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# Stratigraphy and Paleoenvironments of the Soeginina Beds (Paadla Formation, Lower Ludlow, Upper Silurian) on Saaremaa Island, Estonia

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By

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Cover page art work- Soeginina Beds at Kübassaare.

# ABSTRACT

The Soeginina Beds in the Paadla Formation on the island of Saaremaa, western Estonia, are a lower Ludlow (Upper Silurian) sequence of dolostones, marls, and stromatolites. They represent rocks just above the Wenlock/Ludlow boundary, which is distinguished by a major disconformity that can be correlated to a regional regression on the paleocontinent of Baltica. The depositional environments of the Soeginina Beds include a shelfal environment, restricted shallow marine setting, intertidal mudflat and finally a hypersaline supratidal setting. The evidence includes halite crystal molds, oscillation ripples, eurypterid fragments, stromatolites, ostracods, gastropods, *Chondrites* trace fossils, intraclasts and oncoids. Nautiloid conchs are common, probably because storm currents washed them in. I measured two sections of the Soeginina Beds at Kübassaare, eastern Saaremaa in western Estonia. The beds in one section are virtually horizontal; in the second they are steeply dipping, probably because of Pleistocene glacial ice overpressure. The beds begin with fine-grained dolostone and end with large, well-preserved domical stromatolites. The equivalent section at Soeginina Cliff in western Saaremaa (about 86 kilometers away) has larger oncoids, branching coral fragments, and bigger stromatolites. It is also more heavily dolomitized. These differences indicate that the western Soeginina Cliff was deposited in slightly deeper, less saline waters than those in the east at Kübassaare.

# ACKNOWLEDGEMENTS

Firstly, I would like to thank the College of Wooster, Department of Geology, for funding my research project. I would also like to thank Jonah Novek for helping me with my fieldwork in Estonia. I am grateful to Olev Vinn for locating my research site and providing us with the geologic background of the Soeginina Beds. Finally, I would like to thank Dr. Wilson for his constant support and guidance throughout the process.

# INTRODUCTION

The island of Saaremaa, west of the mainland of Estonia, has some excellent outcrops that expose Silurian stratigraphy and paleoenvironments. In July 2012, a team of College of Wooster and Ohio State University geologists went to Saaremaa to do field work and collect samples.

This study measures and describes the stratigraphic column of the Soeginina Beds in the Paadla Formation, Lower Ludlow (Upper Silurian), at Kübassaare, eastern Saaremaa. This study comprises of a detailed description of the Silurian chronostratigraphic chart, graptolite zonations, global series and Estonian stages. It also includes the stratigraphy of Saaremaa and the stratigraphic column of the Soeginina Beds at Kübassaare. The occurrence of halite crystal molds, stromatolites, eurypterids, oncoids, ostracods, *Chondrites* trace fossils, and nautiloid molds, make the analysis of this unit better.

The occurrence of these sedimentary structures and fauna in the Soeginina Beds provide us with evidence that there was a gradual change in paleoenvironmental conditions from a shelfal marine environment to a restricted shallow marine setting followed by a hypersaline supratidal setting.

The base of the section has *Chondrites* trace fossils and marly shale that represent a shelfal marine environment. The next section on top has dolostones with *Herrmannina* ostracods, oncoids, and eurypterid fragments that indicate a shallow marine setting (lagoonal). The next section above has stromatolites that form in exposed intertidal mud flats. The topmost section has halite crystal molds that represent a hypersaline supratidal setting. Thus, we see a gradual change from shelfal marine environment to a restricted shallow marine setting and finally to a hypersaline supratidal setting.

This study also compares two Soeginina Sections, one in eastern Saareema (Soeginina Beds) and the other in western Saaremaa (Soeginina Cliff) that indicates that the Soeginina Cliff in western Saaremaa has a deeper depositional environment than eastern Saaremaa (Soeginina Beds). We also analyzed the development of the Baltic basin and observed that there is an increase in depth as we go west in the Baltic Basin from eastern Saaremaa to western Saaremaa to Gotland, Sweden.

# SILURIAN OF THE WORLD

The Silurian was a geologic period and system that extended from around 443.7 to 416 million years ago. It is preceded by the Ordovician Period and succeeded by the Devonian Period. The Soeginina Beds that are being analyzed in this study are a part of the Paadla Formation which belongs to the Lower Ludlow Series in the Upper Silurian. In 1985, the Silurian system was the first to have a globally applicable classification of series and stages. This was when the present definitions of the four Silurian series (Llandovery, Wenlock, Ludlow and Pridoli) and seven stages (Rhuddanian, Aeronian, Telychian, Sheinwoodian, Homerian, Gorstian, and Ludfordian) were established by the International Subcommission on Silurian Stratigraphy (ISSS) (Cramer et al., 2011). Regional chronostratigraphic terms were used in different parts of the world that are no longer in use due to the stable chronostratigraphic nomenclature and the cosmopolitan nature of the Silurian marine fauna which has led to preference for the global Silurian series and stages (Figure 1) ratified by the

ISSS (Cramer et al., 2011).

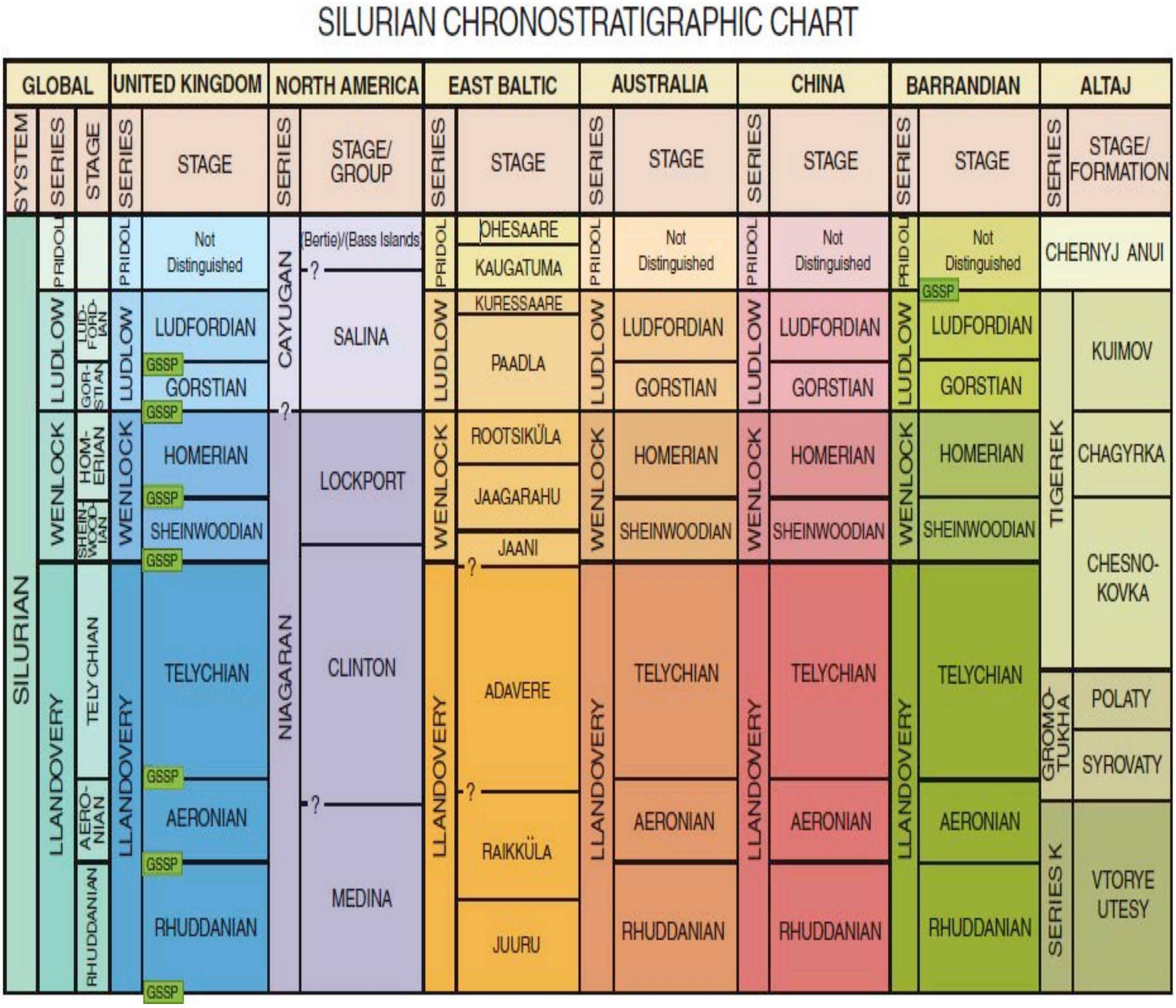


Figure 1: Global and regional stages and series of the Silurian worldwide (Cramer et al., 2011, Figure 1).

During the late 1990s, Silurian biostratigraphy underwent a period of significant progression spearheaded by the publication of a generalized graptolite zonation (Figure 2). The present Silurian timescale correlates the stage, series and system boundaries and graptolite zones; graptolite-bearing successions can now be correlated directly to the global chronostratigraphic classification (Cramer et al., 2011). The United Kingdom is important in Silurian stratigraphy as seven of the eight Silurian Global Boundary Stratotype Sections and Points (GSSP) are there. The British Silurian chronostratigraphy is coupled to the global chronostratigraphic classification, except the base of the Pridoli series (Cramer et al., 2011).

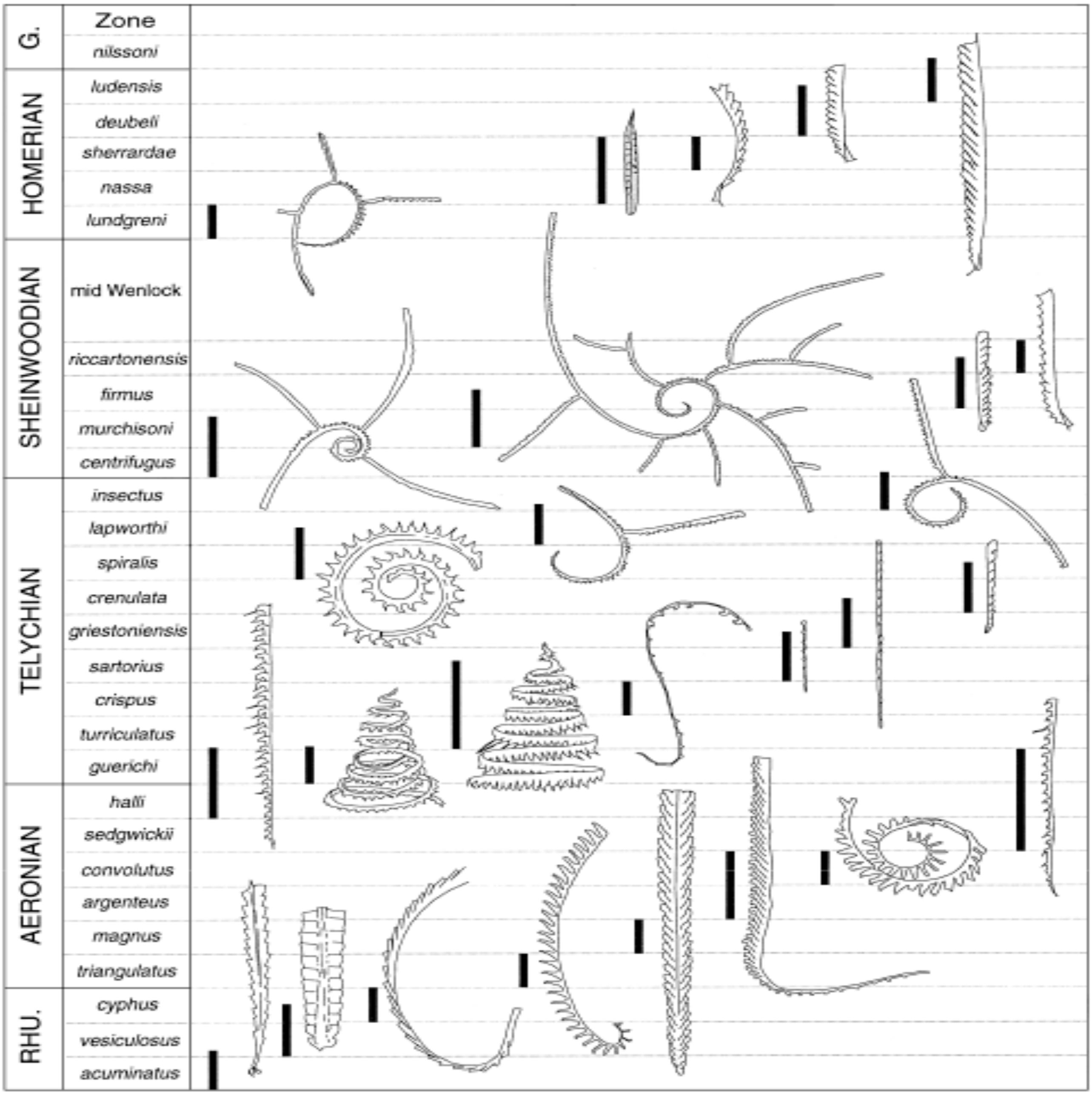


Figure 2: Graptolite zones in their stratigraphical ranges (Loydell, 1998, Figure 1).

## Llandovery Series

The Llandovery Series extended from around 443 to 428 million years ago. It is the oldest of the four main divisions in the Silurian System. This series derives its name from the town of Llandovery in Dyfed, southern Wales. The base of the Llandovery series coincides with the base of the Silurian System. It was formally defined under the authority of the International Commission on Stratigraphy (ICS). The global stratotype section and point (GSSP) for this boundary is defined at 1.6 meters above the base of the Birkhill Shale Formation on the north side of the Linn Branch stream at Dob's Linn, near Moffat in southern Scotland, U.K., at the incoming of graptolites *Parakidograptus acuminatus* and *Akidograptus ascensus.* Two formations occur near the boundary which are as follows: Hartfell Shale, is the lower formation and has a thickness of 48 meters. It consists of pale gray mudstone with subordinate black shales and several interbedded meta-bentonites. Above this formation lies the Birkhill Shale which is 43 meters thick and mostly consists of black graptolitic shale with subordinate gray mudstones and meta-bentonites (Cocks, 1985).

## Wenlock Series

The Wenlock Series lasted from around 428 to 422 million years ago. It consists of two stages: Sheinwoodian and Homerian. This series derives its name from a district at Wenlock Edge which is an escarpment that stretches for about 29 km southwest from the town of Much Wenlock in Shropshire, England. This group contains the following formations: Much Wenlock Limestone Formation, Wenlock Shale, and the Woolhope or Barr Limestone and shale. The GSSP for this boundary is established at Hughley Brooke, U.K at the base of the Buildwas. This unit is comprised of grey-green mudstones at the base, becoming blue-grey upwards, with fragments of bryozoans, pelmatozoans, brachiopods, corals, etc. The primary markers are close to the base of the *Cyrtograptus centrifugus* Graptolite Biozone (Bassett, 1989).

