Biostratigraphy of the Cambrian-Ordovician boundary at Krekling, Norway

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Foreword

I want to thank my supportive and positive supervisors, Dr. Øyvind Hammer and Professor Hans Arne Nakrem for all the effort during my thesis work.
Abstract

The Cambrian-Ordovician boundary interval within Alum Shale at Krekling, Norway, is for the first time investigated for biostratigraphy.

Samples were taken from the Alum Shale levels, within the almost continuous succession of the *Rhabdinopora flabelliformis* graptolite. Specimens were photographed and measured for identification. The following subspecies were identified: *Rhabdinopora flabelliformis socialis, Rhabdinopora flabelliformis norvegica, Rhabdinopora flabelliformis parabola, Rhabdinopora flabelliformis canadensis, Rhabdinopora flabelliformis flabelliformis*.

Biostratigraphy of the Cambrian-Ordovician interval has been made according to ranges of subspecies identified. The biostratigraphic ranges of the graptolites do not match previously reported correlations of early Tremadocian and call into question previous biozonations.

The Cambrian-Ordovician boundary has been estimated to lie slightly below the first occurrence of trilobite *Boeckaspis hirsuta*, graptolites *Rhabdinopora flabelliformis*, within significant increase of vanadium content. Geochemical analysis were made by Dr. Øyvind Hammer and Dr. Henrik Svensen.
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1 Introduction

1.1 General introduction

The Cambrian was a significant period in the evolution of the geobiosphere. The Cambrian paleoclimate, paleogeography, paleoceanography and ocean chemistry and their connection with Cambrian biological explosion and extinction events, are still not fully explained (Hammer and Svensen, 2017). The Cambrian-Ordovician boundary is estimated about 485.4 Ma- according to the latest time scale from International Commission on Stratigraphy (2016/04). The shift from the Cambrian to the Ordovician is like other transitions of periods, a reflection of changes in the biosphere—extinctions of the organisms living in Cambrian, and some new appearances in the base of Ordovician period. In Norway the Cambrian-Ordovician boundary has primarily been described in two localities—Nærnes and Krekling.

![Figure 1. Chronostratigraphic chart, Cambrian-Ordovician. (International Commission on Stratigraphy, 2016)](image_url)
The Krekling locality in southern Norway is a classical section of the Cambrian-Ordovician boundary in Norway, but the boundary interval there has not been studied in detail until now. Stratigraphic work on the Cambrian of the Krekling area started with the work of Brøgger (1879). In this area intervals of conglomerate, sand, silt and shale are exposed above the contact with Precambrian basement (Høyberget and Bruton, 2008), followed by remarkable exposures of the Alum Shale Formation. Within this formation occurrence of graptolites *Rhabdinopora* sp. is a biostratigraphical marker just above the Cambrian-Ordovician boundary.

![Figure 2. Alum Shale Formation at Krekling.](image1)

The graptolites are a group of extinct organisms belonging to Hemichordata, phylum of worm-shaped marine animals, generally considered the sister group of echinoderms. They had external skeleton of chitinous material, growth pattern of half-rings of periderm interfaced by zig-zag structures. Their an external skeleton has the form of a tube (theca) surrounding each zooid, thecae being assembled along branches (stipe) to form the colony (rhabdosome) (Bulman, 1970).

![Figure 3. Graptolite *Rhabdinopora* sp. Vestfossen, Norway. (from: paleontologia.pl)](image2)
Graptolites are known from Upper Cambrian to Lower Carboniferous. (Benton and Harper, 2009). They are considered to be one of the best index fossils in Lower Paleozoic (Benton and Harper, 2009).

The classification and evolution of Rhabdinopora sp. were extensively described by Cooper et al., (1998) and (1999). These authors correlated specimens found in different world-wide localities, determined populations systematics, defined stratigraphic and ecological subspecies, finally proposed composite ranges charts for the earliest Ordovician graptoloids.

1.2 Purpose of study

The purpose of this study is to investigate the fossil assemblages from the Alum Shale Formation at Krekling in order to build a biostratigraphical framework of the Cambrian-Ordovician transition there, together with geochemical data to estimate the Cambrian-Ordovician boundary at this locality.

Samples collected during field work revealed an almost continuous succession of Rhabdinopora flabelliformis graptolites through a several meter long interval. The primary aim here is to make a precise identification of subspecies according to characteristics provided by previous researchers based on material from other localities.

A detailed investigation of the Rhabdinopora succession at Krekling has not been made previously, so hopefully this research can give relevant, new information regarding the graptolite fauna from the Early Ordovician of Krekling.
2 Geological background

2.1 Regional geology

The Cambrian period is estimated to cover 55.6 million years (541-485.4 Ma), and is the first period in the Paleozoic Era (Peng et. al., 2012). The Cambrian period was significant in the history of life on earth, with one of the greatest evolutionary events in the Earth’s history occurring in this period: the Cambrian Explosion (Waggoner and Collins, 1994). The succeeding Ordovician period lasted for 41.2 million years (485.4-443.8 Ma), with its lowest stage the Tremadocian, which is along with the Upper Cambrian, the subject of this study.

2.1.1 Paleogeography and tectonic history

Baltica was a paleocontinent and plate that was formed by the break-up of Rodinia in the Neoproterozoic and existed until the formation of Laurussia during the Caledonian Orogeny in the mid-Paleozoic (Bogdanova et al., 2008). As shown in Figure 4, boundaries of the Baltica terrane are placed along Norway, Franz Josef Land, Ural Mountains, Caspian Sea and close to the boundaries of Ukraine, Poland and Denmark.

Figure 4. Late Paleoproterozoic to Early Neoproterozoic complexes in Baltica. (Bogdanova, 2008)
The core of Baltica was formed by the East European Craton, with the oldest rocks in that area. At 1.9 Ga Baltica contained Fennoscandia, Sarmatia and Volgo-Uralia- and iwas called Protobaltica. (Figure 4) This terrane was a part of the Rodinia supercontinent. During the Vendian period Iapetus Ocean began to open because of rifting movement between Laurentia and Baltica (Cocks and Torsvik, 2005).

Baltica became an independent terrane after splitting off from Laurentia (570 – 550 Ma). The terrane was located in the southern hemisphere, in low paleolatitudes. The orientation of Baltica was different that nowadays, which is an evidence for rotation of this continent. Between 560 and 550 Ma, also in the Vendian, northwestern margin changed its character from passive to active. (Cocks and Torsvik, 2005).

![Figure 5](image)

**Figure 5.** Positions of Baltica in relation to surrounding terranes in Neoproterozoic (Cocks and Torsvik, 2005).

During the Cambrian period Baltica and Laurentia continued their latitudinal movement, and receded. The Ran ocean (located in the south, between Baltica and Gondwana) was not that wide as the Iapetus Ocean. Baltica’s rotation of about 120 degrees through Cambrian and Ordovician started with the event- Finnmarkian Orogeny, when the accretion of islands arcs occurred and counterclockwise rotation started (Bogdanova, 2008).
Figure 6. Baltica during Late Cambrian (Cocks and Torsvik, 2005).

Large parts of the Baltica terrane were submerged under wide seas- The Alum Shale Formation is a sediment complex which was deposited in an epicontinental sea during the Cambrian and earliest Ordovician. The formation has a huge lateral extent from Oslo Region almost to Moscow. Different and warmer conditions of deposition are represented by the Andrarum Limestone from Sweden (Cocks and Torsvik, 2005).

The center of Baltica was tectonically stable and low in topography during Cambrian but its margins were subject to tectonic activity. This included strike-slip movement in the Ran ocean, between Baltica and Gondwana (Bogdanova, 2008).

Baltica was most clearly isolated as a separate continent in the Early Ordovician. Many examples of paleobiological endemicity have been found as an evidence. During Cambrian period Iapetus Ocean was at its maximal width, Ran Ocean started to became much more wider. In the Late Cambrian Baltica travelled northwards, in the Early Ordovician the Iapetus Ocean started to close and the margins of Baltica became to convergent (Cocks and Torsvik, 2005).
Avalonia was a terrane, including the area now forming part of the Maritime Provinces of Canada, Newfoundland, southeastern Ireland and southern Britain. Avalonia detached from Gondwana in the Early Ordovician and approached Baltica in a soft docking process (Rehnström and Torsvik, 2003).

During the Silurian period, movement of Baltica to the north continued, than a collision which ended a Baltica’s history as a separate continent occurred. Avalonia and Laurentia collided with Baltica forming the Caledonides. This orogeny led to uplift in the western Baltica, terrestrial deposits (Old Red Sandstone) can be observed for example in the Ringerike area in Oslo can be observed. (Rehnström and Torsvik, 2003).

The Caledonian Orogeny was initiated during the Late Ordovician and it was a result of the closure of the Iapetus Ocean and the Tornquist Sea (Rehnström and Torsvik, 2003). This process led to deformation and folding of the shelf areas of the Baltic Shield, Lower Paleozoic deposits in the Oslo area were strongly affected by the orogenic event (Buchardt et. al., 1997). This process with Alum Shale working as thrust plane, resulted in a shortening of the Lower Paleozoic complex in the Oslo- Asker region (Bruton and Owen, 1982). Along the margin of Caledonides a foreland basin was formed Figure 8).
During the Carboniferous-Permian transition, due to extensional rifting of the supercontinent Pangea, Upper Paleozoic deposits of Baltica were a subject to erosion (Buchardt et. al., 1997).

2.1.2 The Oslo Region

The Oslo Region is located within a rift structure- the Oslo Rift, which was formed in Carboniferous- Permian time, as a result of complex tectonical processes (Neumann et. al., 2004).

The Oslo Graben is about 200 km long and 35 to 65 km wide, bounded by fault- zones. The region stretches from Langesundfjorden in the south to the Mjøsa district in the north (Neumann et. al., 2004). The rifting process (Figure 9) started about 300-305 Ma with volcanism, sub-surface sill intrusio and faulting. The graben structure forming processes had an influence on Lower Paleozoic deposits in Oslo Region, including the Alum Shale Formation (Buchardt et. al., 1997).

