

Pre-Rhaetian Triassic strata in Scania and adjacent offshore areas – stratigraphy, petrology and subsurface characteristics

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Sveriges geologiska undersökning
Geological Survey of Sweden

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ISSN 0349-2176
ISBN 978-91-7403-157-7

Cover: Cliff exposure in the Bälteberga gorge, east of Helsingborg, displaying beds belonging to the Norian Kågeröd Formation. The up to 15 m exposed sequence consists predominantly of conglomeratic arkose and poorly sorted sandstone. Photo: M. Erlström.

Layout: Jeanette Bergman Weihed, SGU
Print: Davidsons Tryckeri AB, Växjö 2012

SUMMARY

The research performed is partly the result of increasing commercial interest in the use of deep saline aquifers in sedimentary bedrock in Sweden and adjacent areas for geothermal resources and for geological storage of carbon dioxide. Pre-investigations of the geothermal potential of the deep aquifers beneath Malmö and Copenhagen were made in the mid-1990s. These pre-investigations included geological modelling based on data from the Swedish Oil Prospecting Co (OPAB) from the 1970s and an additional seismic survey in Öresund, Copenhagen and Malmö in 1999.

Between 2001 and 2002 Sydkraft AB (now Eon Sverige AB), Danish Oil and Natural Gas (DONG) and Hovedstadens Geotermiske Samarbejde (HGS) drilled four deep boreholes (FFC-1, FCC-2, MAH-1 and MAH-2) for geothermal purposes. The geothermal target was the Jurassic and Triassic sandstone aquifers below a depth of 1 500 m.

The question of other potential uses, such as carbon dioxide storage, of the deep aquifers in south-west Skåne (Scania) has arisen alongside the geothermal interest. The importance of carbon dioxide storage has been stressed by the Intergovernmental Panel on Climate Change (IPCC) and others. Potential areas in Sweden lie within the sedimentary bedrock basins in the Baltic Sea and the areas structurally belonging to the Danish Basin, i.e. south-west Scania and adjacent offshore areas (Erlström et al. 2011). The Triassic succession in south-west Scania includes a number of aquifer sandstone layers that have suitable properties for carbon dioxide storage. An understanding of the Triassic sequence regarding lateral variability in distribution, palaeo-depositional setting and physical properties is of great importance in assessing this type of strata regarding both suitability for carbon dioxide storage and geothermal purposes.

The boreholes in Copenhagen and Malmö penetrate a pre-Rhaetian Triassic sequence dominated by claystone with sandstone interbeds throughout, particularly in the lower parts. The deepest sandstone aquifers, the Bunter Sandstone (MAH-1, Ljunghusen and Hammar Formations), lie at a depth of 2 400–2 600 m and have the capacity to produce 150–300 m³ water per hour with a temperature of about 70 °C at a depth of 2 500 m. However, the various sandstone aquifers have been difficult to correlate laterally due to the lack of consistent stratigraphical control and terminology between countries (Sweden, Denmark and Germany).

Knowledge of the pre-Rhaetian Triassic in the Höllviken Halfgraben and in the marginal parts of the Danish Basin has so far largely been based on the stratigraphical terminology presented by Brotzen (1950) and by OPAB (unpublished reports). This terminology has been found to be inadequate for correlation with corresponding strata in the more central parts of the Danish Basin or with the pre-Rhaetian Triassic deposits in northern Germany.

Results from geophysical well logging and analyses of cuttings from the new wells in Malmö and Copenhagen show that the pre-Rhaetian Triassic succession includes key beds with lithological features that could be used as stratigraphical markers. Using palynology, the research presented in this report has been able to date these intervals in the Höllviken-2 and FFC-1 wells, where fine-grained clastic rocks contain pollen and spores of Ladinian age (Piasecki 2005). These deposits are well known in northern Germany as the Erfurt Formation (Bachmann 1998). This key interval is important for understanding the general stratigraphical framework. A new subsurface model and stratigraphy of the pre-Rhaetian Triassic in the Höllviken Halfgraben is presented in combination with interpretation of geophysical logs, seismic data and petrophysical characteristics. The model also describes the lateral extension and variability of the main pre-Rhaetian Triassic aquifers found in the FFC-1 and MAH-1 wells.

A comprehensive lithological and petrophysical characterisation is presented of the sandstone aquifers. The porosity of the sandstone beds ranges between 3 and 20% and the permeability extends up to 1 350 mD. The aquifers of most interest for geothermal use are the Bunter sandstone beds (Ljunghusen and Hammar formations), the Keuper Vellinge Formation and parts of the Stavsten–Kågeröd formations.

The Bunter aquifers (Ljunghusen and Hammar formations) are only found in the deepest parts of the Höllviken Halfgraben. Potential aquifers are also found in the Upper Triassic Kågeröd Formation. However, their petrophysical characteristics are laterally more variable due to a varying degree of cementation and matrix content. The Bunter sandstone aquifers are more homogeneous in composition and show better lateral continuity.

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INTRODUCTION

This study was performed due to the increasing commercial interest in the deep saline Lower Cretaceous, Jurassic and Triassic aquifers in south-west Scania. Investigations of the geothermal potential in the deep Mesozoic aquifers beneath Malmö and Copenhagen were conducted more or less simultaneously in the mid-1990s.

Besides geothermal interest there has also been increasing interest in evaluating the potential of using deep saline aquifers in Scania to store carbon dioxide (CO₂). Geological storage of carbon dioxide is one of the most interesting geoscientific issues on today's climate agenda. The importance of implementing carbon capture and storage (CCS) techniques has been stressed by the Intergovernmental Panel on Climate Change (IPCC 2005) and others. The IPCC considers carbon dioxide storage in deep saline aquifers to be potentially one of the most promising storage options. In Sweden, however, there is very little scope for finding suitable deep aquifers due to the limited occurrence of sedimentary basins. Suitable aquifers are potentially found in the Cambrian sequence in the Baltic Sea Basin and in the Mesozoic succession in south-west Scania, belonging to the Danish Basin (Erlström 2008, Erlström et al. 2011). In south-west Scania, well data reveal a number of Lower Cretaceous, Jurassic and Lower Triassic sandstone layers that might be suitable for storage. However, they are probably more suitable for research projects than for large-scale storage since they have a limited distribution. Knowledge of the subsurface Triassic succession in south-west Scania can, however, give valuable information regarding evaluation of corresponding sandstone aquifers in the Norwegian–Danish Basin regarding their suitability as candidates for carbon dioxide storage. Nielsen et al. (2007) present a number of potential sites in Denmark where the Bunter sandstone is regarded as a suitable deep aquifer for storage.

The geothermal projects managed by Sydkraft AB (now Eon Sverige AB), Danish Oil and Natural Gas (DONG) and Hovedstadens Geotermiske Samarbejde (HGS) resulted in the completion of four deep wells, two in Copenhagen (MAH-1 and MAH-2) and two in Malmö (FFC-1 and FCC-2). The wells generated new information on the subsurface geology in the Höllviken Halfgraben. Information on the Triassic succession in particular supplemented information from the older OPAB wells in the area.

The pre-Rhaetian Triassic sequence in the Malmö and Copenhagen wells is dominated by variably arenaceous claystone and mudstone layers frequently interbedded with sandstone layers, particularly in the lower part of the sequence. The sequence, which displays great variation of both lithological and petrophysical characteristics, is difficult to correlate on a regional scale due to the lack of consistent stratigraphical terminologies and definitions. Knowledge of the pre-Rhaetian Triassic deposits in the Höllviken Halfgraben and in the marginal parts of the Danish Basin has so far largely been based on the stratigraphical terminology presented by Brotzen (1950) and by OPAB (unpublished reports). This older terminology is found to be inadequate for correlation with the more central parts of the Danish Basin and the Triassic deposits in the north German Basin.

Results from the geological investigations and geophysical well logging operations in the Malmö and Copenhagen wells showed that the pre-Rhaetian Triassic succession displayed characteristic lithological features that could be used for stratigraphical purposes. The strategic locations of the wells in Malmö and Copenhagen also allow lateral correlation of the Triassic deposits in the Öresund region.

The overall aim of the study is to present a consistent stratigraphy that can be used for correlation on a regional scale. The aim has also been to present a comprehensive lithological and petrophysical characterisation of the Triassic sequence. A consistent stratigraphy and characterisation of the pre-Rhaetian Triassic sequence in the area is essential when evaluating the suitability of the Triassic aquifers for geothermal energy production.

The study also focuses on the pre-Rhaetian Triassic in the deepest parts of the Höllviken Halfgraben, in the southernmost parts of the Öresund area, where the Danish and Swedish geological surveys have expressed joint interest in the Triassic subsurface geology.

DISTRIBUTION OF PRE-RHAETIAN TRIASSIC DEPOSITS IN SWEDEN

In Sweden pre-Rhaetian Triassic deposits are only found in the southernmost province of Scania and adjacent offshore areas. The deposits were formed in the marginal parts of the Danish Basin, which joins with the North German Basin in the south and south-east (Fig. 1). During the pre-Rhaetian Triassic the depositional setting was dominated by arid continental conditions periodically interrupted by marine incursions. The marginal position has resulted in an incomplete Triassic sedimentary succession in Scania. Upper Triassic deposits, represented by the Kågeröd Formation, have their widest distribution in western and south-western Scania. Outcrops occur within the Sorgenfrei-Tornquist Zone, particularly in western and north-western Scania. One of the best localities is in the Bälteberga gorge, east of Helsingborg (Fig. 2). Sivhed & Wikman (1986) review the most important research dealing with the Kågeröd Formation. Most of the pre-Rhaetian Triassic strata are otherwise found subcropping younger sedimentary strata in southwestern Scania (Fig. 3).

From seismic data the pre-Rhaetian Triassic sequence is interpreted to reach a maximum thickness of 700–800 m in the deepest parts of the Höllviken Halfgraben. Well data verify a 638 m and 632 m thick Triassic sequence in Ljunghusen-1 and MAH-1, respectively.

MATERIAL AND METHODS

Well data

Pre-Rhaetian Triassic deposits are described in reports from 18 deep wells in the area studied (Fig. 3 and Tab. 1). Most of these were drilled as oil and gas exploration wells by OPAB in the 1970s. In these wells the descriptions of the pre-Rhaetian Triassic strata are performed on drill cuttings and interpretations of geophysical well logs. The quantity and quality of data vary greatly. Before the OPAB wells four deep core drillings had been performed by SGU in the area, i.e. Ljunghusen-1, Höllviken-1, Höllviken-2 and Svedala-1. Alongside data from the recent geothermal wells in Malmö

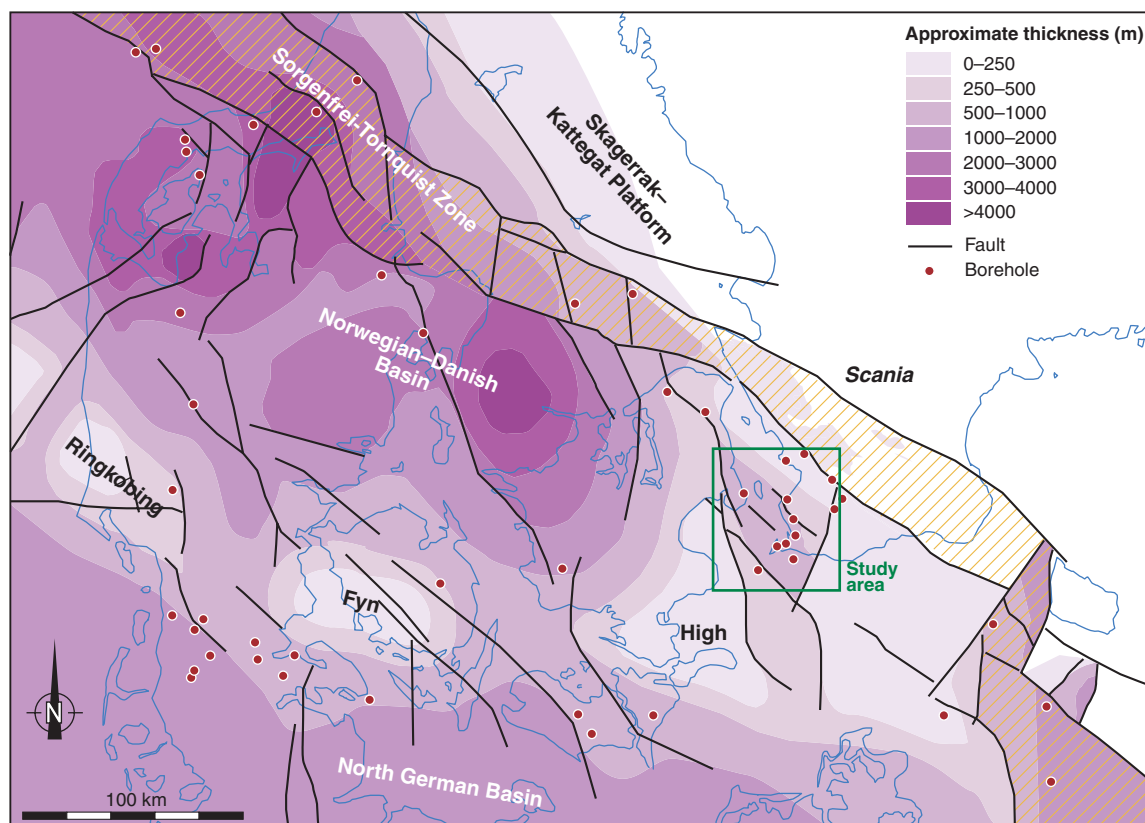


Figure 1. Generalised map showing distribution and thickness of the pre-Rhaetian Triassic in the Danish Basin.



Figure 2. Cliff exposure in the Bälteberga gorge, east of Helsingborg, displaying beds belonging to the Norian Kågeröd Formation. The up to 15 m exposed sequence consists predominantly of conglomeratic arkose and poorly sorted sandstone. Photo: M. Erlström.

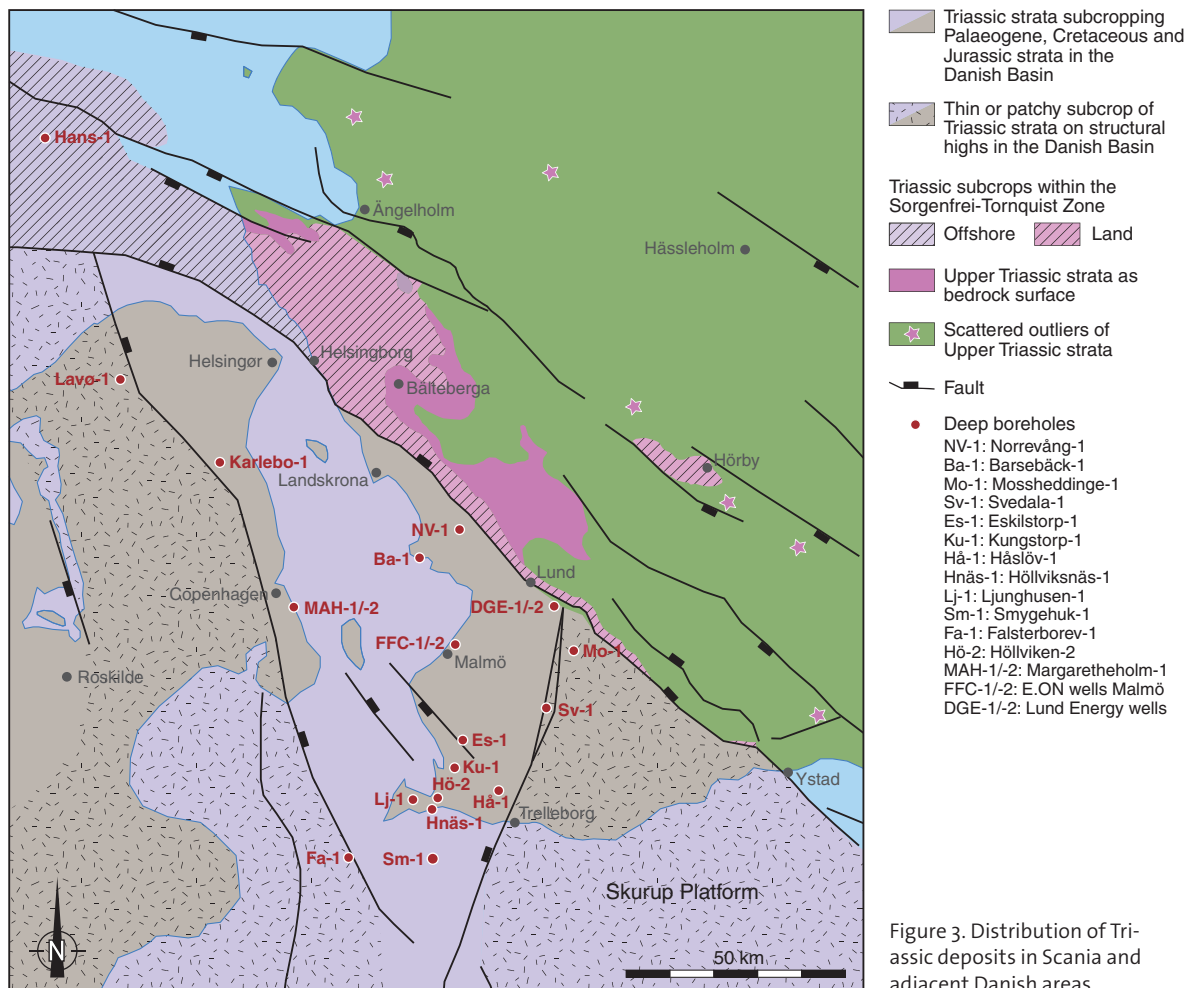


Figure 3. Distribution of Triassic deposits in Scania and adjacent Danish areas.

Table 1. Summary of boreholes drilled through or into pre-Rhaetian Triassic subsurface deposits. All depths are related to kelly bushing (K.B.) in metres. TD means total depth, SWC = side-wall core.

Borehole	Operator	Top (m)	Base (m)	Thickness (m)	Cored pre-Rhaetian Triassic intervals	Location	Comment
DGE-1	Lund Energy/LTH	1200	1310	110	-	Romeleåsen Fault Zone	Tilted strata
DGE-2	Lund Energy/LTH	680	785	105	-	Romeleåsen Fault Zone	Tilted strata
Norrevång-1 (NO-1)	OPAB	1970	2088	118	-	Barsebäck Platform	
Barsebäck-1 (Ba-1)	OPAB	1981	2184	203	SWC intervals 1897.5–1903.0 m 2091.1–2097.0 m	Barsebäck Platform	
FCC-1, FCC-2	Sydskraft/Eon	1840	2070	230	10 scattered SWC samples	Barsebäck Platform	Transition between Barsebäck Platform and the Höllviken Halfgraben
Mossheddinge-1 (Mo-1)	OPAB	1796	1814	18	-	Skurup Platform	
Svedala-1 (Sv-1)	SGU	1576	1642	66	Core drilling	Skurup Platform	
Eskilstorp-1 (Es-1)	OPAB	1632	2138	506	-	Höllviken Halfgraben	
Håslöv-1 (Hå-1)	OPAB	1586	2036	450	-	Höllviken Halfgraben	
Kungstorp-1 (Ku-1)	OPAB	1579	2066	487	7 SWC samples btw 1740–1747 m	Höllviken Halfgraben	TD in Triassic
MAH-1, MAH-2	HGS/DONG	2026	2658	632	-	Höllviken Halfgraben	
Höllviksnäs-1 (Hnäs-1)	HGS/DONG	1498	2067	569	1885.2–1893.2 m 1893.2–1902.6 m 2000–2008 m	Höllviken Halfgraben	
Höllviken-2 (Hö-2)	SGU	1496	+2000	+504	Core drilling	Höllviken Halfgraben	TD in Bunter sandstone
Ljunghusen-1 (Lj-1)	SGU	1512	2150	638	1713.15–1717.65 m 1826.30–1832.30 m 2005.40–2010.22 m 2097.29–2101.54 m 2143.75–2152.22 m	Höllviken Halfgraben	
Maglarp-1 (Ma-1)	OPAB	1533	1906	373	-	Höllviken Halfgraben	
Hammarlöv-1 (Ha-1)	OPAB	1451	1727	286	-	Höllviken Halfgraben	
Falsterborev-1 (Fa-1)	OPAB	1148	1329	181	1246–1250.4 m	Structural high	
Smygehuk-1 (Sm-1)	OPAB	1328	1650	322	-	Höllviken Halfgraben	
Karlebo-1	Tethys Oil	2072	2133	61	-	Barsebäck Platform	TD in Triassic

(FFC-1 and FCC-2) and Copenhagen (MAH-1 and MAH-2), information from these drillings comprises the most valuable documentation for this study.

The Höllviken-2 core (Brotzen 1950) is used as a reference core for the stratigraphical work and correlation with FFC-1 and MAH-1. Although the core has been the subject of various investigations over the past decades, which has resulted in missing parts due to intense sampling, it remains the most complete core of the pre-Rhaetian Triassic in the area. Analytical data from previous sampling campaigns and studies, in parts unpublished (e.g. Larsson et al. 1994, Jacobsson 1993, Ahlberg & Olsson 2001, Ahlberg et al. 2002, Arndorff 1994, Sivhed & Erlström 1997, OPAB reports 1969–1979, Horn af Rantzien 1953), have also contributed to the characterisation of the strata.

Extensive investigations during drilling and testing of FFC-1 and MAH-2 between 2001 and 2004 have significantly contributed to general understanding of the pre-Rhaetian Triassic succession in the Höllviken Halfgraben. The position of these wells made it possible to correlate subunits in the pre-Rhaetian Triassic over larger distances. However, most important was the general knowledge gained of the physical properties, lithological variability, log response, occurrence of key layers and biostratigraphical affinity of the pre-Rhaetian Triassic succession.

Seismic investigations

In the 1970s OPAB performed an extensive survey both on land and offshore (Fig. 4). These seismic data have been used in mapping the subsurface geology of south-west Scania (Erlström et al. 1997,

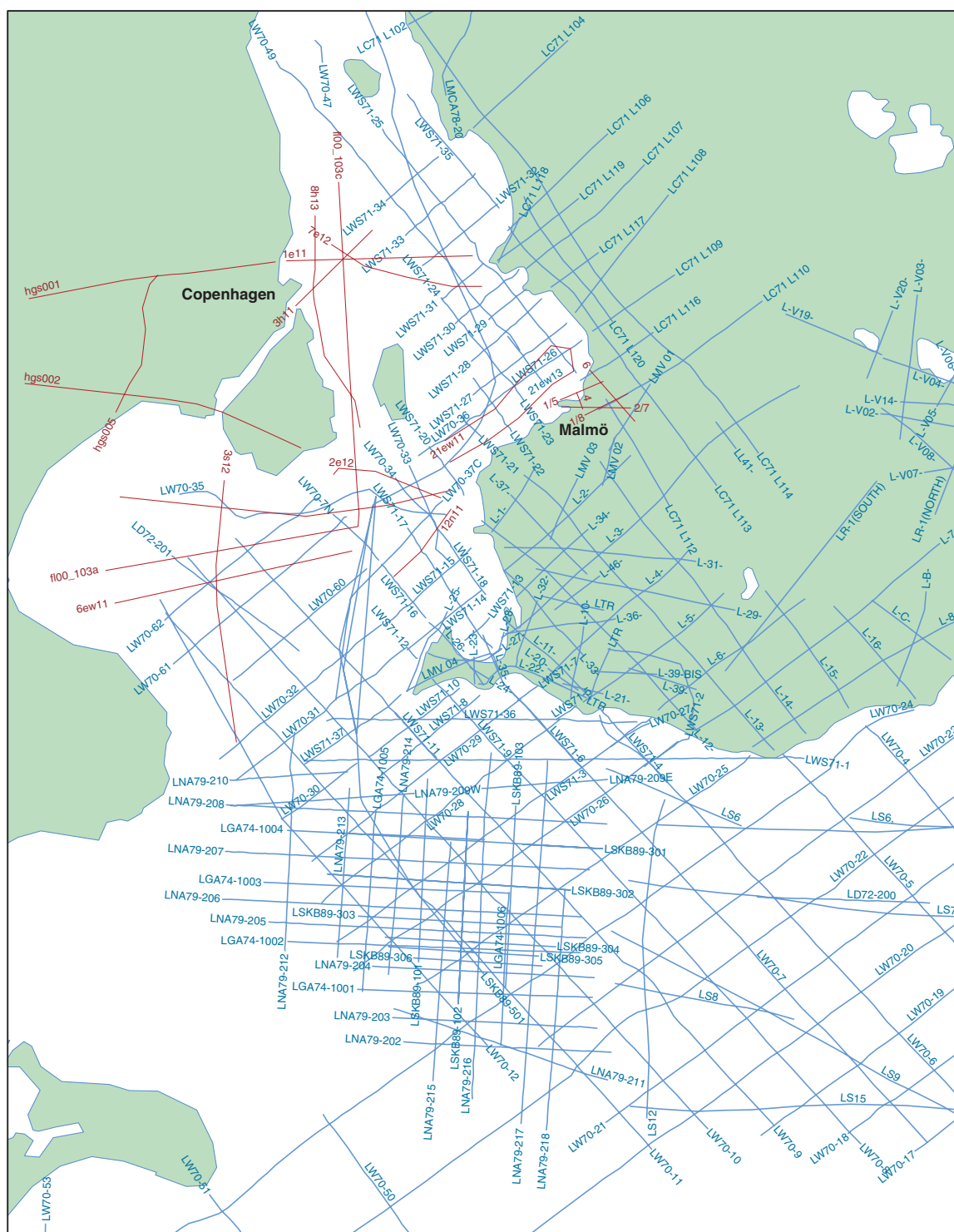


Figure 4. Map showing locations of seismic investigations performed by OPAB and SECAB between 1970 and 1989 (red lines), and DONG and Sydkraft AB investigations in the Malmö and Copenhagen area between 1999 and 2000 (blue lines).

Sivhed & Erlström 1996, Sivhed et al. 1999). The data are supplemented by surveys performed by Swedegas AB and the Swedish Exploration Consortium (SECAB) in the 1980s. A high resolution seismic survey began in the Malmö and Copenhagen area in 1999 with the aim of finding suitable borehole locations for drilling into deep geothermal aquifers (Fig. 4). This survey resulted in a dataset that added valuable local detailed information on the characteristics of the pre-Rhaetian Triassic sequence.

Table 2. Summary of sampled wells and intervals (below K.B.).

Well	Formation	Sample no.
Svedala-1	Kågeröd Formation	111H–114H
Barsebäck-1	Kågeröd Formation	131M–137M
Höllviksnäs-1	Flommen Formation, Hammar Formation	138N–145N
Höllviken-2	Kågeröd, Stavsten, Fuglie, Vellinge, Falsterbo, Flommen and Hammar formations	221O–226O, 227P–233P, 234P–278P, 279Q–292Q, 293Q–294Q

Table 3. Characteristics and stratigraphical affinity of analysed samples from the Höllviken-2 core.

Depth, m K.B.	Main lithology	Formation
1633	Reddish brown, fine-grained to coarse-grained sandstone. High matrix content. Well indurated.	Stavsten Formation
1676.8	Reddish brown, fine-grained to coarse-grained sandstone with carbonate nodules. Pinkish red. Scattered coarse terriclastic grains.	Fuglie Formation
1677.35	Arenaceous claystone with carbonates. Mottled grey-red.	Fuglie Formation
1683	Light red, laminated, medium-grained sandstone. Homogeneous texture.	Fuglie Formation
1740	Light red, medium-grained sandstone, weakly laminated. Micaceous laminae. Minor reddish brown clay clasts.	Vellinge Formation
1761	Greenish grey, micaceous, fine-grained sandstone. Spotted black (organic material?).	Falsterbo Formation
1866.2	Brownish grey, medium-grained to coarse-grained sandstone. In parts laminated.	Flommen Formation
1888	Light grey to greenish grey, medium-grained sandstone. Carbonates?	Hammar Formation

Petrophysical investigations

A large number of core samples were analysed during the pre-investigations of the geothermal potential of the Triassic aquifers beneath Copenhagen (Tab. 2). The analyses were of porosity and gas permeability. Samples were taken from cores in Svedala-1, Barsebäck-1, Höllviksnäs-1 and Höllviken-2. In total 75 samples from the pre-Rhaetian Triassic sequence were analysed. The sampling and analysis were performed by GEUS in 1996.

Petrological investigations

Thin sections

Several geologists have investigated the Höllviken-2 core over the past few decades. Several studies have included petrological investigations on thin sections. Some 75 pre-existing thin sections of different pre-Rhaetian Triassic layers from the Höllviken-2 core were included in this study. Additional thin sections were prepared on samples from the Höllviken-2 core. Most of these were made at levels that had been analysed for porosity and permeability by GEUS in 1996. Here, the main aim was to examine the sandstone beds that could be of interest as reservoirs (geothermal producers and carbon dioxide storage). Additional thin sections have also been made on sidewall cores from FFC-1, and on cores from Barsebäck-1 and Svedala-1. All in all, more than 125 thin sections have been studied using polarised microscopy.

Chemical analyses

Whole rock chemical analyses were performed on eight rock types in the Höllviken-2 core. The samples were selected to give a general chemical characterisation of the typical pre-Rhaetian Triassic rock types and formations (Tab. 3). The analyses were performed by ALS Chemex laboratory.

