Stratigraphy, sedimentology and geophysical assessment of the early Silurian Halla and Klinteberg formations, Altajme core, Gotland, Sweden

Christopher Artursson

Dissertations in Geology at Lund University, Master's thesis, no 548
(45 hp/ECTS credits)

Department of Geology
Lund University
2018

Stratigraphy, sedimentology and geophysical assessment of the early Silurian Halla and Klinteberg format-ions, Altajme core, Gotland, Sweden

Master's thesis
Christopher Artursson

Department of Geology
Lund University
2018

Contents

Cover Picture: Field work picture (2015/12/09) of a tripod with connected wireline logging tool.
Photo: Christopher Artursson

Stratigraphy, sedimentology and geophysical assessment of the early Silurian Halla and Klinteberg formations, Altajme core, Gotland, Sweden

Christopher Artursson

Artursson, C., 2018: Stratigraphy, sedimentology and geophysical assessment of the early Silurian Halla and Klinteberg formations, Altajme core, Gotland, Sweden. *Dissertations in Geology at Lund University*, No. 548, 36 pp. 45 hp (45 ECTS credits) .

Abstract: The Altajme drillcore was recovered from near Buttle in central Gotland in 2015. The core was drilled in outcrop belt of the late Wenlock (Silurian) Klinteberg Formation as a result from an international drilling campaign between the Department of Geology at Lund University and Iowa University, USA. The coring continued to the top of the underlying Ordovician strata at a depth of ca 330 m. In this MSc thesis the carbonate sedimentology and gamma ray log-motifs of the top 137 m of the core has been investigated. The aim was to measure, document and analyze the core by means of core slabs, thin sections and geophysical log measurements, including natural gamma ray, and to perform microfacies analysis. These methods have been used to subdivide the strata into different depositional environments such as the outer, middle and inner ramp and to study the relative sea level evolution. The lower parts of the core, between -137 and -50 m, consists of a successive transition from outer ramp to middle ramp carbonate microfacies associations. Based on literature and comparison to outcrops on Gotland, these strata can be assigned to the Halla Formation. The overlying strata, between -50 and the surface are pure reef limestone is interpreted to be a part of the Klinteberg Formation.

Natural gamma ray measurements show a successively higher CPS (counts per second) downhole, mirroring the downhole transition from inner ramp (Klinteberg Formation) to outer ramp depositional environments (Halla Formation). The combined geophysical data and carbonate sedimentology of the Altajme core implies a relative sea level lowering from bottom to the top of the core. The geophysical data has furthermore been used to correlate data from the nearby well Ala-Fjäle (5 km northeast from Altajme). The Ala-Fjäle and Altajme wells are situated in the same facies belt and are expected to have a similar stratigraphic succession. The natural gamma ray data show a clear similarity between the wells log-motifs.

Keywords: Gotland, gamma ray, stratigraphy, carbonate sedimentology, drill core, Altajme, Ala-Fjäle, Klinteberg Formation, geophysical survey

Supervisor: Mikael Calner

Subject: Sedimentology

Christopher Artursson, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: christopher_a@hotmail.se

Stratigrafi, sedimentologi och geofysisk analys av Halla- och Klintebergformationen från tidig Silur, Altajmeborrkärnan, Gotland, Sverige

Christopher Artursson

Artursson, C., 2018: Stratigrafi, sedimentologi och geofysisk analys av Halla- och Klintebergformationen från tidig Silur, Altajmeborrkärnan, Gotland, Sverige. *Examensarbeten i geologi vid Lunds universitet*, Nr. 548, 36 sid. 45 hp.

Sammanfattning: Altajmeborrkärnan togs upp i närheten av Buttle centrala Gotland 2015. Projektet är ett resultat av en internationell borrkampanj mellan geologiska institutionen vid Lunds universitet och Iowa universitet, USA. Borrningen gick ned till den underliggande ordoviciska lagerföljden på ett djup av ca 330 m. I denna masteruppsats har karbonatsedimentologin och gamma ray-loggen från de översta 137 m av borrkärnan undersökts. Syftet var att mäta, dokumentera och analysera borrkärnan med olika metoder t.ex. genom tunnslip och geofysiska log-mätningar inklusive gamma ray samt mikrofaciesanalys. Nämnda metoder har sedan använts till att beskriva de olika depositionsmiljöer som är representerade i kärnan, såsom yttre, mellersta och inre rampen samt att bedöma den relativa havsnivåförändringen. De undre delarna av borrkärnan mellan –137 och –50 m består av en successiv övergång från yttre till mellan-ramps-microfacies-associationer. Baserat på litteratur och jämförelse av blottningar på Gotland så har de tolkats att vara en del av Hallaformationen. Det överliggande intervallet mellan –50 m och markytan består av ren kalksten och representerar en del av Klintebergformationen.

Gamma ray-loggen visar på successivt högre CPS-värden (counts per second) med djupet. Det speglar en övergång från en inre ramp (Klintebergformationen) till en yttre ramps depositionssystem (Hallaformationen). Den kombinerade geofysiska datan och karbonatsedimentologin i Altajmeborrkärnan visar på en relativ havsnivåsänkning från botten till toppen av borrkärnan. Den geofysiska datan används också för korrelation med den närliggande Ala-Fjäleborrningen (5 km nordöst från Altajme). Borrningarna Ala-Fjäle och Altajme är gjordes i samma faciesbälte och förväntas därför ha en liknande stratigrafisk succession. Gamma ray-kurvorna från dessa borrningar uppvisar stora likheter.

Nyckelord: Gotland, gamma ray, stratigrafi, karbonatsedimentologi, borrkärna, Altajme, Ala-Fjäle, Klinteberg Formationen, geofysisk undersökning

Handledare: Mikael Calner

Ämne: Sedimentologi

Christopher Artursson, Geologiska institutionen, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: christopher_a@hotmail.se

1. Introduction

The Silurian strata of Gotland constitute remnants of a series of carbonate platforms formed in a shallow sea at tropical latitudes between ca 430-418 Ma (Hede 1960; Frykman 1989; Calner & Jeppsson 2003; Cramer et al. 2010). Similar deposits are today to be found in the vicinity of reefs in very shallow water within the tropical latitudes (Hallock 1986). The stratigraphy encompasses some 750 m of reef limestone, bedded limestone, marlstone and subordinate sandstone (<3% of the thickness) and represents one of the best preserved limestone suits of this age globally. It has therefore for long times been the target for both applied and geoscientific research. In 2015, the Department of Geology at Lund University coordinated an international drilling campaign (in collaboration with Iowa University, USA) in the old abandoned quarry at Altajme, near Buttle on central Gotland. For this purpose the national infrastructure Riksriggen at Lund Technical Highschool was used. The strats outcropping at the drill site belong to the Klinteberg Formation outcrop belt and are of latest Wenlock age. The coring continued to the top of the underlying Ordovician strata at a depth of ca 330 m. The aim of this MSc project is to measure, document and analyze the uppermost ca 140 m of the core and to correlate this sedimentary succession by means of geophysical well-logs to a nearby well in the Klinteberg Formation, drilled by the Swedish geological survey (SGU). The combined information from these cores forms the basis for interpretation of relative sea-level and carbonate platform development during the middle Silurian in the Gotland area. For this purpose a general description to the concept of carbonate platforms is first needed as a background.

The term *carbonate platform* is used as an umbrella term for every major shallow carbonate production zone, which cannot be assigned to any subcategories. These subcategories include ramps, rimmed shelves and isolated build ups (Ahr 1973; Read 1980; Burchette & Wright 1992 (p. 4)). For this thesis I will only discuss the carbonate ramp depositional system at more depth. For reason that the Gotland stratigraphic development is a carbonate ramp.

The carbonate ramp is defined as a gentle slope that extends from a shoreline to an adjacent basin and the slope has an angle >1 degree. It is subdivided in three separate parts that is defined by water depth and hydrodynamic energy – the inner, middle and outer ramp (Fig 1). These three are separate depositional environments with their own typical processes and resulting facies associations, and they shift laterally under the influence of relative sea-level change and carbonate production rates (Burchette & Wright 1992).

1.1 Subdivision of carbonate ramps

1.1.1. The inner ramp

The inner ramp is the area above the fair-weather wave base (FWWB) and is the main area of carbonate production and reef growth. It is an area with a diverse set of bioclasts including (depending on time period in Earth´s history) stromatoporoids, ooids, peloids, foraminifera, corals, oysters, calcareous algae and molluscs (Burchette & Wright 1992). The inner ramp can be subdivided into three parts. The open marine part of the ramp with good water circulation and influence by wave action, the reef itself and the peritidal environment, the area behind the reef.

The open- marine inner ramp is an environment with good water circulation and a lot of nutrients for subtidal species to thrive on. The high water circulation ensure that the finest particles, the matrix, remains in the water column and is exported seawards to the mid and outer ramp area where the energy regime is lower allowing accumulation below the wave base. Bioclastic packstones and floatstones with biostromes, oolitic and intraclastic grainstone, bioclastic packstones is associated with an open-marine shallow ramp.

The reef is the area of main carbonate aggradation. Rudstone microfacies is associated to the forereef. It is constituted by gravel-sized bioclasts commonly reworked in the fore-reefs shallow zone. The boundstone microfacies is commonly associated to the reef itself. Microfacies associated with the sand shoal and bank environments are characterized by oolitic grainstone and packstone.

The peritidal inner ramp environment is associated to a lagoon, a tidal setting or adjacent to islands with low water circulation. Due to this condition a mixed matrix particle size is more common compared to the open- marine and reef environment. In the peritidal or lagoonal area behind the reef belt common microfacies associations include lime mud-wackestones, bioclastic packstones and boundstones. Protected and low energy environments are known to have abundancy of echinoderm fragments. Associated skeletal grains occurring in different quantities are bivalve shells, gastropods, bryozoans and benthic foraminifera (Flügel 2010).

1.1.2. The middle ramp

The middle ramp extends from the FWWB to the storm wave base (SWWB). Facies associations are typically a mix of fair-weather mud- and wackestone interbedded with pack- and/or grainstone tempestites deposited through storm activity. The bioclastic content of the tempestites can indicate transport distance or relative sea level changes. Proximal tempestites contain mixed and diverse faunas due to significant reworking of sediments during storm events (Aigner 1985). Water depth can reach some tens of meters and the bottom sediment is typically exposed to reworking of storm waves and swells. The amount of reworking affecting the middle ramp sediments depends on the strength of the storm influence on both inner ramp and middle ramp settings. This since tempestite currents can start from the inner ramp to be deposited in the middle ramp. If there is an existing fore-reef the likelihood and strength of the tempestite currents will be larger, since the potential energy is higher .

The height and slope angle of the existing fore-reef increase the potential energy converted to kinetic energy once the sediment is in movement becoming a tempestite. The composition of the tempestite sediment also has its impact on the movement and thickness. The finer particles in a mud-wackestones have the tendency to be more coherent compared to a grainstone or packstone. The coherency increases the density of the tempestite and also increases the friction it asserts on the sea floor.

A tempestite is a function of storm strength, sediment supply and potential energy. Due to these conditions intraclasts and breccia is common among the microfacies features. Storm related sedimentary features include graded packstone and grainstone beds, hummocky cross stratification and tempestite couplets. Skeletal grains are abraded and show signs of transportation. These are forming packstones and wackestones and sometimes even grainstone. This is called textural inversion meaning that the dominant particles have been transported from high energy to low energy environment. Sediments derived from above the FWWB are represented by sediments consisting mainly of lime mud and/or terrigenous mud forming lime mudstone and marls. These are deposited in a protected environment. Much of these sediments have been transported from offshore to middle ramp area due to sub-surface water activity or inland transportation through rivers or aerial deposition. Offshore transported sedimentation is often thicker in the middle ramp setting compared to inland deposits.

1.1.3. The outer ramp

The outer ramp is the shelf area below the SWWB and is dominated by fine-grained sediments associated with a low energy environment (Burchette & Wright 1992; Trappe 1992). It is characterized by allochtonous, autochthonous and by hemipelagic sedimentation. In the outer ramp there is usually little evidence of direct storm reworking in the sediments. However there can be presence of various storm related deposits. Argillaceous limestone with a wackestone texture interbedded with shale or marl is the most common facies in the outer ramp environment. The Mudstone-wackestone can be bioturbated and contain gastropods, bivalves, echinoderms, brachiopods or/and shell debris (Burchette & Wright 1992; Brady & Bowie 2017). Tempestites that are present in the lower middle and outer ramp environment consist of sediment debris commonly associated with shallow ramp environment, such as thin layers of packstones and grainstones (Trappe 1992).

1.2.1 Exposure, erosion and omission surfaces

A discontinuity surface is any sharp change in facies and reflects a break in sedimentation. The importance of them is vital to understand tectonically and regional events as well as eustatic sea-level change. Furthermore they can be used to correlate locally and globally in a sequence stratigraphic context. The documentation and interpretation of discontinuity surfaces relies on both field and petrographic observations following in the following order: geometry, lateral extent, morphology, associated biological activity (e.g. holdfasts and/or borings), mineralization, associated facies and microfacies, early diagenesis and biostratigraphy (Hillgartner 1998). Discontinuity surfaces in carbonate platforms are sometimes difficult to recognize. However they can take the form of erosion (subaerial exposure or submarine dissolution), hardground (omission of sedimentation or early diagenesis).

