Geophysical characterization and petrographic analysis of cap and reservoir rocks within the Lund Sandstone in Kyrkheddinge

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Cover Picture: Thin section image of a reservoir unit within the Lund Sandstone. Photography: Mikael Jakobsson.

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MIKAEL JAKOBSSON

Abstract: Geophysical investigations in the Kyrkheddinge area including seismic surveys and wire-line logging were carried out by Swedegas AB between 1978-1985. This study has used the data to make a geophysical and petrographic characterization of cap-rock and reservoir sections within the Lund Sandstone in Kyrkheddinge to evaluate the conditions for storing gas in the bedrock. The Lund Sandstone comprises deposits of Campanian and Santonian age. Four lithologies have been identified; quartzose sandstone, calcareous sandstone, arenaceous limestone, and argillaceous limestone. Log correlation between four wells shows a dome-shaped trap structure beneath the surface at approximately 600 m depth and a lateral continuity of several cap-rock and reservoir units. Petrophysical properties show heterogeneous reservoir sandstone units with excellent porosity and permeability values as well as impermeable heterogeneous cap-rock units with varying clay content. The Lund Sandstone displays in general suitable properties for storing gas. However, seismic data revealed the existence of a possible fault that may have affected the closed structure of the B reservoir, which led to abandoning the project beside strategic decision on optimal placing and storage type. Further studies on how the fault affects the storage possibilities is recommended. Moreover, investigations have identified potential sand intervals with overlying cap-rocks at greater depths than the sand B reservoir which could be studied in more detail. There is a great potential to use the vast amount of data and knowledge from the site investigations at Kyrkheddinge for cap-rock and reservoir modeling, and research regarding storage of natural gas and CO_2.

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Geofysisk karaktärisering och petrografisk analys av tak– och reservoarbergarter inom campansekvensen i Kyrkheddinge

MIKAEL JAKOBSSON

Sammanfattning: Geofysiska undersökningar i Kyrkheddingeområdet inkluderande seismiska undersökningar och borrhålsloggning har genomförts av Swedegas AB mellan 1978-1985. Denna studie har använt dessa data för att göra en geofysisk och petrografisk karaktärisering av tak- och reservoarsektioner inom campansekvensen (Lundasandstenen) i Kyrkheddinge för att utvärdera förutsättningarna för lagring av gas i den sedimentära berggrunden. Lundasandstenen består av avlagringar från campan och santon ålder. Fyra litologier har identifierats; kvartssandsten, karbonatcementerad sandsten, sandig kalksten och lerig kalksten. Loggkorrelation mellan fyra brunnar visar en antiklinal struktur under ytan på ca 600 m djup och en lateral kontinuitet för flera tak- och reservo-arenheter. Petrofysiska egenskaper visar heterogena sandstensenheter med utmärkta porositets- och permeabilitets-värden, samt ogenomträngliga heterogena takbergarter med varierande lerhalt. Lundasandstenen visar generellt lämpliga egenskaper för lagring av gas. Dock avslöjade seismiska undersökningar att en förkastning i området kan ha påverkat den slutna strukturen för B-reservoaren, som tillsammans med strategiska beslut om optimal placering och typ av förvaring ledde till att projektet avslutades. Ytterligare undersökningar om hur förkastningen påverkar förvaringsmöjligheterna rekommenderas. Dessutom har undersökningar identifierat potentiella sandintervall med överliggande takbergarter på större djup än sand B-reservoaren, vilka kan studeras närmare. Det finns goda möjligheter att använda den stora mängd data och kunskap från platsundersökningarna i Kyrkheddinge för tak- och reservoarbergartsmodellering, samt forskning om lagring av naturgas och CO_2.

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1 Introduction and background

Rocks can be utilized for a wide range of purposes such as; construction of roads and buildings, food additives and jewelry. Another useful application is storage of natural gas in the bedrock which can be necessary if the production throughout the year is uneven, for instance due to severe weather conditions, contingencies or volume differences. During low production periods natural gas from the reservoir can be extracted, and thus compensate for the existing loss and thereby satisfy the needs.

Storage of natural gas in deep saline aquifers is a widely used technique. In the late 1970's Swedegas AB launched an investigation project in Scania, Sweden with the aim to find a suitable storage site. Their studies included geological field studies as well as seismic investigations. The Kyrkheddinge site fulfilled many of the prerequisites and was chosen for more detailed investigations, including drilling and investigations in seven deep boreholes (Hagconsult AB 1983).

The vast amount of data collected during the preinvestigation phases renders a good possibility to perform more detailed research studies than was conducted during the Swedegas period. Despite the existence of a wide range of geological information about the Kyrkheddinge area, there has been little research published regarding the site and its subsurface geology. Only a few comprehensive studies have been presented regarding the complex geology underneath the surface of southwestern Scania (e.g. Sivhed et al. 1999; Vajda & Wigforss-Lange 2009). Most of the existing material is still unpublished, and only exist in analogue format as reports, maps, documents, charts and so forth. The Swedegas storage project resulted in extensive geophysical data and a large number of unpublished reports cf. SGAB (1983); Hagconsult AB (1985); Erlström (1990).

Thus, the purpose of this study is to review and evaluate some of the geophysical data that has been collected to see if the conditions for establishing an underground storage for gas in the Kyrkheddinge area are fulfilled with respect to cap and reservoir rock properties, bedrock structure and stratigraphy.

1.1 Present investigation

The target reservoir and cap-rock units in the Kyrkheddinge site belong stratigraphically to the Santonian-Campanian Lund Sandstone. This unit has previously been described by e.g. Brotzen (1942); Norling (1976); and Erlström (1990). However, most of the knowledge comes from extensive documentation by the Swedegas AB Company. The Santonian-Campanian deposits were found to comprise properties interesting for storage of natural gas. Thus, investigations for an underground aquifer in Scania suitable for storing natural gas were conducted by Swedegas AB during 1978-1985 (Erlström 1990).

A number of locations in Scania were first investigated as potential storage sites. Of these, the Kyrkheddinge area was selected as the most promising location, and more detailed geological and geophysical studies were conducted in order to make a subsurface characterization of the geology in the area. Several reports describing the geological features such as bedrock structure, stratigraphy and lithological properties of the underlying bedrock in general, and the Lund Sandstone unit in particular were produced during the investigation project. Most of the findings are based on data retrieved from seismic surveys and wire-line well logging in seven drill holes (Hagconsult AB 1985). Properties such as porosity, permeability, reservoir and cap-rock thickness were examined. Also, the lateral continuity and thickness of the separate layers were investigated (Hagconsult AB 1985; Erlström 1990).

However, the data only exist in analogue format, and little work has been done to digitize and compile the vast information available.

1.2 Important parameters for an aquifer gas storage

In order to establish a natural gas storage site there are three main requirements that has to be fulfilled (Hagconsult AB 1985):

- A suitable reservoir. The reservoir rock(s) must possess the right properties, be large enough, and situated at an appropriate depth of 400 to 1000 m to give acceptable pressures.
- A cap-rock resting on top of the reservoir rock tight enough to contain the gas beneath it.
- The bedrock must have a trap structure, that is a shape that holds the gas in place, for example an anticlinal or dome-shape structure.

The reservoir unit will function as the storage chamber for the gas, and the cap-rock will seal the reservoir, preventing the gas from escaping. The structure of the bedrock in the area must ensure that there is no risk for the gas to leak out through different escape paths. To assess whether the requirements are met several parameters are important to examine (Hagconsult AB 1983; SGAB 1983; Hagconsult AB 1985; Erlström et al 2011; Erlström 2014a):

- The reservoir unit must be porous so there is enough space for the gas to be stored in the rock. Porosity > 15 %.
- The reservoir unit must be permeable so fluids and gas can move quite easily within the rock, which is important when injecting and extracting the gas. Permeability > 100 mD (millidarcy).
- The total reservoir must be thick enough to contain sufficient volumes of gas. It is possible to store the gas in several reservoir sections with intermediate cap-rock units. Thickness of 20-50 m.
- The cap-rock must be impermeable so the gas cannot escape from the reservoir and reach the surface. Permeability < 0.1 mD.

- The cap-rock must be thick enough to ensure a tight seal. There is not an exact value given for storage of natural gas, but the requirement for CO_2 storage is a cap-rock thickness > 100 m, due to the specific properties of CO_2.
- The cap-rock should have high clay content in order to ensure a plastic seal. The gas storage volume will fluctuate during the year and thus exert different pressures on the formation. If the cap-rock is not ductile enough, it might crack due to the periodic stress it is subjected to.
- Indications on a tight seal by finding gas in the sandstone units, i.e. the reservoirs. This is a very good indication that the unit will actually function as a gas storage since there already exists trapped gas within the formation.
- No matrix or multimineral detrital components in the reservoir. The less matrix and multimineral detrital components present in the reservoir rock, the better. A quartz rich composition is to prefer because quartz is resistant and do not easily react with other chemical compounds.
- A lateral continuity of the separate layers must be studied in order to determine the extent in which the gas can be safely stored.
- Homogeneity of the layers. Homogenous layers are to prefer, especially within the reservoir sections. Too heterogeneous reservoirs might cause separate gas pockets to form. In the ideal case the gas will be concentrated evenly in the top of the reservoir, but due to heterogeneity gas could concentrate around unconformities making it hard to find, and thus to extract.
- Faults in the immediate and adjacent area must be investigated to ensure that there are no escape paths through fractures, offset layers, incomplete or too thin cap-rock units around the zones.

