Petrological characterization of the Cambrian sandstone reservoirs in the Baltic Basin, Sweden

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Dissertations in Geology at Lund University,
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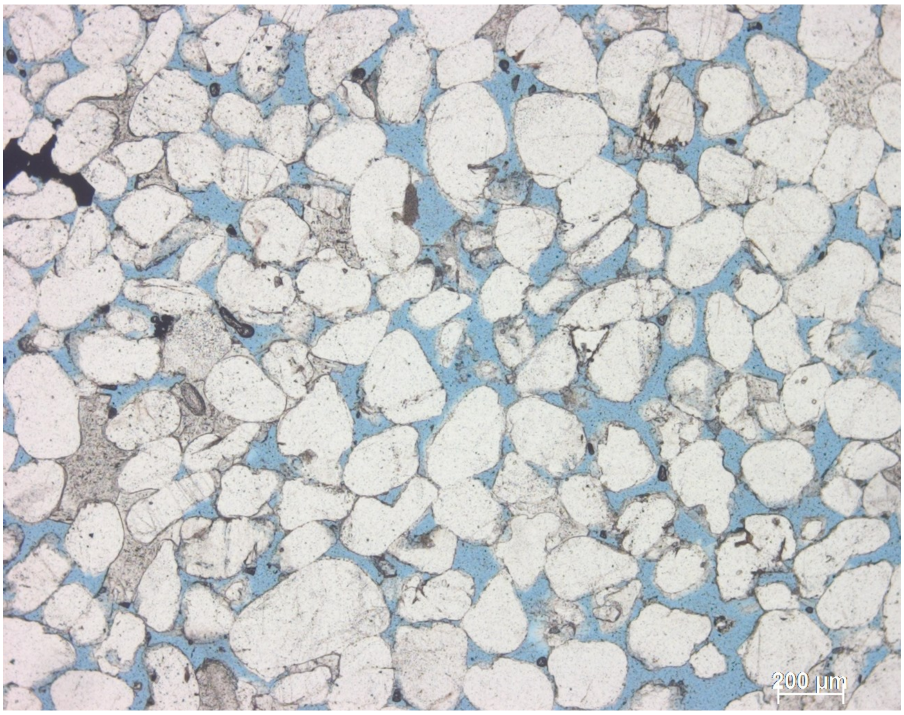

Department of Geology
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Cover Picture: Thin section of porosity highlighted in the blue proxy (by Tawonga Chitindingu)

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Chitindingu, T., 2018: Petrological characterization of the Cambrian sandstone reservoirs in the Baltic Basin, Sweden. *Dissertations in Geology at Lund University*, No. 543, 34 pp. 45 hp (45 ECTS credits) .

Abstract: The Cambrian sandstone reservoirs of the Baltic Basin have been identified by the Geological Survey of Sweden (SGU) as potential CO_2 storage sites in line with regulations regarding Carbon Capture and Storage (CCS). In order to understand the petrological and petrophysical characteristics of the sandstone units, 54 thin sections from the three main Cambrian sandstone units were studied. The description of the thin sections involved the use of scanning electron microscopy, backscatter electron and cathodeluminescence. The sandstone units are the Faludden, När and Viklau sandstones. The Faludden sandstone forms part of the Borgholm Formation whereas the Viklau and När form the File Haidar Formation. In addition to thin sections, core samples were also studied and this data was synthesized with petrophyisical data available at the SGU-archive in Lund. Of the 54 thin sections, 19 from the Faludden sandstone unit were sent to the Geological Survey of Denmark and Greenland (GEUS) for measurement of porosity and permeability, to add to the data already available at the SGU archive in Lund. The purpose is to provide a comprehensive petrological report on the variations of porosity, permeability, mineralogy, texture and cementation with depth. The results show that it is difficult to establish trends with depth in the study area because it is located in the basin peripheries at relatively shallow depth. However, the results showed that calcite and authigenic quartz are significant cement material which may reduce or obliterate porosity. The authigenic quartz is partly euhedral towards the empty pore space, partly filling the pore space and sometimes completely around the detrital quartz grain. The carbonate cements exhibit poikolotopic texture and where it occurs, the detrital grains show a low grain packing density. The results of the modal analyses showed that the Faludden sandstone, the youngest of the reservoirs, has the highest average porosities of 17% and the Viklau and När sandstones have 6.7 and 11.4% respectively. The deeper lying Viklau sandstone unit is made up of coarse grained sandstone which is not homogenous. The study also shows apatite as an early cementation phase and it has not been found elsewhere in the Cambrian reservoirs of the Baltic Basin. Therefore, it is important to carry out further studies of this apatite in order to determine its source and the diagenetic processes behind its formation.

Keywords: Cambrian, Baltic Basin, porosity, permeability, quartz, cement.

Supervisor(s): Mikael Erlström and Mikael Calner

Subject: Bedrock Geology

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Petrologisk karaktärisering av de kambriska sandstenreservoare-rna i Baltiska bassängen, Sverige

TAWONGA CHITINDINGU

Chitindingu, T., 2011: Petrologisk karaktärisering av de kambriska sandstenreservoarerna i Baltiska bassängen, Sverige. *Examensarbeten i geologi vid Lunds universitet*, Nr. 543, 34 sid. 45 hp.

Sammanfattning: De kambriska sandstensreservoarerna i den Baltiska bassängen har klassificerats av Sveriges Geologiska Undersökning (SGU), som potentiella förvaringsområden för koldioxid som uppfyller de regleringar som krävs för så kallad Carbon Capture and Storage (CCS). För att undersöka de petrologiska och petrofysiska förhållanden i tre utvalda kambriska sandstensformationer, studerades 54 tunnslipp. tunnslipen studerades med hjälp av svepelektronmikroskop (SEM-BSE) och katodluminicens. De utvalda sandstensformationerna är Faludden, När och Viklau. Faluddenformationen är en del av Borgholm formationen och resterande Viklau och När utgör en del av File Haidarformationen. Utöver tunnslip studerades även borrkärnsprover som korrelerades med redan existerande petrofysiska data från SGUs arkiv i Lund. Från de totala 54 tunnslipen var 19 tunnslip från Faluddenformationen, vilka skickades till Danmarks geologiska undersökningar samt Grönlands geologiska undersökning (GEUS) för porositet-och permeabilitets analys. Detta för att komplettera existerande data från SGUs arkiv. Syftet är att tillhandahålla en omfattande petrologisk rapport om variationerna av porositet, permeabilitet, mineralogi, konsistens och cementering med djup. Resultaten visar att det är svårt att fastställa trender med djup i studieområdet eftersom det ligger i bassängen på relativt grunt djup. Resultaten visade emellertid att kalcit och authigenisk kvarts är signifikant cementmaterial som kan reducera eller utplåna porositeten. Den authigenic kvarts är delvis euhedral mot tomrummet, delvis fyllning av porrummet och ibland helt runt detritalkvartskorgen. Karbonatscementerna uppvisar poikolotopisk konsistens och där det inträffar visar detritalkornen en låg kornförpackningstäthet. Resultaten av de modala analyserna visade att Faludden sandsten, den yngsta av reservoarerna, har de högsta genomsnittliga porositeterna 17% och Viklau och När sandstenarna har 6,7 respektive 11,4%. Den djupare liggande av sandstenenheterna, dvs Viklau sandstenenheten består av grovkornig sandsten som inte är homogen. Studien visar också apatit som en tidig cementeringsfas och den har inte hittats någon annanstans i de bamburska reservoarerna i Östersjön. Därför är det viktigt att utföra ytterligare studier av denna apatit för att bestämma dess källa och diagenetiska processer bakom dess bildning.

Nyckelord: Kambriska, Baltiska bassängen , porositet, permeabilitets, kvarts, cementering

Handledare: Mikael Erlström och Mikael Calner

Ämnesinriktning: Berggrundsgeologi

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1 Introduction

1.1. Background

The Cambrian sandstone reservoirs in the Swedish sector of the Baltic Basin(figs.1 & 2) are found in the File Haidar and Borgholm formations. These formations consist of alternating sequences of sandstone, siltstone and claystone beds. The sandstone units, which form the basis of this thesis, are the Faludden, När and Viklau sandstones (figs.3 & 4). These sandstone intervals contribute up to approximately 80m of the total c 240 m thick Cambrian succession (Sopher et al., 2014). The Lower Cambrian När and Viklau sandstones are present throughout the Swedish sector whereas the Middle Cambrian Faludden sandstone pinches out in the north, north-west and west. Erlström et al. (2011) noted that the Faludden sandstone is missing in the Yoldia well south of the island of Öland. It is also absent in the Gotska Sandön well, north of Gotland (fig. 1).

The Cambrian sandstones have been found to be the main reservoirs in the Baltic Basin and several oil and gas finds have been made in the south Baltic Sea, e.g. in Poland, Lithuania, and Russia . The reservoirs properties are primarily related to presence of silica cement. Quartz cement completely or partly filling pore spaces has been found to be one of the main causes of porosity loss in the Cambrian sandstone reservoirs in the Baltic Basin (Kilda & Friis, 2002).

Comprehensive studies on the reservoir characteristics have been carried out on the Lithuanian side of the Baltic Basin, where various depth and location models regarding the reservoir properties have been presented by e.g. Cyziene et al. (2001). Their study shows that there is a variation in the diagenetic, petrophysical and syn-depositional properties in an E–W direction in Lithuania. Present-day temperatures of the Cambrian reservoir range from 100 ºC in the shallow parts of the Baltic Basin to 900 ºC in West Lithuania (Šliaupa et al., 2004). This variation in the E–W direction is attributed to a corresponding increasing depth of the Cambrian reservoirs and an increasing heat flow from the basement. However, it is a different case on the Swedish sector of the basin. To date, most of the existing well data and cores on the Cambrian sandstones has not been comprehensively described and interpreted within the scientific community (Erlström et al., 2011, 2014). There is an extensive set of various well data (onshore and offshore) which derives from investigations by the Swedish Oil and Gas Prospecting Company (OPAB)) and from the Geological Survey of Sweden (SGU). The bulk of this data is now available at the geo-archive at SGU. Studies by Mortensen et al. (2017) regarding the potential of storing CO_2 as well as recent research (e.g. Sopher et al., 2016) there is a need to improve the petrophysical, petrological properties as well as the sedimentological characteristics of the Cambrian sandstones and boundary strata based on this data set.

The main aim of this study is, thus, to compile and evaluate existing well information (wire-line logs and analyses) supplemented by investigations on cores (thin sections, and porosity/permeability measurements) to gain a comprehensive description of the Cambrian reservoirs regarding, mineralogy, diagenesis, petrophysical properties, depositional setting and burial history in the Swedish sector of the Baltic Sea. The results are intended to improve the quality of any forthcoming modelling of the reservoir regarding its suitability for storage of CO_2.

1.2. History of oil and gas prospecting and CO_2 storage

1.2.1 Oil and gas exploration in the Baltic Sea and on Gotland

Extensive prospecting in the Baltic Sea has resulted in findings of scattered oil reservoirs located in dome–like structures, primarily in the Lower and Middle Cambrian sandstones in the Lithuanian, Polish and the Russian sector of the Baltic Basin. At present oil- and production occurs in the Russian and Polish sectors in the south-east parts of the Baltic Basin (Erlström et al., 2014).

Traces of oil in the Cambrian succession in the Swedish sector of the Baltic Sea were initially reported in the first deep stratigraphic wells drilled by the SGU in 1967–68 on Gotland, i.e. Grötlingbo-1 and När-1. Based on these findings OPAB launched an extensive prospecting campaign in the 1970s. Most of the OPAB exploration wells in the Swedish sector of the Baltic Basin were drilled between 1972 and 1976. On the island of Gotland, 76 wells were drilled during this first exploration program which targeted only the Cambrian sandstones (fig. 2).

In the offshore area OPAB drilled 13 wells into the Cambrian succession. However, most of the offshore wells did not show any exploitable amounts of oil in the sandstones. The B-10 well, the first offshore well drilled by OPAB, initially showed signs of hydrocarbon potential, but after some further analysis of the core and the log data, it was discovered that it only occurred in a few thin intervals. The B-9 (fig. 2) well, located in the outer parts of the Swedish sector showed good gas shows in the Faludden and När sandstone units. The B-9 well established the following: the Cambrian sandstones showed good reservoir properties; these reservoirs contain possible commercial quantities of hydrocarbons, primarily gas and; there are effective trapping mechanisms of the overlying bedrock and structure of the subsurface, e.g. fault traps and domes.

OPAB concluded that the uppermost one of the potential Cambrian sandstone reservoirs, i.e. the Faludden sandstone showed the most promising potential as an oil and gas reservoir. They also believed that there was a possibility to find oil in the pinch-out areas on Gotland; however, there were no such finds in the successively drilled wells onshore Gotland.

Exploitable oil was, however, later discovered in the Upper Ordovician carbonate build-ups (mounds) on Gotland in 1974 which led to an increasing interest towards these mounds for the following drilling campaigns. The mounds were found to contain enough oil to support small-scale oil production from the mid-1970s where, between 1974 and 1992, total oil production amounted to 100 000 cu. m (Sivhed et al., 2004).

In total OPAB drilled over 300 wells on Gotland of which most targeted the Ordovician succession. After OPAB ended their activities in 1986 due to a fall in oil prices Gotlandsolja AB took over the activities until 1992, drilling another 82 wells and shooting 345 short seismic profiles (Sivhed et al., 2004)

1.2.2 Aspects on the Cambrian reservoirs regarding storage of CO_2

During the last decades Carbon Capture and Storage (CCS) has gained increased recognition as a method to mitigate CO_2-emissions from combustion of fossil fuels. For adapting this technology, it is important to find suitable deep saline aquifers for storage. In this respect, new interest has risen regarding the Cambrian reservoir sandstones suitability for geological storage of CO_2. CCS refers to technologies developed to capture carbon dioxide (CO_2) from the emissions from power plants and industrial sources, the infrastructure for handling the transporting of CO_2 and those for injection and storage in deep geological formations (Blunt, 2010). Oil industries have long practised CO_2 injection into deep formations (aquifers and reservoirs), but for an entirely different purpose. In their case, the reason is either for enhancing oil and gas recovery from almost depleted or low pressured reservoirs or for disposal of excess CO_2 occurring mixed with the natural gas. The Sleipner project in the Norwegian sector of the North Sea is one example. Statoil has been injecting 1 Mt per year of CO_2 since the mid 1990s in order to reduce greenhouse gases (Blunt, 2010). There is today a rapidly increasing number of sites for storage of CO_2 in deep saline aquifers and reservoirs which drives the knowledge on the technique forward and creates an increasing demand on the geo-society to find new suitable sites.

The Swedish government has stated that the Swedish industry should be linked to CCS solutions and has also implemented the EU directive regarding CCS in the legislation. Studies of the possibilities to store CO_2 in the Swedish bedrock performed by SGU has shown that the main alternative is the Cambrian sandstone units in the Baltic Sea (Erlström, 2011, Mortensen et al., 2017). Assessment of the storage capacity is, however, still very uncertain, mainly because of the lack of adequate empirical data on various properties, e.g. the petrophysical properties of the reservoir sandstones. Assessments of storage capacity from studies by Sopher et al. (2014) and by Mortensen et al. (2017) have shown that there is a great need to improve the empirical database. Especially regarding the physical properties, i.e. especially porosity and permeability, of the sandstone intervals as to improve the capacity models. In this lies also a need to assess the heterogeneity factor of the sandstone, i.e. lateral and vertical variations in bedding, texture and diagenetic factors.

1.3. Study area

The investigated wells in this study are in the Swedish sector of the south Baltic Sea belonging to the west and northwest flank of the Baltic Basin (fig. 1). The study area furthermore encompasses the islands of Gotska Sandön, Gotland and Öland where the additional wells included are located. The off-shore area covers the area east of Öland and the area east and south of Gotland. Besides the wells on Gotland and in the off-shore area two wells on Öland, i.e. Segerstad Fyr and Böda Hamn, and the well on Gotska Sandön are included in the study.

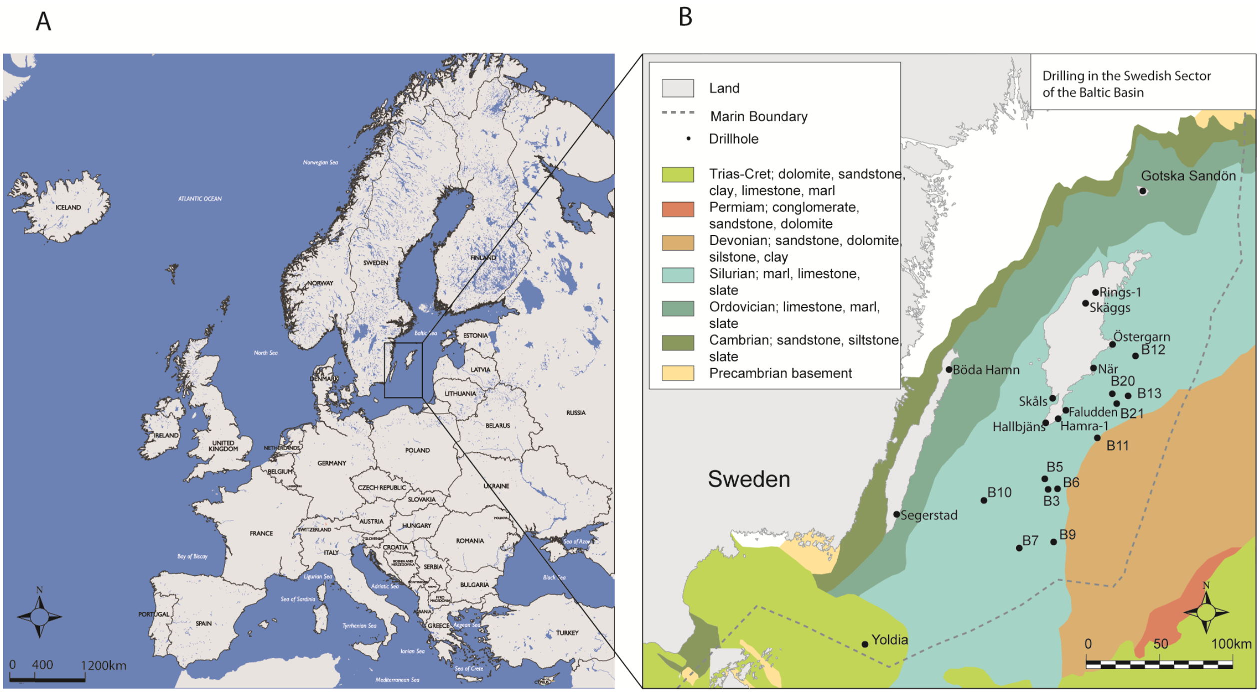

Figure 1. A) Location of the study area on the map of Europe. B) showing the bedrock map of the study area and wells that were considered in this study (modified after Mortensen et al., 2017).

2 Geology

2.1. Regional Geology

The Baltic Basin developed as early as the Late Precambrian in connection to the formation of an E–W trending rift system (Sopher et al., 2016 and references therein). The Baltic Basin occurs in parts of Sweden, Latvia, Poland, Estonia and Lithuania and to the south, it is bounded by the S–E branch of the Tornquist zone (fig. 2), which separates the basin from the middle European geological provinces, e.g. North German-Polish Caledonides (Ziegler, 1990). The Baltic Basin includes a sedimentary succession ranging from the Neoproterozoic Ediacaran (Vendian) at the base and all the Phanerozoic systems. The basin fill is dominated by Lower to Middle Cambrian terrigenous deposits overlain by Ordovician and Silurian strata, dominated by limestone, siltstone and shale (Sopher et al., 2014). Mesozoic–Cenozoic strata are only found outside the Swedish Sector.

The basin is weakly tectonized and the sedimentary layers on the Swedish side are gently dipping to the south and southeast towards the centre of the basin (Šliaupienė & Šliaupa, 2012). The sedimentary succession in the east part of the Baltic Basin has been characterized into four sequences (Shogenova et al., 2009) and these include from the bottom up: 1) Ediacaran sandstone, siltstone and claystone and a lowermost Cambrian claystone the so-called Blue clays; 2) Lower Palaeozoic succession, including an up to c. 170m thick sandstone, siltstone and shale unit, c. 40–250m thick Ordovician shaly carbonate-rich rocks, up to c. 800m thick Silurian shale and over c. 200m thick lowermost Devonian claystone, sandstone and marlstone; 3) the Devonian sequence which is mainly composed of marly carbonate-rich rocks interbedded with sandstone; 4) the Upper Permian succession of carbonates and evaporates, Triassic mudstones, Jurassic sandstones, claystones and limestones, Cretaceous sand and chalky marl and Cenozoic siliciclastic rocks belong to this complex also. Cenozoic strata occur only in southwest Lithuania.

The first two i.e. the Precambrian Ediacaran succession and the Lower Palaeozoic are represented in the Swedish Sector.

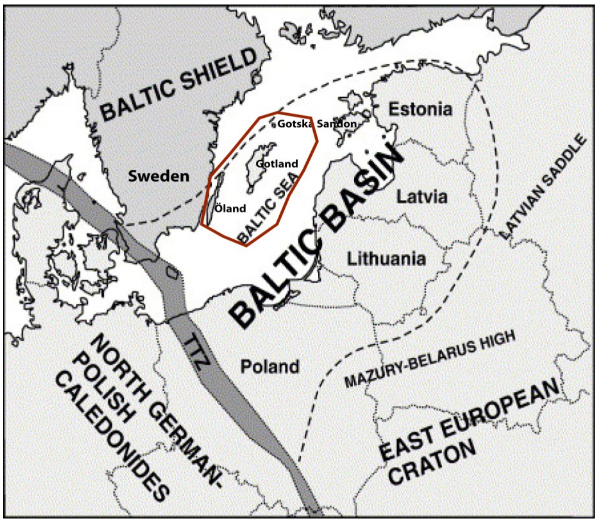

Figure 2. Location of the Baltic Basin and Sweden with the study area marked in the red square (modified after Molenaar et al., 2007) TTZ= Teissyere Tornquist Zone.

	Lithostratigraphy	Thickness (m)	Dominant lithology
Silurian	Undifferantiated	30–50	Argillaceous limestone
	Burgsvik sandstone	8–45	Sandstone
	Undifferentiated	150–400	Argillaceous limestone
Ordovician	Klassen limestone	22–74	Argillaceous limestone with mounds
	Kvarne limestone	2–10	Mudstone and Argillaceous limestone
	Bentonitic limestone	28–58	Limestone with bentonite
Cambrian	Alum Shale	0–4.5	Black shale
	Borgholm Formation	147–152	Sandstone and siltstone
	File Haidar Formation	88-107	Sandstone and siltstone
Precambrian			Sandstone, Granite, Gneiss or quartzite

Figure 3. Generalized stratigraphy of the Palaeozoic succession beneath Gotland (modified after Sivhed et al., 2004).

2.2 Local geology

Figure 3 illustrates the generalized stratigraphy. Throughout the Cambrian, deposition of fine-grained siliciclastic sediments in shallow marine settings dominated (Nielsen & Schovsbo, 2006). The bedrock in the Swedish sector of the Baltic Basin (fig. 1b) makes up the west and northwest flanks of the basin. The basin fill consists hereof a gently dipping sequence of Cambrian to Silurian strata with a successively younger bedrock outcropping towards the south-east (Sopher et al., 2014).

In total the Cambrian to Silurian sedimentary succession is up to c. 1200 m thick in the offshore Swedish sector. The complete Phanerozoic sequence reaches a thickness of > 4km near the Polish side. A schematic illustration of the Lower Palaeozoic stratigraphy of the succession below Gotland is illustrated (fig. 4).

