MASTERARBEIT

Titel der Masterarbeit

Paläoökologische Analyse der mud mounds der Boda Limestone Formation, Dalarna, Schweden, des späten Katiums (O-Ordovizium)

verfasst von

David Klaus Gröbner, BSc

angestrebter akademischer Grad

Master of Science (MSc)

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Studienkennzahl lt. Studienblatt:	A 066 828
Studienrichtung lt. Studienblatt:	Masterstudium Paläobiologie
Betreut von:	Univ. Prof. Mag. Dr. Martin Zuschin

MASTER THESIS

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Abstract

Carbonate mud mounds are fine-grained deposits with a topographic relief and few in situ skeletons of metazoans. Such mounds occur throughout the Phanerozoic, but are abundantly developed in the Palaeozoic. The Boda mud mounds from the Boda Limestone Formation evolved during the late Katian (Late Ordovician). Their occurrence is associated with the Boda-event, a poorly understood interval of strong climate change. They have a rich and well-preserved fauna known from the mound flank and synsedimentary crevices- or cave fillings. This fauna is used to characterize the terminal strata attributed to a mud mound from the location Osmundsberget. The mud mound growth of the Boda Formation stopped at the transition from the Katian to the Hirnantian. The causes for the demise are still not completely understood. There are two probable scenarios: The mud mounds were drained by a global regression attributed to the formation of an icecap around the South Pole. This point of view is supported by the overlying Upper Boda Member with several layers of brachiopod coquinas, interpreted as stormbeds formed under shallow water conditions. The occurrence of dripstones (stalactites) - as an incident for a non-marine environment - at several locations indicate a draining in the Hirnantian as well. The interpretation of the brachiopod coquinas and the dripstones corresponds well with the observed δ^{13}C-excursions in the Hirnantian called HICE. Another explanation focuses on the possibility of a short-time transgression event at the terminal Katian. This scenario is supported by the sedimentary features of strata from the Boda mud mounds beneath the Upper Boda Member. This work provides a description of various reef facies - reef core, flank and intermound facies - according to their fossil content, based on a quantitative dataset. The data gathering took place by collecting material quantitatively from different sites. The data were analyzed with non-metrical multidimensional scaling (NMDS), principal coordinates analysis (PCO), diversity- and ecospace analysis. In total, over 1500 specimens of almost 70 species were collected and identified. Most of the data are from brachiopods and rugosan and tabulate corals. Data from isotope analysis are compared with faunal signals to contribute to the question, whether the Boda mud mounds vanished by drowning or by draining. For this purpose, collected material from late

Katian strata from Osmundsberget was compared to material from the reef core and from the Jonstorp Formation. Faunal compositions show a trend of deepening, because the terminal mud mound associated strata from Osmundsberget were getting more similar to the deeper water Jonstorp Formation. An environmental change is supported by the occurrence of faunal elements such as *Holorhynchus giganteus* and the bryozoan *Diplotrypa.* That leads to the interpretation of a transgression event as the cause for the decrease in the mud mound growth and its final demise.

Introduction

The Boda Limestone Formation and its fossils have been well examined for about 200 years. A lot of detailed work on the various taxa (see Isberg, 1934 on bivalves; Warburg, 1925/1939 on trilobites, Angelin and Lindström, 1880 on brachiopods; Cocks, 2005: strophomenid brachiopods) and stratigraphic data (see Ebbestadt et al., 2015; Bergström et al., 2011) is available. Syndepositional crevices- or cave fillings in horizontal as well as vertical orientation - so called pockets - are well described by Suzuki and Bergström (1999). But most studies focus on single taxa, e.g. trilobites, brachiopods, bivalves, by a qualitative set of data. This work focuses on the faunal composition of different facies from the Boda Limestone Formation based on a quantitative set of data including all found taxa. The samples for the quantitative dataset were taken from six different sites from the abandoned quarries of Osmundsberget and Solberga. Osmundsberget is a well-known site, representing strata from the Kullsberg reefs to the early Silurian. At the site called OB4 one can find the uppermost reef structures corresponding to the Boda reefs. Those structures are supposed to be as a reef core facies at the terminal Katian / Hirnantian. From that sites, isotope data are available (Ebbestadt et al., 2015), showing a major $\delta^{13}C$ excursion above the *Holorhynchus giganteus* (Kiaer, 1902) beds. A shallowing is supported by brachiopod coquina beds from the Upper Boda Member (Suzuki et al., 2009). However, the uppermost Boda reef structures (OB4) show the same sedimentary features like the Jonstorp Formation, assigned to the deeper intermound facies. To compare those late Katian strata, two sites at Osmundsberget, correlating to the Jonstorp Formation were investigated. At Solberga a section was found within the typical core limestone. This section is marked by an extraordinary state of fossil preservation which is very rare within the core limestone. It is of late Katian age but still older than the sites at Osmundsberget. From the Jutjärn quarry, a pocket is described for comparison with the site Solberga_3 to exclude a crevice- or cave filling origin of this site. For statistical analysis non-metrical multidimensional scaling (NMDS) and principal coordinates analysis (PCO) were used including data from all taxa at each of the six sites from Osmundsberget and Solberga and of brachiopods and Anthozoa (Rugosa, Tabulata) separately. Ecological analysis are based on ecospace use and changes in evenness.

Ordovician paleogeography of Baltica

During the Ordovician the palaeocontinents of Laurentia, Baltica and Siberia moved towards north, while the movement of Gondwana is characterized by a rotation around the South Pole. The reconstruction of Cocks and Torsvik (2002) (see figure 1) uses palaeomagnetic and faunal data for a best possible determination of the latitude and longitude of the terranes. The position of Baltica in the early Ordovician is assigned to 30° to 60° latitude south of the equator and started rotating counter clockwise. This rotation continued until the late Ordovician. During the late Ordovician, Baltica was positioned between the equator and 30° south, with the very top of Baltica exceeding the equator. Avalonia collided in the late Ordovician with the south-western part of Baltica. The approaching and final collision can be seen in the faunal composition of both terranes. A converge in trilobite and brachiopod fauna is recognizable (Cocks & Fortey, 1982). In the reconstruction of Cocks and Torsvik (2002), the region of Taimyr, Russia, is assigned to the terrane of Baltica instead of Siberia. This can be seen in the faunal composition which is more similar to the Boda Limestone Formation than to reef complexes in Siberia (Cocks & Modzalevskaya, 1997). Towards the end of the Ordovician and in the early Silurian Baltica and Laurentia merged to Laurussia. This can be seen, as in the case of Avalonia and Baltica, in a reduction of endemism within the terranes and the occurrence of cosmopolitan taxa.

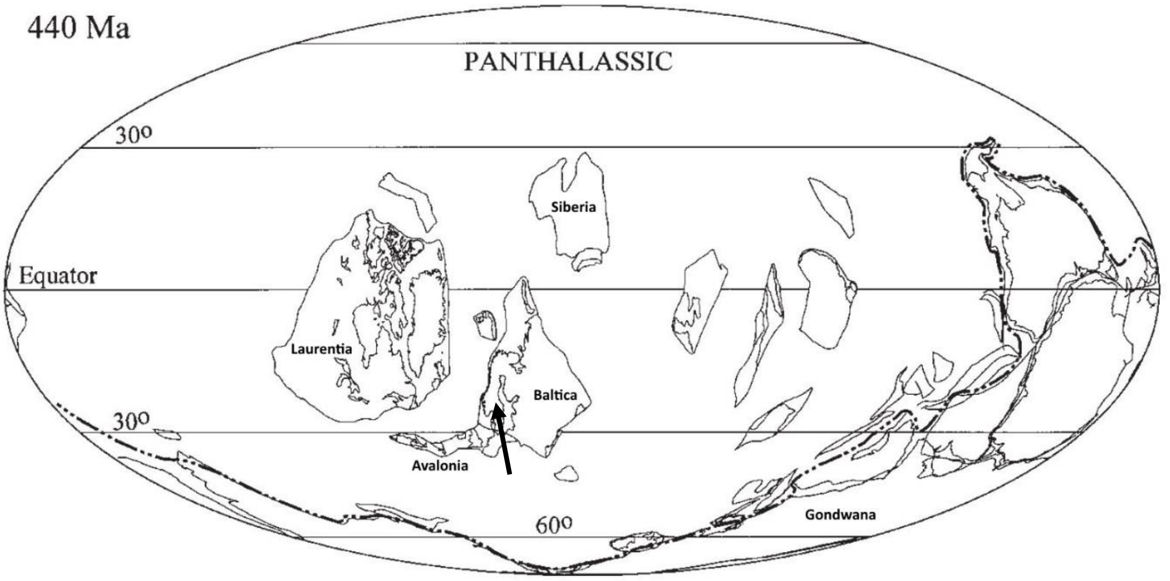


Figure 1: Palaeogeographic reconstruction of the late Ordovician from Cocks & Torsvik. The location of the Boda mud mounds is marked by an arrow. Modified from Cock & Torsvik, 2002.

Late Ordovician climate

The climate in the late Ordovician was relatively warm until the early Katian. There is no evidence for glaciogene depositions from this time. It was a time of raised sea level, so most of the cratons were floated. This led to the formation of large epicontinental seas (Nielson, 2004). In the early Katian (at the transition of the *Diplograptus foliaceus* - to the *Dicranograptus clingani* – zone (graptolite – zones)) a large positive δ^{13}C-excursions, named GICE (Guttenberg Isotope Carbon Excursion) can be found. A relatively high δ^{13}C-value is a signal for enhanced carbonate burial, which led to a reduction in atmospheric carbon dioxide. This can be attributed to anoxic conditions during a time of a high sea level (see Mesozoic, Kump and Arthus, 1999) or to an increased thermohaline circulation (see glaciation events and sea level fall, Brenchley et al., 1994). Due to Saltzman and Young (2005) the lowering level of atmospheric carbon dioxide reached a threshold level for the building of an icecap at the South Pole in the greenhouse climate of the Ordovician (further reading on atmospheric CO_2-levels in the Late Ordovician see Gibbs et al., 1997). Still, this is not the only δ^{13}C-peak in the Ordovician. The largest δ^{13}C-peak is the Hirnantian Isotope Carbon Excursion (HICE). During the ongoing Katian a major event took place which lead to drastic climatic changes which can be seen in the migration of organisms and depositions. This so called Boda–event can be interpreted in different ways. According to Fortey & Cocks (2005) the Boda–event is linked to an episode of global warming. Clastic deposits in high latitudes around Gondwana which are interrupted by carbonate deposits are interpreted as a sign of a period of warming. The carbonate layers mostly consist of remains of bryozoans and pelmatozoans. Due to the widespread occurrence of these carbonates, the authors assume a climatic change (in this case a global warming) and not a change in the behaviour of clastic sedimentation. From depositions in Morocco, assigned to the late Ordovician, stromatoporides are known. Fossils from that group are known only from tropical areas at that time. The carbonate deposits are overlain by glaciogenic depositions from the Hirnantian age. Another evidence for a global warming event is seen in the migration of several taxa, for example trilobites and brachiopods from tropical and lower latitudes to higher latitudes (Villas, 1985; Havlicek et al., 1994). On Gondwana an increasing number of Baltic taxa associated to tropical temperatures can be observed. Deep water communities apparently seem to be unaffected by changing climate (Fortey & Cocks, 2005), while communities living on the extended platforms are subjected to great changes. There is another interpretation of the Boda-event by Cherns & Wheeley (2007). They assume that the climatic changes were attributed to an episode of global cooling. The carbonate deposits in high latitudes on Gondwana overlaying clastic formations are interpreted as cool water carbonates (Cherns & Wheeley, 2007). The change in sequence of clastic to carbonate depositions are also known from mid-latitudes (Cherns & Wheeley, 2007). These assumptions are supported by the occurrence of stromatactis-structures in mud mounds on Gondwana and Baltica. Those reef structures grew on a base former assigned to a deeper ramp facies. The change in facies is interpreted as a result of a regression which is caused by the extension of the icecap on high latitudes around the South Pole of Gondwana. The regression also caused a reduction of clastic sediment input as seen in the sequence of clastic to carbonate deposits on Gondwana (compare Fortey & Cocks; 2005). The extended formation of the southern icecap led to a change in oceanic currents and to the formation of a thermohaline circulation. Due to the downwelling of cool water at the South Pole, anoxic or dysoxic bottom water, which was common in Ordovician greenhouse time, got mixed with oxygen rich water from the surface. This water, rich in oxygen and nutrition, raised to the surface again on continental slopes in upwelling zones. Evidence of this has been documented on outer ramp realms on Avalonia with a typical cool water facies and a warm water facies in the upper part of the ramp (Pope, 2004). The thermohaline circulation led to a rich benthic fauna. The migration of taxa into higher latitudes is explained by the regression and the thermohaline circulation (oxygen rich bottom water), both caused by a global cooling event and the associated extension of the southern polar icecap. The occurrence of mud mounds on offshore realms are also explained by upwelling (due to the thermohaline circulation) and a reduction in clastic sediment input (due to regression). In Laurentia there is a remarkable $\delta^{13}C$-peak of a magnitude comparable to the GICE (Saltzman & Young's, 2005; Fortey & Cocks, 2005), which supports the interpretation of Cherns and Wheeley (2007) as the Boda-event as an event of global cooling instead of warming. Towards the end of the Ordovician, in the Hirnantian, there is an obvious global cooling, which can be seen in glaciogene deposits in southern Gondwana. At the same time the largest Ordovician $\delta^{13}C$-excursion HICE can be observed around the world. The $\delta^{13}C$-excursion is explained by an enhanced productivity-driven carbon burial (Ainssar, 2004). In detail, this was not a single event but two (Melchin, 2013) or three (Ghienne et al., 2014) events with several low magnitude cycles, starting at the Katian/Hirnantian transition to the end of the Hirnantian. The HICE is attributed to a global glaciation event, which led to a global regression but the causes for the glaciation are still in discussion (see Melchin, 2013 and Ghienne et al., 2014). This regression, associated with the HICE was supposed to be the cause for the Boda mud mounds. Shiino et al. (2014) observed *Holorhynchus* from the late Katian strata from Osmundsberget and interpreted the beds as transitional beds from the microbial-sponge-dominated reef framework to a bryozoan-dominated framework from the Upper Boda Member. Shiino et al., 2014 attributed this to a regression event. Ghienne et al. (2014) described a transgression signal from western Laurentia at the late Katian. This contrasts the general view of a global regression at that time, showing regional differences in sea level. The Ordovician ended 443,4 million years ago in a global event of mass extinction (Sheehan, 2001). The extinction event is attributed to glaciation events.

Boda Limestone Formation

The term *Leptaena* (Dalman, 1828) Limestone (Leptaenakalk), deriving from the abundant brachiopod species *Eoplectodonta rhombica* (Angelin & Lindström, 1880) (former *Leptaena*) summarizes the mud mound structures named Kullsberg Limestone Formation and the later Boda Limestone Formation (Thorslund, 1935). The Kullsberg mud mounds are of early Katian age and stopped growing due to regression correlated with GICE (Calner et al., 2009). Later there are the Skalberg and Slandrom limestones, overlain by the Fjäcka shale, a significant marker bed all around the Siljan district (Ebbestad et al., 2007). The Boda Formation is of late Katian to Hirnantian age. The Katian part is exposed in mud mound structures. These isolated, lens shaped reef structures can reach dimensions of up to 1000 meters in diameter and a height of up to 180 meters (Jaanusson, 1982; Schmitz & Bergström, 2007). More than 20 of these mud mound structures can be found in Siljan, Dalarna, Sweden. They are located along a ring-shaped structure called the Siljan Ring (see figure 3). The ring-shaped structure was caused by an impact event in the Devonian (Svensson, 1971; Reimold, 2005). The Palaeozoic rocks alongside the ring structure of the impact are embedded in the

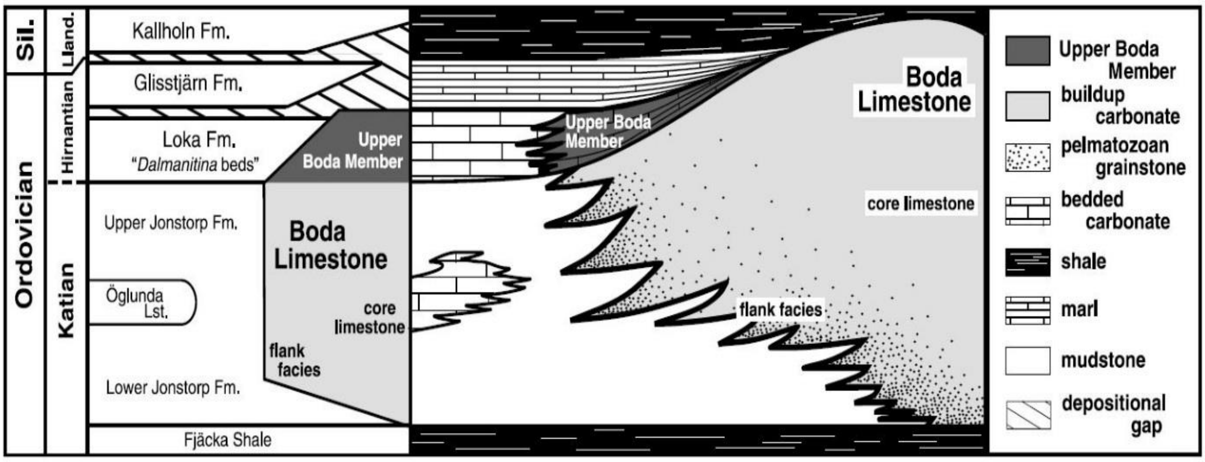


Figure 2: Boda Limestone Formation with core limestone, flank facies and Upper Boda Member. Modified from Suzuki et al., 2009.

surrounding Precambrian shield, which can also be found inside the crater. During the Mesozoic, most of the Palaeozoic rocks were eroded. The remaining Ordovician rocks are barely diagenetically altered (see study on conodont color alteration; Bergström, 1980), but they are heavily disturbed and folded due to the impact event. The Kullsberg and Boda limestones are supposed to be deeper water carbonates formed under relatively quiet water conditions, indicated by the high abundance of articulated brachiopod shells. A study on cephalopods suggests a water depth from 50 to 100 meters (Kröger & Ebbestad, 2014). The Boda Limestone Formation can be classified into three different facies (Suzuki et al. 2009): the Boda Core Member (core limestone), the Boda Flank Member (flank facies) and the Upper Boda Member (figure 2). The core member is characterized by a compact, whitish to reddish colored, poor in stratification and structures, micritic limestone with remarkable abundant stromatactis. The stromatactis is attributed to processes of inorganic origin within cavity fillings (Suzuki & Bergström, 1999; Neuweiler et al., 2001). In this predominantly structure-less core limestone, a large number of fossils can only be found in pockets or patches of extraordinary fossil preservation. Organic mud mounds are generally supposed to be built up by microbial activity but various processes (organic and inorganic) were included in the mound formation (see Riding, 2002). From the Cambrian to the Devonian sponges were a main component of deep water mud mound communities (Bourque & Boulvain, 1993). At the Boda Limestone Formation, sponges are an abundant element (Neuweiler et al., 2001) and can be found in large numbers in thin sections by spicules, but macrofossils of sponges are rare. One of the most noticeable feature of the Boda core limestone are stromatactis. Neuweiler et al. (2001) ascribed those Palaeozoic stromatactis structures to degrading sponges. According to the mud mound classification of Riding, 2002, the Boda mud mounds are high relief mud mounds. On the lower levels of the core facies, patches of *Palaeoporella* (Stolley, 1892) limestone can be found (Jux, 1966). Lateral to the core facies there is the flank facies which is characterized by a massive occurrence of pelmatozoans (pelmatozoan pack-grainstones). The flank facies passes gradually into the Jonstorp Formation. It is characterized by argillaceous to marl-like limestone of reddish to greenish color, rich in fossils (Suzuki et al., 2009, Ebbestad et al., 2015). The Jonstorp Formation is interpreted as an intermound facies formed under well oxygenated conditions due to the development of a north-south current during the late Katian (Kiipli et al., 2009). Beside the Jonstorp Formation, there is the later Loka Formation, laterally attached to the Upper Boda Member, and the Glisstjärn Formation overlaying the Boda Limestone Formation (Suzuki et al., 2009; Ebbestad et al., 2015). Both, Loka as well as Glisstjärn, are of Hirnantian age. The mud mound growth stopped with the end of the Katian. The Upper Boda Member is of Hirnantian age and is divided into various layers of stromatactis bearing limestones (wackestone-mudstone) and brachiopod coquinas (grainstone) (Suzuki et al., 2009). The Boda Limestone Formation provides a very diverse fauna, predominantly known from pockets and the flank facies. Over 100 brachiopod and 90 trilobite species are known (Ebbestad et al., 2007) as well as a rich Mollusca fauna with 61 cephalopods, (Kröger, 2011; Kröger & Ebbestad, 2014) and 120 bivalves (Isberg, 1934). The abundant benthos with a high number of byssate bivalves, brachiopods, cystoids (flank facies) and the diversity of cephalopods as top predators, indicate a high availability of planktonic food resources (Kröger & Ebbestad, 2014). There is a high number of endemic taxa, especially in brachiopods and trilobites (Suzuki & Bergström, 1999; Cock, 2005) and a high diversity in strophomenid brachiopods in the Boda Formation with distinct communities. They do not seem to be very diverse in the core facies, however there is a massive occurrence of *Leptaena bergstroemi* (sp. nov., Cocks, 2005) and *Eoplectodonta rhombica*. The strophomenids show a maximum in diversity and occurrence in the flank facies (Cocks, 2005). The pentamerid *Holorhynchus* can be found at the very top of the Boda mud mounds at the transition from Katian to Hirnantian. This taxa occurred at the terminal Katian only and later in the Silurian. It is not known from Hirnantian rocks. *Holorhynchus* is supposed to be an opportunistic taxon and it occurs in low diversity strata (Shiino et al., 2014). Estonian mud mounds show high similarity in brachiopod genera like *Holtedahlina* (Foerste, 1924), *Luhaia* (Roomusoks, 1956), *Leptaena* and *Eostropheodonta* (Bancroft, 1949), but the total number of strophomenids are lower than in the Boda Formation. The Estonian regional stage Vormsi (see Appendix III) corresponds with the Fjäcka shale and early Boda, while Pirgu is of the same age as the

Boda mud mounds. The Porkuni stage is of Hinrnantian age like the Upper Boda Member and Glisstjärn formation. Reef complexes similar to the Boda mud mounds are known from Estonia (Harris et al., 2004), northern England (Keisley Limestone), Ireland (Kildare Limestone) (Parks, 1994), Kazakhstan (Nikitin & Popov, 1996) and Russia (Taimyr) (Nikiforova, 1989; Cocks & Modzalevskaya, 1997).

