PS Depositional Environment and Facies Architecture of the Lower to Middle Ordovician Carbonate Ramp Succession, Öland, Southern Sweden*

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Abstract

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. Representing a passive margin setting on the west to southwestern part of Baltica micro-plate, yet approached from two sides by advancing continents through the Upper Ordovician, these carbonates were most likely formed in a temperate climate in about 45° to 60° paleo-latitude on the southern hemisphere. However, even though their fossil content is well known since Linné described some extinct species in the 18th century, their sedimentology has largely been left untouched. The scope of this contribution is therefore to clarify some basic aspects of this potential but mostly unexplored petroleum system that stretches through larger parts of the Baltic Sea in the subsurface.

For this study, six localities were sampled comprising the entire length of the island of Öland. All rocks throughout the succession consist of wacke- to packstones containing mostly bioclasts. Well-recognizable grains constitute echinoderms, brachiopods, bryozoans, recrystallized bioclasts, and trilobites, in decreasing abundance. All of these skeletal grains make up between 10 and 45% of these Ordovician rocks. The Lower to Middle Ordovician succession as a whole records a slight coarsening-upward sequence trend.

This Ordovician succession is interpreted to represent the central to lower part of an extensive homoclinal carbonate ramp system facing both Iapetus Ocean and Tornquist Sea: the wackestones represent the distal sediments, whereas the packstones reflect deposition in the central portion of this ramp. The slight coarsening trend observed throughout the studied interval is interpreted to reflect a lowering of overall sea level. This is in contrast to worldwide trends: most of the Lower Ordovician does reflect a highstand, and at the onset of the Middle Ordovician, there should be a drop of sea level, both of which is not recorded in the Swedish Ordovician succession. It is therefore speculated that also tectonics and not only eustasy control base level changes on Baltica during the Lower to Middle Ordovician.

Throughout Öland, the succession shows open and minus-cement porosities of between 4-5%. These carbonates are directly overlying one of the most prominent source rocks of Scandinavia with up to 18% Total Organic Carbon (TOC) content, and overlain by Silurian shales in the subsurface. Therefore, these carbonate units have a high potential for petroleum exploration, especially in the Baltic Sea.

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

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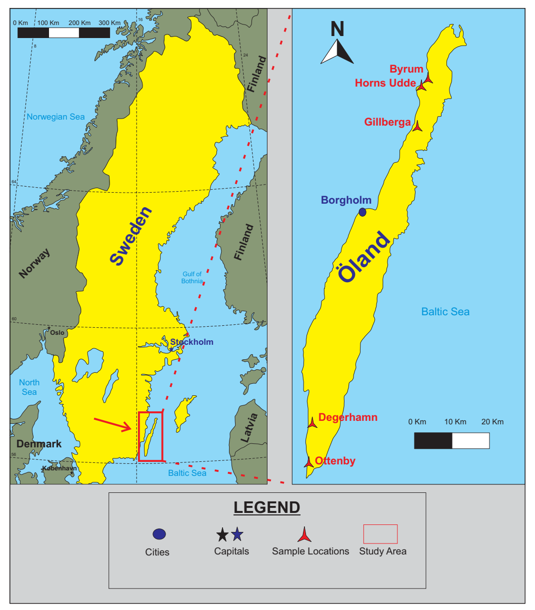
INTRODUCTION & GOALS



The Ordovician carbonate succession in Öland has previously been studied in detail for the purpose of paleontological aspects providing biostratigraphically well-dated examples for this Lower to Middle Ordovician carbonate succession (Webby et al., 2004; Bergström et al., 2009). Very few sedimentological studies describe the Ordovician carbonates from Scandinavia beside paleontological research (Jaanusson, 1972a and b; Männil, 1966; Jaanusson, 1976).

