DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/1

Karlebo-1A: Investigation of cuttings samples from the Lower Cretaceous, Lower Jurassic and Gassum Formation

Contribution to an assessment of the Geothermal potential in the Farum, Helsingør and Hillerød area

Line Skovgaard Nielsen, Nynke Keulen, Lars Kristensen, Jens Therkelsen, Lars Henrik Nielsen & Anders Mathiesen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

GEUS

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2014/1

Karlebo-1A: Investigation of cuttings samples from the Lower Cretaceous, Lower Jurassic and Gassum Formation

Contribution to an assessment of the geothermal potential in the Farum, Helsingør and Hillerød area

Line Skovgaard Nielsen, Nynke Keulen, Lars Kristensen,
Jens Therkelsen, Lars Henrik Nielsen
& Anders Mathiesen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

GEUS

Contents

Preface

This report contains a microscopic investigation of selected cuttings samples from the Lower Cretaceous, Lower Jurassic and Upper Triassic potential geothermal reservoirs in the Karlebo-1A well.

The investigation contributes to the evaluation of the geothermal potential in North and Northeast Sjælland.

The investigation was financed by Farum Fjernvarme, Forsyning Helsingør and Hillerød Varme in common.

Background

The subsurface in the greater North – North-eastern Sjælland is assumed to contain several formations with potential geothermal sandstone reservoirs of which the most promising are (from below) the Bunter Sandstone Formation/Skagerrak Formation and the Gassum Formation, and some unnamed sandstone units embedded in the Fjerritslev Formation and the Lower Cretaceous succession (Mathiesen et al. 2009). However, the well database in this area is very sparse comprising only the Karlebo-1/1A, Lavø-1 and Margretheholm-1 &-2 wells and the wells at Stenlille. Of these are the Margretheholm-1 & -2 and the wells at Stenlille located at great distance from the area of interest, and the Lavø-1 well is an old hydrocarbon exploration well drilled in 1959. In contrast, the Karlebo-1/1A well is located centrally in the area of interest (Fig.1). It was drilled as a hydrocarbon exploration well in 2006. Owing to technical problems the Karlebo-1 well was terminated in the Fjerritslev Formation, and drilling was resumed with the sidetrack Karlebo-1A. Due to stability problems with the well bore, the Karlebo-1A well was terminated before the targeted Bunter Sandstone Formation was reached. Well-logs were only recorded down to ca. 2.218 m b. KB. corresponding to a level slightly below the middle part of the Gassum Formation.

The evaluation of the reservoir properties of the sandstones encountered in the Karlebo-1A well is hampered owing to the limited well log suite and the complete absence of well logs from the lower part of the Gassum Formation. This unfortunate shortage of data, particularly from the lower Gassum Formation was discussed with Farum Fjernvarme, Forsyning Helsingør, Hillerød Varme and DFG, and GEUS proposed to the clients to carry out an investigations of selected cuttings samples from the interesting intervals in the Lower Cretaceous, Fjerritslev and Gassum Formations in an attempt to strengthening the evaluations. The study was proposed by GEUS as a multi-client study co-financed among the three clients, as the potential results was considered to be equally valid for the three local areas of interest. Furthermore, the co-financing is limiting the investment for the individual clients and was proposed as an effort to secure the best possible balance between cost and potential results.

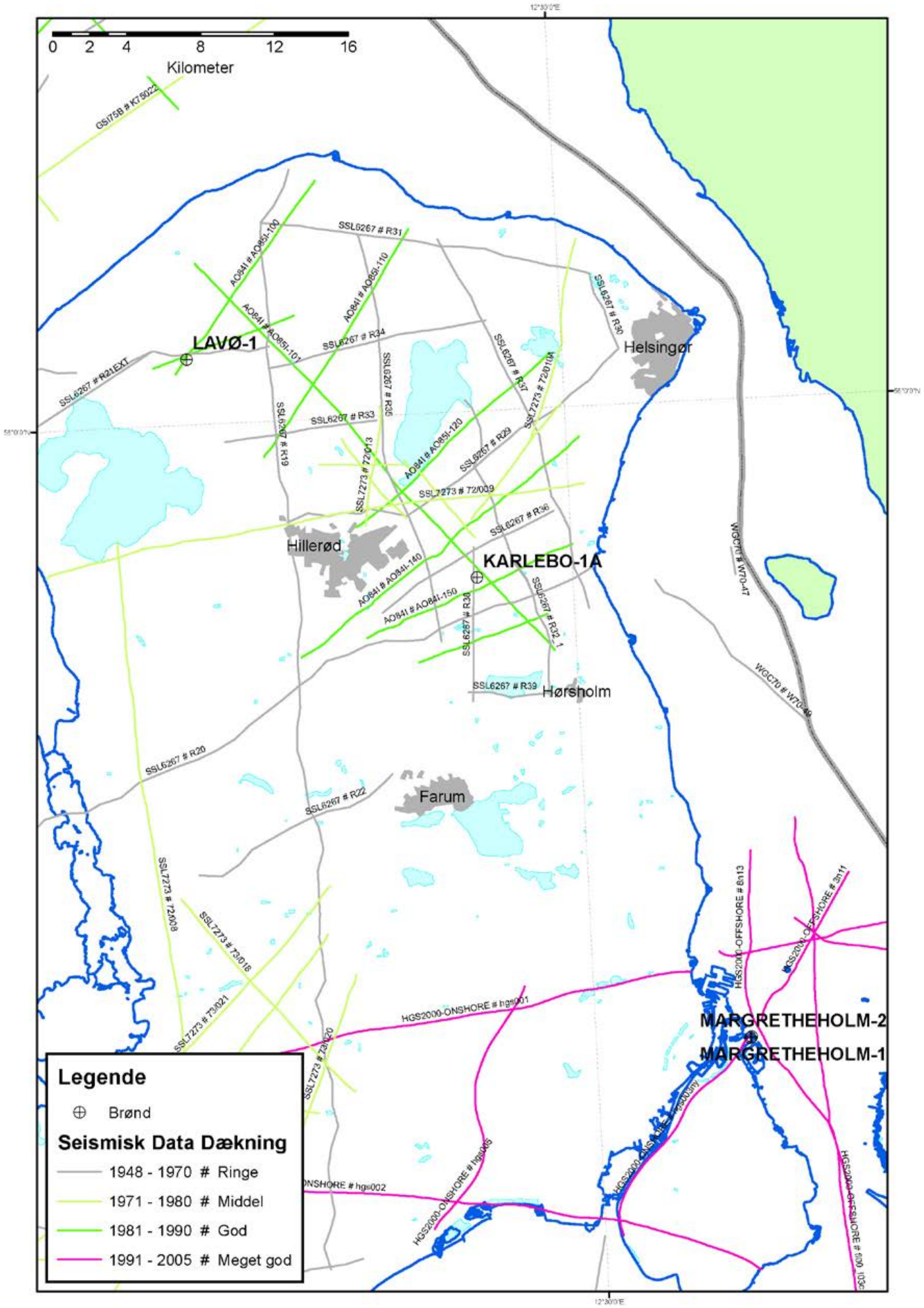

***Figure 1**: Map of North Sjælland. The location of the Karlebo-1 well is indicated on the map along with Lavø-1 and Magretheholm-1 & -2.The seismic coverage (position of seismic lines) is shown and colour coded. The colour code reflects the vintage and quality of the seismic data, assuming a correlation between quality and vintage.*

Methods

To strengthening and improve the quality of the current estimations of the geothermal potential for the Farum-Hillerød-Helsingør areas, the lithology of selected cuttings samples from the Karlebo-1A well were investigated and compared to the well logs acquired in the well. The well logs were interpreted using the Landmark Petroworks software; the three identified potential reservoir sections are shown in Figure 2. In a following section on reservoir parameters their characteristics are listed.

However, the evaluation of the reservoir parameters and ultimately an assessment of their production capacity are related to considerable uncertainty owing to the sparse database without cores or production tests. In addition well logs were not acquired from the lower part of the Gassum Formation (Figure 2). As the Gassum Formation in many places in Denmark constitutes the primary geothermal project, this lack of information is crucial for the local assessment.

Therefore, cuttings samples were selected from the entire Gassum Formation, and from sandstones in the two overlying units, the Lower Jurassic Fjerritslev Formation and the undifferentiated Lower Cretaceous. The samples were selected from the samples in GEUS sample archive on the basis of a log evaluation supported by information in the well completion report.

The approach has been to establish a well-defined relation between the lithology of the cuttings and the well logs in the upper Gassum Formation and to extrapolate this relation down to the lower part of the formation where no well logs were obtained by acquiring as much information as possible on the lithology, mineralogy and porosity of the sandstones in the lower Gassum Formation. For the sandstones in the Fjerritslev Formation and the Lower Cretaceous, the goal has primarily been to establish a better fundament for the well log interpretations.

The cuttings samples were firstly screened on a macroscopic base to discriminate between sandstones and mudstones (non-reservoir). On this basis 8 samples from the Lower Cretaceous unit, 37 samples from the Fjerritslev Formation and 30 samples from the Gassum Formation were selected for a closer investigation using an optical microscope to obtain information on grain sizes, sorting and cement, which influence the porosity and permeability and thus transmissivity (summarised in Table 1). Based on the visual investigation and description, 20 samples, assumed to be representative for the individual sandstones, were analysed with scanning electron microscopy (SEM) with a concentration in the lower part of the Gassum Formation. The SEM analyses were directed toward the identification of type and amount of cement, overgrowths, authigenic clay minerals potentially blocking pore throats etc.

The results of the microscopic analyses were then used to evaluate the results of the conventional well log interpretation presented in the section on reservoir parameters.

It should be noted that information from cuttings samples compared to core samples is subject to several possible errors. When cuttings samples are brought to the surface during the drilling process some mixing of lithology is likely to occur. Furthermore, the well bore (the walls in the borehole) is often somewhat unstable and breaks of small fragments that fall down hole and become included in the cuttings samples causing the samples to be mixture of true cuttings and rock chips from above. It should also be noted that well cemented sandstone samples have a higher survival potential than less cemented sandstone fragments and thus tend to be over-represented in the samples.

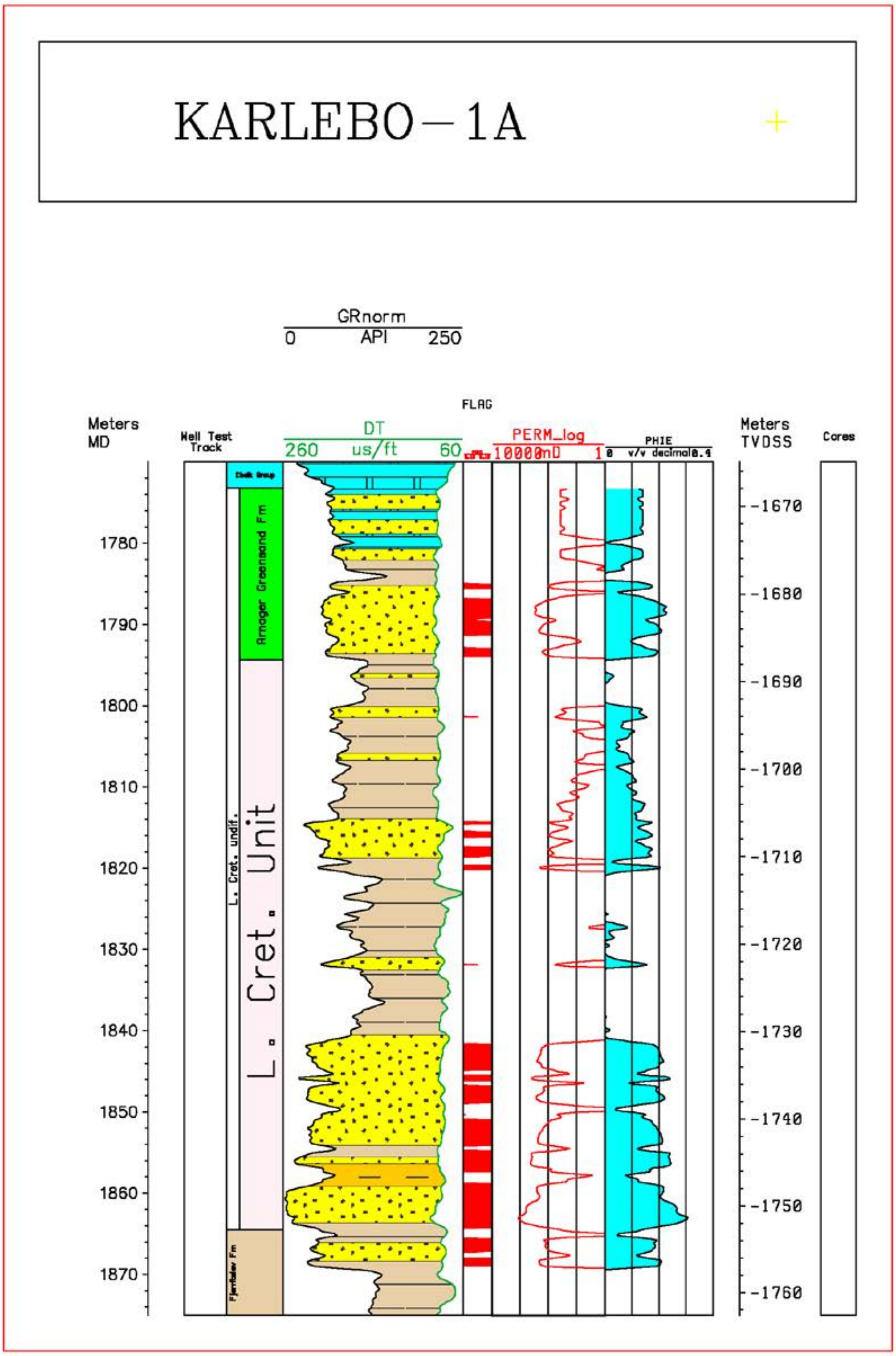

***Figure 2.A**: Petrophysical evaluation and lithological interpretation of the Lower Cretaceous Unit in Karlebo-1A. The log-derived porosity (PHIE) is highlighted by blue colour fill. The calculated permeability curve is plotted left of the porosity (red curve, PERM_log)*

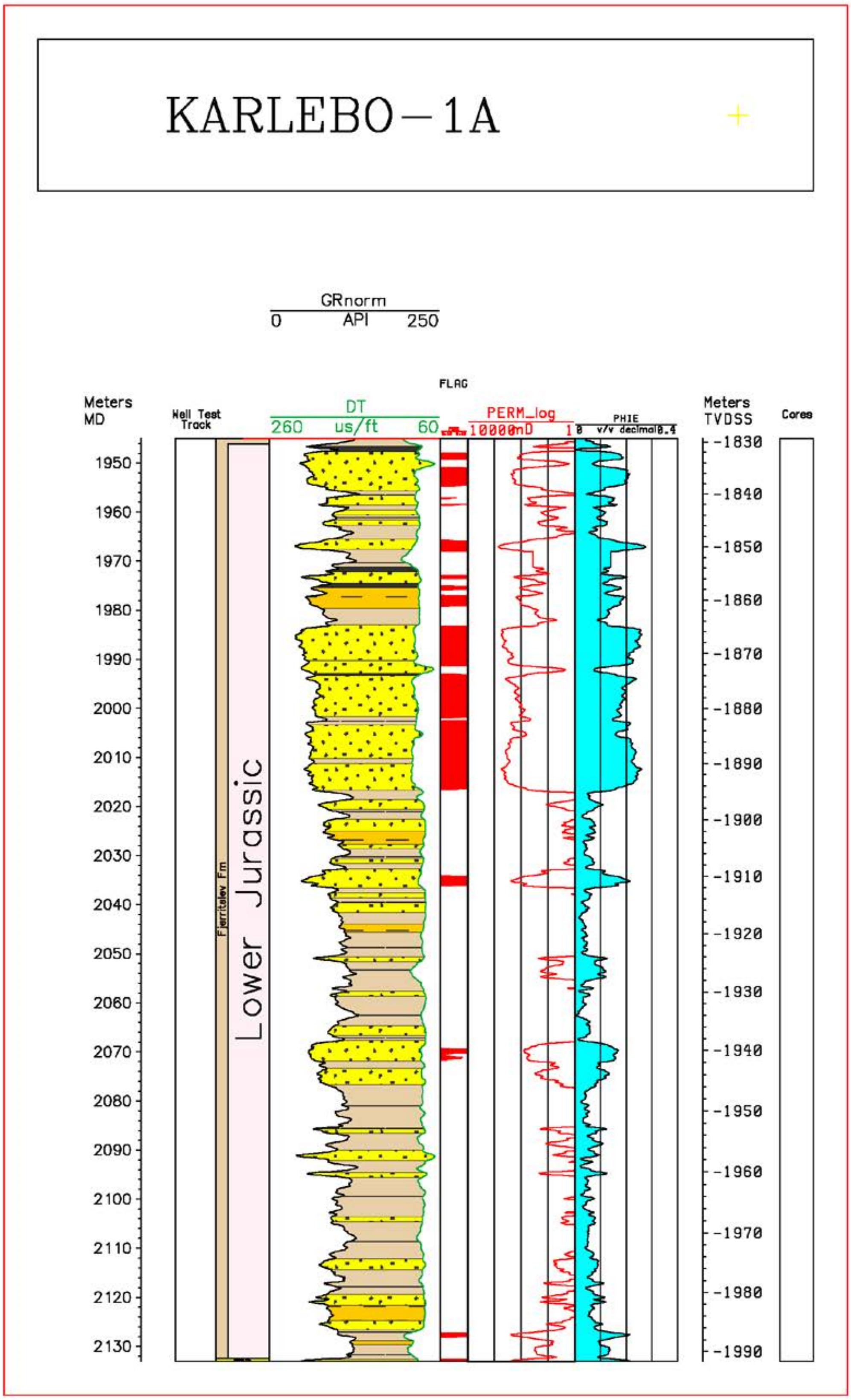

__Figure 2.B__: Petrophysical evaluation and lithological interpretation of the Lower Jurassic Unit in Karlebo-1A. The log-derived porosity (PHIE) is highlighted by blue colour fill. The calculated permeability curve is plotted left of the porosity (red curve, PERM_log)

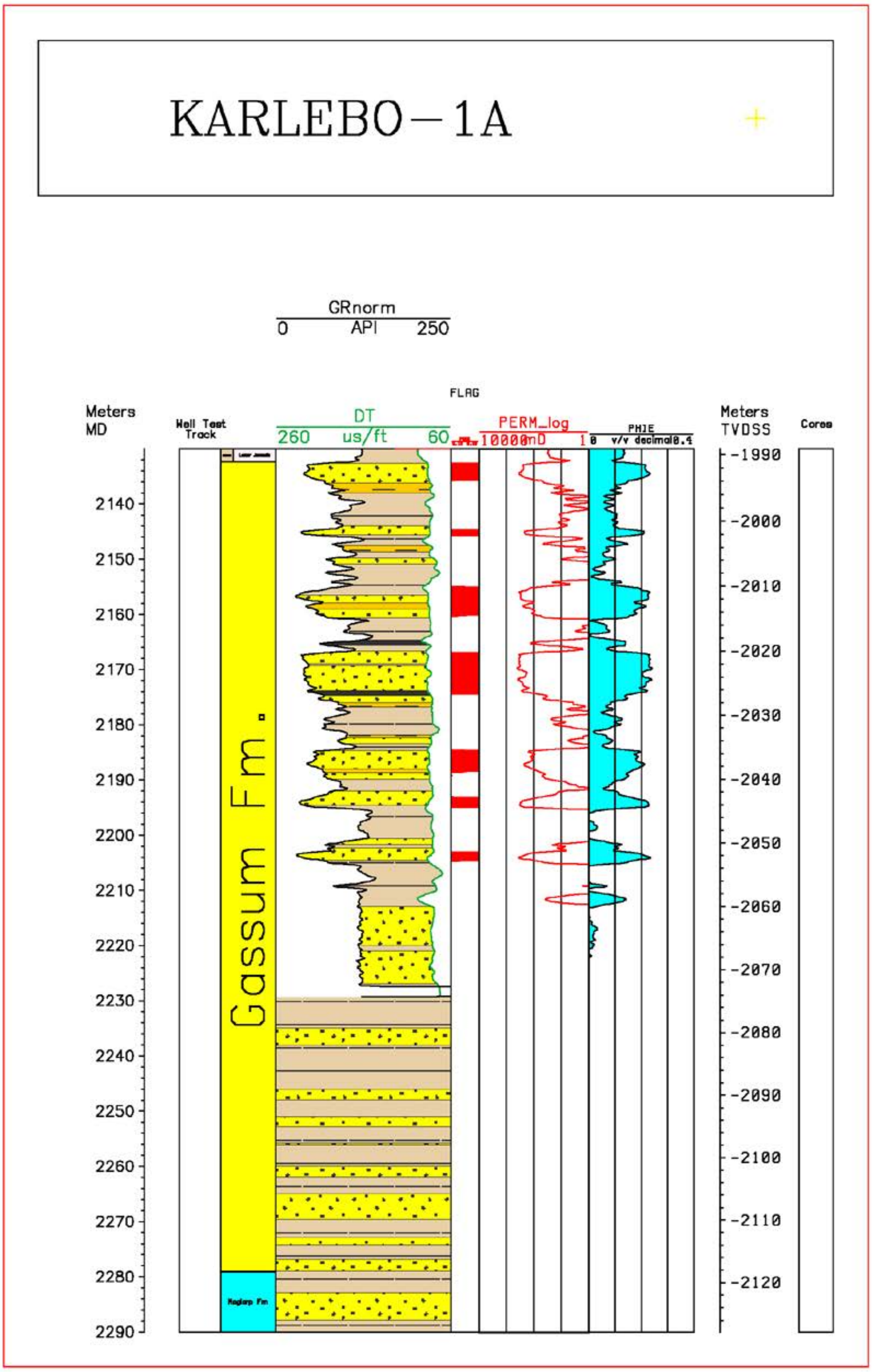

***Figure 2.C**: Petrophysical evaluation and lithological interpretation of the Gassum Formation in Karlebo-1A. The log-derived porosity (PHIE) is highlighted by blue colour fill. The calculated permeability curve is plotted left of the porosity (red curve, PERM_log)*

Legend:

GRnorm: Normalized Gamma-Ray (GR) log
DT: Sonic log
FLAG: Indicator for potential reservoir sand (solid red)
PERM_log: Permeability as estimated from the log-derived porosity (PHIE)
PHIE: Log-derived porosity (calculated from GR and DT). Highlighted by blue color fill
Lithologies:

- Yellow: Sandstone
- Brown: Shale/mudstone
- Orange: Siltstone
- Black: Coal

Karlebo-1A

Overview of examined samples

The petrographic analysis with scanning electron microscope (SEM) of sandstones from the Lower Cretaceous Unit, Fjerritslev Fm- and Gassum Formations in the Karlebo-1A well has been carried out on 20 sandstone samples, all of these are cuttings samples. The investigated samples were divided over these formations as follows:

L. Cret. Unit
- 1810 m below kb.
- 1820 m below kb.

Fjerritslev Fm.
- 1860 m below kb
- 1870 m below kb.
- 1952.5 m below kb.
- 1980 m below kb.
- 1992.5 m below kb.
- 2010 m below kb.
- 2070 m below kb.
- 2120 m below kb.