Pockets

Large fossils within the core facies of the Boda Formation are very rare, but there are syndepositional filled caves or crevices, which are rich in fossils and referred to as pockets. These caves or crevices were formed by tectonics or the breakup of the core limestone into the softer base. These events took place during the mound growth and in later times. Due to the fossil content and isotope analysis the fillings can be dated (i.g., age of Boda Formation or younger). There are two types of pockets in the Boda Formation distinguished by their orientation within the surrounding core limestone – horizontal or vertical – and by their fossil content (Suzuki & Bergström, 1999; Suzuki et al., 2009). Most pockets are dominated by a single group of organisms (Thorslund, 1960), e.g. trilobites (Suzuki & Bergrström, 1999), brachiopods or cephalopods, and within those groups there is an overwhelming number of fossils from a single species. Beside the fossil content internal sediment and calcite cement can be found. Both show properties that on the one hand exclude the case of a sudden burial and on the other hand the presence of water circulation. The first kind of pocket is orientated vertically and its fossil content is characterized by disarticulated parts. In the case of trilobite-dominated pockets, one can only find cranidia and pygidia but no sclerites of smaller size. The fossils show a favored convex-down orientation and traces of microborings. The abundance of cranidia or pygidia depends on their size in different trilobite species. Suzuki and Bergström (1999) interpreted the dominance of parts, belonging to just one species as different faunal assemblages in different parts of the mud mount where the pockets were formed. The lack of smaller parts is explained by the trapping and binding of those by microbial mats on top of the mound. So the filling of that kind of pocket is explained by the transport of large parts of organisms, living on top of the mound in the vicinity of a crevice, falling down and getting buried. The other type of pocket is referred to as horizontal caves. The fossils there are almost complete, but generally smaller in size and randomly orientated. A typical assemblage consists of trilobites, ostracodes and microgastropods. Most of the found trilobites are eyeless. Beside these two types of pockets, there are also complex pockets, containing parts of both types (Suzuki & Bergström, 1999).

Material and methods

This work is based on collected specimens, rock samples and thin sections from seven different sites from three different localities from the Boda Limestone Formation, Siljan region, Dalarna, Sweden. From the investigated strata every specimen within a time-interval was collected. Rock samples for thin section preparation were taken randomly within the strata, except the ones from Jutjärn. The localities are Osmundsberget, Solberga and Jutjärn (figure 3).

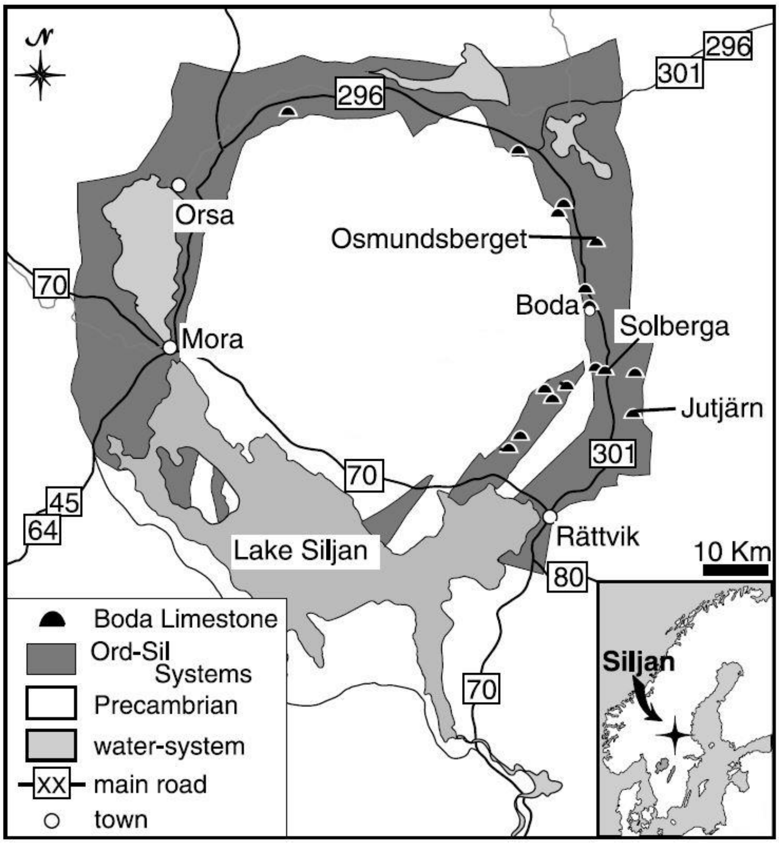


Figure 3: Siljan district, Dalarna, Sweden. The Boda Limestone Formation outcrops are located around a ring-like structure. This is ascribed to a Devonian impact event. The quarries Jutjärn, Solberga and Osmundsberget are shown. Modified from Suzuki et al., 2009.

Every single specimen or fragment counts as a single individual. That does not apply for pelmatozoan segments or bryozoan fragments. If any body part was found, which could be assigned to a single individual it was considered in the data, otherwise there are qualitative data for these taxa only. In the case of Cystoidea (pelmatozoans) the calyces are counted as a single individual. Bryozoans are gathered in a qualitative way due to their fragile anatomy but with a focus on their habitus. The collected material is deposited at Evolutionsmuseet, University of Uppsala.

Statistics

The software program PAST (Hammer & Harper, 2006) was used for the quantitative analysis of the collected material. For comparison of all six sites, a non-metrical multidimensional scaling (NMDS) and in addition to that, a principal coordinates analysis (PCO) is used. For the NMDS the environmental variables are set to 0 and the Bray-Curtis similarity index is used. The NMDS is run several times in the case of an uncertain (not linear) Shepard plot and the result from the most linear Shepard plot was taken. The same index was taken for the PCO. Data sets including all taxa and data sets including brachiopods and Anthozoa (Rugosa and Tabulata) each, are used. To illustrate similarity and grouping a cluster analysis is chosen with the Bray-Curtis similarity index. To examine the diversity of brachiopods rarefaction is used, due to the different amount of collected specimens at each site. The brachiopod communities at the different sites are visualized by abundance diagrams, including the common taxa. The proportion-diagrams of the taxa were made by the program excel (Microsoft office).

Jutjärn

Jutjärn is a still active quarry and from the very top to the bottom a whole mound is accessible. The quarry has an extension of 500 meters (Ebbestad et al., 2007). Different parts of the reef can be found lateral, the flank facies, as well as vertical the typical core limestone with patches of *Palaeoporella* limestone (Jux, 1966) at the base of the mound.

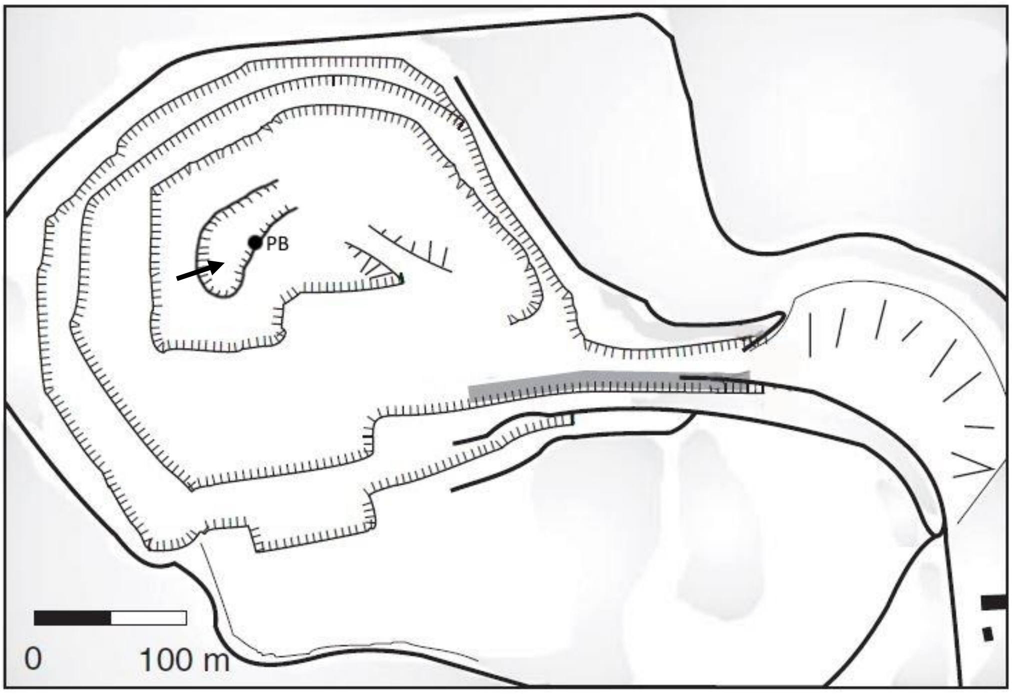


Figure 4: Jutjärn quarry; the pocket named Pocket B (PB) is located at the lowest accessible part (60°59‘04.1“N/15°14‘53.9“E) of the quarry at that time (fourth level, marked by arrow); Modified from Ebbestad et al., 2015.

One pocket with the designation “Pocket B” (PB) was investigated for comparison with the site Solberga_3. This pocket is located at the lower part of the mound complex (60°59‘04.1“N/15°14‘53.9“E) (see figure 4 and 5). Because of the ongoing work in the quarry it is likely that the pocket does not exist anymore. On one side the pocket is narrowed by a pelmatozoan limestone (flank facies) which extends to its very top. At the base of the pocket there is a *Palaeoporella* limestone which passes over into a typical core limestone. The dimension of the pocket itself is about 3 meters in vertical, of which the first two meters look like a duct of a few centimetres in diameter. The duct expands at the third meter to maximum expansion of 50 centimetres and narrows again (figure 6). Samples for thin section preparation were taken in intervals of 50 centimetres of the first two meters of the pocket itself and from the surrounding pelmatozoan and *Palaeoporella* limestone. Macrofossils and bulk samples from the pocket were collected and the orientation of trilobite cranidia and pygidia were measured in situ and later on a larger rock sample.

Figure 5: (above) Entrance to the lowest part of the Jutjärn quarry. The pocket is located at the lowest, fourth level of the quarry; levels are marked.

Figure 6: (right) Pocket B at Jutjärn. The outline of the pocket is coloured in orange, while the pelmatozoan limestone is coloured in blue. Right beneath and on the right side *Palaeoporella* limestone can be found. (scale is 1 m).

Osmundsberget

Osmundsberget is an abandoned quarry (figure 7) and one of the best studied places in the area. Rocks from the Kullsberg Limestone (early Katian) to the Silurian are accessible. Five different sections were investigated there. The core of the Boda mud mound is almost removed, nonetheless one can find parts of the core, interrupted by layers of the Jonstorp Formation. The location presenting the Katian-Hirnantian transition is named “Osmundsberget 4” (OB4) (61° 3'2.98”N / 15°12'11.07"E) (Ebbestad et al., 2007) and is divided from the footwall to the hanging wall into the layers named bed 1 (OB4_B1), bed 2 (OB4_B2) and bed 3 (OB4_B3), shown in figure 8.

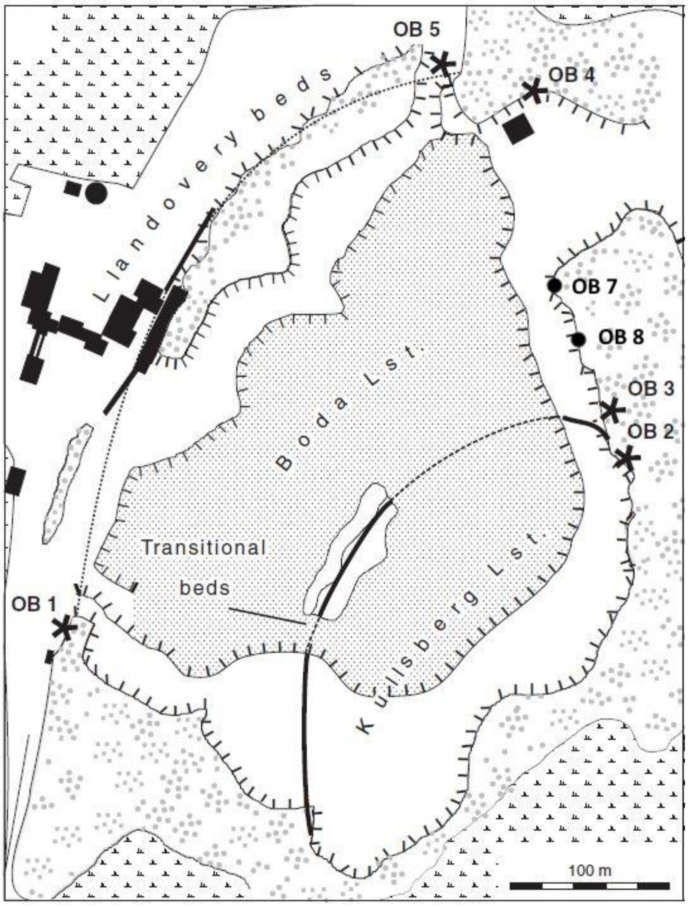


Figure 7: Osmundsberget quarry; the site Osmundsberget 4 (OB4) is located at the north-eastern side of the quarry (61° 3'2.98”N / 15°12'11.07"E). In this work, it is separated into three different beds, named bed 1 to bed 3 (OB4_B1, OB4_B2 and OB4_B3). These are the *Holorhynchus* bearing strata (see Shiino et al., 2014). A detailed view of the sections of OB4 and OB5 are shown in figure 12 (Ebbestad et al., 2015). The two Jonstorp Formation sites Osmundsberget 7 (OB7) (61°03‘00.0“N / 15°12‘08.7“E) and 8 (OB8) (61°02‘58.9“ N / 15°12‘10.0“ E) are located at the eastern wall of the quarry; Modified from Ebbestad et al., 2007

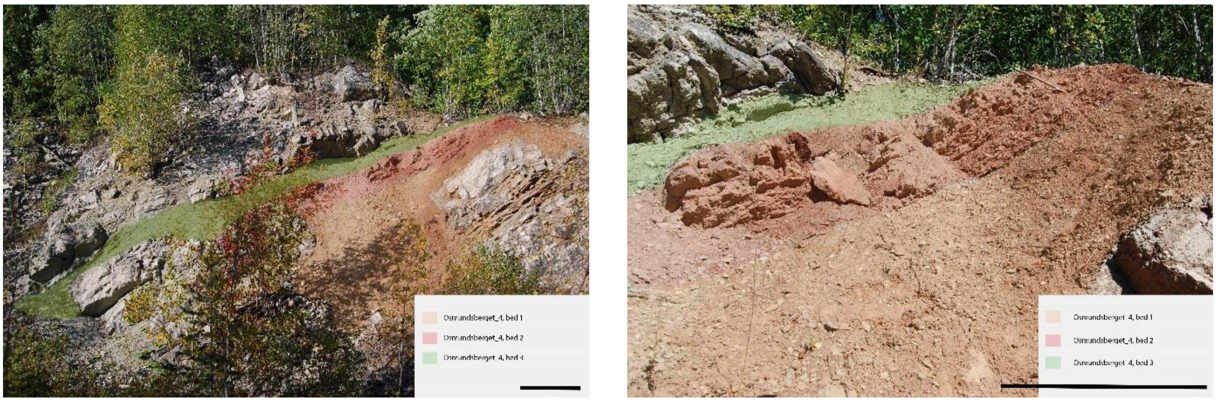


Figure 8: The site OB4 with the three beds. Bed 1 is coloured in brown; the overlaying bed 2 in red and bed 3 in green; right: detailed view. (scales are 1 m).

These sections are characterized by marly limestone, similar to the Jonstorp Formation. The overlaying sections are made up of massive layers of limestone with embedded brachiopod coquinas belonging to the Upper Boda Member (Suzuki et al., 2009) and extend to the early Silurian. The section of OB_4 to OB_5 (see figure 8) are of interest, because they show the transition from the late Katian to the early Silurian. Figure 12 shows the sections including δ^{13}C-values (see Ebbestad et al., 2015). Above the *Holorhynchus* bearing strata there is an increase in δ^{13}C-values (see HICE). The layers with the name Osmundsberget 7 (OB7) (61°03‘00.0“N / 15°12‘08.7“E) and Osmundsberget 8 (OB8) (61°02‘58.9“ N / 15°12‘10.0“ E) (see figure 9) are supposed to correspond with the Jonstorp Formation. OB8 is located in the footwall of OB7 and is three meters thick. OB7 is 2,8 meters thick. Between the two layers there is a core limestone of about 40 meters (see figure 10). Macrofossils, bulk samples and samples for thin section preparation were taken from all five sections. Rugosa, Tabulata, colonies or fragments of bryozoans, pelmatozoan body parts and brachiopods are predominant. Occasionally trilobites and mollusks can be found but in a very poor state of preservation. The fossils were collected randomly from the different strata with no favoured taxonomic affiliation. After two hours of collecting fossils from every stratum, the sampling was stopped. Collecting macrofossils is very easy, because of the high amount of marl of the layers, which is more likely to be weathered than the fossils. The sections were taken from Ebbestad et al., 2015 (see figure 12).

Figure 9: left: The site OB7; the collected material is from the brown coloured area; right: Picture shows the site OB8; brown colored area show the sampling area. (scales are 1 m).

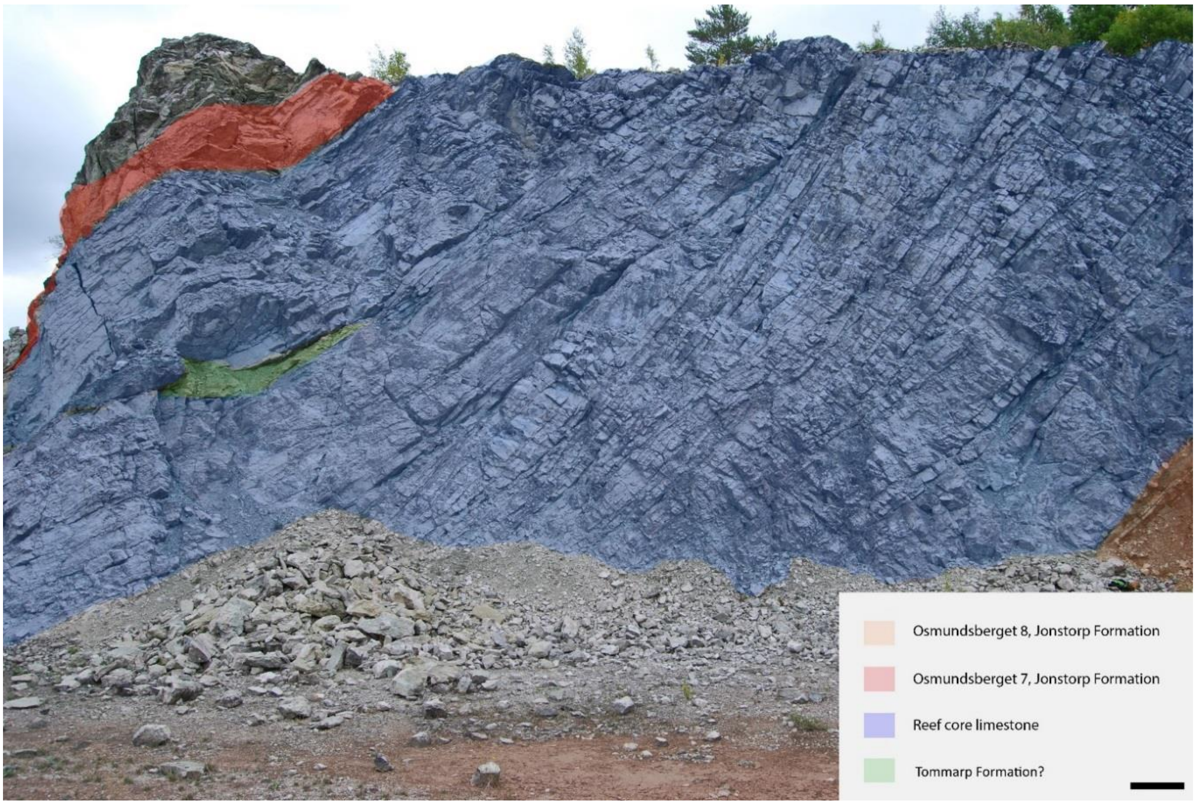


Figure 10: Osmundsberget 7 (red, left) and 8 (orange, right). The layers of typical core limestone between the two Jonstorp Formation strata are about 40 meters thick. The small green layer (right to OB7) could be a Tommarp Formation-like stratum (see Ebbestad et al., 2007). (scale is 1 m).