Figure 5 exemplifies a type well section of the Cambrian–Silurian succession beneath Gotland. The section exemplifies the Palaeozoic succession based on information from the Faludden wells on south Gotland and shows besides the general lithology and stratigraphy, the natural gamma response. High values of the log (deflections to the right) indicate a relatively high clay content in the rock.

2.2.1 Precambrian (Ediacaran)

The sedimentary rocks including e.g. Jotnian sandstones are locally found in fault deliminated basins below the Lower Palaeozoic succession in the study area. Flodén (1980) identified in seismic data, Precambrian strata in the vicinity of Gotska Sandön. Similar

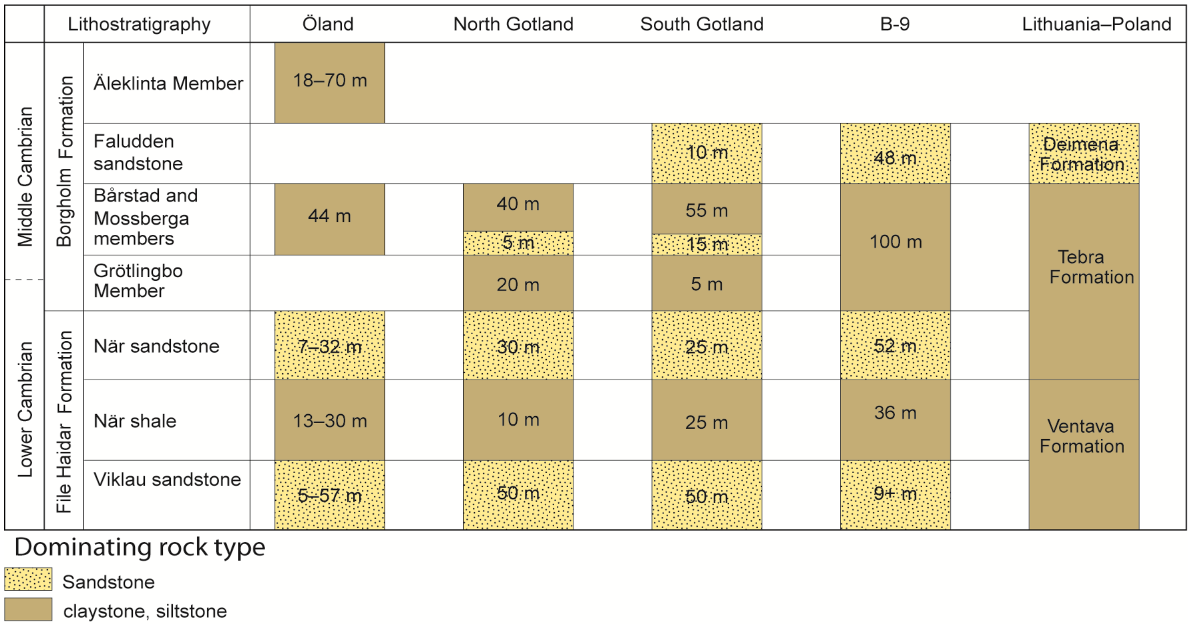

Figure 4. Schematic illustration of the stratigraphy and thicknesses of the dominating sandstone reservoirs in the Baltic Basin (modified after Erlström, 2011).

occurrences are postulated to occur in the south in parts of Baltic Basin (Beckholm & Tirén, 2009).

2.2.2 The Cambrian succession

The Cambrian succession rests on the sub-Cambrian peneplain (a level surface that has been created by erosion over a period of time) dipping gently to the southeast. The work by Sopher et al. (2014) shows that the Cambrian sequence is thickest southeast of Gotland where it reaches c. 200m in thickness. It gradually decreases in thickness towards the north and north–west. The north and westward extension of the Palaeozoic succession in the Swedish sector of the Baltic Basin is truncated by Quaternary deposits and constitutes the remains of a sedimentary cover of formerly much wider extent (Sopher et al., 2016).

The Cambrian is dominated by Lower and Middle Cambrian strata included in the File Haidar and Borgholm formations. Upper Cambrian strata are less widely represented. There are three main sandstone reservoir intervals occurring in the Lower and Middle Cambrian succession. These are the Viklau, När and Faludden sandstones as shown in figure 5.

The Viklau and När sandstone units have been identified in all the wells in this study, whereas the Faludden sandstone tends to pinch out northwards and westwards. This is illustrated in figure 6, which shows a S–N cross section including the Hamra-1, Faludden-2 and the Östergarn-1 well. The cross-section also shows that the När and Viklau units are relatively consistent in thicknesses in the cross section.

The Viklau and När sandstones included in the File Haidar Formation are dominated by fine- to medium-grained quartz sandstone with subordinate interbeds of silt- and mudstones (Nielsen & Schovsbo, 2006). The 5–50m thick Viklau Sandstone, which often rests on the crystalline basement is in its basal most parts often characterized by relatively coarse-grained sandstone, often with conglomerate layers. The Viklau Sandstone is overlain by the När Shale which is dominated by greenish, grey to somewhat reddish siltstone/shale, partly laminated, partly bioturbated and with rare thin sandstone interbeds (Nielsen & Schovsbo, 2006). This unit is present in all wells that are considered in this study. The File Haidar Formation ends with a fine-grained sandstone unit called the När Sandstone. It has a variable thickness of c. 7–52 m. The greater thicknesses seem to occur in the most southerly investigated wells

The overlying up to c. 100 m thick Borgholm Formation comprises the Grötlingbo, Mossberga and Faludden members. The Grötlingbo and Mossberga members are dominated by siltstone and mudstone. One variably occurring very fine-grained sandstone unit, previously called the Grötlingbo siltstone occurs in some of the wells. The Grötlingbo Member is distributed in all the wells on Öland, Gotland and Gotska Sandön. The thickness of the member varies between 3 and 45 m (Hagenfeldt, 1994). The reason for the great variation in thickness is attributed to the difficulties in distinguishing it from the overlying siltstones of the Bårstad and Mossberga members, defined by Nielsen & Schovsbo (2006).

The Mossberga Member comprises siltstones with thin interbeds of sandstone (Hagenfeldt, 1994). The lower part of the unit has been described by Nielsen & Schovsbo (2006), as dark coloured, which is attributed to an increase in organic content. A coarsening upwards trend is also seen in some of the wells.

The Faludden Member consists almost entirely of one major sandstone unit with a few scattered interbeds of mudstone (Hagenfeldt, 1994). The boundary between the Faludden Member and the underlying Mossberga Member is distinct in most wells where it is found (Nielsen & Schovsbo, 2006). The Faludden Sandstone is also up to c. 50 m thick in the distal offshore part of the Swedish sector while being considerably thinner to the west where it successively thins out

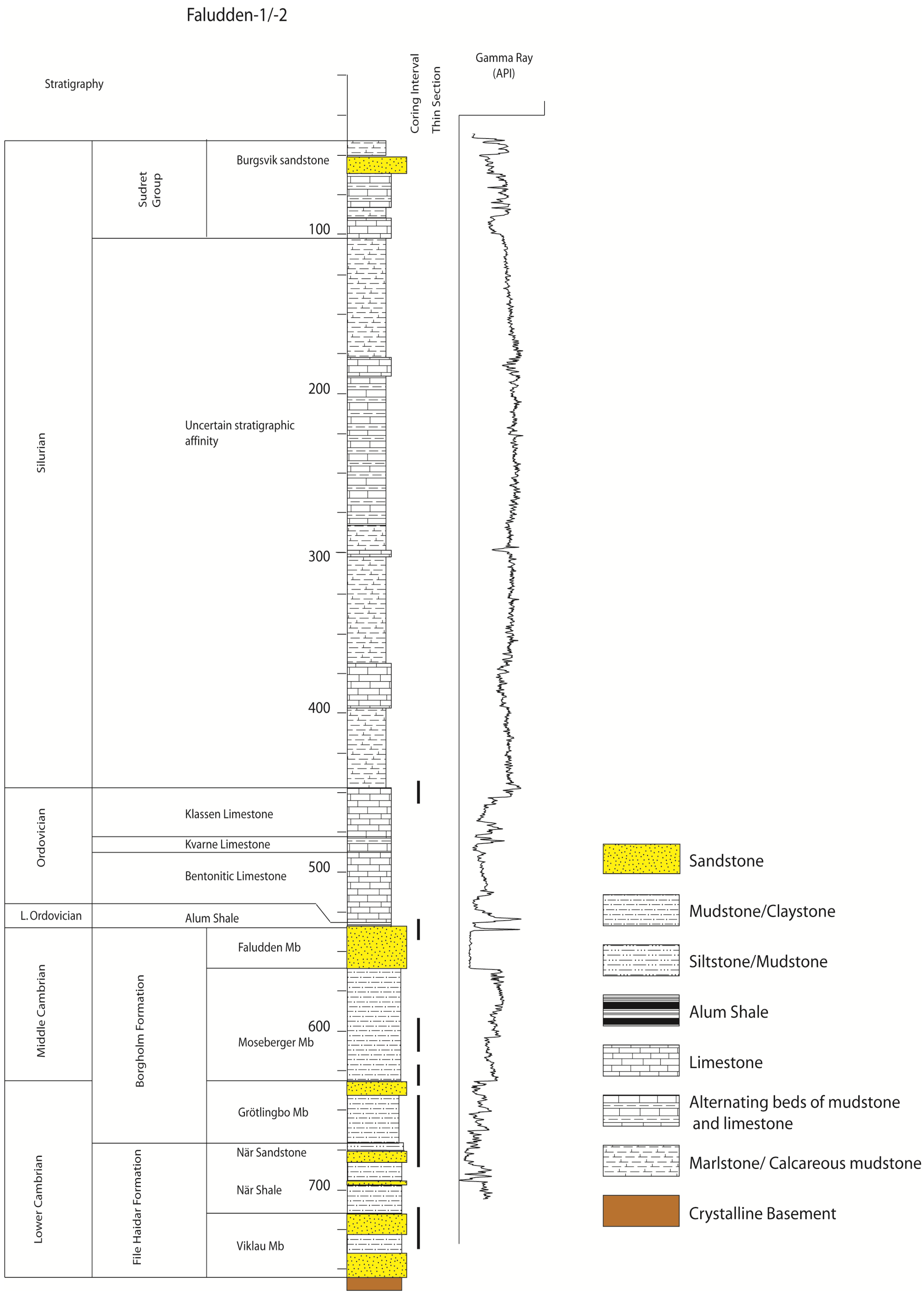

Figure 5. Illustration showing a type section of the Palaeozoic succession, exemplified by a composite litholog of the Faludden-1/-2 well on south Gotland (modified after Sopher et al., 2014).

and disappears. It is largely absent on most of north Gotland and it is neither present in the Gotska Sandön well nor on Öland.

2.2.3 The overlying Ordovician–Silurian succession

The Lower and Middle Cambrian succession is in the offshore south parts of the studied area followed by a few meters of Upper Cambrian–Lower Ordovician Alum Shale. The Alum Shale increases in thickness towards the south and southwest where it reaches c. 20 m in the Segerstad Fyr well on south Öland and adjacent offshore areas to the east and southeast. On Gotland, only a few wells have encountered up to four meters of Alum Shale on top of the Borgholm Formation, e.g. in the När-1 well. Otherwise the Borgholm Formation is directly subcropping an 80–125 m thick Ordovician succession dominated by variably argillaceous limestone, which in the lower c. 10 metres is strongly glauconitic. The Ordovician directly subcrops several hundred metres of Silurian succession comprising marlstone and limestone. In the distal offshore Swedish sector of the Baltic Basin, the Ordovician is characterised by variably argillaceous limestone beds of relatively consistent thickness and composition (Sopher et al., 2016). The lowermost part of the Ordovician is extensively exposed on the island of Öland (Stouge, 2004).

OPAB classified the Ordovician in three informal stratigraphic units which are named from the bottom the Bentonitic, Kvarne and Klasen limestone units (fig. 3). The Bentonitic limestone is composed of relatively homogeneous and dense limestone often synonymous to the so called “ortocertite limestone” with thin layers of bentonite, especially in the upper part. The thickness varies between 28 and 58m on Gotland (Sivhed et

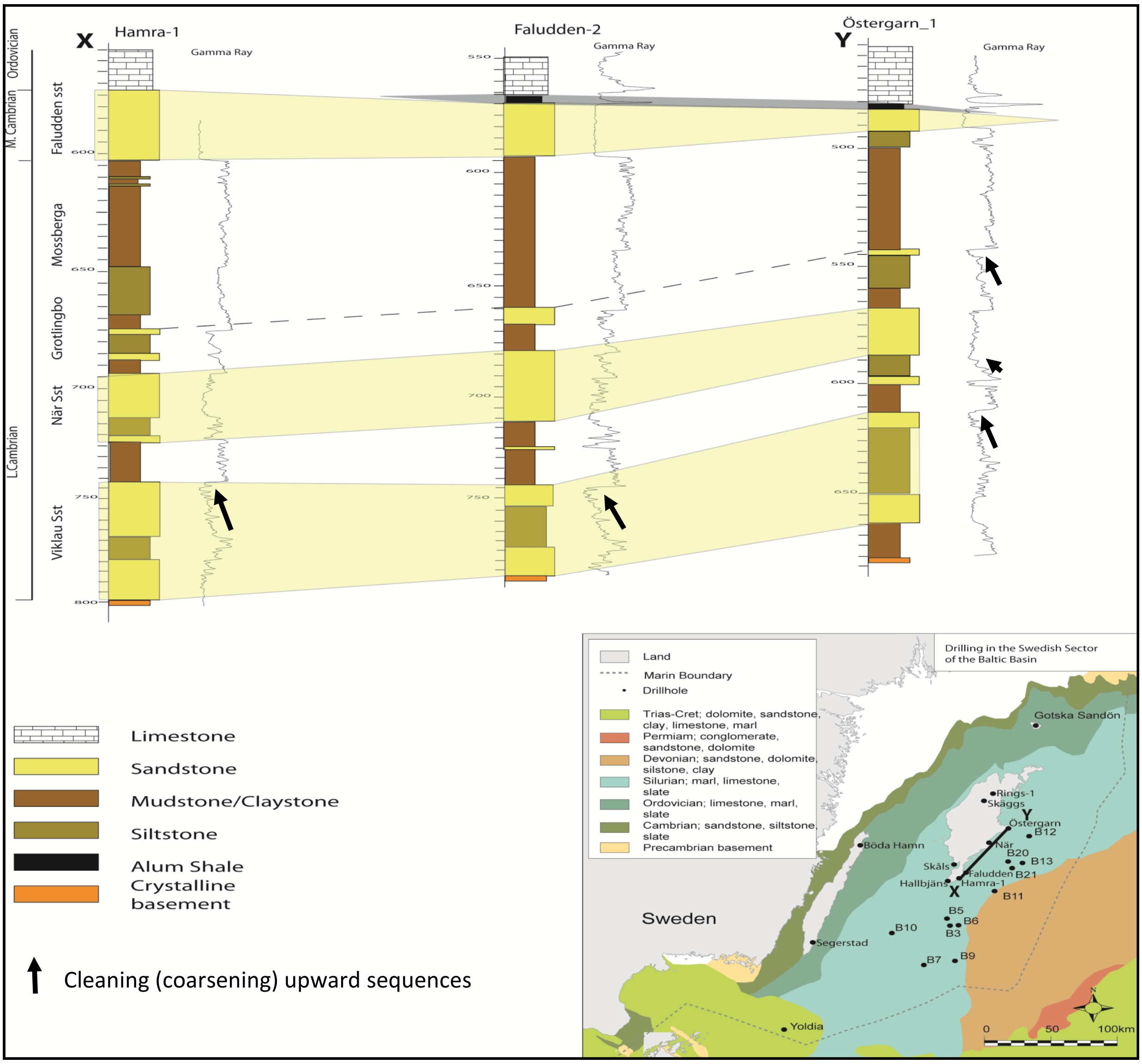

Figure 6. Cross section (X-Y) showing the lateral correlation and thicknesses of the three main sandstone units in the Lower and Middle Cambrian succession. Note how the Faludden sandstone thins out towards the north.

al., 2014). The Kvarne limestone unit is dominated by highly argillaceous carbonates and mudstones. It is clearly seen in the wire-line logging data by relative high gamma ray readings and low density, which relates to the high content of clay minerals and softer lithologies. It is between two and ten metres thick and is found in all the wells on Gotland. The succeeding 25–75 m thick Kvarne limestone is the main interval containing the oil-bearing mounds, which were the main target for the exploration by OPAB and Gotlandsolja.

In contrast to the surface geology dominated by limestone on Gotland the subsurface Silurian succession is largely composed of marlstone and calcareous claystone. So far there are no precise correlation between the subsurface well observations and the established stratigraphic division of the surface geology.

2.2.4 Depositional environment

Most of the work regarding depositional environment has been carried out by Nielsen & Schovsbo (2011). Comprehensive descriptions of the File Haidar Formation and the Borgholm Formation have also been carried out by Hagenfeldt (1994). The Cambrian was divided into various depositional cycles by Nielsen & Schovsbo (2011). Their study was based on various cores such as the Grötlingbo, När-1, File Haidar and Gotska Sandön among others. The sediments building the Cambrian reservoirs were deposited in a shallow marine environment during periods of lowstand (Nielsen & Schovsbo, 2006).

The depositional environment varied from inner shelf to outer shelf with deposition occurring below the storm wave base where the inner shelf is identifiable by the presence of cross bedding in siltstones and sandstones. Shales, glauconitic horizons and laminated mudstones dominate the mid–outer shelf.

The relatively low sea level during the deposition of the När sediments resulted in predominantly sand facies, and during the succeeding gradual transgression which resulted in the deposition of the Mossberga and the Grötlingbo members which are made up of siltstones and mudstones. The fining upward succession is an indication of how the transgression was outpacing the supply of sediments (Nielsen & Schovsbo, 2011).

2.2.5 Tectonic influences

Although the Palaeozoic succession is relatively weakly affected by tectonic events, there are three main tectonic regimes that have influenced the structure and burial history of the Cambrian succession. These are 1) the Caledonian collision which primarily affected strata along the borders of Baltica, 2) Carboniferous rifting associated to the Hercynian Orogen and assembly of Pangea, 3) Mesozoic rifting associated to the breakup of Pangea and finally the Late Cretaceous-Palaeogene inversion coupled to Alpine collision tectonics in south Europe (Beckholm & Tirén, 2009 and Erlström et al., 2014). The Lower Palaeozoic succession in the Swedish sector of the Baltic Basin has been protected from the most intense tectonic impact which render that the primary diagenetic effects are likely related to burial depth and compaction.

The main subsidence occurred in the Silurian which is seen in the successively increasing thickness of the Upper Silurian succession towards the south towards the Caledonian Foreland Basin. A maximum burial depth of the Lower Palaeozoic in the study area is estimated to be in the range of about 2km as shown in figure 7 (Erlström et al., 2014) .

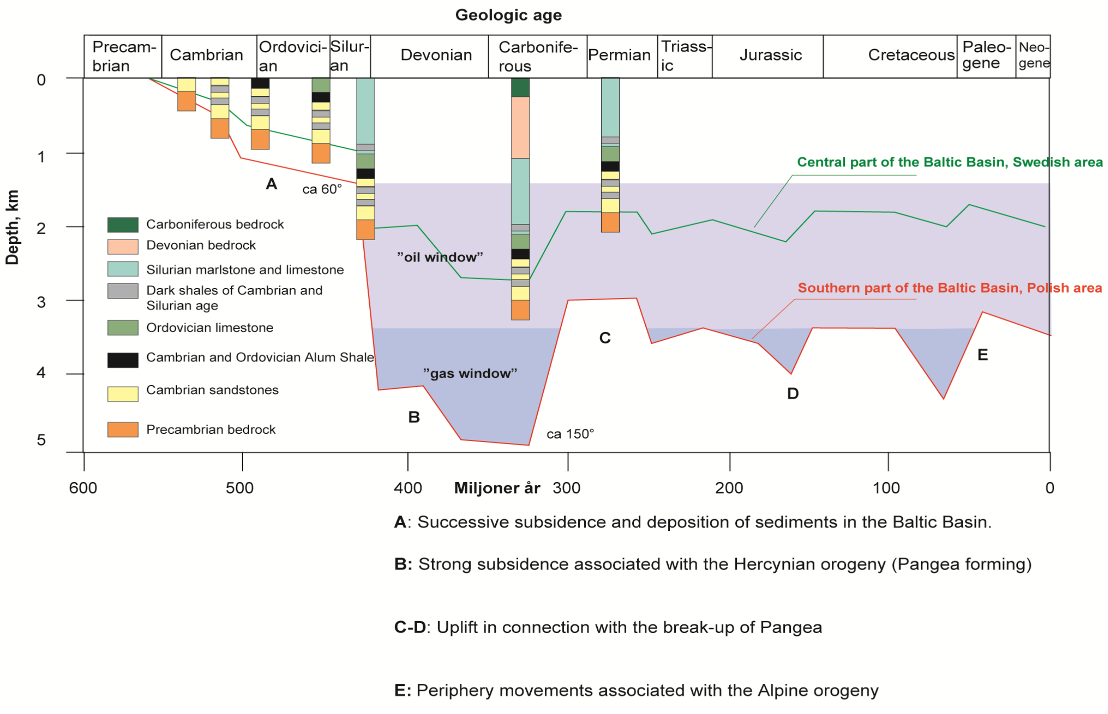

Figure 7. Baltic Basin development and tectonic influences (modified after Erlström et al., 2014). The green and red curves mark the maximum estimated burial depth of the succession in different parts of the Baltic Basin.

3 Database

The materials used in this study comprises wells drilled by OPAB during the 1972–1974 drilling campaigns, one well drilled by Uppsala University, one well drilled by Stockholm University, a few wells drilled by SGU and one well drilled by Skånska Cement AB (Table 1). Geophysical wireline logs are only available for wells that were drilled by OPAB. Material from all the studied wells is managed by SGU and was readily available at the SGU archive. Besides well documentation, the material includes thin sections, hand specimen, chemical data and cores.

3.1. Well documentation and logging data

A total of 19 onshore wells were selected for the study and seven wells offshore. Most of these were selected based on the existence of cored intervals and associated analytical data in the SGU archive. The OPAB well reports for the selected wells have been studied regarding lithological descriptions of cuttings and cores and if there have in connection to the drilling been specific observations that indicate the properties of the sandstone reservoirs. Most of the OPAB wells also include a suite of geophysical wire-line logs that have been studied. The natural gamma ray log (GR) has been the most commonly used log as it is suited for correlation and general lithologic characterization. Also of interest is the Neutron-Density log as it gives an indication of porosity, occurrence of shale

Table 1: Summary of wells included in the investigation together with information on cored intervals and available geophysical wire-line logs. FDL= Formation density log, GR= Gamma Ray Log, IES= Induction, MLL= microresistivity log, CNL= Neutron log, BHL= Sonic log, LL= lateral resistivity.