Gassum Formation
- 2132.5 m below kb.
- 2137.5 m below kb.
- 2155 m below kb.
- 2170 m below kb.
- 2185 m below kb.
- 2210 m below kb.
- 2230 m below kb.
- 2250 m below kb.
- 2267.5 m below kb.
- 2277.5 m below kb.

***Table 1**: Summarized information (grain sizes, sorting and cement) which influence the porosity and permeability and thus transmissivity of the samples.*

	Optical microscope observations of selected cutting samples						**SEM observations**		
	M b. kb	**Colour**	**Dominant features**	**Other features**	**Grain size**	**Sorting (sand)**	**Quartz Cement**	**Car-bonate Cement**	**Clay Cement**
L. Cret. Unit	1810-1820	Greenish grey to grey	Dominated by sand and sandstone fragments	None observed	Increasing with depth. Very fine-medium to fine-coarse	medium	None/Rare overgrowth	Rare	Sample 1810 & 1820: Chlorite.
	1840-1865	Dark grey to black	Dominated by black organic matter	Rare mud/siltstone and sandstone fragments	Fine	good	Overgrowth	None observed	Sample 1860: Kaolinite.
Fjerritslev Fm.	1870	Brownish grey	Dominated by black organic matter	Common sand, sandstone fragments, mud/siltstone and mica	Fine to medium	good	Overgrowth	None observed	Sample 1870: Illite and glauconite.
	1950-1960	Grey to brownish grey	Dominated by sand and mud/siltstone	Common sand-stone fragments and mica	Medium to coarse	Medium/ poor	Overgrowth	Common	Sample 1952,5: Illite, kaolinite, and glauco-nite.
	1962,5-1970	Grey to dark grey	Dominated by sand	Common sand-stone fragments, mud/siltstone and mica	Fine to medium	Good/ medium	N/A	N/A	N/A
	1972,5-1975	Dark grey	Dominated by sand, sand-stone frag-ments and mudstone	None observed	Fine to coarse	Medium/ poor	N/A	N/A	N/A
	1977,5-1980	Grey	Dominated by sand, sand-stone frag-ments and siltstone	None observed	Fine to Medium	Good/ medium	Overgrowth and micro quarz	None observed	Sample 1980: Chlorite and kaolinite.
	1982,5-2010	Yellowish grey to grey	Dominated by sand	Common sand-stone fragments and mud/siltstone	Fine to medium	Good/ medium	Overgrowth	Common	Sample 1992,5 & 2010: Illite and kaolinite.
	2012,5-2020	Yellowish grey to grey	Dominated by sand	Common sand-stone fragments, mica and mud/siltstone	Fine to coarse	Medium	N/A	N/A	N/A
	2060	Brownish grey	Dominated by mudstone	Some scattered sand	Very fine	Good	N/A	N/A	N/A
	2062,5-2115	Grey to brownish grey	Dominated by sand and sandstone fragments	Common mud/siltstone	Fine to medium	Medium	Overgrowth	None observed	Sample 2070: Illite and kaolinite.
	2117,5-2122,5	Grey	Dominated by sand	Common mud/siltstone and carbonates	Fine to medium	Good/ Medium	Overgrowth	None observed	Sample 2120: Illite
	2125-2130	Grey to brownish grey	Dominated by sand and mud/siltstone.	Common sand-stone fragments	Fine to medium	Medium	N/A	N/A	N/A

Gassum Fm	2132,5-2137,5	Light grey to brown-ish grey	Dominated by sand and mud/siltstone	Common sand-stone fragments	Fine to Medium	Good/ Medium	Overgrowth	None observed	Sample 2132,5 & 2137,5: Illite and chlorite
	2140	Brownish grey	Dominated by sand and sandstone fragments	Less common mud/siltstone fragments	Very fine to fine	Good	N/A	N/A	N/A
	2142,5-2145	Dark grey	Dominated by sand and mud/siltstone	Common sand-stone fragments and carbonates.	Fine to medium	Medium	N/A	N/A	N/A
	2147,5	Brownish grey	Dominated by sand and sandstone fragments	Common mud/siltstone and carbonates,	Very fine to medium	Good/ medium	N/A	N/A	N/A
	2150-2160	Grey	Dominated by sand, sand-stone frag-ments and mud/siltstone	None observed	Fine to medium	Good/ Medium	Overgrowth	None observed	Sample 2155: Illite and chlorite
	2162,5-2175	Grey to dark grey	Dominated by sand and sandstone fragments	Common mud/siltstone	Fine to coarse	Medium	Overgrowth and micro quartz	None observed	Sample 2170: Illite
	2180	Dark grey	Dominated by sand and mud/siltstone	Rare sandstone fragments	Fine to medium	Good	N/A	N/A	N/A
	2182,5	Dark grey	Dominated by mud/siltstone	Some scattered sand	Fine	Medium	N/A	N/A	N/A
	2185-2195	Grey to brownish grey	Dominated by sand and mud/siltstone	Common sand-stone fragments	Fine to medium	Medium	Overgrowth	Locally	Sample 2185: Kaolinite
	2200-2210	Light brownish grey	Dominated by sandstone fragments and sand	Common mud/siltstone	Very fine to medium	Good/ medium	Overgrowth	None observed	Sample 2210: Illite
	2215-2230	Light grey to grey	Dominated by sand and mud/siltstone	Common sand-stone fragments	Fine to medium	Fine/ medium	Overgrowth	None observed	Sample 2230: Illite
	2232,5-2235	Dark brownish grey	Dominated by black organic matter	Some scattered sand	Fine to coarse	Poor	N/A	N/A	N/A
	2237,5-2250	Dark brownish grey	Dominated by black organic matter and sand	Some scattered sandstone fragments	Fine to medium	Good/ medium	Overgrowth	None observed	Sample 2250: Illite and kaolinite.
	2255	Grey	Dominated by sand and mud/siltstone	None observed	Very fine to medium	Medium	N/A	N/A	N/A
	2260	Light grey	Dominated by sandstone fragments and sand	Common mud/siltstone	Fine to medium	Medium	N/A	N/A	N/A
	2265-2267,5	Brownish grey	Dominated by sand, sand-stone frag-ments and mud/siltstone	Scattered carbonates	Fine to medium	Medium/ poor	Overgrowth	Locally	Sample 2267,5: Illite and Kaolinite
	2270-2272,5	Light grey to grey	Dominated by sand and sandstone fragments	Common mud/siltstone	Medium to coarse	Medium	N/A	N/A	N/A
	2272,5-2280	Reddish and brownish grey	Dominated by sand and sandstone fragments	Common mud/siltstone	Fine to medium	Medium	Overgrowth	None observed	Sample 2277,5: Illite and chlorite.

The petrography of the cutting samples from the Karlebo-1A well are described in detail below, followed by a description of the samples that were only investigated with optical microscopy.

L. Cretaceous

1810 m below kb.

The sample is greenish grey and dominated by fine to medium grained sand and fine grained, weakly cemented sandstone fragments. Two sandstone fragments were picked for further SEM investigation.

The SEM investigation showed that the sandstone is mainly composed of quartz and feldspar, with minor components of authigenic glauconite, illite, and calcite (Fig 3.A). The quartz grains show authigenic overgrowths (Fig 3.B). Illite is abundantly present and occurs mainly as coating on quartz and as pore-filling. Smectite and minor amounts of chlorite, barite, and KCl, all derived from the drilling mud, are present in the sample.

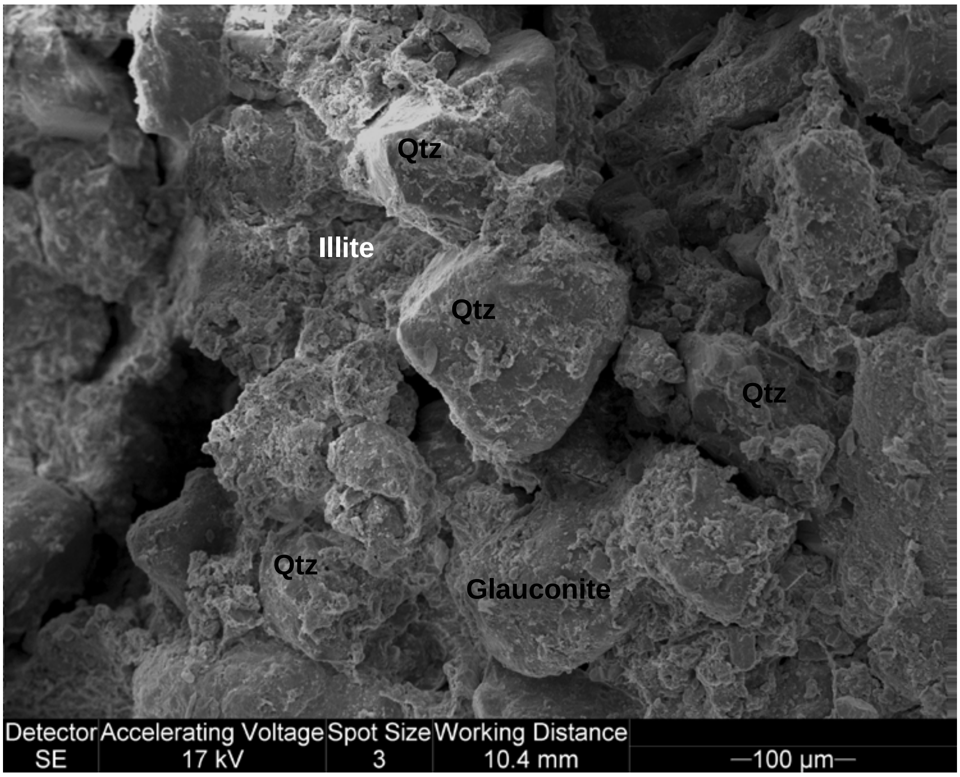

Figure 3.A*: Very fine to fine grained detrital quartz grains (Qtz) consolidated in an illitic matrix.*

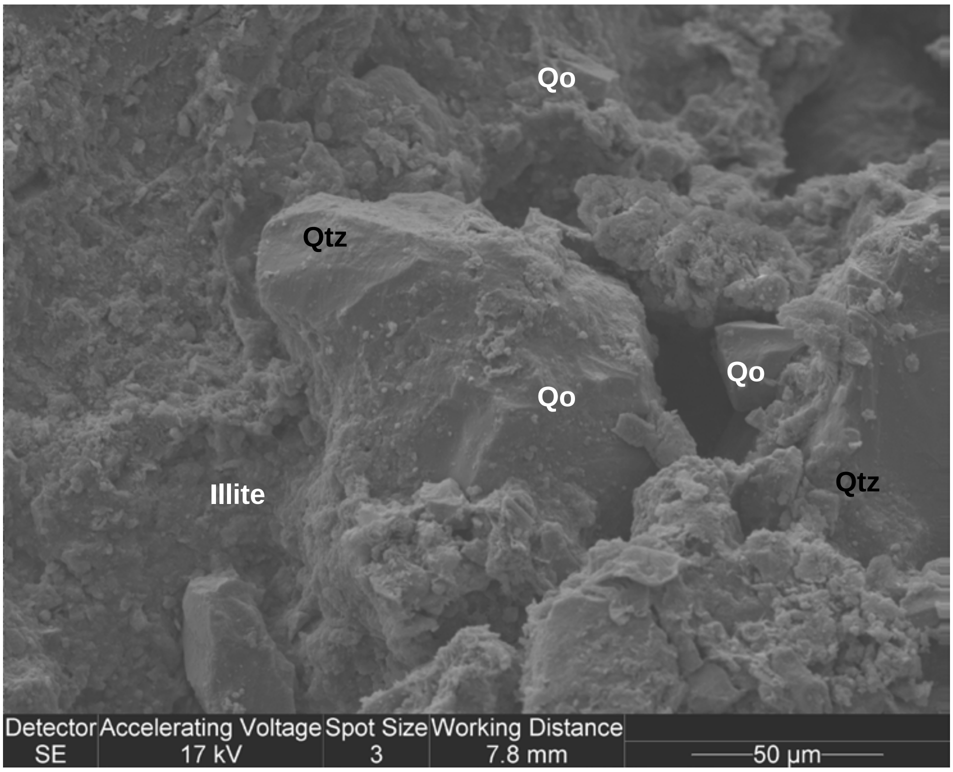

Figure 3.B*: Incipient overgrowths (Qo) on quartz grains consolidated in an illitic matrix.*

1820 m below kb.

The sample is light grey and is dominated by fine to medium grained sand and sandstone fragments. The sandstone fragments are weakly cemented and fine - coarse grained. Three sandstone fragments were chosen for SEM investigation.

The SEM analysis revealed that detrital grains within the sandstone fragments are mainly plagioclase and sub-rounded to rounded quartz with no or incipient quartz overgrowths (Fig 4.A).

The pores have been filled with a clayey matrix which also coats the sand grains. The clay was determined by EDS analysis to consist mainly of smectite which is most likely drill mud, however rare authigenic chlorite was observed in pore spaces (Fig 4.B).

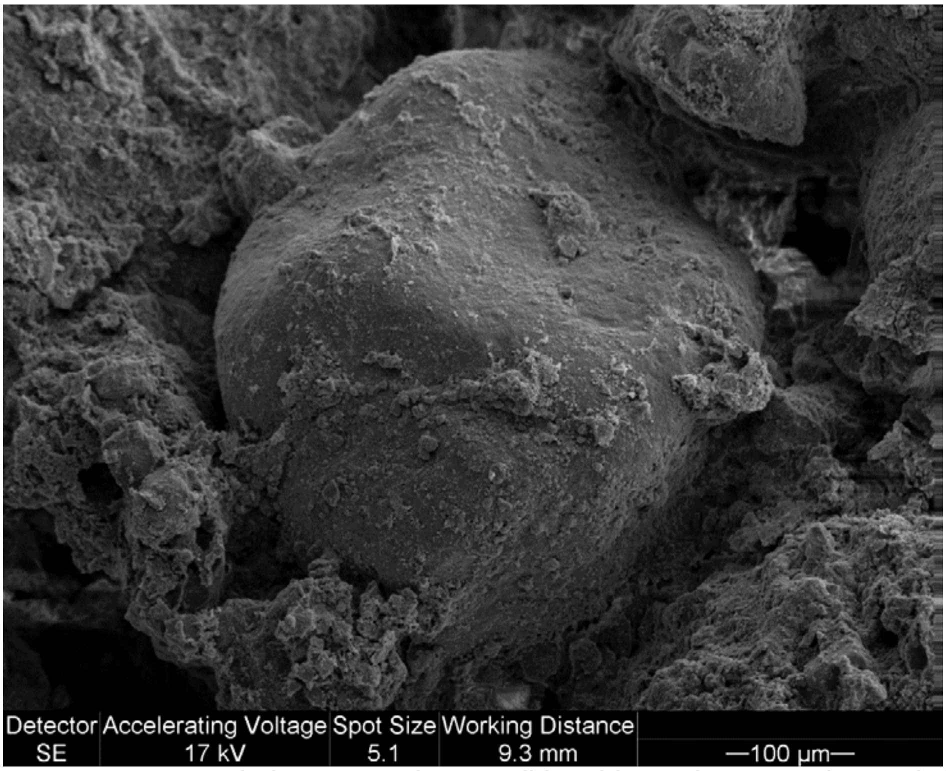

Figure 4.A*: Rounded quartz grain consolidated by a clayey matrix consisting of mainly of smectite (most likely drilling mud).*

Figure 4.B*: Rare chlorite growing within a pore space.*

1860 m below kb.

The sample is dark grey and is dominated by black organic matter (coal) and fine to coarse grained sand. Mudstone and sandstone fragments are less common. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain and two sandstone fragments were chosen for SEM investigation.

The sandstone fragment is loosely cemented, very porous and is dominated by quartz, feldspar and dark organic matter in a clayey matrix (Fig 5.A). Bariumsalt and abundant smectite was determined by EDS analysis and is most likely infiltrated drilling mud. No illite was found, but it may be covered by drilling mud.

Detrital quartz grains display incipient overgrowth (Fig 5.B). Rare authigenic kaolinite was observed.

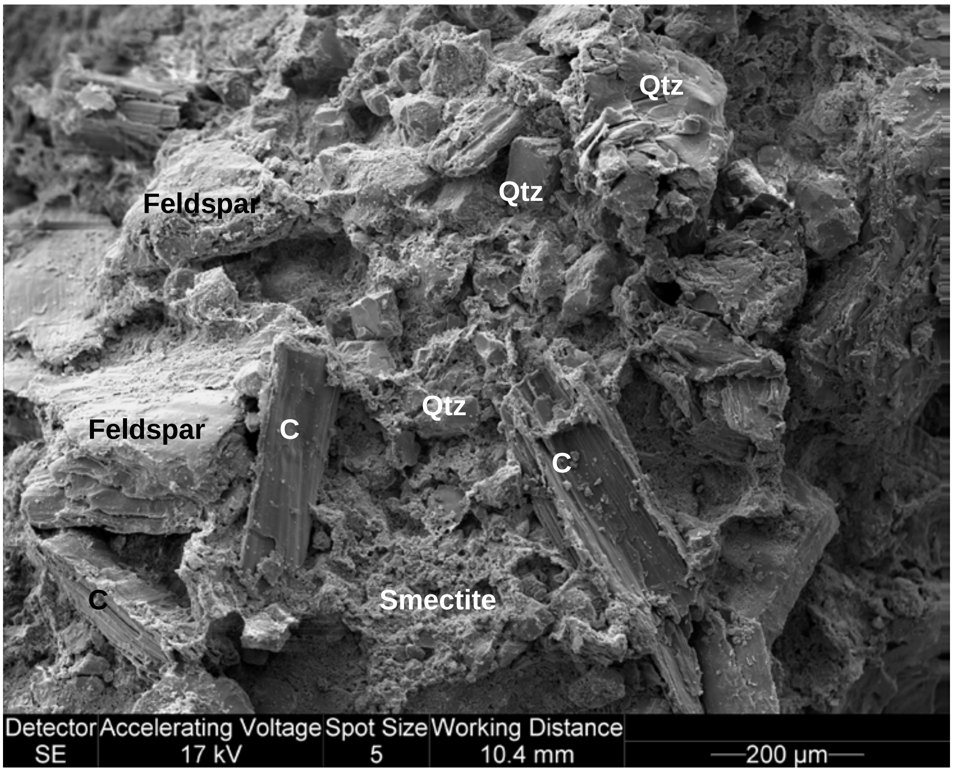

Figure 5.A: *The sandstone fragments mainly display dark organic matter (C), feldspar and quartz consolidated in a smectite matrix. Bariumsalt occur in the smectite why it is most likely drilling mud.*

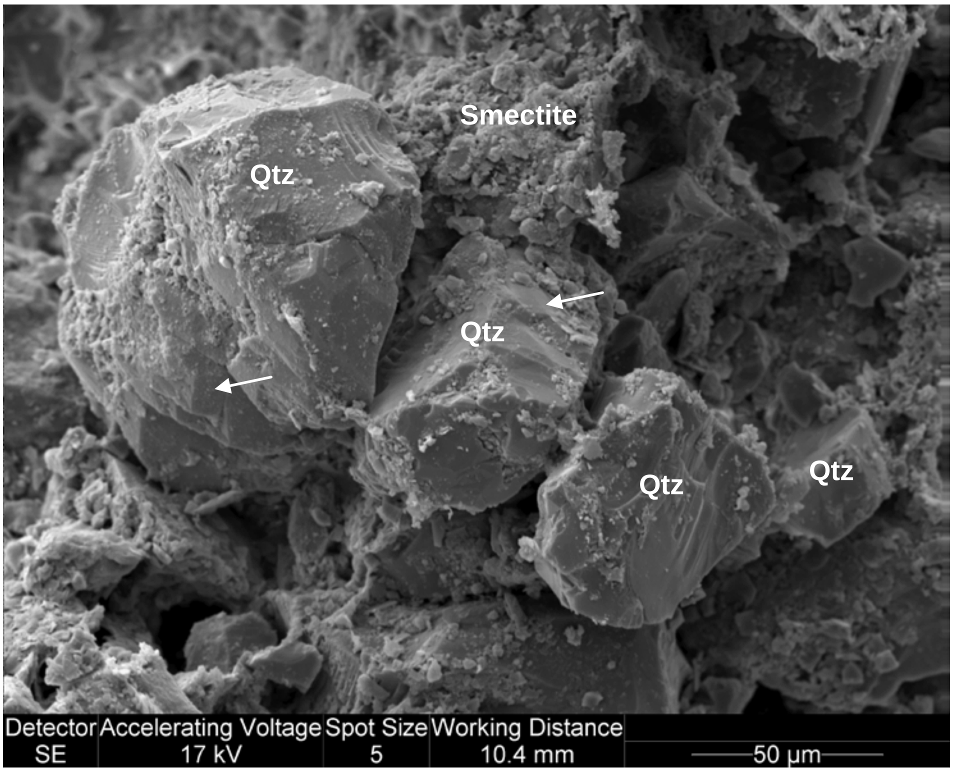

Figure 5.B: *Detrital quartz grains with incipient quartz overgrowths (marked by arrows).*

Fjerritslev Formation

1870 m below kb.

The sample is greyish brown and is dominated by black organic matter and fine to medium grained sand. Sandstone fragments are rare. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain and a sandstone fragment were chosen for SEM investigation.

The SEM investigation reveals that the quartz grains have a coating of clay minerals, mainly illite and chlorite, and some calcite (Fig 6.A). Incipient quartz overgrowths are observed on the quartz grains (Fig 6.B). Glauconite occurs as individual.

The sandstone fragments were fully covered with smectite and KCl, which most likely originate from the infiltrated drilling mud. dark organic matter fragments were observed in the sandstone.