At all sites at Osmundsberget one can identify different colours, from reddish to greenish, in different layers and within the same layer. Even in larger fossils of Rugosa or Tabulata the colouration extends to the interior of the fossils (see figure 11). The data on the pentamerid *Holorhynchus giganteus* were taken in correspondence with Shiino and Suzuki (Shiino et al., 2014).

Figure 11: Tabulate coral. Consider the red colouration of the interior.

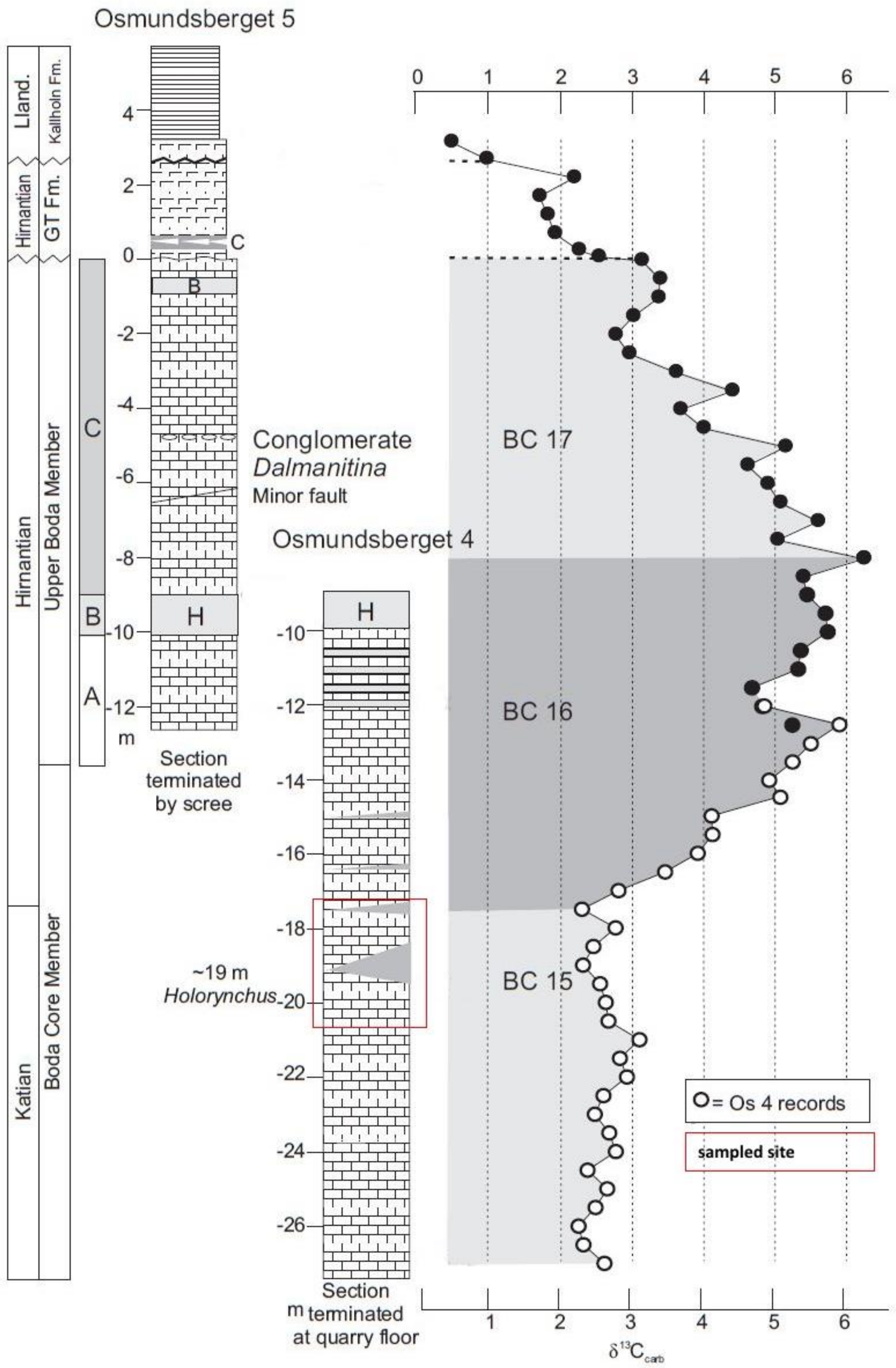
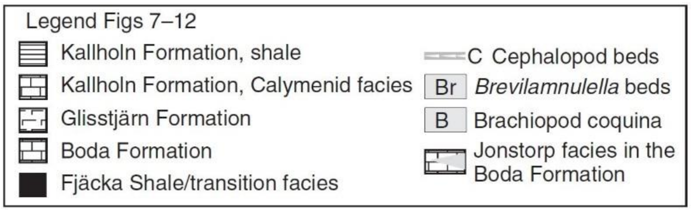


Figure 12: The sections Osmundsberget 4 (OB4 = Os4) and Osmundsberget 5 (OB5) including $\delta^{13}C$-values from the late Katian to the early Silurian. The increased $\delta^{13}C$-values at the Hirnantian are correlated to the HICE. The three beds 1 to 3 from OB4 are marked red, including the *Holorhynchus* bearing strata; Modified from Ebbestad et al,.2015



Solberga

Solberga is an abandoned quarry but of smaller size than Osmundsberget. Like in Osmundsberget, most of the core has already been removed. There is a pocket located at the southern end of the quarry with the designation Solberga_2 (Sol_2) (Ebbestad et al., 2007) (figure 13). It is a complex pocket with several periods of fillings. A section of the core with an exceptional fossil preservation was investigated. There one can find well-preserved fossils surrounded by a typical core limestone. The section is located at the eastern wall of Solberga and named Solberga_3 (Sol_3) (see figure 13 and 14) (60°59'2.35”N/ 15°13'3.24”E).

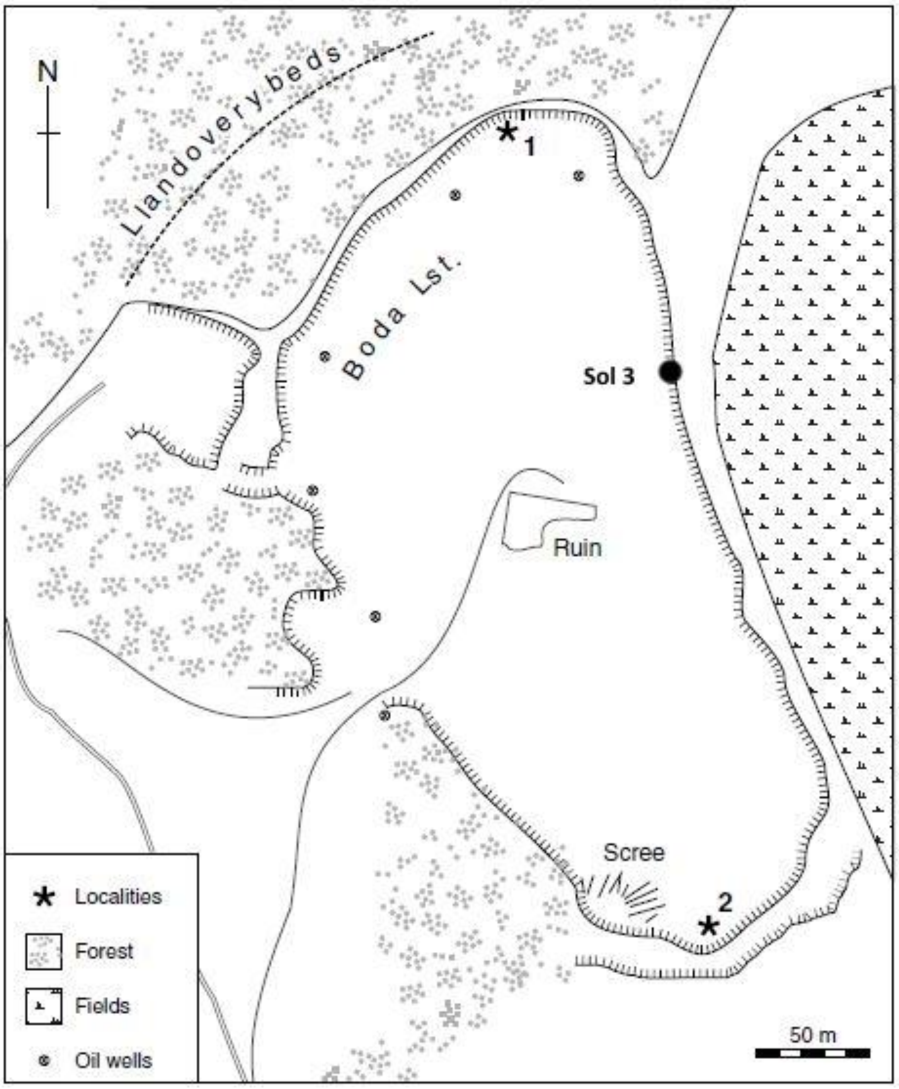


Figure 13: Solberga quarry; the site named Solberga_3 (Sol_3) is located at the eastern wall of the quarry (60°59'2.35”N/ 15°13'3.24”E). Modified from Ebbestad et al., 2007.

Macrofossils were collected and samples for thin section preparation were taken. The collection and preparation of the fossils was more time consuming, because of the compact core limestone. Larger rock samples were taken from the fossiliferous area and were prepared separately. This happened randomly depending on the wall structure. There is no clear boundary between the section of well-preserved fossils and the surrounding core limestone. The section is characterised by massive occurrence of spheroidal structures of 0,5 to about 1 centimetre in diameter. In addition to that spheroidal structures brachiopods, Rugosa, bryozoans and plenty of bivalves, gastropods and cephalopods can be found.

Figure 14: Solberga_3; The fossiliferous area is colored in orange, surrounded by a typical core limestone. B marks the spot where the conjoined bivalve valves were found. Stromatoporid-like structures can be found close to Sol_3.

Results

Taxa total

In total, 68 different taxa from 1395 specimens could be identified to at least the genus level. To get a better overview of the specified taxa they are pooled together into the high ranked taxa Brachiopoda, Rugosa, Tabulata, Mollusca and Trilobita (a more detailed view on these groups will be given later on). The most diverse site in respect of high taxonomic groups is Solberga_3 (Sol_3). Here one can find a very rich mollusk and trilobite fauna in addition to brachiopods and Anthozoa. Figure 15 shows the proportion of taxonomic groups of the different sites.

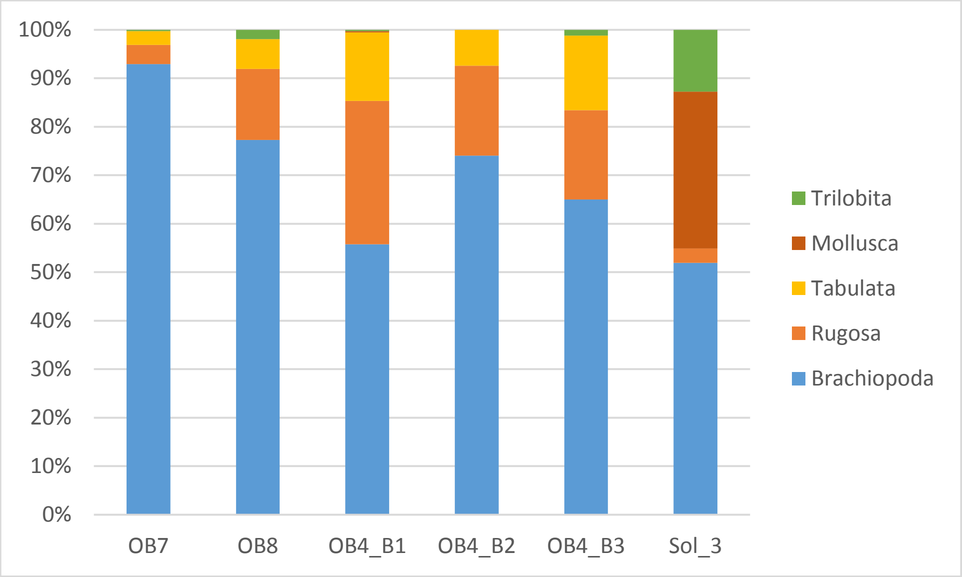


Figure 15: Proportion of different taxa (high taxonomic groups) at the investigated sites. Solberga_3 shows a very rich mollusk fauna, but Tabulata are completely missing. At the sites of Osmundsberget, trilobites and Mollusca are rare and not very well preserved. Rugosa and Tabulata are very common at bed 1 to 3 of OB4 and show a similar distribution.

Generally, Anthozoa (Rugosa and Tabulata) are rare in Solberga. In fact, Tabulata are totally missing and only a few and not well preserved rugosans have been found. Trilobites and mollusks are very rare at the sites of Osmundsberget and the few specimens are not well preserved. However, the brachiopod fauna is very diverse at those sites. Most brachiopod specimens were collected at Osmundsberget 7 (OB7). Including the mode of life of all collected taxa, an overview of the ecospace is given in figure 16. It is a simplified model with six modes included:

- Attached surficial, non-motile suspension feeder: this group includes all brachiopods and tabulate corals.
- Unattached surficial, non-motile suspension feeder: all rugosans are summed up in this group
- Unattached surficial, motile detritus feeder: trilobites of all kind are summed up here, excluding some specific mode of life, e.g. the semi-nektonic ability of *Eobronteus* (Reed, 1928).
- Unattached surficial, slow motile grazers: this group includes all gastropods. They are all assigned to the grazer mode, as very little is known of predatory taxa or other modes of the described taxa.
- Attached surficial, facultative motile suspension feeder: bivalves of any kind are pooled together.
- Pelagic, fast motile predators: although no clear identification of the found cephalopod taxa was possible, they could be assigned to different individuals and are included in the ecospace analysis.

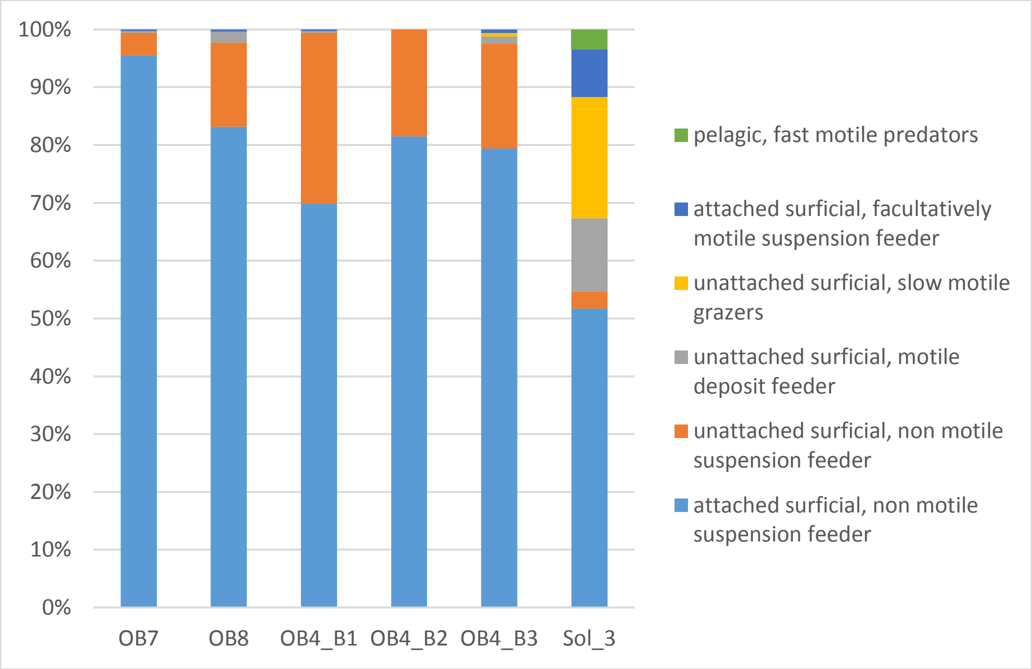


Figure 16: Proportion of ecological modes from the six sites from Osmundsberget and Solberga.

At all sites of Osmundsberget the dominant mode of life is that of attached surficial, non-motile suspension feeder. It is hardly surprising, because most of the fossils collected are brachiopods. OB7 is an extreme example with 95% attached surficial, non-motile suspension feeder. The remaining small amount is taken by unattached surficial, non-motile suspension feeder (Rugosan) and attached surficial, facultative motile suspension feeders from some bivalve fragments. Solberga_3 is, in this respect, very diverse and reflects the taxa composition shown in figure 15.

In a first approach all taxa with a quantitative dataset, Brachiopoda, Rugosa, Tabulata, Trilobita and Mollusca (Gastopoda, Bivalvia) are used for a non-metrical multidimensional scaling (NMDS) and a principal coordinates analysis (PCO). For the NMDS environmental variables are set to 0. For both, the NMDS as well as the PCO, the Bray-Curtis similarity index was chosen. Figures 17 and figure 18 show the results. Both look very similar to each other. The coordinate 1 is almost the same with NMDS and PCO, but with a slight shift. The position on the coordinate 2 axis is the same on both diagrams, but they are inverted to each other.

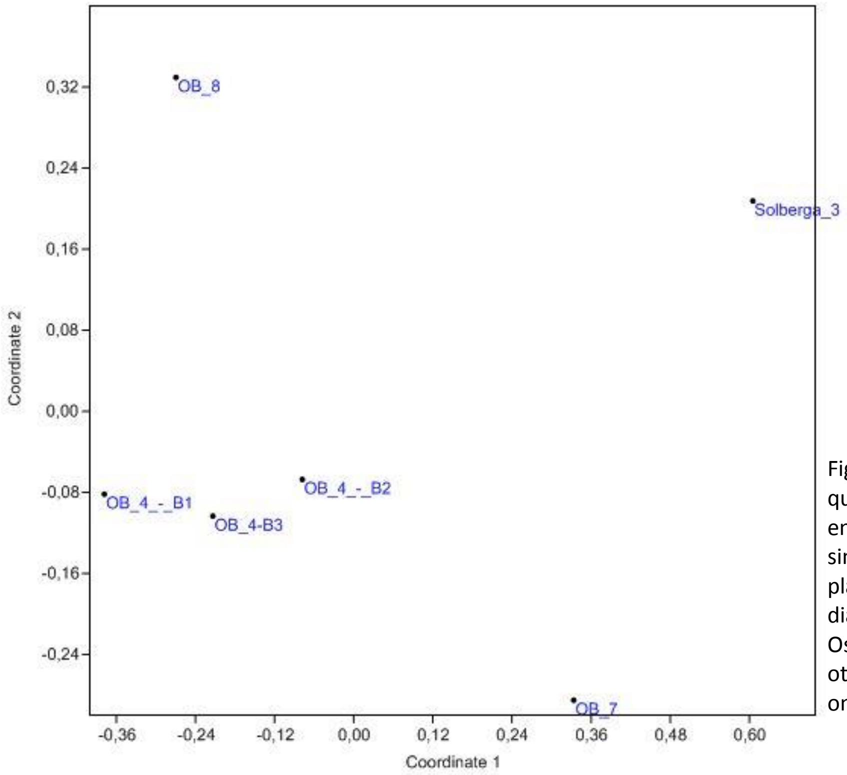


Figure 17: NMDS including quantitative data from all taxa. The environmental variables are 0 with the similarity index Bray-Curtis. Solberga is placed right at the upper part of the diagram. The three beds from Osmundsberget are very close to each other, while OB7 and OB8 are located on opposite sides of the plot.

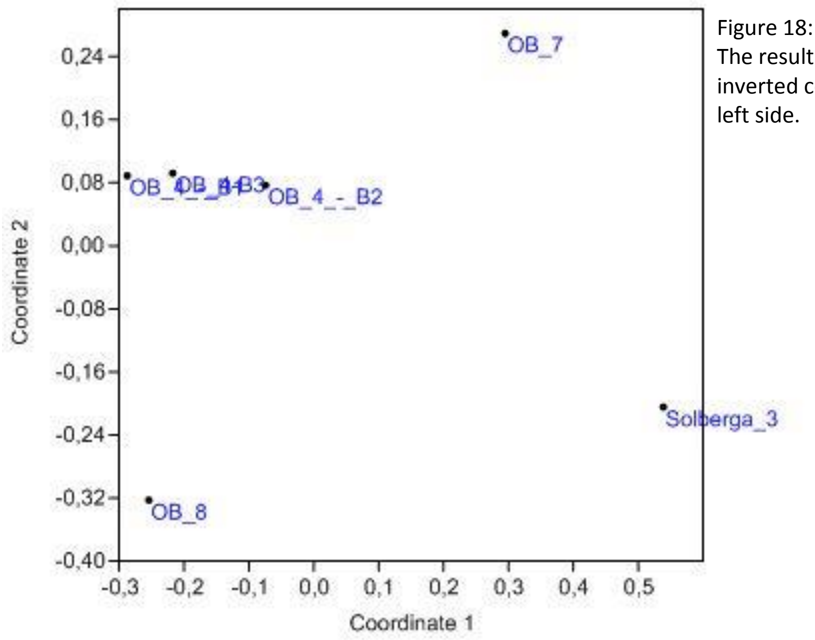


Figure 18: PCO with Bray-Curtis similarity index. The result looks like that for the NMDS but with an inverted coordinate 2 axis and a small shift to the left side.