Biostratigraphical investigations

The pre-Rhaetian Triassic deposits are largely composed of coarse clastic rocks mainly deposited in continental arid environments. Evaporitic and hypersaline conditions were also common. Vegetation was sparse in most parts and the deposits, particularly in the proximal parts of the basin, do not contain any usable biostratigraphical fossil groups. However, in Höllviken-2 and FFC-1 there are beds containing small amounts of organic material, indicating periods of more humid climatic

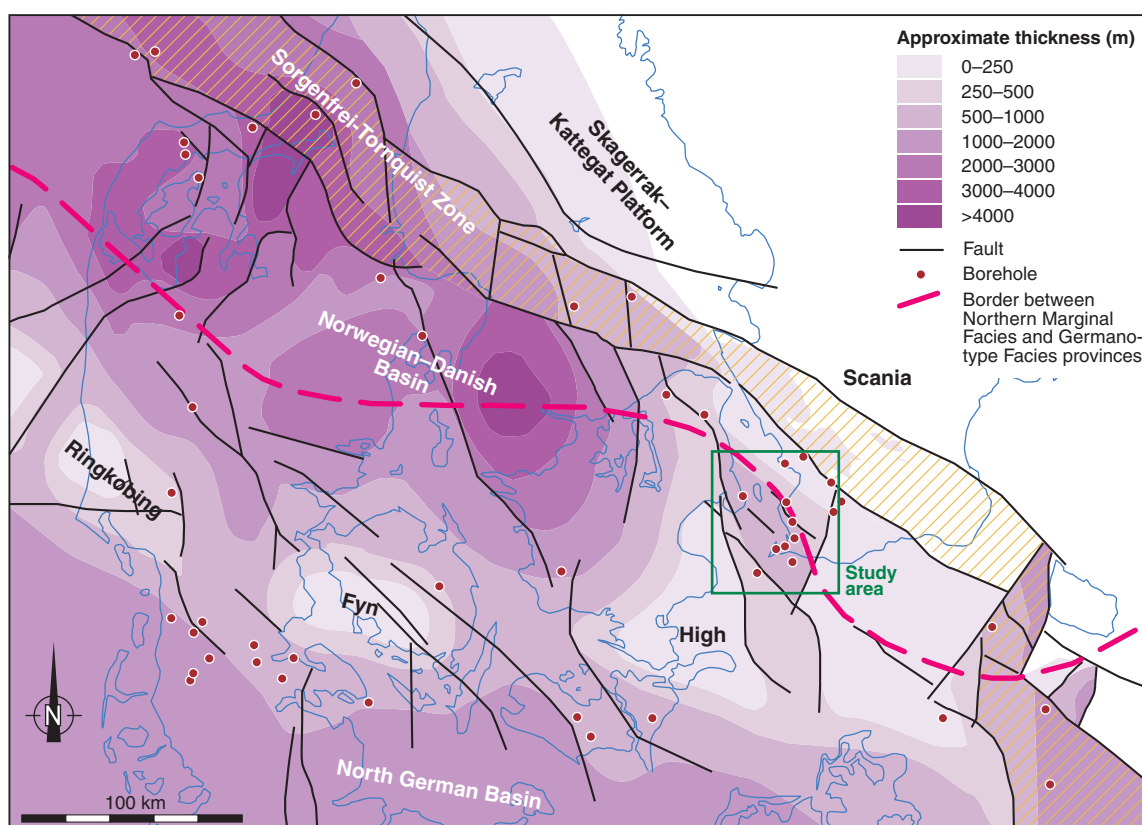


Figure 5. Pre-Rhaetian Triassic facies provinces and approximate thickness of pre-Rhaetian Triassic strata in the Danish Basin. After Beutler & Schöler 1987.

influence. These beds were sampled and analysed for their pollen and spore assemblage. A total of 10 samples from various levels were analysed. Most of them were barren but a few yielded data of great importance. The results are compiled in a GEUS report by Piasecki (2005).

PRE-RHAETIAN TRIASSIC STRATIGRAPHY IN THE DANISH BASIN

In 1980 Bertelsen introduced a modern lithostratigraphy of the Triassic sequence in the Danish Basin. He based the lithostratigraphic nomenclature on various well data and older publications (Bertelsen 1975, 1978, 1980, Dinesen 1960, 1971, 1973, Larsen & Buch 1960, Christensen 1962, 1971, 1973, Rasmussen 1974). For the Lower Triassic he used the British subdivision (Rhys 1974, 1975) and introduced a new one for the Middle and Upper Triassic.

Bertelsen (1980) defined two facies provinces in the Danish Basin (Fig. 5): the Germano-type Facies Province and the Northern Marginal Facies Province.

The Germano-type Facies Province includes the northern part of the North German Basin, the Ringkøbing-Fyn High and the central and southern part of the Danish Basin. The depositional pattern in the Germano-type Facies Province is comparable to that of the North German Basin and the Polish Basin. In this facies province, Bertelsen (1980) divided the Triassic sequence into four groups: the Bacton (Bunter Shale and Bunter Sandstone Formations), Lolland (Ørslev and Falster Formations), Jylland (Jutland) (Tønder and Oddesund Formations) and Mors Group (Vinding and Gassum Formations, Fig. 6). The Bacton and Jylland Groups represent regressive phases and the Lolland and Mors Groups represent transgressive phases.

The Northern Marginal Facies Province is identified in a marginal zone along the Fennoscandian Border Zone and the northern and western part of the Danish Basin. In this marginal zone, the

Stages	Northern Germany		Denmark (Germany-type Facies Province)	Höllviken 2	Sweden			
					Old	New		
Rhaetian	U		Gassum		Höganäs Fm	Höganäs Fm		
Norian	Keuper	Steinmergelkeuper	Skagerrak Fm		1496			
			Vinding Fm			Kågeröd Fm/ Maglarp A	Kågeröd Fm	
Carnian		M	U Gipskeuper		Odde-sund Fm	1604		
			Schilf Ss			1642	— ? —	Stavsten Fm
			L Gipskeuper / Grabfeld FM			Tønder Fm	1691	
Ladinian	L	Erfurt Fm	Falster Fm		1755	Maglarp B	Vellinge Fm	
					1798		Falsterbo Fm	
	Muschelkalk				1862			
Anisian			Ørslev Fm			Maglarp C	Flommen Fm	
Olenkian	Buntsandstein	U			1886			
		M	Solling FM			Bunt- sandstone	Hammar Fm	
Induan		Volpriehausen FM	Bunter Sandstone Fm	1924				
	L	Lower Bunt- sandstein	Bunter Shale Fm		Ljunghusen Ss	Ljunghusen Ss		

Figure 6. Stratigraphic subdivision of the Höllviken-2 core compared with nomenclature after Bertelsen (1980), Aigner & Bachmann (1992) and Beutler (1998).

Triassic sedimentary rocks belong to the undifferentiated Skagerrak Formation. However, this is not so in south-west Scania, where the Triassic sequence is referred to the Germano-type Facies Province.

Beutler & Schüler (1987) correlated the subdivision made by Bertelsen with the established stratigraphic nomenclature in Germany and also the North Sea (Centralgraben) and the Netherlands.

Based on new information from Danish wells, Michelsen & Clausen (2002) made a log-based lithostratigraphic correlation of the Danish area south of the Ringkøbing-Fyn High. They revised the subdivision made by Bertelsen (1980) and used a common nomenclature based on the south North Sea Basin (Van Adrichem & Kouwe 1994) and in Germany (Wolburg 1969, Menning 1995). However, this subdivision does not follow the nomenclature rules used by Hedberg (1976).

It has been difficult to use the stratigraphic nomenclature used by Bertelsen (1980) in the present investigation. The Höllviken-2 core sequence is therefore compared to both the nomenclature used by Bertelsen (1980) and the very detailed nomenclature used in Germany (Kozur 1974, Beutler & Schüler 1987, Aigner & Bachmann 1992, 1998).

THE NORTH GERMAN BASIN

In Germany, the Triassic sedimentation took place in the epicontinental Central European Basin, known as the North Germanic Basin during the Triassic. It belonged to the northern branch of the Peri-Tethyan Basin. There was sporadic connection to the Tethys Ocean in the south-east. Sur-

rounding highland areas produced clastic material, which was transported into the Germanic Basin producing a clastic margin, while limestone and argillaceous sediment dominated the central parts. The Triassic deposits are up to 3 000 m thick in this part of the basin.

The Triassic stratigraphy in the Germanic Basin has been summarised by Bachmann (1998), Aigner & Bachmann (1992, 1998, modified in Bachmann et al. 2005), Lepper & Röhling (1998), Hagdorn et al. (1998) and Beutler (1998). The classic German Triassic is divided into three sections: Buntsandstein, Muschelkalk and Keuper. A subdivision of the Keuper stratigraphy is presented by Beutler (1998). Beutler & Schöler (1987) compared the classic German Triassic subdivision with the division of the Triassic in the Danish area made by Bertelsen (1980).

STRATIGRAPHIC SUBDIVISION OF THE PRE-RHAETIAN TRIASSIC IN THE SWEDISH PART OF THE DANISH BASIN

Before 1947 knowledge of pre-Rhaetian Triassic rocks in Scania was restricted to the Keuper Kågeröd Formation. The Höllviken-2 well (drilled 1943–1947 by SGU) resulted in the first observation of older Triassic rocks in Scania. When interpreting the Höllviken-2 core, Brotzen (1950) identified a sequence ranging from the Kågeröd Formation to the Bunter Sandstone Formation. A few kilometres south-west of the Höllviken-2 well, the Ljunghusen-1 well was drilled some years later (1954–1955 by SGU). It penetrated the whole Triassic sequence and was finally completed in Silurian rocks. During 1971–1973 an additional 15 deep wells were drilled into the Triassic in western and southern Scania and offshore areas by OPAB. Most of the Triassic sequence was identified in the Höllviken Halfgraben. On the Skurup and Barsebäck platforms, however, only upper Triassic Kågeröd Beds have been found. Based on information from cuttings, cores and geophysical logs, OPAB compiled a lithostratigraphic subdivision of the Triassic sequence. The informal Maglarp formation was introduced. This informal formation was divided into three parts: A, B and C. Maglarp A corresponds to the Kågeröd Arkose, B to the rest of Keuper, and C to Muschelkalk. Bjelm et al. (1977) and Sivhed et al. (1999) also followed this subdivision.

In 2002–2003 four deeper wells were drilled for geothermal purposes, two in Malmö (FFC-1 and FFC-2) and two in Copenhagen (MAH-1 and MAH-2). In Copenhagen a complete sequence from the Kågeröd Formation to the Bunter Sandstone was penetrated, whereas the Malmö wells include strata of the Upper Muschelkalk to Lower Keuper sequence according to the German nomenclature.

Subdivision in Sweden presented

The lithostratigraphic subdivision of the Swedish part of the Danish Basin and the adjacent marginal area presented corresponds in many parts to the Germano-type Facies Province of Bertelsen (1980).

For the reasons discussed above, the subdivision made by Beutler & Schöler (1987) and Aigner & Bachmann (1992, 1998, modified in Bachmann et al. 2005) has served as a reference and guide in the present study. However, there are difficulties in fully extrapolating the German stratigraphy into the Höllviken Halfgraben. This is mainly due to the marginal position of Scania in relation to the North German Basin and also the Danish Basin. The marginal position has resulted in an even more pronounced lack of biostratigraphically important fossils. But there are beds with great similarities and verified age as in the North German Basin, which makes a correlation possible for at least parts of the sequence. A local stratigraphy is therefore proposed in this paper, since parts of Scania (the Höllviken Halfgraben) constitute a local structural element, which, periodically at least, had its own depositional history. Parts of the Scanian Triassic succession could be compared to the Triassic subdivision made by Beutler (1998), Beutler & Schöler (1987) and Michelsen & Clausen (2002). Figure 6 compares the Höllviken-2 core with the subdivision in northern Germany and the Germano Facies type province in the Danish Basin.

Since the pre-Rhaetian Triassic in Höllviken-2 is cored, it is used as a reference section for the pre-Rhaetian Triassic sequence in the Höllviken Halfgraben. The nearby Maglarp-1 well is more

recently drilled and includes, in contrast to the Höllviken-2 well, also a set of geophysical wire-line logging data. For this reason the core descriptions from the Höllviken-2 well are supplemented by geophysical measurements from the Maglarp-1 well.

The depositional pattern in Scania and the adjacent offshore area (this study) represents a marginal facies setting to the German Basin (cf. Tab. 4). The sediments were deposited in a tectonically active structure element, the Höllviken Halfgraben. Rifting, subsidence and sea level fluctuations have had a significant impact on deposition. Due to this, unconformities are likely to be frequent in the sequence.

In the data examined (logs, cores, cuttings) there are a number of marker beds, which provide a correlation between the stratigraphy of the Danish Basin and the Germano-type Facies Province. An example is the Lower Keuper Erfurt Formation (Lettenkohl or Lettenkeuper). Equivalent beds in Scania (Falsterbo Formation) are dated to the Ladinian (Piasecki 2005), an age corresponding to datings in the German Basin. The sedimentary rocks also display the same characteristic features, such as dark grey siltstone with coal fragments and thin coal layers, distinguishing them from the predominantly reddish-brown Triassic sequence.

Other examples are the Volprieshausen and Sollingen sandstone units of the lower Triassic Buntsandstein. These beds display the same lithological characteristics as the Ljunghusen Sandstone and the overlying sandy deposits referred to as Buntsandstein in Scania.

In the Scanian material there are also beds dominated by dolomitic limestone tentatively correlated with the Lower Gipskeuper.

In Scania the upper part of the pre-Rhaetian sequence is dominated by the Kågeröd Formation. These beds are probably a marginal facies to the more fine-grained deposits dominating the Steinmergelkeuper in the German Basin.

Buntsandstein–Muschelkalk

On lithological grounds, the lower Triassic unit, the Hammar Formation in the Höllviken-2 core and also the Ljunghusen Sandstone in other wells are referred to the Buntsandstein. However, the transition between the variegated sandstone units and the dark, plant-bearing sedimentary rocks of the overlying Keuper Falsterbo Formation are not dated. These transition beds – the Flommen Formation – could be marginal Keuper facies. Their stratigraphic position will remain unclear until they are dated. Brotzen (1950) referred the sandstone sequence to the Buntsandstein and classified the beds between the Buntsandstein and Falsterbo Formation as transition beds.

Ljunghusen Sandstone

The Ljunghusen Sandstone is best developed in the Ljunghusen-1, Höllviksnäs-1, MAH-1 and MAH-2 wells. Thin occurrences are also found in the Kungstorp-1 and possibly also Eskilstorp-1 wells. The Ljunghusen sandstone is only found in the deepest part of the Höllviken Halfgraben. The name Ljunghusen Sandstone was first mentioned in OPAB unpublished reports. A general description of the formation is given in Sivhed et al. (1999). The formation has not been formally defined until now. Figure 7 presents a compilation of logging data from the Ljunghusen-1 and Höllviksnäs-1 wells.

Local reference section: Ljunghusen-1 well
55° 23' 37" N–12° 54' 48" E
Depth interval: 2 088–2 150 m below K.B.
Thickness in local reference section: 62 m

Lithology

In the Ljunghusen-1, MAH-1 and MAH-2 wells, the lithology is composed of relatively homogeneous, well-sorted, medium-grained quartz sandstone. The Ljunghusen Sandstone is a reddish-green,

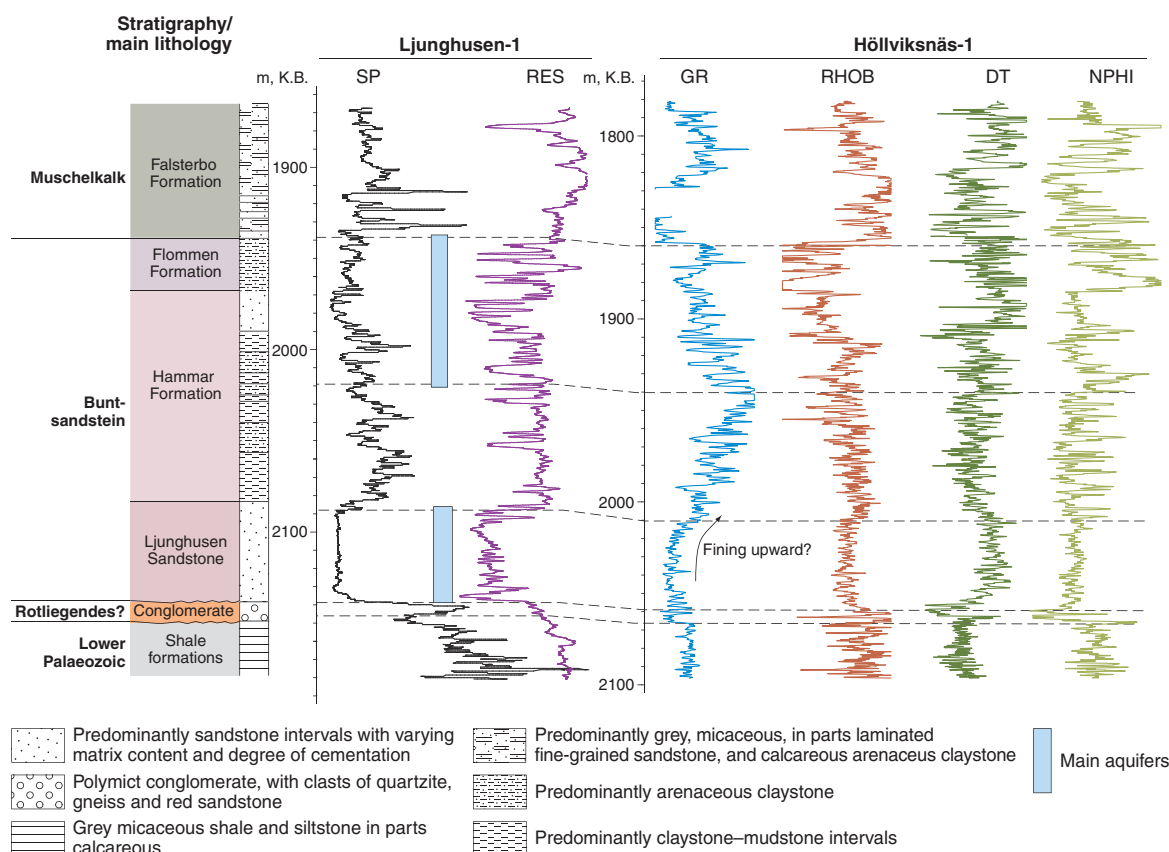


Figure 7. Compilation of log data from Ljunghusen-1 and Höllviksnäs-1 for the definition of the Ljunghusen Sandstone and the Hammar Formation.

medium-grained to coarse-grained soft sandstone with silty layers and traces of carbonate cement. The marginal part of the sandstone unit is not very well documented, e.g. the Ljunghusen deposits in Eskilstorp-1 and Kungstorp-1. The log signal indicates a less homogeneous deposit in these parts. L.-H. Nielsen (GEUS, personal communication), among others, has suggested that parts of the sandstone may be of eolic origin. This is based on the polished surface of the quartz grains and the homogeneous texture.

Boundary definitions

The Ljunghusen Sandstone is well defined by the log signal. Low gamma ray and low resistivity readings distinguish the sandstone from the overlying arenaceous claystone. A rapid change in rate of penetration (ROP) occurred during the drilling of MAH-1 and MAH-2, when entering the homogeneous and loose Ljunghusen Sandstone. The basal boundary is defined by a hard quartzitic and conglomeratic bed, which occurs in most wells beneath the Triassic sequence in the Höllviken Halfgraben. This bed overlies either the crystalline basement, as in MAH-1 and MAH-2, or Lower Palaeozoic strata, as in Ljunghusen-1. The gamma ray log from Höllviksnäs-1 shows a gradual increase of matrix clay towards the top of the Ljunghusen Sandstone (Fig. 7).

Fossils and age

There are no fossils found in the sandstone. However, a Schytian age is the most probable. It is most likely that the Ljunghusen Sandstone forms the lowermost part of the Middle Bunter Sandstone.

Hammar Formation

On lithological grounds, the variegated red and green sandstone forming the basal Triassic sequence in the FCC-1 well is comparable to the Middle Bunter Solling and Volpriehausen sandstones in the German Basin. Further south, in Scania, it rests on the Ljunghusen Sandstone. In this publication the unit is given the name the Hammar Formation, after the village of Hammar in south-west Scania.

Local reference section: Höllviken-2 well
(Brotzen 1950, p. 13–14, Pl. 1)
55° 23' 50" N–12° 56' 40" E
Depth interval: 1886–1923.76+ m below K.B.
Thickness in local reference section: 37.76 m

Local reference log section: Maglarp-1 well
55° 23' 14" N–13° 03' 51" E
Depth interval: 1885–1899 m below K.B.
Thickness in local reference log section: 44 m

Lithology

In the Höllviken-2 core, the Hammar Formation is dominated by speckled, red and green, fine-grained greywackes (Fig. 8). They are interbedded with dark red, coarse-grained arkosic sandstone. Dolomitic concretions are frequent in the upper part of the sequence. No fossils have been recorded.

Boundary definitions

The lower boundary of the Hammar Formation is not known from the Höllviken-2 well. In other deep wells in the area (for instance the Maglarp-1 well, 1899–1906 m) the Triassic sequence rests on a polymict conglomerate, tentatively referred to lower Permian, Rotliegendes (Sivhed et al. 1999).

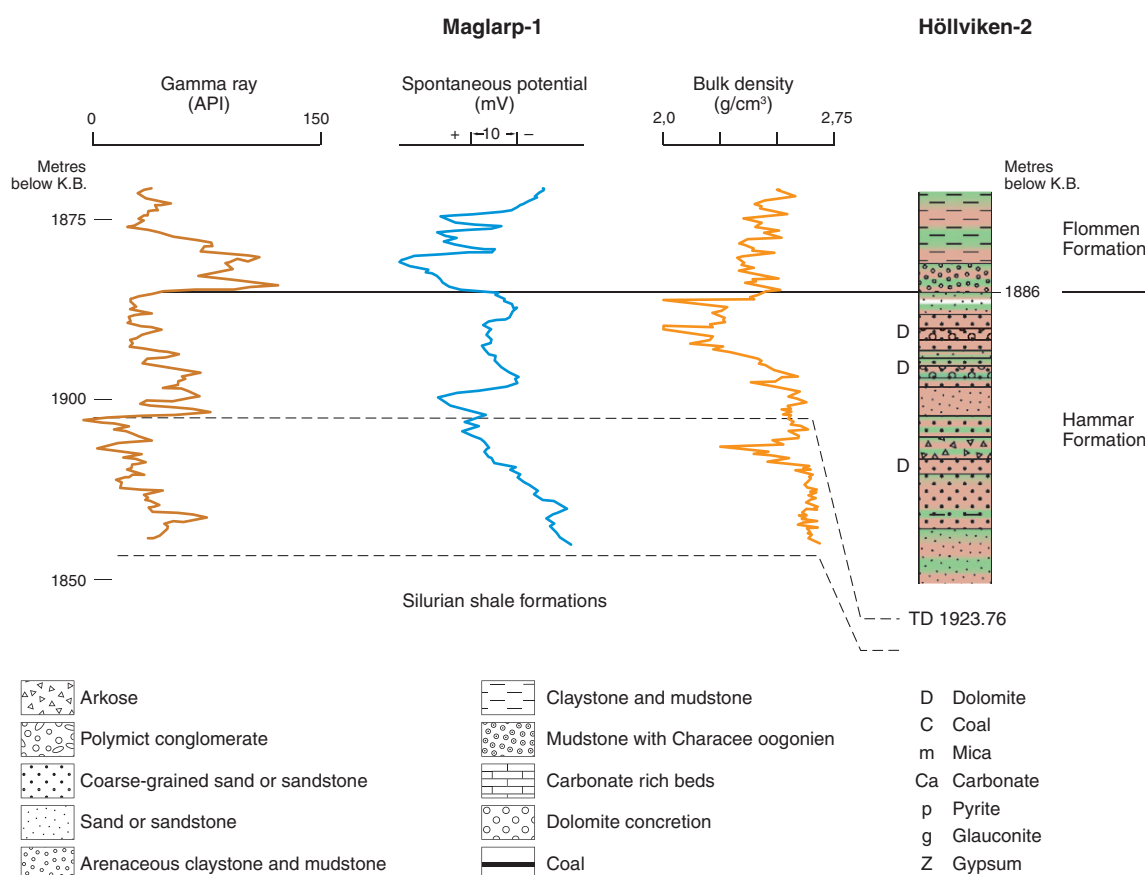


Figure 8. Reference section of the Hammar Formation. The geophysical logs originate from the Maglarp-1 well and the litho-logs from the Höllviken-2 core. The legend for Figures 8–14 and 16 are shown here. The colours illustrated in Figures 8–14 and 16 are the same colours as the rock recorded in the core.

The conglomerate is clearly indicated in the gamma ray and the bulk density logs and by the clear change in the electrical logs. The gamma ray and bulk density logs display declining values upwards in the section.

In the Höllviken-2 well, the upper boundary to the Flommen Formation is drawn between the clean, hard sandstone at 1 886.29 m and the succeeding argillaceous, sub-fissile and partly laminated claystone of the Flommen Formation. This facies change is clearly indicated by low resistivity and pronounced peaks in the gamma ray and bulk density logs.

Fossils and age

Finds of palynomorphs (*Protohaploxypinus pantii*) at 2 625 m and 2 670 m in the MAH-1 well (Dyb-kjaer et al. 2003) indicate the *obsoleta-pantii* Zone (Orlowska-Zwolinska 1983, 1985). This zone is defined in the lower Bunter Sandstone in Poland and represents an early Scythian age (Griensbachian according to Fijakowska-Mader 1999). In Germany, the Middle Bunter Sandstone correlates to the Jakutian to early Olenkian stages of the Scythian (Kozur 1975).

Comments

Drilling in the Höllviken-2 well stopped for technical reasons after penetrating 37.76 m of the Hammar Formation.

Flommen Formation

The variegated red and green claystone sequence forming the boundary between the Hammar Formation and the Falsterbo Formation in the Höllviken-2 core is correlated to the Upper Bunter Sandstone and the Muschelkalk. Brotzen (1950) referred to the same layers as transition beds between the Bunter Sandstone and the Muschelkalk. In this publication the unit is named the Flommen Formation, after the village of Flommen in south-west Scania.

Local reference section: Höllviken-2 well (Brotzen 1950, p. 15, Pl. 1) 55° 23' 50" N–12° 56' 40" E Depth interval: 1862–1886 m below K.B. Thickness in local reference section: 26 m	Local reference log section: Maglarp-1 well 55° 23' 14" N–13° 03' 51" E Depth interval: 1868–1885 m below K.B. Thickness in local reference log section: 17 m
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Lithology

The Flommen Formation consists of laminated sandstone interbedded with siltstone, sandstone and argillaceous, fine-grained sandstone (Fig. 9). The colours are dark red, brownish red, pale red, dark green, green and light green. The matrix alternates between calcitic and dolomitic. The clays show swelling characteristics (smectite, Jacobsen 1993). There are large amounts of coaly fragments in the upper part of the formation.

Boundary definitions

The lower boundary of the Flommen Formation is drawn at the transition from the sandy layers of the Hammar Formation to the argillaceous Flommen Formation. It is also indicated by the significant decrease in the gamma ray signal and in the bulk density log. The more argillaceous part of the Flommen Formation is identified by lower gamma ray values.

The upper boundary is drawn at the transition between the variegated Flommen sandstone beds and the grey sedimentary rocks of the Falsterbo Formation. The upper boundary is identified by a pronounced increase in the gamma ray value.

The bulk density log displays a finely serrated log curve, reflecting the laminated sequence of sandstone and argillaceous, fine-grained sandstone.

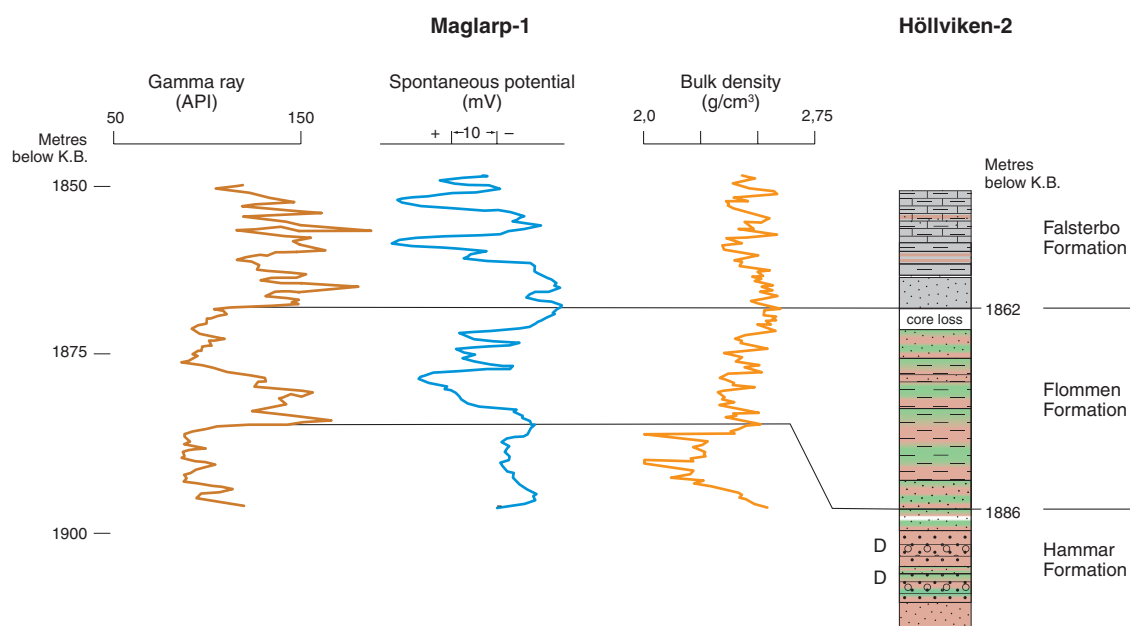


Figure 9. Reference section of the Flommen Formation. The geophysical logs originate from the Maglarp-1 well and the litho-logs from the Höllviken-2 core. Legend is shown in Figure 8.

Fossils and age

The Flommen Formation is not dated in either the Danish Basin or the Swedish marginal part. In Poland and Germany, however, its flora dates the corresponding beds to early Muschelkalk. A late Schytian (late Olenikian) to early Anisian age has been suggested (Kozur 1975, Orlowska-Zwolinska 1977).

Lower to Middle Keuper

In the Danish Basin, Bertelsen (1980) introduced the Jylland Group including the Tønder and Oddeund Formations for the Lower and Middle Keuper and the Vinding Formation of the Mors Group for the Upper Keuper. Michelsen & Clausen (2002) included the whole sequence between the Muschelkalk and the Gassum Formation in the Keuper Formation. They divided the Keuper Formation into six members. The division made by Bertelsen (1980) and Michelsen & Clausen (2002) is difficult to apply in the data studied. However, there are at least some common features, such as a possible correlation of the dolomitic part of the Höllviken-2 core to the Main Keuper Evaporite Member.

According to Beutler (1998), the Lower Keuper in Germany is dominated by the Erfurt Formation, whereas the Middle Keuper is divided into the Grabfeld Formation (Lower Gipskeuper) and the Stuttgart Formation (Schilfsandstein), followed by the Weser Formation (Upper Gipskeuper) and the Arnstadt Formations (Steinmergelkeuper).

In the Höllviken-2 core it is possible to divide the sequence between the Falsterbo and the Rhaetian–Hettangian Höganäs formations into four lithostratigraphic units. A lower formation, the Vellinge Formation, is followed by the Fuglie Formation, which is a possible equivalent of the Main Keuper Evaporite Member of the Grabfeld Formation. The Fuglie Formation is succeeded by the Stavsten Formation, which is probably equivalent to the Stuttgart Formation (Schilfsandstein) and the Vinding Formation. The upper part of the pre-Rhaetic succession consists of the Kågeröd Formation, which is equivalent to the Skagerrak and Arnstadt Formations.