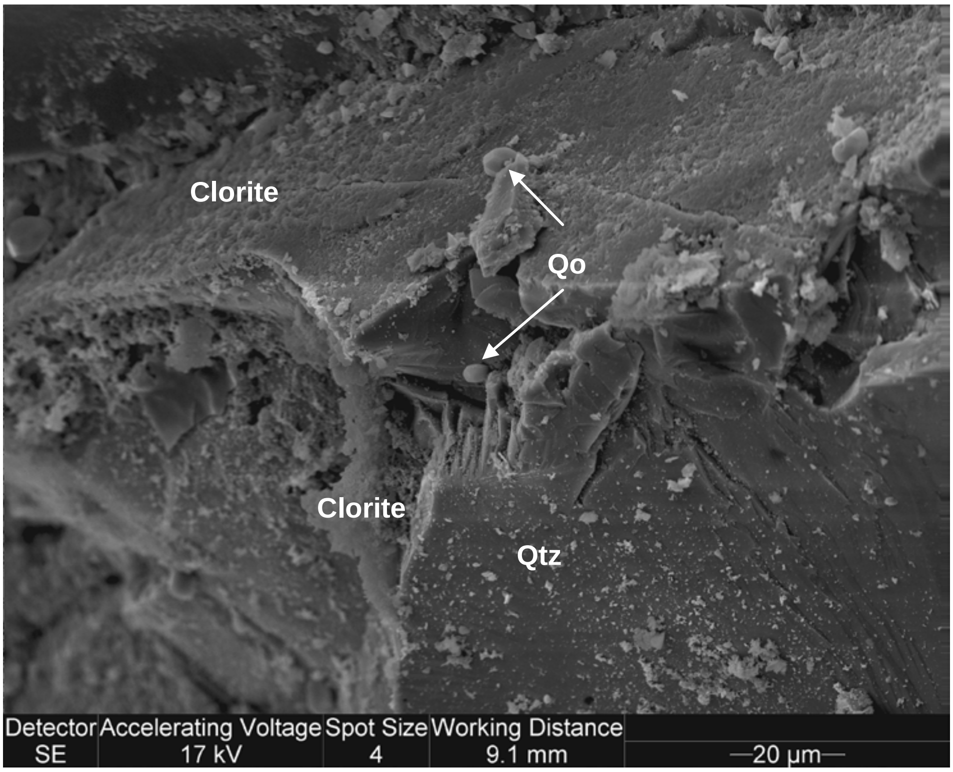

Figure 6.A*: Quartz grain (Qtz) with chlorite coating and micro quartz (Qo).*

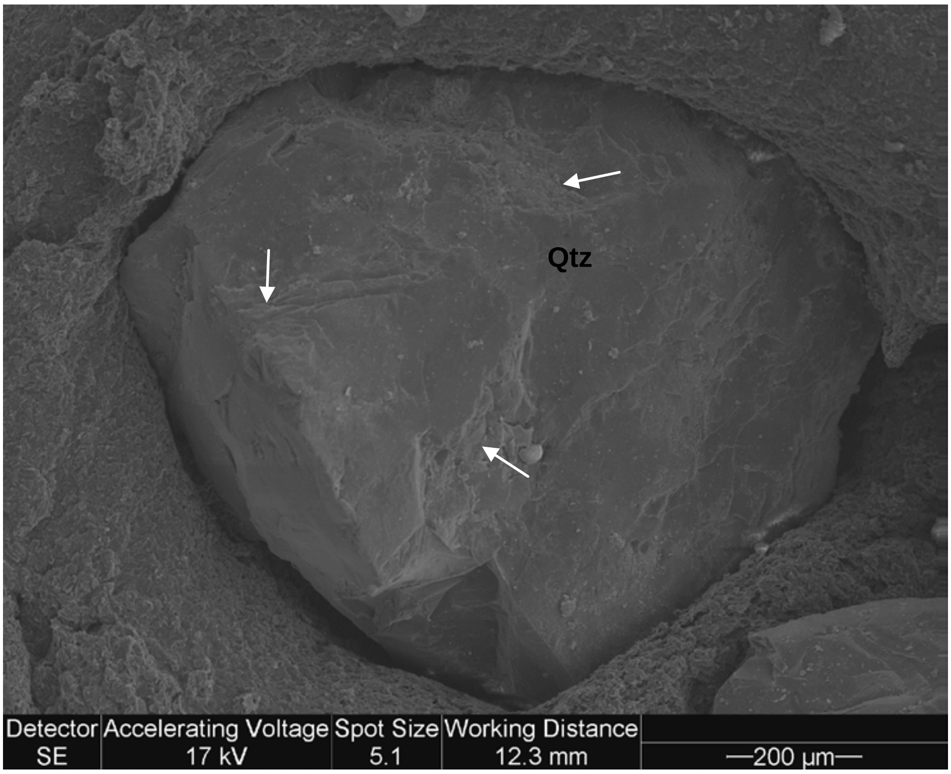

Figure 6.B*: Scattered incipient authigenic quartz (Qtz) on coarse detrital quartz sand grain. Arrows indicate areas with quartz overgrowths.*

1952.5 m below kb.

The sample is brownish grey. It is dominated by medium grained sand and mudstone with sporadic dark mica, dark organic matter and sandstone fragments. The sandstone fragments are weakly cemented and fine to medium grained. A coarse sand grain and a sandstone fragment were chosen for SEM investigation.

The SEM investigation showed small depressions on the surfaces of the quartz grains, which are a sign of incipient consolidation. Small euhedral quartz overgrowths were observed on the surfaces of the grains (Fig 7.A). The quartz grains are generally covered by clay minerals. The latter consists of authigenically grown kaolinite in pseudohexagonal platelets and some illite. Abundant smectite, which is infiltrated from the drill mud, is covering the quartz grains (Fig 7.A).

The sandstone fragments show partially dissolved K-feldspar grains that are now replaced by illite (Fig 7.B). The illite grains are growing between quartz. Detrital quartz occurs abundantly, and is overgrown by authigenic quartz. Glauconite is mainly grown interstitially. Apart from these minerals, minor amounts of biotite, kaolinite, calcite cement, pyrite (probably authigenic), and chlorite (probably authigenic) have been observed in the sample (Fig 7.C). The sample contains smectite and bariumsalt that were infiltrated with the drilling mud.

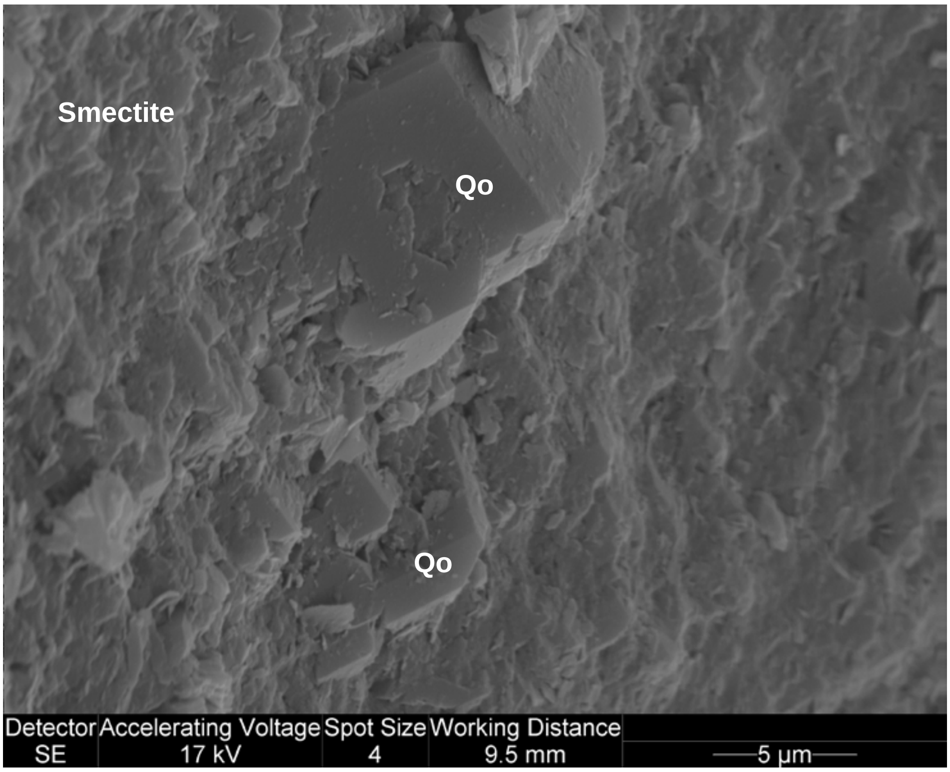

Figure 7.A*: Authigenic incipient quartz (Qo) overgrowths between smectite coverage.*

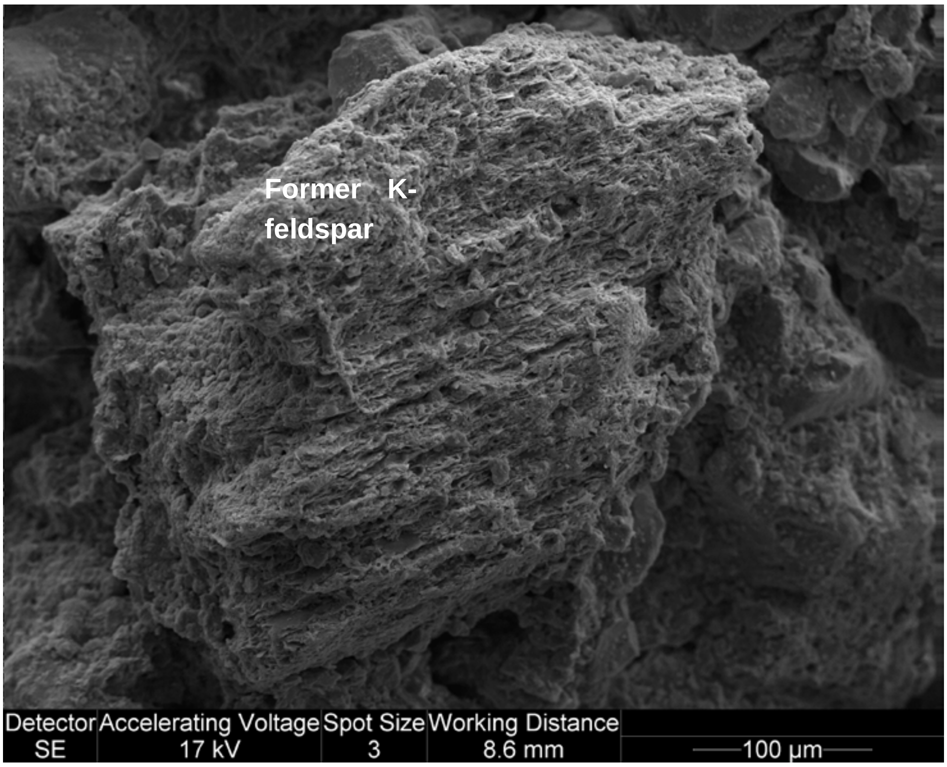

Figure 7.B*: Partially dissolved K-feldspar, now replaced by illite.*

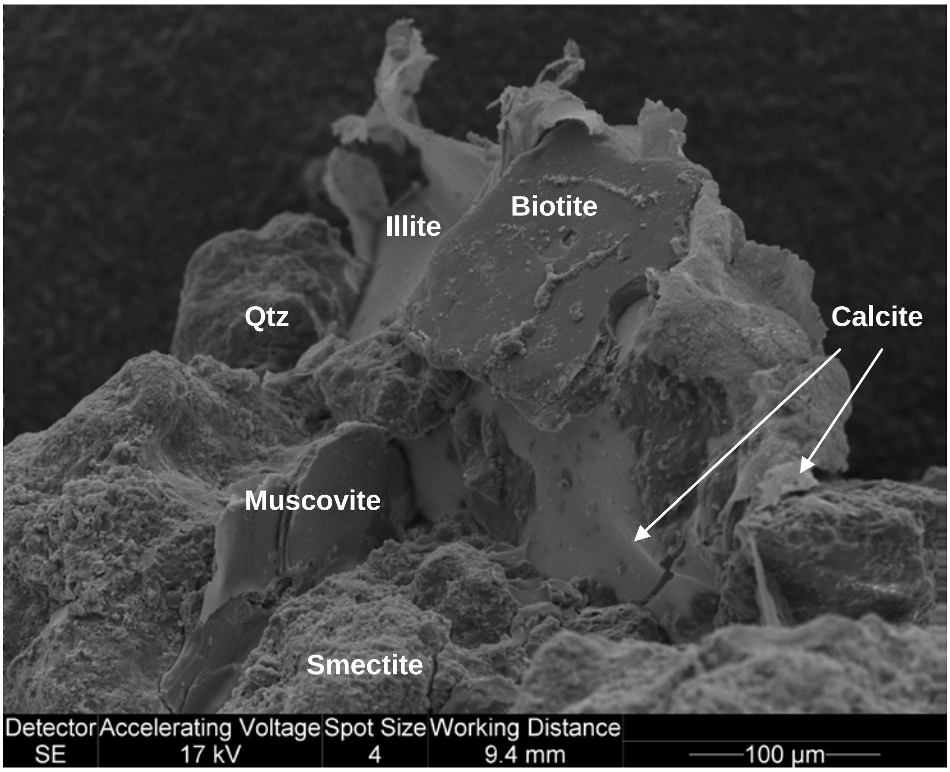

Figure 7.C*: Calcite, quartz (Qtz), biotite, and muscovite, with smectite derived from the drilling mud.*

1980 m below kb.

The sample is greyish brown and is dominated of medium to coarse grained sand and mudstone. Sandstone fragments and carbonates are less common. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain has been chosen for SEM investigation together with two sandstone fragments.

The SEM analysis reveals that the sandstone fragment has poor porosity as it is consolidated with illite which fills the pore spaces (Fig 8.A).

Detrital quartz grains appear with authigenic quartz overgrowth (fig. 8.B) and microquartz. Kaolinite booklets (Fig. 8.C) and illite (Fig 8.D) commonly occur on quartz planes and in fractures.

It was not possible to determine the composition of the clay minerals which coats the sand grain, but they are presumably smectite from the drilling mud.

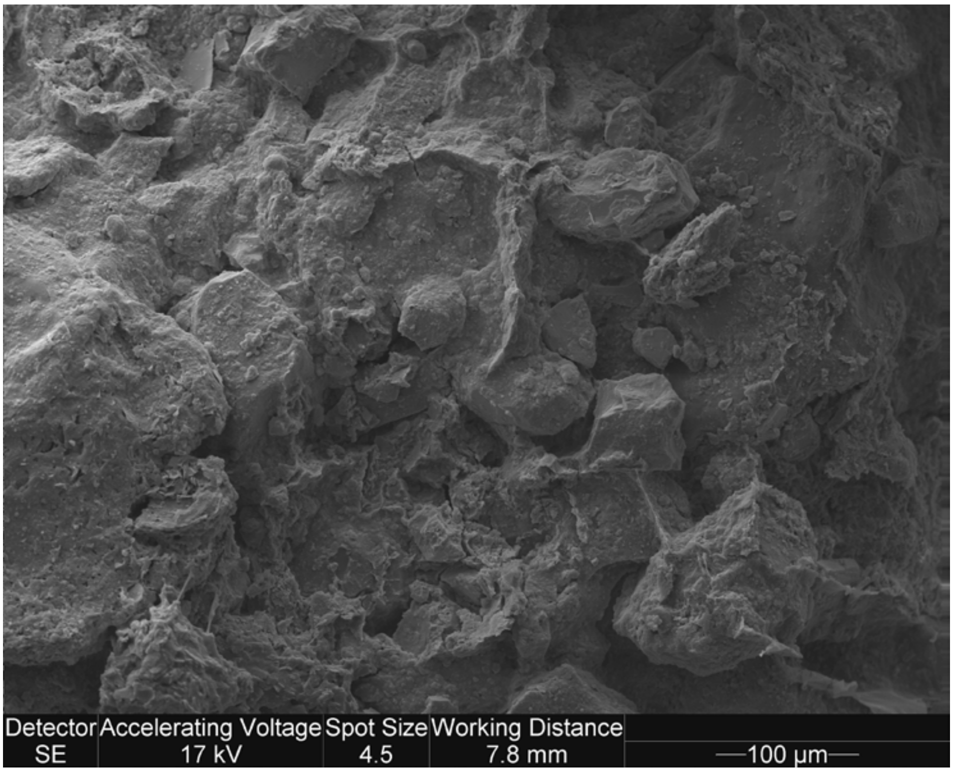

Figure 8.A: *Very fine to fine grained sandstone fragment consolidated in an Illitic matrix.*

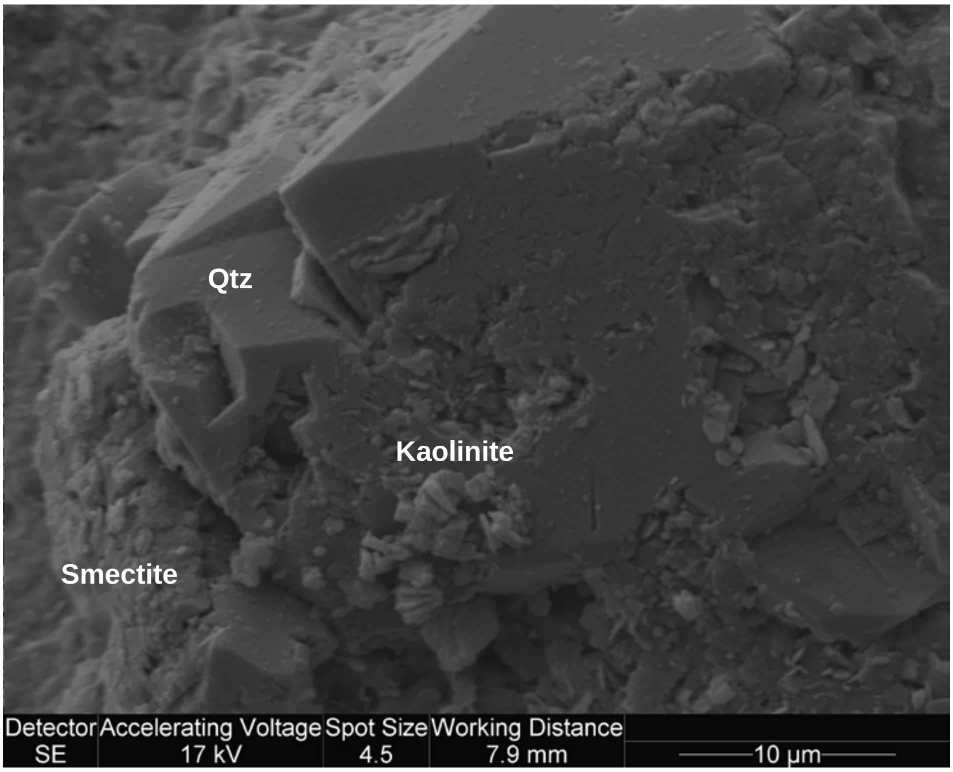

Figure 8.B: *Euhedral quartz overgrowth on detrital quartz grain (qtz) and authigenic kaolinite.*

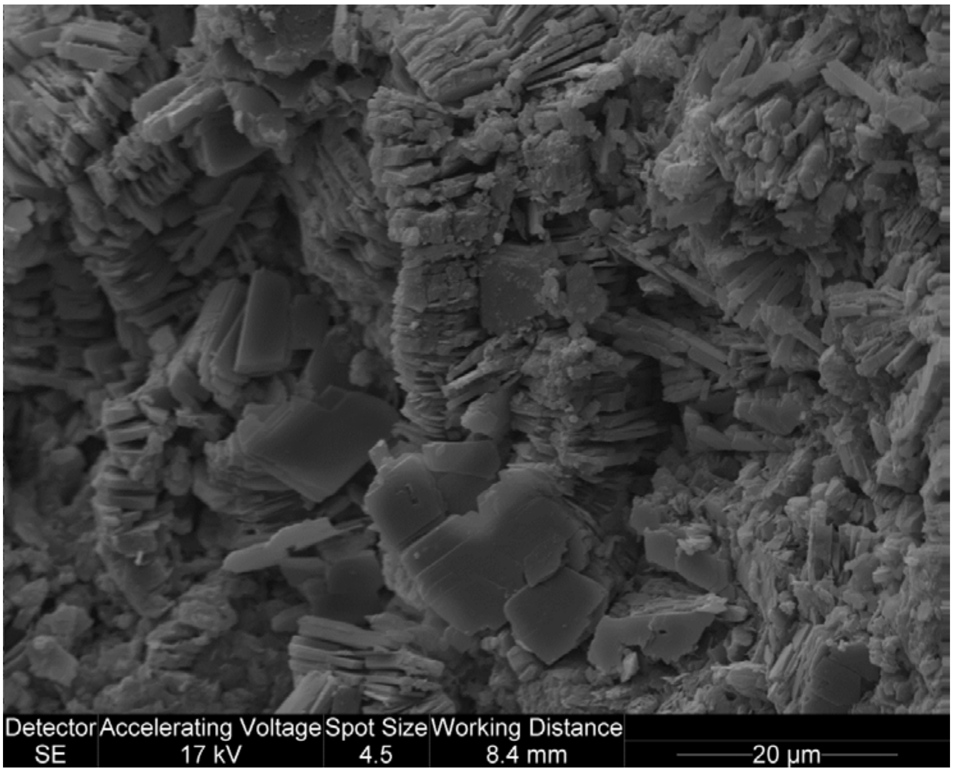

***Figure 8.C**: Kaolinite booklets on a quartz sand grain.*

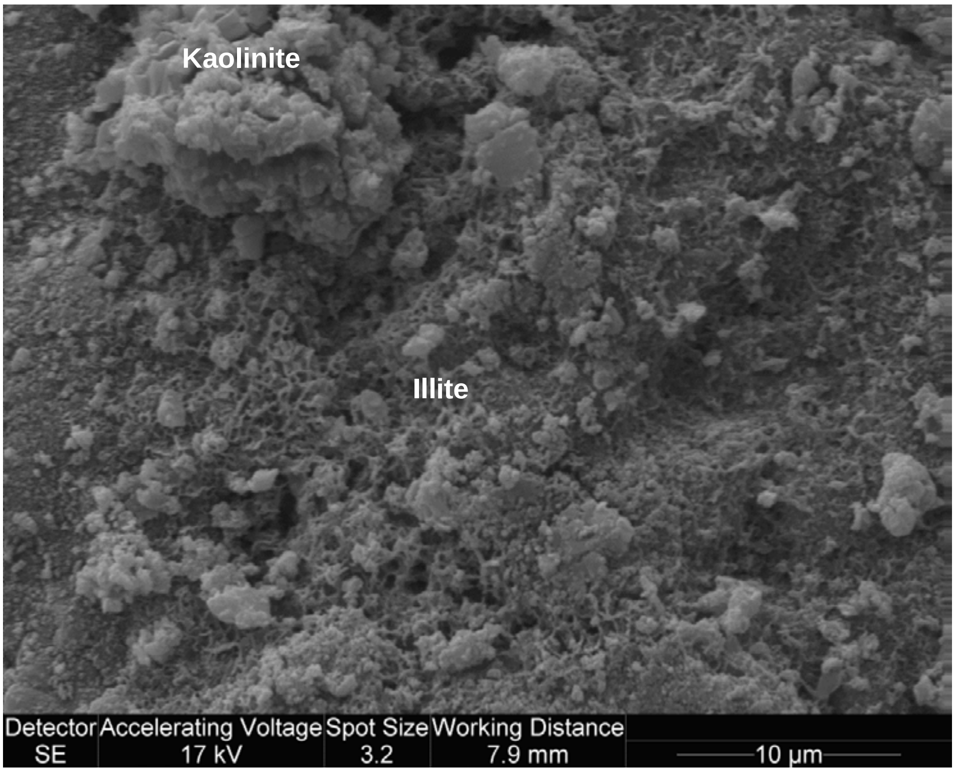

***Figure 8.D**: Illite and kaolinite growing on a quartz sand grain.*

1992.5 m below kb.