The similarity of the sites is shown by a cluster analysis in figure 19. Like for the NMDS and PCO, the Bray-Curtis similarity index is used. The sites OB4_B1 to B3 are close, with B2 and B3 more related to each other than to B1. OB8 is placed right to the three beds of OB4. Solberga_3 and OB7 seem to be related and form a sister group of OB8 and the sites of OB4. Different variations of these analysis are tried, e.g. excluding trilobites and/or mollusks (because of taphonomic causes), but the result is not very different from that above. There is a slight shift in the similarity value to higher similarity of OB7 and Solberga.

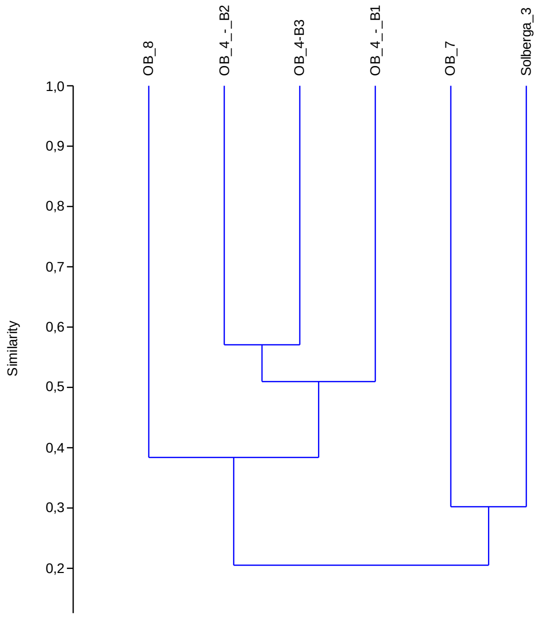


Figure 19: Cluster analysis based on the data from all taxa. OB8 and the three beds from OB4 compared to OB7 and Solberga_3. OB4_B2 and OB4_B3 seem to be very similar with a value of 0,6.

Brachiopoda (plate I – IV)

Brachiopods are the most abundant and diverse taxon occurring at the investigated sites. At the Jonstorp Formation-like sites at Osmundsberget (OB4_B1, OB4_B2 and OB4_B3) as well as the real Jonstorp Formation beds OB7 and OB8, one can find articulated and disarticulated shells. All of the collected specimens belong to the group of articulated brachiopods. There is only one specimen of *Pseudolingula quadrata* (Eichwald, 1829) from Solberga_3 from the group of Inarticulata. The interior of the brachiopod shells is often not well preserved or not accessible, especially at Solberga_3.

The brachiopods from the order Strophomenida (plate I) are represented by 12 taxa. The most common strophomenid is *Eoplectodonta rhombica*; which occurs at every site. It is most abundant in OB7 (59 specimens) and Solberga_3 (39 specimens). Within the genus *Leptaena* two species were collected: *L. bergstroemi* and *L. roomusoksi* (sp. nov., Cocks, 2005). From *L. bergstroemi* four specimens from Solberga_3 and one specimen from OB8 were collected. *L. roomusoksi* was found at OB4_B1 by only one articulated specimen. The identification of the strophomenid *Bimuria popovi* (Cocks, 2005) is uncertain. It occurs at OB4_B2 and OB8, but the specimens are not well preserved. Some of the specimens show similarities to the genus *Lycophoria* (Lahusen, 1885). Unfortunately, none of the specimens show interior parts. Specimens from the small but conspicuous brachiopod *Craspedelia sp*. (Cooper, 1956) are found at the three beds of Osmundsberget 4 but they seem to be rare. The species *Christiania dalarnensis* (Cocks, 2005) can be found at the sites OB7 (6 specimens) and OB8 (20 specimens). All are single valved. The identification of *Eostropheodonta luna* (Angelin & Lindström, 1880) is based on poorly preserved and rare specimens from OB4_B1, OB7 and OB8. The brachiopods identified as *Trondonema bella* (gen. et sp. nov., Cocks, 2005) are common in Solberga_3 (8 specimens). They also occur in OB4_B1 (1 specimen) and OB4_B3 (3 specimens). That genus shows some similarities with *Geniculina* (Roomusoks, 1993), which is not known from Boda. A definite identification needs to include interior parts, but they are mostly not accessible or broken. At OB4_B2 two specimens from the brachiopod *Holtedahlina suedica* (Cocks, 2005) were found, both articulated but the posterior parts were broken. One specimen of *Leangella longae* (sp. nov., Cocks,

2005) was collected at OB7. It is articulated and well preserved. From a specimen from the site Solberga_3, only the beaks (posterior, articulated) are known. It could not assigned to a distinct taxon and is temporarily named Br_40. *Luhaia candelabra* (Cocks, 2005) is, again, known from Solberga_3 by one single valved specimen.

The order Billingsellida (plate I) is represented by one specimen from OB4_B2 only. It was identified as the genus *Vellamo* (Opik, 1930). The specimen is single valved and not well preserved.

From the order Orthotetida (plate I) two genera are identified. The genus *Cliftonia* (Foerste, 1909) was found at OB8 but a clear identification could not be done. It could be an Eospirigerina form. Brachiopod specimen of *Coolinia* (Bancroft, 1949) can be found at OB4_B1. The best preserved specimen is articulated but some parts are broken.

From the brachiopod order Atrypida (plate II), two species could be identified. Both belong to the genus *Eospirigerina* (Schuchert & Cooper 1930) (see plate II). The identification to a distinct species was not possible, however, they are divided into two different taxa, named *Br_2* and *Br_15*. The specimens included in *Br_2* are more flat shaped and circular than the specimens of *Br_15. Br_2* occurs at all sites from Osmundsberget. They are very abundant at OB8 (87 specimens), but rare in OB7 (represented by only one specimen). At OB4_B1 to B2 the number of specimens decreases, but is nearly the same in B3 as in B2. *Br_15* is the most abundant brachiopod taxa at OB7 with 157 specimens. It also occurs at OB4_B2 (12 specimens) and Solberga_3 (25 specimens).

Five different taxa of pentamerid brachiopods could be identified in the samples (plate II). Except for one specimen, all Pentamerida are known from articulated valves. The genus *Parastrophinella* (Schuchert & Cooper 1930) could be found at all sites at Osmundsberget. They are most abundant at OB4_B1 (40 specimens) and OB7 (21 specimens). At the three other sites at Osmundsberget (OB4_B2 and B3, OB8), this taxon occurs occasional. At Solberga_3 no specimen of *Parastrophinella* was found. The genus *Costilamnulella* (Wright & Rong, 2008) occur at OB4_B1 with 19 specimens and with a single one at OB4_B2 and Solberga_3 each. A pentamerid known from OB4_B2 by a single specimen was assigned to the genus *Tscherskidium* (Nikolaev & Sapelnikov, 1969), but the identification is uncertain. It is the only single valved pentamerid in the samples. The genus *Brevilamnulella* (Amsden, 1974) occurs at the site of Solberga_3 with 13 specimens. The data from *Holorhynchus giganteus* are taken from Shiino and Suzuki (Shiino et al., 2014). No specimen of *Holorhynchus* could be found during the fieldwork this work is based on.

The most diverse brachiopod order with 17 species at the investigated sites is that of the Orthida (plate III and Plate IV). Most of the orthids found are articulated and for those which are single valved, the crucial interior is not well preserved. So most of the identification is based on the outer shell morphology. The genera *Dicoelosia* (King, 1850), *Boreadorthis* (Opik, 1934) and *Dalmanella* (Hall & Clarke, 1892) occur at OB4. The first one can be found in all three beds, articulated as well as disarticulated. *Boreadorthis* is restricted to B1 and is represented by 10 specimens, most of them are not well preserved and articulated as well as disarticulated. At OB4_B3 11 specimens of a brachiopod, identified as *Dalmanella*, were found. Unfortunately, none of them is well preserved. The specimens show some similarities to the Hirnantian brachiopod *Hirnantia* (Lamont, 1935). Further on the genera *Sulevorthis* (Jaanusson & Bassett, 1993), *Br_5, Nicolella* (Reed, 1917), *Br_17* and *Laticrura* (Cooper, 1956) are identified from OB4, OB7 and OB8. Of the genus *Sulevorthis*, three different species could be found. The only one, who could be identified definitely to the species level is *S. lyckholmensis* (Jaanusson & Bassett, 1993). It is known from all three beds at OB4 and the two Jonstorp Formation sites OB7 and OB8. One of the other *Sulevorthis* species occur at OB4_B1 and B2 only. They differ from the specimens of *S. lyckholmensis* but could not definitely be assigned to a specific *Sulevorthis* species, so it is named *Br_7*. The third *Sulevorthis* species with the name *Br_32* differs from the previous two and was found at OB4_B1 and OB7. The orthid *Br_5* is known from all sites at Osmundsberget, except from bed 2 from OB4. At OB7 the species is more abundant compared to the other sites. The genus *Nicolella* is represented by two species: *N. oswaldi* (Reed, 1917) and *N.sp.*. *N. oswaldi* is known from all sites at Osmundsberget. All other *Nicolella* specimens that differ from *N. oswaldi* are put together into *N.sp.*. They can be found at OB4_B1 and OB8. The brachiopod *Br_17* occurs at bed 1 of OB4, OB7 and OB8. It is uncertain, whether the specimen from OB4_B1 is the same as that, found in the two Jonstorp Formation sites. Br_5 and Br_17 show similarities to the genera *Onniella* (Bancroft, 1928) and *Howellites* (Bancroft, 1945). At the same sites as *Br_17* specimens of the genus *Laticrura* can be found, with 10 specimens in OB4_B1 and one each at OB7 and OB8. *Resserella pirguensis* (Hints, 1975) is represented in all six sites of Osmundsberget and Solberga_3. It has a peak in abundance at OB8 with 28 specimens, compared to the other sites (see table, Appendix I). Specimens from the two species *Plaesiomys saxbyana* (Oraspold, 1959) and *Barbarorthis foraminifera* (Opik, 1934) were collected at the Jonstorp Formation sites OB7 and OB8 only. Most of the specimens are single valved and the interior is exposed but not very well preserved. A brachiopod exclusively known from OB7 is *Drabovia* (Havlicek, 1950). One well preserved and articulated specimen was collected but its definite assignation to the genus *Drabovia* is not confirmed. One species named Br_45 was found at Solberga by five specimens. A further identification was not possible because of the poor preservation of the specimens. At OB8, one specimen of a brachiopod named Br_46 was found. The specimen is well preserved with articulated valves.

The inarticulate brachiopods are represented by a single specimen identified as *Pseudolingula quadrata* (plate IV) from Solberga_3. It is single valved (ventral valve) and the anterior parts are broken. The interior is not visible. Noticeable is the brownish colour compared to the surrounding fawn limestone.

Figure 20 shows the distribution of the different brachiopod orders at the different sites. The three beds at OB4 have almost the same composition, except from the low occurrence of pentamerids in bed 2. Furthermore bed 2 is the only site with brachiopods from the order Billingsellida. So bed 1 and 3 look more similar to each other than bed 2. All beds show an orthid fraction of nearly 40 percent or more. The two Jonstorp Formation sites OB7 and OB8 are dominated by atrypids with more than 40 percent and a low fraction of pentamerids. The amount of strophomenids is similar to that of the beds from OB4. OB7 shows a smaller percentage of orthids than OB8 (almost by a half).

The dominant order at Solberga_3 are the Strophomenida with nearly 50 percent. Compared to the other sites, the proportion of orthids is very low with about 10 percent. Remarkable is the occurrence of the lingulid *Pseudolingula quadrata*.

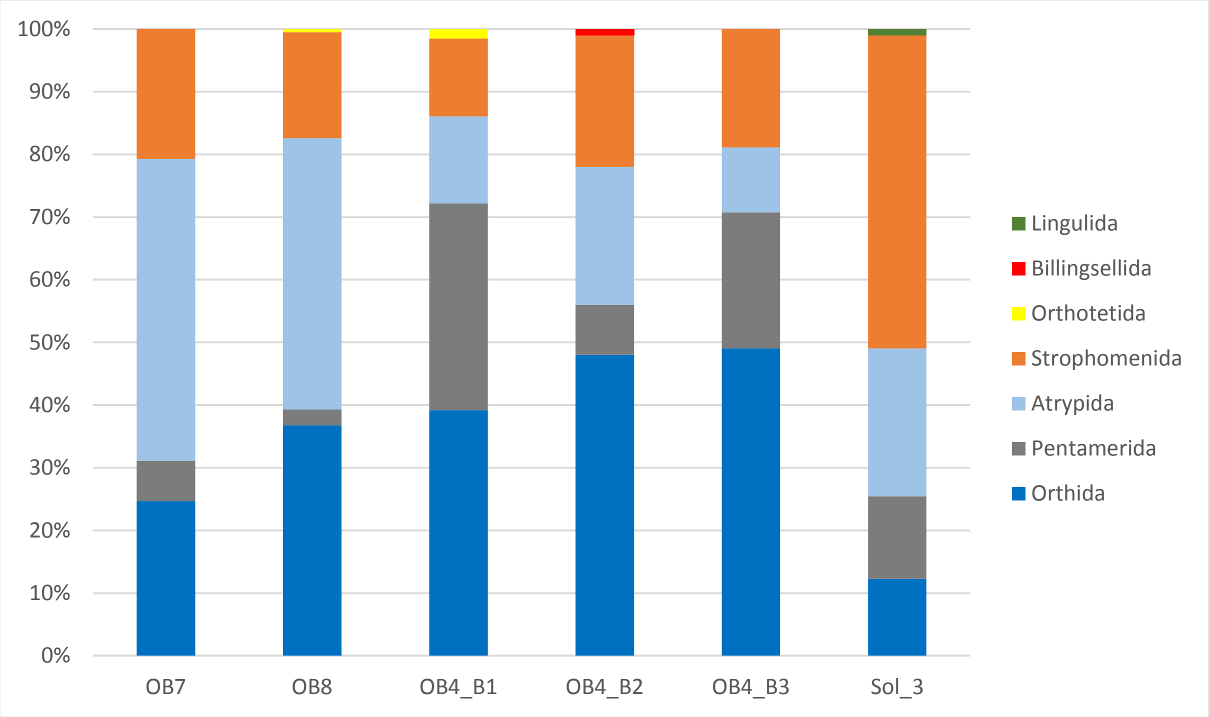


Figure 20: Proportion of brachiopod oders from the five sites from Osmundsberget and the one from Solberga_3. The Jonstorp Formation sites OB7 and OB8 are dominated by atrypids while the side Sol_3 is dominated by Strophomenida.

The site with the most diverse brachiopod fauna is OB4_B1 with 21 different species (S(n)) out of 194 specimens (n). OB7 has a total number of 328 specimens and 17 species. The same number of species can be found in OB8 with a specimen number of 201. The site OB4_B2 has the lowest number of collected specimens with 100 but 16 different species. OB4_B3 shows 12 species out of 106 specimens and the same applies for Sol_3. For better comparison of the six sites, an individual rarefaction was used. The rarefaction results are summarized in table 1.

Site	Number of specimens n_{total}	Number of species $S(n_{total})$	Standardized number of species S(100)
OB7	328	17	12
OB 8	201	17	13
OB4_B1	194	21	17
OB4_B2	100	16	16
OB4_B3	106	12	12
Solberga_3	106	12	12

Table 1: Results from the rarefaction analysis of the six different sites.

At OB4_B3 there is no significant effect on the reduction to n = 100. The species number is still S(100)=12. Applying the rarefaction method on OB7 reduces the number of species to S(100) = 12. Reducing the number of specimens at OB8 to n = 100 decreases the species number to S(100) = 13. In the case of Sol_3, the rarefaction result is the same as in OB4_B3 with no change in the number of species.

To get an impression of the evenness respective to the brachiopods at the sites, the figures 21 to 26 show abundance plots for each site. At OB4_B1 (figure 21) the most abundant species is the pentamerid *Parastrophinella* with 40 specimens. The atrypid *Eospirigerina* (*Br_2*) is the second most abundant species, followed by *Eoplectodonta rhombica* and another pentamerid *Costilamnulella sp.*. The evenness index is 0,59.

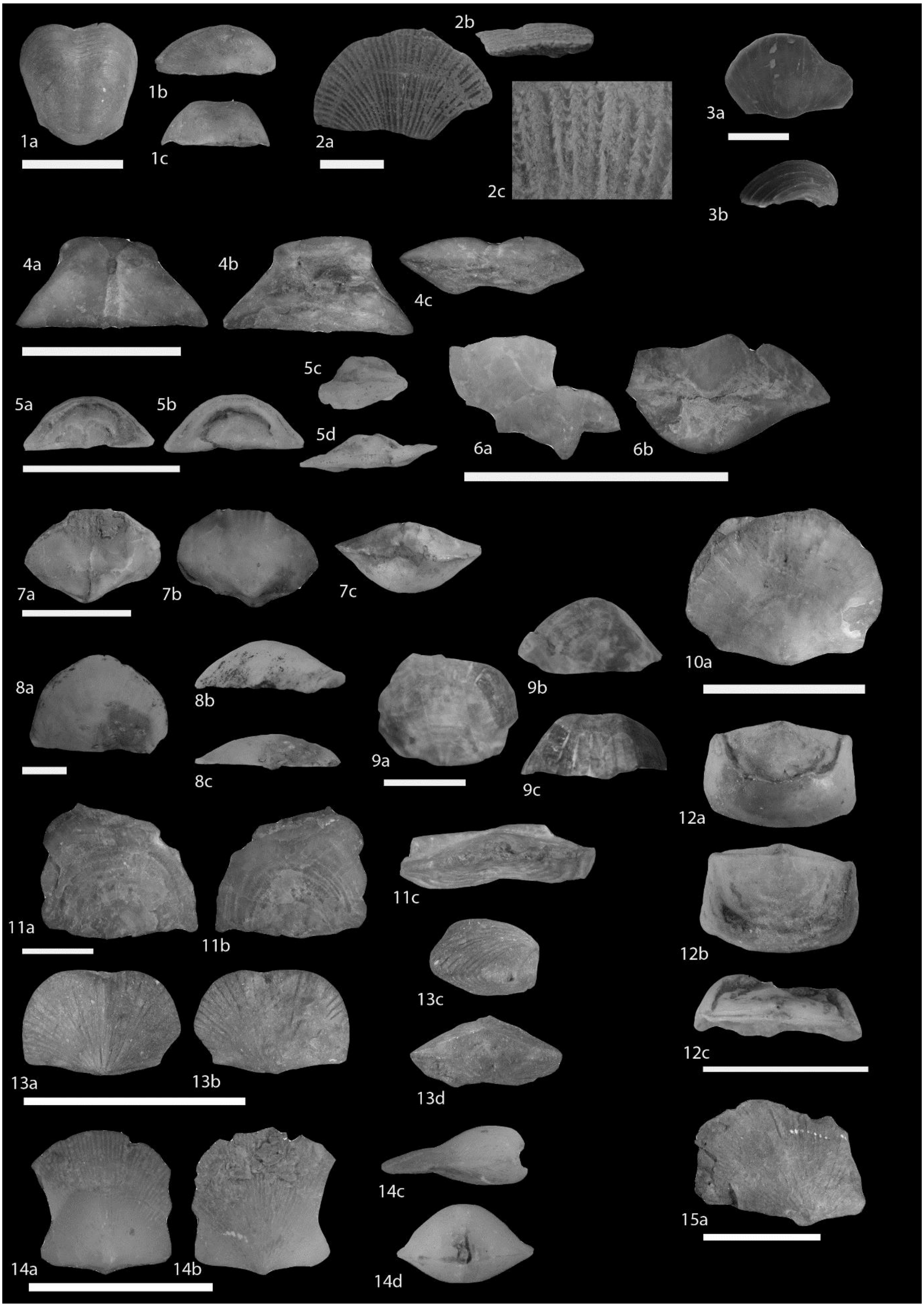


Plate I: Strophomenida, Orthotetida and Billingsellida. (scale is 1cm). For description see p. 36.