![Figure 8. Development of the foreland basin during Caledonian orogenic event (Bruton et al., 2010).](image)

![Figure 9. Continental rifting process scheme (modified from: www.le.ac.uk)](image)
The plutonic rocks of the Oslo Region can be divided into three main groups (Figure 10). Within the northern Akershus graben complex there is the Nordmarka- Hurdalen batholith with mostly syenitic and granitic alkaline rocks also intrusions of biotite granite and monzonite. Second group is biotite granites of the Drammen and Finnemarka batholiths, northern part of the Vestfold rift group, which are dominant in the central part of the Oslo Rift. The drammen batholiths cover area of 650 km², this is the largest granitic complex in the Oslo Graben. Finnemarka batholits cover area of 124 km². Southern, third main group are monzonitic batholiths, parts of southern Vestfold rift group, the Larvik-Siljan and Skrim massifs. The northern extension of the Skrim massif is the largest peralkaline granite complex- the Eikeren massif (Trønnes and Brandon, 1992), which is situated close to the study area at Krekling.

Figure 10. Simplified map of the Oslo Graben area (Andersen et al., 2008)
2.1.3 Paleogeography and paleoclimate in the Cambrian

As a result of the splitting of the Proterozoic supercontinent Rodinia, in the Cambrian period, paleocontinents were diffused on the southern hemisphere (Waggoner and Collins, 1994). Baltica was situated between 45-60 degrees south, but at this paleolatitude, temperature was higher than today. Warm climate caused the reduction of the size of the Proterozoic ice cover, which increased sea levels (Figure 11) (Waggoner and Collins, 1994).

![Figure 11](image_url)  
*Figure 11. Cambrian-Ordovician sea-level changes (modeled from Gradstein et al. and Ogg et al.)*

Conditions described were favourable for carbonates deposition, therefore low-lying parts of Baltica continent were covered by carbonate platforms in shallow epicontinental seas (Figure 12).
Higher temperature during the Cambrian period increased evaporation rate, which caused rise of salinity in shallow waters. High salinity level in epicontinental seas led to density diversification in the water column, then seas became stagnated. The bottom waters turned anoxic due to inability of oxygen rich waters to drop through column layering (Bjørlykke, 2004). These conditions allowed the deposition of the Alum Shale (Figure 13).

2.1.4 The Alum Shale Formation

The Alum Shale Formation is represents the Middle Cambrian to Early Ordovician (Tremadoc) and was deposited in shallow epicontinental sea in Balticaa (Schovsbo, 2001). The boundaries of the Alum Shale basin were the Iapetus Ocean to the north and to the south Tornquist Sea to the South (Scotese and McKerrow, 1990).
According to Thickpenny (1984), the base of formation is diachronus. In Scania, Norway and Bornholm, deposition started in the early Middle Cambrian, the base of the formation is progressively getting older from the east towards the west (Schovsbo, 2001). The Alum Shale Formation has its maximum thickness up to 100 m in southern Sweden (Figure 14), whereas towards east achieve minimum a few centimeters in the St. Petersburg, Russia (Popov, 1997). In Estonia, the formation appears only from the Tremadocian stage (Schovsbo, 2001).

The Alum Shale Formation consists of bituminous brown to black shales and mudstones with diagenetic limestone- and siltstone units (Figure 15). The type section of the formation has been defined in the Gislövshammar-2 core, located in southern Sweden (Buchardt et al., 1997). Formation is gently laminated, almost without bioturbations, present only within some horizons at the lower and upper part (Schovsbo, 2001). High content of organic matter and trace elements (mostly uranium and vanadium) are characteristics of the Alum Shale geochemistry (Bergström and Gee, 1985). The formation contains carbonate concretions, formed during early diagenesis (Schovsbo, 2001).

Shale in the formation is often highly fossiliferous. Characteristic of the fossil content is low diversity but high abundance of fauna within the formation. In Middle Cambrian, fauna is...
dominated by agnostids, in the Upper Cambrian by olenid trilobites and in Ordovician by graptolites (Schovsbo, 2001). Occurrence of orthide and phosphatic brachiopods together, with non-olenid polymerid trilobites indicate an improvement in the paleo-oxygenation level (Bergstrom, 1980).

Figure 15. Early Ordovician deposition of Alum Shale (modified from Ramberg et al, 2010).

The fossil fauna in the Alum Shale Formation, is a basis for reconstruction of the syndepositional changes in the oxygen level of the bottom waters (Schovsbo, 2011). The sea floor were inhabited by brachiopods and non-olenid polymerid trilobites under high oxygen concentration Agnostids were dominant during lower oxygen concentration and olenid trilobites during the lowest oxygen content. Faunal changes are correlated to high content of vanadium, nickel and sulphur. Preservation of calcareous fossils increase under low oxygen concentrations. Generation of corrosive pore waters during reoxidation of sulphide explain of weak preservation of calcareous fossils in high oxygen content. Shale intervals can be devided into trilobitic and non-trilobitic. Non- trilobitic layers are unfossiliferous or contain non-calcareous fossils like phosphatic brachiopods, ostracodes and graptolites (Schovsbo, 2001).

Stratigraphical variations of trilobitic and non-trilobitic intervals within formation, thus reflect main changes of oxygen levels, which could be correlated to sea-level and climatic changes (Schovsbo, 2001).
2.2 The Cambrian-Ordovician boundary

The lower boundary of the Ordovician system is internationally agreed upon by a reference profile, GSSP- Global Boundary Stratotype Section and Point. GSSPs are confirmed by the International Commission on Stratigraphy, a part of the International Union of Geological Sciences. Most of GSSPs are defined based on biostratigraphical data, as transitions in faunal content, with appearance of key fossils. (Remane et al., 1996). According to the Geological Time Scale 2012 (Gradstein et al., 2012) 64 of 101 stages have GSSPs formally defined. The Ordovician was the last system of the Paleozoic era than which have lower boundary formally designated.

An outcrop should follow a list of significant criteria to be considered as GSSP. Profile has to be unaffected by tectonics and metamorphism. The outcrop has to have appropriate thickness, at the profile should be without changes in facies. The boundary horizon has to be defined using primary marker, which is mostly first appearance of species, marker should be facies-independent. Fossils have to be abundant and well preserved. Profile has to have free access and be opened for research. There must also have been continuous sedimentation with sufficient rate (Remane et al., 1996).

Many of GSSPs have bronze disk called a “golden spike” which is placed on the boundary (Figure 16).

![Figure 16. GSSP marker- bronze disk, in Ediacara locality (from: worldfossilssociety.org)](image)

Figure 16. GSSP marker- bronze disk, in Ediacara locality (from: worldfossilssociety.org)
2.2.1 International definition

The Global Stratotype Section and Point for base of the Ordovician system and base of the lowest Ordovician stage- Tremadocian, is established in Green Point, western Newfoundland in Canada (Figure 17). The stratotype sequence consists shales and carbonates, belongings to the Cow Head Group, represents a transect across the continental slope in terms of depositional environment (James and Stevens, 1986).

Figure 17. The Green Point outcrop. A- marked bases of units. B- Wide extent of outcrops in cliff and wave-cut platform (from: Copper et al., 2001)

The Cambrian- Ordovician boundary is placed at the first appearance of the conodont Iapetognathus fluctivagus, 4.8 m below the appearance of the earliest planktonic graptolites Rhabdinopora praeparabola. Within the profile there are no unconformities, sequence has 60 m thickness. Sedimentary beds are unmetamorphosed, conodont colour alteration index is 1.5. There is remarkable preservation of conodonts, graptolites and other fossils. The graptolite
succession is one of the most complete early Tremadocian profile in the world, with *Rhabdinopora flabelliformis* complex (Cooper et al., 2001). The biostratigraphy at Green Point is presented in Figure 18.

**Figure 18.** Detailed stratigraphic column of the boundary interval with graptolites and conodonts occurrence (from: Cooper et al., 2001)
Graptolites, which begin to occur from 4.8 m above the boundary, can for practical purposes be considered as marking the boundary in case of lack of conodonts in shales. Graptolites found at Green Point are reliable for global correlation of early Tremadoc shales. The earliest planktonic species *Rhabdinopora praeparabola* and *Sturograptus dichotomus* (Figure 19) and *Rhabdinopora flabelliformis parabola* (Figure 20) represent evolutionary complex with global distribution. The genus *Rhabdinopora* is subject to huge variety, populations characteristic for each biozons can be termed stratigraphic subspecies, while those typical for certain ecological zones - are ecological subspecies. Within specific biozones, species are divided into: shelf, upper slope, lower slope and ocean floor groups (Cooper, 1999).

**Figure 19.** Earliers planktonic graptolites a-d, *Rhabdinopora praeparabola* Bruton, Erdtmann and Koch 1982, e-k) *Sturograptus dichotomus* Emmons (from: Cooper et al., 1998)

Trilobites also occur within the Green Point interval, such as *Jujuyaspis borealis* and *Symphysurina bulbosa*. Among microfossils there are acritarchs, chitinozoans and scolecodonts. Brachiopods are noticed from more upslope sections from this location (Fortey et al., 1983)
2.2.2 Correlations

According to the Working Group on the Cambrian-Ordovician Boundary (1999), strong facies differentiation is the most significant problem in biostratigraphic correlation of the boundary interval. Correlations based on conodonts and trilobites within shelf carbonate facies or based on graptolites and conodonts within slope-basins sequences are possible, but between shelf and basin sequences remains difficult (Cooper et al., 2001). It is therefore much easier to correlate facies from Early Ordovician, than Late Cambrian, because of rapid evolution of graptolites working as a significant marker (Cooper et al., 2001).

Figure 20 show is the correlation for the boundary, proposed by Working Group. The boundary coincide with the base of the conodont *Iapetognathus* zone. Boundary is placed below the base of traditionally defined Tremadoc Series (Rushton, 1982). Further the boundary is estimated at the base of the Warendian Stage in Australia, in the lower Ibex Series of North America, lower Tremadocian in Kazakhstan, late Fengshanian in China (Cooper et al., 2001).

