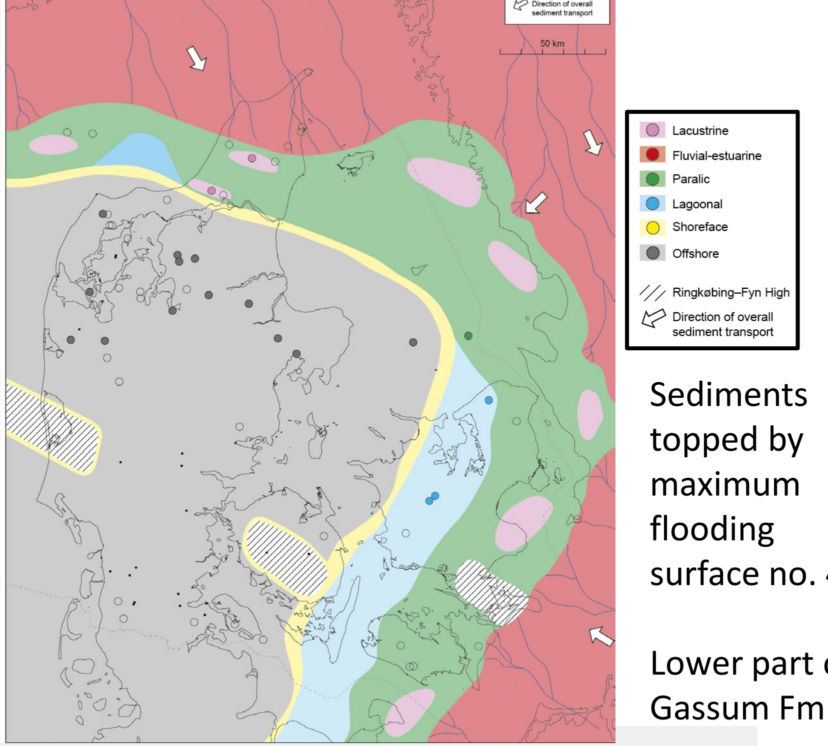


Made with Rob Lander

Pre-MFS4

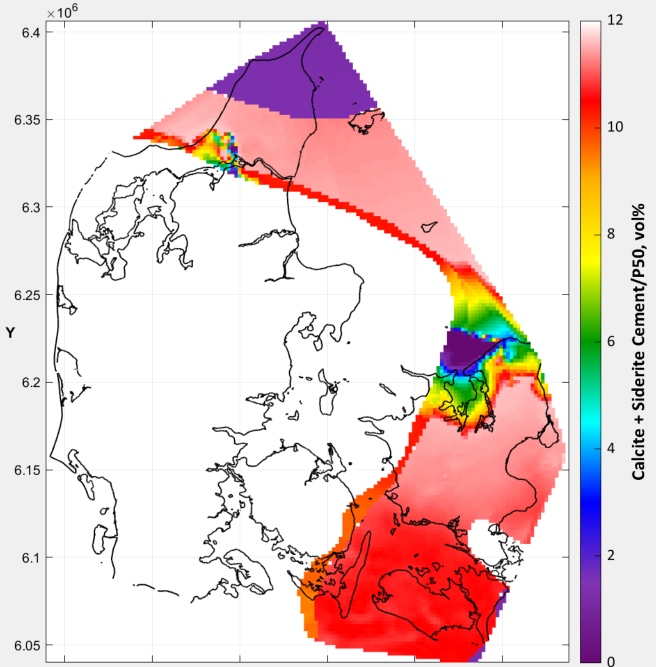


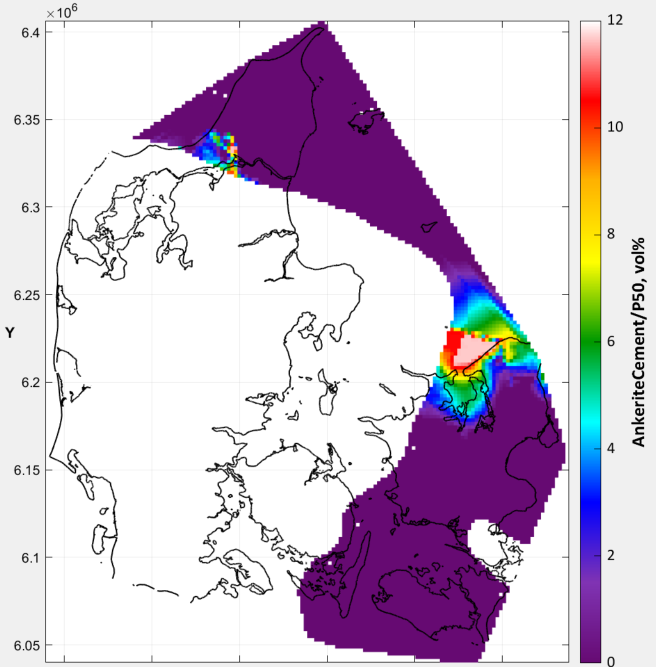


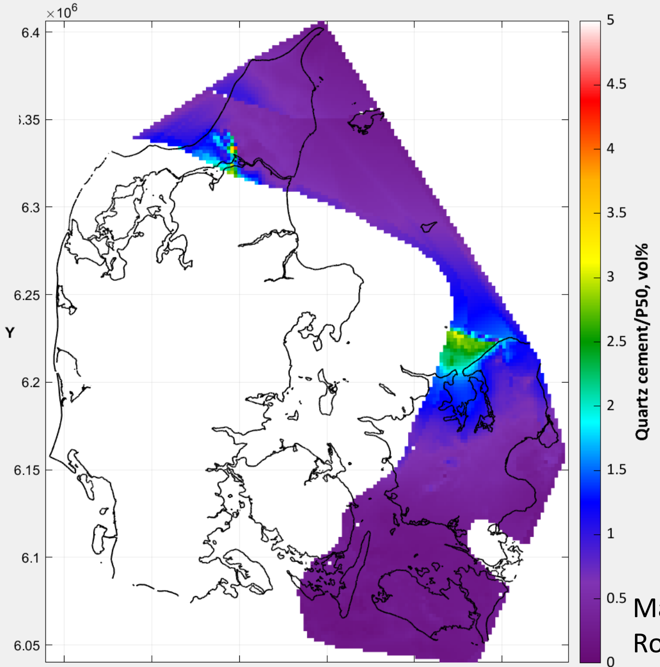


