The Ordovician Orthoceratite Limestone and the Blommiga Bladet hardground complex at Horns Udde, Öland

Magnus Eriksson

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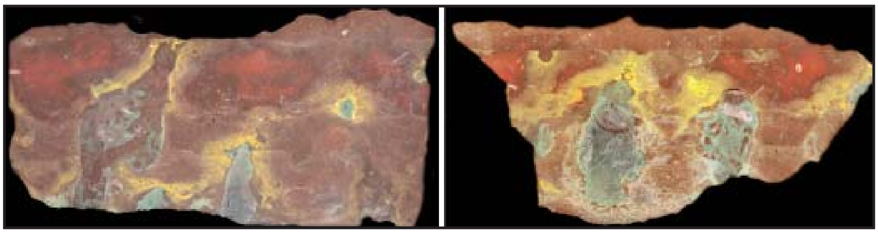

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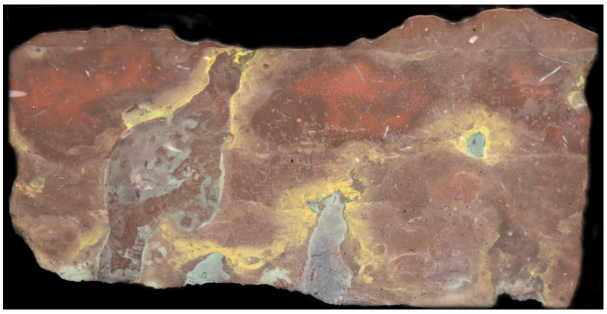
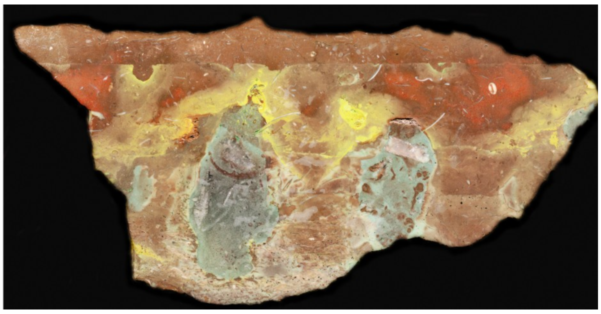

Bachelor Thesis

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Cover Picture: Polished slabs showing the Blommiga Bladet hardground complex from Horns Udde, Öland.

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MAGNUS ERIKSSON

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Abstract: Blommiga Bladet, Flowery Sheet in English, is an Early Ordovician (basal Dapingian) hardground complex in the lowermost part of the Orthoceratite Limestone in southern Sweden. It formed in an epicontinental sea, across Baltoscandia and has been described also from Russia as “Steklo”, from Estonia as “Pustakkith” and from deep borings in Poland, thus covering an area exceeding 500,000 km². The Orthoceratite Limestone spans the Floian, Dapingian and Darriwilian stages and records an extremely low net sedimentation rate (2mm/ka). Recurrent periods of non-deposition allowed hardgrounds to form. These hardgrounds are numerous and probably represents a significant portion of time in the Orthoceratite Limestone. The *Blommiga Bladet hardground complex* displays distinct, clear-cut and abraded hardground surfaces that slowly have been polished by calcareous particles swept across the sea-floor by currents or waves, as well as a few more irregular omission surfaces that may represent firmgrounds. The uppermost hardground surface was colonized by a borer belonging to the ichnospecies *Gastrochaenolites oelandicus*. *G. oelandicus* borings cut trough indurated sediments and earlier omission surfaces, creating a sac-like pit with a small aperture. Blommiga Bladet was mineralized by several ferruginous compounds in the early diagenesis, making it skimmer in red, green and yellow. The cavities were subsequently filled with sediment. In the Early and Middle Ordovician, Baltoscandia was mainly affected by eustasy and Blommiga Bladet probably formed during a sea-level low-stand, when the sea-floor regionally was reworked by waves.

Keywords: Orthoceratite Limestone, hardground, Lanna, Volkhov, Dapingian, Gastrochaenolites oelandicus, Blommiga Bladet, sea-level.

Magnus Eriksson, Department of Earth and Ecosystem Sciences, Division of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: nord_50@hotmail.com

Den ordoviciska Ortoceratitkalkstenen och Blommiga Bladet vid Horns Udde, Öland

MAGNUS ERIKSSON

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Sammanfattning: Blommiga Bladet avser en serie hårdbottnar i den lägre delen av den ordoviciska Ortoceratitkalkstenen i mellersta och södra Sverige. De bildades över ett 500,000 km² stort grundhav som täckte nuvarande Sverige, Baltikum och västra Ryssland (Baltoscandia). Blommiga Bladet har blivit beskriven i bl.a. Ryssland som "Steklo", "Pustakkith" i Estland och från djupa borrkärnor i Polen. Ortoceratitkalkstenen avsattes med en extremt låg sedimentationshastighet (2mm/1000 år) under tidsåldrarna Floin, Dapingian och Darriwilian. Frekvent återkommande perioder med sedimentationsavbrott tillät hårdbottnar att bildas. Det finns många sådana hårdbottnar i Ortoceratitkalkstenen och de representerar troligtvis en stor del av avsättningstiden. Blommiga Bladet består av två distinkta, klart markerade och abraderade plana ytor som långsamt blivit polerade av kalkpartiklar som svept fram över ytan genom vågor och strömmar, samt ett fåtal ojämna omissionsytor som möjligen representerar en slags halvhård botten (*firmground*). Den övre abraderade ytan har blivit genomborrad en okänd evertebrat (*Gastrochaenolites oelandicus* ichnoart) som lämnade efter sig säckliknande borrhål. Innan borrhålen fylldes igen, genom deras smala öppningar, mineraliserades troligtvis de olika lagren av diverse järnhaltiga föreningar. Dessa föreningar gav Blommiga Bladet dess intensiva färger som skimrar i klarrött, grönt och gult. Stenbrottsarbetarna ligger bakom dess något fantasifulla namn. Baltoscandia var, under tidig- och mellanordovicium, huvudsakligen påverkat av globala havsnivåförändringar och Blommiga Bladet bildades troligen då havsnivån var så pass låg att havsbottnen regionalt sett var omarbetad av vågor.

Nyckelord: Ortoceratitkalkstenen, hårdbotten, Blommiga Bladet, havsnivå

Magnus Eriksson, Institutionen för Geo– och ekosystemvetenskaper, Enheten för Geologi, Lunds universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: nord_50@hotmail.com

1 Introduction

Blommiga Bladet is an Early Ordovician hardground complex with extensive distribution in Baltoscandia (Lindström 1963, 1979; Dronov et al. 1999; Dronov et al. 2000; Ekdale and Bromley 2001; Bergström & Löfgren 2008). The hardground complex, in English referred to as the "Flowery Sheet" was nicknamed by Swedish quarry workers after its vivid colors, which are related to the mineralizations that took place during the early diagenesis. Blommiga Bladet is part of the ca 50 m (in Sweden) thick Orthoceratite Limestone that formed during the Floian, Dapingian and Darriwilian. The limestone is widely extensive and outcrops in central and southern Sweden as well as in the East Baltic area and western Russia. Similar limestone formed also in China at this time (Bergström & Löfgren 2008). A hardground similar to, and at the same stratigraphic level as Blommiga Bladet have also been described from the St. Petersburg area in Russia, where it is known as "Steklo" (Dronov et al. 1996; 2000; 2002; Dronov & Holmer 1999; Dronov 2005), and from several places in Estonia, where it is named "Pustakkith" (Dronov & Holmer 1999). It is also known from deep borings in Poland (Lindström et al. 2000). Blommiga Bladet, which is the focus of this thesis, is well exposed in the coastal sections at Horns Udde northwest of Löttorp on northern Öland. Another conspicuous hardground at Horns Udde is Blodläget, referred to as "Bloody Layer" in English, which also has a wide distribution (Lindström 1979; Lindström et al. 2000, p. 255; see also Stouge 2004, fig. 7). The Blodläget hardground was named because of its eye-catching dark-red stripe appearing as a thin layer in the Lanna Limestone but this hardground is not further discussed in the text.