Objectives of this study:

(1) Provide a comprehensive and encompassing facies analysis,

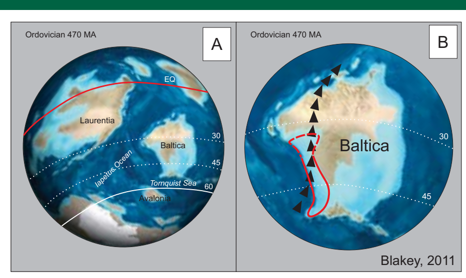
(2) Combine facies into a depositional model,

(3) Identify parameters controlling deposition (e.g. Climate Factors),

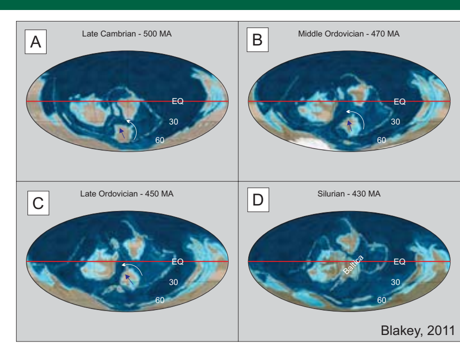
(4) Examine the importance of this carbonate succession within the Paleozoic petroleum system.

The study area comprises five localities (**Figure 1**) containing carbonate rocks outcropping along the west coast of Öland.

GEOLOGICAL SETTING



In the Early to Middle Ordovician, the Baltica micro-continent was located between 45 and 60 degrees paleo-latitude (**Figure 2**) on the southern hemisphere (Blakey, 2011; Cocks and Torsvik, 2005).
On its southwestern margin (Red line), this micro-plate developed a carbonate platform facing both the Tornquist Sea and the Iapetus Ocean in the Early and Middle Ordovician.



Baltica continuously drifted to the northwest, and, parallel to drifting rotated in an anti-clockwise direction (**Figure 3**), most likely since the Upper Cambrian (Torsvik and Rehnström, 2003).

FORMATIONS AND BIOSTRATIGRAPHY

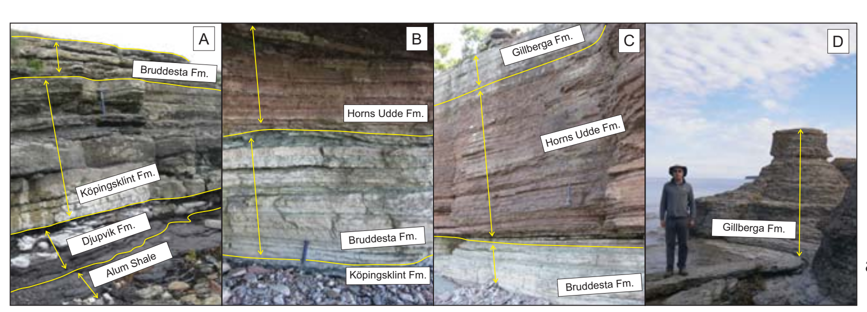


Figure 4. Outcrop display of the Lower to Middle Ordovician carbonate succession. Fig. A: Ottenby, southern Öland. Fig. B and C: the Horns Udde outcrop, Fig. D: the "Rauka" outcrop at Byrum in northern Öland.

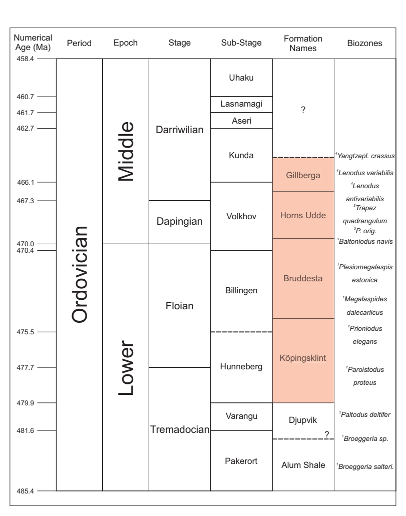


Figure 5. A summary of the biostratigraphy of the Ordovician carbonate succession in Öland, Sweden (Modified from Bergström et al., 2009; ICS, 2014) Biozones after:
1: Tjernvik, 1956;
2: Lindström, 1971;
3: Löfgren, 2000;
4: Zhang, 1998.