## Ludlow Series

The Ludlow Series took place from around 422 to 418 million years ago and has three stages. The stages are as follows: Gorstian and Ludfordian. The Soeginina Beds analyzed in this study are in the Paadla Formation which belongs to the Gorstian Stage. This series derives its name from a district that lies west of the town of Ludlow in Shropshire, England. The base of the Ludlow series is defined at the Pitch Coppice Quarry near Ludlow, U.K. This base coincides with the transition from the Much Wenlock Limestone Formation into softer, chiefly argillaceous siltstones of the Lower Elton Formation (Gorstian Age) (Bassett, 1989). The GSSP is established at the transition from hard nodular limestones to soft argillaceous siltstones. The GSSP is also marked by *nilssoni* (Figure 3) and the *Saetograptus (Colonograptus) varians* (Lawson and White, 1989).

| Series | Stage | Graptolite zone | |
|---|---|---|---|
| Pridoli | | *bouceki–transgrediens* | ✱x |
| | | *branikensis–lochkovensis* | ✱x |
| | | *parultimus–ultimus* | ✱x |
| Ludlow | Ludfordian | *formosus* | ✱p |
| | | *bohemicus tenuis–kozlowskii* | ✱x |
| | | *leintwardinensis* | ✱t |
| | Gorstian | *scanicus* | ✱t |
| | | *nilssoni* | ✱p |
| Wenlock | Homerian | *ludensis* | ✱t |
| | | *praedeubeli–deubeli* | ✱x |
| | | *parvus–nassa* | ✱x |
| | | *lundgreni* | ✱t |
| | Sheinwoodian | *rigidus–perneri* | ✱x |
| | | *riccartonensis–belophorus* | ✱x |
| | | *centrifugus–murchisoni* | ✱x |
| Llandovery | Telychian | *lapworthi–insectus* | ✱x |
| | | *spiralis* interval | i |
| | | *griestoniensis–crenulata* | ✱x |
| | | *turriculatus–crispus* | ✱x |
| | | *guerichi* | ✱?p |
| | Aeronian | *sedgwickii* | ✱p |
| | | *convolutus* | ✱t |
| | | *argenteus* | ✱p |
| | | *triangulatus–pectinatus* | ✱x |
| | Rhuddanian | *cyphus* | ✱t |
| | | *vesiculosus* | ✱p |
| | | *acuminatus* | ✱?t |

Figure 3: Graptolite zonation representing all the series (after Koren et al., 2007, Figure 1).

## Pridoli Series

Pridoli Series stretched from approximately 418 to 416 million years ago and has no stages. The base of the Přídolí Series is established within Bed 96 in the Požáry Section of the Daleje Valley, Prague, Czech Republic, where it coincides with the first occurrence of the graptolite species *Monograptus parultimus* (Kriz, 1989).

# SEA LEVELS DURING THE SILURIAN

Sea level curves provide useful models of sedimentation and thus are invaluable. They offer a working representation of the long-term trends of the base level along continental margins and the individual drainings, desiccations and inundations of interior seaways. In regions where local tectonic influences are few and have not deformed the stratigraphic record, sea level curves can be used to make first-order correlations (Haq and Schutter, 2008).

Global sea levels rose through the Early Silurian and declined through the Late Silurian (Figure 4).

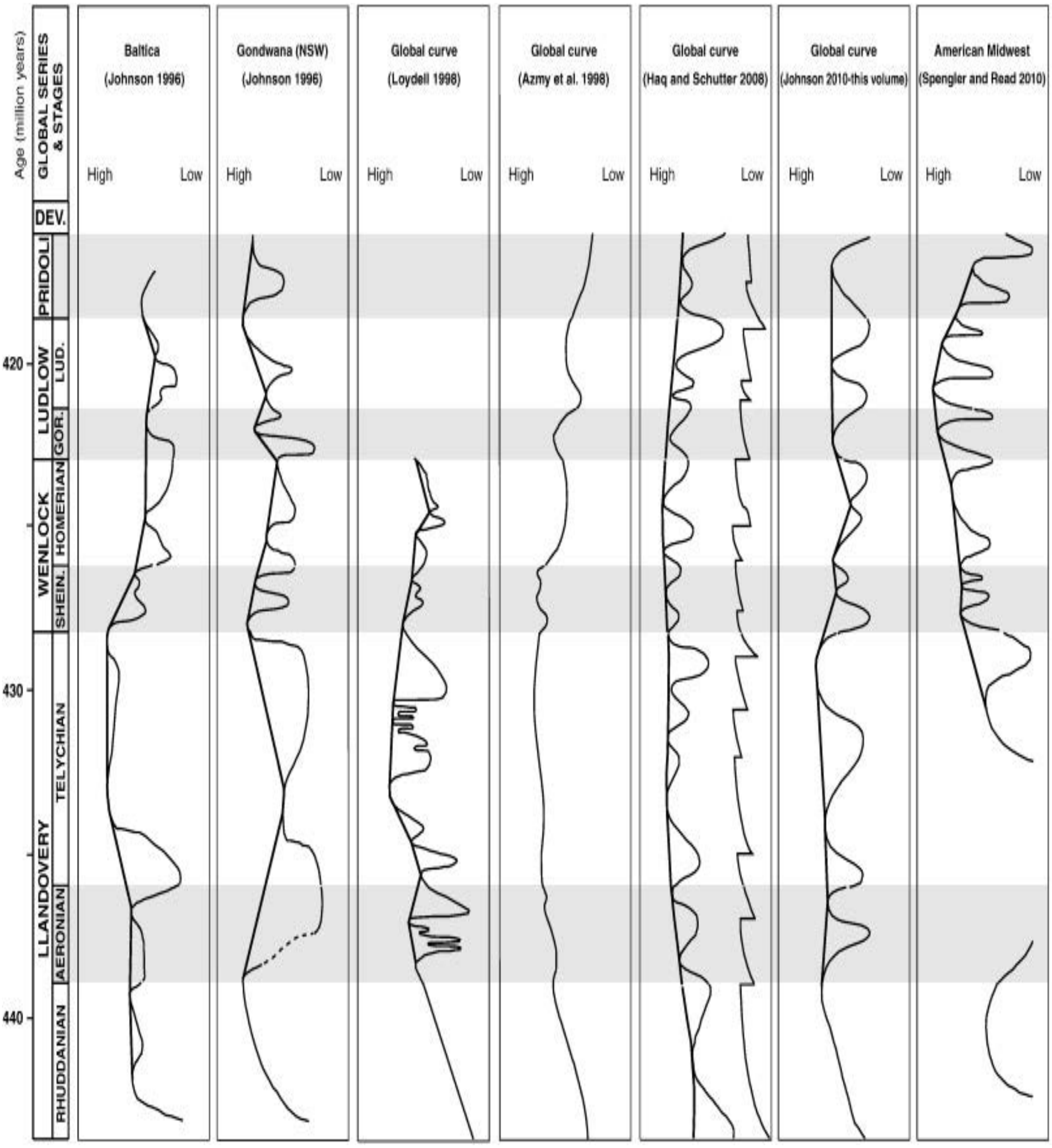


Figure 4: Global and regional compilations of different sea level reconstructions of the Silurian. The line on the left joins the high sea levels in each reconstruction (Munnecke et al., 2010, Figure 2).

The second highest peak in Paleozoic sea level occurred during the Silurian Period through the Homerian Age in the Wenlock Epoch. Mid-Homerian sea level was 200m above today's datum that marks the high spot on long term Silurian curves. The maximum range of sea level fluctuations during the Silurian Period was a little less than 140m (Johnson, 2010).

Global sea levels oscillated during early Silurian due to the mobility of ice sheets in the South American portion of Gondwana. In the Silurian, the highest sea levels are recorded by the Telychian upper *crispus*–lower *griestoniensis* and *spiralis*–lower *lapworthi* biozones. Other high sea levels occurred in the early Aeronian, during the *convolutus* Zone (mid Aeronian), *guerichi* Zone and late *turriculatus* Zone (early Telychian), and early Sheinwoodian. Low sea levels featured graptolite zones such as the *argenteus* and *sedgwickii* zones (Aeronian), the *utilis* Subzone (late *guerichi*–early *turriculatus* zones, early Telychian), the late Telychian (commencing in the mid *lapworthi* Zone) and, after a period of apparently only small amplitude sea-level fluctuations in the late Sheinwoodian and earliest Homerian, the mid–late Homerian, in particular the early *nassa* Zone (Loydell, 1998).

Soeginina Beds in the Paadla formation are in the lowermost Ludlow. They are just above the Wenlock/Ludlow boundary. So the sea-level during the Silurian in the Soeginina Beds is represented by the curves indicating a falling sea-level at the end of Late Wenlock (Homerian Stage). There is evidence from Wales, Welsh Borderland and Gotland that indicate two regressive periods during mid to late Homerian (Loydell, 1998). Lithological changes suggest that the first regression occurred late in the *lundgreni* graptolite zone with the lowest sea-level in the early part of the *nassa* graptolite zone. In southern Sweden, Baltica calcareous silty mudstone like the rock unit C/W-520 found at Kübassaare is interpreted as representing deposition during a regression due to a eustatic sea-level fall caused by glaciations. The regression was dated to *ludensis* graptolite zone, the last zone in the Wenlock before Ludlow Stage begins (Loydell, 1998).

Early Ludlow represents a time of eustatic sea level rise but whether this sea-level rise was rapid or gradual is a debate. The *nilsonni-scanicus* graptolite biozones record the highest Silurian sea-levels (Loydell, 1998). Looking at the sea-level curve of Baltica (Figure 5) we see that in the lowermost Ludlow (Gorstian) the sea-level indicates a regression. This regression changes into a transgression by mid Gorstian. This indicates that at the beginning of the Gorstian Stage the sea-levels were low and that the Soeginina Beds were formed and deposited in a period of low sea-level.

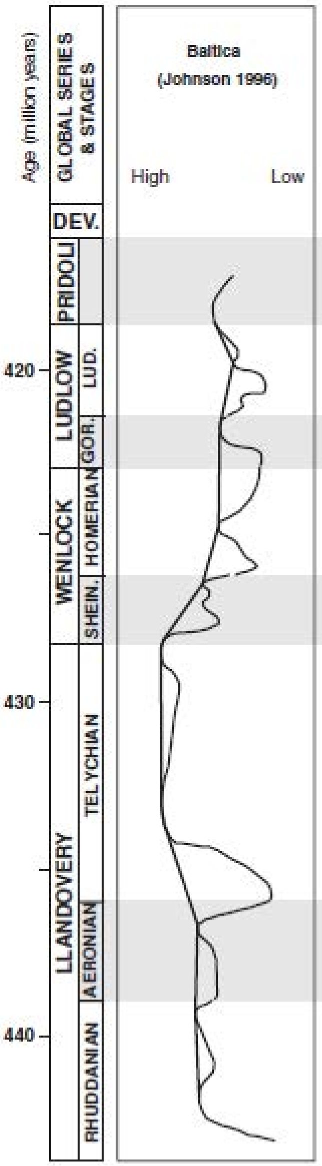


Figure 5: Sea-level curve of the Baltica in the Silurian (after Munnecke et al., 2010, Figure 2).

# LOCATION OF SAAREMAA ISLAND

Saaremaa is the largest island of Estonia, which is a Baltic country located north of Latvia and east of Russia (Figure 6). Saaremaa is located in the Baltic Sea where it lies west of the mainland and south of Estonia's second largest island, Hiiumaa. My research site, the Kübassaare cliff area, is on the southeastern part of the island; its coordinates are N58.4333°, E23.3104° (Figure 7).

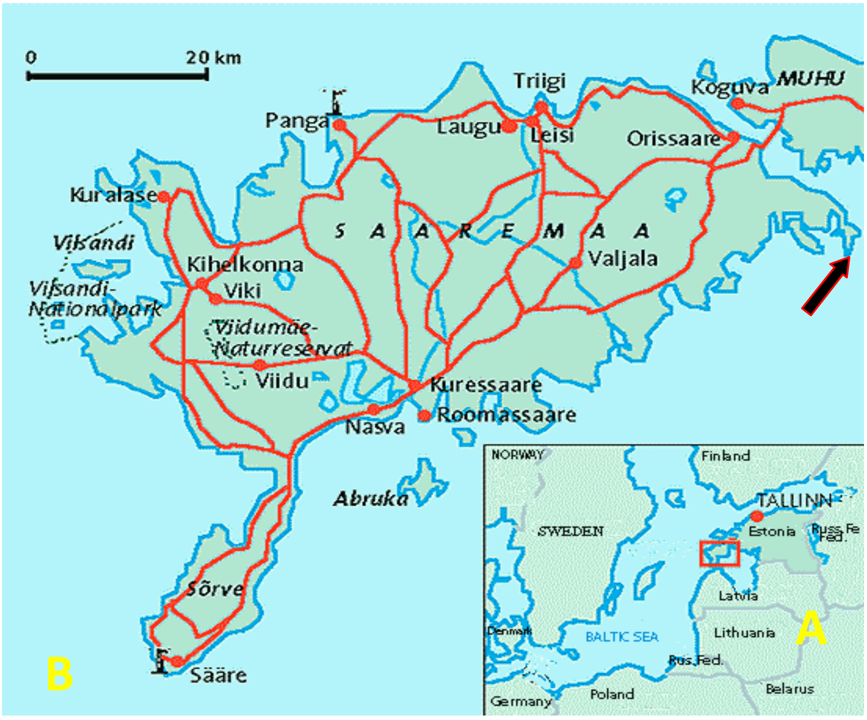


Figure 6: (A) Map of Estonia and its bordering countries. The red box indicates the island of Saaremaa; (B) Map of Saaremaa. The black arrow indicates Kübassaare, the location of this research. At this site samples C/W-514 through C/W-520 were collected (after http://www.baltex-research.eu/conf2007/Travel.html).


Figure 7: Google Earth image of Kübassaare Cliff area in southeastern Saaremaa.

The Kübessaare coastal area is an outcrop of the Soeginina Beds in the Paadla Formation (lowermost Ludlow) that represents a sequence of dolostones, marls, and stromatolites (Figures 8 and 9).

Figure 8: The shoreline at the Kübassaare coastal outcrop.

Figure 9: Stromatolites at the Kübassaare coastal outcrop.

# METHODS

## Field work- Soeginina Beds at Kübassaare.

We did our field work on July 9, 2012, at Kübassaare, Saaremaa, Estonia. We started by measuring the stratigraphic column of the Soeginina Beds using a ruler (Figure 10). Using a Garmin GPS, we took coordinates of the Soeginina Beds. We took detailed pictures of seven different units that we measured. We used a hammer to collect rock samples from each unit (Figure 11).

Figure 10: Ruler used to measure rock units at C/W-517 (see Figure 17 for section locality information).

Figure 11: Hammer used to collect samples at unit C/W-516 (see Figure 17 for section locality information).

**Sample analysis- The College of Wooster**

The rock samples were brought back to the College of Wooster where I labeled the samples and later cut them. The billets from the seven units at Kübassaare were sent to a professional laboratory that made thin sections that I later analyzed (Figure 12).

Figure 12: Billets and thin sections in lab.

Once the thin sections were prepared and sent back to us, I thoroughly analyzed them using Nikon microscopes (Figure 13).


Figure 13: Nikon microscope used to analyze the thin sections.

Later, I took photographs of the thin section using a photomicroscope and software called SPOT. I also used SPOT to add scales to my images (Figure 14).