The aim of this thesis is to describe and discuss the Ordovician sea floor in Baltoscandia, the Orthoceratite Limestone, hardgrounds in general and to describe Blommiga Bladet in particular. Blommiga Bladet is a remarkable hardground complex and the depositional environment is herein being discussed in view of relative sea-level and global events.

1.1 Methods

This Bachelor thesis is mainly a literature study but also comprises some laboratory practical work and analysis of a few rock samples from the lower Ordovician coastal sections at Horns Udde (57°12'271 16° 55'365). The samples (collected by M. Calner) were cut by a rock saw into smaller pieces. Six samples where polished with very fine-grained corundum into a finished surface so that the hardground, omission surfaces and borings could be studied. The polished slabs were scanned in 600 dpi in order to illustrate the material.

2 Geological setting and stratigraphy

During the Cambrian the Baltic shield separated from Gondwana and rotated rapidly counter clockwise until Early Ordovician. The associated sea-floor spreading resulted in a 1,300 km wide ocean called the Tornquist Ocean (Cocks & Torsvik 2002). The major oceans, especially in today's North Atlantic area, were at their widest at this time (Cocks & Torsvik 2002). The Baltoscandian area was covered by a shallow epicontinental sea – the Baltoscandian basin. This basin was situated at approximately 50º S in the Early Ordovician but continued to move slowly northwards and entered the subtropical region in the Late Ordovician (Cocks & Torsvik 2002; Nielsen 2004; Fig. 1). The Baltoscandian basin shows a clear depth zonation from west to east, with the deepest water deposits in the west and successively more shallow-water deposits towards the east. This general depth and resulting facies zonation is referred to as confacies belts (Jaanusson 1976; Fig. 2). Accordingly, the most striking feature of the lithofacies distribution in Baltoscandia, in the Early Ordovician, is the regional change from the deeper-water, dark to grey Töyen Shale in southern Norway and in some areas in south-western Sweden, to shallow-water carbonate sediments in eastern and south-eastern Sweden, Estonia and western Russia (Bergström & Löfgren 2008). The eastern part of Baltoscandia was described by Dronov et al. (2002) and Dronov (2005) as a shallow-marine, storm dominated environment with deposition of tempestites.

A long-term sea level rise took place from the Cambrian to the early Ordovician, followed by a substantial dip in the Middle Ordovician (the Dapingian to the late Darriwilian) before a greater rise occurred in the early Late Ordovician when sea-level was ca 200 m above the present level (Ross & Ross 1996; Nielsen 2004; Haq & Schutter 2008; Fig. 3), probably the highest level in the last ~500 Ma years.

Globally the Early and Middle Ordovician falls within a climatically warm period, the so-called early Palaeozoic Warm Mode that lasted for about 80 Ma (cf. Frakes et al., 1992). This Greenhouse warming was terminated in early Late Ordovician with the initiation of glaciers starting an Ice house period lasting for ca 30-35 Ma, the Early Palaeozoic Icehouse (Page et al., 2007). It is notable that Lindström (1963) reported glacially fractured sand grains from the lower Ordovician of Sweden but never in any larger numbers. He argues that it is not unlikely that Baltoscandia was invaded by drift ice that carried sand populations with glacial markings (Lindström 1984). Mean annual temperatures seem to have been near 8º C, which is quite similar to modern day temperature at the same latitude.

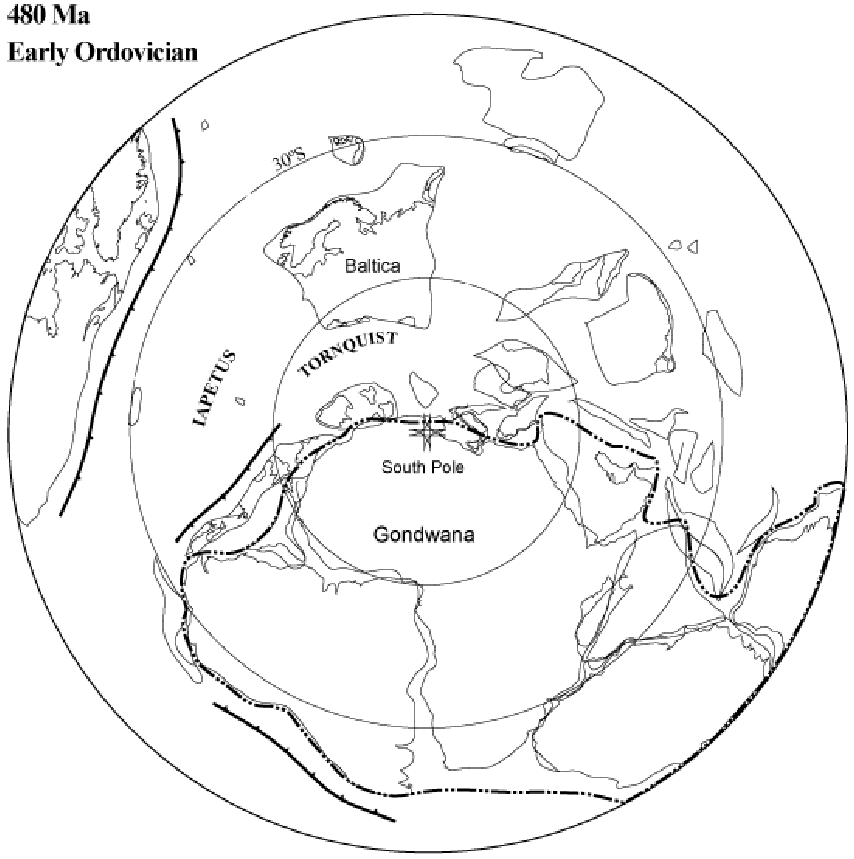

Fig. 1. The Earth's southern Hemisphere at 480 Ma, reconstructed by Cocks & Torsvik (2002). Baltica was moving towards the north at the same time it was slowly rotating counter clockwise.

At Horns Udde, Northwest of Öland, Orthoceratite Limestone of Dapingian age is exposed in a several metres high section along the coastline. The section includes the Latorp and Lanna topoformations. Blommiga Bladet is exposed some three metres up in the section (Figs. 4, 6).

