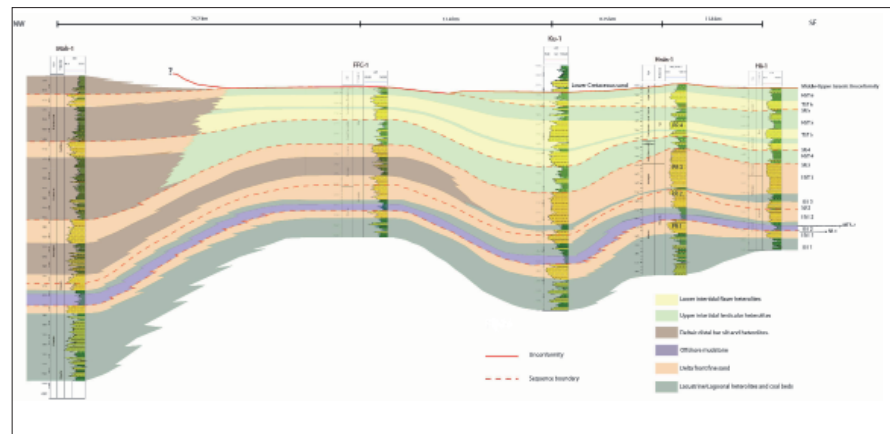


Lithofacies analysis and heterogeneity study of the subsurface Rhaetian–Pliensbachian sequence in SW Skåne and Denmark

Bou Daher Samer

Dissertations in Geology at Lund University,
Master's thesis, no 296
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2012

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and heterogeneity study
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Master's thesis
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Abstract: The geological setting of Skåne is the outcome of successive phases of transtensional tectonics, block-faulting, subsidence, transpression and inversion focused around the Sorgenfrei-Tornquist Zone. The Höllviken Halfgraben is one of the major blocks in southwestern Skåne with a Rhaetian–Pliensbachian succession characterized by interbedding of arenaceous and argillaceous facies of local and regional extent. This study aims at analysing the heterogenous Rhaetian–Pliensbachian strata and is part of a major project focused on assessing the suitability of this succession for CO₂ storage and/or geothermal energy production. Investigation of the lithofacies distribution has been done using Gamma Ray, Self Potential, Resistivity, Sonic, Neutron and Density data from 11 Swedish and Danish boreholes. Five boreholes have been selected for a northwest–southeast transect that is interpreted in a sequence stratigraphic approach supported with outcrop data from Kulla Gunnarstorp and Norra Albert, the Höllviken -2 core, and sidewall cores from the FFC-1 well. The study presents an eustatically controlled Rhaetian deposition and a tectonically controlled Hettangian–Pliensbachian deposition. A generally transgressive sequences dominate the Rhaetian–Pliensbachian succession. A distinctive similarity between the Rhaetian–Pliensbachian succession in southwestern Skåne and northwestern Skåne, though some differences in the relative sea level fluctuation occur during the Hettangian–Sinemurian owing to differential subsidence. Moreover, the Rhaetian–Pliensbachian succession in the Höllviken Halfgraben shows a dominance of fine-grained facies, and thus rendered less favorable conditions for geothermal water production. However, the succession is proved convenient for CO₂ storage having adequate porosities (>20%), enough permeability (>100 mD), occurring at a depth of more than 800 m and sealed by tight claystone layers.

Keywords: Sorgenfrei-Tornquist Zone, Höllviken Halfgraben, Rhaetian, Hettangian, Sinemurian, Pliensbachian, sequence stratigraphy, lithofacies, reservoir, geothermal, CO₂ storage.

Samer Bou Daher, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: samer.boudaher@hotmail.com

Analys av sedimentära facies i Skånes och Danmarks yngre trias och äldre jura

BOU DAHER SAMER

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Sammanfattning: Skåne har formats genom flera tektoniska och geologiska processer kopplade till en stor sprick- och rörelsezon – Sorgenfrei-Tornquistzonen. I sydvästra Skåne finns ett större förkastat block, Höllvikensänkan, med sedimentära lager från trias-juratiden. Denna lagerföljd karakteriseras av sandsten varvat med lersten som avsatts både lokalt och över större områden. Studien har fokuserat på analys av lagerföljden och är en del i ett större projekt för att utvärdera om berggrunden är lämplig för lagring av CO₂ och/eller användas till geotermisk energiutvinning. Geofysisk data från elva svenska och danska borrhål, samt från fältdata, har använts för att göra en sådan utvärdering. Utifrån dessa data har en NV-SÖ sektion skapats och den har påvisat att det dåvarande havet i sydvästra Skåne var influerat av globala havsnivåförändringar i slutet av trias men att havsnivån i början av jura styrdes av lokala till regionala tektoniska rörelser. Berggrunden i det studerade tidsintervallet domineras av finkornigt material vilket gör att det är mindre gynnsamt för geotermisk energiproduktion. Däremot uppfyller berggrunden, på ett djup större än 800 m, kriterierna för att lagra CO₂.

Nyckelord: Sorgenfrei- Tornquistzonen, Höllvikensänkan, Rhaetian, Hettangian, Sinemurian, Pliensbachian, sekvensstratigrafi, lithofacies, reservoar, geotermisk, CO₂ lagring .

Samer Bou Daher, Geologiska institutionen, Lunds Universitet, Sölvegatan 12, SE-223 62 Lund, Sverige. E-mail: samer.boudaher@hotmail.com

1. Introduction

Skåne is situated in the transition zone between the Danish Basin to the southwest, and the stable Precambrian Baltic Shield to the northeast (Fig. 1). This geological setting on the edge of the Baltic Shield has through time endured transtensional tectonics, block-faulting, subsidence, transpression and inversion focused around the Sorgenfrei-Tornquist Zone (STZ), which cuts through Skåne from the northwest to the southeast (Fig. 1). The repeated tectonic movements along the major faults associated with the STZ have altogether contributed to the current mosaic distribution of the Mesozoic strata in Skåne. Much of the present distribution is a direct result from uplift and erosion during compression tectonics related to the Late Cretaceous Alpine orogeny. Neogene uplift and erosion of preexisting strata on the margins of the Baltic Shield has also played a significant role in the present representation of strata (cf. Japsen et al., 2002).

The lithological and stratigraphical characteristics of Triassic and Jurassic sequence are mainly known from outcrops and borings in northwest Skåne where the strata constitute the bedrock surface in the Höganäs Basin and Ängelholm Trough (cf. Norling et al., 1993). Upper Triassic–Jurassic outcrops are elsewhere within the STZ found as scattered erosional remnants in central Skåne (Erlström & Guy-Ohlson, 1999) and in tilted localized rock blocks along the Romeleåsen Fault Zone and in the Fyledalen Fault Zone (cf. Fig. 1). In Skåne Rhaetian and Jurassic strata are additionally found as subcrops in the marginal parts of the Danish Basin, i.e. the Höllviken Halfgraben and Barsebäck Platform, and in the Hanö Bay area (Grigelis & Norling, 1999).

In the Höllviken Halfgraben, the Upper Triassic–Lower Jurassic is represented by a 200–300 m thick succession of strata (Norling et al., 1993).

The marginal position of Skåne, coupled with synsedimentary tectonic activity resulted in a Rhaetian–Lower Jurassic succession characterized by a frequent occurrence of sandstone units interbedded with argillaceous units. The subcrops in southwestern Skåne reveal a number of sandstone units with good reservoir properties which yield a high potential for being utilized for CO₂ storage purposes, and some beds might also be used for geothermal water production. However, the stratigraphical affinity and lateral relationships between the described successions in the different borings in southwestern Skåne has so far been uncertain.

Nielsen (2003) established a stratigraphic comparison and correlation of the Rhaetian–Jurassic going from the central parts of the Danish Basin into the marginal parts and the STZ in Skåne. However, when approaching the marginal zone, sea level changes and differences in accumulation space, along with a laterally shifting depositional setting, lead to significant local variation in the vertical and lateral distribution of the

sandstone units. Thus, turning the correlation of individual units between borings within the Höllviken Halfgraben, southwestern Skåne, into a challenging and complicated task as some intervals may have a greater distribution in the basin while others may be only locally developed.

Geological investigations of the Rhaetian–Lower Jurassic in Skåne started already during the 18th century, due to the national economic interest in the occurrences of coal and fire-clays. Thus, an important amount of data has been produced since then in the form of well data, mining data, and geophysical data archived at the Geological Survey of Sweden (SGU). Moreover, Erdmann (1915), Troedsson (1951) Vossmerbäumer (1969, 1970), Rolle et al. (1979), Norling & Bergström (1987), Ahlberg (1990, 1994), Erlström et al. (1991, 1997, 1999), Pienkowski (1991a, b), Norling et al. (1993), Larsson et al. (1994), Arndorff (1994), Nielsen (2003), Ahlberg et al. (2003), Lindström & Erlström (2006, 2011), Vajda & Wigforss-Lange (2009), and Larsson (2009) have added valuable descriptions and interpretations to the understanding of the depositional conditions and the relationship between the different areas of deposition. The subsurface geology of southwest Skåne is presented by Sivhed et al. (1999). However, much of the data, especially from southwestern Skåne, is still poorly investigated. An increasing interest in utilizing the deep saline Rhaetian–Jurassic aquifers in southwestern Skåne for geothermal energy and the possibility for CO₂ storage compel the need to get a more detailed understanding of the structure and development of the subsurface Rhaetian–Lower Jurassic succession. One important contribution to this has been the biostratigraphic work performed and presented by Lindström & Erlström (2011), which allows a more precise correlation, an interpretation of the depositional setting and basin evolution as well as a possibility to perform a sequence stratigraphical study of the succession.

This study focuses on the Rhaetian–Pliensbachian succession of the Höllviken Halfgraben (Fig. 1), and aims to describe the various facies, facies association and frequency, in order to elucidate the basin evolution. A sequence stratigraphic approach along with statistical analysis is used to explain and anticipate local facies distribution as well as regional correlation with northwestern Skåne and the Danish Basin.

2. Geological setting

2.1 Structural framework and tectonic setting

Skåne is situated at the margin of the Danish Basin, a Permian–Cenozoic basin that formed by Late Carboniferous–Early Permian rifting and subsidence, controlled by thermal cooling and local faulting. The basin is bordered to the northeast by the Sorgenfrei-

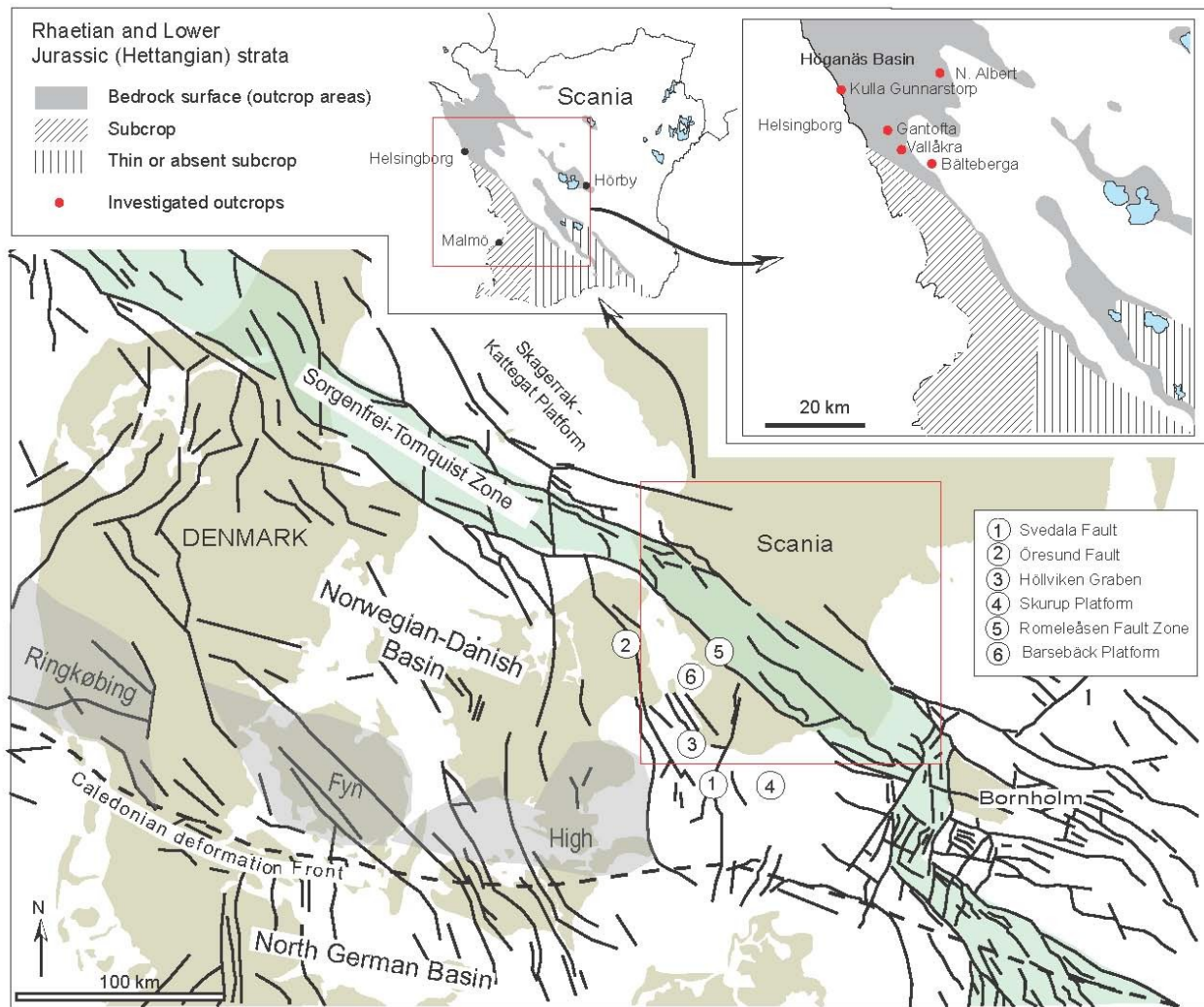


Fig. 1. Map showing the main structural elements of Skåne and the surrounding region, and the distribution of Rhaetian-Hettangian strata in Skåne (Modified after Lindström & Erlström, 2006)

Tornquist Zone (STZ) and to the southwest by the Ringkøbing-Fyn High (Nielsen, 2003) (Fig. 1).

The Tornquist Zone (TZ) is a regional composite tectonic zone controlling the sedimentation history of Skåne and the Baltic Sea region. It consists of a block-faulted zone with its northwestern Sorgenfrei branch traversing Skåne, Kattegat, N Jutland, up into the North Sea area. The southeast Teisseyre branch extends through Poland and down to the Black Sea (Norling et al., 1993). In Skåne, the Sorgenfrei-Tornquist Zone (STZ) is outlined to the northeast by the Kullen-Ringsjön-Andrarum Fault Zone and by the Christiansö Fault, and to the southwest by the Romeleåsen Fault Zone and the Rønne Graben which constitutes the junction between the STZ and the TTZ (Erlström et al., 1997). The STZ was first considered as the unstable southern border of the Baltic Shield and was thus called the Fennoscandian Border Zone (Bartmann & Christensen, 1975). However, later work presented by the EUGENO-S Working Group (1988) clarified that the boundary between the old Precambrian crust and the Palaeozoic European crust

is located to the south of the Ringkøbing-Fyn High and not at the STZ (Hansen et al., 2000). Instead the STZ was proven to be a weak crustal lineament acting as a “buffer zone” whenever the regional tectonic regime changed (Mogensen 1994, 1995; Mogensen & Jensen, 1994).

Since the Late Palaeozoic several tectonic events along the STZ have obscured the earlier tectonic history and evolution of the region. However, a pre-rift succession of clastic sediments and extrusive volcanic rocks, of presumed Late Carboniferous age, unconformably overlain by thick syn-rift alluvial conglomerates, sandstones and lacustrine mudstones in the STZ clearly indicate that the principal phase of rifting of the Danish Basin and the Fennoscandian Border Zone, i.e. the STZ, occurred in the Late Carboniferous – Early Permian, in conjunction with rifting in the Oslo Graben (Michelsen, 1997; Nielsen, 2003). Associated transtensional movements and block faulting lead to the formation of various pull-apart basins, e.g. the Höllviken Halfgraben (Erlström et al., 1997).

The Höllviken Halfgraben consists of a down-

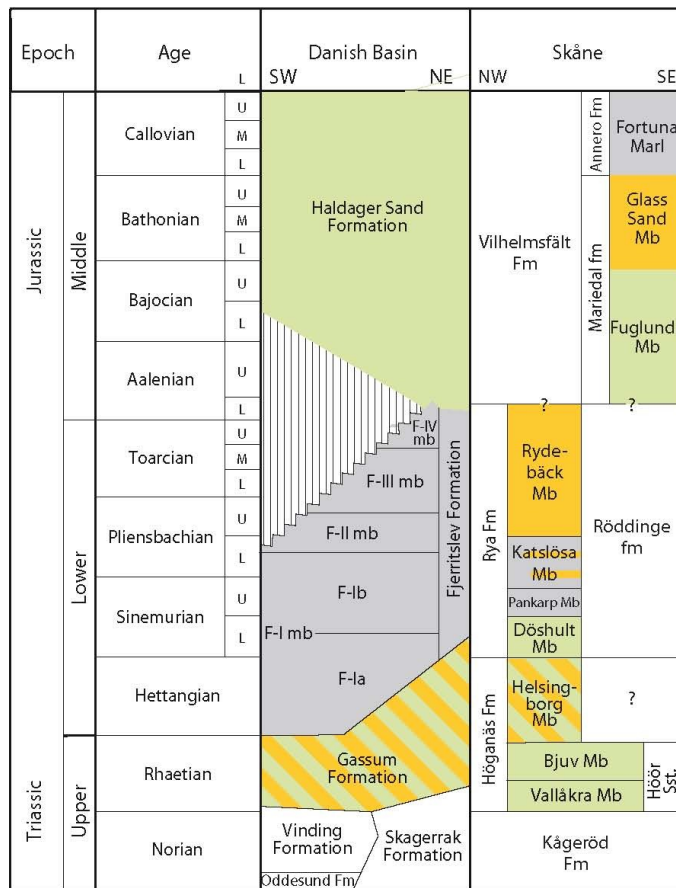
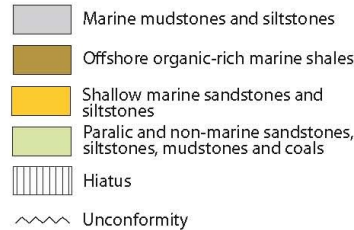


Fig. 2. Lithostratigraphic framework of the Upper Triassic to Middle Jurassic succession in Denmark and Skåne. (Modified after Nielsen, 2003 and Lindström & Erlström, 2011)



faulted tilted and slightly rotated rock block (Lindström & Erlström, 2011) delimited by the synsedimentary Svedala Fault to the east, Malmö Fault to the north, and the Öresund Fault to the west (Norling & Bergström, 1987). The Lower Palaeozoic strata preserved in the deepest parts of the Höllviken Halfgraben are southwestward dipping and unconformably overlain by Upper Permian deposits marking a hiatus and a period of peneplanization (Lindström & Erlström, 2011). Subsidence resumed in the early Triassic and a 500–600m thick Lower and Middle Triassic succession was formed (Erlström & Sivhed, *in press*). Deposition continued in the Höllviken Halfgraben during most of the Triassic and Early Jurassic times (Lindström & Erlström, 2011).

To the east of the Höllviken Halfgraben is the Skurup Platform (Fig. 1). The platform is interpreted as a Jurassic high based on its incomplete or missing Rhaetian–Lower Jurassic strata (Erlström et al. 1997; Sivhed et al. 1999). The redeposited spores and pollen in the Höllviken Halfgraben, also imply a high surrounding (Lindström & Erlström, 2011).

During the Late Triassic to Early Jurassic, most of the Danish Basin was characterized by a relatively calm tectonic regime (Nielsen, 2003) followed by an increased tectonic activity from the Hettangian into the Lower Cretaceous and is known as the Kimmerian orogeny (Norling & Bergström, 1987). This resulted in

the replacement of the Middle Jurassic predominantly transgressive regime by a tectonically controlled regressive phase linked to the volcanic activity in central Skåne (Norling et al., 1993). Tectonic uplift resulted in a major hiatus spanning most of the Middle and Upper Jurassic interval (Lindström & Erlström, 2011), and deposition became localized in fault bounded blocks within the STZ where subsidence continued (Nielsen, 2003).

During the Late Cretaceous, a change in the regional stress orientation to a transpressional regime replaced by the Laramide tectonics lead to the inversion of the pre-existing basin architecture. The inversion was most pronounced within the TZ, and declining significantly with distance to the northeast and southwest (Erlström et al., 1997). In the northeast, the Romelåsen Fault Zone experienced a c.1500m (Lindström & Erlström, 2011) vertical displacement contemporaneous with minor displacement in the southwest along the Öresund Fault during the Late Cretaceous inversion. Thus leading to a northeastward tilting of the whole area, especially the Barsebäck Platform, which constitutes a relay ramp to the Höllviken Halfgraben, with a similar Mesozoic sequence but a missing Lower Triassic and a poorly developed Middle Triassic sequence (Lindström & Erlström, 2011; Erlström & Sivhed, *in Press*).

In the Neogene, uplift of the South Swedish

Dome has resulted in the exposure of sub-Cambrian and sub-Cretaceous surfaces in southern Sweden (Japsen et al., 2002).

2.2 Upper Triassic – Lower Jurassic stratigraphy in NW Skåne

The lithostratigraphic subdivisions spanning the Rhaetian–Pliensbachian/Toarcian interval in Skåne involve the Höganäs and the Rya formations (Fig. 2). These are well known in northwest Skåne (cf. Norling et al., 1993), but not clearly defined in southwest Skåne.

The Höganäs Formation, representing the Rhaetian–Hettangian interval, has an approximate thickness of 250 m and is subdivided into three members. The Vallåkra and Bjuv Members representing the Rhaetian part, and the Helsingborg Member representing the Hettangian part (Grigelis & Norling, 1999). The basal Vallåkra Member is regarded as the transition between the continental redbeds of the Kågeröd Formation and the deltaic, coal bearing Bjuv Member. The Vallåkra Member is estimated to be 30 m thick in northwest Skåne (Grigelis & Norling, 1999), and includes grey and variegated clays with sphaerosiderite and greenish sandstone lenses (Grigelis & Norling, 1999). The Bjuv Member is delimited by a lower coal seam (B-seam) marking its lower boundary to the Vallåkra Member, and an upper seam (A-seam) marking its upper boundary to the Helsingborg Member. The Bjuv Member includes also the Triassic–Jurassic transition in Skåne (Lindström & Erlström, 2006). It has a thickness of approximately 25 m and is represented by sandstones, siltstones, claystones and characterized by paleosols with underclays and autochthonous coal-seams with interfingering channel-shaped sandstone stringers (Ahlberg, 1994). The Helsingborg Member has a thickness of 215 m (Grigelis & Norling, 1999) and it includes floodplain strata similar to those of the Bjuv Member, however, subjected to several marine incursions (Vossmerbäumer 1969, 1970; Ahlberg 1990, 1994; Pienkowski 1991a, b; Ahlberg et al., 2003).

