Upper Ordovician through lowermost Silurian stratigraphy and facies of the Borenshult-1 core, Östergötland, Sweden

Amir Noor

Upper Ordovician through lowermost Silurian stratigraphy and facies of the Borenshult-1 core, Östergötland, Sweden

Master Thesis
Amir Noor

Department of Earth and Ecosystem Sciences
Division of Geology
Lund University
2010

Contents

Cover Picture: Upper Ordovician strata at Osmundsberget quarry in Dalarna, Central Sweden (photo: M. Calner).

Upper Ordovician through lowermost Silurian stratigraphy and facies of the Borenshult-1 core, Östergötland, Sweden

AMIR NOOR

Abstract: The Ordovician is an important period in the Phanerozoic, with remarkable faunal turnovers, several major carbon isotope excursions, and shifting climate. The strata of this time period not only reveal these events but also provide useful information about the palaeoclimate and sea-level. The Borenshult-1 core form Östergötland, southern Sweden constitutes a complete succession of the upper Middle Ordovician through lowermost Silurian. This study describes the sedimentary rocks, fossil fauna and depositional environment of these strata. The observations of the study are based upon cut and polished core slabs and thin sections photograph. Sedimentary data and a generalized facies model are used to reconstruct the depositional environment and changing bathymetry. The ~71 m thick succession is comprised of eight formations. The bioclast composition reflects normal cool-water ecological assemblages with the exception of *Favosites* tabulate corals in the middle Freberga Formation, and ooids in the Loka Formation, indicating tropical climate. On the basis of the facies model of Harris et al. (2004), the strata represent 51% of mixed facies, 32% grain-supported facies and 12% mud-supported facies. Based on the sedimentary data, carbon isotopic values, stratigraphy and the faunal information, four major regressions and four transgressions of the sea-level are recorded.

Keywords: Borenshult-1 core, Palaeoclimate, Upper Ordovician, Sea-level, GICE, HICE,

Baltoscandia.

Amir Noor, Department of Earth and Ecosystem Sciences, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: arfta@hotmail.com

1. Introduction

The Ordovician Period (488-444 Ma) was characterized by one of the most important faunal turnovers in the Phanerzoic (Sepkoski 1993; Sheehan & Harris 2004; Ainsaar et al. 2004; Hansen et al. 2009). It has been estimated that about 86% of the species were eliminated during the main glacial in the Hirnantian stage (Jablonski 1991; see also; Brenchley et al. 2003; Sheehan & Harris 2004). The Great Ordovician Biodiversification Event (GOBE; Servais 2009), the Middle Darriwilian Isotope Carbon Excursion (MDICE) (Ainsaar et al. 2004; Meilda et al. 2004), the Upper Ordovician, Guttenberg Isotope Carbon Excursion (GICE), and the latest Upper Ordovician Hirnantian Isotope Carbon Excursion (HICE), and the associated glaciation and extinction event makes the whole Ordovician period unique and remarkable in the Phanerozoic Eon. The long earliest Palaeozoic greenhouse period shifted into an icehouse period during the Ordovician (the Early Palaeozic Icehouse) and four glacial maxima, including the major Hirnantian glaciation, have been recognized in the Upper Ordovician (Page et al. 2007).

As shown by $\delta^{13}C$ stratigraphy, the upper Middle through Upper Ordovician constitutes repeated changes in the global carbon cycle, interpreted as reflecting the unstable climatic conditions (Kaljo et al. 2004; Bergström et al. 2007, 2009a; Calner et al. 2010a). The oldest carbon isotope excursion of this interval (GICE) was first identified by Hatch et al. (1987) and has later been identified in several palaeocontinents (Ainsaar et al. 1999; Bergström et al. 2009a, 2009c). Between the GICE and HICE there have been several isotopic excursions recorded globally, which have been described and discussed in the recent works by (Kaljo et al. 2004; Bergström et al. 2007; Bergström et al. 2009b, c; Calner et al. 2010a; Ainsaar et al. 2010). The four main excursions between HICE and GICE were documented by Bergström et al. (2009b) who referred to them as Kope, Fairview, Waynesville and Whitewater. Several studies suggest that each of these excursions are associated with distinct environmental and biotic changes (Brenchley et al. 1994; Underwood et al. 1997; Ainsaar et al.1999; Brenchley et al. 2003; Ainsaar et al. 2004; Calner et al. 2010a). In a recent study of Baltoscandia, fluctuation of the carbon isotope data during the Katian-Hirnantian interval suggests a climatic cyclicity of 2 Ma (Ainsaar et al. 2010).

The stratigraphical classifications and the studies of the Ordovician-Silurian succession in Baltoscandia have been discussed for more than 100 years (Törnquist 1875, 1913; Jönsson 1887; Wiman 1908; Troedsson 1918; Waern 1960; Thorslund 1960; Wikman et al. 1980, 1982) but the changes in facies and fauna during the Upper Ordovician of Baltoscandia were first explained by Jaanusson (1976). Several studies have been conducted particularly in Estonia to establish a
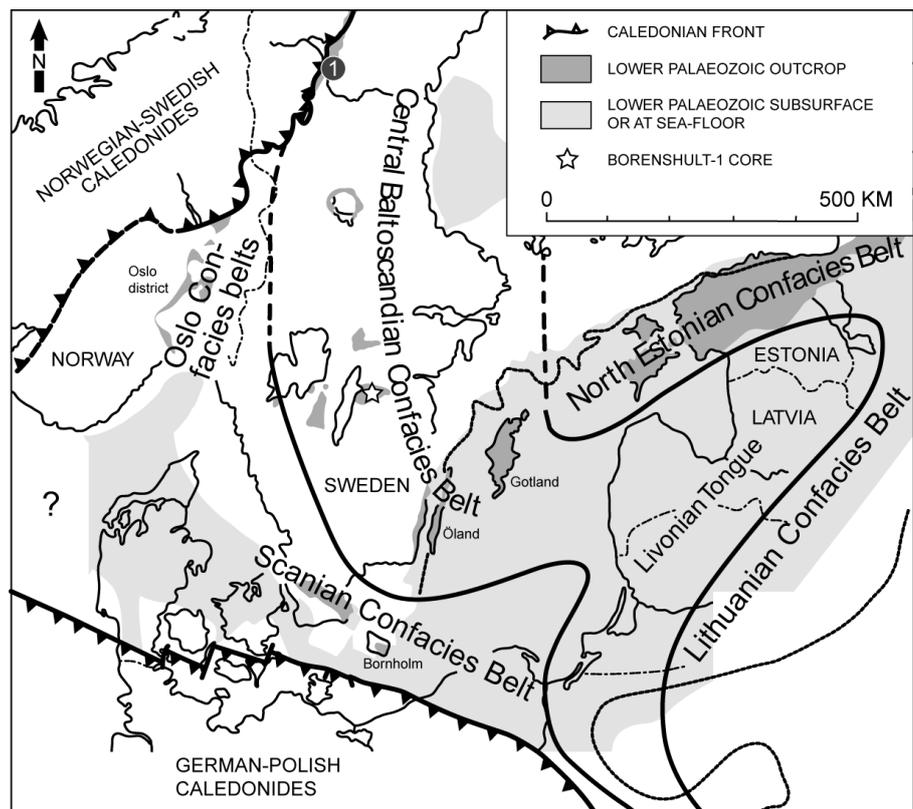

Fig. 1. Palaeogeography of Baltoscandia showing the position of of the Borenshult-1 core in Motala (at the star). The Scanian Confacies Belt, Central Baltoscandian Confacies Belt and the North Estonian Confacies Belt delineate the palaeodepths of the basin. Modified from Nielsen (2004) and Stouge (2004).

global correlation of the stratigraphy, paleontology and general facies of Baltoscandia (Kaljo & Nestor 1990; Raukas & Teedumäe 1997; Harris et al. 2004).

This study focuses on the upper Middle Ordovician through lowermost Silurian sedimentary facies and facies changes in the Borenshult-1 core from Motala in Östergötland (Fig. 1). Based on microfacies analysis it aims to depict sea-level changes and their relationship to the carbon isotope stratigraphy of this time interval in Baltoscandia. The goal of the study is to improve the knowledge about the relationship between sedimentation in the Baltoscandian basin and Late Ordovician climate shifts (*sensu* Page et al. 2007).

2. Geological setting and stratigraphical framework

2.1 Ordovician palaeogeography and tectonic evolution of the Baltoscandian basin

In the Middle to Upper Ordovician, most of the land masses were situated in the southern hemisphere (Fig. 2A). Within this time interval Baltica drifted northwards across the southern hemisphere with a counter-clock wise rotation (Cocks & Torsvik 2002). During the late Ordovician, Avalonia came closer to Baltica, which resulted in a collision and the closure of the Tornquist Sea with the subduction of ocean floor (Torsvik et al.1996; Baarli et al. 2003; Fig 2B). In the late Ordovician to early Silurian, Baltica was situated in the subtropics of the southern hemisphere. The start of the Caledonian Orogeny and the resulting change in the paleogeography of Avalonia, Laurentia and Baltica formed new environmental and depositional settings in the Silurian.

The Upper Ordovician of Baltoscandia is mainly composed of limestone, and fine-grained clastic rocks depending upon the proximity to the active plate margins. Based on the composition of sediments, faunal content and inferred depositional depth, the Baltoscandian basin is divided into three broad facies belts, termed confacies belts and used for describing the general palaeogeography of the basin (Männil 1966; Jaanusson 1976; Kaljo et al. 2007). The Scanian-Oslo Confacies Belt, the Central Baltoscandian Confacies Belt and the North Estonian Confacies Belt are the three main confacies belts of the basin (Fig. 1). The open marine shelf environment of the Central Baltoscandian Confacies Belt constitutes mudstone and argillaceous limestone facies that extends from southern Estonia to eastern Sweden (Kaljo et al. 2007; Fig. 2). The deepening of the depostional environments along the Norwegian-Swedish and German-Polish fronts, started with the Caledonian Orogeny in the Ordovician, led the formation of shale in the west and south; in
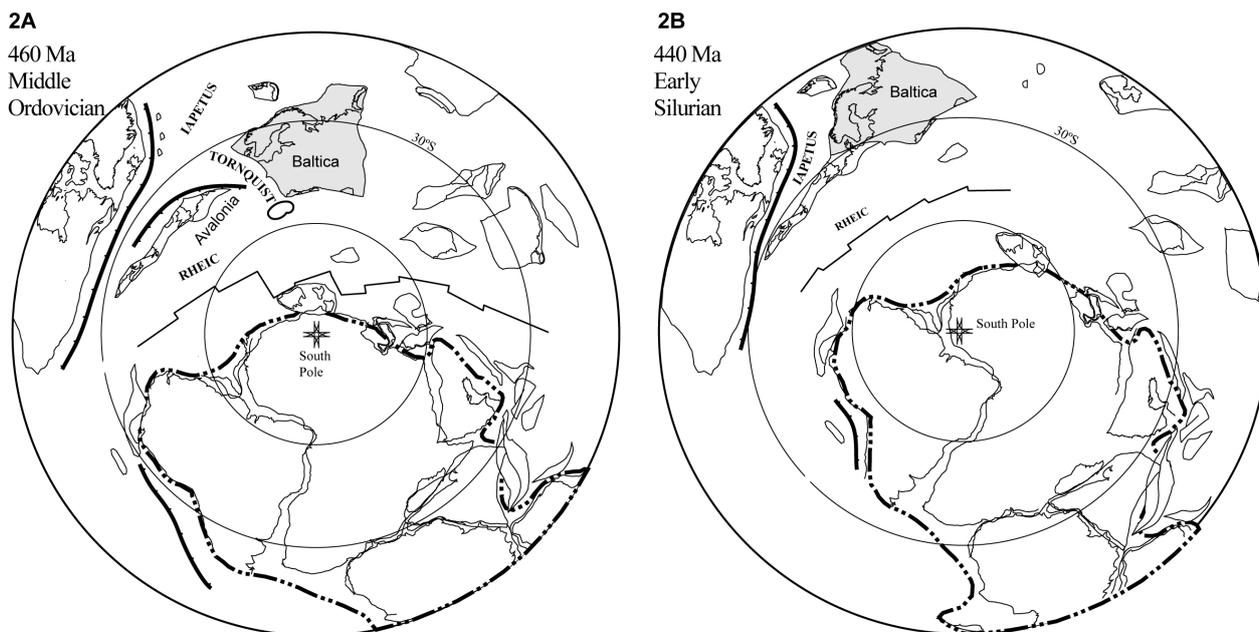