3 Orthoceratite Limestone

The Orthoceratite Limestone represents a stratigraphically condensed sequence that today is typically less than 50 m thick despite its broad geographic distribution (Lindström 1979; Ekdale & Bromley 2001). In addition to central Sweden and Öland a similarly condensed section of limestone can be found in e.g. Russia, Estonia (along the Baltic-Ladoga Klint) and in China (Bergström & Löfgren 2008). It formed in a vast epicontinental sea that, in the Ordovician, covered Baltoscandia (Bergström et al., 2009). The name is a regional term for often reddish, highly condensed limestone with spectacular preservation of large orthocone nautiloids and endoceratoids, which are often filled with white sparry calcite (Ekdale & Bromley 2001). The lower portions of the Orthoceratite Limestone are subdivided into the Latorp, Lanna and Holen limestones, which are topoformations. The net sedimentation rates for the Orthoceratite Limestone were very low and average 2 mm/ka (Schmitz et al. 1996; Dronov & Holmer 1999). The rock is generally very fine-grained and consists mostly of wackestone, with some subordinate pack-grainstone, typically with the dominating skeletal fragments from trilobites and ostracods (Jaanusson 1972; Jaanusson & Mutvei 1982). The general colour is gray, brownish or red with rising oxygenation of the sediments. The average production of organic material was low, resulting in an oxidation of the sediments making it red. Some 10% of the limestone is considered to be clastic particles in the clay to silt fraction. These materials generally derive from cosmic or volcanic dust or from sandstorms from very distant continents (Lindström 1963). It is generally agreed, by many authors, that the composition of the Orthoceratite Limestone reflects cool-water marine carbonate deposition. This is primarily because of the lack of skeletal fragments typical for tropical conditions, e.g. pelletal and oolitic sediments or coral- stromatoporoid reefs (cf. James 1997; Tinn et al., 2006). There is a discussion, however, regarding at what depth the sediments were deposited. Lindström (1963, 1979, 1984) are arguing for deeper depositional conditions, up to several hundred meters. On the other hand, some authors (e.g. Jaanusson 1982) argue for deposition in a more shallow environment within the photic zone (~200 m). Based on ostracodes, Tinn & Meidla (2001) suggest that the sea-floor could have been in the upper part of the aphotic zone during upper Floian to middle Darrwilian, i.e. at a considerable depth.

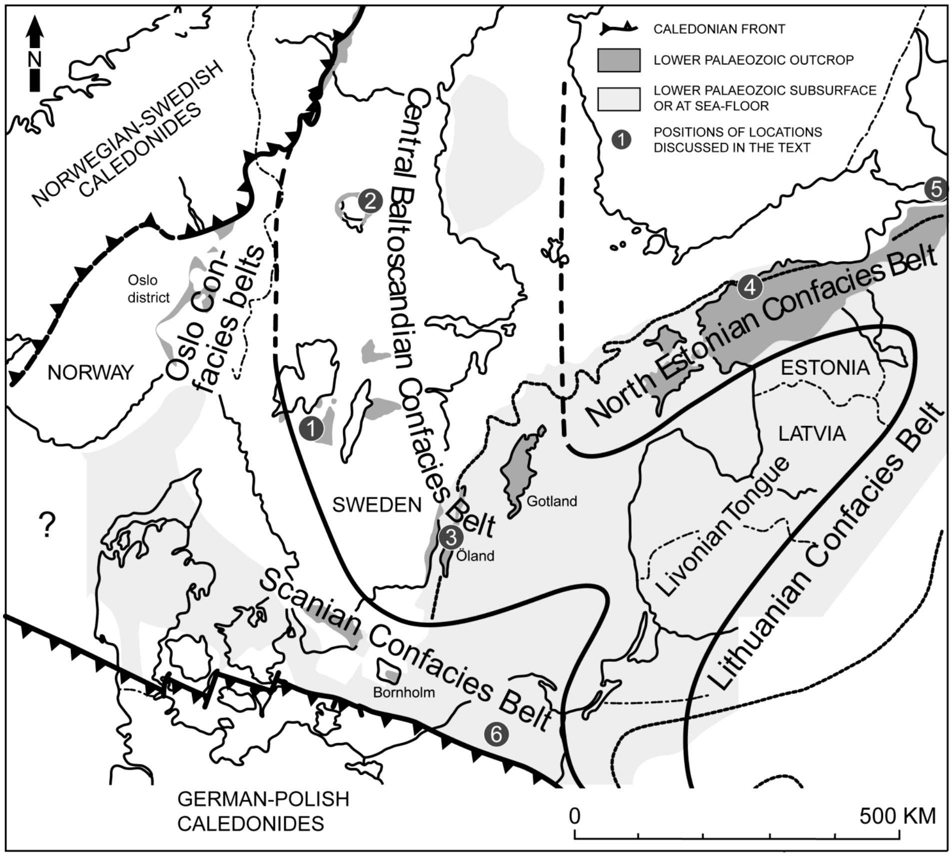

Fig. 2. The confacies belts with known occurrences of the *Blommiga Bladet hardground complex*. 1: Hällekis, and Bjällum in Västergötland. 2: Sjurberg in Dalarna. 3: Horns Udde on Öland. 4-5: The Baltic-Ladoga Klint in northwest Estonia and the St. Petersburg region. 6: Northern Poland. Modified from Stouge (2004).

Small-scale discontinuity surfaces in the form of hardgrounds are a striking feature of the Orthoceratite Limestone. These may vary in colour, shape and amplitude but are fairly constant and may continue over larger areas (Lindström 1979; Dronov & Holmer 1999; Ekdale & Bromley 2001; Bergström & Löfgren 2008). They are usually separated by only a few centimetres to maximum one or two decimetres of sediments. Lindström (1979) concludes that it is probable that the hardgrounds represents the major portion of the total time span involved in the Orthoceratite Limestone. Hardgrounds in general are being described below.

4 Hardgrounds

A hardground is defined as a discontinuity surface of synsedimentary litfication, i.e. a sea-floor that became lithified before the overlaying sediment was deposited (Tucker & Wright 1990; Flügel 2004). They come into existence as a combination of non-deposition or low sedimentation rates, and early lithification. For this reason, they are most common in relatively condensed sedimentary successions. The main controls on condensed sections are: mechanical concentration, chemical concentration, and biological concentration (Flügel, 2004). Mechanical concentration is achieved by filtering (sieving), screening, bypassing or scouring of sediment. Chemical condensation can be caused by either dissolution below the carbonate compensation depth (CCD) or relative sea-level fluctuations and a combination of erosion and bioersion of different lithified substrates. Condensation through biological concentration is caused by bioerosion on hardgrounds. Hardgrounds are most easily identified where they were exposed and exhumed on the sea-floor. The development of hardgrounds was particularly abundant in the Middle and Late Ordovician and in the Jurassic and Late Cretaceous (Flügel 2004). The shape and form of hardgrounds shows little change during the Palaeozoic. As a comparison of middle Palaeozoic hardgrounds the Mesozoic communities differ strongly. The general diversity and composition of the modern hardgrounds was established in the Jurassic.

Hardground surfaces are generally recognized as of two types (Tucker 2001): *abraded hardground* and *corrosional hardground*. Abraded hardgrounds can be identified as smooth, clear-cut bedding planes, where erosion by lime-sand moving over the surfaces took place. They are commonly formed in shallow subtidal sediments where energy level is high and enables oolitic and skeletal sands to move across (semi)lithified sediment to create a planar, sometimes even polished erosional surface. These surfaces may be stronger bioturbated and irregular where more gentle erosion took place and could be subject to some corrosion and dissolution or mineralization. Second type is a corrosional hardground surface that has an irregular, angular surface formed by dissolution. These hardground surfaces are commonly found in pelagic limestones

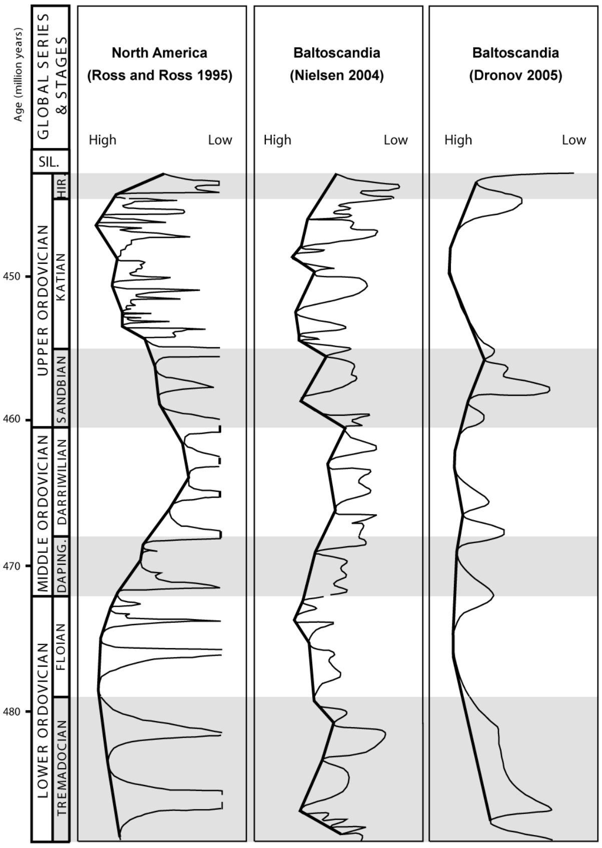

Fig. 3 Regional sea-level curves for the Ordovician. Note the relatively low sea-level in the middle Ordovician. Modified from Munnecke et al. (2010).