![Figure 20](image)

**Figure 20.** Correlation of the boundary for the base of the Ordovician System. Eustatic events are numbered: 1. Lange Ranch Eustatic Event 2-3. Acerocare Regressive Event, 4. Black Mountain Regressive Event. Table contains generalized δ13C curve (from: Cooper et al., 2001)
2.2.3 Nærsens section

The Nærsnes section is located 33 km south-west of Oslo, in the community of Royken (Figure 21). This locality has an excellent preservation of Cambrian-Ordovician boundary and was a candidate for the boundary stratotype for the International Workin Group on the Cambrian-Ordovician Boundary in 1985 in Canada (Bruton et al., 1987).

![Figure 21. Location of the Nærsnes section. A- general b- detailed (from: Bruton et al.,1982)](image)

The Nærsnes locality is the 9 m thick and 18 m long section of Cambrian-Ordovician transitional sequence. The profile contains the limestone concretions with olenid trilobites in a uniform sequence of the black shales (Figure 22) (Bruton et al., 1982). The shales represent stable depositional environment, with limestone nodules (Henningsmoen 1974).

![Figure 22. Limestone concretions with Boeckaspis hirsuta and shales (from: Bruton et al.,1982)](image)

Within the lowermost concretions occurrence of trilobites Acerocare ecorne and Parabolina acanthura is recorded, which mark the topmost zone of Upper Cambrian estimation in Scandinavia (Bruton et al., 1982). Upwards the profile occur concretions with trilobite Boeckaspis hirsuta and shales with graptolites Dictyonema (Rhabdinopora) flabelliforme with
subspecies, and conodont multielement *Cordylodus* sp. Detailed biostratigraphy in the section is shown in Figure 23.

**Figure 23.** Stratigraphic ranges of olenid trilobites in limestone concretions and graptolites in intervening shales from southern profile, Nærsnes (from: Bruton et al., 1982)
The Cambrian-Ordovician boundary in the Nærsnes locality is approximated by the first occurrence of the from trilobite *Boeckaspis hirsuta* (Figure 24), within the *Acerocare ecorne* zone, in a sequence containing graptolites *Dictyonema (Rhabdinipora) flabelliforme* (Figure 25) (Bruton et al., 1982).

![Figure 24](image)

**Figure 24.** Trilobites from the Nærsnes section, 1-4: *Boeckaspis hirsuta* (Brogger, 1882) 5-6: *Jujuyaspis keideli norvegica* Henningsmoen, 1957. 1-PMO 106.495, 2-PMO 106.494, 3-PMO 106.496, 4-PMO 106.492, 5-PMO 106.505, 6-,PMO 106.497 (from: Bruton et al., 1982)

The Cambrian-Ordovician boundary in the Nærsnes locality is placed in a uniform sedimentary sequence, which contains cosmopolitan fossils- non benthonic graptolites and abundant trilobites. Fossiliferous zones are placed above and below the boundary, (Bruton et al., 1982)

![Figure 25](image)

**Figure 25.** Graptolites from the Nærsnes section, 1-2: *Dictyonema (Rhabdinopora) flabelliforme parabola* Bulman, 1954. 1-PMO 105.773, 2-PMO 105.775 (from: Bruton et al., 1982)
2.3 The Krekling locality

2.3.1 Geology of the Krekling area

In Baltoscandia, the middle to upper Cambrian interval is represented by the Alum Shale Formation (Schovsbo, 2001). Deposits of this formation in Norway reach 100 m of thickness, and most of the outcrops are located within the Oslo Rift (Ramberg et al., 2010). The Alum Shale Formation was altered through volcanic and magmatic activity during the Late Carboniferous-Permian resulting in high grade, to low grade contact metamorphism from the (presence of plutons) and low grade metamorphism (Jamtveit et al., 1997).

The logged and sampled sections is located between Stavlum and Krekling in the Øvre Eiker region, southern Norway (Figure 26). The Krekling section is situated at the western boundary of the Oslo Rift and exposes the Lower Ordovician, Middle and Upper Cambrian Alum Shale Formation. Below there is a 2.5 m thick, basal sequence of conglomerate, sand, shale and silt of Early Cambrian age resting on Precambrian crystalline basement (Høyberget and Bruton, 2008).

Figure 26. Localisation of the Krekling section, general and geologic map of the area (from: Hammer and Svensen, in preparation)

Krekling is situated in the foreland of the Caledonide orogeny with generally sub- horizontal bedding, whereas most of Cambrian locations in Norway are much more heavily tectonized. Due to emplacement of Ekerite pluton during the Oslo Rift extensional process, shales in the
Krekling area experienced metamorphic alteration. Shale in contact with peralkine granite was subjected to high temperature matamorphism and recrystallization (Jamtveit et al., 1997). Probably this type of metamorphism occurred after pre-existing low grade metamorphism due to burial (Hammer and Svensen, 2017).

2.3.2 Lithostratigraphy and biostratigraphy

A schematic cross section of the locality is shown in figure 27. The studied section is about 84 meters thick and contains mainly shales from Alum Shale Formation, few limestone-rich intervals and pyrite/pyrrhotite nodules. In the lowermost part of the section, there is a 6 cm igneous dike.

![Figure 27. Schematic cross section of the main locality in Krekling (not to scale). The start and end of the logged section are shown by arrows and given with GPS coordinates (modified from: Hammer and Svensen, 2017)](image)

Figure 28 presents the composite section in the Krekling locality. Section 2, with the Alum Shale Formation, is missing 8 meters at the base and section 1, the basal part of the formation, was logged 200m south west of section 2.

Carbonate beds first appear between 9 and 10 meters, then again around the Cambrian-Ordovician boundary (73m). In between there are sporadic limestone nodules- about 13m, 36-38m and 60m (Figure 28). Black shales are present from the base of the section to 12m and from 19 to 27 m. The pyrrhotite nodules from the section are most probably derived from
finely dispersed pyrite which recrystallized during low grade metamorphism (Hammer and Svensen, 2017).

Figure 28. Litho- and biostratigraphy of the Alum Shale Formation section in Krekling (from: Hammer and Svensen, 2017)

Lower Drumian marker in the studied composite section is at -1.5 m contains the agnostid trilobite *Hypagnostus mammillatus*, of the *Ptychagnostus atavus* zone. At -0.2 m, *Ptychagnostus cf. affinis* ranges from the upper part of the *Ptychagnostus. atavus* Zone through the lower half of the *Ptychagnostus punctuosus* Zone. The agnostid *Goniagnostus*
trilobite from *Goniagnostus nathorsti* Zone- upper Drumian is present at 3.0 m. This zone occur above 6.6 m- where *Paradoxides aff. Rugulosus* was found. At 10.5 m, presence of the *trilobite Liostracus microphthalmus* is noticed, marking *Lejopyge laevigata* Zone- lower Guzhangian. *Agnostus pisiformis* at 25.0 and 29.0 m indicates the *Agnostus pisiformis* Zone- upper Guzhangian (from: Hammer and Svensen, 2017). The base of the Lower Paibian (lowermost Furongian) is defined at 40.0 m by the presence of *Homagnostus obesus* of the *Glyptagnostus reticulatus* Zone, corresponding to the *Olenus* Zones (Peng et al., 2012). At 66.7 m *Peltura scarabaeoides* indicates middle Stage 10 of the upper Furongian. Abundant graptolite *Rhabdinopora flabelliformis* occurrence is noticed from 72.5 to 74.9 m, the Cambrian- Ordovician boundary is slightly below the first occurrence of the *Rhabdinopora* graptolites complex and at the 72.8 m with the basal Ordovician trilobite *Boeckaspis hirsuta* (Hammer and Svensen, 2017).

### 2.3.3 Geochemistry

Extinction events in the Cambrian period are named after their stratigraphic positions, e.g. Steptoean, Sunwaptan, Skullrockian, Stairsian or Tulean. They are associated with anoxic conditions in the ocean waters (Figure 29). Oxygen deficiency in Cambrian oceans was caused by upwelling of anoxic waters during sea level rise (Saltzman et al., 2015). Two of the well described anoxic events are DICE- Drumian positive carbon isotope excursion and the SPICE- Steptoean positive carbon isotope excursion. Within the Cambrian- Ordovician boundary interval several oxygenation periods occurred, with periodically reversible abundance of oxygen (Kump, 1999). Sea level rise may have triggered low oxygenation periods (Gill et al., 2011).

Chemostratigraphy of the Krekling locality, according to samples measured by Hammer and Svensen, is shown in the Figure 30. In the lower parts of the section (-10 to 15m), Total Organic Carbon (TOC) values range from 0.6 to 4.8%. The nitrogen in this part is an average of 0.07-0.19- wt.% which is considered low and uniform. C and N have their highest concentrations in about 50 – 60 m. The TOC maximum content is at 68m- 13.5 wt.%. High TOC value coincides with most $^{13}$C-enriched units. Within the basal part of the section, the negative DICE carbon excursion may be recorded (cf. Ahlberg et al., 2008).
Figure 29. $^{13}$C Isotope excursion and massive extinctions during the Cambrian/Ordovician (from: Saltzman et al., 2000)

Figure 30. Chemostratigraphy of the Krekling section (from: Hammer and Svensen, 2017)

As shown in Figure 31, $\delta^{13}$C$_{TOC}$ curve has substantial correlation with the Andrarum-3 core in Sweden (Hammer and Svensen, 2017). Negative carbon isotope excursion within *P. atavus*
zone in late Drumian are noticed in both locations, and they correspond to international DICE excursion (Ahlberg et al., 2009). Small positive excursions are correlative in the Krekling and Andrarum localities, at Krekling near the base of *P. punctosus* Zone, in Andrarum in *P. atavus* Zone. Low biostratigraphic resolution in Krekling can be an explanation of a little apparent diachroneity (Hammer and Svensen, 2017). The main carbon positive excursion in both localities begin near the base of the *G. reticulatus* Zone. It has been indentified in Andrarum locality as the SPICE by Ahlberg et al. (2009).

The Mo curve (Figure 30) shows, that concentration increases up the section with the peak at 65 m, close to the occurrence of *Peltura scarabaeoides* (66.7 m) and decrease at 73 m, under the Cambrian-Ordovician boundary. Peak Mo value is considered to indicate the most dysoxic interval in the section, Mo content increasing in the section can be the evidence of prolonged anoxia (Hammer and Svensen, 2017).