Well	Operator	Wire-line logs	Cored interval
Böda Hamn	Stockholm University	No logs	
B-3	OPAB	GR, IES,CNL, FDL, BHS	No coring record in the Cambrian
B-5	OPAB	GR, IES,CNL, FDL, BHS	No coring record in the Cambrian
B-7	OPAB	GR, IES,CNL, FDL, BHS	504–518m
B-9	OPAB	GR, IES,CNL, FDL, BHS	1029–1036m
B-10	OPAB	GR, IES, BHL	No coring record
B-12	OPAB	GR, DLL, BHL, CNL, FDL	No coring record in the Cambrian
B-20	OPAB	GR, DLL, BHL	No coring record in the Cambrian
Faludden-1/-2	OPAB	GR, IES, FDL, BHL	
File Haidar	Skånska cement AB	No logs	0–445m
Frigsarve-1	OPAB	GR, CNL, FDL, IES	498–512m
Gotska Sandön		No logs	0–232m
Grötlingbo-2	OPAB	GR,FDL, BHL, IES	474–488m
Hallbjäns-1	OPAB	LL,GR, FDL, BHL	No coring record
Hamra-1	OPAB	IES, GR, FDL	574–604m
Kvarne-1	OPAB	GR, IES, FDL	509–518m, 730–732m
Myrhage-1	OPAB	GR, BHS	No cores
När-1	SGU	No logs	525–598m
Rings-1	OPAB	IES, GR, BHL, FDL	No coring record
Sanda-1	OPAB	IES, MLL, FDL	No coring record
Segerstads Fyr	SGU	NO LOGS	0–258m
Skåls-1	OPAB	IES, GR, BHL	452–470m
Skäggs-1	OPAB	IES, GR, BHL, FDL	300–372m
Visby Cement		No logs	
Vike-1	OPAB	GR, FDL,MLL	No coring record
Östergarn-1	OPAB	IES,, GR, MLL, FDL	476–494m

and the presence of gas. Regarding the core drillings on Öland they do not have any wire-line logs.

3.2 Core samples and thin sections

SGU performed in 2008 in connection to an internal R&D project a comprehensive sampling of core material from wells on Gotland and Öland. This was complemented in 2017 by a sampling of the Kvarne-1, Frigsarve-1 and Hamra-1 wells. These core samples have been made available by SGU at their regional office in Lund. Most samples have previously been analysed regarding porosity and permeability, bulk chemical composition or used for preparation of thin sections. The data has, however not previously been comprehensively described. Hand specimen of the sampled cores have been used for an ocular characterization regarding texture and sedimentological structures. The studies of these core samples were then compared with the results from a microscopical investigation which has been the main work in this study.

In total 54 thin sections including 19 new polished thin sections from Kvarne-1, Frigsarve-1 and Hamra-1 have been investigated regarding grain size, grain roundness, detrital composition, quartz varieties, diagenetic components such as cements and other authigenic minerals. The new thin sections were stained blue for visualising the porosity distribution. The modal analysis (point counting) was carried out on the thin sections to classify the sandstones and determine the amounts of each mineral present. Appendix I shows the wells and what type of data that was made available for this study. An initial total of 500 points were counted, this was then reduced to 250 points per thin sections as it was found that this number gave statistically the same result as that given by 500 points.

3.3 Chemical data

Chemical analyses have been performed on cores from scattered reservoir sandstone intervals in the Segerstads Fyr, När, Gotska Sandön, B-7, B-9, File Haidar and Böda Hamn wells (appendix II-oxides & III-trace elements). The analyses were performed in 2008 on commission from SGU by ALS Chemex. The analyses were performed using ICP-MS and ICP-AES which give results on most oxides and trace elements. The chemical data has been used to support the general mineralogical and chemical characterization which is compared with the results from the thin section studies and modal analysis.

3.4 Petrophysical Data

Petrophysical analyses have been performed on various core samples from the SGU data. The analyses include; porosity-permeability, density, thermal conductivity and thermal diffusion. The analyses on thermal conductivity and diffusion carried out by SGU in Uppsala are however not evaluated in this study. The other analyses were carried out at the GEUS core laboratory in Copenhagen either by commission from SGU or OPAB. The data was used to evaluate the relationship between the petrophysical properties and the textural analyses on thin sections. OPAB was mainly focusing on density, porosity and gas permeability and this was measured on the Visby Cement factory core drilling, Faludden-1 and Skåls-1 wells. SGU expanded their density, porosity and gas permeability to wells such as När-1 and File Haidar.

Appendix IV and V shows the available petrophysical data for the Cambrian reservoirs and information on their stratigraphic location.

4 Methods

The study started with ocular analyses of pieces of core samples that are at the SGU archive in Lund. It involved the use of hand lens to study the grain size, degree of sorting and identify features such as laminations. The porosity was also tested using water and the findings of the ocular study were complimented by thin section analyses.

4.1 Petrography and petrophysics

4.1.1 Microscopy

The thin sections have been studied using a polarized microscope. The mineralogical composition of the sandstones was investigated using point counting equipment at SGU Lund office. The point counting included besides determination of the mineralogy of the detrital grains also amount of pores, matrix and cement. Besides this, the diagenetic components and the degree and type of compaction were studied. Other properties such as roundness, sphericity, sorting and the distinct types of quartz varieties in the sample were determined. The quartz varieties considered were polycrystalline and monocrystalline. The porosity was assessed as either primary porosity or secondary porosity.

4.1.2 Scanning Electron Microscopy (SEM)

The traditional tool for the analyses of thin sections for the geologists since the 1800s has been the optical microscope (Welton, 1984). The advent of SEM enabled the geologist to have an in-depth, high resolution understanding of the grain relationships in 3D and also to give the actual minerals present in a sample. SEM is not intended to replace thin section analysis using optical microscopes, but rather to provide complementary support which enables a detailed model to be produced.

Two thin sections (Kvarne-1: 518m and Hamra-1: 574m) were selected and studied because they are representative of the features that are seen in all the other thin sections that are studied. They were carbon coated in order to be conductive. The Tescan MIRA3 Field Emission Scanning Electron Microscope (FE-SEM) at Lund University was used. The Back Scatter Electron (BSE) and Cathode Luminescence (CL) detectors were used for the analyses of the samples. The field of view was set at a working distance between 10 and 15mm and the resolution was 20keV. To determine the composition of the different detrital grains and cements, spectra were shot and the resulting elements would then allow to determine the composition.

4.2 Porosity and permeability studies

Analytical data from the core samples for the Hamra-1, Frigsarve-1 and Kvarne-1 wells were sent to Geological Survey of Denmark and Greenland (GEUS) for preparation and analysis of the porosity and permeability of the sandstones. Plugs were extracted from the core samples either vertically or horizontally. The horizontal and vertical gas permeability was measured in millidarcies (mD), together with the porosity in percentage (%).

The procedure started with drilling and trimming of the plugs. These plugs were soaked and washed in a Soxhlet extractor. This was done using methanol which is used to remove water and dissolves salts that have precipitated in the pore space of the rock. The plug was then placed on a Hassler core holder and subjected to a confining pressure of 2758 Kpa. This is done to measure the gas permeability of nitrogen gas through the plug. The Klinkenberg gas permeability (equivalent liquid permeability) is calculated from gas measurements performed at three mean pressures in the plug sample.

The porosity and grain density were measured on clean and dried samples. The porosity determined is that of helium gas and using Boyle's Law it is determined by subtracting grain volume and the measure bulk volume. The grain volume is measured by submerging the plug in mercury bath using Archimedes principle. Grain density is calculated from the grain volume measurement and the weight of the clean dried sample.

The B-7, B-9, Segerstad Fyr, Böda Hamn, Visby-1, När-1, File Haidar and Gotska Sandön wells had their porosity and permeability measurements originate from SGU. The porosity-permeability data for the Faludden-1 and Skåls originate from OPAB.

4.3 Chemistry

Chemical analyses were done using inductively coupled plasma atomic emission spectroscopy (ICP-AES). This also complimented the point counting data and the SEM analyses. Various elements were measured in ppm or in percentage. ICP-AES is an emission spectrophotometric method which allows electrons to emit energy at a given wavelength as they return to ground state (Murray et al., 2000). Murray et al., (2000) indicates that each element has its own signature wavelength which then allows the detection, and the sample has to be in solution. Dissolving the samples requires employing acids such as HCl, HF or using a flux-fusion technique. The technique has good detection limits and capabilities to detect multi-elements (Warra & Jimoh 2011). Chemical data was obtained from SGU for 30 samples that were analysed .

4.4 The use of well logs for lithological characterization

Basically, wire-line logging methods can be classified into electrical, nuclear and acoustic methods (Table 2). These are primarily used for interpreting lithology, porosity and density of the formation.

The advantage of wire-line logs is that they give a continuous response of the borehole wall, it can thus significantly improve the identification of sedimentary beds and sequence boundaries as well as distinguish different types of formation fluids and estimation of hydrocarbon reserves. This enables the to make different interpretations such as zone correlations, depth and thickness of zones. Other rock properties such as mineralogy, permeability, porosity and water saturation can also be obtained from well log information.

4.4.1 Gamma Ray (GR) log

The GR log measures the naturally occurring radioactivity of a formation's gamma rays emitted by uranium (U), thorium (Th) and potassium (K) isotopes (Plado et al., 2016). It is mainly applied for lithology identification and stratigraphic correlation. High gamma ray responses are attributed to either fine-grained deposits or clay-rich deposits such as shale, claystone and mudstone. Low gamma ray counts are attributed to the presence of sandstone or limestone (Klaya & Dudek, 2016).

The GR-curve can also be used to interpret sedimentary facies and amount of clay (Nazeer et al., 2016). The shape of the log pattern over a sandstone interval gives often an indication of e.g. gradual changes in the relationship between fines and sand related to successive changes in the depositional setting. Kessler & Sachs (1995) illustrated from a study of GR log responses from sandstones on Ireland the relationship between GR log responses and the deposi-

Table 2: Classification of logging methods.

Method	Example
Electrical logging	Spontaneous Polarization (SP) logging Resistivity logging Induced Polarization Electrode potential
Nuclear Logging	Gamma Ray Logging Density Neutron Logging
Acoustic/Sonic	Acoustic Velocity logging Acoustic attenuation logging

tional setting. They identified GR signals that could be interpreted as aggradation and progradation. The GR log shapes encountered in this study indicate that there are patterns resembling the ones presented by Kessler & Sachs (1995).

4.4.2 Neutron-Density log

The cross-over effect of the neutron and density logs is important because it often indicates the presence of gas. The neutron-density log comprises a density tool that detects hydrogen content and electron densities which are often seen in gas bearing formations (Mallick et al., 1997). To be able to detect what type of fluid the formation has, the neutron-density log is used together with other logging techniques such as the resistivity log, thereby determining if the formation carries water or hydrocarbons.

This technique is predominantly used for determination of the porosity of the formation. Because of the low hydrogen index that gas has (Mallick et al., 1997), the response signal of the neutron log decreases. This is also seen in the density tool, where there is decreased bulk density response signal if the formation is gas bearing as opposed to water or hydrocarbons. A shift of the neutron log to the right of the density log is indicative of a gas bearing zone. The use of this technique has not always been successful (Mallick et al., 1997) but it has been used effectively in the study area. The opposite crossover indicates presence of clay or shale. This has been a useful compliment in the characterization of the lithology in the studied wells

5 Results

This chapter sets out the results of the study, describing firstly, ocular finds on the core samples followed by modal analysis to determine the type of sandstones that are found in the Swedish sector of the Baltic Basin. A description of the mineralogy follows showing how the various minerals occur in the sandstones. This is followed and complemented by the results of the SEM analyses which seek to describe the types of cements encountered together with the accessory minerals. Furthermore, chemical data was used to confirm the results of the modal analysis. The trends of the cementing material and the type of quartz (monocrystalline versus polycrystalline) were assessed against depth. Important reservoir characteristics such as porosity and permeability together with parameters such as grain density and their relationships with depth were also scrutinized. This was then followed by the geophysical signatures of the sandstones in question and what these signatures imply.

Ocular analyses of the hand samples showed that the sandstones from the Viklau sandstone units are more coarse grained and poorly sorted than the sandstones from the När and Faludden units (fig. 8). This is because the unit also contains fragments from the underlying crystalline bedrock. As we move up the stratigraphy, the sandstones become cleaner, medium grained and fairly well sorted.

5.1 Modal analysis, mineralogy and texture

5.1.1 Modal Analysis

Point-counting was carried out on 35 thin section representing 7 wells. Table 3 below provides a summary of the results. The complete dataset from which this table is formulated is found in Appendix VI.

Detrital quartz makes up the bulk of the mineralogical composition of the sandstones in the Baltic Basin wherein the modal analysis results showed >95% of detrital composition. From this data, we can see that the Cambrian sandstones are quartz arenitic sandstones as they contain roughly 95–99% quartz (Cyziene et al., 2001). The quartz crystals are sub-rounded to angular and occasionally sutured grain boundaries are observed. Authigenic quartz is often seen growing in optical continuity with the detrital quartz grains and distinguishable by the presence of dust rims from where the authigenic quartz grows. The other minerals

Table 3. Summary of results from the modal analyses of the sandstone samples included in this study.

Sandstone unit		Detrital quartz %	Cement	Detrital Feldspar %	Other minerals	Porosity %
Faludden	Average	76.3	5.1	1.7	0.0	17.0
N=7	Min	75.2	4.0	1.2	0.0	16.0
	Max	77.0	6.2	2.0	0.0	18.8
När	Average	71.9	12.6	2.6	2.3	11.4
N=12	Min	67.6	4.0	0.0	0.0	2.2
	Max	77.6	23.6	6.0	7.0	22.8
Viklau	Average	69.8	20.6	1.5	1.8	6.7
N=16	Min	65.0	18.0	0.2	0.0	2.2
	Max	77.0	23.4	3.0	5.8	10.6
All sandstones	Average	71.7	15.1	1.9	1.9	10.1
N=35	Min	67.6	4.0	0.0	0.0	2.2
	Max	77.6	23.6	6.0	5.8	22.8

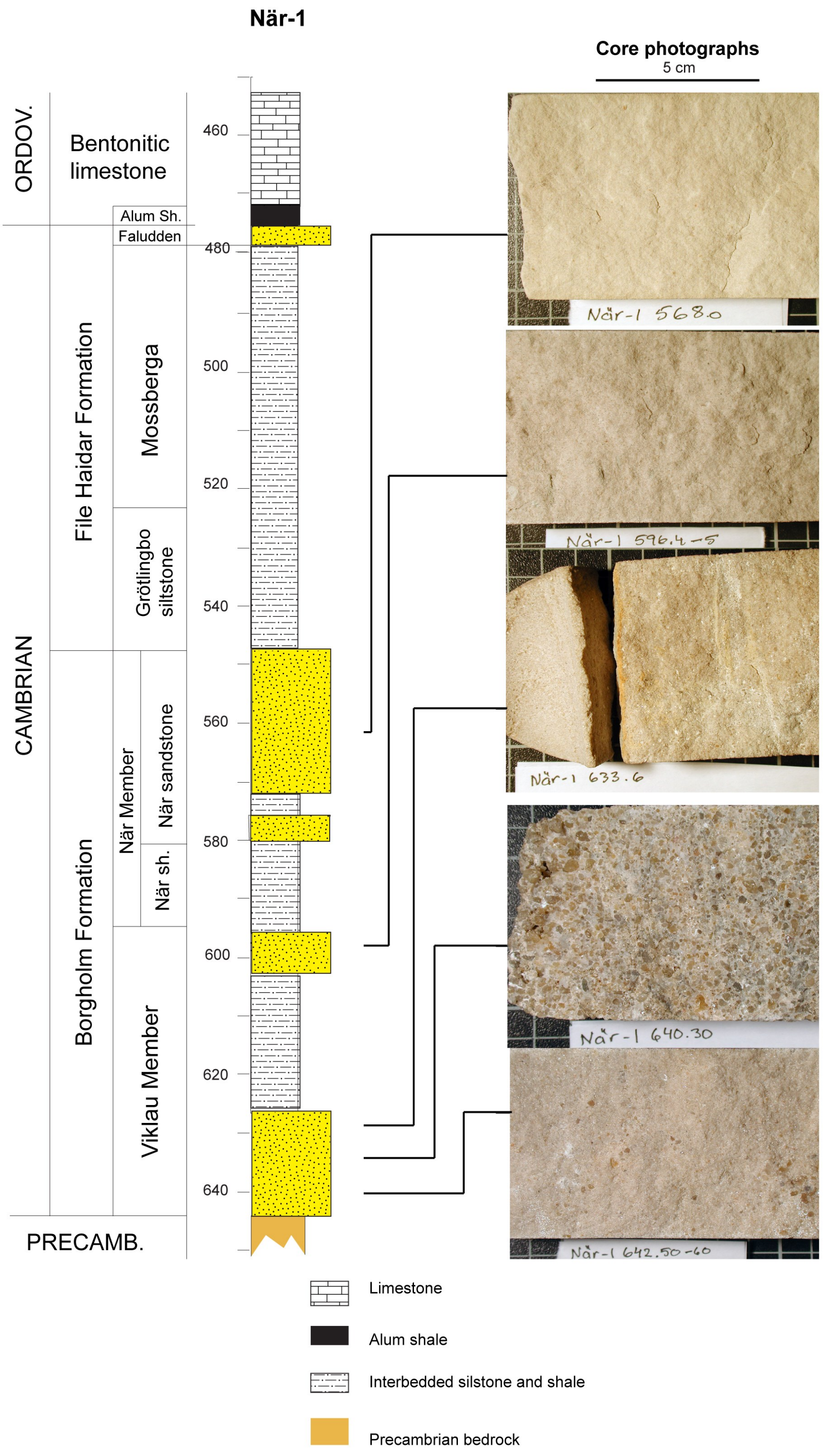

Figure 8. Log of the När-1 well together with the hand samples of the Viklau sandstone unit and the När sandstone unit

are then distributed amongst the remaining 5%. These accessory minerals are scattered and they include feldspars, micas and zircons. Matrix encountered was heterogeneous and contained mainly fine grained quartz and micas. The average porosity of the Cambrian reservoirs in the Swedish sector of the Baltic Basin generally decreases with depth. Modal analysis show a slight decrease in porosity relative to stratigraphic position as samples from the Faludden Member have a higher average porosity. The Faludden Member, which is the uppermost member of the sandstone members, has an average porosity of 17.0%. The När Member has a lower porosity in comparison with the Faludden, with an average porosity of 11.4%. The lowermost member of the sandstone reservoirs is the Viklau Member and it has an average porosity of 6.7%. Combined, the Cambrian reservoirs have an average porosity of 10.1%.

The amount of cement also increases with increasing present-day depth. This is attributed to the increase in, mostly, authigenic quartz. The silica cement occurs as quartz overgrowths on the detrital quartz grains. Although the effects of silica overgrowths on the porosity are more pronounced on the basin centre, the peripheries are moderately affected. This is because the basin peripheries are at shallow depth. This explains the relatively high porosity values that are recorded in the thin sections of the När member of the Gotska Sandön well.

5.1.2 Mineralogy

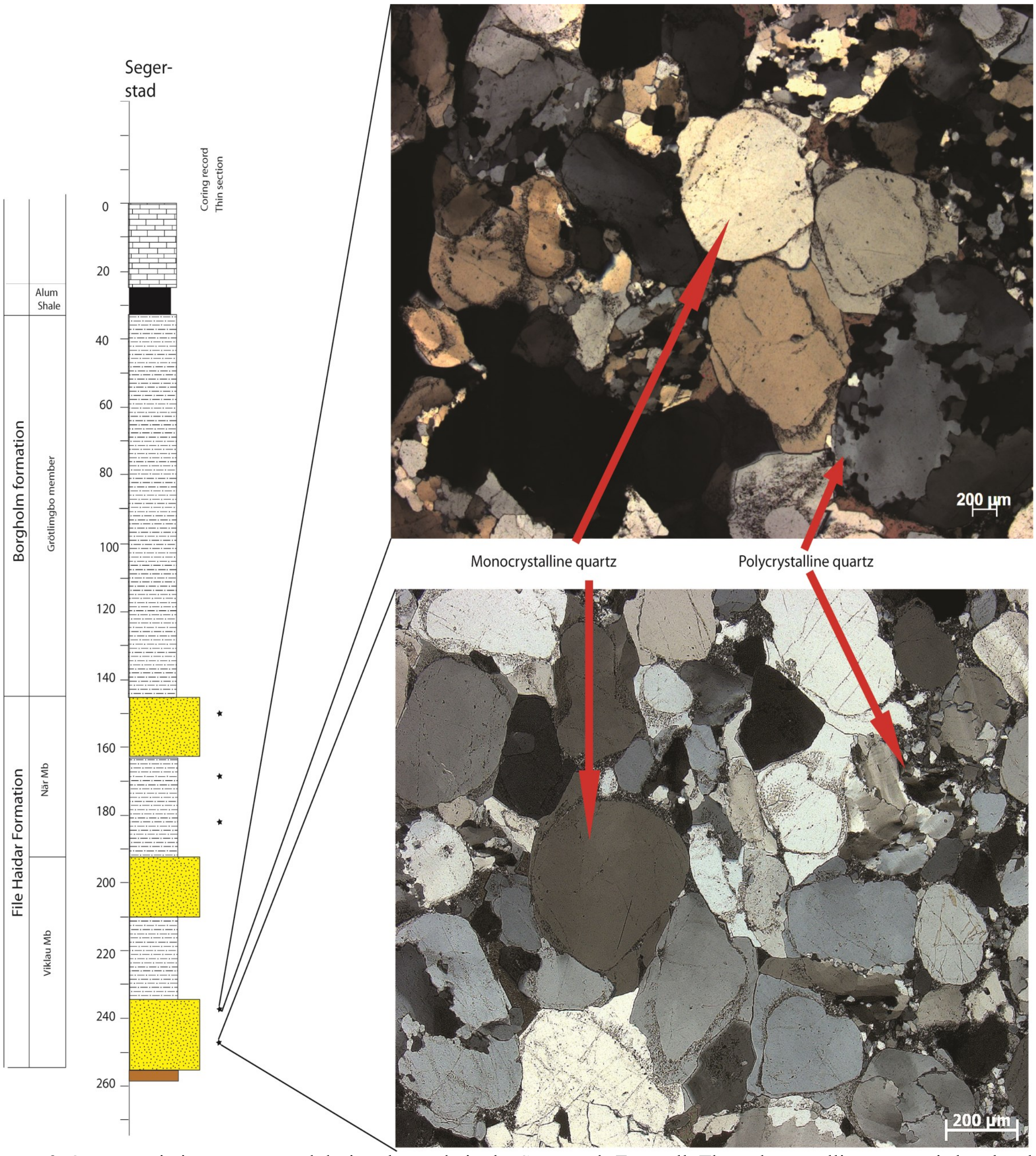

Figure 9. Quartz varieties encountered during the study in the Segerstads Fyr well. The polycrystalline quartz is hereby shown by the grain boundary migration.