The sample is light grey and dominated by fine to medium grained sand. Mudstone, dark mica, carbonates and sandstone fragments are less common. The sandstone fragments are weakly cemented and fine to medium grained. A very coarse sand grain and a sandstone fragment have been selected for SEM investigation.

The SEM investigation revealed that the grains in the sandstone fragment appear to be mainly quartz and feldspar consolidated by calcite and illite (Fig 9.A). The surfaces of the quartz grains display small euhedral overgrowth (Fig 9.B).

The sample contains smectite and bariumsalt which coats the detrital grains why it is most likely infiltrated drilling mud.

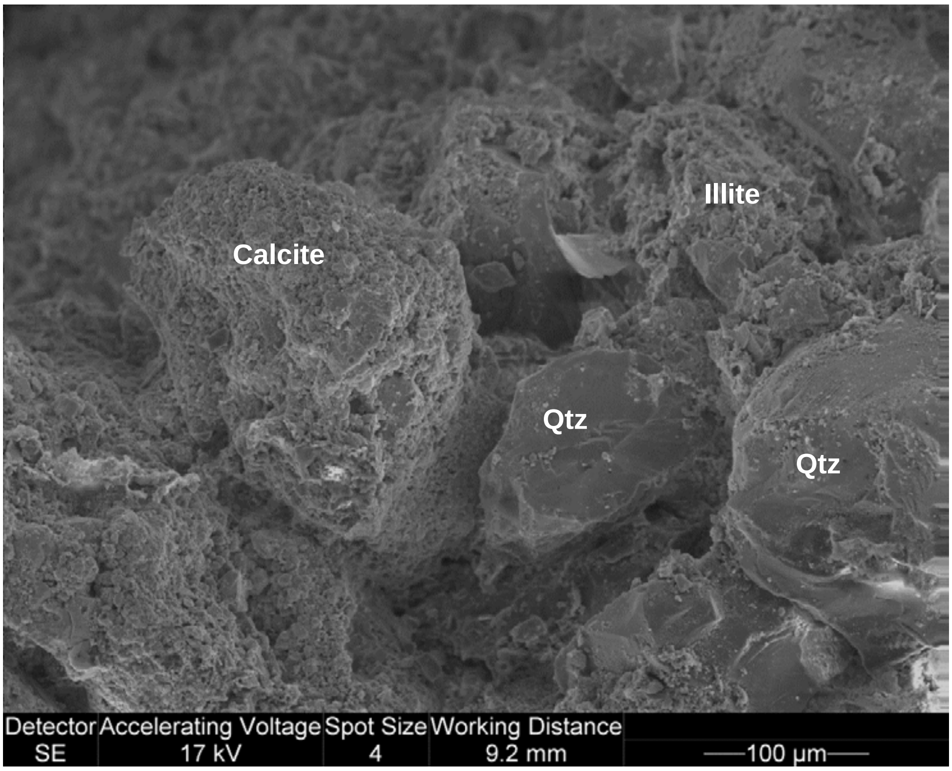

Figure 9.A*: Detrital quartz and feldspar grains consolidated by corroded calcite and Illite matrix.*

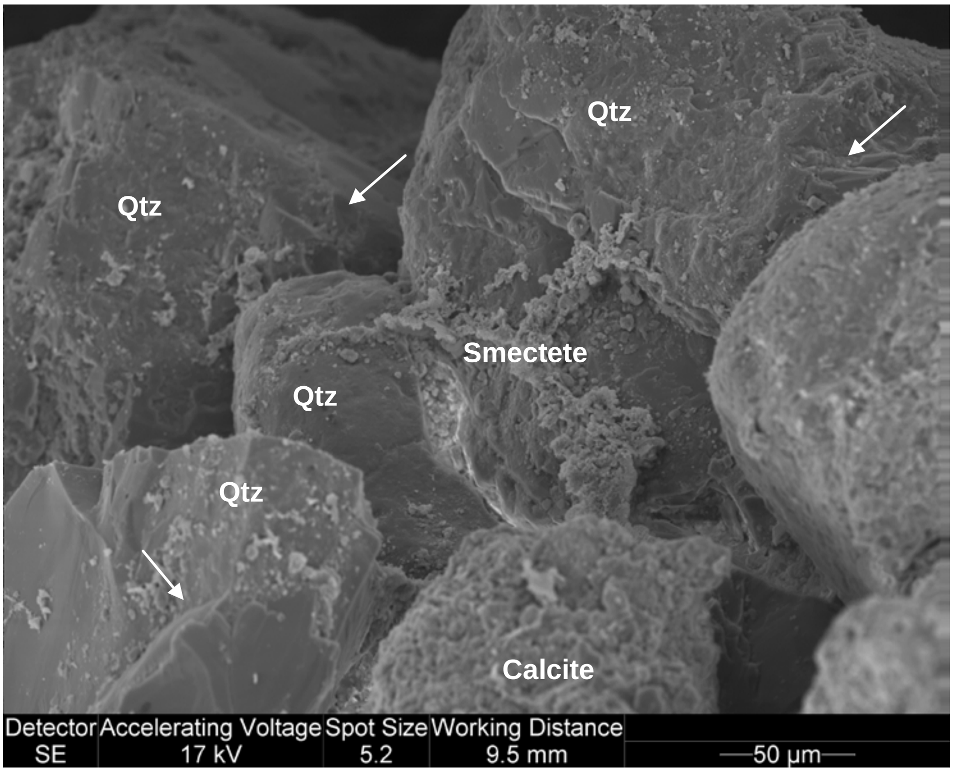

Figure 9.B*: Quartz grains displaying incipient overgrowth (indicated by arrows). Smectite from the drilling mud coats the grains.*

2010 m below kb.

The sample is grey and is dominated by fine to medium grained sand. Less common are mudstone, sandstone fragments, dark organic matter, carbonate and dark mica. The sandstone fragments are weakly cemented and fine to medium grained. A very coarse sand grain and two sandstone fragments have been picked for SEM investigation.

Detrital grains in this sample are mainly quartz consolidated in an illitic matrix. The grains commonly occur with euhedral quartz overgrowths and kaolinite booklets (Fig 10.A & B).

Smectite coats quartz overgrowths and occur within pore spaces in the sandstone fragment and may be infiltrated drilling mud.

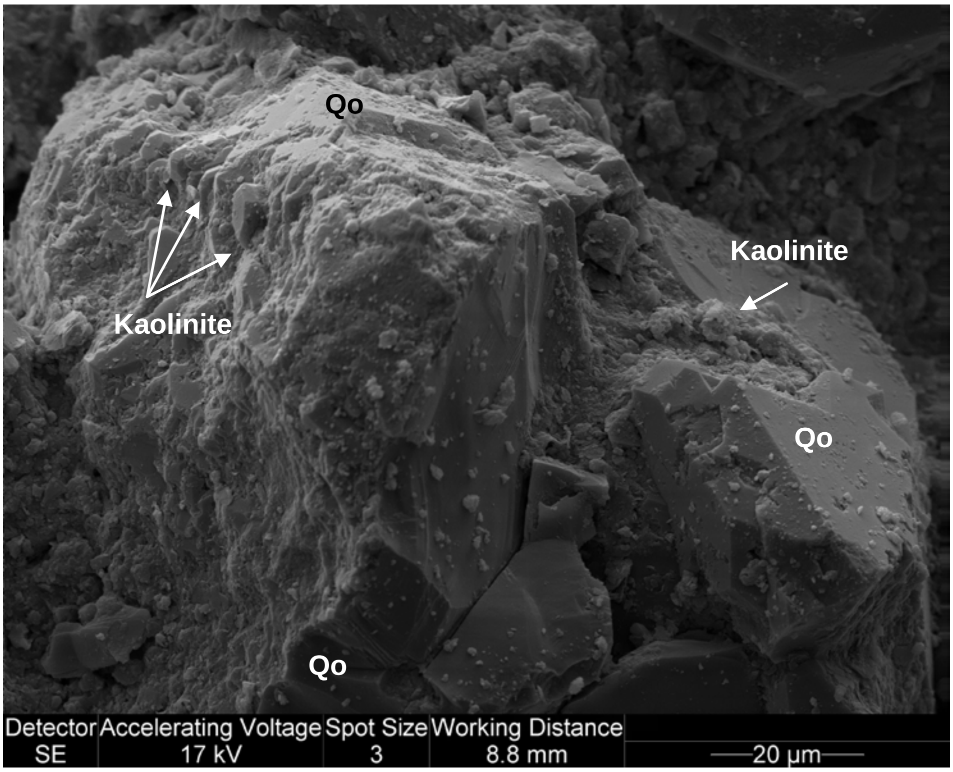

Figure 10.A: *Euhedral quartz overgrowth (Qo) and kaolinite booklets on corroded quartz.*

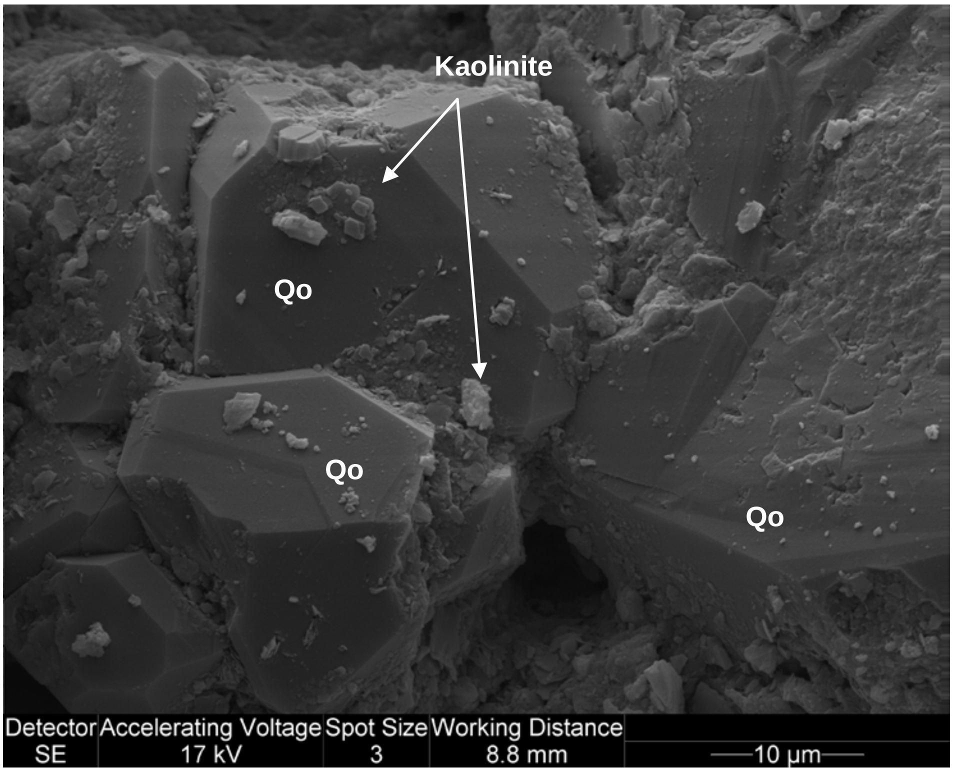

Figure 10.B: *Euhedral authigenic quartz overgrowths (Qo) and kaolinite.*

2070 m below kb.

The sample is grey and is dominated by fine to medium grained sand and sandstone fragments with sporadic mudstone and dark organic matter. The sandstone fragments are very weakly cemented and fine to medium grained. A very coarse sand grain and a sandstone fragment were picked for further SEM investigation.

The SEM analysis reveals that grains in the sandstone fragment are represented mainly by quartz and feldspars. Detrital quartz grains commonly yield euhedral quartz overgrowths (fig 11.A).

Kaolinite booklets occurs within fractures of quartz grains.

Pore spaces are filled by clay of mainly smectitic composition, which also coats detrital grains (fig 11.B). The clayey matrix is probably drilling mud.

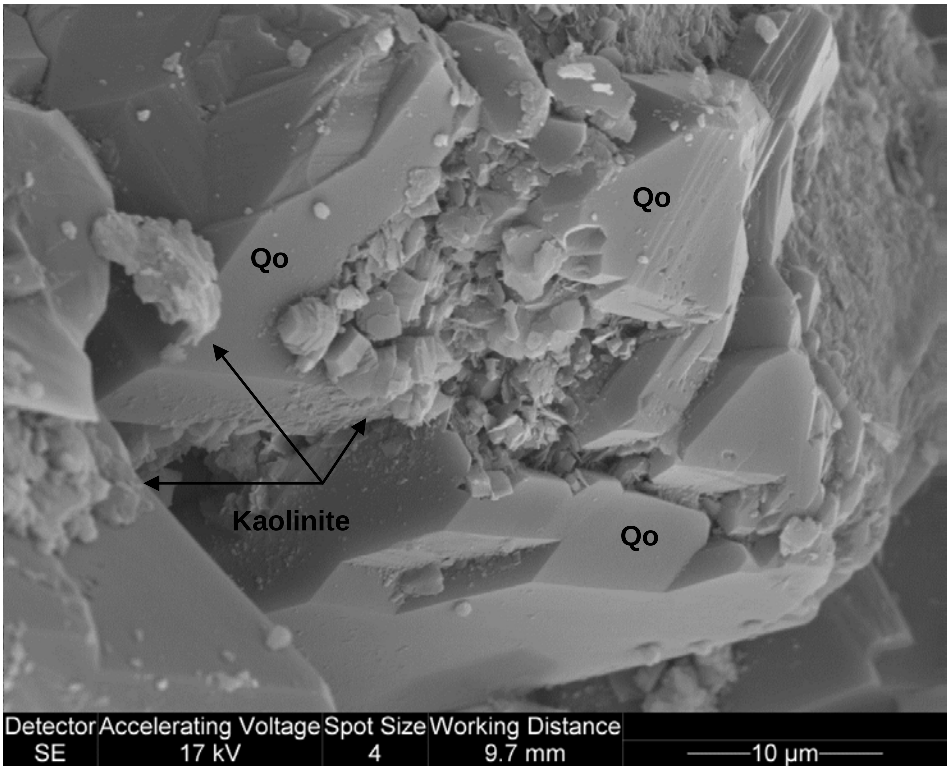

Figure 11.A*: Euhedral quartz overgrowth (Qo) on a detrital quartz grain with associated kaolinite booklets.*

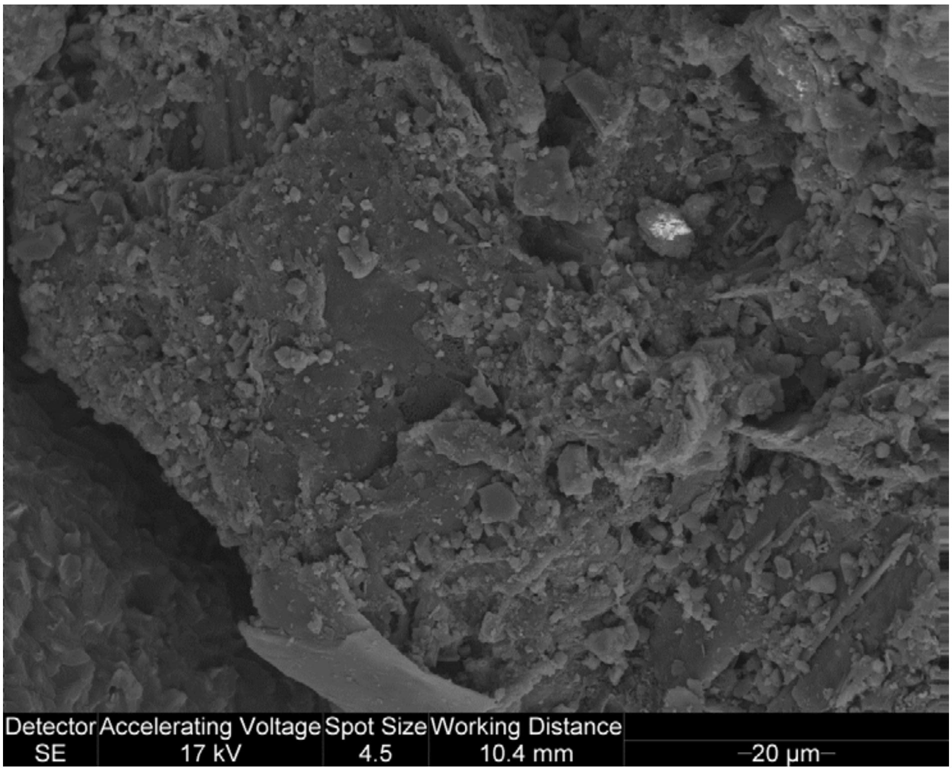

Figure 11.B*: Smectite coats detrital grains and fill the pores reducing the porosity of the specimen, however it is probably drilling mud.*

2120 m below kb.

The sample is grey and dominated by fine to medium grained sand. Mudstone, carbonates and sandstone fragments are less common. The sandstone fragments are weakly cemented and fine grained. For SEM investigation a medium sand grain and a sandstone fragments were picked.

SEM investigations show that the quartz grains showed small authigenic overgrowths, which are locally euhedral in shape (Fig 12.A), and depressions that probably witness incipient compaction of the sample.

Detrital quartz grains in this sample are abundant and display authigenic quartz overgrowth and illite.

Smectite coats quartz grains and is probably infiltrated drilling mud (Fig 12.B).

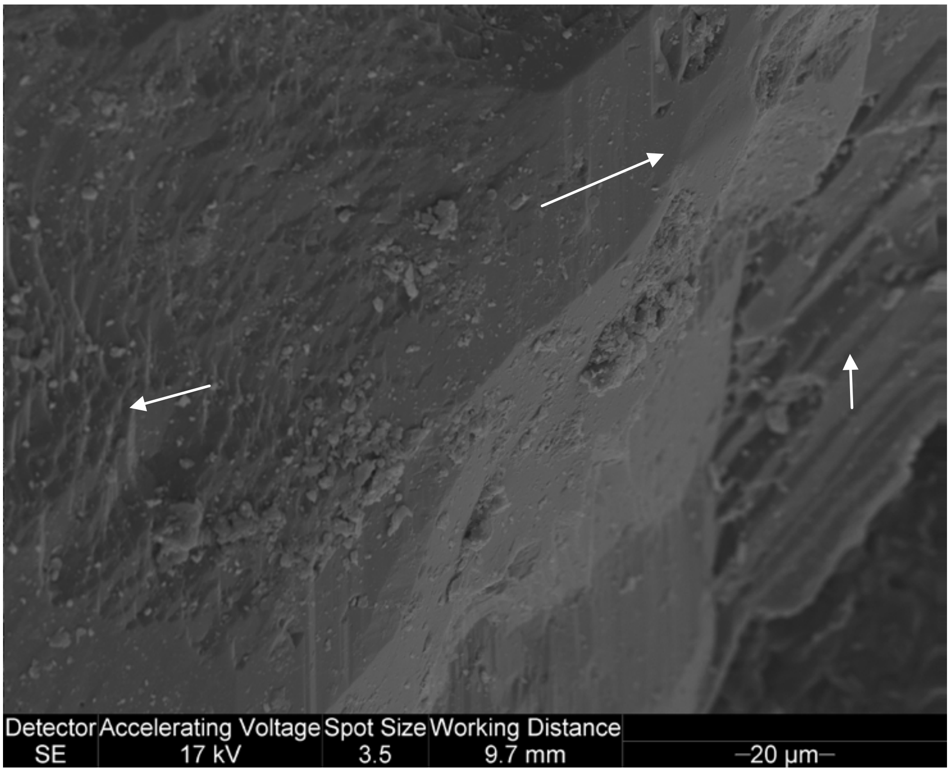

Figure 12.A*: Euhedral quartz overgrowths (arrows) on a quartz grain.*

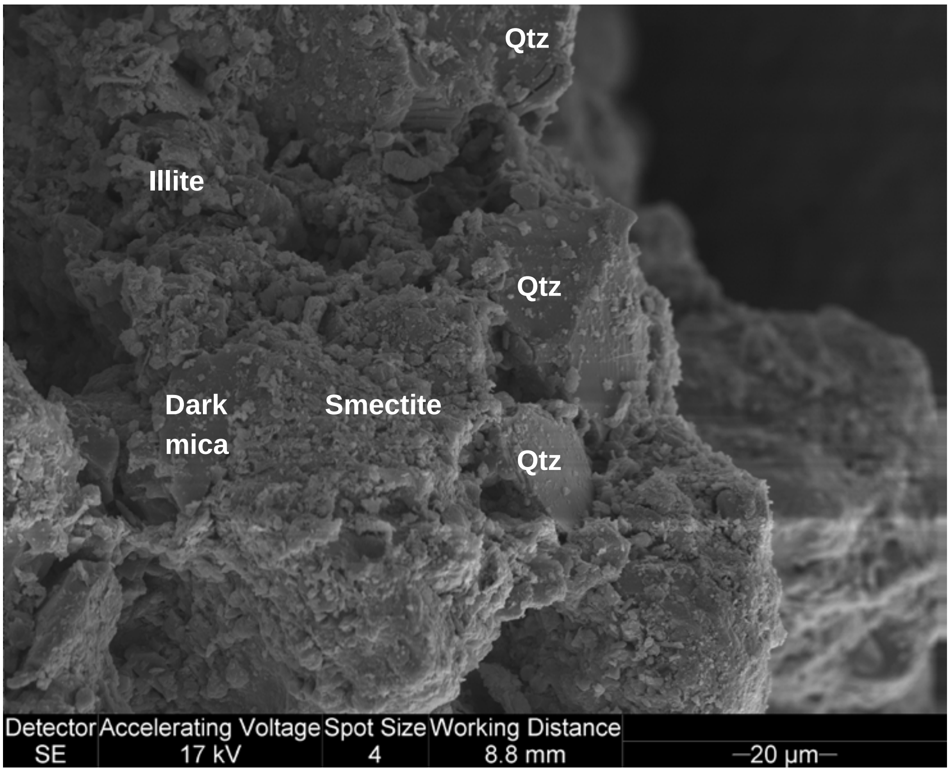

Figure 12.B*: Loosely consolidated quartz grains with illite and biotite. Smectite in the sample is probably derived from the drilling mud.*

Gassum Formation

2132.5 m below kb.