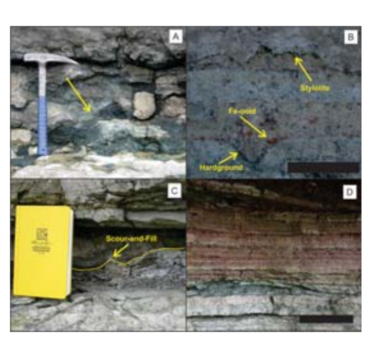
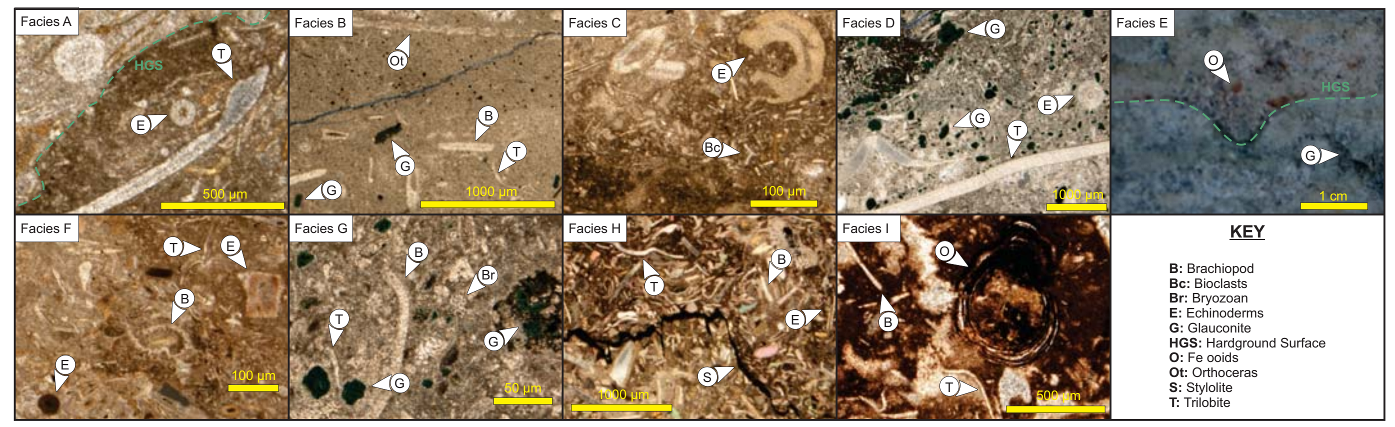


Figure 6. Sedimentological outcrop observations from Öland, Sweden. Fig. A: a glauconite (green to dark green area) pocket in wackestones within the Köpingsklint formation in Ottenby. Fig. B: stylolite, hardground and Fe-ooid occurence in the Bruddesta in Horns Udde; Fig. C: the scour-and-fill structure in the Bruddesta formation, Ottenby. Figure D:Multiple yellowish hardgrounds in the Horns Udde formation, Horns Udde.

FACIES PHOTOS



Microfacies in this study are characterized by limited grain types, both non-skeletal and skeletal grains. The grains range in abundance from "10-15%", "15-25%", "25-35%", and "35% <" for Mud- to Wackestone, Wackestone, Wacke-to Packestone, and Packestone, respectively (Dunham, 1962). Hence, the lower to middle Ordovician succession in Öland is subdivided into 9 distinct carbonate facies (**Figure 7**).

* Echinoderm Mud- to Wackestone (Facies A)
* Trilobite Mud- to Wackestone (Facies B)
* Echinoderm Wackestone (Facies C)
* Trilobite and glauconite bearing Wackestone (Facies D)
* Echinoderm, glauconite, and Fe- Ooid bearing Wackestone (Facies E)
* Echinoderm Wacke- to Packestone (Facies F)
* Trilobite and glauconite bearing Wacke- to Packestone (Facies G)
* Echinoderm and trilobite bearing Packestone (Facies H)
* Echinoderm and Fe- Ooid bearing Packestone (Facies I)

DEPOSITIONAL MODEL

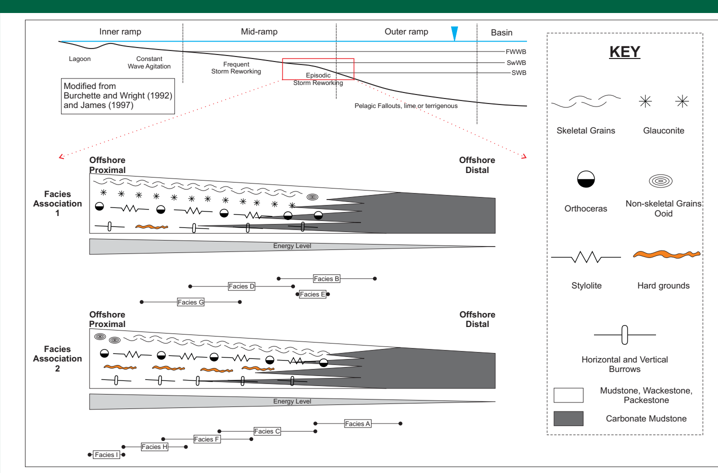


Figure 8. Depositional model for the Lower to Middle Ordovician succession in Öland, Sweden; FWWB: Fair weather wave base, SwWB: Swell wave base, SWB: Storm wave base.