Erosional surface is characterized by a surface with evidence of a change in hydrodynamic process which resulted in a lag in sedimentation. Subaerial exposure is usually expressed as seams, vugs, zone of collapse breccia and stylo-breccia and karstified horizons and primary structures are destroyed and recrystallized (Hillgartner 1998). Submarine or diagenetic dissolution can together with erosion and reworking processes cause brecciated surface appearance. Limestone sections below the karstified surfaces are more

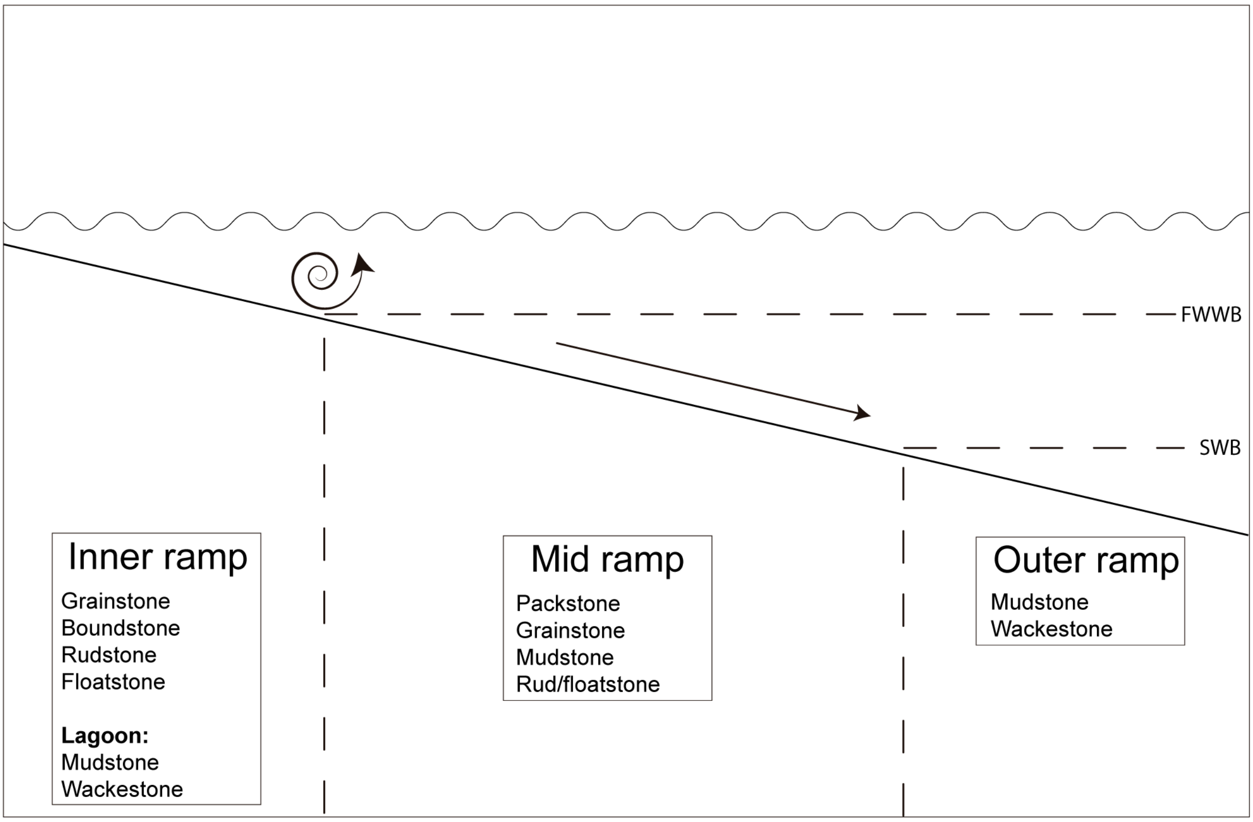

Fig 1. A model depicting a homoclinal carbonate ramp. The ramp is divided into sections. Inner, middle and outer ramp, each with its own typical microfacies associations. These sections are defined by the Fair Weather Wave Base and Storm Wave Base. The inner ramp has a diverse amount of microfacies associations. Grainstone, boundstone, rudstone and floatstone are the most common microfacies associations in this part of a homoclinal carbonate ramp environment. In a lagoon environment mudstone and wackestone are also present. The inner ramp outside the lagoon has turbulent waters and little redeposition and is depicted by the curved arrow in the figure. The midde ramp has the following microfacies associations. Packstone, grainstone, mudstone and rud/floatstone. The arrow within the middle ramp environment simulates inner ramp material transported down slopes and redeposition within the middle ramp. The outer ramp is the least diverse in microfacies composition and generally constituted by mudstone and wackestone.

likely to get in contact with mg-rich water which has initially dissolved the superimposed carbonate section, leading to dolomitization of the rock. Dissolution of unstable calcitic and aragonitic minerals is also able to create pseudomorphs (Brady & Bowie 2017).

Omission surface is characterized by a break in sedimentation that could be due to chemical, anoxic or physical non-presence of terrigenous output of sedimentation. San Miguel et al. (2017) states that low long term accumulation rate with and/or condensed facies regionally wide-spread hardgrounds suggest a suppressed carbonate factory. The lowering of base level and wave base in the subtidal environment can cause long lasting erosion and condensation to the subtidal sediments. They can be exposed to winnowing, sediment starvation and erosion.

Discontinuity surfaces not bound to either omission or erosion surfaces may include changes to texture, sorting, grain size and mineralogy.

2. Geological setting and - stratigraphy

In the Silurian the palaeocontinent Baltica was situated at tropical latitudes, just south of the Equator and a shallow epicontinental sea covered much of the continent (Torsvik 1998). This sea – referred to as the Baltic Basin – covered much of the present-day Nordic countries, the East Baltic area and Ukraine (Baarli 1990). The Baltic Basin is constituted by terrigenous and carbonates rocks, the latter which was particularly dominant during the Silurian.

The Silurian stratigraphy of Gotland have a long scientific history (Hede 1921; Munthe 1927), some sources older than a century. The Silurian strata on Gotland are estimated to be around 500-750 m thick depending on where the measurements are taken (Jeppsson et al. 2007). The strata are the remnants of a series of a carbonate platform that once expanded across the major part of the present day southern Baltic

Sea and northeast to Estonia. The erosional strikes of the strata are southwest-northeast and the dip 0-4 degrees towards the southeast (Hede 1921; Jeppsson et al. 2007).

The oldest strata on Gotland outcrops along the northwestern part of the island, whereas the strata become successively younger towards the southeast (Fig 2). The strata exposed on Gotland range in age from latest Llandovery in the northwest through Ludlow in the southeast and are most recently reviewed by Jeppsson et al. (2006). Ordovician and Cambrian strata occur in the subsurface (Erlström & Persson 2014). The exposed stratigraphy consists largely of limestone and marlstone alternations and reef limestone (Munnecke & Samtleben 1996). Other, less common lithologies, include sandstone and oolite. The composition of lithologies seems also to be related to regional characteristics such as the abundance of shallow water deposits (reef, lagoonal and tidal carbonate facies) is concentrated to the east coast of Gotland. The west coast is however dominated by deeper water carbonate deposition, typically limestone-marl alternations (Munnecke & Samtleben 1996).

2.1 Stratigraphy of the studied interval

The strata of interest for this thesis are the Late Wenlock Halla and Klinteberg formations (Fig 3). The Halla and Klinteberg formations are first detailed by Hede (1927). Based on previous studies the formations have a total thickness of ca 100 m of which the Halla Formation is 28 m thick and the Klinteberg Formation is ca 70 m thick (Hede 1921; Frykman 1989). Beneath the Klinteberg and Halla formations is the Fröjel Formation, constituted by a thin unit rich in fine-grained

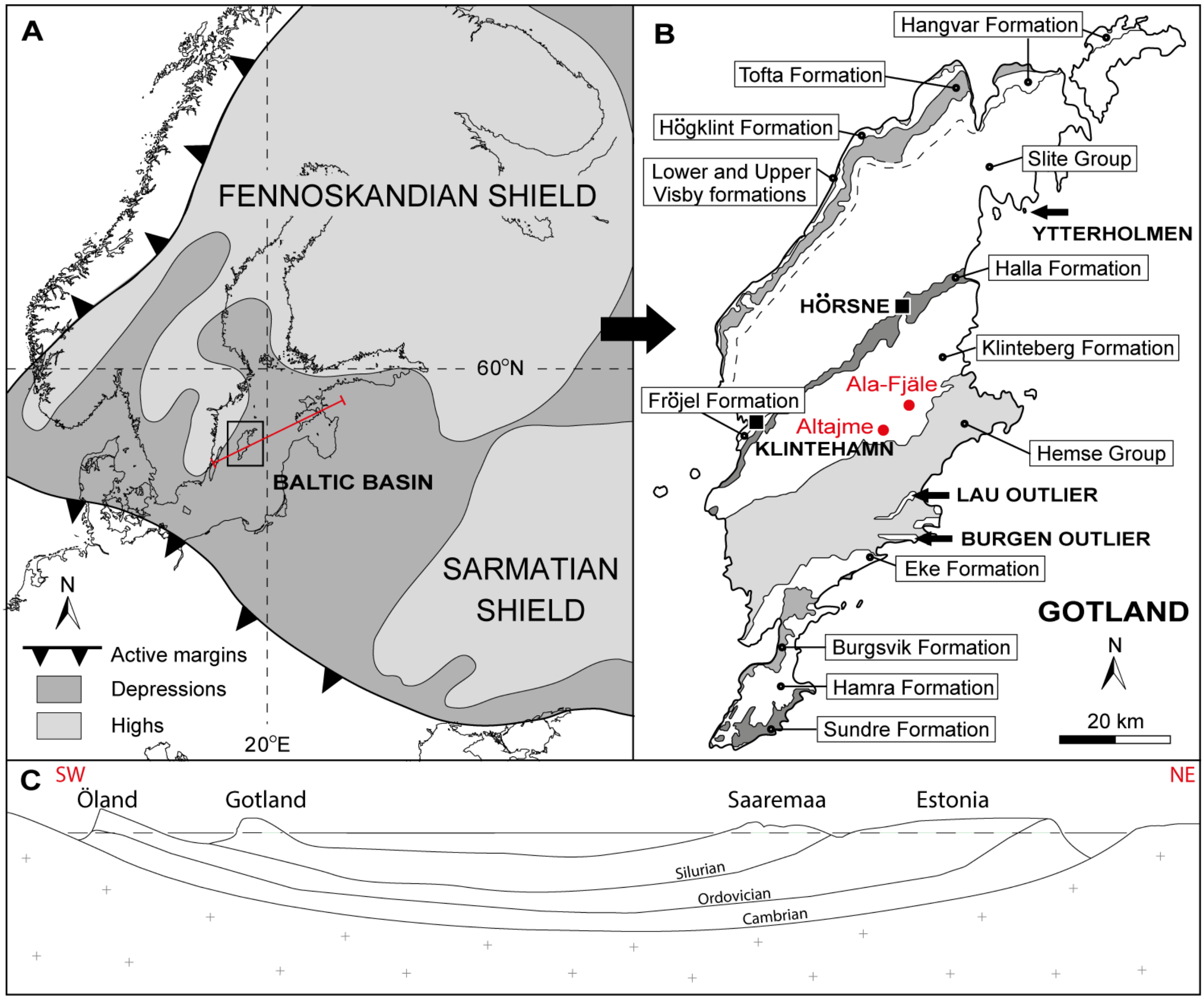

Fig. 2. (A) Paleogeographic map depicting the position of the Baltic Basin, Fennoscandian shield and Sarmatian Shield. The red line represents the cross section on figure C. (B) Map of Gotland highlighting exposed stratigraphies on Gotland including the Fröjel, Halla and Klinteberg formations. The red dots depicts the location of the Altajme and Ala-Fjäle wells. (C) Cross section in the Baltic Basin with bedrock succession from Öland to Estonia (Modified from Calner et al. 2005).

siliciclastic material and has a conspicuous interbedding of mudstone and frequent siltstone tempestites (Calner 1999). In this thesis the Fröjel Formation is of less importance and have not been studied in detail. The Grötlingbo bentonite is situated 1 m above the Fröjel Formation in the Hall Formation and has been used as a marker bed to identify the formation interval. The Fröjel Formation will be described in a greater detail in chapter 4. The bed thicknesses of Halla and Klintberg formations observed by Hede (1921) and Frykman (1989) is different from what is interpreted in the Altajme core as they mainly base their interpretations on outcrop observations.

The Halla Formation in the eastern part of Gotland were deposited on a major erosional unconformity – defined as a rocky shoreline unconformity by Calner & Säll (1999). The formation is subdivided into five members (Calner & Jeppsson 2003). These are the Bara Oolite Member (~10 m), the informal 'Hörsne' and 'Gothemshammar' members, the Mulde brick-clay Member (~30 m) and the Djupvik Member (~10 m). The two latter replaced the name 'Mulde Beds' *sensu* (G. Regnell 1960). The Bara Oolite Member is a clean grainstone blanket deposit that stretch more or less across the entire island constituted by mainly ooids and micro-oncoids. The grains were formed in a high energy depositional environment with frequently interrupted deposition and with large erosional reliefs as indicated by outcrops in the eastern part of its outcrop belt. The 'Hörsne' Member is a unit consisting of biodetrital inter-reef sediments and small bioherms. 'Gothemshammar' member is ten meters thick and is primarily constituted by marl (Munnecke et al. 1997; Calner & Sall 1999; Calner & Jeppsson 2003). The uppermost ca 3 m of the member consists of thin-bedded, extensively bioturbated oncolitic wacke- and packstones arranged as a limestone-marl alternation. Oncoids are several centimeters across and irregular due to periods of stationary growth. Based on facies and stratigraphic relationships, the member is interpreted as representing aggradational back-reef lagoonal environments with local channel deposition. The Mulde brick-clay Member consists of argillaceous wackestones, mudstones and marls with large fragments of brachiopod shells. In some sections 1-2 cm thick packstone beds are common, representing distal tempestites. The Djupvik Member is characterized by its marl and its primary wackestone depositional texture with an influx of skeletal grains, mainly from brachiopods and trilobites. An increased abundance of tempestites also make up for an essential part of the Djupvik Member with the limestone having a blue-grey colour with a nodular to continuous characteristic shape with a thickness of 3-5 cm (Calner & Jeppsson 2003).

The boundary between the Halla and the Klinteberg Formation is characterised by an omission surface and is developed as an abraded hardground on eastern Gotland. The voids of the omission surface are often filled with marl mixed up with well-preserved brachiopods and ostracods (Frykman 1989; Munnecke & Samtleben 1996).

The Klinteberg Formation is named after the hill Klinteberget east of Klintehamn in the western part of Gotland (Hede 1921). In year 1989 the first paper to describe the Klinteberg Formation in detail were published (Frykman 1989). The goal was to study in detail the facies transitions across the Wenlock-Ludlow boundary in the upper Silurian. A larger emphasis was put to the sedimentological features and the Dunham classification scheme was used to subdivide the limestone in different microfacies. Stratigraphic boundaries and microfacies features such as erosional surfaces and dissolution features were also described. In more recent years little has been published about the Klinteberg Formation.

Throughout the Klinteberg Formation there are facies related both to deeper water and shallow-marine environments. Wackestones, packstones, grainstones, bioherms, rudstone and floatstones are common facies that appears in the southwestern exposures of the outcrop belt. The documented north-eastern exposures include floatstone, rudstone, and oolitic limestone. It is challenging to correlate the southwestern to the north-eastern Klinteberg Formation due to the diversity of the northeastern facies ramp associations (Frykman 1989).

The transition from the Klinteberg Formation to the Hemse Group is marked by a microfacies change from float- and rudstone that progressively turn to argillaceous wacke- and packstone (Frykman 1989).