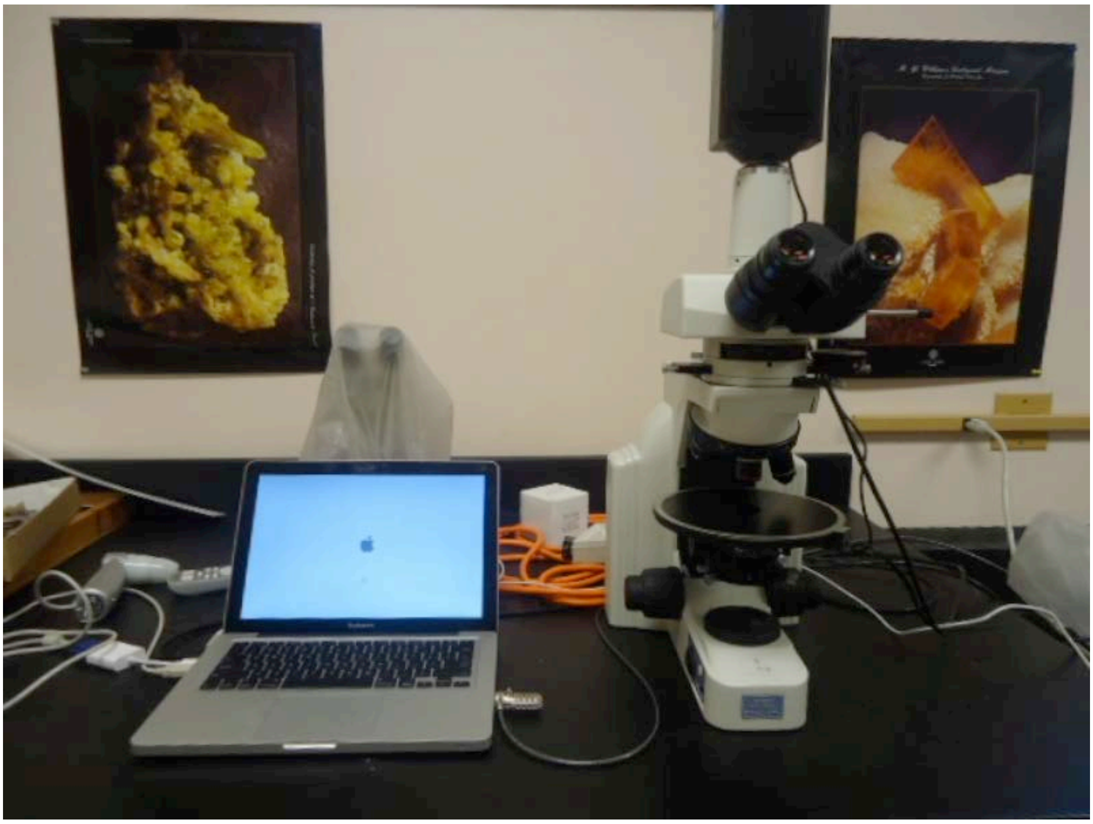

Figure 14: photomicroscope and computer used to take pictures of the thin sections.

# STRATIGRAPHY OF SAAREMAA ISLAND

Estonia's Silurian stratigraphic record consists of ten regional stages (Juuru through the Ohesaare) grouped into four globally recognized series (Figure 15). These series are as follows, from oldest to youngest: Llandovery, Wenlock, Ludlow, and Pridoli. The rocks at Kübassaare are from the Lower Ludlow Series (Gorstian Stage).

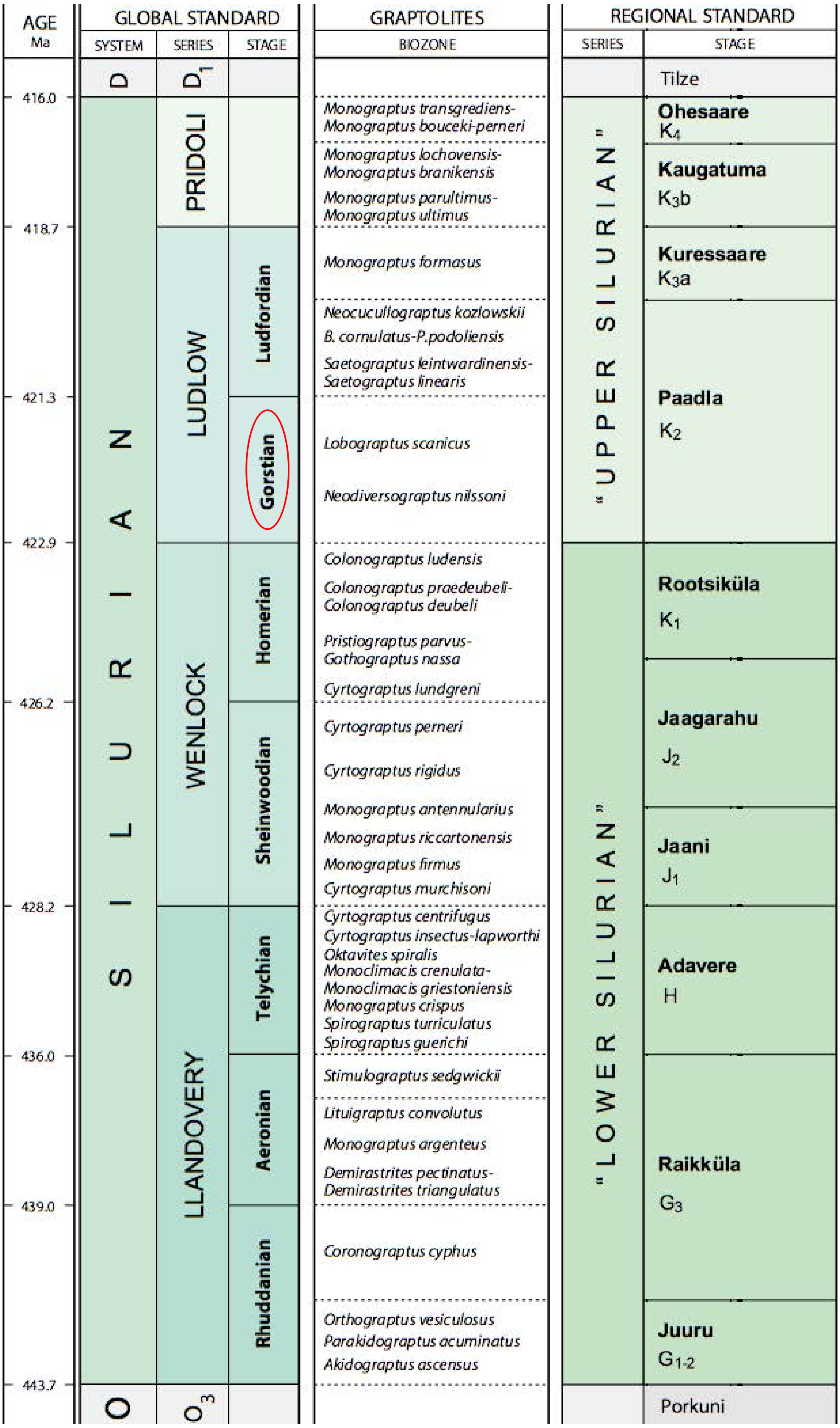


Figure 15: Estonian Silurian Stages and globally recognized Silurian Series. The rocks at Kübassaare belong to the Stage circled in red (after Hints, 2008).

## Paadla Formation

In this study, I am looking at samples from the Soeginina Beds in the Paadla Formation from the coastal outcrop at Kübassaare in eastern Saaremaa (Figure 16). The Paadla Formation belongs to the Ludlow Series and Gorstian Stage in part. It runs through the Paadla Stage.

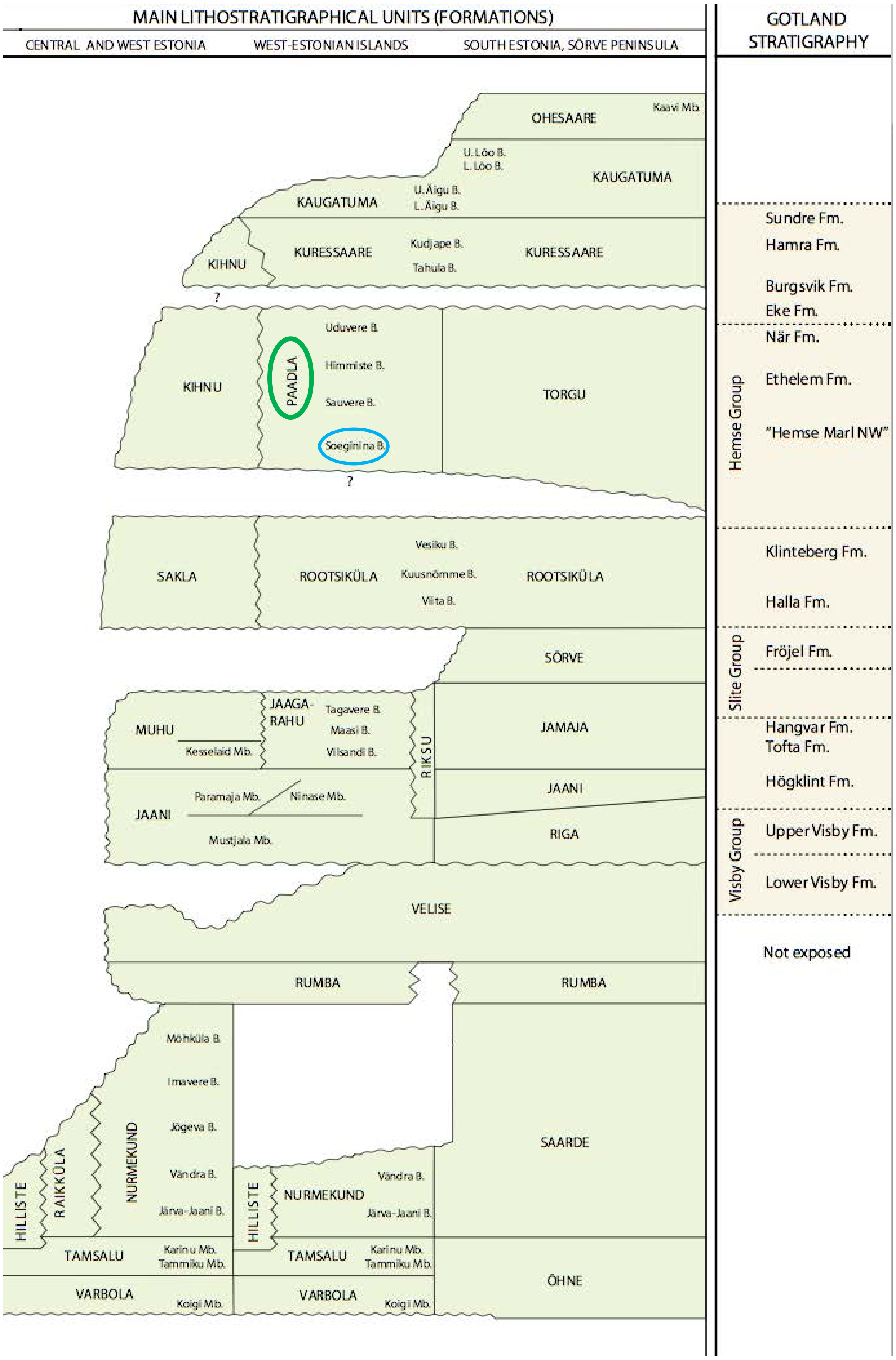


Figure 16: Soeginina Beds (circled in blue) in the Paadla Formation (circled in green) in the Gorstian Stage (after Hints, 2008).

## Stratigraphic column of rocks from Kübassaare

The coastal outcrop at Kübassaare exposes a sequence of dolostones, marls and stromatolites. The rocks include halite crystal molds, oscillation ripples, eurypterid fragments, stromatolites, ostracods, oncoids,nautiloids, *Chondrites* trace fossils and intraclasts.

We measured two sections of the Soeginina beds at Kübasaare. The beds in one section are virtually horizontal; in the second they are steeply dipping, probably because of glacial ice overpressure. The beds begin with fine-grained dolostone and end with large, domical stromatolites. The samples collected from the Soeginina Beds are recorded as C/W-514 through C/W-520 (Figure 17).

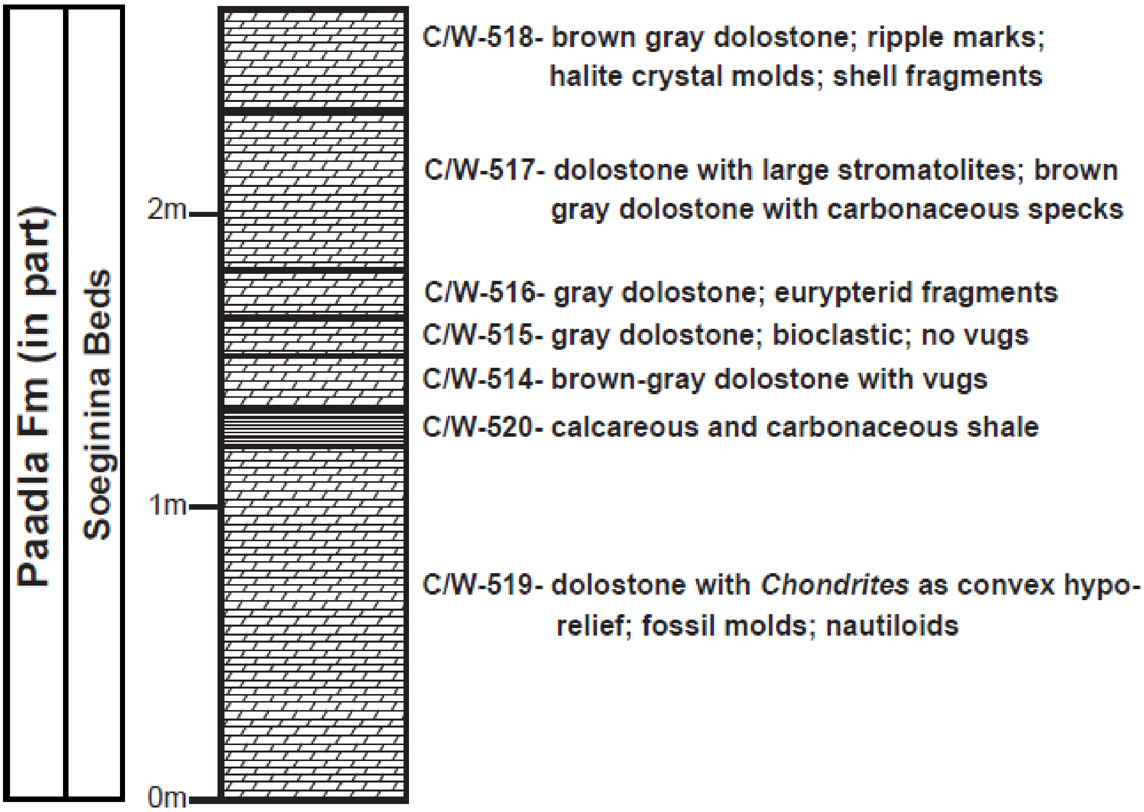


Figure 17: Stratigraphic column of the Soeginina Beds at Kübassaare.

The horizontal beds are represented by C/W-514 through C/W-518, whereas the steeply dipping beds are recorded as C/W-519 and C/W-520. The total height of the stratigraphic column, including the horizontal and dipping beds, is 2.71m.