The sample is dark grey and dominated by fine to medium grained sand and mudstone. Sandstone fragments are common. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain has been chosen for SEM investigation together with a couple of sandstone fragments.

The SEM investigation reveals that detrital grains in the sandstone fragments mainly constituted quartz and feldspar which is consolidated by a clayey matrix (Fig 13.A) consisting mainly of illite. Incipient quartz overgrowth has been observed on detrital quartz grains (Fig 13.B).

Some parts of the sandstone fragments are coated by a thick layer of smectite, bariumsalt and calcite which is most likely infiltrated drilling mud.

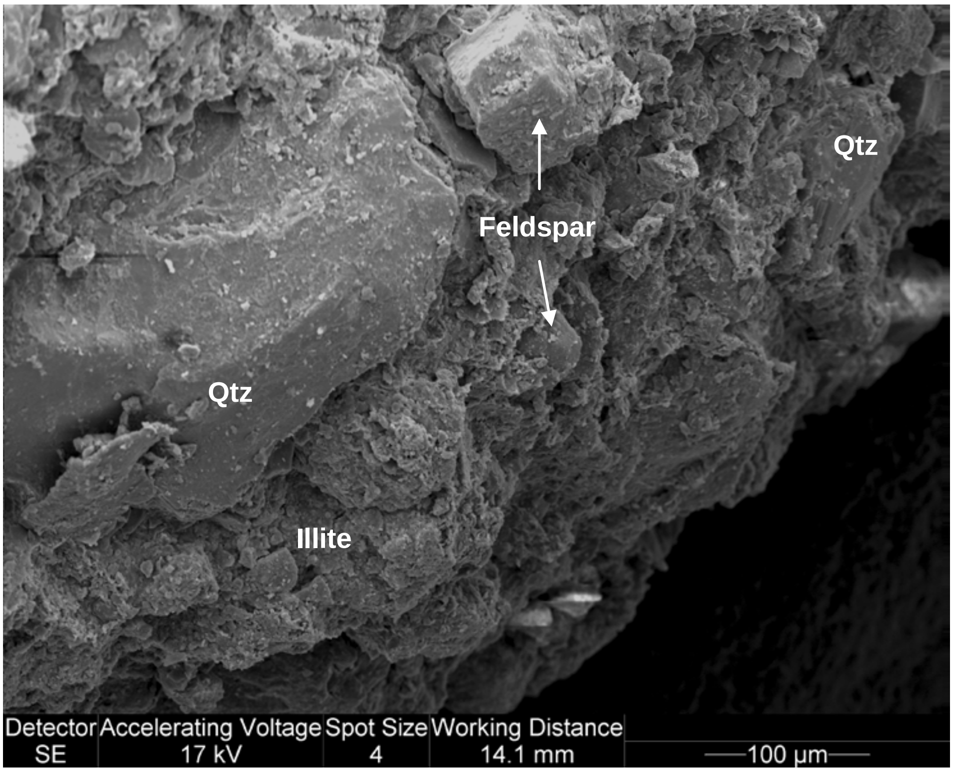

Figure 13.A*: Quartz grains consolidated in a illitic matrix.*

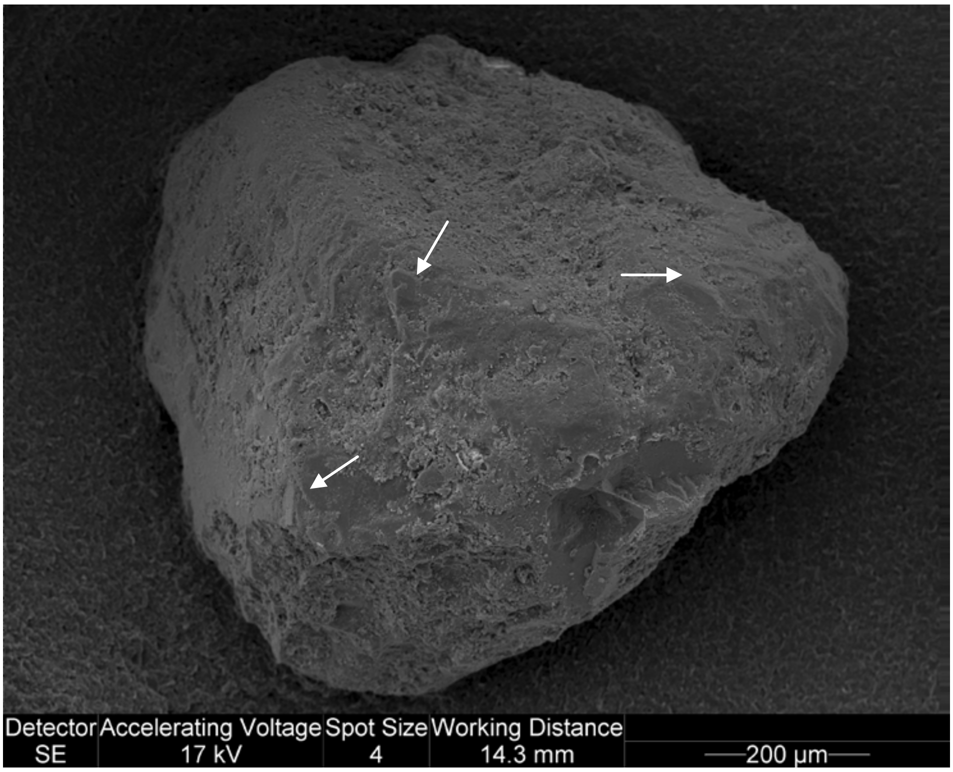

Figure 13.B*: incipient quartz overgrowth on a coarse sand grain. Overgrowth has been marked with arrows.*

2137.5 m below kb.

The sample is grey and dominated by fine – medium grained sand, mudstone and sandstone fragments. The sandstone fragments are weakly cemented and have a fine to medium grain size. A very coarse sand grain and a very fine – medium-grained sandstone fragment have been chosen for SEM investigation.

The SEM analysis shows quartz grains with well-developed euhedral quartz overgrowths and incipient authigenic chlorite growth in many pores (Fig 14.A and 14.B).

Locally dolomite cement and an iron oxide/hydroxide in ring structures (possibly goethite) has been observed.

Large parts of the sample are covered with fine-grained smectite on the surfaces. This smectite is probably derived from the infiltrated drilling mud.

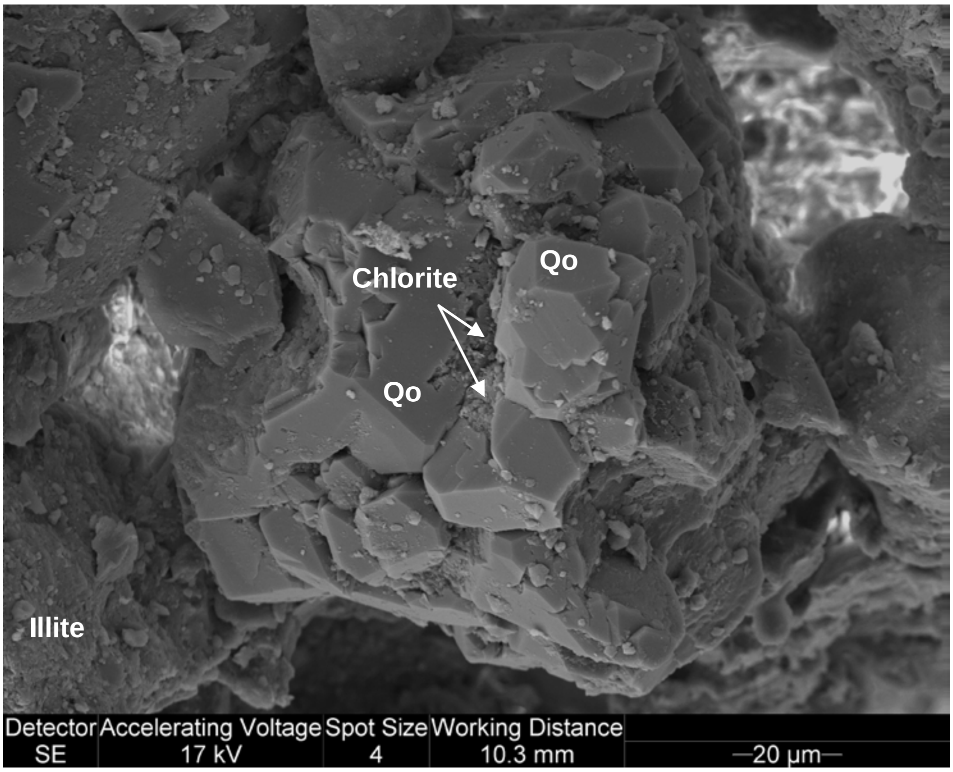

Figure 14.A: *Quartz overgrowths (Qo), chlorite (arrows) and illite in a sandstone sample.*

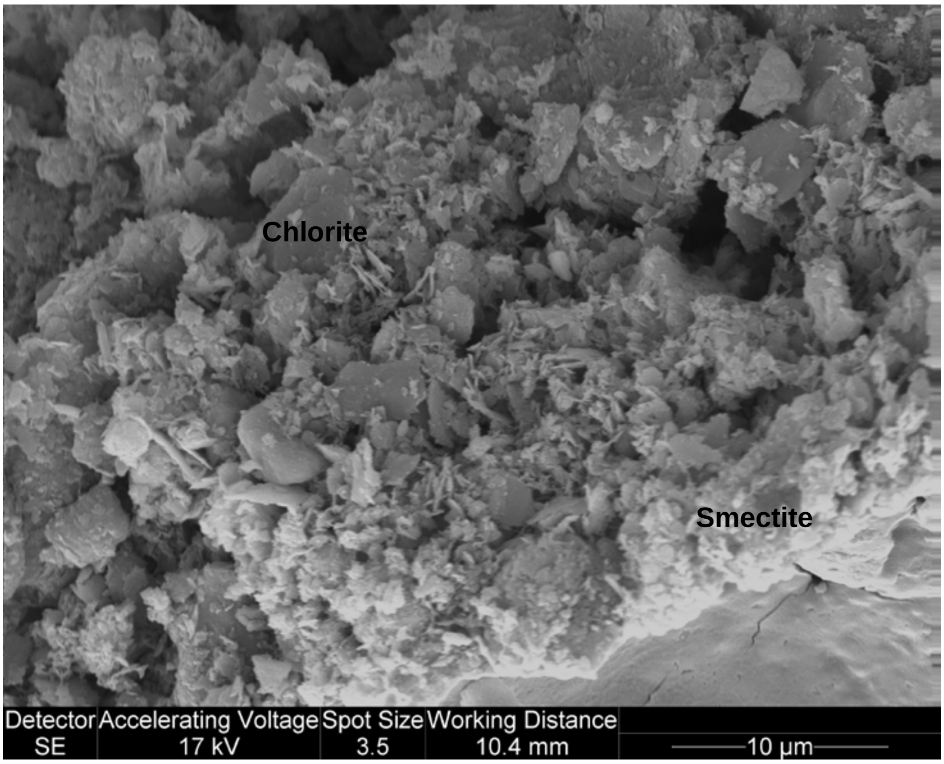

Figure 14.B: *Chlorite and smectite grains on quartz.*

2155 m below kb.

The sample is greyish-brown and dominated by fine to medium grained sand and sandstone fragments. Mudstone is sparsely dispersed. The sandstone fragments are weakly cemented and fine to medium grained. A very coarse sand grain and two sandstone fragments have been chosen for further investigation on SEM.

The SEM analyses revealed rounded quartz grains with depressions after other quartz grains, which were formed during compaction of the sandstone, and development of quartz overgrowths (Fig 15.A and 15.B). Small chlorite and illite grains, which probably are authigenic, are growing on the surfaces of the quartz grains.

The sandstone fragments show moderately consolidated sandstone with thin clay minerals between the quartz grains and on quartz surfaces. These clay minerals are most likely illite (Fig 15.C).

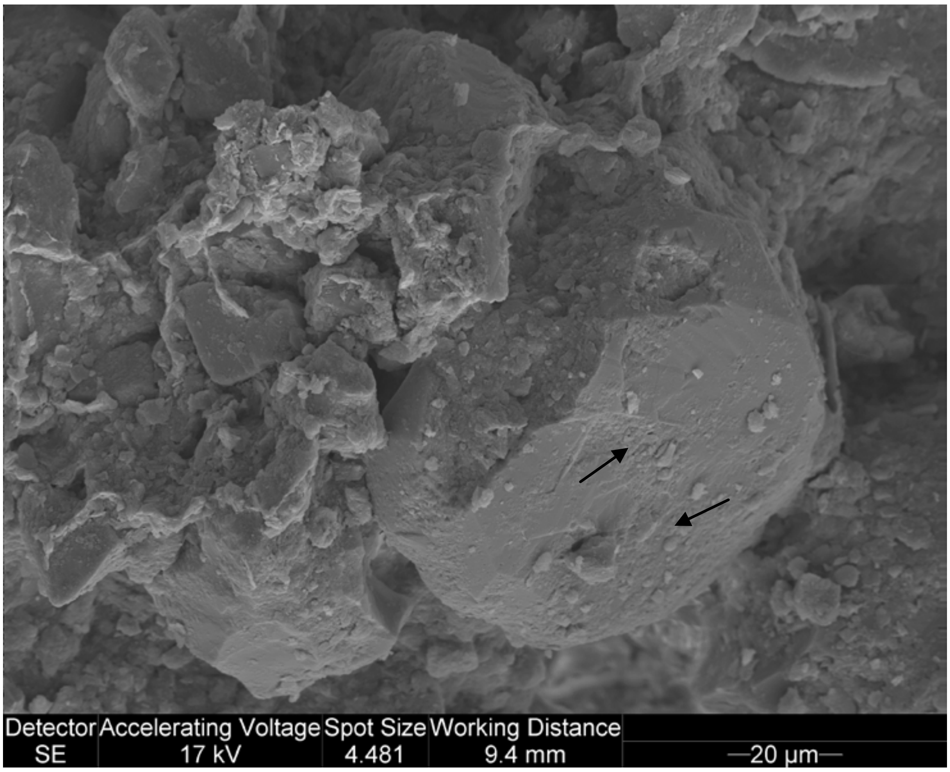

***Figure 15.A**: Rounded quartz grain with incipient quartz overgrowth (arrows) and depression from compaction.*

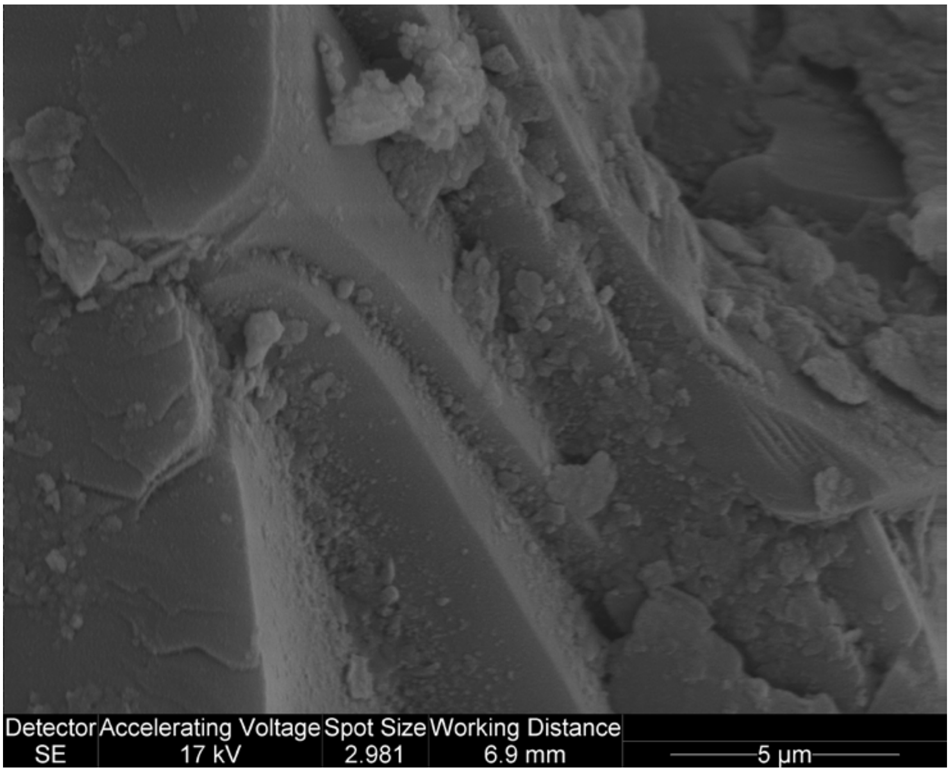

***Figure 15.B**: Quartz overgrowths on a detrital quartz grain.*

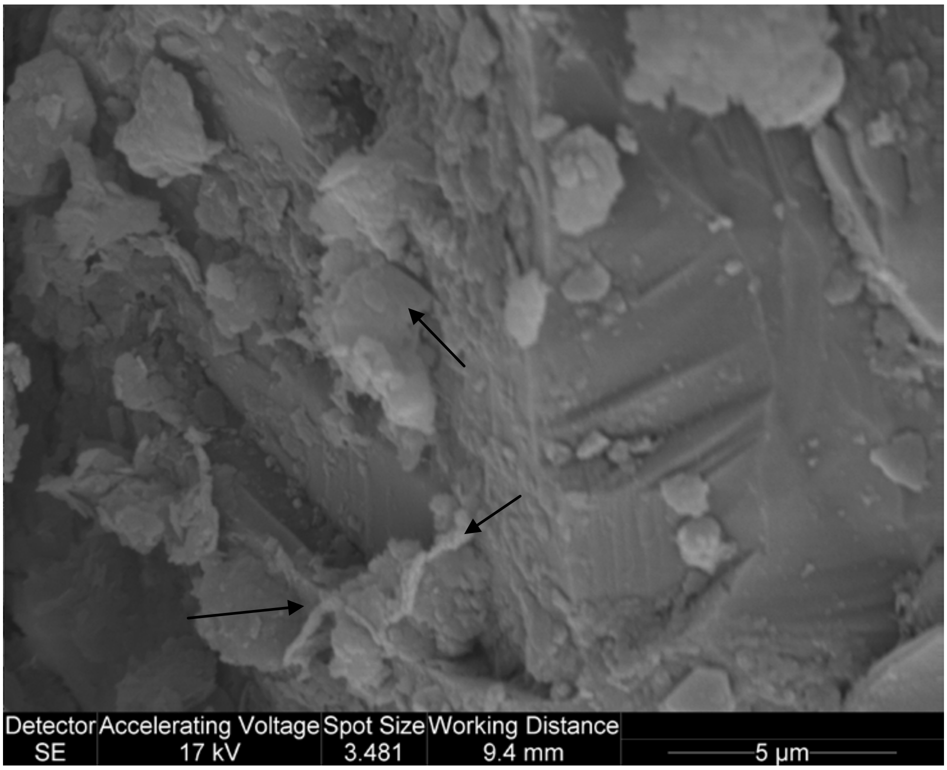

***Figure 15.C**: Thin clay rims, probably illite between quartz grains.*

2170 m below kb.

The sample is dark and greyish-brown. It is dominated by fine to medium grained sand and sandstone fragments. Mudstone is less common. Rare pyrite has been observed. The sandstone fragments are weakly cemented and fine to medium grained. A coarse sand grain and a sandstone fragment have been chosen for further investigation by SEM.

The SEM analysis reveals that sandstone fragment mainly appear as quartz and feldspar grains consolidated by illite (Fig 16.A). Detrital grains are generally coated by smectite which is probably infiltrated drilling mud.

Authigenic micro quartz and platy clay which was determined by EDS analysis to be illite (Fig 16.B) occurs on detrital sand grains, partly covered by euhedral quartz overgrowths.

