THESIS

DEPOSITIONAL ENVIRONMENT AND FACIES ARCHITECTURE OF THE LOWER TO MIDDLE ORDOVICIAN CARBONATE RAMP SUCCESSION, ÖLAND, SOUTHERN SWEDEN

Submitted by

Ali Riza Cigri

Department of Geosciences

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Master's Committee:

Advisor: Sven Egenhoff

John Ridley
Gamze Çavdar

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ABSTRACT

DEPOSITIONAL ENVIRONMENT AND FACIES ARCHITECTURE OF THE LOWER TO MIDDLE ORDOVICIAN CARBONATE RAMP SUCCESSION, ÖLAND, SOUTHERN SWEDEN

The Lower to Middle Ordovician carbonates of Öland, southern Sweden, exhibit outcrops of up to 12 m thickness and rest conformably on Cambrian black shales of the Alum Formation. Based on lithological and sedimentological characteristics, nine carbonate facies were identified within the successions that are grouped into four facies associations (FAs). FA 1 is composed of glauconite- bearing mud- to wackestone facies. FA 2 consists of three glauconite- and one glauconite- and Fe-ooid bearing mud- to packstone carbonate facies. Deposits of FA 3 are carbonate mud- to wackestone facies. FA 4 is characterized by one Fe- ooid bearing and four other mud- to packstone carbonate facies.

The studied carbonate succession is subdivided into three stratigraphic units referred to as Intervals 1 to 3. Interval 1 consists of the Köpingsklint and Bruddesta Formations located at the base of the succession. Interval 2 is composed of the Horns Udde formation in the middle level of the succession, and Interval 3 is characterized by the Gillberga Formation situated at the top of the succession.

FA 1 rocks were deposited in an offshore proximal setting, whereas FA 2 records an offshore distal setting during “starved” times. FA 3 and FA 4 rocks were deposited during the “normal” times reflecting offshore proximal and distal settings, respectively.

Heterozoan assemblages, allochthonous Fe- ooids, and abundance of carbonate mud within the facies suggest that the studied carbonate succession experienced temperate to sub-tropical sea-water conditions during deposition despite its paleo-latitudes equivalence to what would be temperate to cool-water environments of modern examples.

Three 3rd order sequences having regressive systems tracts (RSTs) and transgressive systems tracts (TSTs) bounded by maximum regressive surfaces (MRSs) were determined within the studied succession based on the transgressive versus regressive sequence stratigraphic model. The MRSs are situated at the top of the RSTs reflecting maximum sea-level drops. Interval 1 is interpreted to represent both TST and RST characterized by glauconite-bearing facies, and have a sequence boundary (MRS) at the base. Interval 2 contains two sequence boundaries (MRSs) and is comprised of two TST and one RST characterized by carbonate facies. Interval 3 has a sequence boundary (MRS) at the top and is composed of one RST discriminated by glauconite-bearing facies.

The Lower to Middle Ordovician carbonates and their subsurface equivalence have high potential in terms of conventional and unconventional petroleum exploration based on their lithologic character and positions in the Paleozoic petroleum system in the Baltic Sea of Scandinavia and adjacent areas.

ACKNOWLEDGEMENTS

I would like to express my very great appreciation to my advisor, Dr. Sven Egenhoff, for his endless interest, help, and patience. I am particularly grateful for the discussions and revisions of the text that we had through this degree earning. I wish to acknowledge the help provided by Dr. Jörg Maletz throughout this research. Dr. Jörg Maletz attended to my fieldtrip session also accompanied by Dr. Sven Egenhoff in Öland, Sweden. I sincerely thank to my committee members, Dr. Sven Egenhoff, Dr. John Ridley, and Dr. Gamze Çavdar for their comments and suggestions that improved the quality of the context of this study.

My special thanks are extended to Turkish Petroleum Corporation (TPAO) for providing the scholarship for conducting this research and living expenses through my graduate school education at Colorado State University. Particularly, assistance in various steps provided by Doğan Alaygut, Zeynep Alper, Yiğit Akay, Ömer Eylen, and Sevim Yavuz Bayram in Turkish Petroleum Corporation (TPAO) was greatly appreciated.

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DEDICATION

I dedicate this thesis to my family, Ahmet, Zehra, and Büşra Çığrı, for their unconditional and everlasting love and support…

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

Thick successions of carbonates characteristically form in tropical environments such as the Bahamas (e.g. Ball, 1967), the "beautiful atolls" in the Pacific (e.g. Rankey and Reeder, 2009), and along the coasts of the Indonesian archipelago (e.g. Renema and Troelstra, 2001). Nevertheless, cool-water carbonate platforms gained increasing attention only in the 90s with discoveries of large mounds offshore Norway in about 250 m of water depth (Freiwald et al., 1999) and the detailed description of the Tertiary cool-water carbonate succession from southern Australia (James and Bone, 1991). These two carbonate factories, the tropical and the cool-water, show distinct characteristics that makes it possible to unequivocally recognize them in the geological record (e.g. Pedley and Carannante, 2006). The "link" between these two environments, often referred to as "temperate carbonate environments" that share the characteristics of both of these extremes, are much less well known (Halfar et al., 2004). Relatively well understood examples of temperate carbonate platforms come from modern environments such as the southern Gulf of California, Mexico (Halfar et al., 2000) and the Mediterranean (Fornos and Ahr, 1997), but very few well-exposed temperate carbonates have been analyzed in detail so far. Therefore, it remains largely unknown how such a succession, especially one that spans several tens of millions of years from the distant geological past, may look like today when it is well preserved.

The Ordovician carbonate succession in Öland has previously been studied in detail for the purpose of paleontological aspects focusing on trilobites (e.g. Tjernvik, 1956; Parnaste et al., 2013), graptolites (e.g. Egenhoff and Maletz, 2007), acritarchs (e.g. Bagnoli and Ribecai, 2001), brachiopods (e.g. Rasmussen and Harper, 2008), cephalopods (e.g. Grahn, 1986), and pollen (e.g. Alm, 1986) that allows for an overall well-based biostratigraphic control in this Lower to Middle Ordovician carbonate succession (Webby et al., 2004; Bergström et al., 2009).

Nevertheless, very few sedimentological studies describe the Ordovician carbonates from this island beside paleontological researches. Jaanusson (1972a and b) provided initial facies descriptions and depositional interpretations for the Ordovician carbonates with a focus on the limestone components, and Männil (1966) and Jaanusson (1976) subsequently proposed facies belts based upon lithologies and biozones. Jaanusson and Mutvei (1982) and Stouge (2004) contributed field guide books for the Ordovician carbonates in Öland. However, these studies only show very limited and, overall, superficial facies descriptions for the carbonate litholigies. Additionally, Egenhoff et al. (2010) proposed facies descriptions, a depositional setting, and a sea level trend change, for the Lower Ordovician carbonate succession in the south-east of Norway and Öland, Sweden. Egenhoff et al. (2010), however, concentrate their study on one unit of the Lower Ordovician succession in Scandinavia, and their study is dominantly applicable for southern Norway because of the bulk of their provided dataset.

The objectives of this study are to provide a comprehensive and encompassing facies analysis, propose a depositional model, identify changes in depositional environments, and examine the importance of this carbonate succession within the Paleozoic petroleum system proposed by the study of Pedersen et al. (2007). All of the findings, eventually, shed light on the construction of depositional environment and architecture and sequence stratigraphy of the Ordovician carbonates in Öland, Sweden.

The study area comprises five localities (Figure 1.1.) containing carbonate rocks outcropping along the west coast of Öland, namely Ottenby and Degerhamn in south and Gillberga, Byrum, and Horns Udde in the north.

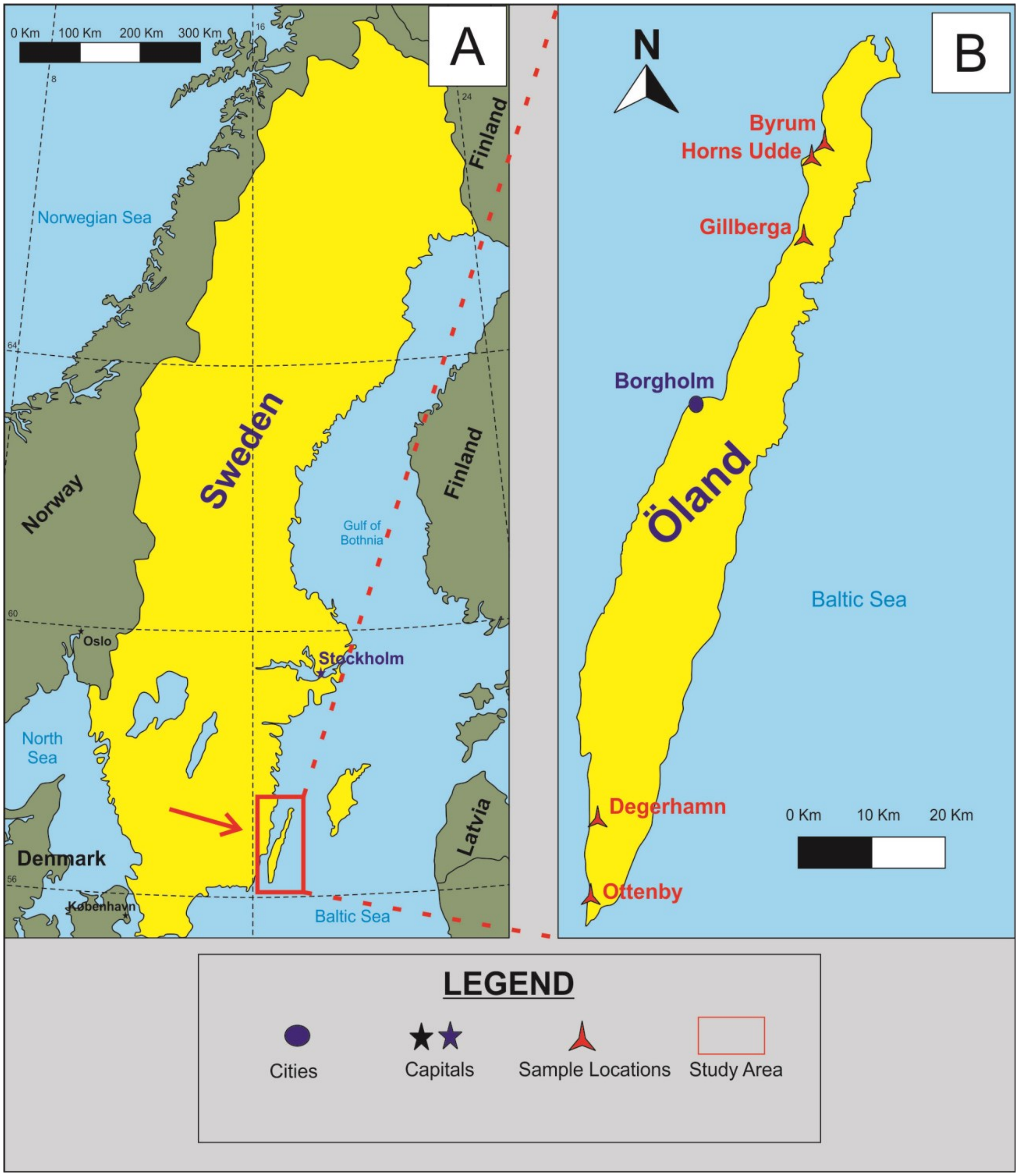

Figure 1.1. Study area: A- General map for the Scandinavia, B- Map of the Öland Island showing locations of study on this work.

CHAPTER 2: GEOLOGICAL SETTING

In the Early to Middle Ordovician, the Baltica micro-continent was located between 45 and 60 degrees paleo-latitude (Figure 2.1.) in the southern hemisphere (Cocks and Torsvik 2005). During this time, Baltica continuously drifted to the northwest, and, while parallel to drifting, rotated in an anti-clockwise direction (Figure 2.2.), most likely since the Upper Cambrian (Torsvik and Rehnström, 2003). On its southwestern margin, this micro-plate developed a carbonate platform facing both the Tornquist Sea and the Iapetus Ocean in the Early and Middle Ordovician. During this time, this carbonate platform still represented a passive margin environment (Beier et al., 2000), whereas from the Upper Ordovician on both margins would transform into foreland basin settings (Beier et al., 2000; Greiling and Garfunkel 2007).

Lower to Middle Ordovician sediments of southwestern Scandinavia represent deposition on a low-inclined carbonate ramp-type platform (c.f. Burchette and Wright, 1992; Kiessling et al., 2003) forming the southwestern Baltica margin (Egenhoff et al., 2010). During deposition the climate was moderately cool to temperate in a time believed to represent warm-house conditions (Stridsberg, 1980; Dronov and Rozhnov, 2007). It is generally assumed that very little of the Baltica plate rose above sea level during the Ordovician in contrast to the Late Cambrian (Beier et al., 2000), and therefore the input of siliciclastic debris was considered to be minor to nearly absent. Moreover, through the Early to Middle Ordovician, the currents responsible for the transportation of sediments within the basin were from SW to NE directions (Figure 2.1.; Kiipli et al., 2008).