Sediments topped by maximum flooding surface no. 4

Lower part of Gassum Fm





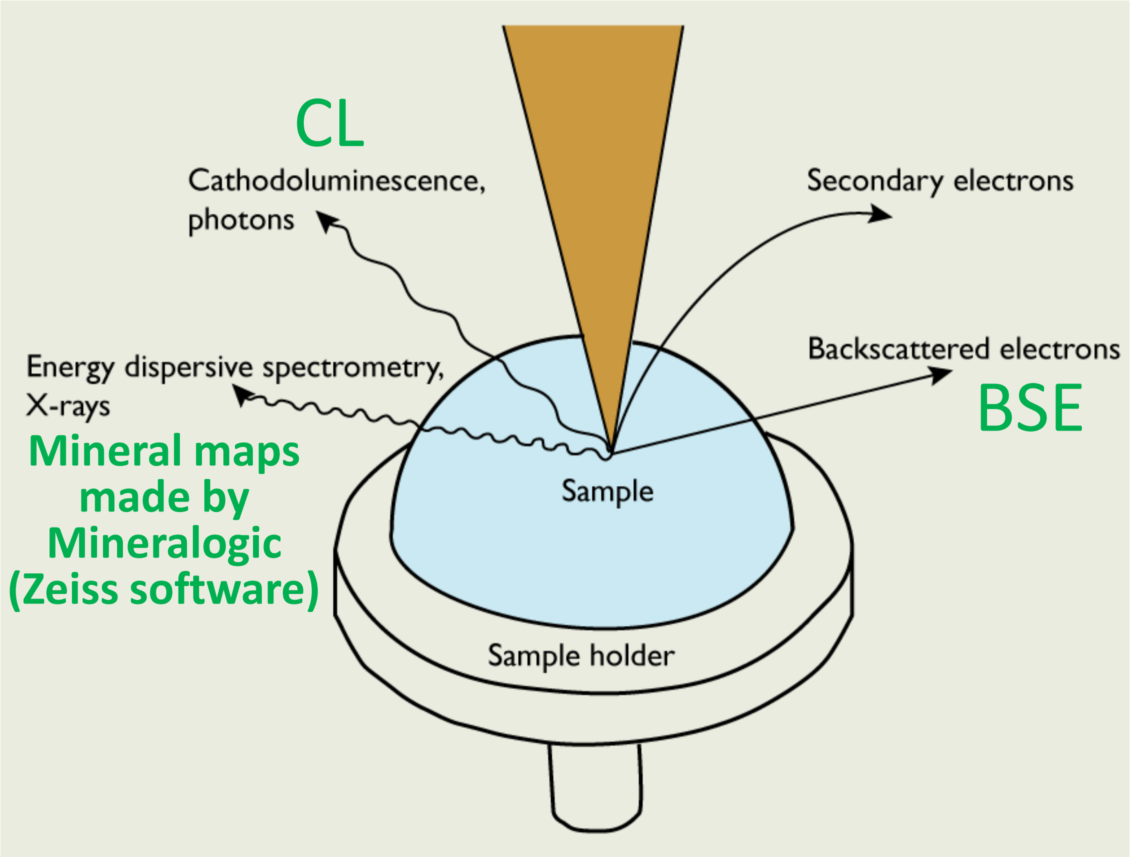


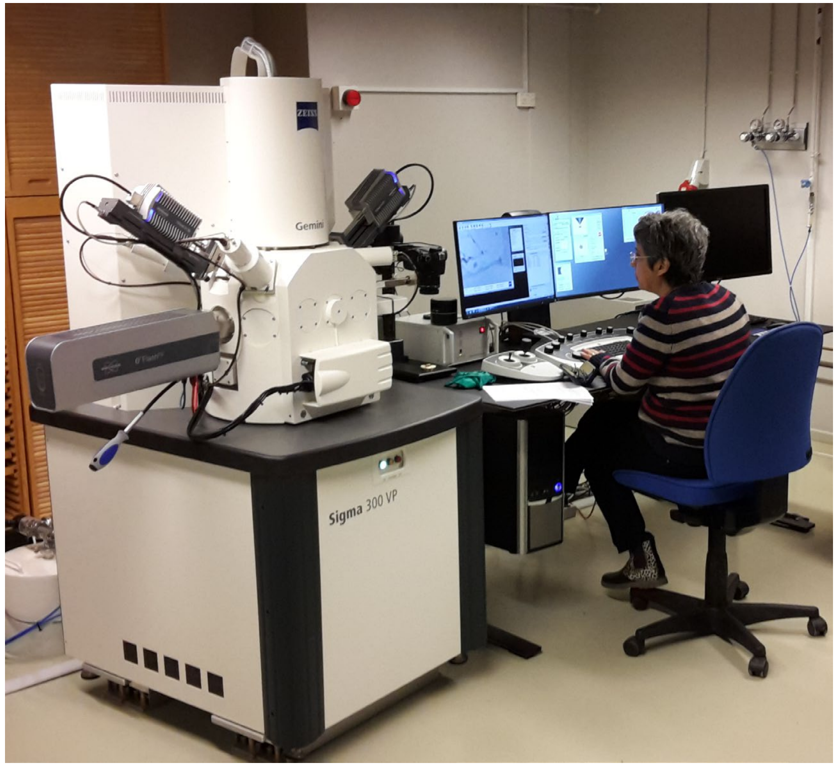
Made with Rob Lander

Mineralogy matters!