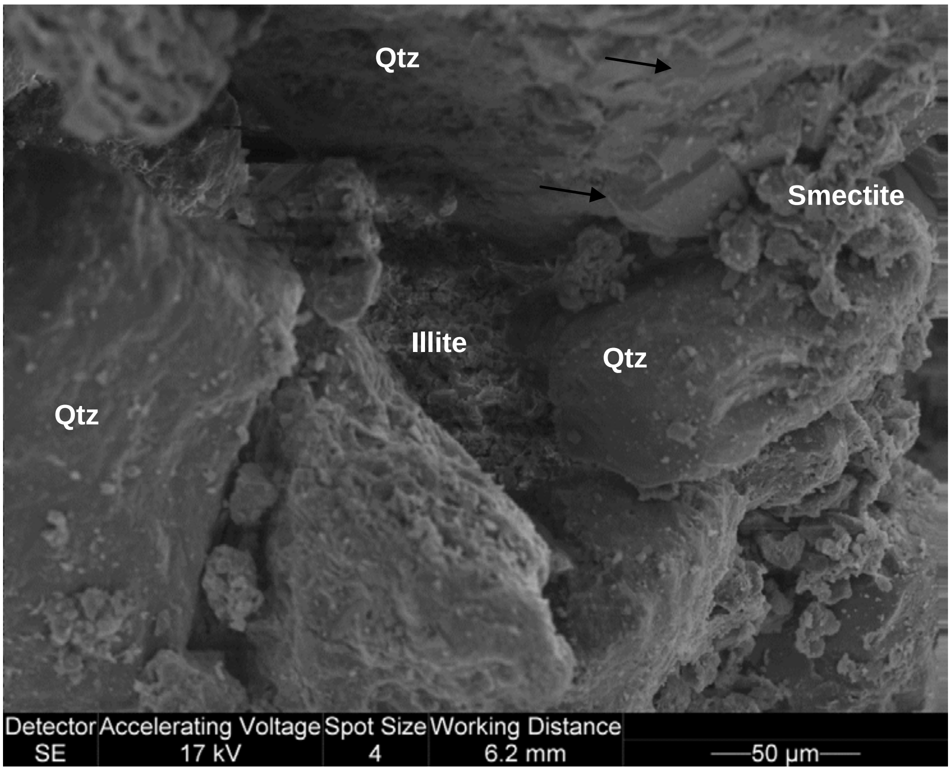

Figure 16.A: *A clayey matrix (mainly illite) consolidates the sample. Smectite coats detrital grains and is most likely drilling mud. Incipient quartz overgrowth has been marked by arrows.*

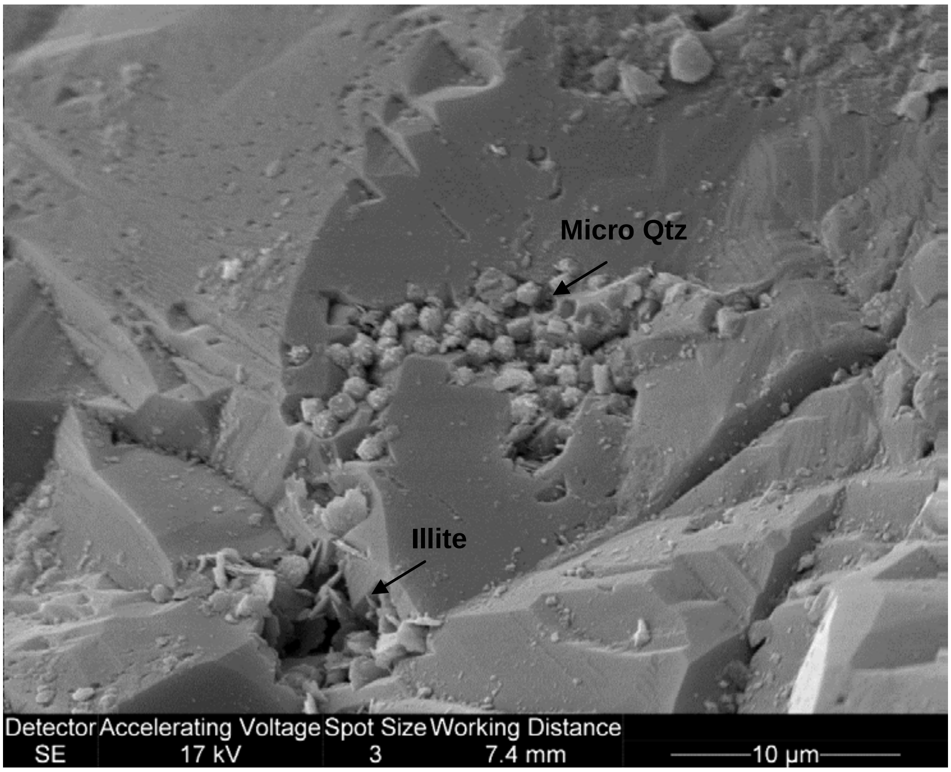

Figure 16.B: *Authigenic micro quartz and illite partly covered by quartz overgrowths.*

2185 m below kb.

The sample is grey and dominated by fine – coarse-grained sand with some mudstone and sandstone fragments. The sandstone fragments are weakly cemented and fine to medium grained. A coarse sand grain and a sandstone fragment were picked for SEM investigation.

The SEM investigation showed abundant kaolinite in the sample, which probably has grown authigenically (Fig 17.A). Quartz shows thin layers of authigenic quartz. Muscovite occurs in the sand stone fragments (Fig 17.B). Locally calcite cement was observed, but no illite has been found.

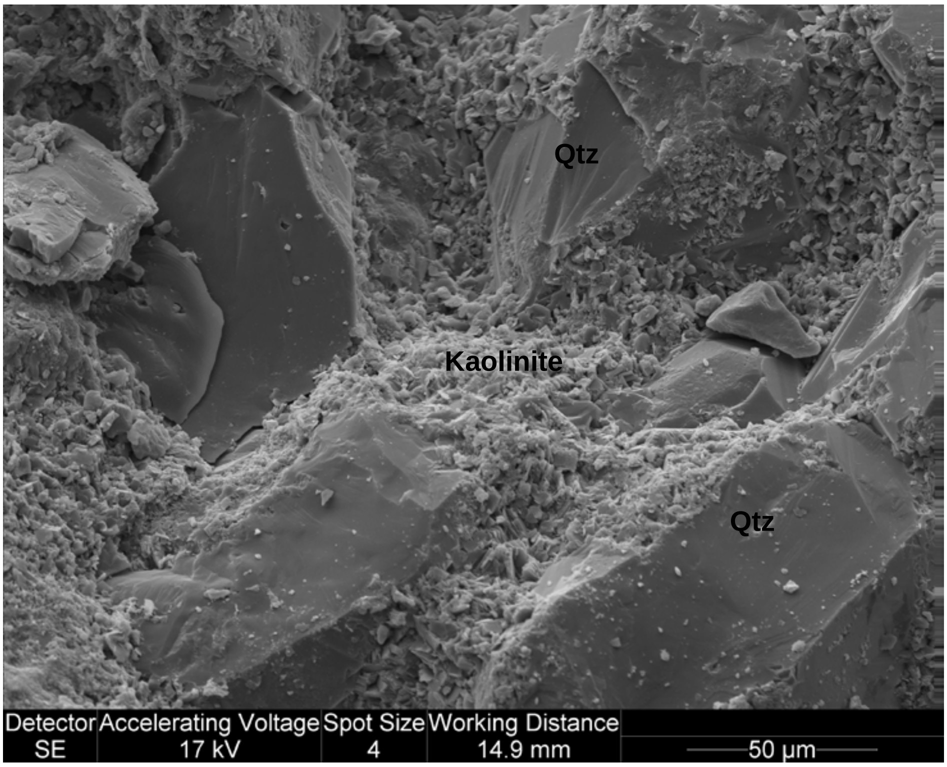

Figure 17.A: *Quartz grains (Qtz) covered with kaolinite.*

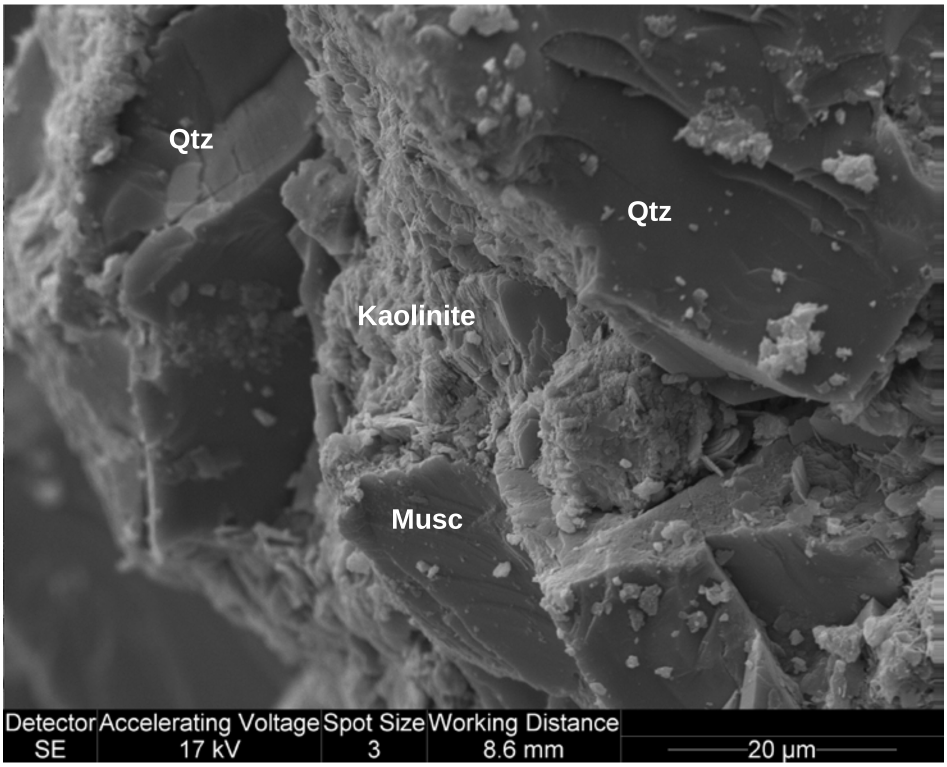

Figure 17.B: *Quartz grains (Qtz) with interstitial muscovite (Musc) and kaolinite.*

2210 m below kb.

The sample is greyish brown and dominated by fine to medium grained sand and sandstone fragments. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain and a sandstone fragment were chosen for further SEM investigation.

The SEM analysis reveals that the detrital grains in the sandstone fragment are fine grained and represented mainly by plagioclase, quartz and rare muscovite (Fig 18.A). The grains are consolidated by illite and quartz grains display common euhedral overgrowth (fig 18.B).

Smectite, bariumsalt and calcite coats detrital crystal planes and are most likely infiltrated drilling mud.

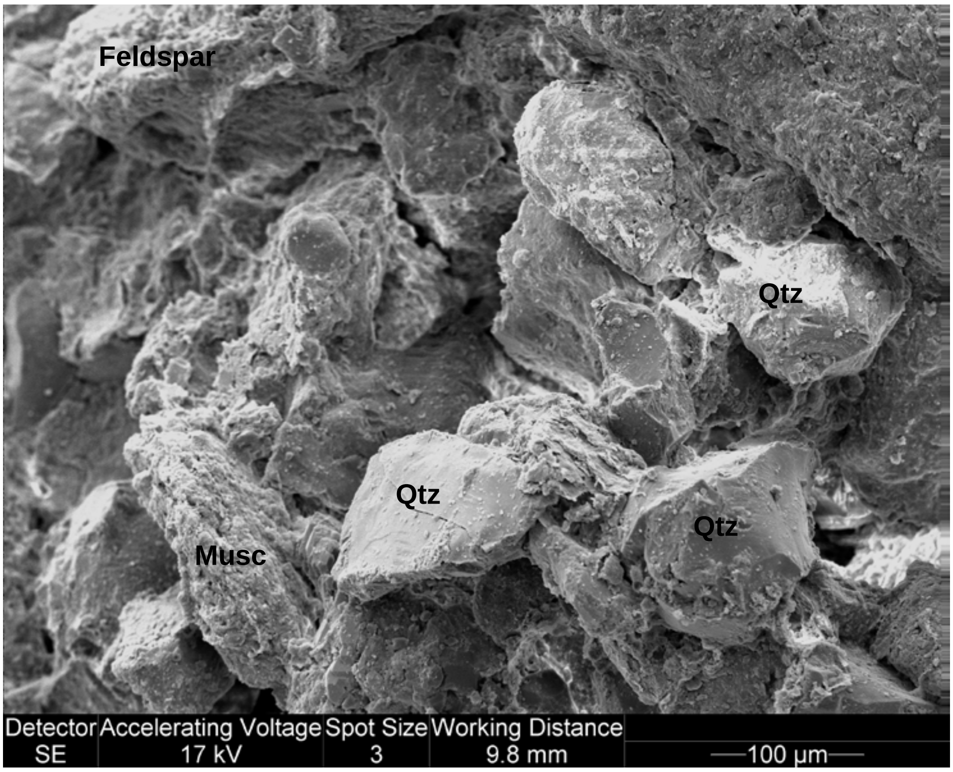

Figure 18.A*: Fine grained quartz (qtz), feldspar and muscovite (musc) in an illite matrix.*

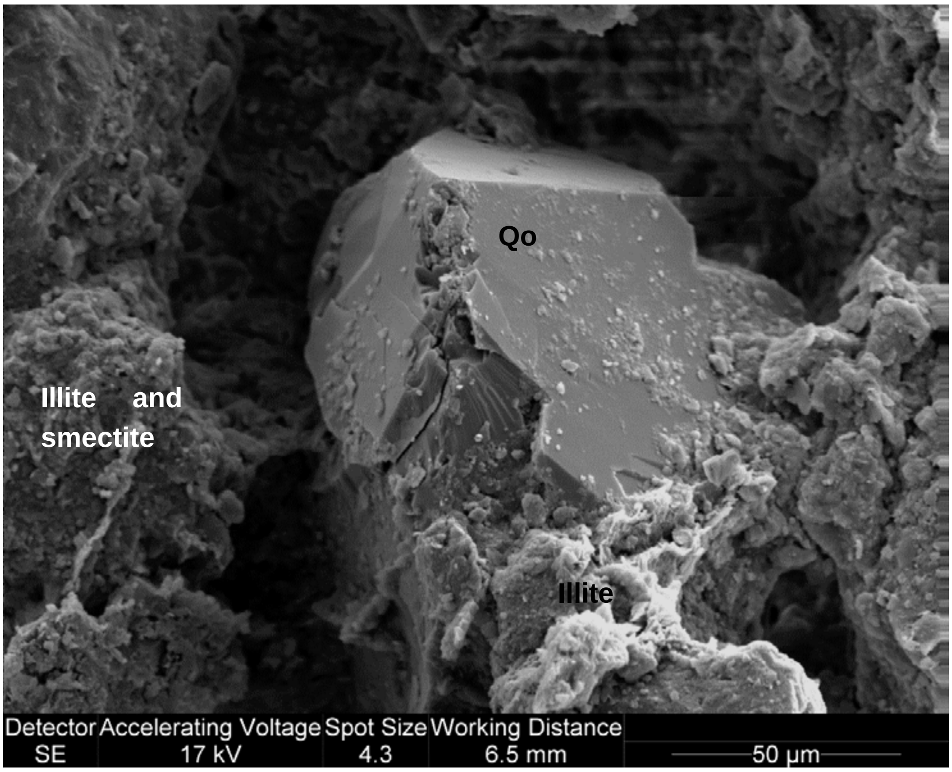

Figure 18.B*: Euhedral overgrowth (Qo) on a detrital quartz grain consolidated in an illite matrix.*

2230 m below kb.

The sample is light grey and dominated by fine to medium grained sand, mudstone and sandstone fragments. The sandstone fragments are weakly cemented and fine - medium grained. Two very coarse sand grains and a sandstone fragments were collected for investigation by SEM.

SEM investigation of the subrounded sand grains reveals evident quartz overgrowths (Fig 19.A). Authigenic illite is abundant on the grains occurring either as a thin film or as accumulations of flaky crystals.

The sample yield mainly detrital quartz and feldspar grains consolidated in a clayey matrix Fig 19.B). EDS analysis of the cement display illite composition. Common smectite coating is most likely derived from drilling mud. Needle shaped iron-rich minerals was observed in the sandstone fragment. They are rare and probably authigenic.

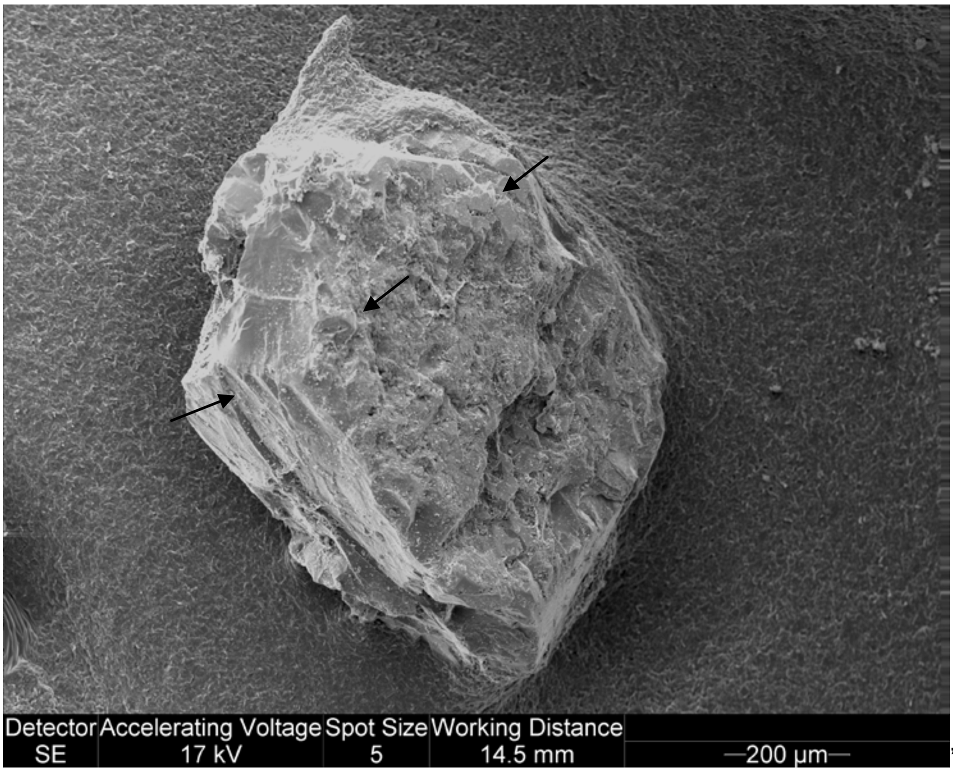

Figure 19.A: *A coarse quartz grain with evident overgrowths marked by arrows.*

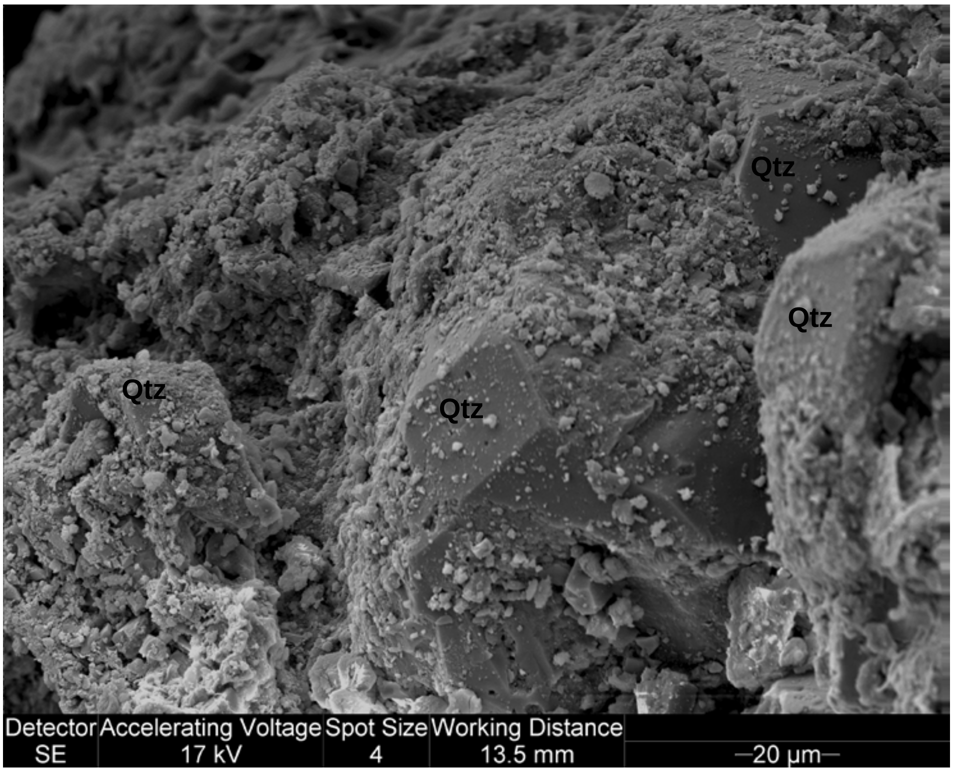

Figure 19.B: *Detrital quartz grains (Qtz) with incipient overgrowths. The grains are cemented by authigenic illite and coated by smectite (drilling mud).*

2250 m below kb.

The sample is dark grey and is dominated by fine to medium grained sand and dark organic matter. Less common are mudstone, carbonates and weakly cemented fragments of sand and dark organic matter. A very coarse sand grain and two sandstone fragments were collected for investigation by SEM.

The SEM investigation confirms that the sandstone is loosely consolidated. Most of the grains are quartz, with filamentous pore-lining and pore-bridging illite grains growing over the quartz grains (Fig 20.A), and as rather large grains in the pores (Figure 20.B). The quartz grains are rounded, with small authigenic, often euhedral, overgrowths. The illite grains seem to replace feldspar grains.

Apart from quartz and illite, sporadic chlorite and kaolinite have been observed. Kaolinite grew authigenically (Fig 20.C), chlorite might also have been derived from the drilling mud. Rare iron oxide (probably hematite), gibbsite and zeolite were also observed.