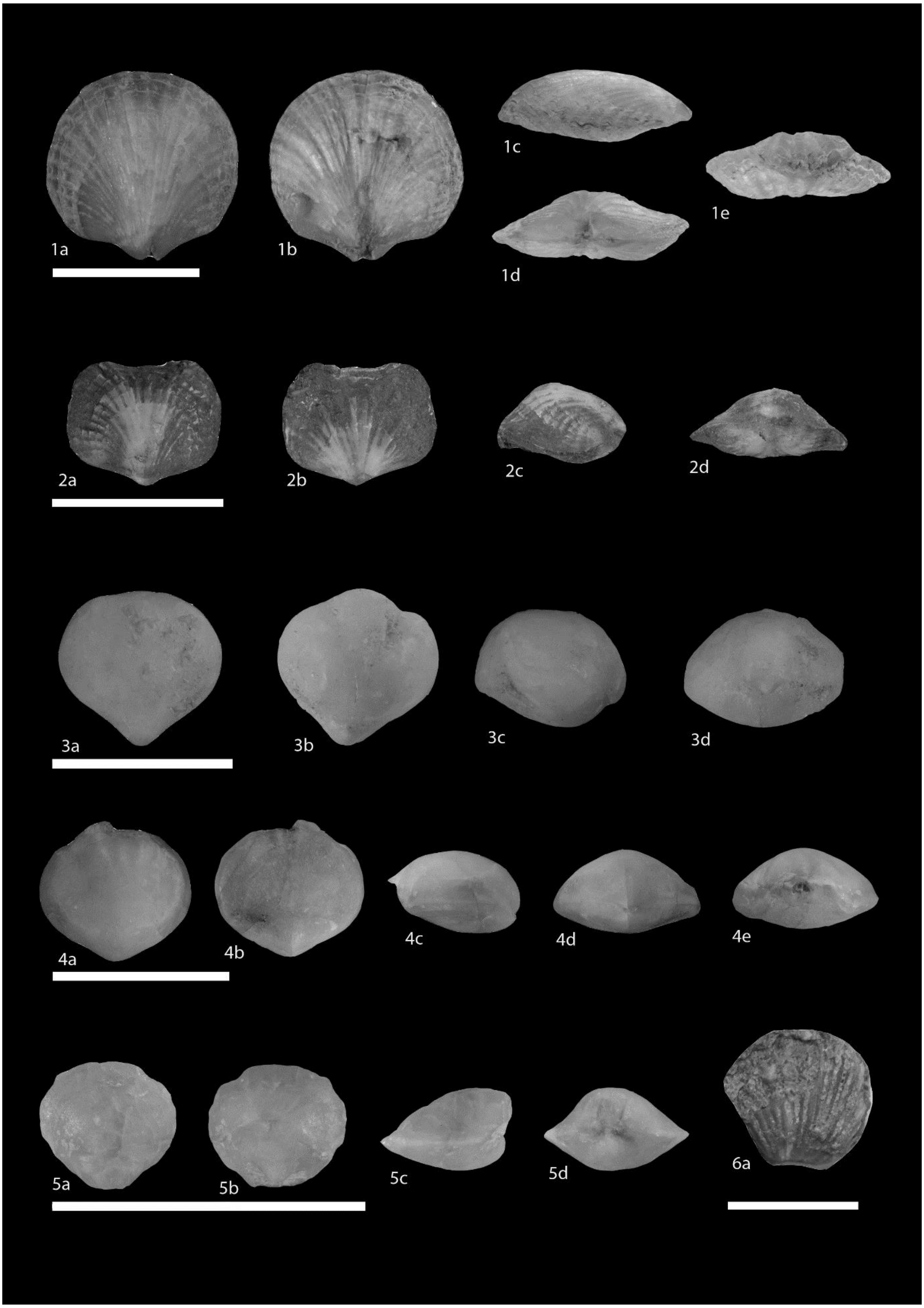


Plate II: Atrypida and Pentamerida, (scale is 1cm). For description see p. 36.

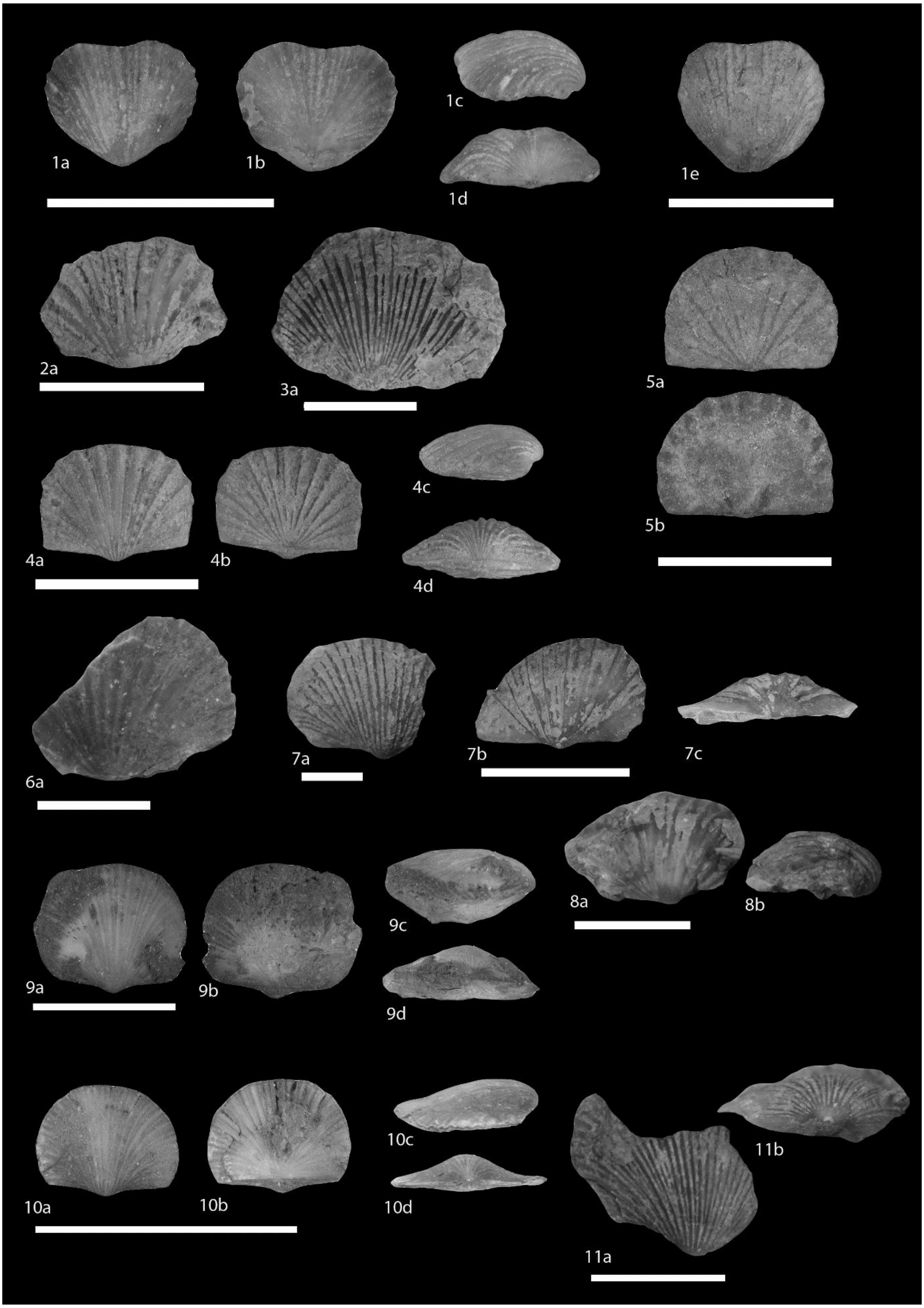


Plate III: Orthida, (scale is 1cm). For description see p. 36.

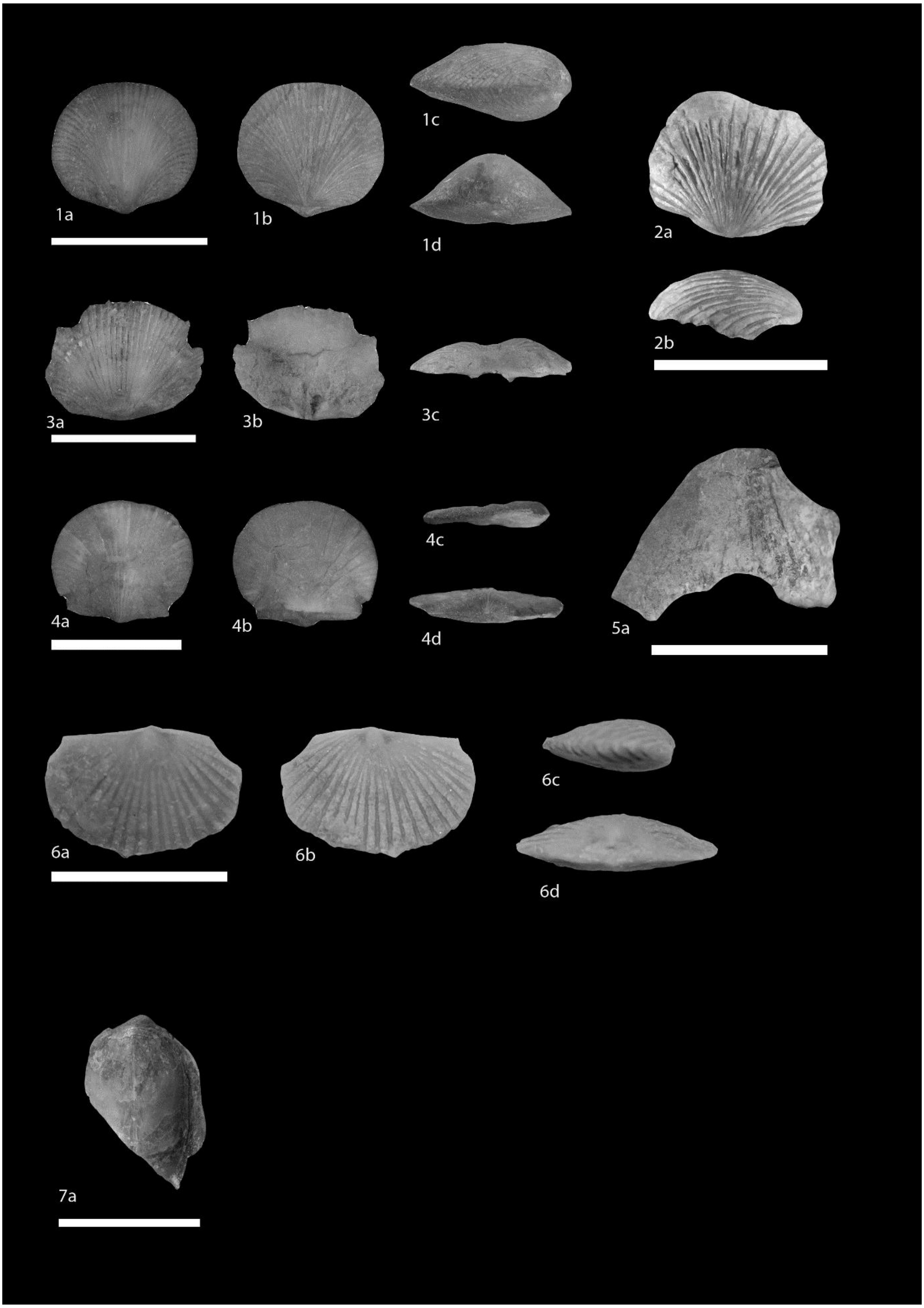


Plate IV: Orthida and Lingulida, (scale is 1cm). For description see p. 36.

Plate I: Strophomenida: 1a-c: *Christiania dalarnensis*, a) ventral valve, b) lateral, c) posterior; 2a-c: *Holtedahlina suedica*, a) ventral valve?, b) lateral, c) detail; 3a-b: *Eoplectodonta rhombica*, a) ventral valve, b) lateral c) detail; 4a-c: *Leangella longae*, a) ventral valve, b) dorsal valve, c) posterior; 5a-d: *Craspedelia*, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 6a-b: Br_40, a) ventral valve, b) posterior; 7a-c: *Bimuria popovi*?, a) ventral valve, b) dorsal valve, c) posterior; 8a-c: *Trondonema bella*, a) ventral valve, b) lateral, c) posterior; 9a-c: *Luhaia candelabra*, a) ventral valve, b) lateral, c) anterior; 10a: *Eostropheodonta luna*, ventral valve; 11a-b: *Leptaena bergstroemi*, a) ventral valve, b) dorsal valve, c) posterior; 12a-c: *Leptaena roomusoksi*, a) ventral valve, b) dorsal valve, c) posterior; Orthotetida: 13a-d: *Cliftonia sp*.?, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 14a-d: *Coolinia dalmani*, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; Billingsellida: 15a: *Vellamo sp*.?, ventral valve. (scale is 1cm)

Plate II: Atrypida: 1a-e: Br_2, a) ventral valve, b) dorsal valve, c) lateral, d) posterior, e) anterior; 2a-d: Br_15, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; Pentamerida: 3a-d: *Parastrophinella sp*., a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 4a-e: *Brevilamnulella sp*.?, a) ventral valve, b) dorsal valve, c) lateral, d) posterior, e) anterior; 5a-d: *Costilamnulella sp*.?, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 6a: *Tscherskidium sp*.?, ventral valve. (scale is 1cm)

Plate III: Orthida: 1a-e: *Dicoelosia sp*., a) ventral valve, b) dorsal valve, c) lateral, d) posterior, e) ventral valve; 2a: *Boreadorthis sp*., ventral valve; 3a: *Dalmanella testudinarius*, ventral valve; 4a-d: *Sulevorthis lyckholmensis*, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 5a-b: Br_7, a) ventral valve, b) ventral valve interior; 6a: Br_32, a) ventral valve; 7a-c: *Nicolella oswaldi*, a) ventral valve, b) ventral valve, c) posterior; 8a-b: *Barbarothis foraminifera*, a) ventral valve, b) lateral; 9a-d: Br_5, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 10a-d: Br_17, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 11a-b: *Laticrura sp*.?, a) ventral valve, b) posterior. (scale is 1cm)

Plate IV: Orthida: 1a-d: *Resserella pirguensis*, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 2a-b: *Barbarorthis foraminifera*, a) ventral valve, b) lateral; 3a-c: *Plaesiomys saxbyana*, a) dorsal valve?, b) dorsal valve interior, c) posterior; 4a-d: *Drabovia sp*.?, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; 5a: Br_45, ?; 6a-d: Br_46, a) ventral valve, b) dorsal valve, c) lateral, d) posterior; Lingulida: 7a: *Pseudolingula quadrata*, ventral valve. (scale is 1cm)

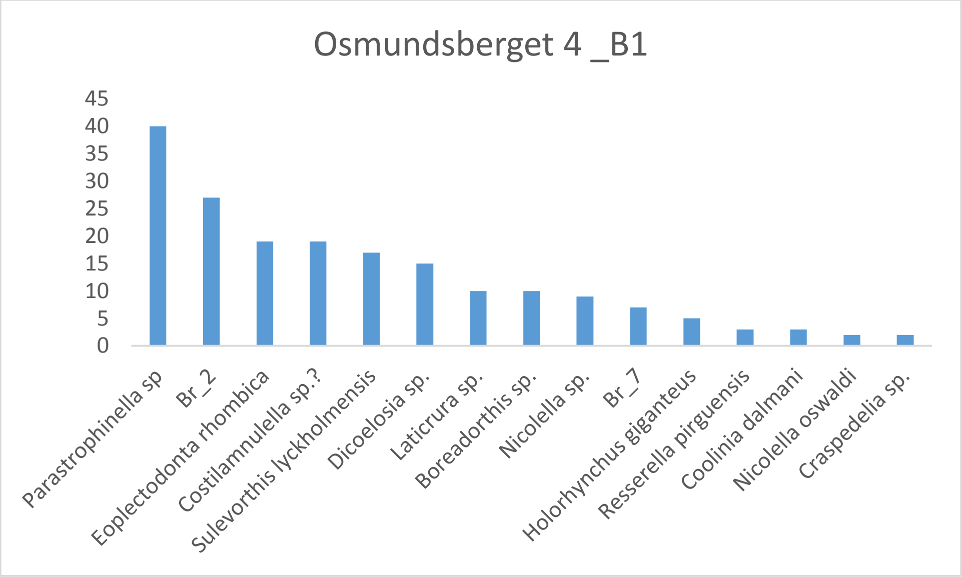


Figure 21: Abundance plot of the site OB4_B1. Evenness index is 0,59.

The species distribution for OB4_B2 is shown in figure 22. Like in bed 1, *Eoplectodonta rhombica* is one of the dominant elements. The most abundant species is the orthid *Sulevorthis lyckholmensis* with 27 specimens. The atrypids are also an important element with Br_15 and Br_2, both belonging to the genus *Eospirigerina*. In this bed, the orthids are more dominant than in bed 1. With 0.54 the evenness index is similar to that of OB4_B1

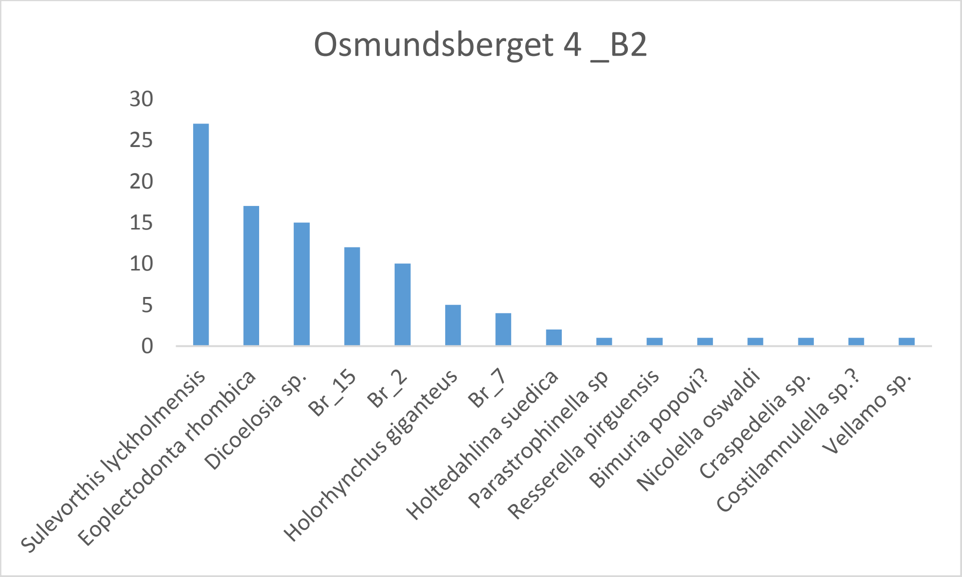


Figure 22: Abundance plot of the site OB4_B2. Evenness index is 0,54.

The orthid *Sulevorthis lyckholmensis* is the dominant species in bed 3 (figure 23), again, like in bed 2, closely followed by *Holorhynchus giganteus. Eoplectodonta rhombica* and the eospirigerine species *Br_2* are also an abundant element. With 0.80 this bed shows the highest evenness index of all investigated sites.

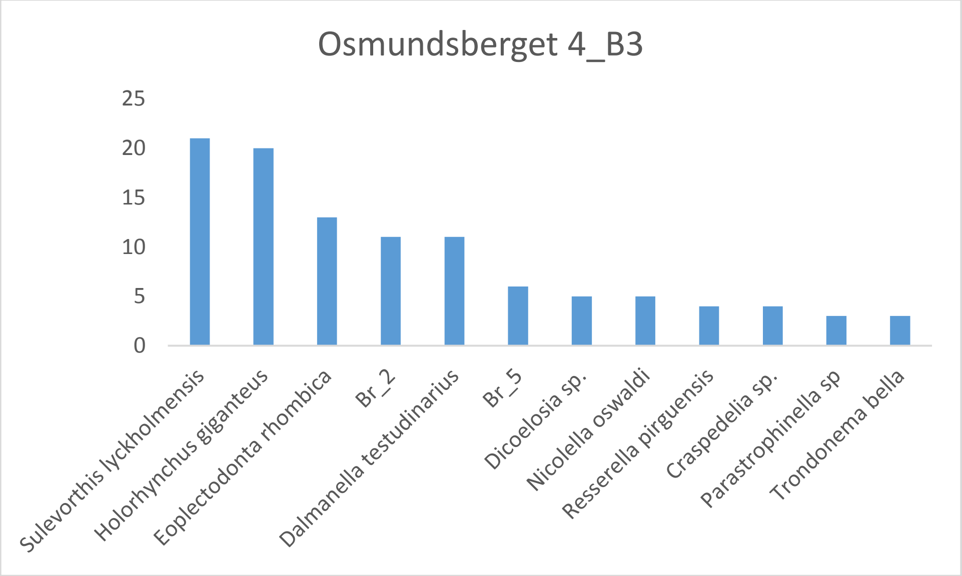


Figure 23: Abundance plot of the site OB4_B3. Evenness index is 0,80.

At the Jonstorp Formation sites OB7 (figure 24) and OB8 (figure 25) the high dominance of one species compared to other species is remarkable. At OB7 this is *Br_15*, followed *by Eoplectodonta rhombica*, the orthid *Nicolella oswaldi* and the pentamerid *Parastrophinella sp*.. Compared to that, OB8 shows a very different distribution. The dominant element here is *Br_2*, followed by several orthids like *Resserella pirguensis* and *Sulevorthis lyckholmensis*. Pentamerids are rare at this site. The evenness indices of the two sites are 0,34 for OB7 and 0,40 for OB8. These are the lowest indices of all sites sampled.