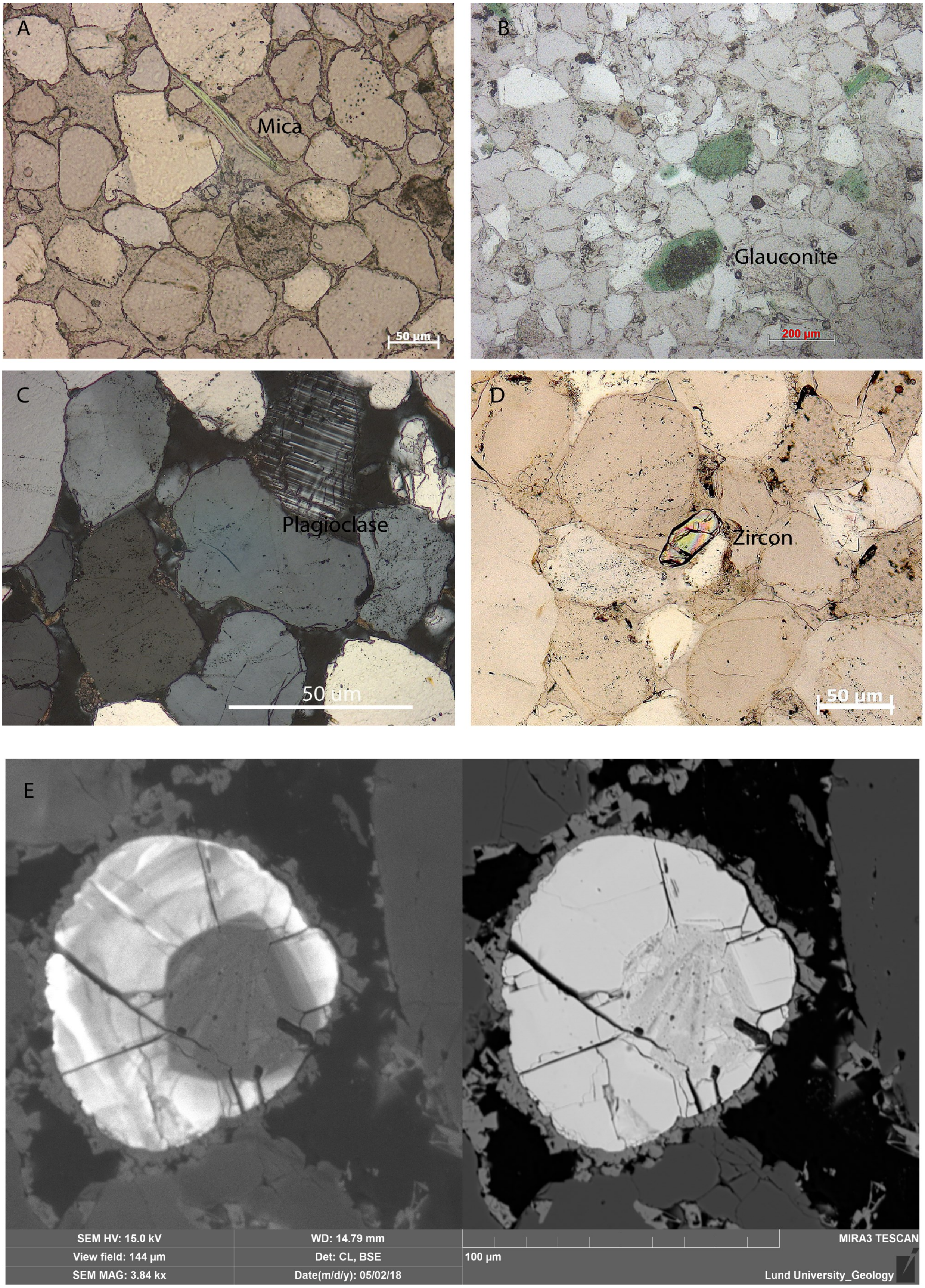

Figure 10. The accessory minerals that were encountered in this study. A) shows a mica sheet. (File Haidar: 498.2m), B) shows glauconite which is green in colour (När-1: 586m), C) shows a plagioclase exhibiting the albite twinning (När-1: 582m), D) an isolated zircon crystal (Böda Hamn: 160.3m), E) a zoned zircon crystal as viewed from SEM-CL and BSE (Kvarne-1: 518m).

Quartz

The detrital quartz grains in the Baltic Basin occur in two forms, i.e. monocrystalline and polycrystalline quartz. The polycrystalline variety is more common in the Viklau Member which sits directly on top of the basement rock. Different sandstone classifications include this as either a quartz grain or a rock fragment (Scholle, 1979). In this study, they have been considered as quartz grains. As shown in figure 9, the monocrystalline quartz grains have more pronounced quartz overgrowths as compared to the polycrystalline quartz. In the thin sections considered in this study, it was very difficult to find any quartz overgrowths in the polycrystalline quartz.

The most common type of quartz encountered in this study is detrital grains which show straight extinction under the optical microscope. A second type of quartz is polycrystalline quartz which shows a fair degree of grain boundary migration. Grain boundary migration is more apparent in the Viklau Member which is probably due to the proximity to the crystalline basement. Figure 9 exemplifies both of these quartz varieties. The polycrystalline quartz resembles underlying Precambrian basement rocks.

Glauconite

Glauconite is commonly occurring in most thin sections studied but is more pronounced in samples from the Segerstad Fyr, När-1, and Gotska Sandön wells. It occurs as subrounded pellets which are green in colour as shown in figure 10b. The Glauconite pellets are commonly characterized with an inner microgranular core surrounded by halo zones of lighter green material.

Feldspars and accessory minerals

Scattered detrital grains of feldspars were encountered during this study and some showed the typical albite twinning exhibited by feldspars. This is because the sandstones are mineralogically mature and made up almost entirely of quartz, therefore, the amounts of the minerals are negligible.

Other minerals such as micas, pyrite and zircons are found, but mostly as scattered isolated grains. The mica is interpreted as muscovite since muscovite is more chemically stable than biotite in sedimentary rocks.

Figure 10e shows a chemically zoned Zircon with a core though the growth rings are not visible on the images. The Zircon is a detrital zircon and because of its robustness in terms of physical and chemical stability, it is able to survive the effects of diagenesis.

5.1.3 Cements

Silica cement

Silica cement encountered during this study is mainly due to idiomorphic silica overgrowths. The authigenic quartz is partly euhedral towards the empty pores pace, partly filling and sometimes in contact with authigenic quartz from an adjacent grain. The authigenic cement is commonly found surrounding the complete detrital quartz grains.

This type of cement is more pronounced in the deeper sandstone members, i.e., the Viklau Member. Also, of interest are the 'dust' rims that form around the detrital quartz thereby marking a clear divide between the detrital quartz grain and the authigenic silica overgrowths.

The green arrows in figure 11 indicate the dust rims that formed around the detrital quartz grains whereas the blue arrows show the authigenic quartz overgrowths

Carbonate cement

Carbonate cement is very common in the Cambrian sandstones of the Swedish sector of the Baltic Basin, occurring in all three sandstone members in different abundances. The cement exhibits a poikolotopic phenomenon where the carbonate crystals grow embed several detrital grains. The carbonate cement shown (figs. 12a–f) engulfing the detrital grains.

Dolomite is also common in the deposits and its occurrence has been verified by SEM as it contains Fe and Mg. Occurs as a solid solution of Fe-rich ankerite and the Mg rich end-member of kutnohorite The open framework commonly occurring where there is carbonate cement (fig. 12b).

Apatite and pyrite

The SEM analysis carried out on a sample from a relatively shallow depth of ca. 574m in the Faludden Member. This sample displayed the occurrence of crystallized apatite surrounding detrital grains. The apatite affinity is evidenced by the SEM spectrum that shows the presence of Ca, P, C, O and F which are all the elements that make up the chemical formula of Apatite: $Ca_5(PO_4)_3(F,Cl,OH)$. The occurrence of this apatite is attributed to horizons of slow sedimentation in a shallow marine environment by Scholle (1979) the apatite is seen in figure 13a as grey dirt around the detrital quartz grains. This 'dirt' is different from the dust rims occurring between the detrital quartz grains and authigenic quartz.

Pyrite occurs as a filling in the intergranular pore spaces between the detrital quartz grains or as distinct crystals. Pyrite crystals and cement were not visible under polarized microscope, but visible under SEM analyses. The figure 13b shows pyrite in the Faludden Member. It is seen as nodular scattered precipitations of pyrite engulfing detrital grains.

5.2 Chemical composition

Quartz arenites are sedimentary rocks with more than 95% composition of detrital quartz and less than 5 % of 'contaminants' (Pettijohn et al., 1972) whereas Williams et al. (1954) defines quartz arenites as containing more than 80% detrital quartz. The chemical data thus also prove that the Cambrian reservoirs are mostly quartz arenitic sandstones (table 4). In the tables (table 4 and 5), the main elements and most significant trace elements are shown. In addition, the complete analytical data are shown in appendix II.

The sandstones in this study are made up of almost entirely quartz with a few accessory minerals such as feldspars, muscovite, glauconite and heavy minerals

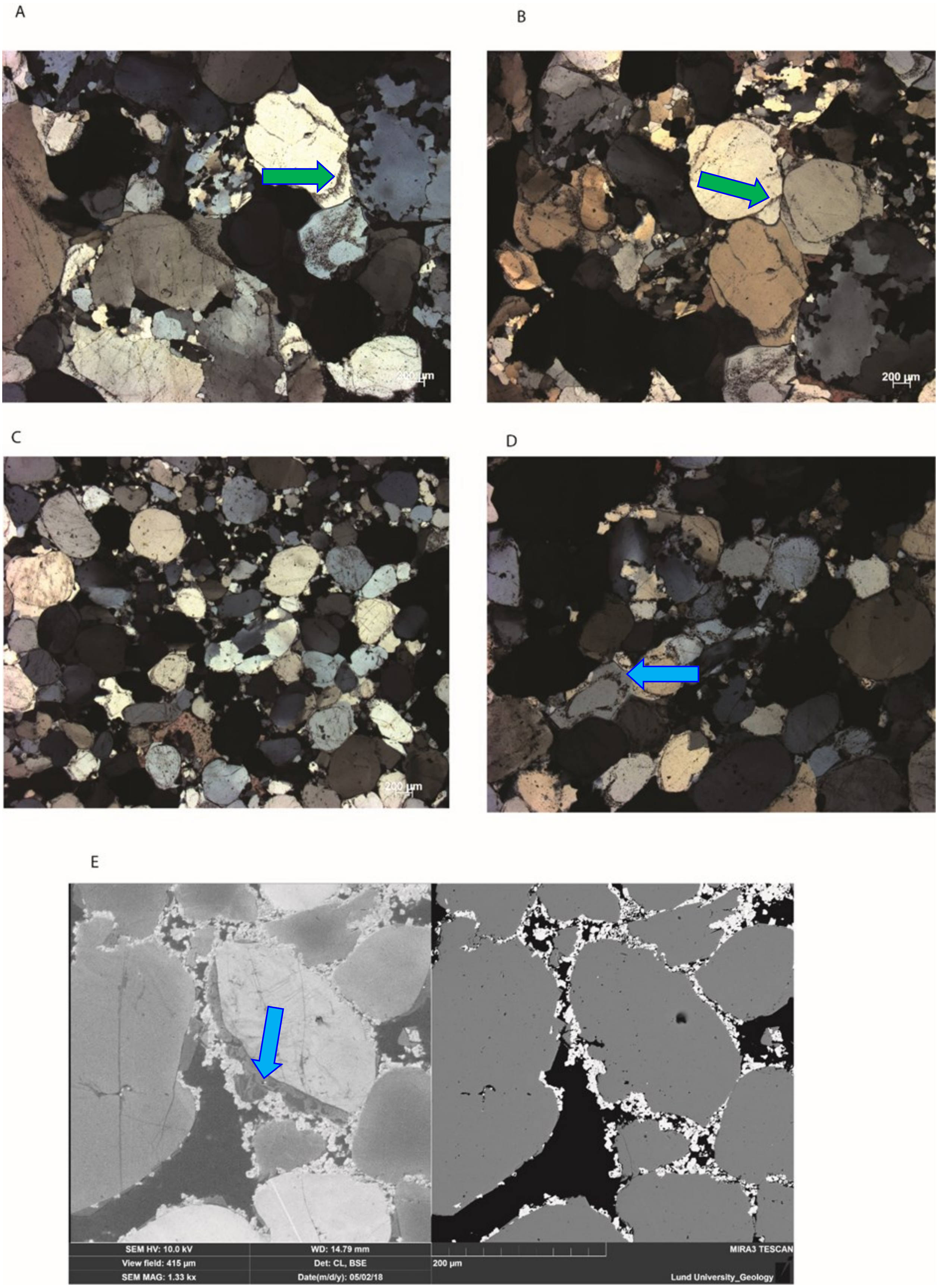

Figure 11. A)–D) microphotographs of quartz overgrowths cement in polarized microscope causing porosity loss in the Segerstad well close to the basement (File Haidar: 596m, Segerstad: 259m, Böda Hamn: 158m, Böda Hamn: 106m respectively). The overgrowths are illustrated in blue arrows and the dust rims are illustrated with green arrows, E) quartz cement in SEM in the Hamra-1: 574m.

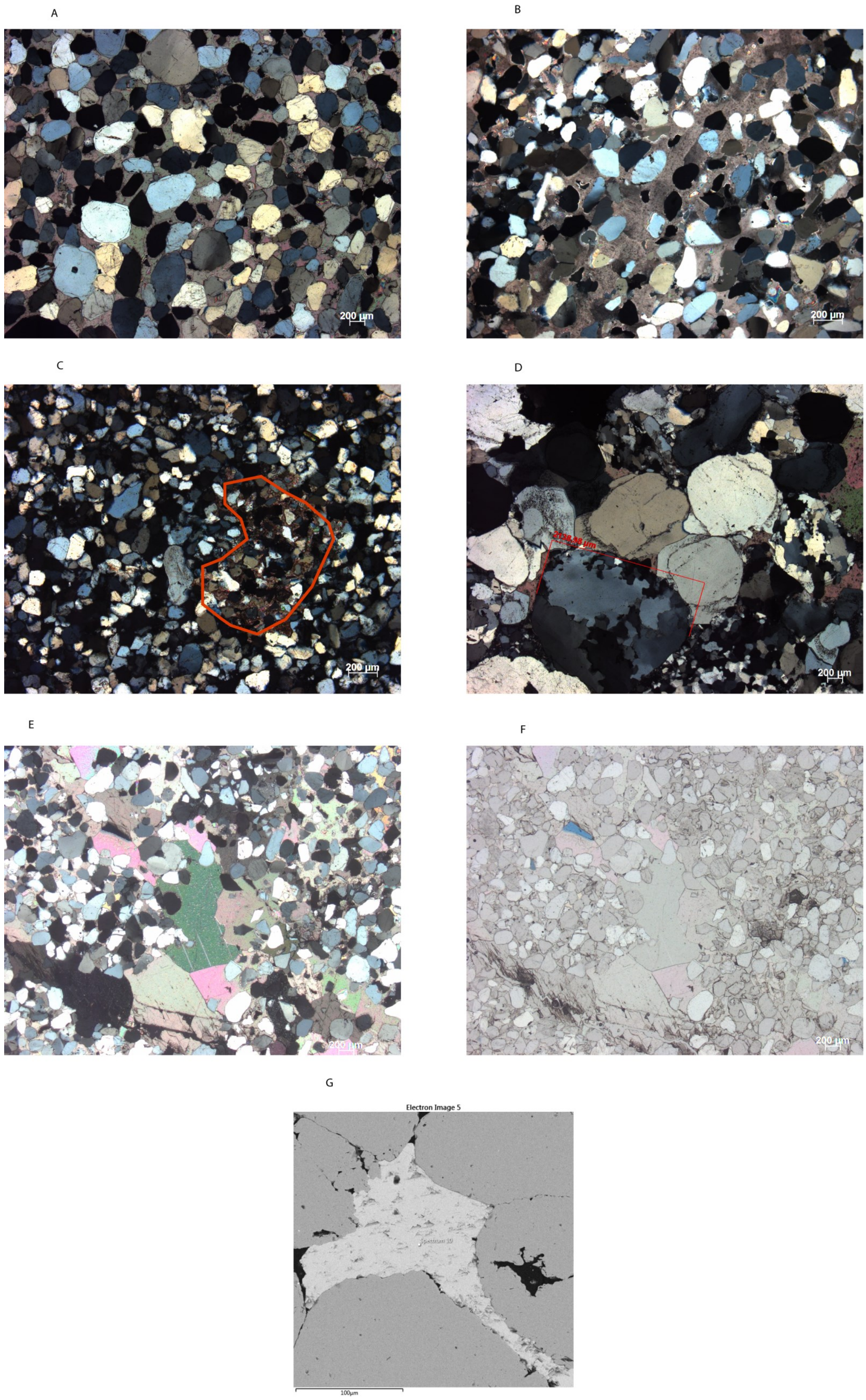

Figure 12. Microphotographs of calcite cement as it occurs in the Cambrian sandstones in the study area, A) and B) show the low grain packing density (När-1: 642m B-7: 858m respectively), C) shows the poikolotopic nature of the carbonate cement. (När-1: 549m), D) illustrates the occurrence of calcite and silica cement (Segerstad: 259m), E)and F) illustrate how calcite cement destroys porosity in PPL and XPL (Frigsarve:-1 509m). G) show calcite and dolomite respectively in SEM BSE (Kvarne-1: 518m).

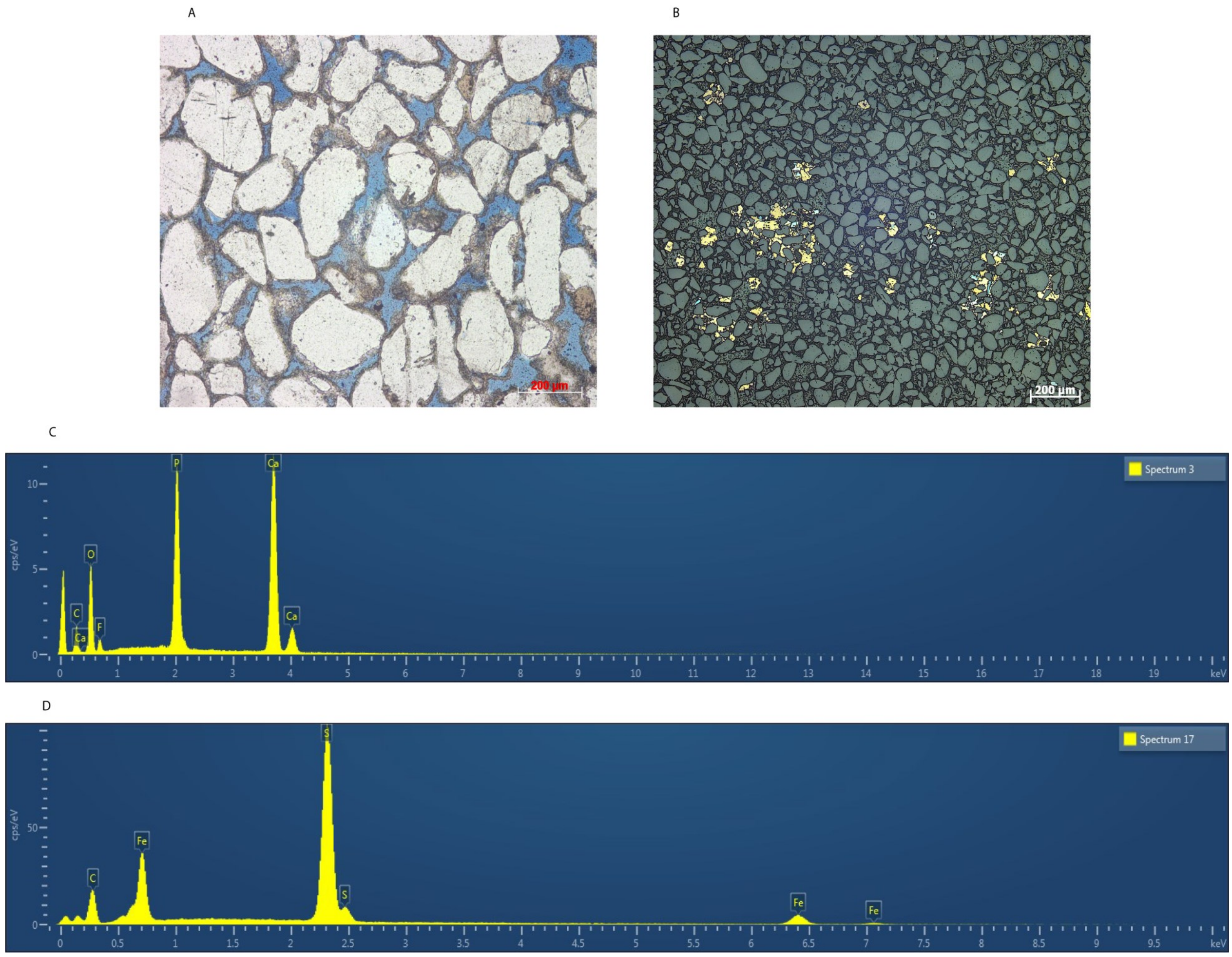

Figure 13. A) Microphotograph of apatite seen here as greyish films surrounding the detrital quartz grains (Hamra-1: 574m), B) microphotograph of pyrite cements seen with a bright yellow colour seen as patchy cements in the (B-7: 858m), C) apatite spectrum from SEM analyses, D) Pyrite spectrum from SEM analyses.

Table 4: Summary of main elements in samples from the various sandstone units (in %).

Sandstone unit		SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O
Faludden	Average	95.3	0.48	1.78	0.34	0.04	0.05
N= 2	Max	95.7	0.52	2.27	0.34	0.06	0.05
	Min	94.8	0.44	1.28	0.34	0.02	0.05
När	Average	93.7	1.08	1.23	0.78	0.05	0.44
N= 7	Max	98.0	2.99	4.00	3.44	0.15	1.36
	Min	84.7	0.48	0.41	0.02	0.02	0.06
Viklau	Average	94.6	1.25	0.62	0.95	0.06	0.61
N=11	Max	97.2	3.65	0.82	7.68	0.16	2.06
	Min	85.0	0.08	0.45	0.00	0.02	0.02
All sandstones	Average	94.4	1.12	0.95	0.82	0.05	0.50
N= 20	Max	98.0	3.65	2.27	3.44	0.16	2.06
	Min	84.7	0.44	0.41	0.00	0.02	0.02

Table 5: Summary of trace elements in samples from the various sandstone units (in ppm).

Sandstone Unit		Ba	Mn	P	Pb	Zr
Faludden	Average	25	207	40	153	20
N=2	Max	30	280	60	267	21
	Min	20	134	20	39	18
När	Average	71	264	281	129	103
N= 7	Max	130	1165	1120	872	343
	Min	10	24	30	2	23
Viklau	Average	94	125	51	6	90
N=11	Max	290	718	100	20	181
	Min	10	23	40	2	25
All sandstones	Average	85	182	131	64	87
N=20	Max	290	1165	1120	872	343
	Min	10	23	20	2	18

such as zircon. The När Member has an average amount of quartz of about 94.7% and the Faludden and Viklau which have 95.2% and 94.6% respectively. Trace element occurrence shows high Mn, P, and Pb in all the three Cambrian units (appendix III). Zr also occurs in relatively high amounts, thereby explaining the regular frequency zircon grains observed in SEM analyses. This bulk chemical analysis serves to confirm the mineralogical maturity of the sandstone reservoirs of the Swedish sector of the Baltic Basin.

5.3 Porosity and permeability

Porosity is inclusive, as it not only describes the number of pore spaces, but also the size, shape, distribution and the connectivity of the pore spaces (Molenaar et al., 2007). Porosity is highest in the Faludden Member of the Cambrian sandstone reservoirs.

The variation of porosity with present-day burial depth is plotted and the scatter plot shows no significant correlations especially in terms of the sandstone reservoirs and their positions in relation to each other. The plot in figure 15a illustrates this.