At a thickness of 1.19 m, C/W-519 is composed of fine-grained, brownish dolostone with *Chondrites* as convex hypo-relief, fossil molds and nautiloids. C/W-520 is 0.12 m thick and comprises of calcareous and carbonaceous shale. C/W-514 with a thickness of 0.20 m consists of brown-gray dolostones with vugs. 0.12 m thick, C/W-515 has bioclastic dolostone. With a thickness of 0.17 m, C/W-516 consists of fine grained, gray dolostone with eurypterid fragments, range of dark gray platy intraclasts (1 mm to 10 cm), nautiloid molds, ostracods and spherical oncoids. C/W-517 has a thickness of 0.57 m and comprises of dolostone with large domical stromatolites with banding. In C/W-517, small stromatolite domes join to form larger domes and they have flat bases. The topmost part of the column is C/W-518 with a thickness of 0.34 m comprises of fine grained, brown-gray dolostone with shell fragments, ripple marks measured as crests bearing NNW; 5 cm wavelength with a height of 4 mm, and halite crystal molds.

# SEDIMENTARY STRUCTURES AND FAUNA IN THE SOEGININA BEDS

## *Chondrites*

Trace fossils are of primary importance to geologists as they can be used to reconstruct numerous aspects of ancient depositional settings. *Chondrites* trace fossils are burrows, which indicate biological activity in geologic history (Figure 18). They are common in several sedimentary rocks deposited over the past half billion years. The nature of its occurrence usually shows that the burrow was kept open by its inhabitant and was later filled in with sediment from above which shows the thixotropy of the sediment. *Chondrites* is easily recognized but cannot be generalized as an exclusive feature of any particular sedimentary facies (Bromley and Ekdale, 1984).

When represented by small forms, *Chondrites* occurs as the single ichnogenus in an assemblage. Larger forms occur following the appearance of other ichnotaxa that need more oxygenation. *Chondrites* is associated with calcareous sediments but is found both in waters several thousand meters deep and in extremely shallow waters (Uchman, 1991).

Figure 18: *Chondrites* in dolostones at Kübassaare. Diameter of coin is 25.75 mm.

## Ostracods

Ostracods are small bivalved crustaceans whose fossils can be recorded back to Early Ordovician. They are one of the most diverse arthropods in the fossil record and are represented by over 65,000 described species. Ostracod species flourished during the Late Ordovician but experienced a significant decline during the End-Ordovician mass extinction. There was a slow recovery of ostracods in the Early Silurian, but their biodiversity recovered to Ordovician levels by the Wenlock Epoch (Hairapetian et al., 2011).

The ostracods found at Kübassaare have been identified as the leperditicopid genus *Herrmannina* Kegel, 1933 because of their large size (adults ranging from 5-50 mm long), and their asymmetric carapace (Figure 19). Leperditicopids came into existence in the Early Ordovician and became extinct by the end of the Devonian. This group constitutes a magnificent case of gigantism among many often minute ostracods (Vannier et al., 2001). Possibly since the Ordovician but definitely since the Silurian, the leperditicopid *Herrmannina* was a recurrent part of low diversity communities associated with shallow marginal marine habitats (tidal flats, reef flats and embayments), brackish or lagoonal settings, which suggest that some leperditicopids were successfully adapted to the stresses of elevated salinity and temperature. They were possibly the first bivalved arthropods to experience life in hypersaline waters and on freshwater alluvial plains (Vannier et al., 2001).

Figure 19: Larger than usual ostracods found at Kübassaare. Diameter of coin is 25.75 mm.

## Oncoids

Oncoids, or oncoliths, are biosedimentary structures generally in the shape of spherical nodules, usually made of a laminated micritic cortex enveloping a biogenic or abiogenic nucleus (Figure 20). They are irregularly shaped coated grains with a diameter greater than 2mm and can from in both marine and freshwater environments. It is common for oncoids to be reported from shallow water environments where they are formed by photosynthetic cyanobacteria and algae. However, there are examples of oncoid formation in deeper water environments formed by non-photosynthetic microorganisms like bacteria and fungi in dim or dark settings (Zatoń et al., 2012). Apart from cyanobacteria, algae, bacteria, and fungi, there are several records of oncoid-forming benthic foraminifera (Schlagintweit and Gawlick, 2009).

Figure 20: Oncoids found at Kübassaare. Diameter of coin is 25.75 mm.

Each form of an oncoid indicates a different depositional environment. Equidimensional oncoids in peloidal packstones are formed by continuous rolling. Larger, branched forms enclosed in loosely packed wackestones developed below wavebase in calmer conditions (Ratcliffe, 1988).

Generally, oncoids form in shallow marine or fresh water photic zones by the trapping and binding activity of cyanobacteria around minute nuclei of either inorganic or organic origin, due to the frequent rolling of these nuclei in a highly agitated depositional environment. The conditions imperative in the formation of oncoid deposits are: a significant regional global sea level drop and simultaneously, proliferation of cyanobacteria. Regression is required to produce the regionally to globally widespread shallow water, high-energy hydrodynamic conditions to facilitate the rolling activity of the carbonate grains, while the explosion of cyanobacteria is essential for initiating and sustaining the growth of the concentric laminae around the nuclei by the binding and trapping activity (Shi and Chen, 2006).

## Eurypterids

Eurypterids, or sea scorpions (Subclass Eurypterida), are an extinct group of aquatic predatory arthropods that have been proposed as the closest relatives of either horseshoe crabs (Class Merostomata, Order Xiphosura) or arachnids (Class Arachnida) (Kamenz et al., 2011). Eurypterida is a monophyletic subclass of aquatic, Paleozoic predatory chelicerates, which are possibly the largest arthropods (Figure 21). The first eurypterid to be described was *Eurypterus remipes* from the Upper Silurian Bertie Formation of New York State, USA, which was originally described as a catfish in 1818. Later, *Eurypterus* was the first eurypterid genus to be recognized *Eurypterus remipes* as an arthropod by DeKay (1825). The genus *Eurypterus* existed for a short 10-14 million years. They tend to dominate faunas in which they occur. One of the best-known *Eurypterus*-bearing horizons is the Rootsikula Formation in Estonia (Tetlie, 2006). The Rootsikula Formation is just below the Paadla Formation studied here.


Figure 21: *Eurypterus* from Kübassaare. Diameter of coin is 25.75 mm.

Eurypterids showed greatest abundance and diversity during the Silurian. They were large creatures that possibly occupied high trophic levels as primary carnivores. It is suggested that they provoked the development of protective dermal armor in their vertebrate contemporaries. For swimming, eurypterids used the rowing principle and they could likely reach a maximum velocity of 2.5x its body length per second. They are almost always found in strata with scarce occurrence of many other marine fauna. Eurypterids are found in three ecological phases in the Silurian: the Carcinosomatidae-Pterygotidae Phase is the most marine, the Eurypteridae Phase represents sheltered marine bays, lagoons, or estuaries, and the Hughmilleriidae-Stylonuridae Phase represents the brackish bays and estuaries (Selden, 1984).

The Eurypteridae Phase is represented in the Saaremaa Fauna of Estonia, the island on which Kübassaare is located. These eurypterids are associated with restricted marine bays, lagoons and estuaries. This phase is a transition between the other two phases and has a tendency to hypersalinity (Selden, 1984).

There are four eurypterid modes of life. First, swimmers with streamlined bodies, marginal eyes, swimming legs, and commonly broad telsons. The second mode consisted of crawlers and burrowers with scorpioniform bodies, marginal frontal eyes, swimming legs, and styliform telsons. The third were generalized forms that were capable of swimming, burrowing and crawling, with slender or broad bodies, dorsal eyes, swimming legs, and styliform telsons. Finally there were the walkers with slender bodies, dorsal-subapical eyes, stilt-like legs, and styliform telsons. The eurypterids at Kübassaare belong to the third mode of life where eurypterids were capable of swimming, burrowing and crawling, and had slender or broad bodies, dorsal eyes, swimming legs, and styliform telsons (Selden, 1984).

## Nautiloids

Nautiloids are a group of marine cephalopods that began in Late Cambrian and are still represented today by the *Nautilus*. *Nautilus* is cited as an archetypal living fossil, it appears to have survived for a long time at low species diversity (Ward and Saunders, 1997). Nautiloids (Figure 24) are found in the Soeginina Beds of the Paadla formation at Kübassaare.


Figure 24: A fossil of a phragmoceratid nautiloid found at Kübassaare. Diameter of coin is 25.75 mm.

Nautiloids provide useful data for paleobiogeographic and climate reconstruction. Phragmoceratids are a characteristic part of Silurian nautiloid faunas, which lived mainly in tropical carbonate platforms of Baltica and Laurentia. The Silurian family of Phragmoceratidae consists of two genera: *Phragmoceras* and *Tubiferoceras.* They are discosorid nautiloid genera with a cyrtoconic or rarely orthoconic or coiled breviconic endogastric shell, with a modified T-shaped contracted aperture (Manda, 2008). Phragmoceratids are considered to have been microphages because of their constricted aperture. The constriction of the aperture appeared during the late ephebic stage (period of adolescence). Preceding ontogenetic stages possessed a brevicone shell with an open aperture, indicative of nectobenthic predatory life style. The apertural constriction most probably improved hydrodynamic control and protected the soft body parts. The attachment sites for distinct retractor muscles suggest evidence of fast movement of the head-foot complex out of the aperture with consequent capture of larger prey. Phragmoceratids have a broadly expanded siphuncle and thick connecting rings (Manda, 2008).

The nautiloids found in the Soeginina beds are most likely *Phragmoceras. Phragmoceras* represents Silurian nautiloid faunas as they appear immediately after the beginning of the Silurian and survive through until the middle Ludfordian of the Ludlow Series. Several of its species have been described from Estonia (Manda, 2008).

## Stromatolites

A stromatolite (Figure 22) is a laminated benthic microbial deposit as defined by Riding (1999). It is an internally laminated, macroscopic sedimentary structure, commonly of biological origin that is a dominant part of Earth's early fossil record (Allwood et al., 2009). The 3.430 billion year old stromatolites found in the Strelley Pool Chert (SPC) in Pilbara Craton, Australia, makes them the oldest identifiable fossil assemblages from the Earth's early biosphere (Allwood et al., 2006).


Figure 22: Stromatolites of the Soeginina Beds.

Logan et al. (1964) defined three main geometric structures that occur in modern stromatolites are: Laterally linked hemispheroids (LLH), discrete spheroids, either randomly stacked hemispheroids or concentrically arranged spheroids (SS), and discrete, vertically stacked hemispheroids (SH). Modern stromatolites are associated with restricted environments thus; ancient environments can be interpreted by recognition of fossil stromatolite forms. For instance, protected intertidal mud flats, where there is little wave action may be recognized by the presence of type LLH stromatolites (*Collenia*). The presence of type SS structures represents low intertidal areas that are exposed to waves and agitated shallow water below low-water mark. The presence of type SH structures represents exposed, intertidal mud flats, where scouring action of waves and other interacting factors prevent growth of blue green algae mats between stromatolites (Logan et al., 1964).

The stromatolites found at my research site are of type SH structure (vertically stacked hemispheroids) that represents exposed intertidal mud flats.

## Halite Crystal Mold

Halite crystal molds indicate that the evaporate mineral halite was present in the depositional environment. Evaporites show a wide range of chemical precipitates that form on the Earth's surface or near-surface environments from brines concentrated by solar evaporation in restricted basins. Depositional settings for evaporites like halite occur in three environments: marginal (mixed shallow-subaqueous and subaerial), shallow subaqueous and deep subaqueous (Schreiber and Tabakh, 2000).

The halite crystal mold found at my research site represents a shallow water subaqueous evaporite depositional environment. A study of halite deposition was done in an artificial salina by Schreiber and Tabakh (2000). Halite precipitation in artificial salinas can be divided by crystal forms. The first halite crystals form in the narrow range from 320-325 g $L^{-1}$ and are usually perfect cubes of very milky color. As salinity rises the crystal forms change. In the next range of salinity, between 325-370 g $L^{-1}$ halite crystallizes at the surface in the form of floating, inverted halite pyramids (hollow shells), or as thin sheets of floating crusts (1-2 mm thick) that sink to the bottom almost as soon as they form (Schreiber and Tabakh, 2000). In waters with higher salinity than 370 g $L^{-1}$, halite crystals grow with hollow depressed faces and pronounced raised corners and edges (Schreiber and Tabakh, 2000). While doing field work we found this halite crystal mold which indicates a higher salinity than 370 g $L^{-1}$ with a hollow depressed face and raised corners and edges (Figure 23).

Figure 23: Halite crystal mold at Kübassaare. Diameter of coin is 25.75 mm.

# Thin Section petrography of the Soeginina Beds at Kübassaare

The thin sections analyzed are from seven distinctive units of the Soeginina Beds. They are described below in Table 1 in ascending order.

| Unit | Description | Protolith |
|---|---|---|
| C/W518 | It has ostracods shells with remnants of biofilms. It has some fenestrae that are gas bubbles formed when bacterial mats decay and cause sediment to crack. | Biomicrite |
| C/W517b<br><br>Stromatolites | Dolostone with stromatolites. | Micrite |
| C/W517a<br><br>Matrix around the stromatolite. | Dolostone with sediment coloration that indicates stylolites. It has some intraclasts and an abundance of rounded bioclasts. | Intrabiosparite |
| C/W-516 | Dolostone with shell fragments and intraclasts in a sparry matrix. | Biointrasparite. |
| C/W-515 | Dolostone with intraclasts and bioclasts. It has some intraclasts within intraclasts. The intraclasts are more dominant than bioclasts in this sparry matrix. | Biointrasparite |
| C/W-514 | Dolostone with a dominance of bioclasts over intraclasts. There is a structure that looks like disarticulated preserves of a coral or a bryozoan. There are no corals or bryozoans found in the unit but it is possible that they could have been washed up into this unit by storm waves. | Intrabiomicrite |
| C/W-520 | Dolostone with bioclasts. | Biomicrite |
| C/W-519 | Dolostone with peloids and burrows. | Pelmicrite |

Table 1: Description of thin sections from the Soeginina Beds at Kübassaare, Saaremaa, Estonia. Location C/W-519 is the base of the section.

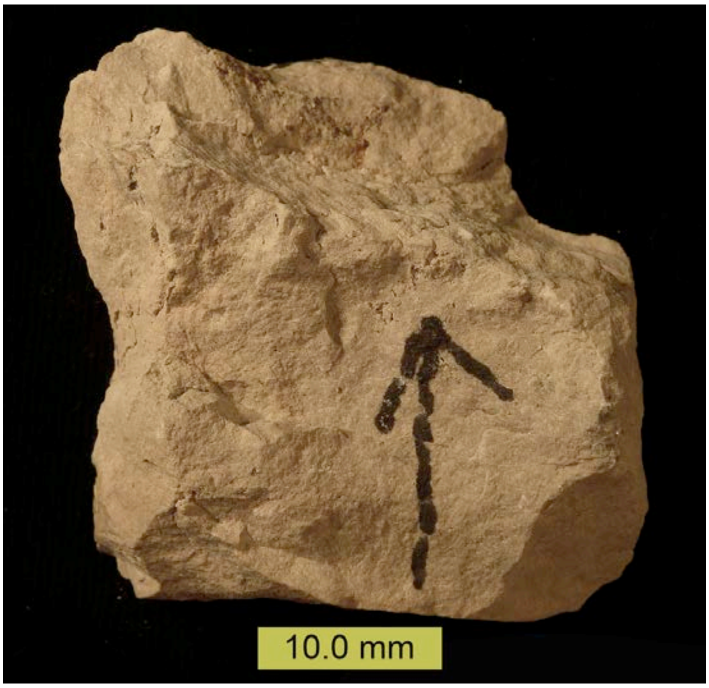


Figure 25: Rock sample from C/W-519. Fine grained dolostone with *Chondrites* and nautiloids.