- Knowledge of mineralogical somposition, provenance, depositional regime, and burial history can be integrated to predict the type and amount of diagenesis and the effect on reservoir properties to find the best sites and avoid drilling tight sandstones
- Knowledge of mineralogy and brine composition can be used to prevent clogging, corrosion and precipitation during production by taking the necessary precautions

The dataset is made on a Zeiss Sigma 300VP Field Emission scanning electron microscope (SEM) with a combination of detectors that can produce these signals:





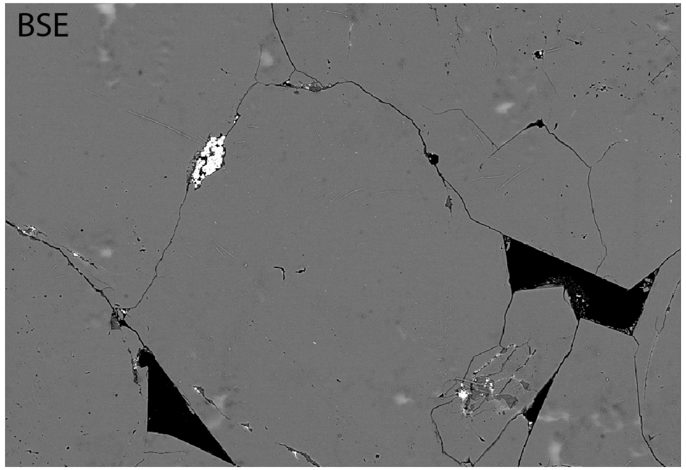
Images for the hackathon:

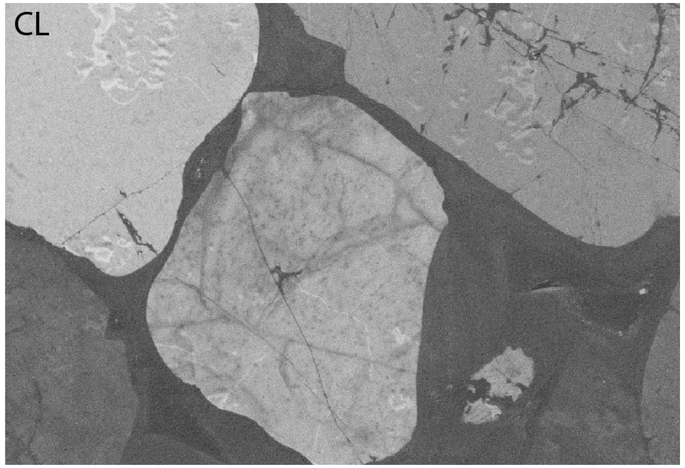
- **Mineral maps**
- **CL images**
- **BSE images**

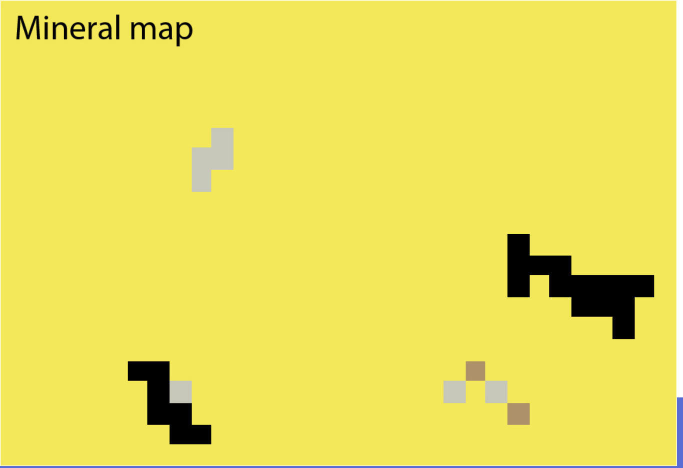
Information from these images must be combined

Images for hackathon:

SEM images of quartz-rich sandstones







BSE:
Backscattered electrons
(material contrast imaging)

CL:
Cathodoluminescence, photons
(mineral growth information)

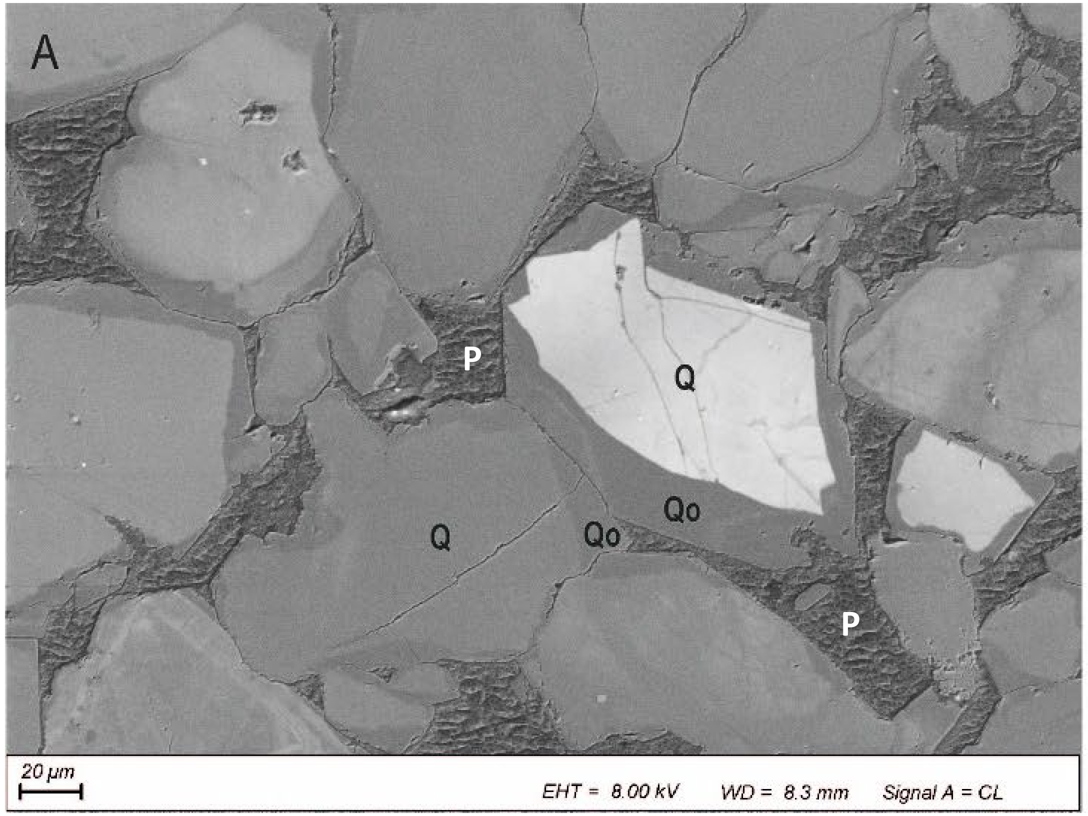
Mineral map:
Mineralscan by chemistry, X-rays
(automated quantitative mineralogy)