The average porosity in the Faludden Member is measured to be 15% with the maximum value of

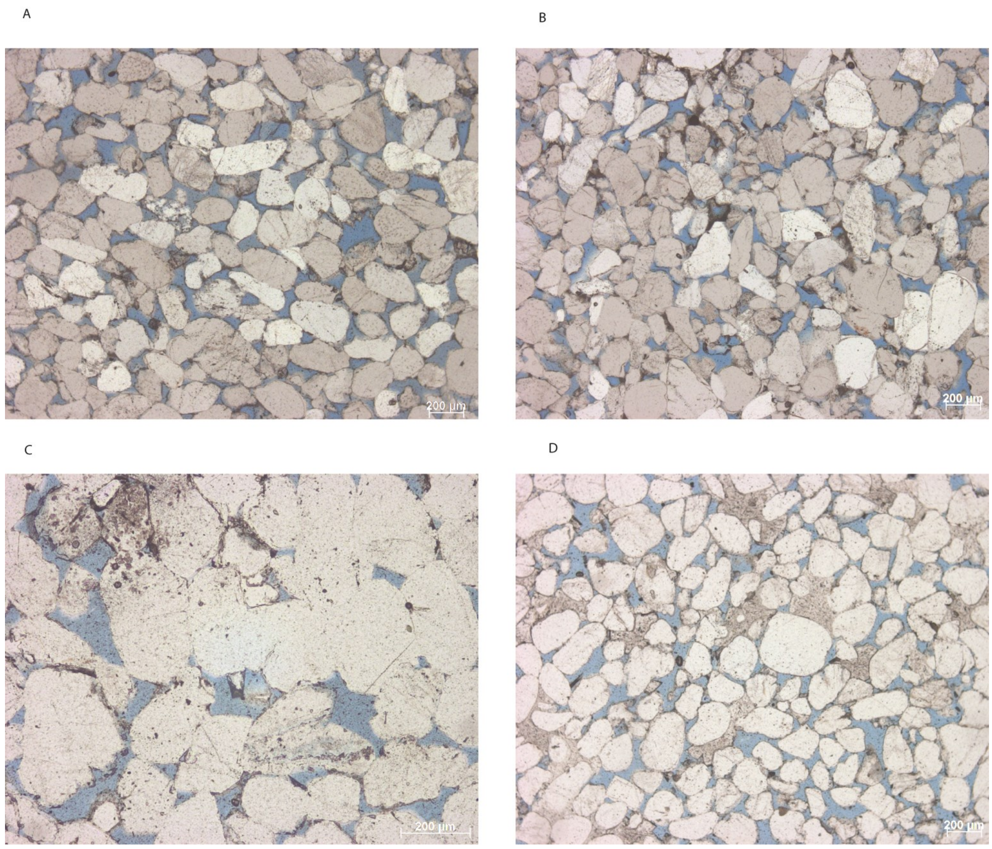

Figure 14. Porosity of the Faludden Member at various depths where the thin sections have been injected with a proxy (blue stain) to show the porosity. A) Loosely packed sandstone (Frigsarve:-1 500m), B) a relatively more densely packed sandstone (Kvarne-1: 518m), C) effects of authigenic quartz on porosity (Hamra-1: 586m), D) effects of carbonate cement (Hamra-1: 572m).

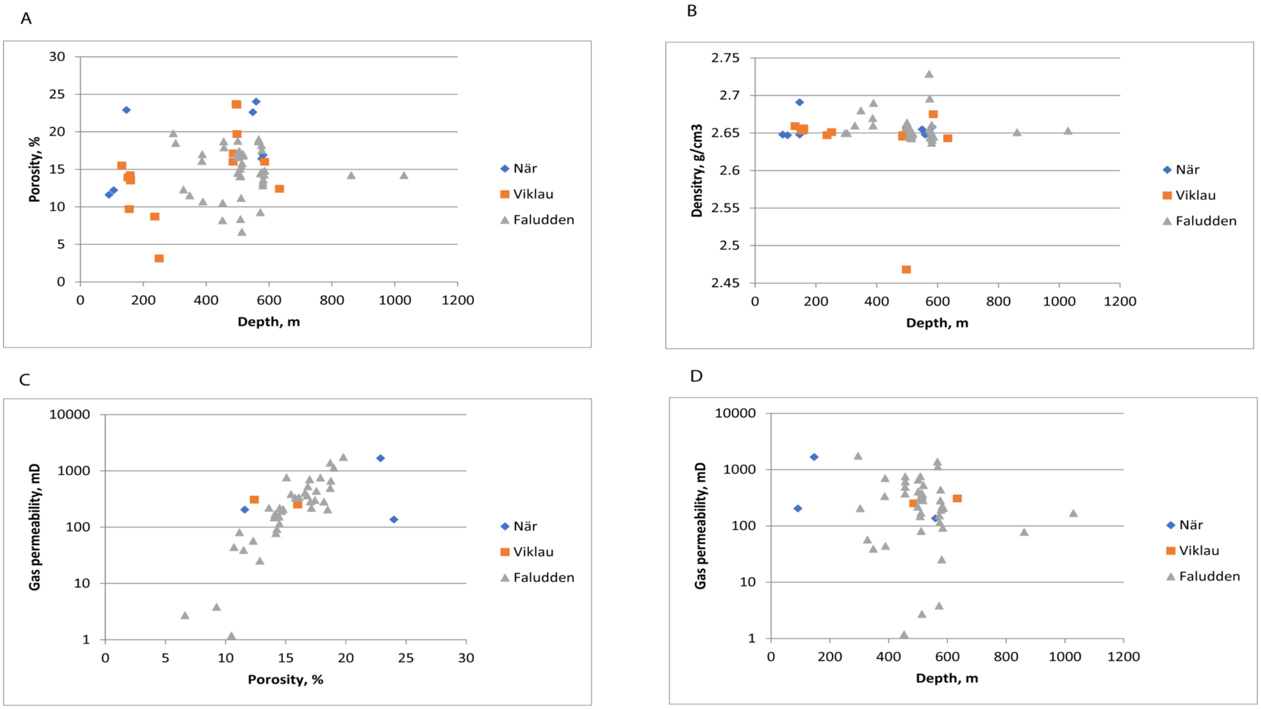

Figure 15. Graphs of A) Depth against porosity where there is no correlation B) density against depth C) gas permeabilty against porosity where a positive correlation is observed D) Depth against gas permeability.

18.8% and a minimum value of 8.4%.

A graph of log10 of the gas permeability is plotted against the porosity and against the depth. There seems to be a positive correlation between the porosity and gas permeability (fig. 15c) but no such correlation is seen with gas permeability versus depth in the data measured. The gas permeability measurements were mostly done on the Faludden Member. For the Viklau and När members, it is not possible to give any correlation as there are too few data points

Figure 15d does not show a positive correlation between depth intervals in metres from the Kelly bushing and the measured values of gas permeability expressed to log10. The Faludden samples were collected around the same depth area for the wells from which the samples were collected, except in the B-7 and B-9 well where the Faludden Member occurs at deeper levels i.e. c. 850m and 1029 m respectively.

However, an interesting trend is observed in figures 15a, 15b and 15d where a cluster of the results are around 600m depth. This is because most of the data is occurring between 400 and 600m depth interval.

The gas permeability ranges from 0.47–1700.00 mD, which are somewhat lower values than those that were determined in then Lithuanian sector by Sliaupa et al. (2004) where the range was determined to be 100.00–2300.00mD. There the permeabilities are much lower. The porosity is found to be in the same region as that determined in the Swedish sector of the Baltic Basin with average of 15.3% on all the reservoirs combined.

With an average depth of about 352m, the Viklau sandstone unit shows an average grain density of 2.63 g/cm^3.Samples from the När sandstone unit shows an average depth of 394m with an average grain density of 2.66 g/cm3. The Faludden sandstone unit samples have an average depth of 559m and an average grain density of 2.66 g/cm3. This is a fairly consistent value in all the sandstones in regard.

5.4 Well-log motifs

The gamma ray motifs encountered in this study are similar to those exemplified by Kessler & Sachs (1995). A set of these are exemplified (fig. 16) and described below as: a) Cylindrical shape - this shape of the GR log is most evident in the Faludden sandstone. It basically shows an aggradation, b) Funnel shape- the Grötlingbo and Mossberger members exhibit this shape often. This shape shows a coarsening upwards sequence (progradation), c) Bell shape- mostly visible in the När and Viklau members. This shape illustrates a fining upwards sequence (retrogration), d) Symmetrical shape- mostly visible in the Viklau Member. Pro-

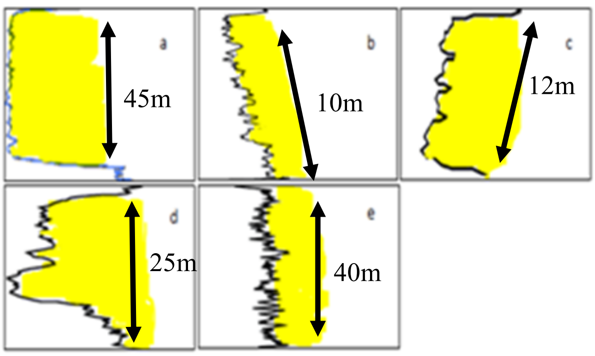

Figure 16. Examples of different typical GR log patterns encountered in the wells under study in this thesis. A) well ID: B-9, Depth:1025 b) Well ID: Rings-1, Depth: 430m c) Well ID Grötlingbo, Depth: 575m d) Well ID: Myrhage, Depth: 365m e) Well ID: Skäggs, Depth: 240m.

gradation and retrogradation often showing both coarsening and fining upward sequences, e) Saw tooth- mostly in the Ordovician limestones. Like the cylindrical shape, it also shows aggradation.

The motifs from the GR log were typically cylindrical shaped in all wells for the Faludden Member. Cylindrical shape shows an aggradation, thereby having a uniform grain size in the sandstone member. On occasion, there occurred a few shale intercalations within the Faludden which illustrated by a deflection to the right of the GR log.

As can be seen from figure 17 in the B-9 well, the Faludden takes an aggrading profile. The När sandstone unit shows a fining upward sequence, indicating shallow marine facies in the top of the sandstone member.

The Faludden Member in the B-3 well shows some shale intercalations within the sandstone. This is the reason why the GR log deflects to the right. This trend is also visible in the När sandstone member of the B-3 well.

The Alum Shale shows very high GR readings. This is due to the higher radioactivity in comparison to carbonates and sandstones. The very high GR readings produced by the Alum Shale made it possible to identify its location in the wells.

Offshore Gotland, the neutron-density survey was conducted on a few wells. One example is the B-9 well shown in figure 17.

The neutron-density log indicates clayey interval in the Mossberga and Grötlingbo members. The Faludden Member is cemented in the first 3–5 metres and this is shown in the neutron density log where the neutron curve (blue) is to the left of the density curve (red). Below the first interval, there is a cross-over point which indicates the presence of gas in the Fa-

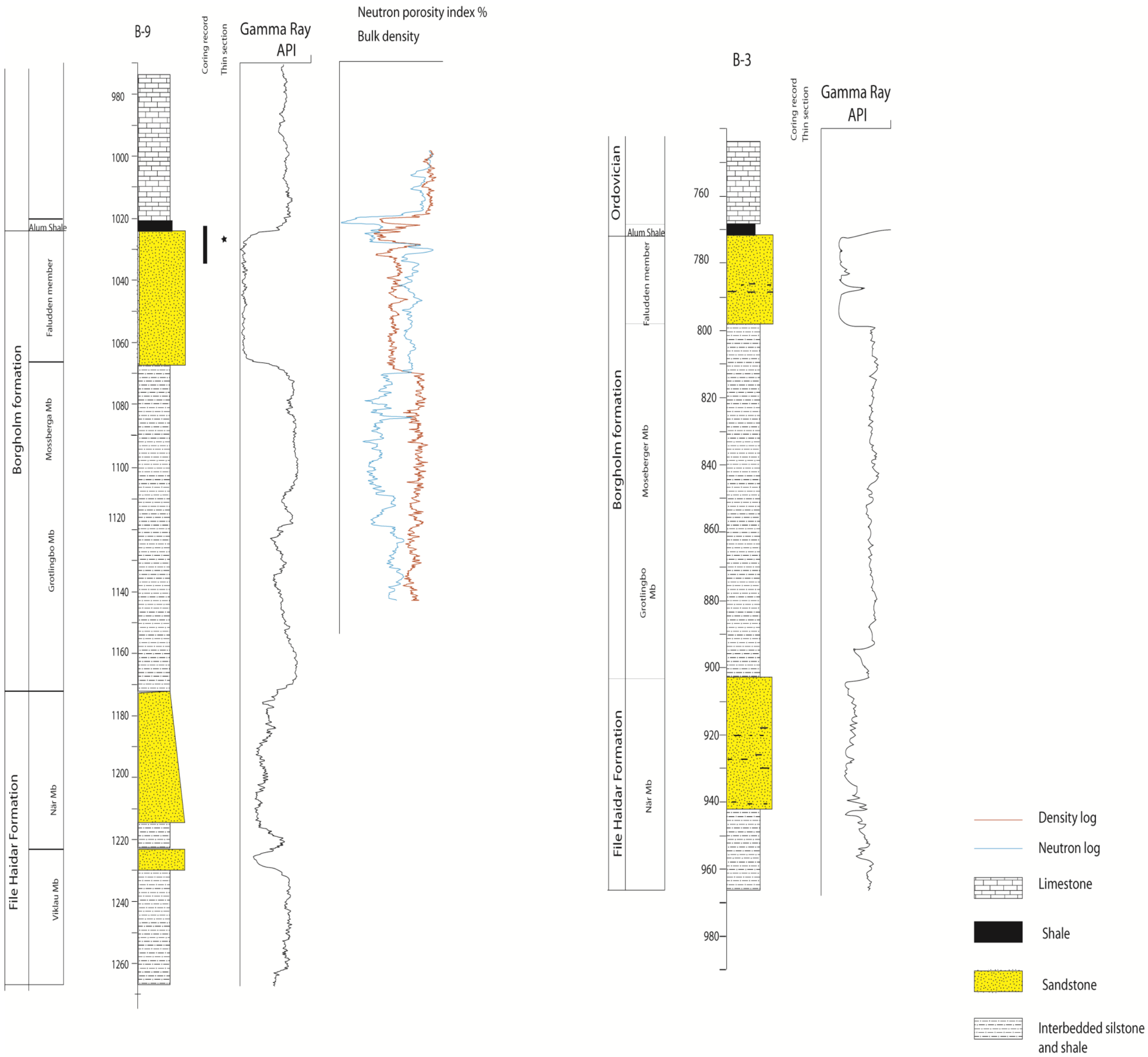

Figure 17. Well logs from the B-9 and B-3 wells exemplifying the typical wire-line log responses for the Cambrian succession.

ludden member. This trend is also seen in the B7 well in Appendix VII. This shift of the neutron curve to the right is caused by lower hydrogen concentration in the gas.

6 Discussion

This chapter seeks to give a broader perspective of the results. The mineralogy, cementation, porosity and permeability are discussed to explain their trends in the study area.

6.1 Mineralogy

6.1.1 Quartz

Quartz overgrowths are almost entirely distinguishable from the detrital quartz by the presence of dust rims. The dust rims pre-date the authigenic quartz. This consistent occurrence seems to illustrate that the dust rims form a favourable nucleation sites for the authigenic quartz to grow from. The source of the silica may be from the dissolution of quartz grains due to overburden pressure which resulted in sutured grain boundaries.

Intergranular solution resulted in sutured grain boundaries between the quartz grains. These sutured grain boundaries are visible in the Faludden member of the B-9 well occurring at 1029m depth from the Kelly bushing and this depth may explain this phenomenon.

The sutured boundaries occur like interfingerings where the grains seem to be locking into each other. There is an increase in sutured grain contacts with depth and this could be related to the downward increase in dissolution and re-precipitation in the formation. These sutured grain contacts are an indicator of the thermal conditions at depths greater than 800m. This phenomenon is rarely visible at all the samples that were analysed at depths less than 800m.

Figure 18 shows quartz grains with different colours. The quartz grains looked very homogeneous under the optical microscope but under the Cathode Luminescence (CL) the compositional variations are apparent. The different colours of the quartz are probably indicative of the different sources of the quartz grains. The lighter the grains are the heavier elements the quartz grain contains.

Some of the quartz grains show chemical zonation. The differing temperature and or pressure conditions during crystal growth may be the attributing factor to the composition variations in the quartz crystals. Magma compositional changes as crystallization progresses

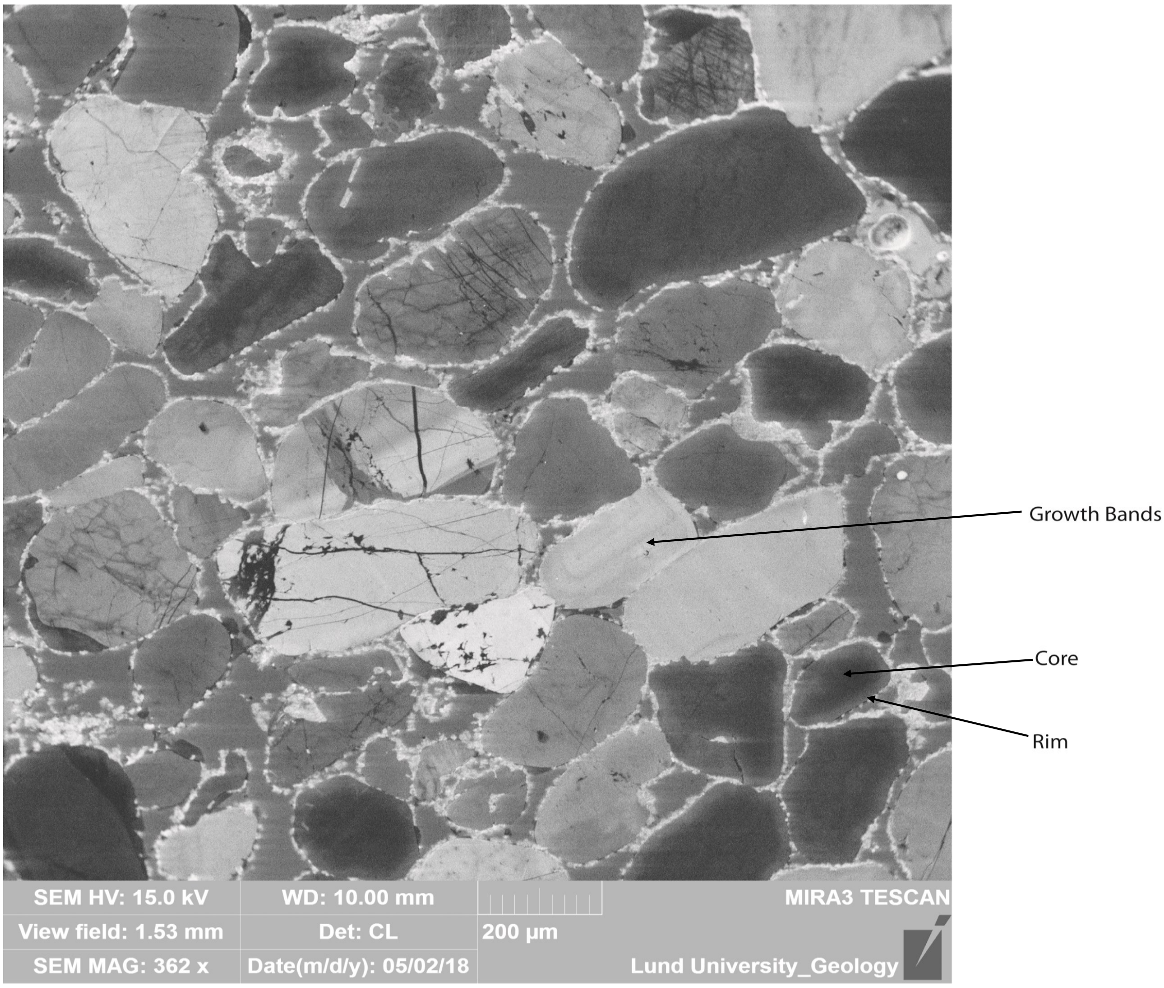

Figure 18. Quartz grains of differing composition in the Cambrian sandstones as seen in CL for the well Hamra-1: 574m.

could also be used to explain these trends

The grains are mostly sub-rounded to sub-angular indicating a fair degree of transportation before deposition.

6.1.2 Other minerals

Glauconite is thought to have been produced as fecal pellets *in situ* (Scholle, 1979). Molenaar et al. (2007) associated glauconite to sequence boundaries. It is more common in the lower parts of the Cambrian succession i.e. the När member. The När sandstone has been observed to be strongly bioturbated. This may imply that the glauconite is originating from the faecal pellets of the organisms responsible for the bioturbation. It is thus detrital is opposed to authigenic. Glauconite is a good indicator of a marine depositional environment according to Scholle (1979).

Zircons are found in sedimentary rocks because of their chemical stability as well as physical stability. The zircons showed chemical zonation illustrating distinct geochemical packages with differing chemical composition. These zonation patterns are not visible on regular polarized microscopes but very visible under Back Scatter Electron (BSE) and CL in SEM analysis.

Not many accessory minerals are found in the Cambrian sandstones of the Baltic Basin because of their mineralogical maturity but minor occurrences of muscovite and feldspars are also observed.

6.2 Cements

6.2.1 Silica cement

Silica cementation does not reduce porosity to zero in the study area. Present day burial depth could be the attributing factor. This study establishes that variations with depth and temperature are less apparent in the basin periphery as silica cement becomes more extensive at depths greater than 1200m.

Idiomorphic quartz overgrowths tend to be more pronounced with present day burial depth and have an optical continuity with the detrital quartz grain. The silica overgrowths were identified by Kilda & Friis (2002) as the main cause of reduction in porosity of the Cambrian reservoirs of the Baltic Basin.

Quartz as a cement influences the porosity and permeability of sandstones. It can severely reduce the porosity and permeability of siliciclastic sandstones and the controls of quartz cementation on the petrophysical properties of these sandstones need to be better understood (Molenaar et al., 2007). Petrographic studies carried out by (Sliaupa et al., 2004) show that quartz cement occurs at temperatures higher than 40 ° C, with the most notable reductions occurring at temperatures higher than 60–70 °C. Depositional and diagenetic processes both influence the porosity and permeability of siliciclastic sandstones (Cyziene et al., 2001). Byrnes (1994) suggests that reservoir properties of quartzose sandstones decrease, in general, with an increase in the age of the deposit and present-day burial depth.

6.2.2 Carbonate cement

Calcite may obliterate porosity, although here it is occurring as isolated crystals forming poikolotopic (luster-mottled) texture where the carbonate cement surrounds the detrital quartz grains. Fig. 13 shows how the calcite cement has affected the porosity. Scholle (1979) relates the patchy poikolotopic cement to irregular distribution of nuclei necessary for the crystallization of calcite such as shell fragments and pellets. Because of this irregular distribution, it is difficult to

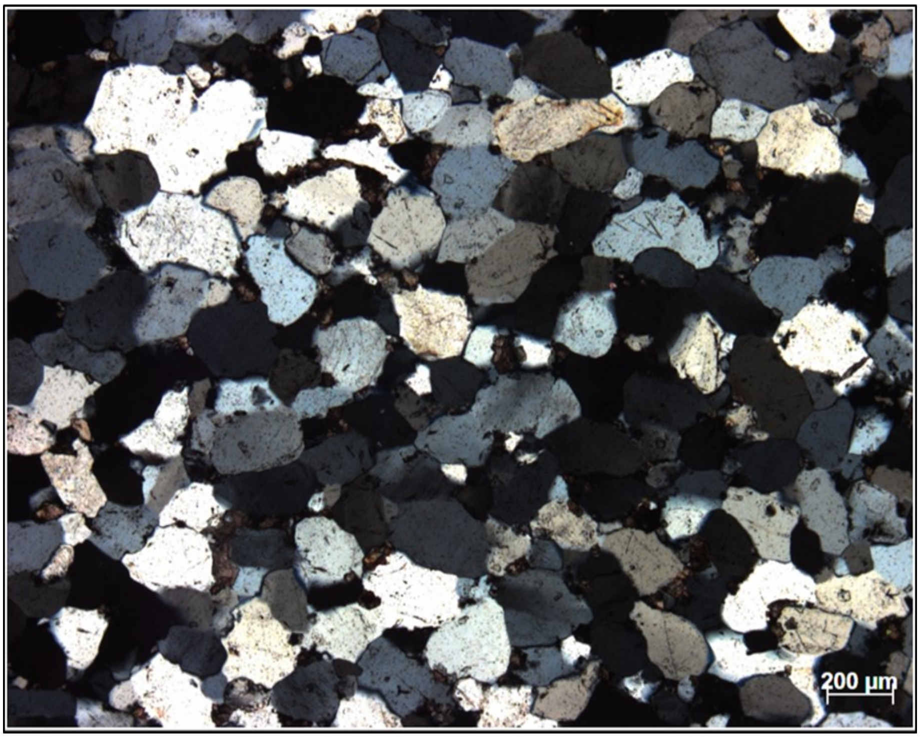

Figure 19. Microphotograph showing an example of sutured grain boundaries in the Faludden Member (B-7: 587m).

trace the character of this cement with present day burial depth. However, Cyziene et al. (2001) established a trend in which the calcite cement decreases with increasing present day burial depth but due to profound variations of petrophysical and petrological properties, even on adjacent wells, it is thus difficult to draw conclusions from that.