and are related to periods of non-sedimentation which allow sea-floor cementation and dissolution. A longer-lasting stability of the sediment-water interface is a basic requirement for all hardground formation and is best developed in areas of slow sedimentation and high current activity, where precipitation of iron-hydroxides (goethite-limonite), phosphorite and glauconite are common (Tucker &Wright 1990). Repeated erosion can be identified in some hardground surfaces by truncated borings (Tucker & Wright 1990). Intraclasts are commonly associated with hardgrounds, which may themselves be encrusted and bored. Hardgrounds are common in, but not restricted to, deeper-marine settings.

Hardgrounds may be exposed by currents and storms and thereby bored and encrusted. Common encrusters of hardgrounds are oysters, serpulids, crinoids, sponges, calcareous algae and corals. Hardground borings originate from polychaete worms (such as the simple borings of *Trypanites* and *Polydora*), sponges, lithophagid bivalves and endolithic algae (Tucker & Wright 1990). The oldest hardground macroborings in the world are *Trypanites* from the lower Cambrian. No other Cambrian macroboring has been described from anywhere in the world (Ekdale & Bromley 2001). The next oldest macroborings are Early Ordovician in age. The relatively complex ichnofabrics of the Orthoceratite Limestone indicate that the sea-floor substrate was changing from soft-ground to firmground to hardground from one place to another (Ekdale & Bromley 1995; Bromley & Ekdale and Bromley 2001).

Hardgrounds also occur in the marginal marine to terrestrial environment. The so called tropical lateritic hardpans can be found in terrestrial onshore and estuarine zone throughout supra and intertidal environments and various marine regions (Flügel 2004).

4.1 The formation and development of hardgrounds

Submarine hardgounds mark a hiatus in deposition and can be regarded as omission or condensation surfaces. Flügel (2004) listed processes which might trigger non-deposition and the formations of hardgrounds as follows:

- a break of carbonate mud input through emergence or drowning of supplying platforms
- extreme carbonate and silica dissolution at the sea-floor
- irregular scouring events at the ocean floor caused by changing of the bottom currents
- nutrient depletion

Flügel (2004) also describes two types of hardground formation. These are long-lived, which requires major changes in environmental conditions, and short-lived that form over shorter time-scales

Long-lived:

- shallowing, caused by eustatic drop or tectonic uplift or filling of shallow-water basins, to the point that seawater circulation becomes too restricted for important biogenic carbonate production.
- sea level rise or tectonic subsidence or deepening beyond the phototrophic zone or
- major increase in salinity due to barriers

Short-lived:

- sediment distribution patterns changed by local factors
- climatic changes affecting the frequency and travel pattern of storms. Firmgound can be the source of lithoclast dominating in the subtidal sediments.

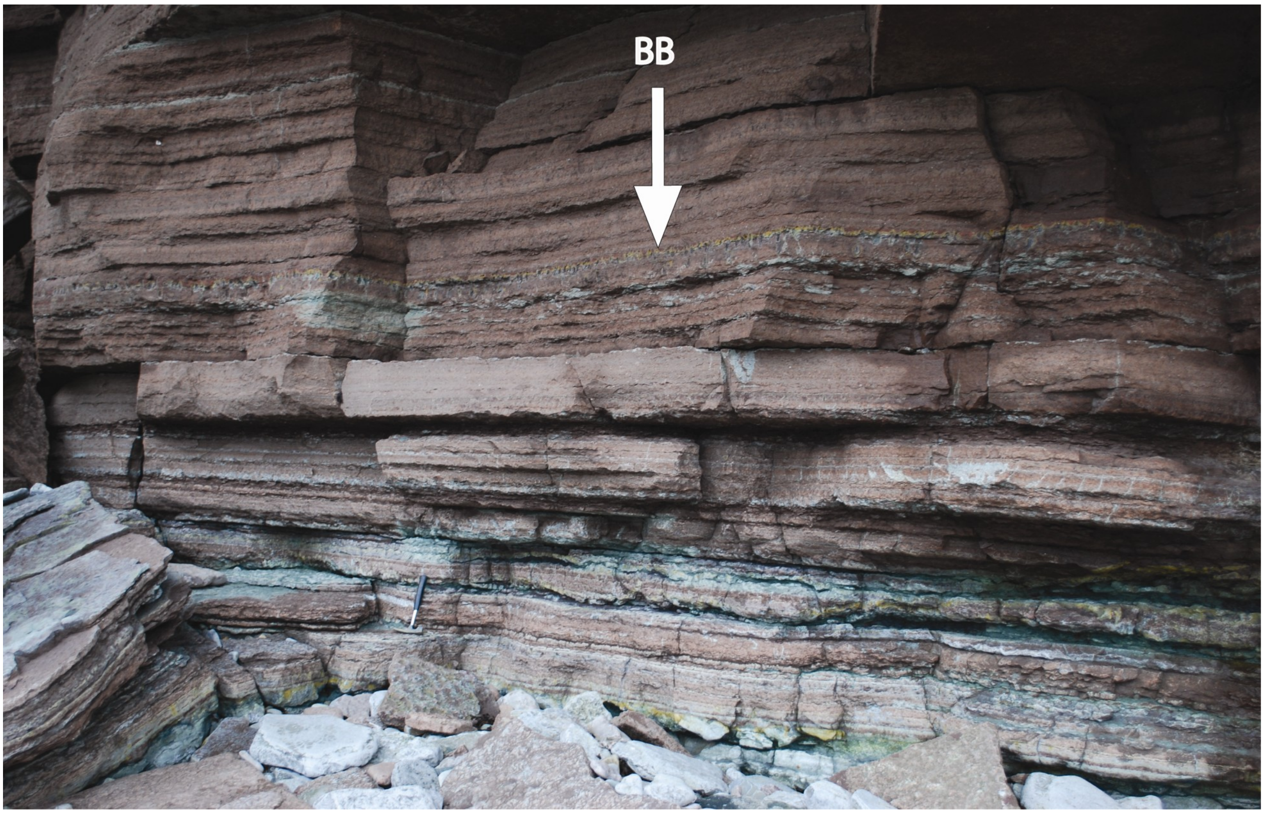

Fig. 4. The sampled coastal section at Horns Udde. The exposed limestone belongs to the Latorp and Lanna topoformations, which boundary correlates with the Blommiga Bladet hardground complex (BB), seen as a yellow stripe in the upper part of photograph. Blodläget is situated ca 2 m above Blommiga Bladet and is not visible in the photograph. (photo: M. Calner).