Falsterbo Formation

In the predominantly reddish and greenish pre-Rhaetian Triassic beds there is a more than 100 m thick sequence of grey, argillaceous sedimentary rocks. Plant fossils as well as fish remains have been recorded in these beds. A minor coal seam is also found in the Höllviken-2 core (1805 m). Coal remains have also been identified in cuttings from other wells, for instance FFC-1 (2029–2080 m), FFC-2 (2700–2785 m), Maglarp-1 (1834 m), Hammarlöv-1 (1534–1542 m) and Eskilstorp-1 (1784–1842 m).

Brotzen (1950) was of the opinion that the layers in the Höllviken-2 core were a Muschelkalk–Lettenkohl equivalent. He postulated that the Muschelkalk limestone facies did not reach into the Scanian epicontinental sea.

The deposits in the Höllviken-2 core display the same characteristics, namely colour, plant remains and coal layers, as the Erfurt Formation (cf. Beutler & Schöler 1987). According to Beutler (1998), the Lower Keuper comprises one formation, the Erfurt Formation, which was formerly called Lettenkeuper or Lettenkohlkeuper. In Germany the Erfurt Formation is divided into three parts. The lower and upper parts are dominated by argillaceous and coaly beds, whereas the middle part consists of sandy beds – the Hauptsandstein. In general, the same subdivision could be made in the Höllviken-2 core. According to Kozur (1974), the palynomorph flora indicates a Middle Muschelkalk age for the interval 1862–1854 m, Upper Muschelkalk for the interval 1798–1854 m and a Lower Keuper age down to 1798 m. However, in their sequence stratigraphic framework, Aigner & Bachmann (1992, modified in Bachmann et al. 2005) gave the Lettenkeuper and Hauptsandstein a late Ladinian age. This dating corresponds to the dating made by Piasecki (2005). He identified the late Ladinian *Protodiploxypinus* assemblage in the Höllviken-2 core and in cuttings from the FFC-1 and FCC-2 wells.

Deposits related to the Erfurt Formation are not noted in the stratigraphic table of the Triassic in the Danish Basin and southern and central North Sea Basin (Michelsen & Clausen 2002). Here, the Keuper Formation directly succeeds the Muschelkalk Formation. However, in south-west Scania and in Copenhagen (MAH-1 and MAH-2 wells), deposits comparable to the Erfurt Formation are identified by lithological characteristics and also by dating (palynomorphs, Piasecki 2005).

Local reference section: Höllviken-2 well (Brotzen 1950, p. 16–21, Pl. 1) 55° 23' 50" N–12° 56' 40" E Depth interval: 1755–1862 m below K.B. Lower Keuper: 1862–1755 m below K.B. Thickness in local reference section: 107 m	Local reference log section: Maglarp-1 well 55° 23' 14" N–13° 03' 51" E Depth interval: 1790–1868 m below K.B. Thickness in local reference log section: 78 m
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Lithology

The Falsterbo Formation is characterised by grey argillaceous sandstone, sub-fissile and partly laminated sandstone and calcareous sandstone (Fig. 10). The grey colours clearly distinguish the Falsterbo Formation from the predominantly variegated red and green pre-Rhaetian Triassic formations.

Brotzen (1950) made a detailed subdivision of the sequence in the Höllviken-2 core. He distinguished six lithostratigraphic units (a–f), split into different beds. He based these subdivisions on lithological characteristics as well as biostratigraphic evidence. Based on the work by Brotzen (1950) and Horn af Rantzien (1953), Kozur (1974) correlated the Höllviken sequence with the classic German subdivision.

Unit a (1854–1862 m) consists of light grey and grey fine-grained sandstone and sub-fissile and partly laminated mudstone. There are two 0.3 m thick layers of red sub-fissile and partly laminated mudstone in the upper part. No fossils are recorded.

Unit b, the “Characeae zone” (1843–1854 m) consists of grey marlstone, sub-fissile and partly laminated mudstone and some minor fine-grained sandstone beds, locally mottled red. A relatively

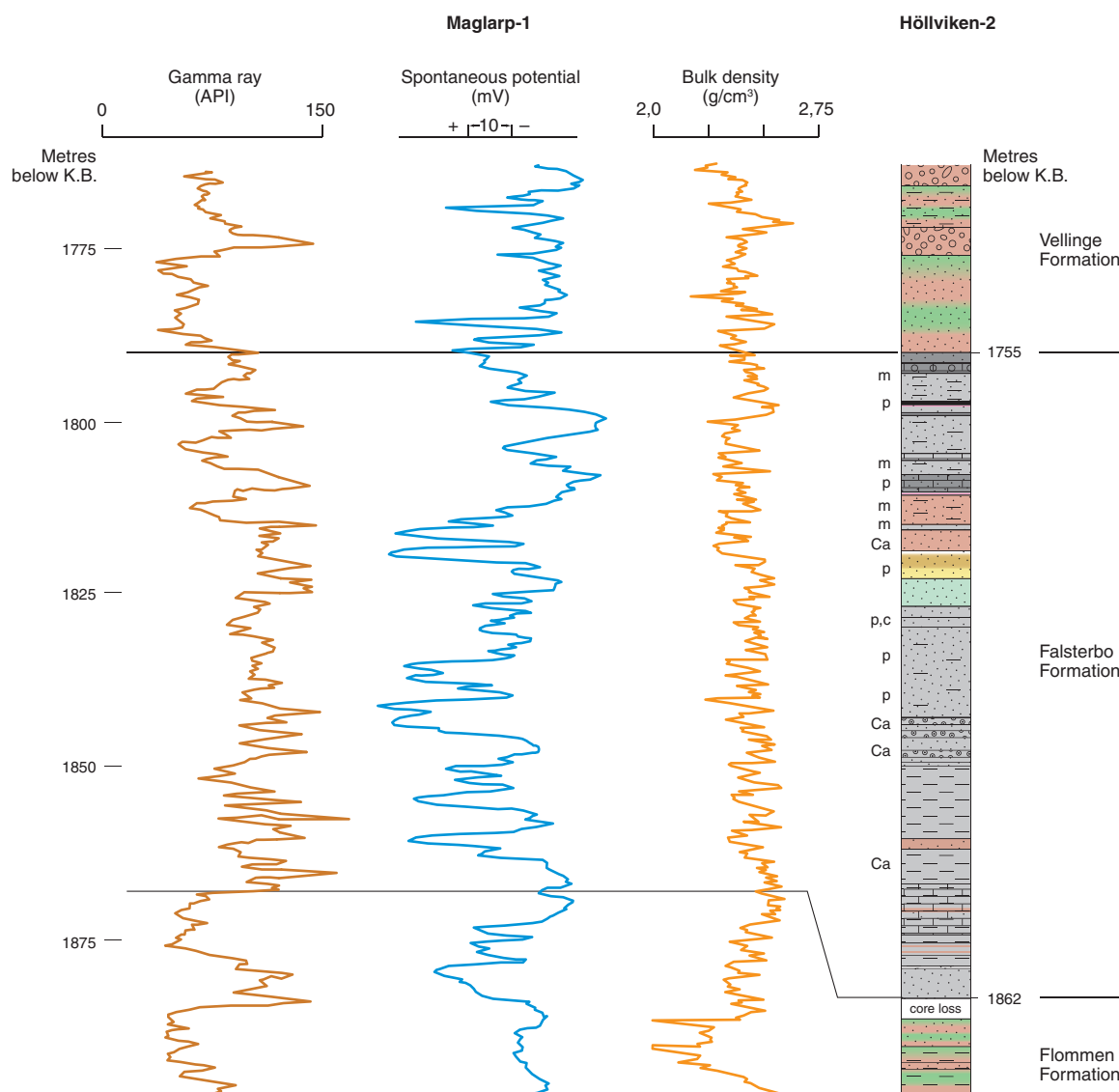


Figure 10. Reference section of the Falsterbo Formation. The geophysical logs originate from the Maglarp-1 well and the litho-logs from the Höllviken-2 core. Legend is shown in Figure 8.

high carbonate content is characteristic of the zone. Characeae oogons (Horn af Rantzien 1953) are frequent in certain layers, together with bone and fish remains.

Unit c (1827–1843 m) consists of grey, loose, sub-fissile and partly laminated mudstone (poor core recovery).

Unit d (1800–1827 m) consists of grey, sub-fissile and partly laminated mudstone and beds with calcareous concretions and marls. Carbonate concretions are frequent in the marlstone. The concretions have a diameter varying between 1 and 50 mm. Plant and fish fossils are frequent in this unit, together with a few ostracods. Fragments of carbonised plant remains occur. A minor coal seam occurs at 1805 m. Gymnosperm cuticles from the 1800–1827 m interval are described by Lundblad (1949) and Characeae oogons by Horn af Rantzien (1953).

Unit e (1800–1784 m) consists of reddish grey and brown, fine-grained sandstone and mudstone. A light grey to white, in parts coarse-grained, sandstone with high porosity occurs at a depth of 1796–1800 m. OPAB reports named this the Falsterbo sandstone. Core recovery is poor.

Unit f (1755–1784 m) consists of greyish sandstone, sub-fissile and partly laminated mudstone, and marls with calcareous concretionary beds. The beds are similar to those of unit d. They are fossiliferous, like those of unit e, and contain plant fossils as well as fish remains and ostracods.

Boundary definitions

The lower boundary of the Falsterbo Formation is drawn at the transition between the variegated Flommen Formation and the grey deposits of the Falsterbo Formation. A pronounced drop in gamma ray values coincides with the lower boundary.

The upper boundary is drawn at the transition from the grey, argillaceous sedimentary rock of the Falsterbo Formation to the sandy, variegated red and green Vellinge Formation. This can be seen from the drop in gamma ray values.

The Vellinge Formation is characterised by higher gamma ray values than the underlying Flommen and the overlying Falsterbo Formations. A thin-bedded sequence of variably argillaceous and indurated sandstone beds is displayed in the gamma and density logs.

Fossils and age

The fossil fauna and flora described by Brotzen (1950), Lundblad (1949) and Horn af Rantzien (1953) showed similarities to the fauna and flora in the Lettenkohl and Muschelkalk deposits in Germany.

Larsson et al. (1994) described a poorly preserved palynoflora in a sample from 1804 m in the Höllviken-2 core, indicating a Ladinian–Carnian age.

Based on the findings of charophytes and ostracods, Brotzen (1950), Horn af Rantzien (1953) and Kozur (1974) assigned a Carnian–Ladinian–Anisian age to the Höllviken-2 section at a depth of between 1755 and 1862 m. A new charophyte species, *Stellatochara sellingsii*, was described by Horn af Rantzien (1953) in zone d in the Höllviken-2 core at a depth of 1805 m.

The *Protodiploxylinus* assemblage was described by Piasecki (2005) in a palynological analysis of cuttings from the FFC-1 (2029–2080 m) and FFC-2 (2700–2785 m) cores. The assemblage is characterised by *Aratrisporites* spp., *Protodiploxylinus* spp. (*Minutosaccus* spp. from Mädler 1964), *Alisporites*, *Triadispora* and *Voltzaceasporites*, *Nevesisporites lubricus*, *Retisulcites perforatus* and *Ovalipollis brutus*.

Vellinge Formation

Brotzen (1950) defined the rock sequence at a depth between 1755 and 1691 m in the Höllviken-2 core as the lower sandstone series in the lower part of the Upper Keuper. Kozur (1974, Tab. 4) tentatively referred the lower part of the sequence to the Lettenkeuper (Erfurt Formation). The sequence may correspond to the Tønder Formation in Denmark in some respects (Bertelsen 1980). In this publication the unit is named the Vellinge Formation, after the village of Vellinge in south-west Scania.

Local reference section: Höllviken-2 well (Brotzen 1950, p. 21–23, Pl. 1) 55° 23' 50" N–12° 56' 40" E Depth interval: 1691–1755 m below K.B. Thickness in local reference section: 64 m	Local reference log section: Maglarp-1 well 55° 23' 14" N–13° 03' 51" E Depth interval: 1725–1790 m below K.B. Thickness in local reference log section: 65 m
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Lithology

In Höllviken-2 the rock sequence of the Vellinge Formation consists of reddish, reddish-brown and green sandstone (Fig. 11). The sandstone is argillaceous, fine-grained to medium-grained and locally contains carbonate concretions. Carbonate cemented beds of conglomerate are relatively frequent in the sequence.

Table 4. Compilation of distinguishing characteristics in the pre-Rhaetian Triassic formations.

Formation	Colour	Significant character	Environment	Other characteristics
Kågeröd Formation	Red, green	Extremely poorly sorted, angular, arkosic, calcite cemented, conglomeratic. Uppermost part composed of arenaceous clay.	Arid, temporary alluvial conditions, fanglomeratic.	Large calcite crystals, angular grains, rock fragments.
Stavsten Formation	Reddish brown in parts mottled red-green	Arkoses, angular grains, carbonate cemented, often "floating" detrital grains, calcretes. Local arenaceous limestone beds, especially in most basal parts.	Arid, alluvial.	
Fuglie Formation	Mottled red-grey-green, white	Poorly sorted arenaceous claystones and mudstones and matrix-rich sandstones dominate. Mottled texture, nodular, chaotic texture, dolomite-rich, calcite, evaporitic, calcretes. Overgrowth of silica in basal beds.	Arid, evaporitic, palaeosols, ephemeral rivers, shallow local basins.	Often dense, i.e. well cemented by calcite. Significant log pattern (low gamma ray).
Vellinge Formation	Red-brown	Dominated by "dirty" sandstones with scattered conglomerates. Carbonate nodules. Overgrowth of quartz is a common feature as well as a chloritic-siliceous matrix. Parts of the deposits are cross-bedded.	Alluvial plain, arid.	Overgrowth of silica.
Falsterbo Formation	Grey colours dominate	Typically laminated, organic material, coal fragments, mica, fossils.	Humid, lacustrine, shallow marine.	Pollen-spores.
Flommen Formation	Red and green	Laminated and uniformly composed of fissile claystone and fine-grained sandstone beds.	Transition into more humid conditions.	
Hammar Formation	Purple, brown colours dominate	Dense arenaceous claystones alternating with poorly sorted medium-grained and coarse-grained sandstone, conglomerate, dolomite, calcite, calcretes.	Arid, proximal facies to the Danish Basin, braided river system, low relief, and local subsidence in basins (Höllviken?).	Divided into three subsequences: a basal dominated by claystone, a middle with numerous porous and permeable sandstone beds, and an upper unit dominated by dense arenaceous claystone.
Ljunghusen Sandstone	Pink, light red	Sorted, fine-grained, uniform.	Arid, eolian?	Loose. Typical log pattern for homogeneous sand.

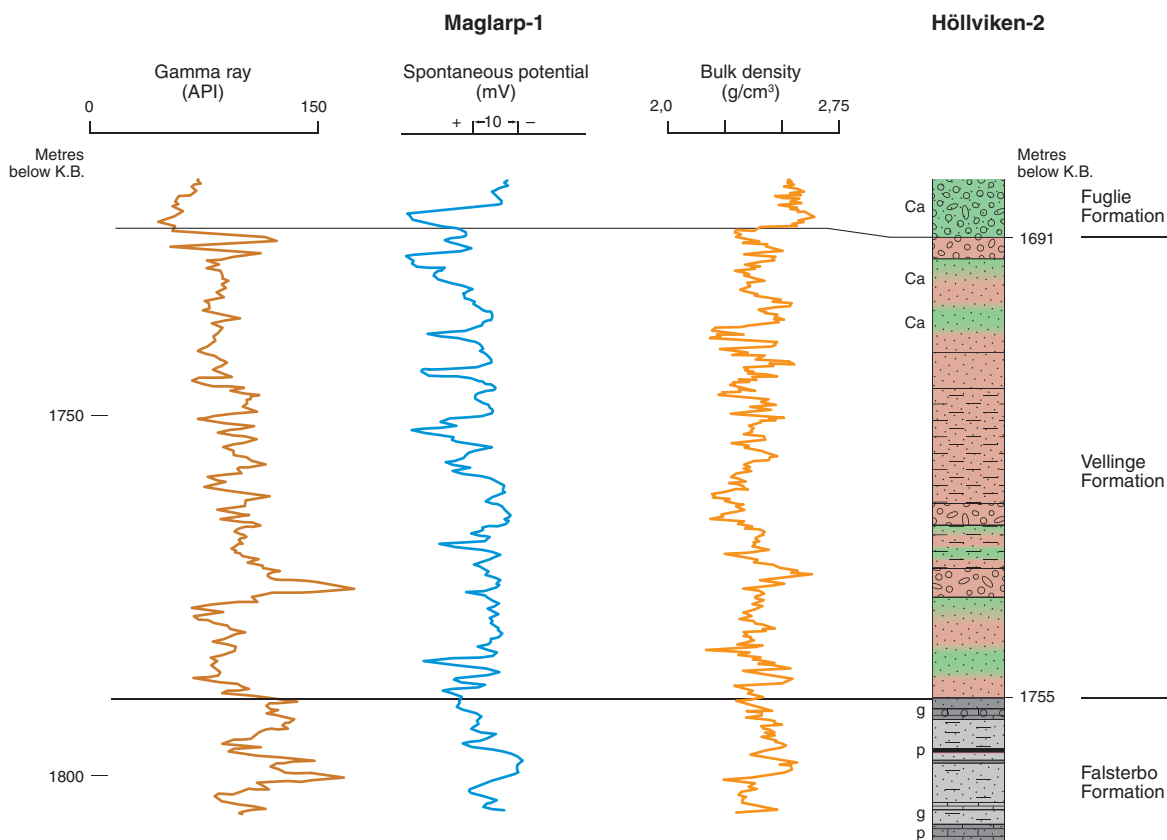


Figure 11. Reference section of the Vellinge Formation. The geophysical logs originate from the Maglarp-1 well and the litho-logs from the Höllviken-2 core. Legend is shown in Figure 8.

Boundary definitions

The lower boundary of the Vellinge Formation is drawn in the transition zone from the greyish deposits of the Falsterbo Formation to the variegated sandstone of the Vellinge Formation. The upper boundary is defined as the top of the uppermost conglomeratic bed, which is 3 m thick in the Höllviken-2 core. The Vellinge Formation is characterised by lower gamma ray values than the underlying Falsterbo Formation and higher values than the Fuglie Formation.

The lower boundary is defined as the interface between the grey, argillaceous sedimentary rock of the Falsterbo Formation and the sandy, variegated red and green Vellinge Formation. This boundary is characterised by a marked upwards decrease in gamma ray values. Conglomerate beds are also identified by distinct peaks in the gamma ray log, indicating the presence of fragments of crystalline rock.

Fossils and age

No fossils have been found in the Vellinge Formation. According to Bertelsen (1980), corresponding beds in the North German Basin and the Polish Basin are dated by their flora to late Ladinian (Langobardian).

Fuglie Formation

Brotzen (1950) assigned the sequence between 1642 and 1691 m in the Höllviken-2 core to the Gipskeuper. He named it the dolomitic series because of the high content of dolomite. In this publication the unit is named the Fuglie Formation, after the village of Fuglie in south-west Scania.

Local reference section: Höllviken-2 well (Brotzen 1950, p. 21–26, Pl. 1) 55° 23' 50" N–12° 56' 40" E Depth interval: 1642–1691 m below K.B. Thickness in local reference section: 49 m	Local reference log section: Maglarp-1 well 55° 23' 14" N–13° 03' 51" E Depth interval: 1680–1725 m below K.B. Thickness in local reference log section: 45 m
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Lithology

The lower part of the Fuglie Formation (1642–1691 m) is dominated by beds of variegated red, brown and green dolomitic sandstone, conglomerate and breccia (Fig. 12). The strata display a higher degree of consolidation than the bounding formations. Oolitic layers are found in the sequence.

The carbonate content is less significant in the upper part (1604–1642 m) of the formation. The deposits are characterised by variegated red and green sandstone and arkose, partly carbonate impregnated. The sandstone is fine-grained with a few coarse-grained beds. Oolitic layers also occur as interbeds in the lower unit.

Boundary definitions

The lower boundary of the Fuglie Formation is defined where the dolomitic and brecciated strata of the Fuglie Formation are underlain by carbonate cemented strata of the Vellinge Formation. A distinct peak in the gamma ray log identifies the lower boundary.

The lower part of the Vellinge Formation is characterised by lower gamma ray values than the underlying formation. The gamma ray curve is characterised by frequent, narrow peaks with high values, probably indicating massive dolomite impregnation.

The upper boundary is defined as the base of the carbonate beds of the Stavsten Formation. A distinct peak value in the gamma ray log probably coincides with the upper boundary. Narrow and scattered peaks are interpreted as dolomitic and argillaceous deposits.

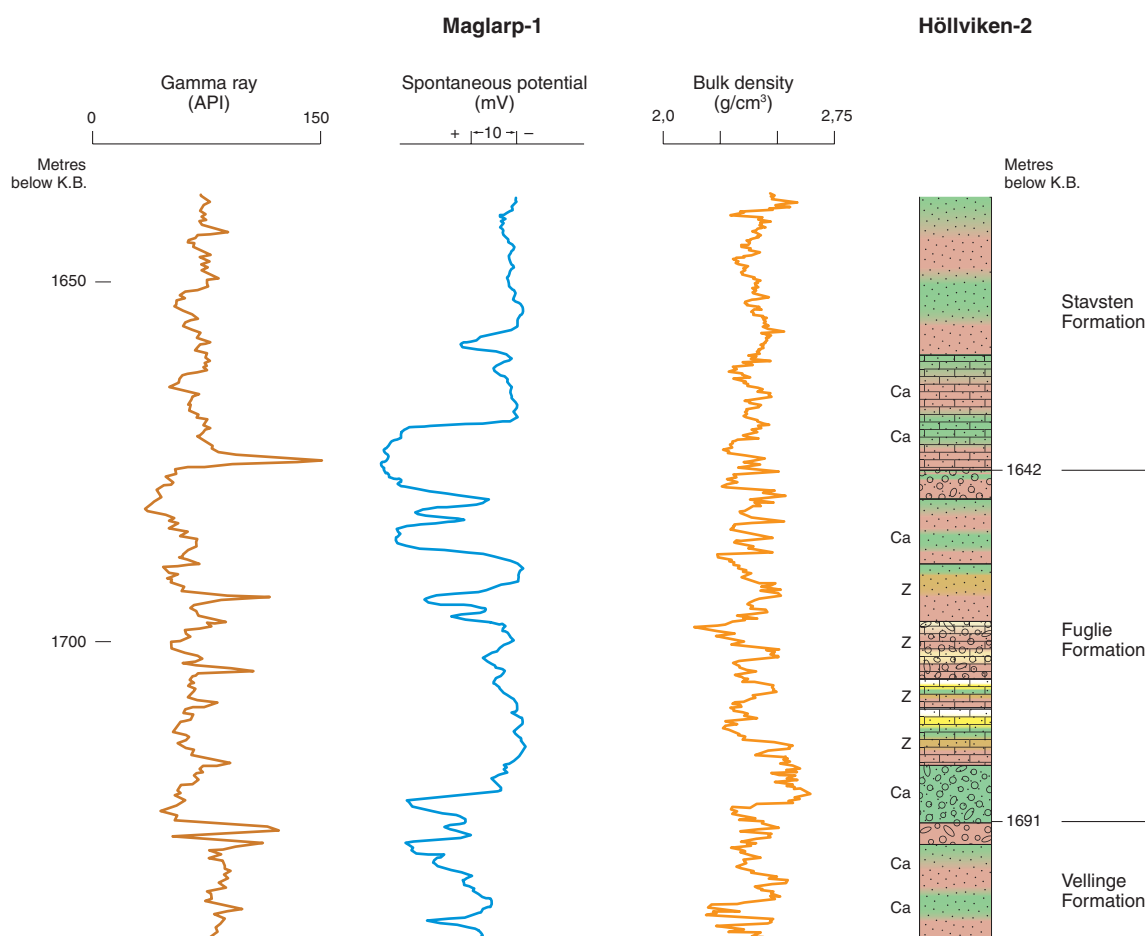


Figure 12. Reference section of the Fuglie Formation. The geophysical logs originate from the Maglarp-1 well and the litho-logs from the Höllviken-2 core. Legend is shown in Figure 8.

Fossils and age

According to Bertelsen (1980), a Carnian age is indicated by palynomorphs in corresponding core material from the Gassum-1 well. Based on ostracods as well as palynomorph studies in the overlying Vinding Formation, an early Norian age is suggested by Bertelsen (1978, 1980) for the Main Keuper Evaporite Member.

Discussion

The gamma ray log pattern in the lower part of the Fuglie Formation is interpreted to correspond to the log pattern of the Lower Evaporite Beds of the Ørslev Formation (Bertelsen 1980). According to Michelsen & Clausen (2002), these beds correspond to the Main Keuper Evaporite Member in the Lower Gipskeuper strata of the Grabfeld Formation by Beutler & Schüller (1987).

Limestone beds form the basal part of the overlying Vinding Formation in the Danish Basin (Bertelsen 1980). There are limestone and strongly carbonate impregnated sandstone beds in the lower part of the Fuglie Formation in the Höllviken-2 core. These beds are coupled with a significant peak in the gamma ray log curve. This log response in the same stratigraphic position is characteristic in other wells in south-west Scania.

The carbonate beds in the lower part of the Fuglie Formation could be lithostratigraphically assigned to the Main Keuper Evaporite Member. Alternatively, they may represent the Vinding Formation or the Stuttgart Formation (Schilfsandstein).

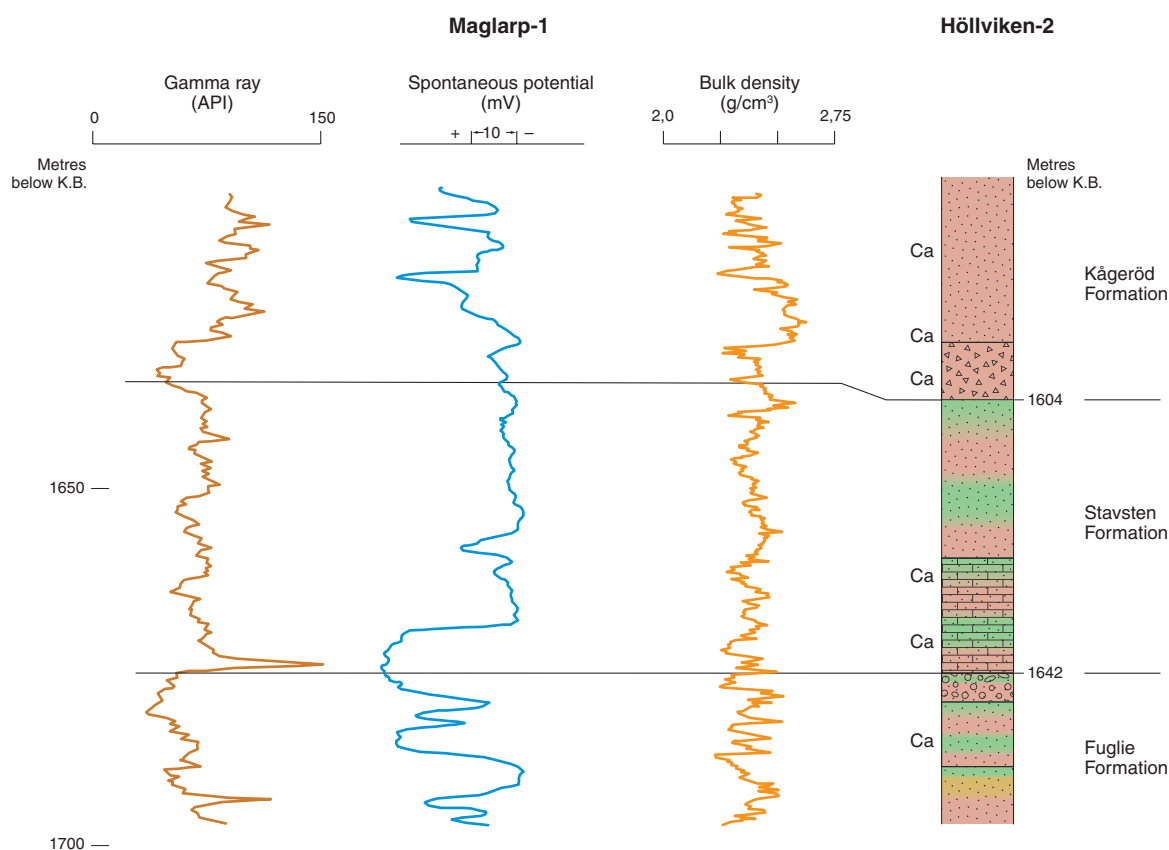


Figure 13. Reference section of the Stavsten Formation. The geophysical logs originate from the Maglarp-1 well and the litho-logs from the Höllviken-2 core. Legend is shown in Figure 8.

According to Bertelsen (1980, p. 33), the Oddesund Formation (Main Keuper Evaporite Member of Michelsen & Clausen 2002) probably grades laterally into the Kågeröd Formation in Scania. However, no major trace of evaporitic beds has been observed in the Kågeröd beds. In the Höllviken-2 core, the common occurrence of dolomite in the lower part of the Fuglie Formation clearly shows the evaporitic influence. Since these beds are older than the Kågeröd Formation, it is difficult to correlate the lower part, at least, of the Kågeröd Formation.

Stavsten Formation

A sandy sequence with carbonate impregnation occurs at a depth of 1 604–1 642 m in the Höllviken-2 core. In this publication this unit is named the Stavsten Formation, after the village of Stavsten in south-west Scania.

Local reference section: Höllviken-2 well (Brotzen 1950, p. 21–26, Pl. 1) 55° 23' 50" N–12° 56' 40" E Depth interval: 1 604–1 642 m below K.B. Thickness in local reference section: 38 m	Local reference log section: Maglarp-1 well 55° 23' 14" N–13° 03' 51" E Depth interval: 1 635–1 680 m below K.B. Thickness in local reference log section: 45 m
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Lithology

Red and green sandstone beds with interbeds of conglomerate and arkose dominate the deposits of the Stavsten Formation (Fig. 13). The lower part of the sequence also includes limestone and calcareous sandstone beds.

Boundary definitions

The lower boundary of the Stavsten Formation is at the base of the limestone and calcareous sandstone beds, where a pronounced peak in gamma ray values occurs. The upper boundary is marked by a decrease in the gamma ray log values, representing the basal conglomerate of the Kågeröd Formation.