Facies belt 1: An intercalation of mudstone, wackestone, and packestone facies. Reflecting varying energy regimes. The low-energy mudstones reflecting tranquil conditions during fair weather conditions. Mud introduced by suspension, likely from shallow parts of the ramp (cf. Flügel, 2010), or bed load transport (Schieber et al., 2013).
Facies belt 2: Exclusively of wacke- and mudstone facies. This generally calm environment occasionally interrupted by storm events that concentrated shell debris in wackestone lag layers. Mud deposited mostly by suspension rather than bed load transport because of being located further away.
Fe-ooids rare in the succession record unusual sedimentary conditions. Typical for shallow-water condensed environments (Burkhalter, 1995). Therefore interpreted as allochthonous grains transported into this environment, likely by storms.

SEA-LEVEL CHANGES

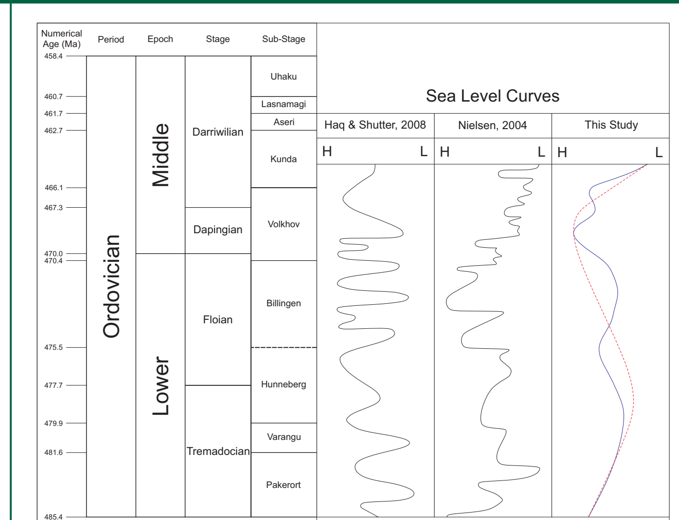


Figure 11. Relative sea-level curve for the Lower to Middle Ordovician carbonate succession in Öland, Sweden in comparison to worldwide sea-level reconstructions from Haq and Shutter (2008) and Nielsen (2004) (Numerical Age: ICS, 2014; Sub-Stage: Bergström et al., 2009).