**Figure 31.** Bulk organic δ13C curves from Krekling ((Hammer and Svensen, 2017) and Andrarum, Sweden (Ahlberg et al., 2009).
According to Hammer and Svensen, shales in Krekling locality have low hydrocarbon potential and organic matter is post mature and affected by metamorphism.

The data from the Krekling locality, confirm that occurrence of taxonomic groups within Alum Shale Formation is controlling by oxygen level discussed by Schovsbo (2011). Non olenid trilobites including: *Paradoxides* occur about 6-15 m in the profile, within the interval of lowest Mo and TOC values. Most dysoxic (Mo peak value) corresponds with occurrence of olenid trilobites *Peltura* (Hammer and Svensen, 2017).
3 Paleontological background

3.1 Graptolites

3.1.1 General features of graptolites

Graptolites (class Graptolithina) are extinct group of hemichordates living in the early Paleozoic- from the Late Cambrian to Early Carboniferous (Figure 32). The name graptolite comes from the Greek “graptos”- written, and “lithos”- rock (Fortey, 1997).

Class Graptolithina contains the orders: Camaroidea, Crustoidea, Dendroidea, Dithecoidea, Graptoloidea, Stolonioidea, Tuboidea. An interesting related group is the extant hemichordates. The orders have similar morphology with some differences of each parts, they also have varied mode of life (Bulman, 1970).

Graptolites are colonial organisms that evolved external skeleton of chitinous material. Their skeleton has a form of a cup or tube, surrounding each zooid, which is a theca (Figure 32). There are three types of thecae, vary between Graptolithina’s orders. Thecae are assembled along one or more branches- stipes. Several stipes form the complete colony- a rhabdosome. A conical tube secreted by the first member of the colony is called the sicula. An extension of the sicula, thin tube possibly used to attach to a floating object is called the nema (Bulman, 1970).

In several orders of graptolites, the budding process of their zooids is related to a chitinized stolon. One of the thecae types is stolotheca (Figure 33)- a form of continuous closed chain along tergal side of their branch. The stolotheca is as tube-shaped, slender structure. Each stolotheca gives rise to one autotheca, second type of thecae, which is the largest one and comprises a relatively long stolon. Moreover, each stolotheca also can give rise to one bitheca, and one daughter stolotheca, according to the alternating triads principle- the “Wiman rule”. Bitheca is a third type of thecae, shorter and narrower than authotheca (Bulman 1970; Zhang and Erdtmann, 2004).
Figure 32. Simplified morphology of graptolites. A- pendent shape, B- reclined shape, C- horizontal shape (from: Boardman et al. 1987)

Figure 33. A) BSE picture of Airograptus furciferus, showing the detailed structures of stolothecae, autothecae and bithecae (Zhang and Erdtmann, 2004) B) Transverse section of Koremagraptus sp. stipe showing tissue surrounding complete tubes of autothecae, bithecae and stolothecae (Bulman, 1970).
Regarding mode of life, graptoloids represent gradual changes, reconstructed from interpretation of their rhabdosomal structures. The orders Tuboidea, Camaroidea and Stolonidea appear to be sessile but their ecology is not well understood. Dendroidea and Graptoloidea however, belong to much more ecologically characterized orders. Theory of epiplanktonic character most probably explains wide geographical distribution of graptolites, which is one of their typical features. According to this theory graptoloidea were attached by their nema to masses of floating weed or to a flotation organ that is not preserved. Controlling factor of the evolution of graptoloids is considered to be their readaptation from sessile organisms to free moving existence in plankton (Kirk, 1978).

Graptolites are important index fossil for dating rocks from Paleozoic, because they evolved with time rapidly as a variety of species formed. Because of their characteristics: evolution rate, distribution, quantity and preservation they mark biozones in Ordovician and Silurian periods. Graptolites can be used to estimate paleotemperature and water depth values (Fortey, 1998). Stratigraphical distribution of graptolites genera in Ordovician and Silurian periods is shown in Figure 34.

Geographical distribution of graptolites is mostly world-wide. That phenomenon was possible because of drifting process and the nature of ocean currents. Exceptions to distribution trend are local species like *Goniograptus sp.* which is characteristic only to Australia and North America, or *Schizograptus sp.* distributed in north-western Europe (Bulman, 1970).

All ecological models for graptoloids assume that they moved relative to the water mass in which they were living, but their means of locomotion of are only presumed (Rickards, 1975).

By analogy with modern pterobranchs, graptolites filtered food particles using ciliated lophophores from the water. It is hypothesized that they were able to migrate vertically through the water column for feeding efficiency and avoiding predators (Cooper et al., 2012).

Graptoloid habitat was divided vertically and horizontally in the neritic and pelagic waters. Group one occurred in a deep water biotope (mesopelagic zone), Group two occupied epipelagic zone and third group in the inner shelf waters of the epipelagic zone (Cooper et al., 2012).
Figure 34. Stratigraphical distribution of certain graptoloid genera. Number of species only approximately indicated (from: Bulman, 1970).
Graptolites are found in a wide range of sedimentary facies: terrigenous (allogenic) shales, sandstones and carbonates, authigenic cherts, and limestones. They are however, best known and most abundant in black shales, cherts and siliceous shales, generally within the facies specific for the outer shelf to the ocean floor (Cooper et al., 2012).

3.1.2 Genus Rhabdinopora

3.1.2.1 Introduction

*Rhabdinopora* is a genus among graptolites which indicates lowermost Ordovician stage in Scandinavia, and world-wide, and is then main subject of this research at the Krekling locality.

Morphology of the genus Rhabdinopora, shown on Figure 35 is consistent with general features of graptolites, with some specific sections. Branches comprise thecal structures—stolotheca, autotheca and bitheca. Stipes are united by hollow transverse threads—dissepiments, which are either erratic or regular. Sicula has an extensional, thin tube (nema), possibly used to attach to a floating objects (Figure 36). Presence of nema is a distinctive feature in evolution of graptoloids adapted for an epiplanktonic mode of life (Benton and Harper, 2009)

![Figure 35](image.png)

**Figure 35.** A) Schematic illustration of Rhabdinopora colony with stipes attached by dissepiments and sicula B) Stipes with details of thecal structures and dissepiment connection (modified from: Benton and Harper, 2009)

In the Tremadocian period, genus Rhabdinopora and its family the Anisograptoideae, became epiplanktonic, acquired a wide distribution in northwestern Europe, North and South America, New Zealand, Australia and China.
3.1.2.2 Systematic paleontology

Hall (1851) erected the genus *Dictyonema*, with *Gorgonia retiformis* Hall, 1843 as the lectotype. This specimen was suggested to be a benthonic root-bearing taxon. During the next century over the 200 graptolite taxa have been classified to the genus *Dictyonema*. A separation of sessile and planktic dictyonemids based on proximal structure has been conducted by Westergard (1909) and Bulman (1927). In 1982, Erdtmann reported that the planktic *Dictyonema* with certain nema or buoyancy structures should be separated from the benthic dendroids and considered as early taxa of the family Anisograptidea Bulman, 1950. Erdtmann (1982) has made a shift of 28 coni-siculate planktic *Dictyonema* to the planktonic nematic genus *Rhabdinopora* Eichwald, 1855 with *Rhabdinopora flabelliforme* (Eichwald, 1840) as the type species (Wang and Servais, 2015). The relationships of the Family Anisograptidae have been discussed by Bulman (1950) and Erdtmann (1982), and Fortey and Cooper (1986) classified it from Dendroidea, to paraphyletic stem group of Graptoloidea (Cooper et al., 1998).

A commonly used term is Dictyonema Shale, they represent Tremadocian shale rich in organic matter and mainly graptolitic fossils (*Rhabdinopora flabelliformis*), this name comes from the genus *Dictyonema* described above. Presently, the taxa that have been classified in the original Dictyonema are recognized as either of mostly planktonic (*Rhabdinopora*) or benthic (*Dictyonema s.s.*). Therefore the majority of formations, called formerly “Dictyonema shales” do not represent appropriate *Dictyonema*, but planktonic *Rhabdinopora flabelliformis*. 

![Figure 36. Schematic illustration of stipe, exposing nema structure and thecal details (Benton and Harper, 2009).](image)
However the name “Dictyonema shales” has been used for more than a century and its mentioned in many scientific descriptions (Althausen, 1992).

Taxonomy of *Rhabdinopora*:

Kingdom Animalia Linnaeus, 1758  
Phylum Hemichordata Bateson, 1885  
Class Pterobranchia Lankester, 1877  
Subclass Graptolithina Bronn, 1843  
Order Graptoloidea Lapworth, 1875  
Suborder Graptodendroidina Mu et Lin, 1981  
Family Anisograptidae Bulman, 1950  
Genus *Rhabdinopora* Eichwald, 1855

Previous research aiming to build a proper taxonomy of earliest Ordovician *Rhabdinopora* populations, revealed many difficulties of this process (Bulman 1954, Erdtmann 1982, Cooper et al. 1998). A particular challenge to classification comes from the huge variability of *Rhabdinopora* specimens among studied material (Cooper et al., 1998) “The variability of *Rhabdinopora* is so great that hardly any of two specimens ever seem exactly comparable and in any large collection of these organisms the range of variation and diverse combination of characters is bewildering” (Bulman, 1954).

Extensive and complex classification of the earliest Ordovician graptoloids, including *Rhabdinopora* has been made by Cooper et al, 1998. This study contains elaborate attempt to arrange *Rhabdinopora*’s taxonomy, based on material from world-wide locations, Cooper et al. suggest that reliability of identification should be based on population analysis, not a single specimen.