Dolomite occurs together with calcite, and like apatite, it seems to be early diagenetic. It is early diagenetic because it has been observed to undergo dissolution during late diagenesis. It has been determined to be the more common type of cement in the Lithuanian sector as opposed to Calcite. It also exhibits the luster-mottled clusters as calcite. As can be seen from figure 12b where there is carbonate cements there is low grain packing density further supporting that carbonate cements are relatively early in the diagenetic sequence as this proves that the carbonate cements predate mechanical compaction.

6.2.3 Phosphate and other cements

The occurrence of apatite, which is an early grain coating, is attributed to horizons of slow sedimentation in a shallow marine environment by Scholle (1979). It is probably an early phase of diagenesis. Its occurrence may need to be further analysed to identify any patterns within the different sandstone units. It may occur during hiatus intervals where phosphate-rich water was upwelling in the marine environment. Another possible explanation for the source of apatite is that it comes from the shales above where phosphorous-rich solutions percolate from the Alum Shale during compaction.

6.3 Porosity and Permeability

The Cambrian reservoir properties in the Baltic Basin are controlled by lithology and cementation (Cyziene et al., 2001). In the Baltic Basin, the porosity and the permeability decrease with depth (Molenaar et al., 2007). However, this trend is not showing in figure 15, which may be related to the fact that most of the samples were taken from the periphery of the Baltic Basin where the depth is not great enough for quartz cementation to prove significant. Silica cementation starts to be of particular importance at depths greater than 1000m, although the sample at 800m in Faludden sandstone unit showed some sutured grain boundaries which may be due to compaction. The geothermal gradient plays an important part in understanding the silica cementation mechanism. The geothermal gradient has been measure on Gotland to be around 4.1 °C per 100m. Assuming that the geothermal gradient is homogenous, this will make authigenic quartz significant at a depth of c 1000m thereby reducing porosity. Cyziene et al (2001) noted that higher porosities do not necessarily imply higher permeability.

Calcite cement significantly reduces the porosity which is the reason why the minimum values obtained for the porosity values in the Faludden sandstone are 8.36%. Studies carried out by Cyziene et al. (2001) showed a decrease in the porosity from eastern Lithuania to western Lithuania into areas very close to the marine boundary of the Swedish Sector. However, it is difficult to draw conclusions from this as there are wide-ranging variations in the petrophysical properties sometimes on adjacent wells.

Porosity also affects the density. This is illustrated by the minimal variation in the densities at the depths at which the samples were taken. Most of the Viklau samples were taken at lower present day burial depths, which may attribute to their lower grain densities as opposed to the Faludden and the När which were collected on average higher depths.

6.4 Thermal history

Factors such as burial depth and heat flow intensity have a significant effect on the Cambrian reservoir, thereby making the thermal conditions of the reservoirs vary considerably (Sliaupa, 2004). The geothermal gradient of the sedimentary cover of the basin varies from 1.3–1.7 ºC/100 m in the east up to 4.5 ºC in the west (Sliaupa, 2001). He further attributed this change in the geothermal gradient to hydrodynamic cooling, deep heat flow, lithological variations and heat transfer along faults. The porosity also influences the thermal conductivity and thereby affecting the geothermal gradient (Sliaupa, 2004).

6.5 Chemistry

The SiO_2 is high (greater than 80%) and reflects the amount of quartz in the sandstones. The Al_2O_3 is occurring in very low amounts (0.08%–3.32%) thus reflecting the varying clay compositions within the sandstones. The Na and K are related to the feldspars and or the shales. This is because Na, and K like Al, are found more abundantly in shales than in sandstones. TiO_2 ranges from 0.05–0.52%, its concentration being attributed to shales. The iron content is of particular interest as the Fe^{3+} is reflected in the glauconite, giving it the green colour.

The Ca, attributed to the calcite cement shows some relatively high values as compared to the other elements. It ranges from 0–7.68%. Feldspars may also contain Ca.

7 Conclusions

This study primarily resulted in the following conclusions:

- Modal analysis established that there are two quartz varieties which are polycrystalline and monocrystalline. It is the monocrystalline variety that experiences authigenic quartz overgrowths.
- The Faludden sandstone unit has a high porosity (15%) and permeability of 555 mD. These values make the sandstone unit a suitable candidate for CCS because for effective storage, the porosity should be between 10–15% and the gas permeability should be ≥100mD.
- The cement components are mainly authigenic quartz and carbonate cement with minor apatite and pyrite. This is however the first time apatite is observed as a cement in the Cambrian succession in the Swedish sector of the Baltic Ba-

sin.

- Silica seems to have precipitated first, and the fact that it precipitated first shows that it is more likely from an external source as opposed to compaction during diagenesis. The apatite precipitated later during diagenesis and the carbonate cement precipitated last as it is seen in the study engulfing quartz grains
- There is a high variation of compaction structures such as sutured grain boundaries. These are a possible source of Silica. Another possible source is external percolation of silica rich fluids during compaction of shales.
- Of particular importance is to further investigate the observed apatite cementation regarding origin and diagenetic process behind its formation. Therefore there is a need to have more empirical studies of thin sections

The results indicate that it is difficult to establish clear correlations between the different petrophysical properties with e.g. depth. This is because the wells and samples studied are either in the basin periphery or only available for the Faludden sandstone in the offshore wells implying that we miss cores from the När and Viklau sandstone units in the deeper parts of the basin.

It is thus important to carry out further study in the deeper potions of the basin by having more drill-cores from that area as it is important to fully understand the controls on the reservoir properties. Large variations also occur in adjacent wells thereby making it easier to give a more general interpretation as opposed to an accurate holistic one.

However, the consistency of the GR log, especially in the Faludden member such that it is possible to combine the log Neutron-Density log to provide an indication of the porosity.

At depths greater than 1000m, quartz cementation is of particular importance and calcite cement has been modelled by Molenaar et al (2007) to reduce with depth as quartz cement increases.

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9 References

Beckholm, M, & Tirén, S.A, 2009. The geological history of the Baltic Sea a review of the literature and investigation tools. Report number 2009:21.

Blunt, M., 2010. Carbon dioxide storage. Grantham Institute Briefing Paper, 4.

Byrnes, A.P., 1994. Empirical methods of reservoir quality prediction.

Cyziene, J., Molenaar, N. & Sliaupa, S., 2001, May. Syn-depositional, diagenetic and petrophysical characterization of the Cambrian reservoir of Lithuania along a regional East-West scale-profile. In Proceedings of the 6th Nordic Sym posium on Petrophysics (pp. 15-16).

Erlström, M., 2011. Lagring av koldioxid i berggrun den: krav, förutsättningar och möjligheter. Sveriges geologiska undersökning.

Erlström, M. & Persson, L., 2014. Radiomagnetotell uric mapping of marlstone and limestone in the Silurian bedrock of Gotland. GFF, 136(4), pp.571-580.

Erlström, M., Elhammer, A. & Zillén Snowball, L., 2014. Bedömning av olja och gas inom svenskt marint territorium och ekonomisk zonen över sikt. SGU rapport 2014:26, 46 pp.

Flodén, T., 1980. Seismic stratigraphy and bedrock geology of the central Baltic (Doctoral disserta tion, Almqvist & Wiksell).

Hagenfeldt, S.E., 1994. The Cambrian File Haidar and Borgholm Formations in the Central Baltic and south central Sweden. Stockholm Contributions in Geology, 43, pp.69-110

Kessler, L.G. & Sachs, S.D., 1995. Depositional setting and sequence stratigraphic implications of the Upper Sinemurian (Lower Jurassic) sandstone interval, North Celtic Sea/St George's Channel Basins, offshore Ireland. Geological Society, London, Special Publications, 93(1), pp.171-192.

Kilda, L. & Friis, H., 2002. The key factors control ling reservoir quality of the Middle Cambrian Deimena Group sandstone in West Lithuania. Bulletin of the Geological Society of Denmark, 49(1), pp.25-39.

Klaja, J. & Dudek, L., 2016. Geological interpretation of spectral gamma ray (SGR) logging in selected boreholes. Nafta-Gaz, 72(1), pp.3-14.

Liu, H., 2017. Principles and Applications of Well Logging. Springer Berlin Heidelberg.

Mallick, R.K., Choudhuri, B. & Vishunavat, P., 1997. An innovative technique resolves apparent anomalies in detection of gas zones based on neutron—density logs. Journal of Petroleum Science and Engineering, 18(3-4), pp.201-213.

Molenaar, N., Cyziene, J. & Sliaupa, S., 2007. Quartz cementation mechanisms and porosity variation in Baltic Cambrian sandstones. Sedimentary Geology, 195(3-4), pp.135-159.

Mortensen, G.M., Erlström, M., Nordström, S., & Nyberg, J., 2017. Geologisk lagring av koldioxid i Sverige – Lägesbeskrivning avseende för utsättningar, lagstiftning och forskning samtolje- och gasverksamhet i Östersjöregionen, Rapporter och meddelanden 142. Geological Survey of Sweden.

Murray, R.W., Miller, D.J. & Kryc, K.A., 2000. Analysis of major and trace elements in rocks, sediments, and interstitial waters by inductively coupled plasma–atomic emission spectrometry (ICP-AES).

Nazeer, A., Abbasi, S.A. & Solangi, S.H., 2016. Sedimentary facies interpretation of Gamma Ray (GR) log as basic well logs in Central and Low er Indus Basin of Pakistan. Geodesy and Geo dynamics, 7(6), pp.432-443.

Nielsen, A.T. & Schovsbo, N.H., 2006. Cambrian to basal Ordovician lithostratigraphy in southern Scandinavia. Bulletin of the Geological Society of Denmark, 53, pp.47-92.

Nielsen, A.T. & Schovsbo, N.H., 2011. The Lower Cambrian of Scandinavia: depositional environment, sequence stratigraphy and palaeogeography. Earth-Science Reviews, 107(3-4), pp.207-310.

Pettijohn, F.J., Potter, P.E. & Siever, R., 1972. Sand and Sandstone. Springer, New York, NY, pp. 618

Plado, J., Preeden, U., Joeleht, A., Pesonen, L.J. & Mertanen, S., 2016. Palaeomagnetism of Middle Ordovician Carbonate Sequence, Vaivara Sinimäed Area, Northeast Estonia, Baltica. Ac ta Geophysica, 64(5), pp.1391-1411.

Sea, O.B., 1976. Exploration activities 1971-1976. Geology and petroleum prospects. OPAB re port. SGU archive, 40274.

Shogenova, A., Sliaupa, S., Vaher, R., Shogenov, K. & Pomeranceva, R., 2009. The Baltic Basin: structure, properties of reservoir rocks, and capacity for geological storage of CO 2. Estonian Journal of Earth Sciences, 58(4).

Scholle, P.A., 1979. A color illustrated guide to constituents, textures, cements, and porosities of sandstones and associated rocks (No. 552.5 SCH).

Sivhed, U., Erlström, M., Bojesen-Koefoed, J.A. & Löfgren, A., 2004. Upper Ordovician carbonate mounds on Gotland, central Baltic Sea: distribution, composition and reservoir characteristics. Journal of Petroleum Geology, 27(2), pp.115-140.

Sliaupa, S., 2001. Geothermal data base of Lithuania. Annual report of the Lithuanian Geological Survey for, pp.51-53.

Sliaupa, S., Cyziene, J. & Molenaar, N., 2004. Impact of thermal regime on quartz cementation in Cambrian sandstones of Lithuania. Geologija, 47, pp.35-44.

Šliaupienė, R. & Šliaupa, S., 2012. Risk factors of CO2 geological storage in the Baltic sedimentary basin. Geologija, 54(3).

Sopher, D., Juhlin, C. & Erlström, M., 2014. A probabilistic assessment of the effective CO_2 storage capacity within the Swedish sector of the Baltic Basin. International Journal of Green house Gas Control, 30, pp.148-170.

Sopher, D., Erlström, M., Bell, N. & Juhlin, C., 2016. The structure and stratigraphy of the sedimentary succession in the Swedish sector of the Baltic Basin: New insights from vintage 2D marine seismic data. Tectonophysics, 676, pp.90-111.

Stouge, S., 2004. Ordovician siliciclastics and carbonates of Öland, Sweden. In International Symposium on “Early Palaeozoic Palaeogeography and Palaeolimate” (IGCP 503) pp. 91-111.

Warra, A.A. & Jimoh, W.L.O., 2011. Overview of an Inductively Coupled Plasma(ICP) system. International Journal of Chemical Research, 3(2).

Welton, J.E., 1984. SEM petrology atlas.

Williams, H., Turner, F.J. & Gilbert, C.M., 1954. Petrolog 5 W.H Freeman, San Francisco. Calif., pp. 406.

Ziegler, P.A., 1990. Collision related intra-plate compression deformations in Western and Central Europe. Journal of Geodynamics, 11(4), pp.357 -388.

Appendix I-Table summarizing available analyses from wells in the study area

Well	Core Sample	Thin section	Chemistry	Porosity-Permeability	Modal analyses	Formation
Segerstad	146.86	Y	Y			När
Segerstad	146.8			Y		När
Segerstad	153.38		Y			När
Segerstad	157.8					När
Segerstad	169	Y	Y			När
Segerstad	182.4	Y	Y		Y	När
Segerstad	191.99					När
Segerstad	202.94					När
Segerstad	208.53					När
Segerstad	210.55					När
Segerstad	236.71		Y	Y		Viklau
Segerstad	237.1	Y	Y	Y	Y	Viklau
Segerstad	243.85					Viklau
Segerstad	251.33		Y	Y		Viklau
Segerstad	259	Y				Viklau
När-1	525.8	Y	Y	Y		Mossberga/Grötlingbo
När-1	532.45					Grötlingbo
När-1	542.05	Y	Y	Y		Grötlingbo
När-1	549			Y		När
När-1	555			Y	Y	När
När-1	559.55	Y		Y	Y	När
När-1	570					När
När-1	577			Y		När
När-1	582	Y		Y	Y	När
När-1	586.3	Y		Y		Viklau
När-1	596	Y	Y		Y	Viklau
När-1	600.8	Y	Y			Viklau
När-1	604.1					Viklau
När-1	606					Viklau
När-1	610.1					Viklau
När-1	612.3					Viklau
När-1	616.05					Viklau
När-1	630					Viklau
När-1	633.6	Y	Y	Y	Y	Viklau
När-1	636.1					Viklau
När-1	640.3					Viklau
När-1	642.55	Y	Y		Y	Viklau
Gotska Sandön	180.8					Cambrian unspec sst
Gotska Sandön	183					Cambrian unspec sst
Gotska Sandön	185	Y		Y		Cambrian unspec sst
Gotska Sandön	188.8	Y		Y	Y	Cambrian unspec sst
Gotska Sandön	197	Y	Y			Cambrian unspec sst
Gotska Sandön	201	Y	Y			Cambrian unspec sst
Gotska Sandön	219.2					Cambrian unspec sst
Gotska Sandön	228.5	Y		Y		Cambrian unspec sst
Gotska Sandön	238			Y		Cambrian unspec sst
Böda Hamn	84.1					När
Böda Hamn	91.5	Y		Y		När
Böda Hamn	106.53	Y		Y		Viklau
Böda Hamn	131.7	Y		Y		Viklau
Böda Hamn	152			Y		Viklau
Böda Hamn	155.7			Y	Y	Viklau
Böda Hamn	158.6	Y		Y		Viklau
Böda Hamn	160.3			Y		Viklau

Well	Core Sample	Thin section	Chemistry	Porosity-Permeability	Modal analyses	Formation
File Haidar	342.8	Y	Y	Y		Mossberga/Faludden
File Haidar	343.81	Y		Y		Mossberga/Faludden
File Haidar	389.32	Y		Y		Base Grötlingbo
File Haidar	478.5					När Shale
File Haidar	485.85	Y				Viklau
File Haidar	486.85					Viklau
File Haidar	487.1	Y		Y	Y	Viklau
File Haidar	496	Y		Y	Y	Viklau
File Haidar	498	Y		Y	Y	Viklau
File Haidar	498.2			Y		Viklau
File Haidar	549	Y				Viklau
B-7	857.05	Y	Y		Y	Faludden
B-7	858.2	Y				Faludden
B-7	862	Y		Y	Y	Faludden
B-9	1029.5	Y	Y	Y	Y	Faludden
Frigsarve-1	499	Y		Y		Faludden
Frigsarve-1	500	Y		Y	Y	Faludden
Frigsarve-1	509.3	Y		Y	Y	Faludden
Hamra-1	572	Y		Y	Y	Faludden
Hamra-1	574	Y		Y		Faludden
Hamra-1	577	Y		Y		Faludden
Hamra-1	579	Y		Y	Y	Faludden
Hamra-1	580	Y		Y		Faludden
Hamra-1	582	Y		Y		Faludden
Kvarne-1	512	Y		Y		Faludden
Kvarne-1	514	Y		Y		Faludden
Kvarne-1	518	Y		Y		Faludden
Visby-1	321.9			Y		Cambrian unspec sst
Visby-1	375.9			Y		Cambrian unspec sst
Visby-1	394.9			Y		Cambrian unspec sst
Faludden-1	566.3			Y		Faludden
Faludden 1	567.8			Y		Faludden
Hemse 1	452.5			Y		Faludden
Hemse 1	453			Y		Faludden
Skåls 1	456			Y		Faludden
Skåls 1	456			Y		Faludden
Skåls 1	457			Y		Faludden
Skåls 1	457			Y		Faludden
Källstäde 1	328.55			Y		Faludden
Audungs 1	296.1			Y		Faludden
Audungs 1	303.4			Y		Faludden
Furilden 1	348.1			Y		Faludden
Furilden-1	389.8			Y		När
Hangre-1	386.67			Y		Faludden
Hangre-1	387.97			Y		Faludden

Appendix II-Chemical data (Oxides)

Sample ID	SiO_2	Al2O3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Cr_2O_3	TiO_2	MnO	P2O5	BaO	LOI	Total
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Segerstad 146,15-146,22	91.5	0.49	4	0.75	0.02	0.02	0.06	<0.01	0.06	0.01	0.22	<0.01	2.62	99.8
Segerstad 153,33-153,43	98	0.48	0.41	0.1	0.01	0.02	0.1	<0.01	0.06	<0.01	0.03	<0.01	0.55	99.8
Segerstad 169,27-169,37	96.4	0.68	0.63	0.73	0.05	0.03	0.28	<0.01	0.19	0.03	0.01	<0.01	1.01	100
Segerstad 182,4	84.7	2.99	1.99	3.44	0.25	0.15	1.36	<0.01	0.18	0.16	0.15	0.01	4.31	99.7
Segerstad 236,62-236,80	97.2	0.7	0.52	0.05	0.03	0.03	0.29	<0.01	0.05	<0.01	0.03	<0.01	0.39	99.3
Segerstad 237,01-18	95.1	1.1	0.58	0.11	0.03	0.04	0.55	<0.01	0.09	0.01	0.02	0.01	0.41	98.1
Segerstad 238,4-241,2	94.6	2.43	0.61	0.1	0.1	0.09	1.4	<0.01	0.18	<0.01	<0.01	0.02	0.63	100
Segerstad 254,08-18	96.7	1.08	0.64	0.22	0.06	0.09	0.58	<0.01	0.13	0.01	0.07	0.01	0.26	99.9
Segerstad 251,3-251,35	92.1	3.65	0.82	0.05	0.13	0.16	2.06	<0.01	0.23	0.01	0.09	0.04	0.67	100
När-1 525,8	98.1	0.33	0.49	0.13	0.04	0.03	0.14	<0.01	0.06	0.01	<0.01	<0.01	0.4	99.7
När-1 542,0-10	80.5	0.46	3.4	4.66	1.66	0.02	0.07	<0.01	0.1	0.37	0.07	<0.01	7.11	98.4
När-1 549,0	94.7	0.85	0.69	0.26	0.11	0.02	0.23	<0.01	0.57	0.03	<0.01	<0.01	0.75	98.2
När-1 568,0	95.6	0.83	0.5	0.13	0.06	0.03	0.36	<0.01	0.27	0.01	0.02	0.01	0.45	98.3
När-1 596,4-596,5	95.4	0.4	0.58	1.18	0.04	0.02	0.09	<0.01	0.1	0.05	<0.01	<0.01	1.38	99.2
När-1 600,8	97	1.28	0.54	<0.01	0.03	0.05	0.49	<0.01	0.13	<0.01	0.09	0.01	0.62	100
När-1 633,6	96.1	1.18	0.63	0.06	0.02	0.03	0.52	<0.01	0.11	<0.01	0.03	0.01	0.47	99.2
När-1 642,5-642,6	85	0.08	0.45	7.68	0.04	0.01	0.02	<0.01	0.05	0.1	0.01	<0.01	6.25	99.7
Gotska sandön 197,0	95.5	1.7	0.55	0.02	0.07	0.07	0.74	<0.01	0.52	0.01	0.05	0.01	0.54	99.8
Gotska sandön 201,0	90.9	3.32	0.78	0.04	0.08	0.07	1.7	<0.01	0.48	0.04	<0.01	0.03	0.84	98.3
B-7 857,0-10	95.7	0.44	2.27	0.34	0.1	0.06	0.05	<0.01	0.08	0.02	0.05	<0.01	1.58	100.5
B-9 1029-1030	94.8	0.52	1.28	0.34	0.15	0.02	0.05	<0.01	0.06	0.04	0.01	<0.01	1.12	98.4
File Haidar 342,71-344,9	97.8	0.34	0.61	0.05	0.01	0.03	0.09	<0.01	0.19	<0.01	0.03	<0.01	0.39	99.5
File Haidar 470,0	95.3	1.28	0.41	0.02	0.04	0.05	0.7	<0.01	0.21	<0.01	0.07	0.01	0.29	98.4
Böda Hamn 126,05-126,30	95.6	0.88	0.71	0.04	0.03	0.04	0.35	<0.01	0.15	<0.01	0.02	0.01	0.56	98.4
Böda Hamn 124,7-125,0	96	1	0.71	0.02	0.03	0.04	0.38	<0.01	0.12	<0.01	0.03	0.01	0.52	98.9

Appendix III-Chemical data (Trace elements)