Fig. 2. Palaeogeographic map showing the distribution of the continents and Baltica during Middle Ordovician to latest Silurian. **A.** Distribution of the palaeocontinents in the southern hemisphere during Middle Ordovician. **B.** Distribution of the palaeocontinents in the early Silurian and also showing the closure of the Tornquist sea. Modified from Cocks & Torsvik (2002).

6

Global Division Series Stages	Time slices	Regional Ser./Sub Ser.	Stages	Graptolite zones	Chitinozoan zones	Conodont zones	sub-zones	Dalarna Siljan district	Östergötland Borenshult-1	Southern and Central Estonia
LATE ORDOVICIAN — KATIAN — HIRNANTIAN (HARJU / ATLA)	6c		Porkuni	*Normalograptus persculptus*	*Conochitina scabra*			Glisstjärn	Loka Formation	
				Normalograptus extraordinarius	*Spinachitina taugourdeaui*			Tommarp Beds		Saldus Formation
	6b		Pirgu	*Dicellograptus anceps*	*Belonech. gamchiana* / *T. anticostiensis* / *Conochitina rugata*	*Amorphognathus ordovicicus*		Jonstorp Formation / Boda Limestone	Jonstorp Formation	Jelgava Formation
	6a			*D. complanatus*	*Tanuchitina bergstroemi*					Jonstorp Formation
(KOHILA)	5d		Vormsi	*Pleurograptus linearis*				Fjäcka Shale	Fjäcka Shale	Fjäcka Shale / Saunja Formation
			Nabala					*palaeokarst horizon*		Mõntu Formation
(VINNI)	5c		Rakvere		*Fungochitina spinifera*	*Amorphognathus superbus*		Slandrom Limestone / Skålberg Limestone	Slandrom Limestone	Rägav. Fm / Variku Fm / Mossen Fm / Priekule
			Oandu	*Dicranograptus clingani*				Moldå Limestone (Freberga Formation)	Moldå Limestone (Freberga Formation)	Plunge
VIRU (KURNA)			Keila		*Spinachitina cervicornis*	*Amorphognathus tvaerensis*		Skagen Limestone / Kullsberg Limestone	Skagen Limestone	Blidene Formation
								Kinnekulle K-bentonite		
SANDBIAN	5b		Haljala	*Diplograptus foliaceus*	*B. hirsuta* / *Lagenoch. dalbyensis* / *Angochitina curvata* / *Armoricoc. granulifera*		*B. alobatus*	Dalby Limestone	Dalby Limestone	Adze Formation
							B. gerdae			
	5a	(PURTSE)	Kukruse	*Nemagraptus gracilis*	*Laufeldochitina stentor*		*B. variabilis*			Dreimani Formation
Da.	4c		Uhaku	*Gymnograptus linnarsoni*			*Pygodus anserinus*	Furudal Limestone	Furudal Limestone	Taurupe/Körgekallas

Fig. 3. Stratigraphic framework of the upper Darriwilian through the early Silurian of Sweden and the East Baltic area. See Bergström (2007) for a recent discussion on the conodont biostratigraphy of this interval and Ebbestad et al. (2007) for full reference to the non-conodont zonation. Modified from Ebbestead et al. (2007). The unconformity (grey shaded) is coeval with the sequence boundary at the top of the Skagen Limestone in Borenshult-1 core and the base of the Mossen Formation in the Livonian Basin as reported by Ainsaar et al. (2004; see Calner et al. 2010a).

the Scanian and Oslo confacies belts (Jaanusson 1976, 1995; Calner et al. 2010b). The two foreland basins caused efficient sediment-traps and also accounted for the sediment-starved character of the slowly subsiding inner part of the basin (Calner et al. 2010b).

2.2 Upper Ordovician stratigraphy of southern and central Sweden

Southern Sweden has an almost complete succession of the Upper Ordovician as shown in Fig 3. The area surrounding the city of Motala has received little attention in the past due to few exposed Ordovician-Silurian boundary sections (Bergström & Bergström 1996). The studied Borenshult-1 core includes upper Middle through basal Silurian strata and eight stratigraphical units have been identified. These are, in ascending order, the Furudal Limestone, Dalby Limestone, Freberga Formation (including the Skagen and Moldå topoformations), Slandrom Limestone, Fjäcka Shale, Jonstorp Formation (including the Öglunda bed), Loka Formation, and the Motala Formation (see also; Bergström 2007; Ebbestad et al. 2007; Calner & Lehnert 2008). These units are mainly composed of bedded limestone with subordinate shale.

The stratigraphic units of the Borenshult-1

core are well-known from other areas in south and central Sweden. Several Ordovician-Silurian boundary sections are well exposed in Västergötland (Bergström 1968; Stridsberg 1980; Bergström & Bergström 1996). In Östergötland, the Ordovician-Silurian boundary section is exposed at Råssnäsudden in western Motala (Bergström & Bergström 1996) and the entire Upper Ordovician-lowermost Silurian succession is known from the nearby Smedsby Gård core (Jaanusson 1963). In central Sweden, the Amtjärn quarry in the Siljan District exposes parts of the upper Ordovician (Jaanusson 1982; Calner et al. 2010a). For example, the exposed section of the Amtjärn quarry includes, from below, the Kullsberg Limestone, Skålberg Limestone, Slandrom Limestone, Fjäcka Shale and the lower portions of the Jonstorp Formation (Calner et al. 2010a).

3. Material and methods

This study is mainly based on the succession in the Borenshult-1 core, which was drilled in Motala (Östergötland province) in July 2007. Unpublished carbon isotope data of O. Lehnert and M. Calner has also been used in this study. Dunham's classification (1962), as revised by Embry & Klovan (1971), is used to classify the

microfacies of the different units and subunits of the core section. These were investigated by means of several tens of cut and polished slabs under a binocular light microscope. Also 175 thin section photographs were studied, sample levels are shown in the Appendix. 1. The terminology for the carbonate petrography was obtained from Flügel (2004). In the previous sampling of the core a micro-drill was used to collect the carbon isotope samples, later analysed by using a ThermoFinnigan 252 mass spectrometer in Kiel III, at the Geocenter of Northern Bavaria in Erlangen, Germany. The Values of $\delta^{13}C$ are reported in per mil relative to V-PDB (Vienna Peedee belemnite). Laboratory standards and replicate analysis of NBS 19 were used to check the accuracy and precision of the carbon isotope measurements. The one sigma error is under the limit of $\pm$ 0.005‰. The Borenshult-1 core is stored at the Department of Earth and Ecosystem Sciences, Lund University. Thin sections are kept in the collection of O. Lehnert at the GeoZentrum Nordbayern in Erlangen, Germany.

4. Results and core description

The Borenshult-1 core was recovered in july 2007, from Syréngatan, Borenshult, Motala. It is one of few complete Ordovician-Silurian sections in Östergötland. The lithology of the whole core is limestone that varies in the clay content. It has three to four bentonites. The upper part of the core has more calcimudstone to wackestone texture while the lower has packstone to wackestone texture. The core has eight formations, which were subdivided into 28 subunits (see Table 1) based on their textural properties. These are detailed below:

4.1. Furudal Limestone (14.82 m)

4.1.1. Subunit 1: Furudal Limestone: -71.33 to -56.51 (14.82 m)
The Furudal Limestone is composed of nodular bedded limestone, with a wacke to packstone texture, which is intercalated with marl. It includes frequent irregular, and sometimes bored, limestone clasts ranging in size from a few millimeters to 1.5 cm (Fig. 4A). The main skeletal fragments are crinoids, trilobites, brachiopods ostracodes and bryozoans. This facies also has a *Planolites*-like bioturbation.

4.2. Dalby Limestone (18.16 m)

The Dalby Limestone has a grainstone to packstone texture, and it is divided into two subunits on the basis of texture and other observations. Dalby also has three or possibly four bentonites.

4.2.1. Subunit 2: Lower Dalby Limestone with cystoids: -56.51 to -42 (14.51 m)
This subunit has a dominating texture of grainstone with few intercalations of calcimudstone and wackestone (Fig. 4B). Skeletal fragments of crinoids, trilobites, brachiopods, ostracodes, echonoid spines, bryozoans, gastropods, and bivalves are present. This subunit also has *Echinosphaerites aurantium*, commonly called cystoids. The cystoids vary in their sizes, the biggest cystoid is at the depth of -46.6 m with a size of about 5-6 cm in diameter. The first cystoid appears at the depth of -54.1 m and the last is at the depth of -42.7 m. Cystoids which are filled with two generations of sediments of fine and coarse grains are also found above the depth of -47.3 m. Hardgrounds that have clearly mineralized boundaries are frequent. It has *Planolites*-like bioturbation. This subunit also yields s bentonite at the depth of -55.655 m with an undulating thickness of 1 to 1.5 cm.

4.2.2. Subunit 3: Upper Dalby Limestone: -42 to -38.350 (3.65 m)
This subunit has a texture of packstone to grainstone, while packstone is the dominant texture, with skeletal fragments of crinoids, trilobites, brachiopods, ostracodes, gastropods and bivalves (Fig. 4C). This subunit is based on facies very similar to the overlying Skagen Limestone. Cystoids are absent. Hardgrounds and bioturbation is also present in this lower Dalby subunit. It yields two or possibly three bentonites, the lowermost one is uncertain because of very few grains of mica. This interval has a undulating thickness of 1 to 2 cm, and starts at the depth of -41.32 m, the second and the thickest bentonite has a thickness of 19 cm and starts from the depth of -39.14 m goes up to -38.95 m, and the third and final bentonite is around 1.5 cm thick and lies just below the top of the unit, at the depth of -38.365 to -38.350 m.

4.3. Subunit 4: Kinnekulle K-bentonite: -38.350 to -36.75 (1.55 m)
This unit has a thickness of a 1.55 m. It is a volcanic ash with mica.