The post-Hettangian Lower Jurassic sequence is represented in northwestern and western Skåne by the Rya Formation. The Rya Formation is subdivided into four Members (Fig. 2). The Döshult Member representing the lower Sinemurian is characterized by coarse-grained, cross-bedded sandstone beds in the lower part (Fig. 3), and clays and marls in the upper part (Grigelis & Norling, 1999). The upper Sinemurian Pankarp Member consists of around 60–75 m as a complete sequence known from boreholes, with variegated clays and shales in the lower part, a thin middle part of sand and sandstone with rootlet beds, and an upper part of variegated clays and shale (Grigelis & Norling, 1999). The Katslösa Member represents the upper Sinemurian and lower Pliensbachian and consists of a 30–40 m thick sequence of greenish, brown

and dark grey claystones, siltstones, and sandstones with a varying content of iron and carbonate (Grigelis & Norling, 1999). The Rydebäck Member represents the Upper Pliensbachian–Toarcian/Aalenian interval, this unit is known from boreholes only and varies in thickness between 50 m and 100 m. It includes sandy and silty, partly oolitic sediments with a varying content of clay and calcium carbonate (Grigelis & Norling, 1999).

In southwestern Skåne, i.e. in the Höllviken Halfgraben and on the Barsebäck Platform, the Rhaetian–Lower Jurassic succession of strata displays characteristics which are very similar to the ones described above. There are unfortunately very few lithostratigraphic markers that can be used to delimit and define the different units as in the Helsingborg area. Initial interpretation was that the sequence was dominated by Hettangian strata with great similarities to the Hettangian Helsingborg Member. However, biostratigraphical datings (Lindström & Erlström, 2011) have revealed that this is not the case. Instead there are at least deposits ranging into the Toarcian–Aalenian, thus corresponding to the Rya Formation in the Helsingborg area.

In the Danish Basin, the equivalent Upper Triassic–Lower Jurassic lithostratigraphic subdivisions include the Skagerrak, Vinding, Gassum and Fjerritslev formations (Fig. 2) (Nielsen, 2003).



Fig. 3. Photograph showing an example of cross-bedded sandstones from the lower Sinemurian, basal part of the Döshult Member at Kulla Gunnarstorp.

2.3 Depositional setting in NW Skåne

The deposition of Lower, Middle, and Lower Upper Triassic strata was restricted to the Höllviken Halfgraben (Erlström & Sivhed, *in press*). In the latest Triassic (Rhaetian), a change from local graben development to a general lowering of the Danish Basin (Norling & Bergström, 1987), and a primarily eustatically controlled progressive overstepping of the Höllviken Halfgraben took place, resulting in a wider deposition of the Rhaetian strata, contemporaneous with a climate change in Skåne from seasonally arid to per-

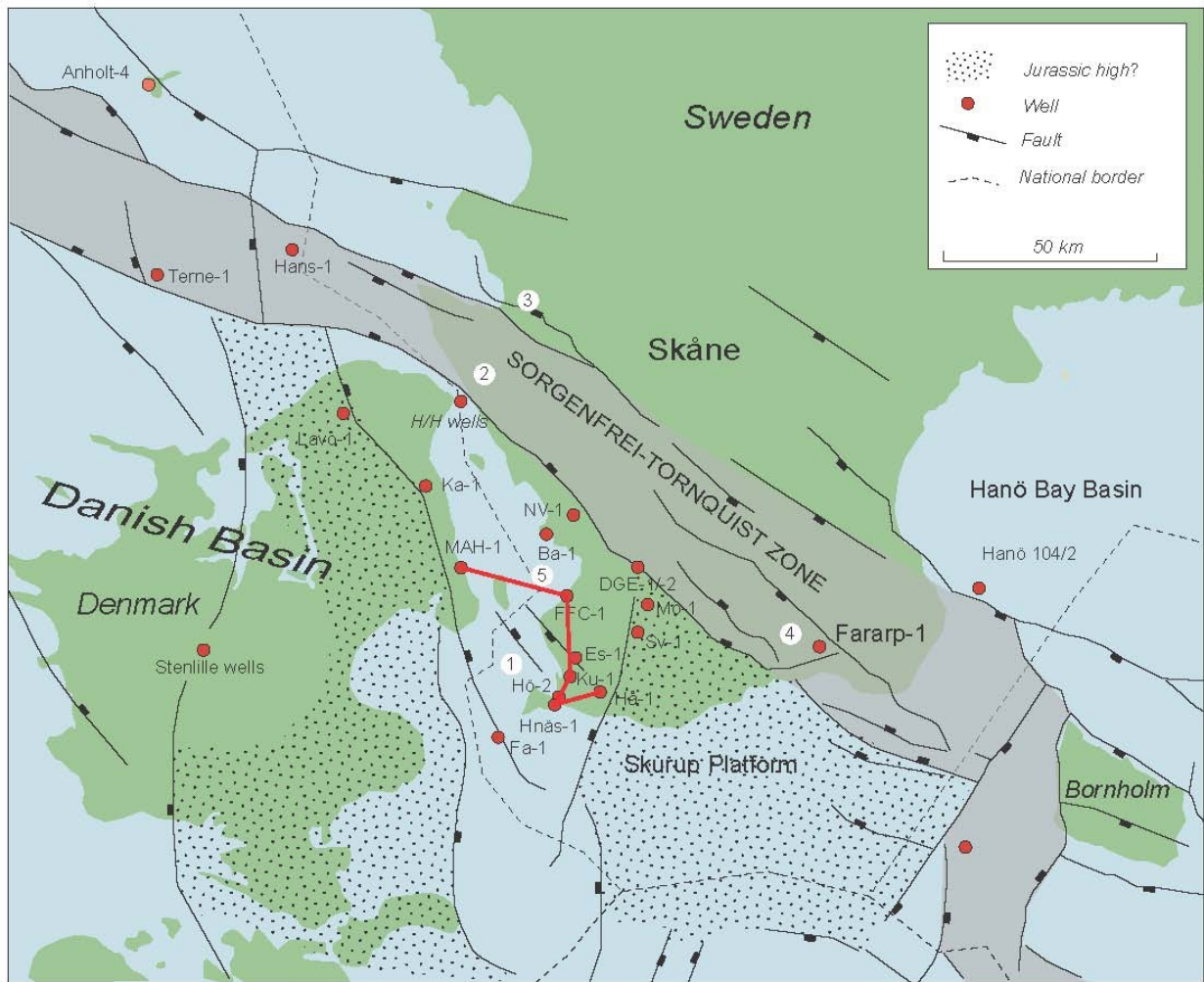


Fig. 4. Base map showing the location of the studied boreholes in SW Skåne. Red line marks the cross section illustrated in fig. 24. (1: Höllviken Halfgraben 2: Höganäs Basin 3: Ängelholm Trough 4: Vomb Trough 5: Barsebäck Platform)

manently humid conditions (Ahlberg et al., 2002).

These were the main reasons for a very sharp change in the style of sedimentation at the onset of the Rhaetian. The texturally immature clastic sediments of the Norian Kågeröd Formation were followed by Rhaetian–Hettangian chemically and texturally mature quartz arenites deposited in turbulent lacustrine, alluvial, and deltaic environments (Norling et al., 1993).

During the deposition of predominantly continental to deltaic sediments in the Rhaetian–Hettangian, several marine incursions invaded Skåne. The marine influence did not, however, have any major impact until the Early Sinemurian, with the deposition of the Döshult Member of the Rya Formation (Norling & Bergström, 1987; Norling et al., 1993). The lower Sinemurian is dominated by nearshore mature coarse-grained arenites with herringbone cross-bedding and an uppermost part composed of dark marine mudstone (Norling et al., 1993). The presence of several ammonites, large fossil logs, and coarse-grained arenites confirms the marine influence and indicates a near-shore high energy depositional setting (Troedsson, 1951; Norling et al., 1993). The succeeding upper Sine-

murian deposits of the Pankarp Member are dominated by dull homogeneous mudstone with marine fossils, however, an intermittent proximity to the shore is indicated by one coal-seam recorded from boreholes (Norling et al., 1993). Quiet shallow marine environments persisted in the upper Sinemurian–lower Pliensbachian forming the predominantly muddy Katslösa Member, which is occasionally interrupted by sandy horizons and intercalations of oolitic limestone (Norling et al., 1993). The Upper Pliensbachian–Toarcian Rydebäck Member is dominated by a series of arenites and wackestones rich in marine microfossils with minor intraformational conglomerates implying a regressional tendency emplaced by increased tectonic activity (Norling et al., 1993).

3. Material and methods

The data used in this project has been provided by the Swedish Geological Survey (SGU) and the Geological Survey of Denmark and Greenland (GEUS). The study has involved interpretation of geophysical wire line logs (Gamma Ray, Self Potential, Resistivity,

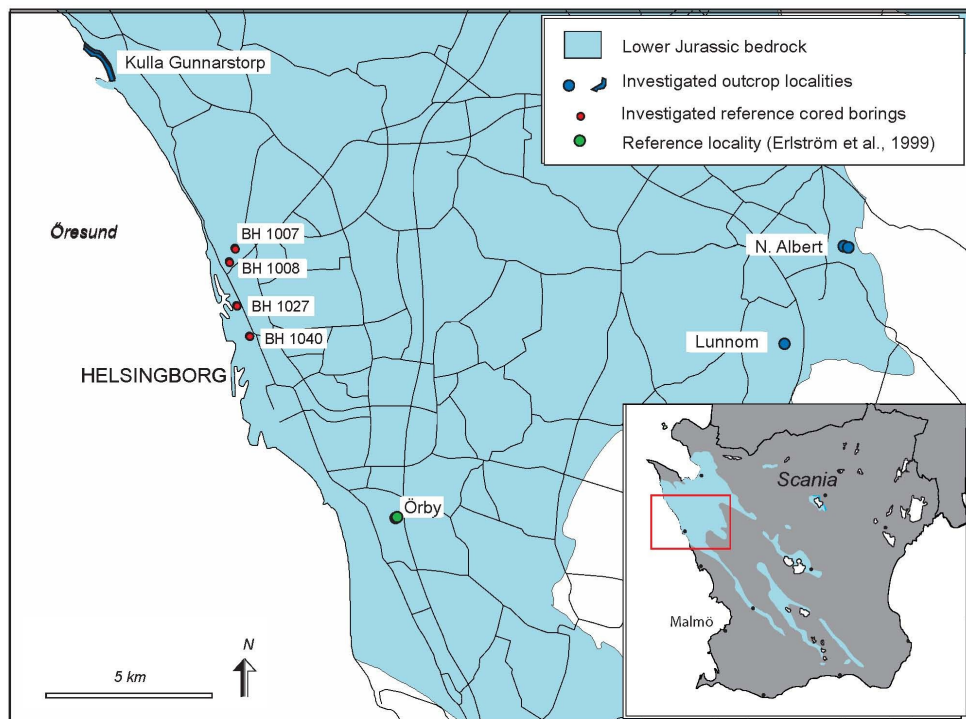


Fig. 5. Map showing location of the reference boreholes in Helsingborg area.

Sonic, Neutron and Density) from the following boreholes in southwestern Skåne (Sweden): Barsebäck-1, Eskilstorp-1, Haslöv-1, Falsterborev-1, FFC-1, Höllviksnäs-1, Kungstorp-1, Ljunghusen-1, and in Denmark: Margrethholm-1, Margrethholm-1A, Karlebo-1A (Fig. 4).

The lithology of the subsurface Rhaetian–Pliensbachian sequence in southwestern Skåne has mainly been described from studies and investigations of the Höllviken-2 core and sidewall cores from the FFC-1 well. In addition, thin sections from the Örby previously exposed lower Sinemurian succession (Erlström et al., 1999) and cores from the Helsingborg area (Fig. 5) were studied. The biostratigraphic zonation and chronostratigraphic framework of the study area were provided by Sofie Lindström (GEUS). The processing of the geophysical (LAS-files) data has been done using the *LogPlot 7* software from *RockWare*. Moreover, a reconnaissance field trip has been conducted at the early stages of the project to Norra Albert and Kulla Gunnarstorp in order to get acquainted with the lithofacies and the depositional environments of the studied interval. Altogether, this data along with a comprehensive literature study enable empirical correlation between boreholes, and construction of a 2D model anticipating the vertical and lateral distribution of various sand units, and clarifying the tectonic development and depositional history of the Rhaetian–Pliensbachian succession in southwestern Skåne.

The investigation has included a step-wise approach to the presented interpretation of the Rhaetian–Lower Jurassic succession in the Höllviken Halfgraben and Barsebäck Platform.

I have initially started with a comprehensive literature review followed by processing and interpre-

tation of the geophysical data to produce the logs illustrated in the appendix. These logs were then used to perform a statistical analysis that elucidates the distribution of various facies within the studied basin. These statistics along with the interpreted logs have been used to produce isopach maps as well as facies distribution maps that altogether have helped in the understanding of the basin evolution summarized in a northwest-southeast transect illustrated in figure 24.

The interpretation of the lithofacies in most of the boreholes was mainly based on the gamma ray log (GR) response with the support of the resistivity and porosity logs (SONIC, Neutron, Density) (Dewan, 1983). However, the GR-values for a specific lithology are not consistent due to different drilling muds, varying hole geometries and logging tools used in the different wells. Some boreholes are more than 50 years old and others are recent, which leads to a kind of inconsistency of the data. Thus, to make the log interpretation more objective and the lithofacies analysis more consistent, several well logs along with their core samples from the Helsingborg area (Fig. 5) penetrating strata of equivalent age and similar lithologies to the succession in the Höllviken Halfgraben have been used for calibration. Thus providing a way to compare the log responses and patterns to the lithologies present in the succession (Fig. 6).

4. Facies description and sedimentology

In contrast to the Rhaetian–Hettangian sequence in the Danish Basin, which is considered as deltaic to marine, with long and pronounced marine intervals,

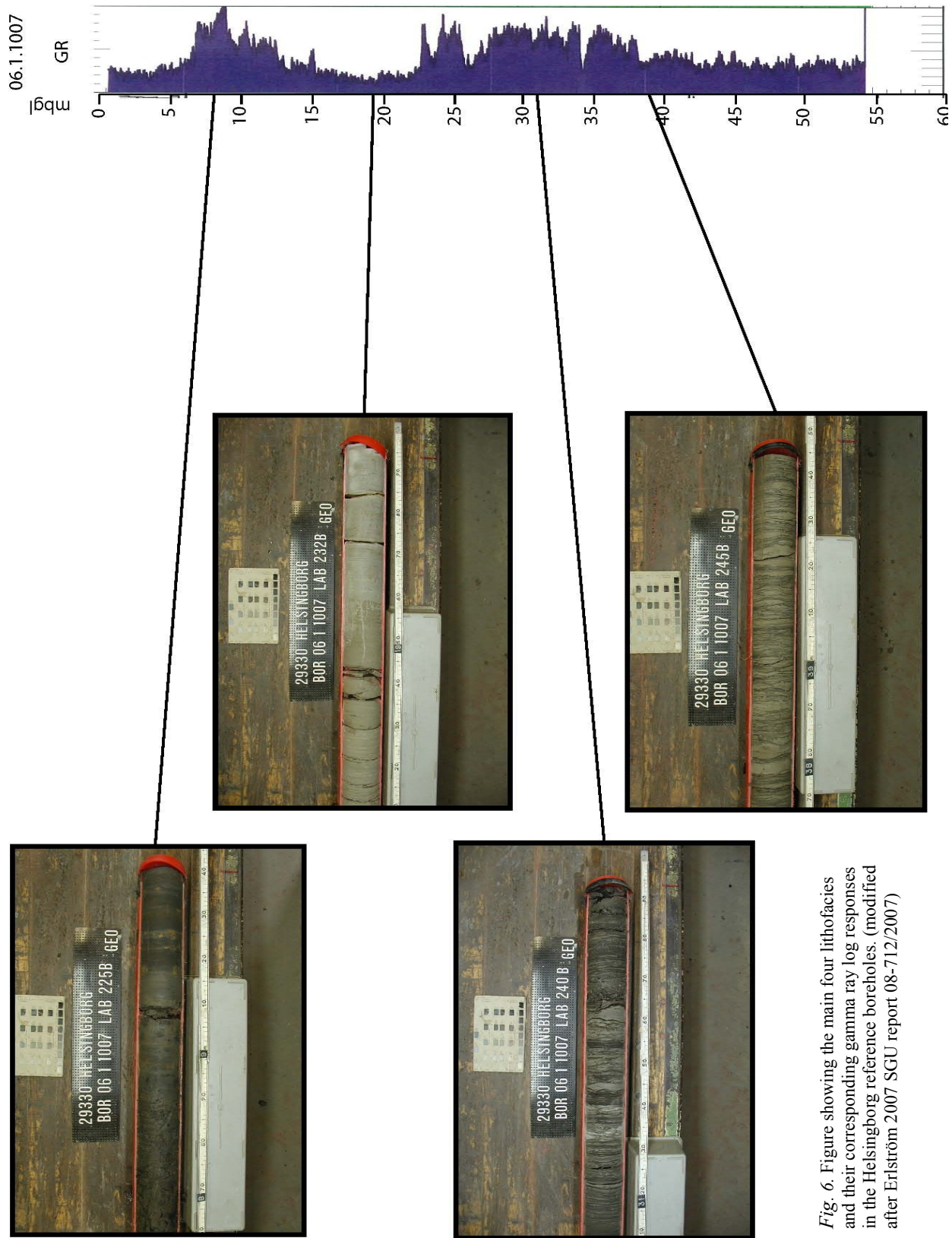


Fig. 6. Figure showing the main four lithofacies and their corresponding gamma ray log responses in the Helsingborg reference boreholes. (modified after Erlström 2007 SGU report 08-712/2007)



Fig. 7. Very fine-grained claystone with flint like texture representing facies 1 from the upper-Rhaetian in the Höllviken-2 core at a depth of 1444m KB.



Fig. 9. A typical clay and silt dominated heterolite with fine sand lenses, facies 2, from the Pliensbachian–Lower Toarcian of the Höllviken-2 core at a depth of 1348m KB.

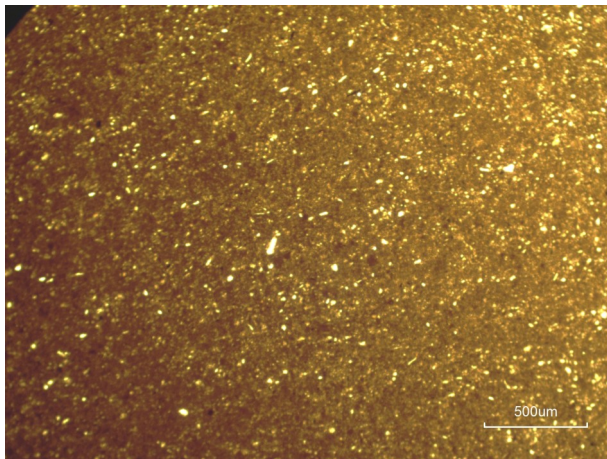


Fig. 8. Microphotograph from the Upper Rhaetian of the Höllviken-2 core at a depth of 1445.8m KB showing the texture of the claystone facies 1, (PPL).



Fig. 10. Bioturbation and water escape structures in facies 2, in the Pliensbachian–Lower Toarcian of Höllviken-2 core at a depth of 1346m KB.

the corresponding strata in northwestern and southwestern Skåne are considered as deltaic with few marine incursions, marking the transition from the Norian continental redbeds to the Late Liassic open marine strata.

Previous sedimentological work by Ahlberg (1994), Larsson et al. (1994), Erlström et al. (1999), Frandsen & Surlyk (2003) genetically describes facies and facies associations from various sections representing parts of the Rhaetian–Pliensbachian succession of southwestern and northwestern Skåne. However, for the purpose of this study, a general facies description has been conducted and resulted in five main sedimentary facies presented below.

4.1 Sedimentary facies

The definition of the different facies in the investigated boreholes is largely supported by the Höllviken-2 core and shallow cores in the Helsingborg area along with their corresponding geophysical logs (Fig.

6), in addition to thin sections taken from sidewall cores in FFC-1 and the previously exposed section in Örby (cf. Erlström et al., 1999).

4.1.1 Claystone (facies 1)

This facies is characterized by very fine silt and clay. In core samples it varies in color from dark grey to light grey, occasional green and red layers are probably caused by diagenetic alteration. Some levels are rich in organic matter, hence the dark grey color. No clear sedimentary structures can be observed in the core samples. The very fine claystones show a flint like texture with conchoidal fractures (Fig. 7). In thin sections, the clay is homogeneous and does not show any structures or laminations (Fig. 8). In well logs, this facies has the highest GR values generally ranging between 120 to 180 API, a very high resistivity, and a variable porosity, related to variations in clay content vs. silt sized detrital clastics, mainly quartz. (see logs in Appendix)

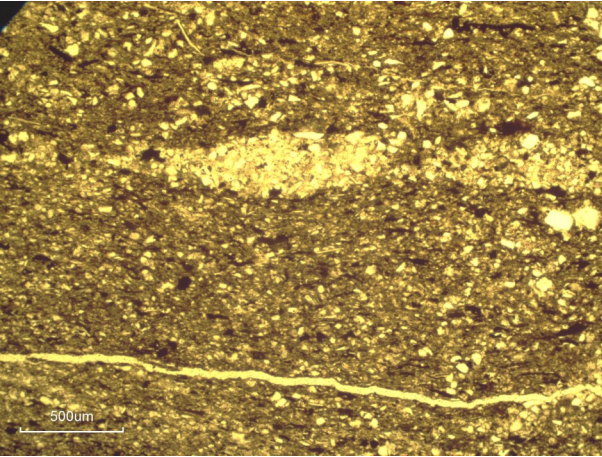


Fig. 11. Microphotograph showing the texture in facies 2, from the Hettangian of FFC-1, sidewall core, at a depth of 1769m KB. (PPL)

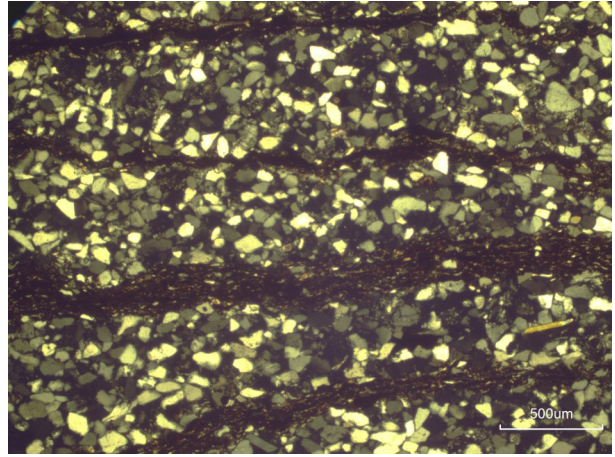


Fig. 13. Microphotograph showing the texture of facies 3 with sand lamina and thin clay/silt drapes from the Hettangian of the Höllviken-2 core at a depth of 1410m KB, in XPL.



Fig. 12. Illustration of the fine-grained yellowish sand of facies 3 with thin clay drapes, from the Pliensbachian–Lower Toarcian of the Höllviken-2 core at a depth of 1362.5m KB.