3. Material and methods

This study is based on carbonate microfacies analysis of the Altajme core (Fig 4 - 10). The core was drilled between the 10th and 24th of August 2015 by Riksriggen at the abandoned quarries at Altajme southwest of Buttle (Lat 57°23'4.90"N, Long 18°30'47.12"O). The drilling penetrates the entire Silurian in this area and was terminated in the uppermost Ordovician at a total depth of 330 m. The core diameter is 90 mm in the uppermost nine meters and 63 mm in the reminder of the core. For this study, the uppermost ca 140 m of the core has been investigated (Fig 11) by means of pol-

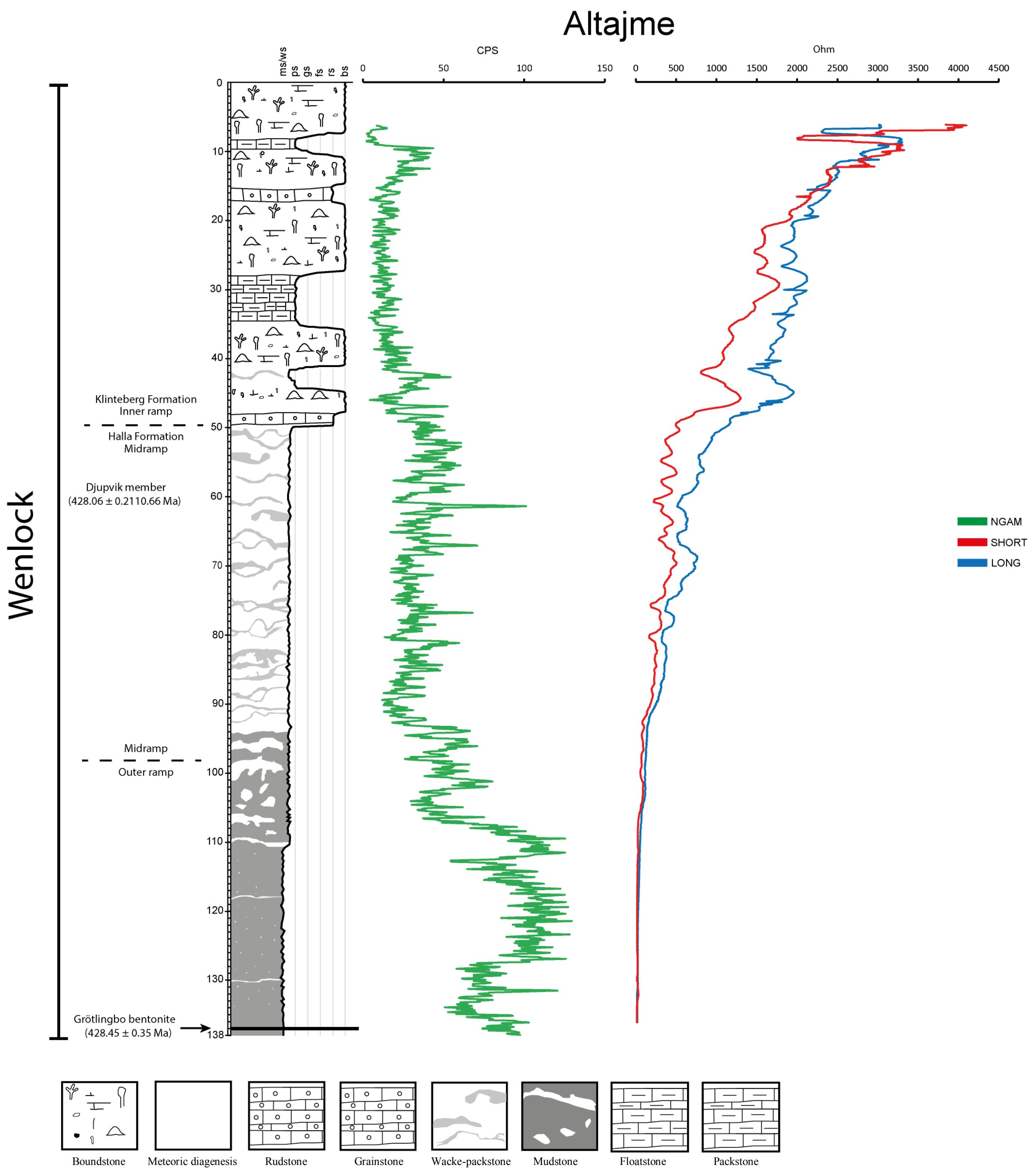

Fig. 3. A generalised core log of the Altajme core with geophysical data from the corresponding well. On the y-axis ages based on high-precision isotope-dilution U-Pb (zircon) dating have been used as a age reference for the upper Halla Formation (Djupvik member) and the Grötlingbo bentonite (Cramer 2012). Interpretation of ramp facies boundries are also present. The gamma ray show an increasing counts per second (cps) with depth as the lithology changes from shallow ramp to deep ramp carbonates. The SHORT/LONG resistivity has a clear seperation with the SHORT resistivity showing lower values to its corresponding LONG resistivity counterpart . The black line low in the core log represents the Grötlingbo Bentonite. A meter below the Grötlingbo Bentonite is the Fröjel Formation.

ished slabs and-, thin sections. In addition, geophysical data from the well has been used to correlate the stratigraphy with that of the nearby Ala-Fjäle well (Fig 2B). The geophysical data acquisition was made during the 9th (Altajme) and the 10th (Ala-Fjäle) of December 2015. The field work was conducted by Per-Gunnar Alm and Johan Kullenberg from Lund University, faculty of engineering and by Christopher Artursson, faculty of geology.

Two tools were used to obtain geophysical data from the Altajme and Ala-Fjäle wells. These were Thermal Conductivity Detectors (TCD), Electronic log (E-log) and an acoustic tele viewer. The former is used to measure the temperature and conductivity in the bore hole. E-log measures the self-potential, single point resistivity and short/long normal resistivity. Natural gamma ray is used in both in the E-log and in TCD tool. The acoustic tele viewer was only used in Ala-Fjäle. Its purpose is to reflect sound waves to obtain density difference along the well hole. It also measures the speed of the reflected soundwave. This can be used to detect joints in the well hole wall. The data collected when these tools transcends down into the well consists of the following: *natural gamma ray*, resistivity/conductivity, single point resistivity and temperature. The natural gamma ray measures the total gamma ray output. The resistivity/conductivity measures the flow of electricity. The single point resistivity measures the total resistance from a single point in the well to surface. The temperature measures the total temperature increase and decrease. In this thesis resistivity and natural gamma ray has been the primary geophysical tools used for investigation.

The TCD, the E-log and the Acoustic tele viewer is connected to the *tension unit*, which is a safety device that has the purpose to warn if the tension changes in the wire while logging. For reason of stability in the wire and the tool it is mounted on a tripod. This gives an indication if the tool is stuck in the well. The tools and the tension unit are also attached to a computer with logging software that is connected to a technical printer and prints the data from the borehole onto paper. These instruments provide the basis of the Altajme core geophysical results.

4. Carbonate sedimentology of the Altajme core

The sedimentology of the uppermost 137 metres of the Altajme core have been studied and documented in a sedimentary profile (Fig. 11). This part of the core section is composed of calcareous mudrock (marl), argillaceous limestone, and limestone. Overall, the lower portion of the core is dominated by marls and argillaceous limestone and only the upper part by limestone and reef limestone. These lithologies, however, show a great variation in grainsize and texture and are best described utilizing the Dunham (1962) classification system. A lithostratigraphic subdivision of the studied core interval is possible due to recognition of a few lithologically distinct units and beds previously described from outcrops in the Klintehamn area. Among these are the Fröjel Formation (Calner 1999) and the Grötlingbo Bentonite (Calner & Jeppsson 2003; Dahlqvist et al. 2012).

As mentioned in chapter in chapter 2.1 the Fröjel Formation is a thin unit rich in fine-grained siliciclastic material and has a conspicuous interbedding of mudstone and frequent siltstone tempestites (Calner 1999). The Fröjel Formation is constituted by the Svarvare and Gannarve members. Especially the Gannarve Member is lithologically conspicuous. It consists of silty limestones, mixed carbonate siliciclastic mud-, silt- and, locally fine sandstones - siliciclastic rocks that otherwise are absent in the Wenlock of Gotland. Wave/current ripples, planar laminations and hummocky cross stratification are common in the upper part of this member (Calner 1999).

The Gannarve Member is identified just beneath -138 m and has therefore not been depicted in the core logg. Another important marker bed in this stratigraphic interval is the Grötlingbo Bentonite (named by Calner & Jeppsson (2003)). This is the thickest bentonite known from the Silurian part of the Baltic basin and was studied in detail by Dahlqvist et al. (2012). This corresponds to the thick bentonite at -137 m in the Altajme core. The thick mudstone and wackestone interval between -137 and -50 m in the core is assigned to the Halla Formation based on similarities with the Mulde Brick- clay and Djupvik members in the outcrop belt and in the Hunninge-1 core (Calner et al. 2006). A provisional boundary between the Halla and Klinteberg formations has been drawn at -50 m depth in the core where coarse grained and reef associated microfacies typical for the Klinteberg Formation become important.

5. Microfacies analysis

Variations in depositional environment are reflected in carbonate microfacies and carbonate microfacies associations. The characteristics of each microfacies description is provided in the sections below. Microfacies analysis has been conducted qualitatively on polished core slabs and in thin sections.

5.1 Core slab description

The core slabs and thin sections have been sampled to depict the most representative microfacies as possible. The core slabs are represented in figures 3-6 and thin sections in figures 7-9.

- *Sample 1 (-134,45 m):* Bioturbated dark grey mudstone. This microfacies is strongly domi-

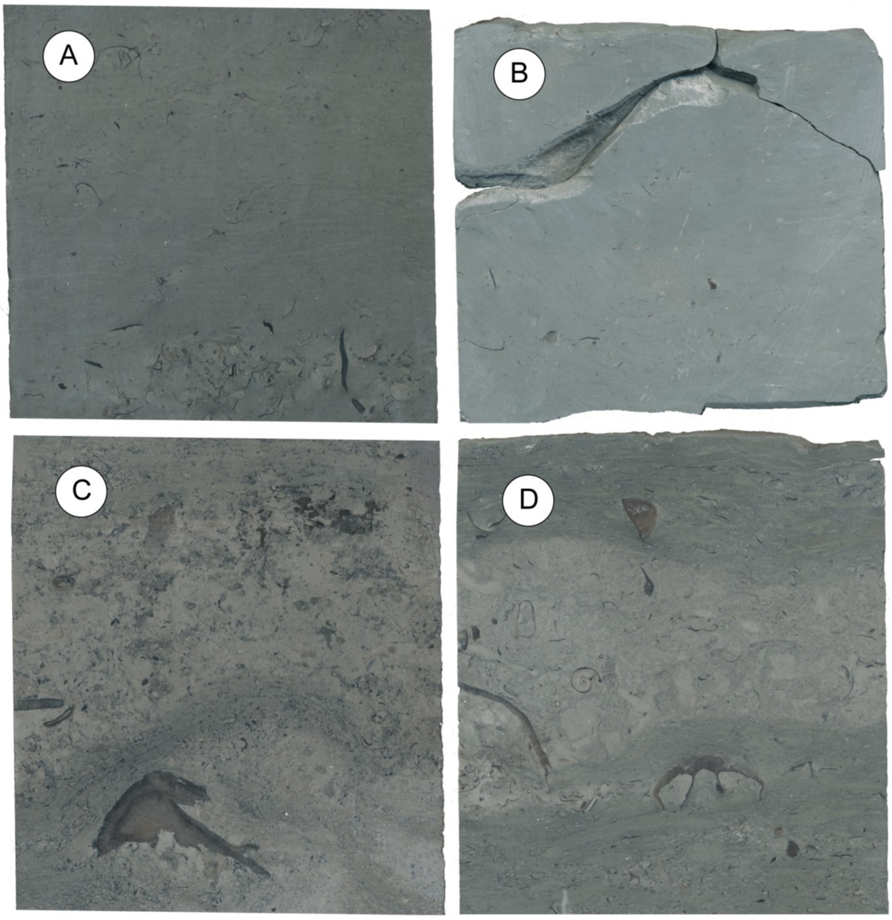

Fig. 4. Core samples from the interval -134.45 m to -96.4 m in the Halla Formation. A. Bioturbated dark mudstone with presence of trilobite and brachiopod bioclasts. The bioturbation is observed as light greyish planar indistinct scours across the sample. The bottom part of the sample has a higher density of bioclasts (sample 1) (core width 63 mm). B. Grey uniform mudstone with few fragments of brachiopods and trilobite bioclasts. The sample has a recrystallised $CaCO_3$ grain in the middle of the sample (sample 2) (core width: 63 mm). C. Intensely bioturbated wackestone (approaching packstone) with numerous identifiable skeletal debris. The top part of the sample consists of marl lamina superimposing a grey micrite layer with abundant of bioclasts also including pyrite inclusions. At the bottom part of the sample a similar marl layer is present superimposing a stromatoporoid bioclast sample (sample 3) (core width: 63 mm). D. Bioturbated wackestone with frequent bioclasts including trilobite, brachiopod and rare gastropods. The top part of the sample shows abundant bioturbation. The traces of bioturbation are wavy to planar. The grey wackestone is as bioturbated as the top marl layer but does not possess its laminar to wavy distribution. Beneath the grey wackestone there is a similar marl layer comparable to the top and contains a stromatoporoid clast. (sample 4) (core width: 63 mm).

nated by fragments of brachiopod shells and trilobite parts (e.g. shepards hook) unevenly distributed across the core slab.

- *Sample 2 (-125,2 m):* Grey mudstone. The microfacies include few fragments from brachiopods and trilobites. Its light colour suggests a higher $CaCO_3$ content as compared to *sample 1*.
- *Sample 3 (-110 m)* Wackestone dominated by strongly fragmented bioclasts from trilobites and brachiopods, and numerous minute unidentifiable skeletal debris (approaching packstone). The sediment is intensely bioturbated. Inclusions of pyrite are present.
- *Sample 4 (-96,4 m)* Wackestone. This core sample show evidence of nodular bedding (limestone-marl alternation), and frequent bio-

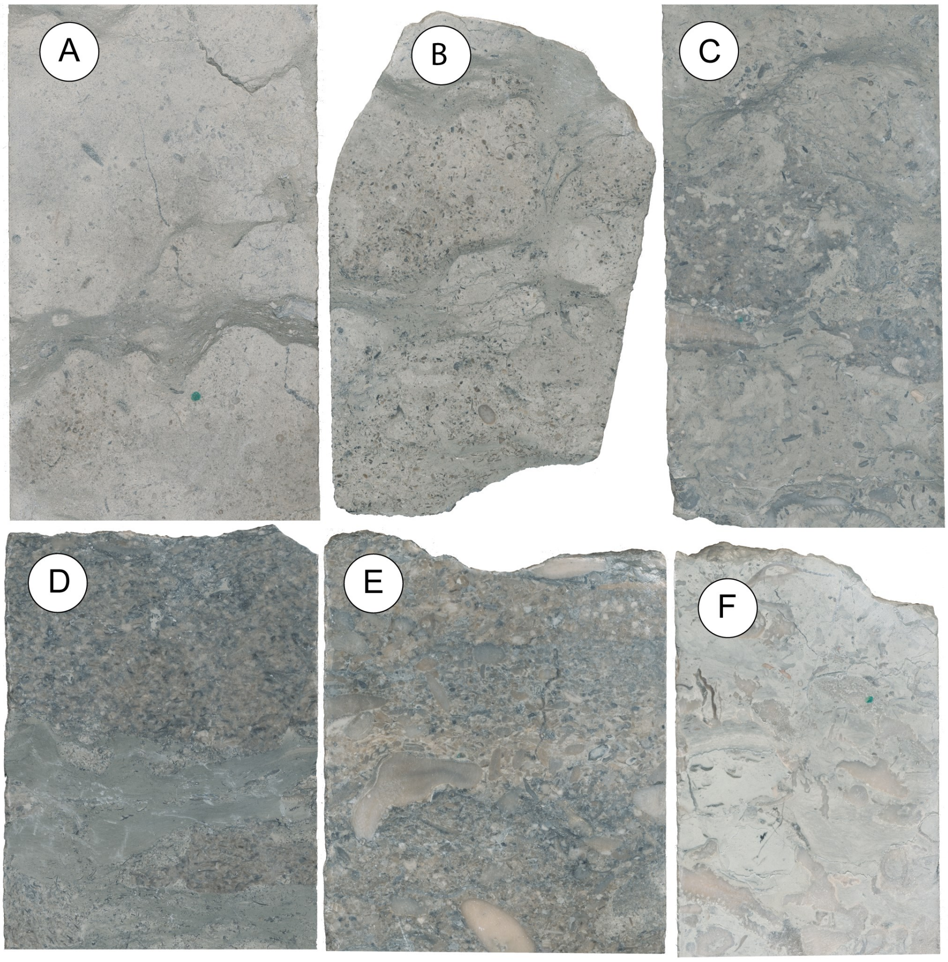

Fig. 5. Core samples from the interval -88 and -36.5 m in the Halla and Klinteberg formations. A. Wackestone- packestone dominated by crinoid fragments and marl seams in between thick layers of micrite (sample 5) (core width: 63 mm). B. Packstone with abundance of crinoids, brachiopods and trilobites. There is a present thick micrite layer in between marl seams (sample 6). C. Crinoidal grainstone alternating with marl seams and brachiopod-trilobite dominated packstone. Present whirls suggests sediment redistrubution through bioturbation (sample 7) (core width: 63 mm). D. Crinoidal grainstone alternating with marl seams and brachiopod-trilobite dominated packstone. Its main feature is its erosional surface seperating the packstone and the marl seams with the grainstone (sample 8) (core width: 63 mm). E. Poorly sorted rudstone consisting of mainly stromatoporids and crinoidal frgments. The sample is denser between the grains at the bottom half of the sample. In the middle there is a present wavy lamina of micrite. The top part has a layer like sequence that is dominated by crinoid bioclasts (sample 9) (core width: 63 mm). F. Reef boundstone with light grey carbonate rich matrix with presence of stromtoporoids, crinoids, brachiopods, bivalves and rare corals. The sample is relative homogeneous with bioclasts distributed evenly across the sample (sample 10) (core width: 63 mm).

turbation. Bioclasts include trilobites, brachiopod shells and rare gastropods.