Fossils and age

No fossils have been found in the Stavsten Formation.

Discussion

The Stavsten Formation is tentatively correlated to the Stuttgart Formation (Schilfsandstein). This means that the Upper Gipskeuper is missing and the sedimentary rocks of the Kågeröd Formation follow on top of the Stuttgart Formation. This also applies if the Stavsten Formation is correlated to the Vinding Formation.

Bertelsen (1978) interpreted the Kågeröd and Skagerrak Formations as marginal facies of the Vinding Formation. If so, the Stavsten Formation should be included in the basal part of the Kågeröd Formation.

Kågeröd Formation

The Kågeröd Formation is well known and defined from outcrops in north-western and central Scania. It is also identified in deeper wells and seismic sections in south-west Scania and adjacent offshore areas (Sivhed & Wikman 1986, Erlström et al. 1996, Sivhed et al. 1999).

The name Kågeröd sandstone was introduced by Angelin (1877) for the red and green sandstone beds that he defined as older than Rhaetian strata in Scania. He also assigned a Keuper age to these strata. Sixty-five years later, Troedsson (1942) made a comprehensive study of the Kågeröd Formation. He based his study on outcrops and core material. Brotzen (1950) described a sequence of 108 m Kågeröd layers in core material from the Höllviken-2 well. Köster (1956) described a 271 m long core sequence in the same layers from the Klappe core from north-west Scania.

The Kågeröd Formation is divided into two members: the lower Kågeröd Arkose and the upper Kågeröd Clay.

As discussed above (see Vinding Formation), Bertelsen (1978) suggested that the Kågeröd and Skagerrak Formations are marginal facies to the Vinding Formation. There is also a possibility that the Stuttgart Formation (Schilfsandstein) corresponds to the basal part of the Kågeröd Formation.

Kågeröd Arkose

Local reference section: Höllviken-2 well (Brotzen 1950, p. 27–28, Pl. 1) 55° 23' 50" N–12° 56' 40" E Depth interval: 1528–1604 m below K.B. Thickness in local reference section: 76 m	Local reference log section: Maglarp-1 well 55° 23' 14" N–13° 03' 51" E Depth interval: 1547–1635 m below K.B. Thickness in local reference log section: 88 m
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Lithology

The Kågeröd Arkose is composed of red, green and grey arkose, sandstone and claystone (Fig. 14). Distinguishing characteristics in older Triassic rocks are a high frequency of feldspar and a low carbonate content. In addition, conglomerate beds are found fairly frequently in the sequence. Most of the conglomerate pebbles in the Höllviken area are composed of redeposited Triassic rocks. However, further north-east the pebbles are dominated by crystalline bedrock or Palaeozoic rocks.

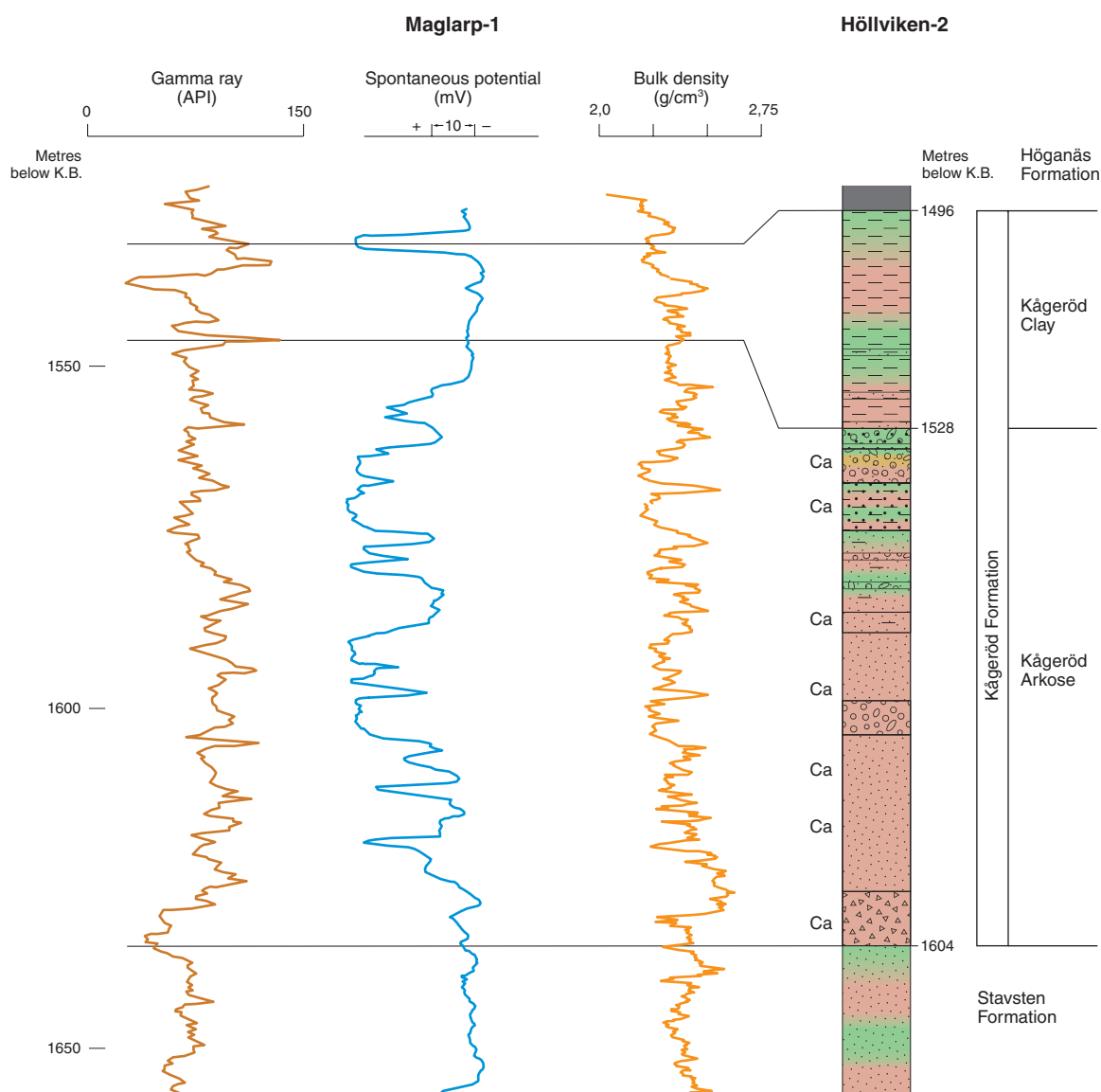


Figure 14. Reference section of the Kågeröd Formation. The geophysical logs originate from the Maglarp-1 well and the litho-logs from the Höllviken-2 core. Legend is shown in Figure 8.

Boundary definitions

The lower boundary of the Kågeröd Arkose is drawn at the base of a coarse-grained arkose with feldspar grains up to and more than 1 cm in size. This bed is clearly indicated by a drop in gamma ray values and bulk density. The upper, more argillaceous part of the Kågeröd Arkose is indicated by an increase in gamma ray values.

The interface between a green, coarse-grained sandstone bed and a green, sub-fissile and partly laminated clay of the Kågeröd Clay forms the boundary between the Kågeröd Arkose and the overlying Kågeröd Clay. There is also a marked peak in gamma ray values at the transition to the Kågeröd Clay.

Fossils and age

No fossils have been found in the Kågeröd Arkose.

Kågeröd Clay

Local reference section: Höllviken-2 well (Brotzen 1950, p. 28, Pl. 1) 55° 23' 50" N–12° 56' 40" E Depth interval: 1496–1528 m below K.B. Thickness in local reference section: 32 m	Local reference log section: Maglarp-1 well 55° 23' 14" N–13° 03' 51" E Depth interval: 1533–1547 m below K.B. Thickness in local reference log section: 14 m
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Lithology

The Kågeröd Clay is characterised by its bright red and green colours (Fig. 14). Carbonate concretions with a diameter of 6–7 cm occur frequently. There is a gradual decrease in arenaceous content upwards in the unit.

Boundary definitions

The transition between the green, coarse-grained sandstone bed of the Kågeröd Arkose and the green sub-fissile and partly laminated claystone of the Kågeröd Clay forms the lower boundary. There is a marked peak in gamma ray values at the boundary.

The upper boundary is drawn at the pronounced lithological change from the variegated red and green clays of the Kågeröd Clay into the dark clays of the Vallåkra Member (Höganäs Formation).

Fossils and age

No fossils have been found in the Kågeröd Arkose. However, the overlying Höganäs Formation (Vallåkra Member) is dated by its palynoflora to the Rhaetian *Rhaetipollis*–*Limbosporites* Zone (Lund 1977) and by dinoflagelates to the *Rhaetogonyaulax rhaetica* Zone (Poulsen & Riding 2003).

PETROLOGICAL AND PETROPHYSICAL CHARACTERISTICS OF THE PRE-RHAETIAN TRIASSIC

In general, the pre-Rhaetian Triassic rocks encountered in Scania and in the Höllviken Halfgraben are composed of poorly sorted matrix-rich sandstone and arenaceous claystone deposits (Tab. 4). The beds are commonly reddish-brown, purple and green. Examples of various claystones encountered when drilling the Hammar Formation in the MAH-2 well are illustrated in Figure 15. The sandstone layers display a wide range of grain sizes and there are also frequent conglomeratic interbeds. Several geologists have previously described the Norian Kågeröd Formation. Reviews of these are given in Sivhed & Wikman (1986) and Sivhed et al. (1999).

Most of what is known about the lithological composition of the subsurface pre-Rhaetian Triassic sequence in south-west Scania derives from descriptions of cuttings and geophysical logs from rotary drillings. One core drilling, Höllviken-2, constitutes the key drilling for interpretation of the other wells. Continuous monitoring during drilling of the recent wells in Malmö (FFC-1 and FCC-2) and Copenhagen (MAH-1 and MAH-2) has also provided interesting additional data. Detailed studies on cuttings and scattered sidewall cores from these wells have also yielded valuable knowledge.

Höllviken-2

Brotzen (1950) was the first to describe the Triassic deposits in the Höllviken-2 core (Fig. 16). His description gives a good overview of the different rocks present. However, no detailed textural descriptions based on investigations of thin sections were included in this study. Jacobsson (1993) made an additional investigation focusing on a lithological description of thin sections. His work included modal analyses covering the different rocks at a depth of between 1800 and 1919 m (i.e. the Hammar–Flommen interval). He grouped the succession into seven lithofacies based on their different texture and petrological composition. His conclusions partly coincide with the descriptions given below.



Figure 15. Examples of different claystone types encountered in cuttings during drilling in the Hammar Formation in MAH-2.

Upper Bunter transition beds between Bunter and Muschelkalk, Hammar and Flommen Formations, 1923–1861 m

Lithological characteristics

The interval between 1923 m (total depth) and 1861 m in the Höllviken-2 core (Hammar and Flommen formations) is characterised by frequent changes in colour between layers. A patchy and mottled colour varying between dark red, light grey and green is common. Reddish-brown hues predominate, however.

The basal part of the interval (1923–1880 m) consists mainly of poorly sorted, matrix-rich, light red and grey sandstone beds. Sub-angular quartz and feldspar make up most of the detrital sand fraction. Calcrete nodules and finely crystallised dolomite occur fairly frequently. Scattered large feldspar grains and a high amount of accessory minerals, i.e. hornblende, apatite and zircon, are also common. The variably carbonate cemented sandstone beds have a matrix composed of thin clay minerals (chlorite and illite).

The upper part of the Flommen Formation (1880–1861 m, Fig. 17a) is mainly composed of argillaceous fine-grained sandstone and arenaceous mudstone. Finely dispersed organic material is frequently found. The unit is defined by Brotzen (1950) as the transition beds between the Buntsandstein and the overlying greyish units referred to as belonging to the Muschelkalk, i.e. the Falsterbo Formation.

Petrophysical and chemical characteristics

Two chemical analyses of sandstone layers (1866.2 and 1888 m, Appendix 1, cf. Figs. 17b–c), verify a relatively high calcium content (8.5%, cementations of calcite) and also a significant presence of dolomite (magnesium content of 0.4–2.2%), at least in the 1888 m sample. Of significance are relatively high proportions of manganese (1190–1710 ppm), molybdenum (10–12 ppm), copper (3–44 ppm) and chromium (97–106 ppm), related to amorphous minerals (cf. microscopy report sheet for 1888 m in Appendix 1). Petrophysical analyses of the above samples indicate a compact rock with low permeability (Tab. 5). However, loose and poorly consolidated sandstone beds are noted in the core description of the Hammar Formation at a depth of between 1886 and 1923 m (Brotzen 1950). These layers probably constitute permeable and porous beds.

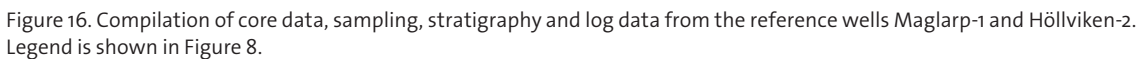




Figure 17. **A.** Flommen Formation, Höllviken-2, 1865–1868 m. The interval displays the characteristic variation in colour and in-dururation in the core material. **B.** Flommen Formation, Höllviken-2, 1866.2 m, core sample. Photomicrograph (plane-polarised light). The sand fraction is dominated by sub-angular quartz with patchy occurrence of organic-rich matrix. The grains are embedded in sparitic cement. The texture is poorly sorted. **C.** Hammar Formation, Höllviken-2, 1888 m, core sample. Bioturbated mottled grey and green sandstone. **D.** Hammar Formation, Höllviken-2, 1888 m, core sample. Photomicrograph (cross-polarised light). Poorly sorted calcite cemented sandstone. The cement is commonly poikilotopic, thus large crystals of calcite is embedding several detrital grains.

Table 5. Statistic compilation of performed measurements on porosity and permeability on sandstone samples from Höllviken-2.

Formation	N	Porosity, %				Permeability, mD					
		mean	median	standard deviation	max	min	mean	median	standard deviation	max	min
Kågeröd	24	9.2	8.3	6.5	27.9	3.0	15	2.7	31	8250	0.17
Stavsten	6	13	12.9	3.4	18.7	8.3	33	16	41	99.7	0.16
Fuglie	15	7.2	7.6	4	16.7	2.3	2.3	0.6	4.3	4.6	0.15
Vellinge	27	10.2	8.9	5.9	26.3	3.6	118	1.6	341	1336	0.03
Falsterbo	15	21.3	25.3	7.4	26.5	4.7	356	405	298	957	0.13
Hammar and Flommen	11	12.3	12.7	3.4	18.6	8.6	59	48.5	53	139	19

Upper Muschelkalk and Lower Keuper, Falsterbo Formation, 1861–1755 m

Lithological characteristics

Although the Upper Muschelkalk and Lower Keuper layers are commonly reddish-brown, they are clearly distinguished from overlying and underlying units by the frequent greyish, in parts laminated character (Figs. 18 & 19a). Another significant characteristic is the occurrence of finely dispersed organic material and findings of fossils (fish remains, characeans and ostracods, Brotzen 1950) as well as spores and pollen (cf. Piasecki 2005). Enrichment of detrital coal is found in light grey sandstone layers at 2 015 m true vertical depth (TVD) in the FFC-2 well (Fig. 19b). Large coal fragments are also noted in the Höllviken-2 well (1 825 m) and in the MAH-2 well at approximately 2 450–2 500 m TVD. The carbonate content is fairly high throughout the interval. The sandstone beds are generally composed of moderately sorted, fine-grained quartz. Mica is frequent in the finely laminated, argillaceous sandstone beds (Figs. 19b–c). Smectite is the predominant clay mineral (Jacobsson 1993).

Petrophysical and chemical characteristics

The predominantly fine-grained deposits display a varying degree of hardness. A more or less unconsolidated, reddish sandstone interbedded with red clay occurs at a depth between 1 788 and 1 789.2 m. The matrix content varies as well as the degree of cementation. Overall, porosity is relatively high. The permeability is due to the fine-grained texture, calcite cementation and commonly a smectitic matrix. The vertical permeability is significantly less than the horizontal due to lamination of clay minerals. The clayey beds have also been noted as swelling (Brotzen 1950) and thus cause technical problems during drilling.



Figure 18. Falsterbo Formation, Höllviken-2, 1757–1785.45 m. Examples of the lithological variation in the core material.



Figure 19. **A.** Falsterbo Formation, Höllviken-2, 1761 m, core sample. Grey, laminated micaceous and argillaceous fine-grained sandstone. **B.** Falsterbo Formation, FFC-2, 2 695 m MD (2 015 m TVD). Cuttings with coal fragments in fine-grained quartz sand. **C.** Falsterbo Formation, Höllviken-2, 1761 m, core sample. Photomicrograph (plane-polarised light) displaying the laminated texture of an argillaceous fine-grained sandstone. Mica is enriched in the argillaceous laminae.

A whole rock chemical analysis of the grey, argillaceous and micaceous sandstone at 1 761 m yields a chemical signature that is closely related to the high content of mica and clay minerals. This is indicated by high contents of aluminium (6.2%), magnesium (1.4%) and potassium (1.2%) as well as relatively high contents of some trace elements such as cobalt (21.4 ppm), chromium (100 ppm), copper (55.2 ppm), nickel (48.8 ppm) and zinc (48 ppm; Tab. 6).

Lower Keuper, Vellinge Formation, 1755–1691 m

Lithological characteristics

The Lower Keuper is mainly composed of red, brown and green mottled sandstone beds, frequently interbedded with conglomerates (Fig. 20). Intraclasts of reddish-brown claystone and mudstone are commonly found (Fig. 21a). The rock is mainly cemented by carbonates, of which dolomite constitutes a significant part. Besides carbonate there are frequent characteristic overgrowths of silica on detrital quartz, which acts as meniscus cement (Fig. 21b). A number of fining-upward cycles composed of basal conglomerate layers succeeded by laminated red-green, medium-grained sandstone beds are found in the cores from Höllviken-2. The lowermost part of the Vellinge Formation is developed as a relatively uniform sandstone-dominated sequence. Variably weathered mica occurs in laminae, giving the beds a slightly fissile character. Zircon and amorphous heavy minerals are commonly found.

Petrophysical and chemical characteristics

The degree of cementation is not as complete in the Lower Keuper as in the other parts of the Keuper sequence. Frequent sandstone beds are poorly cemented and have an open and communicative pore system, which yields high permeabilities (700–1 300 mD, cf. Figs. 21 c–d and Tab. 5).



Figure 20. Vellinge Formation, Höllviken-2, 1739.7–1742.5 m. Alternating sequence composed of variably carbonate cemented conglomerate and sandstone layers.

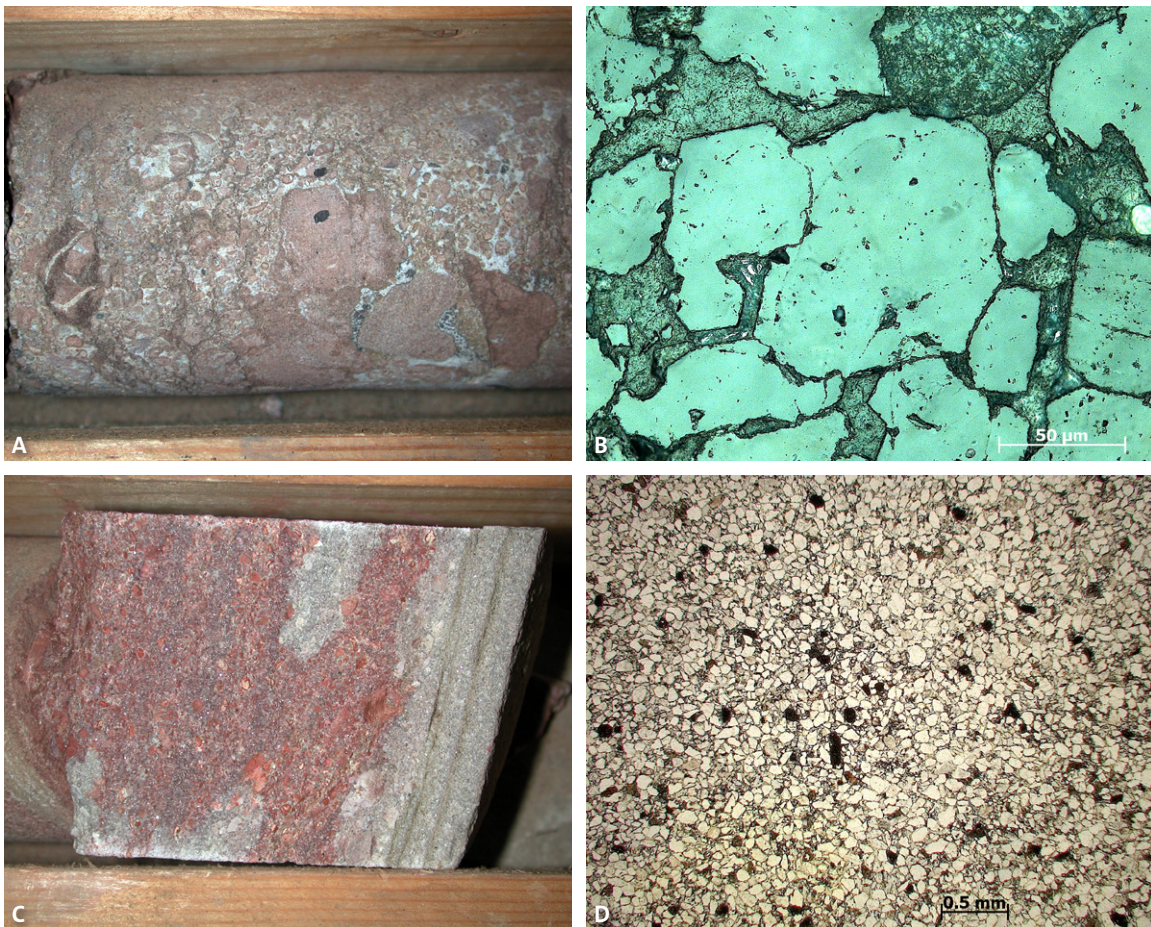


Figure 21. **A.** Vellinge Formation, Höllviken-2, 1740 m, core sample. Carbonate cemented nodular conglomeratic bed. Centimetre-large clasts of red-brown claystone or mudstone are common. **B.** Vellinge Formation, Höllviken-2, 1717.88 m, core sample. Photomicrograph (reflected light) showing overgrowth of silica on detrital quartz acting as meniscus cement. **C.** Vellinge Formation, Höllviken-2, 1742 m. **D.** Vellinge Formation, Höllviken-2, 1717 m. Photomicrograph (cross-polarised light) of a highly permeable sandstone. Permeability=1336 mD.

The chemical analysis of a sample from 1740 m in Höllviken-2 (Tab. 6) shows a similar chemical composition to the underlying analysed samples of the Falsterbo, Flommen and Hammar Formations. There are relatively high amounts of manganese, cobalt, barium, copper, phosphorus, molybdenum and chromium in comparison with the overlying Keuper formations. This may be partly related to the presence of amorphous minerals formed in pedogenic environments (cf. Figs. 22 a–c). Similar conditions occur in the Triassic sequence in northern Germany (Lepper & Röhling 1998).

Table 6. Core sample Höllviken-2, depth in metres below kelly bushing. Analyses of oxides in per cent, of elements in ppm.

	1633.35– 1633.40	1676.80– 1676.85	1677.35– 1677.40	1683.70– 1683.75	1740.00– 1740.05	1761.00– 1761.05	1866.20– 1866.25	1888.00– 1888.05
SiO ₂	72.70	53.30	69.50	44.60	62.10	64.60	65.30	56.40
Al ₂ O ₃	8.94	7.83	8.86	2.76	7.02	12.70	5.70	6.65
Fe ₂ O ₃	1.68	2.60	2.49	0.55	2.24	3.38	0.81	1.01
CaO	2.06	14.05	0.90	27.10	12.35	3.86	12.3	12.15
MgO	2.27	2.62	4.10	0.28	0.64	2.57	0.68	3.78
Na ₂ O	1.18	0.52	0.41	0.32	1.05	1.52	0.75	1.24
K ₂ O	4.03	2.83	3.10	1.58	1.18	2.31	3.10	2.90
Cr ₂ O ₃	0.01	0.01	0.01	0.01	0.03	0.02	0.03	0.03
TiO ₂	0.43	0.46	0.49	0.17	0.49	0.64	0.22	0.58
MnO	0.03	0.05	0.02	0.02	0.13	0.09	0.16	0.22
P ₂ O ₅	0.03	0.05	<0.01	<0.01	0.08	0.09	0.04	0.08
SrO	0.01	0.01	0.01	0.01	0.02	0.03	0.01	0.02
BaO	0.07	0.05	0.06	0.03	0.23	0.11	0.07	0.20
LOI	6.84	15.95	9.52	22.40	12.00	7.98	11.05	14.30
Total	100.5	100.5	99.5	99.8	99.6	99.9	100.0	99.6
Ag	0.06	0.10	0.07	0.03	0.07	0.07	0.03	0.11
As	<0.2	5.9	0.8	<5.0	2.1	<0.2	<0.2	<0.2
Ba	610	410	530	270	1940	920	540	1700
Be	1.02	1.31	0.91	0.24	0.61	1.49	0.42	0.83
Bi	0.06	0.09	0.08	0.02	0.05	0.10	0.01	0.04
Cd	0.02	0.15	<0.02	0.36	0.11	0.03	0.10	0.07
Ce	26.90	39.70	22.40	11.35	22.50	53.30	29.80	40.90
Co	2.2	7.6	5.4	1.3	6.6	21.4	1.9	4.2
Cr	63	62	45	46	102	100	97	106
Cs	1.06	2.62	2.30	0.37	1.07	4.25	0.78	1.05
Cu	2.2	7.2	6.5	2.0	14.4	55.2	3.0	44.1
Ga	10.20	10.95	10.60	3.03	7.34	16.05	6.06	7.06
Ge	0.18	0.25	0.25	0.25	0.23	0.27	0.20	0.20
Hf	3.6	2.9	2.6	1.1	1.3	1.8	1.4	5.4
In	0.019	0.033	0.027	0.005	0.023	0.046	0.013	0.029
La	11.5	29.7	9.5	10.4	29.2	24.3	13.2	18.4
Li	11.2	25.7	17.0	2.8	15.2	40.2	6.8	8.7
Mn	211	386	170	157	984	667	1190	1710
Mo	3.92	4.05	2.45	4.85	8.95	2.15	11.65	10.20
Nb	8.7	9.4	8.3	3.1	9.1	12.4	3.5	8.5
Ni	6.0	15.6	14.0	<0.2	12.4	48.8	4.3	5.3
P	30	110	30	30	210	400	40	380
Pb	13.5	18.8	12.5	6.3	12.8	12.0	12.3	11.7
Rb	152.0	117.5	111.0	58.4	40.5	85.6	102.5	95.0
Re	0.002	0.003	<0.002	<0.002	0.003	0.002	0.002	0.004
Sb	0.13	0.38	0.29	0.08	0.16	0.20	0.08	0.21
Se	1	2	1	2	2	2	1	2
Sn	1.0	1.4	1.3	0.3	1.0	1.7	0.6	1.0
Sr	103.5	127.0	91.9	104.5	160.0	220.0	101.0	159.0
Ta	0.61	0.67	0.62	0.22	0.64	0.84	0.24	0.64
Te	<0.05	0.07	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Th	3.6	13.8	9.3	3.6	4.3	6.7	4.5	21.5
Tl	0.65	0.58	0.55	0.25	0.20	0.55	0.41	0.42
U	1.1	1.2	0.9	0.5	0.7	2.1	0.8	1.9
V	22	31	30	14	52	76	21	23
W	0.8	1.4	0.8	1.2	2.1	1.1	2.4	2.5
Y	11.0	20.2	6.1	10.0	19.4	15.5	12.1	20.9
Zn	9	21	14	2	14	48	12	24
Zr	124.5	90.6	78.6	34.0	38.9	59.4	42.2	174.5

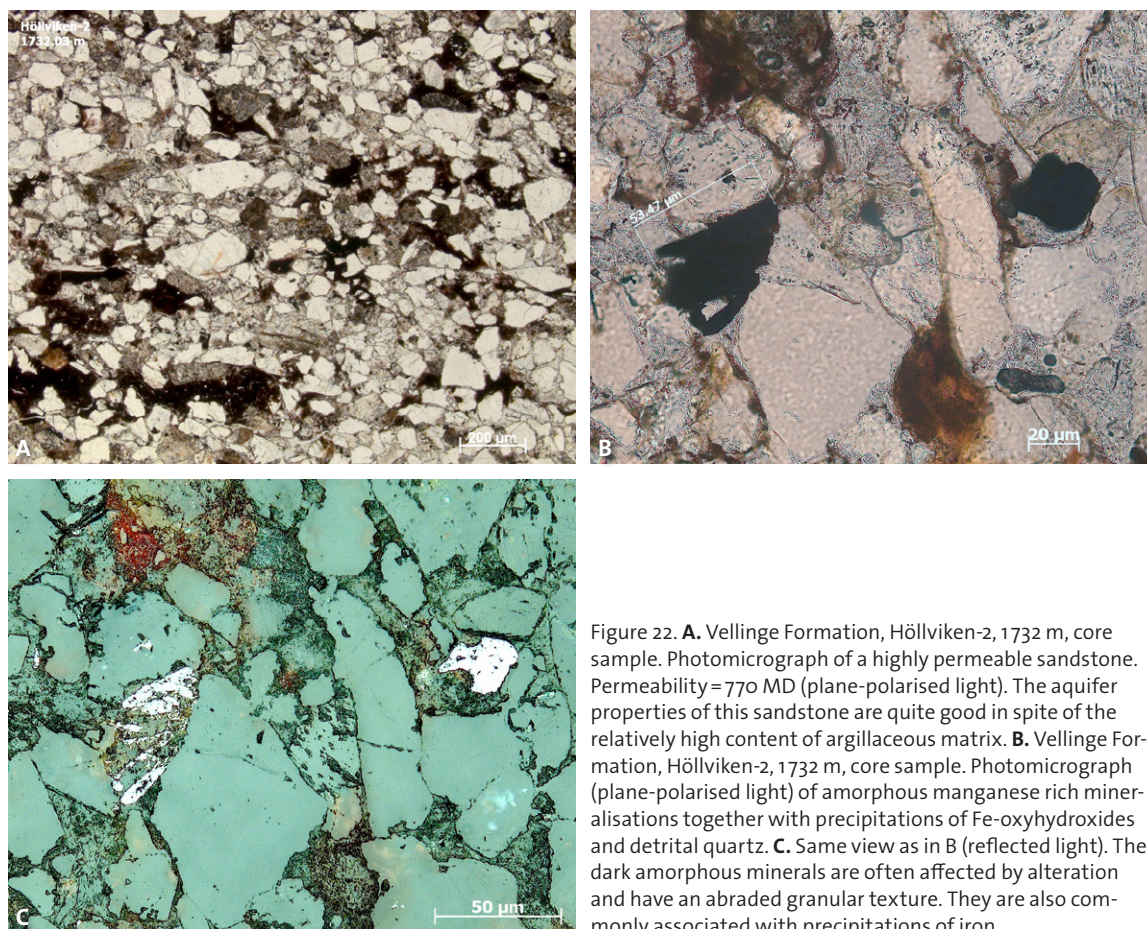


Figure 22. **A.** Vellinge Formation, Höllviken-2, 1732 m, core sample. Photomicrograph of a highly permeable sandstone. Permeability = 770 MD (plane-polarised light). The aquifer properties of this sandstone are quite good in spite of the relatively high content of argillaceous matrix. **B.** Vellinge Formation, Höllviken-2, 1732 m, core sample. Photomicrograph (plane-polarised light) of amorphous manganese rich mineralisations together with precipitations of Fe-oxyhydroxides and detrital quartz. **C.** Same view as in B (reflected light). The dark amorphous minerals are often affected by alteration and have an abraded granular texture. They are also commonly associated with precipitations of iron.