TRANSECT

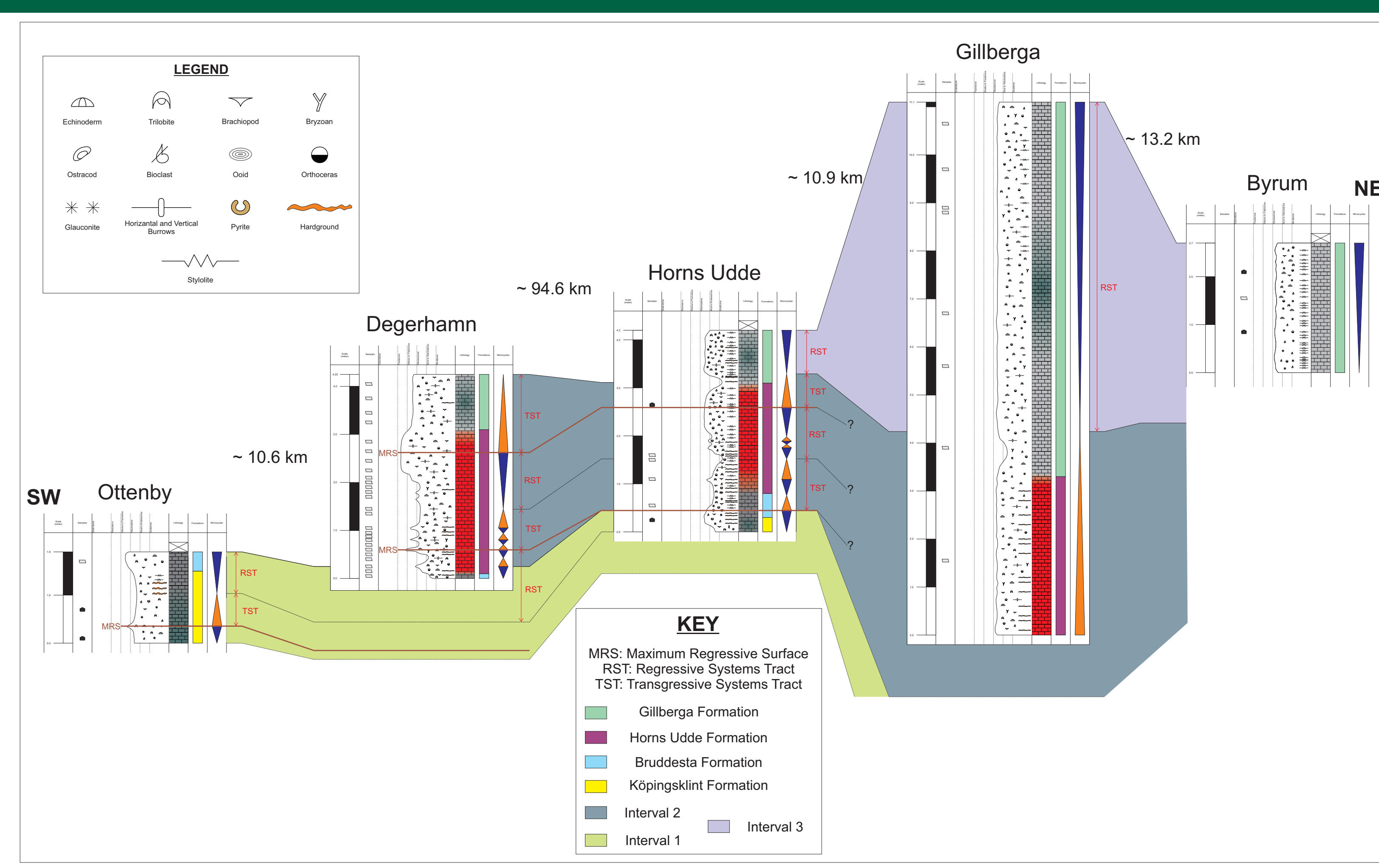
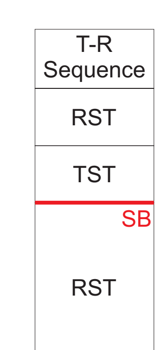


Figure 12. Transect of the five studied outcrops through the Lower to Middle Ordovician carbonate succession in Öland, Sweden showing detailed sedimentary structures and correlation of stacking patterns.

The succession records three sequences bounded by **maximum regressive surfaces (MRS)**. Each sequence is composed of **transgressive (TST)** and **regressive (RST)** system tracts. Transgressive system tracts are indicative of relative sea-level increase, whereas regressive system tracts document base level drops (Johnson and Murphy, 1984; Embry and Johannessen, 1992; c.f. Catuneanu et al., 2009).



Nomenclature of systems tracts and timing of sequence boundaries for the Transgressive versus Regressive sequence stratigraphic model (Catuneanu et al., 2009).

PETROLEUM EXPLORATION POSSIBILITIES

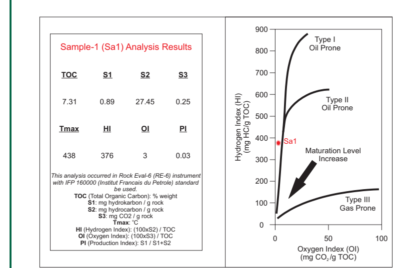


Figure 13. The Rock Eval. test results and van Krevelen diagram of the Alum Shale sample underlying the Carbonate succession in Ottenby, Öland.

Stage of Thermal Maturity for Oil	Maturation R₀ (%)	Maturation T_{max} (°C)	Maturation TAI	Generation Bitumen/TOC	Generation Bitumen (mg/g rock)	Generation PI [S_1/(S_1 + S_2)]
Immature	0.2–0.6	<435	1.5–2.6	<0.05	<50	<0.10
Mature						
Early	0.6–0.65	435–445	2.6–2.7	0.05–0.10	50–100	0.10–0.15
Peak	0.65–0.9	445–450	2.7–2.9	0.15–0.25	150–250	0.25–0.40
Late	0.9–1.35	450–470	2.9–3.3	—	—	>0.40
Postmature	>1.35	>470	>3.3	—	—	—

Figure 14. Geochemical parameters describing level of thermal maturation of shales in general (Peters and Cassa, 1994).