4.1.2 Silt and clay dominated heterolites (Facies 2)

This facies is characterized by isolated sand ripples in a clay and silt dominated matrix (i.e. lenticular bedding) and variegated mudstones. In core samples, the clay and silt range in color from dark grey to light grey depending on the organic content. The sand lenses are white to yellow and with very fine grain size (Fig. 9). Bioturbation and water escape structures are common and obscuring some of the primary sedimentary structures (Fig. 10). In thin sections, the fine silt is brown in Plane Polarized Light (PPL). There is also a minor mica component in the detrital material. The sand lenses are composed of very fine subrounded well sorted quartz (Fig. 11). In well logs, this facies shows moderately high GR values between 100 and 120 API, a relatively high resistivity, and a variable porosity in neutron, density and sonic logs. (See logs in Appendix)

4.1.3 Sand dominated heterolites (Facies 3)

This facies is characterized by sand dominated lamina ranging in thicknesses from few millimeters to few centimeters draped with thin lamina of clay, silt, and/or coal, resulting in flaser bedded strata. In core samples, the sand has a yellowish white to light brown color, while the clay drapes are mostly dark grey with varying degree of darkness controlled by the organic content (Fig. 12). Cross lamination is common in addition to bioturbated zones and water escape structures. In thin sections, the sand fraction is dominated by very fine moderately sorted, subangular to subrounded quartz grains and few grains of feldspars and micas (Fig. 13). In well logs, this facies shows GR values generally between 80 and 100 API and moderately low resistivity signals, and a moderate porosity in neutron, density and sonic logs. (see logs in Appendix)

4.1.4 Fine-grained sandstone (Facies 4)

In core samples, this facies is characterized by white to yellow fine quartz sand with variable degree of consolidation (Fig. 14 a, b) and includes some fossils and allochthonous coal fragments. In thin sections, this facies shows sub-rounded well sorted very fine quartz grains, cemented by quartz overgrowth and/or calcite cement (Fig. 15 a, b), however the degree of cementation is variable within this facies. This facies shows the lowest GR values ranging from 30 to 80 API, the lowest resistivity log response, and a variable porosity in neutron, density and sonic logs probably due to the variation in the degree of cementation. (see logs in Appendix)

4.1.5 Paleosols, coal, fine- to medium-grained sand (Facies 5)

This facies is included to describe the Rhaetian–Lower Hettangian and which shows an interbedding of heterolites, coal, fine- to medium-grained sand sheets, and paleosols.

5. Sedimentology and facies in the Höllviken-2 core

Höllviken-2 constitutes a reference well since it is the only cored borehole with preserved cores from the Höllviken Halfgraben. The Rhaetian–Pliensbachian interval is here represented by a 190 m thick succession with a top depth of 1329.8 m (KB, Kelly Bushing) and a bottom depth of 1520 m KB (Lindström & Erlström, 2011). The Rhaetian (1428–1520 m KB) in Höllviken-2 has a low core recovery. Based on the recovered portion it could, however, be described as heterolites with coal beds and some sand intervals.

The base of the Rhaetian starts with a coarse- and medium-grained sand that fines upwards (Fig. 16a). The thickness of this sand is hard to estimate due to low core recovery, but it is at least 2 m thick. This sand is followed by around 1.5 m of coal overlain by at least 2 m of very fine-grained sand (Fig. 16b). This is followed by at least 10 m of intercalating fine-grained sand, clay and heterolites (flaser, wavy, and lenticular) (Fig. 16c). This is overlain by 7 m of claystone and siltstone (Fig. 16d) followed by 10 m of sand dominated heterolites with convolute lamination and intercalations of 20 cm to 1 m of pure fine sand beds (Fig. 16e). The following 5 m are composed of white to yellow fine sand with some thin allochthonous coal lamina (Fig. 16f). The Hettangian has an extremely low core recovery (Fig. 16g). However, it is tentatively assumed that the recovered cores are representative of the Hettangian lithology. The recovered cores are composed of fine-grained white to yellowish sand with some thin drapes of allochthonous coal (Fig. 16g). The Sinemurian shows a very low core recovery as well (Fig. 16h). The recovered part of the lower Sinemurian shows a well cemented fine sand (Fig. 16h). The upper Sinemurian starts with a 2 m thick clay dominated (lenticular bedded) heterolites that change gradually upwards into wavy and then to flaser bedded heterolites with some strongly bioturbated horizons and convolute beds in the Pliensbachian (Fig. 16i). The Pliensbachian–Lower Toarcian part of the core has a very good core recovery and displays a heterolitic lithology gradually changing from lenticular to flaser with increasing sand content upwards (Fig. 16j).

6. Relative occurrence of the observed facies in the studied wells

Among the boreholes mentioned earlier, six have been biostratigraphically dated (Lindström & Erlström, 2011), and five out of these six have been used for a statistical study on the frequency of the identified lithofacies, i.e. FFC-1, Håslöv-1, Höllviks-



Fig. 14 a & b. Photographs of the sandstone facies 4 in the Höllviken-2 core showing variable degree of consolidation, from the Sinemurian (1380m) and the Uppermost Rhaetian (1435m) respectively.

näs-1, Margretheholm-1 and Karlebo-1A. Statistics have been conducted in every borehole on the whole Rhaetian–Pliensbachian interval as well as on each stage separately (i.e. Rhaetian, Hettangian, Sinemurian and Pliensbachian).

Starting with the FFC-1 well, the whole Rhaetian–Pliensbachian interval (Fig. 17a) shows a dominance of the two intermediate facies with around 38% of sand and silt (facies 3), 37% for clay and silt (facies 2), leaving 14 % for sand (facies 4), and 10 % for clay (facies 1). Statistics for the separate stages show similar numbers (Fig. 17b), though a very small increase in the amount of sandy facies is noticed upward in the section.

In Håslöv-1, the whole interval (Fig. 18a) shows a slight dominance of sandy facies with 23% sand (facies 4), 34% sand and silt (facies 3), 33% clay and silt (facies 2), and 10% clay (facies 1). In the separate stages statistics (Fig. 18b), the Rhaetian shows a relatively equal distribution of sandy (facies 3 & 4) and clayey facies (facies 1 & 2), the Hettangian shows a dominance of sandy facies with 69% of sand and silt (facies 3), and the Sinemurian–Pliensbachian–Toarcian? interval shows a dominance of sandy facies though a high content of clay and silt (facies 2) is also observed.

In Höllviksnäs-1, the whole interval (Fig. 19a) shows a clear dominance of sand with 28% sand (facies 4), 37% sand and silt (facies 3), 26% clay and silt (facies 2), and 9% clay (facies 1). The separate stages statistics (Fig. 19b) show similar trend to the whole interval with a dominance of sand, and a very distinctive dominance of sandy facies in the Hettangian resulting 59% sand (facies 4), 38% sand and silt (facies 3), 4% clay and silt (facies 2), and 0% clay (facies 1).

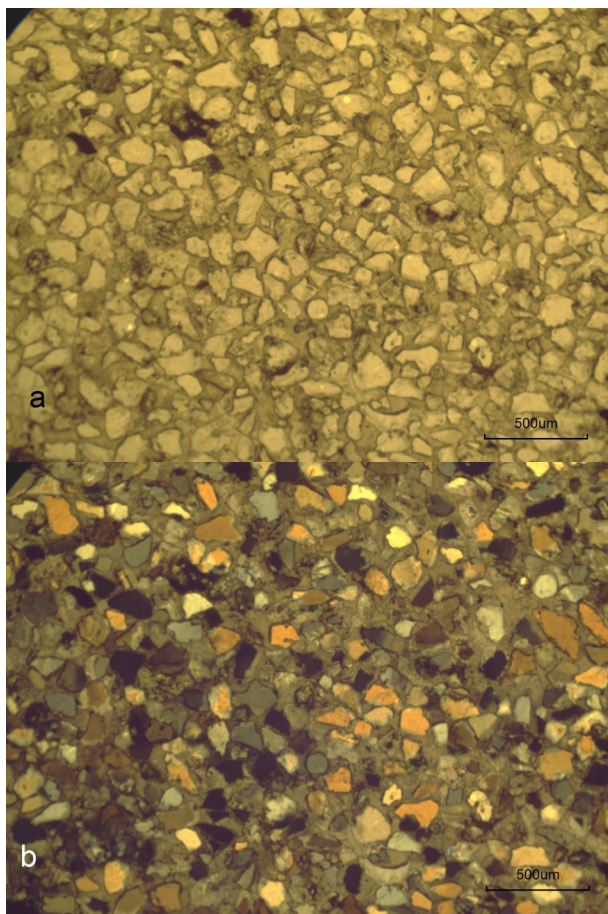


Fig. 15 a & b. Microphotograph showing the texture of facies 4 from the Lower Hettangian of the Höllviken-2 core at a depth of 1430.72m KB, in PPL and XPL respectively.

In Margrethholm-1, the whole interval (Fig. 20a) shows a more or less equal distribution between sandy facies and clayey facies. The separate stages statistics (Fig. 20b) show a dominance of sandy facies over clayey facies in the Rhaetian, and a noticeable increase in the sand content in the Hettangian with 36% sand (facies 4), 37% sand and silt (facies 3), 21% clay and silt (facies 2), and 6% clay (facies 1). This is followed by a dramatic change in the Sinemurian–Pliensbachian interval and a huge drop in the sand content compared to clay resulting 12% sand (facies 4), 17% sand and silt (facies 3), 49% clay and silt (facies 2), and 22% clay (facies 1). Note that the Rhaetian statistics do not represent the whole Rhaetian due to disturbed/missing gamma ray data at the base of the interval.

In Karlebo-1, the whole interval (Fig. 21a) shows a more or less equal distribution of sandy facies and clayey facies. The separate stages statistics (Fig. 21b) show a dominance of sand in the Hettangian with 30% sand (facies 4), 32% sand and silt (facies 3), 33% clay and silt (facies 2), and 5% clay (facies 1). The following Sinemurian–Pliensbachian interval shows a decrease in the sand content and a dominance of clay and silt with 13% sand (facies 4), 37% sand and silt (facies 3), 45% clay and silt (facies 2), and 5% clay

(facies 1). The Rhaetian statistics are not very reliable due to disturbed/missing gamma ray data for most of the Rhaetian.

7. Interpretation

7.1 Facies and depositional environment

The gradual transition from one facies to another within the Rhaetian–Lower Jurassic succession implies a genetic relation between the five different facies described above. Owing the differences observed in texture and composition to relative sea level fluctuation coupled with tectonic activity. Thus, the first 4 above described facies can be assigned to a tide dominated deltaic setting, and the 5th facies to a more continental setting. These facies could be further divided into sub-environments based on proximity to the shoreline.

The very fine silt and clay in facies 1 indicate a deposition from suspension. The homogeneity and lack of prevalent sedimentary structures suggest a very calm offshore marine environment probably below wave base.

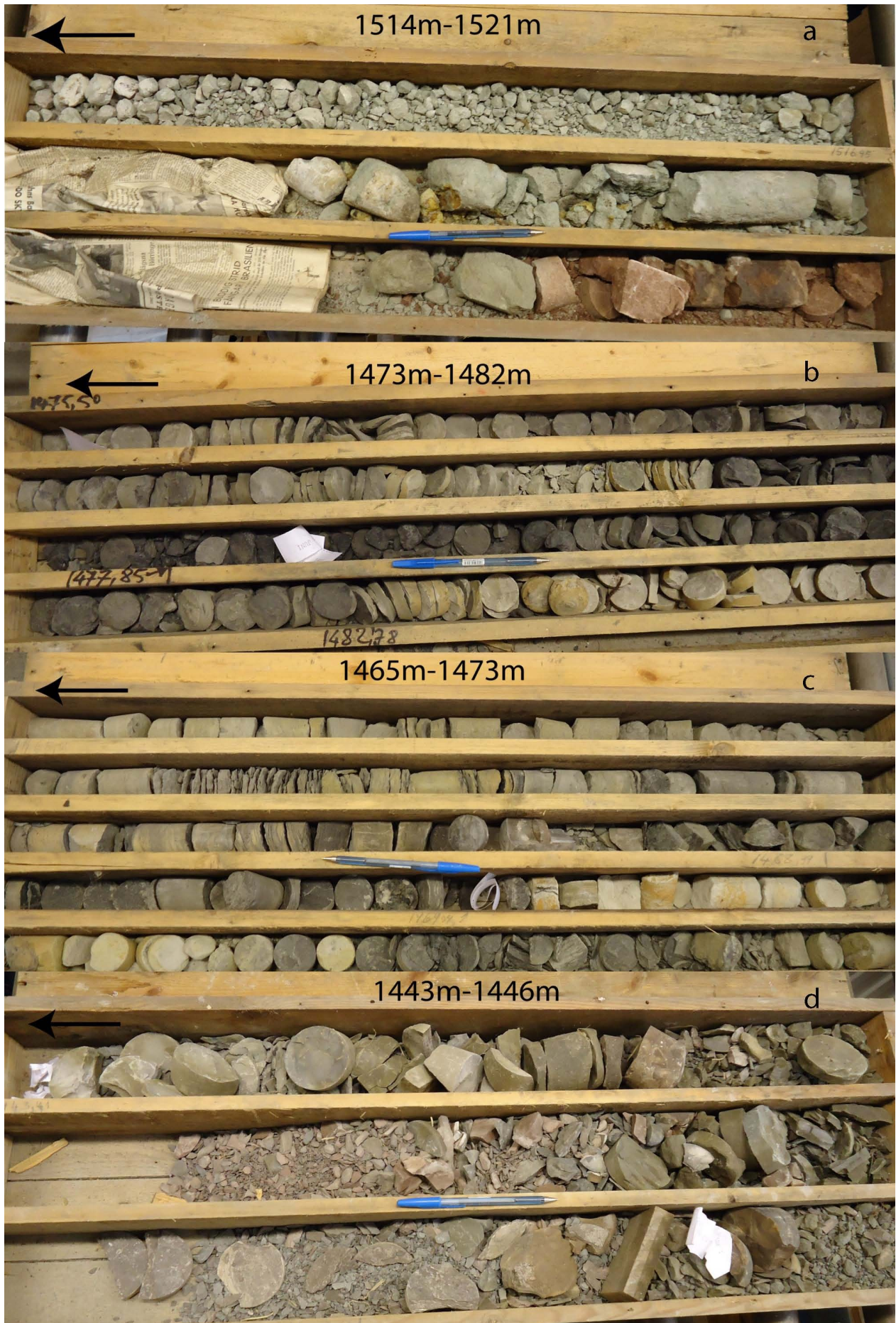
The heterolites described in the second and third facies imply deposition in an environment where fluctuating currents and/or sediment supply permit the deposition of both sand and mud, which could be in the tidal flat zone and/or distal bar deltaic deposits.

The high degree of textural and chemical maturity of the sand in facies 4, the fine grain size, and the occurrence of small scale cross-lamination imply deposition in a sand ripple zone along tidal current paths and/or delta front mouth bar sheet sands. These sands reflect times of relatively lower base-line.

Facies 5 includes lagoonal/lacustrine heterolites, coal beds, palaeosols, and some sand intervals supplied by a delta distributary channel entering the bay or by a lacustrine prograding delta.

7.2 Facies – distribution and relative occurrence

The frequency of the different facies in the five wells is illustrated in four maps (Figs. 22 a-d). Figure 22a shows the amount of sand (facies 4) in each borehole over the whole Rhaetian–Pliensbachian interval. In this interval Margrethholm-1 and Häslöv-1 show high percentage of sand, Karlebo-1A shows a slightly lower percentage of sand, Höllviksnäs-1 shows the highest percentage of sand, and FFC-1 shows the lowest percentage of sand. This could imply a distal position for FFC-1 and/or a lack of accumulation space, which goes well with its position on the Barsebäck





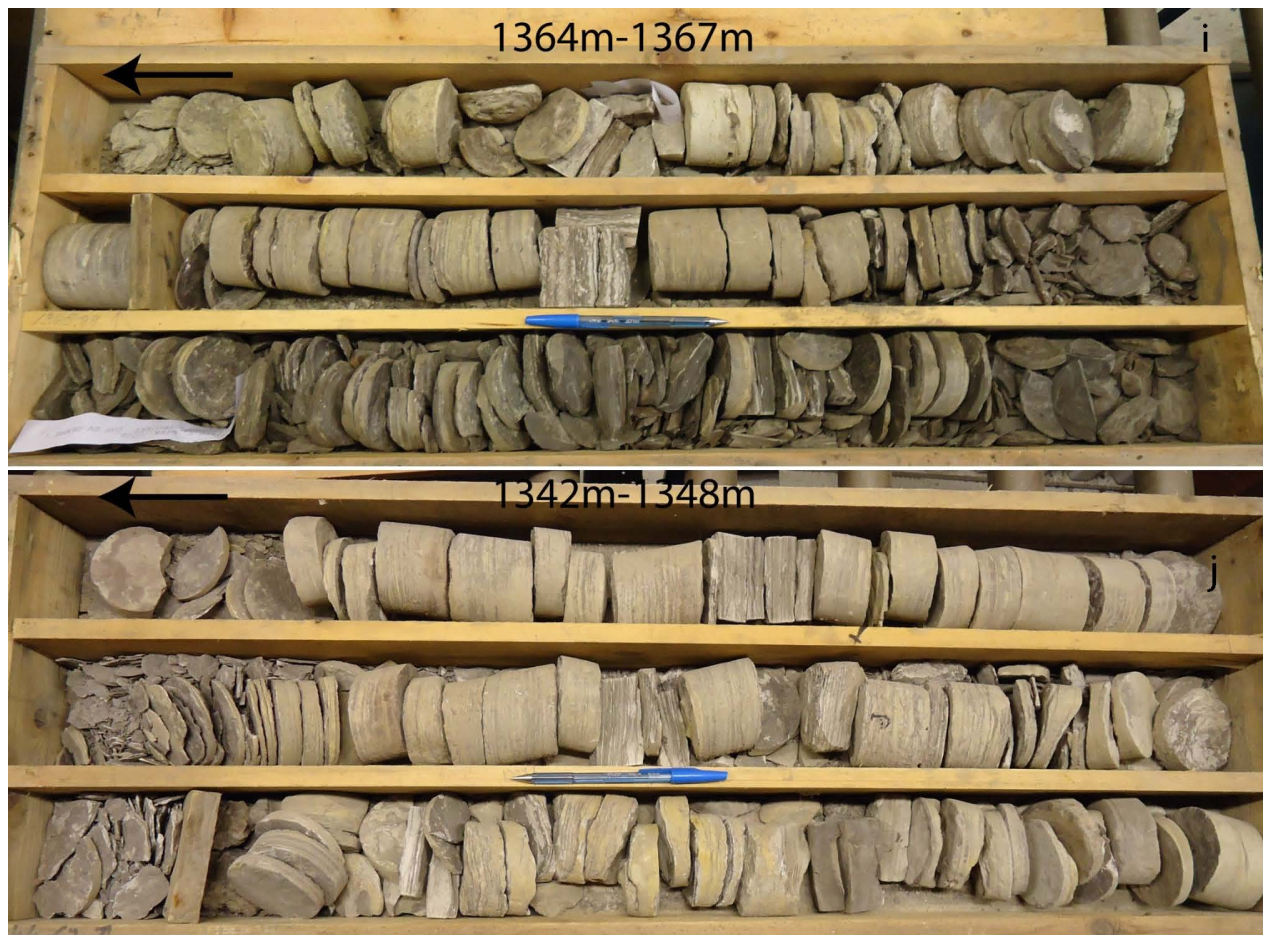


Fig. 16. Core boxes from the Höllviken-2 core a) Lower Rhaetian. b–c) Middle Rhaetian. d–f) upper Rhaetian. g) Lower Hettangian. h) Lower-upper Sinemurian. i) Lower Pliensbachian. j) Upper Pliensbachian.

platform, and an increasing accumulation space towards the south and southwest.

The Rhaetian facies distribution pattern (Fig. 22b) is similar in Höllviksnäs-1, Margrethholm-1, and Håslöv-1. Lower percentages of sand are seen in Karlebo-1A and FFC-1, implying a similar depositional setting in the first three wells, and confirming a different setting for FFC-1 and Karlebo-1A on the Barsebäck platform.

In the Hettangian (Fig. 22c), a dramatic change in the frequency of sandy facies is seen. An increase in the percentage of sand is spotted in all the boreholes and especially in Höllviksnäs-1. The only exception is Håslöv-1 which apparently shows a low percentage of sand, however this value should be interpreted with caution, because the low value of sand does not imply a high value of clay. Figure 18b shows a big dominance of sandy facies over clayey facies. This overall increase in the sand content could be the result of a relative sea level fall leading to the deposition of arenaceous sediments, with the biggest sand supply in Höllviksnäs-1.

The Sinemurian–Pliensbachian interval (Fig. 22d) shows a very big difference in the sand distribution compared to the Hettangian. The highest percentages of sand in the Sinemurian–Pliensbachian interval

are seen in the Höllviksnäs-1 and Håslöv-1, and the lowest in Karlebo-1A and Margrethholm-1, and an intermediate value for FFC-1. Thus implying a deepening of the depositional environment towards Margrethholm-1 and Karlebo-1A.

7.3 Thicknesses of the Rhaetian and the Lower Jurassic

Two isopach maps have been constructed based on the available data showing the general trend and paleobathymetry of the Rhaetian (Fig. 23a) and the early Jurassic (Fig. 23b) (including Rhaetian). Note that the thickness used in these maps in Karlebo-1 are less than the thickness seen in the log (Appendix Log E) since Karlebo-1A is not a vertical well, and thus a correction has been made to get the true vertical depth.

The Rhaetian thickness map (Fig. 23a) reflects a relatively homogenous subsidence throughout the Höllviken Halfgraben with a local depocenter somewhere in the southern part of the basin around Falsterbo Peninsula, e.g. the Höllviken-2 and Höllviksnäs-1 wells. And a gradual deepening to the west into the central part of the Danish Basin. This homogeneous character of the Rhaetian implies a eustatically con-

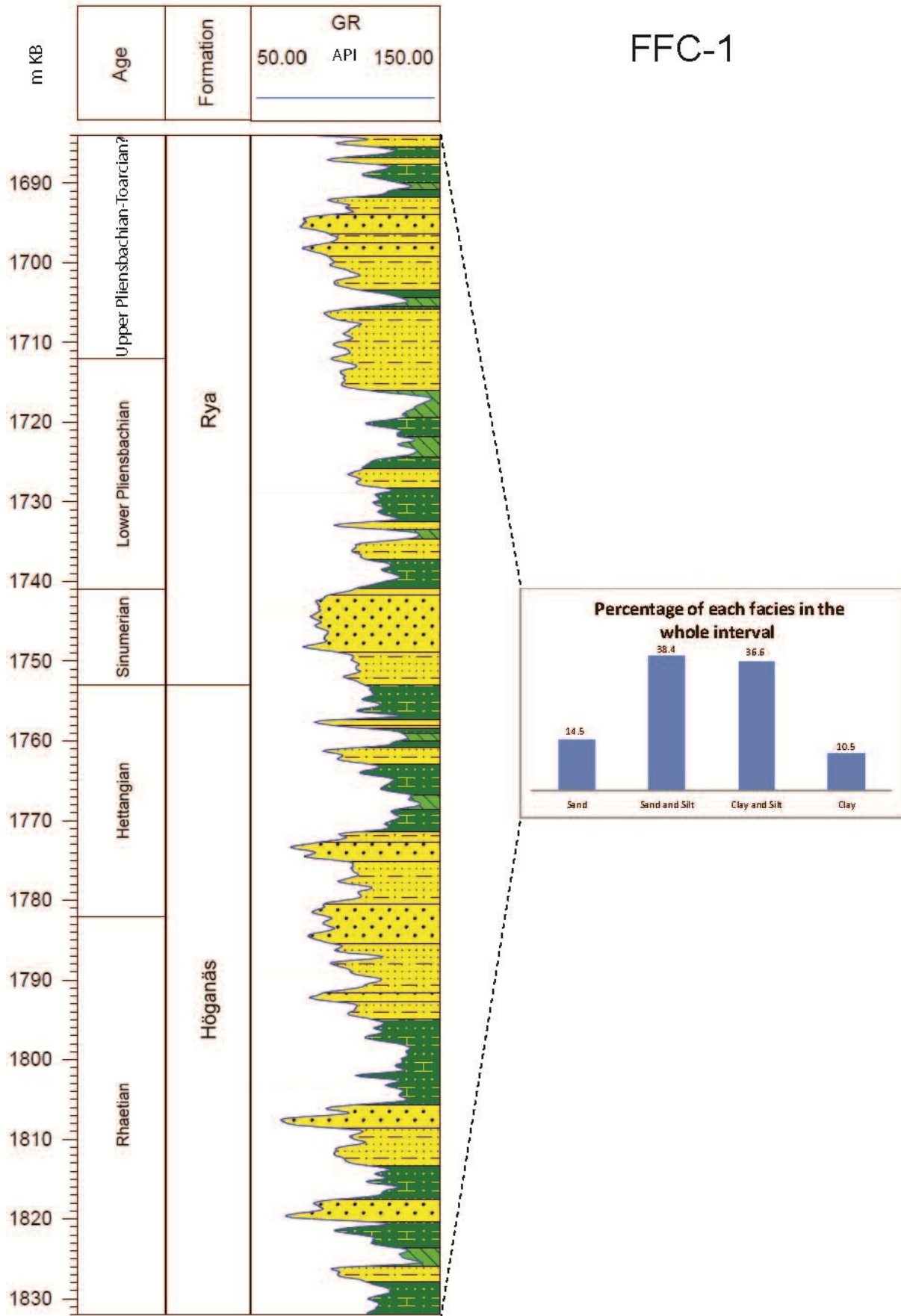


Fig. 17 a. FFC-1 well log with the percentage of each facies in the whole Rhaetian-Pliensbachian interval.