	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Ce	Co	Cr	Cs	Cu
	ppm	%	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm	ppm
Segerstad 146,15-146,22	0.02	0.27	10.3	10	0.09	0.09	0.58	<0.02	29.5	3.3	12	0.11	2.2
Segerstad 153,33-153,43	<0.01	0.33	1.2	50	0.09	0.02	0.09	0.06	11.2	0.5	5	0.15	1.3
Segerstad 169,27-169,37	<0.01	0.38	0.9	50	0.14	0.02	0.54	0.02	21.3	0.8	9	0.21	1.2
Segerstad 182,4	<0.01	1.61	2	130	1.58	0.02	2.57	0.03	36.1	2.2	15	2.26	1.3
Segerstad 236,62-236,80	<0.01	0.39	0.9	40	0.25	0.01	0.06	<0.02	25.2	1.1	8	0.24	1.5
Segerstad 237,01-18	<0.01	0.62	0.4	90	0.31	0.01	0.1	<0.02	32.4	1.1	9	0.37	1.7
Segerstad 238,4-241,2	<0.01	1.23	0.4	170	0.55	0.02	0.04	<0.02	52.7	0.9	9	0.89	2
Segerstad 254,08-18	<0.01	0.57	<0.2	120	0.46	0.01	0.15	<0.02	49.6	0.9	9	0.4	2
Segerstad 251,3-251,35	<0.01	1.75	0.2	290	0.85	0.05	0.04	<0.02	32.3	1.6	9	1.62	2
När-1 525,8	<0.01	0.21	0.2	30	0.07	0.01	0.07	<0.02	8.94	0.9	5	0.15	1.4
När-1 542,0-10	0.01	0.26	1.7	10	0.13	0.04	3.38	0.02	26.5	4.7	9	0.18	2.3
När-1 549,0	<0.01	0.54	1.1	70	0.14	0.04	0.18	<0.02	33.5	3.8	14	0.27	3.6
När-1 568,0	<0.01	0.47	0.3	70	0.12	0.02	0.08	0.03	14.75	0.6	7	0.26	1.5
När-1 596,4-596,5	0.05	0.23	1.3	20	0.1	0.04	0.85	<0.02	22.9	4.2	4	0.14	2.6
När-1 600,8	0.01	0.68	0.6	90	0.1	0.04	0.01	<0.02	66.5	2.6	6	0.28	2
När-1 633,6	0.01	0.63	<0.2	80	0.1	0.12	0.03	<0.02	48.7	3.5	5	0.33	3.9
När-1 642,5-642,6	0.02	0.06	<0.2	10	0.08	0.03	5.49	<0.02	32.6	0.5	2	0.06	4
Gotska sandön 197,0	<0.01	0.88	0.6	110	0.23	0.04	0.08	0.03	26	2.1	11	0.64	1.5
Gotska sandön 201,0	<0.01	1.77	0.9	270	0.26	0.02	0.02	0.02	30.7	1	11	0.81	0.6
B-7 857,0-10	0.04	0.21	10.4	30	0.06	0.02	0.25	0.06	11.2	1.5	8	0.07	4.9
B-9 1029-1030	0.02	0.28	1.1	20	0.11	0.05	0.24	0.02	28.2	3.5	12	0.12	7.6
File Haidar 342,71-344,9	0.02	0.19	4.6	30	0.07	0.04	0.02	0.02	17.9	1.9	12	0.11	2.2
File Haidar 470,0	<0.01	0.68	0.5	120	0.18	0.06	0.01	<0.02	22	0.9	6	0.44	1.3
Böda Hamn 126,05-126,30	0.03	0.47	2.3	60	0.16	0.03	0.02	0.26	30.3	6.1	5	0.23	2.2
Böda Hamn 124,7-125,0	0.04	0.52	3.3	60	0.14	0.03	<0.01	0.19	33.6	3.9	5	0.22	2.2

	Fe	Ga	Ge	Hf	In	K	La	Li	Mg	Mn	Mo	Na	Nb
	%	ppm	ppm	ppm	ppm	%	ppm	ppm	%	ppm	ppm	%	ppm
Segerstad 146,15-146,22	2.95	0.84	0.08	1.1	<0.005	0.05	15	3.5	0.01	88	5.02	0.01	1.6
Segerstad 153,33-153,43	0.36	0.63	<0.05	0.8	<0.005	0.07	6	3.3	0.03	33	1.03	<0.01	1.2
Segerstad 169,27-169,37	0.48	0.89	0.05	1.6	<0.005	0.21	9.5	4	0.03	236	0.29	<0.01	2.8
Segerstad 182,4	1.43	4.87	0.11	2.6	0.026	1.08	12.1	14	0.15	1165	1.8	0.09	3
Segerstad 236,62-236,80	0.41	1.2	0.05	1.4	<0.005	0.22	13.5	29.9	0.02	44	0.64	<0.01	1
Segerstad 237,01-18	0.44	1.74	0.05	3.5	<0.005	0.42	16.3	26	0.03	45	0.52	0.01	1.5
Segerstad 238,4-241,2	0.42	3.7	0.07	6.1	0.011	0.96	21.6	18.9	0.04	29	0.63	0.03	3.1
Segerstad 254,08-18	0.47	2.06	0.07	3	0.009	0.41	16.7	40.5	0.02	61	2.21	0.03	2.1
Segerstad 251,3-251,35	0.53	5.96	0.06	5.4	0.023	1.34	11	22.4	0.07	35	0.39	0.07	3.5
När-1 525,8	0.37	0.46	<0.05	0.5	<0.005	0.09	4.4	3.1	0.02	53	0.36	<0.01	0.9
När-1 542,0-10	2.38	1.08	0.07	1.2	0.097	0.06	7.7	7	0.99	2660	0.58	<0.01	1.7
När-1 549,0	0.56	1.2	0.06	9.6	0.013	0.18	18.2	2.9	0.07	225	0.46	<0.01	6.6
När-1 568,0	0.39	0.96	<0.05	2.7	<0.005	0.28	7.5	3.5	0.04	79	0.38	<0.01	3.7
När-1 596,4-596,5	0.43	0.62	0.06	1.7	0.03	0.07	9.7	2.4	0.02	331	1.33	<0.01	1.6
När-1 600,8	0.4	1.45	0.13	1.7	<0.005	0.37	19.4	3.7	0.01	22	0.41	<0.01	2.3
När-1 633,6	0.46	1.25	0.07	3.1	0.005	0.4	21.6	3.8	0.01	29	1.57	<0.01	1.8
När-1 642,5-642,6	0.33	0.38	0.08	0.8	0.036	0.01	15.1	2.9	0.02	718	0.25	<0.01	0.7
Gotska sandön 197,0	0.41	2.05	0.08	6.8	<0.005	0.54	13	4.9	0.04	45	0.39	0.01	6.2
Gotska sandön 201,0	0.58	3.31	0.08	5.2	0.009	1.33	15	6.2	0.05	318	0.61	0.03	6.8
B-7 857,0-10	1.59	0.43	0.05	0.6	<0.005	0.03	5.4	5	0.06	134	2.02	<0.01	1.2
B-9 1029-1030	0.94	0.71	0.06	0.5	0.007	0.04	12.5	3.7	0.09	280	0.57	<0.01	1
File Haidar 342,71-344,9	0.46	0.42	<0.05	1.9	<0.005	0.06	8.4	7	0.01	26	1.34	<0.01	2.4
File Haidar 470,0	0.32	1.37	0.05	3	<0.005	0.53	10.6	4.1	0.02	24	0.36	<0.01	3.6
Böda Hamn 126,05-126,30	0.53	1.04	0.05	3.5	0.013	0.26	11.8	4.9	0.02	32	0.47	<0.01	2.7
Böda Hamn 124,7-125,0	0.52	1.11	0.06	2.5	0.007	0.28	10.1	4.9	0.02	23	1.56	<0.01	2.1

	Ni	P	Pb	Rb	Re	S	Sb	Sc	Se	Sn	Sr	Ta
	ppm	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm	ppm
Segerstad 146,15-146,22	4.2	1120	872	2.7	<0.002	2.98	0.24	0.6	1	0.2	19.3	0.1
Segerstad 153,33-153,43	0.8	40	7	3.9	<0.002	0.02	0.13	0.2	<1	0.2	10.8	0.05
Segerstad 169,27-169,37	1.4	80	3.2	9.2	<0.002	0.01	0.09	0.5	<1	0.2	16.2	0.14
Segerstad 182,4	3.4	620	4.8	57.6	<0.002	0.01	0.13	2.5	1	0.4	35.5	0.2
Segerstad 236,62-236,80	1.2	40	2.1	11.4	<0.002	<0.01	0.08	0.8	<1	0.2	11.2	0.05
Segerstad 237,01-18	1.1	40	4.8	19.6	<0.002	0.01	0.07	1.2	<1	0.3	16.8	0.09
Segerstad 238,4-241,2	1.4	50	12.6	47.4	<0.002	<0.01	0.08	2	1	0.4	25.8	0.2
Segerstad 254,08-18	1.1	40	2.3	21.1	0.002	<0.01	0.07	1.1	1	0.9	11.9	0.12
Segerstad 251,3-251,35	1.9	100	4.9	69.8	<0.002	<0.01	0.09	2.4	1	0.5	29.9	0.24
När-1 525,8	0.8	70	2.8	4	<0.002	<0.01	0.07	0.4	<1	<0.2	7.7	<0.05
När-1 542,0-10	2.3	330	4.2	3.6	<0.002	0.03	0.1	1.4	1	0.3	16.6	0.09
När-1 549,0	1.6	50	10.6	7.4	<0.002	0.06	0.17	1.6	1	1	16.1	0.45
När-1 568,0	1	30	2.4	9.7	<0.002	0.01	0.15	0.8	1	0.3	11	0.24
När-1 596,4-596,5	2.6	40	4.4	3.2	<0.002	0.14	0.12	0.6	1	0.2	18	0.06
När-1 600,8	2.4	60	3.8	13.2	<0.002	0.12	0.14	0.6	1	0.2	17.4	0.16
När-1 633,6	1.2	70	4.6	11.7	<0.002	0.1	0.07	1.2	1	0.2	26.8	0.14
När-1 642,5-642,6	<0.2	30	2.1	0.7	<0.002	0.01	0.06	0.6	2	0.3	25.3	<0.05
Gotska sandön 197,0	2.7	50	3.7	19	<0.002	0.01	0.2	1.5	1	0.5	16.8	0.43
Gotska sandön 201,0	1.9	30	5	41.7	<0.002	<0.01	0.2	2.1	1	0.5	25.9	0.49
B-7 857,0-10	2.9	20	38.5	1.4	<0.002	1.31	0.21	0.6	1	0.2	10.4	0.08
B-9 1029-1030	2.9	60	267	2.1	<0.002	0.33	0.18	0.8	1	0.9	24.5	0.06
File Haidar 342,71-344,9	1.7	70	8.1	2.5	<0.002	0.18	0.17	0.4	1	0.3	11.1	0.16
File Haidar 470,0	1.6	30	5.2	18.9	<0.002	<0.01	0.12	0.9	1	0.3	20.6	0.22
Böda Hamn 126,05-126,30	2.7	40	19.7	10.3	<0.002	0.08	0.13	0.7	2	0.3	16.4	0.2
Böda Hamn 124,7-125,0	2.2	50	7.1	10.8	<0.002	0.1	0.14	0.6	2	0.2	15.6	0.16

	Te	Th	Ti	Tl	U	V	W	Y	Zn	Zr
	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Segerstad 146,15-146,22	<0.05	2.8	0.033	0.1	1.1	11	0.3	7.1	9	32.9
Segerstad 153,33-153,43	<0.05	1.1	0.038	<0.02	0.3	2	0.4	2.3	45	23.3
Segerstad 169,27-169,37	<0.05	3	0.107	0.03	0.6	3	0.2	6	9	54.3
Segerstad 182,4	<0.05	6.3	0.096	0.19	0.7	20	0.5	25.3	9	80.9
Segerstad 236,62-236,80	<0.05	1.6	0.03	0.05	0.8	3	0.2	7.4	<2	42
Segerstad 237,01-18	<0.05	1.8	0.055	0.1	1.6	5	0.3	14.2	2	102
Segerstad 238,4-241,2	<0.05	3.7	0.104	0.2	2.6	10	0.4	35.9	13	181
Segerstad 254,08-18	<0.05	4.4	0.074	0.11	1.3	5	0.7	23.8	2	81.7
Segerstad 251,3-251,35	<0.05	3.2	0.113	0.29	1.6	14	0.4	14.7	4	156.5
När-1 525,8	<0.05	1.4	0.031	<0.02	0.2	6	0.2	1.5	<2	15.1
När-1 542,0-10	0.23	2.7	0.057	<0.02	0.4	66	0.3	15.8	7	36.3
När-1 549,0	<0.05	4.8	0.293	0.04	2.1	8	0.6	11.5	8	343
När-1 568,0	<0.05	2	0.145	0.04	0.7	5	0.4	6.1	2	90.1
När-1 596,4-596,5	<0.05	1.2	0.056	0.04	0.5	3	0.4	8	<2	59.1
När-1 600,8	<0.05	1.6	0.076	0.09	0.9	4	0.3	7.4	3	53.5
När-1 633,6	<0.05	3.5	0.063	0.05	2.2	5	0.8	10	2	95.6
När-1 642,5-642,6	<0.05	1.7	0.024	<0.02	0.6	1	0.2	24.4	2	24.5
Gotska sandön 197,0	<0.05	4	0.268	0.09	1.4	10	0.6	9.6	3	231
Gotska sandön 201,0	<0.05	5.1	0.256	0.2	1.6	10	0.6	10	13	176
B-7 857,0-10	<0.05	0.8	0.04	0.03	0.2	1	0.2	2.9	4	21.4
B-9 1029-1030	<0.05	1	0.036	0.02	0.2	3	0.2	3.3	5	17.8
File Haidar 342,71-344,9	<0.05	2.8	0.09	0.08	0.8	4	0.3	3.7	8	63.1
File Haidar 470,0	<0.05	2.7	0.116	0.09	0.8	3	0.3	7.9	2	93.7
Böda Hamn 126,05-126,30	<0.05	2.1	0.085	0.1	3	4	0.2	10.5	63	112.5
Böda Hamn 124,7-125,0	<0.05	1.9	0.07	0.13	1.2	3	0.4	7.5	40	82.8

Appendix IV-Petrophysical data

Well_ID	Depth m KB	Porosity (%)	Gas perm (mD)	Density. (g/cm^3)	Stratigraphy	Data origin
När-1	525.8	15	182 (h)*	2.646	Mossberga/Grötlingbo	SGU/2006
När-1	532.45				Grötlingbo siltstone	SGU/2012
När-1	542.05	14.8		2.694	Grötlingbo siltstone	SGU/2006
När-1	549	22.6		2.655	När	SGU/2006
När-1	555				När	SGU/2012
När-1	559.55	24	136 (h)	2.648	När	SGU/2006/2012
När-1	570				När	SGU/2012
När-1	577	16.4		2.647	När	SGU/2006/2012
När-1	582	16.9		2.658	När	SGU/2006
När-1	586.3	16		2.675	Viklau	SGU/2006
När-1	600.8				Viklau	SGU/2012
När-1	604.1				Viklau	SGU/2012
När-1	606				Viklau	SGU/2012
När-1	610.1				Viklau	SGU/2012
När-1	612.3				Viklau	SGU/2012
När-1	616.05				Viklau	SGU/2012
När-1	633.6	12.4	308 (h)	2.643	Viklau	SGU/2006
När-1	636.1				Viklau	SGU/2012
När-1	640.3				Viklau	SGU/2012
När-1	642.55				Viklau	SGU/2012
File haidar	342.8	10.2			Mossberga/Faludden	SGU/2006/2012
File haidar	343.81	10.2		2.645	Mossberga/Faludden	SGU/2006
File haidar	389.32	16.7		2.66	Base Grötlingbo	SGU/2006
File haidar	478.5				När Shale	SGU/2012
File haidar	485.85	16	251 (h)	2.645	Viklau	SGU/2006
File haidar	486.85				Viklau	SGU/2012
File haidar	487.1	17.1		2.647	Viklau	SGU/2006
File haidar	496	23.7		2.645	Viklau	SGU/2006
File haidar	498	23.6		2.468	Viklau	SGU/2006
File haidar	498.2	19.7		2.654	Viklau	SGU/2006
B-7	857.05				Faludden	SGU/2012

Well_ID	Depth m KB	Poro-sity (%)	Gas perm (mD)	Density. (g/cm^3)	Stratigraphy	Data origin
B-7	858.2				Faludden	SGU/2012
B-7	862	14.2	77.6 (h)	2.651	Faludden	SGU/2006/2012
B-9	1029.5	14.2	169 (v)	2.653	Faludden	SGU/2006
Segerstad	146.86			2.648	När	SGU/2/2012
När-1	633.6	12.4	308 (h)	2.643	Viklau	SGU/2006
När-1	636.1				Viklau	SGU/2012
När-1	640.3				Viklau	SGU/2012
När-1	642.55				Viklau	SGU/2012
File haidar	342.8	10.2			Mossberga/Faludden	SGU/2006/2012
File haidar	343.81	10.2		2.645	Mossberga/Faludden	SGU/2006
File haidar	389.32	16.7		2.66	Base Grötlingbo	SGU/2006
File haidar	478.5				När Shale	SGU/2012
File haidar	485.85	16	251 (h)	2.645	Viklau	SGU/2006
File haidar	486.85				Viklau	SGU/2012
File haidar	487.1	17.1		2.647	Viklau	SGU/2006
File haidar	496	23.7		2.645	Viklau	SGU/2006
File haidar	498	23.6		2.468	Viklau	SGU/2006
File haidar	498.2	19.7		2.654	Viklau	SGU/2006
B-7	857.05				Faludden	SGU/2012
B-7	858.2				Faludden	SGU/2012
B-7	862	14.2	77.6 (h)	2.651	Faludden	SGU/2006/2012
Segerstad	146.86			2.648	När	SGU/2/2012
Segerstad	146.8	22.9	1667 (h)	2.691	När	SGU/2006
Segerstad	153.38				När	SGU/2012
Segerstad	157.8				När	SGU/2012
Segerstad	182.4				När	SGU/2012
Segerstad	191.99				När	SGU/2012
Segerstad	202.94				När	SGU/2012
Segerstad	208.53				När	SGU/2012

Well_ID	Depth m KB	Poro-sity (%)	Gas perm (mD)	Density. (g/cm^3)	Stratigraphy	Data origin
Segerstad	210.55				När	SGU/2012
Segerstad	236.71	8.7			Viklau	SGU/2006/2012
Segerstad	237.1	8.7		2.647	Viklau	SGU/2006
Segerstad	243.85				Viklau	SGU/2012
Segerstad	251.33	3.1		2.651	Viklau	SGU/2006
Böda hamn	84.1				Faludden/Grötlingbo	SGU/2012
Böda hamn	91.5	11.6	203 (h)	2.648	När	SGU/2006
Böda hamn	106.53	12.2		2.647	När	SGU/2006
Böda hamn	131.7	15.5		2.659	Viklau	SGU/2006
Böda hamn	152	13.9		2.654	Viklau	SGU/2006
Böda hamn	155.7	9.7		2.653	Viklau	SGU/2006
Böda hamn	158.6	14.2		2.656	Viklau	SGU/2006
Böda hamn	160.3	13.5		2.654	Viklau	SGU/2006
Gotska Sandön	180.8				Cambrian unspec sst	SGU/2012
Gotska Sandön	183				Cambrian unspec sst	SGU/2012
Gotska Sandön	185	14.2		2.647	Cambrian unspec sst	SGU/2006
Gotska Sandön	188.8	14.2		2.649	Cambrian unspec sst	SGU/2006/2012
Gotska Sandön	219.2				Cambrian unspec sst	SGU/2012
Gotska Sandön	228.5	12.3		2.666	Cambrian unspec sst	SGU/2006
Gotska Sandön	238	6.5		2.689	Cambrian unspec sst	SGU/2006
Visby-1	321.9	24.5	354 (v)	2.648	Cambrian unspec sst	SGU/2006
Visby-1	375.9	20.8		2.645	Cambrian unspec sst	SGU/2006
Visby-1	394.9	18.4	140 (v)	2.642	Cambrian unspec sst	SGU/2006
Faludden-1	566.3	18.7	1380		Faludden	OPAB/1976
Faludden 1	567.8	19	1130		Faludden	OPAB 1976
Hemse 1	452.5	8.2	0.15		Faludden	OPAB 1976
Hemse 1	453	10.5	1.18		Faludden	OPAB 1976
Skåls 1	456	18.7	493 (h)		Faludden	OPAB 1976
Skåls 1	456		373 (v)		Faludden	OPAB 1976
Skåls 1	457	17.9	752 (h)		Faludden	OPAB 1976
Skåls 1	457		611 (v)		Faludden	OPAB 1976
Källstäde 1	328.55	12.3	57 (v)	2.66	Faludden	OPAB 1983
Audungs 1	296.1	19.8	1750 (v)	2.65	Faludden	OPAB 1983
Audungs 1	303.4	18.5	205 (v)	2.65	Faludden	OPAB 1983
Furilden 1	348.1	11.5	39 (v)	2.68	Faludden	OPAB 1983
Furilden-1	389.8	10.7	44 (v)	2.69	När	OPAB 1983
Hangre-1	386.67	16.1	335	2.67	Faludden	OPAB 1986
Hangre-1	387.97	17	703	2.66	Faludden	OPAB 1986

Appendix V-Petrophysical data for the 19 new samples

Plug id.	Well	Depth	Plug	Gas perm	Porosity	Grain dens	Comment
		m	orienta-tion	mD	%	g/cm^3	
1	Frigsarve-1	499.00	Horiz.	218.81	17.14	2.657	
2	Frigsarve-1	500.00	Horiz.	218.54	14.50	2.664	
3	Frigsarve-1	501.00	Horiz.	406.49	16.60	2.657	
3V	Frigsarve-1	501.00	Vertical	661.39	18.76	2.659	
4	Frigsarve-1	506.00	Horiz.	300.15	17.43	2.646	
5	Frigsarve-1	507.71	Horiz.	147.34	14.04	2.654	
6	Frigsarve-1	508.38	Horiz.	757.63	15.07	2.647	
7	Frigsarve-1	509.45	Horiz.	0.47	8.36	2.656	
8V	Frigsarve-1	510.40	Vertical	169.35	14.12	2.648	
9	Frigsarve-1	511.35	Horiz.	80.82	11.17	2.644	
10	Kvarne-1	512.12	Horiz.	384.12	15.44	2.652	
11V	Kvarne-1	513.85	Vertical	2.71	6.64	2.643	
12	Kvarne-1	514.50	Horiz.	332.38	15.80	2.645	
13	Kvarne-1	515.90	Horiz.	363.02	16.79	2.648	
14V	Kvarne-1	517.20	Vertical	283.93	17.06	2.648	
15	Kvarne-1	518.15	Horiz.	528.85	16.85	2.650	
16	Hamra-1	572.28	Horiz.	3.80	9.25	2.729	
17V	Hamra-1	572.95	Vertical	152.62	14.46	2.655	
18	Hamra-1	574.17	Horiz.	114.97	14.48	2.696	
19V	Hamra-1	576.36	Vertical	282.56	18.19	2.645	
20	Hamra-1	577.35	Horiz.	439.46	17.55	2.644	
21	Hamra-1	579.23	Horiz.	192.44	14.66	2.652	
22(1)	Hamra-1	580.92	Horiz.	25.16	12.85	2.637	
22(2)	Hamra-1	580.92	Horiz.	#N/A	13.21	2.661	Fractured - no perm
23	Hamra-1	582.03	Horiz.	219.59	13.61	2.641	
24V	Hamra-1	584.59	Vertical	92.15	14.28	2.647	
25	Hamra-1	586.96	Horiz.	207.98	14.80	2.645	