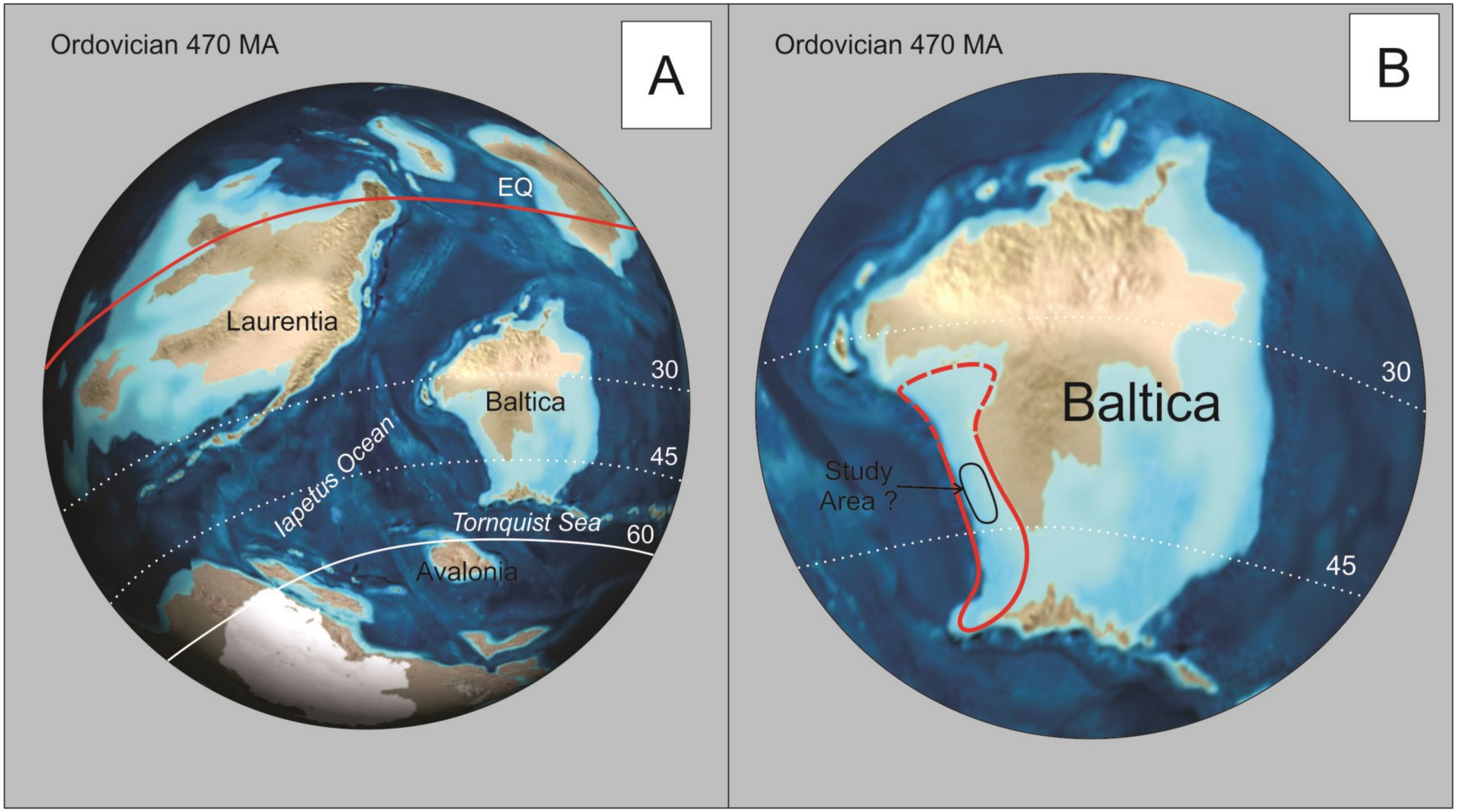

Figure 2.1. A: The position of the Baltica micro-plate in Ordovician. B: The carbonate factory (Red lines) on the west to south-west coast of the Baltica (Blakey, 2011; Cocks and Torsvik 2005; Kiessling et al., 2003).

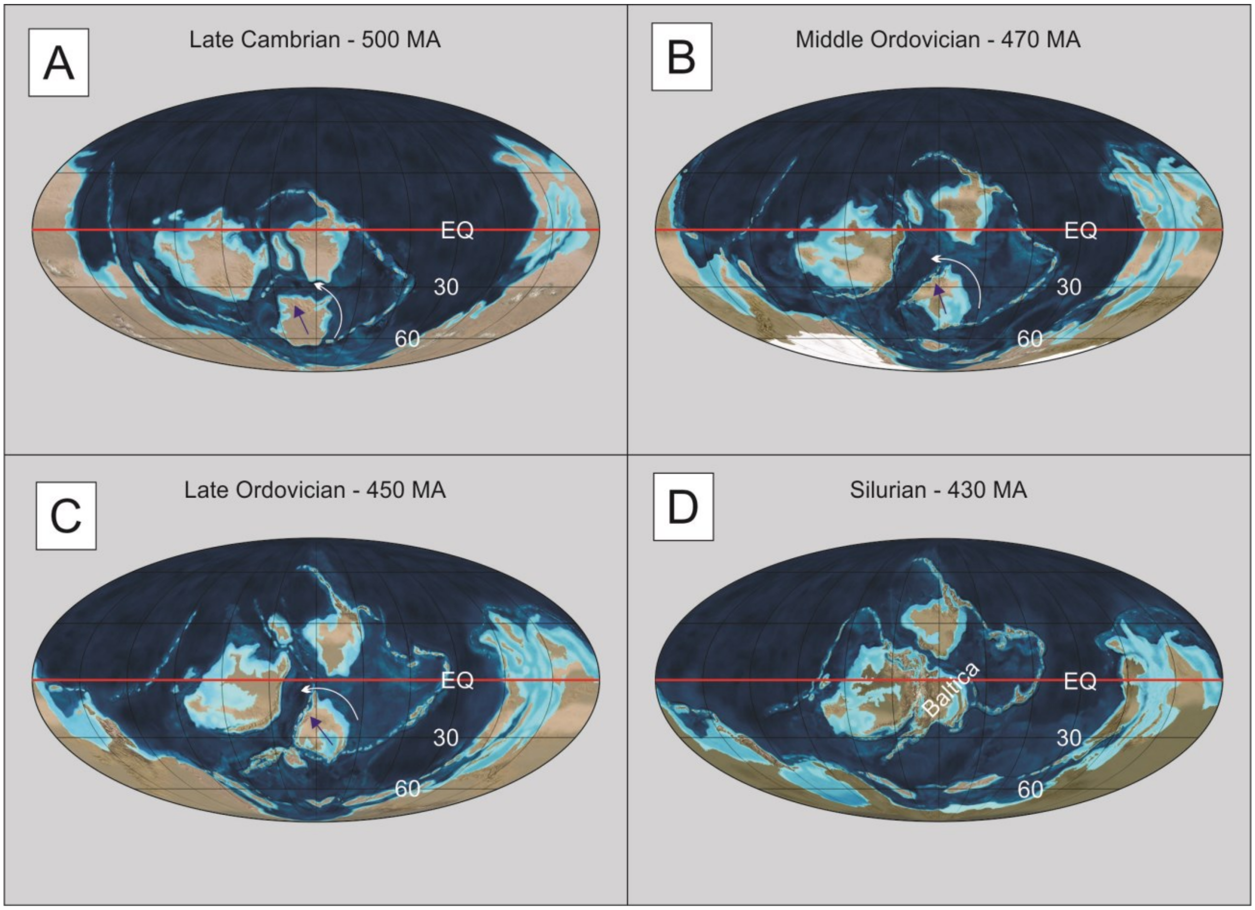

Figure 2.2. The evolution of Baltica from Late Cambrian to Silurian. Dark blue arrows display drift directions, while white arrows show anti-clockwise rotation (Blakey, 2011; Cocks and Torsvik 2005).

CHAPTER 3: BIOSTRATIGRAPHY

Two index fossils can be best used for obtaining biostratigraphic ages of the Lower to Middle Ordovician succession in Öland, southern Sweden (Figure 3.1. and Figure 3.2.), which are trilobites (Tjernviek, 1956) and conodonts (Lindström, 1971; Zhang, 1998; Löfgren, 2000). Based on these two fossil groups, a biostratigraphic subdivision of the succession was established by Jaanusson and Mutvei (1982) and Stouge (2004). These two studies define the Köpingsklint Formation as encompassing the *Paroistodus proteus* and *Prioniodus elegans* conodont biozones (Lindström, 1971). The overlying Bruddesta Foramtion contains the *Megalaspides dalecarlicus* and *Plesiomegalaspis estonica* trilobite (Tjernviek, 1956) biozones which is equivalent of the *Baltoniodus navis* conodont biozone (Löfgren, 2000). The Horns Udde Formation encompasses the *Paroistodus Orig., Trapez quadrangulum* (Löfgren, 2000), and the *Lenodus antivariabilis* (Zhang, 1998) conodont biozones, and the topmost Gillberga Formation is envisioned to represent the *Lenodus antivariabilis, Lenodus variabilis,* and *Yangtzepl. crassus* (Zhang, 1998) conodont biozones.

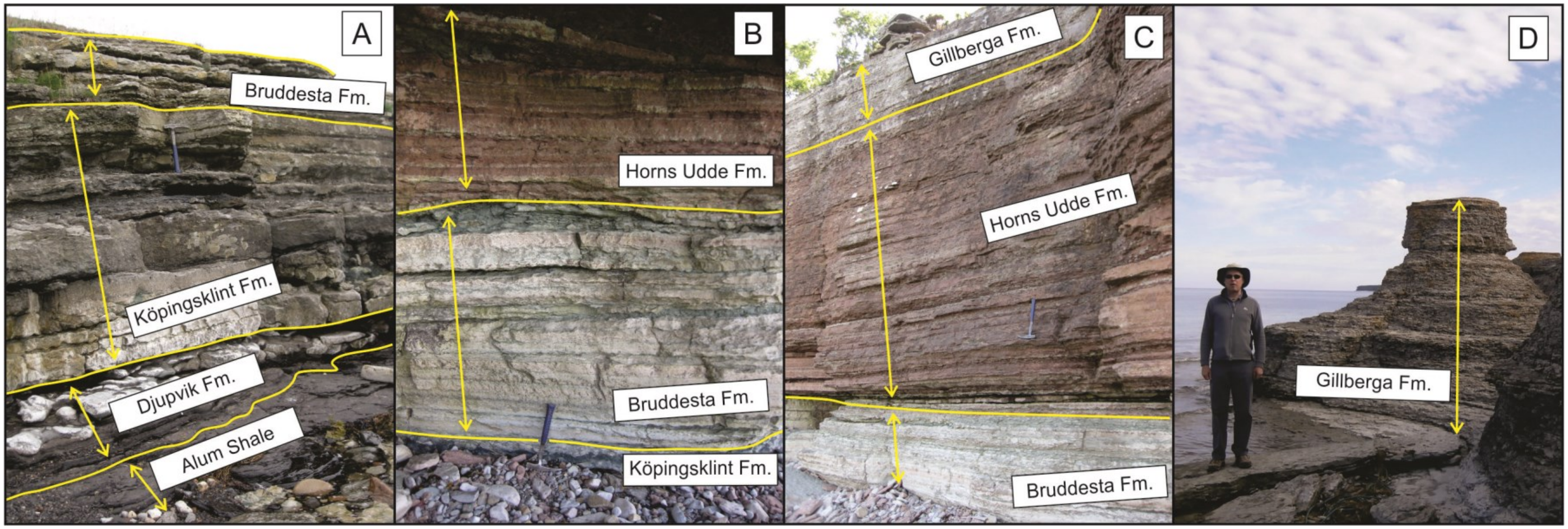

Figure 3.1. Outcrop display of the Lower to Middle Ordovician carbonate succession. Figure A is captured in Ottenby on southern Öland. Figure B and C show the Horns Udde outcrop, while figure D displays the "Rauka" outcrop at Byrum in the northern Öland. The Bruddesta and Horns Udde Formations contain horizontal hardground surfaces in Figure B and C, while the Gillberga Formation has parallel-to-bedding stylolite formations shown in Figure D.