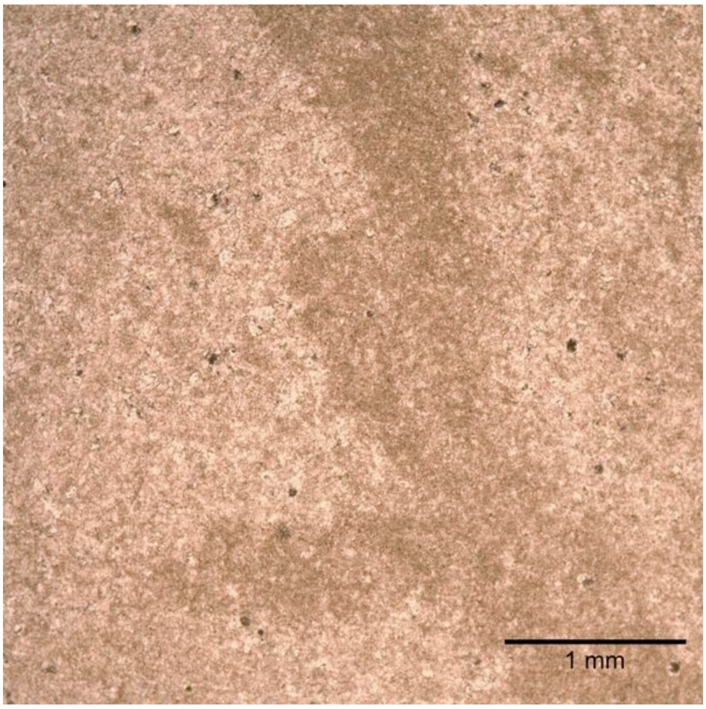


Figure 26: Thin section from C/W-519 is a dolostone with peloids in it. The protolith of this rock was pelmicrite.


Figure 27: Rock sample from C/W-520. It is bioclastic calcareous shale.

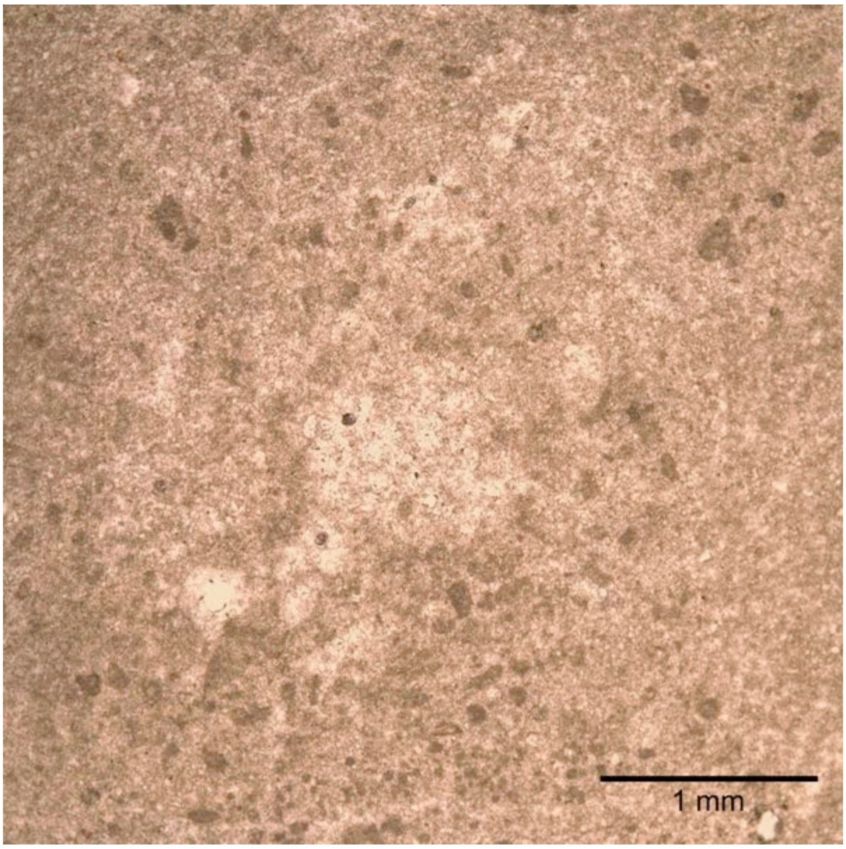


Figure 28: Thin section from C/W-520 is a dolostone that has bioclasts in it. The protolith of this rock was biomicrite.

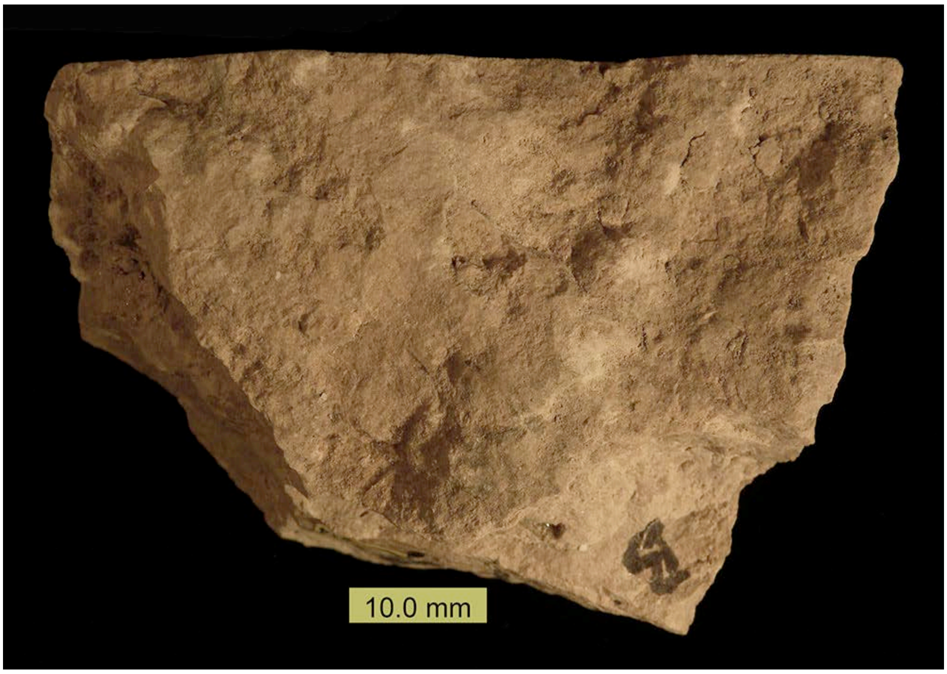


Figure 29: Rock sample from C/W-514. It is a dolostone with vugs.

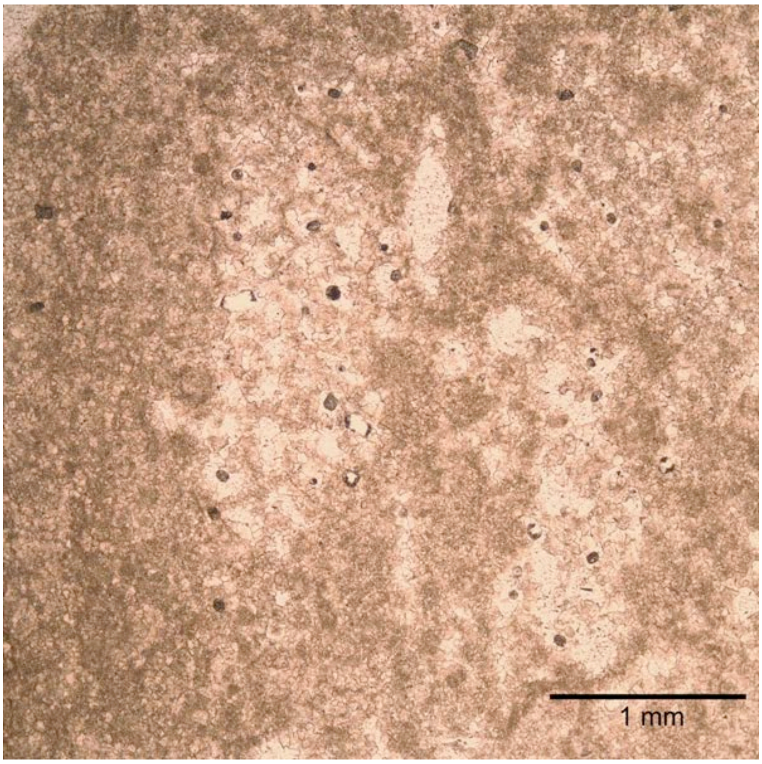


Figure 30: Thin section from C/W-514 is a dolostone with a dominance of bioclasts over intraclasts. In one corner of the slide there is a structure which looks like disarticulated preserves of a coral or a bryozoan. There are no corals or bryozoans found throughout the unit but it is possible that they could have been washed up into this unit by storm waves. The protolith of this rock was intrabiomicrite.


Figure 31: Rock sample from C/W-515. It is a dolostone with dark particles.

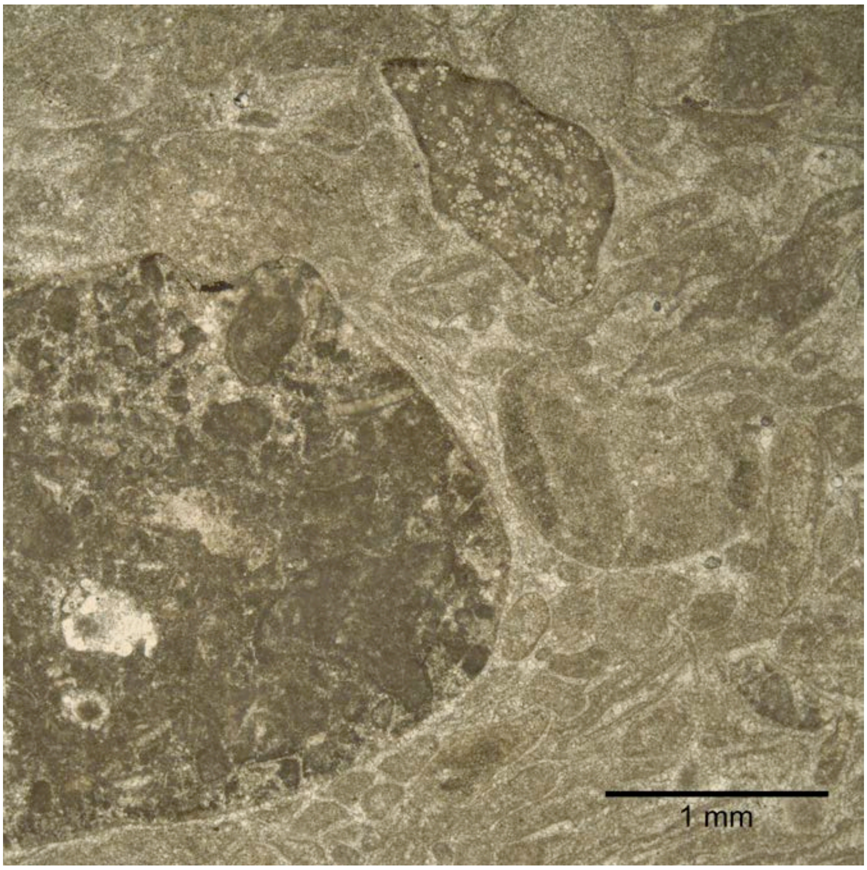


Figure 32: Thin section from C/W-515 is a dolostone. It has intraclasts and bioclasts. It has some intraclasts within intraclasts. The intraclasts are more dominant than bioclasts. The protolith of this rock was biointrasparite.

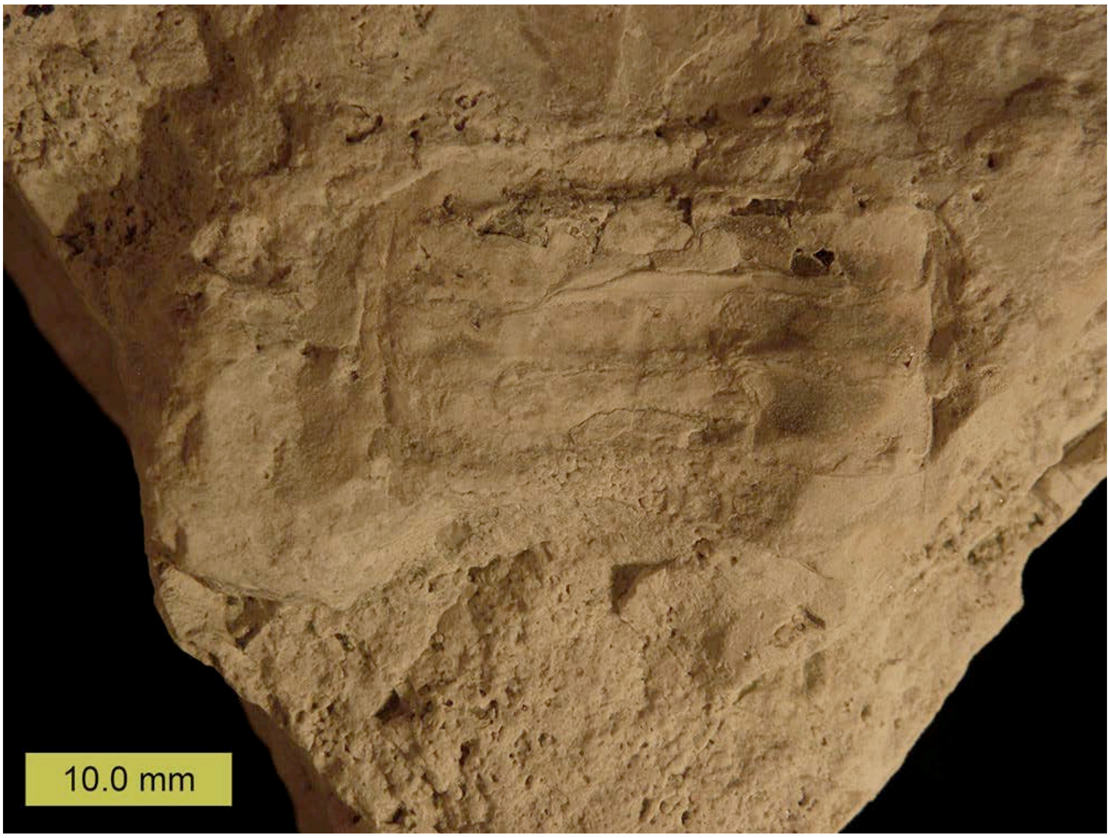


Figure 33: Rock sample from C/W-516. It is a dolostone with a eurypterid fossil.