4.4. Freberga Formation (16.85 m)
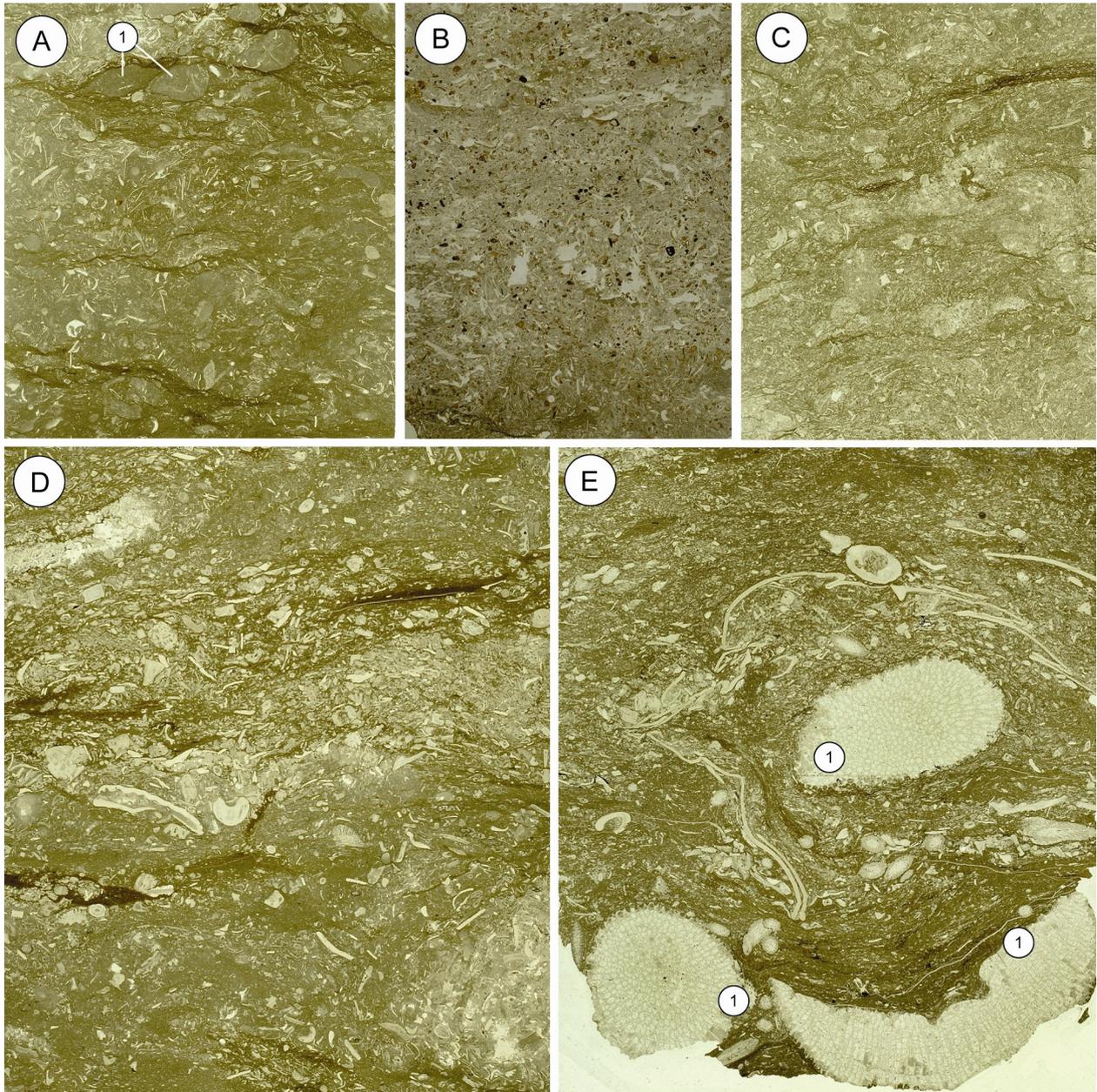
Fig. 4. Photographical plate showing thin sections of different formations of the Borenshult-1 core, the width of photographs are 4 cm. **A.** Furudal Limestone showing a texture of wackestone to packstone and also showing irregular limestone clasts (1). **B.** Lower Dalby subunit, showing the grainstone texture. **C.** Upper Dalby subunit, showing a texture of packstone to grainstone. **D.** Freberga Formation, subunit 1 showing a texture of wackestone to packstone. **E.** Freberga Formation, subunit 2 showing a texture of packstone, and also showing bryozoans colonies

The Freberga Formation is mainly composed of wackestone to grainstone, where wackestone is the dominant texture within the formation. Skeletal fragments of crinoids, trilobites, brachiopods are common but few colonies of bryozoans were also identified in the thin sections. The Freberga Formation has been divided into nine subunits on the basis of texture, skeletal fragments and bioturbation. The Freberga Formation constitutes the Skagen Limestone and Moldå Limestone which are topo-formations. The most striking macrofossils are corals that are found just above the GICE in this formation.

4.4.1. Subunit 5: -36.75 to -29.37 (7.38 m)

This subunit is composed of nodular bedded limestone with reworked bioclasts. The texture is wackestone to packstone (Fig. 4D). It has crinoids, trilobites, brachiopods and echinoids fragments. Hardgrounds are also present within this subunit.

9

It has moderate bioturbation. At the depth of -34.35 m, thin section shows the presence of ostracodes. The facies also includes thin clay seams.

4.4.2. Subunit 6: -29.37 to -26.90（2.47 m）

This subunit yields calcimudstone to packstone with intercalations of reworked limestone intraclasts. The main skeletal fragments are crinoids, trilobites and brachiopods. This subunit has the Skagen and Moldå boundary somewhere at the depth of -29.3 m depth. Striking macrofossils of the tabulate coral of *Favosites* is found at the depth of -27.73 m. A thin section from -27.3 m depth includes a colony of bryozoans (Fig. 4E). This subunit has sparse bioturbation.

4.4.3. Subunit 7: -26.90 to -24.55（2.35 m）

This subunit consists of wackestone to packstone with two bentonites. The first bentonite has a thickness of 1.5 to 2 cm, at a depth of -24.235 m. The second bentonite has a thickness of 1 to 1.5 cm and marks the top of this subunit at -24.549 m. Coarse-grained mica is apparent in this latter bentonite. The main skeletal fragments are brachiopods and crinoids. This subunit has fossils of brachiopods and bryozoans with *Planolites*-like bioturbation with fills of clay. The limestone show some pyrite grains and is interbedded with thick and thin greenish clay seams.

4.4.4. Subunit 8: -24.55 to -22.27（2.28 m）

This subunit is composed of bedded limestone with limestone clasts. The texture is a wackestone to packstone where the packstone is approaching rudstone/floatsone. The uppermost 0.1 m resembles the facies of the overlying Slandorm Formation. A possible coral along with crinoids, trilobites and brachiopods are the skeletal fragment present in this mixed facies subunit. Grains are abraded. *Trypanites* trace fossils occur at a few levels. The interbedded clay seams is a mixture of thick and thin veins filled with dark green argillaceous material. It has altered pyrite of dark orange colour and unaltered pyrite grains.

4.4.5. Subunit 9: -22.27 to -21.88（0.39 m）

This subunit is composed of nodular bedded limestone and yields the texture of wackestone to grainstone, at some intervals a coarse grained texture of the grainstone approaches a rudstone/floatstone texture. Skeletal fragments of crinoids, trilobites, and brachiopods are present. It also has a few clay seams of dark green colour.

4.4.6. Subunit 10: -21.88 to -21.38（0.50 m）

This subunit has a bedded limestone lithology with a texture of wackestone to crinoidal packstone, in which the wackestone texture is extremely fine-grained and resembles the Slandrom Formation. This subunit also has some glauconite. Skeletal fragments are mainly from crinoids and trilobites. Throughout this subunit thin clay seams occur at regular intervals, which is not the case in the preceding units. These are light to dark green in colour.

4.4.7. Subunit 11: -21.38 to -20.80（0.58 m）

This subunit is composed of nodular bedded limestone with a texture of wackestone to grainstone, and also grainstone that approaches rudstone/floatstone. The main skeletal fragments are crinoids and trilobites. Thick and light to dark greenish clay seams are present in the mud-wackestone texture whereas grainstone facies only has thin bands of light green clay seams.

4.4.8. Subunit 12: -20.80 to -20.20（0.6 m）

The lithology of this subunit is composed of bedded limestone with a texture of wackestone. Skeletal fragments of crinoids, trilobites, brachiopods and bryozoans are present in it. This subunit also has clay seams. In the upper part these are light green in colour while in the lower part they have has dark green colour. The subunit also has some pyrite.

4.4.9. Subunit 13: -20.20 to -19.90（0.3 m）

This subunit is composed of limestone and includes reworked intraclasts. The texture of the subunit is wackestone to packstone. Crinoids, trilobites and brachiopods fragments are the main skeletal fragments. It has pyrite patches. It also has thick and thin clay seams, thin in the upper part and thick in the lower part.