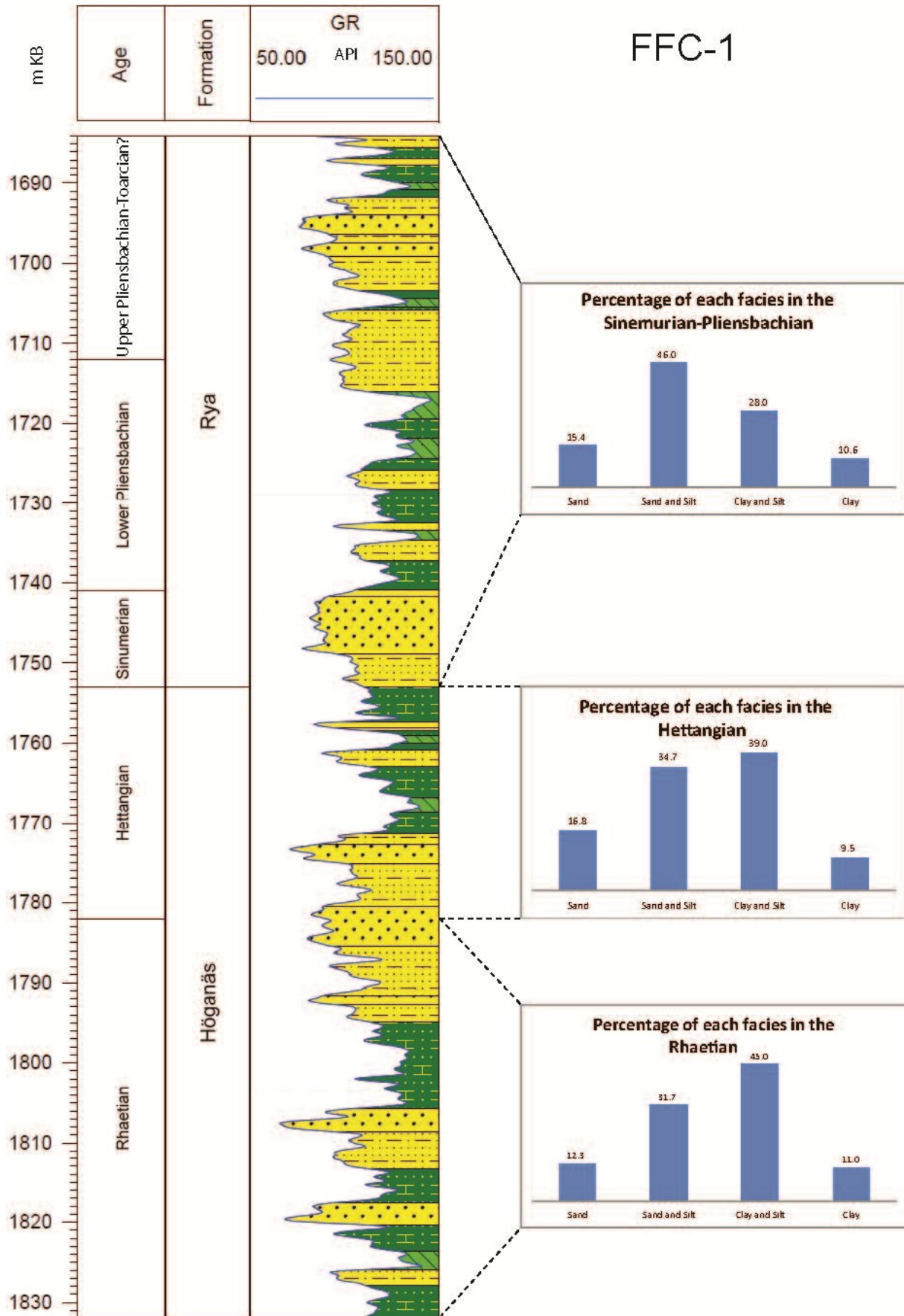


Fig. 17 b. FFC-1 well log with the percentage of each facies in each stage.

Håslöv-1

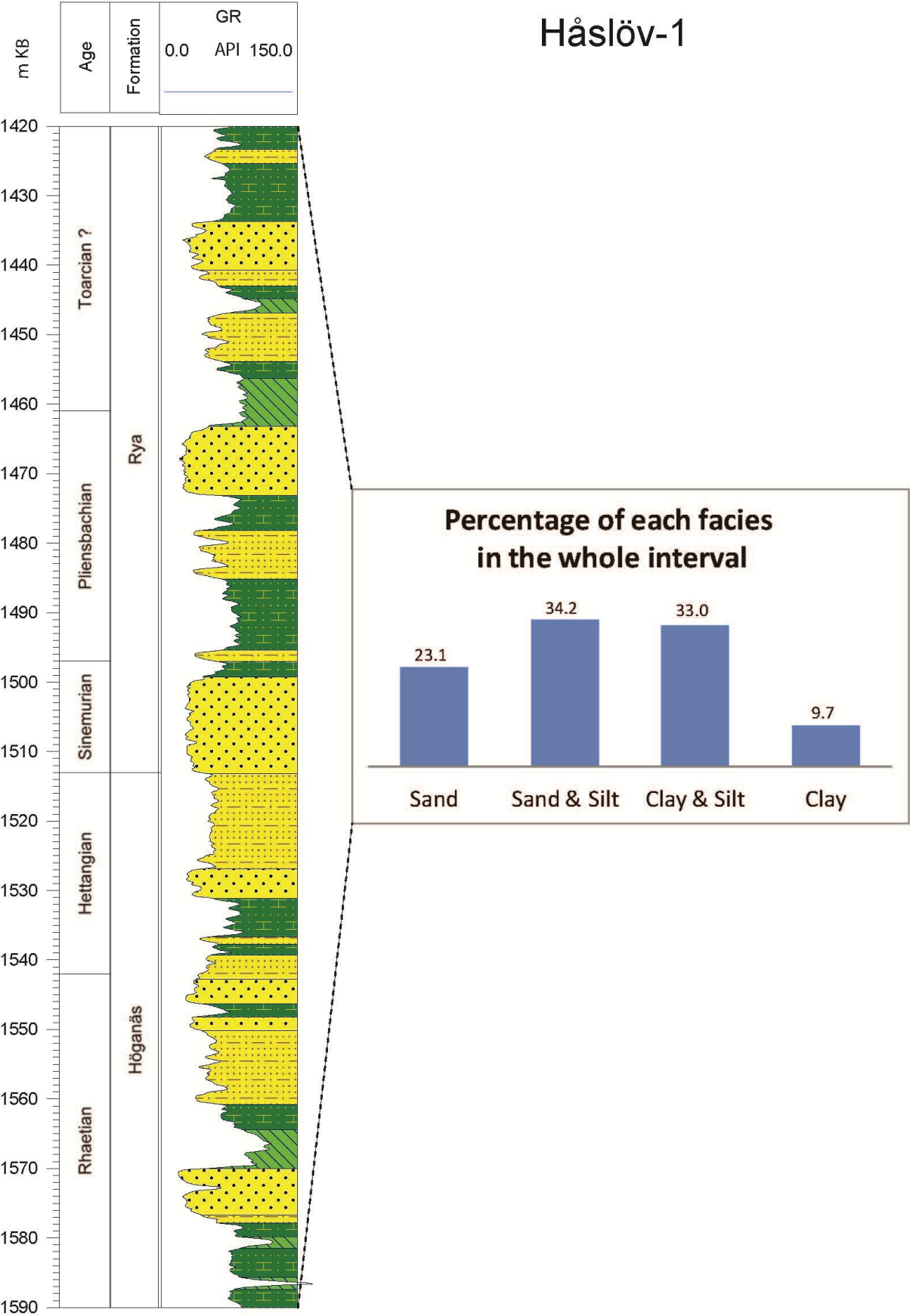


Fig. 18 a. Håslöv-1 well log with the percentage of each facies in the whole Rhaetian-Pliensbachian interval.

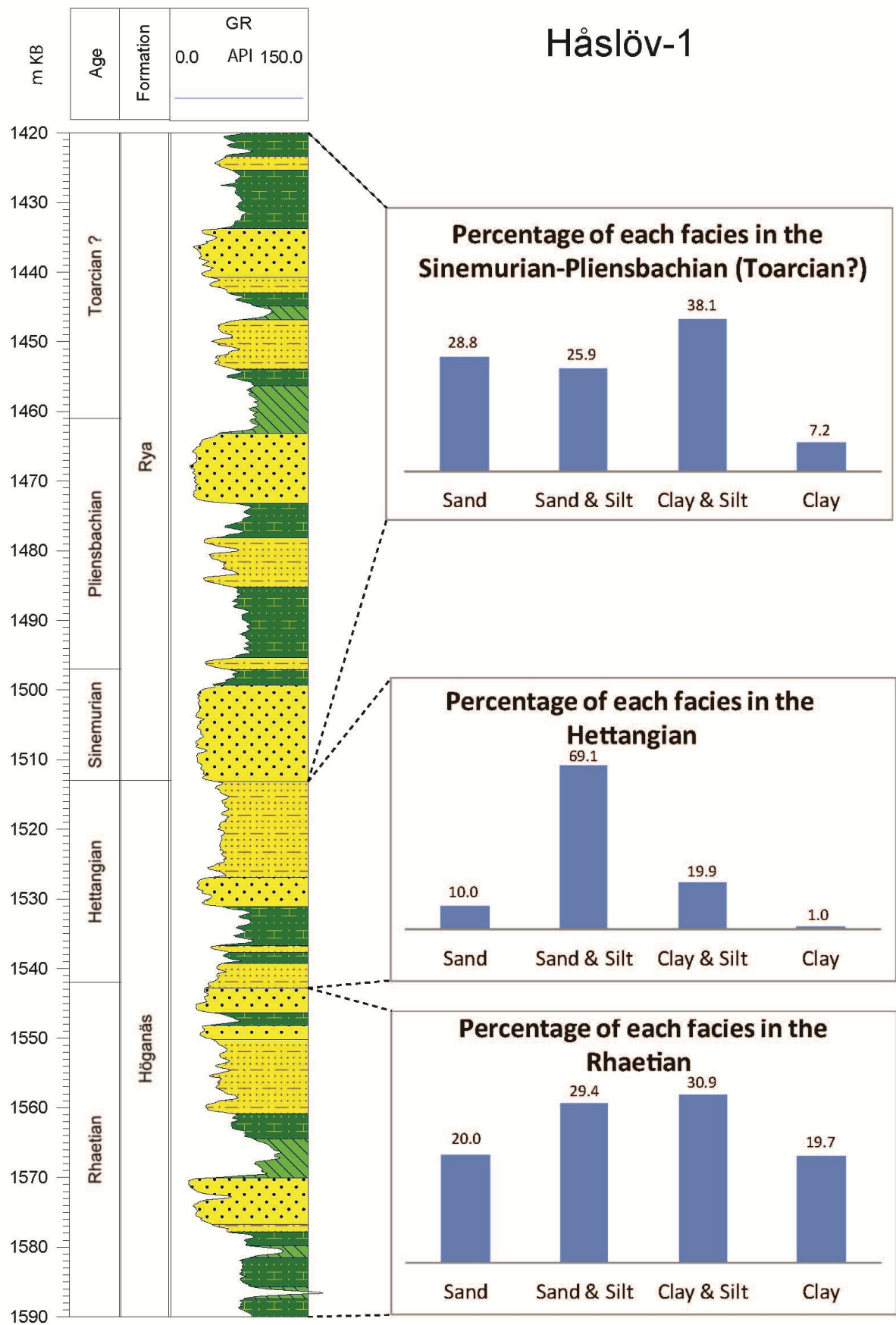


Fig. 18 b. Håslöv-1 well log with the percentage of each facies in each stage.

Höllviksnäs-1

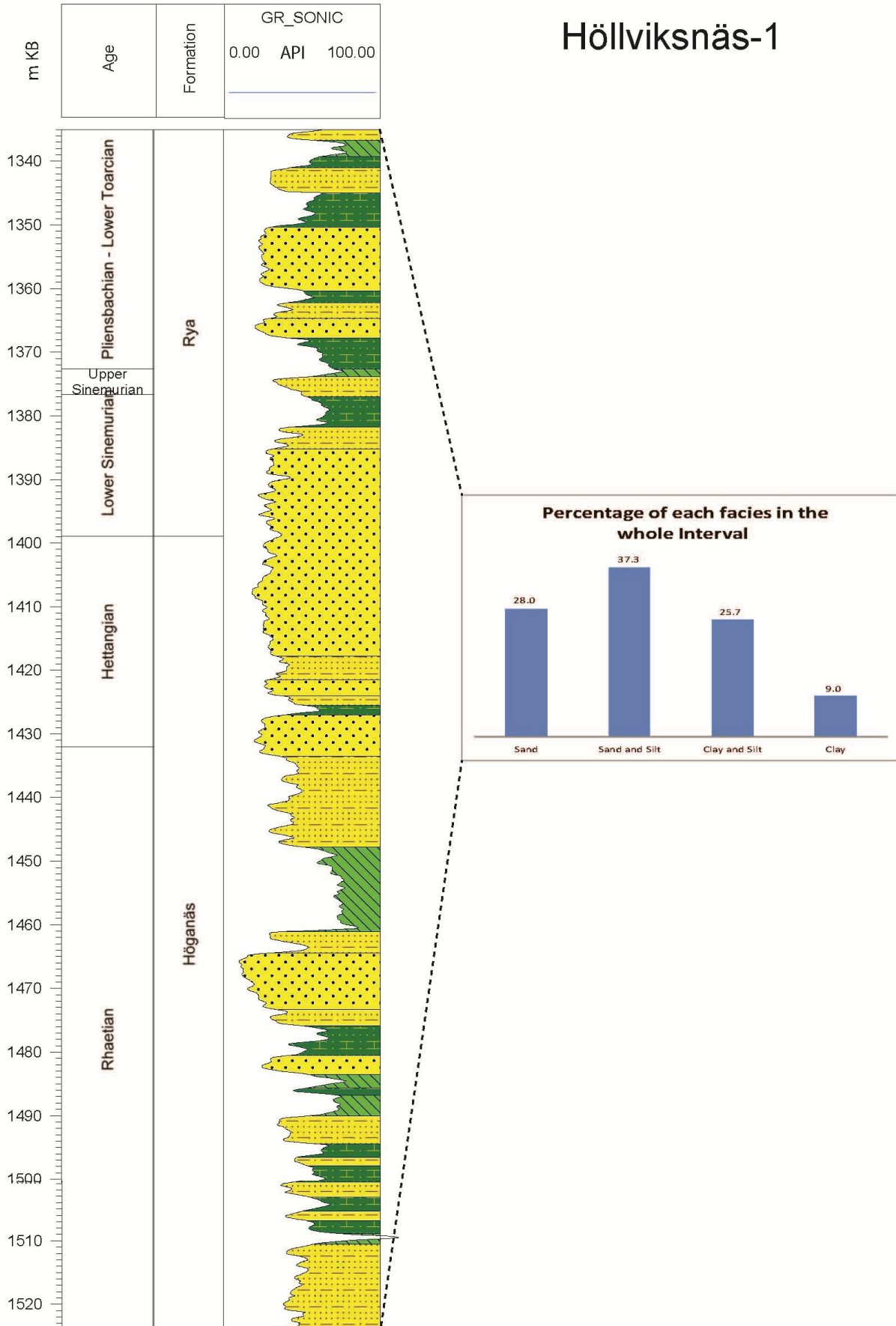


Fig. 19 a. Höllviksnäs-1 well log with the percentage of each facies in the whole Rhaetian-Pliensbachian interval.

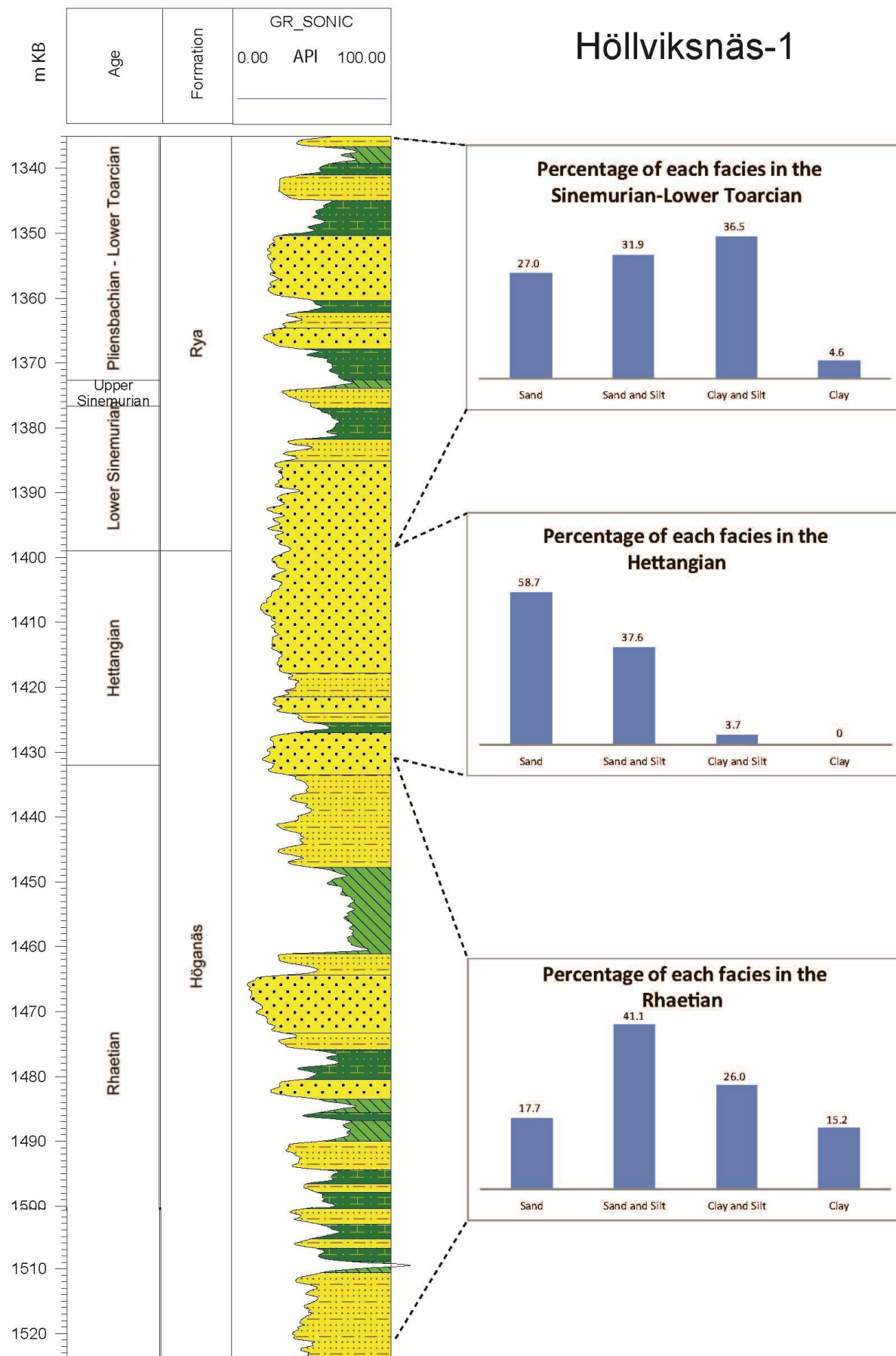
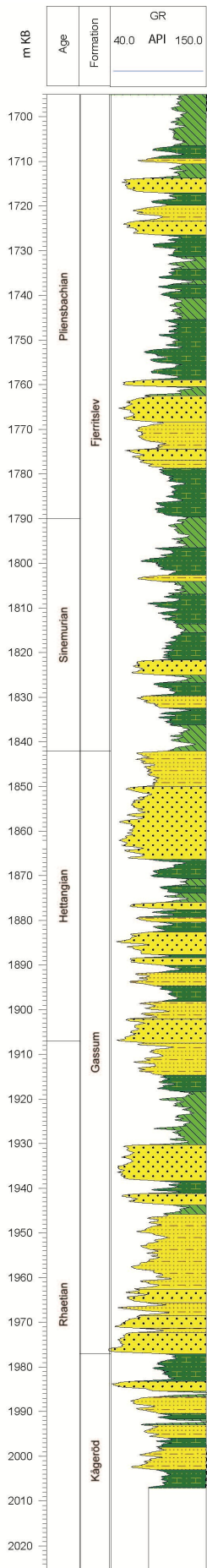


Fig. 19 b. Höllviksnäs-1 well log with the percentage of each facies in each stage.



Margrethholm-1

m KB	Age	GR	
	Formation	40.0	API 150.0

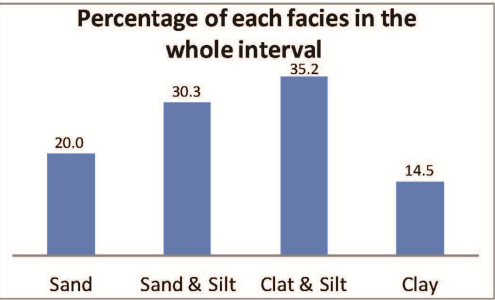


Fig. 20 a. Margrethholm-1 well log with the percentage of each facies in the whole Rhaelian -Pliensbachian interval.