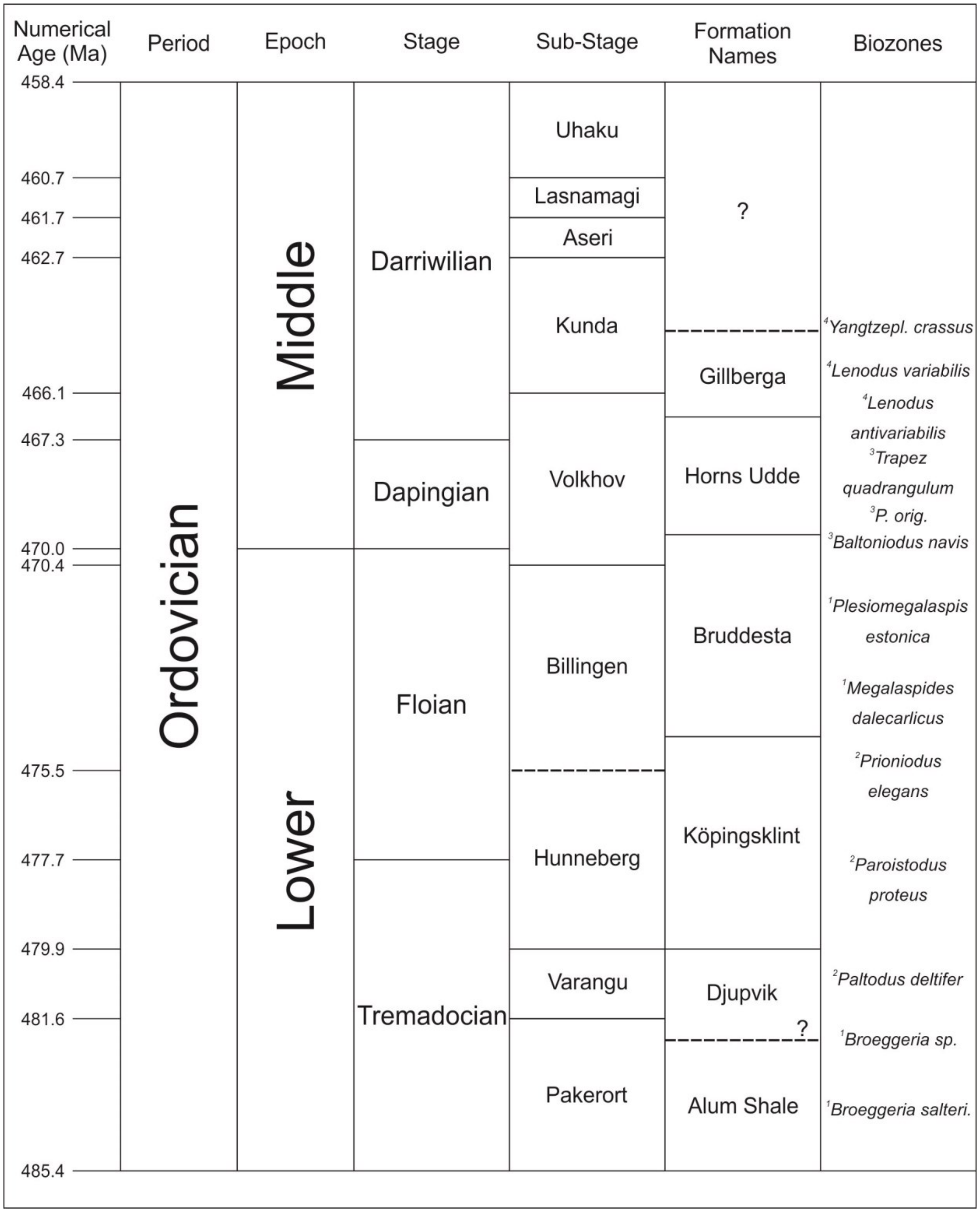

Figure 3.2. A summary of the biostratigraphy of the Ordovician carbonate succession in Öland, Sweden (Modified from Bergström et al., 2009; ICS, 2014; 1: Tjernvik, 1956; 2: Lindström, 1971; 3: Löfgren, 2000; 4: Zhang, 1998).

CHAPTER 4: METHODS

This study combines outcrop descriptions and petrographic examinations on around 30 μm thick standard thin sections (Flügel, 2010) to identify individual carbonate facies for the Lower to Middle Ordovician carbonates, on Öland, southern Sweden.

Successions exposed at the five investigated localities were measured and described in great detail in the field and subsequently digitized with CorelDraw X6. The carbonate succession exhibits outcrops of up to 12 meters in thickness. Representative hand specimens were collected during measurement of the succession for thin section preparation for petrographic examinations. The collected samples were cut in thin section sizes, and sent to Spectrum Petrographics Inc. and Turkish Petroleum Corporation Labs. Thin sections were prepared with blue epoxy in order to see inter- and intra-granular porosity, and diamond polished. Scholle (2003) and Flügel (2010) were used for the determination of carbonate grains, fabrics, and diagenetic processes of this Ordovician carbonate succession in order to establish facies. The thin sections were examined with a Nikon SMZ 1500 binocular and a H550S transmitted light petrographic microscope. Percentages of grains and matrix were obtained by using the method of Baccelle and Bosellini (1965).

A sample from the shale unit underlying the carbonate section in Ottenby was collected in order to perform total organic carbon (TOC) and Rock-Eval. pyrolysis analyses. The sample was treated with hydrochloric acid (HCl) to remove carbonate components and, later, the TOC analyses were pursued with standard induction furnace techniques at the Turkish Petroleum Corporation Research Center. Rock Eval-6 instruments and IFP 160000 (Institut Francais du Petrole) standards were used to acquire TOC content, maximum temperature of the S2 peak (T_{max}), and maturation level features of the Alum Shale Formation as a possible source rock for the Ordovician carbonate succession as a potential conventional resource.

CHAPTER 5: SEDIMENTOLOGY

5.1. Facies Analysis

The lower to middle Ordovician succession in Öland consists exclusively of mud-rich carbonate lithologies. In general, all facies are highly bioturbated having bioturbation indices (BI) of 4 to 5 (Taylor and Goldring, 1993) and, therefore, individual facies boundaries are often not well defined in the field. Bedding is influenced by both hardground and stylolite formations. Grain types in the carbonate facies are mainly echinoderms, trilobites, brachiopods, bryozoans, and trilobites (cf. Scholle, 2003). Facies in this study are defined by the presence and the quantity of these grain types as well as Fe-ooids composed of chamosite (Sturesson, 1986) and glauconite in rock samples. These ranges are defined as “10-15%”, “15-25%”, “25-35%”, and “> 35%” for Mud- to Wackestone, Wackestone, Wacke-to Packstone, and Packstone, respectively (modified from Dunham, 1962). Based on this classification scheme, the lower to middle Ordovician succession in Öland is here subdivided into 9 distinct carbonate facies (Table 5.1.; Figure 5.1.1.). Vertically, these facies change on a cm-scale throughout the measured succession.

Table 5.1. A summary table of sedimentologic characteristics of the individual facies (A - I) determined in the Lower to Middle Ordovician carbonate succession, Öland, Sweden.

Micro-facies Names	Facies Associat. (FA)	Composition	Description	Interpretation
Echinoderm Mud- to Wackestone (*Facies A*)	FA 3 & FA 4	Skeletal: 10-15 % Mud: 81.5 - 87.5 % Cement: 1-2.5 % Dolomite: <1 %	Composed of heavily bioturbated (BI 4-5) light and dark micrite. Contains echinoderms, brachiopods, bryozoans, trilobites, recrystallized bioclasts, and rare ostracods in decreasing abundance as skeletal components. Grains randomly dispersed. Patchy dolomitization rare. Burrows oriented parallel to bedding (*Planolites*) are filled with micrite and cement. Porosity filled with blocky cement. Sedimentary structures absent.	Intact skeletal grains most likely largely in place, fragments probably transported as bed load. Micrite deposited by suspension or as bed load (Schieber et al., 2013). Random orientation of skeletal grains reflects intense burrowing and well oxygenetad conditions on the sea-floor and several cm into the sediments. Blocky cement displays one cement generation.
Trilobite Mud- to Wackestone (*Facies B*)	FA 1 & FA 2	Skeletal: 10 - 12.5 % Mud: 80 - 85 % Glauconite: 2.5 - 5 %	Consists mostly of bioturbated (BI 4) carbonate muds. Skeletal components include trilobite, echinoderm, and bioclasts in decreasing abundance. Grains randomly oriented. Contains silt to fine-sand size glauconites. Bedding - parallel burrows (*Planolites*) common. Sedimentary structures absent.	Unbroken skeletal grains in place, pieces likely introduced by bed load. Carbonate mud deposited by suspension or as bed load (Schieber et al., 2013). Bioturbation indicated by randomly distributed grains. Benthic life points to oxygenated condition on the sea-floor. Glauconite indicates low sedimentation rate (Amorosi, 1993).
Echinoderm Wackestone (*Facies C*)	FA 3 & FA 4	Skeletal: 15-25 % Mud: 66.5 - 76.5 % Cement: 5 % Open Porous: 2.5 % Dolomite: <1 %	Bioturbated (BI 4) light and dark carbonate muds. Skeletal grains: echinoderm, brachiopod, bryozoan, trilobite, and recrystillized bioclasts in decreasing abundance. Grains randomly oriented in micritic matrix. Burrows are oriented parallel to bedding (*Planolites*). Patchy dolomitization is present in places. Some echinoderm remains show partial pyrite replacement. Stylolites occur in places. Moldic and microfracture openings. Blocky calcite cements. No sedimentary structures.	Deposited under fluctuating low to moderate conditions (Flügel, 2010). Low energies represented by energy deposition through suspension and moderate energies represented by storm reworkings. Light carbonate mud is likely a product of recrystallization. Bioturbation randomly oriented grains. Benthic life indicative of oxygenated condition on the sea-floor. Stylolites formation by pressure dissolutions (Logan, 1984). Blocky calcite cement shows one cement generation.

Table 5.1. Continues.

Micro-facies Names	Facies Associat. (FA)	Composition	Description	Interpretation
Trilobite and glauconite bearing Wackestone (*Facies D*)	FA 1 & FA 2	Skeletal: 15-17.5 % Mud: 66.5 - 76.5 % Glauconite: 5 - 7.5 % Cement: 2.5 % Open Porous: 2.5 % Dolomite: <1 %	Composed of bioturbated (BI 4) light and dark carbonate muds. Contains echinoderm, brachiopod, bryozoan, recrystillized bioclasts, and trilobite in decreasing abundance for skeletal grains. Both skeletal and non-skeletal grains are randomly distributed. Sand-size glauconite. *Planolites* burrows occur filled with both carbonate mud and cement. Dolomitization rare, if present occurs in patches. Pyrite occurs locally on echinoderm debris. Bedding - parallel stylolites common. Moldic, vuggy and microfracture openings. Contains Blocky and microcrystalline calcite cements. Devoid of sedimentary structures.	Intact skeletal grains are in place, fragments likely deposited by bed load (Flügel, 2010). Light micritic mud is probably a product of recrystallization. Bioturbation dispersed grains. Benthic life reflects oxygenated condition on the sea-floor. Stylolites formation by pressure dissolutions (Logan, 1984). Blocky and microcrystalline calcite cements indicate two cement generations. Presence of glauconite reflects low sedimentation rate (Amorosi, 1993).
Echinoderm, glauconite, and Fe- Ooid bearing Wackestone (*Facies E*)	FA 1	Skeletal: 15-21.5 % Non-Skeletal: 2.5 % Mud: 66.5 - 76.5 % Glauconite: 2.5 - 5 %	Made of bioturbated (BI 4) carbonate mud with echinoderms, brachiopods, and trilobites in decreasing abundance for skeletal components. Fe - ooids present. Both skeletal and non-skeletal grains randomly oriented. Coarse silt to fine sand-size glauconite. *Planolites* burrows filled with carbonate mud occur. Pyrite concretions present locally. Stylolites and Hardgrounds abundant. Lacks sedimentary structures.	Skeletal debris likely in place and authochthonous; randomly oriented grains reflect bioturbation; signs of abundant benthic life displays oxygenated conditions on the sea floor; glauconite and hardgorunds indicate starved sedimentary conditions during deposition; Fe-ooids likely allochthonous from shallow shelf; stylolites indicate pressure dissolution, two cement generations reflect two successive cementation events
Echinoderm Wacke- to Packstone (*Facies F*)	FA 3	Skeletal: 25-35 % Mud: 59 - 69 % Cement: 2.5 % Open Porous: 2.5 % Dolomite: <1 %	Consists of bioturbated (BI 4) light and dark carbonate muds. Echinoderm, brachiopod, bryozoan, platy bioclasts, and trilobite in decreasing abundance making up skeletal debris. Grains randomly dispersed. Horizontal burrows (*Planolites*) filled with micritic mud. Dolomitization rare, if present occurs in patches. Pyrite locally replaces echinoderm pieces. Stylolites are arranged parallel to bedding surface. Vugs and microfractures occur as open porosity. Blocky cement is present in places. Sedimentary structures are absent.	Skeletal fragments likely deposited as bed-load under fluctuating moderate to high energy conditions (Flügel, 2010) with episodic storm reworking represented by local grain accumulations. Dark carbonate micrite deposited, light carbonate mud likely recrystallized; random orientation of grains reflects intense bioturbation. Abundance of benthic organisms displays well-oxygenated conditions on the sea-floor. Stylolites formed by pressure dissolutions parallel to bedding. Blocky calcite cement reflects one cementation event.