4.5. Slandrom Formation（1.12 m）

4.5.1. Subunit 14: Slandrom Formation – 19.90 to -18.78 (1.12 m)

This subunit consists of fine-grained limestone
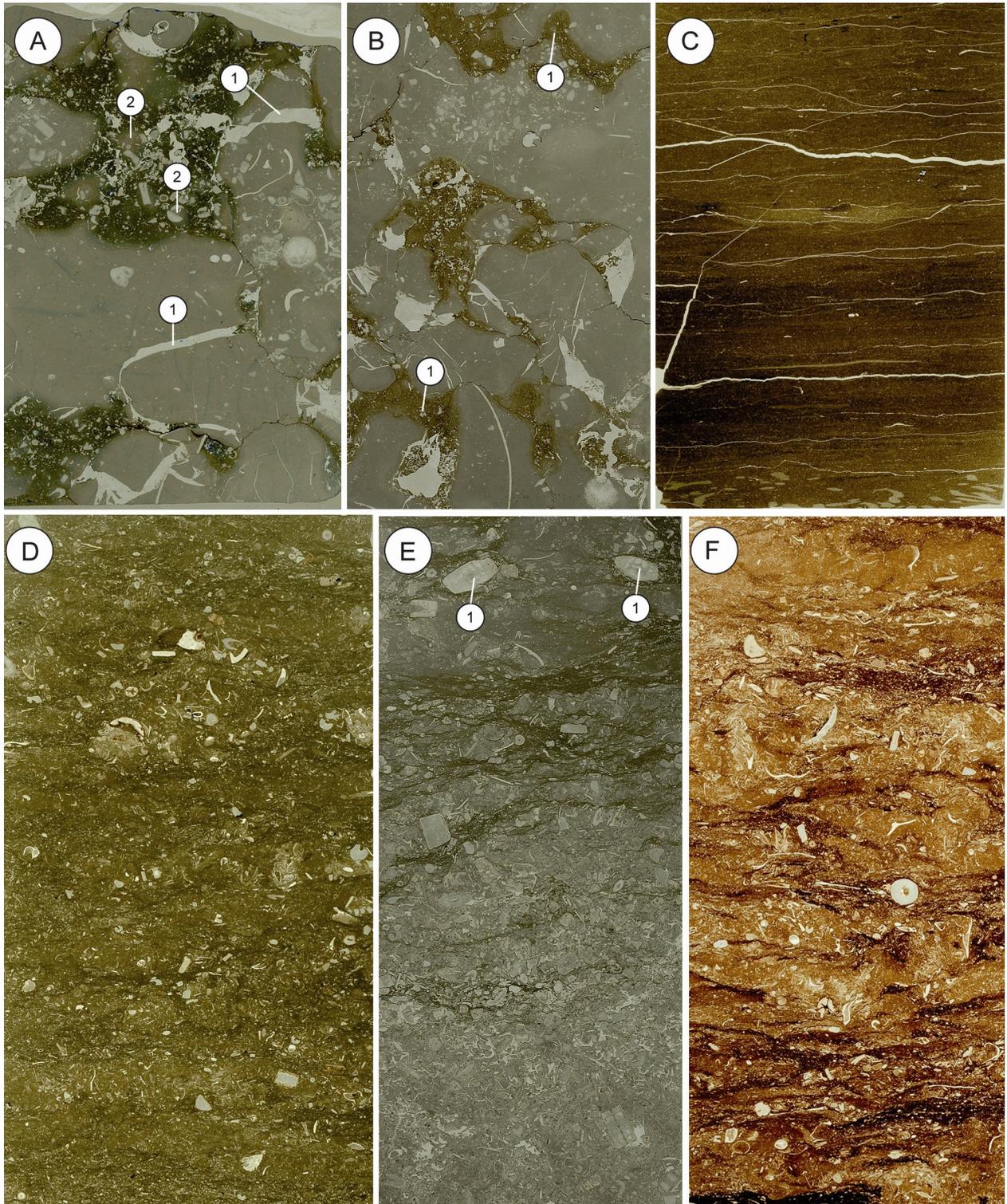
Fig. 5. Photographical plate showing thin sections of the Slandrom Formation, Fjäcka Shale, and the Jonstorp Formation with the Öglunda bed. The width of the photographs are 4 cm. **A.** Slandrom Formation, showing a texture of calcimudstone to packstone, it also shows **1**calcite filled cracks **2** dissolved clasts. **B.** Slandrom Formation, showing the general lithology of the very fine grained limestone, **1** preserved conduits. **C.** Fjäcka Shale, lower dark grey subunit. **D.** Lower green Jonstorp subunit showing a texture of wackestone to packstone. **E.** Jonstorp green subunit with the Öglunda bed, showing a texture of wackestone to packstone, with frequent crinoids stem parts (1). **F.** Upper red Jonstorp subunit, showing a texture of wackestone.

11

with a texture of beige to brownish colour aphanitic mudstone to packstone (Fig. 5A, 5B). The main skeletal fragments are crinoids. It also constitutes frequent angular to rounded clasts with irregular bands. Pyrite patches and calcite filled cracks are common.

4.6. Fjäcka Shale Formation (1.14 m)

The Fjäcka Shale is a dark grey to black shale that contains the fossils of trilobites and brachiopods. It is subdivided into two subunits with thicknesses of 0.17 m and 0.97 m respectively.

4.6.1. Subunit 15: Fjäcka-dark grey mudstone -18.78 to -17.81 (0.97 m)

This subunit is composed of dark grey to almost black mudstone. The main skeletal fragments are brachiopods and trilobites. It also include a disarticulated specimen of *Tretaspis* sp. mainly fragments of the cephala. At the depth of -17.78 m, there is a 3 cm thick *Chondrites* band (Fig. 5C).

4.6.2. Subunit 16: Fjäcka- grey mudstone -17.81 to -17.64 (0.17 m)

This subunit is composed of a limestone with a texture of mudstone. The main skeletal fragments are trilobites and brachiopods. It also has patches of pyrite.

4.7 Jonstorp Formation (7.68 m)

The microfacies texture of the Jonstorp Formation varies from calcimudstone to grainstone but it mainly consists of calcimudstone. Skeletal fragments are mostly crinoids and trilobites. Within the Jonstorp Formation there are zones of two colours: a greenish grey and light pink to brownish. It is subdivided into six subunits and the thicknesses are 0.29 m, 3.72 m, 0.46 m, 0.32 m, 2.4 m and 0.49 m respectively from the bottom of the formation.

4.7.1. Subunit 17: Pyrite-rich Jonstorp -17.64 to -17.15 (0.49 m)

This subunit yields limestone with a texture of greenish calcimudstone to wackestone. The lithology is a nodular bedded limestone with reworked intraclasts. Skeletal fragments are brachiopods, crinoids and trilobites. It has grains of pyrite.

4.7.2. Subunit 18: Lower Green Jonstorp -17.15 to -14.75 (2.4 m)

This subunit is composed of a nodular bedded limestone with a texture of greenish wackestone to packstone (Fig. 5D). Skeletal fragments are mainly crinoids with some trilobite fragments. Between the depths of -15.27 m to -15.12 m, it lacks limestone nodules and has more skeletal fragments of trilobites. At the depth of -17.15 m till -15.3 m, the facies is homogeneous. At the depth of 15.8 m, thin section reveals the fragments of brachiopods and smaller aragonitic gastropod shells.

4.7.3. Subunit 19: Thin Red Jonstorp -14.75 to -14.43 (0.32 m)

This thin red oxidized subunit is quite homogeneous and has a wackestone to packstone texture. Skeletal fragment are mostly crinoids, trilobites and gastropods.

4.7.4. Subunit 20: Green Jonstorp with Öglunda: -14.43 to -13.97 (0.46 m)

This subunit can be further divided into three subfacies. From the depth of -14.43 m, a 0.23 m thick subfacies, with a texture of packstone with limestone nodules and pyrite grains occurs. At the depth of -14.45 m, fragments of brachiopods, trilobites, crinoids and gastropods are found in the thin section. Above this subfacies, at the depth of 14.25 m, there is a mixed subfacies called Öglunda bed with a thickness of 0.12 m. This subfacies has a texture of beige coloured, very fine-grained calcareous mudstone to wackestone with some pyrite. A matrix of packstone is interfiguring within the calcareous calcimudstone of the Öglunda bed. Throughout the Öglunda bed, both the mudstone and packstone facies have crinoids and trilobite fragments. The last subfacies is 0.11 m thick till the end of the subunit. It has a texture of wackestone to packstone and nodular bedding. This subfacies is light greenish in colour. Skeletal fragments are crinoids and trilobites (Fig. 5E).

4.7.5. Subunit 21: Upper Red Jonstorp -13.97 to -10.25 (3.72 m)

This subunit is composed of reddish nodular bedded limestone and has a wackestone texture. The main skeletal fragments are crinoids and trilobites
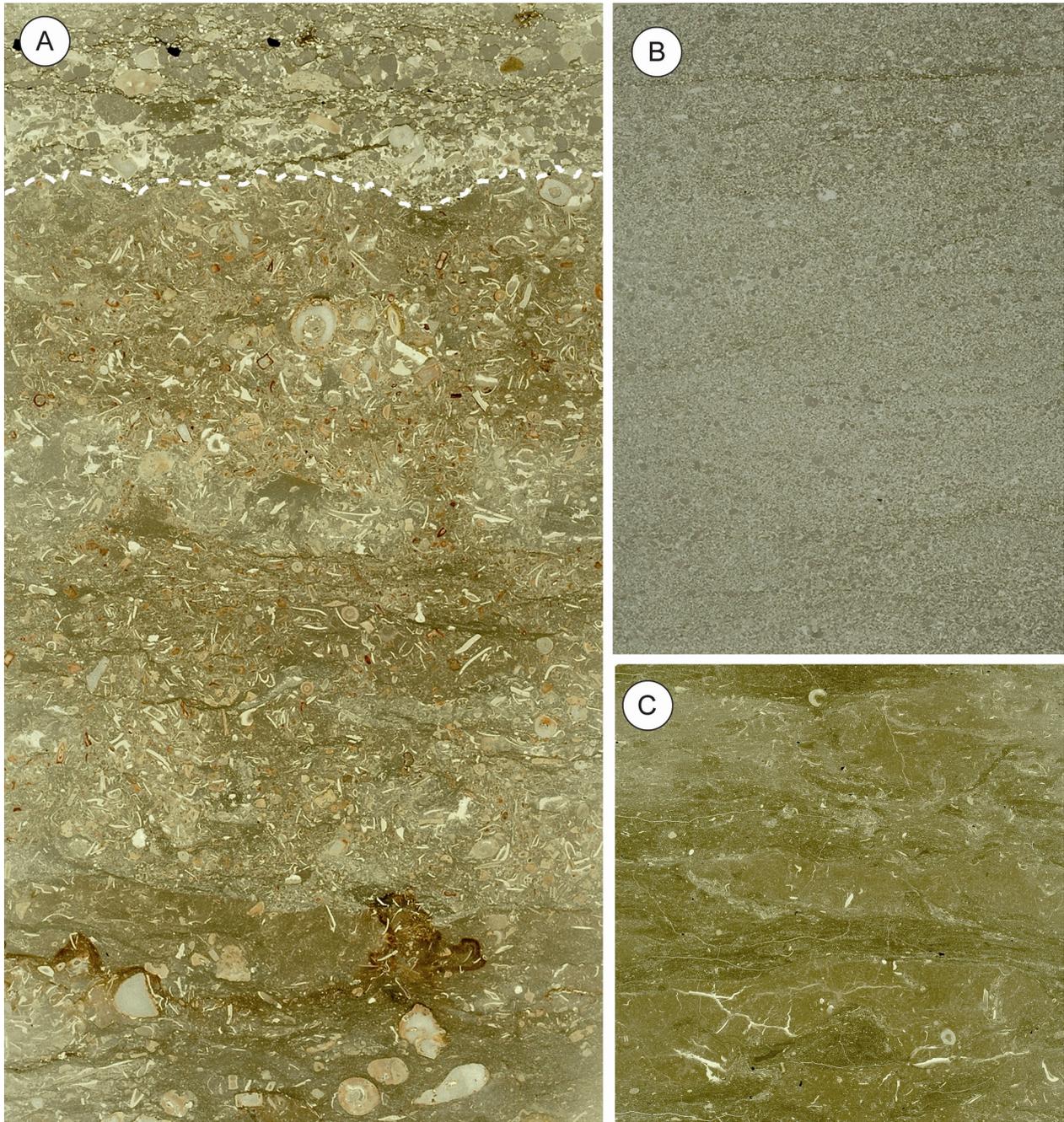
Fig. 6. Photographical plate showing thin sections of the Jonstorp Formation, Loka Formation and Motala Formation. The width of the photographs are 4 cm. **A.** Upper Jonstorp subunit, showing a texture of calcimudstone to grainstone. Dashed line demarcates the boundary between Jonstorp Formation and Loka Formation. **B.** Loka Formation, subunit1 showing a texture of grainstone. **C.** Motala Formation, subunit 3 showing a texture of calcimud-

(Fig. 5F). Skeletal fragments of crinoidal stems, brachiopods and gastropods are found in the thin section. From the bottom till the depth of -11.47 m, the facies is homogeneous. The changes of colour and skeletal fragments with nodules above the depth of -11.47 m are prominent. Slightly sharp red and the frequency of the trilobite's fragments are higher than the crinoidal fragments as compared to the interval of -13.97 till -11.47 m.