1.3   The Lund Sandstone

The Lund Sandstone is part of the Höllviken Formation that exists in southwestern Scania. The succession is mostly dominated by carbonate rocks from Upper Cretaceous to lower Paleogene. However, it includes two major sandstone sequences; the Hansa Member and the Lund Sandstone Member (Sivhed & Erlström 1999; Lindström et al. 2011).

The Lund Sandstone is a complex sedimentary unit that occurs along the northeastern margin of the Danish Basin (Erlström 1990) parallel to the Romeleåsen Horst Fault and Flexure Zone. It formed in the Upper Santonian and Campanian (Norling 1976) due to erosion of the uplifted Romeleåsen Horst. The sediments comprise well to weakly consolidated sandstone beds interbedded by argillaceous and arenaceous limestone. Four main lithofacies; quartz sandstone, calcareous sandstone, arenaceous limestone and argillaceous limestone make up the sedimentary succession of the Lund Sandstone. These bedding sequences are fre-

quently alternating between the different facies types (Norling 1976; Erlström 1990). The structure and lithology varies both vertically and laterally; it is thickest close to the Romeleåsen Horst Fault and Flexure Zone and decreases in thickness southwestwards (Lindström et al. 2011).

2 Geological setting

2.1   Regional geological setting

Santonian-Campanian deposits occur in the Vomb Trough, Kristianstad, Båstad, Hanö Bay and Danish Basin. However, the greatest deposits are located at the Danish Basin's northeastern margin, in the Kyrkheddinge area. The other four localities show only thin and sometimes incomplete sequences (Erlström 1990).

Based on structural outline the Scania region can be divided into three major structural units, from the southwest to the northeast: the Danish Basin, the NW-SE trending Fennoscandian Border Zone, and the Fennoscandian Shield (Fig. 1) (Erlström 1990).

Southwest Scania comprises the northeast marginal part of the Danish Basin. The entire basin measures approximately 150-200 km across and stretches in a NW-SW direction from the North Sea through Zealand and Jutland into the SW of Scania on to the southern Baltic and Poland. The Danish Basin in Scania is bounded to the northeast by the Fennoscandian Border Zone (Norling 1980; Sivhed & Erlström 1999).

Between the Danish Basin in the SW and the Fennoscandian Shield in the NE lies the Fennoscandian Border Zone, trending in a NW-SE direction. It stretches from the Skagerrak through the Kattegatt and Scania on to Bornholm. The Border Zone has been strongly affected by tectonic movements, and in the central parts of Scania by volcanism. The entire area is structurally characterized by horsts, faulted and tilted blocks, depressions and troughs as well as dolerites and some volcanic rocks (Norling 1980; Erlström 1990; Vajda & Wigforss-Lange 2009).

The Romeleåsen Horst Fault and Flexure Zone is part of the southwestern limit of the Fennoscandian Border Zone and is transecting Scania in a NW-SW direction, from Helsingborg to Ystad. It is bordered in the SW by the northeastern margin of the Danish Basin. The zone was developed during Late Createcous Alpine compression and thrusting. The Santonian-Campanian sediments is thickest close to the Romeleåsen Horst in the northeast, and thins out towards the southwest (Norling 1980; Erlström 1990).

Northeast to the Fennoscandian border zone lies the more stable Fennoscandian shield which constitutes the third major structural outline in Scania. It is composed of Precambrian crystalline rocks (Erlström 1990).

2.1.1   Evolution of the Danish Basin
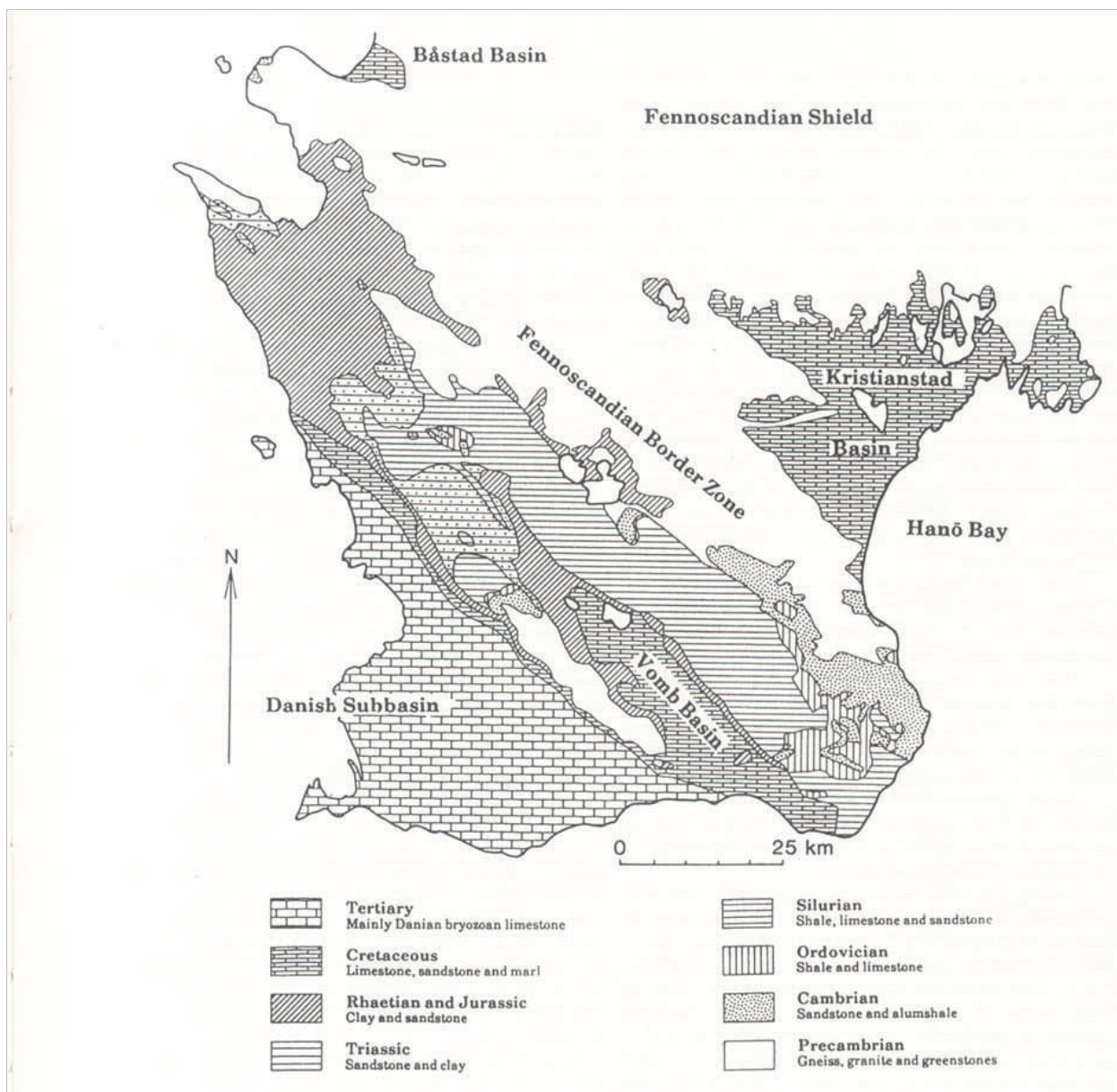
A sedimentary basin is a tectonically lowered area in

Fig. 1. Simplified bedrock map of Scania, including the three major structural patterns from southwest to northeast; the Danish Basin, the Fennoscandian Border Zone, and the Fennoscnadian Shield. After Erlström (1990).

the Earth's crust that has been filled with sediments. It is due to such events the Danish Basin was created (Erlström 2014a).

The evolutionary history of the Danish Basin dates back to the Permian period , some 250-280 Ma ago. It has since the start and throughout the Triassic, Jurassic and Cretaceous periods undergone major transformations as well as affecting adjacent areas to a great extent (Norling 1980; Erlström 1990; Vajda & Wigforss-Lange 2009).

The earliest development of the Danish Basin is related to a tectonic plate collision which took place in southern Europe during the Permian. The tectonic movements made the Danish Basin to subside and lead to extensive fracturing and faulting of the Scanian bedrock, allowing magmas to penetrate through NW-SE striking fractures (Norling 1980; Erlström 1990).

Subsidence and tectonic movements persisted throughout the Triassic and the Jurassic to Lower Cretaceous. Tension and downward shifts of the Scanian crust caused widespread fracturing ,faulting and volcanic activity in Scania, creating a wide range of sedimentary environments (Erlström 1990).

As the depression of the Danish Basin increased thick layers of siliciclastic sediments were deposited. Further subsidence lead to the formation of thick Upper Cretaceous deposits, including the Santonian-Campanian deposits that make up the Lund Sandstone unit. This was coupled to an uplift of the Fennoscandian Border Zone and the Sorgenfrie-Tornquist Zone (Erlström et al. 1997). The total net subsidence of the Late Cretaceous generally exceeded 1000 m and was greatest in the Santonian, Campanian and Maastrichtian stages (Erlström 1990).

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2.2 Geological setting of the Kyrkheddinge site

2.2.1 Location

The Kyrkheddinge area is located in the northeastern margin of the Danish Basin, approximately 5 km southeast of the city Lund in Scania, Sweden (Fig. 2). The area is bordered to the southwest by the Danish Embayment and to the northeast by the Romeleåsen Horst. Beside storage of gas, the Lund Sandstone constitutes such properties that it is also interesting for geothermal extraction. In addition, the geothermal field wells in Lund are plotted in Fig. 2.

2.2.2 Subsurface structure

The upper subsurface structure of the Kyrkheddinge area has a dip towards the SSW. Reaching depths of around 600 m, a dome-like shaped structure (anticline) commence with an increasing areal extent downwards.