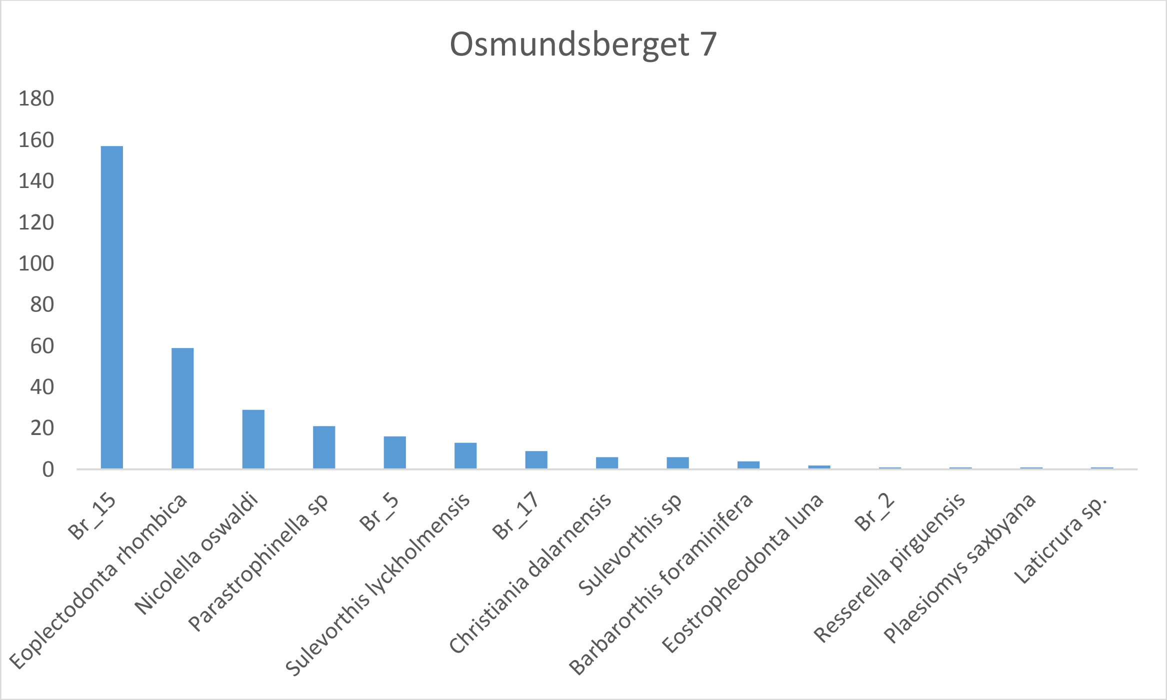


Figure 24: Abundance plot of the site OB7. Evenness index is 0,34.

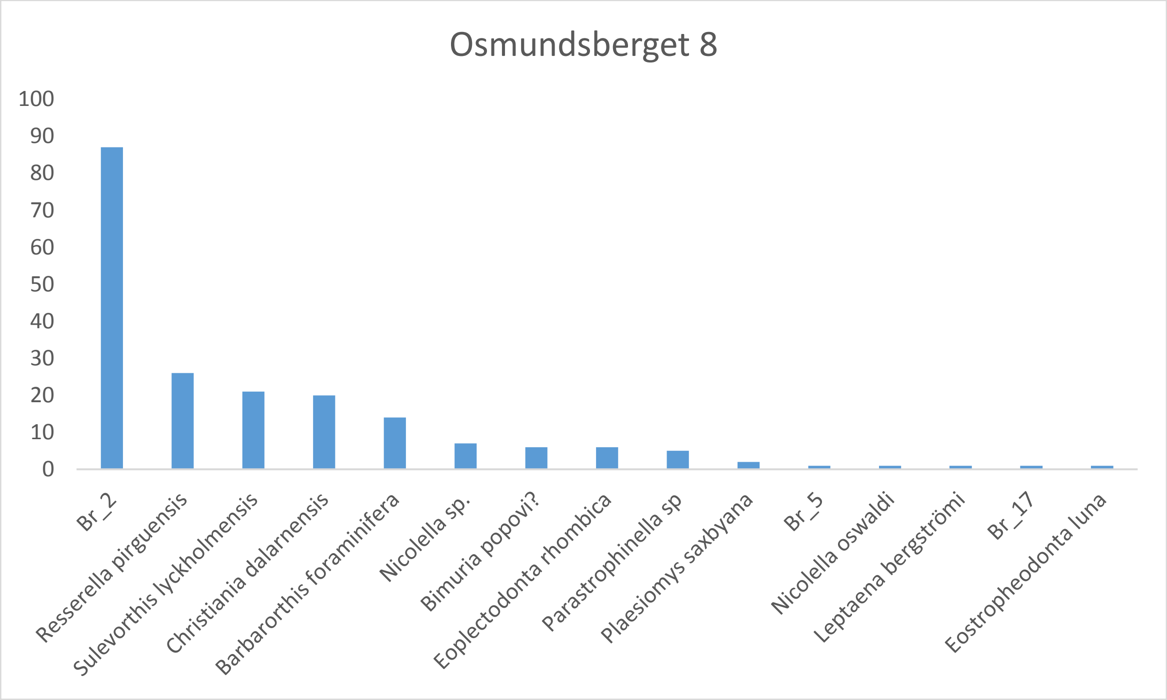


Figure 25: Abundance plot of the site OB8. Evenness index is 0,40.

At Solberga_3 (figure 26) *Eoplectodonta rhombica* is the species with the highest number of specimens, followed by *Br_15* and the pentamerid *Brevilamnulella sp.*. The evenness index is 0,52.

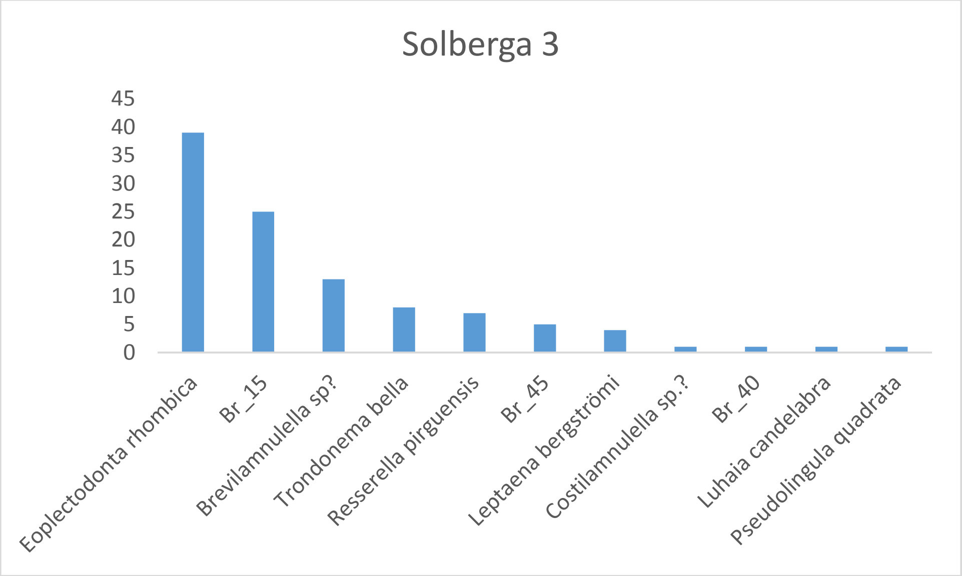


Figure 26: Abundance plot of the site Sol_3. Evenness index is 0,52.

Having done a NMDS including all taxa, another NMDS including only brachiopod taxa was done (see figure 27). The environmental variables are set to 0 with a Bray-Curtis similarity measure. The beds 1 and 2 from OB4 are placed in a middle range and differ significant from OB4_B3 in distance on the coordinate 2 axis. OB8 can be found at the upper left corner. The sites OB7 and Solberga_3 are relatively close, concerning the composition of the brachiopod taxa.

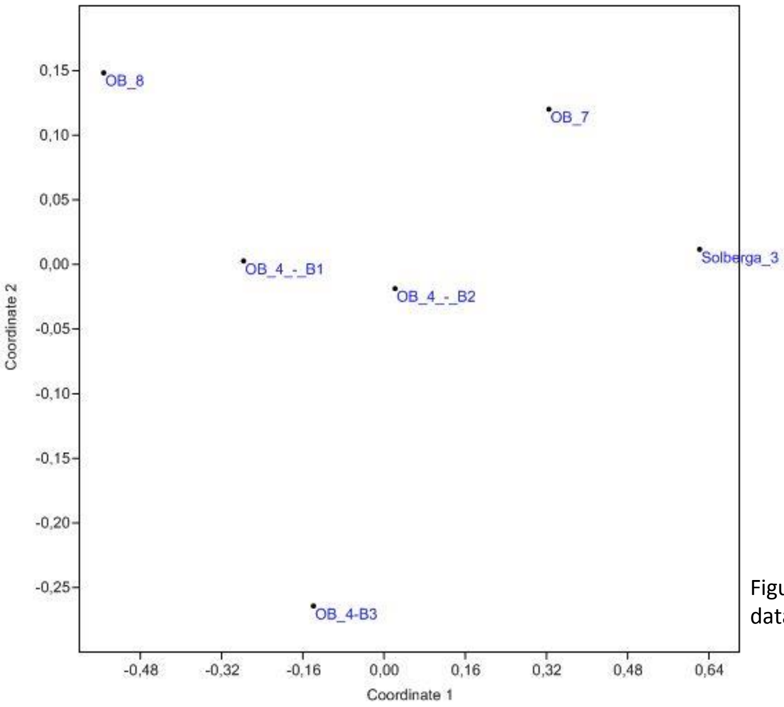


Figure 27: Results from the NMDS including data from brachiopods.

Doing a PCO using the brachiopod data shows a similar result but with a switched coordinate 1 axis (see figure 28). Noticeable is the change in the position of OB4_B2 and B3 in relation to B1.

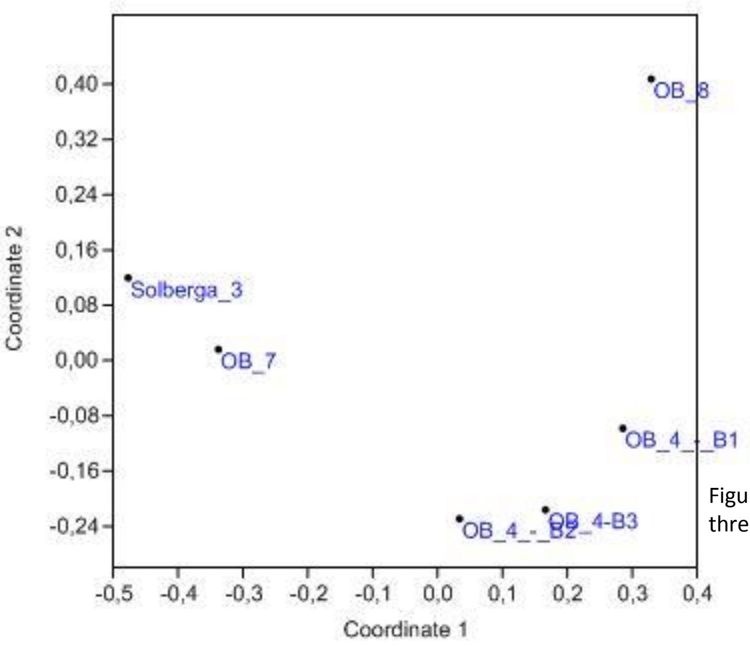


Figure 28: PCO results from brachiopod data. The three sites from OB4 are close together.

The cluster analysis in figure 29 shows basically the same results as the cluster analysis including all taxa did. OB4_B2 and B3 are more related to each other than to OB4_B1. The Jonstorp Formation site OB8 is allied to the three sites of OB4 and together they are opposed to OB7 and Solberga_3.

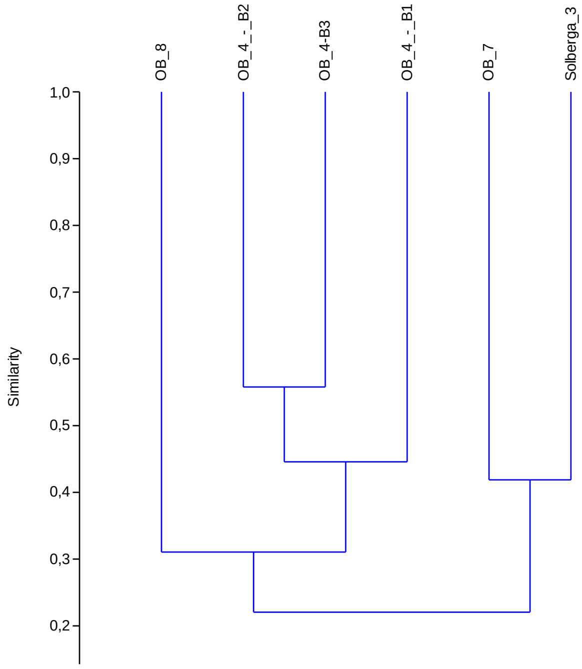


Figure 29: Results from the cluster analysis, reflecting the results from the PCO. The three sites from OB4 are close.

Anthozoa: Rugosa and Tabulata (plate V – VIII)

Apart from the brachiopods, the Rugosa (see plate V, VI and VII) and Tabulata (see plate VIII) are very abundant at the five sites at Osmundsberget. From Solberga_3 only three rugosan specimens and no Tabulata are known. In figure 30 the proportion of Rugosa to Tabulata is illustrated. Except from OB4_B3, all of the Osmundsberget sites seem to have almost the same proportion. In total 216 specimens of rugosa were found and 162 specimens could be identified to the species level. They belong to the genera *Grewingkia* (Dybowski, 1873), *Streptelasma* (Hall, 1847), *Bodophyllum* (Neuman, 1969) and *Borelasma* (Neuman, 1969). All of them are from the order Stauriida. Two species of the genus *Grewingkia* are known: *G. bilateralis* (Neuman, 1969) and *G. context* (Neuman, 1969). Specimens from *G. bilateralis* and *G. contexta* were collected at OB4_B1 and OB7. *G. contexta* is known from each site, except OB7 and it is the only Rugosa found in Solberga_3 represented by three specimens. *Streptelasma primum* (Wedekind, 1927) occur in the samples taken from all sites at Osmundsberget. The species *Bodophyllum osmundense* (Neuman, 1969) and *Borelasma crassitangens* (Neuman, 1969) are most abundant at OB4_B1 but can be found again at all five sites from Osmundsberget. Plates V to VII show some collected specimens. Most of the Rugosa specimens show unilateral erosive marks (see plate V: 2 and 4; plate VI: 2; plate VII: 7 and 9). Within the Tabulata four different taxa could be identified. From the order Heliolitida two subtaxa could be identified based on the habitus: one heliolitid with coralites close together (*Heliolitida_c*) (Appendix II, Ta_2) (plate VIII: 3a – c) and the other one with coralites wide apart (*Heliolitida_w*) (Appendix II, Ta_1) (plate VIII: 1a – c, 2a). The *Heliolitada_c* occur in all three beds of OB4 and at OB8, while the *Heliolitida_w* occur in all sites of Osmundsberget. A third heliolitid could be identified as the genus *Halysites* (Waldheim, 1828) (plate VIII: 4a – b). It can be found at all sites of Osmundsberget, like *Heliolitida_w*. One genus from the order Lichenariida is known, namely *Lichenaria* (Winchell and Schuchert, 1895) (plate VIII: 5a – c). It is most abundant in OB4_B1 and it could not be found in OB7.

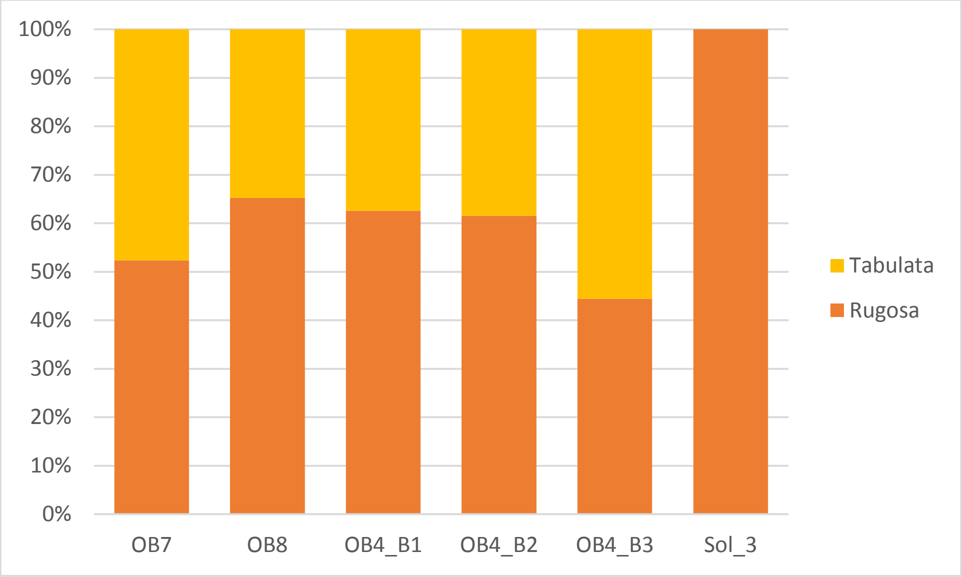


Figure 30: Proportion of Tabulata and Rugosa. The five sites from Osmundsberget show almost the same proportion.

To compare the different sites based on their content of Tabulata specimens with each other, two major approaches were tried: the first one is the proportion of the different identified taxa (*Heliolitida_c, Heliolitida_w, Lichenaria* and *Halysites*), shown in figure 31. Solberga_3 is not shown, because there were no Tabulata found. All five sites from Osmundsberget seem to be quite different. At bed 1 and 3 of OB4, *Lichenaria* is the dominant element with about 40 percent but they show different values in their *Heliolitida_c* and *Halysites* proportion. Regarding to the *Halysites* proportion, bed 3 is similar to bed 2, but the proportion for *Heliolitida_w* is very different. The two Jonstorp Formation sites OB7 and OB8 are dominated by *Halysites*. At OB7 there are two taxa only: *Halysites* with 70 percent and *Heliolitida_c* with 30 percent. OB8 is more diverse than OB7 but *Halysites* is with almost 65 percent the predominant taxon. The values for *Lichenaria* and *Heliolitida_c* are similar to that of OB4_B2. It shows a very low fraction of *Heliolitida_w* (about 5 percent).

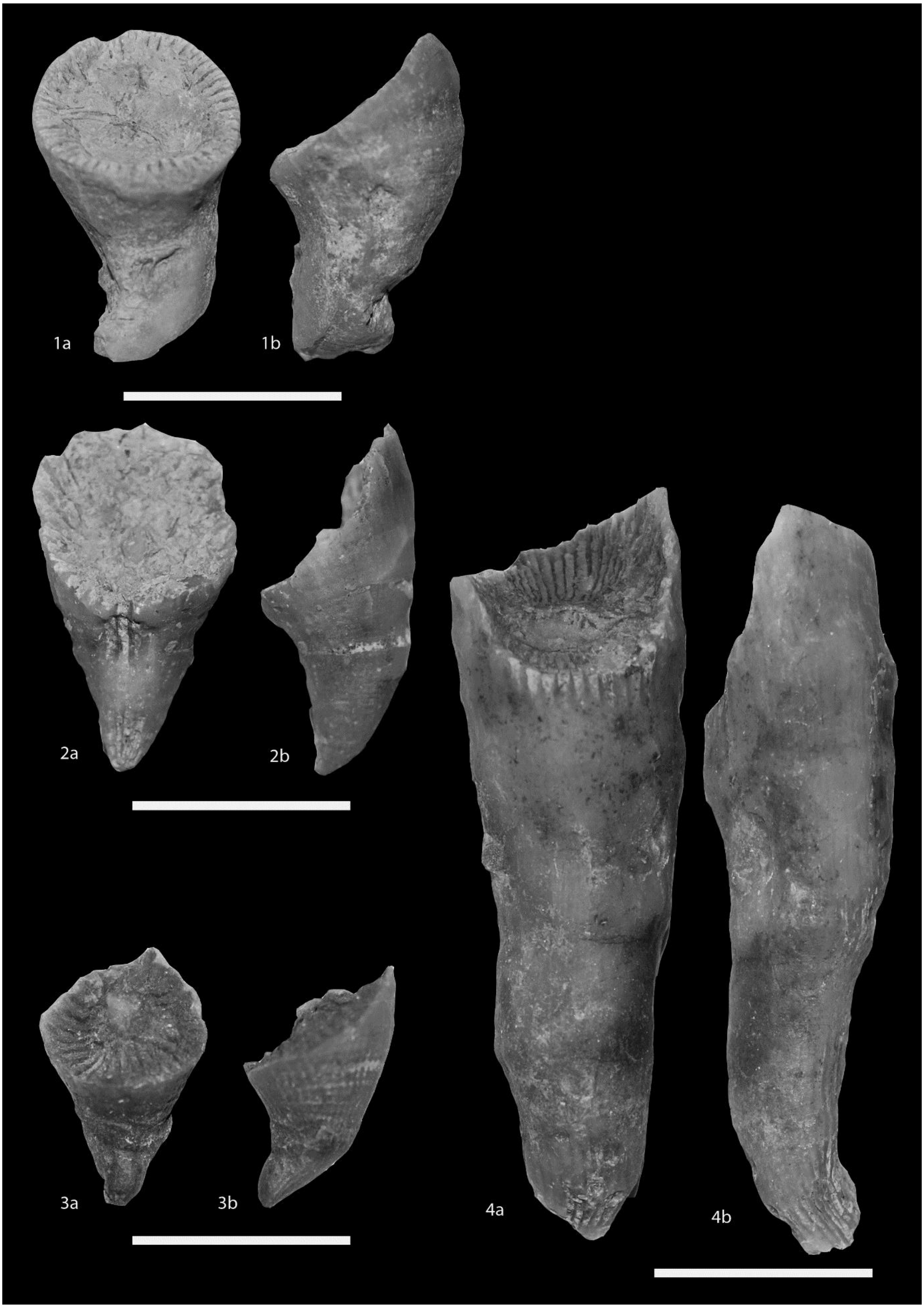


Plate V: Rugosa from Osmundsberget 4, bed 1: 1a – b: *Grewingkia bilateralis*; 2a – b: *Grewingkia contexta* with unilateral erosive marks; 3a – b: *Grewingkia contexta*; 4a – b: *Streptelasma primum* with erosive marks. (scale is 1cm).