4.7.6. Subunit 22: -10.25 to -9.96（0.29 m）

The texture of this subunit is calcimudstone to grainstone. The main skeletal fragments are crinoids and trilobites but in thin section fragments of gastropods and brachiopods are also present. It also constitutes the boundary between the Jonstorp and overlying Loka formations (Fig. 6A). At the depth of -9.975m, there is a 1.5cm thick

13

interval of grainstone. The boundary of the Loka and Jonstorp formations is at a depth of 9.975 m and is associated with a clear facies shift. Above the boundary there is grainstone and below the boundary wackestone to packstone. The boundary is slightly undulating and yields truncated crinoids grains, suggesting erosion of at least semi-lithified sediment. The facies above the boundary shows the pattern of thick and thin lamination. Skeletal fragments are mainly crinoids and trilobite and most of them are oxidized and light reddish in colours. At the depth of -10.25 m the lithology is again of mudstone with limestone nodules and it continues till the depth of -10.5 m.

4.8. Loka Formation (3.48 m)

The Loka Formation is 3.48 m thick and consists of grainstone and calcimudstone. Based on stable isotope stratigraphy and facies, the upper boundary of the Loka Formation coincides with the Ordovician-Silurian boundary. The unit yields skeletal fragments of trilobites and crinoids. It is subdivided into three subunits with thicknesses of 0.62m, 0.9m and 1.96m respectively from the bottom of the formation.

4.8.1. Subunit 23: -9.96 to -8.0 (1.96 m)

This subunit is a sandy grainstone, light grey coloured and laminated (Fig. 6B). The upper boundary is marked by a rapid transition to mudstone. Limestone with abundant and rounded mudstone intraclasts of medium to coarse grain size is present. The carbonate fractions consist of current transported crinoidal grains and radial to concentric ooids. Lamination is irregular due to small-scale variation in grain size. The lower boundary is distinct and slightly undulating. The boundary appears to be sharp but loss of a small bit of core make this observation uncertain.

4.8.2. Subunit 24: -8.0 to -7.1 (0.9 m)

This is a quite homogeneous subunit. It is a light grayish colour with a texture of mudstone. It has very few skeletal fragments of trilobites and shows the evidence of bioturbation.

4.8.3. Subunit 25: -7.1 to -6.48 (0.62 m)

In the upper argillaceous interval, skeletal fragments of crinoids and trilobites are present. It is a silty mudstone till 6.88 m. As indicated by isotopic data, the upper boundary of the Loka Formation correlates with the Ordovician-Silurian boundary.

This subunit is composed of marl and mudstone. It also has skeletal fragments of crinoids and trilobites with a clear signature of bioturbation. A 7 cm thick interval with sharp mineralized boundary demarcates the Ordovician Silurian boundary. This 7 cm thick interval has two colours bands light greenish bands with more of the skeletal fragments and the light grayish with very few skeletal fragments. At the depth of 6.88 m the interval is mudstone with nodular texture, skeletal fragments of crinoids and trilobites are rare, this homogeneous interval continues till the depth of 6.63 m.

4.9. Motala Formation (6.48 m)

The Motala Formation is 6.48m thick and is composed of calcimudstone to wackestone with a nodular bedding of limestone. It has three subunits with thicknesses of 2.4m, 2.46m and 1.62m respectively from the top of the Formation.

4.9.1. Subunit 26: -6.48 to -4.86 (1.62 m)

This subunit is composed of massive calcareous mudstone. From 5.1 to 4.86 m depth there is succession of red bands within the otherwise greenish fine clay. The red band has little grains on the other hand greenish band has matrix with no skeletal grain.

4.9.2. Subunit 27: -4.86 to -2.4 (2.46 m)

This subunit is composed of bedded limestone with a calcimudstone to wackestone texture. It is dark reddish in colour with dark and light red colour bands. Trilobite and crinoid fragments are dominant in the lighter bands of wackestone while the dark reddish is more toward mudstone with few skeletal fragments of crinoids. Thin section analysis reveals few skeletal fragments of brachiopods. This unit ends with a texture of calcimudstone, dark red in colour. At the depth of 2.5 m, a 7cm thick interval with trilobite and crinoids skeletal fragments occur. At the depth of 3.625 m till 3.57 m there is dark reddish matrix with no grains.

4.9.3. Subunit 28: -2.4 to 0 (2.4 m)

This subunit has a lithology of nodular bedded limestone with texture of dark grey coloured calcimudstone to wackestone (Fig. 6C). Motala Formation ends with calcimudstone. Skeletal fragments throughout the 2.4 m unit are mainly crinoids. At the depth of 1.5 m, a 5 cm thick interval of wackestone, where the skeletal fragments is most abundant within the 2.4 m unit of Motala for-

mation, occurs. This 5 cm thick interval has light yellowish and greenish zone, light yellowish zone has most of the skeletal fragments of trilobites, crinoids and some unknown skeletal fragments while greenish zone has less fragments. From the depth of 1.8 m, core is rubbly till the depth of -1.65 m.

4.10. Depositional environment and relative sea-level

The studied core is from the Central Baltoscandian Confacies Belt, which represents an intermediate shelf setting (Jaanusson 1976). The lithofacies that occurs in the core is dominated by limestone with an abundance of different microfacies. The common textural variations associated with this type of intermediate setting is present in the core; mainly wackestone, but also calcimudstone, packstone, grainstone and rudstone/floatstone are present. Most of the subunits have two or more microfacies mixed with each other but boundaries between these can usually not be clearly demarcated. Depositional environment can easily be described, however, by applying the microfacies variations to the model proposed by Harris et al. (2004) for the East Baltic part of the basin. They grouped the microfacies into four generalized associations, including grain-supported facies, mixed facies, mud-supported facies and shale facies. These facies were interpreted in terms of depositional depth and relationship to the fair-weather wave base /FWWB) and storm wave-base (SWB). This is a simple way to present also the depositional environment graphically as shown in Figure 7. All the four facies associations occur also in the Borenhult-1 core.

4.10.1. Grain-supported facies

The grain-supported facies association consists of packstone and grainstone textures. Three subunits of the core have completely grain-supported facies and represent around 32.6 % of the core section (Table 1). The biota present in this facies is quite diverse as it derives from a high energy and shallow water environment. The association also includes radial to concentric ooids in the lower, laminated subunit of the Loka Formation. The packstone texture is mixed with other textures and is quite common throughout the entire core.

4.10.2. Mixed facies

Wackestone and packstone are the textures that constitute the bulk of the mixed facies association

(Harris et al. 2004). Nodular bedding and intercalation of intraclasts is quite frequent in this facies. The fauna present is the typical marine biota of the Ordovician period and also *Favosites* tabulate corals are found in this mixed facies. The wackestone-textured microfacies has higher clay contents and burrows than the packstone-textured microfacies. This facies association is typical for the sea-floors between the FWWB and SWB, where there is an abrupt change of the slope gradient in the generalised facies model. This facies accounts for approximately 51.3% of the core section, the highest proportion among all the facies.

4.10.3. Mud-supported facies

The most common texture within the mud-supported facies is calcimudstone while some of the wackestone texture is also part of this facies. In the generalized facies model, this facies represents a depositional environment below the storm wave-base that starts with the constant variation in the slope of the basin and ends with the abrupt change in the slope taking off into the deeper environment of the basin. The biota present in this facies is very much similar to the mixed facies and occurs predominantly in the upper Loka and Motala formations and are of Hirnantian age. In some portions of the mudstone-textured microfacies silt is more frequent than the clay, and is silty mudstone with very little carbonate. This facies accounts for 11.8% of the core section.

4.10.4. Shale facies

This facies is only represented by the black to dark grey Fjäcka Shale. It accounts for 1.58% of the core section and represents the smallest portion of the core. The facies also has *Chondrites*-like bioturbated bands. The facies has a sparse fauna consisting of brachiopods and trilobites. In the generalized facies model this facies forms in the deepest part of the basin.

4.11. Main facies shifts

As noted above, there are 28 subunits with different microfacies recognized in the core section. The temporal variation of microfacies helps to subdivide the core section into a number of facies shifts that either reflects deepening or shallowing of the depositional environment. All these shifts are based upon the information concluded from visual observations. The intra-subunit shifts do not reflect significant sea-level change whereas shifts from one association to another are interpreted as

either clear transgressions or regressions (Appendix. 1). Sedimentary data (Table 1) suggests that ten such shifts occurred in the Borenshult-1 core.

The first main facies shift is at the top of the Furudal Formation. The whole Furudal Formation is a single subunit due to the little variation in the texture and belongs to the mixed facies association. With the first major shift in the texture, the Dalby Formation starts with a grainstone texture and the whole Dalby Formation belongs to the grain-supported facies association as shown in Appendix. 1. A clear variation in the texture of Dalby Formation, however, makes it reasonable to subdivide into a lower and upper subunit. The 1.55 m thick Kinnekulle K-bentonite marks the boundary to the overlying Freberga Formation. The Freberga Formation shows four shifts in the generalised facies associations, and the Formation is subdivided into nine subunits. The lowermost three subunits (5, 6 and 7) of the Freberga belong to the mixed facies association, in which the texture is quite homogeneous except for some variation in subunit 6 that has calcimudstone to wackestone texture. The Skagen and Moldå boundary and fossils of *Favosites* provides the basis for textural subdivision in the Freberga Formation (Table 1). The subunits (8 and 9) belong to the grain-supported facies association. These two subunits are quite similar in the texture but *Trypanites* bioturbation, possible coral fossils, and abraded grains in subunit 8 constitute the difference between these two subunits. The second shift is expressed as a shift from grain-supported facies in subunit 9 to mixed facies in subunit 10. The description and interpretation of subunit 10 is not consistent with the sedimentary data, so the shift is insignificant. The third shift is also associated with subunit 10, and it is also insignificant. The fourth shift shows a major change in generalised facies. The fourth shift starts with subunit 12 and top most three subuints (12, 13 and 14) of the Freberga Formation belong to mixed facies association. The subdivision of subunits 12 and 13 are based upon texture and fossil fauna while subunit 14 belongs to the Slandrom Formation. According to the sedimentary data the Slandrom Formation constitutes a texture of calcimudstone to packstone that belongs to mixed facies association but its description and interpretation does not match with the mixed facies (Calner et al. 2010b). The sixth shift shows the highest sea-level rise in the Ordovician as shown in (Appendix. 1), it starts with the subunit 15. The subunits 15 and 16 belong to the shale facies association. The subdivision of the Fjäcka Shale is based upon their colour and degree of bioturbation, subunit 15 has *Chondrites* and dark grey to almost black coloured shale. The seventh shift takes a texture into calcimudstone to wackestone of the subunit 17 of the Jonstorp Formation and belongs to the mud-supported facies association. The number