This study does not include any further analysis on the upper part of the Lund Sandstone section. This due to the prerequisite that a suitable structure that traps and holds the gas is required. This is found in the lower section of the Lund Sandstone unit, which also comprises alternating reservoir and cap-rock intervals. Thus, for the evaluation of reservoir and cap-rock properties within the Kyrkheddinge structure, only levels below 600 m are considered (Hagconsult AB 1983).

2.2.3 Lithology and stratigraphy

A schematic lithological and stratigraphical succession in the Kyrkheddinge area is illustrated in Fig. 3. The KY-7 well is a type well and is used to illustrate the general strata of the Kyrkheddinge subsurface. The top unit (0-35 m) is composed by Quaternary deposits, followed by bryozoan limestone and chalk deposits with chert from Paleogene, at a depth of around 35-70 m. From 70 to 350 m depth Maastrichtian deposits are identified, comprising four distinguishable lithological units: the first (70-125 m) consist of bryozoan limestone and chalk with chert, the second (125-145 m); coarse-grained, glauconitic, conglomeratic arkose, the third (145-200 m); arenaceous limestone, and the fourth layer (200-350 m) is composed by argillaceous limestone and mudstone. This fourth layer is 150 meters thick and is meant to function as the primary caprock unit.

Upper Cretaceous deposits from Santonian and Campanian age, i.e. the Lund Sandstone, are found at around 350 m depth and deeper. The upper boundary of the Lund Sandstone is in KY-7 set at 350 m depth, and the lower boundary at a depth of 1070 m, where a lithology change towards more glauconitic and marly sediments occur (Erlström 1990).

3 Objective and goals

The objective of this work is to review and compile the geophysical data that has been collected from the Kyrkheddinge site to see if the conditions for establishing a bedrock gas storage outside Kyrkheddinge are fulfilled with respect to cap and reservoir rock properties, bedrock structure and stratigraphy.

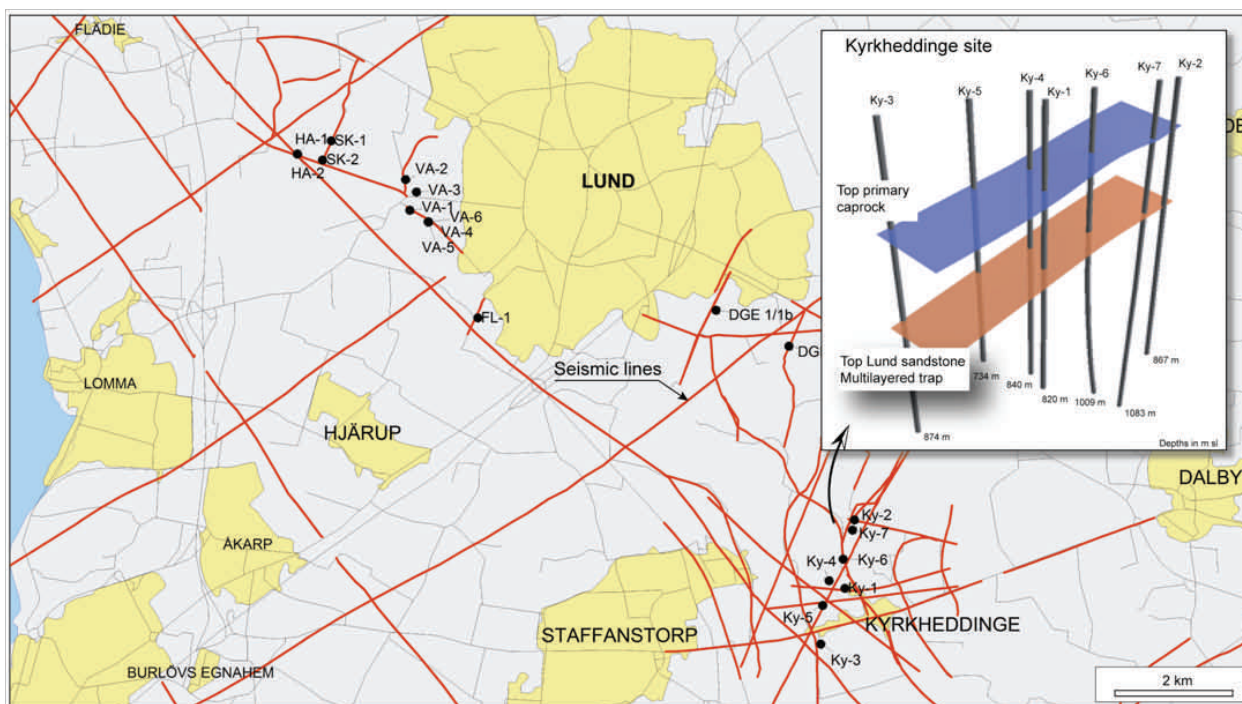The aim is to make an assessment of whether the

Fig. 2. Location of the Kyrkheddinge area in southwestern Scania, situated about 5 km southeast of the city Lund. The seven wells KY-1 – KY-7 are plotted. The wells for the geothermal field west of Lund are also plotted. Red lines indicate seismic profiles. Modified after Erlström et al. (2014).
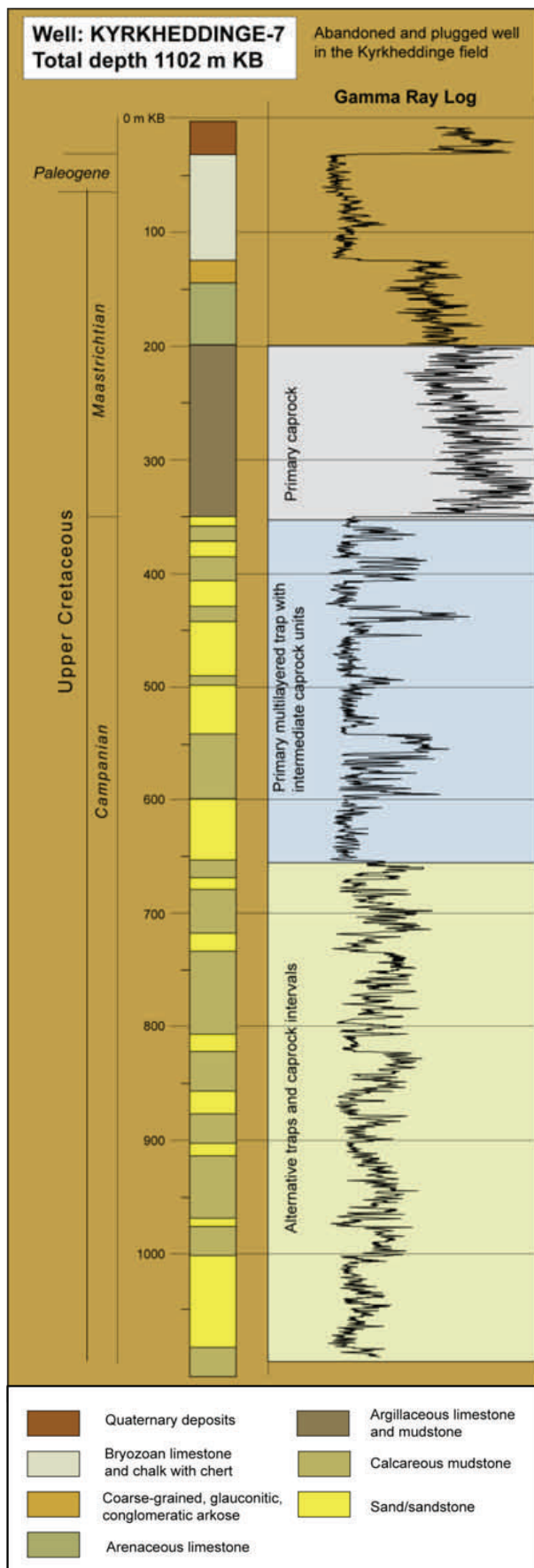
Fig. 3. Type section of the general subsurface geology in the Lund-Kyrkheddinge area exemplified by the KY-7 well. Modified after Erlström et al. (2014).

Lund Sandstone is suitable for storage of natural gas, what factors influence, and if further investigations are necessary to decide if a new gas storage project should open up.

Different rock types exhibit different properties depending on their mineralogy, density, porosity and permeability. By using different geophysical methods these parameters can be measured and identified in order to describe the stratigraphy of a unit, the individual rocks within it and the subsurface structure of the area. Thus, the goals of this work are to:

- Analyze the subsurface structure with seismic surveys of the Kyrkheddinge area and complement these studies by creating a cross-section based on gamma ray logs from the four wells KY-3, -4, -6 and -7.
- Identify cap-rock and reservoir sections in the in the drilled wells (KY1-7) outside Kyrkheddinge, primarily based on gamma ray logs from wire-line logging.
- Make a geophysical characterization of cap-rock and reservoir units based on available geophysical logs.
- Correlate the geophysical signature with petrographic analysis made on thin sections retrieved from drill cores.
- Compare the results with existing porosity and permeability data and evaluate cap-rock and reservoir possibilities.

4 Material and methods

In order to describe and correlate the lithology, stratigraphy and properties of the Lund Sandstone following material and methods have been used:

- Geophysical logs (porosity, gamma ray) from wire-line well logging.
- Seismic profile S4.
- Thin section analysis from drill cores.
- Porosity and permeability data from analyses on cores.
- Cross section between boreholes KY-3,-4,-6 and -7.
- Unpublished reports on the Kyrkheddinge gas storage project.

Reports, maps, charts and wire-line logs have been scrutinized at the Geological Survey of Sweden, where they are stored. The material available on this project is extensive why this study has focused on a detailed investigation of the wire-line data and trying to define the Lund Sandstone from these as well as performing a lateral correlation between different sedimentary units.