- *Sample 5 (-88 m)* Wacke-packstone interval with marl seams between the beds. The matrix yields an abundance of minute crinoid fragments. The sample also has inclusions of sub-rounded micrite clasts which distinguishes it from the surrounding micrite matrix by its colour variation. Similar sub-rounded micrite clasts exist also in the marl seams between the wackestone-packstone microfacies.
- *Sample 6 (-78,4 m)* Packstone with thin marl seams. Bioclasts constitute finely fragmented trilobite and brachiopod remains as well as a substantial amount of crinoid remains.
- *Sample 7 (-52,4 m)* Packstone. The sample contains fragments of brachiopods, trilobites (indicated by the presence of shepard hook), abundant crinoid remains and subordinate bryozoans. It also includes a cm-sized coral fragment. As compared to *sample 6* it is more re worked and less sorted.

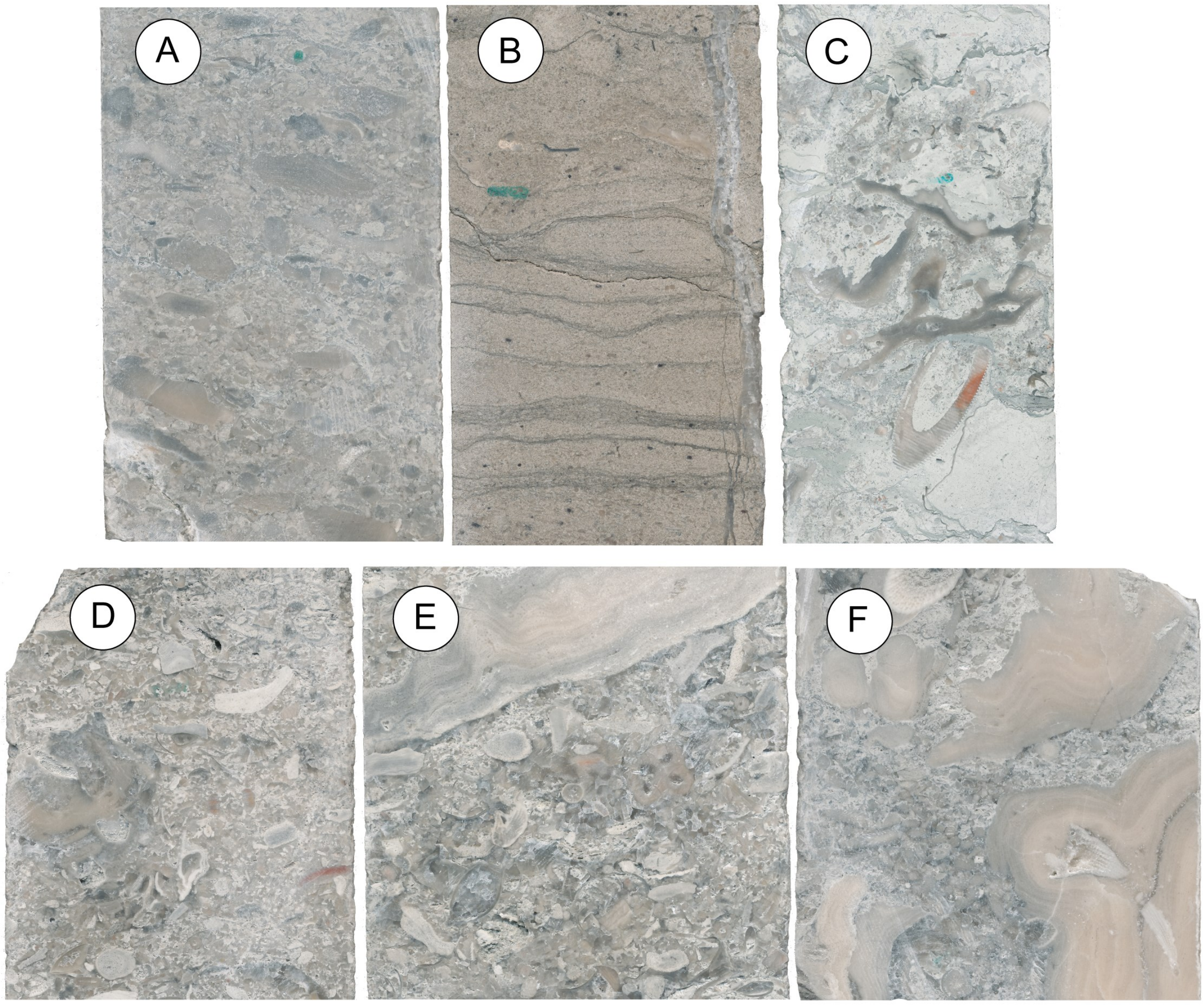

Fig. 6. Core samples from the interval -43 and -14 m in the Klinteberg Formation. A. Rudstone with bryozoans and skeletal clasts. The bioclasts are evenly distributed across the sample (sample 11) (core width: 63 mm). B. fine grained pack-grainstone interlayered with thin marl seams (sample 12) (core width: 63 mm). C. Inhomogeneous floatstone with large bioclasts of stromatoporoids and crinoids and minor bryozoans (sample 13) (core width 63 mm). D. Crinoial stromatoporoidal rudstone. There is precence of minor and major bioclasts with intragranular porosity (sample 14) (core width: 90 mm). E. Rudstone characterised by large stromatoporoid at the top of the sample. There is presence of minor and major bioclasts with intragranular porosity (sample 15) (core width: 90 mm). F. Rudstone charachterised by large stromatoporoid clasts with granular matrix (sample 16) (core width: 90 mm).

- *Sample 8 (-49,9 m)* Crinoidal grainstone alternating with marl seams and brachiopod-trilobite dominated packstone. Other subordinate grans include bryozoans. There is a sharp cut erosional surface at the top that separates the grainstone from the underlying packstone and marl.
- *Sample 9 (-48,9 m)* Rudstone. Poorly sorted in which the larger clasts are mainly stromatoporoids. Crinoidal fragments are also important. Bryozoans could also be identified.
- *Sample 10 (-47,9 m)* Reef boundstone with light grey carbonate rich matrix. The main reef building components include stromatoporoid.
- *Sample 11 (-43 m)* Rudstone. The major clasts are made up by stromatoporoids. Other clasts include bryozoans and skeletal grains.
- *Sample 12 (-33,1 m)* Pack-grainstone; very well sorted and interlayered by thin marl seams.
- *Sample 13 (-28,7 m)* Floatstone with bioclasts of highly variable size, including fragments of stromatoporoids, bryozoans and crinoids. Matrix is light grey and has a wackestone to packstone texture.
- *Sample 14 (-17,4 m)* Moderately sorted crinoidal-stromatoporoidal rudstone with subordinate bryozoans, crinoids, and brachiopods.
- *Sample 15 (-16,8 m)* Rudstone. Identified fossil occurrences include fragments of bryozoans, stromatoporids and brachiopods.
- *Sample 16 (-14 m)* Rudstone. Identified fossil occurrences include fragments of bryozoans, stromatoporids, brachiopods and rare corals.
- *Sample 17 (-7,4 m)* Boundstone and floatstone. Brachiopods and crinoids are present.
- *Sample 18 (-5,9 m)* Boundstone. In the section there is presence of wavy shell parts, infill of larger grains, bryozoans and traces of brachiopod parts.

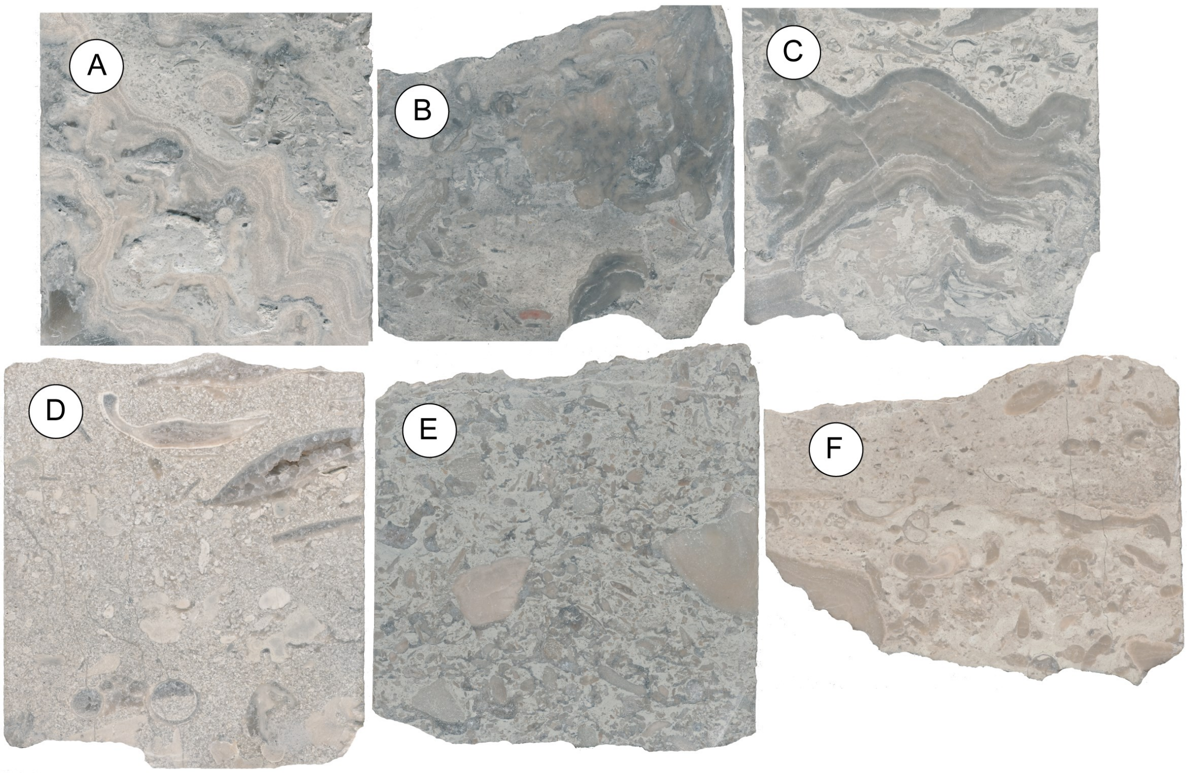

Fig. 7. Core samples from the interval -7.4 and -0.6 m in the Klinteberg Formation. A. Boundstone characterised by its branching stromatoporoids and intergranular porosity with packstone matrix (sample 17) (core width: 90 mm). B. Boundstone charachterised by large strommatoproid clast and packstone matrix (sample 18) (core width: 90 mm). C. Boundstone with packstone matrix. The sample is characterised by a large in situ stromatoporoide clast in the center and the packstone matrix at the top and bottom of the sample (sample 19) (core width 90 mm). D. Poorly sorted grainstone. The sample is charachterised by the dissolved and recrystallised stromatoporoid clasts and its sparry calcite texture. At the bottom of the sample there is a grain with infill indicating in situ infill and lateral deposition (sample 20) (core width 90 mm). E. Rudstone charachterised by its dark grey and packstone like matrix (sample 21) (core width: 90 mm). F. Poorly sorted packstone charachterised by its light brown colour. It also has an erosional surface in the middle of the sample. The top part of the section has smaller bioclasts compared to the bottom half (sample 22) (core width: 90 mm).

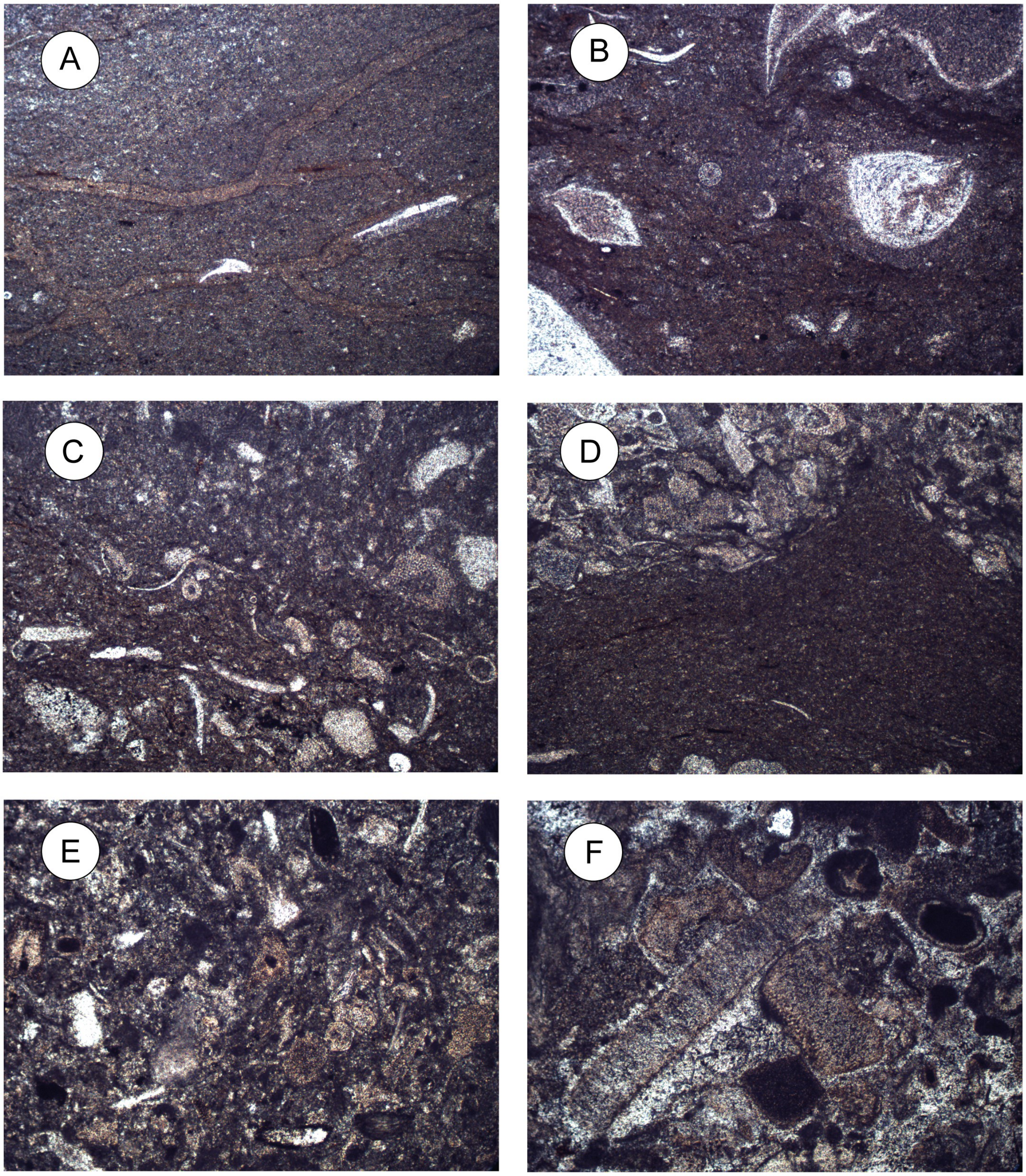

Fig. 8. Thin sections from the interval -132.7 and -50.5 m in the Halla Formation. A. Mudstone characterised by narrow cylindrical traces (thin section is 2 cm) (AC-1-16). B. Mud-wackestone characterised by it brachiopod clasts (thin section is 2 cm) (AC-2-16). C. Wackestone characterised by its poor sortation and diverse bioclasts (thin section is 2 cm) (AC-3-16). D. Dense wackestone characterised by mudstone like lamina at the center of the sample (AC-4-16) (thin section is 2 cm). E. Packstone characterised by its poor sortation and diverse colour of bioclasts (AC-5-16) (thin section is 2 cm). F. Pack-grainstone characterised by its large bioclasts (AC-6-16) (thin section is 2 cm).