Identification by Cooper et al. (1998) was made based on morphometrics, mainly the character of the rhabdosome: Stipe spacing value (Fig. 37A), mesh character (Fig. 37C), templates of rhabdosome shape (Fig. 37B) and expansion of the rhabdosome (Fig. 37D).
Figure 37. A) Stipe spacing/10 mm in population of Rhabdinopora flabelliformis species. The mean value and range are given for each. B) Templates of rhabdosome shape and distribution of Digermulen (Norway) specimens of *Rhabdinopora flabelliformis parabola*. 1-4: angle of stipe divergence, a-c: sharpness of stipe divergence. C) Templates for mesh character, number of Digermul specimens of *Rhabdinopora flabelliformis parabola* for each. D) Expansion variability of the rhabdosome in the Digermulen *Rhabdinopora flabelliformis parabola*. Mean rhabdosome shape, average, and the range (from: Cooper et al., 1998).
Proximal development type can be recognized mainly from flattened specimens, preserved discoidally (in dorsal view). Four primary stipes emerging from the proximal end define the quadriradiate type, three stipes - triradiate, and two of them define the biradiate development system. Proximal development of specimens (Fig. 38), despite its distinction, has not been taken as core-feature to classify Rhabdinopora in Cooper et al. (1998) work, because of not common preservation of the structure. It has been also acknowledged that biradiate and triradiate structure have not been recognized undoubtedly as a characteristic feature of any precise subspecies, but quadriradiate type of proximal development can be observed in Rhabdinopora praeparabola, Rhabdinopora flabelliformis flabelliformis, Rhabdinopora flabelliformis parabola, Rhabdinopora flabelliformis canadensis and Rhabdinopora flabelliformis anglica (Cooper et al., 1998)

Figure 38. Thecal diagrams of quadriradiate and triradiate proximal development types (from: Maletz, 1992)

Rhabdinopora classification, proposed by Cooper et al. (1998) is as follows:

Rhabdinopora praeparabola (Bruton, Erdtmann & Koch 1982)- quadriradiate proximal development, nema undivided if present. Rhabdosome small in general, uncommonly 20 mm length, stipes have wavy character, 0.3 mm in lateral width from the lower part of the stratigraphic range to 0.4 in upper part. 7 or 8 terminal stipes in pendant specimens, to 15-30 in more cone-shaped forms. Diffused distal dissepiments observed in larger specimens.

Rhabdinopora flabelliformis flabelliformis (Eichwald 1840)- wide range of mesh character, quadriradiate proximal development, in Estonian and Norwegian localities (Pakerort,
Naersnes, Oslo region) stipe spacing 7 to 9, average 8 in 10 mm. Wide spacing of dissepiments, locally tight or duplicated. Stipes are 0.3-0.4 in lateral width, thecae spacing 14-16 in 10 mm. British specimens have 8-8.5 stipe spacing in 10 mm.

*Rhabdinopora flabelliformis parabola* (Bulman 1954) (Fig. 39 A,B,C): sicula 1.3 mm long, rhabdosome from wide parabolic to narrow cone shape, shape corresponds to template pattern 2A and 3A (Fig. 37B), mean stipe spacing from 8 to 11 in 10 mm, average 9.92. Rhabdosome length usually no more than 40 mm, in rare cases 70 mm. Stipe lateral width from 0.35 to 0.5 mm. Due to huge variability, recognition should be based on small size, irregular meshwork, common parabolic rhabdosome shape, tight stipes spacing, commonly sinous stipes and nematic threads.

*Rhabdinopora flabelliformis canadensis* (Lapworth 1898) (Fig. 42 A,B): variable rhabdosomal shape, mostly parabolic, corresponding with shape template 4A (Fig. 37B). Length of rhabdosome commonly 50-60 mm, reaching 150 mm in largest ones. Stipes spacing 7.5 to 10.2 in 10 mm, average 8.82 in Naersnes succession, and 9.04 in Green Point. Stipe width is 0.4-0.5 mm, with straight to reservedly sinous shape. In well preserved species, quadririradiate proximal development is observed.

*Rhabdinopora flabelliformis anglica* (Bulman 1927) (Fig. 41 A): variable rhabdosomal shape from wide cones of 40 mm length to narrow cones about 100 mm. Straight stipes, with 0.3-0.4 width, stipes spacing is 4.5 to 7.8 in 10 mm, average 6.4 in lower interval at Green Point and 5.71 in upper interval in this location. Commonly perpendicular dissepiments, with spacing 2-3 in 10 mm. Mesh type is very characteristic.

*Rhabdinopora flabelliformis socialis* (Salter 1858) (Fig. 43 A,B): most distinctive features are tight stipes spacing, 11-13 in 10 mm and dense structure of dissepiments. Typical for continental shelf environments.

*Rhabdinopora flabelliformis norvegica* (Kjerulf 1865)- wide stipes and wide, closely spaced dissepiments. In some specimens stipes and dissepiments are very thick, with round holes as reduced spaces between them. Stipes spacing is 9-12 mm in 10 mm, with average 10.9 mm in Slemmestad, Norway. Spacing of dissepiments is 7-12 in 10 mm. Proximal end is not investigated. Typical for shallow and mid-shelf environment. Very characteristic, coarse meshwork allows even broken specimens to be recognized.
Figure 39. *Rhabdinopora flabelliformis parabola* A) PMO 155.454 B) PMO 155.455 C) PMO 155.456a (Cooper et al., 1998).

Figure 40. *Rhabdinopora flabelliformis norvegica* A) The most completed specimen found, Slemmestad, Norway. PMO 155.464 (Cooper et al., 1998). B) Dissepiments structure, Brabant Massif, Belgium. IRSNB a12911 (Wang and Servais, 2015).
Figure 41. A) *Rhabdinopora flabelliformis anglica*, borehole Nova, Estonia. Va 1042
B) *Rhabdinopora flabelliformis flabelliformis* Otten by, Oland, Sweden Lo 7511 C) *Rhabdinopora praeparabola* Dayangcha, China (Cooper et al., 1998).

Figure 42. *Rhabdinopora flabelliformis canadensis*. A) Nearsens, Norway. PMO 155.421 B) Greeon Point. GSC 115819 (Cooper et al., 1998).
3.1.2.3 Biostratigraphy

The *Rhabdinopora flabelliformis* fauna is relevant for biostratigraphy, because its appearance is considered to be substantially useful for indicating the base of the Ordovician System at a global level (Wang and Servais, 2015).

The Cambrian-Ordovician boundary stratotype in Green Point of western Newfounland provides a complete base for comparison with early Ordovician sequences from other world localities. In addition to GSSP, several other sections have been considered by Cooper et al. (1998) and (1999) as key strata for international correlation (Fig. 44). These localities allow a graptolite biozonation of the Tremadocian. Graptolite populations obviously differ in some aspects depending on ecological emplacement- shore-to-ocean depositional depth profile.

The earliest Ordovician biostratigraphicaly zonation, proposed by Cooper et al. (1998), on the basis of material from: Green Point (Canada), Nærsens (Norway), Dayangcha (China), Pakerort (Estonia), Eichwald (Russia), and the Digermul Penninsula (Norway) is presented below:
Zone of *Rhabdinopora praeparabola*: The markers of this zone are the first planktonic graptoloids: *Rhabdinopora praeparabola* and *Staurograptus dichotomous*. This is most probably short time zone, represents deep-water sequences, continental slope from low and mid-latitude areas: western Newfounland, eastern New York and the Oslo region.

Zone of *Rhabdinopora flabelliformis parabola*: The base marker here is *Rhabdinopora flabelliformis parabola*, which is considered to be also the earliest marker of the Tremadoc Series, and the first graptolite with well-developed mesh structure. Occurrence of *Rhabdinopora flabelliformis socialis* and *R. f. canadensis* is also a proper part in this zone, as well as *Staurograptus* species. The zone is known from all latitudes in shelf to oceanic successions: western Newfounland, eastern New York, Youkon province of Canada, Naersnes and Oslo region in Norway, north China, Taimyra peninsula.

Zone of *Anisograptus matanensis*: The basal marker is Anisograptus, usually *Anisograptus matanensis* or *Anisograptus richardsoni*. Complex of *Rhabdinopora flabelliformis flabelliformis* contains *Rhabdinopora f. canadensis* substituted by *Rhabdinopora f. flabelliformis*, occurring in large numbers in shelf and upper slope sequences in global distribution. In the upper part of the zone graptolite *Rhabdinopora f. norvegica* is found in shelf and upper slope sequences. This zone is world-wide, recognized in all depth facies and latitudes.

Zone of *Rhabdinopora flabelliformis anglica*: The base marker is *Rhabdinopora f. anglica*, abundant in shelf to lower slope sequences. *Anisograptus matanensis* is also found, *Rhabdinopora f. norvegica* remains through the zone in shallow successions. This zone is found in shelf and slope sequences from all latitudinal zones.

Zone of *Adelograptus*: The basal marker is frequently *Adelograptus tenellus*. The taxonomy and biostratigraphy of this zone is not well known. In the upper part of the zone, appearance of *Kiaregraptus, Triograptus, Adelograptus, Paradelograptus* and *Bryograptus* is noticed.
Figure 44. Ranges chart of graptolite and conodont species and subspecies based on taxonomic revisions (Cooper, 1999)

Regarding occurrence of the earliest Ordovician graptoloids populations, the phenomenon of reciprocal exclusivity is observed. By population analysis there is no concreted co-occurrence of two specimen forms in a single bedding plane (Cooper et al., 1998). This state is explained by geographic and stratigraphic differentiation (Bulman, 1970), habitat differentiation in the water mass and ecological distribution of growth stages (Erdtmann, 1982). Cooper et al. (1998) reported that genus *Rhabdinopora* is represented by a succession of populations, showing progressive modal shift in time and throughout facies, with extensively overlapping morphological ranges- in one bedding plane to another, therefore across ecological zones.

Model of distribution of *Rhabdinopora* subspecies in time and space, proposed by Cooper et al. (1998) is presented in Fig. 45. *Rhabdinopora* forms are considered as a gradual system of populations, stratigraphical subspecies- typical for horizon, and ecological subspecies-
specific for an ecological zone. Cooper et al. consider *Rhabdinopora flabelliformis norvegica* and *Rhabdinopora f. socialis* as ecological subspecies.

**Figure 45.** The succession of *Rhabdinopora flabelliformis* subspecies in time and in ecological space. Open arrows indicate inferred evolutionary transitions, double ended arrows- transitions in ecological space (from Cooper et al., 1998).
4 Material and methods

4.1 Field work

The fieldwork of this study was done during the autumn 2015. Sections of the Alum Shale Formation were investigated and sampled at the Krekling location (Fig. 46), situated in southern Norway, Buskerud region, Øvre Eiker municipality.