Cementation is the most noticeable early diagentic process affecting shallow-marine carbonates. This tends to happen in areas of strong currents and waves, especially where sedimentation rates are low. Initially the cements are precipitated within bioclasts in intra-skeletal pores, shells and tests. Bioclasts that often contain cements within them are gastropod and foraminiferal grains (Tucker & Wright 1990). According to Tucker & Wright (1990) hardgrounds develop just below the sediment surface, where grains are not being moved very frequently, but seawater is continuously being pumped through and $CaCO_3$ is precipitated between the grains. The diagenetic processes operating in shallow-water carbonate sands and muddy sands depend basically on the energy level. In areas that are affected by high energy levels, such as shelf margins, lime sands get produced in abundance and sea water is pumped through them, which increase the chances of rapid cementation. The more porous the sediments are the easier cementation and hardground development gets. During storms, the hardgrounds may be exposed on the seafloor, and then they can be encrusted and bored (Tucker & Wright 1990).

The majority of recent hardgrounds are formed in less than a few meters depth, e.g. in the Bahamas (Dravis 1979) and in the Persian Gulf (Shinn 1969). The development of recent hardgrounds is probably related to surface water saturation relative to calcium carbonate. These case studies also consider the idea that cessation of sedimentation and development of hardgrounds can form within a few months (Flügel 2004).

Some hardgrounds have been described from great depths, between several hundreds of meters to more than 3000 meters (Flügel 2004, and references therein).

The time involved in the formation of hardgrounds is unclear but it has been proven from antique Greek pottery that it has been incorporated into a hardground, of the Persian Gulf (a few thousand years) (Shinn 1969).

4.2 Recognition of hardgrounds

Hardgrounds can be confused with several other types of discontinuity surfaces such as omission surface, stylolites and erosional surfaces. Flügel (2004) listed a series of criteria useful for their recognition. These are summarized below and in Figure 5. (For references, see Flügel 2004).

Contacts: The upper contact is sharp whereas the lower contact is diffuse. Along the upper contact grains and cement may be truncated. A micrite rind can sometimes be found on the upper surface. In some cases the hardground surface can be covered by micritic microbial crusts. Cavities, borings or undercut recesses in the hardground may be infilled by overlaying sediments.

Surfaces: Characteristic for the upper surface is a smooth or irregular surface. Irregular protuberances separated by pits and grooves are shown on many surfaces. Abrasion may form smooth planar surfaces that are more common in shallow-marine high energy environments (abraded hardgrounds). Surface solution creates angular surfaces and is more common in deep-marine shelf and basinal settings (corrosional hardgrounds). The upper surface of the shelf hardgrounds may be buckled into tepee-like expansion ridges or show signs of corrosion. The lack of encrustations on these surfaces proves relatively short exposure time and/or high energy conditions.

Mineralization: Mineralization on the uppermost layers may form crusts or impregnations. Depending on the environment and the composition, the form and intensity of the mineralization may vary. Mineralization on shelf hardgrounds is usually glauconite, calcium phosphate salts and iron hydroxides (goethite, limonite). Hardgrounds covered by ferruginous crusts frequently consist of irregular laminae of iron hydroxide, sometimes forming a cauliflower structure, changing with sheet of calcareous skeletons from encrusting organisms (e.g. foraminifera, serpulids). A good indication of long omission phases and low energy hydrodynamic conditions is the existence of limonite on the hardground surface.

Biogenic encrustations: Encrustations on the upper surface of the hardground can be found by organisms that require a hard substrate to settle. Bryozoans, brachiopods and oysters also occur as encrustations on the lower surface of the hardground. Variations in the encrustations indicate rates of sedimentation, turbulence level and changes in fauna according to light intensity. Foraminifera, bryozoan corals, serpulid polychaetes, cirripeds and some brachiopods are common encrusters restricted to hardground.

Borings: In many hardgrounds it is common with macro- and microborings on the upper surface. Borings on hardgrounds provide sedimentological information about the consistency of the ancient sea floor as well as paleoecological information about environmental and depositional conditions. Animals restricted to boring of hardgrounds include some bivalves, phoronids, sponges, algae and fungi. Several animals can penetrate firm grounds as well as hardgrounds, e.g. bivalves and polychaete worms.

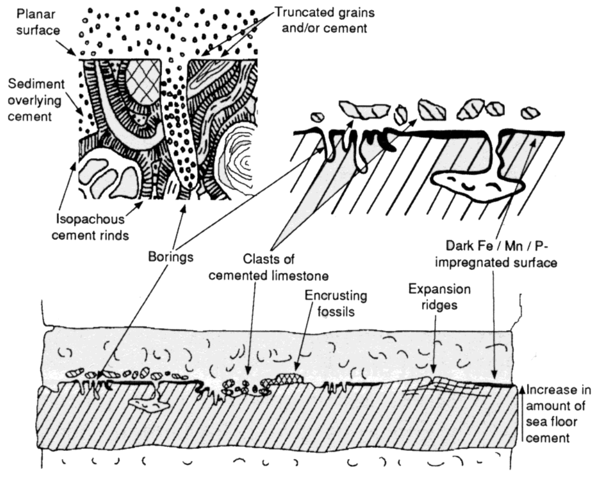

Fig. 5. Sketch showing common criteria of carbonate hardgrounds. Flügel (2004).

Burrowing: The layers overlaying and underlying the hardground are containing specific associations of trace fossils indicating the changes in substrate types. The temporal relationship of bioturbation, boring and encrustation are reflections of the changes from firmground to hardground stages.

Clasts of cemented limestones: Similar lithoclast found in the hardground occur above the upper surface, as infill of depressions or along the discontinuities. Typical features of the clasts are sharp edges and signs of borings, encrusted or coated with Fe/Mn crusts. These clasts can be related to a complex reworking from both biological and erosional origin.

Small-scale sedimentary intercalations: Cavities, beneath the upper surface, are mixed with interlayered sediments with marine fossils and cements.

Alteration of hardground surfaces and cement: Many hardgrounds can contain multiple surfaces spaced by millimetres apart, characterized by a high volume of carbonate cement causing laterally continuous cement, crust and layers.

Carbonate cements: Most hardgrounds are characterized by low-Mg-calcite cements occurring as blocky mosaics, syntaxial rim cement and palisade-like fibrous cement, or radial aggregates. The so called ant-egg (microspar) spar is abundant. Glauconite, goethite and pyrite may be intergrown with calcite crystals.

5 Blommiga Bladet

Blommiga Bladet is a stratigraphically well defined hardground complex. Based on the classical and well-studied locality Horns Udde it corresponds to the Billingen and Volkhov regional stage boundary and the boundary between the Latorp and Lanna topoforma-