Table 1. Formations and textural composition and thickness of the 28 subunits in the Borenshult-1 core and their grouping into the facies associations adopted in the facies model.

| Main Units | Subunits | depth (m) | thickness (m) | Dunham Textures | | | | | | | | | | bentonite |
				Shale	calcimud	mud-wack	mud-wack-pack	mud-wack-pack-grain	wack	wack-pack	wack-pack-grain(rud/float)	pack-grain	grain	bentonite
Furudal	1	71.33-56.51	14,82							20,7				
Dalby	2	56.51-42	14,51										20,3	
Limestone	3	42-38.350	3,65									5,11		
Kinne Kulle	4	38.350-36.75	1,6											2,24
F	5	36.75-29.37	7,38							10,3				
r	6	29.37-26.90	2,47			3,46								
e	7	26.90-24.55	2,35							3,29				
b	8	24.55-22.27	2,28								3,19			
e	9	22.27-21.88	0,39								0,546			
r	10	21.88-21.38	0,5							0,7				
g	11	21.38-20.80	0,58								0,813			
a	12	20.80-20.20	0,6						0,841					
	13	20.20-19.90	0,3							0,42				
Slandrom	14	19.90-18.78	1,12				1,57							
Fjäcka	15	18.78-17.81	0,97	1,35										
Shale	16	17.81-17.64	0,17	0,238										
Jonstorp	17	17.64-17.15	0,49			0,686								
	18	17.15-14.75	2,4							3,36				
	19	14.75-14.43	0,32							0,448				
	20	14.43-13.97	0,46				0,644							
	21	13.97-10.25	3,72						5,21					
	22	10.25-9.96	0,29					0,406						
Loka	23	9.96-8.0	1,96										2,74	
	24	8.0-7.1	0,9		1,26									
	25	7.1-6.48	0,62		0,869									
Motala	26	6.48-4.86	1,62		2,27									
	27	4.86-2.4	2,46				3,44							
	28	2.4-0	2,4		3,36									
			71,33	1,588	7,759	4,126	5,674	0,406	6,051	39,218	4,549	5,11	23	2,24
Facies Associations				black shale	mud-supported facies		mixed facies				grain-supported facies			no textur
				1,588	11,885		51,349				32,699			2,24
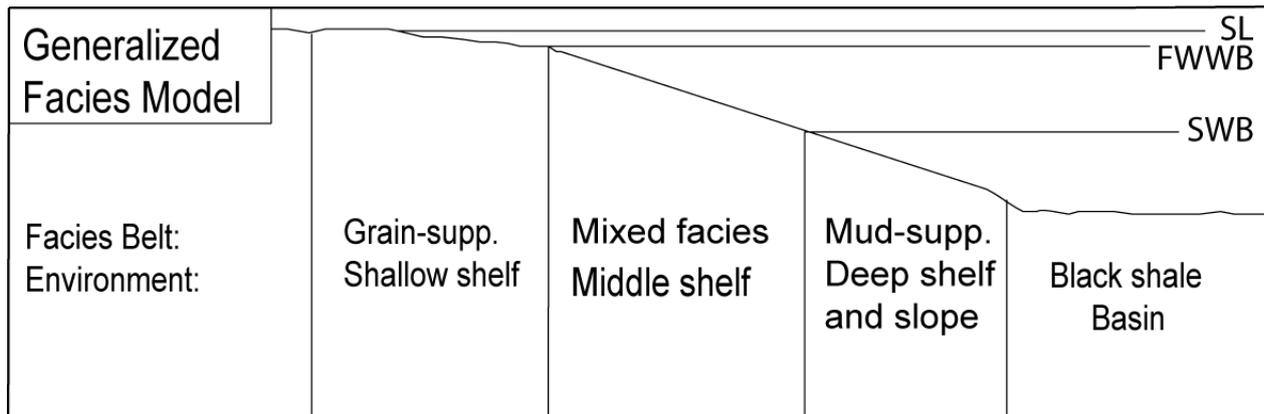
Fig. 7. Facies model for the Upper Ordovician of southern Sweden. Key to abbreviations: SL = sea-level, FWWB = fair-weather wave-base, SWB = storm wave-base. Modified from Harris et al. (2004).

eight shift is at the base of subunit 18 and the overlying starta belong mixed facies association, and it has four subunits (19, 20, 21 & 22). All these four subunits including subunit 18 belongs to the Jonstorp Formation, the subdivision of all these subunits are based upon their textures. Subunits 18 and 19 have almost the same textures, although subunit 18 is green while subunit 19 is red in colour. Subunit 20 is a prominent subunit within the Jonstorp Formation due to the Öglunda bed. Subunits 21 and 22 have differences in their texture, subunit 21 has wackestone while subunit 22 has calcimudstone to grainstone texture. The ninth shift takes into the grainstone texture of the Loka Formation of subunit 23 and belongs to the grain-supported facies association. This shift is associated with a major regression as shown in Appendix. 1. The tenth shift occurs at the base of subunit 24 and five subunits (24, 25, 26, 27 and 28) belong to the mud-supported facies association. All these five subunits also belong to the upper Loka and Motala formations. The subunits 24 and 25 of the Loka Formation have almost the same texture the only difference in both the subunits is clay contents, subunit 25 has more clay than the subunit 24. Subunits 26, 27 and 28 of the Motala Formation, deposited in Silurian, have only little differences in them. Subunit 26 composed of a texture of calcimudstone, while subunits 27 and 28 have the same texture of calcimudstone to wackestone, the only difference in them is colour, subunit 27 is dark red and subunit 28 is dark grey in colour.

4.12. Stable isotope stratigraphy

The carbon isotope analysis of the studied core shows six positive peaks (Appendix. 1). Almost all the peaks lie in the Katian Stage except the biggest peak, HICE, which corresponds to the Hirnantian. The two most prominent excursions, GICE and HICE, have previously well established global correlation and are found in a number of localities in North America, Baltoscandia and China (Kaljo et al. 2004; Bergström et al. 2007; Bergström et al. 2009b; Schmitz et al. 2010), whereas the four small excursions are currently less well known and only three of these small excursions are traced from North America to Baltoscandia (Schmitz et al. 2010). From the bottom of the core, carbon isotopic values are very much constant and close to the value of +1 per mil. The δ^{13}C values show a smooth curve with very little variations in the values within the Furudal and Dalby limestone and continue till the Kinnekulle K-bentonite time. The δ^{13}C analysis does not show the MDICE peak in the core, and hence the recovered core section does not include the mid-Darriwilian.

The first peak of the Upper Ordovician is GICE that reaches a maximum carbon isotopic value of +1.88 per mil just below the conglomerate at the Skagen and Moldå boundary in the Freberga Formation. The δ^{13}C peak-value of GICE in the Borenshult-1 core is less than the generalized global carbon isotope curve of Bergström et al. (2009b) and the regional carbon isotope curve of Ainsaar et al. (2010). The two almost equal in terms of their absolute carbon isotopic value peaks, namely Kope and Fairview in the Katian Stage, also have lower values than in the generalized carbon isotopic curves while the Fairview seems to be absent in the Baltoscandian regional curve. Both the Kope and Fairview peaks lies in the Freberga Formation with the values of 1.38 and 1.40 respectively. Waynesville is the next

value than the corresponding peak in the global curve but less than in the regional curve. It is associated with the Slandrom Formation. The next peak is Whitewater and it has a lower value than the Waynesville while both the global and regional generalized curves represent the bigger excursions. The value of Whitewater peak in the core is +1.53 per mil and lies in the Lower green Jonstorp. The highest carbon isotopic value among all excursions is in the latest Ordovician (Hirnantian Stage) with a value of +3.72 per mil , This value has comparatively lower value than the generalized curves of the global and regional carbon isotopic values that shows a value higher than +5.

5. Discussion

The observation about the facies and the fauna described in the core description section and the carbon isotope data provide the basis for interpretation of Ordovician sea-level and climate. The upper Ordovician is coupled with major sea-level changes globally (Nielsen 2004; Page et al. 2007), and have left marks also in the Baltoscandian Basin. The four glacial maxima and associated regressions of the upper Ordovician are closely related with high carbon isotope values (Page et al. 2007). This is also the case in Baltoscandia.

The first regression is marked by the first facies shift (Table 1) at the top of the Furudal Formation, which has a wackestone to packstone texture to the grainstone of the lower Dalby Limestone (Appendix. 1). δ^{13}C values at this level do not show any indication of a regression but the strong textural shift shows a local sea-level change within the basin. A transgression is evident with a shift from grainstone to packstone in the upper Dalby Limestone. The absence of the cystoids and the packstone texture are the evidences which support the transgression in the upper Dalby. From the bottom of the Borenshult-1 core, the δ^{13}C is quite constant before the upper Sandbian, where the GICE started Appendix. 1. The δ^{13}C value of GICE is high and corresponds to the Guttenberg regression of Page et al. (2007). At the end of the GICE regression the second transgression and deepening of the basin is evident from the calcimudstone texture in subunit 6. The middle Katian also has high δ^{13}C values within the Slandrom Formation and corresponds to the early Asghill regression of Page et al. (2007). The isotope curve based on the Borenshult-1 core shows three small δ^{13}C peaks between GICE and the early Asghill regression. The strata formed during the first peak yield fossils of the *Favosites* coral reflecting a shallowing of the sea. The subsequent two peaks have the microfacies of wackestone to packstone, also interpreting the shallower sea. At the end of the early Asghill regression, a transgression is evident in the Fjäcka Shale (Calner et al. 2010a, b). The large δ^{13}C peak associated with the Hirnantian glaciation corresponds to one of the most

significant sea-level changes in the Ordovician. In the Jonstorp Formation calcimudstone is a dominant texture indicating a deeper depositional environment before the start of the HICE glaciation. In the Ordovician the last transgression of the Borenshult-1 core is defined by a texture of calcimudstone in the upper Loka Formation just after the HICE. The three main regressions of the Borenshult-1 core are well correlated with global sea-level changes of the Ordovician Period. The five possible transgressions and four regressions occurred during the upper Ordovician to lower most Silurian of the Borenshult-1 core.

The interpretation of the microfacies in terms of sea-level change and other evidences for sea-level changes is convincing and consistent with the chronostratigraphic evidences of the global sea-level curve with few exceptions. In the Freberga Formation, subunit 6 has a texture of calcimudstone to packstone, and belongs to the mixed facies association. At the base of subunit 6, the calcimudstone texture is interpreted as a deepening of the basin that continues untill the Skagen and Moldå boundary where conglomerates are found and interpreted as a hiatus, above this hiatus a texture changes significantly to a more packstone texture that reflects a regression. The isotopic, faunal and textural information suggest that the regression is Guttenberg regression of Page et al. (2007). The microfacies is wackestone to packstone and fossils of coral reflects a shallowing of the sea. In subunit 10 of the Freberga Formation, texture is not compatible with the interpretations and the evidences. Sedimentary data suggest that subunit 10 belongs to the mixed facies association with a texture of wackestone to packstone although subunit 10 resembles the Slandrom Formation and also has glauconite which reflects shallower marine environment as shown in the sea-level curve (Fig. 8). The next sea-level fall is represented by the early Asghill regression. This regression is manifested in the Slandrom Limestone by solution structures and several types of karst type morphologies (Calner et al. 2010b). These karst features are interpreted as a major sea-level drop. The last regression in the upper Ordovician is the Hirnantian glaciation, which has a well established global correlation. The microfacies is a laminated grainstone with radial to concentric ooids, reflecting the shallowing of the sea in Hirnantian time.