Table 5.1. Ends.

Micro-facies Names	Facies Associat. (FA)	Composition	Description	Interpretation
Trilobite and glauconite bearing Wacke- to Packstone (*Facies G*)	FA 1	Skeletal: 25-35 % Mud: 57.5 - 67.5 % Glauconite: 5 % Cement: 2.5 %	Echinoderm, brachiopod, bryozoan, and trilobite in decreasing abundance for making up shell debris. Comprising bioturbated (BI 4) light and dark micritic muds. Both skeletal and non-skeletal grains randomly aligned. Fine-sand size glauconites. Horizontal (*Planolites*) burrows filled with micritic mud and cement. Pyrite precipitation. Stylolites bedding - parallel. Blocky calcite cement rare. Sedimentary structures absent.	Shells and shell debris likely accumulated by bed load transport during episodic storms (?), carbonate mud either also moved by bed load (Schieber et al. 2013) or filling pore spaces as suspension; bioturbation oriented grains in varying ways; abundant benthic life, indicated by diversity of fossils, points to plentiful life on sea floor and therefore oxic conditions; presence of glauconite reflects starved sediment conditions; stylolites formed during diagenesis by pressure solution, one cement generation reflects only a single cementation event.
Echinoderm and trilobite bearing Packstone (*Facies H*)	FA 3	Skeletal: 35 < % Mud: < 56.5 % Cement: 5 % Open Porous: 2.5 % Dolomite: <1 %	Consists of echinoderms, brachiopods, bryozoans, recrystallized bioclasts, and trilobite bioclastic grains in decreasing abundance; they are embedded in light to dark-colored micrite, and generally randomly oriented; Planolites-type burrows are filled with both carbonate mud and cement; Dolomitization is rare, if present it occurs in patches; pyrite is locally present preferentially on echinoderm pieces; stylolites are frequent and oriented parallel to bedding; open porosity is present in the form of vugs and molds; both microcrystalline and blocky cement occur; sedimentary structures are absent.	Grains represent accumulation during high-energy events, likely storms. Carbonate mud was either infilled during the event, or thereafter; random orientation of grains reflects intense bioturbation and hospitable, oxic conditions on the sea floor; stylolites indicate pressure dissolution (Logan, 1984); the two cement generations likely reflect two successive cementation events.
Echinoderm and Fe- ooid bearing Packstone (*Facies I*)	FA 3	Skeletal: 35 < % Non-skeletal: 2.5 % (Fe- ooids) Mud: < 56.5 % Cement: 2.5 %	This facies contains echinoderms, brachiopods, bryozoans and play bioclasts in order of decreasing abundance; Additionally, Fe-ooids are present. All grains are randomly oriented; Some Planolites burrows occur and filled with micrite; pyrite is moderately abundant and occurs as cubic crystals; one generation, blocky calcite cement, occurs in places; sedimentary structures are absent.	Both the skeletal and non-skeletal grains were most likely transported and deposited by bed load processes; however, the process of micrite deposition remains unclear as these packstones are heavily bioturbated throughout causing the random orientation of all grains; the Fe-ooids are interpreted as allochthonous derived from shallow-water environments; Living conditions on the sea floor were favorable, and the environment was likely oxic; one generation of cements indicates just one cementation event.

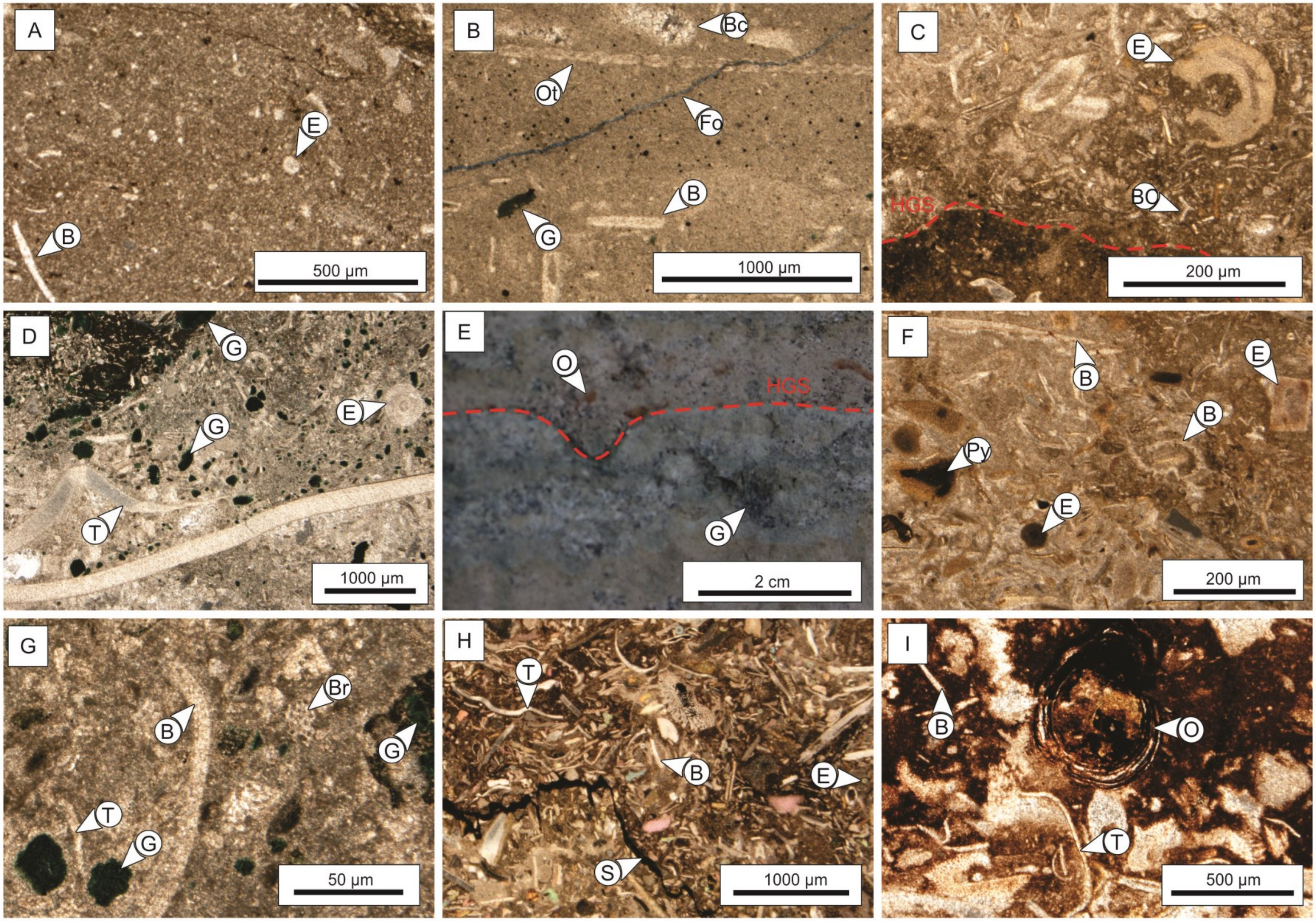
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Figure 5.1.1. Facies of the Lower to Middle Ordovician carbonate ramp succession in Öland, Sweden. (A) Echinoderm Mud- to Wackestone; (B) Trilobite Mud- to Wackestone; (C) Echinoderm Wackestone; (D) Trilobite and glauconite- bearing Wackestone; (E) Echinoderm, glauconite, and Fe- ooid bearing Wackestone; (F) Echinoderm Wacke- to Packstone; (G) Trilobite and glauconite- bearing Wacke- to Packstone; (H) Echinoderm and Trilobite bearing Packstone; (I) Echinoderm and Fe- ooid bearing Packstone. *Key for the photographs: Brachiopods (**B**), Blocky cement (**Bc**), Bryzoans (**Br**), Bioclasts (**BC**), Echinoderms (**E**), Fracture openings (**Fo**), Glauconites (**G**), Hardground Surfaces (**HGS**), Fe- Ooids (**O**), Orthoceras (**Ot**), Pyrite (**Py**), Stylolites (**S**), and Trilobites (**T**).*

5.2. Facies Associations

In this study, the facies of the Lower to Middle Ordovician are arranged into four facies associations (FAs). Each of the FAs reflects the co-occurrence of a number of facies within distinct stratigraphic parts of the succession that are in the following referred to as FA 1 to FA 4.

5.2.1 Facies Association – 1 (FA 1)

FA 1 is composed of three glauconite-bearing (Facies B, D, and G) and one glauconite- and Fe-ooid-bearing (Facies E) carbonate facies. The carbonate facies encompass both mud- to wackestones and wacke- to packstones. These facies are predominantly made up of varying amounts of randomly oriented intact and broken skeletal grains and glauconite grains (up to 7.5%), and exclusively Facies E additionally contains some allochthonous Fe-ooids (~2.5 vol%). The facies within this FA are generally heavily bioturbated and show a BI of about 4. Hardgrounds are generally rare in FA 1, but stylolites occur commonly.

5.2.2. Facies Association – 2 (FA 2)

FA 2 consists of exclusively carbonate mud-dominated facies that contain glauconite. These rocks are facies B and D and represent only mud- and wackestones with little shell debris. The glauconite forms a maximum of 7.5% of the volume in each of the facies. All of the carbonates are heavily bioturbated, with a bioturbation index (BI) of about 4, and contain rare hardgrounds and stylolites.

5.2.3 Facies Association – 3 (FA 3)

FA 3 consists of the Fe-ooid-bearing (Facies I) and four other litholigies which are Facies A, C, F, and H. The carbonate facies range from mud- to packstones. Skeletal grains occur throughout this FA randomly oriented with varying amounts of carbonate mud forming the matrix. Additionally, however, facies I shows rare allochthonous Fe-ooids (~2.5 vol%). All facies of this FA show heavy bioturbation and the BIs are estimated to be between 4 and 5. Hardgrounds are especially abundant in this FA, but stylolites are generally rare.

5.2.4. Facies Association – 4 (FA 4)

The two carbonate facies A and C form the FA 3. These facies represent mud- to wackestones. Unbroken and fragmented skeletal grains are randomly oriented in these carbonate mud dominated facies. All carbonate facies in this FA are highly bioturbated with a BI varying from 4 to 5. Hardgrounds occur abundantly in this FA.

CHAPTER 6: FACIES ARCHITECTURE

The lower to middle Ordovician carbonate succession in Öland is represented by five detailed sections in this study that are arranged on a northeast to southwest transect. It is subdivided into three stratigraphic intervals that are vertically distinct in their lithological expression in each of the measured sections, and laterally traceable across the island of Öland (Figure 6.1.; Appendices 1 for details). The boundary between the three intervals is conformable, and lithological differences of the intervals are discussed in detail below.