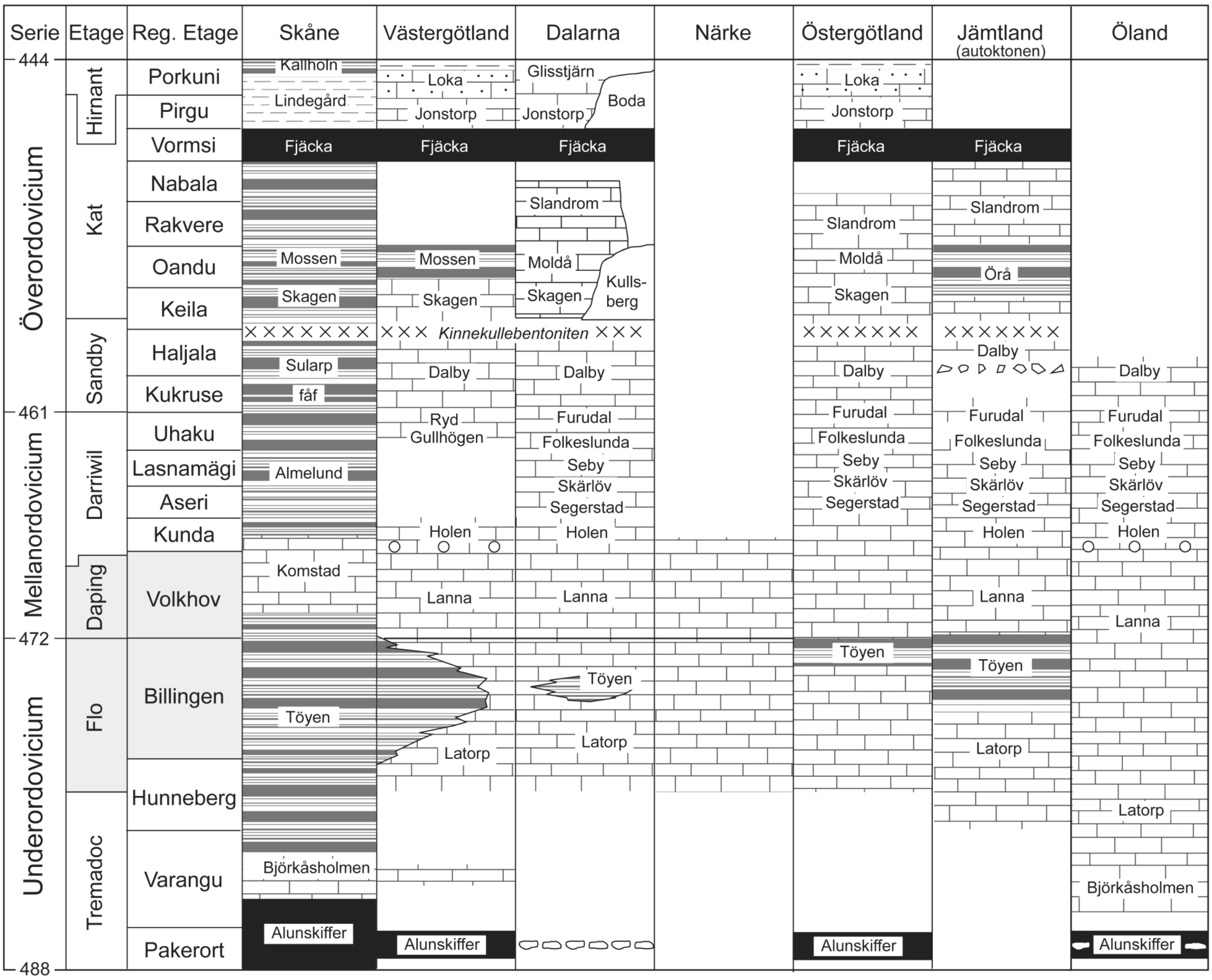

Fig. 6. Ordovician stratigraphy of Sweden. Blommiga Bladet marks the lower Lanna boundary and the base of Volkhov regional stage and the Dapingian international stage (grey shading). The Töyen Shale is thickest to the west and the south whereas in the east it may only be very thin or not exist (Lindström et al., *in prep*. For Sveriges Geologi 3rd ed).

tions (Lindgren 1979; Dronov & Holmer 1999; Ekdale & Bromley 2001; Bergström & Löfgren 2008; Fig. 6). The first appearance of the stratigraphically important conodont *Baltoniodus triangularis* appears just below Blommiga Bladet at Hällekis in Västergötland (Bergström & Löfgren 2008), suggesting that this hardground complex is close in time with the base of Dapingian.

Quarry workers on Öland gave Blommiga Bladet its name because of the hardground complex structure and vivid colours. It is characterized by its brightly coloured horizons and vertical, vase-shaped macroborings. Blommiga Bladet can be traced over vast distances; from Västergötland in the west to St. Petersburg region in Russia, in the east and from Dalarna in the north to Poland in the South (Lindström 1979; Dronov & Holmer 1999; Ekdale & Bromley 2001). This means that Blommiga Bladet stretched more than 1000 km in the east-west and at least 500 km in the north-south direction (Lindström 1979), and thus covered an area of at least 500,000 km² (Fig. 2.). Blommiga Bladet is further known as the Steklo surface (Russian for glass) in western Russia where it corresponds to the base of the Volkhov formation along the Baltic-Ladoga Klint (Fig. 7). It is recognized as Pustakkiht in Estonia where it forms part of the Toila Formation. In China there is a stratigraphic gap at this level (Bergström & Löfgren 2008).

According to Ekdale and Bromley (2001) the burrowed and bored omission surfaces testify to a dynamic sedimentary environment and the extensive discontinuity surfaces therefore were colonized by a broad spectrum of burrowing and boring infauna whose distribution and activities were strictly controlled by the substrate character.

Blommiga Bladet is characterized by two main discontinuity surfaces, or hardground surfaces, with relatively big sac-like pits and a bright colorization of red, yellow and greyish green. At the Horns Udde locality, Lindström (1979) described Blommiga Bladet to lie 2.7 m above the base of the Ordovician. Here the

Fig. 7. Weathered buildingstone showing the Steklo surface, which is a clear-cut abraded hardground with several borings and an upper complex of corrosional hardgrounds with significant undulating and uneven surfaces (photo: A. Dronov).

two main hardgrounds are developed as distinct, clear-cut and abraded omission surfaces separated by about 10 cm of limestone that yields another 1-4 irregular discontinuity surfaces. These surfaces together form the *Blommiga Bladet hardground complex*, which is believed to have undergone extremely complex diagenesis (Lindström 1979; Ekdale & Bromley 2001). The host limestone consists essentially of red carbonate mudstone to trilobite-rich wackestone (Lindström, 1979). Most number of borings can be seen in the upper hardground (Fig. 8). Evidence for erosion and abrasion can be seen on these smooth hardground surfaces in fossils and other pre-existing structures that are being cut through (Fig. 9-10). The vase-shaped borings are commonly about 5-6 cm deep and 1-3 cm in diameter (Lindström 1979; Ekdale and Bromley 2001). Lindström (1979) described that Blommiga Bladet sometimes dould have as much as 20 borings/100 cm² said to be relatively close spacing, though in some cases there can be spaces between the borings up to tens of centimetres. The borings cut trough trilobite remains as well as older hardgrounds implying that they penetrated indurated material. This is further supported by that the apertures appear to coincide with the upper omission surfaces (Ekdale & Bromley 2001). It is not uncommon that some borings were re-excavated.

The boring have been described as made by the ichnospecies *Gastrochaenolites oelandicus* by Ekdale & Bromley (2001), which has the distinctive Cod's bottle (flask) shape typically made by lithophagid bivalves. The next oldest reported *Gastrochaenolites* have been found 160 Ma years later, in the middle of Carboniferous (Ekdale & Bromley 2001, and references therein). The host sediment is generally reddish green and infilling sediment of the borings are typically greenish grey in the lower parts of the boring and in the upper parts more brown reddish filling (Figs. 9-10). The filling consists of fine-grained carbonate with recrystallized bioclasts floating in the matrix-supported texture. There are tubes interconnecting some of the borings in Blommiga Bladet, both described by Lindström (1979) and Ekdale & Bromley (2001). These are horizontal, about 4 mm wide, and might be tunnels of some kind burrowed when the sediment was less indurated. Evidences of this can be found in the *G. oelandicus* borings that cut trough these tunnels (Ekdale & Bromley 2001). It is further stated that the tunnels contain similar filling, as the borings, with regard to colour and texture but it is not likely that they belong to the same trace fossil. The tubes can be irregular, sinuous and may branch and anastomose.