Manganese minerals are known to form in pedogenic vertisol environments when there are rapid shifts between dry and wet conditions (cf. Nordt et al. 2004). There may thus be a relationship between these minerals and the more humid conditions verified at the Muschelkalk–Keuper transition. These minerals have not been observed in thin sections above 1740 m in the Höllviken-2 core.

Middle Keuper, Carnian, Fuglie Formation, 1691–1642 m

Lithological characteristics

A characteristic feature of the Fuglie Formation is the nodular and mottled sequence of strata. The lithology is dominated by calcareous, dolomitic and, in parts, evaporitic mudstone, argillaceous sandstone and mudclast conglomerate (Figs. 23 & 24). The beds have been described as formed during pedogenic processes in which calcrete palaeosols were formed (Arndorff 1994). A minor amount of silica overgrowth occurs on detrital quartz in some of the sandstone layers. Otherwise, carbonate cement predominates. The deposits were mainly laid down in arid to semi-arid conditions in a playa-like environment with temporal influence of coarse clastic sediments from alluvial fans.

Petrophysical and chemical characteristics

The deposits of the Fuglie Formation are mostly dense due to high amounts of calcareous cement and argillaceous matrix (Fig. 25). Most of the deposits can be defined as a variably arenaceous and calcareous mudstone. The log response of the deposit is quite distinct due to its relatively low gamma values. The chemical analysis from a depth of 1740 m in the Höllviken-2 core also confirms the very high content of carbonate (Tab. 6).

The permeability and porosity values well illustrate the compact and more or less impermeable nature of most of the layers (Tab. 5).

Middle Keuper, Stavsten Formation, 1642–1604 m

Lithological characteristics

The characteristics of the beds in the basal parts of the Stavsten Formation in the Höllviken-2 core are very similar to the underlying Fuglie Formation (Fig. 26). Fine-grained argillaceous sandstone layers become gradually more predominant higher up in the sequence. Nonetheless, pedogenic



Figure 23. Fuglie Formation, Höllviken-2, 1675–1678 m.



Figure 24. Fuglie Formation, Höllviken-2, 1676–1677.8 m, core samples. The photographs display the heterogeneous composition of the sediments. **A.** 1676 m. **B.** 1676.2 m. **C.** 1677.4 m. **D.** 1678 m.

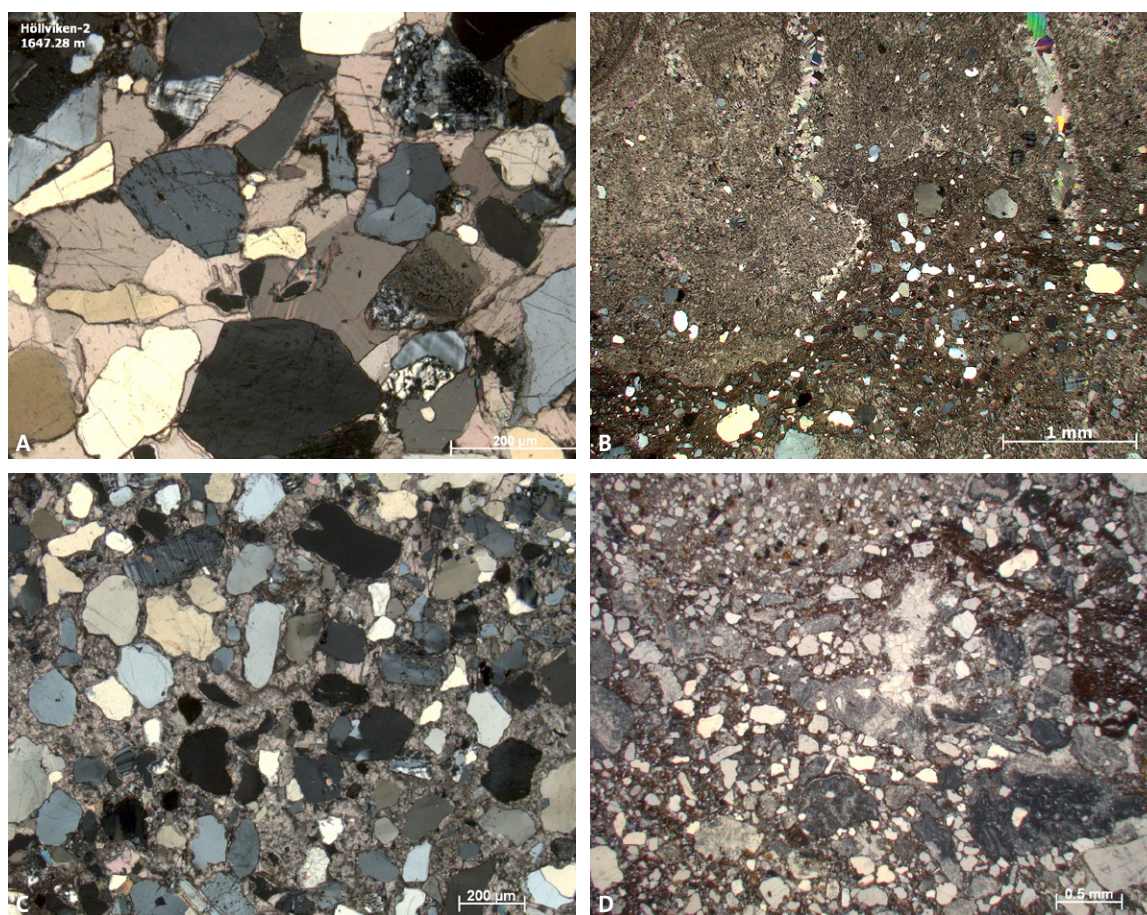


Figure 25. Fuglie Formation, Höllviken-2, core samples. Photomicrographs of some of the different rock types. **A.** 1647 m (cross-polarised light). Carbonate cemented sandstone. **B.** 1677.35 m (cross-polarised light). Nodular arenaceous mudstone (calcrete). **C.** 1683.7 m (cross-polarised light). Dolomitic sandstone. **D.** 1676 m (plane-polarised light). Arenaceous mudstone with mud clasts.



Figure 26. Stavsten Formation, Höllviken-2, 1631–1636 m. Example of the lithological character in the basal parts of the formation.

processes had a pronounced influence on the depositional environment. Carbonate nodules embedded in arenaceous mudstone are frequent. There is less carbonate cement than in the underlying and overlying formations. Instead, a microcrystalline mixture of silica and clay minerals seems to constitute the predominant cementing substance and pore filling component.

Petrophysical and chemical characteristics

The sandstone beds in the Stavsten Formation are generally more porous than the rocks in the Fuglie Formation (Tab. 5). The difference is explained by a less complete cementation of the sandstone layers in the Stavsten Formation. The permeability does not correspond to the porosity, which can be related to the high matrix content. The chemical analysis of a sample from 1633.35 m (cf. Tab. 6, Figs. 26–27) verifies a high content of silica. The carbonate content is considerably lower than in the sample from the Fuglie Formation.

Middle Keuper, Norian, Kågeröd Formation, 1406–1604 m

Lithological characteristics

The Kågeröd Formation includes a wide range of rock types, e.g. conglomerate, arkose, mudstone and clay, which all indicate deposition in an arid to semi-arid environment (Fig. 28). Several fining upward cycles typical of alluvial deposits occur in the Höllviken core. The pronounced lack of organic material, hematite staining, the overall coarse grain sizes and the high content of rock fragments and feldspars indicate a proximal depositional setting in the main part of the formation. There is a high frequency of polymict conglomerate beds alternating with sandstone beds in the FFC-1 well. However, in the upper part of the Kågeröd Formation there is a gradual increase in the content of clay and finer clastic sediments, indicating a low relief in the late Norian.

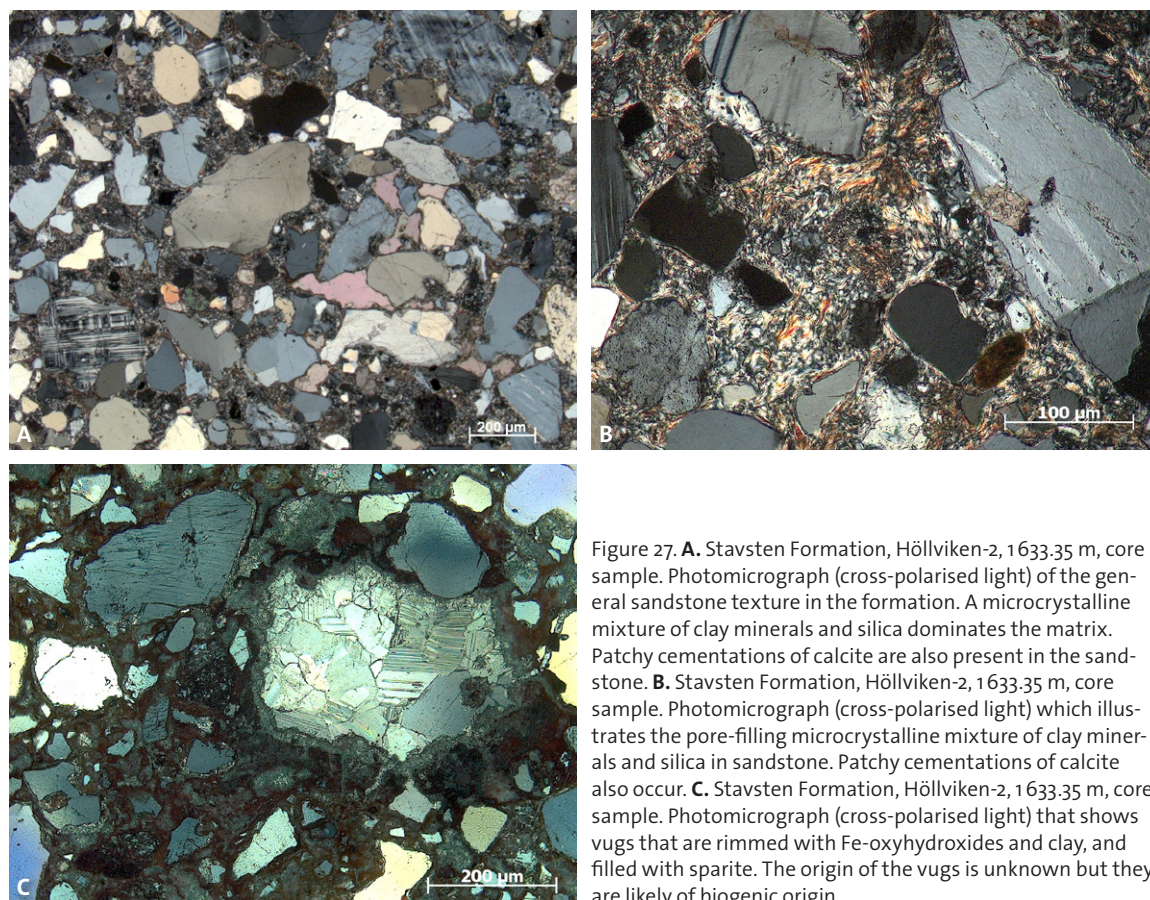


Figure 27. **A.** Stavsten Formation, Höllviken-2, 1633.35 m, core sample. Photomicrograph (cross-polarised light) of the general sandstone texture in the formation. A microcrystalline mixture of clay minerals and silica dominates the matrix. Patchy cementations of calcite are also present in the sandstone. **B.** Stavsten Formation, Höllviken-2, 1633.35 m, core sample. Photomicrograph (cross-polarised light) which illustrates the pore-filling microcrystalline mixture of clay minerals and silica in sandstone. Patchy cementations of calcite also occur. **C.** Stavsten Formation, Höllviken-2, 1633.35 m, core sample. Photomicrograph (cross-polarised light) that shows vugs that are rimmed with Fe-oxyhydroxides and clay, and filled with sparite. The origin of the vugs is unknown but they are likely of biogenic origin.

Petrophysical and chemical characteristics

The Kågeröd Formation displays a highly heterogeneous petrophysical composition. Well cemented and dense beds alternate with more or less unconsolidated beds. In general, the degree of consolidation is related to the amount of calcite cementation. A cement composed of large poikilotopic calcite crystals is common (Fig. 29a). The arkosic sandstone beds are also partly cemented by microcrystalline silica, often also with a mixture of clay minerals (cf. Figs. 29 b–d). There is also considerable lateral variation of the petrophysical characteristics due to the marginal position of the Höllviken Halfgraben in the Danish Basin.

A few highly permeable sandstone beds occur in the FCC-1 and FCC-2 wells. Apart from locally distributed permeable sandstone beds, most of the Kågeröd Formation must be considered to be a relatively compact and impermeable part of the Triassic.

Summary of lithological characteristics

The study performed of the pre-Rhaetian Triassic sequence in the Höllviken Halfgraben shows that there are distinguishing properties and features that can be used as formational signatures. The characteristics are summarised in Table 4.

The general reflection is that the Triassic can be subdivided into a Lower Triassic (Buntsandstein) sequence, characterised by dense, predominantly dark brown and purple claystone beds interbedded with medium-grained and coarse-grained, poorly consolidated sandstone (Hammar and Flommen



Figure 28. **A.** Kågeröd Formation, Höllviken-2, 1601.5 m, core sample. Argillaceous, fine-grained and medium-grained carbonate cemented sandstone. **B.** Kågeröd Formation, Höllviken-2, 1548 m, core sample. Nodular mudstone–claystone. **C.** Photomicrograph (cross-polarised light) of the core sample shown in A. Detrital grains of varying grain sizes are embedded in calcite cement. **D.** Kågeröd Formation, FCC-1, 1923 m, sidewall core. Poorly sorted calcite cemented arkose.

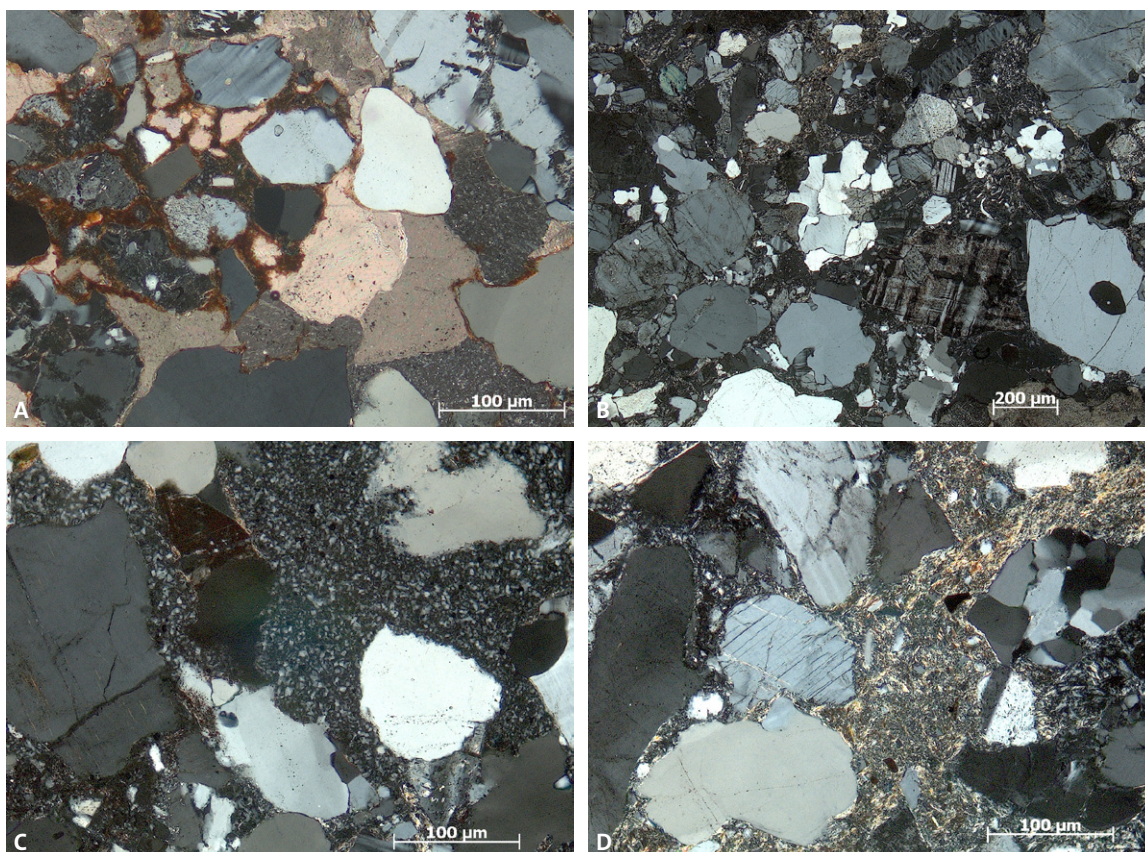


Figure 29. **A.** Kågeröd Formation, FFC-1, 1908 m, sidewall core. Photomicrograph (cross-polarised light). Arkosic sandstone cemented by macrocrystalline calcite and precipitations of Fe-oxyhydroxides. **B.** Kågeröd Formation, FFC-1, 1908 m, sidewall core. Photomicrograph (cross-polarised light). Arkosic sandstone. **C.** Kågeröd Formation, FFC-1, 1910 m, sidewall core. Photomicrograph (cross-polarised light). Arkosic sandstone cemented by microcrystalline silica. **D.** Kågeröd Formation, FFC-1, 1908 m, sidewall core. Photomicrograph (cross-polarised light). Arkosic sandstone. Microcrystalline matrix composed of silica and clay minerals.

Formations). These deposits are followed by a Middle Triassic to Lower Keuper unit of predominantly greyish, laminated and relatively well-sorted sandstone beds with organic material. This constitutes an important unit for correlation in the Höllviken Halfgraben as well as with deposits in the North German Basin. Much more coarse-grained deposits predominate in the overlying pre-Rhaetian Upper Triassic (Keuper) sequence (Vellinge Formation). Overgrowth of quartz is very common, which seems to be a significant characteristic of this unit. The character of the succeeding Fuglie Formation is very distinct. Calcrete layers and the generally mottled and nodular texture, together with high amounts of dolomite and scattered evaporitic minerals give the formation a characteristic signature. This is also confirmed by the geophysical log response, particularly the low gamma ray values. In the Höllviken Halfgraben the Kågeröd Formation is dominated by coarse clastic rocks, which are commonly cemented with poikilotopic calcite crystals. Overgrowth of quartz has not been found in this unit, in contrast to the most basal parts of the Fuglie Formation and the Vellinge Formation.

Correlation between Höllviken-2 and Svedala-1

The Svedala-1 core borehole is located on the westernmost part of the Skurup Platform, adjacent to the north–south striking Svedala Fault, which forms the eastern border of the Höllviken Halfgraben. The Triassic sequence of the Skurup Platform reaches no more than 100 m in thickness. It is composed of arkose and conglomerate beds in a couple of fining upward cycles. The sequence has hitherto been assigned to the Norian Kågeröd Formation (e.g. Larsson et al. 1994) by its general lithological characteristics. However, the stratigraphical position could be questioned after study-

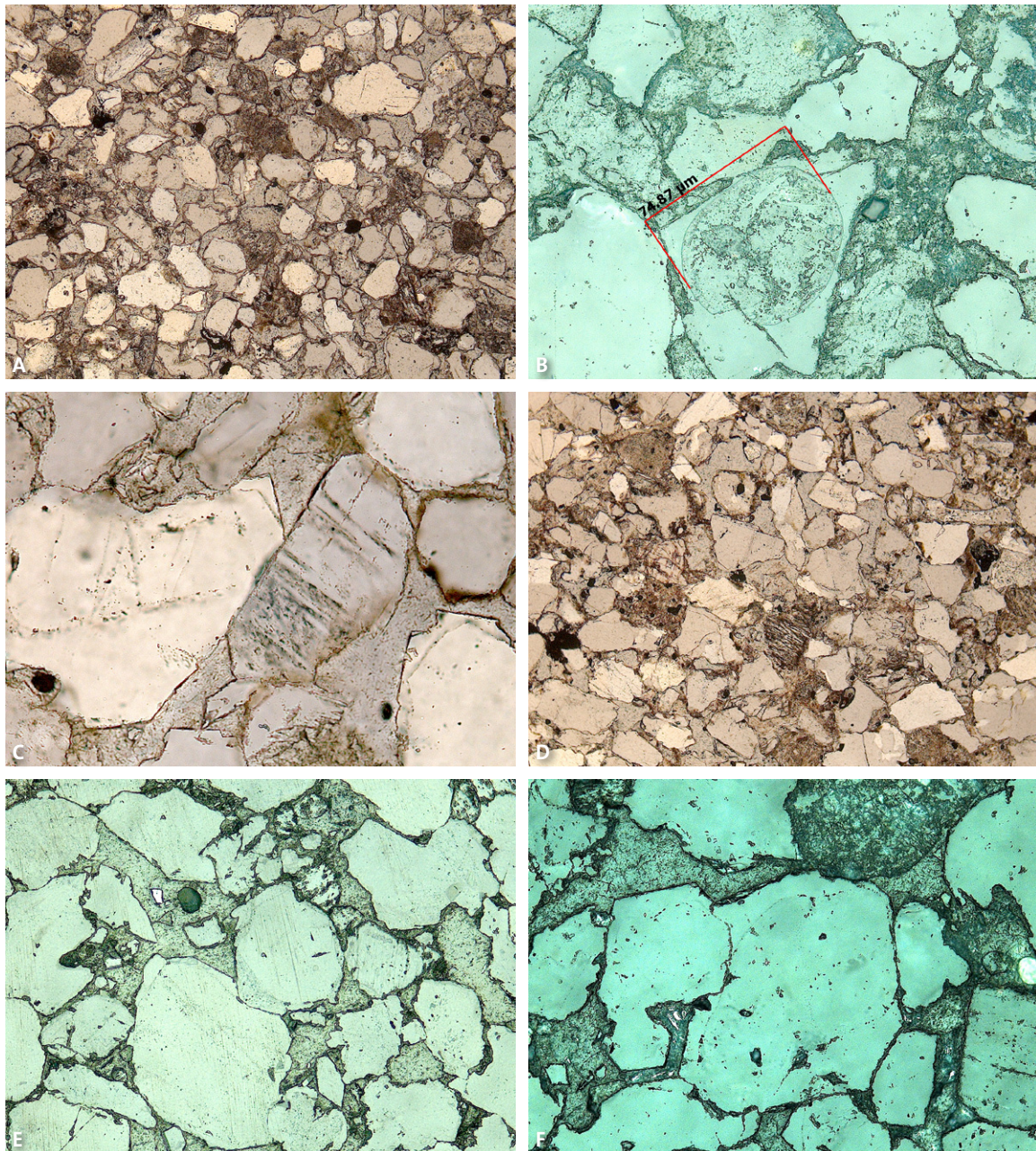


Figure 30. Comparison between sandstone beds in core samples at 1593 m depth in Svedala-1 and similar rock types in core samples from Höllviken-2, the Vellinge Formation. Note the striking textural resemblance and the quartz overgrowths, which are characteristic features of the Vellinge Formation. **A.** 1593 m Svedala-1 (plane-polarised light). **B.** 1593 m Svedala-1 (reflected light). **C.** 1593 m Svedala-1 (plane-polarised light). **D.** 1732.03 Höllviken-2 (plane-polarised light). **E.** 1732.03 m Höllviken-2. (reflected light). **F.** 1717.88 m Höllviken-2 (reflected light).

ing the textural and petrological characteristics in detail. At a depth of 1593 m the deposits in the Svedala-1 core display textural features strongly resembling those observed in the Vellinge and Fuglie Formations in the Höllviken-2 core. Besides the significant amounts of silica overgrowth, a further resemblance is the presence of fine mudclasts and amorphous minerals of the same kind as in the basal parts of the Vellinge Formation. The permeability is also very high, similar to that measured for parts of the Vellinge Formation in the Höllviken-2 core.

Sandstone samples from the Svedala-1 core are very similar to the sandstone samples from the Vellinge Formation in the Höllviken-2 core (cf. Fig. 30).

The Vellinge Formation has a relatively uniform thickness and distribution in the Höllviken Halfgraben (cf. Fig. 31). It is therefore possible that the Skurup Platform also acted as a depocentre during this time. If so, this suggests that the main uplift of the Skurup Platform occurred as long ago as the early Norian. This may then correspond to a major hiatus, which is identified in Germany and the Netherlands (above the Heldburggips, Bachmann et al. 2005) as being related to strike-slip movements and a rifting phase caused by Kimmerian tectonic movements in the Tethys realm. It is postulated that the hiatus lasted approximately 10 million years. An activation of the faults bordering the Höllviken Halfgraben, including the Svedala Fault, could also have occurred at this time.

As yet, however, there are insufficient conclusive data supporting this interpretation. Detailed supplementary studies focusing on petrophysical characteristics and chemical signatures could possibly verify the postulated age of the Triassic on the Svedala Platform.

PRE-RHAETIAN TRIASSIC AQUIFERS

The Triassic sequence contains several sandstone layers that have been investigated for their potential as hydrocarbon reservoirs (OPAB investigations in the 1970s) and also recently as geothermal aquifers. These investigations have provided valuable information on petrophysical, hydrogeological and hydrochemical characteristics.

Four main aquifers are recognised in the pre-Rhaetian Triassic of the Höllviken Halfgraben. These are found within the Ljunghusen, Hammar and Vellinge Formations and in the Stavsten to basal Kågeröd Formation (cf. Fig. 32).

Results from permeability and porosity measurements (Springer 1997) show that aquifer properties vary greatly. Permeabilities of less than 10 mD in pore aquifers are considered to represent poor aquifers, whereas values above 1000 mD represent aquifers with excellent hydraulic properties. The samples tested all come from above the Buntsandstein aquifers. The results from the overlying sandstone aquifers in the Höllviken-2 core display mostly poor permeabilities. The best results are found in the Vellinge Formation. Here, permeabilities of about 1000 mD were measured in a few samples. The variability in permeability and porosity is related to the general characteristics of the deposits. Lateral variations in degree of cementation and matrix content are common. Based on correlation of geophysical logs, it seems that the aquifers in the Bunter sequence have a better lateral continuity than other Triassic formations. The geophysical logs in Ljunghusen-1 and MAH-1 are very similar and there are several matching sections. This makes a lateral correlation between the two wells possible.

Chemical analyses on the formation fluids and solute gases have been performed on downhole samples at depths of 1840 and 1860 m in the FFC-1 well. The results show that the 86 cm³ per litre of solute gases consist almost exclusively of nitrogen with small admixtures of hydrocarbons (less than 2%) and carbon dioxide (0.52%). A relatively high proportion of helium (5.7%) is striking.

The formation fluid has a density of 1.12 g/cm³ as a result of a high amount of dissolved sodium chloride. In general, the salinity of the Triassic formation fluids vary between 12 and 17% at depths between 1500 and 2100 m in south-west Scania.

The Ljunghusen aquifer

The Ljunghusen Formation is found only in the deepest parts of the Höllviken Halfgraben and has been drilled through in the wells Ljunghusen-1, Höllviksnäs-1, Kungstorp-1, MAH-1 and MAH-2. The Ljunghusen Formation is composed of relatively well-sorted, poorly consolidated, medium-grained quartz sandstone with a low matrix content (Fig. 33). Iron occurs as thin coatings on the grains.

The Ljunghusen Formation has not been hydraulically tested but the geophysical wire-line logs indicate a permeable, porous and up to 50 m thick homogeneous sandstone at the base of the Triassic sequence. The lateral continuity is predicted to be good, based on a fairly uniform depositional

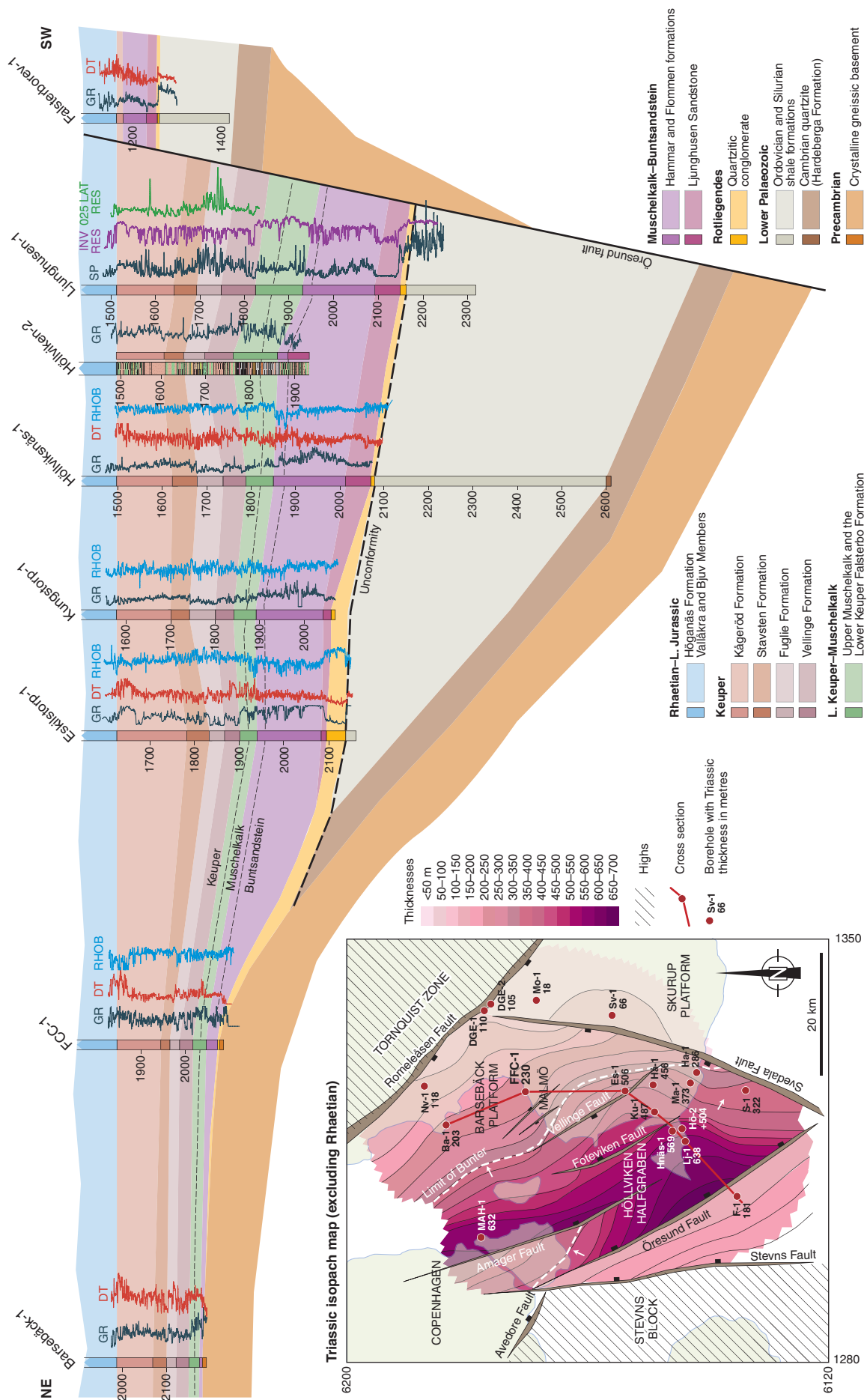


Figure 31. Conceptual model of the subsurface correlation of the Triassic in a cross-section shown in the inset map.