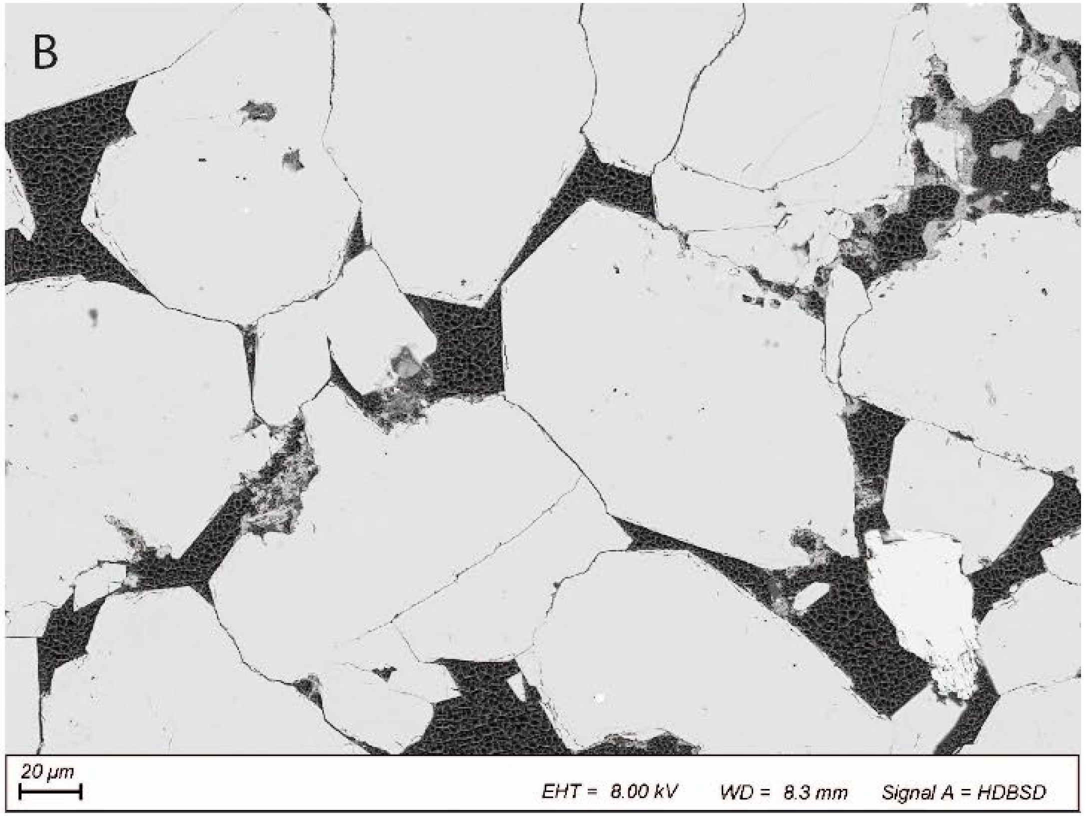
CL

growth
information

BSE

material
contrast





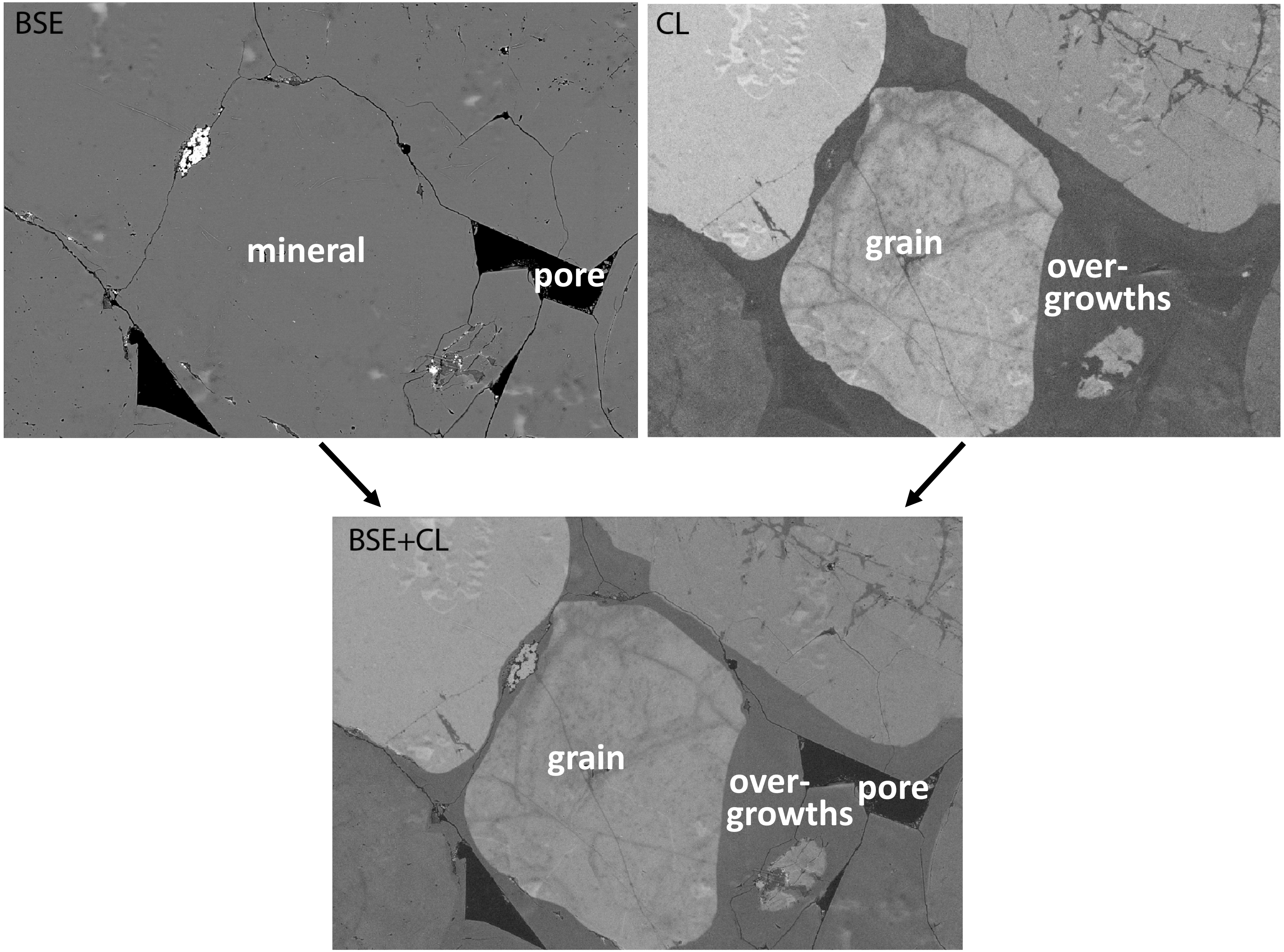
Q: quartz grain (original sand grain)