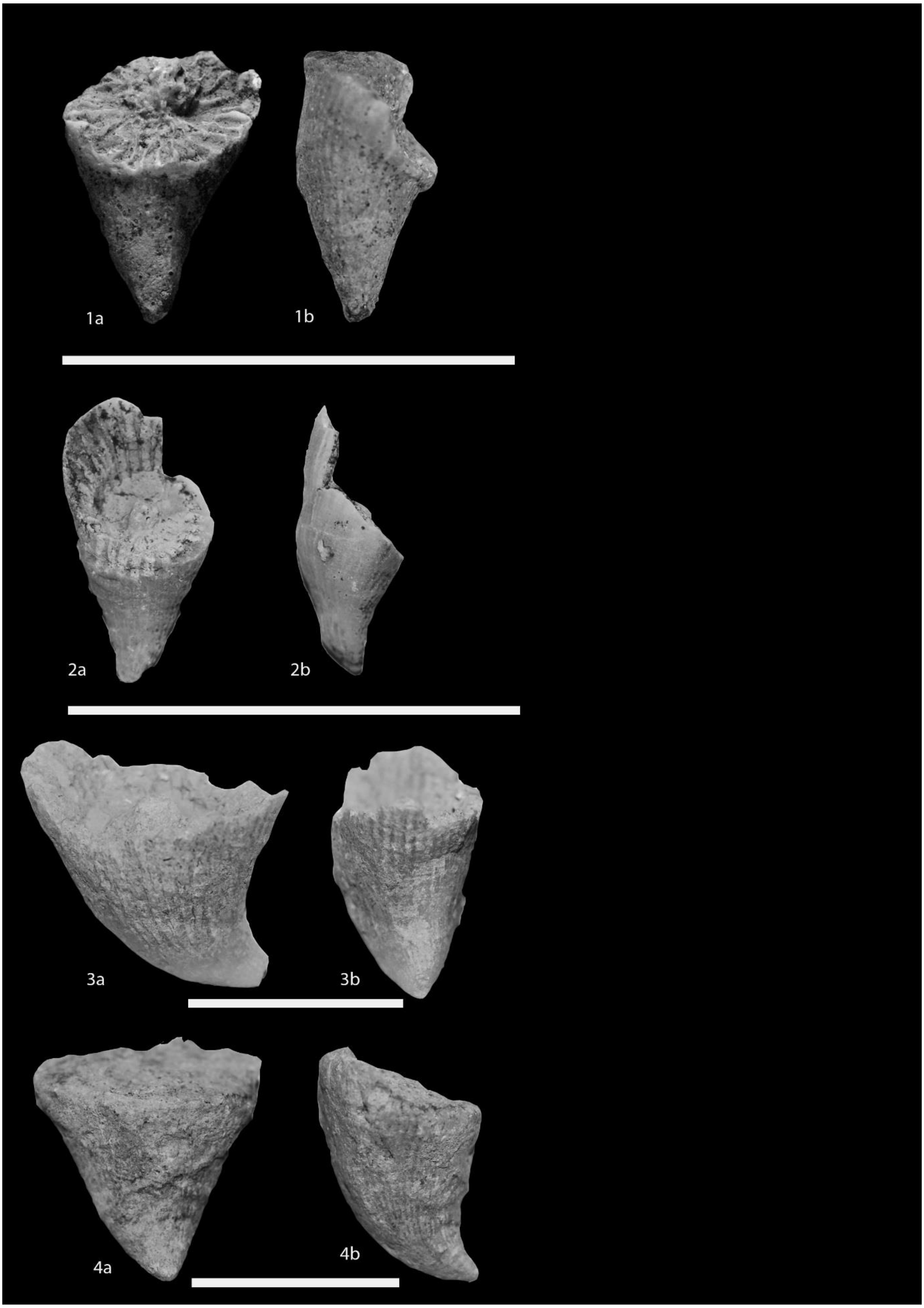


Plate VI: Rugosa from Osmundsberget 4, bed 3: 1 – 4: *Grewingkia contexta*; 2a – b show unilateral erosive marks; (scale is 1cm).

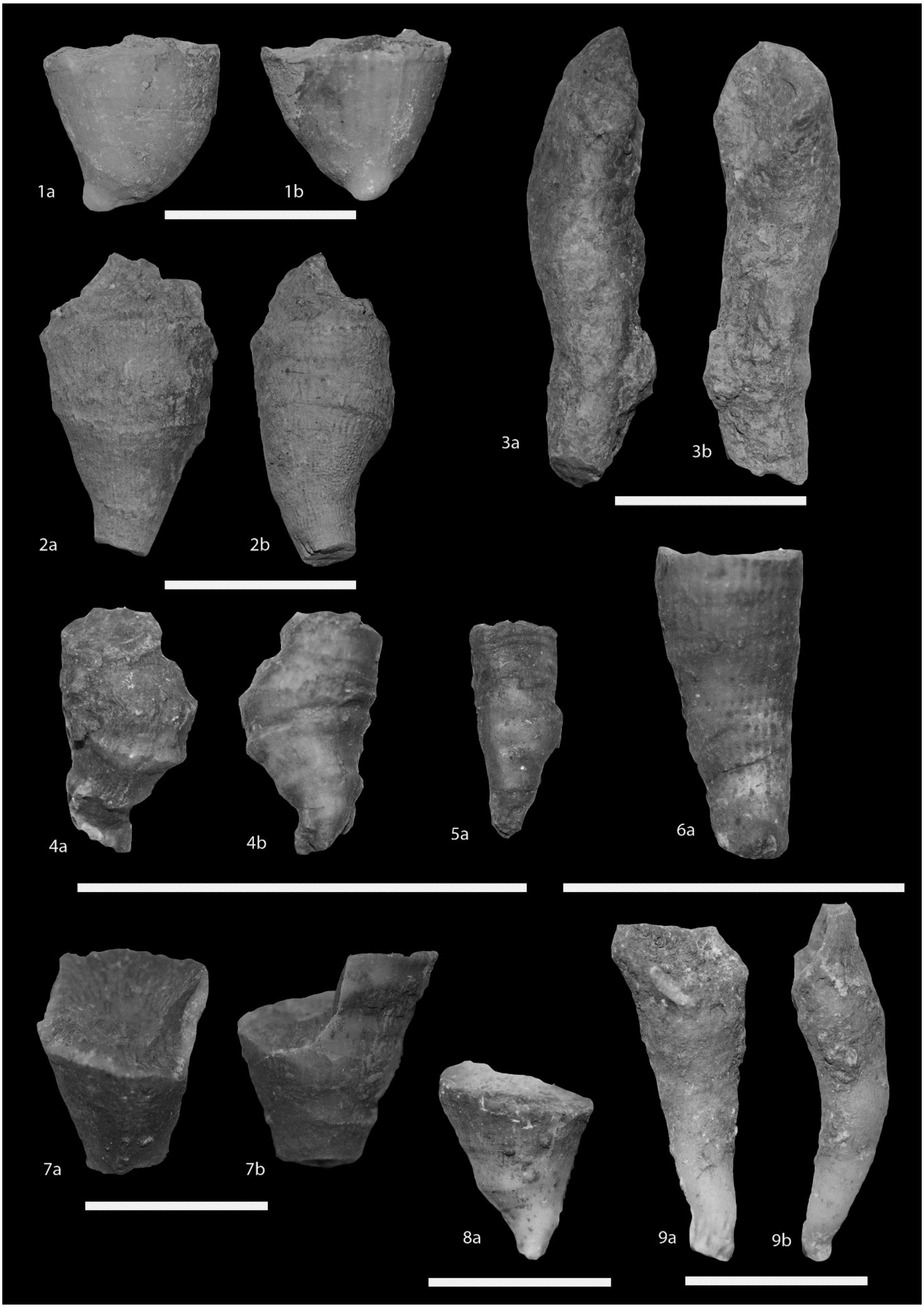


Plate VII: Rugosa from Osmundsberget: 1 – 3 from OB4_B2; 1a – b: *Grewingkia contexta*; 2a – b: *Streptelasma primum*; 3a – 3b: an indet. rugosan, elongated form, septa heavily eroded; 4 – 5 from OB7: 4a – b: *Streptelasma primum*; 5a: *Bodophyllum osmundense*; 6 – 9 from OB8: 6 - 8: *Grewingkia contexta*; 7a – b show unilateral erosive marks; 9a – b: *Bodophyllum osmundense* with erosive marks; (scale is 1cm).

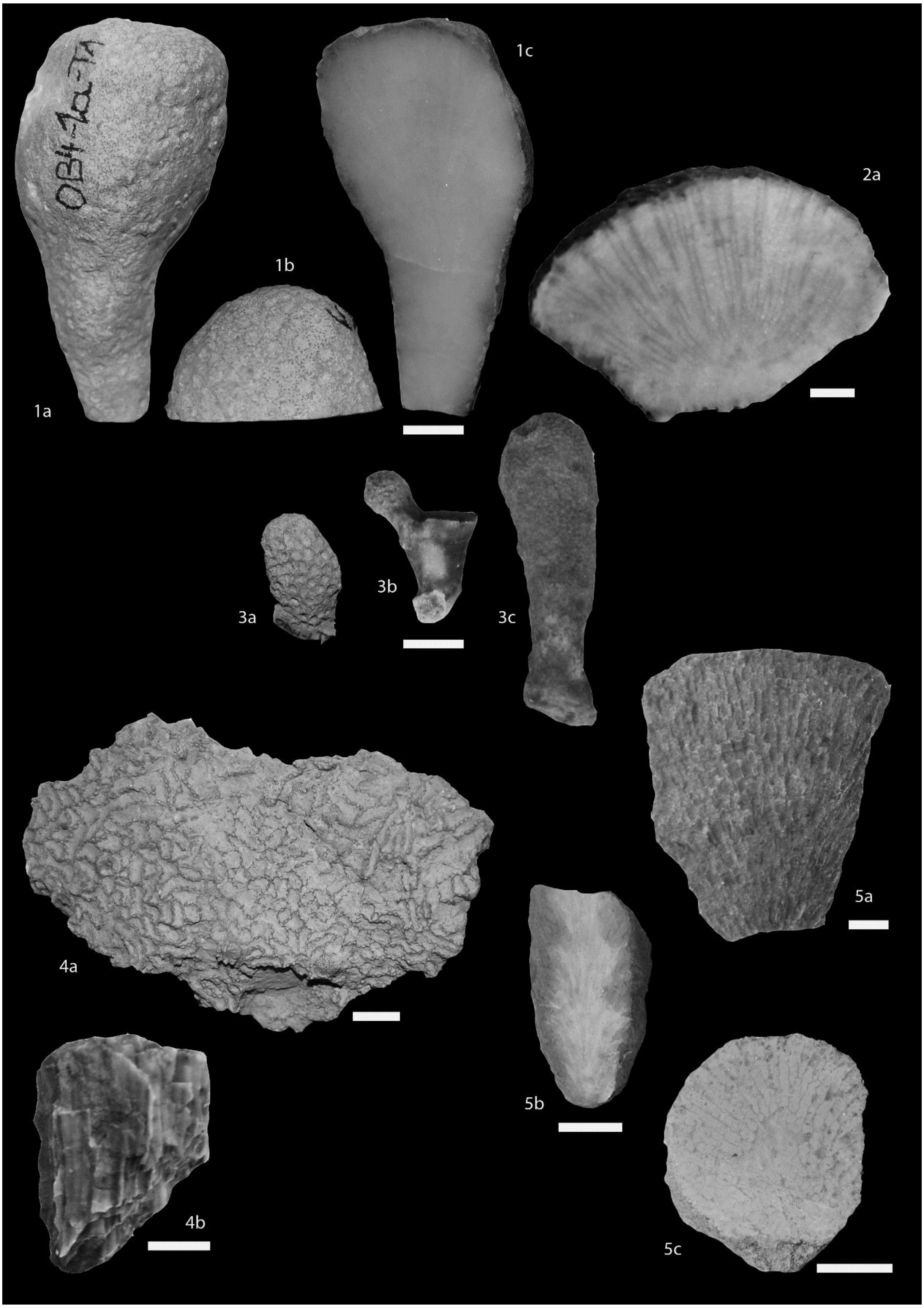


Plate VIII: Tabulata, various forms; 1a – c: Heliolitida, form with coralites wide apart from OB4_B1, 1c interior; 2a: Heliolitida, from with coralites close together from OB8, interior view, the red color (outside) can be seen also in the interior; 3a - c: Heliolitida, form with coralites close, OB4_B1; 3b shows Tabulata colony grew on a Rugosa; 4a – b: *Halysites*; 4a from OB8; 4b from OB7; 5a – c: *Lichenaria*; 5a from OB4_B2; 5b from OB3_B3, interior view, red – green color also on the inside; 5c: specimen from OB4_B1, interior view; (scale is 1cm).

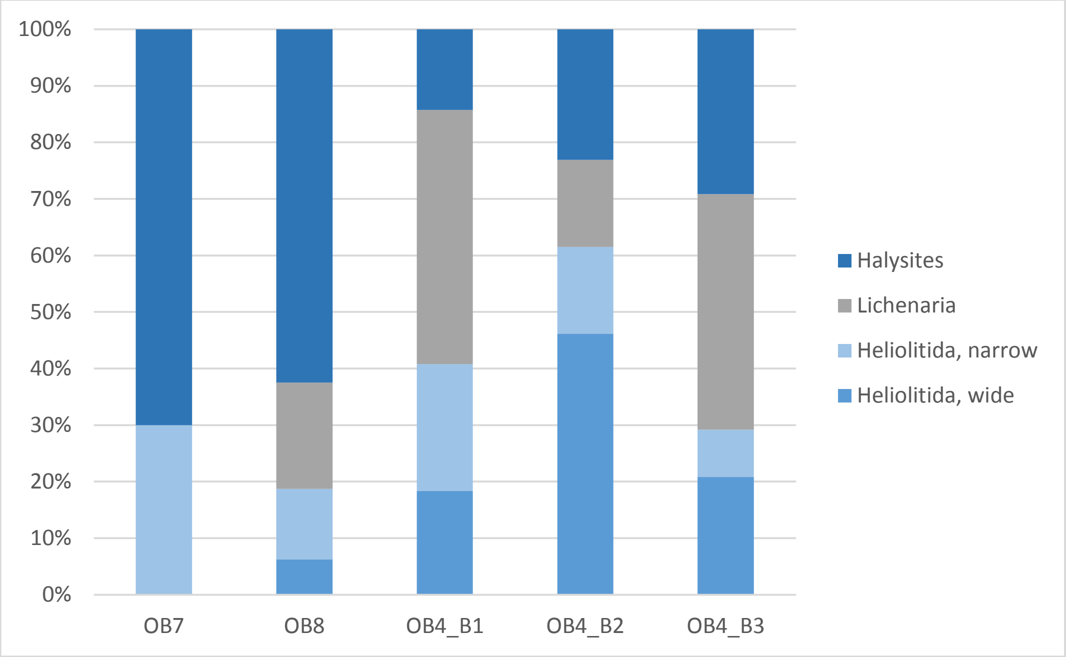


Figure 31: Proportion of tabulate corals. The Jonstorp Formation sites OB7 and OB8 show a dominance of *Halysites*. At OB4_B1 and B3 *Lichenaria* is a common element.

The second approach is based on the habit of the Tabulata found at the different sites of Osmundsberget. The Tabulata are distinguished by their different mode of habit. Leg means "like a mace-shaped". These Tabulata have a narrow base which diverges upwards (see plate VIII, 1a – c). Similar to that growth form is the one called "tree". It is similar to the leg-form, but the base is extended and the widening upwards is not that much expressed as in the leg-form (see plate VIII, 3c). The third habitus is called "plate". It is characterized by a large horizontal diameter compared to the height of the colony. The last habitus named "dome" is used for more or less spherical-shaped colonies. *Halysites* is indeed no separate habitus, but is included. Figure 32 shows the proportion of the different habitus at the sites of Osmundsberget. As when using the first approach, based on taxa of Tabulata, the sites look quite different from each other. The plate-shaped forms are dominant at OB4_B2. The habitus tree occurs at bed 1 of OB4 only by a small amount of specimens. In respect to the different habitus OB4_B1 seems to be the most diverse site. The values for the plate-type are very similar in OB7, OB8 and further in OB4_B1. Dome-like colonies occur at OB4_B1 with about 30 percent, at OB4_B3 (15 percent) and OB8 with about 5 percent.

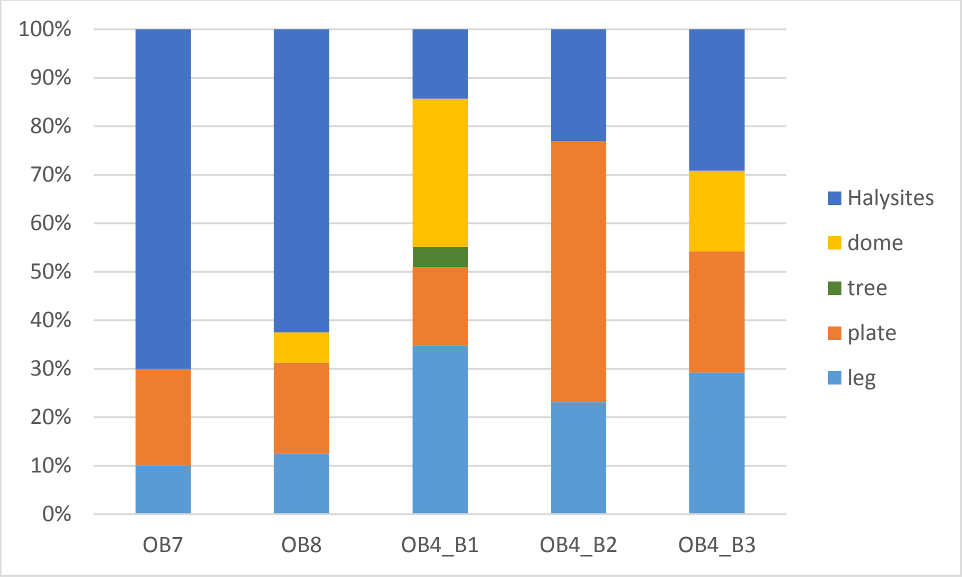


Figure 32: Proportion of tabulate growth forms and *Halysites*.

As before, the data from Rugosa and Tabulata were used for doing NMDS (shown in figure 33) and PCO (shown in figure 34). The parameters are the same as before: environmental variables 0, similarity measure: Bray-Curtis. Solberga_3 is included although there are only a few Rugosa and no Tabulata. The five sites of Osmundsberget are all located on the very left side of the coordinate 1 axis. They differ strongly in values of coordinate 1. OB8 can be found in the middle, with the three sites of OB4 beneath and OB7 above it. OB4_B2 is closest to OB8. Solberga_3 is as expected not even

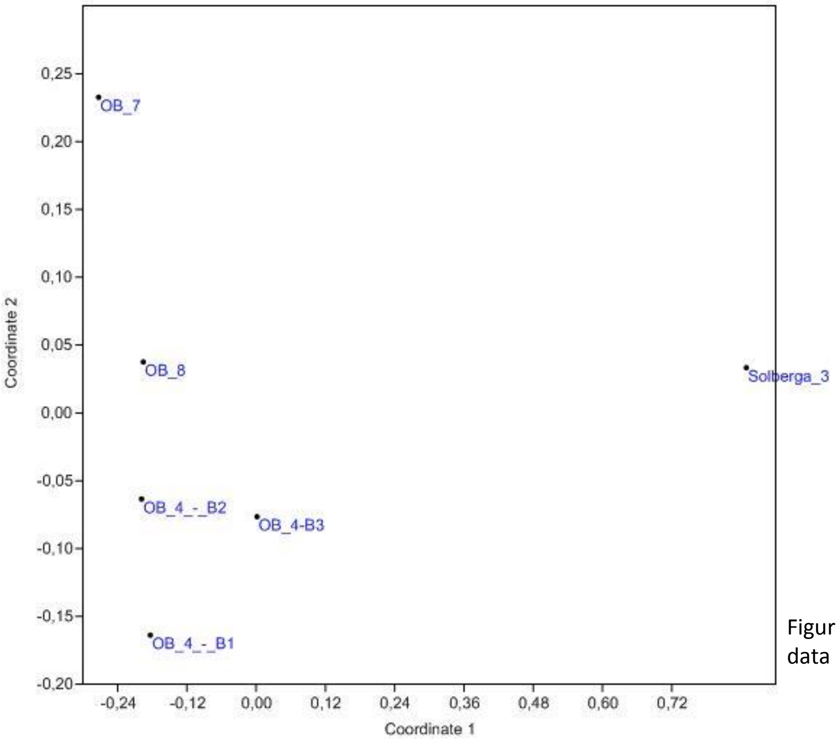


Figure 33: Results from the NMDS including data from rugosan and tabulate corals.

close to the other sites. The PCO (figure 34) shows a similar result but bed 1 of OB4 more close to bed 2.