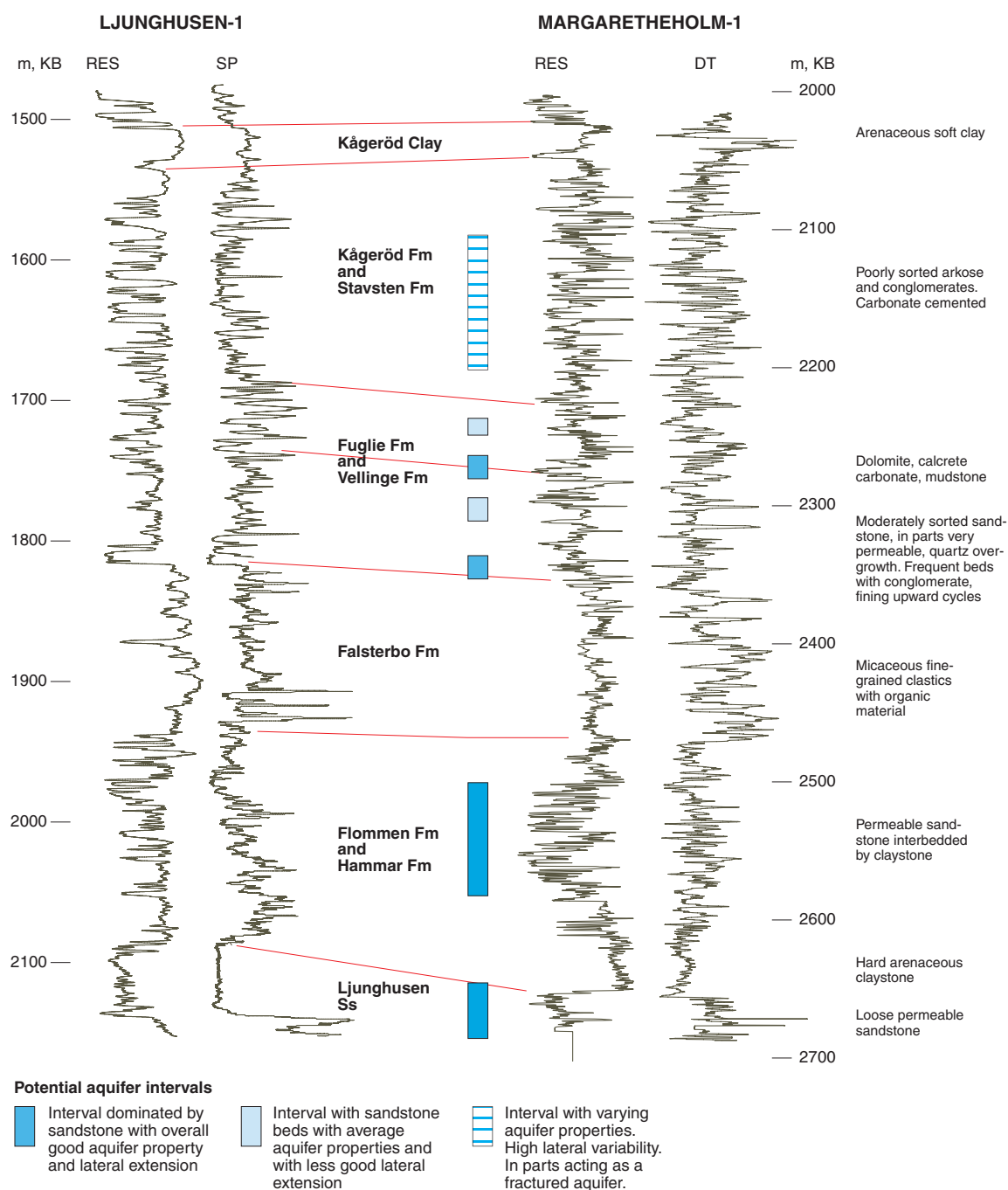


Figure 32. Proposed correlation between Ljunghusen-1 and Margaretheholm-1 (MAH-1) and potential aquifer intervals.

setting. The deposit thins and disappears to the north-east. The Ljunghusen Formation directly overlies a hard conglomeratic quartzite, probably of a Permian (Rotliegendes) age, which marks the unconformity against the underlying Lower Palaeozoic succession (cf. Fig. 31).

The Ljunghusen Formation is most likely synchronous with the Volpriehausen Sandstone in northern Germany.

The Hammar aquifer (Middle Buntsandstein)

At depths of 2 500–2 600 m in the MAH-1 and MAH-2 wells and at 1 940–2 030 m in the Ljunghusen-1 core, the Hammar Formation is dominated by coarse-grained and medium-grained sub-



Figure 33. Ljunghusen sandstone, MAH-2, 3180 m MD, 2700 m TVD, cutting sample.

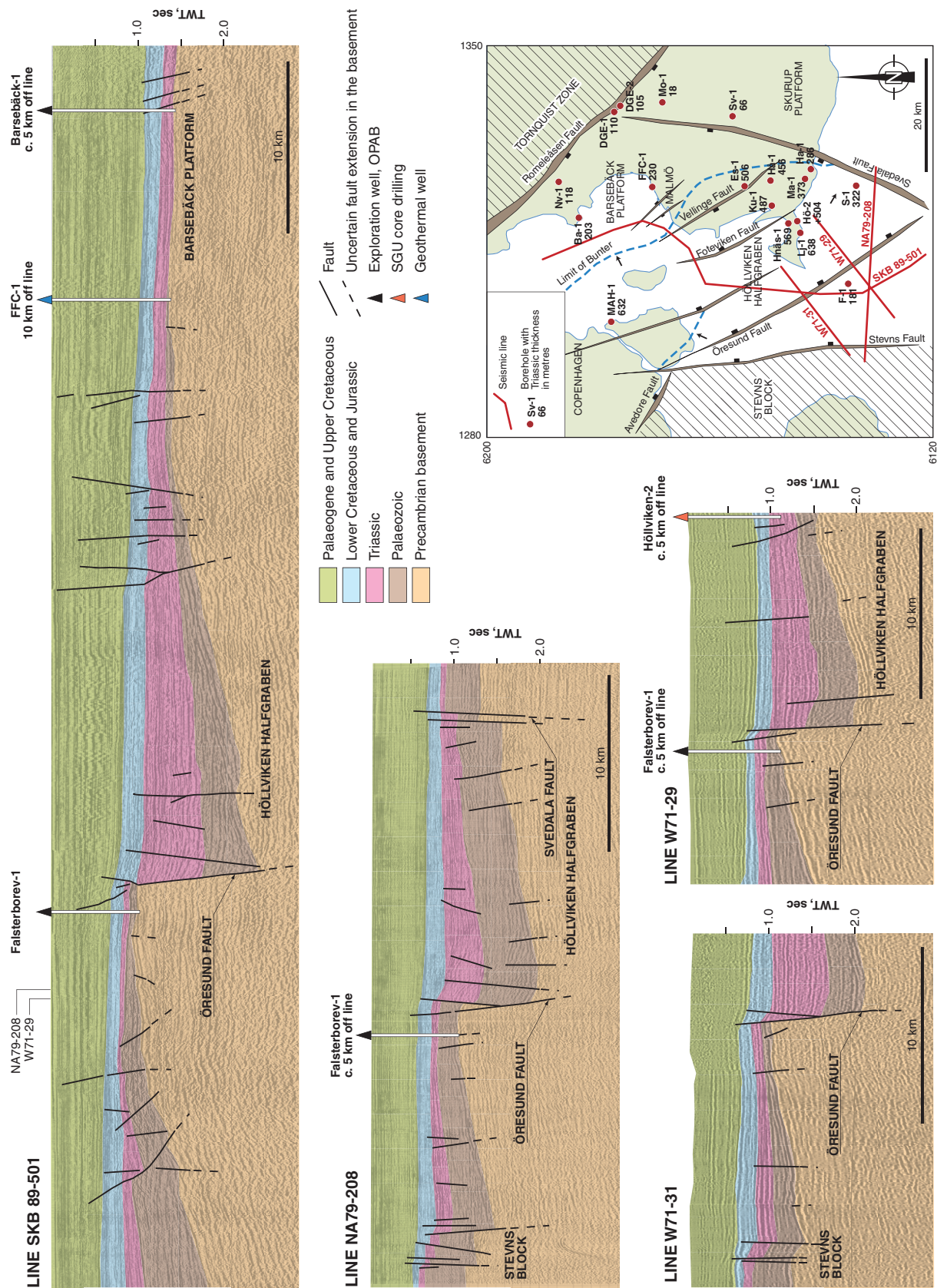
arkosic sandstone beds interbedded with variably coloured red-green-brown and purple claystone and mudstone beds. The sandstone beds are in parts poorly consolidated and highly permeable. In the MAH-1 and MAH-2 geothermal wells, sandstone beds were chosen as the most suitable for geothermal energy production.

The hydraulic test of the perforated MAH-1 well gave permeabilities higher than 1000 mD for the sandstone beds. The 73 °C warm formation water at a depth of 2500 m has a Cl^- content of approximately 130 g/l.

There is a good overall correlation of the Middle Buntsandstein between the Ljunghusen-1 and the MAH wells, i.e. in a north-west to south-east direction along strike of the deepest parts of the Höllviken Halfgraben (cf. Fig. 31). The correlation of the same beds to the north-east is less obvious. The same sequence is progressively more difficult to identify in a section between the wells Höllviksnäs-1, Kungstorp-1 and Eskilstorp-1. Most of the Hammar Formation was probably formed in a landscape with low relief. Playa systems (mudflats) interfingering with fluvial systems (braided river) of an ephemeral character dominated the depositional environment. These conditions prevailed in much of the North German Basin (Lepper & Röhling 1998) during the deposition of the middle Buntsandstein, e.g. the Detfurth and Hardeggen Formations. A similar depositional pattern also most likely occurred in the Höllviken Halfgraben but with a more pronounced influx of coarse clastic sediments from the Fennoscandian high to the north-east. Several unconformities are verified in Germany (Lepper & Röhling 1998) as a result of the rift-related tectonic realm and the shift in erosional base level. The Solling Formation is marked by a widely distributed erosional base cutting into underlying formations (Hardeggen etc.), marking one of the most prominent Triassic unconformities in the North German Basin. This has resulted in the formation of a proximal thick sandstone unit. A similar situation is interpreted in the Höllviken Halfgraben, where the Hammar Formation is considered to correlate to the Solling Formation.

The Vellinge aquifer

The Vellinge Formation marks a change from the relatively humid climate, as witnessed by the character of the underlying Falsterbo Formation (cf. cuttings, cores and outcrop data), into a more arid, continental climate with proximal deposition of variably sorted sandstones interbedded with



numerous conglomerate beds. Parts of the sequence are composed of laminated fluvial sandstone beds with a greyish overprint, indicating there were still periods with a more humid climate.

Analyses of some of the sandstone layers show high permeabilities (the best in this study). The high permeabilities (more than 1 000 mD) can be explained by relatively poorly cemented sandstone beds. The cementing agent is mainly meniscus silica and quartz overgrowth (cf. Appendix 1, 1 712.88 m). Calcite occurs in subordinate amounts in the sandstone beds analysed. However, calcite is very common as pore-filling cement in the conglomerates.

Based on geophysical logging data and core analyses, the best aquifer in the Vellinge Formation seems to be a 15–20 m thick sandstone unit immediately overlying the greyish, micaceous, fine clastic beds of the Falsterbo Formation. This unit can be correlated between several wells in the Höllviken Halfgraben, e.g. Ljunghusen-1, MAH-1 and Höllviksnäs-1. The base of the sandstone was probably developed in a regressive system tract, resulting in the deposition of more proximal sediments in the Höllviken Halfgraben, as indicated by the high frequency of conglomerate beds in the deposits of the Vellinge Formation.

Another good aquifer unit occurs in the middle of the Vellinge Formation, where laminated, relatively well-sorted sandstone beds occur. The Vellinge sandstone aquifers are difficult to correlate outside the Höllviken Halfgraben. They could possibly be correlated with the Hauptsandstein of the Erfurt Formation in the North German Basin.

The aquifer in the Stavsten Formation and the base of the Kågeröd Formation

The permeable sandstone beds in the Stavsten Formation and the basal part of the Kågeröd Formation are generally extremely poorly sorted and variably cemented by pore-filling sparitic and poikilotopic calcite. Pedogenic related features (nodules, dendritic calcite, rhizoliths and calcrete) and conglomerate beds occur frequently in the sequence. Loose permeable sandstone beds occur, but the overall aquifer is of poor quality. In the upper part of the Kågeröd Formation (1 880–1 920 m) in the FFC-1 well, there are permeable beds of light grey sandstone alternating with dense conglomerate beds that have quite good aquifer properties. It is not inconceivable that parts of the Stavsten–Kågeröd aquifer act as a fractured aquifer rather than a pore aquifer, due to more or less complete calcite cementation.

Analyses of core samples generally yield very poor permeability and porosity results for the Stavsten and Kågeröd Formations (Tab. 5). The lateral variability of the lithological composition (grain size, sorting, cementation etc.) is estimated to be high, which is also confirmed by the heterogeneous character of the log signals for these strata.

SUBSURFACE CONCEPTUAL MODELS

Seismic interpretation

The model of the subsurface distribution of Triassic rocks in the Höllviken Halfgraben is based on interpretations of seismic investigations of varying resolution and quality. The best offshore surveys are the SKB-501, Na-79 and W71 surveys, of which four examples are illustrated in Figure 34. The Triassic sequence in the Höllviken Halfgraben is characterised by a set of laterally discontinuous reflectors showing the lateral variability of the petrophysical characteristics, which is a result of the mainly proximal depositional setting. The top of the Kågeröd Clay is a significant marker where it occurs, particularly in the north-eastern parts of the halfgraben. Persistent reflectors are also present beneath the laterally and petrophysically varying sequence of the Kågeröd, Stavsten and Fuglie Formations. This sequence of strata is frequently characterised by interfingering, short, undulating reflectors, which in some places form mound-like structures. This could be related to the calcretic nature of the deposits and the presence of dolomitic carbonate precipitations. The seismic data also show that the pre-Rhaetian Triassic sequence thickens considerably towards the Amager and Öresund faults. This is mainly due to the presence of a Bunter sequence beneath the Kågeröd Forma-

tion. However, there are reflectors also in the Upper Triassic that pinch out towards the north-east, indicating there was possibly erosion of uplifted areas to the south-west (Stevns High) and not only transport of clastic material from the Fennoscandian area to the north-east.

Isopach map

A pre-Rhaetian Triassic isopach map is presented in Figure 31. The map shows the distinct increase in sediment thickness towards the south-west approaching the bounding Öresund and Amager Faults. The maximum thickness of the pre-Rhaetian sequence is about 700 m in the deepest parts of the halfgraben. There are two main fault directions that delineate the Höllviken Halfgraben. One is a dominant north-north-west to south-south-east striking system, with faults that are sub-parallel to the Sorgenfrei-Tornquist Zone. Many of these are probably pre-Triassic in origin, although they may have been repeatedly active during the Mesozoic era. There is also a more or less north-south striking system of faults connected to the Svedala Fault. These formed as rift faults in response to extensional stress, possibly during Kimmerian tectonic movements in the Late Triassic. They could, however, already have been initiated during rifting phases in connection with the Variscan orogeny in the Late Permian.

There is a thin Triassic sequence on the Skurup Platform. In addition, there is a thin, rudimentary Triassic sequence preserved on the Stevns Block and in the Sorgenfrei-Tornquist Zone. During much of the Triassic era the Stevns High and other blocks of the Ringkøbing-Fyn High system acted as a barrier between the Danish Basin and the North German Basin. The Höllviken Halfgraben was thus positioned in a narrow depression between these two basin systems: the Stevns High and the Fennoscandian massif. Its structural and depositional history is therefore strongly affected by this setting.

Subsurface correlation between wells

Figure 31 shows a correlation model of the subsurface pre-Rhaetian Triassic strata in the Höllviken Halfgraben. In the deeper part of the halfgraben there is a clear correlation of most stratigraphic units. A good correlation is also confirmed to the north-west, i.e. with the MAH wells in Copenhagen (Fig. 32). There are greater difficulties in correlating the Triassic succession to the north-east. It is also difficult to correlate the Keuper strata between wells. The lateral variation of lithofacies is probably the reason for this, as well as the fact that the deposits to the north-east become more proximal in character.

In spite of the difficulties in fully verifying the proposed stratigraphical correlation between wells, there are lithological and geophysical markers, particularly in the Buntsandstein to Lower Keuper, that make the proposed model relatively certain.

The stratigraphic affinity of the Triassic in the Falsterbo-1 well is still uncertain. The wire-line logs and the geological report from the well site indicate that the basal part of the Triassic sequence is dominated by homogeneous sandstone overlain by arenaceous claystone. This part displays a very similar log pattern to the transition sequence between the Ljunghusen Sandstone and the Hammar Formation. This study therefore contends that the basal Triassic sequence in the well is composed of Lower Triassic strata of the same character as in the Höllviksnäs-1 and Ljunghusen-1 wells, i.e. Ljunghusen Sandstone and basal parts of the Hammar Formation. The overlying sequence in the Falsterbo-1 well is considered to represent Upper Keuper deposits, thus indicating that much of the Hammar, Flommen, Falsterbo and Vellinge Formations are missing due to erosion during Kimmerian rifting and local subsidence of the Höllviken Halfgraben.

Correlation between the wells MAH-1 and Ljunghusen-1

Based on geophysical logs, there is a very good correlation between the MAH-1 and Ljunghusen-1 wells (Fig. 32). They display more or less the same succession of strata. There are several markers in the wire-line logs that correlate to the established stratigraphy and depositional pattern in the Höll-

viken Halfgraben. The pre-Rhaetian Triassic is equally thick in both wells (638 m in Ljunghusen-1 and 632 m in MAH-1), and they represent the deeper parts of the halfgraben (cf. Fig. 31).

The Ljunghusen Sandstone is present in both wells and its upper boundary to a homogeneous claystone unit of the basal Hammar Formation is well defined by a marked change in the wire-line logs, as illustrated in Figure 32.

TECTONIC AND STRUCTURAL EVOLUTION OF THE HÖLLVIKEN HALFGRABEN

The Triassic period was unique in many ways. In the Early Triassic the landmasses were joined into the supercontinent Pangea. Palaeoeurope was bordered to the south by the Palaeotethys or Tethys Ocean, which periodically invaded the shallow epicontinental basins of Europe, particularly during the Middle Triassic. From the Early Triassic the Pangean supercontinent experienced extensional forces, which resulted in the development of a rift valley system between Laurasia and the African part of Gondwana, i.e. the Atlantic rift. At the same time microplates on the eastern side of Gondwana drifted north across the Palaeotethys Ocean, causing a subduction zone to form in the southern part of the European plate. This Kimmerian rifting phase resulted in the formation of transtensional faults as well as the reactivation of Permian fault systems in the Sorgenfrei-Tornquist Zone (Vejbæk 1990, Mogensen 1994, Michelsen 1997). In the North German Basin the rifting resulted in the predominance of north-north-east to south-south-west striking rift zones such as the Glückstadt Graben and the Horn Graben, subdividing the Ringkøbing-Fyn High (RFH) into separate blocks (Vejbæk 1997). The Stevns Block became the easternmost block neighbouring the Höllviken Halfgraben. The RFH was formed during the Permian, and during much of the Triassic constituted a basement high acting as a depositional barrier between the Danish Basin and the North German Basin. The Triassic succession on the RFH is thinner than the adjacent basins, where thick sequences were formed as a result of thermal subsidence (Vejbæk 1997).

The Höllviken Halfgraben lies in the transition zone between the Danish Basin, the Polish Basin and the North German Basin. The north-north-west to south-south-east striking Öresund Fault borders the halfgraben to the south-west, and the north-north-east to south-south-west striking Svedala Fault borders the halfgraben to the south-east. These structures are interpreted as having been formed during east-west tension in Early to Middle Triassic times, with a peak phase during the early Carnian. The orientation of the faults coincides with the main orientation of the fault systems and rift valleys occurring in the North German Basin.

The deposition in the Höllviken Halfgraben experienced an evolution similar to much of the northern parts of the North German Basin and the Danish Basin. Although thinner, a more or less complete Triassic succession of strata exists. Missing sequences probably include the lower part of the Bunter Shale and parts of the Muschelkalk sequence. In parts, the lithofacies are very similar to those found in the North German Basin (Bachmann 1998). There is a successive onlap of younger strata to the north-east. Lower Triassic (Buntsandstein) deposits occur in the deepest part of the halfgraben, adjacent to the bounding Öresund Fault. During the Early to Middle Triassic, the Skurup Platform probably constituted an area above the erosional base level. It was not until the Early Keuper that the Skurup Platform again formed part of the depositional area. The oldest Triassic deposits on the Skurup Platform are possibly synchronous with the Early Keuper Vellinge Formation. Later during the Early Norian it was probably subject to erosion, which removed much of the pre-existing Triassic strata on the platform. This may have been related to Kimmerian rifting, which in the North German Basin is regionally described as the D4 unconformity, spanning a period of almost 10 million years.

The Triassic units on the uplifted flank of the Stevns Block, represented by the Falsterborev-1 well, are not dated. However, geophysical information from wire-line logs in the lower part of the Triassic in the Falsterborev-1 well strikingly resemble the geophysical response of the Ljunghusen Sandstone and units included in the Bunter Sandstone. The uppermost part of the Triassic sequence

is composed of clays that are very similar in character to the Norian Kågeröd Formation. A major unconformity is found on the southern flank of the Stevns Block, exemplified in the Ørslev-1 well. The unconformity represents a hiatus from the Ladinian to the early Carnian.

During the Early Triassic, deposition in the Höllviken Halfgraben began with clastic sediments corresponding to the Volpriehausen and Solling Formations in North Germany. The bounding faults experienced peak activity during the initial Kimmerian rifting phase. For most of the Middle Triassic there seems to have been non-deposition in the area, which may correspond to a main unconformity during the early Ladinian. Sedimentation probably resumed in the Ladinian to early Carnian, with deposition of fine-grained clastic sediments with a minor influence of organic material permitting age determination by the use of palynomorphs (Piasecki 2005).

The Triassic tectonic realm in north Germany, Denmark and the Sorgenfrei-Tornquist Zone was characterised by rifting in north–south striking zones, e.g. the Glückstadt Graben, and east–west extension resulting in north-east to south-west striking extensional faults, e.g. the Svedala and Öresund Faults. Transtensional strike-slip movements occurred in the Sorgenfrei-Tornquist Zone. Three major north-north-west to south-south-west striking rift zones (Horn Graben, Glückstadt, Brunswick Gifhorn) formed in the North German Basin (Frisch & Kockel 1998a, b). West-north-west striking faults transecting the North German Basin were also active in mid-Keuper times. The rifting movements generally ceased before deposition of the Steinmergelkeuper, corresponding to the Kågeröd Formation in Scania. The Kågeröd Clay marks the end of the Triassic redbed deposition in the Höllviken Halfgraben. By then the landscape was denuded and the amount of coarse clastic sedimentation had significantly decreased. When the Rhaetian sea invaded the area, it extended over vast areas of lowlands leading to the formation of fine clastic sediments in marginal, mixed marine to brackish environments, such as lagoons, low profile deltas and flood plains in a more humid and moist climate.

CLIMATE

The climate of the Triassic was strongly influenced by the supercontinent Pangea. Much of the landmasses were positioned around the equator, which led to mostly arid conditions. Large inland areas were isolated from the cooling and moist effects of the ocean. The result was a globally arid climate, although regions near the coast most likely experienced seasonal monsoons and somewhat more moist and humid conditions. There were no polar ice caps, and the north–south temperature gradient is assumed to have been lower than today.

The shallow continental basins were temporarily invaded by the Tethys Ocean, which caused evaporitic conditions when the sea withdrew from the area. Calcrete soils were formed in the marginal part of shallow basins. These playa-like environments were also influenced by seasonal rainfall, which induced ephemeral braided river systems to form. Vegetation was sparse.

During the Middle Triassic, invasion of the Tethys Ocean over the central European continent led to more humid conditions, which caused the development of a vegetated hinterland area. This is indicated by findings of wood fragments and coal in cuttings of Ladinian age, e.g. in the FFC-1 well.

CONCLUSIONS

The study performed of the pre-Rhaetian Triassic in the Höllviken Halfgraben has primarily resulted in increased knowledge of the composition and characteristics of the Triassic succession. The main results are:

- a revised and updated stratigraphy of the Triassic sequence in the Höllviken Halfgraben;
- an identification of marker beds for regional correlation with deposits in the North German Basin;
- descriptions of a Triassic pollen and spore assemblage that significantly contributes to dating the sequence;

- isopach maps and cross-sections that illustrate the subsurface distribution of the pre-Rhaetian Triassic sequence in the Höllviken Halfgraben;
- a detailed petrographic description (texture, cementation, matrix, detrital components etc.) of the various rock types, which gives an understanding of the petrophysical and reservoir characteristics;
- a description and interpretation of the chemical and reservoir properties (porosity, permeability and grain density);
- a comprehensive description of the different Triassic aquifers of potential interest for geothermal energy, and
- a preliminary model of the structural evolution of the Höllviken Halfgraben.

ACKNOWLEDGEMENT

This study was performed within the R&D programme at the Geological Survey of Sweden and as a part of the project “The geothermal energy potential in Denmark – reservoir properties, temperature distribution and models for utilisation” (DSF-No.: 2104-09-0082) within the programme Sustainable Energy and Environment funded by the Danish Agency for Science, Technology and Innovation.

Special gratitude is expressed to DONG and Eon for letting us use valuable data from the geothermal wells in Malmö and Copenhagen. Thanks are also expressed to the geologists from the University of Halle, especially Gerard Beutler and Gerard Bachmann, for valuable comments and discussions during the field workshop on the Triassic in the Halle–Erfurth area. Niels Springer, Sofie Lindström and Stefan Piasecki (GEUS) are thanked for valuable data and communication regarding the petrophysical properties of the reservoirs and biostratigraphical assessments of the Triassic succession.

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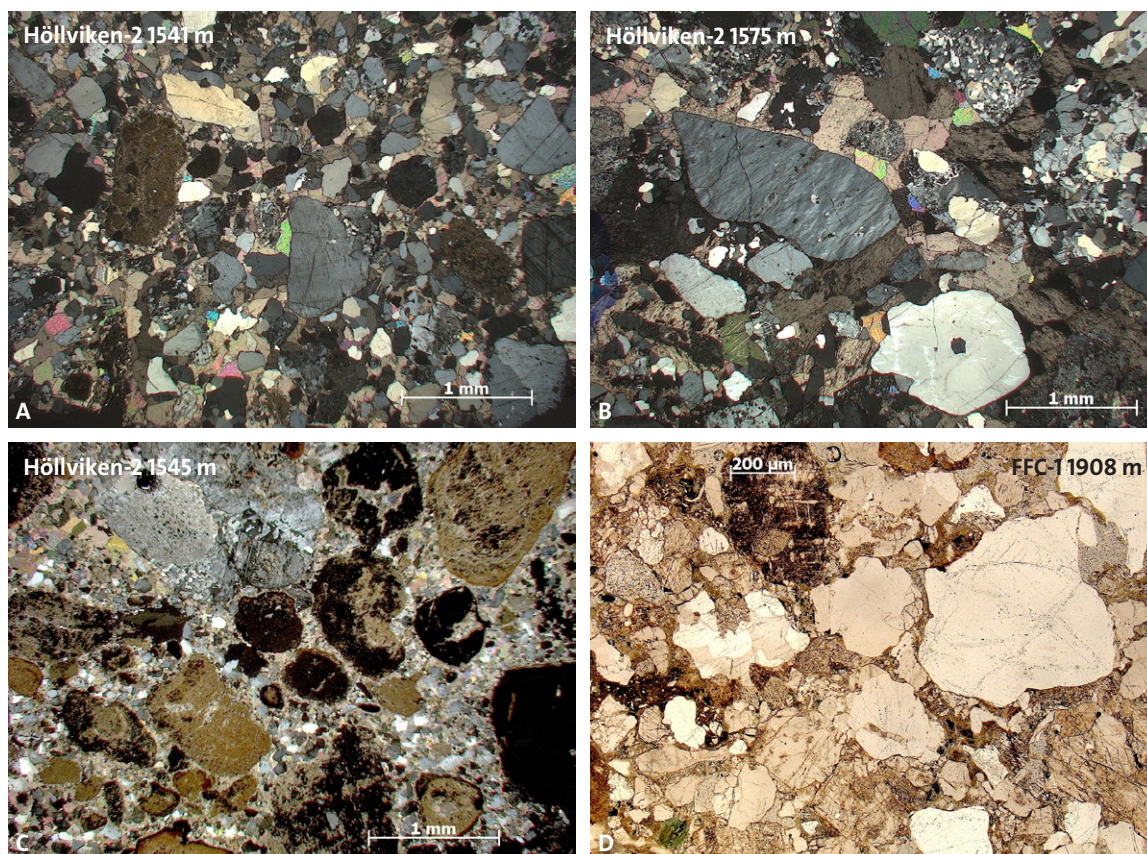
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APPENDIX 1. COMPILATION OF RESULTS FROM A MICROSCOPY STUDY ON THIN SECTIONS OF THE TRIASSIC SEQUENCE

1. Kågeröd Formation, Höllviken-2 and FFC-1

Lithology: Red-brown, green, poorly sorted, mostly carbonate cemented sandstone and conglomerate.