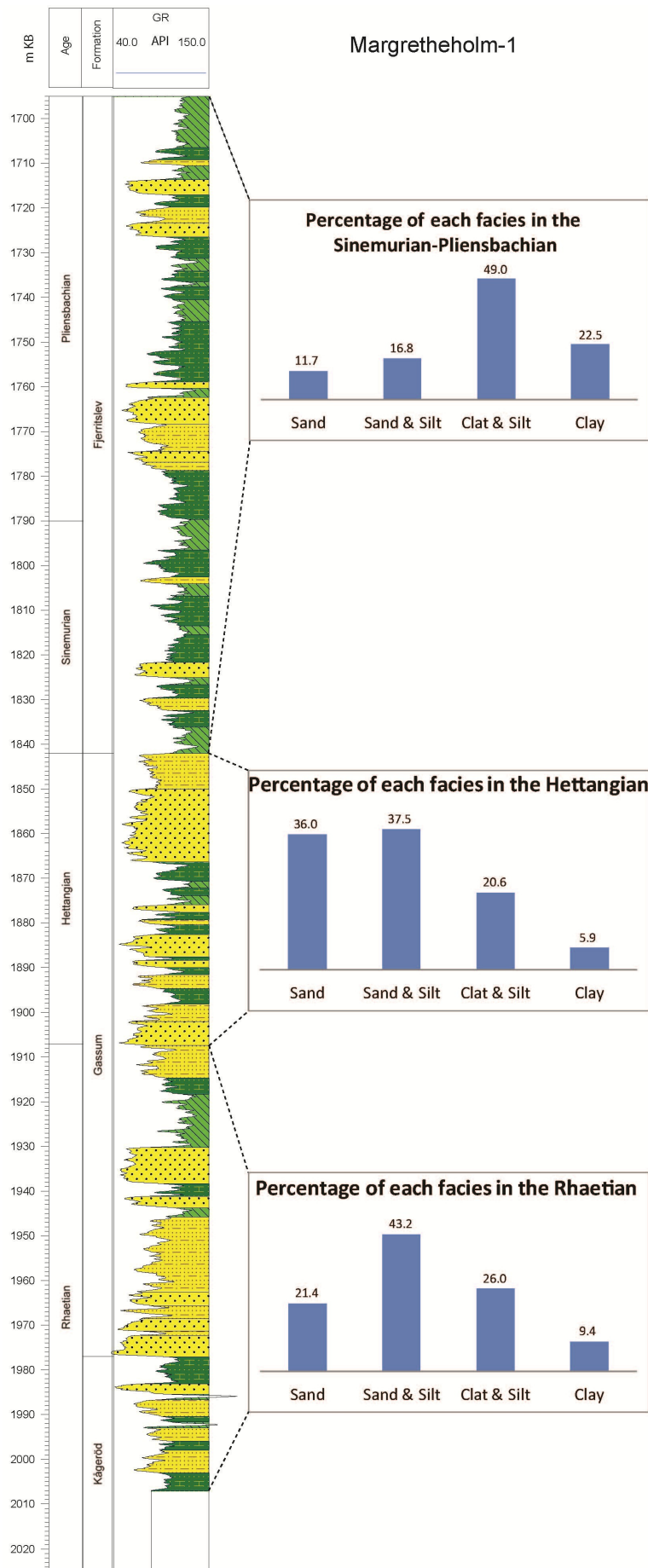


Fig. 20 b. Margretheholm-1 well log with the percentage of each facies in each stage.

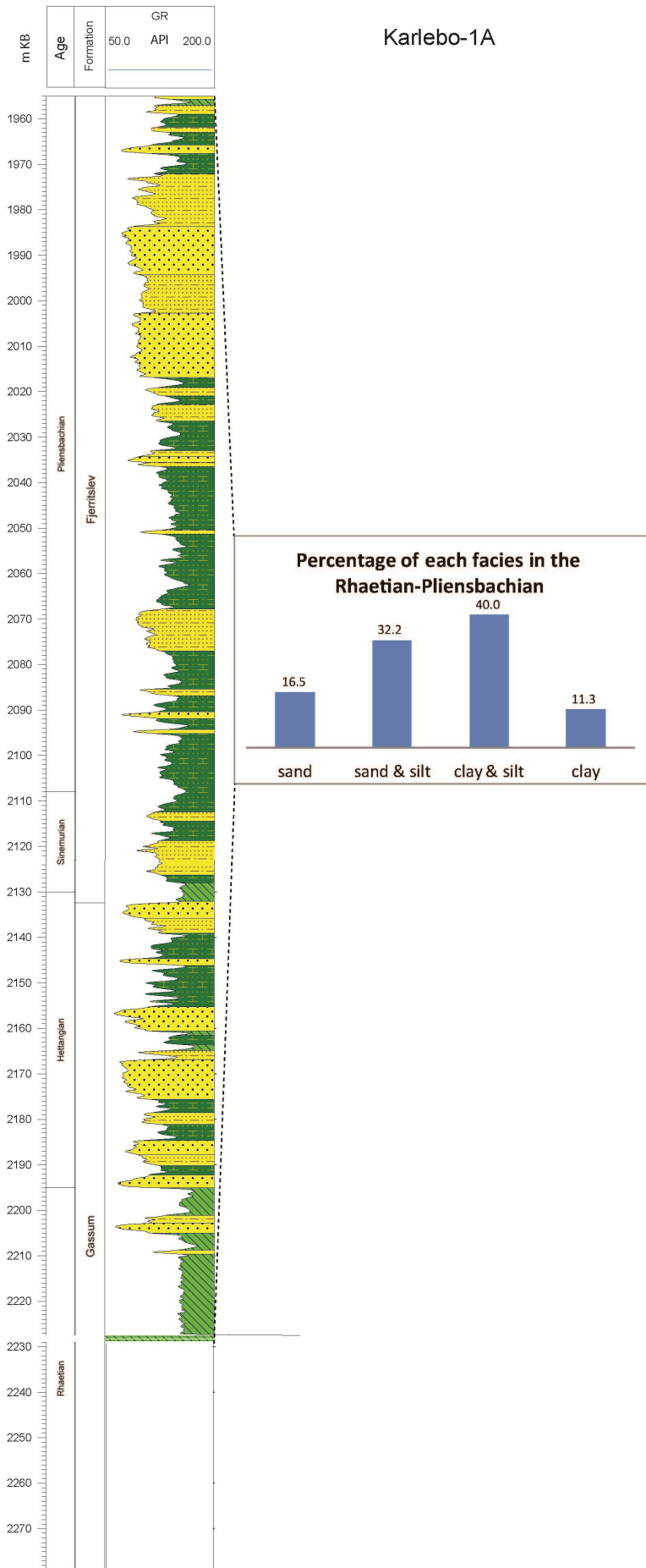


Fig. 21 a. Karlebo-1A well log with the percentage of each facies in the whole Rhaetian-Pliensbachian interval.

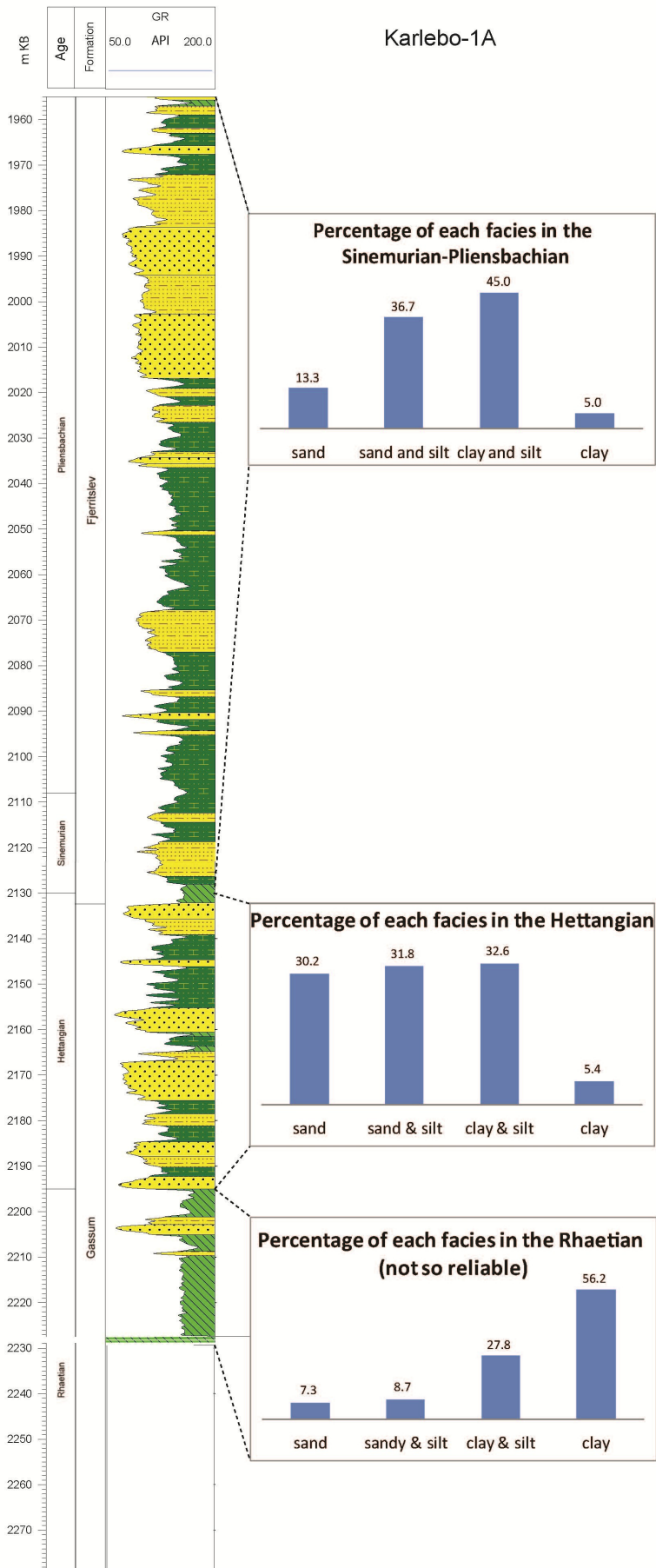


Fig. 21 b. Karlebo-1A well log with the percentage of each facies in each stage.

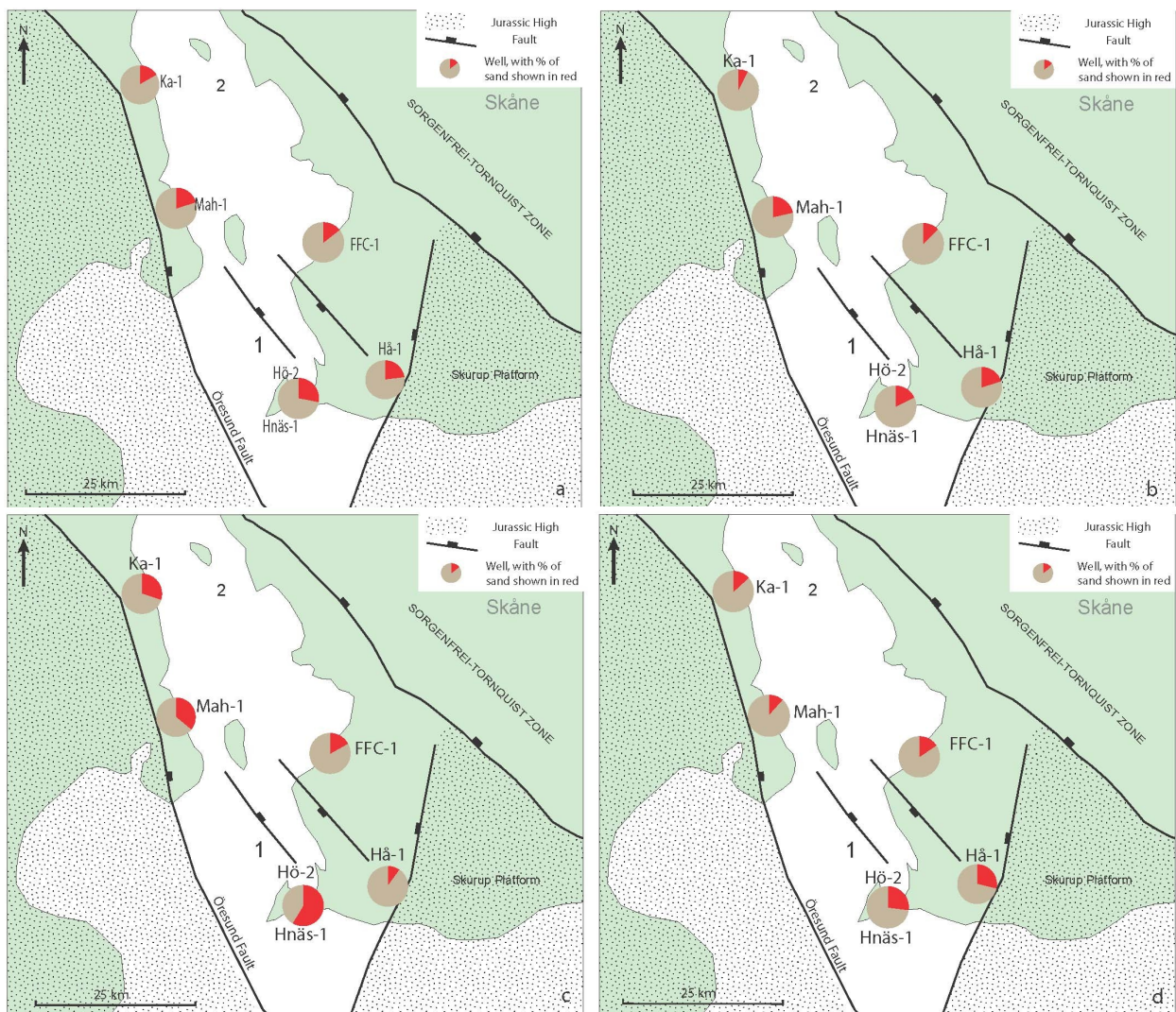


Fig. 22. a) Map showing the relative amount of sand (in red) in the Rhaetian–Pliensbachian interval for all the investigated boreholes (1: Höllviken Halfgraben; 2: Barsebäck Platform). b) Same for the Rhaetian stage. c) Same for the Hettangian. d) Same for the Sinemurian–Pliensbachian–Toarcian?

trolled subsidence. Fig. 23b shows a more localized subsidence in the western part of the basin along the Öresund fault and thus implying a tectonically induced differential subsidence during the Hettangian–Pliensbachian.

7.4 Sequence stratigraphical interpretation

The Rhaetian and Lower Jurassic along the margins of the Danish Basin were dominated by a highly dynamic coastline, which along with differential subsidence, and possible multiple sediment sources has resulted in a difficulty to correlate between boreholes. However, a cross section for the southern part of the Höllviken Halfgraben has been constructed (Fig. 24) by the use of distinctive log responses (Fig. 25), biostratigraphic zonations, and sequence stratigraphic key surfaces (Fig. 26), and tied to the chronostratigraphic

scheme produced by Nielsen (2003) (Fig. 28).

The Rhaetian–Pliensbachian succession within the Höllviken Halfgraben includes prograding, aggrading, and retrograding sequences. However, the overall trend in the Rhaetian–Pliensbachian is transgressive, indicated by the generally deepening upward depositional setting throughout the succession, emplaced by the early Jurassic transgression affecting large parts of Northwestern Europe (Hallam 1960, 1964).

At the onset of the Rhaetian, a sea level rise resulted in a high vertical to lateral alluvial accretion due to rise in the stratigraphic base level, preventing laterally shifting fluvial channels from eroding floodplain deposits and thus forming channels separated by floodplain deposits in the Höganäs Basin (Ahlberg & Arndorff, 1994). In the Höllviken Halfgraben, a similar trend is seen at the base of the Rhaetian depositing coal beds, alluvial sands, and lacustrine heterolites (Fig. 16c) interpreted here as a transgressive systems tract (TST 1) (Fig. 24). These transgressive deposits are

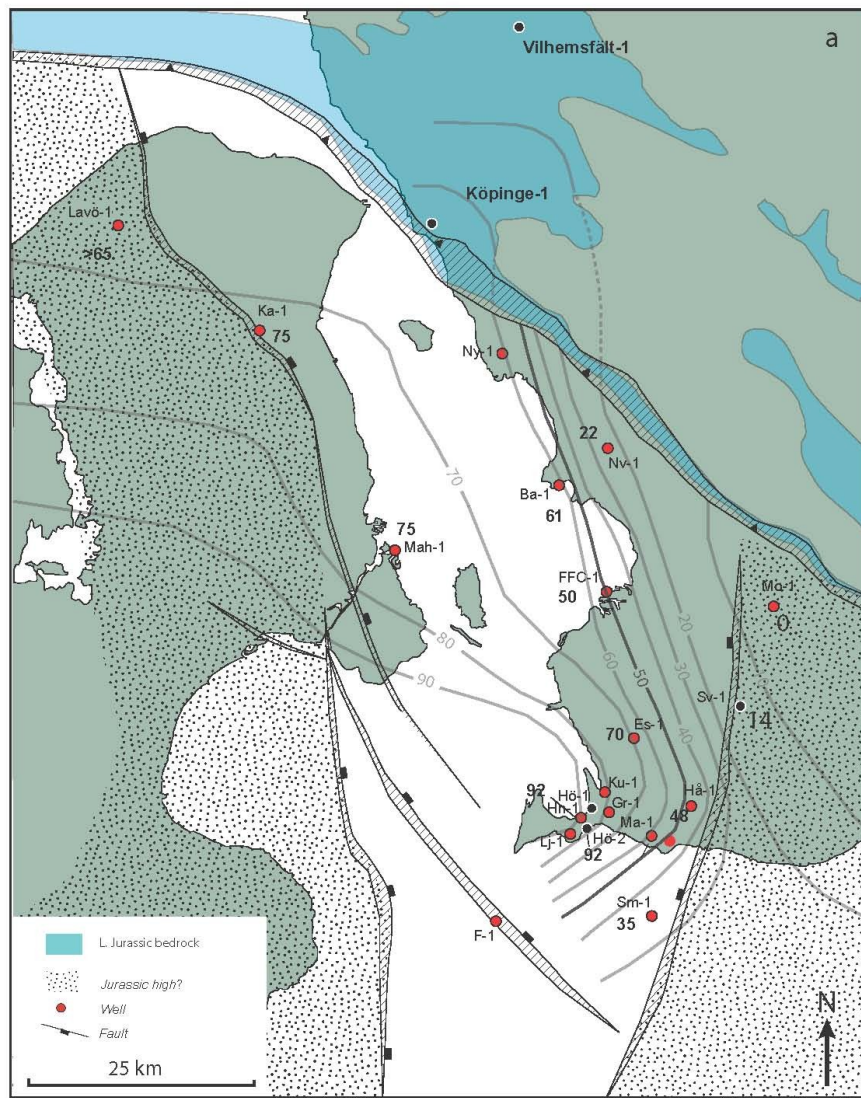


Fig. 23 a. Isopach map of the Höllviken Halfgraben showing thickness of Rhaetian beds.

overlain by a coarsening upward sand forming a highstand systems tract (HST 1) culminated with a fourth order sequence boundary (SB 1). This is followed by a transgressive systems tract (TST 2) and a maximum flooding surface (MFS 2) depositing offshore mudstone (Fig. 7). A highstand systems tract (HST 2) coarsening upward succession follows, topped by SB 2 which marks the Rhaetian–Hettangian boundary. The base of the Hettangian starts with a layer of sand gradually fining upward into more clayey material interpreted here as a transgressive systems tract (TST 3) capped by a maximum flooding surface (MFS 3) (facies 1). This is overlain by a thick aggradational sand unit covering most of the Hettangian and up to the middle/upper Sinemurian forming a highstand systems tract (HST 3) which ends with a sequence boundary (SB 3).

The Pliensbachian–Toarcian succession in the proximal (eastern/northeastern) part of the Höllviken Halfgraben is herein interpreted as tidal flat deposits based on the core samples from Höllviken-2 which show extremely bioturbated heterolites (Fig. 10), in addition to some diagnostic tidal flat features like the

ripple form sets interfingering into mud (Figs. 12 & 27) (Van Den Berg et al., 2007), indicating that the sand and mud came from opposite directions.

In a tidal flat environment, the interpretation of shallowing and deepening sequences is different in comparison with other environments, since in a tidal flat there is usually a decrease in sediment grain size upwards across the flat, from sand in the low intertidal zone to silt and clay in the higher part (Tucker, 2001). Thus the sequence stratigraphic interpretation is different, with fine grains being deposited in a highstand systems tract and coarse grains being deposited in a transgressive systems tract. On that basis, the tidal succession seen in FFC-1, Kungstorp-1, Höllviksnäs-1, and Håslöv-1 is subdivided into three 4th order fining upward sequences, that correlate with coarsening upward sequences in Margrethholm-1 in the more distal and rapidly subsiding part of the basin (Fig. 24).

7.4.1 Correlation between the Höllviken Halfgraben and the Danish basin

The chronostratigraphic scheme presented by

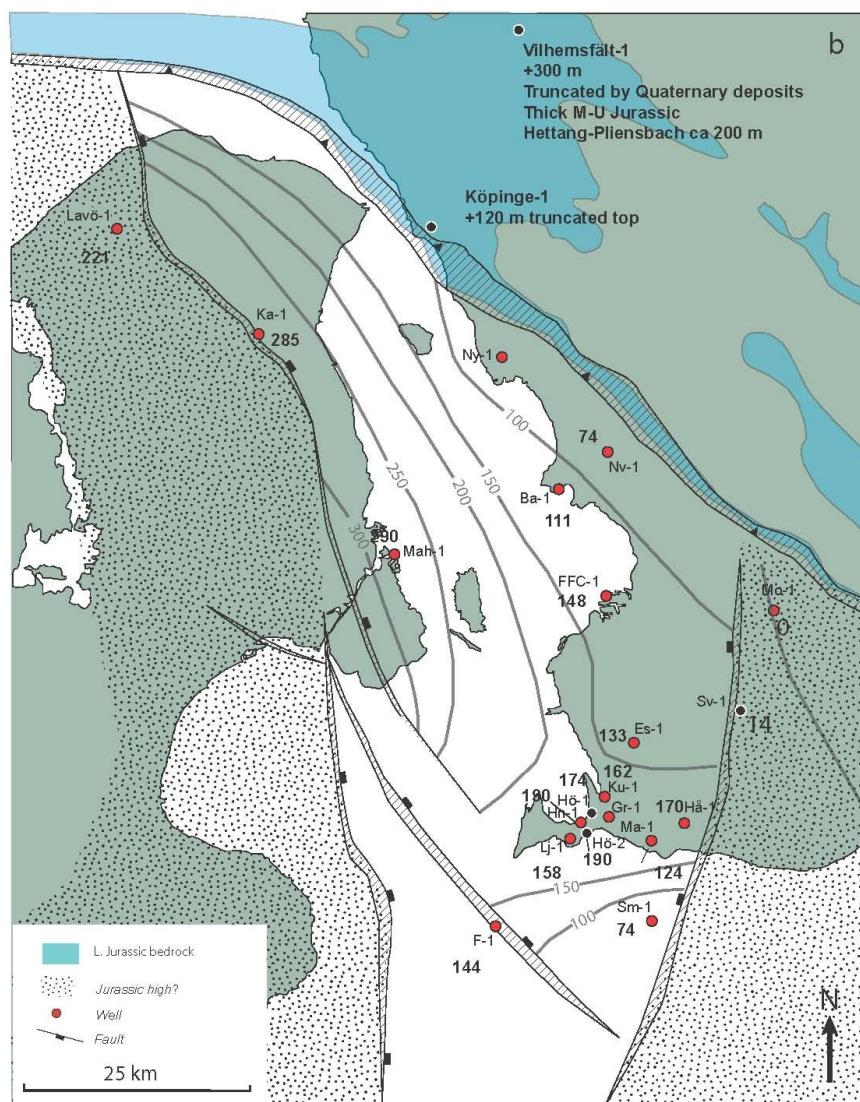


Fig. 23 b. Isopach map of the Höllviken Halfgraben showing thickness of Jurassic beds including the Rhaetian.