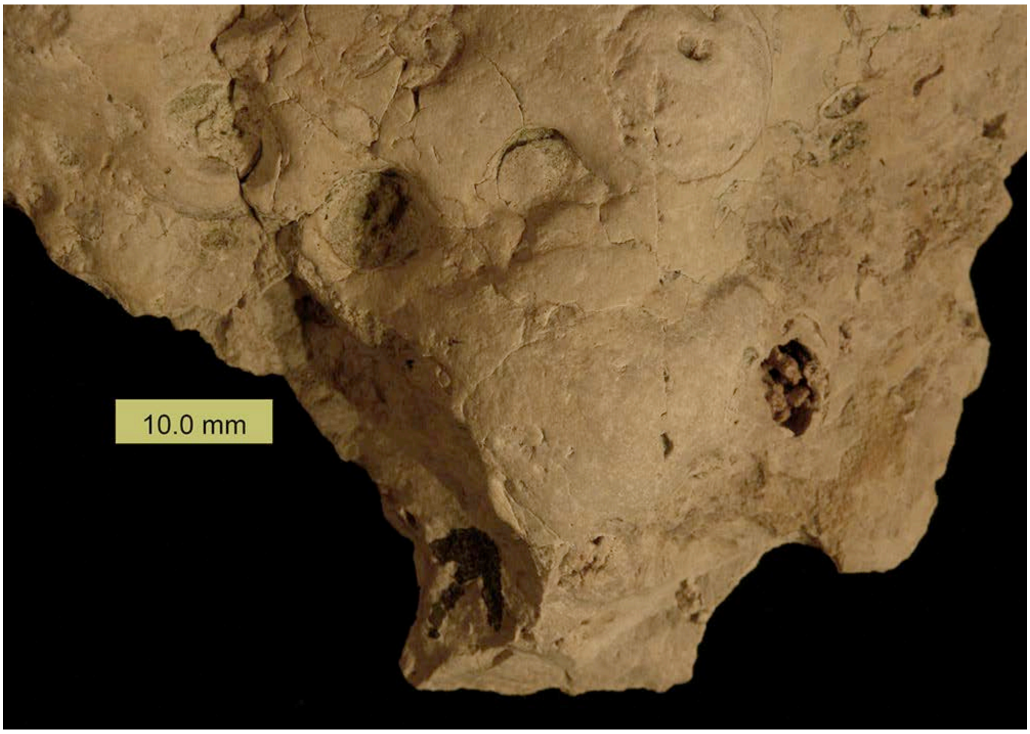


Figure 34: Rock sample from C/W-516. It is a dolostone with oncoids.


Figure 35: Rock sample from C/W-516. It is a dolostone with ostracods.

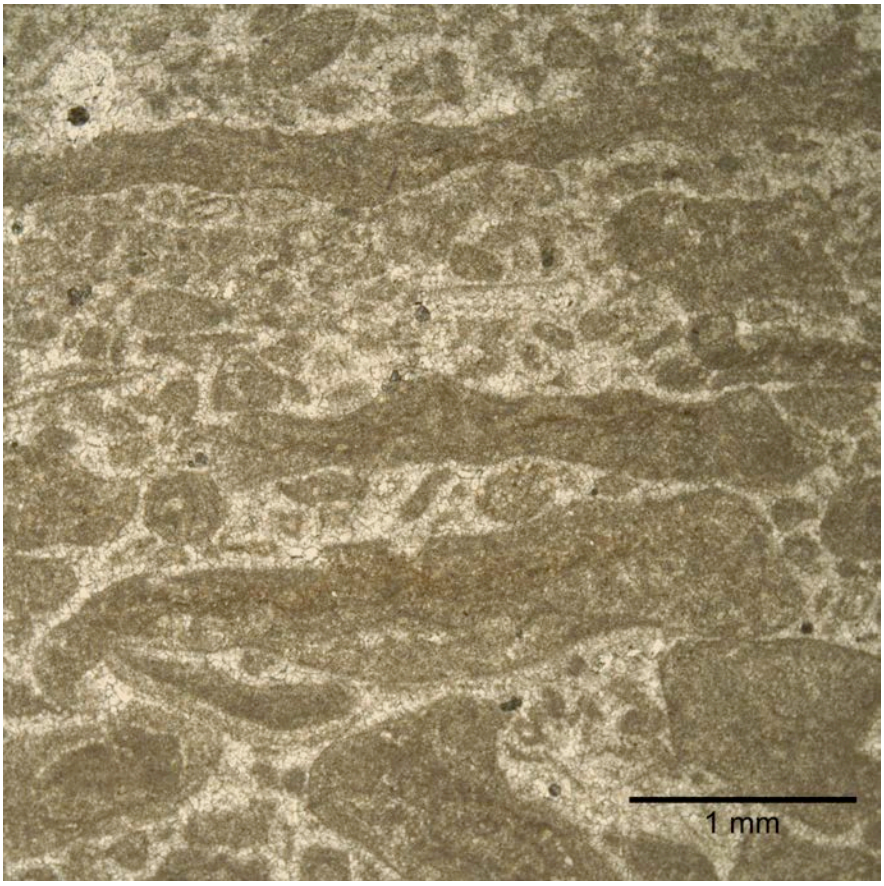


Figure 36: Thin section of C/W-516. It has shell fragments and intraclasts. There are more intraclasts than shell fragments. The protolith of this rock was biointrasparite.

C/W-517 consists of stromatolites. We collected samples of the stromatolites and the matrix around the stromatolites separately. The matrix around the stromatolite is named as C/W-517a and the stromatolites are referred to as C/W-517b.

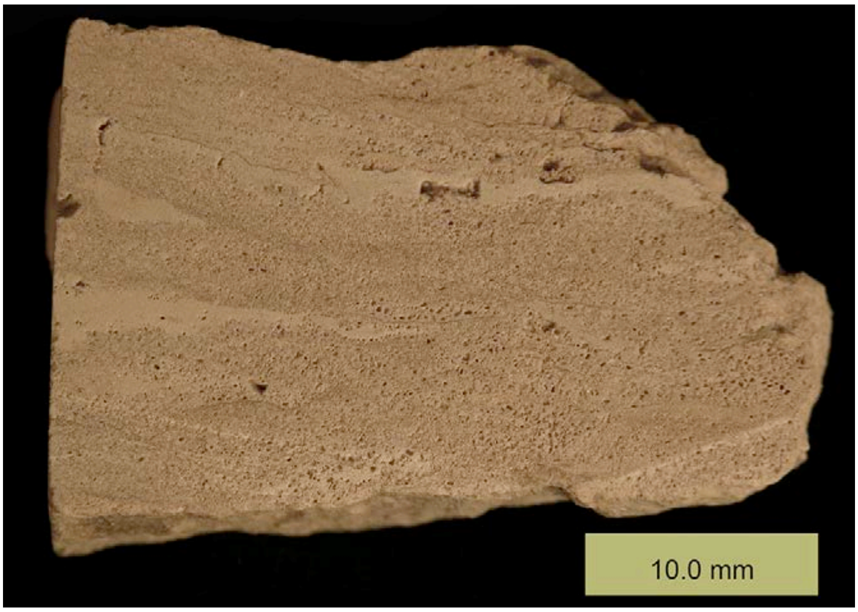


Figure 37: Rock sample from C/W-517a. It is a dolostone with stylolites.

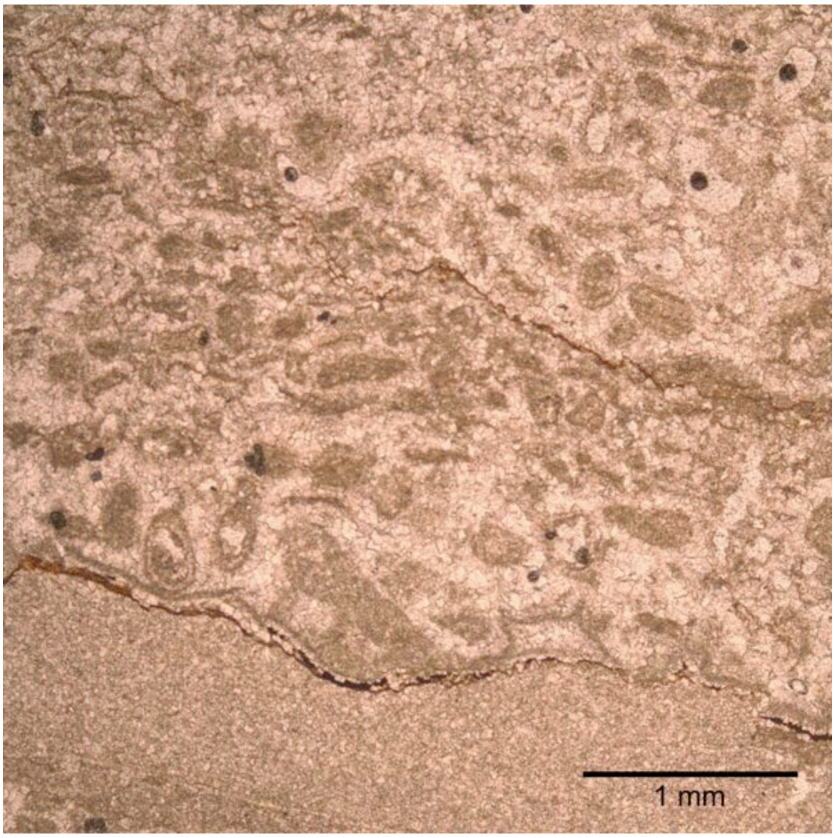


Figure 38: Thin section of C/W-517a. It has sediment coloration which is an indication of stylolites, some intraclasts and an abundance of rounded bioclasts. The protolith of this rock was intrabiosparite.

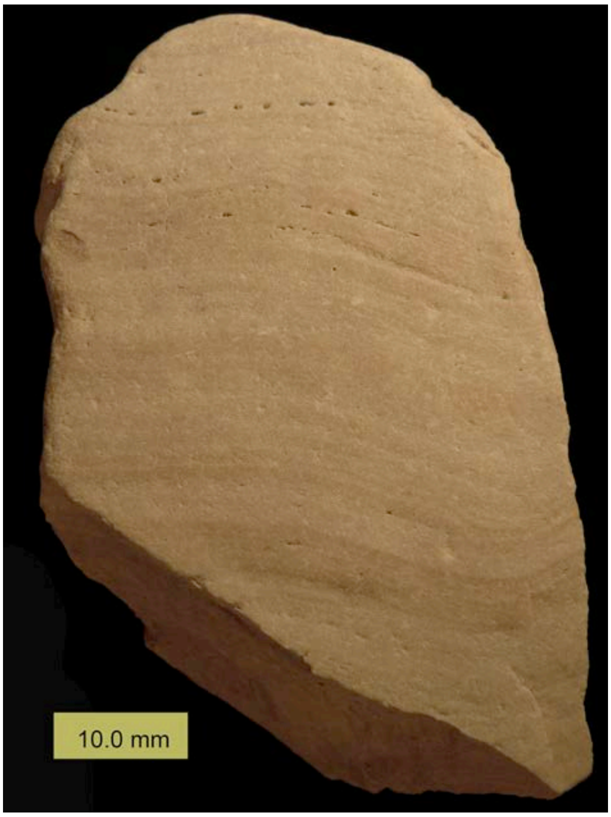


Figure 39: Rock sample from C/W-517b. It is a dolostone with stromatolites.

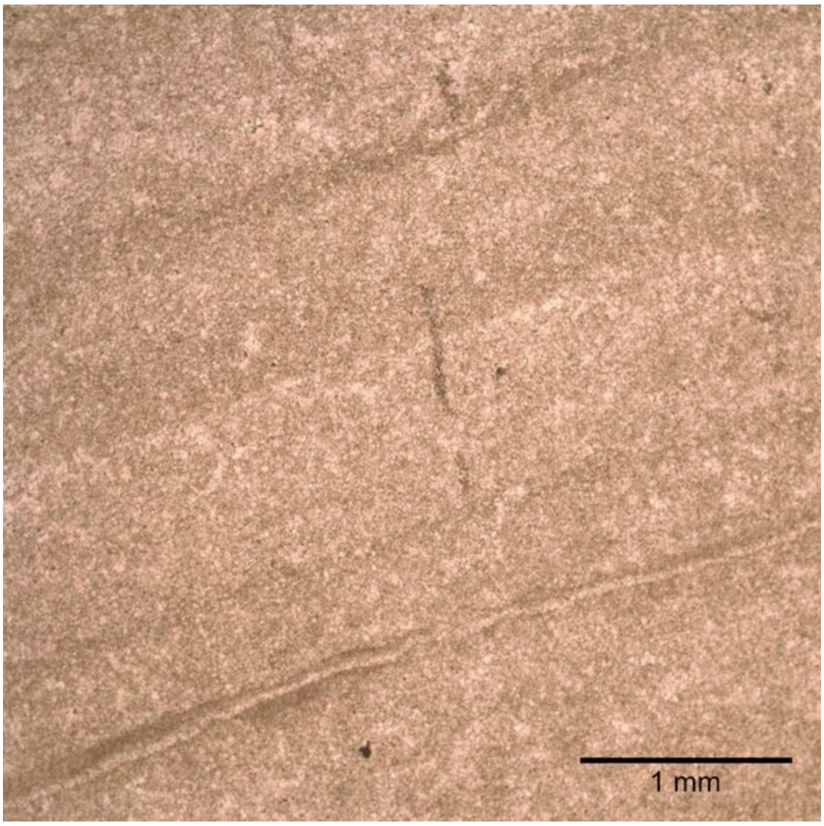


Figure 40: Thin section of C/W-517b. The protolith of this rock was micrite.

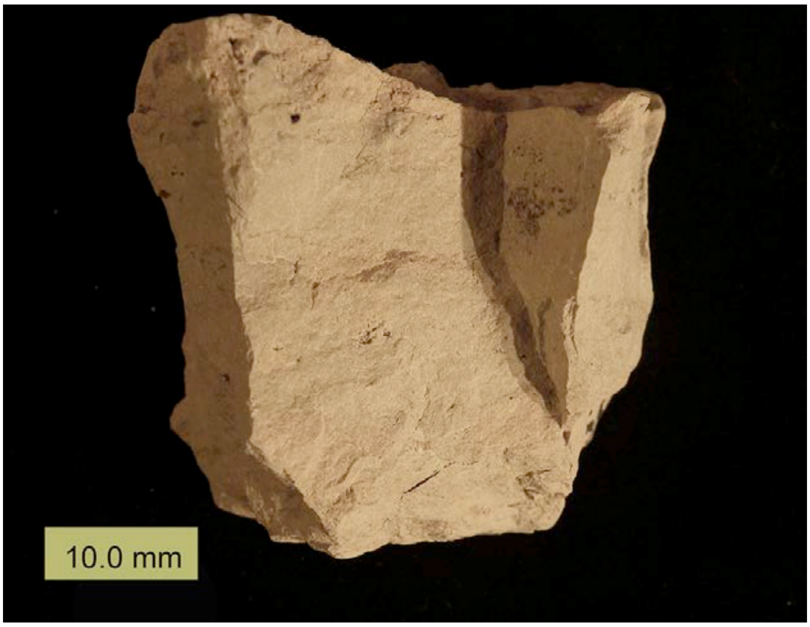


Figure 41: Rock sample from C/W-518. It is a dolostone.