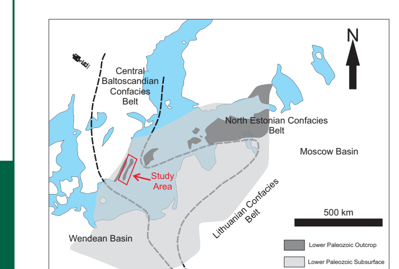


Figure 15. Location of the study area within the model of Ordovician facies belts featuring similar lithologies ("confacies belts") based on Jaanusson (1976).

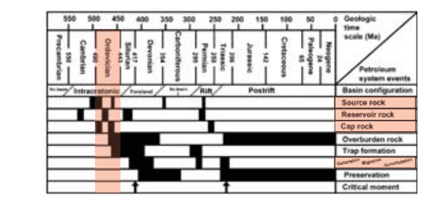


Figure 16. Petroleum system event chart for the Paleozoic in Scandinavia (Pedersen et al., 2007).

CONCLUSION

(1) The Lower to Middle Ordovician carbonate succession in Öland, Sweden contains nine carbonate microfacies, which can be grouped into two 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 (Burchette and Wright, 1992; James, 1997).

(3) The Öland carbonate succession records three sequences bounded by maximum regressive surfaces (c.f. Catuneanu et al., 2009). The initial sea-level drop ended in the Hunneberg, and the major sea-level rise continued untill the Volkhov from the Lower to Middle Ordovician as a-second-order-cycle. It is also important to emphasize that influence of sea-level fluctuations are not well documented in distal settings. However, our findings propose more accurate interpretation of the Ordovician sea-level fluctuations for Scandinavia than the study of Nielsen (2004) and Haq and Shutter (2008).

(4) Heterozoan assemblages and allochthonous Fe- ooids suggest that the studied carbonate succession experienced a temperate to sub-tropical paleo-climate despite its paleo-position between 45 to 60 pale-latitudes during the Lower to Middle Ordovician that are not comparable to modern examples.

(5) The Cambrian to Ordovician succession in Scandinavia and Estland represents a perfect petroleum system in the subsurface of the Baltic Sea basin (Pedersen et al. 2007) and is therefore 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, likely equivalent to the Fjäcka Shale Formation directly overlie and seal the Lower to Upper Ordovician carbonate reservoir (Pedersen et al., 2007; Ulmishek, 1990). 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 so far.