A great number of reports have also been studied to complement this study and describe the project as a whole. The porosity and permeability data have been compiled by Erlström et al. (2014) to correlate and add to the wire-line log studies.

4.1 Well data

The range of well data is vast (Table 1) why some have been excluded due to the scope of this study and the limited time horizon in which this study has to be completed. Thus, only the key logs (see description below) have been used. Seven wells (KY-1 to KY-7) reaching depths between 842 and 1102 meters were drilled, but these are all plugged and abandoned today. Even though data from all of the wells have been briefly examined, the main focus has been to investigate the wells KY-3, -4, -6, and -7 in greater detail.

Table 1. Compilation of geophysical well logging performed in the Kyrkheddinge wells. Depths in meters below Kelly Bushing (KB). Marked logs are those used to create the cross section and the evaluation of the porosity and lithology. (Modified after Erlström et al. 2014).

	KY–1	KY–2	KY–3	KY–4	KY–5	KY–6	KY–7
Gamma Ray[1]	0–421	0–546	0–561	2–200	63–595	63–524	66–624
	421–TD[5]	546–TD	561–TD		595–753.9	420–589[3]	594–1102
						447–1028[4]	
Single Point resistivity[1]	0–421	0–546	0–561	200–500			
SONIC[1]	0–421	0–546	0–561	32–200		570–879	594–1092
	421–TD	546–TD	561–TD	200–500			
R$_m$[1]	421–TD	546–TD	561–TD				
ES[1]	421–TD	546–TD	561–TD				
VSP[1]	421–TD	546–TD	561–TD	503–860			
Temperature[1]	421–TD	546–TD	561–TD				
FDC[1]	421–TD	546–TD	561–TD				
Caliper[1]	421–TD	546–TD	561–TD	2–200	63–595	63–524	66–624
				200–500	595–753.9	570–1028	594–1102
Deviation[1]	421–TD	546–TD	561–TD				66–624
							594–1100
SP[1]		546–TD	561–TD	32–200	63–595	63–524	66–624
				200–500	595–753.9	570–1028	594–1102
Induction[1]					63–595		66–624
					595–753.9		594–1100
Resistivity. deep DRL[1]					63–595	570–952	
					595–753.9		
NPHI[1]							594–1092
Gamma-Gamma[1]				200–500			
RHOB. density[1]						570–941	594–1092
DIL-GR. LDL-CNL-NGS. SHDT. MSFL. BHC-GR. RFT[2]			503–860				

[1]Geophysical Microlog AB [2] Schlumberger [3] inside casing [4]447-570 inside casing [5] Total depth

4.2 Wire-line well logging

Wire-line logging, or well logging, is used to obtain information about the sedimentary succession as a complement to the descriptions of cuttings, to define bed boundaries and obtain petrophysical information about the rocks such as acoustic velocity, density and porosity (Erlström 2013).

4.2.1 Types of wire-line logs

There are three types of wire-line logging methods (Erlström 2013):

- Open Hole Logging – logging in an open hole immediately after drilling; e.g. sonic logs, caliper logs, radioactive measurements (gamma ray, density, and neutron logs).
- Cased Hole Logging – logging inside cased holes; e.g. gamma ray, neutron, and temperature.
- Production Logging – logging during production, commonly during production tests; e.g. flow meter, pressure, and temperature.

Depending on the borehole conditions and the purpose of the studies different wire-line logs are assessed. The Kyrkheddinge project has used both open and cased hole logging methods.

4.2.2 Logging measurements

Well logging has the advantage that it gives a continuous record of a section and is a relatively inexpensive method given the information it provides. It is based on direct or indirect geophysical measurements of a rock. Rock properties that affect logging measurements are (Erlström 2013):

- Porosity
- Lithology
- Mineralogy
- Permeability
- Water Saturation
- Resistivity

Since few of these petrophysical parameters can be directly measured different types of well logs use derived or inferred measurements of other physical parameters such as (Erlström 2013):

- Resistivity
- Bulk density
- Interval transit time
- Spontaneous potential
- Natural radioactivity
- Hydrogen content of the rock

By combining the most interesting logs, known as key logs, it is possible to determine the lithology, stratigraphy and properties of a rock unit (Erlström 2013). The following section presents the key well logs used in this study followed by a brief description of each method and how the results can be used and interpreted.

4.2.3 Overview of used key logs

The following logs are distinguished as key logs in this study:

- Lithology logs – gamma ray; differentiate sedimentary rocks by analyzing clay content.
- Porosity logs – sonic porosity, density porosity and neutron porosity.
- Sonic logs – relate wells to seismic investigations.

4.3 Gamma ray (GR) log

A gamma ray log measures the natural radioactivity of a formation. All formations continuously radiate gamma rays due to the higher or lower content of radioactive elements present in the rock, primarily from the degradation of Uranium (U), Potassium (K), and Thorium (Th) (Dewan 1983; Erlström 2014b).

The fact that radioactive elements tend to concentrate in rocks with high content of clay makes the gamma ray very useful for determining the lithology and stratigraphy of sandy-shaly formations; shales have high clay content and thus give high gamma ra-

dioactive response, whereas clean sands and limestones have least clay content and thus record a relatively low response (Dewan 1983; Erlström 2014). It is therefore possible to separate different sedimentary strata and distinguish the lithology in good detail by analyzing the gamma ray log; shales appear as strong deflections to the right, clean formations to the left on the chart (Dewan 1983). This makes it very practical for correlation between layers of wide laterally extent that exhibit unique response signatures. By identifying the same response signature on gamma ray logs retrieved from different boreholes it is possible to make a correlation between wells and construct a cross section that visualizes the subsurface framework of the geology.

Gamma ray logs are also good indicators on the depositional environment, and are often used for facies analysis and for evaluation of changes in the depositional setting. Since the gamma ray response generally is a direct function of the clay content it is an indicator of relative changes in the grain size, and thus the depositional energy, which is a good indicator on the depositional environment (Erlström 2014b). Hence, the gamma ray log can be used to identify trends such as fining upwards sections, i.e. intervals that is coarse-grained in the base layer and gradually becomes finer towards the top layer, typical for deltaic and marine environments. The top fine-grained layer is bounded by another fining upwards section, that is a layer of coarse grains that once more is gradually fining upwards the section. Other trends that usually can be identified are coarsening upwards sections and beach sands (Erlström 2014a).

The gamma ray log response is measured in counts per seconds and converted into the calibrated standard API (American Petroleum Industry) unit. The calibration standard is an artificial formation located in Houston, monitored by the American Petroleum Institute. It contains exactly known amounts of the radioactive elements U, K and Th, and the response it generates is defined as 200 API. The formation, and consequently the calibration standard is designed to have twice the activity of an average shale which is considered to comprise 6 ppm (parts per million) Uranium, 12 ppm Thorium, and 2% Potassium. Hence, shales, which have the highest concentrations of radioactive elements, read around 100 API on the gamma ray logs (Dewan 1983).

The gamma rays log is the key log in this study in order to correlate between wells included in the constructed cross section (see section 5.1 below) and determination of the main lithology of the Lund Sandstone. It can be used in both open and cased hole for correlation purposes, lithology identification, identification of formation tops, and detection of radioactive ore beds (Erlström 2013).

Gamma ray logs are quite effective in distinguishing permeable from impermeable zones since shales, which are impermeable, have much higher concentrations of radioactive elements than carbonates and sands, which are generally permeable. Given this fact, gamma ray logs are widely used in shaly sand formations in order to separate different rock types (Dewan 1983). Table 2. shows the typical gamma ray responses to different rock types.

Table 2. Average API response intervals for different types of rocks. Modified after Dewan (1983).

Type of rock	Average API
Limestone & Anhydrite	15-20
Dolomites & Clean Sands	20-30
Shale	75-150

4.4 Porosity logs

As the name implies, porosity logs are used to estimate the porosity of a rock. There are three types of porosity logs of particular interest; density, neutron and sonic. None of these logs measure porosity directly; the density and neutron logs are based on nuclear measurements while acoustic measurements are applied to the sonic log. The design of these indirect measurement methods makes the tools respond to more than simply the porosity, they also react to the type of rock matrix and to the composition of the fluid filling the pores (Dewan 1983). Because the three porosity logs measure different parameters they respond differently to these compositions, and consequently a combination of these three logs gives the best lithology interpretations and more accurate estimates of the porosity (Dewan 1983; Erlström 2014b).

4.4.1 Sonic log

The sonic log, also known as acoustic or velocity log, measures compressional sonic waves, i.e. the speed of sound in a rock. This gives a good indication on the density of the material in which the acoustic signal travels through. By converting the typical matrix travel time (Table 3) for a compressional wave it is possible to get an appreciation of the formation's porosity. The disadvantage with sonic porosity is that the lithology must be known to compute porosity (Erlström 2014b).

The sonic log records the time it takes for an acoustic signal to travel through the formation and reach two detectors. The space between the two detectors is known allowing calculations of the travel time

Table 3. Common matrix travel times used for different lithologies. Modified after Erlström (2014b).

Lithology	Typical Matrix Travel Time, $\Delta t_{ma,}$ μsec/ft
Dolomite	43.5
Limestone	47.5
Anhydrite	50.0
Sandstone	55.5
Salt	66.7

to be made, which is presented on the log as the interval transit time (Δt) in microseconds per foot (µsec/ft) which is actually an inverse velocity; high interval transit time corresponds to low velocity and vice versa. Transit times vary from 40 µsec/ft in hard formations to 150 µsec/ft in soft ones, and it is this scale that is most commonly presented on the sonic log (Dewan 1983; Erlström 2014b).