Description: Photomicrographs show the typical characteristics of the Kågeröd Formation. The deposits are extremely poorly sorted. Conglomerates as well as mudstones alternate in the sequence. Calcite is common as cement. The degree of consolidation varies considerably. The grains are angular, abraded and often fragmented. Argillaceous material is common as matrix. Clay clasts also commonly occur (rip-up clasts).

A. Poorly sorted arkosic, in parts conglomeratic calcite cemented sandstone, Höllviken 2, 1545 m (cross-polarised light).

B. Similar lithology as in A, Höllviken-2, 1575 m (cross-polarised light).

C. Enrichment of mud-clasts in conglomeratic sandstone, Höllviken-2, 1545 m (cross-polarised light).

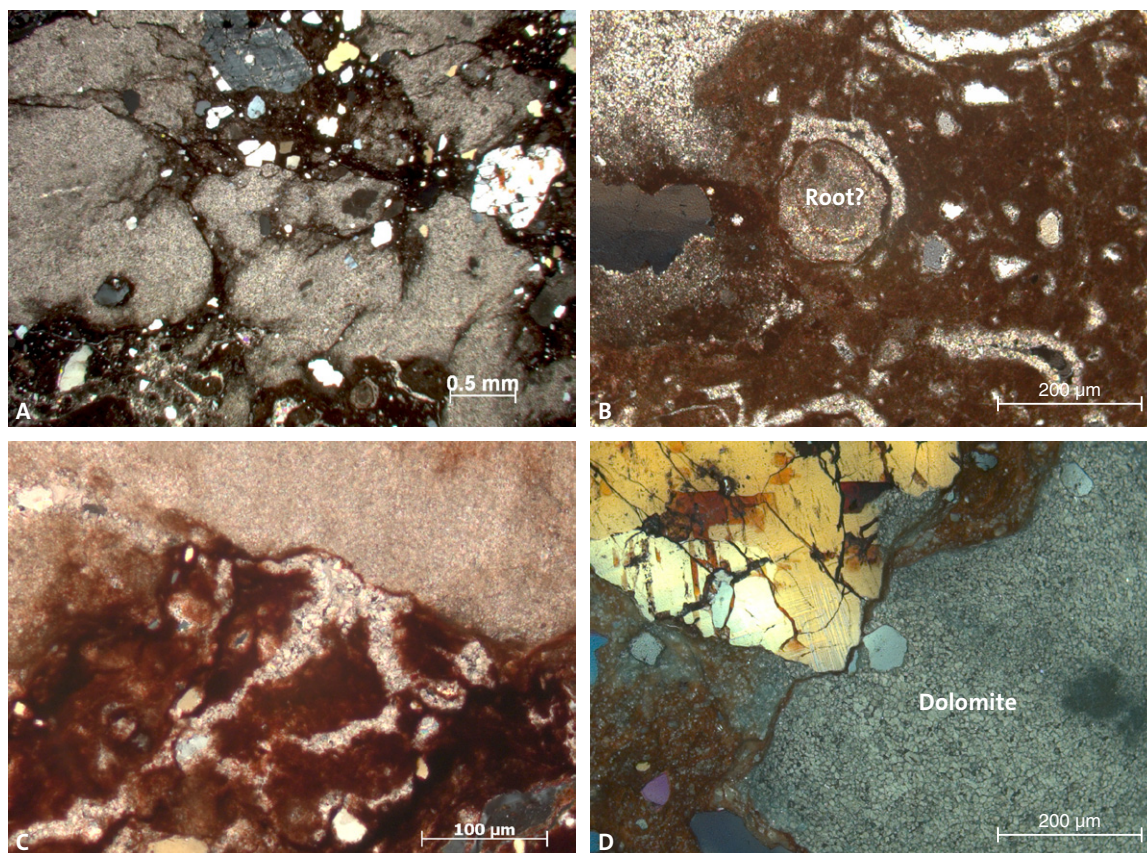
D. Catastrophic texture of an arkosic, poorly sorted sandstone, FFC-1, 1908 m (plane-polarised light).

Porosity: Variable.

Permeability: Variable.

2. Stavsten Formation, Höllviken-2, 1622.8 m

Lithology: Mottled red-brown with white streaks, nodular, arenaceous, calcareous mudstone (calcrete).



Description: Nodular, calcareous mudstone. The photomicrographs show clearly the chaotic texture with a mixture of calcareous nodules, detrital quartz, feldspars and rock fragments. Dendritic structures are common. These are exclusively filled with calcite. Microcrystalline dolomite occurs as large nodular precipitations. Semicircular ghost structures from pre-existing roots are frequent. All characteristics are typical of calcrete-palaeosol deposits.

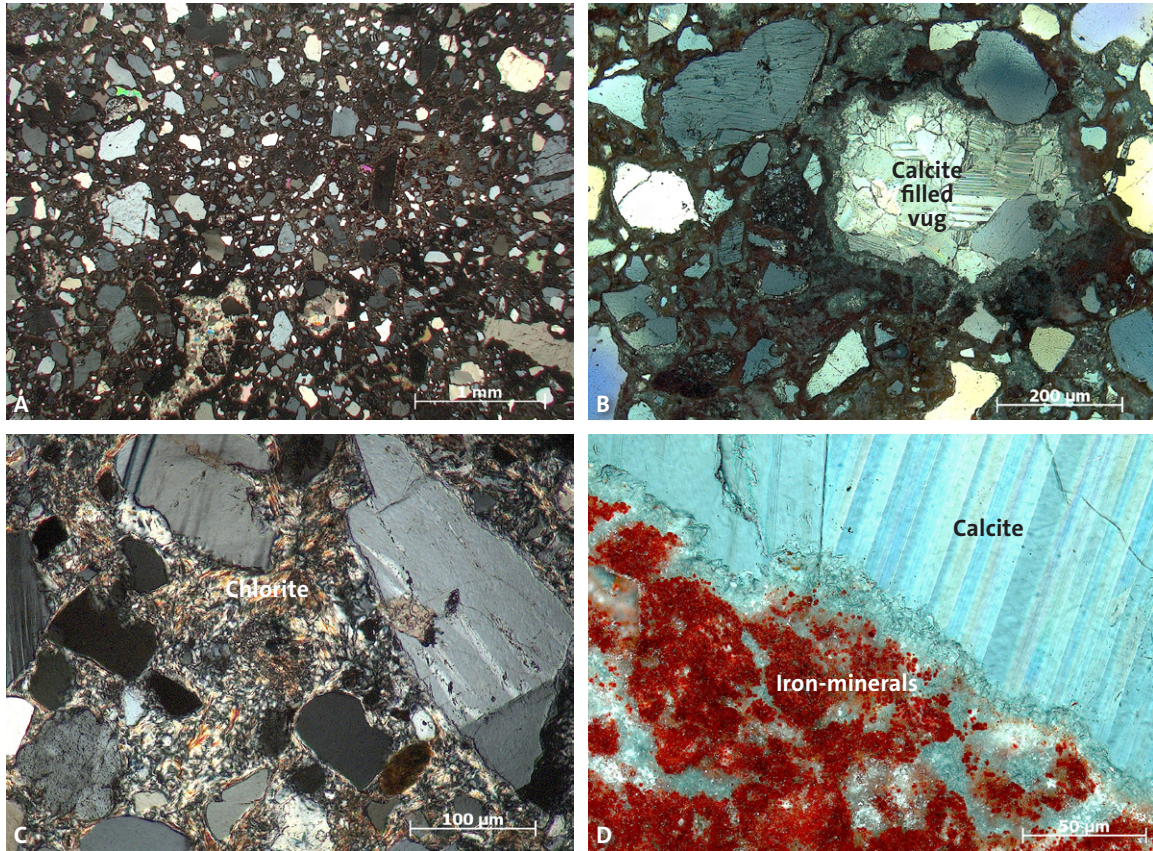
- A. General overview of the nodular and heterogeneous texture (cross-polarised light).
- B. Ghost structure of a root (plane polarised light, plane-polarised light).
- C. Dendrites filled with sparite (cross-polarised light).
- D. Microcrystalline dolomite. Upper left is a large crystalline rock fragment (reflected light).

Porosity: 8–18%.

Permeability: 0.16–68 mD.

3. Stavsten Formation, Höllviken-2, 1 633.35 m

Lithology: Reddish brown argillaceous sandstone with grey patches.



Description: Poorly sorted arkosic sandstone. Mineralisation of chlorite and illite constitute the main cementing agent together with calcite. Detrital clay minerals occur also as matrix. Calcite is also found as sparitic crystallisations filling vugs rimmed by iron-oxyhydroxides and clay. Feldspars and crystalline rock fragments are common.

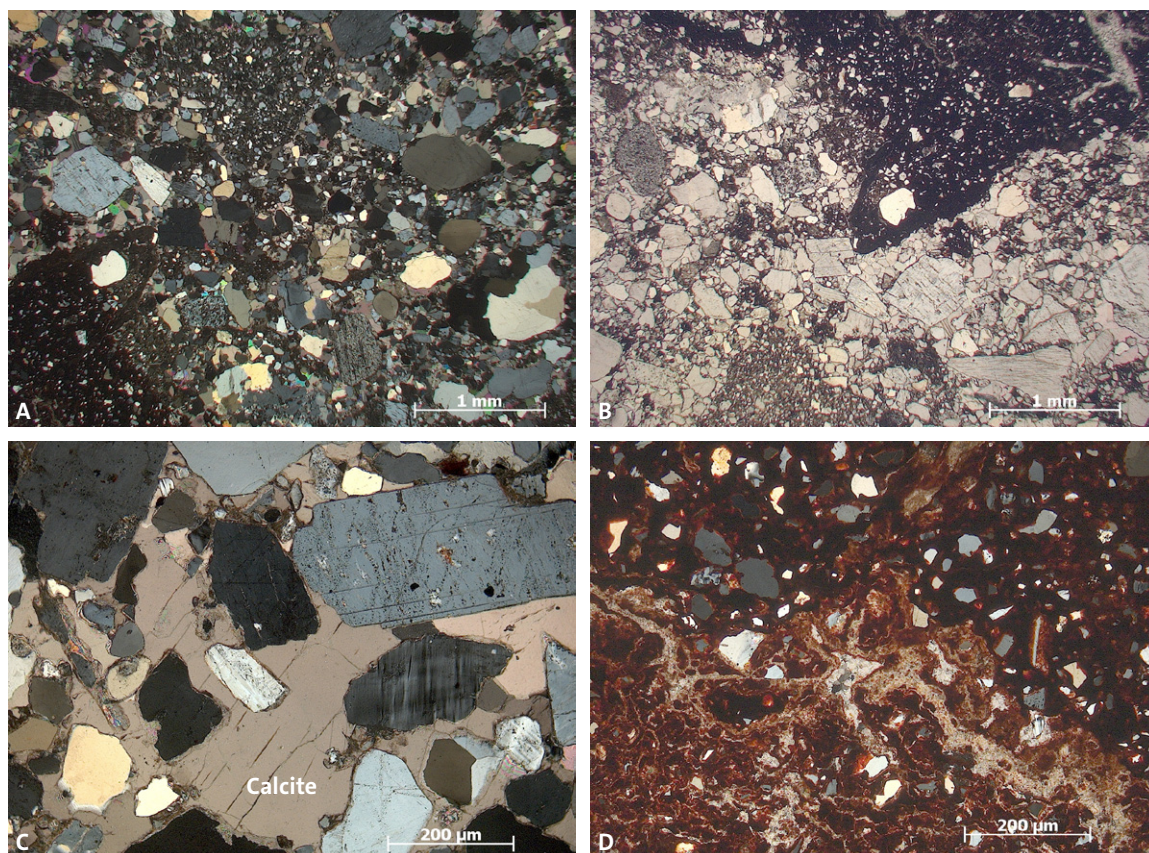
- A. Overview of the texture. Note the wide range in grain size (cross-polarised light).
- B. Vug of unknown origin rimmed by clay and iron-oxyhydroxides and filled by sparitic calcite (reflected light).
- C. Matrix and cement composed mainly of chlorite and illite minerals. Most of this phase is interpreted as authigenic (cross-polarised light).
- D. Microspherulitic precipitations of iron adjacent to macroscopic calcite crystals filling a vug (reflected light).

Porosity: 8–18%.

Permeability: 0.16–68 mD.

4. Fuglie Formation, Höllviken-2, 1647.28 m

Lithology: Mottled green-grey conglomeratic sandstone with reddish patches. Calcareous.



Description: The lithology is extremely poorly sorted. Large pebbles and clay clasts are common. The rock is variably cemented by calcite. Large crystals often embed the detrital components. In connection to the reddish patches dendritic and laminar structures with clay and iron-oxyhydroxides can be seen. These resemble in parts structures seen in the typical calcrete deposits of the same formation. Here the overall character of the deposit is coarser, which contributes to the less significant characteristics of a calcrete even if the processes likely have been active.

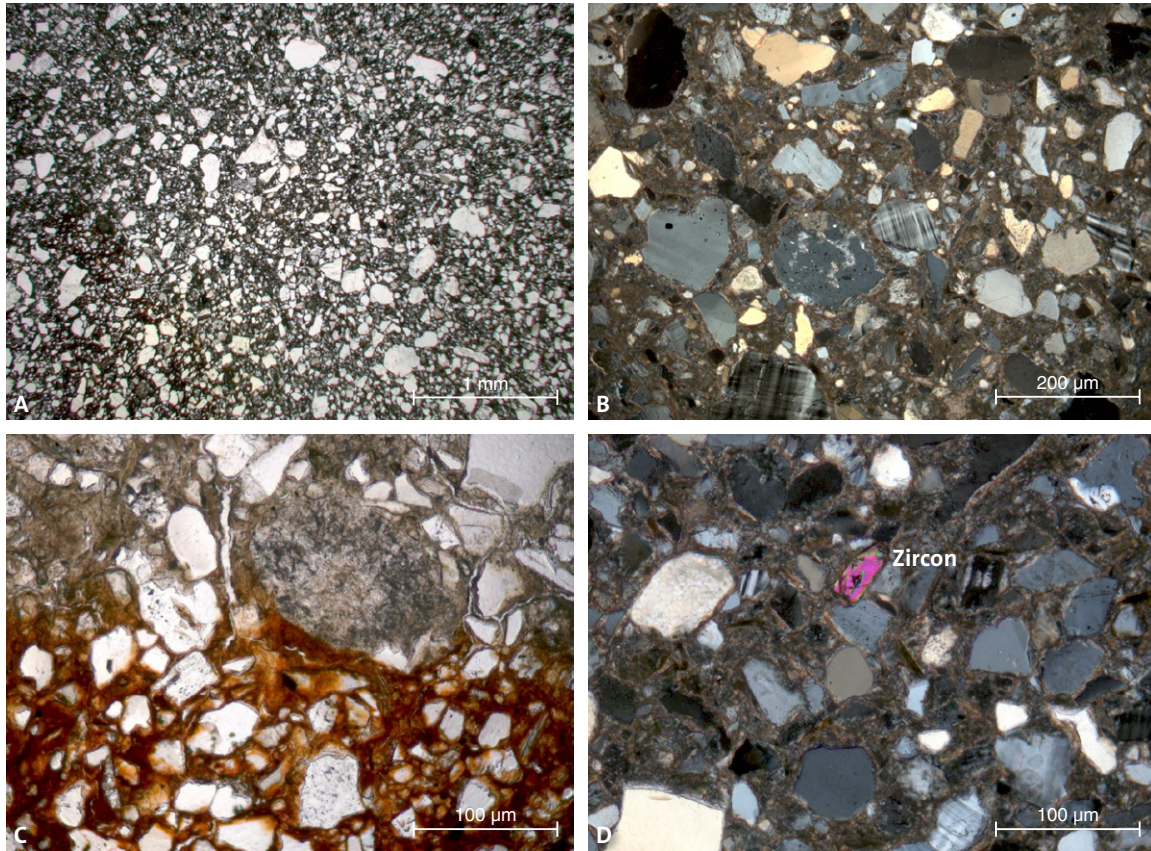
- A. Overall texture (cross-polarised light).
- B. Overall texture (plane-polarised light).
- C. Large calcite crystals embedding detrital quartz and feldspars (cross-polarised light).
- D. Crust-like precipitation of calcite together with argillaceous mudstone rich in iron precipitations (cross-polarised light).

Porosity: 8.1%.

Permeability: 0.35 mD.

5. Fuglie Formation, Höllviken-2, 1655.4 m

Lithology: Mottled greyish green and reddish brown, poorly sorted, matrix rich, parts conglomeratic sandstone and mudstone.



Description: The lithology is characterised by a high matrix content. This is mainly composed of an argillaceous and iron-rich material. There is a relatively high amount of feldspars. Scattered heavy minerals of e.g. zircon occur throughout the sample.

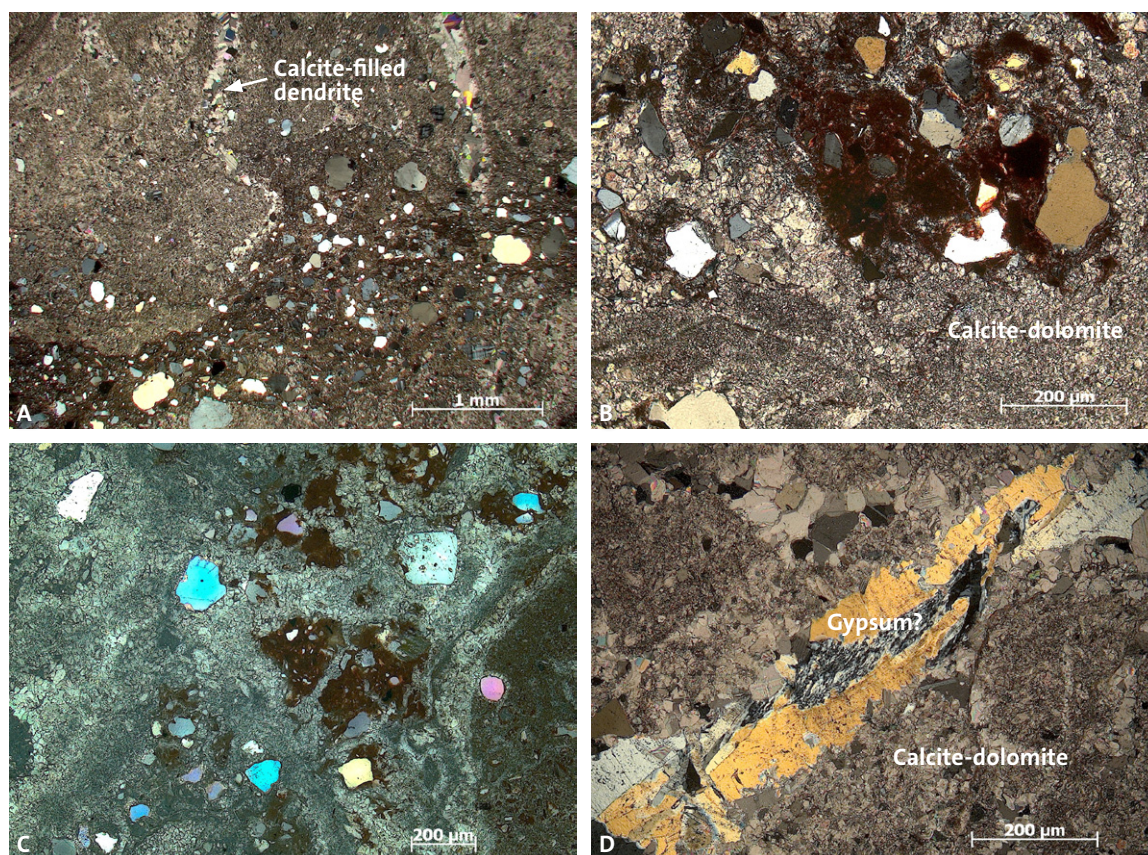
- A. General overview of the texture. Note the wide range in grain size (plane-polarised light).
- B. Detrital quartz and feldspar embedded in brownish grey, argillaceous matrix (cross-polarised light).
- C. Patches of reddish brown iron-oxyhydroxides are common (plane-polarised light).
- D. Up to 50 microns large crystals of zircon occur scattered in the sedimentary rock (cross-polarised light).

Porosity: 10%.

Permeability: 6 mD.

6. Fuglie Formation, Höllviken-2, 1677.35 m

Lithology: Mottled red-brown, nodular and calcareous mudstone–sandstone (calcrete).



Description: Heterogeneous, variably carbonate cemented mudstone–sandstone. The rock type is characterised by a dendritic and nodular texture (calcrete) as well as patches of sandy mudstone. The dendritic structures are commonly mineralised by dolomite and calcite. The sedimentary rock is mottled red-brown to grey with light grey to white streaks and patches. There are in addition weak indications of evaporitic mineralisations of gypsum.

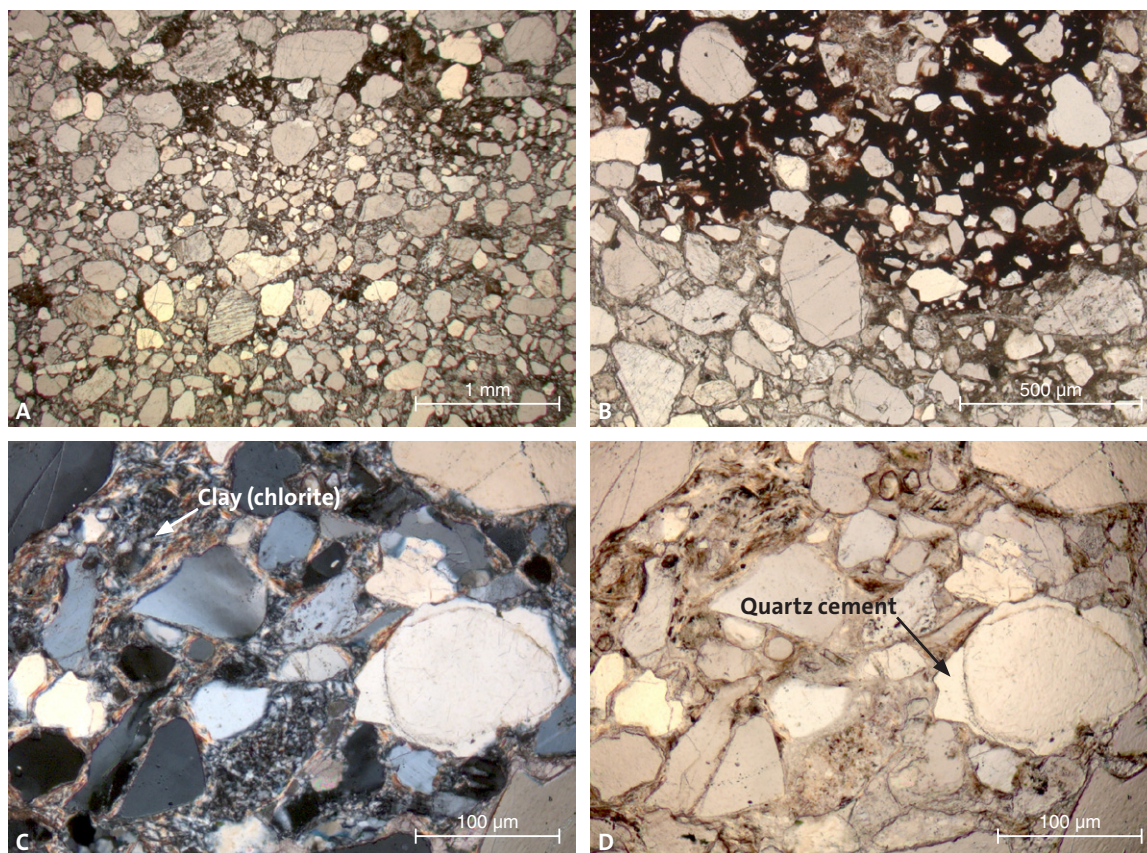
- A. General overview of the heterogeneous texture (cross-polarised light).
- B. Patches of iron-rich and argillaceous material (cross-polarised light).
- C. Sucrosic calcite and dolomite mineralisation surrounding argillaceous nodules (right, reflected light).
- D. Evaporitic mineralisation of gypsum surrounded by calcite and dolomite (cross-polarised light).

Porosity: 3–10%.

Permeability: 0.1–4 mD.

7. Fuglie Formation, Höllviken-2, 1683.7 m

Lithology: Mottled greyish green and reddish brown, poorly sorted, in parts conglomeratic sandstone.



Description: The Fuglie Formation is commonly characterised by lower amounts of carbonate and higher amounts of argillaceous matrix in comparison to overlying and underlying formations. The matrix also frequently contains a microcrystalline, siliceous component mixed with mainly chloritic clay minerals. Irregular, centimetre-large patches of brown arenaceous mudstone is common in the sample. Significant, as in many other samples from the Fuglie Formation, is the existence of secondary authigenic quartz in the form of overgrowth on detrital quartz. Euhedral crystal terminations are common. Carbonate cement occurs in subordinate amounts.

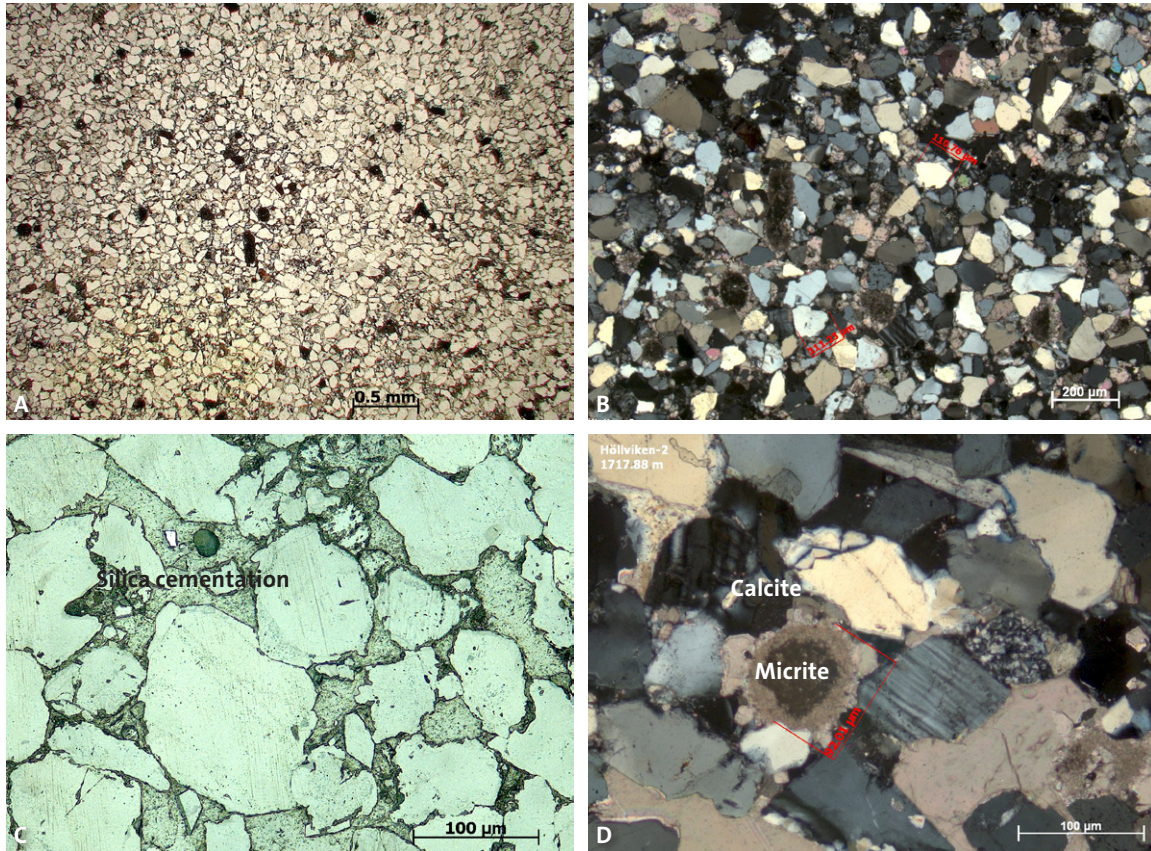
- A. General textural overview (plane-polarised light).
- B. Patches of brown arenaceous mudstone are frequent in the sample (plane-polarised light).
- C. A microcrystalline mixture of siliceous and chloritic cement and matrix (cross-polarised light).
- D. Quartz overgrowth on detrital quartz (plane-polarised light).

Porosity: 8.7%.

Permeability: 4 mD.

8. Vellinge Formation, Höllviken-2, 1717.88 m

Lithology: Greyish green and light purple, fine-grained sandstone.



Description: The rock is moderately sorted and incompletely cemented by sparry calcite and quartz overgrowths. The sparite is mainly found around micritic clasts of unknown origin. Subrounded quartz dominates the sand fraction. Overgrowth of quartz is commonly found on the quartz grains, often as meniscus cement holding adjacent grains together.