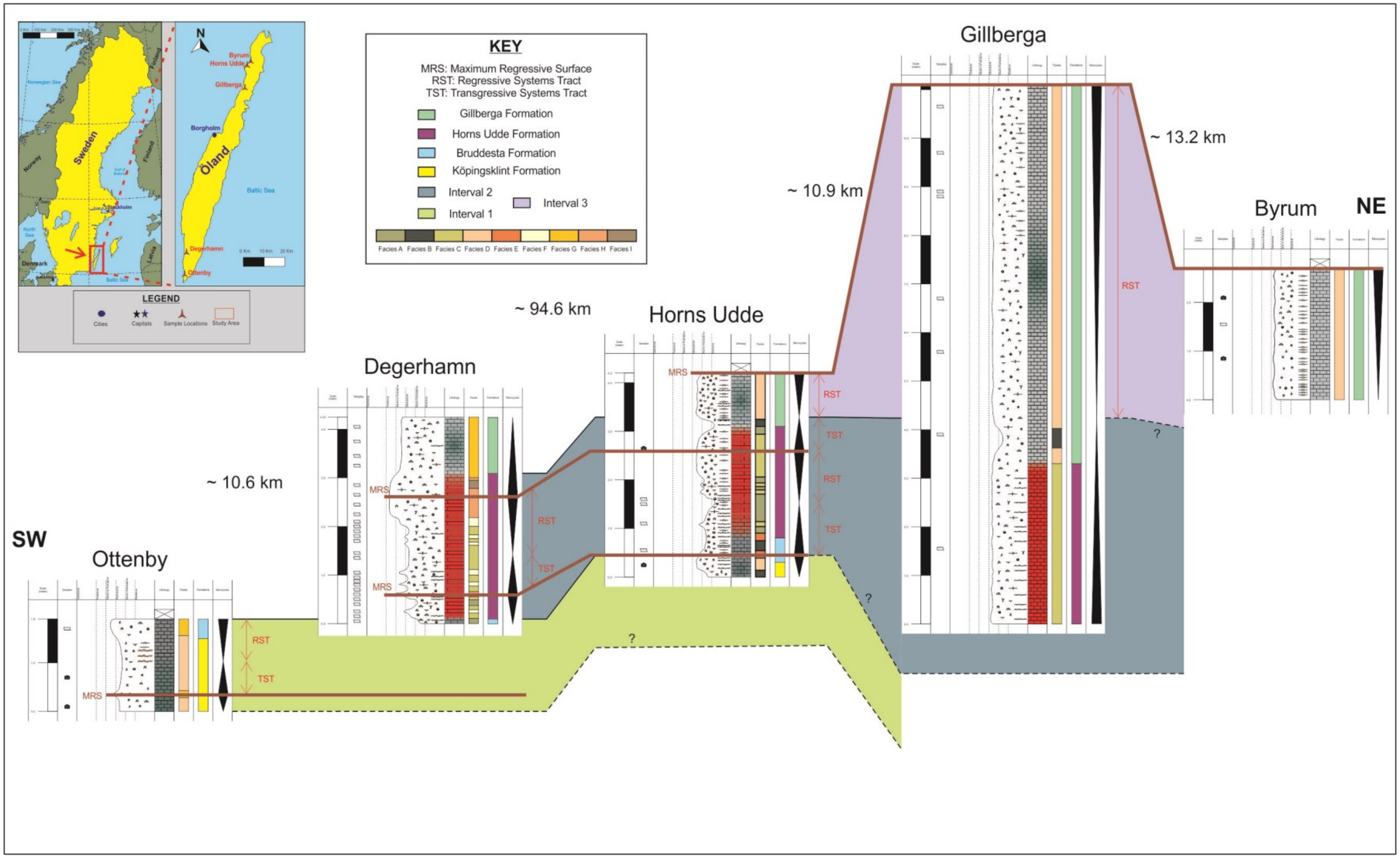

Figure 6.1. Transect consisting of five outcrop exposures through the Lower to Middle Ordovician carbonate succession in Öland, Sweden, showing sedimentary structures and correlation of stacking patterns. Legend for samples and symbols see Appendix 1.

Interval 1

Interval 1, consisting of the Köpingsklint and Bruddesta Formations and representing the *Paroistodus proteus* (Lindström, 1971) and *Baltoniodus navis* (Löfgren, 2000) conodont biozones, respectively, is only well exposed in the outcrop at Ottenby (Figure 6.1.) in the southern part of the island. Based on the occurrences and frequency of echinoderms, glauconite, and Fe- ooids, it is here correlated with the Bruddesta formation at Horns Udde (Figure 6.1.) in the northern part of Öland. The succession is on average 1.1 m thick and consists of the glauconite-bearing Facies D, E and G. The most dominant facies is Facies D within this interval. These facies are arranged into two coarsening-upwards (CU) cycles separated by a fining-upward (FU) unit in its central portion.

Interval 2

This interval, containing predominantly the Horns Udde formation along with the lowermost part of the Gillberga formation represent the *Paroistodus originalis* (Löfgren, 2000) to *Lenodus antivariabilis* (Zhang, 1998) conodont biozones. It is well exposed in the outcrop at Degerhamn (Figure 6.1.) in the southern part of the island, and is laterally traceable to the Horns Udde and Gillberga outcrops (Figure 6.1.) in the northern part of Öland. It is readily distinguished from the underlying Interval 1 and overlying Interval 3 by the lack of glauconite-bearing facies. The succession is about 3.4 m thick and consists of the carbonate facies A, C, F, H and I. The Facies C is making up the larger volume of this stratigraphic unit. In general, the sediment is much more grain-rich in the south versus the north, and similarly contains higher amounts of carbonate mudstone in the northern part of the island versus the southern part of Öland.

Interval 3

Interval 3, consisting of the Gillberga Formation and representing the *Lenodus variabilis* and *Yangtzepl. crassus* (Zhang, 1998) conodont biozones, is well exposed in the outcrops at Horns Udde, Gillberga, and Byrum (Figure 6.1.) and occurs only in the northern part of the island. It is easily discriminated from the underlying Interval 2 by the presence of glauconite in the outcrop at Horns Udde, and easily traceable into the northern part of Öland. The succession is on average 4 m thick and consists of the glauconite-bearing Facies B and D. More than three quarters of this stratigraphic unit is composed of Facies D. These facies are arranged into one coarsening-upward cycle through this stratigraphic interval.

CHAPTER 7: DEPOSITIONAL MODEL

The lower to middle Ordovician carbonate succession forms part of a homoclinal carbonate ramp, in which sedimentation occurred below normal but above storm wave base (Burchette and Wright, 1992; James, 1997). The studied succession is here interpreted as encompassing the carbonate mud-rich distal portion of the mid-ramp and proximal portion of the outer ramp environments (Burchette and Wright, 1992; James, 1997). The four facies associations therefore represent distinct facies belts during two different episodes of deposition on this ramp system: during “starved” periods (*Time 1 & 3*), facies associations 1 and 2 represent two facies belts of the middle to outer ramp environment that are characterized by an abundance of glauconite next to all other carbonate grain types. During “normal” times (*Time 2*), however, the system is not as heavily condensed, and facies associations 3 and 4 represent this stage of exclusively carbonate deposition during this Ordovician ramp evolution (Figure 7.1.).

During the times of sediment starvation (*Time 1 & 3*), the most proximal depositional zone, here referred to as facies belt 1, shows an intercalation of glauconite-bearing mudstone, wackestone, and packstone facies (Facies B, D, E, and G) which are making up FA 1. This reflects varying energy regimes, even though intense bioturbation has blurred distinct boundaries of individual thin beds and laminae. The low-energy mudstones in this facies zone are interpreted to reflect tranquil fair weather conditions. It is here proposed that most of the mud was introduced into this environment by suspension, likely from shallow parts of the ramp (cf. Flügel, 2010). Alternatively, the carbonate mud may have been moved by bed load transport (Schieber et al., 2013), but intense bioturbation inhibits differentiation of suspension- versus bed load derived parts of the succession. It is envisioned that the shells and fossil debris were transported during high-energy events as bed load along the sea floor and concentrated in patches and laminae (cf. Aigner, 1985). The carbonate mud present in the interstices of the packstones was either deposited together with the shells as bed load (Schieber et al. 2013), or filled available pore space of the storm deposits when the storm was decreasing and mud started to get deposited. In wackestone storm layers, however, the mud forming a large part of the laminae itself must have been deposited by bed load together with the shells. As this ramp environment was sediment – starved during these episodes, all facies are also characterized by the presence of glauconite (cf. Amorosi, 1993; Amorosi, 1995).

The distal depositional zone during the times of sediment starvation (*Time 1 & 3*) here referred to as facies belt 2, consists exclusively of glauconite-bearing wacke- and mudstone facies (facies B and D) which form FA 2. Because it is located further away from the coast and likely in deeper water than the facies belt 1 sediments, it seems probable that the carbonate mud that is dominant in this facies was deposited mostly by suspension rather than bed load transport. This generally calm environment was occasionally interrupted by storm events that concentrated shell debris in wackestone lag layers. The water depth of this environment, however, must have been so deep that even though intense storms did move shell debris together with carbonate mud along the sea floor, they likely were not strong enough to concentrate exclusively shell lags and form packstone layers.

During “normal” times, the proximal depositional zone, here referred to as facies belts 3, was characterized by the deposition of interbedded mudstone, wackestone, and packstone facies (Facies A, C, F, H, and I) which comprise FA 3. The abundance of grains indicates high-energy conditions especially during events such as storms, accumulating the grains in abundant tempestite layers. During fair weather, however, the depositional setting must have been calm as mostly carbonate mud accumulated. Whether this mud accumulated through simple suspension settling or by bed load processes must remain unclear as all facies have been heavily bioturbated, destroying all primary sedimentary structures.

The facies belt located distally of facies belt 3, facies belt 4 during “normal times” (*Time 2*), consists exclusively of wacke- and mudstone facies (facies A and C) which form FA 4. This facies belt was characterized by mostly carbonate mud deposition, likely also dominated by suspension settling as the environment was definitely more tranquil than the neighboring facies belt 3. However, bed load transport of some of the mud cannot be excluded. Episodic rare storms were still strong enough to concentrate shell debris in wackestones, yet the water depth of this portion of the ramp was likely deep enough to prohibit the reworking of much of the sediment by storms, or an accumulation of shells in packstone laminae.

The iron ooids that occur two times in the succession in Facies E and I record unusual sedimentary conditions. In general, they are typical for shallow-water condensed environments (Burkhalter, 1995). They are therefore interpreted as allochthonous grains in these mid-ramp strata and likely represent shallow-water sediments that have been transported into this environment, probably by storms. It is assumed that because of their density and size they could probably only be transported into the mid-ramp realm and not further distally. The ooids therefore most likely represent detrital input onto the mid-ramp during relative lowstands when the distance to the coast was significantly shorter than during other sea-level positions. The formation of Fe-ooids during lowstands in shallow water is therefore here used as additional evidence for this succession representing a condensed setting similar to the Jurassic units in Switzerland (Burkhalter, 1995). This suggests that shallow-water environments were also most likely condensed during the deposition of this Lower to Middle Ordovician succession and not exclusively the mid- to deep-ramp setting.

Heavy bioturbation in all facies belts of the Öland carbonate succession indicates abundant benthic life on the sea floor during deposition, which is represented by parallel-to-bedding burrows (*Planolites*). Nevertheless, diagenesis, compaction, and the lack of heterolithic bedding hampers trace fossil recognition in Ordovician shallow-marine carbonates (Mangano and Droser, 2004). Additionally, macroboring biota (Jaanusson 1961, cf. Mangano and Droser, 2004) are present within hardground zones of this carbonate succession. The diversification and abundance of both vertical and horizontal burrows slightly declined towards deeper part of the depositional environment (Figure 7.1.). This implies either a decrease in oxygen saturation levels of bottom sea-waters as observed on modern shelves (Diaz and Rosenberg, 1995; Levin, 2003; Levin and Gage, 1998; Wu, 2002) or a decrease in the activity and/or abundance of benthic burrowing organisms down-shelf.

Sediment-size differences within the same stratigraphic interval of the studied succession were most likely controlled by the paleo-relief on this carbonate ramp during deposition. The carbonate ramp in Baltica was sloping towards the southwest with its landward side located northeast of the study area (Jaanusson, 1976). Sediments on this ramp are generally overall richer in carbonate mud towards the north which suggests an inclination of the ramp towards the north during deposition. This northwards inclination, however, must be a local phenomenon as during the Ordovician, the general trend was a deepening of the environment towards the south and not the north (see Jaanusson, 1976).