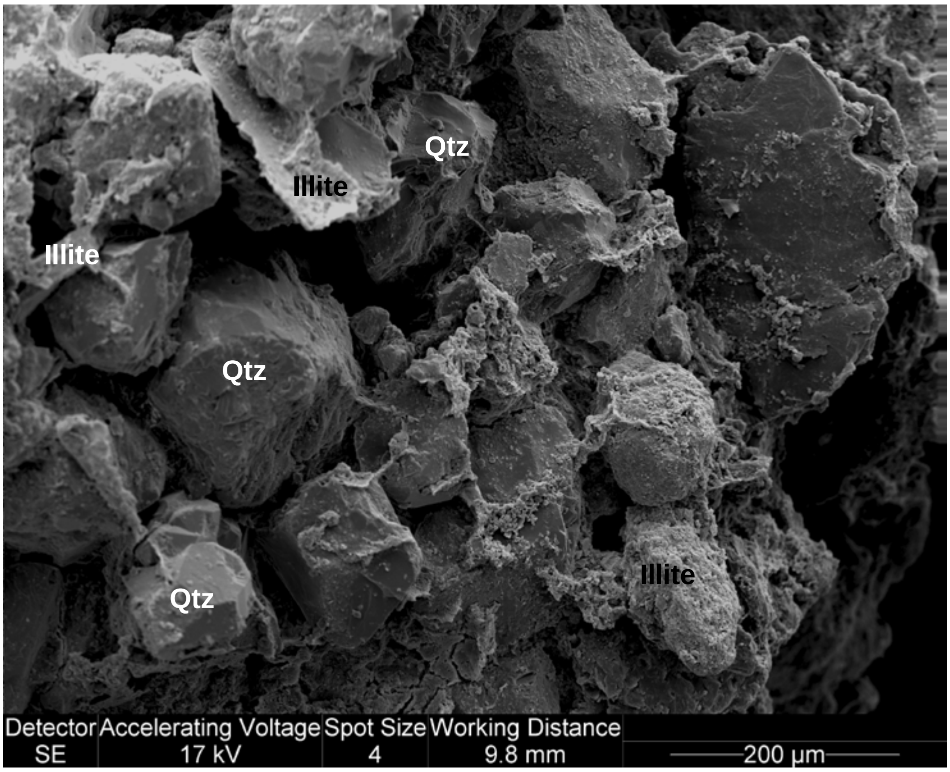

Figure 20.A*: Sandstone fragment with rounded quartz (Qtz) grains and illite growing between the grains.*

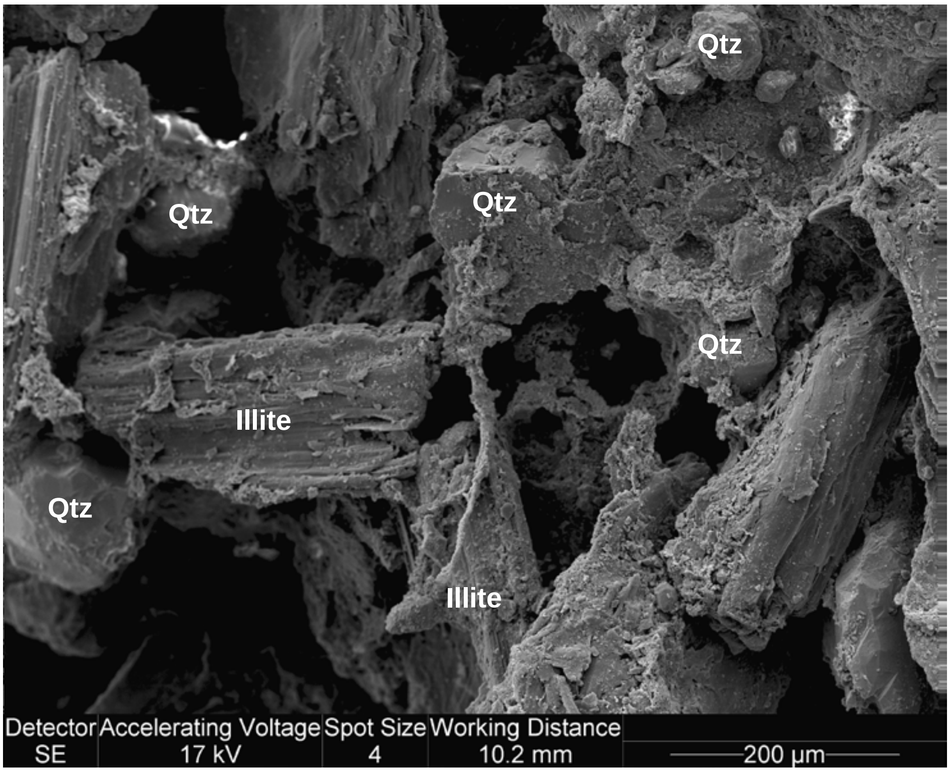

Figure 20.B*: Loosely consolidated sandstone with illite and quartz (Qtz) grains.*

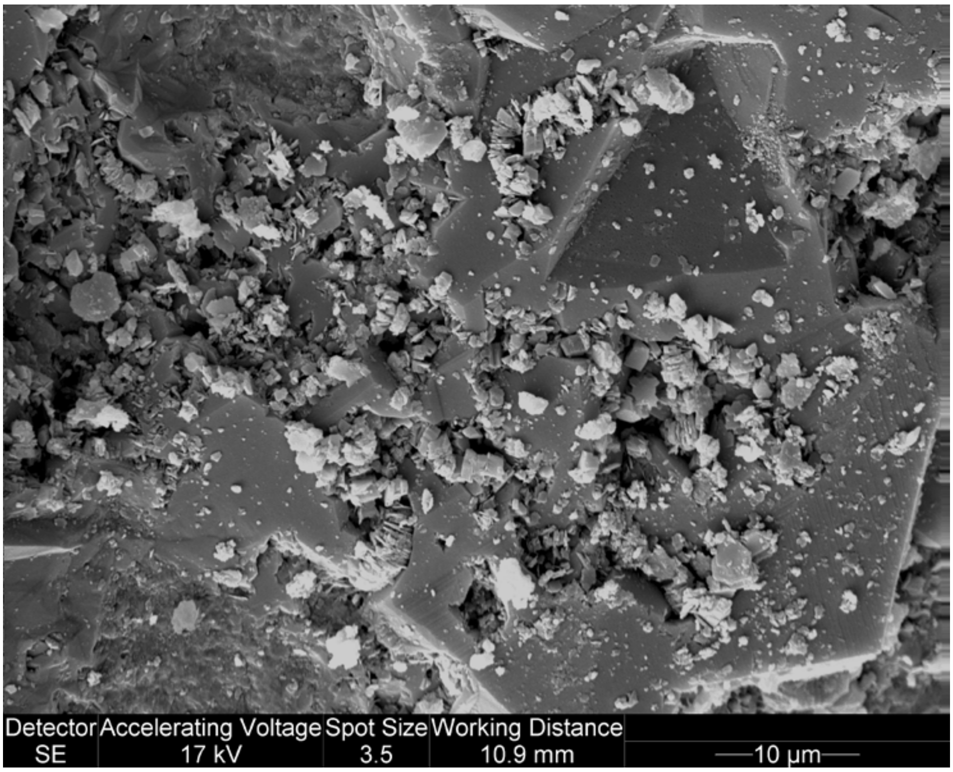

Figure 20.C*:* Quartz overgrowth on a sand grain, envelope kaolinite booklets.

2267.5 m below kb.

This sample is grey and dominated by fine to medium grained sand, sandstone fragments, mudstone and carbonates. The sandstone fragments are weakly cemented and fine to coarse grained. Two coarse sand grains and a sandstone fragment have been chosen for further SEM investigation.

The SEM analysis shows that small quartz overgrowths form on the corroded surfaces of quartz grains (Fig 21.A). Small clay minerals (probably illite and kaolinite) form on the overgrown quartz surfaces (Fig 21.B). Locally carbonate has grown on the quartz grains.

The same features have been observed on the sandstone fragment. Smectite is abundant and probably derived from the infiltrated drilling mud. Locally chlorite has been observed, which is interpreted as authigenically grown material, but could also be derived from the drilling mud.

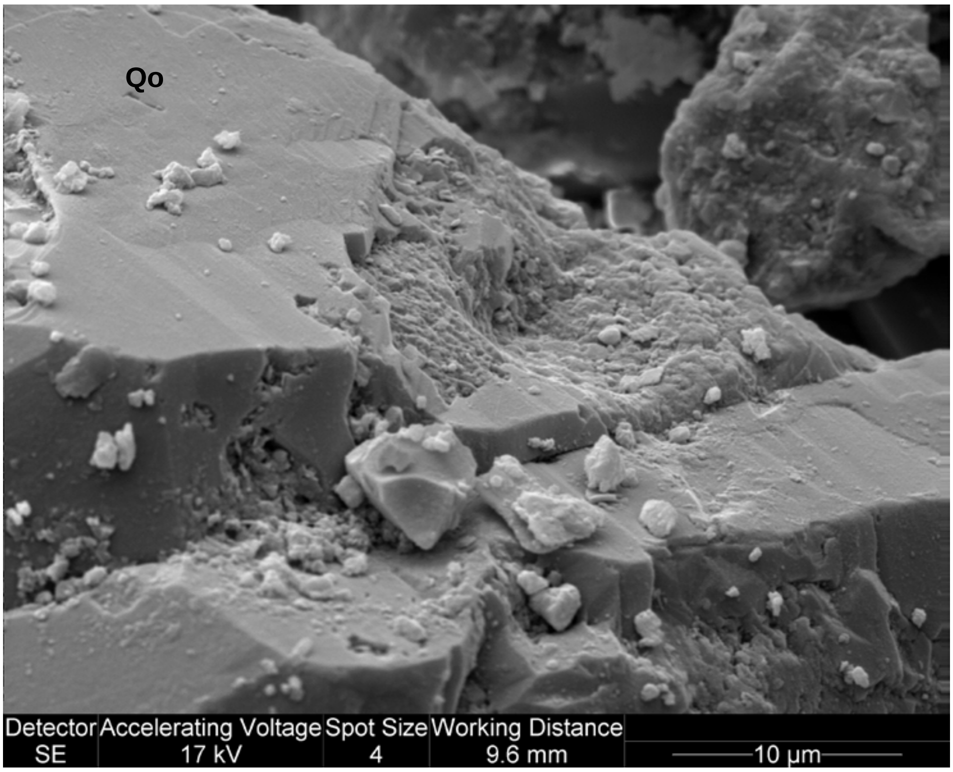

Figure 21.A: Quartz overgrowth (Qo) on corroded surfaces.

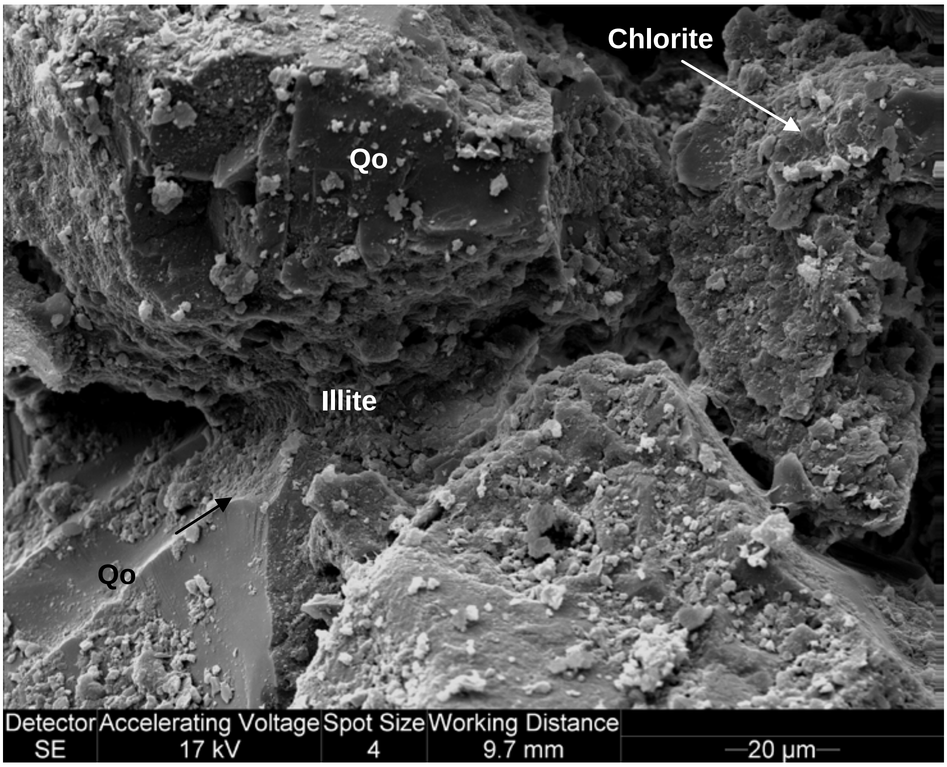

***Figure 21.B**: Incipient quartz overgrowths (Qo), chlorite (authigenic) and illite growing in pores (plus drilling mud).*

2277.5 m below kb.

The sample is reddish grey and dominated by fine to medium grained sand and sandstone fragments. Mudstone is less common. The sandstone fragments are weakly cemented and have a fine to medium grain size. Two coarse sand grains and a sandstone fragment have been selected for further SEM investigation.

The SEM analysis shows that quartz is abundant and shows small overgrowths. Locally an iron oxide or iron hydroxid, which might be goethite, has been observed. It forms ring structures with a porous surface (Fig 22.A). In the sample dissolved K-feldspar, which is replaced by illite grains, has been observed. The illite grains maintained the former K-feldspar crystal structure (Fig 22.B).

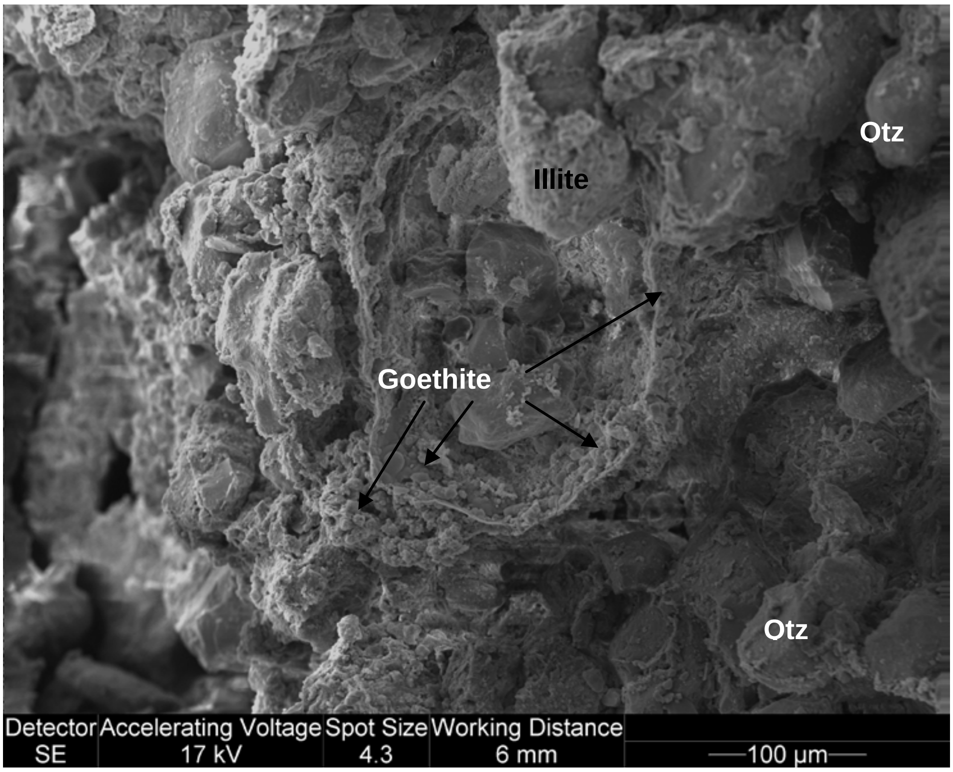

Figure 22.A: *Iron oxide or hydroxide (possibly goethite) in quartz-rich sandstone.*

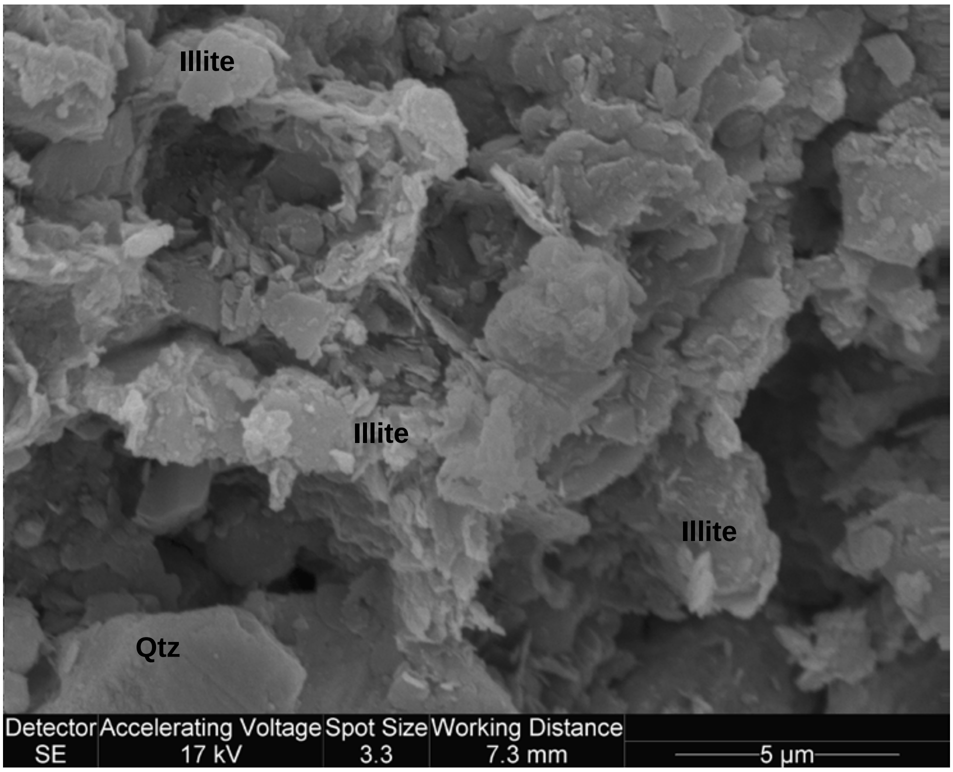

Figure 22.B: *Illite grains following former K-feldspar structure.*

Samples investigated with optical microscopy

L. Cretaceous Unit

1810 m b. kb.
The sample is greenish grey and dominated by fine to medium grained sand and fine grained, weakly cemented sandstone fragments. Two sandstone fragments were picked for further SEM investigation.

1815 m b. kb.
The sample is greenish grey and dominated by fine to medium grained sand and sandstone fragments. The sandstone fragments are weakly cemented and fine grained.

1820 m b. kb.
The sample is light grey and is dominated by fine to medium grained sand and sandstone fragments. The sandstone fragments are weakly cemented and fine - coarse grained. Three sandstone fragments were chosen for SEM investigation

1840 m b. kb.
The sample is dark grey and black and dominated by dark organic matter and fine grained sand. Mudstone and sandstone fragments are rare. The sandstone fragments are weakly cemented and fine grained.

1845 m b. kb.
The sample is dark grey and black. It is dominated by dark organic matter and fine grained sand. Mudstone and sandstone fragments are rare. The sandstone fragments are weakly cemented and fine grained.

1850 m b. kb.
This sample is dark grey and black. It is dominated by dark organic matter and some fine grained sand. Mudstone and sandstone fragments are rare. The sandstone fragments are weakly cemented and fine grained.

1855 m b. kb.
The sample is dark grey and black. It is dominated by dark organic matter and fine grained sand. Mudstone and sandstone fragments are rare. The sandstone fragments are weakly cemented and fine grained.

1860 m b. kb.
The sample is dark grey and is dominated by dark organic matter and fine to coarse grained sand. Mudstone and sandstone fragments are less common. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain and two sandstone fragments were chosen for SEM investigation.

Fjerritslev Formation

1865 m b. kb.
The sample is greyish brown and is dominated by dark organic matter, fine to medium grained sand and sandstone fragments. The sandstone fragments are weakly cemented and fine grained.

1870 m b. kb.
The sample is greyish brown and is dominated by dark organic matter and fine to medium grained sand. Sandstone fragments are rare. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain and a sandstone fragment were chosen for SEM investigation.

1950 m b. kb.
The sample is greyish brown and dominated by mudstone. Fine to medium grained sand, dark organic matter and mica is less common.

1952,5 m b. kb.
The sample is brownish grey. It is dominated by medium grained sand and mudstone with sporadic dark mica, dark organic matter and sandstone fragments. The sandstone fragments are weakly cemented and fine to medium grained. A coarse sand grain and a sandstone fragment were chosen for SEM investigation.

1955 m b. kb.
The sample is brownish grey. It is dominated by medium to coarse grained sand and mudstone with sporadic appearances of dark mica, carbonates, dark organic matter and sandstone fragments. The sandstone fragments are weakly cemented and fine to medium grained.

1960 m b. kb.
The sample is brownish grey and is dominated by medium to coarse grained sand and mudstone with less frequent dark mica, carbonates, dark organic matter and sandstone fragments. The sandstone fragments are weakly cemented and fine to medium grained.

1962,5 m b. kb.
The sample is brownish grey and is dominated by medium – coarse-grained sand, weakly fragments and mudstone. Carbonates are observed but rare. The sandstone fragments are weakly cemented and fine to medium grained.

1972,5 m b. kb.
The sample is brownish grey and dominated by medium to coarse grained sand, sandstone fragments and mudstone. The sandstone fragments are weakly cemented and fine to medium grained.

1975 m b. kb.
The sample is brownish grey and is dominated by mudstone and medium to coarse grained sand. Carbonates and sandstone fragments sandstone fragments are less common. The sandstone fragments are weakly cemented and fine grained.

1977,5 m b. kb.
The sample is brownish grey and is dominated by mudstone and medium to coarse grained sand. Sandstone fragments, dark organic matter, carbonates and dark mica are less common. The sandstone fragments are weakly cemented and fine grained.

1980 m b. kb.
The sample is greyish brown and is dominated of medium to coarse grained sand and mudstone. Sandstone fragments and carbonates are less common. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain has been chosen for SEM investigation together with two sandstone fragments.

1982,5 m b. kb.
The sample is yellow and dominated by medium grained sand and dark colored mudstone. Sandstone fragments and dark organic matter are less common. The sandstone fragments are weakly cemented and fine grained.

1985 m b. kb.
The sample is yellow and dominated by medium grained sand and dark colored mudstone. Sandstone fragments, dark mica and dark organic matter are less common. The sandstone fragments are weakly cemented and fine grained.

1992,5 m b. kb.
The sample is light grey and dominated by fine to medium grained sand. Mudstone, dark mica, carbonates and sandstone fragments are less common. The sandstone fragments are weakly cemented and fine to medium grained. A very coarse sand grain and a sandstone fragment have been selected for SEM investigation.

1997,5 m b. kb.
The sample is grey and dominated by fine to medium grained sand, sandstone fragments and mudstone. Dark mica is less common. The sandstone fragments are weakly cemented and fine to medium grained.

2000 m b. kb.
The sample is light grey and is dominated by fine – coarse-grained sand. Mudstone, sandstone fragments, dark organic matter and dark mica are less common. The sandstone fragments are loosely cemented and fine to medium grained.

2007,5 m b. kb.
The sample is light grey and is dominated by fine to coarse grained sand with sporadic mudstone, sandstone fragments, dark organic matter and dark mica. The sandstone fragments are weakly cemented and have a fine to medium grain size.

2010 m b. kb.
The sample is grey and is dominated by fine to medium grained sand. Less common are mudstone, sandstone fragments, dark organic matter, carbonate and dark mica. The sandstone fragments are weakly cemented and fine to medium grained. A very coarse sand grain and two sandstone fragments have been picked for SEM investigation.

2012,5 m b. kb.
The sample is grey and dominated by fine to medium grained sand, mudstone and sandstone fragments. Less common are dark mica, dark organic matter and carbonates. The sandstone fragments are weakly cemented and have a fine to medium grain size.