Nielsen (2003) for the Danish Basin and the Fennoscandian Border Zone displays the Rhaetian to Lower Aalenian sequence stratigraphic key surfaces (Fig. 28). A pronounced fluvial incision surface occurs in the lower Rhaetian of the Danish basin, referred to as SB 5 in Nielsen's correlation scheme. This fluvial incision is not clearly seen in the eastern part of the Höllviken Halfgraben. However, it could be tentatively correlated to the basal Rhaetian succession in the distal part of the Höllviken Halfgraben, exemplified in the section seen in the Margrethholm-1 well. An important key surface pointed out in Nielsen's scheme is the MFS7, which is a maximum flooding surface that could be traced throughout the whole basin, indicating that the entire basin including the platform was flooded. This surface is herein correlated with the MFS 2 in Fig. 24. The unconformable base of Hettangian sandstones, tentatively interpreted as the Boserup beds, is correlated to SB9 by Nielsen (2003) and is here correlated to SB2 in Fig. 24 which also marks the base of the lower Hettangian sand in the Höllviken Halfgraben. The Hettangian–Sinemurian in the Höllviken Halfgraben shows an aggrading succession that

implies a clear difference in subsidence rate when compared to the fining upward succession in the Danish Basin culminated with a sequence boundary (SB 12) in Nielsen's model which probably correlates with the upper Sinemurian SB 3 in Fig. 24. The correlation of the upper Pliensbachian–Toarcian succession between both areas is not really clear with the data at hand.

7.4.2 Correlation between the Höllviken Halfgraben and NW Skåne

According to Larsson et al. (1994), striking biostratigraphical, petrographical, and depositional similarities between Triassic–Jurassic strata in southwestern Skåne allow the extension of the formal stratigraphy of northwestern Skåne to the proximal areas of the Danish Basin, i.e. the Höllviken Halfgraben. However, repeated downfaulting and uplift of individual blocks (Bolau, 1951) lead to differential subsidence and thus different sedimentation rates.

As mentioned above, the Rhaetian shows very similar successions in the Höllviken Halfgraben and the Höganäs Basin (northwestern Skåne), though the

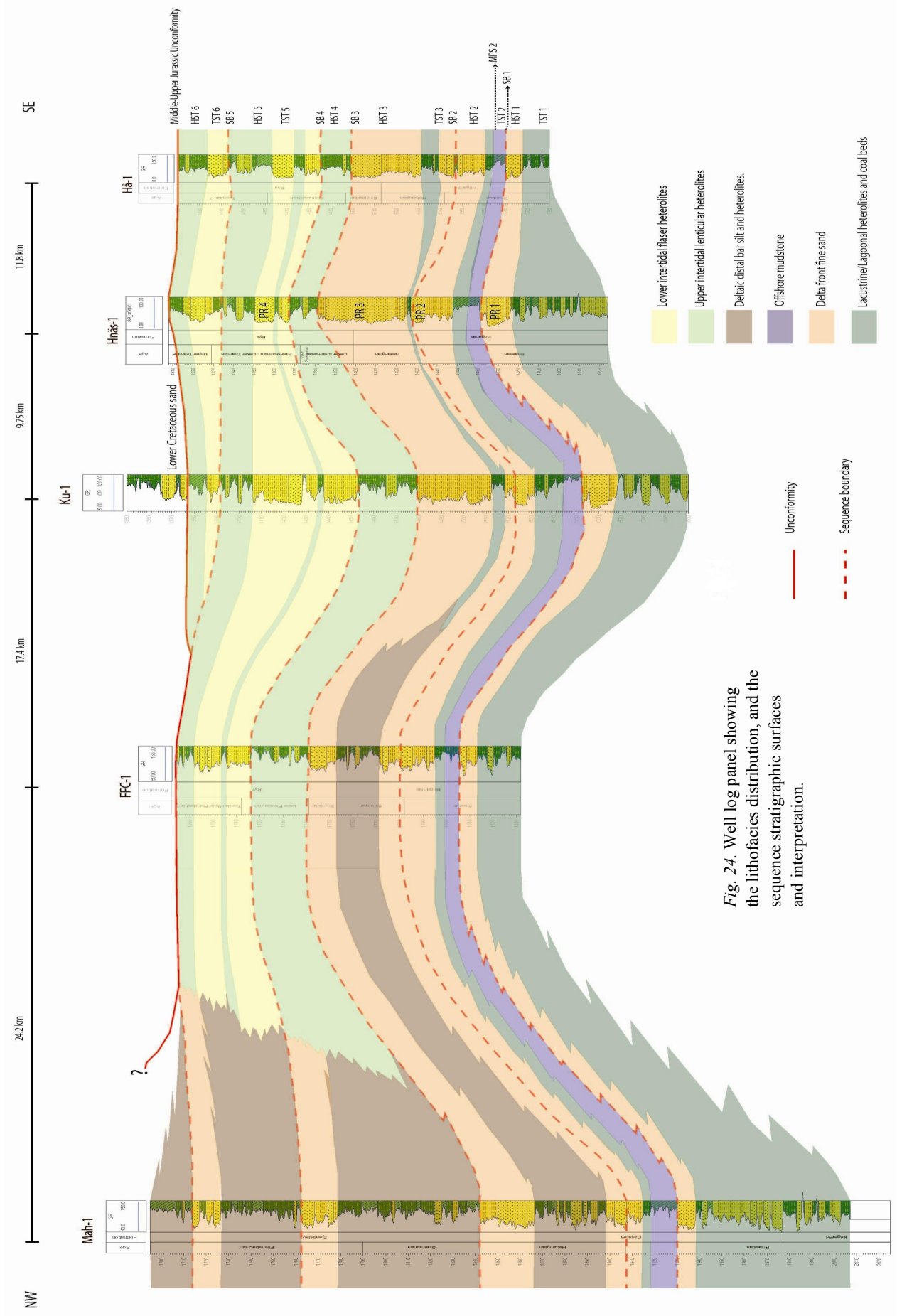


Fig. 24. Well log panel showing the lithofacies distribution, and the sequence stratigraphic surfaces and interpretation.

Höllviken Halfgraben was probably less subject to subaerial exposure than the Höganäs Basin in the Rhaetian. This is seen in the occurrence of thicker coal beds and paleosols in northwestern Skåne. One of the sequence stratigraphic surfaces in the Höllviken Halfgraben presented in Figure 24 that could confidently be extended to northwestern Skåne is SB 2 which marks the base of the Helsingborg Member of the Höganäs Formation. i.e. the Boserup beds.

The Hettangian of northwestern Skåne has been described by Ahlberg (1994) as an intermediate coastal unit deposited in lakes, lagoons, bays, and deltas within the Liassic transgressive sequence showing gradual deepening of the depositional environment, occasionally interrupted by massive influx of trough and herringbone cross-bedded sand supplied by delta distributary channels entering the bay. Ledje (1985) also describes a transgressive sequence at the south Kulla Gunnarstorp outcrop, belonging to the upper part of the Helsingborg Member and lower part of the Döshult Member. This retrogradational sequence seen in the Hettangian of the Höganäs Basin in the Helsingborg area is not seen in the Höllviken Halfgraben. In fact the Hettangian in Fig. 24 shows a fining upward basal part interpreted here as a transgressive systems tract (TST 3) followed by an aggradational succession going up to the Sinemurian and marked here as HST 3. This difference in depositional patterns between both areas might hint that differential subsidence has played a more important role than eustasy in this transgression.

The Sinemurian in the Höganäs Basin is represented by the Döshult and the Pankarp members (Fig. 2) with the Döshult Member represented by at least a 60 m thick unit, based on description of the Örby 2 section by Erlström et al. (1999), and the Gantofta section by Frandsen and Surlyk (2003), and the Pankarp Member represented by a 60–75 m thick succession (Grigelis & Norling, 1999). In the eastern part of the Höllviken Halfgraben, exemplified by the sections in FFC-1, Höllviksnäs-1, Häslöv-1, and Kungstorp-1, the Sinemurian shows a maximum thickness of around 25 m dominated by sand. This supports that in the Sinemurian, differential subsidence has also played a more important role than eustasy.

A conglomerate layer observed in the lower Sinemurian at Kulla Gunnarstorp (Fig. 29) is interpreted by Ledje (1985) as an angular unconformity with tidal beds and prograding deltaic deposits underlying it and unidirectional fluvial deposits overlying it. This conglomerate is a very good candidate for a sequence boundary that correlates well with SB 3 in the Höllviken Halfgraben (Fig. 24). Subsidence clearly continues in the Höganäs Basin resulting in the Sinemurian succession described in Örby 2 and Gantofta, which show no clear similarity to the Sinemurian in the Höllviken Halfgraben implying a local subsidence and resumption of deposition in the Höganäs Basin but not in the Höllviken Halfgraben, indicating a probable hiatus in the upper Sinemurian in the Höllviken Halfgraben.

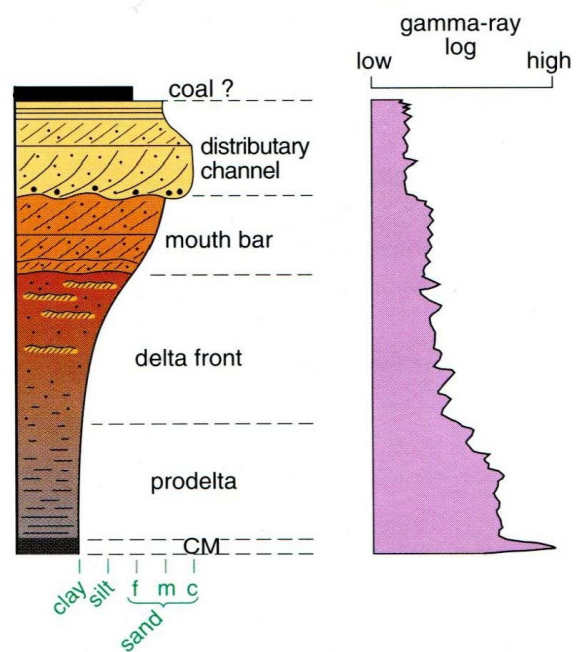


Fig. 25. Example of a typical Gamma ray log response for a deltaic parasequence. (The sedimentary record of sea level change. Edited by Coe et al., 2003)

The Pliensbachian–Toarcian succession in the Höganäs Basin is presented by the marine Katslösa and Rydebäck members of the Rya Formation showing up-section deepening of the depositional environment (Ahlberg et al., 2003) which goes in harmony with the Pliensbachian–Sinemurian succession in the Höllviken Halfgraben, however no clear sequence stratigraphic correlation could be made with the data at hand.

8. Assessment of reservoir properties

Several sandstone reservoirs are found within the Rhaetian–Pliensbachian succession in the Höllviken Halfgraben. Many of these sandstones are considered as potential aquifers for geothermal energy and possibly also for CO₂ storage. The latter is likely uncertain for southwestern Skåne because the area is densely populated. However, there is a great interest in pilot studies from which the results can be transferred to other areas of the Danish Basin.

Among these sandstone units, within the Rhaetian–Pliensbachian interval, only the Rhaetian sandstone unit (PR1) (Fig. 24) and the Lower Cretaceous sandstone unit could be confidently correlated throughout the Höllviken Halfgraben and the Danish Basin. The other sandstone units are of local extent and hard to correlate.

A suitable aquifer for carbon storage should have a thickness of more than 10m, a porosity of more than 15%, and a permeability that preferably exceeds

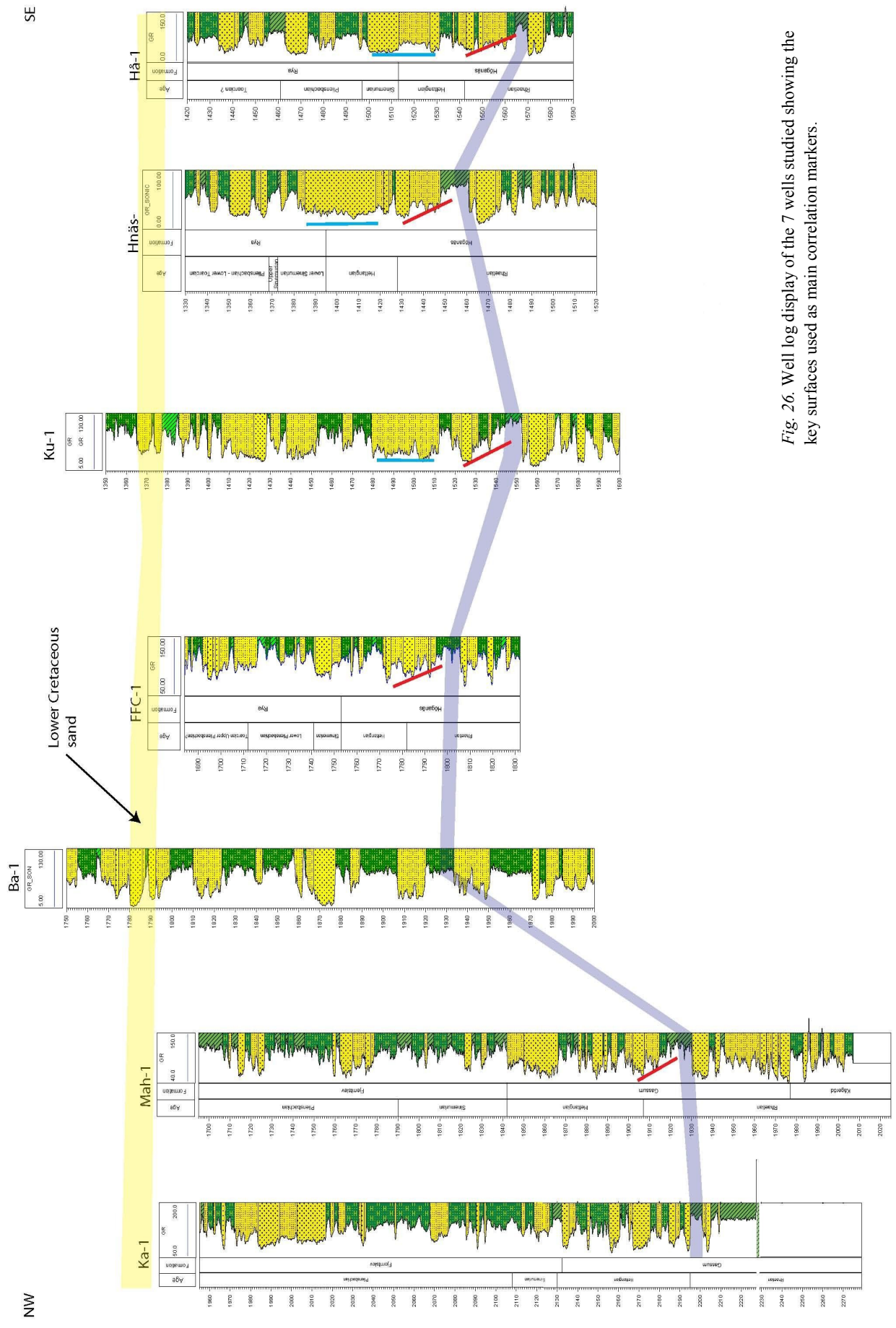


Fig. 26. Well log display of the 7 wells studied showing the key surfaces used as main correlation markers.

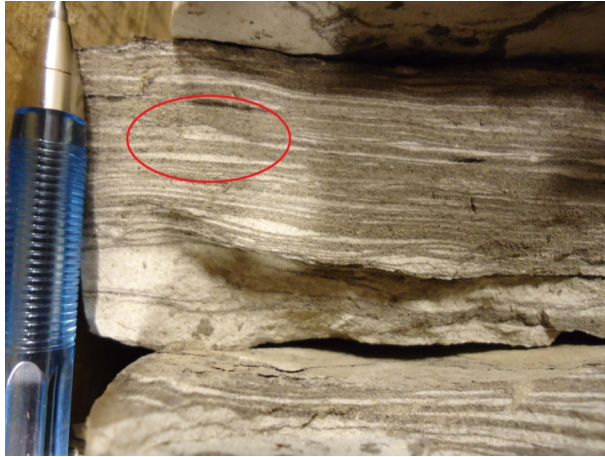


Fig. 27. Photograph of a core sample from the Pliensbachian in the Höllviken-2 core, showing sand ripples interfingering with mud.



Fig. 29. Photograph of the Lower Sinemurian conglomerate at Kulla Gunnarstorp.

100mD. The aquifer should also be at a depth of more than 800m in order to provide a temperature and pressure high enough to keep the CO₂ in a liquid state. Moreover, the aquifer should be overlain by a seal or a cap rock, which could be any impermeable rock unit (Erlström et al., 2011).

Evaluation of the capability of the various sand horizons in being suitable aquifers is based mainly on permeability and porosity data from FFC-1, and core samples from Höllviken-2/Höllviksnäs-1.

Starting with the deepest potential reservoir (PR 1) (Fig. 24) in the middle–upper Rhaetian, which is composed of fine to very fine-grained well sorted sandstone (Fig. 30). In FFC-1 this sand body is around 9 m thick, it slightly thickens to the south and reaches a maximum of 15 m in Höllviksnäs-1, and it probably correlates with sand bodies in the upper Rhaetian in Margrethholm-1 and Barsebäck-1. According to data from sidewall coring in FFC-1, this sand shows a permeability of 341mD, and a porosity of 24.05% (Olsen, 2002) and thus could be a very promising reservoir overlain by a 7 m to 12 m of clay that can act as a very good seal. Unfortunately, in Höllviken-2 core, this sand horizon could not be examined because the core

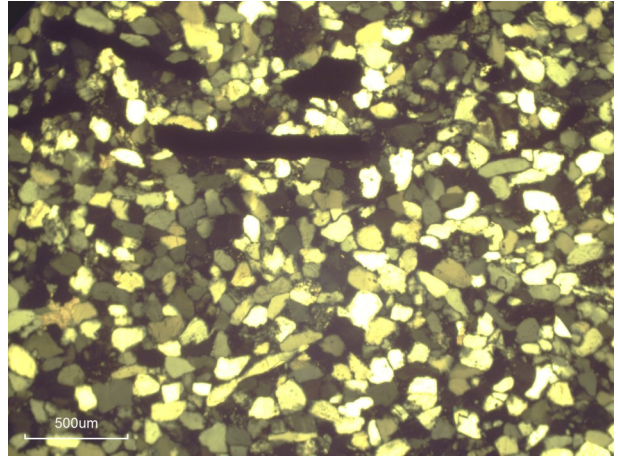


Fig. 30. Microphotograph (XPL) showing the texture of the potential Rhaetian reservoirs sands (PR1). Sidewall core from the middle Rhaetian of FFC-1 at a depth of 1807m KB.

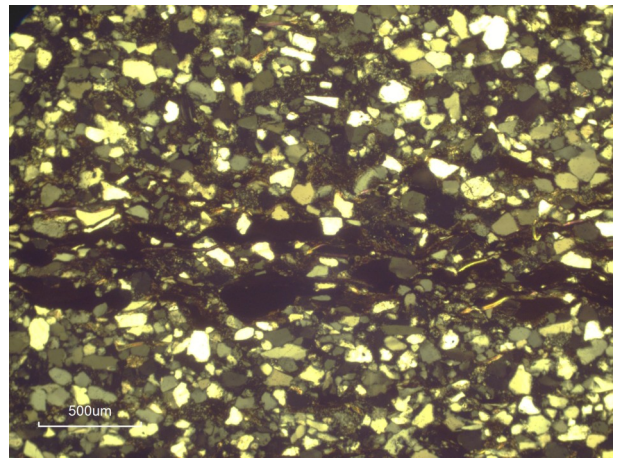


Fig. 31. Microphotograph (XPL) showing the texture of the potential upper Rhaetian – lower Hettangian sand (PR 2). Sidewall core FFC-1 at a depth of 1782m KB.

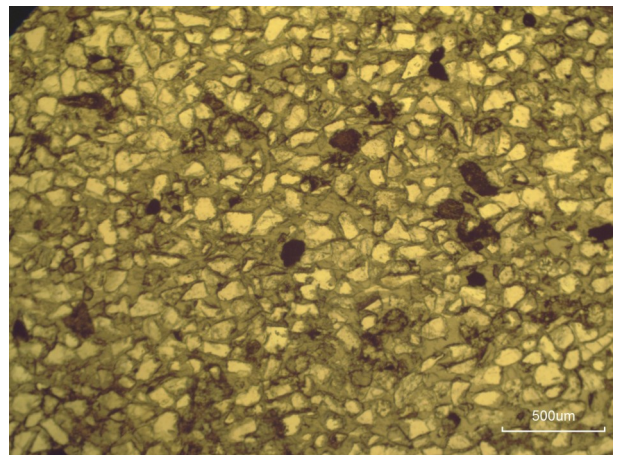
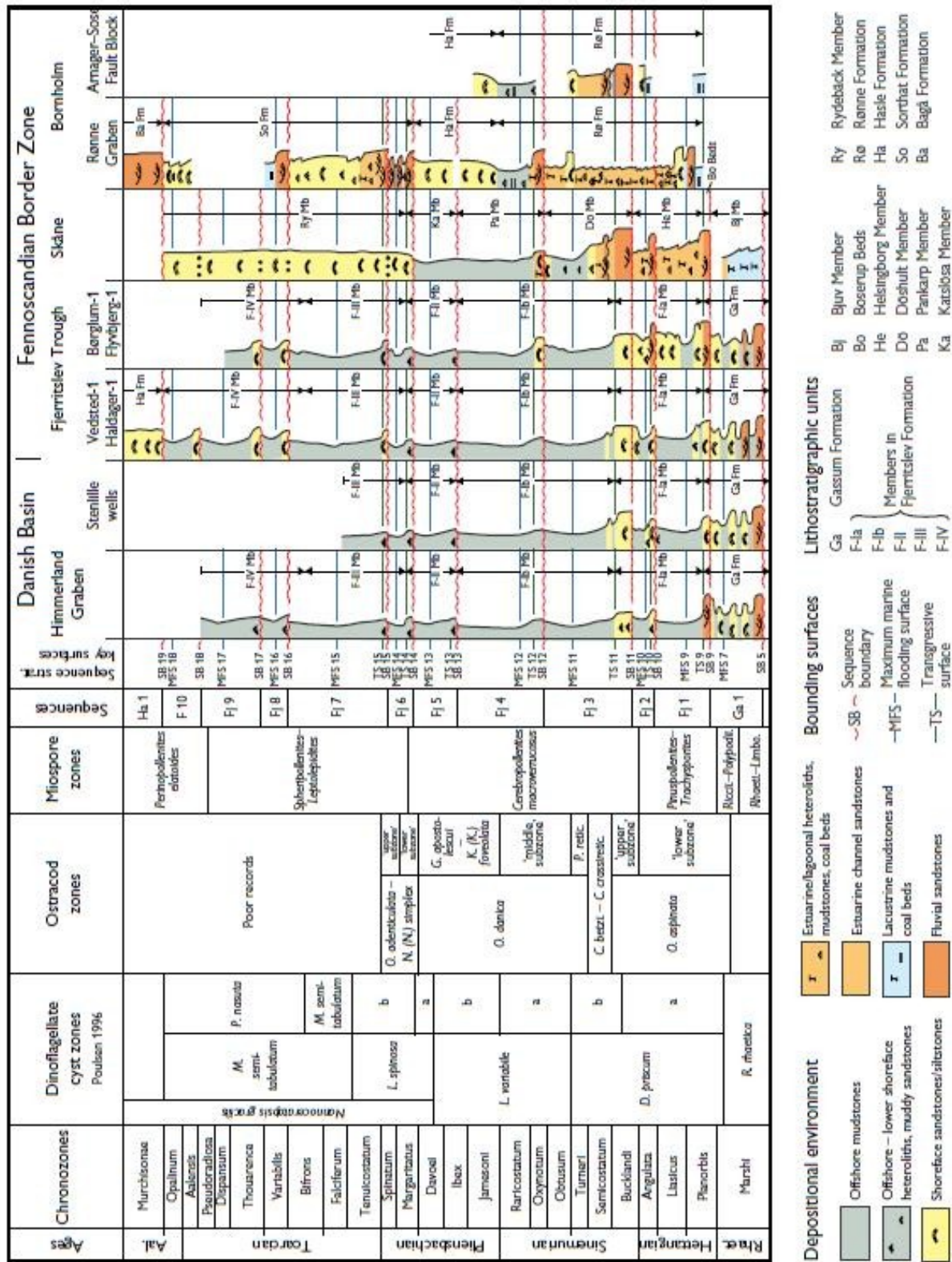


Fig. 32. Microphotograph showing the texture of the potential Hettangian-Sinemurian sand unit (PR 3). Höllviken-2 core at a depth of 1380.35m KB. (PPL).

boxes representing this interval were not found.