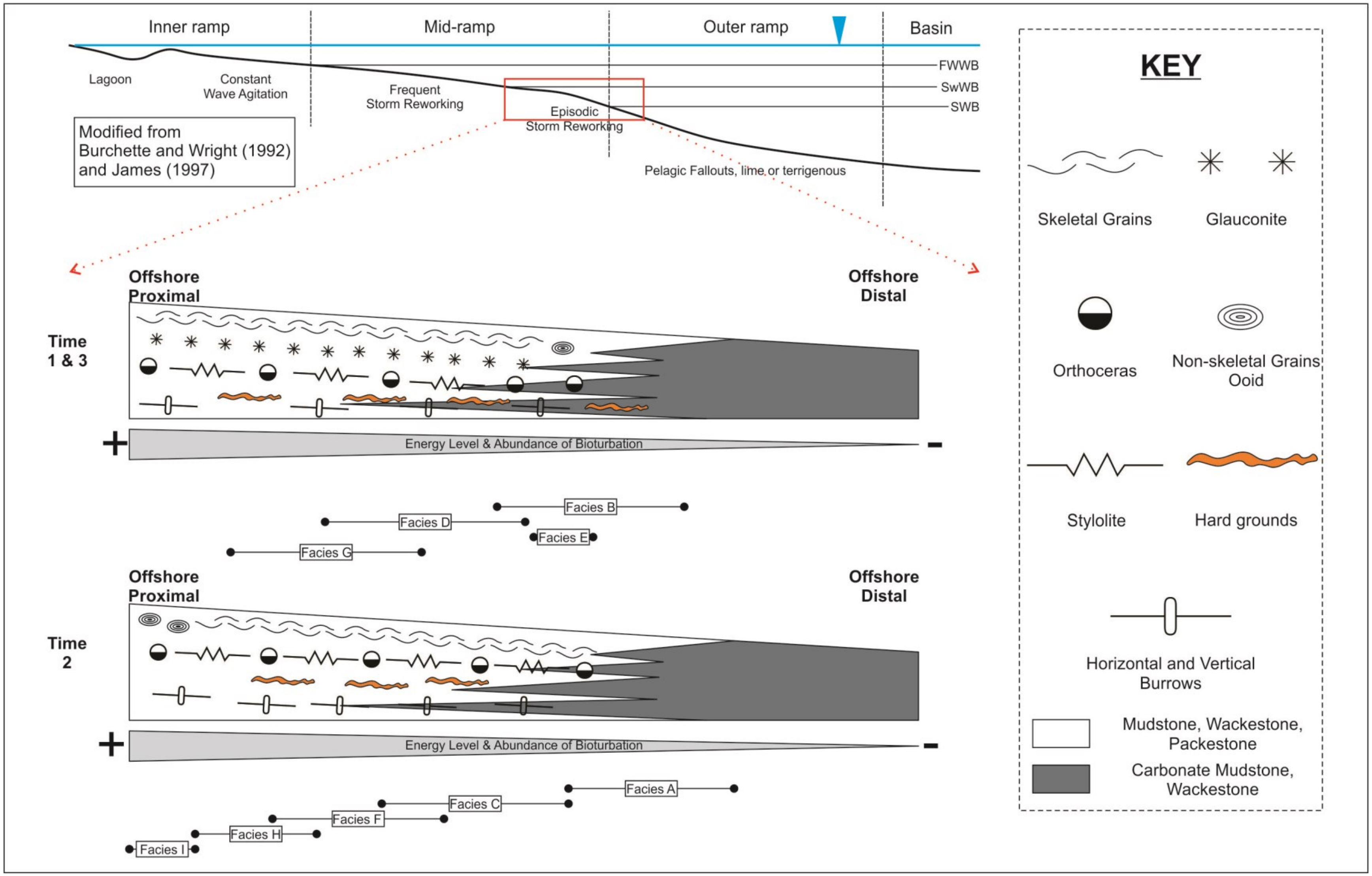

Figure 7.1. Depositional model of facies zones for the Lower to Middle Ordovician succession exposed in Öland, Sweden; FWWB: Fair weather wave base, SwWB: Swell wave base, SWB: Storm wave base.

CHAPTER 8: DISCUSSION

In this chapter, depositional environment, sequence stratigraphy, and petroleum exploration possibilities of the Lower to Middle Ordovician carbonate succession in Öland will be respectively discussed in details.

8.1. Depositional Environment

Particular grain components of carbonate facies on both platform and ramp settings have been widely considered to indicate the climatic setting of modern depositional environments and also provide to information on the formation of carbonate rocks in the geological record (e.g. Halfar et al., 2000; Fornos and Ahr, 1997; James et al., 1999). Echinoderms, brachiopods, and trilobites are ubiquitous constituents in Paleozoic carbonate successions and not limited to distinct warm or cold water environments (Scholle, 2003). However, bryozoans and "*orthoceras*" are components that are typical for "*heterozoan*" or cold water assemblages. An abundance of these types of fossil grains has therefore been considered crucial to recognize cold-water carbonates from the geological past (James 1997). However, the occurrence of one of these grain types alone, such as the bryozoans, does not necessarily indicate a cool-water environment (Taylor and Allison 1998). Therefore, the presence of bryozoans in some of the Öland samples does not reflect a cold-water carbonate setting but may just indicate relatively high water depth of the Öland portion of this sedimentary system. The presence of Fe ooids in the same succession, in contrast, is characteristic of rather warm-water and not cold-water depositional conditions (see below).

Fe-ooids exclusively form in warm water tropical to sub-tropical environments (e.g. Opdyke and Wilkinson, 1990) and are generally used as indicators for medium temperatures above 22-24 ^{0}C in geological successions (Lees 1975). However, Fe-ooids can also form in temperate-water environments if the water body, e.g. the ocean or basin they formed in experienced a significant salinity increase (Lees 1975). The presence of Fe-ooids in the Ordovician succession in Öland, mainly composed of chamosite minerals (Sturesson, 1986) that were influenced by the Floian to Katian volcanism (Sturesson et al., 1999) therefore offers two possible scenarios of how they formed: either they do represent an indicator for at least transient warm-water conditions, or they reflect increased salinities of the water body where the ooids originated.

The Ordovician succession on Öland represents deposition on an open shelf interpreted to represent a temperate sedimentary environment (Egenhoff and Maletz, 2012; this study). In order to obtain a water body with high salinities this would have to affect the entire Iapetus Ocean during at least parts of the Middle Ordovician. Such a scenario is unlikely, and no increased salinities have been reported from elsewhere along the coast of this ocean around Baltica for this time-span (cf. Cocks and Torsvik, 2005). Therefore, it seems more likely that the Fe-ooids indeed represent at least sub-tropical if not tropical sea-water temperatures along the coast of Baltica during the lower Middle Ordovician. According to this study, the succession represents exclusively a middle to outer ramp environment. These relatively deep-water settings may show characteristics of cool-water even though the coastline itself may represent a warm-water environment (cf. Brandley and Krause, 1997). It is therefore well possible that sub-tropical to even tropical sea-water temperatures were common along the Öland coast forming the Fe-ooids whereas the middle to deep ramp was characterized by relatively cool-water conditions. Exclusively during major lowstands, sea-level fell enough so that the Öland environments did capture and preserve some reworked grains from shoreline settings whereas most of the Lower and Middle Ordovician succession was deposited too far distally to reflect sedimentary conditions in shallow water. The Fe-ooids are therefore here used as an indicator of how the sedimentary conditions really were at the time of deposition in contrast to what much of the succession seems to reflect. Alternatively, warm-water conditions that could form ooids may also have occurred only at distinct times of each sea-level fluctuation, on Öland exclusively during lowstands of sea-level, and would therefore reflect a higher-order cyclicity, perhaps of the Milankovitch type, to have influenced deposition during the Lower and Middle Ordovician.

Direct precipitation of aragonite out of the water column requires an oversaturation of sea-water with calcium carbonate, and warm-water, normally tropical conditions (cf. Schlager, 2003). Whereas tropical conditions may have prevailed at times in the study area and aided in producing carbonate mud, Öland was most likely located in a temperate climatic environment during deposition of this succession, probably between 45º and 60º (Cocks and Torsvik 2005). It therefore remains unclear how much direct precipitation of calcite has added to the mud present in this Ordovician carbonate system. It seems likely, though, that green algae have not contributed much or at all to the mud production in this carbonate system as not a single piece of green algae has been recorded from the entire succession to date. Therefore, the carbonate mud in the Lower to Middle Ordovician succession in the study area was most likely mainly introduced in a temperate to sub-tropical environment by the disintegration of skeletal particles with the likelihood of slight contribution of direct-precipitation.

This study concludes that the overall high amounts of carbonate mud contained in the Ordovician succession in Scandinavia originated most likely from abrasion of mm- to cm-size carbonate particles, most likely organic hardparts that are frequent throughout the succession. This origin of carbonate mud, however, is unusual for carbonate facies models; generally either direct precipitation of aragonite needles are invoked for the recent (e.g. Kinsman, 1969, for the Trucial Coast), or the decay of shallow-water green algae such as *Penicillus* and *Halimeda* are held accountable for producing large amounts of carbonate mud (cf. Granier, 2012).

Climate as emphasized through this chapter is one of the driving factors controlling different types of carbonate factories. Multiple parameters contribute to climate zones such as e.g. latitudes and the CO_2 content of the atmosphere. The carbonate factory was situated on the south – western coast of Baltica in between 45^0 to 60^0 paleo-latitudes through the Lower to Middle Ordovician (Cocks and Torsvik 2005; Kiipli et al., 2008; Kiessling et al., 2003). The mean annual sea surface temperatures of modern oceans is between 4 ^{0}C and 14 ^{0}C (Fedorov et al., 2013) for these latitudes, which is restricted to non-tropical carbonate settings, particularly cool water carbonate realms (James, 1997). However, drastic differences of CO_2 contents of modern and Ordovician atmospheres are documented, as ~ 400 ppm CO_2 represent ice-house periods and ~ 5600 ppm CO_2 represent green-house periods, respectively (Royer, 2006). The striking difference of the CO_2 contents of the atmospheres would have likely increased overall sea surface temperatures, so the climate belts experienced between 45^0 to 60^0 latitudes in modern times are not comparable to the Ordovician ones.

8.2. Sea – Level Changes and Sequence Stratigraphy

The Lower to Middle Ordovician carbonate succession in Öland records laterally correlatable vertical facies and grain-size trends that allow for a sequence stratigraphic interpretation of the succession. Because the succession is generally mud-dominated, was deposited in a medial to distal ramp setting and does therefore not show distinctive facies trends comparable to shallow-water ramp systems, the more simple Transgressive-Regressive model (Johnson and Murphy, 1984; Embry and Johannessen, 1992; cf. Catuneanu et al., 2009) and not the modified Exxon-model (cf. van Wagoner et al., 1990; Catuneanu et al., 2009) are used in this study to distinguish individual sea-level positions and trends that are reflected by the succession on Öland.

The Lower to Middle Ordovician carbonate succession in Öland is composed of three 3rd order sequences (Figure 8.2.1.) based on the transgressive versus regressive sequence stratigraphic model. These sequences are bounded by maximum regressive surfaces (MRS) (Appendix 1). Each sequence has both transgressive (TST) and regressive systems tracts (RST) representing episodic base level changes that are laterally traceable within the basin.

The vertical succession of distinct intercalated facies for each stratigraphic interval shows that the entire studied succession reflects an initial regression and a subsequent transgression that is followed by a slight regression at the very top of the succession (Figure 8.2.1., red dashed line). This overall trend indicates a second order cycle based on the amount of time represented by the studied succession.

Haq and Shutter (2008) showed a slight sea-level increase along with multiple overriding fluctuations for the exact same stratigraphic intervals which are Lower to Middle Ordovician. Their sea-level curve, however, does not reflect the same trends that have been observed in the Öland succession (Figure 8.2.1.), even though Haq and Schutter's (2008) reconstruction is much more detailed. It should be noted, however, that their approach lacking error bars and not being able to provide unbiased results (Miall, 1992) may not be an ideal comparison to the Öland sea-level fluctuations as it may not really reflect worldwide traceable sea-level events even though the authors claim it does.

Nielsen's (2004) reconstruction which is entirely based on a Scandinavian data set is generally showing a good overlap with the present study. Nevertheless, there are several distinct differences between this study and the suggestions of Nielsen (2004) even when only looking at the overriding second-order sea-level trend: Nielsen's (2004) study suggests that the initial regression culminates in the Pakerort, whereas this study indicates a maximum lowstand much later in the lower part of the Hunneberg stage.

Also the smaller-scale, third-order "cycles" are much less detailed in the present study than shown in Nielsen (2004): only three small-scale "cycles" could be detected in the Öland succession, whereas Nielsen (2004) indicated 16. While it remains a question where he got all this detail from the present study concludes that deep ramp carbonates such as the succession exposed on Öland generally do not show the detail near-shore successions would show. The reason for this is that most likely some of the sea-level fluctuations will only lead to facies changes in the shallow-water realm and not be reflected in facies changes on mid- to outer ramp settings. Additionally, the Öland succession has been heavily bioturbated leading to overall blurred facies transitions, and therefore subtle facies changes cannot be recognized any more even though they may have been originally present.