Sound travels faster in harder material and slower in porous, due to the presence of air or fluids, and soft material (Dewan 1983). The sonic log readings are thus closely linked to the formation's porosity and lithology; shales have higher transit time (lower velocity) than sandstones if the porosity is the same which consequently gives an indication on the grain size (Erlström 2013). Organic rich sections such as coals and condensed sections also show low velocity readings. Notice that the degree of compaction strongly affects the log response; lack of compaction in shallow sands makes it difficult for the sonic log to detect any traces. Other factors affecting sonic log response are unconsolidated formations, naturally fractured formations, hydrocarbons – especially gas that lowers the speed of the acoustic signal significantly, and rugose salt sections (Erlström 2013).

4.4.2   Density porosity log (RHOB)

The density porosity log measures the bulk (average) density of the formation, including rocks and fluids. Commonly used together with a neutron log in order to differentiate lithologies. The log uses a radioactive source to generate gamma rays. The gamma ray interacts with the electrons in the formation, resulting in an energy loss. The more electrons within the formation, the more likely this will happen. A detector measures the intensity of back-scattered gamma rays, which is related to electron density of the formation. The electron density is a measure of bulk density (Erlström 2014b).

Bulk density is dependent upon lithology, porosity, and density and saturation of fluids within the pores of a rock. Therefore, if gas is present the density log shows too high porosity response than is actually the case. This because the fluid density equation assumes that fluid density lies between 1.0-1.1 g/cc (grams per cubic centimeter). If gas is present, the fluid density will be less than 1.0 and consequently the calculated porosity will be too high (Erlström 2014b).

4.4.3   Neutron porosity log (NPHI)

The neutron porosity log measures amount of hydrogen in a formation, by transmitting neutrons, giving an apparent porosity. Neutrons and hydrogen atoms are similar in size leading them to easily collide. The most energy is lost when colliding with a hydrogen atom nucleus, resulting in a sufficient energy loss by the neutron that becomes captured by the nuclei. The capturing nuclei becomes excited and emit gamma rays (Erlström 2014b).

If hydrogen is present in the pore space, porosity is related to the ratio of neutrons emitted to those counted as captured. The neutron log tool is usually calibrated against a limestone equivalent porosity and fresh water in the pores. It responds to the hydrogen index (HI) of the formation. Hydrogen index is a measurement of the amount of hydrogen per unit volume of a formation. The HI-index for water is 1.

A lower neutron reading (more neutrons captured) indicates abundant hydrogen within a formation (high porosity). Clay rich formations contain hydrogen in the crystal structure of the clay minerals and give divergent values for liquid filled pore volume, i.e. too high porosity response (Erlström 2013; Erlström 2014b).

The effect of gas within a formation makes the neutron log show too low porosity. This due to the fact that the neutron log measures the hydrogen concentration in the rock. The gaseous hydrocarbons take up greater volume of pore space compared to an equal hydrogen content in the form of water (Erlström 2014b).

4.4.4   Combination of density and neutron logs

When density and neutron logs are used together lithologies and gas within the formation can be distinguished.

When both curves are overlain they usually indicate carbonates. If the neutron log records significantly higher porosity than the density log it is usually an effect of higher clay content, or shale, due to high hydrogen concentration within the formation. Gas is indicated by a crossover of the two curves; the density log shows too high porosity, and the neutron log shows too low porosity (Erlström 2013; Erlström 2014b).

4.5   Cross section

The geophysical gamma ray log data that have been used in order to correlate the lateral continuity of the strata by creating a cross section of wells KY-3, -4,-6 and -7 were scanned into pdf format and imported in Adobe Illustrator. The curves were in this software digitized and a cross section of the area was made.

However, it is important to notice that the well log data were collected during a span of several years by different companies using different well logs in different boreholes. Thus, presentation of the data with respect to type of log, details, scale, and log response is not always coherent, which makes it somewhat more difficult to distinguish and correlate the lithology in great detail. Therefore, a comprehensive classification of the different strata in the Lund Sandstone has been made, and where uncertainties occur these have been pointed out with a question mark.

4.6   Seismic surveys

Seismic surveys are carried out to get a general picture of the subsurface structure in order to determine the most suitable location for the drillings. The drilling

data provides more detailed geological information and can be used to better interpret the seismics, and also to depth convert the seismic profile using a sonic or VSP log. This combination is valuable to verify the results by more than one method.

In total there are three sets of seismic data from the area (Erlström et al. 2014). The one presented in this study was performed in 1983 and includes a grid of four lines (S1-S4) covering the Kyrkheddinge structure, the most interesting for this study being the S4 profile (Fig. 4).

The S4 profile crosses the wells of interest in a SSE-NNE direction, that is in the same direction as the cross section (see section 5.1 below) is made. Hence, the S4 profile is as a good complement to the structure outline identified in the cross section. An interpreted cross section and correlation with the wells have been made by Erlström et al. (2014) (see section 5.6 below).

4.7   Thin section analysis

Thin section analysis on drill core samples were carried out at the Geological Survey of Sweden, Lund. Pictures of typical cap-rock and reservoir units were taken. Two of them are presented in this study (see section 5.5 below)

5 Results

5.1   Description of cross section and lateral subsurface distribution

The results on lateral subsurface distribution of cap and reservoir sections, and other units with a distinguishable continuity is based on the evaluated cross section between the wells KY-3, -4, -6, and -7, presented in Fig. 5.
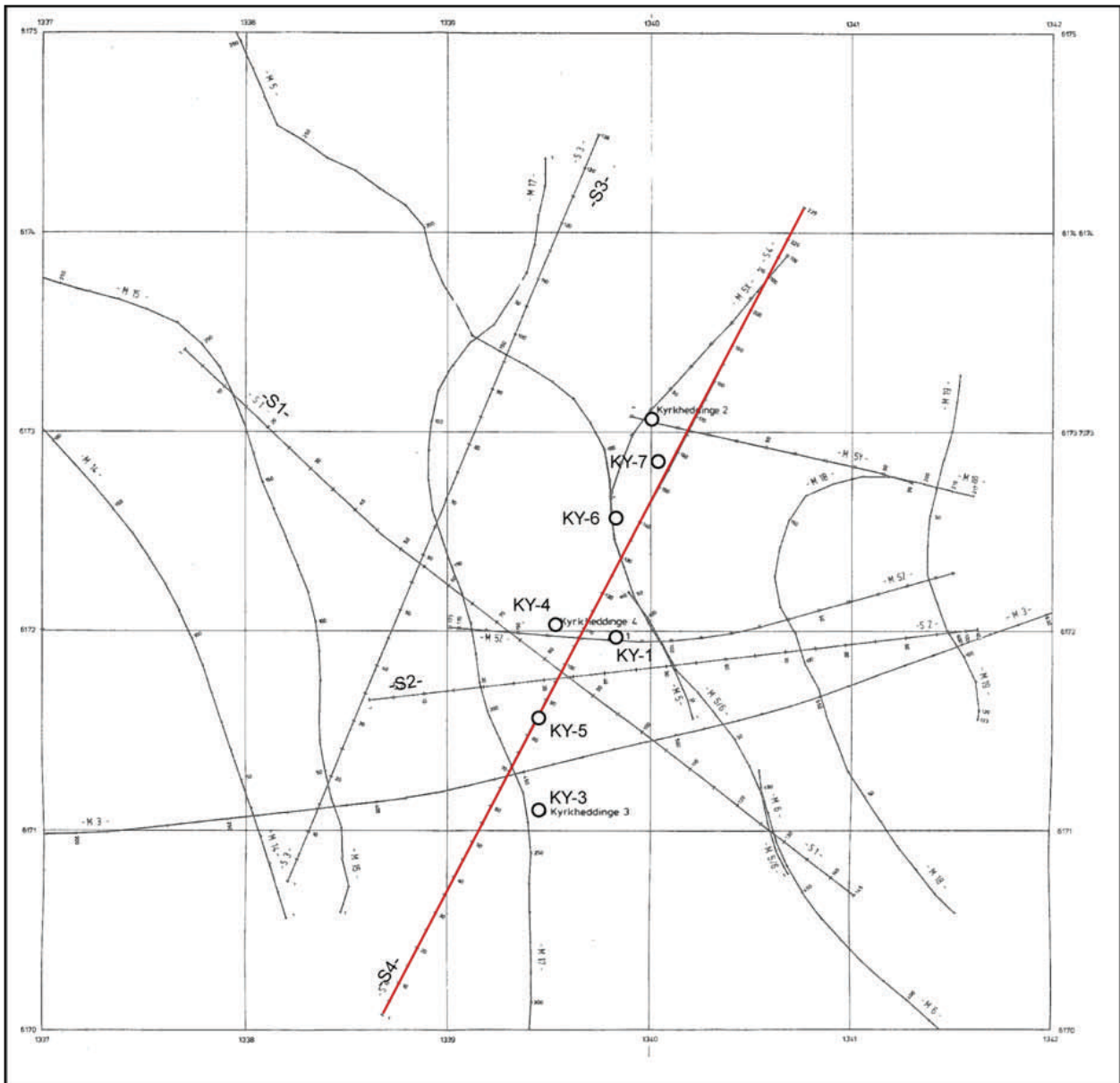

Fig. 4. Illustration of the seismic surveys carried out in 1982 and 1983 in the Kyrkheddinge area. The red line (S4) is together with the existing wells illustrated in Fig. 10.The grid is 1x1 km. From Erlström et al. (2014)

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The depth is presented as meters below Kelly Bushing (KB) i.e. the difference between ground level and the floor of the drill rig from which all depth measurements in the well are performed. For example, KY-3 has a ground level of 19.06 m above mean sea level, and a KB-level of 22.61 m. The difference (22.61 – 19.06) equals 3.55 m. That is, a depth on the chart of 100 m includes the KB-level. The true depth below ground level (i.e. the subsurface) is thus 100 – 3.55 = 96,45 m. KY-6 and KY-7 only include KB above drill floor/ground level because no values on ground level above sea level were available. Since there is little difference between the included wells the KB level is used as reference level. Normally the mean sea level is used as reference.