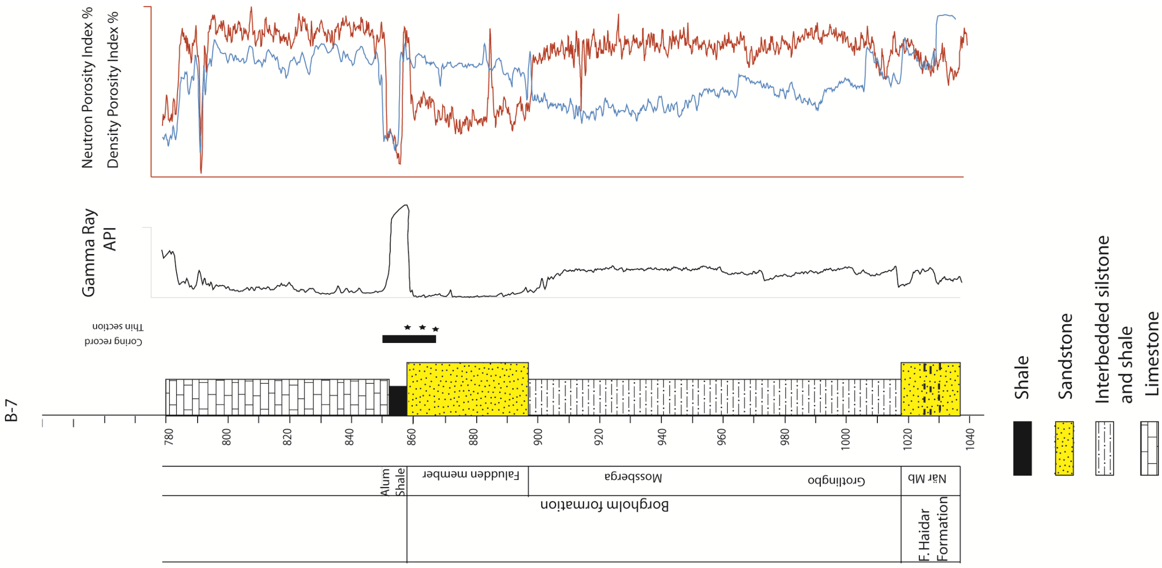
Appendix VI-Results of modal analyses

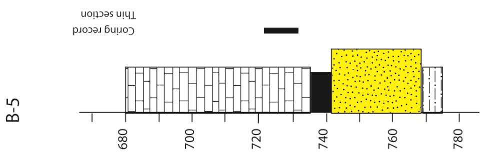
Sample	Detrital quartz %	Cement	Detrital Feldspar %	Other minerals	Porosity %	For-mation
B7 857	76.4	6	1.2	0	16.4	Faludden
B-7 858	76.6	6.2	1.2	0	16.0	Faludden
B-7 862	76.4	5.2	2	0	16.4	Faludden
B-9 1029	75.2	4.0	2.0	0	18.8	Faludden
När 469	75.6	4.8	1.8	0	17.8	Faludden
När 525	77.6	12.8	0.8	0	8.4	När
När 542	73.6	23.6	0	2	2.6	När
När 549	77.4	15.6	0.4	2	4.6	När
När 568	77	20	0.8	0	2.2	När
När 559.5	74.0	18.0	0.6	2.0	7.2	När
När 596	70.4	20.4	2	0	7.2	Viklau
När 582	70.2	23.2	0.2	0	6.4	Viklau
När 642	77.0	20.0	0.8	0	2.2	Viklau
När 600	76.2	18.4	0.6	0	4.8	Viklau
File Haidar 342	77.0	5.0	1.8	0	16.2	Faludden
File Haidar 343	77.0	4.8	2.0	0	16.2	Faludden
File 487	69.0	22.0	2.0	0	7.0	Viklau
File Haidar 496	70.0	20.6	2.0	1.2	6.2	Viklau
File Haidar 498	69.2	21.4	1.6	0.0	7.8	Viklau
Segerstad Fyr 146	67.6	15.0	3.0	7.0	7.4	När
Segerstad Fyr 236	67.0	23.2	2.0	2.0	5.8	Viklau
Segerstad Fyr 237	68.0	18.6	2.0	0.8	10.6	Viklau
Segerstad Fyr 238	70.0	20.0	0.4	1.2	8.4	Viklau
Segerstad Fyr 251	67.6	20.0	2.0	2.0	8.2	Viklau
Segerstad Fyr 259	70.0	23.2	0.4	0.2	6.2	Viklau
Gotska Sandön 185	70.0	6.0	0.0	4.0	20.0	När
Gotska Sandön 188	70.0	4.0	0.0	3.2	22.8	När
Gotska Sandön 197	70.0	5.0	5.0	0.0	20.0	När
Gotska Sandön201	67.6	4.8	6.0	1.2	20.4	När
Gotska Sandön 228.5	68.2	23.4	1.5	1.6	6.8	Viklau
Böda Hamn 91.5	67.6	12.8	4.0	2.0	13.6	När
Böda Hamn 106.96	70.0	10.0	5.0	4.0	11.0	När
Böda Hamn 152	65.0	20.2	3.0	4.8	7.0	Viklau
Böda Hamn 155.7	64.8	19.6	3.0	5.8	6.8	Viklau
Böda Hamn 158	70.0	18.0	2.6	3.2	6.2	Viklau

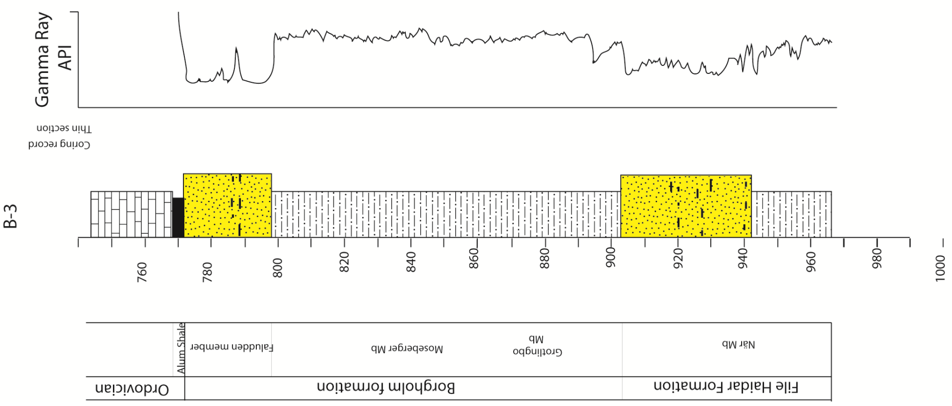
Precision of analytical data

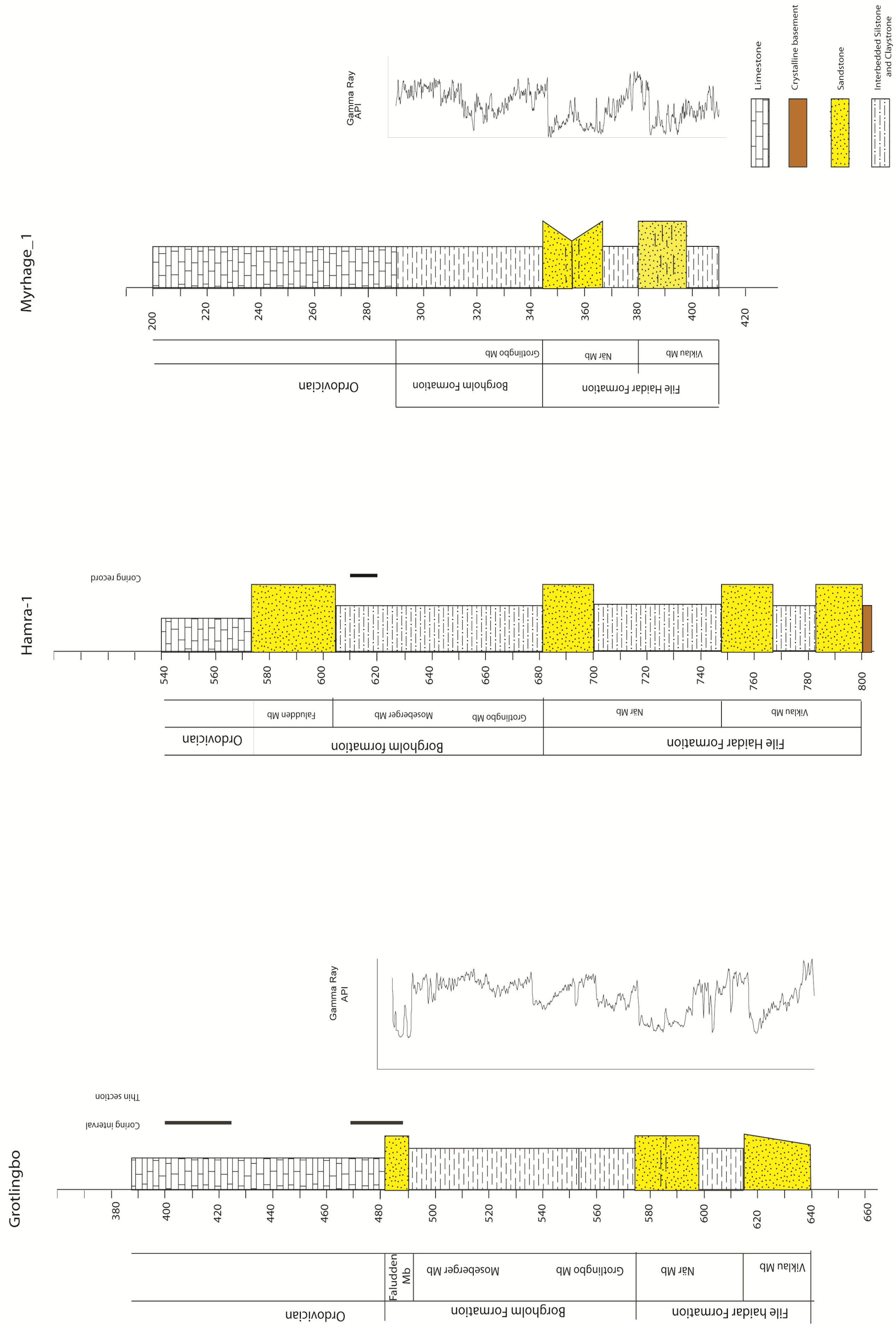
Measurement	Range, mD	Precision
Grain density		0.003 g/cc
He-Porosity		0.1 porosity-%
Gas Permeability: (Klinkenberg)	0.01-0.1 0.1-1 > 1	15% 10% 4%
Gas Permeability: (Conventional)	0.001-0.01 0.01-0.1 > 0.1	25% 15% 4%

Appendix VII-Well Log data including geophysical response signals









Myrhage_1
Hamra-1
Grotlingbo
Gamma Ray API
Coring record
Coring interval
Thin section
Ordovician
Borgholm Formation
File Haidar Formation
File haidar Formation
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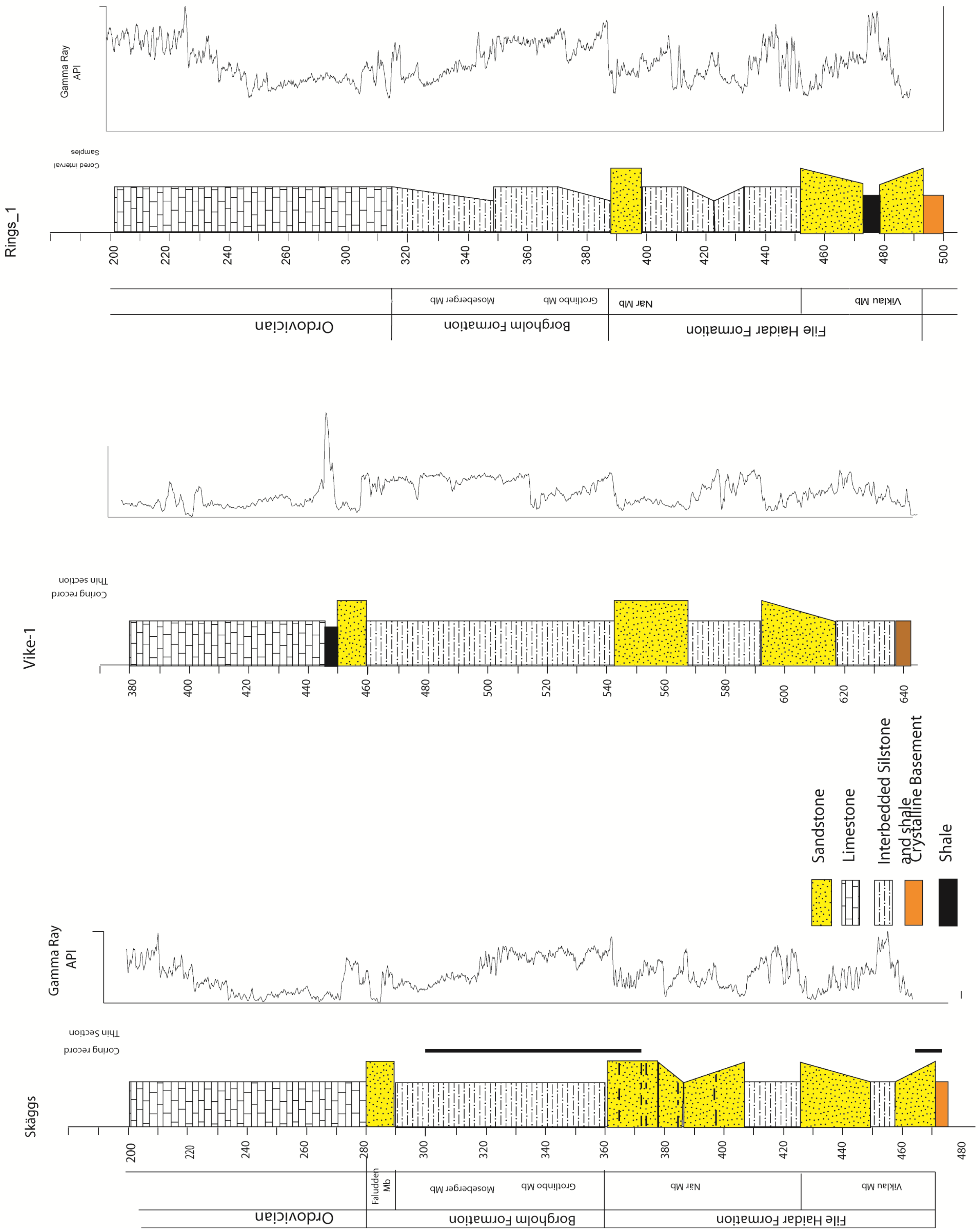
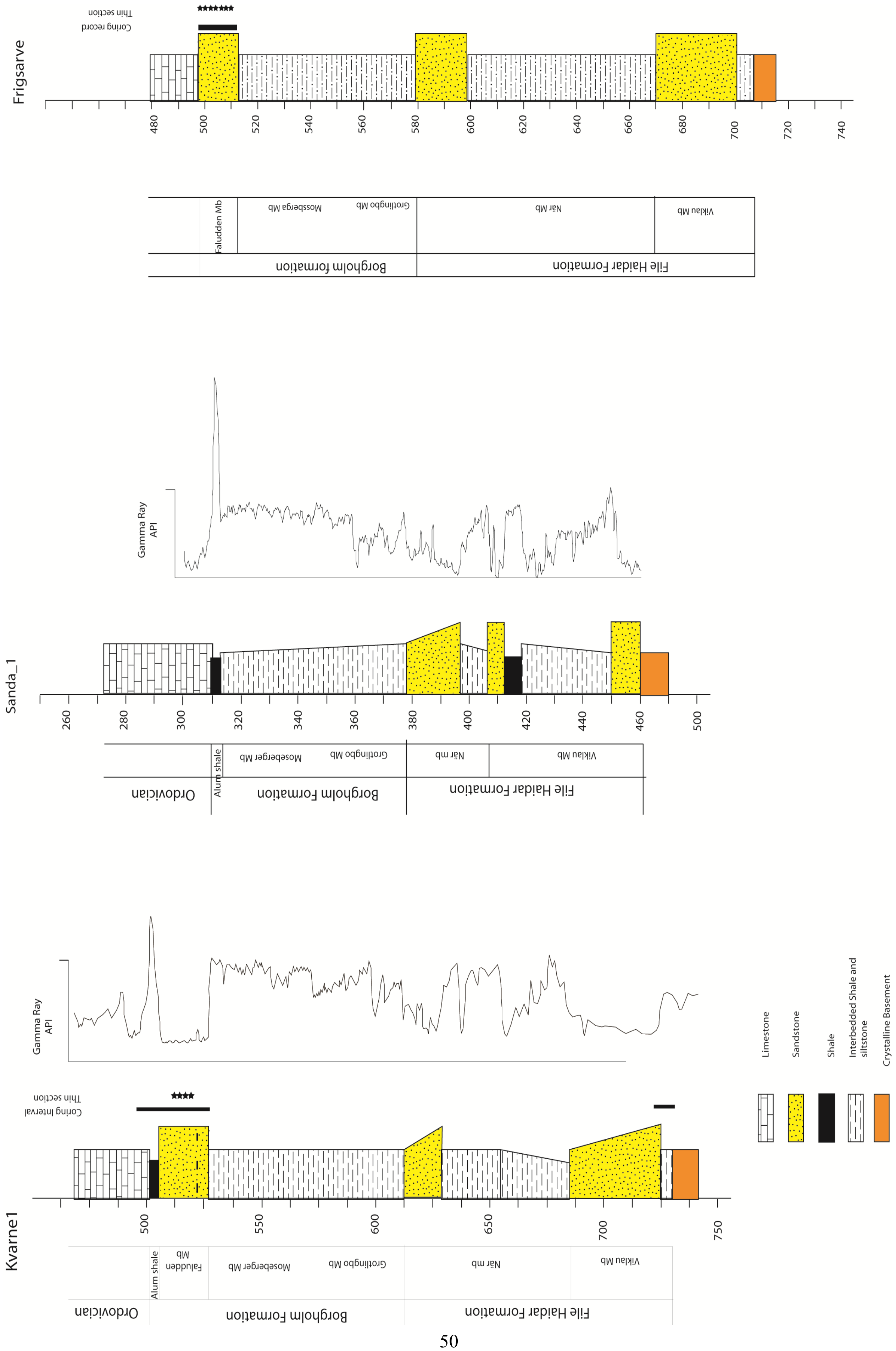
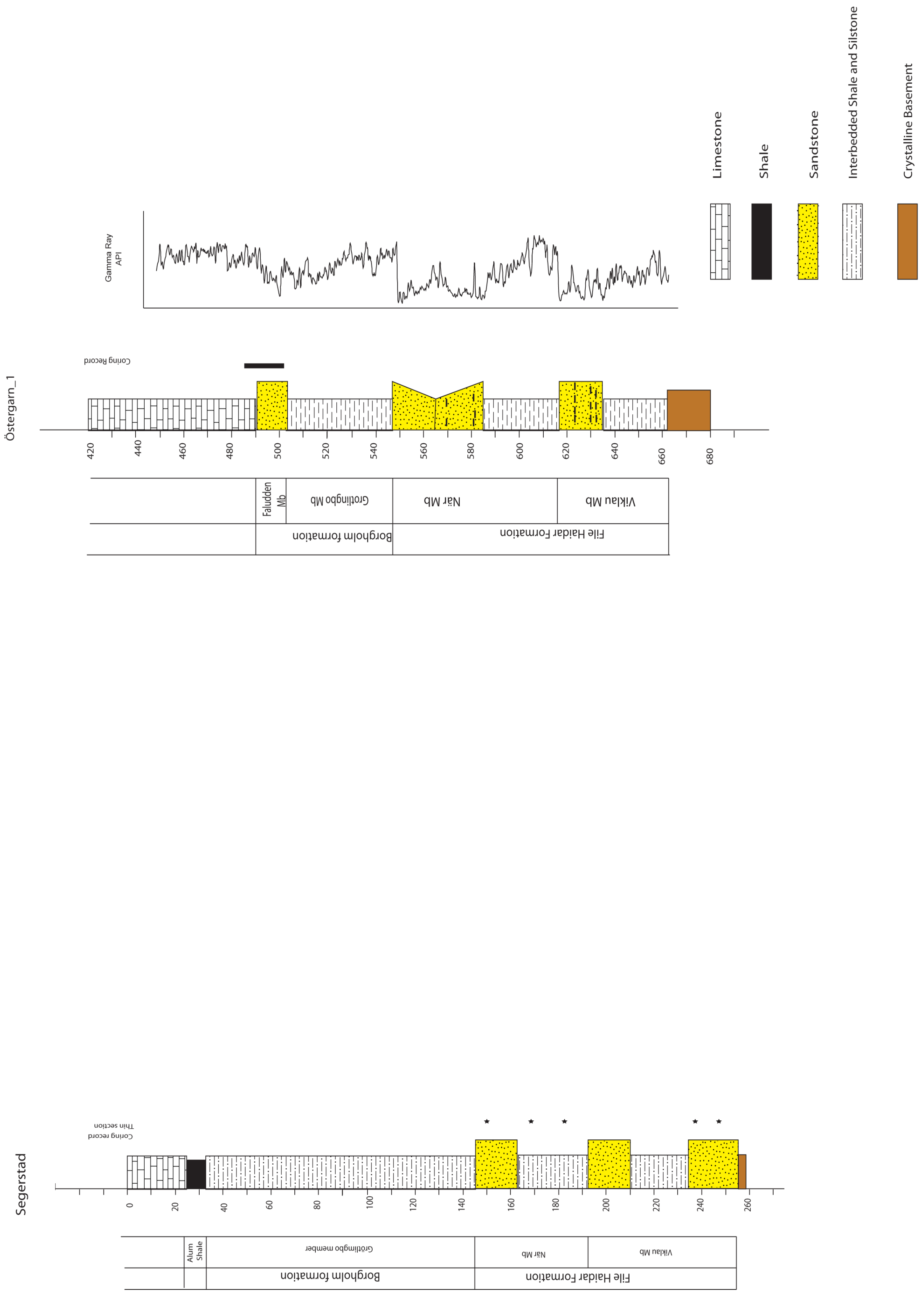
Moseberger Mb
Grotlingbo Mb
När Mb
Viklau Mb
Limestone
Crystalline basement
Sandstone
Interbedded Silstone and Claystone


Skäggs
Vike-1
Rings_1
Gamma Ray
API
Coring record
Thin Section
Cored interval
Samples
Ordovician
Borgholm Formation
Fjile Haidar Formation
Faludden Mb
Moseberger Mb
Grotlingbo Mb
När Mb
Viklau Mb
Sandstone
Limestone
Interbedded Silstone and shale
Crystalline Basement
Shale


Kvarne1
Sanda_1
Frigsarve
Gamma Ray
API
Coring Interval
Coring record
Thin section
Ordovician
Borgholm Formation
Borgholm formation
File Haidar Formation
Alum shale
Faludden Mb
Mosebergar Mb
Grotlingbo Mb
När mb
När Mb
Viklau Mb
Limestone
Sandstone
Shale
Interbedded Shale and siltstone
Crystalline Basement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Gamma Ray
API
Coring Record
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Faludden Mb
Grotlingbo Mb
När Mb
Viklau Mb
Borgholm formation
File Haidar Formation
Limestone
Shale
Sandstone
Interbedded Shale and Silstone
Crystalline Basement
Segerstad
Coring record
Thin section
0 20 40 60 80 100 120 140 160 180 200 220 240 260
Alum Shale
Grötlingbo member
När Mb
Viklau Mb
Borgholm formation
File Haidar Formation

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