Qo: quartz overgrowth (rim grown on grain)

P: pore space (open pore between grains)

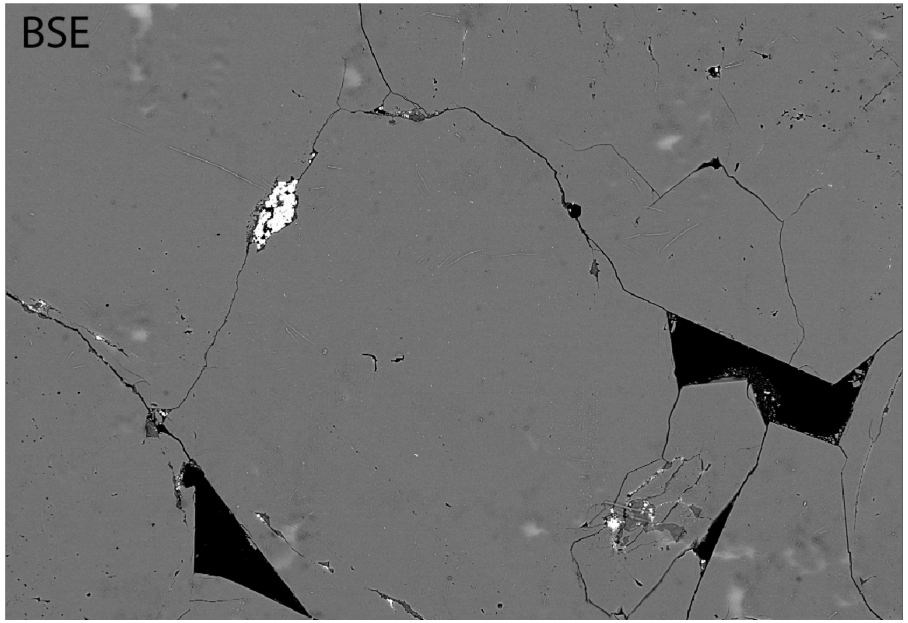
Hackathon assignment

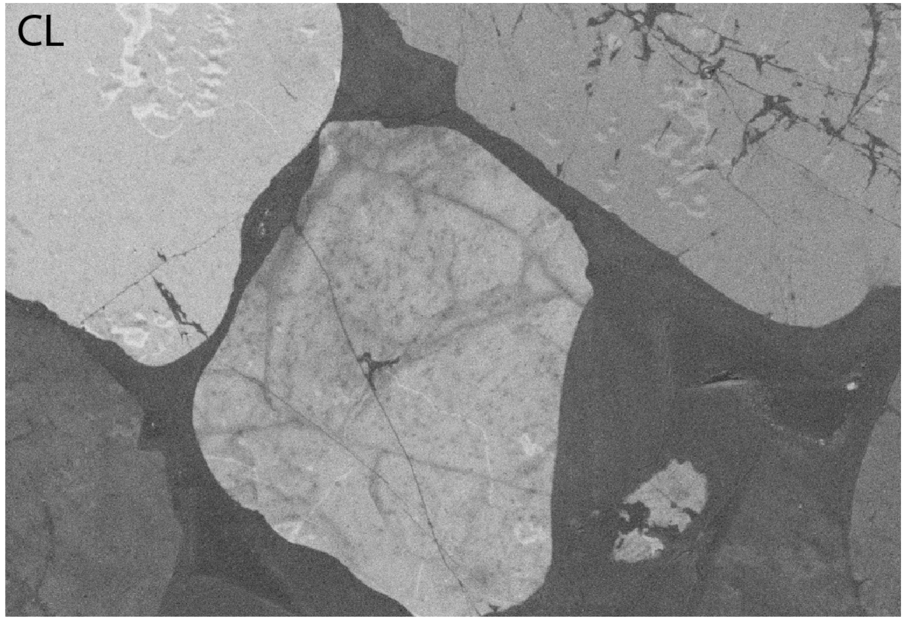
Step 1: Combine BSE and CL images

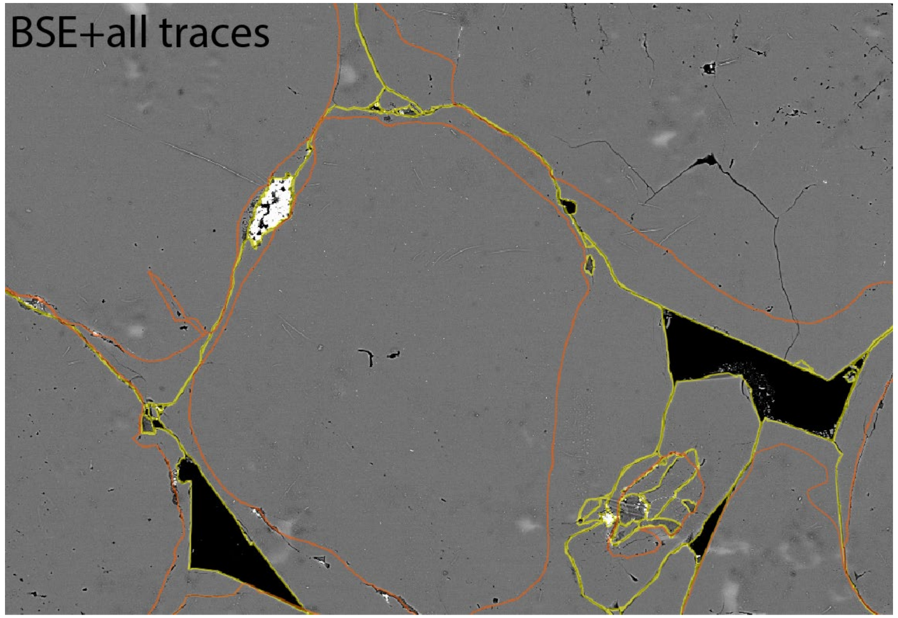


Hackathon assignment

Step 2: Trace boundaries on images