The interpretations based upon the observations suggest three prominent regressions and five transgressions. The problem arises in constructing the sea-level curve, when using all type of observations like microfacies, δ^{13}C data, and faunal observation. The subunits within the formations have varied texture, from calcimudstone to grainstone, in order to resolve the textural problem a table of sedimentary data is constructed by using the textural observations. The generalised facies model of Harris et al. (2004) is also used in generalizing the microfacies of the sedimentary data. Sedimentary data, carbon isotope data, faunal and other observations

are combined to interpret in light of evidences, available information and knowledge to construct Ordovician sea-level curve.

6. Conclusions

The conclusions inferred by the study are as follow:

● The Upper Ordovician through lowermost Silurian succession of the Borenshult-1 core can be subdivided into nine main units which furthermore are subdivided into twenty-eight subunits.

● The lithofacies, microfacies textures, and faunal information reflect a cool-water carbonate shelf setting of intermediate depths but which varied with sea-level regressions and transgressions. Four regressions with subsequent transgressions are recorded in the starta of the Borenshult-1 core. Lower Dalby, middle Freberga, Slandrom and the Loka formations show evidences of regressions in their stratigraphic interval, while subsequent sea-level rises are evidenced by transgressive facies in the upper Dalby, middle Freberga Formation, Fjäcka Shale and upper Loka Formation.

● The fauna found in the Borenshult-1 core stratigraphy reflects the normal cool-water Ordovician ecological assemblages. With the exceptions of the finding of *Favosites* sp. specimens in the Freberga Formation and radial to concentric ooids in the Loka Formation, which are indicative of tropical climates.

● The carbon isotopic data shows six positive peaks and have well defined correlation globally.

7. Acknowledgements

8. References

Ainsaar, L., Kaljo, L., Martma, T., Meilda, T., Männik, P., Nõlvak, J. & Tinn, O., 2010: Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology*.

Ainsaar, L., Meidla, T. & Martma, T., 2004: The Middle Caradoc Facies and Faunal Turnover in the Late Ordovician Baltoscandian palaeobasin. *Palaeogeography, Palaeoclimatology, Palaeoecology 210,* 119-1333.

Ainsaar, L., Meilda, T. & Martma, T., 1999: Evidence for a widespread carbon isotopic event associated with late Middle Ordovician sedimentological and faunal changes in Estonia. *Geological Magazine 136,* 49-62.

Baarli, B.G., Johnson, M.E. & Antoshkina, A.I., 2003: Silurian stratigraphy and paleogeography of Baltica. In E. Landing & M.E Johnson (eds): *Silurian Lands and Seas-Paleogeography outside of Laurentia,* 3-34. New York State Museum Bulletin 493.

Bergström, J., 1968: Upper Ordovician brachiopods from Västergötland, Sweden. *Geologica et Palaeontologica 2,* 1-35.

Bergström, S.M. & Bergström, J., 1996: The Ordovician -Silurian boundary successions in Östergötland and Västergötland, S. Sweden. *GFF 118,* 25-42.

Bergström, S.M., Chen, X., Gutiérrez-Marco, J.C. & Doronov, A., 2009b: The new chronostratigraphic classification of the Ordovician System and its relation to major regional series and stages and to $\delta^{13}C$ chemostratigraphy. *Lethaia 42,* 1-11.

Bergström, S.M., Schmitz, B., Saltzman, M.R. & Huff, W.D., 2009c: The Upper Ordovician Guttenberg $\delta^{13}C$ excursion (GICE) in North America and Baltoscandia: occurrence, chronostatigraphic significance, and palaeoenvironmental relationship. *Geol Soc Am Spec Paper* (in press).

Bergström, S.M., Xu, C., Schmitz, B., Young, S., Jia-Yu, R. & Saltzman, M.R., 2009a: First documentation of the Ordovician Guttenberg $\delta^{13}C$ excursion (GICE) in Asia: chemostratigraphy of the Pagoda and Yanwashan formations in southeastern China. *Geological Magazine 146,* 1-11.

Bergström, S.M., Young, S., Schmitz, B. & Saltzman,

M.R., 2007: Upper Ordovician (Katian) $^{\delta 13}$C chemostratigraphy: a transatlantic comparison. *Acta Palaeontol Sin 46,* 37-39.

Brenchley, P.J., Carden, G.A., Hints, L., Kaljo, D., Marshall, J.D., Martma, T., Meidla, T. & Nõlvak, J., 2003: High-resolution stable isotope stratigraphy of Upper Ordovician sequences: Constraints on the timing of bioevents and environmental changes associated with mass extinction and glaciations. *GSA Bulletins 115,* 89-104.

Brenchley, P.J., Marshall, J.D., Carden, G.A., Robertson, D.B.R., Long, D.G.F., Meidla, T., Hints, L. & Anderson, T, F., 1994: Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciations in a greenhouse period. *Geology 22,* 295-298.

Calner, M., Lehnert, O. & Joachimski, M., 2010a: Carbonate mud mounds, conglomerates, and sea-level history in the Katian (Upper Ordovician) of central Sweden. *Facies 56,* 157-172.

Calner, M., Lehnert, O. & Nõlvak, J., 2010b: Palaeokarst evidence for widespread regressionand subaerial exposure in the middle Katian (Upper Ordovician) of Baltoscandia: Significance for global climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* in press.

Cocks, L.R.M. & Torsvik, T.H., 2002: Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. *Journal of the Geological Society, London 159,* 631-644.

Dunham, R.J., 1962: Classification of carbonate rocks according to depositional texture. *In* W.E. Ham (ed.): *Classifiaction of carbonate rocks,* 108-121. *Memoirs – American Association of Petroleum Geologists 1.*

Ebbestad, J.O.R., Wickström, L.M. & Högström, A.E.S., 2007: *WOGOGOB 9th meeting of the Working Group on Ordovician Geology of Baltoscandia IGCP503 Ordovician Palaeogeography and Palaeoclimate Regional Meeting 2007. Field guide and Abstract . Sveriges geologiska undersökning, Rapporter och meddelanden 128.*

Embry, A.F. & Klovan, J.E., 1971: A late Devonian reef tract on northeastern Banks Island, Northwest Territories. *Bulletin of Canadian Petroleum Geology 19,* 730-781.

Flügel, E., 2004: *Microfacies of carbonate rocks: analysis, interpretation and application,.* Springer Verlag. 976 pp.

Hansen, J., Nielsen, J.K. & Hanken, N.M., 2009: The relationships between Late Ordovician sea-level changes and faunal turnover in western Baltica: Geochemical evidence of oxic and dysoxic bottom-water conditions. Palaeogeography, Palaeoclimatology, Palaeoecology *271,* 268-278.

Harris, M.T., Sheehan, P.M., Ainsaar, L., Hints, L., Männik, P., Nõlvak, J. & Madis, R., 2004: Upper Ordovician sequences of western Estonia. *Palaeogeography, Palaeoclimatology, Palaeoecology 210,* 135-148.

Hatch, J.R., Jacobson, S.R., Witzke, B.J., Risatti, J.B., Anders, D.E., Watney, W.L., Newel, K.D. & Vuletich, A.K., 1987: Possible late Middle Ordovician organic carbon isotope excursion: evidence from Ordovician oils and hydrocarbons source rocks, mid-continent and east central United States. *Am Assoc Pet Geol Bull 71,* 1342-1354.

Jaanusson, V., 1976: Faunal dynamics in the Middle Ordovician (Viruan) of Baltoscandia. *In* M.G. Bassett (ed.): The Ordovician System. *Proceedings of a Palaeontological Association Symposium, Birmingham, September 1974,* 301-326. University of Wales Press and National Museum of Wales, Cardiff.

Jaanusson, V., 1995: Confacies differentiation and upper Middle Ordovician correlation in the Baltoscandian basin. In: *Proceedings of the Estonian Academy of Sciences. Geology 44*, 73-86.

Jaanusson, V. 1982. Description of the sequence. In *Ordovician of Öland. Guide to Excursion 3 – IV International Symposium on the Ordovician System. In* Jaanusson, V. & Mutvei, H (eds) , 1– 9.

Jablonski, D., 1991: Ectinctions: A Paleontological perspective. *Science 253,* 754-757.

Jönsson, A.J,. 1887: Beskrifning till kartbladet Motala. *Sveriges Geologiska Undersökning Aa 102,* 1-50.

Kaljo, D. & Nestor, H., 1990: Field meeting Estonian 1990: An Excursion Guidebook. *Estonian Academy of Sciences, Tallinn.*

Kaljo, D., Hints, L., Martma, T., Nõlvak, J. & Oraspõld, A., 2004: Late Ordovician carbon isotope trend in Estonia, its significance in stratigraphy and environmental analysis. *Palaeogeogr Palaeoclimatol Palaeoecol 210,* 165-185.

Kaljo, D., Martma, T. & Saadre, T., 2007: Post-Hunnebergian Ordovician carbon isotope trend in Baltoscandia, its environmental implications and some similarities with that of Nevada. *Palaeogeography, Palaeoclimatology, Palaeoecology 245,* 138-155.

Männil, R., 1966: Istoriya razvitiya Baltiiskogo basseina

v ordovike. *Valgus Publishers, Tallinn* (in Russian with English Abstr.).

Meilda, T., Ainsaar, L., Backman, J., Dronov, A., Holmer, L. & Sturesson, U., 2004: Middle-upper ordovician carbon isotope record from Västergötland (Sweden) and East Baltic. *In:* Hints, O & Ainsaar, L. (eds) *WOGOGOB-2004* conference materials. Tartu university press, Tartu, 67-68.

Nielsen, A.T., 2004: Ordovician sea level changes: a Baltoscandian perspective, In: Webby, B.D., Paris, F., Droser, M., Percival, I., (Eds.) The Great Ordovician Diversification Event. Columbia University Press, New York, 84-93.

Page, A., Zalasiewicz, J., Williams, M. & Popov, L., 2007: Were transgressive black shales a negative feedback modulating glacioeustasy in the Early Palaeozoic Icehouse?. I*n* Williams, M., Haywood, A.M., Gregory, F.J. & Schmidt, D.N. (eds) *Deep time Perspective on Climate Change: Marrying the Signal from Computer Models and Biological Proxies. The Micropalaentological Society, The Geological Society of London,* 67-101pp. Springer, Berlin.

Raukas, A. & Teedumäe, A., 1997: Geology and Mineral Resources of Estonia. *Estonian Academy Publishers, Tallinn 436.*

Schmitz, B., Bergström, S.M. & Xiaofeg, W., 2010: The middle Darriwilian (Ordovician) δ^{13}C excursion (MDICE) discovered in the Yangtze Platfrom succession in China: implication of its first recorded occurrences outside Baltoscandia. *Journal of the Geological Society 167,* 249-259.