During the diagenesis the omission surfaces have been affected by processes creating goehtite and other iron mineralizations (Lindström 1979; Ekdale & Bromley 2001). In connection to the omission surfaces and along the edges of the borings there appears a yellowish thin zone that commonly extend further downwards along the borings (Figs. 9-10). According to colour, the yellow mineralization appears to be goethite (Lindström 1979). At some parts of the edges of the borings there exist glauconitic grains that are glimmering in green (Fig. 9). The reddish stains are considered to be hematitic. Based on relative stratigraphic relationships the goethite and the glauconite mineralizations, as well as oxidation of skeletal grains, took place after that *G. Oelandicus* produced the borings, but before the cavities were filled with sediments.

Lindström (1979) has described Blommiga Bladet at Horns Udde and compared it to other localities where this hardground complex is exposed, e.g. at Hällekis and Bjällum in Västergötland and at Sjurberg in Dalarna. The thickness of the hardground complex were not very unlike those associated with Blommiga Bladet at Horns Udde, but the most distinct changes spatially were the mineralizations. Borings existed as frequently and the same two generations of boring was also described similar to Blommiga Bladet at Horns Udde.

Fig. 8. Showing two distinct abraded surfaces with vivid colour (arrows). Borings are more frequent in the upper hardground. (Photo: M. Calner)

It is reasonable to believe that the borings on Steklo, in west Russia and in Estonia are of the same affinity as the borings at Horns Udde judging on the form and shape.

6. Discussion

It is generally agreed that the Orthoceratite Limestone was deposited during a period of slow sedimentation rate in a tranquil environment (Lindström 1963, 1979; Jaanusson 1972). To exactly determine the depth of deposition of the Orthoceratice Limestone and Blommiga Bladet is very hard considering that the fossil fauna has no present day similarities (Schmitz et al. 1996). There are some factors, however, that can be taken in consideration when estimating the relative sea-level. First, the Orthoceratite Limestone was deposited on a continental shield ruling out pelagic depths. Secondly, the abraded and clear-cut character of the two main hardgrounds (Figs. 9-10) is firm evidence for erosion of the sea-floor. At the time Blommiga Bladet was developed, the sea-floor regionally seems to have been above the wave-base, implying shallow-water conditions across wide areas. Dronov et al. (2002) discuss that the major borings, *Gastrochaenolites* and *Trypanites,* are associated with a sequence boundary and the shallowest deposits during the Ordovician. Similarly, a stratigraphic gap implying a sea-level lowstand is associated with this boundary also in China (Bergström & Löfgren 2008).

Tucker & Wright (1990) describe that a high precipitation of iron-hydroxides (goethite-limonite), phosphorite and glauconite are common in areas of slow sedimentation and in high energy areas. The yellow goethite, that can be seen on the omission surfaces and adjacent to the borings (Fig. 9-10), indicate that the mineralization took place after the *G. oelandicus* borings but before the pits where filled with material. Since the hardground is not fully lithified, it allows the sea-water to pump through in between the grains oxidizing the material and making it yellow. This also suggest for a depth above the wave-base or an area affected by currents. Although the clear red hematite appears to be connected below as above the hardground it most probably mineralized before the upper layer was deposited (Fig. 10C.).

The borings have been described as ending above the lower clear-cut surface but it is not uncommon that the borings extend also below the lowermost hardground. This could also mean that some borings could have started above the topmost hardground but been eroded down and left all evidences. There is no fossil evidence from the borers in the borings suggesting that it was a soft-bodied invertebrate, devoid of shell, and of unknown affinity (Ekdale & Bromley 2001). Though, it is possible that it was a calcareous-shelled creature because of the poor preservation potential for $CaCO_3$. The hardground complex itself suggests that the environment was aggressive and could have dissolved the aragonite and calcite during intervals of non-sedimentation.

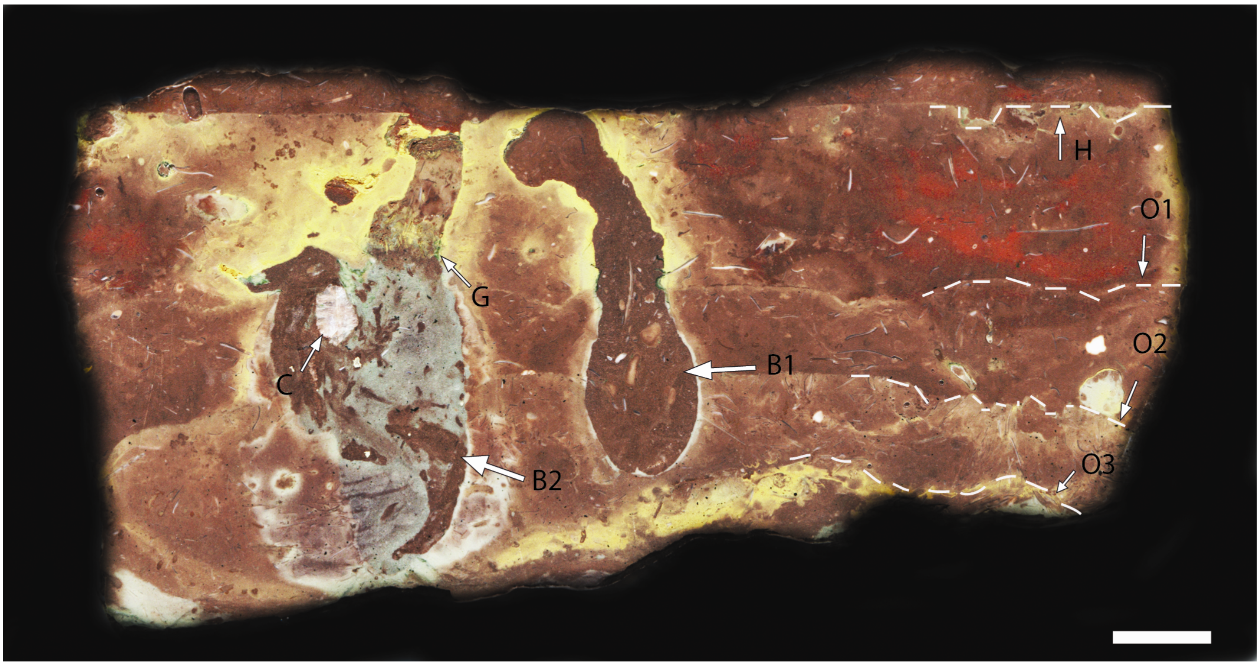

Fig. 9. Polished rock sample from Horns Udde. Scalebar = 1 cm. It illustrates the complexity of Blommiga Bladet. The main upper hardground can be seen as an omission surface (H). The aperture of *G. oelandicus* corresponds to H. Three more omission surfaces are visible as O1, O2 and O3 but are not as distinct as H. They are also not as smooth and clear-cut as H and have not been affected by the same abrasion processes as H. The O3 has been mineralized by goethite showing a thin yellow zone along the omission surface. The H surface have a few minor cavities and two borings, referred to as B1 and B2 that cut through at least two omission surfaces. The morphology of the borings shows some variation but B1 is a representative example of the sac-like pits described by Lindström (1979) and Ekdale & Bromley (2001). Note the small aperture and the wider bottom as well as the stained yellowish goethitic mineralization that appear in connection to the upper part of the borings and along each omission surface. Clear red stains appear in the upper right part of the slab, between H and O1. The fill in B2 have similar material as above H. B2 seems to be connected to another boring and is slightly bigger. The fill material in B2 is a little different and includes more grayish material mixed with brown reddish material similar to B1. Glauconite grains occur irregularly on the sides of the borings referred to as G. Crystallizations can be seen on C.

Lindström (1979) calculated that the Billingen substage represents somewhere between 1-5 millions years of Ordovician time, which makes an average time-span, of one of the ca 40 hardgrounds at Horns Udde is, 25,000-125,000 years. According to a more recent datings of the new international stages (e.g. Nõlvak et al. 2006) the former number is the most likely. Bergström & Löfgren (2008) notes, however, that we currently do not have the biostratigraphic resolution required to assess the precise magnitude of the relatively small stratigraphic gaps associated with hardgrounds, and it is not likely that such fine scaled resolution may ever become available.