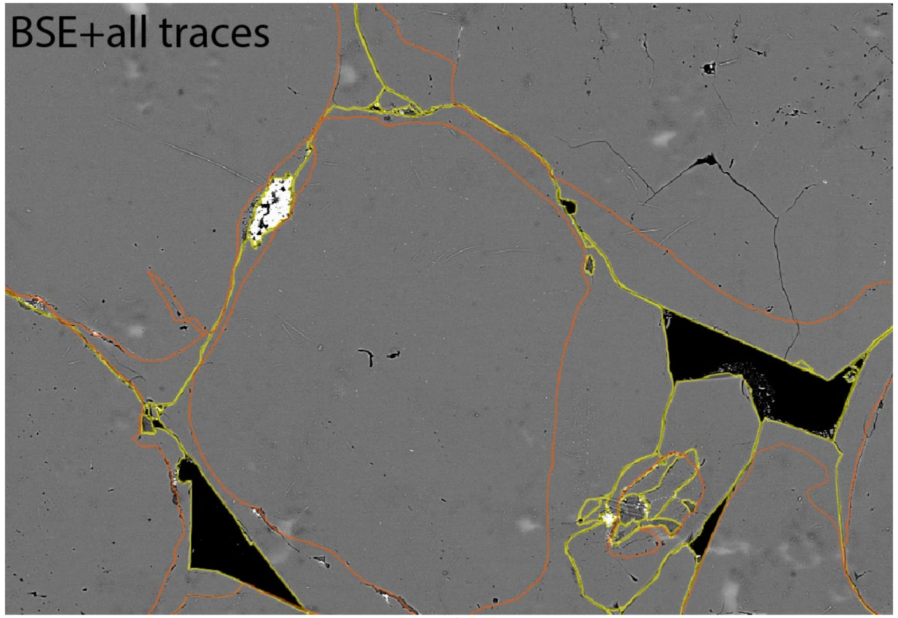
Traced lines:

Traced on BSE image

Traced on CL image

Hackathon assignment

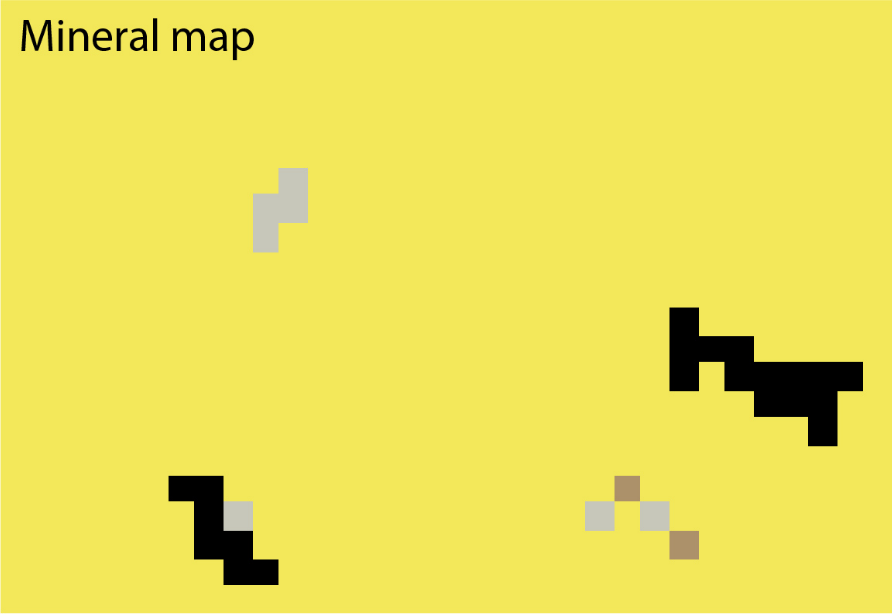
Step 3: Calculate areas of the phases



Traced lines:

Traced on BSE image

Traced on CL image

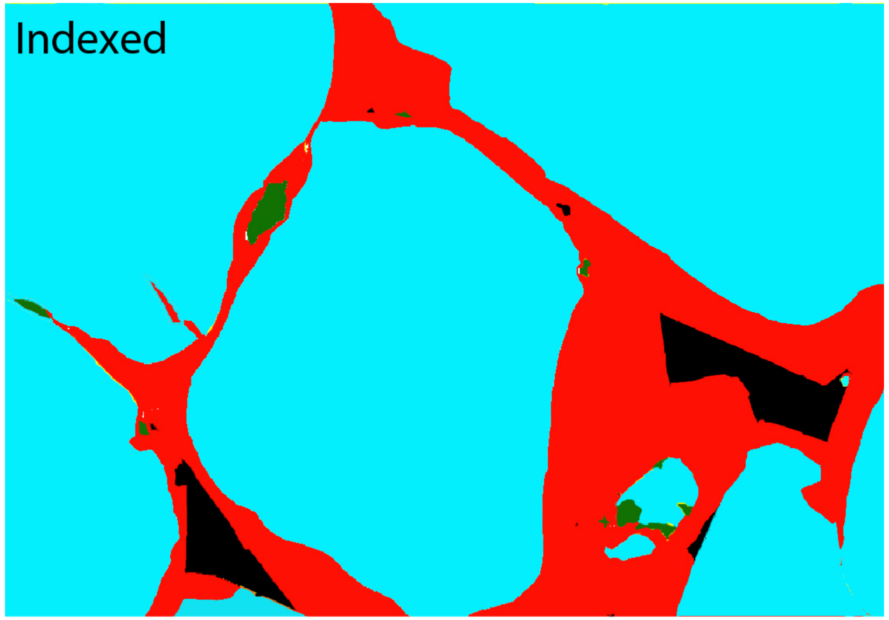


Mineral map:

Quartz

Other mineral than quartz

Pore



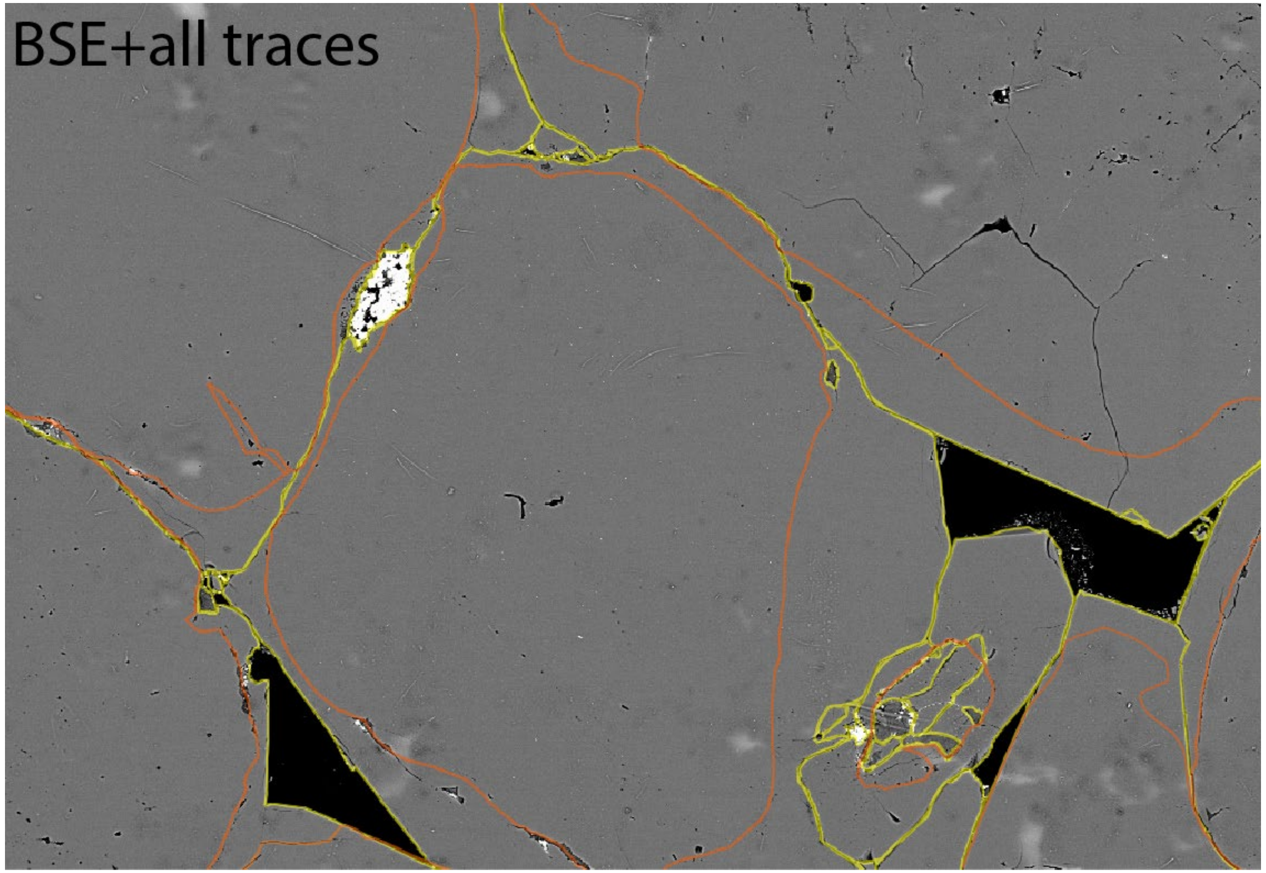
Indexed colours:

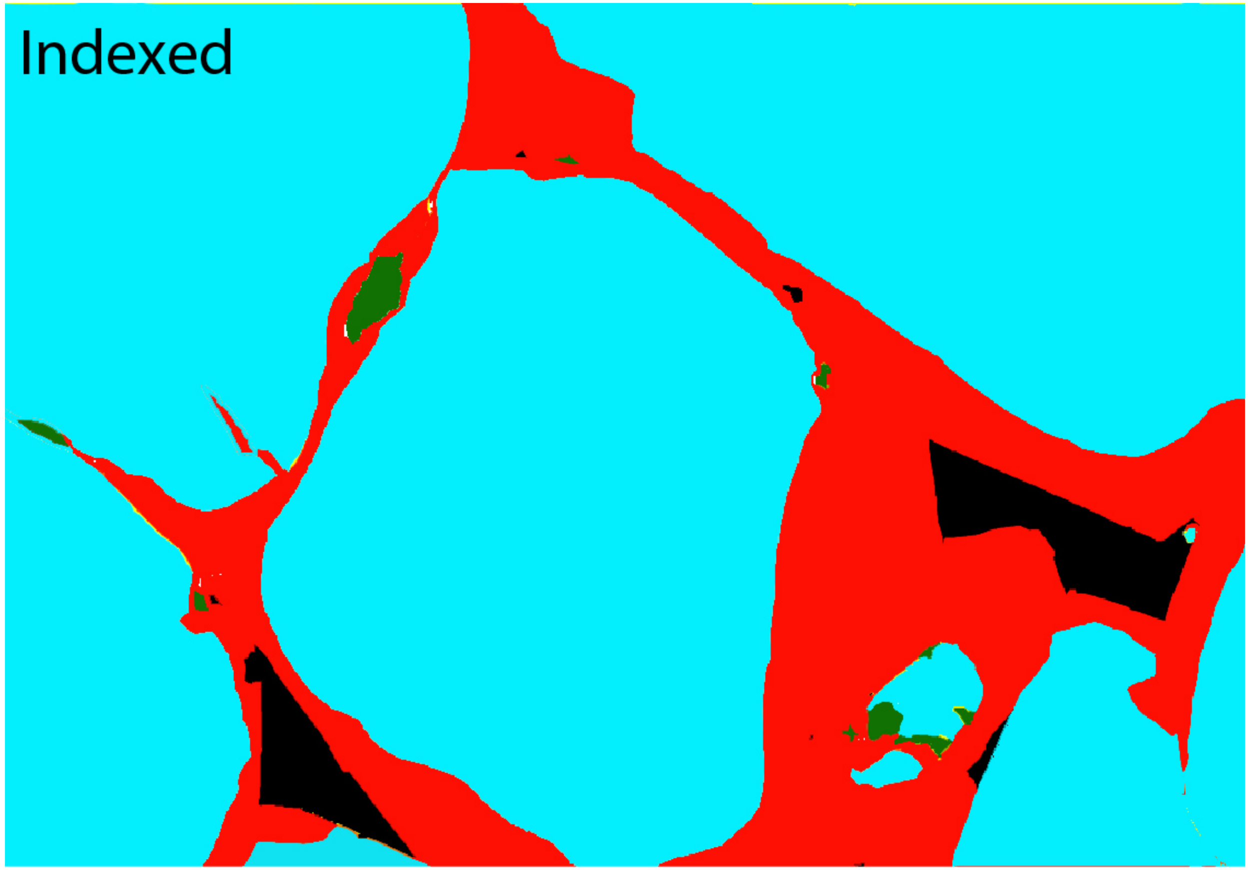
Quartz

Pore

Quartz overgrowth

Other mineral than quartz

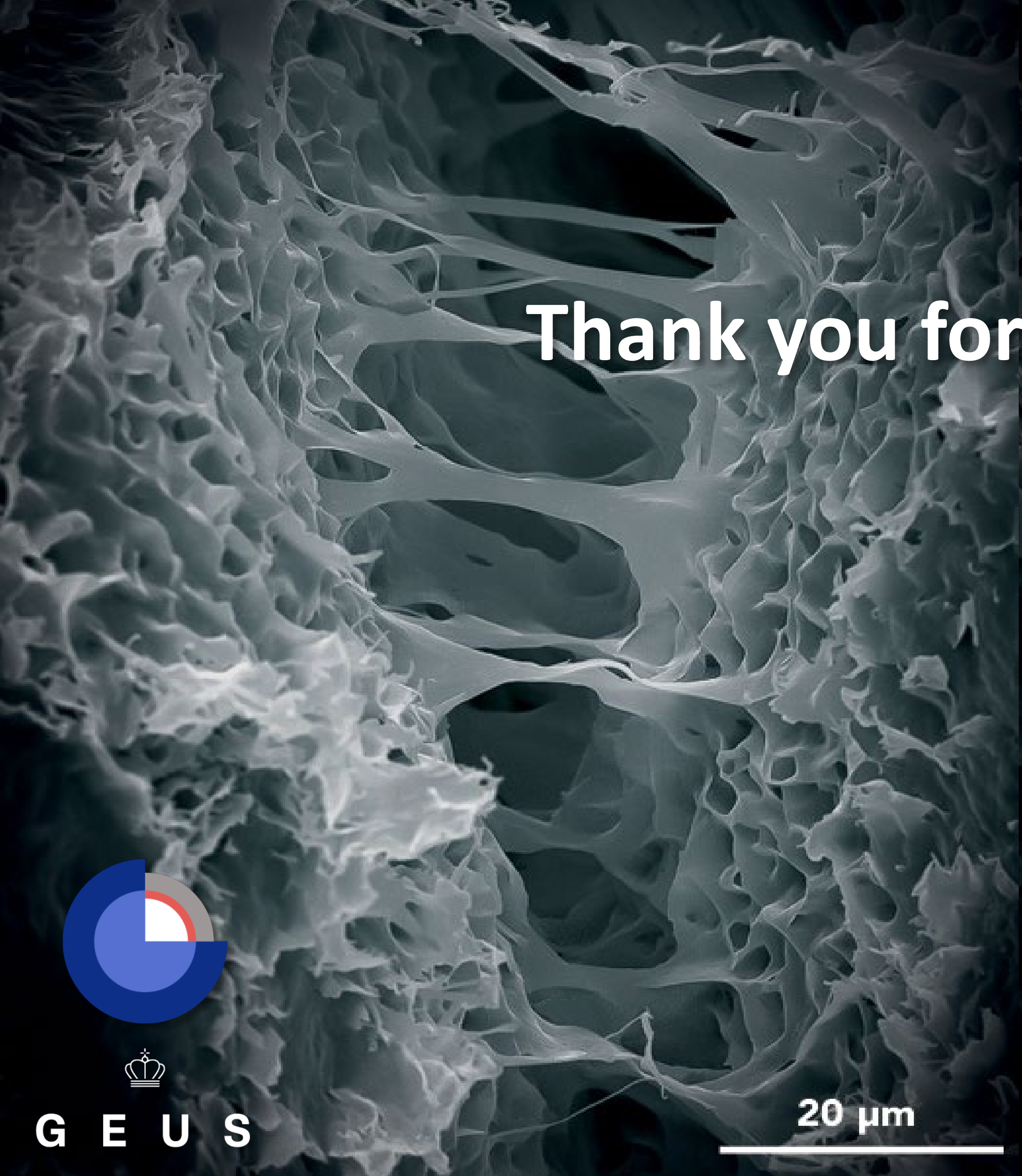




Delivery at end of hackathon:

- **Calculated areas of quartz grains, overgrowths, and pores**
- **Python code that shows how you have performed the tasks**
- **Short report and video summarizing procedure and results**

Thank you for your attention



Images: Geoviden, Rikke Weibel

G E U S

ENERGY GeO Hackathon
Society of Petroleum Engineers

SPE International Italian Section | SPE International London Section | SPE International Netherlands Section | SPE International Romanian Section | SPE International Copenhagen Section | SPE International Geothermal Technical Section

Q&A

Please, type your Question in the Zoom Chat

SPE International®

SPE Europe Region

#WeAreSPE

Be One of Us!

www.spe.org

ENERGY GeO Hackathon

Society of Petroleum Engineers

www.spehackathon-eu.com

#DatafyingEnergy