Sepkoski, J.J., Jr., 1993: Ten years in the library: New data confirm paleontological patterns. *Paleobiology 19,* 43-51.

Servais, T., Harper, D.A.T., Li, J., Munnecke, A., Owen, W.A. & Sheehan, P.M., 2009: Understanding the great ordovician biodiversification event (GOBE): Influences of paleogeography, paleoclimate or paleoecology. *GSA today 19,* 4-10.   Till here & check

Sheehan, P.M. & Harris, M.T., 2004: Microbialite resurgence after the Late Ordovician extinction. *Nature 430,* 75-78.

Stouge, S., 2004: Ordovician siliciclastics and carbonates of Öland, Sweden. International Symposium on ''Early Palaeozoic Palaeogeography and Palaeoclimate'' (IGCP 503), September 1-3, 2004, Erlangen, Germany: In: Munnecke, A., Servais, T., Schulbert, C, (Eds.), Erlanger Geologische Abhandlungen Sonderband , *vol 5,* 91-111.

Stridsberg, S., 1980: Sedimentology of Upper Ordovician regressive strata in Västergötland, *Geologiska Föreningens i Stockholm Förhandlingar 102,* 213-221.

Thorslund, P., 1960: The Cambro-Silurian of Sweden. *Sveriges Geologiska Undersökning Ba 6,* 69-110.

Törnquist, S.L., 1875: Berättelse om en geologisk resa genom Skånes och Östergötlands paleozoiska trakter, sommaren 1875, inlemnad till Kongl. Vetenskaps-Akademien. *Öfversikt af Kongl.Vetenskaps-Akademiens Förhandlingar 1875, 10,* 43-70.

Törnquist, S.L., 1913: Några anmärkningar om indelningar inom Sveriges kambro-silur. *Geologiska Föreningens i Stockhom Förhandlingar 35,* 407-438.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A. & Walderhaug, H.J., 1996: Continental breakup and collision in the Neoproterozoic and Palaeozoic-A tale of Baltica and Laurentia. *Earth Science Review 40,* 229-258.

Troedsson, G.T., 1918: Om Skånes brachiopodskiffer. *Lunds Universitets Årskrift, N.F., 2, 15(3),* 1-111.

Underwood, C.J., Crowley, S.F., Marshall, J.D. & Brenchley, P.J., 1997: High-resolution carbon isotope stratigraphy of the basal Silurian stratotype (Dob's Linn, Scotland) and its global implication. *Geological Society (London) Journal 154,* 709-718.

Waern, B., 1960: On the middle Llandrovery of Dalarna. *International Geological Congress, Report of 21st Session, VII,* 126-133.

Wikman, H., Bruun, Å., & Dahlman, B., 1980: Beskrivning till berggrundskartan Linköping NV. *Sveriges Geologiska Undersökning Af 119,* 1-105.

Wikman, H., Bruun, Å., Dahlman, B., & Vidal, G., 1982: Beskrivning till berggrundskartan Hjo NO. *Sveriges Geologiska Undersökning Af 120,* 1-112.

Wiman, C., 1908: Studien über das nordbaltische Silurgebiet II. *Bulletin of the Geological institution of the University of Upsala 8,* 73-168.

Tidigare skrifter i serien ”Examensarbeten i Geologi vid Lunds Universitet”:

210. Erlandsson, Maria, 2007: Den geologiska utvecklingen av västra Hamrångesyn-klinalens suprakrustalbergarter, centrala Sverige.
211. Nilsson, Pernilla, 2007: Kvidingedeltat – bildningsprocesser och arkitektonisk uppbyggnadsmodell av ett glacifluvialt Gilbertdelta.
212. Ellingsgaard, Óluva, 2007: Evaluation of wireline well logs from the borehole Kyrkheddinge-4 by comparsion to measured core data.
213. Åkerman, Jonas, 2007. Borrkärnekartering av en Zn-Ag-Pb-mineralisering vid Sten-brånet, Västerbotten.
214. Kurlovich, Dzmitry, 2007: The Polotsk-Kurzeme and the Småland-Blekinge Defor-mation Zones of the East European Craton: geomorphology, architecture of the sedimentary cover and the crystalline basement.
215. Mikkelsen, Angelica, 2007: Relationer mellan grundvattenmagasin och geologiska strukturer i samband med tunnelborrning genom Hallandsås, Skåne.
216. Trondman, Anna-Kari, 2007: Stratigraphic studies of a Holocene sequence from Taniente Palet bog, Isla de los Estados, South America.
217. Månsson, Carl-Henrik & Siikanen, Jonas, 2007: Measuring techniques of Induced Polarization regarding data quality with an application on a test-site in Aarhus, Denmark and the tunnel construction at the Hallandsås Horst, Sweden.
218. Ohlsson, Erika, 2007: Classification of stony meteorites from north-west Africa and the Dhofar desert region in Oman.
219. Åkesson, Maria, 2008: Mud volcanoes - a review. (15 hskp)
220. Randsalu, Linda, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta1 and Ta3 basins. (30 hskp)
221. Fredh, Daniel, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta4 basin. (30 hskp)
222. Anjar, Johanna, 2008: A sedimentological and stratigraphical study of Weichselian sediments in the Tvärkroken gravel pit, Idre, west-central Sweden. (30 hskp)
223. Stefanowicz, Sissa, 2008: Palyno-stratigraphy and palaeoclimatic analysis of the Lower - Middle Jurassic (Pliens-bachian - Bathonian) of the Inner Hebrides, NW Scotland. (15 hskp)
224. Holm, Sanna, 2008: Variations in impactor flux to the Moon and Earth after 3.85 Ga. (15 hskp)
225. Bjärnborg, Karolina, 2008: Internal structures in detrital zircons from Hamrånge: a study of cathodolumine-scence and back-scattered electron images. (15 hskp)
226. Noresten, Barbro, 2008: A reconstruction of subglacial processes based on a classification of erosional forms at Ramsvikslandet, SW Sweden. (30 hskp)
227. Mehlqvist, Kristina, 2008: En mellanjuras-sisk flora från Bagå-formationen, Bornholm. (15 hskp)
228. Lindvall, Hanna, 2008: Kortvariga effekter av tefranedfall i lakustrin och terrestrisk miljö. (15 hskp)
229. Löfroth, Elin, 2008: Are solar activity and cosmic rays important factors behind climate change? (15 hskp)
230. Damberg, Lisa, 2008: Pyrit som källa för spårämnen – kalkstenar från övre och mellersta Danien, Skåne. (15 hskp)
331. Cegrell, Miriam & Mårtensson, Jimmy, 2008: Resistivity and IP measurements at the Bolmen Tunnel and Ådalsbanan, Sweden. (30 hskp)
232. Vang, Ina, 2008: Skarn minerals and geological structures at Kalkheia, Kristiansand, southern Norway. (15 hskp)
233. Arvidsson, Kristina, 2008: Vegetationen i Skandinavien under Eem och Weichsel samt fallstudie i submoräna organiska avlagringar från Nybygget, Småland. (15 hskp)
234. Persson, Jonas, 2008: An environmental magnetic study of a marine sediment core from Disko Bugt, West Greenland: implications for ocean current variability. (30 hskp)
235. Holm, Sanna, 2008: Titanium- and chromium-rich opaque minerals in condensed sediments: chondritic, lunar and terrestrial origins. (30 hskp)

236. Bohlin, Erik & Landen, Ludvig, 2008: Geofysiska mätmetoder för prospektering till ballastmaterial. (30 hskp)

237. Brodén, Olof, 2008: Primär och sekundär migration av hydrokarboner. (15 hskp)

238. Bergman, Bo, 2009: Geofysiska analyser (stångslingram, CVES och IP) av lagerföljd och lakvattenrörelser vid Albäcksdeponin, Trelleborg. (30 hskp)

239. Mehlqvist, Kristina, 2009: The spore record of early land plants from upper Silurian strata in Klinta 1 well, Skåne, Sweden. (45 hskp)

239. Mehlqvist, Kristina, 2009: The spore record of early land plants from upper Silurian strata in Klinta 1 well, Skåne, Sweden. (45 hskp)

240. Bjärnborg, Karolina, 2009: The copper sulphide mineralization of the Zinkgruvan deposit, Bergslagen, Sweden. (45 hskp)

241. Stenberg, Li, 2009: Historiska kartor som hjälp vid jordartsgeologisk kartering – en pilotstudie från Vångs by i Blekinge. (15 hskp)

242. Nilsson, Mimmi, 2009: Robust U-Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland: constraints on the coherency of crustal blocks of the North Atlantic Craton. (30 hskp)

243. Hult, Elin, 2009: Oligocene to middle Miocene sediments from ODP leg 159, site 959 offshore Ivory Coast, equatorial West Africa. (15 hskp)

244. Olsson, Håkan, 2009: Climate archives and the Late Ordovician Boda Event. (15 hskp)

245. Wollein Waldetoft, Kristofer, 2009: Svekofennisk granit från olika metamorfa miljöer. (15 hskp)

246. Månsby, Urban, 2009: Late Cretaceous coprolites from the Kristianstad Basin, southern Sweden. (15 hskp)

247. MacGimpsey, I., 2008: Petroleum Geology of the Barents Sea. (15 hskp)

248. Jäckel, O., 2009: Comparison between two sediment X-ray Fluorescence records of the Late Holocene from Disko Bugt, West Greenland; Paleoclimatic and methodological implications. (45 hskp)

249. Andersen, Christine, 2009: The mineral composition of the Burkland Cu-sulphide deposit at Zinkgruvan, Sweden – a supplementary study. (15 hskp)

250. Riebe, My, 2009: Spinel group minerals in carbonaceous and ordinary chondrites. (15 hskp)

251. Nilsson, Filip, 2009: Föroreningsspridning och geologi vid Filborna i Helsingborg. (30 hskp)

252. Peetz, Romina, 2009: A geochemical characterization of the lower part of the Miocene shield-building lavas on Gran Canaria. (45 hskp)

253. Maria Åkesson, 2010: Mass movements as contamination carriers in surface water systems – Swedish experiences and risks.

254. Elin Löfroth, 2010: Elin Löfroth, 2010: A Greeland ice core perspective on the dating of the Late Bronze Age Santorini eruption. (45 hskp)

255. Óluva Ellingsgaard, 2009: Formation Evaluation of Interlava Volcaniclastic Rocks from the Faroe Islands and the Faroe-Shetland Basin. (45 hskp)

256. Arvidsson, Kristina, 2010: Geophysical and hydrogeological survey in a part of the Nhandugue River valley, Gorongosa National Park, Mozambique. (45 hskp)

257. Gren, Johan, 2010: Osteo-histology of Mesozoic marine tetrapods – implications for longevity, growth strategies and growth rates. (15 hskp)

258. Syversen, Fredrikke, 2010: Late Jurassic deposits in the Troll field. (15 hskp)

259. Andersson, Pontus, 2010: Hydrogeological investigation for the PEGASUS project, southern Skåne, Sweden. (30 hskp)

260. Noor, Amir, 2010: Upper Ordovician through lowermost Silurian stratigraphy and facies of the Borenshult-1 core, Östergötland, Sweden. (45 hskp)

LUNDS UNIVERSITET