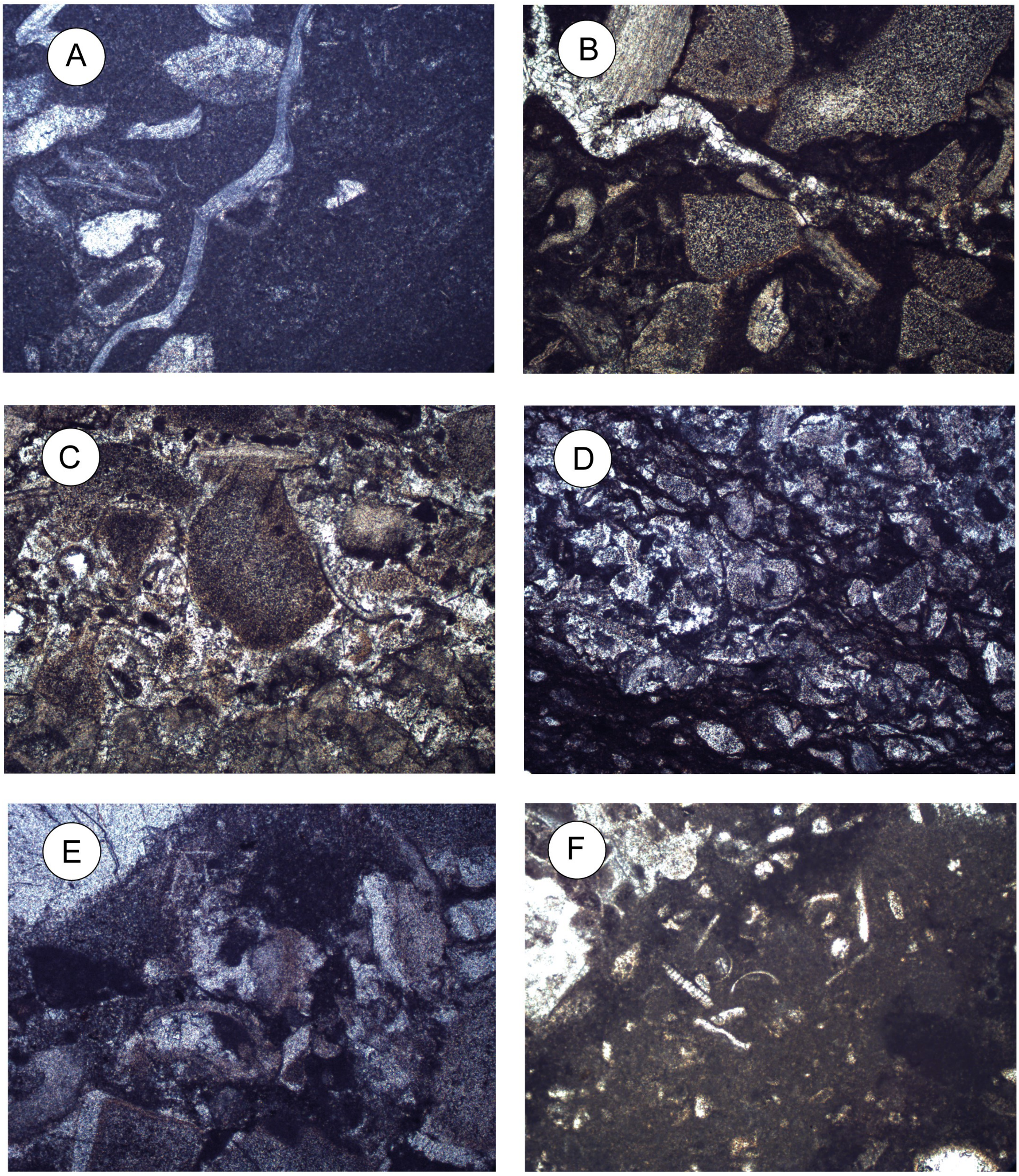

Fig 9. Thin sections from the interval -46.6 and -19.9 m in the Klinteberg Formation. A. Boundstone and abundant of bryozoans in a mudstone matrix. The sample is charachterised by a brachiopod bioclast cutting through it from top to bottom (AC-7-16) (thin section is 2 cm). B. Boundstone in a wackestone matrix charachterised by a dissolution crack from top right to bottom left (AC-8-16) (thin section is 2 cm). C. Criniodal grainstone with a divere set of grain sizes (AC-9-16) (thin section is 2 cm). D. Peloidal crinoidal grainstone. The sample consists of white unsorted bioclasts (AC-10-16) (thin section is 2 cm). E. Crinoidal floatstone with large coral fragments. The sample is charachterised by its poor sorting (AC-11-16) (thin section is 2 cm). F. Crinoidal pack-grainstone . A large part of the sample consists of brachipod bioclasts (AC-12-16) (thin section is 2 cm).

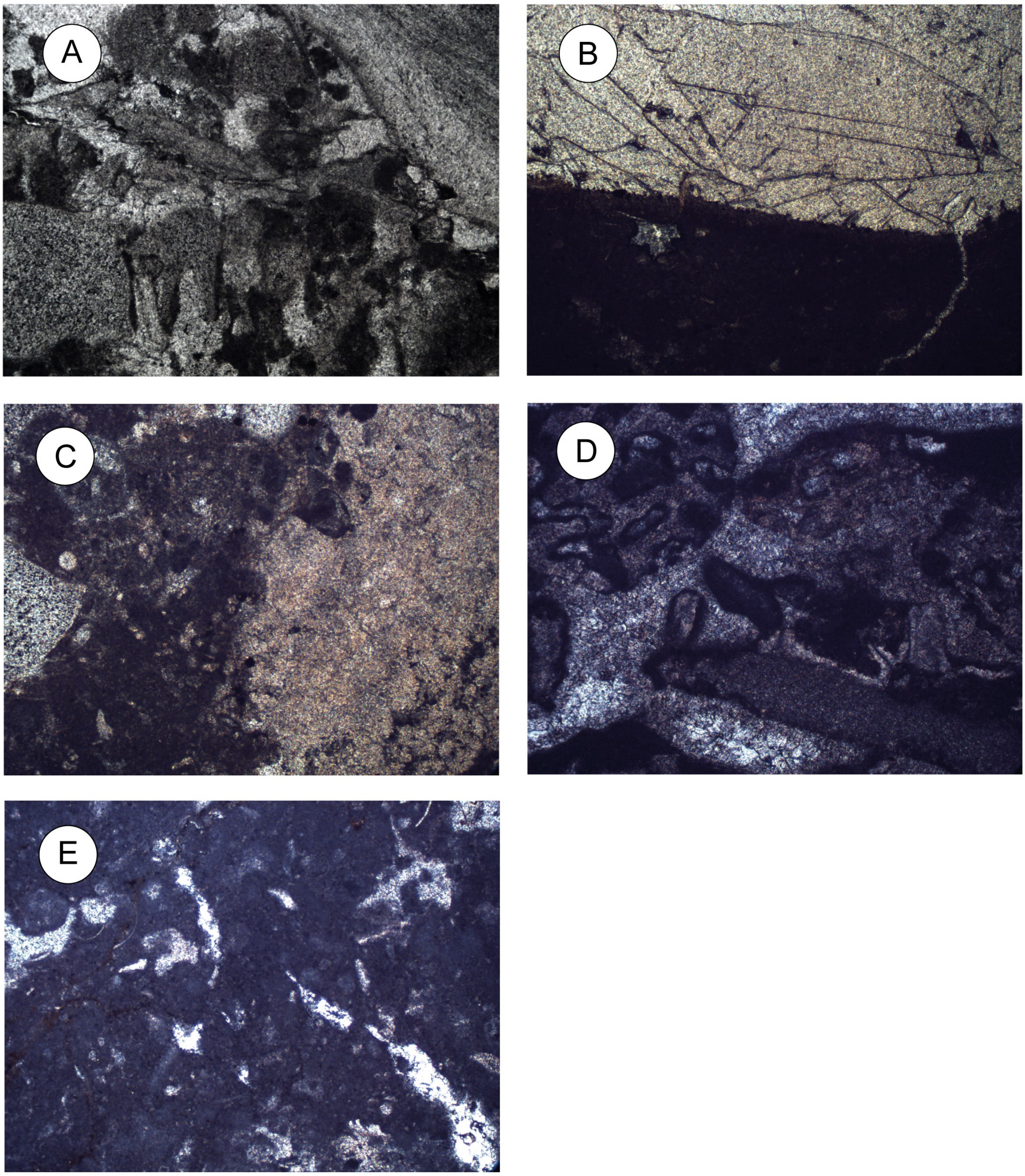

Fig. 10. Thin sections in the interval -12 and -17 m in the Klinteberg Formation. A. Bioclastic rudstone dominated by stromatoporoids (AC-13-16) (thin section is 2 cm). B. Bioclastic floatstone dominated by brachiopods (AC-14-16) (thin section is 2 cm). C. Stromatoporid boundstone with bioclastic floatstone matrix rich in crinoids and bryozoans (AC-15-16) (thin section is 2 cm). D. Crinoidal grainstone-rudstone with coral fragments. (AC-16-16) (thin section is 2 cm) E. Bioclastic floatstone with wackestone matrix. Rich in stromatoporoids and brachiopods (AC-17-16) (thin section is 2 cm).

- *Sample 19 (-4,6 m)* Boundstone with some elements of packstone in between the wavy stromatolite. There is presence of bryozons, brachiopods, cephalopods, minor oolitic grains. Dissolution seams are also present indicating minor pressure solution.
- *Sample 20 (-2,1 m)* Poorly sorted grainstone; some bioclasts are several centimetres in size and filled with large sparite crystals.
- *Sample 21 (-0,9 m)* Rudstone. The sample contains bryozoans and stromatoporoids.
- *Sample 22 (-0,6 m)* Poorly sorted packstone to rudstone dominated by stromatoporoids.

5.2 Thin section description

- *Sample AC-1-16 (-132.7 m)* Dark greenish grey mudstone with delicate and well-defined trace fossils.
- *Sample AC-2-16 (-119.4 m)* Mud-wackestone with abundant articulated brachiopods and subordinate trilobite fragments.
- *Sample AC-3-16 (-107.5 m)* Dense crinoidal wackestone with brachiopod fragments.
- *Sample AC-4-16 (-68.3 m)* Dense wackestone alternating with packstone (and patches of grainstone) with one *in situ* halysites coral. Bioclast includes abundant crinoids and brachiopods. In the lower part of the thin-section is homogeneous wavy-crinkly laminated mudstone.
- *Sample AC-5-16 (-58.3 m)* Crinoidal packstone.
- *Sample AC-6-16 (-50.5 m)* Crinoidal packgrainstone. Long fragment is interpreted as a bivalve.
- *Sample AC-7-16 (-46.6 m)* Boundstone with corals and abundant bryozoans in a mudstone matrix.
- *Sample AC-8-16 (-39.3 m)* Boundstone with wackestone matrix.
- *Sample AC-9-16 (-38 m)* Crinoidal grainstone with subordinate bryozoan, brachiopod and trilobite bioclasts, frequent fecal peloids, and a large quantity of bioclastic gravel. Few dissolution seams with enriched clay occur.
- *Sample AC-10-16 (-36.5 m)* Peloidal crinoidal grainstone with abundant brachiopod fragments and subordinate ostracods.
- *Sample AC-11-16 (-30.5 m)* Poorly sorted crinoidal floatstone with large coral fragment.
- *Sample AC-12-16 (-19.9 m)* Poorly sorted crinoidal pack-grainstone with large brachiopod fragments.
- *Sample AC-13-16 (-12 m)* Bioclastic rudstone dominated by stromatoporoids (AC-13-16).
- *Sample AC-14-16 (-10.1 m)* Bioclastic floatstone dominated by brachiopods.
- *Sample AC-15-16 (-8.1 m)* Stromatoporid boundstone with bioclastic floatstone matrix rich in crinoids and bryozoans.
- *Sample AC-16-16 (-1 m)* Crinoidal grainstone -rudstone with coral fragments.
- *Sample AC-17-16 (-0,3 m)* Bioclastic floatstone with wackestone matrix. Rich in stromatoporoids and brachiopods.

6. Geophysical wireline logging in the Altajme and Ala-Fjäle wells

The wireline logging conducted at the Altajme and Ala-Fjäle wells make it possible to characterize the Halla and Klinteberg formations from a geophysical perspective. The data obtained was reviewed at the method section and include natural gamma ray, temperature, resistivity, conductivity and single point potential. The natural gamma ray is the total radioactivity from all sources emitted from the sides of the well hole. As the TCD or E-log transcends downwards the responses of the signals for the radioactivity will vary. This is a function of the deposited sediments within selected intervals that contains uranium, thorium or potassium but also could answer to heavy radioactive elements such as zircon and apatite. Matrix-dominated microfacies such as mudstone and wackestone have a tendency to include some or all of these elements in the detrital clay. They will hence emit a higher signal than other deposited microfacies containing less or no clay, such as packstone and grainstone (Fig 12).