Figure 46. Location of the Krekling outcrop. Map based on http://geo.ngu.no/kart/berggrunn/

The field work was done together with supervisor Øyvind Hammer and Henrik Svensen, the research being part of a project focused on biostratigraphic and geochemical investigation of the Krekling locality and its Cambrian-Ordovician boundary estimation.
The main part of the fieldwork was to collect samples within the Alum Shale Formation (Fig. 47), from each intervals of 5 cm, containing fossils of graptolites for biostratigraphic investigation. Logging has been made by Øyvind Hammer and Henrik Svensen during previous work in the locality, as well as biostratigraphy of the Cambrian succession (Chapter 2.3.2).

Figure 47. A) The lower interval sampled in the Alum Shale Formation near Krekling B) Ravine near Krekling- location of the field work, upper section with Alum Shale Formation along the stream C) Shale sample from Krekling, packed and labeled before lab work

4.2 Samples

Samples of shales were taken from measured stratigraphical levels, labeled and transported to NHM. From approximately 40 samples collected during three field work sessions in Krekling, 25 of them have been selected for further lab work. Samples are in the form of slabs, bearing rare graptolite specimens with upper, whole part of the rhabdosome preserved, or, more frequently fragments. From each slab, a part was cut, for isotope analysis made by Henrik Svensen. For conodont analysis, a few shale samples also have been collected. Use of special
preparation techniques for the taken samples was not necessary, they were simply cleaned by gentle washing and drying.

4.3 Graptolites

4.3.1 Photography

For further detailed investigation, it was required to conduct an adequate photographic process of slabs with graptolites and their elements. Photographs have been taken at NHM, using the following equipment (Fig. 48): two fluorescent lamps producing diffused light, placed on the left and right side of photographed specimen, and an SLR camera pointing downwards, mounted on a stand. Shale slabs were placed on a black canvas.

Some of the samples were covered by a thin film of water to obtain a better photographic contrast, because of remarkable difficulty of photographing process. Even well preserved specimens require many attempts to set an appropriate light angle, or using several lamps at once to photograph them with satisfactory results. Other techniques such as alcohol immersion and use of UV light were not used.

Figure 48. Specimen photography set at NHM. A) SLR digital camera B) Canvas for specimen photographed C) Diffused lights.
4.3.2 Measurements and species identification

The crucial part of the methodical work was morphometrics and species identification. Measurements have been made in several ways, most of them to identify species according to methods used in the work by Cooper et al., (1998), explained in Chapter 3, (Fig. 37 A). Those measurements include:

A) Stipe spacing (Fig. 49)- measured using the photographs taken: each photo was taken with a scale, and measurements made based on that scale by tpsDig2 1.1 software (Rohlf F.J.) The measuring in the mature part of each specimen, and the stipe spacing was calculated as the width of the rhabdosome in mm, divided by number of stipes, minus one (all in mm). Every measurement was repeated twice to avoid errors.

\[ S = \frac{W}{(N-1)} \text{ mm} \]

Where: \( S \) - stipe spacing, \( W \)-rhabdosome width, \( N \)- number of stipes

However Cooper et al. (1998), reported stipe spacing as number of stipes for 10mm (N10), therefore to obtain Cooper’s values, the measured stipe spacing measured was converted: 
\[ N_{10} = \frac{10}{S} \]

B) Rhabdosome shape observation, based on templates (Fig. 37 B). by matching rhabdosome shape and distant stipe angle was matched to the templates given. Several species re-described by Cooper et al., have specified shape model.

C) Mesh character, according to templates (Fig. 37 C, E). The type of meshwork is based on dissepiments system, width, conciseness and extension of stipes.

D) Expansion variability of the rhabdosome (Fig. 37 D).

In addition to the calculations and templates match, species identification was also made by consideration of key features based on literature. Identification made by comparison and detection of morphological characteristics, described by previous researchers as characters for subspecies identification within *Rhabdinopora flabelliformis*. This was done in two ways: by comparing specimen found in Krekling with photos of specimens already identified by Bulman (1970); Cooper et al., (1998); Wang & Servais, (2015); and by comparing with characteristics described by authors.
4.3.3 Statistics

Stipe spacing results was analyzed and plotted in the PAST 3.14 software (Hammer et al., 2001), using linear regression model, with bivariate regression.

4.4 Conodonts

4.4.1 Acid processing of samples

Samples were processed using standard conodont procedures. First samples were placed in 10-15% diluted acetic acid to desintegrate them. Undissolved fractions of 63μm – 500μm were sieved and dried. The fractions over than 63-500μm have been treated by heavy liquid separation, using the heavy liquid diodomethane diluted with acetone, having a density of ±3.00g/ml. The heavy liquid gradually decreased its density to ±2.75g/ml, and the fractions between were washed with acetone, dried, placed in packages for handpicking under the reflected light microscope at NHM.
5 Results

5.1 Graptolites

5.1.1 Previous work

The Krekling locality is a classical section of the Cambrian-Ordovician boundary in Norway, but the boundary interval there has not been studied in detail before. There are several research about Cambrian section, but the border transitional levels and especially the *Rhabdinopora flabelliformis* succession studied in this thesis has no previous scientific description.

The research at Krekling started with the work of Brøgger (1879). Author described Cambrian succession and provided a detailed biostratigraphy, mostly consisting the trilobite fauna within the Alum Shale Formation. In Brøgger's scheme (Fig. 49a), the range of *Rhabdinopora* generally defines the stratigraphic unit ("Etage") called 2e ("Dictyonema Shale"), but it has no further elaboration.

![Figure 49a](image)

*Figure 49a.* The part of Brøgger's profile at Krekling locality, with “diktyonemaskifer”-“Dictyonema Shale” and stratigraphic units “etage” (from: Brøgger, 1879).

Henningsmoen in his unpublished logs from Krekling (1947), kept at NHM in Oslo, mentioned the genus “Dictyonema”, without differentiation between species.
5.1.2 Stipe spacing

Stipe spacing values, measured as a width of the mature Rhabdinopora rhabdosome, divided by number of stipes minus one (S) and number of stipes for 10 mm (N10), as reported by Cooper et al. (1998), are shown in Table 1. The dependance of Rhabdinopora stipe spacing value on stratigraphic position in the Krekling profile is presented in a diagram in Figure 50.

<table>
<thead>
<tr>
<th>Profile (m)</th>
<th>S- Stipe spacing (mm)</th>
<th>N10-Stipe spacing (stipes/10mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72.50</td>
<td>0.84</td>
<td>11.9</td>
</tr>
<tr>
<td>73.05</td>
<td>1.11</td>
<td>9.0</td>
</tr>
<tr>
<td>73.10</td>
<td>1.23</td>
<td>8.1</td>
</tr>
<tr>
<td>73.15</td>
<td>1.22</td>
<td>8.1</td>
</tr>
<tr>
<td>73.20</td>
<td>1.02</td>
<td>9.8</td>
</tr>
<tr>
<td>73.30</td>
<td>1.35</td>
<td>7.4</td>
</tr>
<tr>
<td>73.40</td>
<td>0.87</td>
<td>11.4</td>
</tr>
<tr>
<td>73.45</td>
<td>1.14</td>
<td>8.7</td>
</tr>
<tr>
<td>73.70</td>
<td>0.97</td>
<td>10.3</td>
</tr>
<tr>
<td>73.80</td>
<td>1.06</td>
<td>9.4</td>
</tr>
<tr>
<td>73.85</td>
<td>1.38</td>
<td>9.2</td>
</tr>
<tr>
<td>73.90</td>
<td>1.01</td>
<td>9.9</td>
</tr>
<tr>
<td>74.00</td>
<td>0.92</td>
<td>10.8</td>
</tr>
<tr>
<td>74.05</td>
<td>0.97</td>
<td>10.3</td>
</tr>
<tr>
<td>74.10</td>
<td>0.70</td>
<td>14.2</td>
</tr>
<tr>
<td>74.20</td>
<td>0.99</td>
<td>10.1</td>
</tr>
<tr>
<td>74.25 A</td>
<td>1.48</td>
<td>6.7</td>
</tr>
<tr>
<td>74.25 B</td>
<td>1.18</td>
<td>8.4</td>
</tr>
<tr>
<td>74.30 A</td>
<td>1.13</td>
<td>8.8</td>
</tr>
<tr>
<td>74.30 B</td>
<td>1.18</td>
<td>8.4</td>
</tr>
<tr>
<td>74.40</td>
<td>0.93</td>
<td>10.6</td>
</tr>
<tr>
<td>74.65</td>
<td>1.22</td>
<td>8.2</td>
</tr>
<tr>
<td>74.80</td>
<td>1.61</td>
<td>6.2</td>
</tr>
<tr>
<td>74.90 A</td>
<td>1.01</td>
<td>9.9</td>
</tr>
<tr>
<td>74.90 B</td>
<td>0.82</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Table 1. Stipe spacing values in the Rhabdinopora succession in Krekling, measured as “S” and “N10”.

Stipe spacing (N10) through the Rhabdinopora succession at Krekling shows values from 6.2 to 14.9 mm per 10 mm. The data show no visible trend in stipe spacing (Fig. 50), values are
very variable throughout the interval. Between adjacent bedding planes there is very little correlation, indicating lack of pattern, in contrast to Cooper et al., (1998).

**Figure 50.** Dependence of stipe spacing (mm) on stratigraphic position (m) in the Rhabdinopora flabelliformis interval from Krekling.

### 5.1.3 Statistics

Linear regression model is shown in Figure 51. The model does not report a relevant trend. Based on correlation coefficient and the associated p value, there is no significant correlation between stratigraphic level and stipe spacing (R2 = 0.01, p = 0.63), where 2 in R2 is in superscript, and R is squared.