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REFERENCES

Bergström, S.M., Chen, X., Gutierrez-Marco, J.C., and Dronov, A., **2009**. The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and the x13C chemostratigraphy, Lethaia, v. 42, p. 97 – 107.
Blakey, R., **2011**, Global Paleogeography, < http://jan.ucc.nau.edu/rcb7/globaltext2.html> Accessed August 27, 2014.
Burchette, T.P. and Wright, V.P., **1992**, Carbonate ramp depositional systems, Sedimentary Geology, v. 79, p. 3-57.
Burkhalter, R.M., **1995**, Ooidal ironstones and ferruginous microbialites: origin and relation to sequence stratigraphy (Aalenian and Bajocian, Swiss Jura mountains), Sedimentology, v. 42, p. 57-74.
Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fischer, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., and Winker, C., **2009**, Towards the standardization of sequence stratigraphy, Earth-Science Reviews, v. 92, p. 1-33.
Cocks, L.R.M. and Torsvik T.H., **2005**, Baltica from the late Precambrian to mid-Palaeozoic times: The gain and loss of a terrane's identity, Earth-Science Reviews, v. 72, p. 39-66.
Dunham, R.J., **1962**, Classification of Carbonate Rocks According to Depositional Textures, AAPG Special Volumes (Pub. ID: A038), p. 108-121.
Embry, A.F. and Johannessen, E.P., **1992**, T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, Western Sverdrup Basin, Arctic Canada, Arctic Geology and Petroleum Potential, v. 2, p. 121-146.
Flügel, E., **2010**, Microfacies of carbonate rocks: Analysis, interpretation, and application (2nd edition): Verlag Berlin Heidelberg, Springer, 984 p.
Haq, B.U. and Schutter, S.R., **2008**, A chronology of Paleozoic sea-level changes, Science, v. 322, p. 64-68.
ICS, **2014**, International Chronostratigraphic Chart, <http://www.stratigraphy.org/ICSchart/ChronostratChart2014-02.jpg> Accessed September 4, 2014.
Jaanusson, V., **1972a**, Constituent analysis of an Ordovician limestone from Sweden, Lethaia, v.5, p. 217-237.
Jaanusson, V., **1972b**, Aspects of carbonate sedimentation in the Ordovician of Baltoscandia, Lethaia, v. 6, p. 11-34.
Jaanusson, V., **1976**, Faunal dynamics in the middle Ordovician (Viruan) of Balto-Scandia, *in* M.G. Bassett, eds., The Ordovician System: Proceedings of a paleontological association symposium, p. 301-326.
James, N.P. and Bone, Y., **1991**, Origin of a cool-water, Oligo-Miocene deep shelf limestone, Eucla Platform, southern Australia, Sedimentology, v. 38, p. 323-341.
Johnson, J.G. and Murphy, M.A., **1984**, Time-rock model for Siluro-Devonian continental shelf, western United States, GSA, v. 95, p. 1349-1359.
Lindström, M., **1971**, Lower Ordovician conodonts of Europe, GSA, v. 127, p. 21-61.
Löfgren, A., **2000**, Early to early Middle Ordovician conodont biostratigraphy of the Gillberga quarry, northern Öland, Sweden, GFF, v. 122, p. 321-338.
Männil, R., **1966**, History of the evolution of the Baltic basin in the Ordovician. Tallinn: Valgus Publishers: 1-210 (in Russian with English abstract).
Nielsen, A.T., **2004**, Ordovician sea level changes: A Baltoscandian perspective, in Webby, B.D., et al., eds., Great Ordovician biodiversification event: New York, Columbia Press, p. 84–93.
Pedersen, J.H., Karlsen, D.A., Spjeldnaes, N., Backer-Owe, K., Lie, J.E., and Brunstad, H., **2007**, Lower Paleozoic petroleum from southern Scandinavia: Implications to a Paleozoic petroleum system offshore southern Norway, AAPG Bulletin, v. 91, no.8, p. 1189-1212.
Peters, K. E. and Cassa. M. R., **1994**, Applied source rock geochemistry. In L. B. Magoon & W. G. Dow (Ed.). The Petroleum System-- ,from Source to Trap. American Association of Petroleum Gelogists Memoir 60, p. 1-24.
Royer, D.L., **2006**, CO_2-forced climate thresholds during the Phanerozoic, Geochimica, v. 70, p. 5665-5675.
Schieber, J., Southard, J.B., Kissling, P., Rossman, B., and Ginsburg, R., **2013**, Experimental Deposition of Carbonate Mud from Moving Suspensions: Importance of Flocculation and Implications for Modern And Ancient Carbonate Mud Deposition, Journal of Sedimentary Research, v. 83, p. 1026-1032.
Tjernvik, T.E., **1956**, On the early Ordovician of Sweden, Bulletin of the Geological Institutions of Uppsala 35, p. 108-284.
Torsvik, T.H. and Rehnström, E.F., **2003**, The Tornquist Sea and Baltica-Avalonia docking, Tectonophysics, v. 362, p. 67-82.
Ulmishek, G., **1990**, Geological Evolution and Petroleum Resources of the Baltic Basin, AAPG Memoir, v. 51, p. 603-632.
van Krevelen, D.W., **1961**, Coal: Typology, Chemistry, Physics, Constitution, Elsevier.
Webby, B.D., Cooper, R.A., Bergstrom, S.M., and Paris, F., **2004**, Stratigraphic framework and time slices, *in* B.D. Webby, F. Paris, M.L. Droser, and I.G. Percival, eds., The Great Ordovician Biodiversification Event: Columbia University Press, p. 41-47.
Zhang, J., **1998**, Middle Ordovician conodonts from the Atlantic Faunal Region and the evolution of key conodont genera, Meddelanden från Stockholms universitets institution för geologi och geokemi, v. 298, p. 5-27.