Potassium and thorium are usually associated with the original sedimentary burial while the uranium is more associated to diagenesis. In presence of a significant amount of uranium it is therefore possible to mask the original depositional natural gamma ray values. This can in turn lead to misinterpretation of lithology (Lucia 2007). Usually this can be solved through having spectral gamma ray data that can distinguish radioactive elements from one another. This has not been used in the assessment of the Altajme and Ala-Fjäle wells. The natural gamma ray should for this reason be treated with caution when interpreting lithological composition. One of the main elements in certain bentonites is potassium which causes abnormal spikes in the gamma ray log, with API values reaching

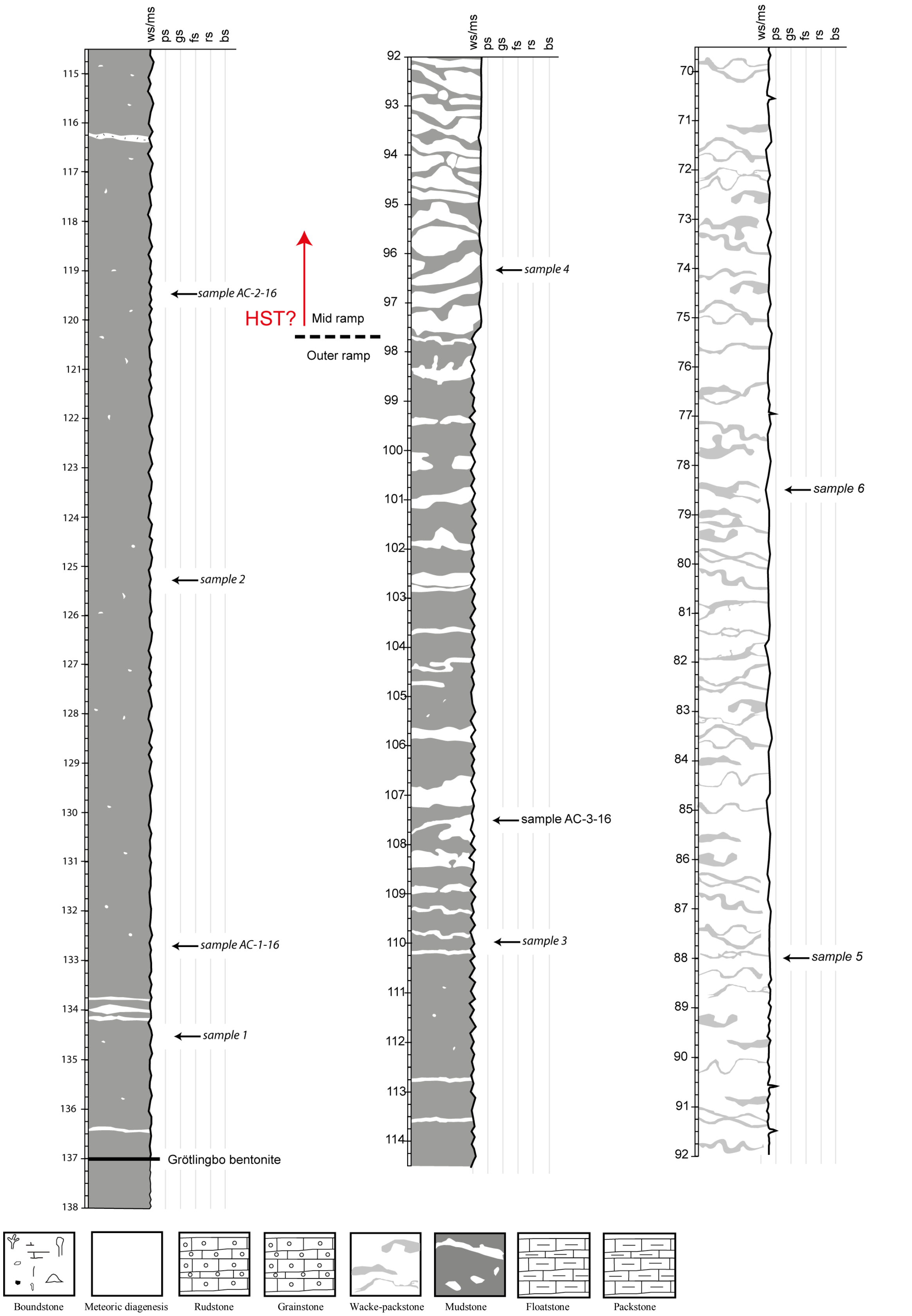

Fig. 11. (A) A high-resolution core log showing the interval between -137 m to -70.5 m of the Altajme core. The interval is showing a general shallowing upward of depositional facies from mud-wackestone to wacke-packstone. The core slab samples are marked as "sample X" while the thin section samples are marked as "AC-X-16". The interpreted boundary between the outer and middle ramp environments is also highlighted. The abbrevation TST stands for Transgressive systems tract and HST for Highstand systems tract (p. 28).

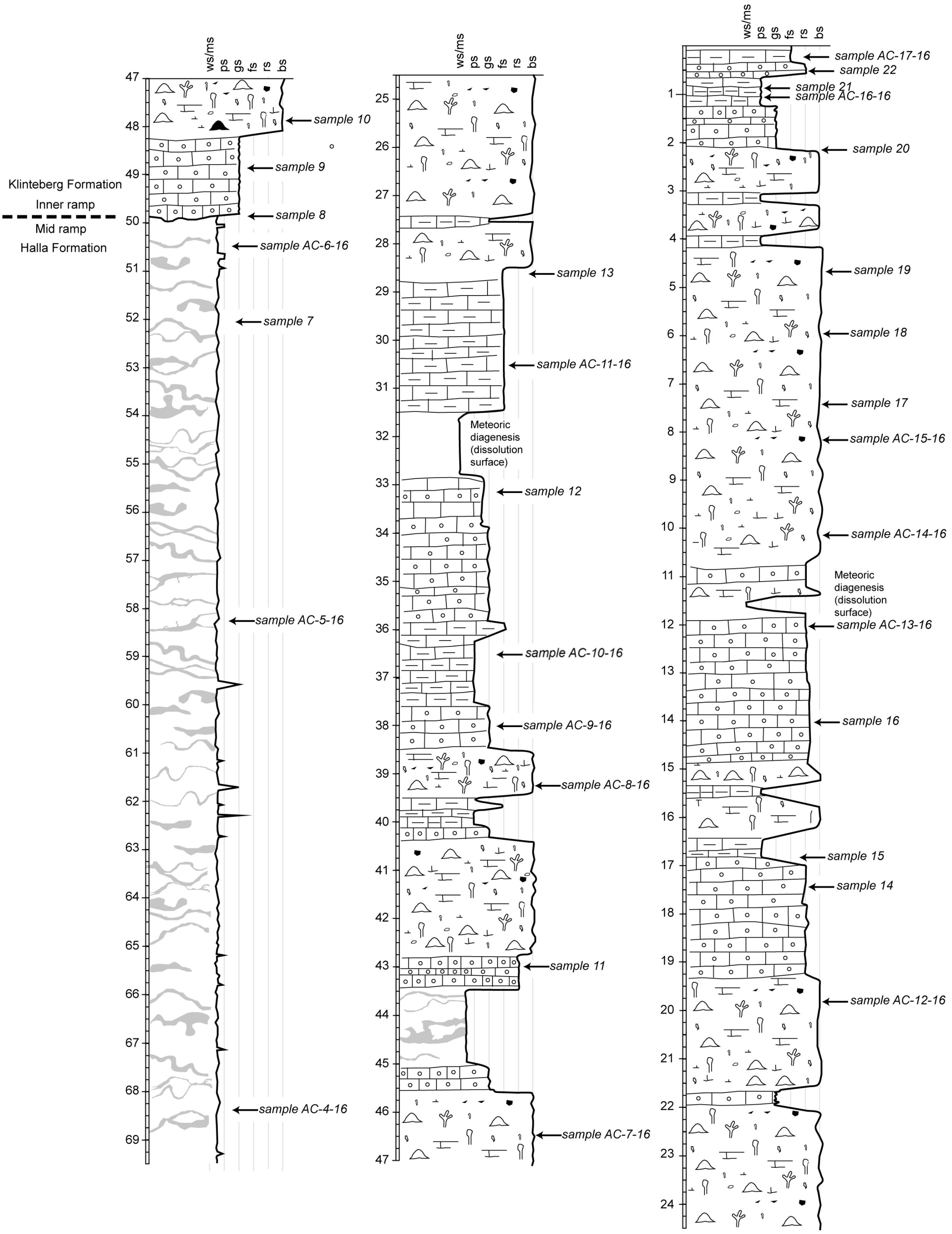

Fig. 11. (B) A high-resolution core log showing observed -69.5 to 0 m of the Altajme core interval. The interval is showing a general shallowing upward from wacke-packestone to boundstone, rudstone and floatstone. The core slab samples are marked as "sample X" while the thin section samples are marked as "AC-X-16". The interpreted boundary between the middle ramp Halla Formation and inner ramp Klinteberg Formation is also highlighted.

up to 120 API (Catuneanu et al. 1999). Bentonite is for this reason a great tool to use as a stratigraphic marker to depth correlate stratigraphic sequences.

Electrical properties are also important and can mainly be used to identify lithological trends. An increased electrical conductivity of sediments is a result from the amount of ions in the mineralogical content as well as in the water in the pore system (Lu et al. 1990). A higher resistivity relates to disconnected pore system or less water content, but it also have a strong anti-correlation with the cation exchange capacity (CEC). Usually lithologies with a strong negatively charged ion are able to hold more positive ions. For instance, bentonite which is a swelling clay has a high CEC and is easily able to absorb water molecules. A high CEC means less resistance for electricity to flow through an object which can be detected on the LONG/SHORT resistivity log (Kaufhold et al. 2015). The long and short resistivity reacts differently depending on the heterogeneity and homogeneity of the well hole wall. If the well hole wall is homogeneous, meaning the formation has similar resistive attributes next to the tool and further in the formation, the LONG/SHORT resistivity won't separate and will have similar values. If the formation is heterogeneous LONG/SHORT resistivity will separate reflecting difference in resistivity.

7. Microfacies associations, resistivity and gamma ray

The microfacies described above can be summarised in a few *microfacies associations* that relate to distinct depositional processes that in turn reflect different parts of the carbonate ramp system.

7.1 Mudstone-Wackestone Microfacies Association (137-92 m)

This is an interval with strong dominance of mudstone -wackestone microfacies between -137 and -92 m in the core (*samples 1-4*). It consists of a limestone-marl alternation that is dark in colour and sporadically grey. It is mainly composed by alternating mudstone and wackestone with occasional occurrence of packstone beds in the upper part of the section. There are no major shell-lags or tempestites present in this section. It is bioturbated with barely visible traces, shafts and tunnels. The section has an abundance of brachiopods and trilobites with sporadic presence of gastropods and minute skeletal debris. A well preserved trilobite of the *Dalmanitidae* family (P. Ahlberg, pers. comm. 2017), with a missing cephalon, is present within this interval.

The mudstone-wackestone microfacies association has a higher average natural gamma ray signal compared to other microfacies associations of the core. The microfacies association has usual value range from 90-125 counts per second (cps). The successive increase in limestone to marl ratio between ca 111 and 92 m lowers these cps values to around 50-65. The resistivity in this section microfacies association is around 10-30 ohm which represents the lowest value throughout the core interval.

7.2 Wackestone-Packstone Microfacies Association (95 - 50 m)

Between 95-50 m the core consists of alternating wacke-packstone (*samples 5-8*). It is grey and bluish in its colour with interbedded dark marl seams. Tempestites, 2-10 cm thick, are present as grainstone and packstone beds. The section is bioturbated with poorly sorted bioclasts. Bioclast content include fragmented crinoids, trilobites, brachiopods and to a lesser extent bryozoans and coral fragments.

The first indication of a change in gamma ray occurs at ~90 m core depth. The gamma ray decreases gradually as the microfacies shifts from mud-wackestone to wacke-packstone.

The bottom part of the wacke-packstone interval has a higher gamma ray compared to the reminder of the facies association due to an upward gradual shift of decreasing marl content. The gamma ray in this part of the core fluctuates between 30-80 cps. The gamma ray interval then decreases to 20-70 cps for the reminder of the microfacies association.

The LONG/SHORT resistivity within this interval decreases from the initial 10-30 ohm range and splits where the LONG resistivity is below 1000 ohm and the SHORT resistivity below 500 ohm.

7.3 Boundstone Microfacies Association (48,25 - 45,5, 42,75 - 40,25, 28,5 - 22, 22,75 - 19,25, 10,75 - 4,25, 3 - 2,25 m)

The boundstone microfacies association is abundant in the top 50 m of the core. It is characterised by stromatoporoids, covering large or whole parts of the core section. Alternatively the stromatoporoids branches out in planar, crinkly and/or irregular laminations. The colours in the sections vary. The reef boundstone has an abundance of micritic matrix and has a white colour with light brown stromatoporoids (*sample 10*). The stromatoporoid are in other parts blueish and dark in colour (*sample 17-19*).

Within this part of the core the gamma ray cps is the lowest, the gamma ray interval here is between 5 -40 cps. The resistivity measurement throughout this carbonate-rich microfacies association (including boundstone, floatstone, rudstone and grainstone) has the most contrast in resistivity. The highest contrasts in resistivity happen at 46,38 m of depth with a difference of 697,61 ohm between the LONG/SHORT resistivity.

7.4 Rudstone Microfacies Association (43,50 - 42,75, 19-17, 15-12 m)

The rudstone microfacies association is present at 43, 50-42,75, 19-17 and between 15-12 m. The colour is a mix between dark grey, white and grey. It is reworked with no traces of bioturbation. Within the rudstone interval the bioclasts consists of crinoids, bryozoans, stromatoporoids, bryozoans, skeletal grains and corals. The rudstone microfacies association is diverse depending on bioclast content best observed in *sample 11, 14, 15* and *16*.

7.5 Floatstone Microfacies Association (31,5-28,5 m)

The floatstone microfacies association is present between the interval 28,5-31,5 m. The colour is dominated by white wackestone-packstone micrite matrix and decimetre-sized bioclasts. The bioclast content include fragments of stromatoporoids, bryozoans and crinoids. Samples of the floatstone microfacies association include *sample 13*.

7.6 Grainstone Microfacies Association (49,75-48,2, 35,75-34,75)

The Grainstone microfacies association is present within the intervals 48,25 - 49,75 and 34,75 - 35,75 m. The lowermost interval (48,25 - 49,75 m) constituted by dark crinoidal grainstone. The grainstone microfacies association includes *sample 8*.

8. Microfacies associations and depositional environment

The core slabs and thin sections have been studied and grouped in microfacies associations based primarily on the sediment composition of each sample. *Samples 1-4* consist of mudstone to mud-wackestone microfacies. The bioclast content within the samples contains brachiopods, skeletal debris and stromatoporoids. The thin sections covering the same interval; e.g. *sample AC-1-16* and *sample AC-2-16,* include brachiopods. From the lithology and bioclast composition these samples have been interpreted to be a part of the outer ramp facies association below the SWB. According to Flügel (2010) bioclasts such as brachiopods, trilobites and echinoderms are commonly present in the outer ramp environment during the Silurian. An abundance of mud-wackestone microfacies are also typical of distal ramp environments (Flügel 2010).

Samples 4-8 consist primarily of mud-wackestone microfacies. Other lithologies within this section contain tempestite pack and grainstone. The bioclast contents in the sections are diverse and consist of stromatoporoids, brachiopods, trilobites, bryozoans and skeletal debris. The thin sections samples *AC-4-16* to *AC-6-16,* representing the same similar interval, contain the following bioclasts: bivalves, brachiopods, stromatoporoids and crinoids. From a lithological and bioclast composition these samples have been interpreted to be a part of the middle ramp facies association. The shift from mudstone-wackestone facies association to the wackestone-packstone microfacies association at -111 m, and the increased presence of tempestites above this level, is interpreted as the beginning of the middle ramp facies association. Within this interval 2-5 cm thick beds of packstone and grainstone tempestites occur. The grainstone tempestites start to occur at a lesser depth in the core than the packstone tempestites. The grainstone tempestites are also less frequent in occurrence compared to its packstone counterpart. The first packstone occurs at -90, 5 m and packstone beds then continue to occur infrequently until -50 m of depth. In the entire 0-137 m thick core section there are only two clear visible grainstone tempestites; the first at a depth of -61,75 m and the second at -59,5 m depth.

Sample 9-22 consist of a varied mix of microfacies associations. These include mudstone, mud-wackestone, wackestone, grainstone, rudstone, boundstone and crystalline microfacies. Bioclast contents within this interval include the following: bryozoans, trilobites, skeletal debris, crinoids, stromatoporoids and brachiopods. Thin section samples *AC-7-16* to *AC -16-16* covering a similar interval contain brachiopods, bivalves and stromatoporoids. The increase in shallow-water microfacies associations, such as boundstone, rudstone and crystalline microfacies is interpreted as the inner ramp microfacies association.