**Figure 51.** Linear regression model of profile (m)-stipe spacing (mm).
5.1.4 Species identification

5.1.4.1 *Rhabdinopora flabelliformis socialis*

Specimens from levels: 72.5 m (Fig. 52 A) and 73.4 m (Fig. 52 B) have been identified as *Rhabdinopora flabelliformis socialis*. The identification has been done based on stipe spacing value N10 and structure of dissepiments. The stipe spacing value for *Rhabdinopora flabelliformis socialis* according to Cooper et al. is 11-13 mm per 10 mm, and therefore is the largest value of stipe spacing among *Rhabdnopora flabelliformis* subspecies, for stipes meaning also the highest stipe density. Stipe spacing for the specimens from Krekling are accordingly 11.9 and 11.4 mm, the largest values within measured specimens. Structure of dissepiments is also dense, which confirms the identification, according to Cooper et al., (1998).

![Figure 52. A) Rhabdinopora flabelliformis socialis, 72.5 m, Krekling. PMO 226.889 B) Rhabdinopora flabelliformis socialis, 73.4 m, Krekling PMO 226.894](image)

5.1.4.2 *Rhabdinopora flabelliformis norvegica*

Specimens from levels: 73.3 m (Fig. 53 A), 73.2 m (Fig. 53 B), and 73.1 m (Fig. 54) have been identified as *Rhabdinopora flabelliformis norvegica*. Identification has been done based on dissepiments character and stipe spacing value. According to Cooper et al., Wang & Servais, 2015, dissepiments appearance is the most distinctive feature for *Rhabdinopora flabelliformis norvegica*. Their dissepiments form explicit “balconies”, with thick stipes and dissepiments forming round holes as reduced spaces between them. A second distinguishing feature is the stipe spacing value, is 9-12 mm in 10 mm, with average 10.9 mm in Slemmestad. Measured specimens from Krekling have: (73.3 m)-9.9 mm (73.2 m)-9.8mm (73.1 m)-9.1 mm. The range of stipe spacing values together with clearly visible dissepiments structure confirm affiliation of these specimens to *R.f. norvegica.*
Figure 53. A) *Rhabdinopora flabelliformis norvegica*, 73.1 m, Krekling, PMO 226.891. B) *Rhabdinopora flabelliformis norvegica* 73.2 m, Krekling, PMO 226.892.

Figure 54. *Rhabdinopora flabelliformis norvegica*, 73.3 m, Krekling, PMO 226.893.
5.1.4.3 *Rhabdinopora flabelliformis parabola*

Specimens from intervals: 73.90 m (Fig. 55A) and 73.80 m (Fig. 55B), have been identified as *Rhabdinopora flabelliformis parabola*. The identification was based on stipe spacing values, rhabdosome shape templates and mesh character. Stipe spacing for this subspecies is 8 to 11 in 10 mm, average 9.92 mm, according to Cooper et al., 1998. Stipe spacing values measured among collected specimens is for 73.90 m - 9.9mm, and for 73.80 – 9.43 mm, those values correspond perfectly with base average spacing, given by Cooper et al.

An important part of the identification was matching each rhabdosome shape with templates provided by Cooper et al. First step was to mark the rhabdosome shape by red colour, highlighting along external stipes (Fig. 56A), then fitting to the proper shape model (Fig. 56B,C). Specimen from 73.90 m level, fits with template 4A. Second specimen (73.80 m) is a fragment of bigger rhabdosome, was unable to check rhabdosome shape template, therefore was identified based on stipe spacing and mesh type.

Typical meshwork for this subspecies is rather irregular with frequent dissepiments, slender and straight, perpendicular to stipes. The specimens from 73.90 m and 73.80 m fit to this description.

![Figure 55](image)

**Figure 55.** A) *Rhabdinopora flabelliformis parabola* 73.90 m, Krekling, PMO 226.899. B) *Rhabdinopora flabelliformis parabola* 73.80 m, Krekling, PMO 226.897.
Figure 56. Rhabdosome shape match procedure, specimen from 73.90 m, Krekling, PMO 226.899
A) Highlighting external stipes with red colour B) comparison of the specimen’s contour with rhabdosome shape templates C) Direct comparison of rhabdosome shape by superposition of specimen’s contour on the template.
5.1.4.4 *Rhabdinopora flabelliformis canadensis*

Specimens from levels: 74.30 (B) m (Fig. 57A) and 74.65 m (Fig. 57B), have been identified as *Rhabdinopora flabelliformis canadensis*. According to Cooper’s work, this subspecies has stipes spacing 7.5 to 10.2 in 10 mm, average 8.82 in the Nearens succession. Specimens from Krekling represent 8.4 and 8.2 mm in 10 mm, very close to Nearens average.

Second main distinctive feature was rhabdosome shape match, based on previous researchers it should be type 4A (Fig. 39 B). Shape matching was been done following the same procedure (Cooper, 1998) with specimens of *Rhabdinopora flabelliformis parabola*. Both rhabdosome, from 74.30 (B) m and 74.65 m match the type 4 A (Fig. 58 A,B,C) and (Fig. 59 A,B,C).

*Figure 57.* A) *Rhabdinopora flabelliformis canadensis*, 74.30 (B) m, Krekling, PMO 226.906
B) *Rhabdinopora flabelliformis canadensis*, 74.65 m, Krekling, PMO 226.909.
Figure 58. Rhabdosome shape match procedure, specimen from 74.30 m, Krekling, PMO 226.906
A) Highlighting external stipes with red colour B) comparison of the specimen’s contour with rhabdosome shape templates C) Direct comparison of rhabdosome shape by superposition of the specimen’s contour on the template.
Figure 59. Rhabdosome shape match procedure, specimen from 74.65 m, Krekling, PMO 226.909
A) Highlighting external stipes with red colour B) comparison of the specimen’s contour with rhabdosome shape templates C) Direct comparison of rhabdosome shape by superposition of the specimen’s contour on the template.
5.1.4.5 Rhabdinopora flabelliformis flabelliformis

The specimen from level 74.90 m (Fig. 60), has been identified as *Rhabdinopora flabelliformis flabelliformis*. The identification process was based on stipe spacing values, rhabdosome and dissepiments character. Cooper et al., (1998) reported stipe spacing in Norwegian locations as 7 to 9, with average 8 in 10 mm. The specimen from Krekling has value of 7.8 in 10 mm. Rhabdosome of *Rhabdinopora flabelliformis flabelliformis* according to Cooper, (1998) should be narrow to broad conical, with 6-30 mm length and 4-25 mm width. The specimen from interval of 74.90 m is narrow, with 17 mm length and 11 mm width.

![Image](image1.png)

Figure 60. Rhabdinopora flabelliformis flabelliformis, 74.90 m, Krekling, PMO 226.912

5.1.4.6 Unidentified specimens

The rest of collected specimens have not been identified, although photos of them are presented below. All of these unidentified material consists of broken parts of specimens, being problematic to assign into one of the *Rhabdinopora flabelliformis* subspecies groups. Their stipe spacing values do not represent enough distinctive features for systematic classification, without other auxiliary characteristics which could be recognized, e.g. special type of dissepiments, exceptional meshwork, of the character of a larger part of the rhabdosome.
**Figure 61.** *Rhabdinopora flabelliformis* Krekling: A) 73.05 m PMO 226.890 B) 73.45 m PMO 226.895

**Figure 62.** *Rhabdinopora flabelliformis*, Krekling: A) 73.70 m PMO 226.896 B) 73.85 m PMO 226.898

**Figure 63.** *Rhabdinopora flabelliformis*, Krekling: A) 74.0 PMO 226.900 B) 74.05 m PMO 226.901
**Figure 64.** *Rhabdinopora flabelliformis*, Krekling: A) 74.10 PMO 226.902 B) 74.20 m PMO 226.903

**Figure 65.** *Rhabdinopora flabelliformis*, Krekling: A) 74.40 PMO 226.907 B) 74.60 (B) m PMO 226.908

**Figure 66.** *Rhabdinopora flabelliformis*, Krekling: A) 74.80 PMO 226.910 B) 74.90 (A) m PMO 226.911
5.2 Conodonts

During the handpicking process, unfortunately only a few broken parts of conodont elements was found, which could not be identified and used for biostratigraphy.

5.3 Biostratigraphy

Biostratigraphy of the Cambrian-Ordovician boundary in Krekling, based on graptolites and trilobites is shown in Figure 68. Stratigraphic ranges chart includes the last reported trilobite from Upper Cambrian in Krekling locality, *Peltura scarabaeoides* (66.7 m) found by Oyvind Hammer and Henrik Svensen during earlier field research, and the first marking fossils from Lower Ordovician. Succession of graptolite *Rhabdinopora flabelliformis* and its several subspecies, occur from 72.5 m, being the marker of Tremadocian as well as basal trilobite *Boeckaspis hirsuta*, from 72.80 m.
Stratigraphic ranges of *Rhabdinopora flabelliformis* subspecies differs from models proposed before by Cooper et al. (1998); Cooper (1999); Wang and Servais (2015). In this case, biozonation described in previous work is difficult to apply for Krekling’s succession.

<table>
<thead>
<tr>
<th>Section 1</th>
<th>Stratigraphical ranges</th>
<th>Zone, stage, series</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boeckiastrum hirsuta</td>
<td>A. matanensis</td>
</tr>
<tr>
<td></td>
<td>R.f. socialis</td>
<td>Tremadocian</td>
</tr>
<tr>
<td></td>
<td>R.f. norvegica</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R.f. parabola</td>
<td>Lower Ordovician</td>
</tr>
<tr>
<td></td>
<td>R.f. flabelliformis</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 68.** Biostratigraphy of the Cambrian-Ordovician boundary in Krekling, Norway, correlated with lithological log and geochronological units.

The stratigraphic appearance of the *Rhabdinopora flabelliformis* subspecies come out in a changed order than in the composite range model by Cooper (1999) (Fig. 37) making it difficult to place them into the *Rhabdinopora flabelliformis parabola* zone, where *R.f. parabola* is considered to be the lowermost marker, and into the *Anisograptus matanensis*
zone, where certain marker is *Anisograptus matanensis* and other graptolites are auxiliary to estimate the base of the biozone, like *R.f. norvegica* and *R.f. flabelliformis*.

From material collected in Krekling, *Rhabdinopora flabelliformis socialis* first occurrence (FO) is below the FO of *Rhabdinopora flabelliformis parabola*. According to Cooper’s model (1999) this should be reversed, with *Rhabdinopora flabelliformis socialis* first appearing close to the last occurrence of *Rhabdinopora flabelliformis parabola*.