The cross section displays several cap-rock and reservoir units of interest. They are in the Swedegas project referred to as Horizon A-G (reservoir units), and Caprock A-G (cap-rock units) (SGAB 1983). To be consistent, this study also uses the same terminology.

The gamma ray recordings vary in appearance and detail (for example, compare the responses on KY-3 and KY-4,) due to reasons mentioned in section "4.5 Cross section". This makes the correlation a bit more difficult to perform, and thus uncertainties on the lateral distribution are marked with a "?". However, some units are quite easy to distinguish between the wells in the profile (e.g. Caprock B and Horizon B), thus indicating a good lateral distribution of similar facies.

The KY-4 well is set to represent the type well, in which the separate units from the other wells are correlated to. This because KY-4 has the clearest gamma ray recordings and most distinguishable cap-rock and reservoir sections.

The yellow solid line, "behind" the blue gamma ray curve, indicates the sandstone base line, i.e. the level on the chart where sandy sediments dominate (reservoir intervals). Where the yellow line is absent (hidden behind the blue curve), argillaceous limestone dominate (cap-rock intervals). The sandstone base line is set to 20-25 API. The different values is due to scale differences between the different logs. It does not affect the gamma ray response signature, which is the main factor when correlating the lateral stratigraphical distribution.

5.2 Log characteristics of cap-rocks and reservoirs

In the upper part of the type well KY-4, down to approximately 600 m depth, thick sections of alternating cap-rock and reservoir units can be identified. Below this level through the entire well, a clear change towards thinner and more frequently alternating cap-rock and reservoir units are recognized. This trend can be seen in KY-3 at 660 m, KY-6 at 660 m and at KY-7 at 655 m depth.

The cap-rock thicknesses below 600 m range between 10 and 40 m. The reservoir thicknesses are between 5 and 25 m, most of them being thicker than 10 m. On the gamma ray curve fining upwards, coarsening upwards, and clean sandstone sections can be identified. This is most evident in the KY-7 well. A clear coarsening upwards section is located at 950-900 m depth. A fairly homogenous sandstone section is situated at 870-855 m depth, and a fining upwards section can be distinguished between 825 and 730 m depth.

These sections indicate a deltaic environment with fluctuating depositional energy. The relationship between rate of sediment influx and rate of basin subsidence strongly affects what kind of depositional environment is formed (Erlström 2014a). Fining upwards sequences is associated with low energy environments and could thus indicate greater sediment influx relative the subsiding basin. This leads to an infilling of the basin resulting in low energy environment and finer sediment deposits. A coarsening upwards section indicates an offshore environment. The more homogeneous sandstone units are interpreted by Erlström (1990) as beach sands as a result of waves and currents reworking the sediments.

The lower part of the succession (below 600 m depth) shows higher API readings for the cap-rock interval units, the peak almost reaching 50 API. An evident anticline structure can be traced throughout the profile. The layers elevate from SSW in the KY-3 well in a NNE direction. The anticline reaches its maximum in the KY-4 well, before it drops towards the NNE as seen by the correlation with well KY-6, and eventually is almost flattened at the eastern flank of the profile (KY-7). This structural pattern is supported by the seismic profile given in Fig. 10. in section 5.7.

The cap-rock and reservoir thicknesses vary laterally. The general trend is an increase of cap-rock units, and to some extent thicker cap-rock units, towards the SSW. The opposite applies for the reservoir units, which instead decreases in layer thickness towards the western flank of the profile.

This observation indicates a laterally change in depositional environment, which can be related to the distance from the erosion source – the uplifted Romeleåsen Horst to the NNE. The closer to the source the thicker sandy deposits due to higher energy, whereas more distal facies including clay deposits are increasing towards the SSW due to low energy environment.

5.3 Lithology

The gamma ray responses show that there are frequent vertical and lateral changes in lithology in the Lund Sandstone, which can be seen by the great fluctuations on the gamma ray curve for all the wells (Fig. 5). This is consistent with petrographical analyzes presented by Erlström (1990) who distinguished four main lithofacies; quartzose sandstone, calcareous sandstone, arenaceous limestone, and argillaceous limestone. These lithofacies can all be identified in the gamma ray log; increasing gamma ray response indicates finer grains (higher clay content), and lower gamma ray response
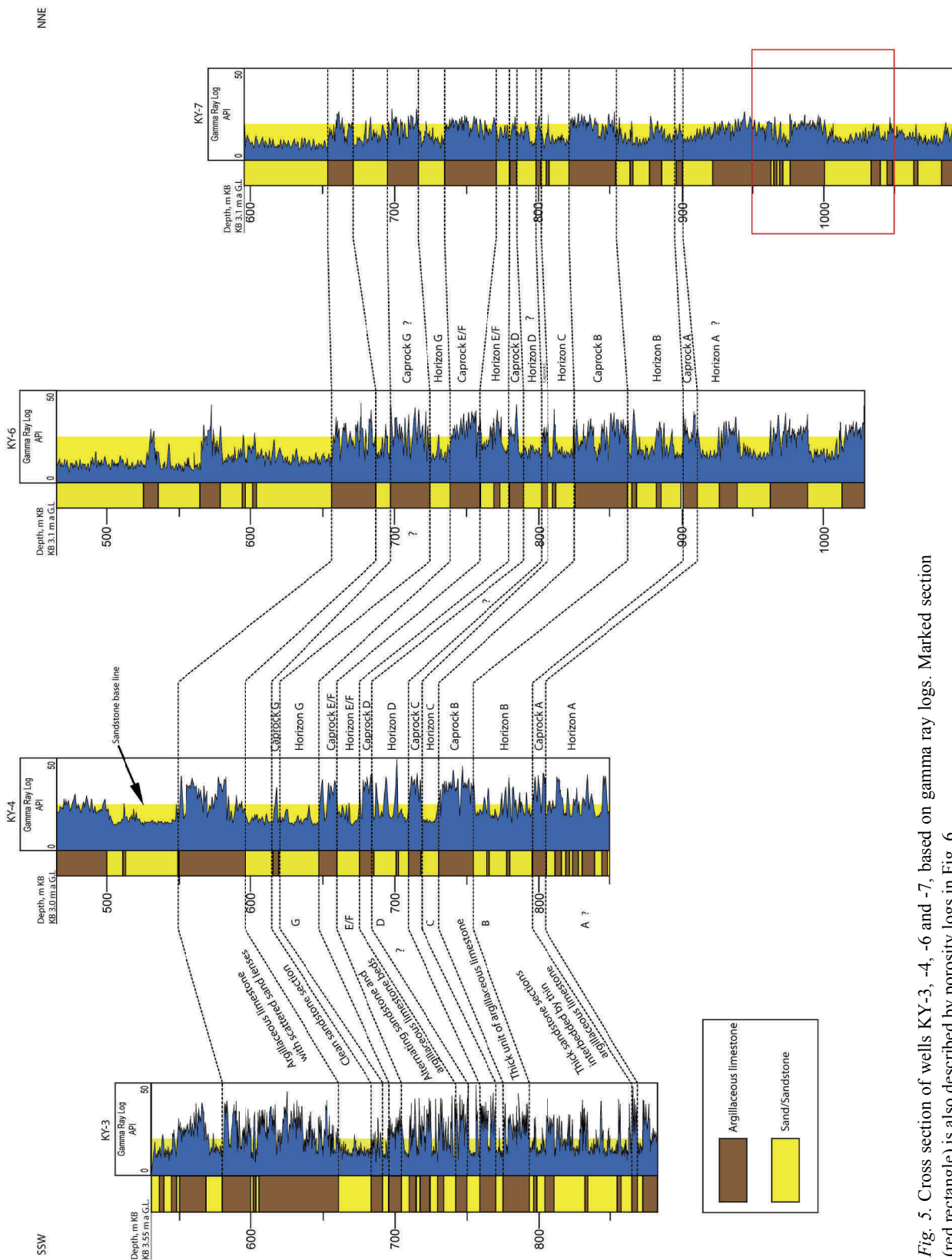
Fig. 5. Cross section of wells KY-3, -4, -6 and -7, based on gamma ray logs. Marked section (red rectangle) is also described by porosity logs in Fig. 6.

indicates coarser grains (less clay and more sandy lithofacies).

A constant trend of higher gamma ray readings for the cap-rock intervals, increasing with depth, indicates a more fine grained composition and higher clay content. The lithology for the Lund Sandstone succession based on the gamma ray response is given in Fig. 6. It is based on data from well KY-7, but the same response applies for the other wells, even though the depth for where the different lithology changes occur may vary due to the anticline structure.

The upper part of the Lund Sandstone from 350 m down to around 600 meters depth comprises mostly coarse and medium-grained calcareous sand and sandstone beds interbedded by arenaceous and argillaceous limestone (Erlström 1990).

The lower part of the Lund Sandstone, below 600 meters, constitutes alternative reservoir and cap-rock intervals. The interbedded arenaceous limestones are characterized by higher argillaceous content. The thickness of the sand/sandstone units decreases somewhat in comparison with the upper part of the unit (Erlström 1990).