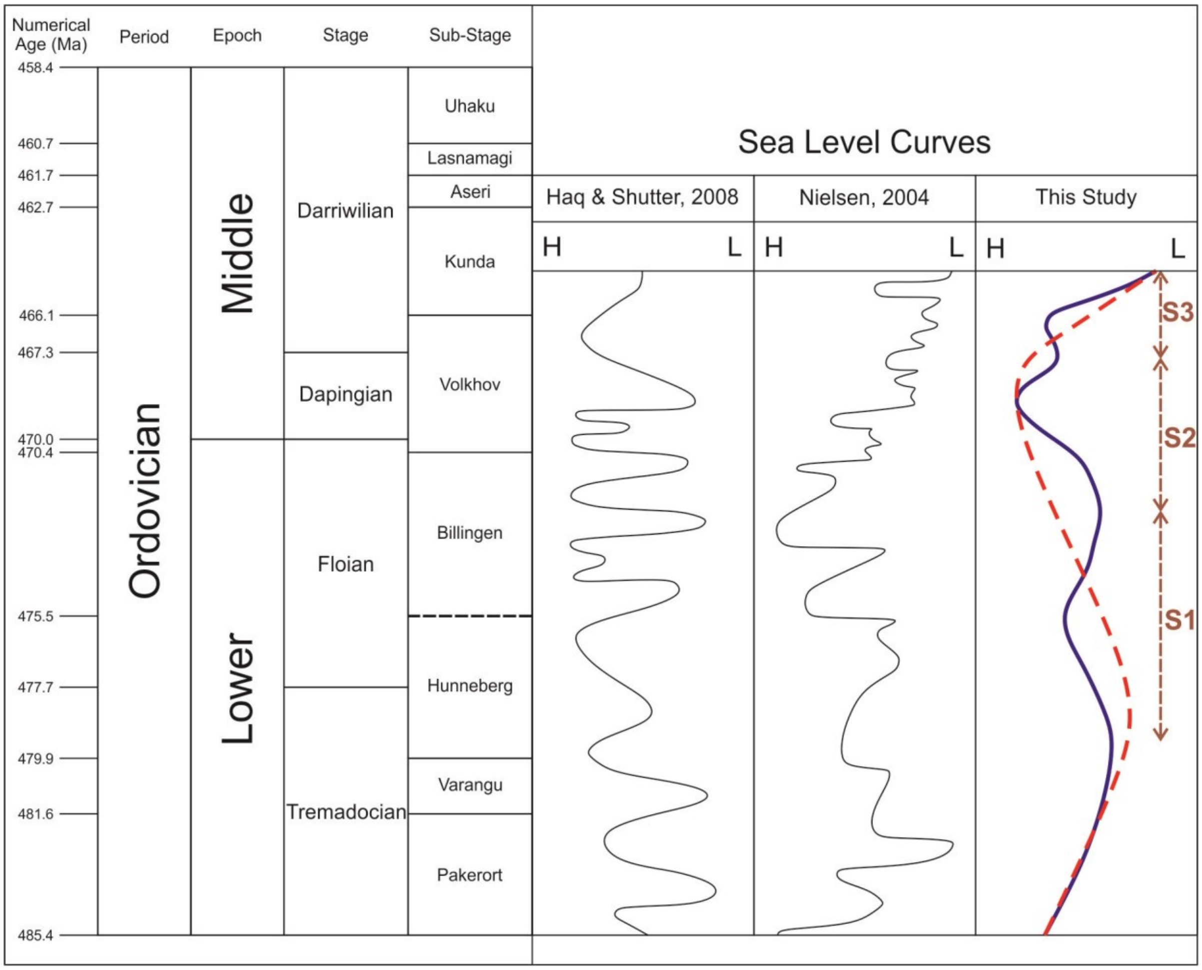

Figure 8.2.1. Relative sea-level curve comparisons for the Lower to Middle Ordovician carbonate succession in Öland, Sweden (Numerical Age: ICS, 2014; Sub-Stage: Bergström et al., 2009). Solid blue line refers to 3rd order, while dashed red line represents 2nd order cycle. S: Sequence.

8.3. Petroleum Exploration Potentials

The Ordovician succession in southern Sweden is generally not recognized as a prospect for hydrocarbon exploration. Yet, a single study (Pedersen et al., 2007) does identify its enormous potential, and based on this study, the Ordovician rocks of Scandinavia are here discussed in terms of their potential for having stored hydrocarbons.

The Ordovician carbonates in the Baltic region have been a focus of petroleum explorations since the late 19th century, and Upper Ordovician carbonate reservoirs produced about 630.000 bbl of oil from 1873 to 1966 on Gotland, Sweden (Sivhed et al., 2004). However, all of the conventional petroleum exploration was only localized around the island of Gotland in the Baltic Sea. This study, in contrast, focuses on the Lower to Middle Ordovician carbonate succession that forms a well-exposed outcrop equivalent of potential reservoirs in the subsurface of the entire Baltic Sea region spanning Swedish, Polish, and potentially Lithuanian, Estonian, and Russian territory (Figure 8.3.1.).

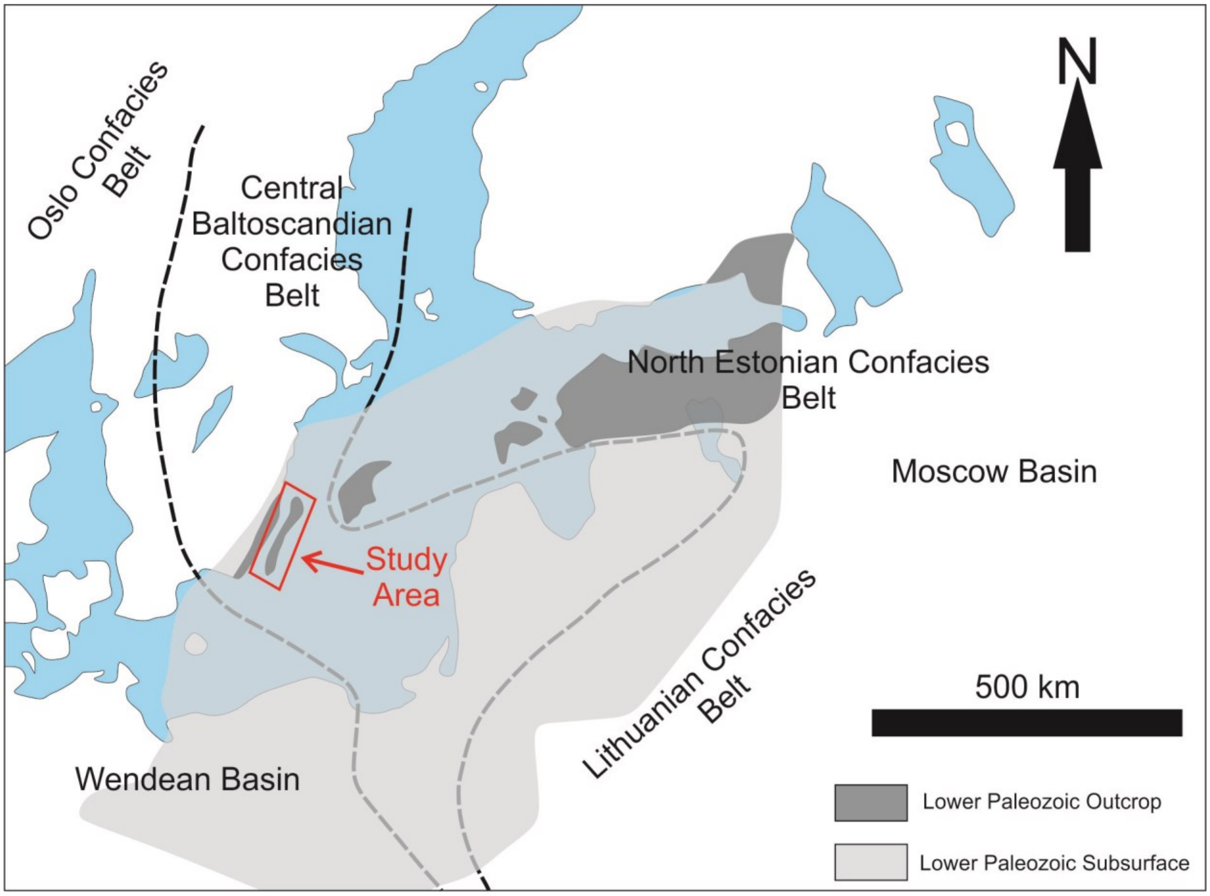

Figure 8.3.1. The study area with approximate boundaries of Ordovician confacies belts proposed by Jaanusson (1976). The figure is modified from Stouge (2004).

The Lower to Middle Ordovician carbonate succession in Öland only represents the reservoir and seal portion of a well-defined Cambrian to Ordovician petroleum system. The carbonates are overlying one of the most famous source rocks in Europe, the Alum Shale Formation. These black shales show highly variable thicknesses of up to 200 meters (Andersson et al., 1985; Schovsbo, 2000), and record total organic carbon (TOC) contents of up to 18% (Andersson et al., 1985; Pedersen et al., 2007). The Alum Shale formation is considered to be the source of oil produced from the Upper Ordovician carbonate rocks on Gotland, Sweden (Vlierboom et al., 1986; Buchardt et al., 1986; Bondar et al., 1998), and has also been proven to be source for carbonate rocks in the Siljan impact crater in the central Sweden (Ebbestad and Högström 2007). It is therefore expected to also have sourced oil in the Lower to Middle Ordovician succession in the subsurface of the Baltic Sea. In order to test the potential of the local Alum Shale Fm. in outcrop, a random sample from this black shale unit from Ottenby in southern Öland was examined for its hydrocarbon potential (Fig. 8.3.2). This sample from the top portion of the Alum Shale Formation contains 7.31% TOC, and in a Rock-Eval-6 analysis (Lafargue et al., 1998) showed a maximum temperature of 438 ^{0}C (T_{max}). The equivalent vitrinite reflectance value of the sample was determined to be 0.72% VR_0 calculated based on the formula provided by Jarvis et al. (2001):

$$\text{Cal. }\%VR_0 \text{ (from } T_{max}) = 0.0180 \times T_{max} - 7.16 = 0.72VR_0$$

Its high hydrogen (HI) versus oxygen indices (OI) (Fig 8.3.2) and equivalent vitrinite reflectance value indicate that the Alum Shale from southern Öland is oil-prone, has excellent source rock qualities, and is at an “early to peak” maturation level (cf. Peters and Cassa 1994). However, this also means that this rock has already produced oil. It is therefore reasonable to assume that an equivalent rock in the subsurface of the Baltic Sea in the vicinity of Öland will show at least equivalent maturation levels, maybe even slightly higher than the ones observed in the sample from Öland. This is likely because of high amounts of overburden that characterize the region and spans from its deposition in the Ordovician to end of Devonian in the Baltic Sea. The Cambrian Alum Shale in the subsurface of the Baltic Sea will therefore most likely already have released hydrocarbons that could be potentially stored at least in part in the Lower to Middle Ordovician carbonate succession in this area.

Sample-1 (Sa1) Analysis Results

TOC	S1	S2	S3
7.31	0.89	27.45	0.25
Tmax	**HI**	**OI**	**PI**
438	376	3	0.03

This analysis occurred in Rock Eval-6 (RE-6) instrument with IFP 160000 (Institut Francais du Petrole) standard be used.
TOC (Total Organic Carbon): % weight
S1: mg hydrokarbon / g rock
S2: mg hydrocarbon / g rock
S3: mg CO2 / g rock
Tmax: °C
HI (Hydrogen Index): (100xS2) / TOC
OI (Oxygen Index): (100xS3) / TOC
PI (Production Index): S1 / S1+S2

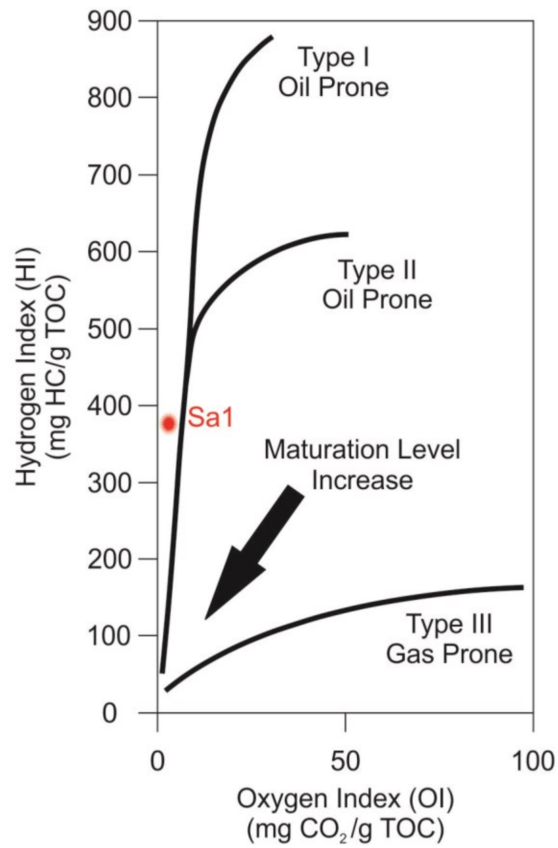

Figure 8.3.2. The Rock Eval. test results of the sample collected in Ottenby, Öland along with its position on the van Krevelen diagram (van Krevelen, 1961).

The Cambrian to Ordovician succession in Scandinavia and Estland therefore represents a perfect petroleum system in the subsurface of the Baltic Sea basin (Pedersen et al. 2007) and is likely to store hitherto non-discovered hydrocarbons: the carbonates have been deposited directly on the world-class source rock of the Alum Shale Formation, and Upper Ordovician shales, probably equivalent to the Fjäcka Shale Formation directly overlie and seal the Lower to Upper Ordovician carbonate reservoir (Pedersen et al., 2007; Ulmishek, 1990). Hydrocarbons must have passed through the Lower and Middle Ordovician rocks in order to charge reservoirs in the Upper

Ordovician part of the succession offshore Gotland. As also the Lower and Middle Ordovician units contain several tight horizons, e.g. the heavily cemented and laterally extensive hardgrounds of the Horns Udde Formation exposed in Öland, it is likely that these hardgrounds as well as the overlying marls of the Bruddesta Formation served locally as a seal.