9. Exposure, erosion and omission surfaces

In the outer ramp setting of the Altajme core there are no interpreted erosional or omission surfaces. This suggests a stable carbonate factory with little interruption in sedimentation. Above it in the middle ramp setting, local erosion surfaces are present as a consequence of eroding tempestites. The tempestites contain proximal microfacies such as packstone and grainstone, derived from the upper middle and inner ramp settings. Perhaps the most important erosional surface (because of the change from Halla to the Klinteberg Formation) is found at the facies shift from middle to inner ramp setting at -50 m (*sample 8*). Frykman (1989) interpreted this boundary as an omission surface. In the Altajme core I interpret this boundary as an erosion surface due to the absence of a hardground and biological activity, but also bottom mineralization such as glauconite and pyrite. Another minor erosional surface in the inner ramp is seen in *sample 22*. The interpretation of this sample is based on the sharp erosional cut through bioclasts. Omission surfaces in the middle ramp are absent. In the inner ramp setting the omission and erosional surfaces are scarce but evidence for exposure to meteoric dissolution occurs at -31.75 - 32.75 m and at -11,5 m and -22,5 m. These intervals are characterized by recrystallized 0-5 cm wide grains with low porosity in between them.

10. Discussion

The first 137 m of the Altajme core contain a shallowing upward sequence (Fig 13). The bottom is dominated by outer ramp mud-wackestone progressively shifting to middle ramp wacke-packestone. Then there is a sharp shift towards inner ramp microfacies such as reef- associated grain-, float-, rud- and boundstone. The geophysical data from the Altajme well supports the lithological observation of a shallowing upward sequence with higher gamma ray signal at the bottom and lower gamma ray signal on the top (Fig 3).

Dunham (1962) classification have been used together with general core description to divide them into different depositional environments (Fig 12).

10.1 Relative sea-level and sequence stratigraphy

Microfacies associations and facies associations are directly related to sequence stratigraphy. Sequence stratigraphy is a stratigraphic method to describe a basin fill in terms of relative sea level changes. The shoreline could either be prograding (shallowing upward), retrograding (deepening upward) or aggrading (no temporal change in depositional facies). The package of facies deposited during one relative sea-level cycle is named *sequence* or *depositional sequence* and is bounded below and above by sequence boundaries, representing major unconformities. A sequence is subdivided in four *systems tracts*, each reflecting a specific part of the relative sea-level cycle. These are the falling stage (FSST), lowstand (LST), transgressive (TST) and highstand systems tracts (HST). The reef facies associations are normally associated to TST and HST where the water conditions allow vertical growth of reef ecosystem. Sequence boundaries and especially the maximum flooding surface at the top of the TST can represent an important break in sedimentation (Hillgartner 1998). The FSST and LST are associated to non-deposition, erosion and dissolution. Following subsections describes each of the system tracts in detail.

10.2 Falling stage systems tract (FSST)

Sedimentary successions related to a falling stage systems tract are uncommon in carbonate basins. The reason is its erosive nature where exposure to aerial physical and/or chemical forces leaves little remains to deposit a stratigraphical interval.

10.3 Lowstand systems tract (LST)

During an LST the setting is characterised by a proximal emerged facies belt where non depositional of continental sediments prevailed. It is separated by a facies belt restricted environment characterised by peritidal, lagoonal or brackish conditions. Behind this facies area there is an open-marine low energy facies belt separating the inner from the middle ramp area. Common microfacies types during this interval are typically grainstones with terrigenous quartz associated with sandstones and claystones, fenestral mudstones and quartz bearing dolomites of peritidal carbonates, mudstones to wackestones with abundant foraminifera of protected inner ramp environments and wackestone to packstones with brackish water ostracods. In a lowstand karstification is where acidic charged water has dissolved carbonate.

$$acidic\ water + H_2CO_3 \rightarrow H^+ + HCO_3^-$$

The karstification is a function of availability of water CO_2 and right temperature condition for optimal effi-

Microfacies	Description	Interpretation	Common Facies association	CPS counts per second
Mud-Wackstone	Uniform dark mud matrix with few to absent bioclasts	Outer ramp	Deep water environment	~26-125
Wack-Packstone	White micrite Matrix together with mixed amount of bioclasts.	Mid ramp/ Inner ramp	Off-reef environment	~12-60
Grainstone	Dark colored bioclast supported	Mid ramp/ Inner ramp		~19-25
Rud/floatstone	Dark to light colored matrix with Large unbounded stromatoporoides	Inner ramp	Reef environment	~19-25
Boundstone	Abundance of stromatoporoides with white to blueish matrix	Inner ramp		~19-25

Fig. 12. Table showcasing carbonate microfacies based on Dunham (1962) to its corresponding description in the Altajme core. The table also includes related ramp interpretation, facies association and gamma ray CPS.

ciency. The acidic water is usually derived from rain but also from soil derived gases. These events lead to collapse of sinkholes and irregularities associated to a karst system. The water acidic water travels a distance and leaks into the matrix or spills into open joints, fractures, vugs or other conduits. Once base level rises these holes created by acidic water can later be filled with bioclastic, oolitic and intraclastic grainstones and other facies types associated with a transgressive system (Handford & Loucks 1993; Flügel 2010).

In an arid system however the availability to acidic charged rain water is much less and as such the evidence of karstification is more difficult to identify this could depend on the following factors. The length of exposure may have been too brief for fractures to form, surface-formed karst and associated caliche features on arid climate have been diminished of proof by erosive force, or high intergranular porosity and permeabilities have hindered formation of conventional karst (Handford & Loucks 1993).

10.4 Transgressive systems tract (TST)

The transgressive systems tract is the area of which encompasses those deposits between the transgressive surface and maximum flooding surface. A subtidal typical transgressive cycle has the duration of between 20-200 ka and the accumulation rates of stratigraphic sections is between 0,01-0,2 m/ka (Osleger 1991). In the transgressive systems tract the transition from a lowstand systems tract changes the condition of the hydraulic regime with an increase in sea level and thus affects the sedimentation. Edges are quickly established during sea level rise and rims usually formed thicker accumulation compared to adjacent lagoons and shelves (Handford & Loucks 1993). During the transgressive phase the change in base level across the shallow ramp provides difference in hydraulic regimes which gives two facies belts. Microfacies formed during these high energy regimes includes various bioclastic, oolitic and some intraclastic grainstones, dominated with bioclastic and intraclastic packstones, bioclastic floatstones, bioclastic floatstones and organic crusts, and oolitic and oncolytic packstones. Microfa-

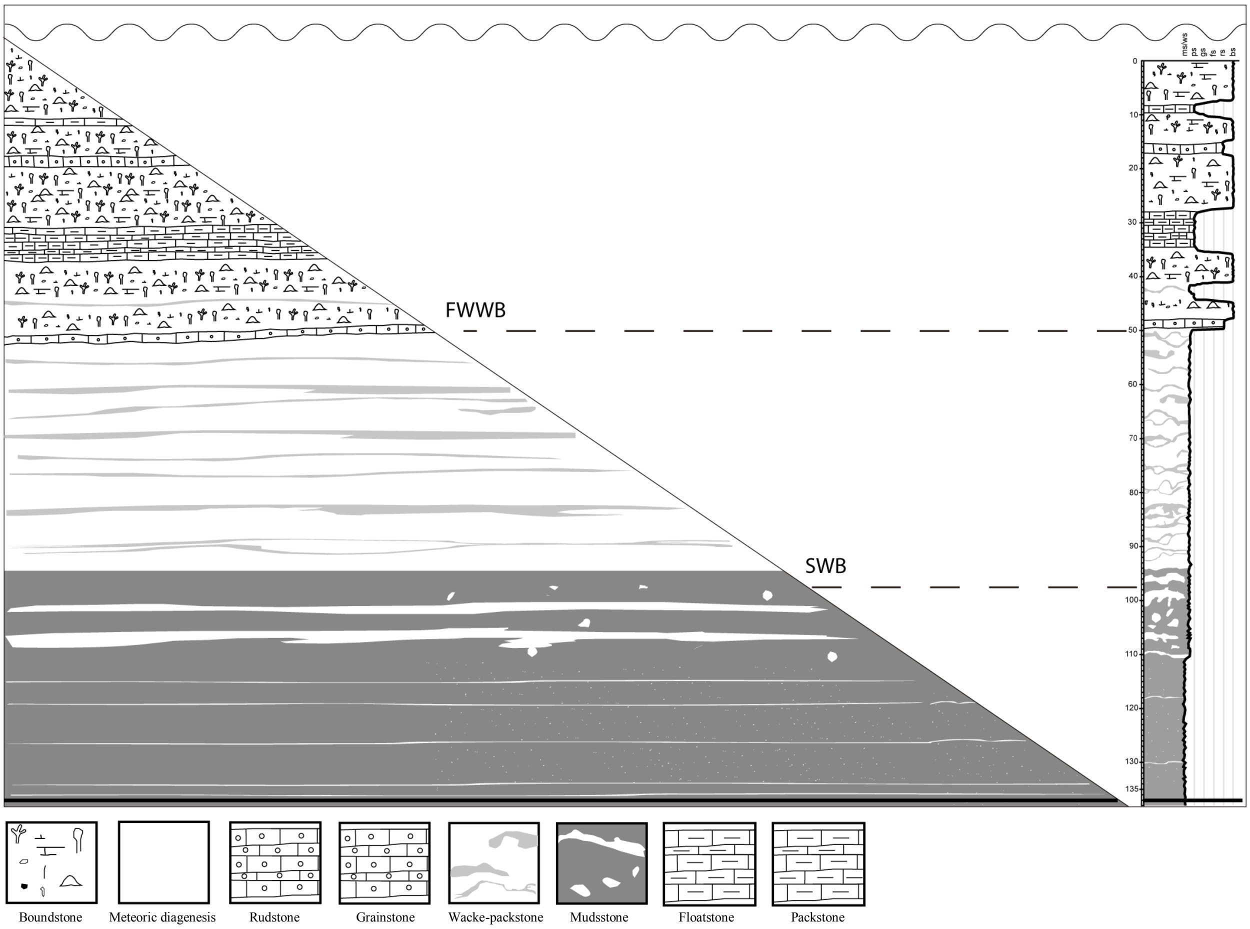

Fig. 13. Picture showing the Altajme core together with a model of a homoclinal carbonate ramp. The picture also shows the approximate interpreted boundary of the Fair Weater Wave Base and the Storm Wave Base. The black line in the core log represents the Grötlingbo Bentonite.

cies formed during low energy conditions (protected inner ramp) include bioclastic wackestones and packstones (Handford & Loucks 1993).

10.5 Highstand systems tract (HST)

Highstand systems tract is characterized by major changes in the distribution of microfacies and is also the facies where sediment production is at its peak. It is dependent on accommodation space and on local water conditions for maximum carbonate generation to occur. The aggradation and progradation takes place as *in situ* carbonate sediment generation accumulate. The shallowing in these sediment systems usually depend on the aggradation of the sea floor and progradations islands, shoals and build ups. The progradation rate is usually dependent on water depth, bathymetry, depositional processes, sediment production, tectonically controlled subsidence and accumulation rates. The high carbonate productivity means that the high stand systems tract has an abundance of microfacies diversity. Common microfacies types in these systems is diverse and range from grainstone, packstone, bioclastic floatstone, peloidal and bioclastic wackestone and packstones (Handford & Loucks 1993; Flügel 2010).

10.6 Local geophysical correlation between Altajme and Ala-fjäle

The Altajme core was drilled on a height of ~60 m above the sea level whereas Ala-Fjäle starts at ~30 m above the sea level. The geophysical survey of the Altajme core shows that the natural gamma ray increases with the depth of the core. The log motif of the gamma ray signal resembles a fining up bell shaped format notably starting at -13 m depth and ends at -128 m depth. The upper tens of meters are dominated by grainstone and boundstone (-48.5-0 m). The lower half, which is emitting a clear higher gamma signal, is dominated by mud-wackestone-packstone (-137-48.5 m). The gamma ray record in the Ala-Fjäle well has a similar shape to that of Altajme between -10 and -98 m, permitting correlation of the two wells (Fig 14). It can be assumed the log motif would be similar to other geographical places within the corresponding interval in the outcrop belt of the Halla and Klinteberg formations. In the observed gamma ray intervals there are four peak gamma ray anomalies which have been recognized to occur in both Altajme and the Ala-Fjäle wells. These have been used as stratigraphic markers to correlate the cores (Fig 14). The most common reason for a higher gamma ray signal is usually due to small contrasting clay layers. The first at -54,2 m (53, 98 cps), the second, which also is the largest peak, is located at a depth of -62,31 m (100,25 cps), the third at -68,09 m (70,71 cps), and the fourth at -77,96 m (68 cps).

10.7 The Altajme core

In a sequence stratigraphic context it can be difficult to interpret system tracts just based on the Altajme core itself. More information is needed to come to a conclusion. Calner (2006) implies the Fröjel Formation to be regressive. As mentioned in section 10.1 reefs grow preferably in the TST and the HST. The slow progressive shift from the mudstone-wackestone facies association to the wacke-packstone facies association is interpreted to be the result of a stable relative sea level during the TST (Fig 11A). The boundary between the TST and HST is interpreted to be at ca -98 m. The interpretation of the HST is motivated by the observed difference in microfacies, that is related to a shallowing upward facies transition (mud-wackestone to pack-wackestone). Since it is a successive transition and not sharp boundary the HST can be motivated and be placed differently depending on the observer.

Reef facies associations present at -50-0 m is interpreted to be the result of the ramp prograding outwards, resulting in a grainstone erosion surface (*observable at sample 8*). During the reef facies interval there are interbedded sequences of boundstone, floatstone, packstone and grainstone indicative of complex areal distribution of reefs in the area and perhaps also minor sea level fluctuations. Dissolution marks are mostly present in the boundstone sequences. These are thought to be a result of meteoric water in contact with the carbonate reefs at short-lived relative sea level lows. The -50 to -137 m part of the core consists mainly of marl with mudstone, wackestone and packstone microfacies (*samples 1-8*). Fine grained sediments can only be deposited in low energy environment, typically below the FWWB. The facies can easily be misinterpreted as a setting of enclosed bays, estuaries, lagoons, inner platform areas, lagoonal environment (Flügel 2010). It is possible to distinguish this setting from the lagoonal through the presence of tempestites and an open marine bioclastic composition. Post storm activity, the sediment is redistributed across the ramp and finally deposited in the form of sheets of limited extension in low-energy environments below storm-wave base. The absence of a slope break in a homoclinal ramp can make the tempestite pick up less speed which in turn lessens the amount of debris that are carrying along the slope. Slopes with less potential energy could also mean that the amount of larger particles is less in a typical homoclinal ramp without a fore reef. Storms will rarely affect the outer ramp unless the strength of the storm is stronger than usual. In the -137-95.5 m part of the core which is interpreted as the outer ramp facies no storm deposit have been observed. In what has been interpreted as the middle ramp wackestone-packstone microfacies increases and so does also the tempestites which consists of bioclastic packstones and grainstones, mainly of redeposited debris of reef material and skeletal fragments with similar contents to *sample 5-9* (Fig 10).

The Geophysical data collected at Altajme and Arla-Fjäle have similarities in their log-motifs (Fig 14). Strong stratigraphical markers such as bentonites and other high indicative gamma ray signals serve as an important tool to correlate sediment packages. The Grötlingbo Bentonite has due to its high natural gamma ray value previously been used in context to correlate the Mulde Event to other parts of the Baltic basin (Kiipli et al. 2008).