A second potential reservoir (PR 2) is the uppermost Rhaetian–lowermost Hettangian very fine well sorted sandstone (Fig. 31). This sand unit is 12m

Fig. 28. Chronostratigraphic scheme for the Danish Basin and the Fennoscandian Border Zone showing the Rhaetian to Lower Aalenian sequence stratigraphic key surfaces, depositional environments, biozones and lithostratigraphy (Nielsen, 2003).



to 25m thick and could be easily correlated between FFC-1, Höllviksnäs-1, Håslöv-1, Kungstorp-1, and Margrethholm-1 (Fig. 24). Data from sidewall corings in FFC-1 shows a permeability of 2.08mD, a porosity of 17.87% (Olsen, 2002), and thus renders this sand unit unsuitable for carbon storage because of its very low permeability.

In the Hettangian–Sinemurian a 30 m to 40 m thick sand unit (PR 3) could be easily correlated between Håslöv-1, Kungstorp-1, and Höllviksnäs-1, and pinches out toward FFC-1 to reach a thickness of 10m in the Sinemurian. In the Höllviken-2 core this sand unit has an extremely low core recovery, but it is still clear from the recovered samples that the uppermost part of this sand unit is a very well cemented fine sand (Fig. 32) (Fig. 14a) and the lower part is a poorly cemented very fine sand, which is most probably the reason for the very low core recovery. Data from the uppermost part of this sand unit in FFC-1 shows a permeability of 30.7 mD, and a porosity of 19.53% (Olsen, 2002) which makes it not suitable for carbon storage. However, these porosity and permeability measures are in this case not necessarily representative of the whole unit since they have been taken from the very well cemented part of the interval and thus showing a reduced porosity and permeability. Thus, this sand unit could be a potential reservoir, especially that the core samples recovered from the lower part look promising in terms of providing a high permeability and porosity (Fig. 16g). Nevertheless, more detailed investigation for this sand unit is needed in order to prove or refute its reservoir potential.

Another potential reservoir (PR 4) detected from the well logs at a depth of 1350–1360m in Höllviksnäs-1 within the Pliensbachian, and is a 9m to 14m sand body that could be correlated between FFC-1, Höllviksnäs-1, Kungstorp-1, Håslöv-1. Unfortunately, there is no permeability and porosity data available for this unit, however, this unit could be seen in the Höllviken-2 core (Fig. 16j) and it shows a sand dominated heterolites which could be promising if it has the needed permeability and porosity.

9. Conclusions

Based on the data presented in this study, and the conducted evaluation of the distribution, frequency and characteristic of the various facies of the Rhaetian–Pliensbachian succession within the Höllviken Halfgraben, the following conclusions could be deduced:

- Four main facies have been recognized in the well logs and cores in SW Skåne, i.e. offshore claystone facies, tidal heterolites facies, fine-grained sand facies, and alluvial/lacustrine facies (present only in Rhaetian–Early Hettangian)
- The facies associations and pattern of the Rhaetian–Pliensbachian sequence in the Höllviken

Halfgraben show very close similarities to the Rhaetian–Pliensbachian facies associations within the Höganäs Basin (NW Skåne) implying a generally similar depositional setting in both basins. And thus allowing the extension of the lithostratigraphic divisions of northwestern Skåne to southwestern Skåne.

- The distribution of the different facies shows a predominance of sandy lithologies adjacent to the Öresund Fault and in the Höllviken area, i.e. Falsterbo Peninsula.
- The Rhaetian relatively homogenous strata imply an eustatically controlled deposition under a tranquil tectonic conditions and shows a gradual sloping basin to the west.
- The Hettangian–Pliensbachian succession shows a higher subsidence rate towards the western part of the Höllviken Halfgraben along the Öresund Fault, i.e. a tectonically controlled deposition. Thus, there was likely a submarine high to the west of the Öresund Fault.
- The high amounts of redeposited spores and pollen in the Höllviken wells, the absence of L. Jurassic strata on the Skurup Platform to the east, and the increased amount of the arenaceous facies at the onset of the Hettangian indicate that the Skurup Platform as well as the surroundings to the south were likely a high area subject to erosion during most of the Jurassic.
- The Hettangian–Sinemurian strata in the eastern–southeastern part of the Höllviken Halfgraben show an aggradational succession compared to the retrogradational Hettangian–Sinemurian in northwestern Skåne, thus also supporting the previous conclusion of differential subsidence at that time.
- The dominating fine-grained facies in the whole succession imply a low relief in the hinterland.
- The Rhaetian–Pliensbachian sequence includes a high frequency of sandstone beds with varying reservoir properties. The beds are in majority fine-grained and, thus have permeabilities that are below 200 mD rendering transmissivities that disqualifies most of these beds for production of geothermal water. However, the properties qualifies them for CO₂ storage since they have adequate porosities (>20%), enough permeability (>100 mD), occur at depths below 800 meters and also sealed by tight claystone layers.

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12. Appendix

Log A : Höllviksnäs-1 composite well log

Log B: FFC-1 composite well log

Log C: Håslöv-1 composite well log

Log D: Margrethholm-1 composite well log

Log E: Karlebo-1A composite well log

Log F: Kungstorp-1 composite well log

Log G: Barsebäck composite well log

Appendix Log A

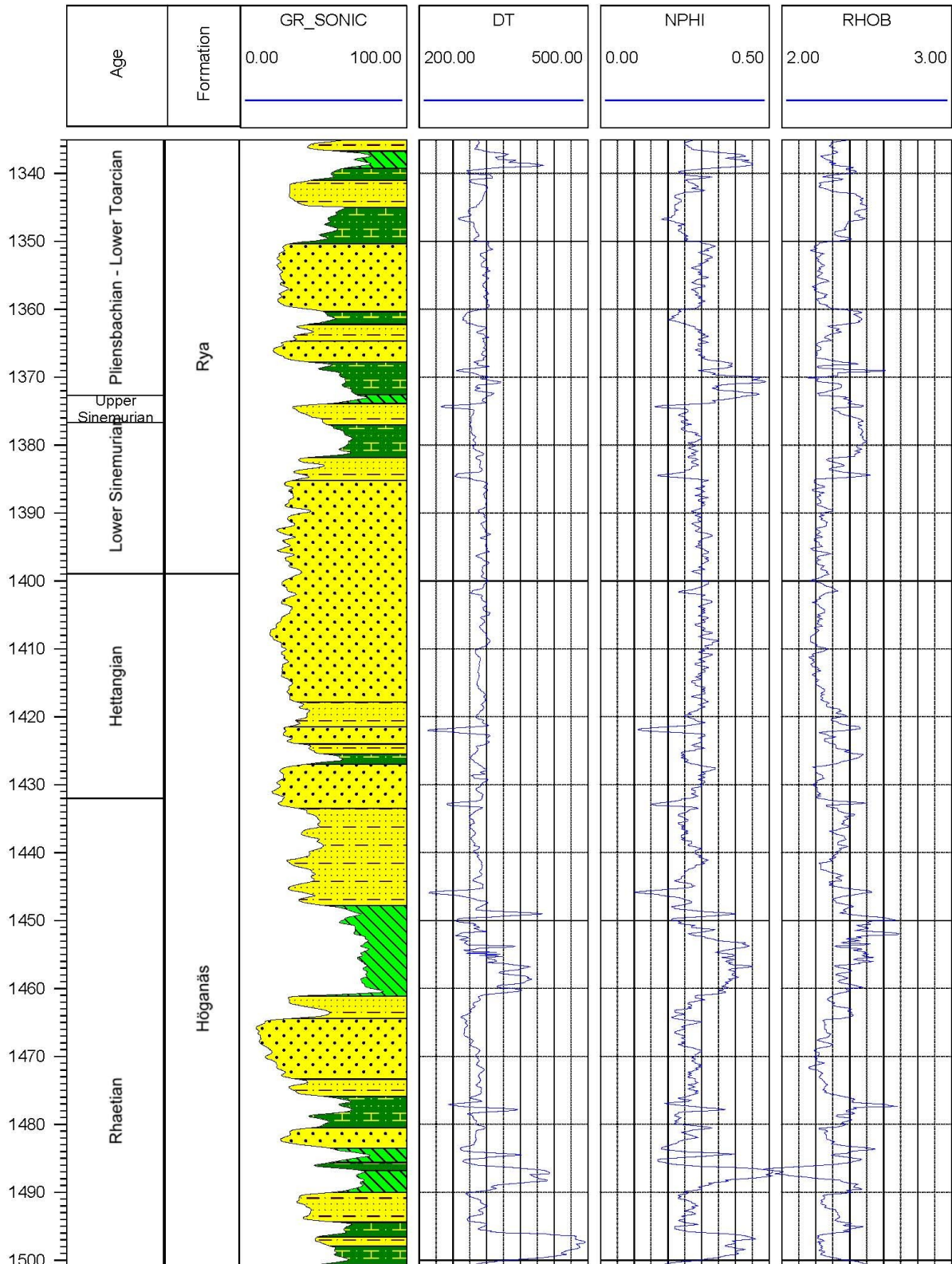
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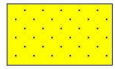
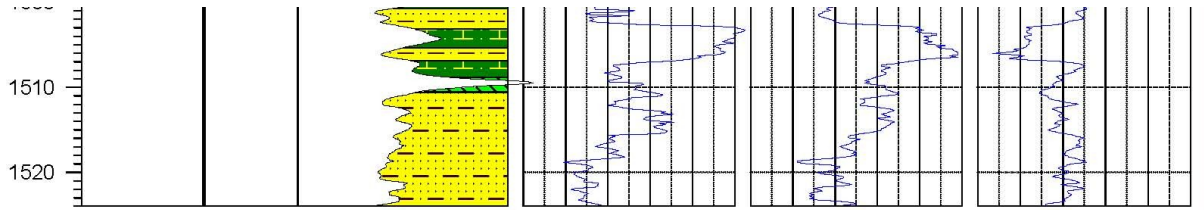
Interval: 1335m - 1524m

KB Elevation: 7.8000

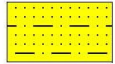
Longitude: 12.939850



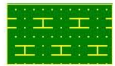
Appendix Log A continued



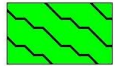
Sand



Sand and Silt



Clay and Silt



Clay

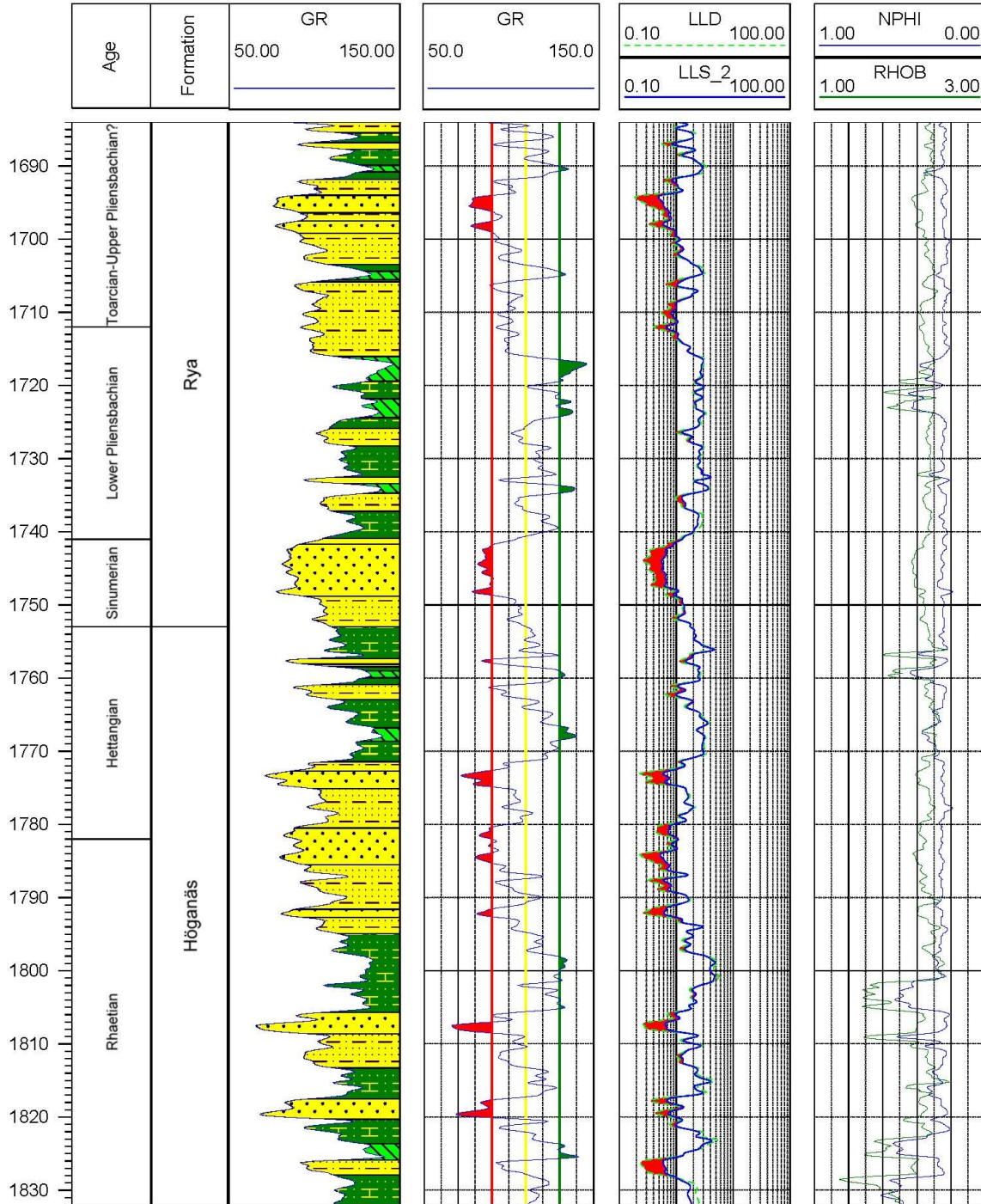
Appendix Log B

Well name: FFC-1

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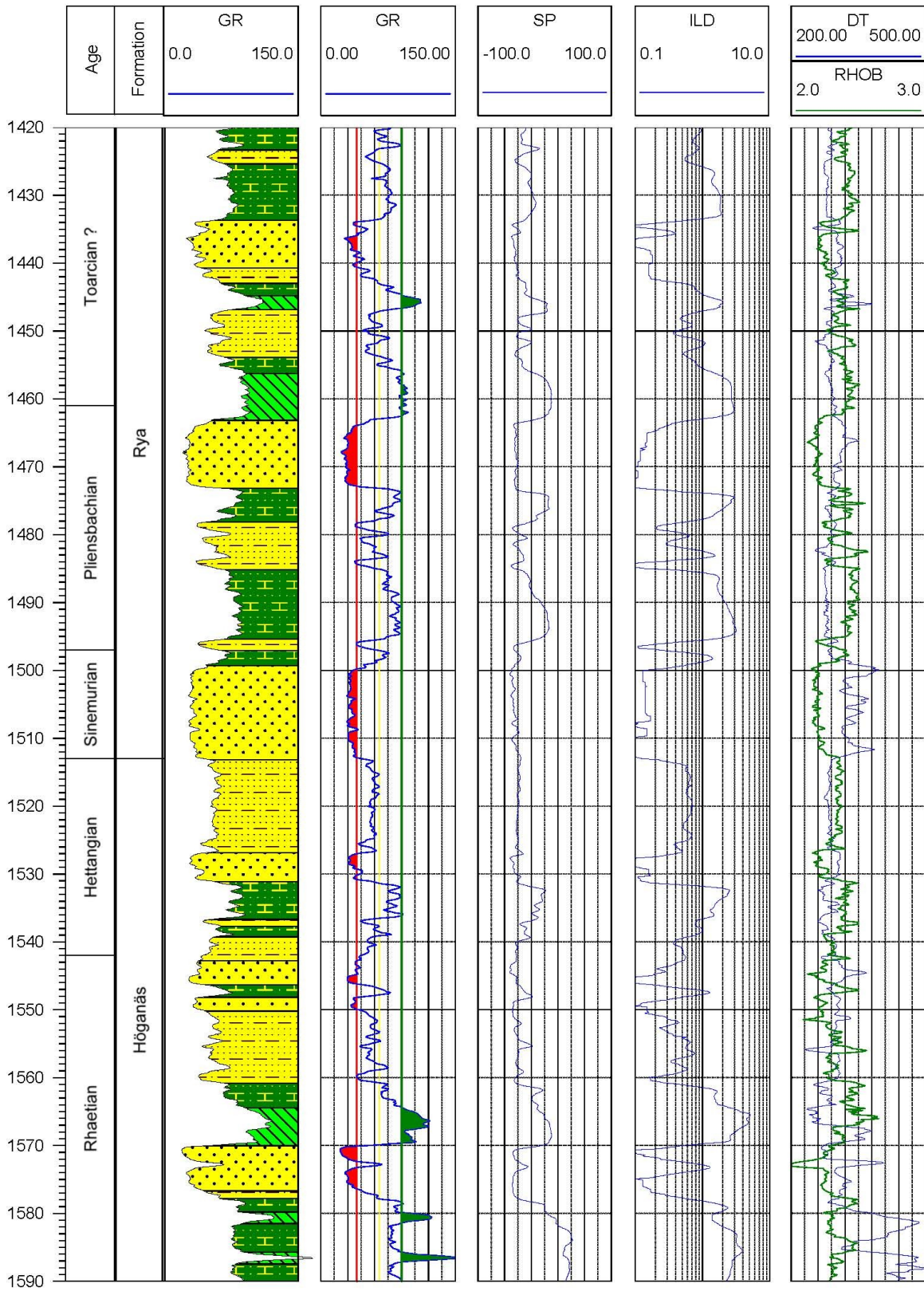
KB Elevation (m): -98765.0000