The same opposite situation is noticed in the *Anisograptus Matanensis* zone, where according to Cooper’s (1999) sequence, *Rhabdinopora flabelliformis norvegica* has FO, above the FO of *Rhabdinopora flabelliformis parabola* while in the Krekling’s material *Rhabdinopora flabelliformis norvegica* has its entire observed range below the FO of *Rhabdinopora flabelliformis parabola*.

Cooper (1999) suggested also an evolutionary transition with a sequence of the following taxa from bottom to top (Fig. 38) of *R. preaparabola* – *R.f. parabola* – *R.f. canadensis* – *R.f. flabelliformis* – *R.f. anglica* – *R.f. bryograptides* in slope environments. Ecological space transitions are from *R.f. canadensis* to *R.f. socialis* to *R.f. norvegica*.

In the *Rhabdinopora* succession at Krekling, the evolutionary order appears to be: *R.f. parabola* – *R.f. canadensis* – *R.f. flabelliformis*, which is in accordance to the Cooper’s model, but ecological shift is different and disruptive to this model, *R.f. socialis* to *R.f. norvegica* should appear in upper intervals, to match the proposed scheme.

According to Cooper (1999), specimens occurring within adjacent bedding planes should be either transients or forms in continuous morphologic series. Based on stipe spacing values, which show no visible trend, confirmed by graptolites subspecies identification showing their different order, it can be found that the succession at Krekling’s does not fit this model and calls into question previously proposed biozonations.

5.4 **The Cambrian-Ordovician boundary at Krekling**

At the Krekling locality there is an almost continuous Middle Cambrian to Lower Ordovician succession within the Alum Shale Formation. Precise definition of the Cambrian-Ordovician boundary in this case is difficult, and should be based on biostratigraphy and geochemical
data. Previous research of the Cambrian-Ordovician boundary in Scandinavia is also of high importance.

Correlating with the work of Schovsbo (2001), and with geochemical data obtained by Oyvind Hammer and Henrik Svensen and taxon ranges within the Cambrian-Ordovician transitional levels, the boundary can be estimated to lie slightly below first occurrence of graptolites *Rhabdinopora flabelliformis*, trilobite *Boeckaspis hirsuta* and a significant increase in vanadium. Correlation and boundary estimation is shown in Figure 70.

*Rhabdinopora flabelliformis*, is considered to be at lowermost Tremadocian marker, and as trilobite *Boeckaspis hirsuta*, is also at basal Ordovician species (Hammer and Svensen, in preparation)

A Cambrian-Ordovician boundary estimation in Scandinavia is presented by Schovsbo (2001), where a geochemical data together with taxon ranges, reflecting main changes in oxygen levels are described. Correlation of these data series from the Gislovshammar -2 core in Sweden is shown in Figure 71.

Importantly, TOC and vanadium content corresponds with the Krekling data in the Tremadocian. This vanadium peak is an important chemostratigraphical marker for the Tremadocian in Scandinavia (Schovsbo 2001 and references therein). The up-section increase in Mo (Fig. 69) and V can be interpreted as a result of increasingly anoxic conditions.

![Figure 69. XRF values of vanadium and molybdenum concentration at Krekling.](image)

66
Figure 70. Correlation of vanadium content (XRF value), TOC(%), $d^{13}$C(TOC), taxon ranges and graptolite stipe distance, with lithological log and geochronological units, from 65 m – 75 m levels at Krekling.

Figure 71. Profiles in the Gislovshammar-2 drillcore in Scania, Southern Sweden. A) Fossil content B) Total organic carbon C) Total sulphur D) Vanadium concentration E) Nickel concentration.
Biostratigraphy is shown on the right: Trilobite zones in the Cambrian. Tremadoc graptolite assemblages according to Cooper (1999). (From: Schovsbo, 2011)
6 Discussion

The results of this study are not in accordance with previous models, of the stratigraphical order and ecological distribution pattern of *Rhabdinopora flabelliformis* in the lower Tremadocian. This chapter gives a discussion of the identification, ecology and biostratigraphy of *Rhabdinopora flabelliformis*.

6.1 Species identification

Identification of *Rhabdinopora flabelliformis* subspecies was here only attempted when more than one differentiating character was available for a specimen. An exception to this rule was made for *Rhabdinopora flabelliformis norvegica*, having very characteristic dissepiments, that can be identified well even on broken specimens. In other cases one character (mainly stipe number) was insufficient to proceed with the identification process and to include the specimen in the biostratigraphy. Stipe number can be measured in every specimen that has at least a fragment of probably mature part of rhabdosome, but these values are sometimes similar among *Rhabdinopora flabelliformis* subspecies which can therefore be precisely distinguished only by consideration of additional characteristics. Therefore, incomplete preservation of the whole or at least a major part of the rhabdosome makes identification very difficult. It is therefore very important for stratigraphy that, the nearly lowermost and uppermost specimens are preserved as complete specimens, which allows their designation.

Considering that several discrepancies from previous work (e.g. Cooper 1998) have been found, what is the likelihood of wrong subspecies identification? There are two possibilities: Exchange of samples in labelled bags or inadequate identification. The first possibility can be undoubtedly excluded, because from each collected slab, a sample for geochemical analysis was also cut. The geochemical curves from Krekling are almost the same as from the Cambrian-Ordovician transition from Sweden in the, Gislovshammar-2 core, presented in Figure 71. I tried to avoid the second possibility of mistake by identifying only specimens with many distinctive features, as described in a previous paragraph. Moreover, each measurement was double-checked.

The significant issue is the systematic paleontology of *Rhabdinopora flabelliformis*. Taking into consideration identification methods proposed by previous researchers, and evaluating morphological appearance of subspecies, it should be possible to discuss which subspecies are
most distinct as individual subspecies, and which can be considered variations within one taxon. One subspecies—\textit{Rhabdinopora flabelliformis norvegica}, has a truly unique morphology, with characteristic dissepiments which allow identification from small, broken specimens. All the other \textit{Rhabdinopora flabelliformis} subspecies differ from each other by features which are very similar and present continuous ranges of variability: density of stipes, rhabdosome shape patterns, more narrow or broad rhabdosome, its length and meshwork type. The last one is particularly confusing, because of huge variety of mesh types and often very poor preservation of dissepiments, it is hard to define if dissepiments within one specimen do not follow the accepted model or they are just not well preserved.

It is of interest, that previous researchers admit the vast diversity of \textit{Rhabdinopora flabelliformis} forms (e.g. Bulman 1954, Erdtmann 1982, Cooper et al. 1998), and at the same time appoint subspecies within this group, where only one of the characters could be considered as really distinctive and division of the rest may be over-interpretation.

6.2 Biostratigraphy

The biostratigraphic ranges of the \textit{Rhabdinopora flabelliformis} from Krekling do not match ranges reported in the composite correlation of many Tremadocian successions worldwide by Cooper (1999). What kind of interpretation should be proposed for this phenomenon? It is remarkable that adjacent bedding planes do not contain morphologically continuous material, there is no visible pattern. Previous research suggests the opposite, but it needs to be mentioned that several subspecies have relatively short ranges at Krekling.

Presumably, the stratigraphical order of \textit{Rhabdinopora flabelliformis} subspecies is partly distorted by the quite limited number of specimens collected. The true ranges at Krekling are most likely longer than shown in our range chart. Some of the previous extensive research, as described by Cooper et al. (1999) has been done using a large number of specimens and mostly complete rhabdosomes.

A possible explanation for the order of subspecies at Krekling, may be undiscovered occurrence of specimens below the lowest found (72.50 m). If there is a \textit{R.f. parabola} further down, and its range could be continued down the section, then the whole range chart would change its appearance, because the occurrence of \textit{R.f. socialis} in the lowest part of the succession and \textit{R.f. parabola} in the middle are the most disruptive considering previously
published range orders. Further down, unfortunately no specimens have been found. It is important to mention here that the, sampling profile is located within a stream section, which is not accessible for every meter. Down-section is a carbonate bed and covered, stream banks.

It should be also mentioned that *Rhabdinopora flabelliformis* subspecies do not occur in exactly the same ranges in every locality (Cooper, 1999). In several localities, subspecies occur only locally. *R.f. norvegica* in the Baltic regions is abundant within the top of the Anisograpsaptus matanensis zone as a local replacement of *R.f. flabelliformis*, which in turn does not occur in the same range everywhere, as can be seen on Figure 38, some ranges are marked with stippled lines. Therefore, Krekling may represent just an extension of the geographical variation, in local ranges order. The lack of previous biostratigraphical work from Krekling’s *Rhabdinopora* succession makes this explanation uncertain however.

Still, the succession at Krekling constitutes a remarkable point of interest for re-investigating the sequence of *Rhabdinopora flabelliformis* in the lower Tremadocian. Further research should be conducted, including quantitative stratigraphy methods.
7 Conclusions

The research described in this thesis confirms a very large variety of the *Rhabdinopora flabelliformis*. Stipe spacing values measured in specimens indicate no significant trend. Differences between the specimens within adjacent beds are meaningful, confirming lack of pattern in the *Rhabdinopora flabelliformis* succession at Krekling.

Based on stipe spacing values and other distinctive features, subspecies in the *Rhabdinopora flabelliformis* have been identified. Biostratigraphy of the Cambrian-Ordovician interval has been made accordingly. The biostratigraphic ranges of the graptolites do not match previously reported correlation (Cooper et al., 1998) from early Tremadocian.

The Cambrian-Ordovician boundary has been estimated to lie slightly below the first occurrence of trilobite *Boeckaspis hirsuta*, graptolites *Rhabdinopora flabelliformis*, within significant increase of vanadium content.

**Further research**

Biostratigraphical framework of the Cambrian-Ordovician boundary at Krekling has not been made before and results of this work call into question previous biozonations. Therefore further research should be conducted to re-investigate *Rhabdinopora flabelliformis* succession at Krekling, quantitative stratigraphy methods should be included, to compare ranges at Krekling to other successions correlated.
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University of Leicester, http://www.le.ac.uk


World Fossil Society http://worldfossilsoociety.org
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