11. Conclusions

The Altajme core was drilled and recovered from the old Altajme quarries southwest of Buttle in central Gotland (Klinteberg Formation outcrop belt). The core section has been studied with respect to carbonate microfacies, gamma ray well logging, and faunal composition. The strata represent a carbonate ramp succession formed in the intracratonic part of Baltica. The Grötlingbo bentonite has been recognised and used as a stratigraphic bottom of the studied core interval, located at -137 m in the core section. The Halla and Klinteberg formations have been identified in the core based on their typical rock properties in their areas of outcrops north of the drill site. The following bullet points represent the overall conclusions of the study.

- Based on carbonate microfacies analysis the studied strata reflect a shallowing upward succession. This shallowing-upward succession can be subdivided into a low energy outer ramp

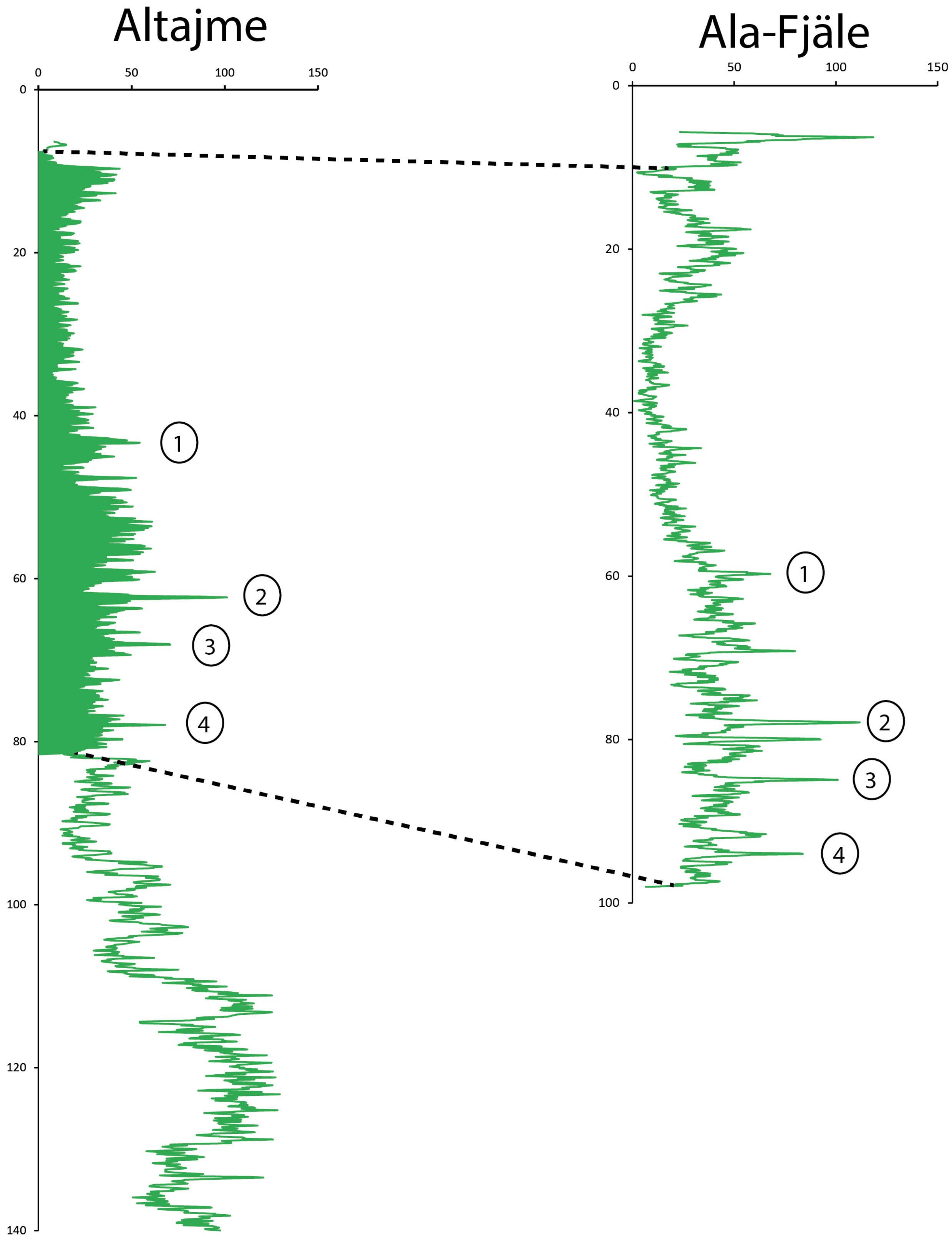

Fig. 14. Comparison between gamma ray well-data from Altajme and Ala-Fjäle. The log-motif and the gamma ray peaks at (1) -54.2 m, (2) -62.31, (3) -68.09 and (4) -77.96 have been used together with the log-motif to correlate Altajme to the Ala-Fjäle well.

(lower Halla Formation), moderate energy middle ramp (upper parts of Halla Formation) and high energy inner ramp (Klinteberg Formation) depositional environment. No major unconformities occur within this interval, although dissolution from meteoric water diagenesis is evident in the upper parts of the Klinteberg Formation.

- The gamma ray cps values show a clear decrease up-section from high values in the argillaceous outer ramp facies of the basal Halla Formation, to low values in the clean inner ramp limestone facies of the Klinteberg Formation.
- The gamma ray log-motifs of the Altajme and Ala-Fjäle wells correlate very well, suggesting a highly similar development of the Halla and Klinteberg formations in the two areas.
- The resistivity log of the Altajme well show an overall increase up-section from low resistivity argillaceous outer ramp facies of the basal Halla Formation, to high resistivity inner ramp reef carbonates in the Klinteberg Formation.

12. Acknowledgement

First and foremost I would like to express my sincere gratitude to Professor Mikael Calner without his encouraging support, guidance and constructive criticism this thesis would never have become a reality. I would also like to express my gratitude to Per-Gunnar Alm and Johan Kullenberg who assisted with the geophysical data acquisition. I would also like to thank my family for morally support throughout the thesis. I would lastely like to thank Lund University and the geology department and everyone I have had the privilege to meet. It has been a journey I will never forget. Thank you all.

13. References

Ahr, W. M., 1973: Carbonate Ramp - Alternative to Shelf Model. *American Association of Petroleum Geologists Bulletin 57***,** 1826-1826.

Aigner, T., 1985: Storm depositional systems : dynamic stratigraphy in modern and ancient shallow-marine sequences. *Springer-Verlag***.** viii, 174 p. pp.

Baarli, B. G., 1990: Peripheral Bulge of a Foreland Basin in the Oslo Region during the Early Silurian. *Palaeogeography Palaeoclimatology Palaeoecology 78***,** 149-161.

Baarli, B. G. J. M., Antoshkina Ai, 2003: Silurian stratigraphy and palaeogeography of Baltica. In: Landing E, Johnson ME(eds) Silurian lands and seas—paleogeography outside of Laurentia.

Brady, M. & Bowie, C., 2017: Discontinuity surfaces and microfacies in a storm-dominated shallow Epeiric Sea, Devonian Cedar Valley Group, Iowa. *Depositional Record 3***,** 136-160.

Burchette, T. P. & Wright, V. P., 1992: Carbonate Ramp Depositional Systems. *Sedimentary Geology 79***,** 3-57.

Calner, M., 1999: Stratigraphy, facies development, and depositional dynamics of the Late Wenlock Frojel Formation, Gotland, Sweden. *Gff 121***,** 13-24.

Calner, M., 2005a: Silurian carbonate platforms and extinction events - ecosystem changes exemplified from Gotland, Sweden. *Facies 51***,** 584-591.

Calner, M., 2005b: Silurian carbonate platforms and extinction events - ecosystem changes exemplified from Gotland, Sweden. *Facies 51***,** 603-610.

Calner, M. & Jeppsson, L., 2003: Carbonate platform evolution and conodont stratigraphy during the middle Silurian Mulde Event, Gotland, Sweden. *Geological Magazine 140***,** 173-203.

Calner, M., Kozlowska, A., Masiak, M. & Schmitz, B., 2006: A shoreline to deep basin correlation chart for the middle Silurian coupled extinction-stable isotopic event. *Gff 128***,** 79-84.

Calner, M. & Sall, E., 1999: Transgressive oolites onlapping a Silurian rocky shoreline unconformity, Gotland, Sweden. *Gff 121***,** 91-100.

Catuneanu, O., Sweet, A. R. & Miall, A. D., 1999: Concept and styles of reciprocal stratigraphies: Western Canada foreland system. *Terra Nova 11***,** 1-8.

Cramer, B. D., Kleffner, M. A., Brett, C. E., Mclaughlin, P. I., Jeppsson, L., Munnecke, A. & Samtleben, C., 2010: Paleobiogeography, high-resolution stratigraphy, and the future of Paleozoic biostratigraphy: Fine-scale diachroneity of the Wenlock (Silurian) conodont Kockelella walliseri. *Palaeogeography Palaeoclimatology Palaeoecology 294***,** 232-241.

Cramer, B. D., 2012: U-Pb (zircon) age constraints on the timing and duration of Wenlock (Silurian) paleocommunity collapse and recovery during the 'Big Crisis'. Geological Society of America Bulletin. 124. 1841-1857.

Dahlqvist, P., Calner, M., Kallaste, T., Kiipli, T. & Siir, S., 2012: Geochemical variations within the mid-Silurian Grotlingbo Bentonite (Gotland, Sweden): discriminating between magmatic composition, ash transport fractionation and diagenetic effects. *Gff 134***,** 273-282.

Dunham, R.J. 1962. Classification of carbonate rocks according to depositional texture. In Classification of carbonate rocks (ed. W. E. Ham), pp. 108–21.Tulsa, Oklahoma: American Association of Petroleum Geologists.

Eriksson, M. J., 2004: Formation and significance of a middle Silurian ravinement surface on Gotland, Sweden. *Sedimentary Geology 170***,** 163-175.

Erlstrom, M. & Persson, L., 2014: Radiomagnetotelluric mapping of marlstone and limestone in the Silurian bedrock of Gotland. *Gff 136***,** 571-580.

Flügel, E., 2010: Microfacies of carbonate rocks. *Springer***.** 1005 pp.

Frykman, P., 1989: Carbonate ramp facies of the Klinteberg formation, Wenlock-Ludlow transition on Gotland*,* Sweden. Vol. *820*.

G. Regnell, J. E. H., 1960: The lower Palaeozoic of Scania The Silurian of Gotland.

Hallock, P. W., Schlager, 1986: Nutrient Excess and the Demise of Coral Reef's and Carbonate Platforms. *1***,** 389-398.

Handford, C. R. & Loucks, R. G., 1993: Carbonate Depositional Sequences and Systems Tracts - Responses of Carbonate Platforms to Relative Sea-Level Changes. *Carbonate Sequence Stratigraphy 57***,** 3-41.

Harff, J., Bjorck, S. & Hoth, P., 2011: The Baltic Sea Basin: Introduction. *Baltic Sea Basin***,** 3-9.

Hede, J. E., 1921: Gottlands silurstratigrafi. *Kungl. Boktryckeriet. P.A Norstedt & Söner* . pp. 100.

Hede, J.E., 1927a: Berggrunden (Silursystemet). In H. Munthe, J.E. Hede & G. Lundquist. Beskrivning till kartbladet Klintehamn, 12–48. Sveriges Geolo-giska Undersökning Aa 160.

Hede, J.E. 1960. The Silurian of Gotland. In G. Regnell & J.E.Hede. The Lower Palaeozoic of Scania. The Silurian of Gotland. Guide to excursions A22 and C17, 21st International Geological Congress, Norden 1960, pp. 44–89.

Hillgartner, H., 1998: Discontinuity surfaces on a shallow-marine carbonate platform (Berriasian, Valanginian, France and Switzerland). *Journal of Sedimentary Research 68***,** 1093-1108.

Jarochowska, E. & Kozowski, W., 2014: Facies development and sequence stratigraphy of the Ludfordian (Upper Silurian) deposits in the Zbruch River Valley, Podolia, western Ukraine: local facies overprint on the delta C-13 (carb) record of a global stable carbon isotope excursion. *Facies 60***,** 347-369.

Jeppsson, L., Eriksson, M. E. & Calner, M., 2006: A latest Llandovery to latest Ludlow high-resolution biostratigraphy based on the Silurian of Gotland - a summary. *Gff 128***,** 109-114.

Jeppsson, L., Talent, J. A., Mawson, R., Simpson, A. J., Andrew, A. S., Calner, M., Whitford, D. J., Trotter, J. A., Sandstrom, O. & Caldon, H.-J., 2007: High-resolution Late Silurian correlations between Gotland, Sweden and the Broken River region, NE Australia: Lithologies, conodonts and isotopes. *Palaeogeography Palaeoclimatology Palaeoecology 245***,** 115-137.

Kaufhold, S., Dohrmann, R., Klinkenberg, M. & Noell, U., 2015: Electrical conductivity of bentonites. *Applied Clay Science 114***,** 375-385.

Kershaw, S., 1993: Sedimentation control on growth of stromatoporoid reefs in the Silurian of Gotland, Sweden. *Journal of the Geological Society 150***,** 197-205.

Kiipli, T., Radzevicius, S., Kallaste, T., Motuza, V., Jeppsson, L. & Wickstrom, L. M., 2008: Wenlock bentonites in Lithuania and correlation with bentonites from sections in Estonia, Sweden and Norway. *Gff 130***,** 203-210.

Lu, R., Banerjee, S. K. & Marvin, J., 1990: Effects of Clay Mineralogy and the Electrical-Conductivity of Water on the Acquisition of Depositional Remanent Magnetization in Sediments. *Journal of Geophysical Research-Solid Earth and Planets 95***,** 4531-4538.

Lucia, F. J., 2007: Carbonate Reservoir Characterization. *Springer***.** 341 pp.

Munnecke, A. & Samtleben, C., 1996: The formation of micritic limestones and the development of limestone-marl alternations in the Silurian of Gotland, Sweden. *Facies 34***,** 159-176.

Munnecke, A., Westphal, H., Reijmer, J. J. G. & Samtleben, C., 1997: Microspar development during early marine burial diagenesis: a comparison of Pliocene carbonates from the Bahamas

with Silurian limestones from Gotland (Sweden). *Sedimentology 44*, 977-990.
Munthe, J. E. H., G. Lundqvist, 1927: Beskrivning till karbladet Klintehamn. Geologiska kartblad i skala 1:50 000 med beskrivningar. *Kungl. Boktryckeriet. P.A Norstedt & Söner.*
Osleger, D., 1991: Subtidal Carbonate Cycles - Implications for Allocyclic Vs Autocyclic Controls. *Geology 19*, 917-920.
Read, J. F., 1980: Carbonate Ramp-to-Basin Transitions and Foreland Basin Evolution, Middle Ordovician, Virginia Appalachians. *Aapg Bulletin-American Association of Petroleum Geologists 64*, 1575-1612.
Samtleben, C., Munnecke, A., Bickert, T. & Patzold, J., 1996: The Silurian of Gotland (Sweden): Facies interpretation based on stable isotopes in brachiopod shells. *Geologische Rundschau 85*, 278-292.
San Miguel, G., Aurell, M. & Badenas, B., 2017: Diagenetic evolution of a shallow marine Kimmeridgian carbonate ramp (Jabaloyas, NE Spain): implications for hydrocarbon reservoir quality. *Arabian Journal of Geosciences 10*.
Torsvik, T. H., 1998: Palaeozoic palaeogeography: A North Atlantic viewpoint. *Gff 120*, 109-118.
Trappe, J., 1992: Microfacies zonation and spatial evolution of a carbonate ramp - Marginal Moroccan phosphate sea during the paleogene. *Geologische Rundschau 81*, 105-126.