Additionally, some of the Lower Ordovician units, particularly the carbonates of the Köpingsklint and Bruddesta Formations that are directly overlying the Alum Shale siliciclastic mudstones could well represent unconventional petroleum reservoirs. Because they consist predominantly of carbonate, it is assumed here that they will most likely react in a brittle way to “fracking” (Britt and Schoeffler, 2009; cf. Josh et al., 2012). This process may therefore liberate some of the hydrocarbons that are currently stored in small pore spaces within these mud- to wackestone facies, and that are likely sealed by the heavily cemented hardgrounds of the Horns Udde Formation on top.

Overall, testing the Lower to Middle Ordovician succession in the subsurface of the Baltic Sea therefore has to be considered a potential future target with a high likelihood of encountering hydrocarbons despite or maybe even because these potential reservoirs have not been explored to date.

CHAPTER 9: CONCLUSION

(1) The Lower to Middle Ordovician carbonate succession in Öland, Sweden is composed of the Köpingsklint, Bruddesta, Horns Udde, and Gillberga Formations, and contains nine carbonate facies, which can be grouped into four facies associations.

(2) The studied succession forms the carbonate mud-rich distal portion of the mid-ramp and proximal portion of the outer ramp environments of a homoclinal carbonate ramp, in which sedimentation occurred below normal but above storm wave base.

(3) The presence of glauconite throughout most of the succession, Fe-ooids, and the reduced thickness of this Lower to Middle Ordovician succession indicate a condensed setting for the ramp carbonates in Öland, Sweden.

(4) Heterozoan assemblages, allocthonous Fe- ooids, and abundance of carbonate mud suggest that the studied carbonate succession experienced temperate to sub-tropical paleo sea-water temperatures despite of its paleo-position between 45^0 to 65^0 south equivalence to modern temperate to cool-water carbonate ramp examples.

(5) The Öland carbonate succession records three 3^{rd} order sequences bounded by maximum regressive surfaces situated on top of each regressive systems tracts. The sequence boundaries are situated at the base of Köpingsklint, lower and upper part of Horns Udde, and top of Gillberga Formations. The oldest sequence boundary is at the base of Interval 1 that is overlain by deposits representing TST and RST from the Köpingsklint to Horns Udde Formations. The second and third

sequence boundaries are situated at the base and top of the Horns Udde Formation within Interval 2. Deposits of oldest TST reaching from the Horns Udde to Gillberga Formations overly the third MRS in Interval 2. Interval 3 is only comprised of RST sediments of the Gillberga Formation showing a tentetive sequence boundary at its top. The overall second-order sea-level curve therefore records an initial sea-level drop that had its minimum in the Hunneberg, and was followed by a sea-level rise that continued until the top of the succession in the Volkhov.

(6) This study suggests that the Cambrian to Ordovician succession represents a perfect petroleum system: the carbonates have been deposited directly on the organic-rich siliciclastic mudstones of the Alum Shale Formation, and upper Ordovician fine-grained rocks that are probably equivalent to the Fjäcka Shale Formation directly overlie and seal this Lower to Upper Ordovician carbonate reservoir.

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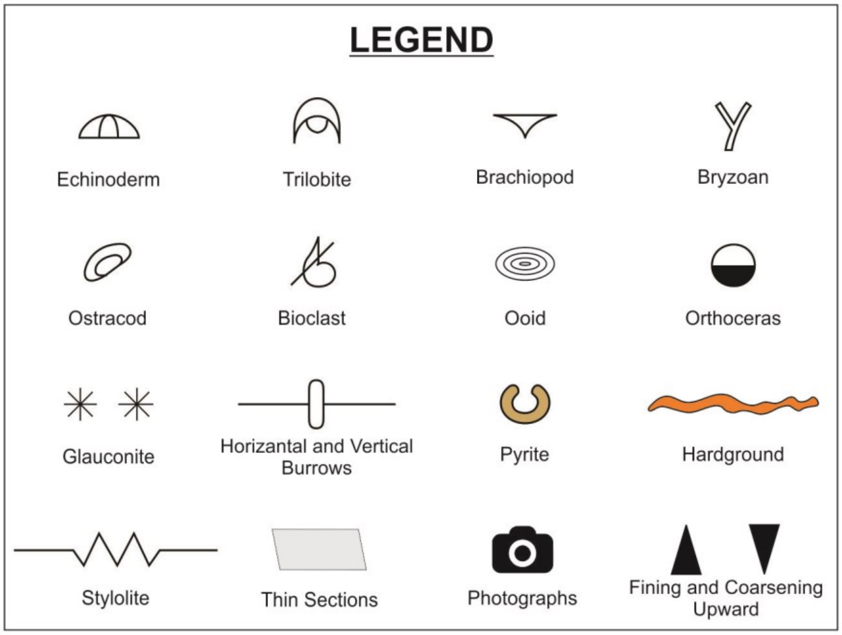
CHAPTER 11: APPENDICES

Appendix 1: Northeast – Southwest transect of the Lower to Middle Ordovician carbonate ramp succession in Öland, Sweden. A folded transect located in the back pocket.

Appendix 2: Measured and digitized successions of the Lower to Middle Ordovician carbonates in Öland, Sweden.

Appendix 2
1/6



KEY

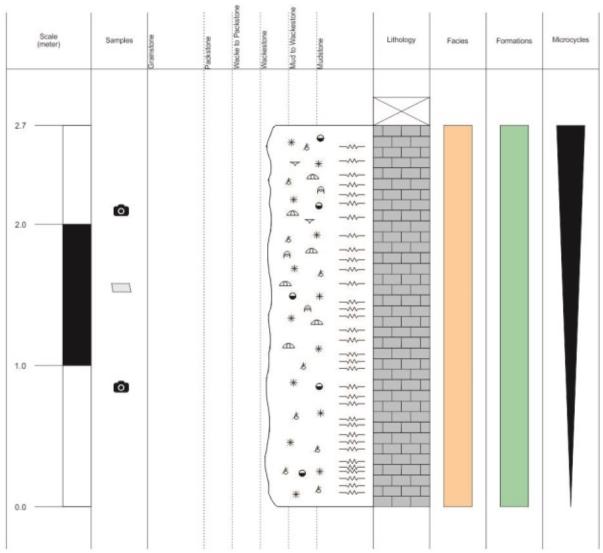
MRS: Maximum Regressive Surface
RST: Regressive Systems Tract
TST: Transgressive Systems Tract

- Gillberga Formation
- Horns Udde Formation
- Bruddesta Formation
- Köpingsklint Formation
- Interval 2
- Interval 1
- Interval 3

Facies A · Facies B · Facies C · Facies D · Facies E · Facies F · Facies G · Facies H · Facies I

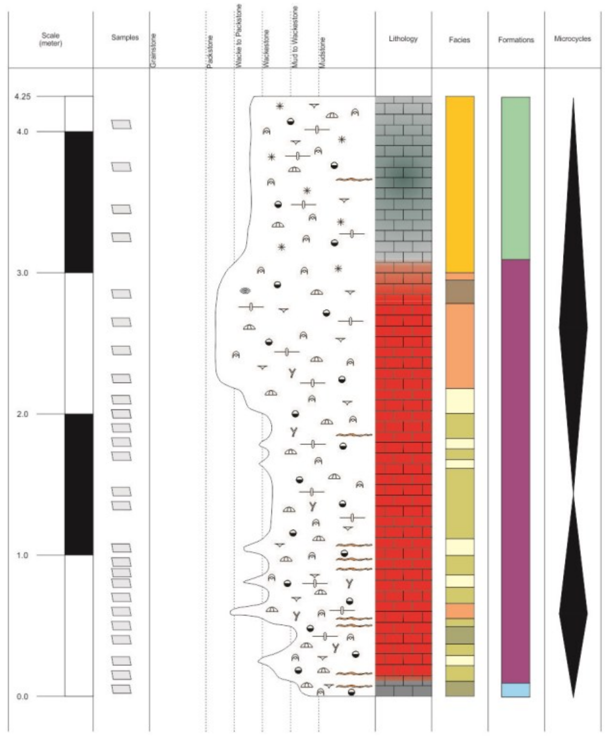
Locality:
Byrum

Appendix 2
2/6



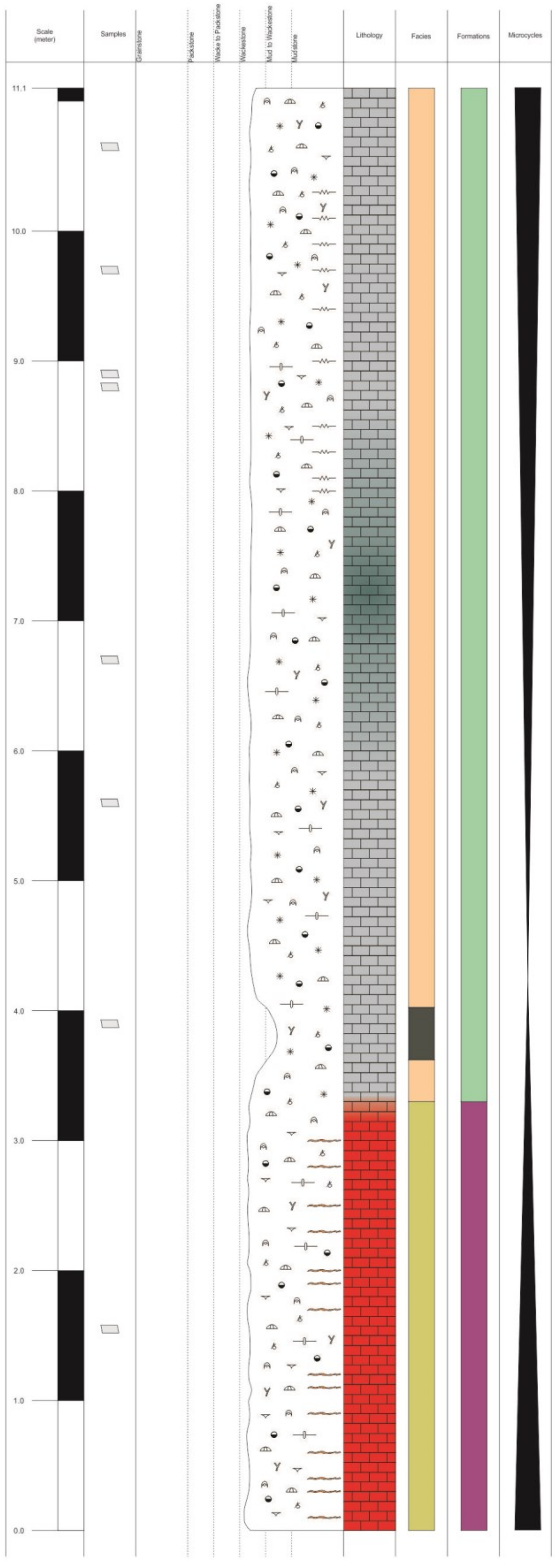
Locality: Degerhamn

Appendix 2 3/6



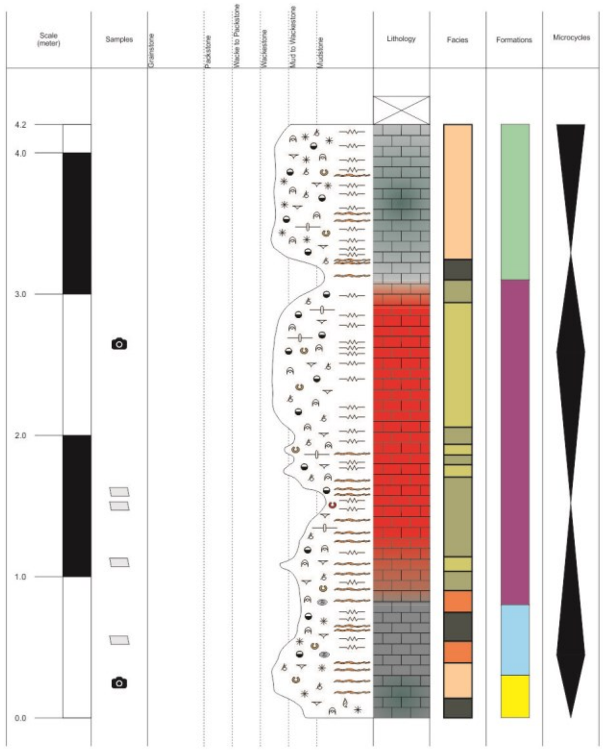
Locality: Gillberga

Appendix 2 4/6



Locality:
Horns Udde

Appendix 2
5/6



Locality:
Ottenby

Appendix 2
6/6