5.4   Neutron/Density porosity for cap-rocks and reservoirs

Porosity responses for the section between 950 and 1050 m depth in KY-7 are given in Fig. 6. Evaluation of the neutron porosity and density porosity logs in KY-7 show four major response changes. At 810-820 m and 1015-1020 m depth the log curves cross each other; the porosity log records very low porosity, while the density log records much higher porosity.

This is usually an indication for gas in the formation, which suggests that these two reservoir sections are permeable and porous enough to contain gas. Moreover, it is also an indication that the two overlying cap-rock units are impermeable enough to keep the gas in place. The porosity responses are consistent with the gamma ray readings, that also indicate reservoir sections, i.e. sandstone in these intervals.

The other two response changes are detected at 825-850 m and 975-1000 m depth. They react exactly the opposite to the previously described intervals. Here the porosity log shows very high porosity, while the density log records much lower porosity values.

This is an indication for high clay content within these cap-rock intervals, indicating a more argillaceous, i.e. clayey lithology. In other cap-rock intervals, e.g. 690-725 m, there is not the same change meaning that such units are related to a more limestone dominated caprock. A high clay content generally leads to a decreasing vertical permeability, and in addition a ductile property which gives these units high cap-rock value. Limestone dominated units are more brittle and less favorable due to risk of fracturing in a pressurized gas storage.
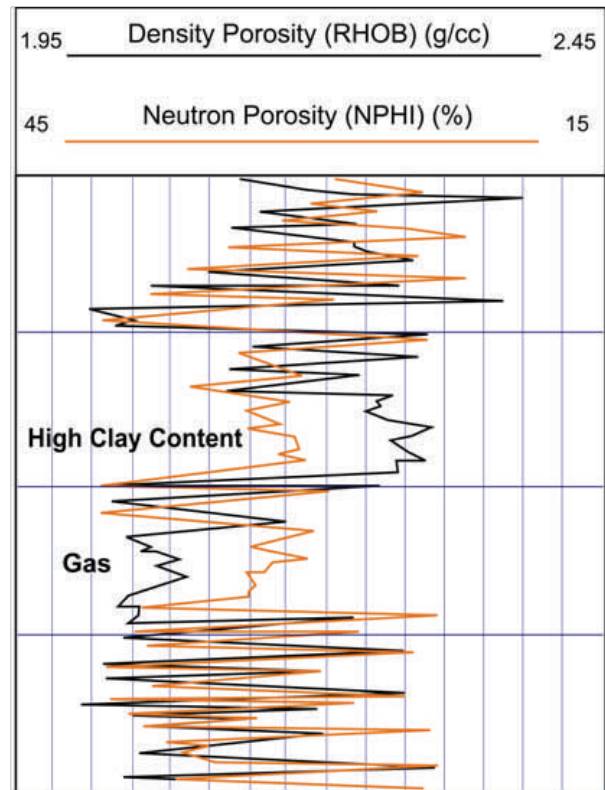

Fig. 6. RHOB and NPIH log responses in KY-7, between 950 to 1050 m depth. Each interval is 25 m thick.

5.5   Porosity and permeability core tests for cap-rocks and reservoirs

A summary of results from porosity and permeability analyzes on cores from cap-rock and reservoir intervals at required depths, i.e. below 600 m, are given in Table 4.

The reservoir thicknesses vary between 11 to 56 m, most being over 25 m thick. The total reservoir thickness is 136 m in KY-1, 100+ m in KY-2, and 102 m in KY-3. The permeability tests show values ranging from 1876 to 6098 mD. Every reservoir but one show permeability values exceeding 2400 mD, the general permeability being over 3500 mD. Air porosity values range from 25.2 to 32.3 %, the majority having values over 30 %.

The total reservoir thickness are much higher than required (20-50 m) in all the investigated wells, indicating sufficient capacity for storing the gas. The permeability values are excellent, and exceeds the requirements (>100 mD) extremely well. Air porosity values are also much higher than required (>15 %). To summarize, the reservoir properties indicate very suitable conditions for storing gas. They are comparable to the best reservoirs in the North Sea, i.e. the Utsiraformation in the Sleipnerfields, that have porosity values of 25 % and permeability values of 4000 mD (Erlström 2014a).

The cap-rock intervals show thicknesses between 6 to 37 m, most of them having thicknesses greater than 10 m. The permeability ranges from 0.01 to 0.08 mD, especially the vertical permeability being much lower

Table 4. Summary table of porosity and permeability from lab test on cores from Ky-1, -2, and -3. Cap-rock intervals in brown and reservoirs in yellow. (h)=horizontal, (v)=vertical, Th.=Thickness. Modified after SGAB (1983) and Erlström *et al.* (2014).

Depth, m KB			Air porosity, %			Liquid permeability, mD			Th.	Th.	Th.
KY-1	KY-2	KY-3	KY-1	KY-2	KY-3	KY-1	KY-2	KY-3	KY-1	KY-2	KY-3
628-635	705-715	694-704							7	10	10
635-650	715-733	704-715			30.5	2453			15	18	11
650-679	733-770	715-750		11.7	12.8		0.06	0.06	29	37	35
679-710	770-799	750-777	26.8 25.6 (h) 28.0 (v)		25.2	3484 3464 (h) n.d (v)	3458	1876	31	29	27
710-723	799-802	777-791	15.1 17.0 (h) 13.5 (v)			0.08 0.13 (h) 0.04 (v)			13	3	14
723-734	802-819	791-804	32.3 32.3 (h) 32.2 (v)			6098 6151(h) 6017 (v)			11	17	13
734-753	819-839	804-810	15.8		17.2	0.04		0.05	19	20	6
753-809	839- (+875)	810-861	30.2 30.0 (h) 30.3 (v)		30.4	4318 5040 (h) 3163 (v)		3220	56	36+	51
809-819	-	861-867		15.8	9.8	0.01			10	-	6
819-842	-	867-?	29.9 30.6 28.9			4078 4871 2492			23	-	?

than the horizontal. Porosity values range from 9.8 to 17.2 %.

The cap-rock thicknesses are good, but most importantly the tests show a very low vertical permeability, also these exceeding the requirements (<0.1 mD) with margin. Porosity values are not essential to make a good cap-rock but are relatively low, which is good.

A cross-plot of porosity and permeability on all lab tests performed on cores from KY-1, -2, -3, -4, -4, -5 and -6 is given in Fig. 7. The figure illustrates that the prerequisites to make good reservoir and cap-rock units are concentrated within the limits. The figure especially shows very good and consistent permeability and porosity values for the reservoirs, some reaching almost 40 % porosity. In all, the porosity and permeability core tests for cap-rocks and reservoirs indicate very feasible rock properties for the Lund Sandstone to constitute a natural gas storage.

5.6 Thin section analysis

A thin section image of a typical cap-rock unit in KY-4, at 827.25 m depth, is given in Fig. 8. It shows the heterogeneity within the cap-rock intervals. A matrix rich composition with varying grain size fractions of sub angular to sub rounded carbonate and silica minerals are identified. Visible laminations of clay are also recognized as well as cementation in the upper, middle
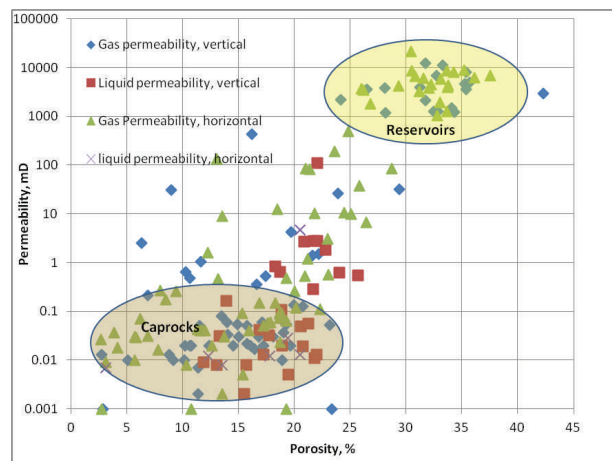
Fig. 7. Cross-plot of porosity and permeability on all lab tests performed on cores from KY-1, -2, -3, -4, -4, -5 and -6. Encircled areas show in which interval the most suitable properties to function as cap-rocks and reservoirs are found. After Erlström *et al.* (2014)

and lower parts. It is interpreted as an argillaceous limestone with low vertical and horizontal permeability.

Fig. 9 shows a thin section image of a typical reservoir unit for the Lund Sandstone in KY-3, at 757 m depth. It is characterized by sub-rounded or sub- angu-
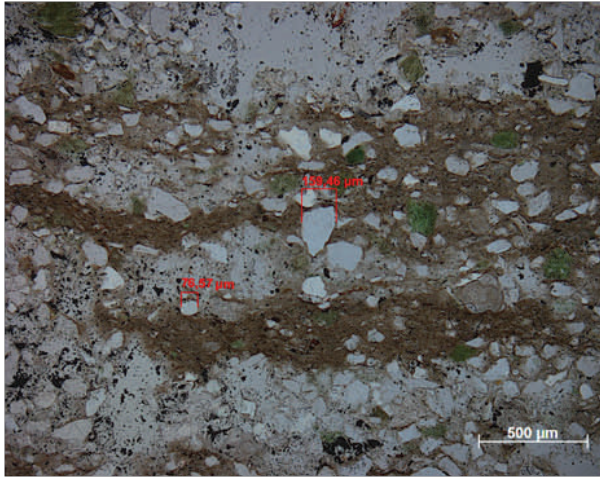
Fig. 8. Thin section image of a cap-rock interval in KY-4, at 827.25 m depth.
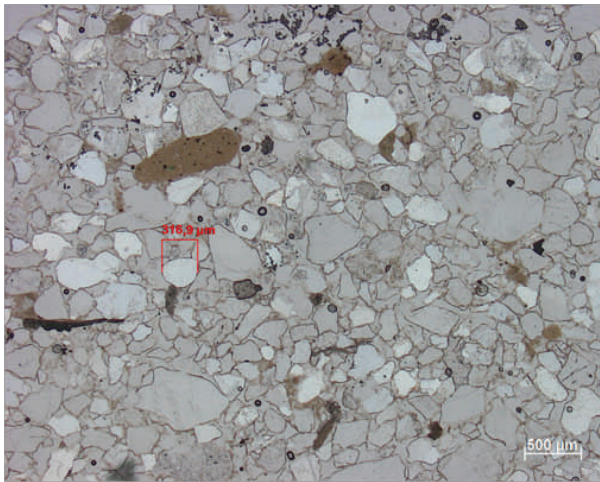

Fig. 9. Thin section image of a reservoir unit in KY-3, at 757 m depth.

lar quartz grains with calcareous content. Glauconite minerals (dark green minerals) are abundant. Contact surfaces between the grains are scarce and the space between the grains relatively high, indicating high porosity and permeability. The quartz mineral sizes vary from around 100 to 500 μm.