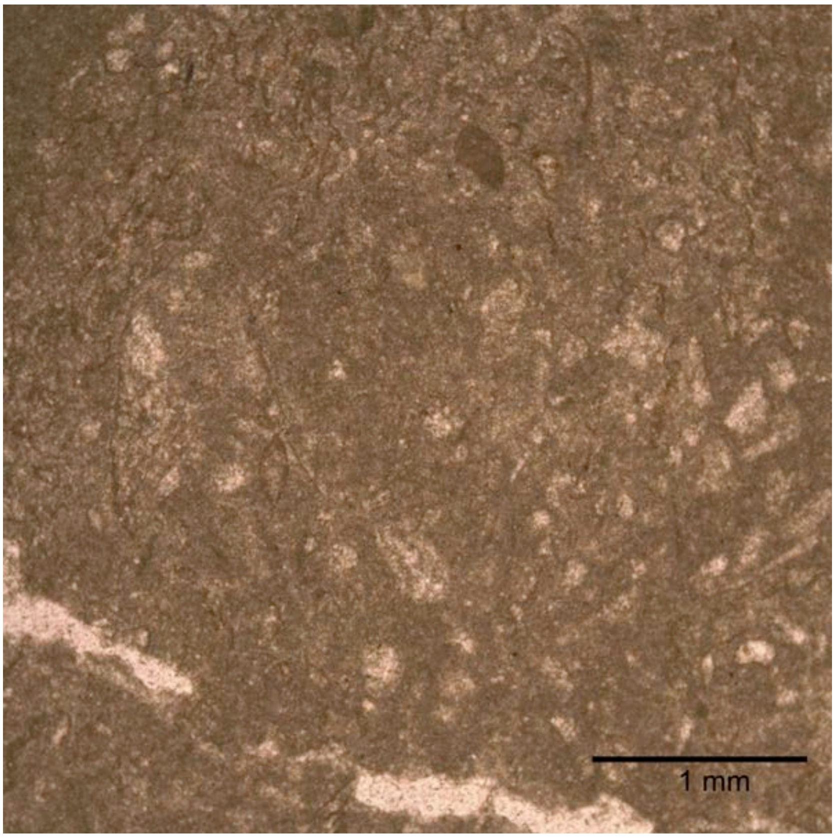


Figure 42: Thin section of C/W-518. It has ostracods shells with remnants of biofilms. The protolith of this rock was biomicrite.

# COMPARISON OF THE KÜBASSAARE SOEGININA BEDS WITH THE SOEGININA CLIFF SECTION

During the summer of 2011, Nick Fedorchuk from the College of Wooster did his independent study research at the Soeginina Cliff section (Figure 43) in the western part of Saaremaa (Fedorchuk, 2012). The Soeginina cliff section belongs to the same stage as the Soeginina Beds that are in the eastern part of the island of Saaremaa. The distance between the two research sites is 86 kilometers. It is the same unit but they have some similarities and differences worth pointing out due to their geographic location.

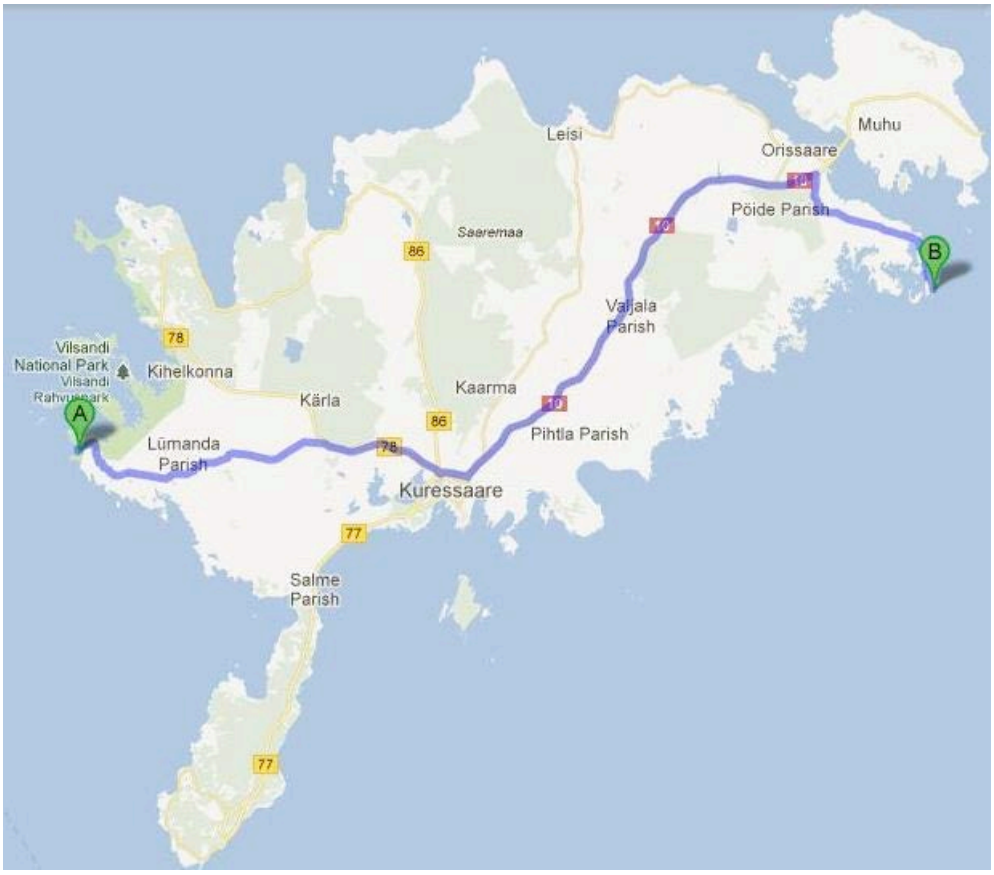


Figure 43: (A) Soeginina Cliff in the western part of Saaremaa that was Nick Fedorchuk's research site. (B) Soeginina Beds lies in the far-east region of Saaremaa which is my research site (https://maps.google.com/maps?hl=en).

Twelve different units were measured and analyzed from the Soeginina Cliff. The first five belong to the Wenlock Epoch and the remaining seven belong to the Ludlow series. We measured seven units from the Ludlow Epoch in the Soeginina Beds at Kübassaare.

The differences and similarities from the Ludlow Series found at the two locations are described below in Table 2.

| Unit | Soeginina Cliff (western Saaremaa) | Soeginina Beds (eastern Saaremaa) |
|---|---|---|
| 7 | Gray weathered dolomite. | Brown-gray dolostone with halite crystal molds, ripple marks and some shell fragments. |
| 6 | Laminated dolomitized mudstones and grainstones with domical stromatolites that are up to one meter in diameter. | Domical stromatolites not as big as the ones found at the Soeginina Cliff. Many small domes join to form larger domes. |
| 5 | Light gray dolomicrite with small moldic fossils and trace fossils. | Dolostone with oncoids, *Eurypterus*, ostracods and nautiloids. The oncoids in this unit are nucleated around intraclasts unlike the oncoids from the cliff that nucleated around gastropods. |
| 4 | Gray, slightly fossiliferous, moldic dolomicrite. | Gray dolostone that has intraclasts inside intraclasts. |
| 3 | Light brown and less fossiliferous dolomicrite. | Brown gray dolostones with bioclasts and intraclasts. |
| 2 | Light brown, fossiliferous dolomitized biomicrite with oncoids. | Dolomitized biomicrite. |
| 1 | The base of the section has bioturbated, white dolomicrite with irregular occurrences of oncoids. The oncoids found in these units are bigger than the ones found at Soeginina Beds. The oncoids at the cliff nucleated around gastropods. | Bioturbated dolostones with peloids and *Chondrites*. |

Table2: Description of the Soeginina units in western and eastern Saaremaa.

By comparison and observation, it is seen that the Soeginina Cliff in western Saaremaa had a depositional environment that was deeper than the Soeginina Beds in eastern Saaremaa. The units belonging to the Soeginina Beds (eastern Saaremaa) have halite crystal molds and *Herrmannina* ostracods which are found in very shallow highly saline waters. The Soeginina Cliff (western Saaremaa) is lacking of halite crystal molds and *Herrmannina* ostracods, this indicates that there was a deeper depositional environment at the Soeginina Cliff (western Saaremaa) than at the Soeginina Beds (eastern Saaremaa).

# PALEOENVIRONMENTAL CONTEXT OF THE EASTERN BALTIC BASIN

Seven units from the Soeginina Cliff in western Saaremaa and the Soeginina Beds in eastern Saaremaa are in the Lower Ludlow immediately on top of the Wenlock/Ludlow discontinuity boundary. This discontinuity has been traced from Gotland, Sweden, across the east Baltic Sea to Estonia (Calner et al., 2004).

The strata of Gotland were formed in the Baltic Basin, which was a low-latitude epicontinental embayment on the southern margin of the Baltic Shield and the East European Platform (Figure 44). The Silurian Baltic Basin covered large parts of southern Scandinavia and the East Baltic area. The basin-fill is dominated by fine-grained siliciclastic sediments, and the carbonate platforms are usually confined to the marginal parts of the East Baltic Basin (Gotland and Estonia) (Eriksson and Calner, 2008).

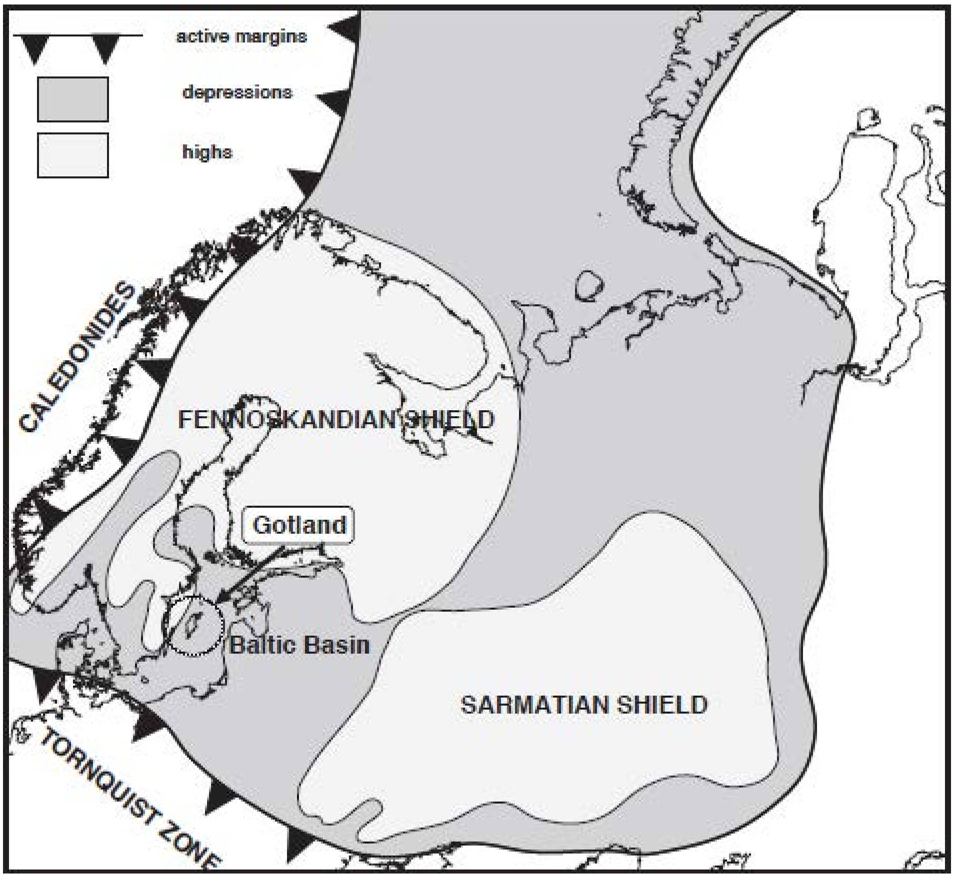


Figure 44: Location of Gotland, Sweden, in the Baltic Basin (Calner et al., 2004a, Fig. 1).

The southwestern margin of the Baltic Shield was active from Late Ordovician when the Avalonia Composite Terrane was amalgamated to Baltica. Subsidence curves indicate that this collisional event caused a change in tectonic regime from passive margin to a foreland basin. This is reflected by the more than 3000m thick Silurian deposits in Poland (Calner et al., 2004).

The Silurian bedrock of Gotland is an erosional remnant of an extensive carbonate platform complex that evolved along the margins of the Baltic Basin. On a broad scale there are three major depositional environments of bedrock in Gotland. First, slope and basin areas with argillaceous skeletal limestones and marls with a mud-wackestone texture and thin shell coquinas dominate seaward of reef barriers. Bioturbation was abundant (Calner et al., 2004). Second, biostromal, biohermal and shoal areas that were dominated by stromatoporoid-coral reef complexes, related coarse-grained skeletal float and reef flank deposits and well sorted peloidal and crinoidal grainstones. Patch reefs towards the basin were less than 100m in diameter and towards the shallower regions there were biostromes. The patch reefs consisted of tabulate corals and stromatoporoids. Bryozoans, crinoids and rugose corals were common. The reefs of Gotland are made of pale boundstones with a micritic matrix. The third major depositional environment is back-reef and lagoonal comprising of mostly light brownish, strongly bioturbated wackestones and mudstones with various benthic organisms. Sediments were deposited in sheltered, calm areas behind the reef-fringe (Calner et al., 2004).

Gotland's stratigraphy represents a deeper depositional environment than that found in the Soeginina units at Saaremaa, Estonia.

In the early 1980s a closer comparison of the Silurian sections between Saaremaa and Gotland was initiated. New technology and data allowed the facies belts on Saaremaa to be extended across the Baltic Sea to the Swedish island of Gotland (Tuuling and Floden, 2011).

Placed on the southern slope of the uplifted Baltic Shield, Estonia remained in the shallowest northeastern corner of the Baltic Silurian basin that by the means of a distally steepening basinal slope got deeper towards the Baltic Syneclise in the south to southwest (Figure 45). This explains the sediment accumulation and facies distribution in Estonia and around Gotland that in the Silurian was greatly influenced by a slope-like transition between shallow (Saaremaa) and deeper areas (Gotland) (Figure 46) (Tuuling and Floden, 2011).