Longitude:13.014441



Appendix Log C

Well name: HASLOV-1



Appendix Log D

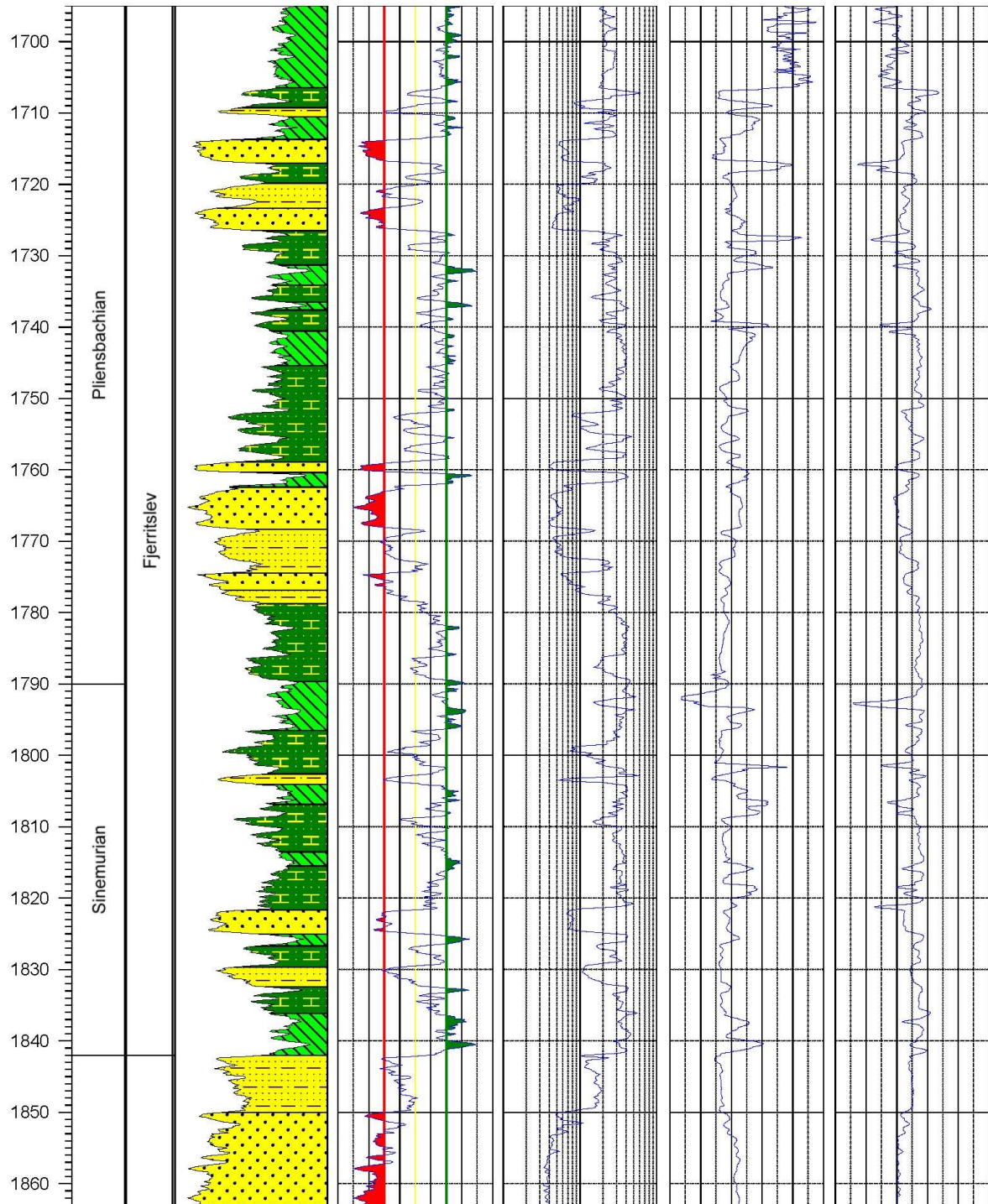
Well name: MARGRETHEHOLM-1

Latitude: 55.689300

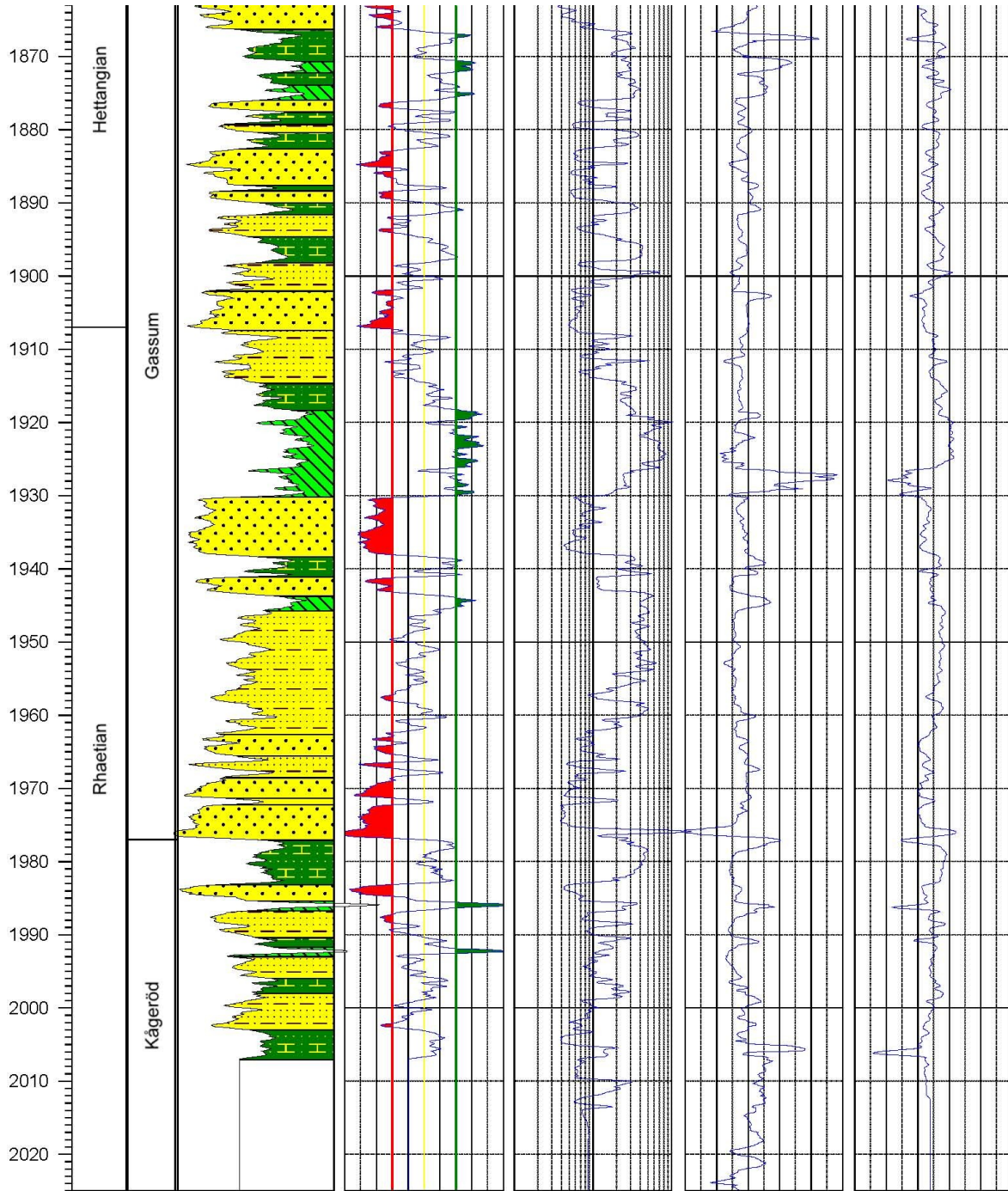
RT Elevation (m): 9.2000

Longitude: 12.634000

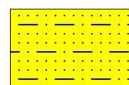
Age	Formation	GR 40.0 150.0	GR 40.00 150.00	RT_HRLT 0.10 10.00	DTSM 80.00 260.00	RHOZ 1.40 3.40
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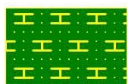
Appendix Log D continued



Sand



Sand and Silt



Clay and Silt



Clay

Appendix Log E

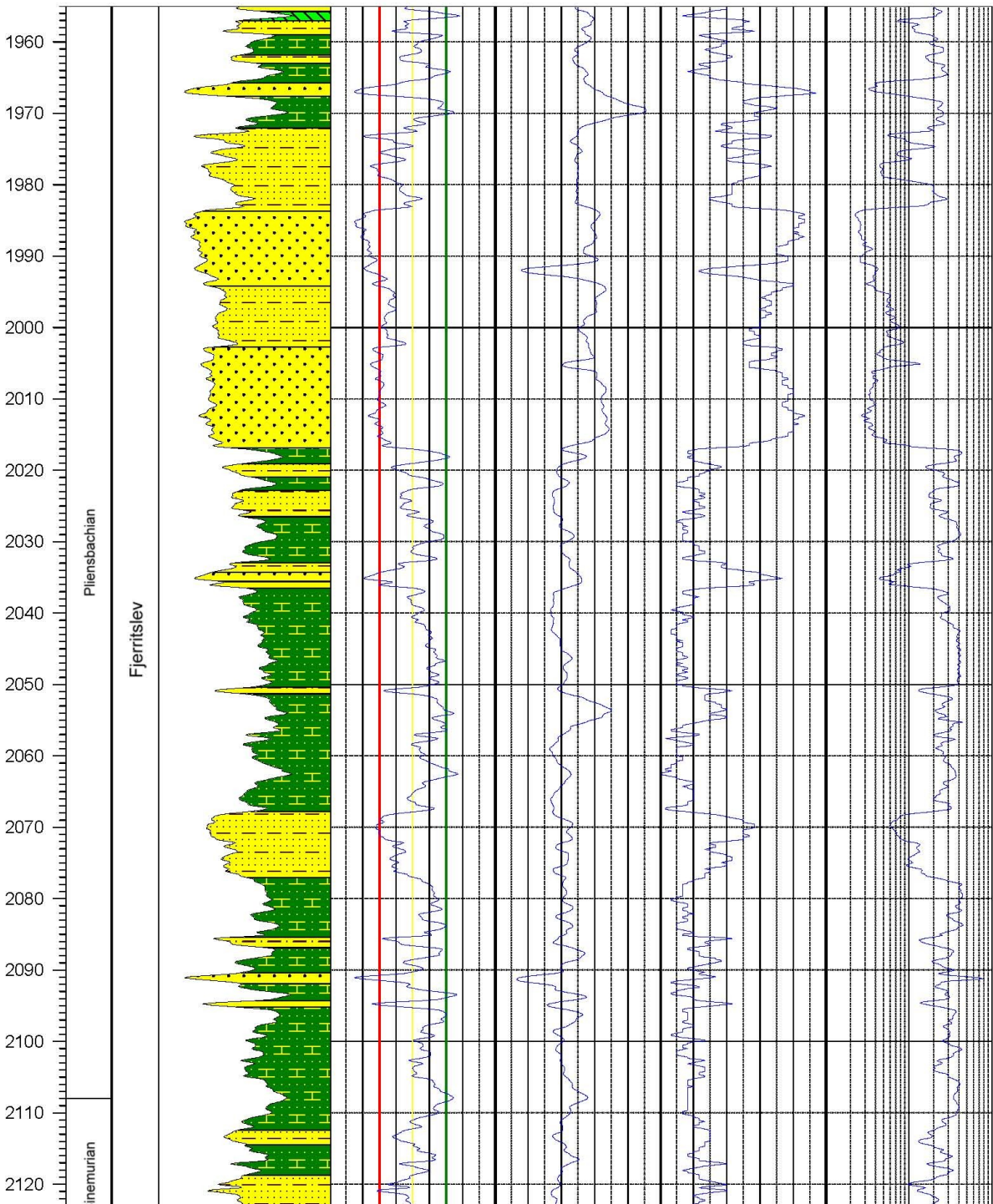
Well name: KARLEBO-1A

Latitude: 55.919024

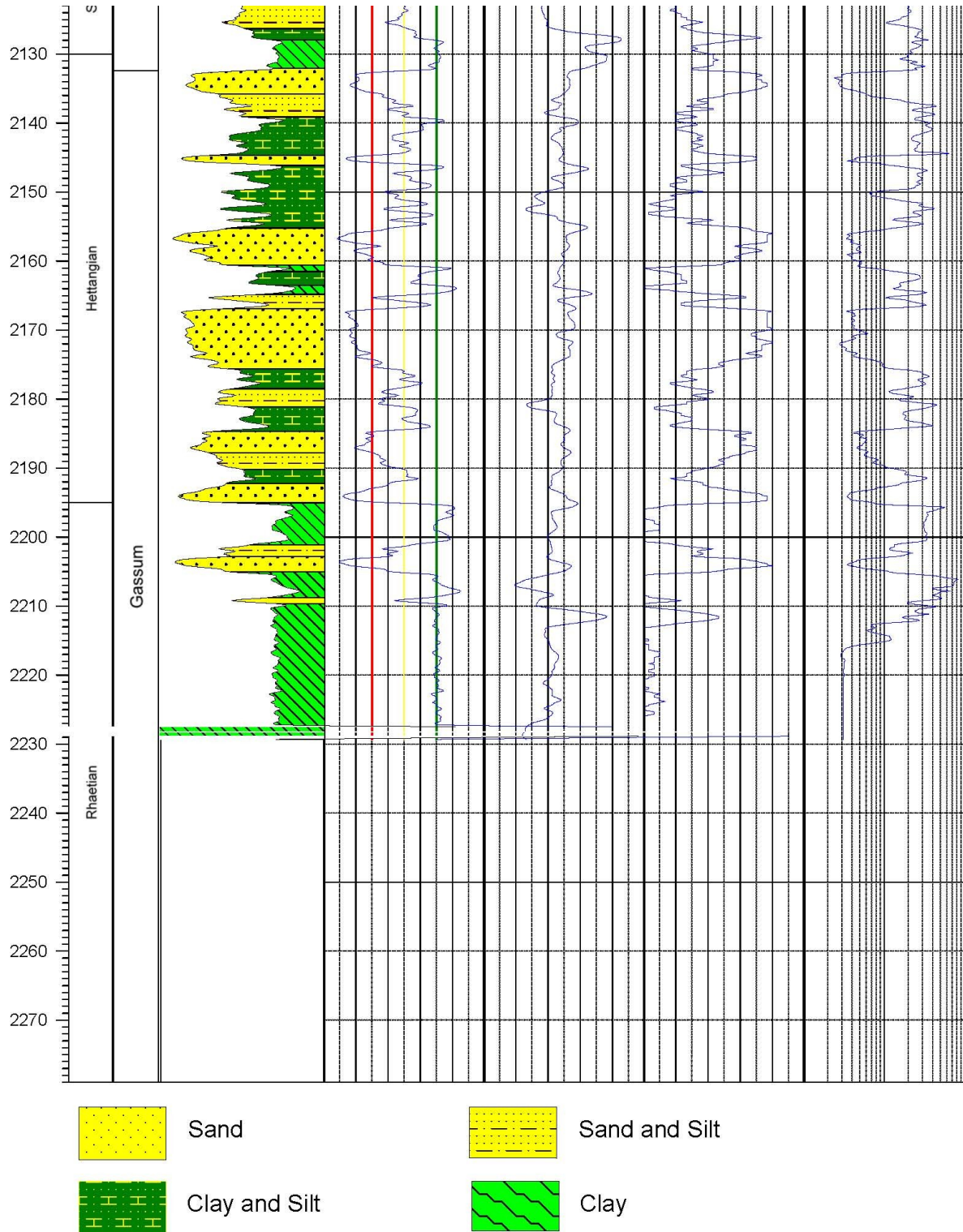
RT Elevation (m):45.0000

Longitude: 12.417998

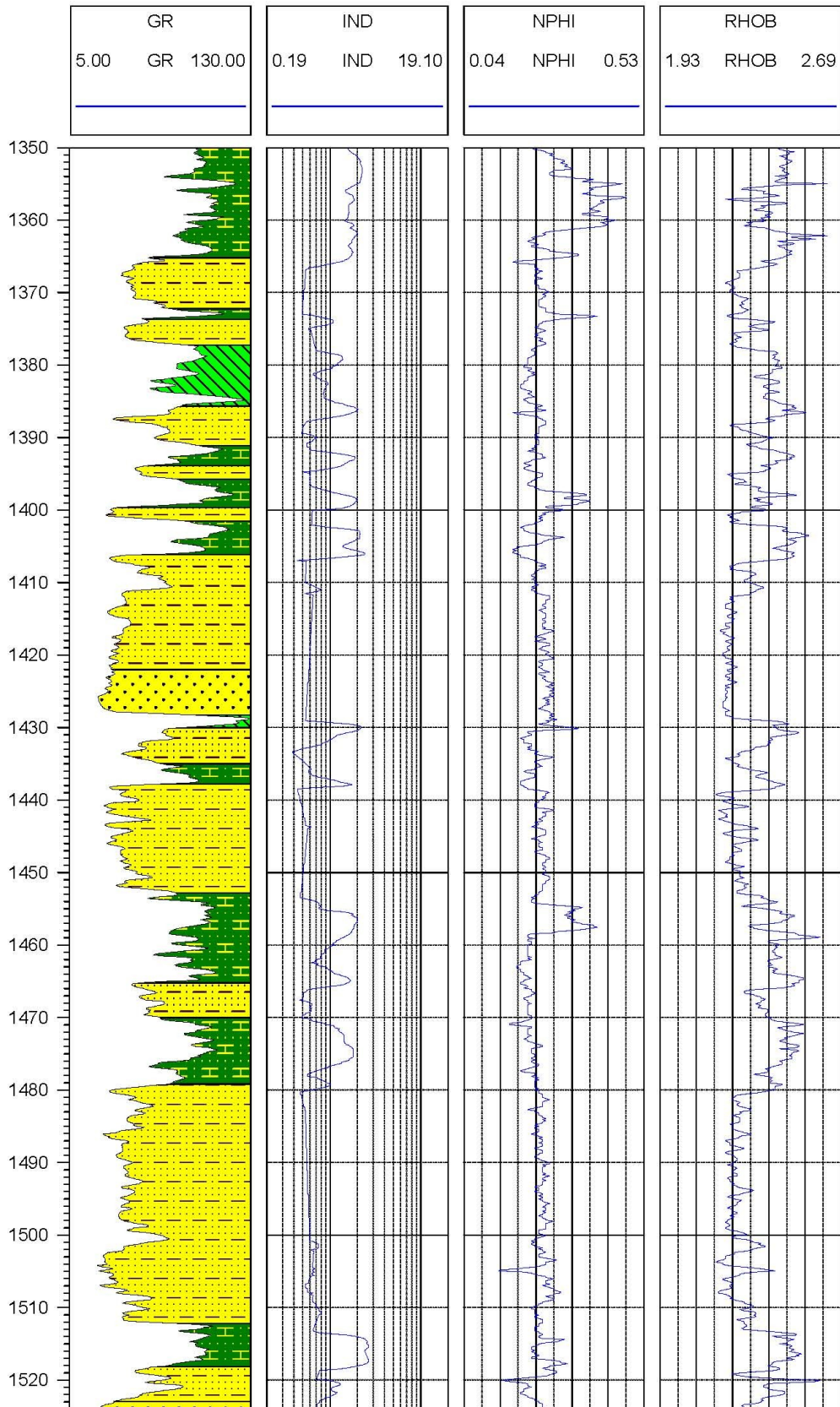
Age	Formation	GR		GR		DT		PHIE			S10C		
		50.0	200.0	50.00	GR 200.00	60.00	DT 110.00	0.00	PHIE	0.30	0.10	S10C 10.00	
		<hr/>											



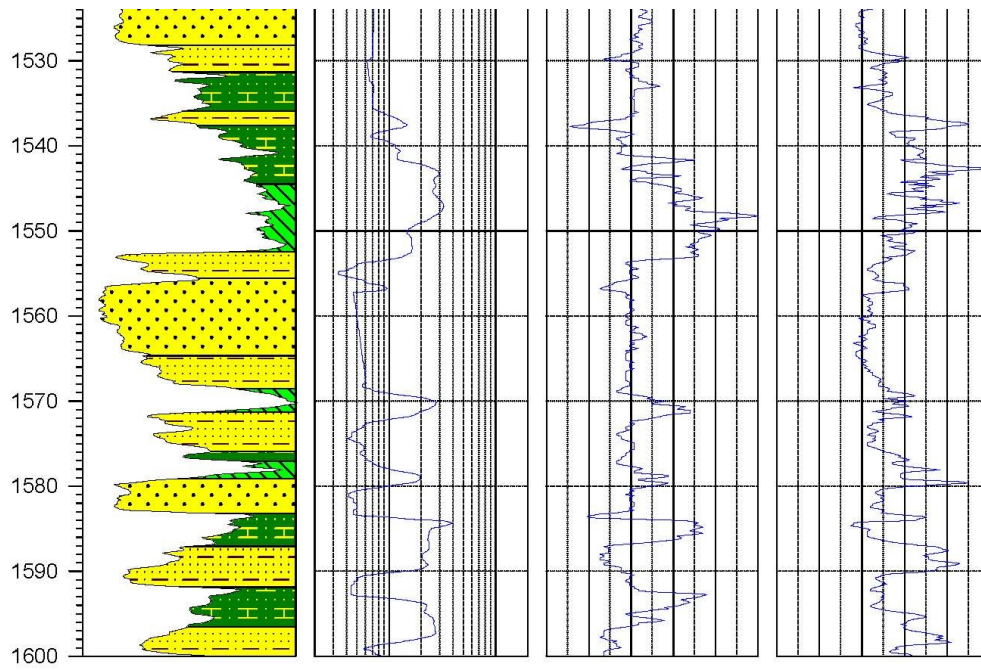
Appendix Log E continued



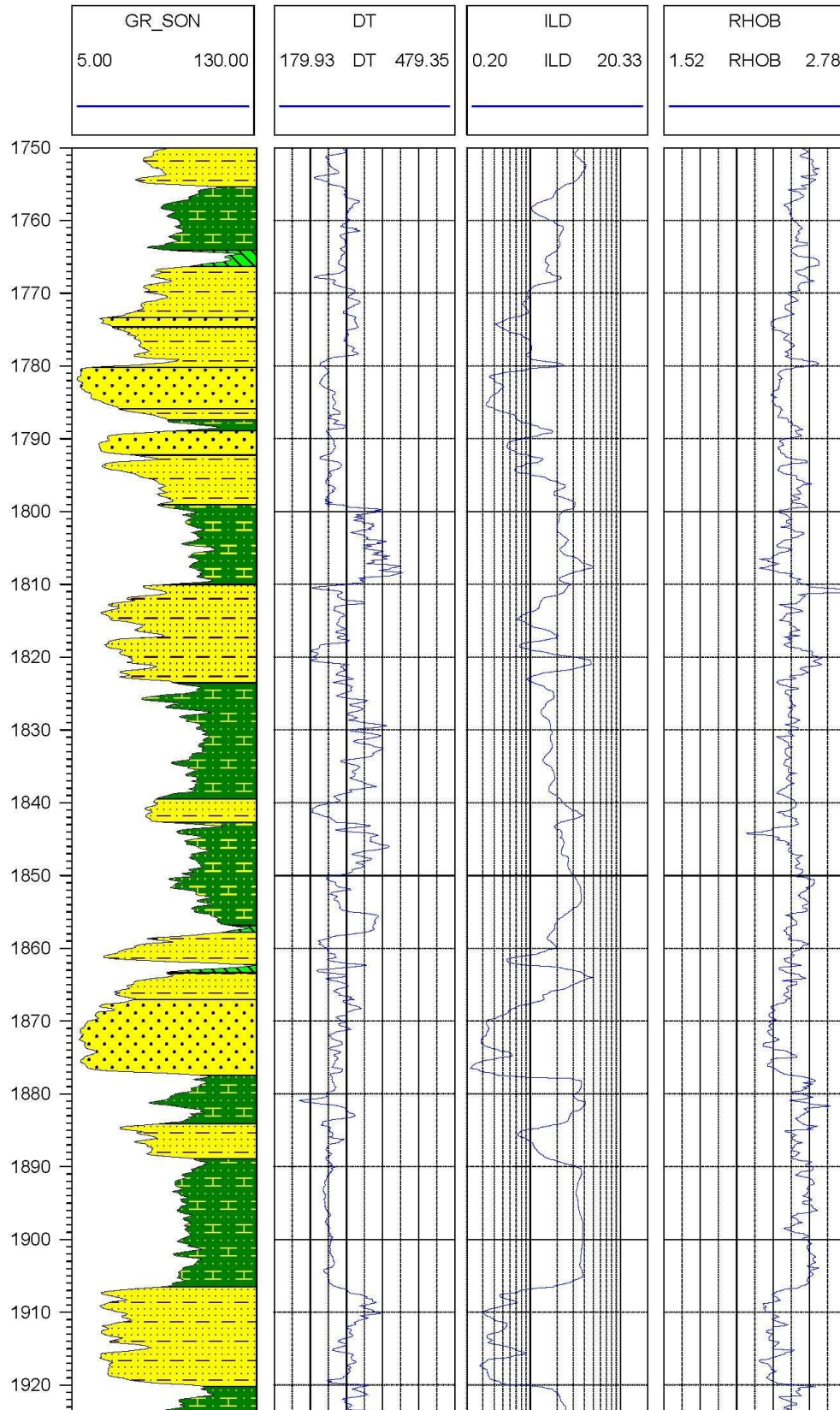
Well Name: KUNGSTORP-1



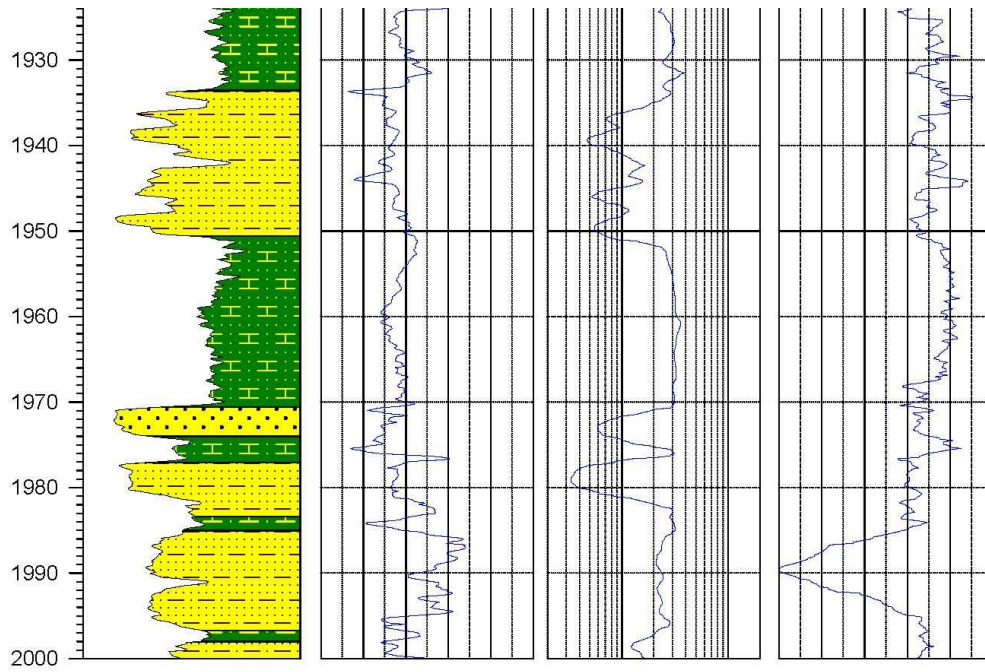
Appendix Log F continued



Well name: BARSEBAEK-1



Appendix Log G continued



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