5.7 Seismic signature

A seismic signature of the Kyrkheddinge area correlated with the location of the seven wells KY-1-KY-7 and depth is given in Fig. 10. The seismic profile, located more or less perpendicular to the Romeleåsen Fault and Flexure Zone to the NE, clearly visualizes that the top of the Lund Sandstone (orange marker) dips towards the SW and that the Lund Sandstone comprises numerous reflectors, indicating stacked sequence of loose and hard beds, i.e. reservoir sands and cap-rocks. Blue lines indicate fault zones. Another trend is that with depth the reflectors show an anticlinal form, which from c. 600 m comprises a closed dome as shown in the set map. This closed dome structure will trap the gas and hold it within the storage chamber.

6 Discussion

The knowledge about gas storage in the sedimentary bedrock was at the time the Kyrkheddinge gas storage project was launched limited. Much of what has been learned about geophysical characterization and the Lund Sandstone is due to the investigations carried out by the Swedegas Company.

The Lund Sandstone in the Kyrkheddinge area displays in general suitable properties for an underground gas storage. The bedrock has a structure suitable for trapping gas, and some of the results on specific parameters are remarkably good. If there was a closed structure in the uppermost part of the Lund Sandstone this would be even more suitable for storage as the overlying argillaceous limestone and mudstone deposits exhibit excellent cap-rock properties with a thickness of over 100 m.

Several reservoir units are located at appropriate depths and show porosity and permeability values much higher than required. Their thickness and lateral distribution seem sufficient enough to contain the gas, even though thicker and more homogenous units would be desirable.

The cap-rock units varies in thickness and have heterogeneous lithology, comprising variably argillaceous limestone and calcareous claystone. Some units could preferably comprise higher clay content in order to ensure a plastic seal. Most of the cap-rock units show very low permeability values, and thus meets the requirements to function as a tight seal above the reservoir sandstone intervals. This is furthermore evident over some sections that show that there is already gas trapped within the Lund Sandstone. The lateral continuity of the cap-rocks are sometimes hard to correlate. However, there are units which are quite easy to follow through the horizontal plane, both in the cross section and in the seismic signatures.

In spite of these favorable conditions the gas project at Kyrkheddinge was shut down in 1985 partly due to that the main reservoir section, sand B, did not attain sufficient feasible results regarding the production. The heterogeneous lithology within this unit made it very difficult to complete successful gas wells (Hagconsult AB 1985). There was in addition an uncertainty regarding faulting affecting the closed structure, which would limit the amount of gas that could be contained as well as risk of leakage. Another reason, not explicitly reported, is that Swedegas started to look for other alternatives regarding a buffer storage of natural gas. A more suitable location on the west coast of Sweden, close to the main pipeline, was a primary wish. Later a LNG (Liquid Natural Gas) storage was constructed in a cavern in crystalline rocks at Getinge in southern Halland (Erlström 2014a).
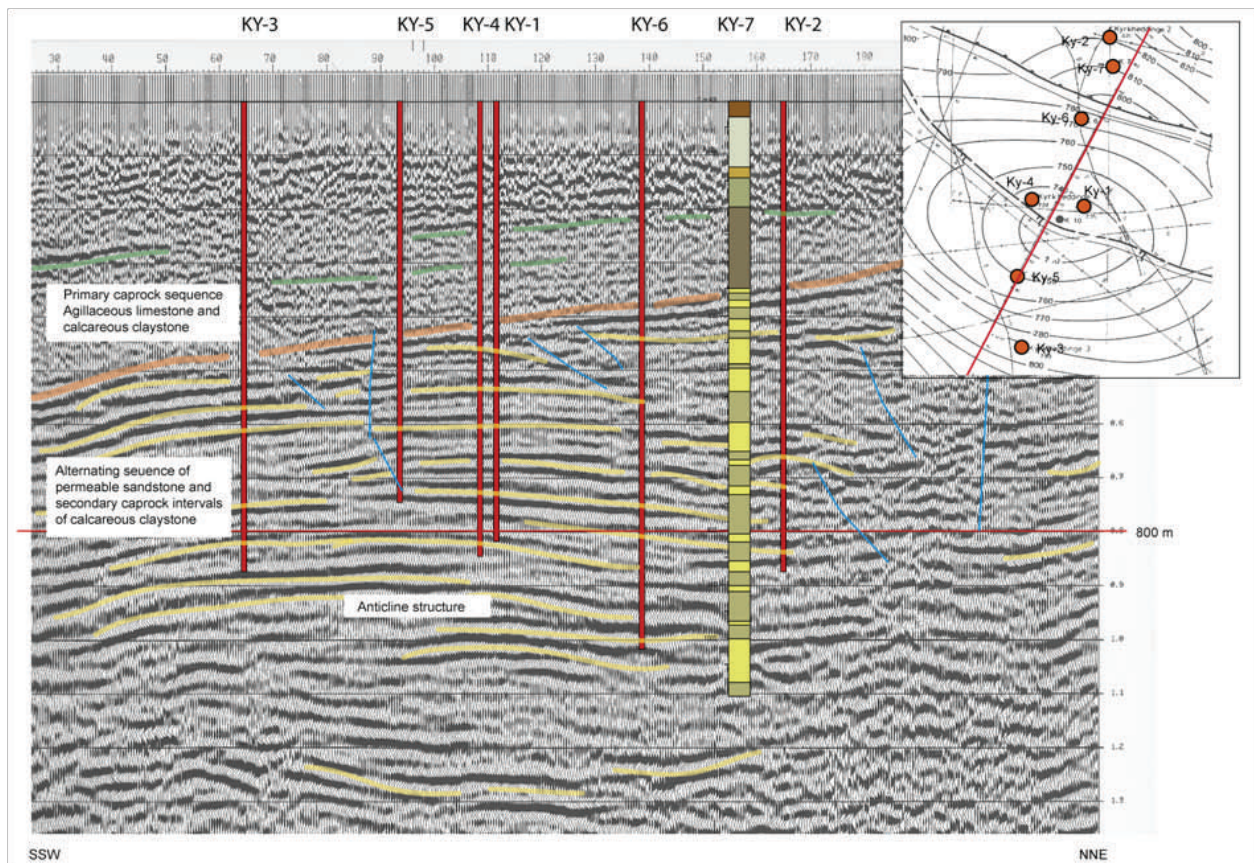
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Fig. 10. Schematic depth converted cross section with wells and seismic profile 4. Blue lines indicate fault zones. The orange lines marks the top of the Lund Sandstone. Yellow lines mark reservoir/sand beds. Dark grey lines indicate cap-rock boundaries and green lines the Maastrichtian deposits composed by argillaceous limestone and mudstone. After Erlström et al. (2014).

7 Conclusions

- The work has resulted in a subsurface log correlation of cap-rock and reservoirs in the Lund Sandstone at Kyrkheddinge, Scania, Sweden.
- The log correlation show an anticline structure suitable for trapping gas commencing at c. 600 m depth and a lateral continuity of several cap-rock and reservoir units.
- The different geophysical logs show intervals with enhanced cap-rock properties due to high clay content, reservoir units indicating good storing possibilities due to presence of gas, and the different lithologies including quartzose sandstone, calcareous sandstone , arenaceous limestone, and argillaceous limestone, which are clearly distinguished in the log responses.
- Evaluation of the petrophysical properties show highly porous and permeable reservoir sandstone units, impermeable cap-rock units that varies in thickness and have heterogeneous lithology, comprising variably argillaceous limestone and calcareous claystone.
- The seismic data reveals existence of a possible fault that may affect the closure of the reservoir, which led to abandoning the project beside strategic decision on optimal placing and storage type.

- Further investigations on to what extent the nearby fault zone affects the storing possibilities should be made, i.e. how are the layers affected, and does the fault constitute an escape path for the gas? If it does, what volumes can be stored on safe distance from the fault zone without risking gas leakage?
- There are still unresolved questions regarding the deeper reservoirs. Investigations in this study and in the Swedegas project have identified potential reservoir sections with cap-rocks at greater depths than the sand B reservoir. Due to the extra costs in terms of work, time and risk it was decided to not continue any additional investigations on these sections. Therefore, further studies on these sections are recommended since they could comprise good storing possibilities.
- The Lund Sandstone unit exhibit in general very good properties for natural gas storage, and a new project is recommended to evaluate the possibilities for such a purpose.
- There is moreover a great potential to use the vast amount of data and knowledge from the site investigations at Kyrkheddinge for cap-rock and reservoir modeling, and research regarding storage of natural gas and CO2.

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8 Acknowledgements

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