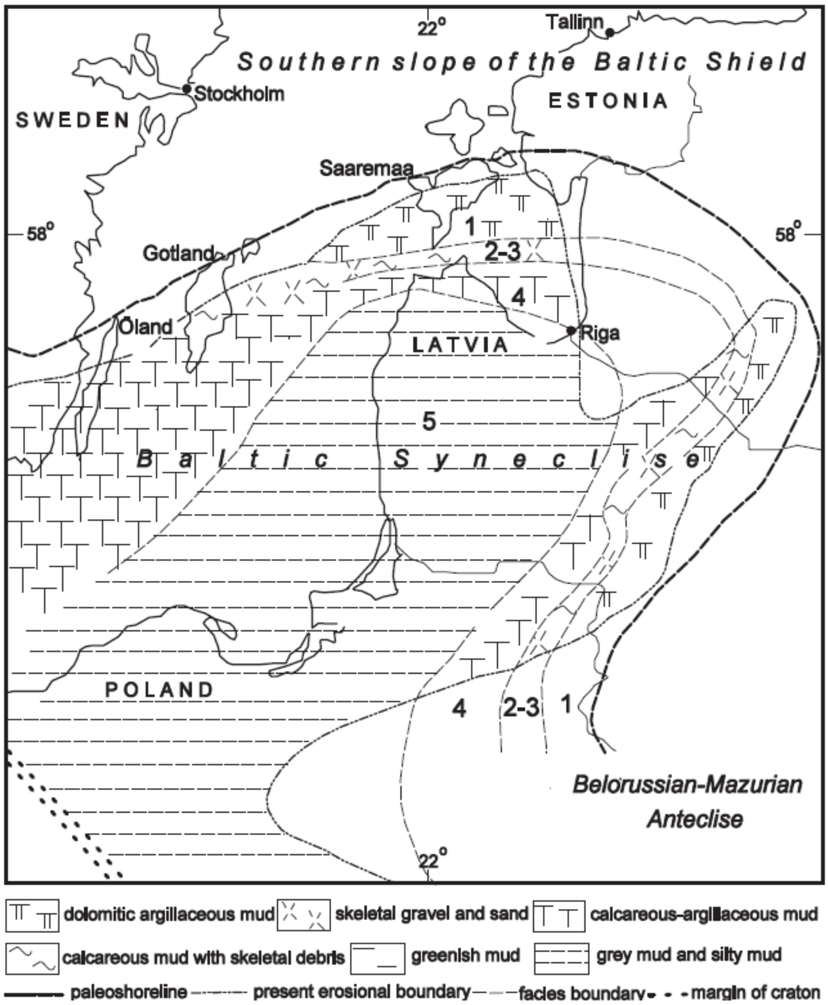


Figure 45: Facies belts and stratigraphical structural settings of the Baltic Basin during the late Wenlock. The numbers 1-5 correspond with Figure 46 (Tuuling and Floden, 2011, Figure 1).

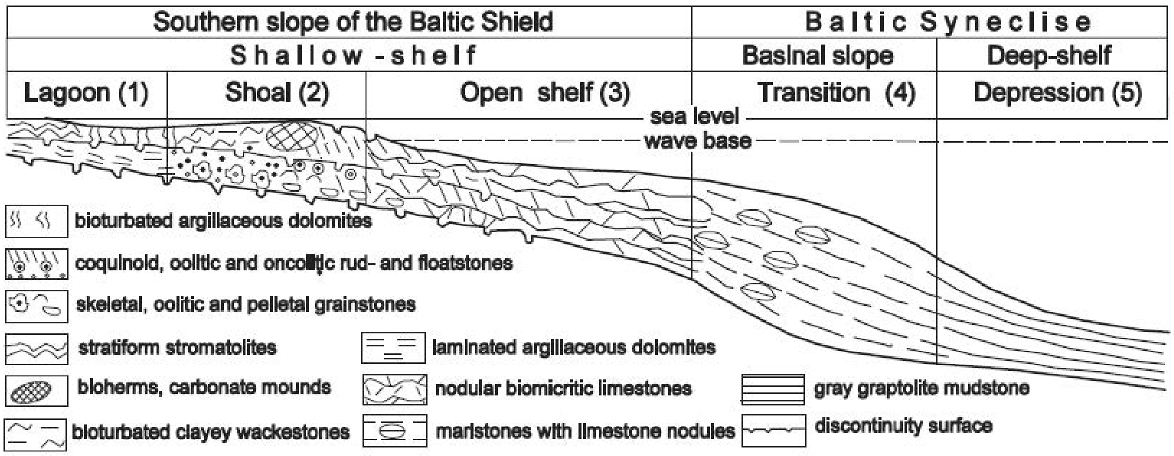


Figure 46: Lateral distribution of facies belts 1-5 that correspond with Figure 2 showing the slope trending from shallow in the Baltic Shield (Saaremaa) to deeper marine in the Baltic Syneclise (Gotland) (Tuuling and Floden, 2011, Figure 2).

Therefore we see an increase in depth in the Baltic basin as we go from eastern Saaremaa (Soeginina Beds) to western Saaremaa (Soeginina Cliff) to Gotland, which explains the difference in lithologies even though their deposition took place at the same time (Figure 47).

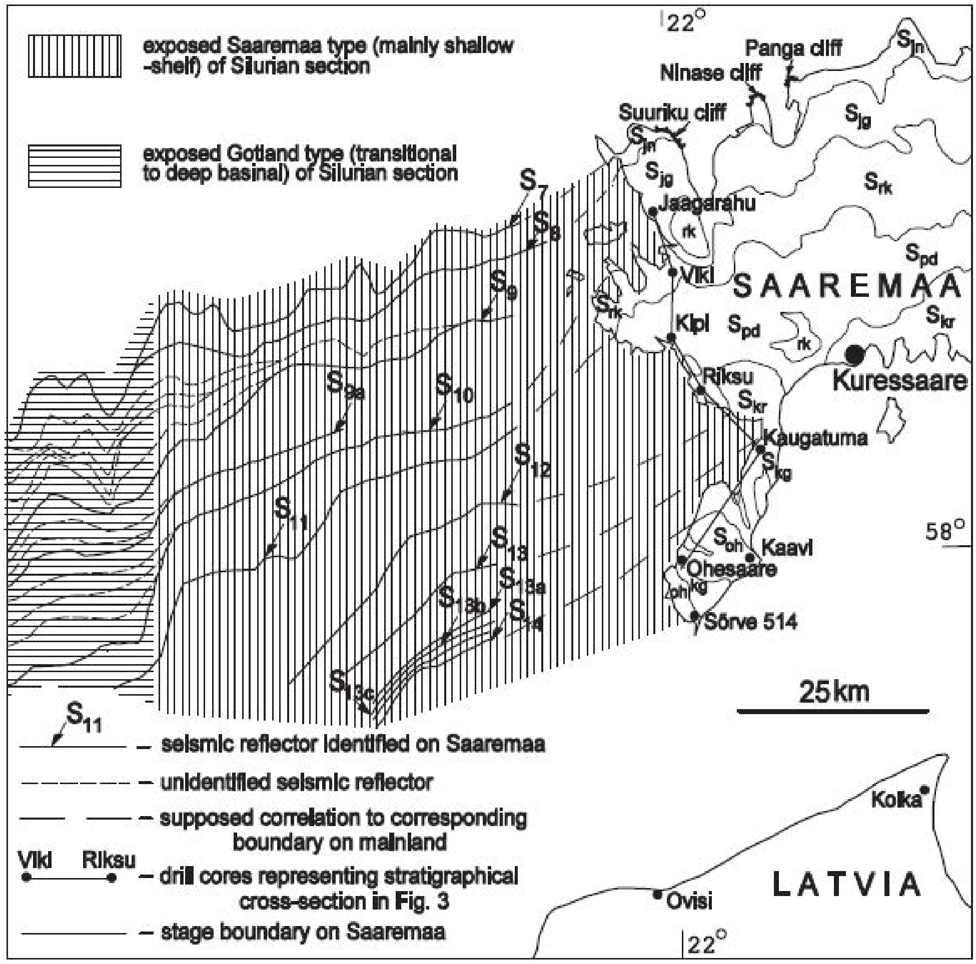


Figure 47: Offshore seismic stratigraphy showing the increase in depth as the facies change from a mainly shallow shelf to transitional to deep basin (Tuuling and Floden, 2011, Figure 4).

During the Lower Ludlow (Gorstian), Baltica experienced low sea levels with intraclastic, bioclastic, mudstones to grainstones that are interpreted as representing deposition during a regression due to a eustatic sea level fall caused by glaciations (Loydell, 1998).

In the Prague Basin (Bohemia) (Figure 48), mudstone-wackestone with cephalopods and low-diversified benthic fauna had been deposited in the early Gorstian at the shallowing bottom that became better oxygenated by surface currents. The shallowing corresponds to the early Gorstian local rise of the sea bottom controlled by volcanic activity (Manda and Kříž, 2007).

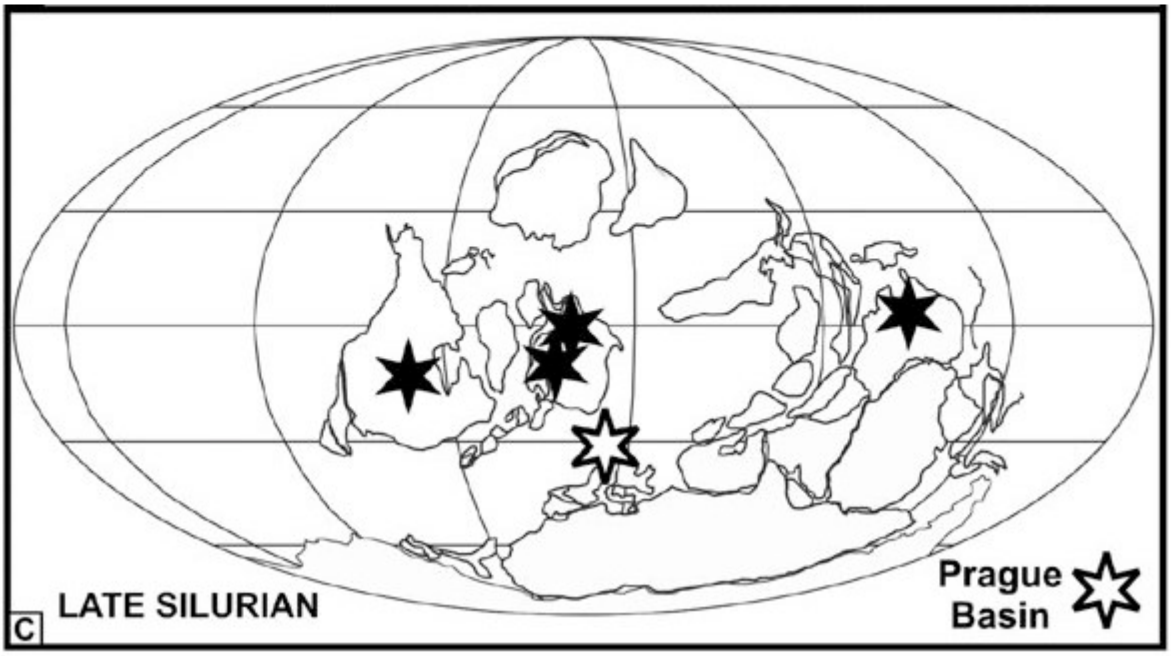


Figure 48: Prague Basin in Late Silurian (http://www.insugeo.org.ar/libros/cg_18/23.htm)

On a global scale there is a fall in sea level during the Gorstian (Lower Ludlow). In the Wabash Platform in North America, a eustatic signal would be expected due to the very slow subsidence rates on the platform, implying that tectonics had less an influence on sequence development. Comparison of the Silurian Wabash platform (Figure 49) sea-level cycles with inferred global and local sea level curves supports this eustatic influence (Spengler and Read, 2010).

In figure 49, the Wabash platform corresponds with Baltica, Avalonia, Laurentia, Gondwana, and Bohemia, showing a trend of low sea levels during the Gorstian.

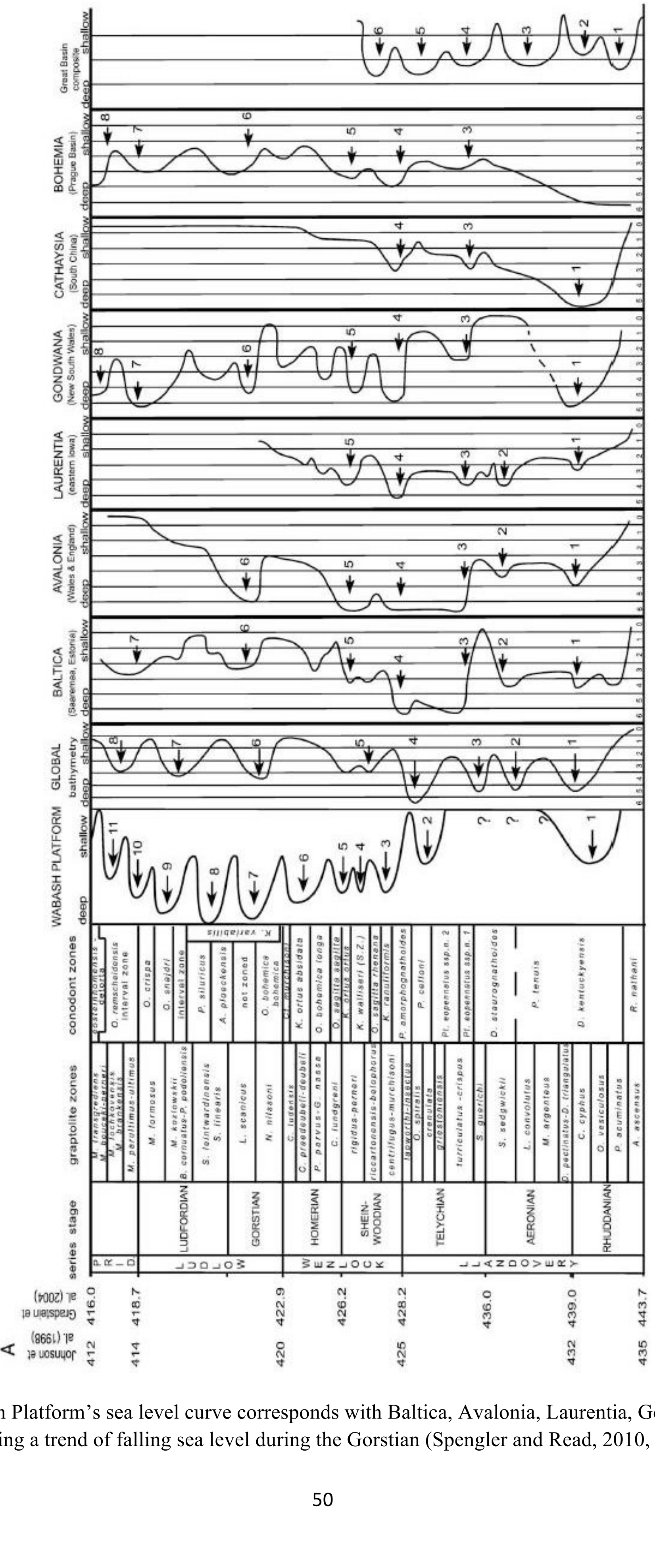


Figure 49: Wabash Platform's sea level curve corresponds with Baltica, Avalonia, Laurentia, Gondwana, and Bohemia, showing a trend of falling sea level during the Gorstian (Spengler and Read, 2010, Figure 11).

# CONCLUSIONS

The paleoenvironmental conditions change from a shelfal marine environment to a restricted shallow marine setting to a hypersaline supratidal environment as we go up the section at the Soeginina Beds.

At the base of the section we find dolostones with *Chondrites* trace fossils and marly shale that represent a shelfal marine environment. This section is followed by dolostones with fauna such as ostracods, oncoids, and eurypterids that indicate the depositional environment to be a restricted shallow marine setting (lagoonal). Then we find an abundance of stromatolites in the next section that form in exposed intertidal mudflats. The topmost section comprises of halite crystal molds that represent a hypersaline supratidal setting. Thus, we see a gradual change from shelfal marine environment to a restricted shallow marine setting and finally to a hypersaline supratidal setting.

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