The ecological significance of Blommiga Bladet is not fully understood. It has not been proved to be associated with any major world-wide event such as a mass -extinction or faunal diversification (Webby et al. 2004). Blommiga Bladet is ,however, interesting both in terms of its associated fauna and in geological reference. Why was the sea-floor during the early Dapingian so beneficial for *G.oelandicus* to settle? For how long was the sea-floor settled by *G. oelandicus*? How much of two hardgrounds are abraded/eroded, i.e. what is the degree of the stratigraphic incompleteness?

I have put together some criteria that could be the main reasons for the formation of *G. oelandicus*:

- Tectonically stable – Baltoscandia was, during Blommiga Bladet development, an epicontinental sea without major tectonic movements.
- A global sea-level lowstand allowing higher energy levels and abrasion of the hardground surface making it an ideal environment for *G. oelandicus* to settle.
- Slow and exceptionally uniform sedimentation across wide areas as well as slow sedimentation rates or non-deposition in an oxidizing environment, allowing regional hardground development.
- Impoverished benthic faunas – The absence of other borers or encrusters in Blommiga Bladet suggests a brief period of low benthic diversity in both vagile and sessile groups.

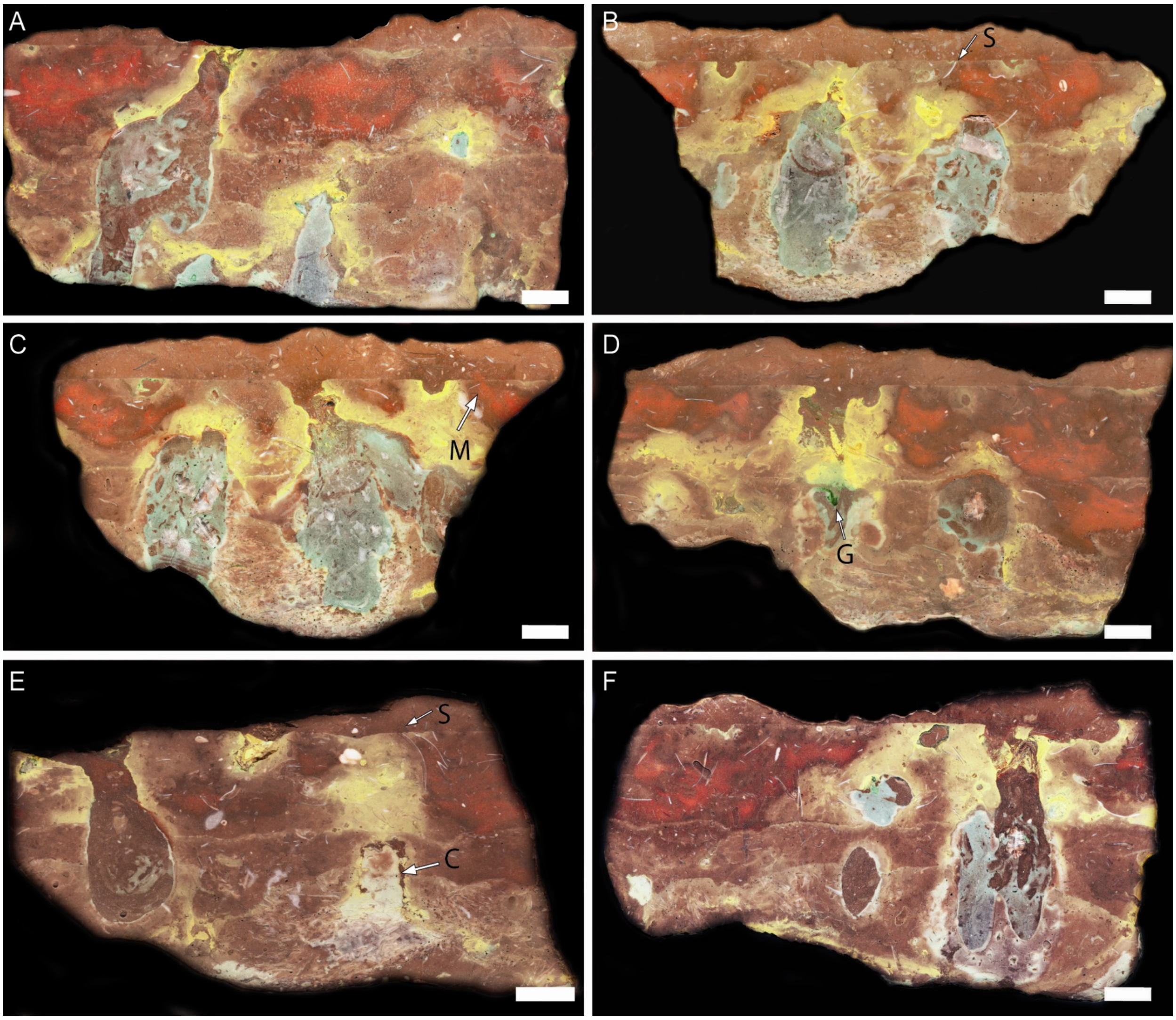

Fig. 10. Scanned polished slabs (A-F) that illustrate the great variation of the Blommiga Bladet hardground complex. Noticeable for all of the slabs are the clear-cut upper hardground that were bored by borer of the ichnospecies *G. oelandicus*. The mineralization of yellow goethite and red hematite was taking place before the borings was filled with sediment, maybe even when the *G.oelandicus* inhabited the borings? Scalebar = 1 cm. **A** Show a clear-cut upper hardground and three omission surfaces (see also Fig. 9). The yellow goethite is visible in connection to the borings and as a zone along the lower omission surface. **B** The striking feature with this slab is the truncated trilobite skeletal grain on the main hardground surface marked as S. No apertures of the borings are visible but they are likely just some centimeters inwards or outwards in the slab. **C** As in the three first pictures, the red hematitic (M) mineralization sometimes stretches above the upper hardground surface. This is probably a leakage from the hematite below the hardground surface. **D** This slab shows the great variation of different mineralizations. A pronounced glauconite mineralization, referred to as G, which is located just below an omission surface that is smooth and almost as distinct as the upper hardground. **E** This slab is somewhat smaller than the rest but contain a characteristic sac-like boring that has a bigger aperture than previous studied borings. In the upper right corner a truncated trilobite skeletal grain appears (S). A major crystallization seems to have taken place on C probably in connection to a boring either inwards or outwards. **F** In this slab two borings are connected to each other but it is likely to that they were bored at two different occasions. The aperture of the left boring protruded to the sea-floor outside the cut surface and is therefore not visible.

7 Conclusions

Blommiga Bladet was created in a shallow epicratonic sea with fairly high energy-level allowing sea-water to be pumped through the carbonate grains making them lithified. The loose covering sediment was slowly removed by waves (or currents) and the grains polished and smoothed the surface, allowing the ichnospecies *Gastrochaenolites oelandicus* to form. The borer created characteristic sac-like borings and managed to successfully settle an area that covered more than 500,000 km². Blommiga Bladet was probably formed during a sea-level low-stand. It is not fully determined when Blommiga Bladet was mineralized and received its vivid colours in terms of the diagenesis, but goethite and hematite evidently mineralized after the borings were made, but before they were filled with sediment. The time represented by the Blommiga Bladet is highly uncertain and more research needs to be done with regards to this aspect.

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Geologiska enheten
Institutionen för geo- och ekosystemvetenskaper
Sölvegatan 12, 223 62 Lund