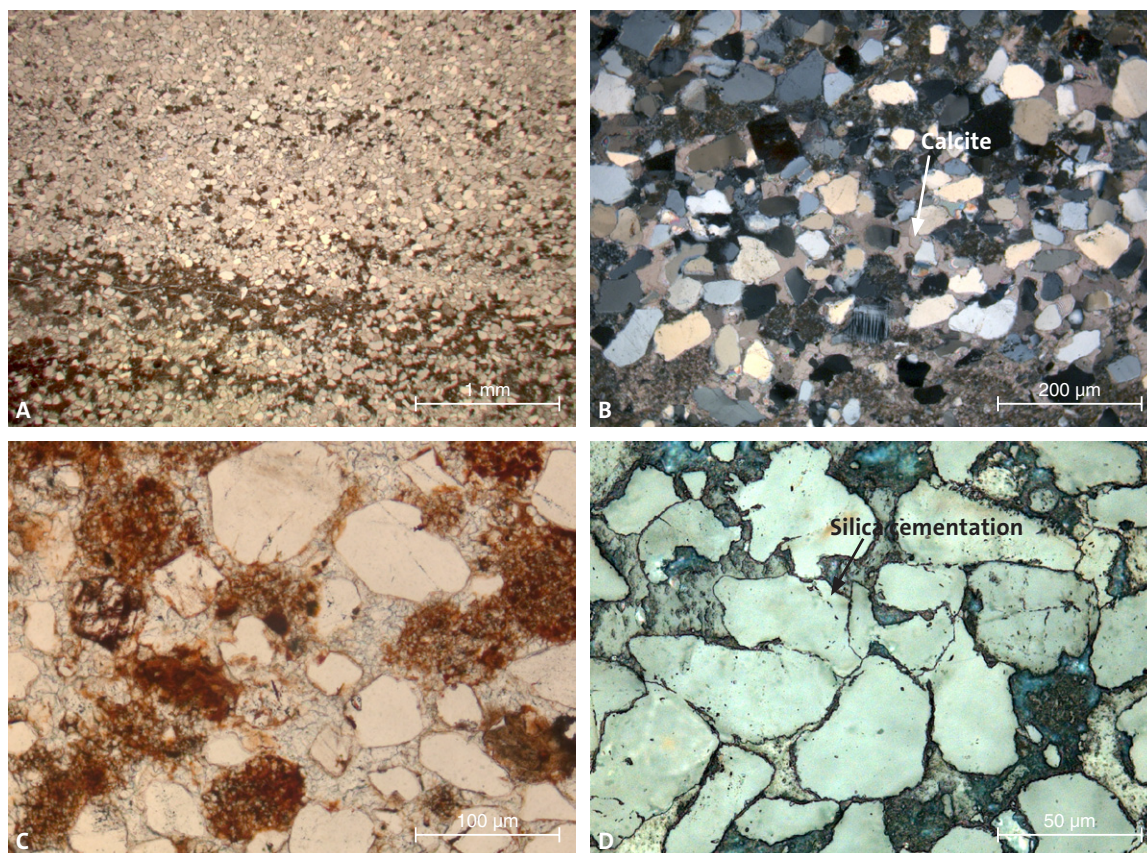
- A. General overview of the sandstone texture (plane-polarised light).
- B. Patchy, sparry calcite cement (cross-polarised light).
- C. Secondary quartz overgrowth on detrital quartz (reflected light).
- D. Micritic clast surrounded by sparry calcite (cross-polarised light).

Porosity: 20.3%.

Permeability: 1336 mD.

9. Vellinge Formation, Höllviken-2, 1726.58 m

Lithology: Laminated grey to reddish brown, fine-grained sandstone.



Description: The rock is relatively well sorted. The detrital grains are in general 50–100 µm large. Quartz is the dominant grain type. Irregular discontinuous laminations are relatively frequent. These consist of enrichments of argillaceous material which often have been oxidised. Calcite is common as cement. In the contact between quartz grains, a silica cement often occurs which is syntaxial with the grain. A dust rim commonly outlines the original grain boundary. The silica cementation precedes the calcite cement.

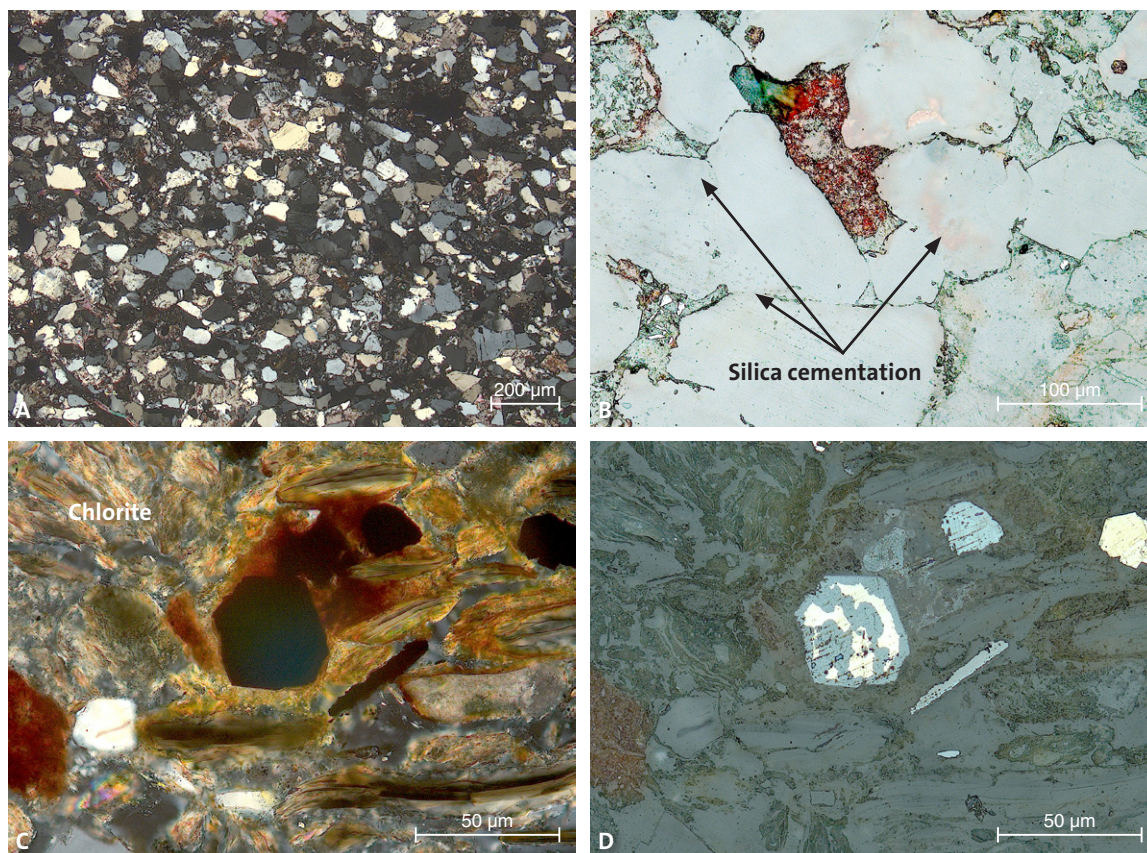
- A. General overview of the laminated texture (plane-polarised light).
- B. Calcite cement (cross-polarised light).
- C. Iron-rich argillaceous aggregates enriched in the darker laminae (plane-polarised light).
- D. Precipitations of silica at grain intersections (reflected light).

Porosity: 13.1%.

Permeability: 2.83 mD.

10. Vellinge Formation, Höllviken-2, 1741–1745 m

Lithology: Red-brown, green, poorly sorted, mostly carbonate cemented sandstone.



Description: The Vellinge formation is in this section dominated by “dirty sandstones”. The sandstones are rich in variably altered mica. Chlorite minerals are common in connection with the altered mica flakes. The induration varies considerably from relatively hard to more or less unconsolidated layers. Calcite is the main cement. However, silica precipitations in grain contacts are common. Amorphous minerals of unknown affinity are also relatively frequent as well as zircon minerals. Precipitations of iron-oxyhydroxides are often seen around the amorphous minerals.

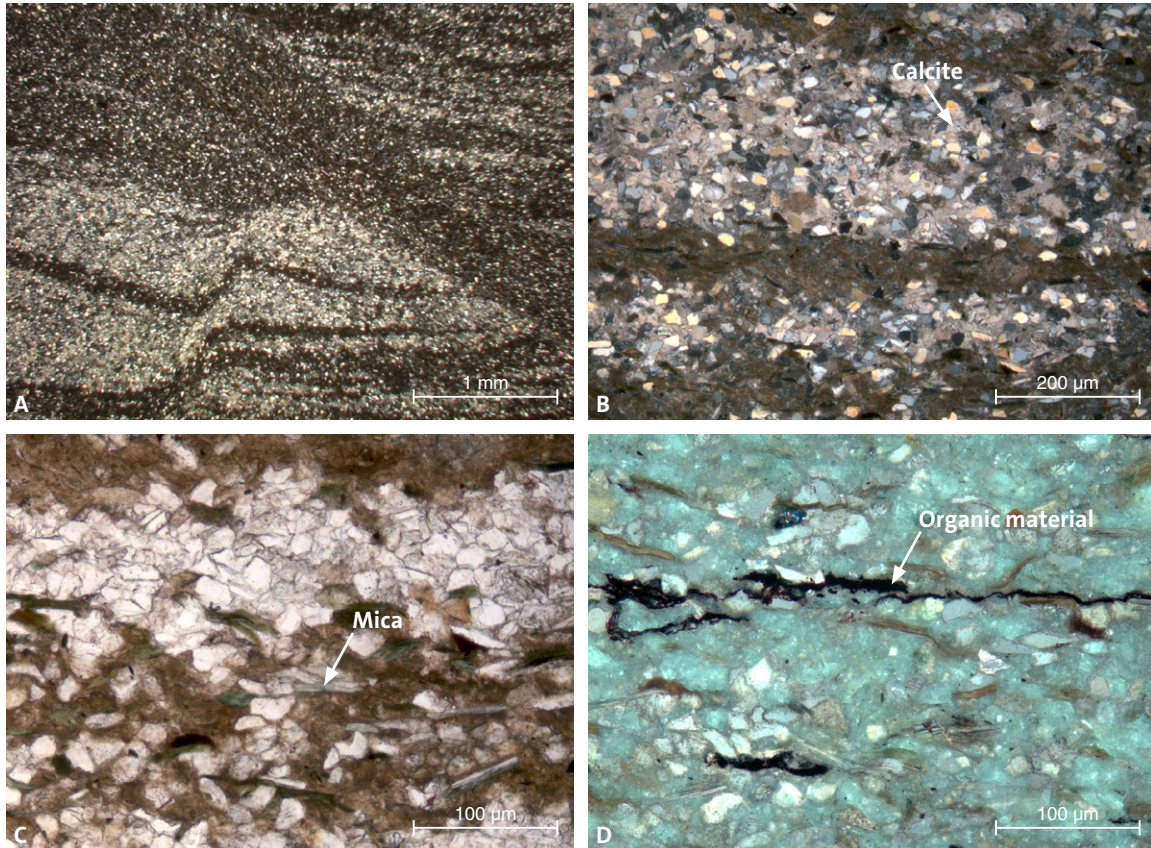
- A. General overview of a moderately carbonate cemented sandstone at 1741 m (cross-polarised light).
- B. Meniscus precipitations and overgrowth of silica. Red area is iron-oxyhydroxides (reflected light).
- C. Amorphous minerals, precipitation of iron together with variably altered mica and precipitations of chlorite (cross-polarised light).
- D. Same view as in C (reflected light).

Porosity: 10–20% (assumed).

Permeability: <100 mD (assumed).

11. Falsterbo Formation, Höllviken-2, 1761 m

Lithology: Laminated, grey, argillaceous, fine-grained sandstone.



Description: The rock is characterised by a wavy, non-parallel lamination which is mainly related to laminar enrichments of variably altered mica, clay and organic material. The less argillaceous parts are cemented by calcite.

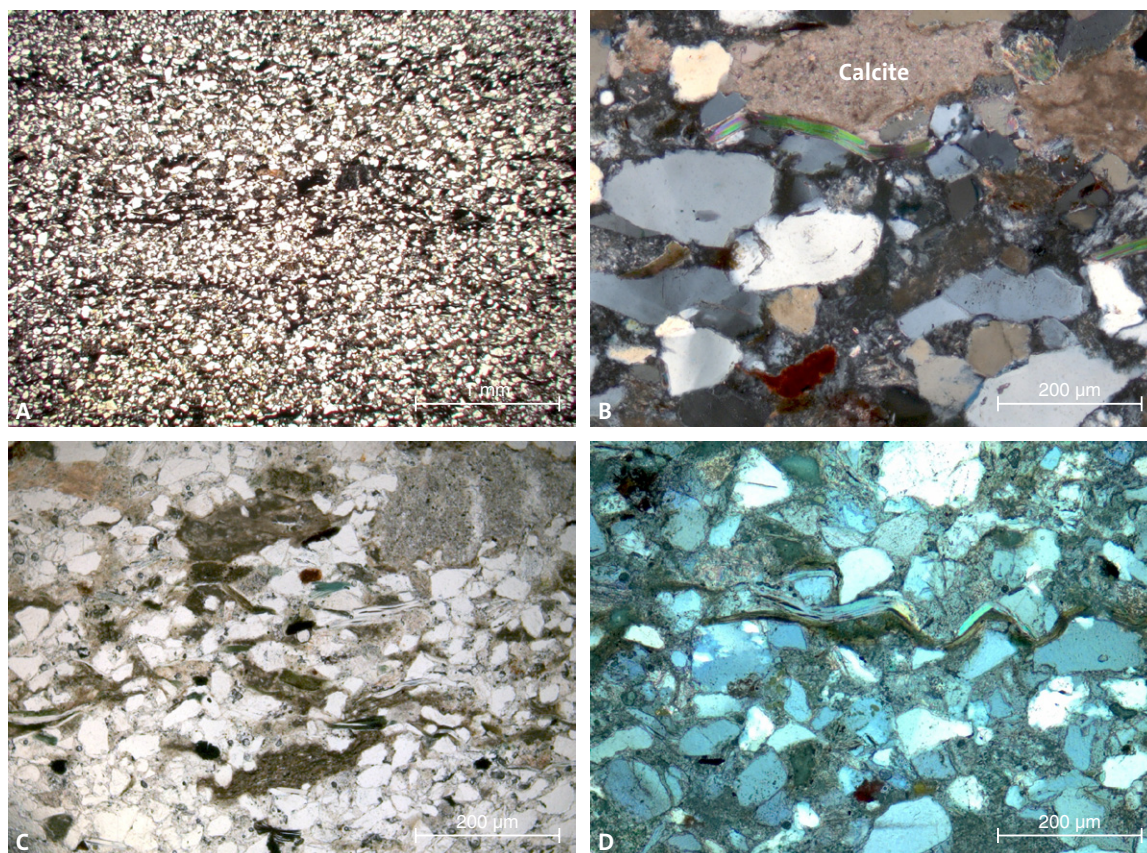
- A. General overview of the laminar texture (plane-polarised light).
- B. Calcite cementation in the sandy parts (cross-polarised light).
- C. Variably altered mica is common in the argillaceous laminae (plane-polarised light).
- D. Organic material is often found as elongated thin films and streaks in the rock (reflected light).

Porosity: 15–20% (assumed).

Permeability: <50 mD (assumed).

12. Falsterbo Formation, Höllviken-2, 1798.9 m

Lithology: Grey, in parts laminated, argillaceous, micaceous, fine-grained sandstone.



Description: The sandstone is laminated by thin micaceous flakes and organic material. The mica is frequently affected by chemical alteration. The moderately sorted rock is variably cemented by calcite. An argillaceous matrix is significant.

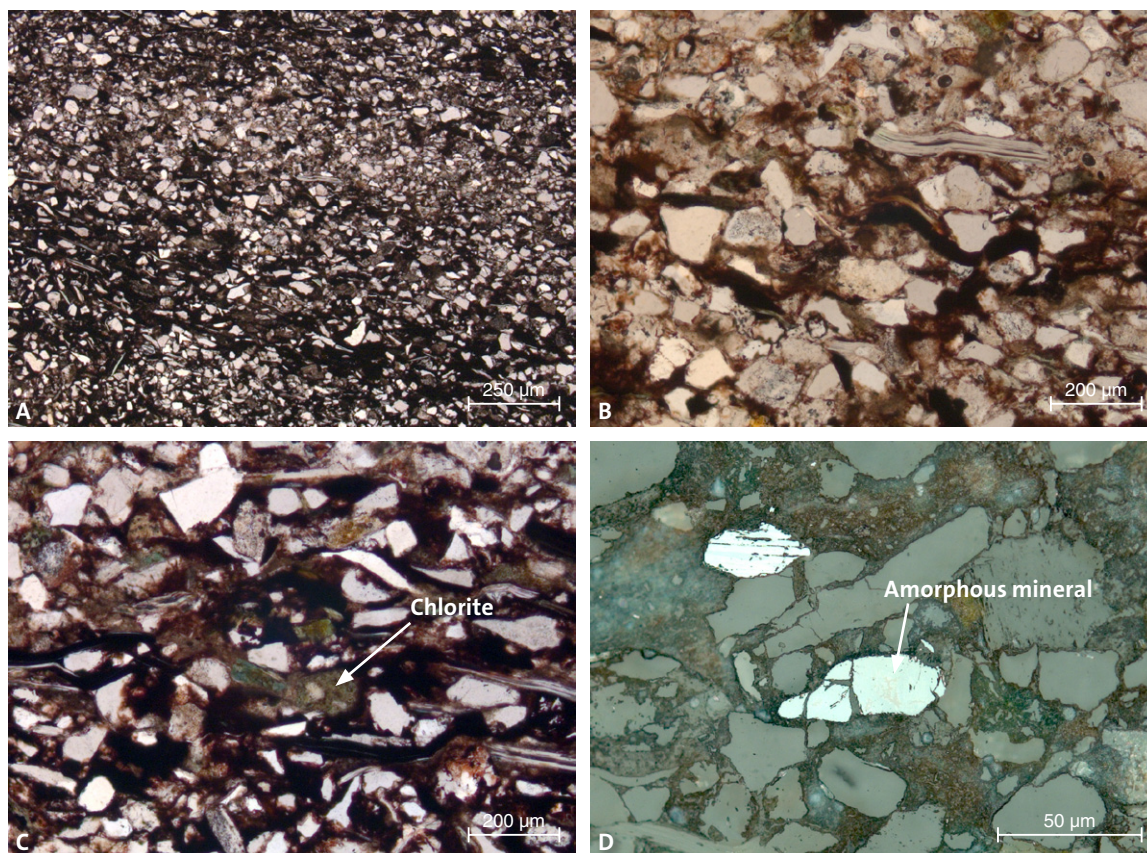
- A. General overview displaying the laminated texture (plane-polarised light).
- B. Mixture of calcite cement, clay matrix, quartz and mica (cross-polarised light).
- C. The rock is rich in argillaceous and micritic matrix as well as micaceous material (cross-polarised light).
- D. Deformation of mica (reflected light).

Porosity: 20.7%.

Permeability: 39 mD.

13. Falsterbo Formation, Höllviken-2, 1795.7 m

Lithology: Variably laminated, mottled red and grey, argillaceous, fine-grained sandstone.



Description: The most conspicuous character of the sample is the high amount of variably altered mica. Chlorite minerals are common as well as a high amount of iron-rich, brownish, argillaceous material. Amorphous minerals are relatively frequent.

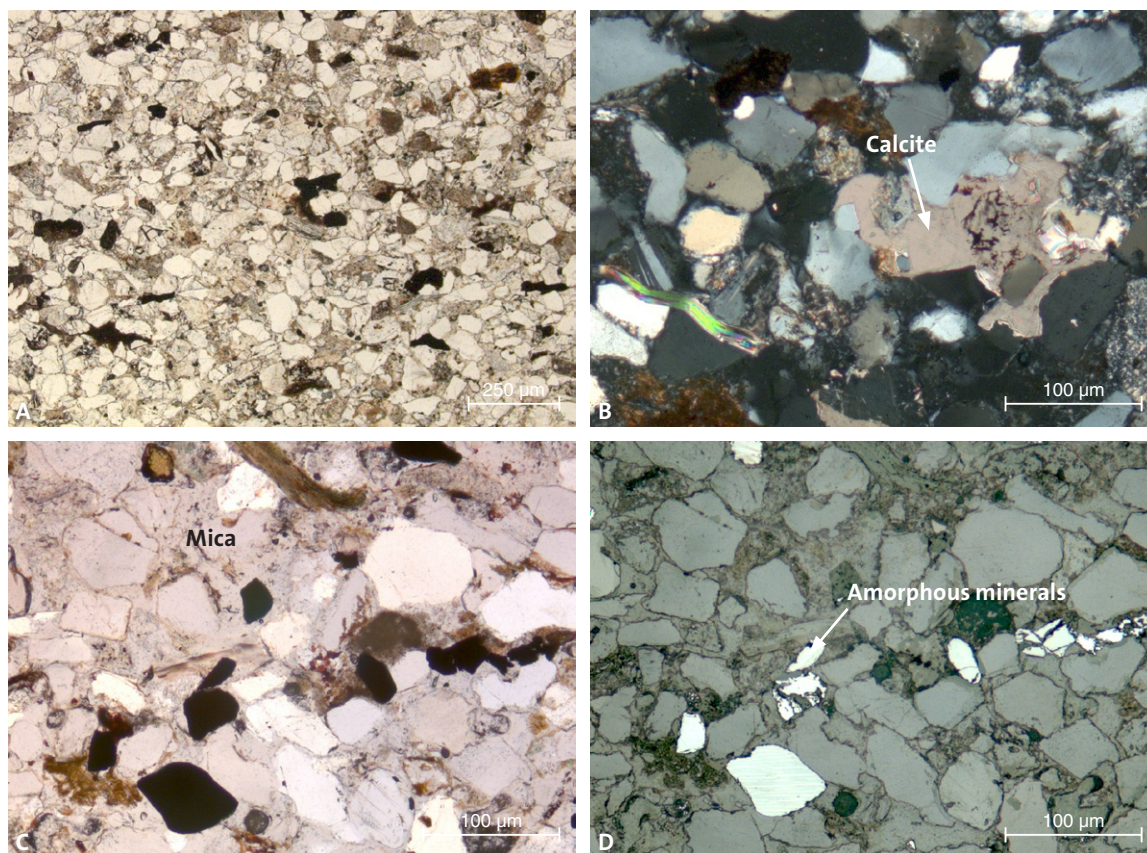
- A. General overview of the argillaceous, fine-grained texture (plane-polarised light).
- B. Photomicrograph showing variably altered mica and the argillaceous iron-rich matrix (plane-polarised light).
- C. Chlorite is commonly found as pale green, authigenic mineralisations (plane-polarised light).
- D. Amorphous minerals (reflected light).

Porosity: 16.3%.

Permeability: 2.02 mD.

14. Falsterbo Formation, Höllviken-2, 1796.75 m

Lithology: Variably laminated, red and grey, argillaceous, fine-grained sandstone.



Description: The sample is similar in its characteristics to Höllviken-2 1795.7 and 1798.9 m. However, it is slightly better sorted and contains lower amounts of argillaceous matrix and micaceous material. Amorphous minerals are relatively frequent, often enriched in scattered, discontinuous laminae. The sample is variably cemented by sparry calcite.

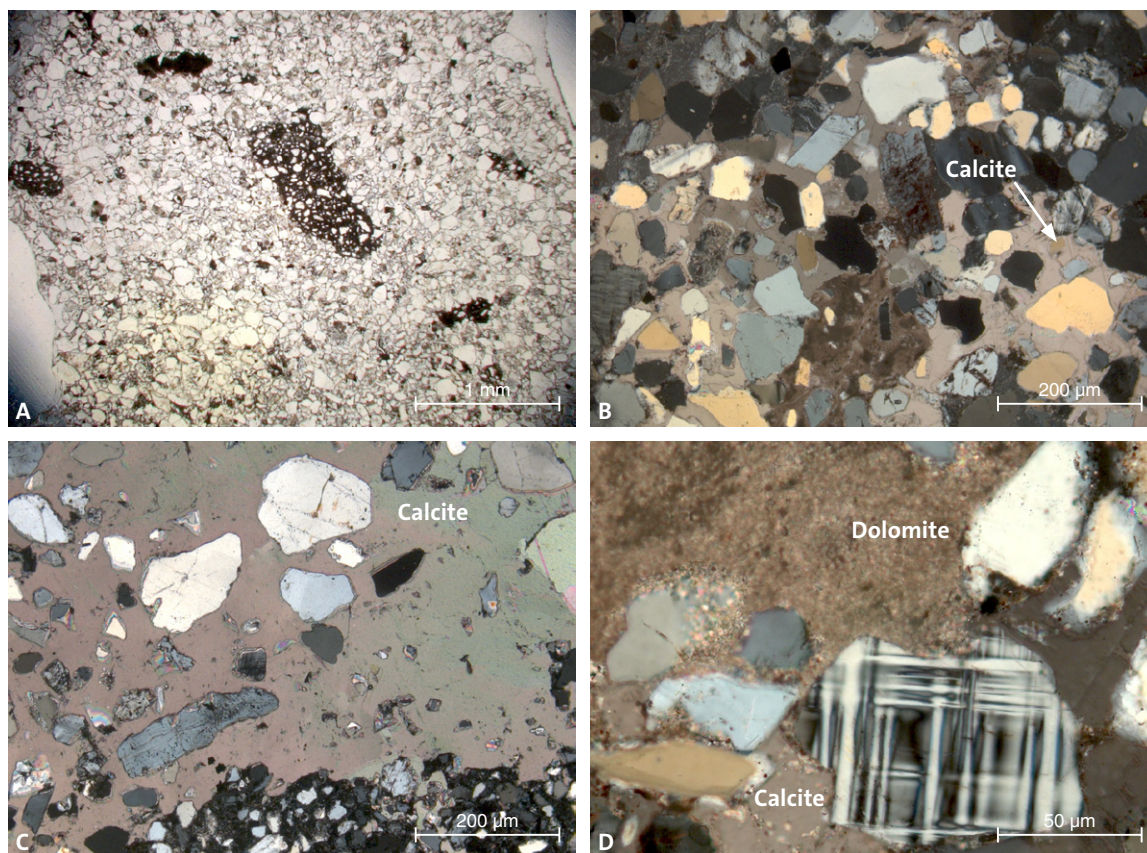
- A. General textural overview (plane-polarised light).
- B. Patchy calcite cements the sample (cross-polarised light).
- C. Occurrences of amorphous minerals in discontinuous laminae (plane-polarised light).
- D. Same as in C (reflected light).

Porosity: 26.1%.

Permeability: 466 mD.

15. Flommen Formation, Höllviken-2, 1866.2 m

Lithology: Grey, in parts purple, hard, calcareous sandstone.



Description: The sample is dense as a result of a more or less complete cementation of calcite and dolomite. Large calcite crystals often embed the detrital grains (poikilotopic cement). Olive green mud clasts occur scattered in the rock. Microcrystalline dolomite is mostly found associated with more argillaceous parts of the sample.

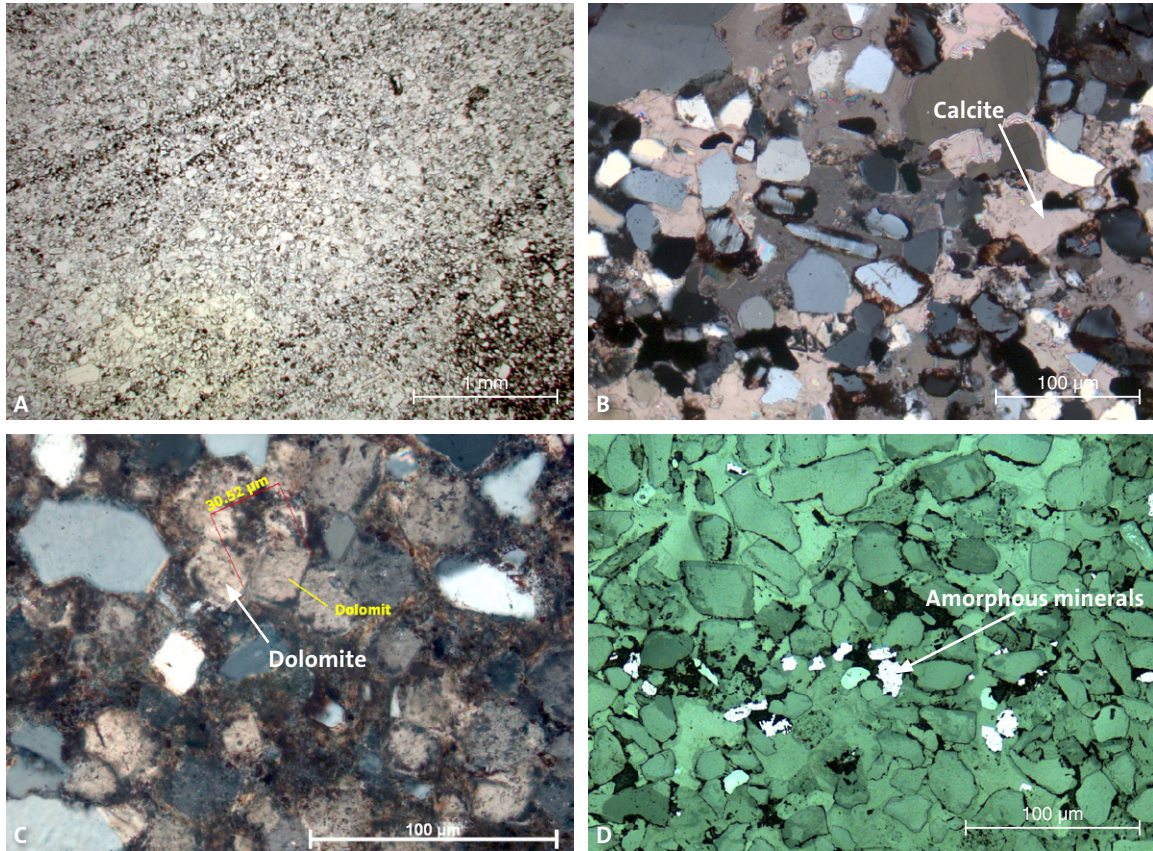
- A. General overview showing the occurrence of scattered mudstone clasts (plane-polarised light).
B & C. The sandstone is more or less completely cemented by large calcite crystals (cross-polarised light).
D. Microcrystalline dolomite and calcite surround a microcline crystal (cross-polarised light).

Porosity: <10% (assumed).

Permeability: <1 mD (assumed).

16. Hammar Formation, Höllviken-2, 1888 m

Lithology: Predominantly grey and purple, dense and in parts laminated, fine-grained and medium-grained sandstone.



Description: The rock is well indurated by calcite and dolomite cement. Argillaceous material occurs as thin discontinuous laminae in the rock. The rock is relatively well sorted. The grains are mainly subrounded. Amorphous minerals are frequently enriched in the argillaceous laminae.

- A. General texture with laminae of argillaceous material (plane-polarised light).
- B. Calcite cementation (cross-polarised light).
- C. Subeuhedral crystals of dolomite (cross-polarised light).
- D. Enrichment of amorphous minerals (reflected light).

Porosity: 9–10%.

Permeability: 1–4 mD.



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Uppsala 2012
ISSN 0349-2176
ISBN 978-91-7403-157-7
Tryck: Davidsons Tryckeri AB, Växjö