2015 m b. kb.
The sample is grey and dominated by fine to medium grained sand, mudstone and sandstone fragments. Less common are dark mica, dark organic matter and carbonates. The sandstone fragments are weakly cemented and have a fine to coarse grain size.

2017,5 m b. kb.
The sample is light grey and is dominated by sandstone fragments, fine to medium grained sand and carbonates. Mudstone and dark mica are less common. The sandstone fragments are weakly cemented and have a fine to coarse grain size.

2020 m b. kb.
The sample is greyish yellow and is dominated fine to medium grained sand, mica and mudstone. Sandstone fragments are rare. The sandstone fragments are weakly cemented and have a fine to medium grain size.

2062,5 m b. kb.
The sample is greyish and is dominated by fine to medium grained sand, sandstone fragments and mudstone with sporadic carbonates. The sandstone fragments appear weakly cemented and have a fine to medium grain size.

2067,5 m b. kb.
The sample is grey and is dominated by fine to medium grained sand, sandstone fragments and mudstone with sporadic dark organic matter and dark mica. The sandstone fragments are weakly cemented and have a fine to medium grain size.

2070 m b. kb.
The sample is grey and is dominated by fine to medium grained sand and sandstone fragments with sporadic mudstone and dark organic matter. The sandstone fragments are very weakly cemented and fine to medium grained. A very coarse sand grain and a sandstone fragment were picked for further SEM investigation.

2075 m b. kb.
The sample is grey and is dominated by very fine – medium-grained sand, sandstone fragments, mudstone and carbonates. The sandstone fragments are weakly cemented with a fine to medium grain size.

2077,5 m b. kb.
The sample is greyish and is dominated by fine to medium grained sand with sandstone fragments, mudstone and carbonates. The sandstone fragments are weakly cemented and have a fine – medium grain size.

2110 m b. kb.
The sample is greyish brown and is dominated by very fine to medium grained sand and sandstone fragments. Mudstone is less common. The sandstone fragments have a fine to medium grain size and are weakly cemented.

2112,5 m b. kb.
The sample is greyish brown and is dominated by very fine to medium grained sediments and sandstone fragments. Mudstone, dark organic matter and carbonates are less common. Sandstone fragments are weakly cemented and have a very fine to medium grain size.

2115 m b. kb.
The sample is greyish brown and dominated by very fine to medium grained sediments and sandstone fragments. Mudstone and carbonates are less common. Sandstone fragments are fine to medium grained and weakly cemented.

2117,5 m b. kb.
The sample is grey and dominated by fine to medium grained sand with sporadic mudstone, carbonates and sandstone fragments. Sandstone fragments have a fine to medium grain size and are weakly cemented.

2120 m b. kb.
The sample is grey and dominated by fine to medium grained sand. Mudstone, carbonates and sandstone fragments are less common. The sandstone fragments are weakly cemented and fine grained. For SEM investigation a medium sand grain and a sandstone fragments were picked.

2122,5 m b. kb.
The sample is grey and dominated by fine to medium grained sand. Mudstone, carbonates and sandstone fragments are less common. The sandstone fragments are fine to medium grained and weakly cemented.

2127,5 m b. kb.
The sample is brownish grey and dominated by fine to medium grained sand, mudstone and sandstone fragments. Carbonates are less common. The sandstone fragments are weakly cemented and have a fine – medium grain size.

Gassum Formation

2132,5 m b. kb.
The sample is dark grey and dominated by fine to medium grained sand and mudstone. Sandstone fragments are common. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain has been chosen for SEM investigation together with a couple of sandstone fragments.

2135 m b. kb.
The sample is greyish-brown. It is dominated by fine to medium grained sand and mudstone. Sandstone fragments are common and are weakly cemented with a fine to medium grain size.

2137,5 m b. kb.
The sample is grey and dominated by fine – medium grained sand, mudstone and sandstone fragments. The sandstone fragments are weakly and have a fine to medium grain size. A very coarse sand grain and a very fine – medium-grained sandstone fragment have been chosen for SEM investigation.

2145 m b. kb.
The sample is grey and dominated by fine to medium grained sand. Mudstone and sandstone fragments are present. Sandstone fragments are weakly cemented and are fine to medium grained.

2147,5 m b. kb.
The sample is grey and dominated by fine to medium grained sand. Mudstone and sandstone fragments are less common. Sandstone fragments are fine – medium grained and weakly cemented.

2155 m b. kb.
The sample is greyish-brown and dominated by fine to medium grained sand and sandstone fragments. Mudstone is sparsely dispersed. The sandstone fragments are weakly cemented and fine to medium grained. A very coarse sand grain and two sandstone fragments have been chosen for further investigation on SEM.

2157,5 m b. kb.
The sample is greyish-brown and dominated by fine to medium grained sand. Mudstone and sandstone fragments are less common. Rare pyrite is observed. Sandstone fragments in this sample are weakly cemented and appear with a fine to medium grain size.

2160 m b. kb.
The sample is grey and dominated by fine to medium sand and sandstone fragments. Mudstone is less common. Sandstone fragments are weakly cemented and fine to medium grained.

2162,5 m b. kb.
The sample is grey and dominated by fine to medium sand, mudstone and sandstone fragments. Sandstone fragments are weakly cemented and fine to medium grained.

2165 m b. kb.
The sample is dark grey and dominated by fine – medium grained sand and sandstone fragments. Mudstone is less common. The sandstone fragments are fine to medium grained and weakly cemented.

2170 m b. kb.
The sample is dark and greyish-brown. It is dominated by fine to medium grained sand and sandstone fragments. Mudstone is less common. Rare pyrite has been observed. The sandstone fragments are weakly cemented and fine to medium grained. A coarse sand grain and a sandstone fragment have been chosen for further investigation by SEM.

2175 m b. kb.
The sample is grey and dominated by fine to medium grained sand. Mudstone and sandstone fragments are less common. The sandstone fragments are fine – medium grained and weakly cemented.

2185 m b. kb.
The sample is grey and dominated by fine – coarse-grained sand with some mudstone and sandstone fragments. The sandstone fragments are weakly cemented and fine to medium grained. A coarse sand grain and a sandstone fragment were picked for SEM investigation.

2190 m b. kb.
The sample is grey and dominated by fine to coarse grained sand, sandstone fragments, mudstone and carbonates. The sandstone fragments are weakly cemented and have a fine to medium grain size.

2205 m b. kb.
The sample is light grey and dominated by fine to medium grained sand and sandstone fragments. Mudstone is less common. The sandstone fragments are weakly cemented and fine grained.

2210 m b. kb.
The sample is greyish brown and dominated by fine to medium grained sand and sandstone fragments. The sandstone fragments are weakly cemented and fine grained. A coarse sand grain and a sandstone fragment were chosen for further SEM investigation.

2215 m b. kb.
The sample is greyish brown and dominated by fine to medium grained sand, sandstone fragments and sporadic mudstone. Rare pyrite has been observed. The sandstone fragments are weakly cemented and fine grained.

2220 m b. kb.
The sample is grey and dominated by fine to medium grained sand, mudstone and sandstone fragments. The sandstone fragments are weakly cemented and fine grained.

2230 m b. kb.
The sample is light grey and dominated by fine to medium grained sand, mudstone and sandstone fragments. The sandstone fragments are weakly cemented and fine - medium grained. Two very coarse sand grains and a sandstone fragment were collected for investigation by SEM.

2235 m b. kb.
The sample is dark grey and dominated by dark organic matter. Fine grained sand and mudstone are less common. Fragments are very weakly cemented and consist of a mixture of dark organic matter and fine grained sand.

2240 m b. kb.
The sample is dark grey and dominated by dark organic matter and fine grained sand. Less common are mudstone and weakly cemented fragments of sand and dark organic matter. Fragments are very weakly cemented and consist of a mixture of dark organic matter and fine grained sand.

2250 m b. kb.
The sample is dark grey and is dominated by fine to medium grained sand and dark organic matter. Less common are mudstone, carbonates and weakly cemented fragments of sand and dark organic matter. A very coarse sand grain and two sandstone fragments were collected for investigation by SEM.

2255 m b. kb.
The sample is grey and dominated by fine to medium grained sand. Mudstone, dark organic matter, sandstone fragments and carbonates are less common. Sandstone fragments are fine to medium grained and weakly cemented.

2260 m b. kb.
The sample is light grey and dominated by fine to medium grained sand, sandstone fragments and dark organic matter. Mudstone and carbonates are less common. Sandstone fragments are weakly cemented and fine to medium grained.

2267,5 m b. kb.
The sample is grey and dominated by fine to medium grained sand, sandstone fragments, mudstone and carbonates. The sandstone fragments are weakly cemented and fine to coarse grained. Two coarse sand grains and a sandstone fragment have been chosen for further SEM investigation.

2270 m b. kb.
The sample is grey and dominated by fine to medium grained sand, sandstone fragments, mudstone and carbonates. Sandstone fragments are weakly cemented and have a fine to medium grain size.

2272,5 m b. kb.
The sample is grey and is dominated of fine to medium grained sand and sandstone fragments with sporadic mudstone and carbonates. Sandstone fragments are weakly cemented and have a fine to medium grain size.

2275 m b. kb.
The sample is greyish brown and dominated by fine to medium grained sand and sandstone fragments. Mudstone is less common. Sandstone fragments are weakly cemented and have a fine to medium grain size.

2277,5 m b. kb.
The sample is reddish grey and dominated by fine to medium grained sand and sandstone fragments. Mudstone is less common. The sandstone fragments are weakly cemented and have a fine to medium grain size. Two coarse sand grains and sandstone fragment have been selected for further SEM investigation.

2280 m b. kb.
The sample is greyish brown color and dominated by fine to medium grained sand. Mudstone and sandstone fragments are less common. The sandstone fragments are weakly cemented and have a fine to medium grain size.

Reservoir Parameters

The Mesozoic succession in the area of interest contains several sandstone units in the Lower Cretaceous, Fjerritslev and Gassum Formations that possess a geothermal potential (Figure 2). However, owing to sparse and incomplete data precise evaluations are hampered. In an attempt to strengthening the database, selected cuttings samples have been investigated as described in the previous sections for:

1) the amount and type of cement in the sandstones, and their sorting and grain size;
2) critical characteristics of the Gassum Formation sandstones in the upper part where well-log exist and from lower part the formation where well-logging failed.

The tables below present the results of the standard GEUS analyses of the well-logs (Table 2) and the combined results where the un-logged section is evaluated based on the similarities between the logged section and the un-logged section (Table 3).

Table 2: *Reservoir parameters for the sandstone-rich units drilled in the Karlebo-1/1A well. Data from previous GEUS studies published prior to July, 2013. Cut-offs applied: Vshale < 30% and Porosity > 15%. The Net sand thickness corresponds to the accumulated thickness of potential reservoir sandstone layers within a particular unit.*

Unit	Top - Base of unit (m)	Unit thick. (m)	Thickness (m) Gross Sand	Net Sand	Avg. Por. (%)	Avg.gas perm. (mD)	Avg.reser -voir perm (mD)	Trans-missivity (Dm), gas
L. Cret	1794 - 1865	71	29	22.2	20.7	243		5.4
L.Jurassic	1946 - 2132	186	81	47.5	20.3	219		10.4
Gassum logged	2132 - 2224	92	40	26.6	19.5	202		5.3
*Gassum unlog.**	2224 - 2279	55	*n/a*	*n/a*	*n/a*	*n/a*		*n/a*
*Gassum total**	2132 - 2279	147	*n/a*	*n/a*	*n/a*	*n/a*		*n/a*

Table 3: *Reservoir parameters for the sandstone-rich units drilled in the Karlebo-1A well. Data from this study. Cutoffs applied: Vshale < 30% and Porosity > 15%. The Net sand thickness corresponds to the accumulated thickness of potential reservoir sandstone layers within a particular unit.*

Unit	Top - Base of unit (m)	Unit thick. (m)	Thickness (m) Gross Sand	Net Sand	Avg. Por. (%)	Avg.gas perm. (mD)	Avg.reser -voir perm (mD)	Trans-missivity (Dm), #
L. Cret	1794 - 1865	71	29	22.2	20.7	243	300	6.7
L.Jurassic	1946 - 2132	186	81	47.5	20.3	219	275	13.1
Gassum logged	2132 - 2224	92	40	26.6	19.5	202	250	6.7
*Gassum unlog.**	2224 - 2279	55	*24*	*16*	*20*	*200*	*250*	*4.0*
*Gassum total**	2132 - 2279	147	*64*	*43*	*19.7*	*201*	*250*	*10.7*

*Rough estimates;   #: At reservoir scale (field scale)

The procedure of deriving reservoir parameters for the various formations (reservoir units) is described in the following text.

The average porosity is interpreted from wireline log data acquired in the Karlebo-1A well, primarily the gamma-ray and sonic logs. No cores were cut in the Karlebo-1A well, and thus the gas permeability is based on a general porosity-permeability relationship derived from core material from various wells located outside the area of interest. Due to lack of core data, it is assumed that this relationship also is valid for Karlebo-1 area, and this relationship forms the basis of producing a gas-permeability curve using the log-derived porosity curve as input data. For further details on the methodology used for estimating gas permeability and transmissivity, reference is made to Mathiesen et al. (2013).

The gas permeabilities were converted into liquid permeabilities (dividing by 2) and subsequently up-scaled to reservoir level - or field scale - using an appropriate permeability enhancement factor (multiplying by 2.5). The combined scale factor is then 1.25. Gas permeabilities are normally measured on core plugs at laboratory conditions and up-scaling is thus needed prior to estimating reservoir permeabilities. The up-scaled permeabilities are considered to be comparable with test permeabilities, i.e. permeabilities interpreted from an analysis of well test data (e.g. pumping test data).

The up-scaling from core plugs measurements (i.e. laboratory scale) to reservoir scale is not trivial. As a first step, log-derived permeabilities were generated on the basis of a general porosity-permeability relationship that has been established from cross-plotting core porosity data versus core permeability data. GEUS is currently carrying out an internal study, aiming at comparing these log-derived permeabilities with test permeabilities. The initial results of this study have indicated the log-based permeabilities to be somewhat conservative. In order to solve the issue of up-scaling along with the challenge of converting gas permeabilities into liquid permeabilities, GEUS suggests applying a scale factor of 1.25 as described above. The derivation of this factor is based on an analysis of a limited dataset, since both core analysis data and corresponding well test data are needed for the analysis. This database includes e.g. data from the Gassum Formation in the Stenlille-1, -2, -3, -4, -5 and -19 wells, and these data allows a direct comparison between test permeabilities derived from analysis of well test data and core permeabilities originating from intervals that match the tested intervals. So far, the examination of this limited database indicates that multiplying the gas-permeability by 1.25 provides a reasonable estimate of the actual reservoir permeability. **Data from the Karlebo area well do not contribute directly to the derivation of this 1.25 scaling factor, because neither core data nor test data are available from the Karlebo-1/1A well.**

To sum up: the particular factor of 1.25 accounts for the up-scaling from laboratory to field scale and it also incorporates the effect of converting gas permeability into liquid permeability. However, the value of 1.25 may be discussed and is likely to be changed somewhat, when more data and analyses become available. The scaling factor is thus associated with uncertainty, and it is envisaged that the factual range of scaling factor is 1–2.

The transmissivity is calculated as flow weighted transmissivity based on the estimated gas permeability log and net sand thickness, followed by up-scaling as described above. The uncertainty on the transmissivity is related primarily to the uncertainty on the permeability estimate, and in previous studies GEUS suggested to set up a permeability envelope defined by multiplying (and dividing) the permeability by 5. This range is defined via cross-plotting core porosity and core permeability data from a large number of wells. A similar methodology is suggested for addressing the uncertainty on the transmissivity, i.e. the transmissivity range is likewise defined by multiplying (and dividing) by a specific factor (5 or higher, see Table 4). The intention of presenting a transmissivity range is to account for the uncertainties related to permeability, net sand thickness and up-scaling.

The parameters assigned to the un-logged part of the Gassum Formation are estimates only, and are based on a combined analysis of the available log data and the present analysis of cuttings, which includes samples from both the logged and un-logged part of the Gassum Formation. Furthermore, information from the mud log description and the lithology screening of the cuttings samples performed in this study provide the net-to-gross ratios for the un-logged interval, and this ratio is utilized for estimating gross and net sand thicknesses in the un-logged part of the Gassum Formation. The cuttings analyses indicate that the un-logged part of the Gassum Formation does not form any anomaly in geological terms, and it has thus been assumed that the net-to-gross ratios for the un-logged and logged parts are comparable. The net-to-gross-ratio is about 0.43, when defined as gross sand thickness divided by unit thickness. Similarly, the net-to-gross ratio is approximately 0.67, when defined as net sand thickness divided by the gross sand thickness.

The average gas and reservoir permeabilities listed in Table 3 are estimated on the basis of the assumption that sandstones are dominantly fine to medium-grained. The cuttings descriptions indicate that the majority of the sandstones samples actually are dominated by fine to medium-grained sandstones.

The SEM analyses of both the logged and un-logged parts of the Gassum Formation indicate that the Gassum Formation sandstones are generally weakly cemented, suggesting that the porosity level interpreted from the log data acquired in the upper part of the formation also apply to the lower un-logged part. Furthermore, this similarity in degree of cementation also suggests that the log-derived permeability level achieved in the upper part of the Gassum Formation apply to the un-logged part.

Table 4: *Estimated reservoir transmissivity and associated range (uncertainty band)*

Unit	Top and Base of unit (m)	Reservoir Transmissivity (Dm)	Specific factor for multiplication, and division	Transmissivity range
L. Cretaceous	1794 - 1865	6.7	5	1 – 34
L. Jurassic	1946 - 2132	13.1	5	3 – 66
Gassum, logged	2132 - 2224	6.7	5	1 – 34
Gassum, unlogged	2224 - 2279	*4.0*	*6***	*½ – 24*
Gassum, total	2132 - 2279	*10.7*		*2 – 58*

(**) Note the factor 6 is used for the unlogged part of the Gassum Formation to accommodate for the uncertainty related to the absence of well-logs.

Table 5: *Main lithology intervals based on selected cuttings samples; sand is the dominating lithology in the mentioned intervals. Sand is also present in small and varying amounts in some of the intervals between those mentioned in the table.*

Depth m b. kb	Gassum Fm.
2132,5 – 2137,5	Sand and mudstone
2140	Sand
2142,5 – 2145	Sand and mudstone
2147,5	Sand
2150 – 2160	Sand and mudstone
2162,5 – 2175	Sand
2180	Sand and mudstone
2182,5	Mudstone
2185 – 2195	Sand and mudstone
2200 – 2210	Sand
2215 – 2230	Sand and mudstone
2237,5 – 2250	Sand and dark organic matter
2255	Sand and mudstone
2260	Sand
2265 – 2267,5	Sand and mudstone
2270 – 2280	Sand

Concluding remarks

The primary scopes of the performed cuttings samples analyses were to contribute to the assessment of the geothermal potential in North and Northeast Sjælland by investigating the samples from the sandstones in the Gassum Formation and from the overlying Lower Jurassic and Lower Cretaceous sandstones encountered in the Karlebo-1A well. As the amount and quality of the available data from the area of interest is very limited, it is of importance to estimate, where possible, if the potential geothermal reservoirs are composed as expected and predicted from the general and regional models (e.g. Mathiesen et al. 2009).

The macroscopic visual screening of all the available cuttings samples together with the microscopically examined selected samples (8 from the Lower Cretaceous, 37 from the Fjerritslev Formation and 30 from the Gassum Formation) confirm in general the validity of the acquired well logs in the Karlebo-1A well. Further, they support the general geological model of GEUS for this part of the Mesozoic succession. The performed investigation thus provides confidence to the general assessment of the presence and distribution of the three potential reservoirs in the Upper Triassic– Lower Cretaceous succession of North and Northeast Sjælland, an area with very limited data available from the deep subsurface.

The microscopically investigation and SEM analyses confirm that the amount of cement in the sandstones is limited in accordance with the patterns and readings of the well logs. Based on GEUS´ general geological model of the area and the interpreted maximum burial depth of the sandstones, it is likewise suggested that the extent of cementation is limited. On the basis of the present cuttings study, it is further assumed that pore throat reducing cement is limited and not affecting the permeability notably.

Furthermore, the investigation has made it possible to include the lower part of the Gassum Formation in the transmissivity estimate of the entire formation by comparing the samples form the logged and un-logged parts of the formation (see table 3 & 4). In addition, the cutting study indicates that the sandstones in both the logged and un-logged parts are fine- to medium-grained, weakly cemented, and that the distribution of sandstones and mudstones is fairly similar, suggesting that the net-to-gross ratios of the two intervals are comparable.

The study has thus confirmed the expected composition of the sandstones, and therefore the investigation has reduced the potential risk of occurrence of negative geological anomalies in the studied succession. The assessment of the geothermal potential in the area of North and Northeast Sjælland is hence strengthened.

In addition to the investigation of the cuttings samples, an attempt to upscale the estimated permeabilities to reservoir conditions has been performed based on preliminary results from ongoing GEUS research into the relation between log-derived permeabilities (derived from core analysis data) and test permeabilities (derived from analysis of pumping test data). It is emphasized that this upscaling is largely based on limited and mainly empiric data. The applied upscaling factor is thus due to revision, when further data become available in the future.

According to the Well Completion Report a caliper logging tool was rigged-up on the well, but a caliper log is not presented in digital format or displayed on any of the well log sheets included in the report; thus it is neither possible to evaluate the stability of the well bore nor to estimate the amount of caving and furthermore, it is not possible to address the quality of the acquired well logs.

References

Hjuler, M.L., Kristensen, L., Mathiesen, A., Bidstrup, T. & Nielsen, L.H. 2013. Evaluation of possible geothermal reservoirs in the Helsingør area. Danmarks and Grønlands Geologiske Undersøgelse Rapport 2013/20.

Mathiesen, A., Kristensen, L., Bidstrup, T. & Nielsen, L.H. 2009: Vurdering af det geotermiske potentiale i Danmark. Danmarks og Grønlands Geologiske Undersøgelse rapport 2009/59, 85 pp.

Mathiesen, A., Kristensen, L., Nielsen, C.M., Weibel, R., Hjuler, M.L., Røgen, B., Mahler, A., & Nielsen, L.H. (2013): Assessment of sedimentary geothermal aquifer parameters in Denmark with focus on transmissivity. *EGC Paper, 9 pp, Pisa June 2013.*