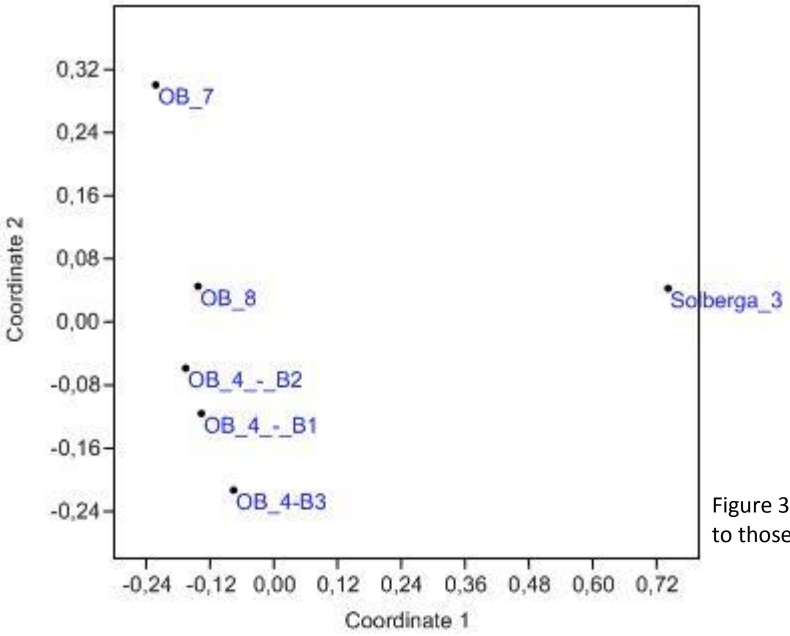


Figure 34: Results from the PCO. They are similar to those from the NMDS.

A cluster analysis (see figure 35) reflects the results from the NMDS. OB8 is close to OB4_B2 with OB4_B1 as a sister group. OB4_B3 is located next to them. Due to the similarity values, all sites at Osmundsberget seem to be very closely related. Even OB7 shows a similarity value of nearly 60 percent.

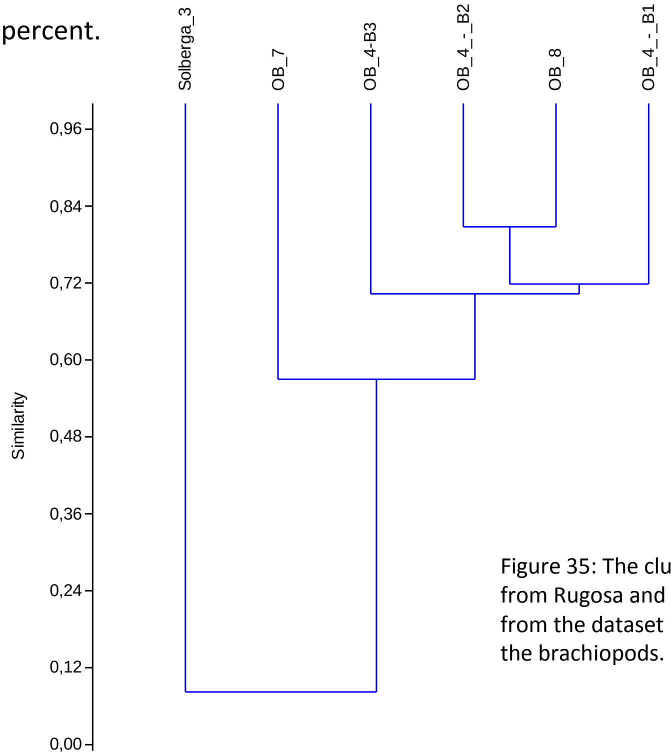


Figure 35: The cluster analysis including data from Rugosa and Tabulata. The result differs from the dataset including all taxa and that from the brachiopods.

Mollusca (plate X and IX)

Most of the Mollusca in this work are from the site Solberga_3. The only specimen found outside Solberga is a bivalve fragment from OB4_B1. It was not possible to identify it further. Almost all of the molluscs found at Solberga_3 are well-preserved but the interior is not accessible. In total, 43 specimens of Gastropoda (plate X), 16 specimens of Bivalvia (plate IX) and 7 specimens of Cephalopoda were collected from this site. The bivalves are represented by 16 specimens belonging to six different taxa. The most abundant taxon is assigned to the genus *Cyrtodonta* (Billings, 1858) with 11 specimens. All other taxa are known from one only specimen. From the genus *Ambonychinia* (Isberg, 1934) two species could be identified. This is *Ambonychinia ernugata* (Isberg, 1934) and *Ambonychinia extudima* (Isberg, 1934). The other two species are *Modiolopsis pygmaea* (Isberg, 1934) and *Amphicoelia transplicata* (Isberg, 1934). One taxon could not be further identified and is named *B_4*. Specimens from *Cyrtodonta* could be recovered at Solberga_3 as whole, articulated ones in a very well state of preservation. The gastropods are represented by six taxa. Three of them could be identified to the genus level. Those are the genera *Lophospira* (Whitfield, 1886), with one specimen, *Holopea* (Hall, 1847) with two specimens and *Bucania* (Hall, 1847) with two specimens again. The other three taxa are named *G_1, G_5* and *G_6*. *G_5* with 19 found specimens is the most abundant taxon, followed by *G_1* with 10 specimens and *G_6* with 9 specimens. *Lophospira* is represented by a single specimen. *Holopea* and *Bucania* are represented by two specimens each.

Bryozoa (plate XI and XII)

Bryozoans can be found at all investigated sites. At OB4_B2 and B3 only a few fragments were collected. Except from the massive forms, most of them are fragmented so it is difficult to distinguish between erected / ramose and fenestrate or pinnate forms, but most of them seem to be erected / ramose forms. At Solberga_3 small, fragile bryozoans are dominant and no massive form could be found. From OB7 some large and massive forms are known. Like some Tabulata specimens (figure 11), an interior coloration is recognizable but in this case it is limited to the central part of the specimens. Beside the massive and erected / ramose form, very small colonies can be found, especially at location OB4_B1, shown in plate XI, 5 and plate XI, 6 – 7. They are plate-shaped and smaller than half a centimeter. Forms found at OB4_B1 and B3 are identified as *Diplotrypa* (Nicholson, 1879). The specimen shown in plate XI: 11 from OB7 could be *Diplotrypa* too, but it is not certain.

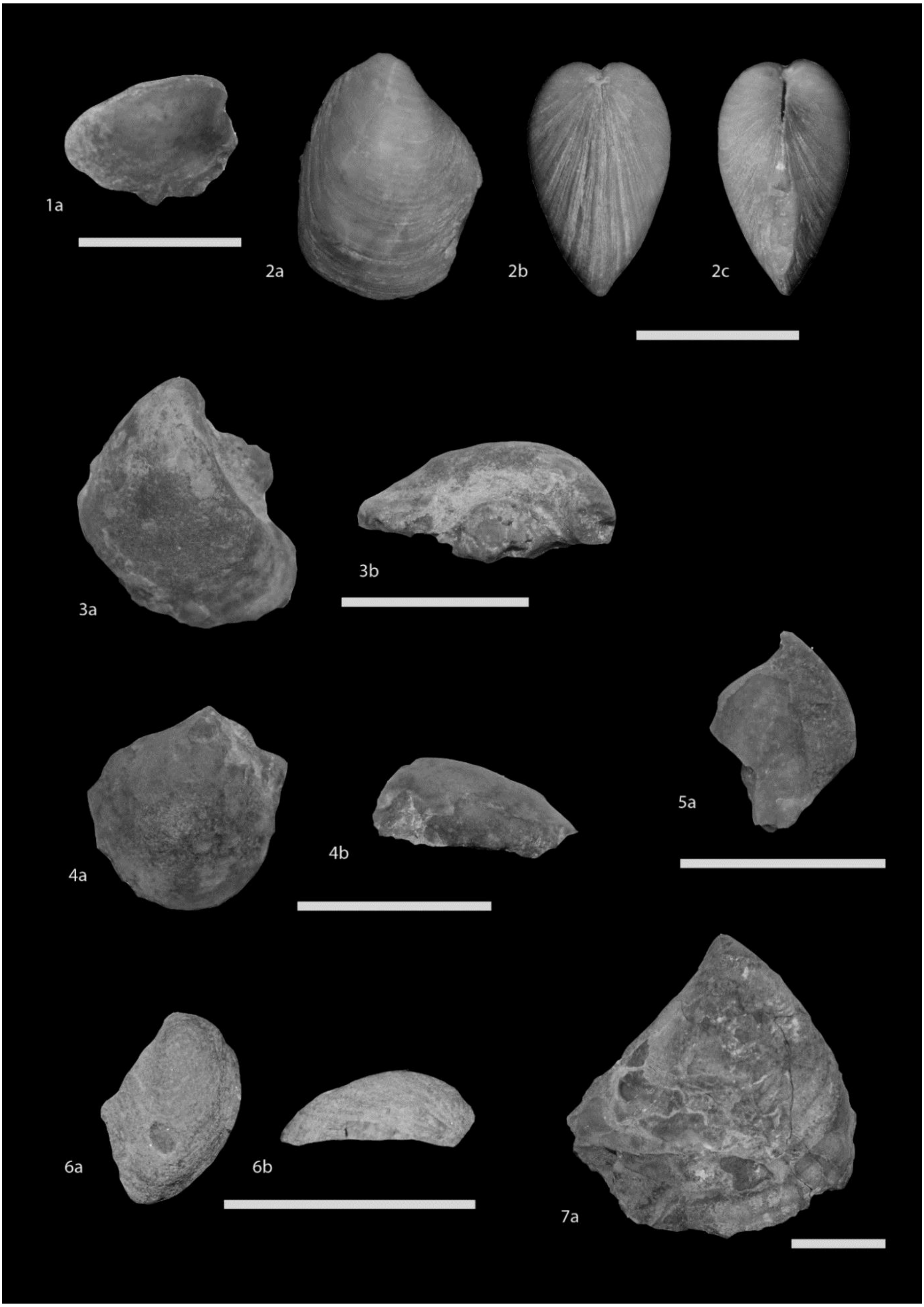


Plate IX: Bivalvia from Solberga_3: 1 – 2: *Cyrtodonta sp*., 2a – 2c is one of the best preserved specimen found with both valves together; 3a – b: *Ambonychinia extudima*, single valved; 4a – b: *Amphicoelia transplicata*, single valved; 5a: B_4, taxonomic assignation unknown, single valved; 6a – b: *Modiolopsis pygmaea*, single valved; 7a: *Ambonychinia ernugata*, large specimen, single valved; (scale is 1cm).

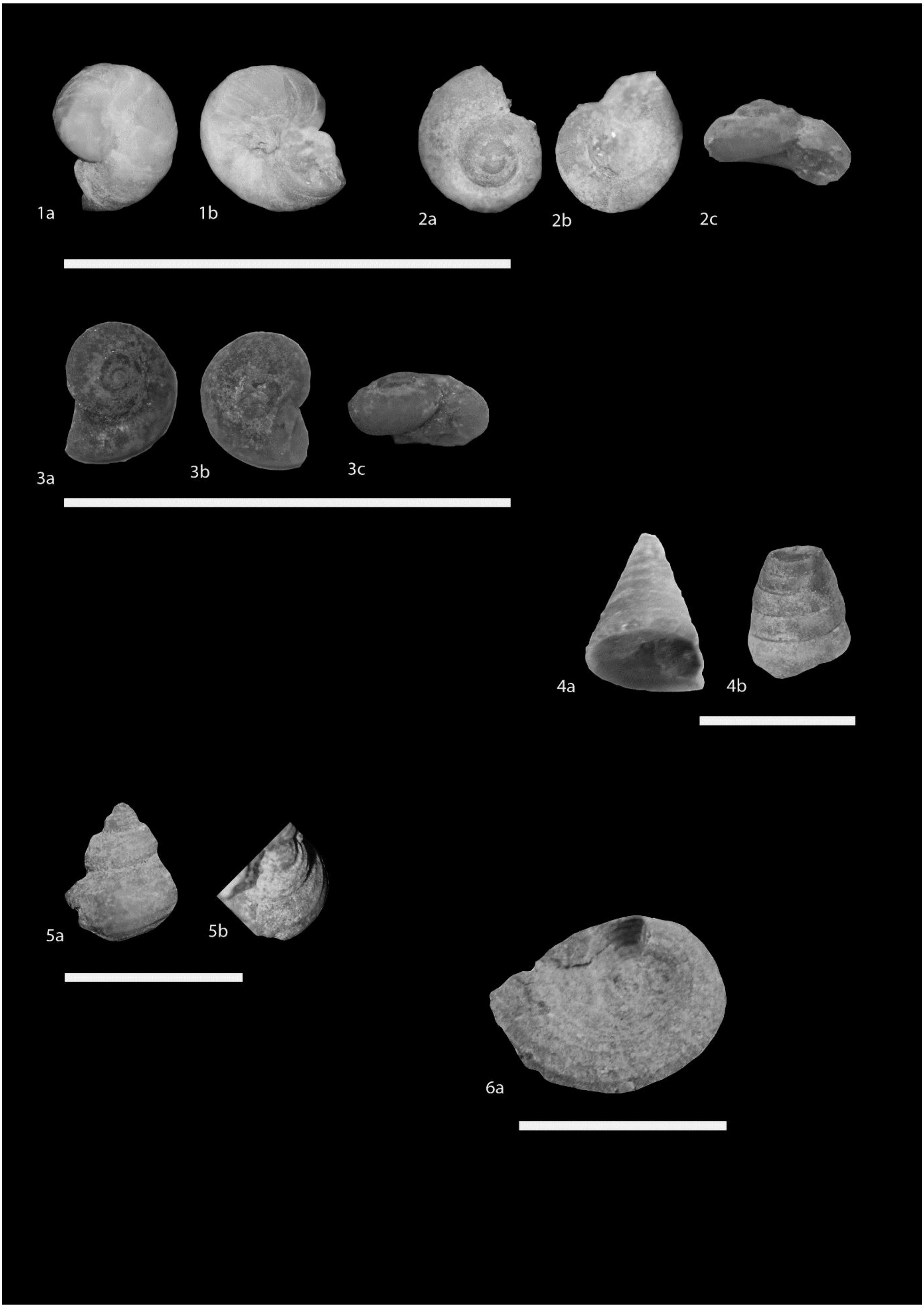


Plate X: Gastropods from Solberga_3: 1 - 3: small gastropods, named G_5, most abundant taxon at Solberga_3; 4a – 4b: G_1, known by 10 specimens from Solberga_3, probably a new genus; 5a – 5b: G_6, another gastropod, not further identified; 6a: *Bucania*, known from Solberga_3 and the pocket at Solberga_2; (scale is 1cm).

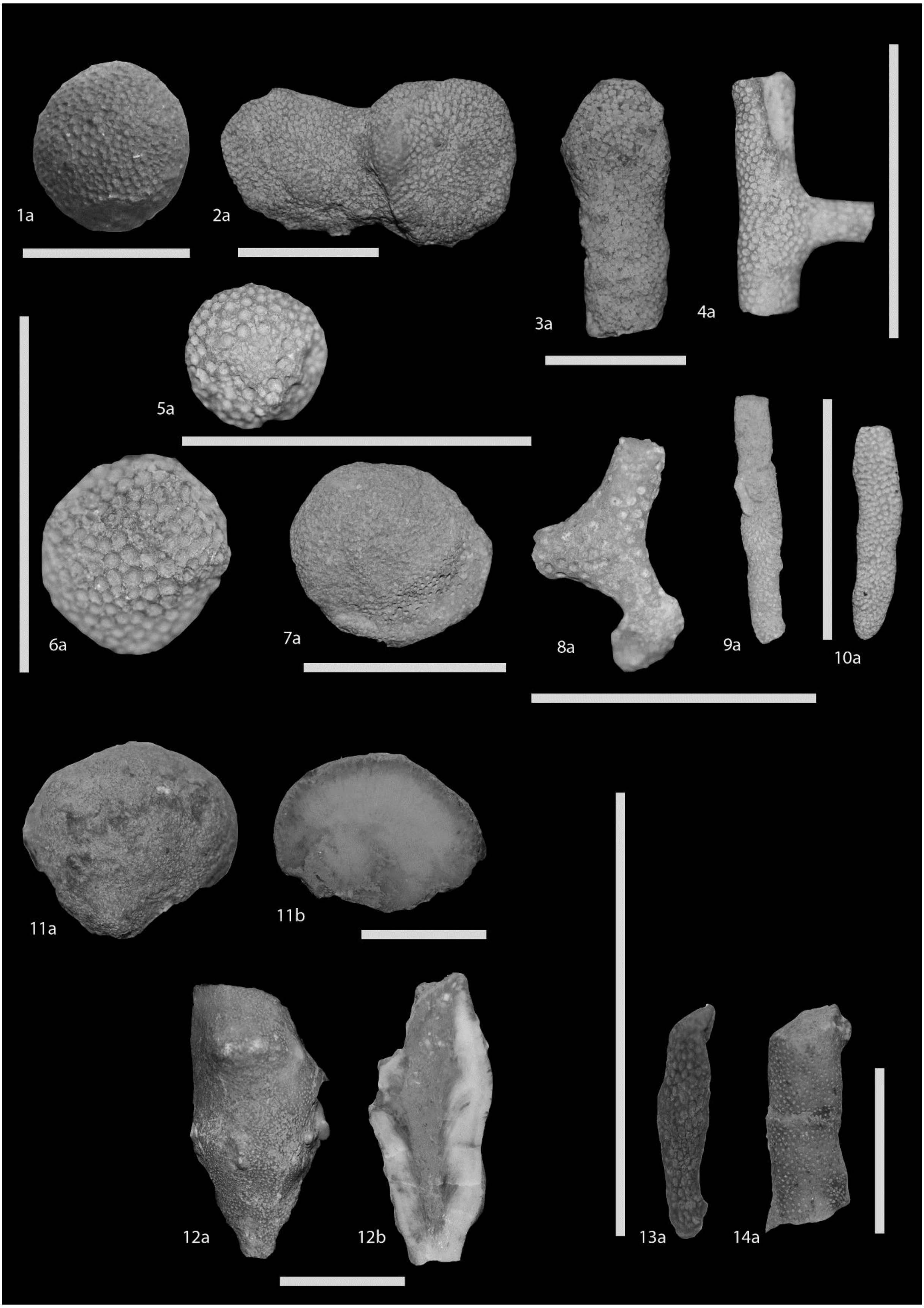


Plate XI: Bryozoa from different sites; 1-5: bryozoans from OB8; 6-10: bryozoa from OB4_B3, 7a: *Diplotrypa*; 11-14: broyzoans from OB7, 12b: interior coloration similar to that of tabulate corals is shown. (scale is 1cm).

Plate XII: Bryozoa from OB7 and Solberga_3; 1-2: Bryozoa from OB7, 1a-b could be *Diplotrypa*; 3-7: various forms from Solberga_3. Most of the found specimens from Solberga_3 are of the type shown in 3-5. (scale is 1cm).

Trilobita (plate XIII)

Massive occurrence of trilobites can be observed as pocket assemblages, mostly consisting of one taxon only. This is the case at Pocket B (PB). Most of the parts are pygidia and cranidia. It seems as if all found trilobite parts belong to only one taxon. Only in section three there is a trend in the orientation of the parts to convex-down (see figure 44). At the six sites of Osmundsberget and Solberga_3, most of the trilobites found belong to the order of Phacopida. Those are the genera *Pompeckia* (Warburg, 1925) and *Amphilichas* (Raymond 1905). The other two orders are Proetida with the genus *Holotrachelus* (Holm, 1898) and the order Corynexochida with the genus *Eobronteus*. In total 35 trilobite specimens were found from the sites outside Jutjärn, of which 26 are from Solberga_3. Twenty-nine of the 35 specimens could be identified. The genus *Pompeckia* is represented by two species: *P. minor* (Warburg, 1925) and *P. regelini* (Warburg, 1925). *P. minor* is represented with three specimens at OB8 and 19 specimens at Solberga_3. The other species *P. regelini* is known from Solberga_3 by one specimen only. This also holds true for *Amphilichas wahlenbergi* (Warburg, 1925). The fourth pacopid species is *Amphilichas periformis* (Warburg, 1925), which occur at OB8 with two specimens and Solberga_3 by one specimen. The other orders are Proetida, with the species *Holotrachelus sp.*, and the order Corynexochida, with *Eobronteus sp*.. Both are represented by a single specimen from Solberga_3.

Problematica (plate XIV)

At the site of Solberga_3 there is a massive occurrence of spheroidal-shaped fossils with a dimension of 0,5 cm to about 1 cm. Plate XIV shows some of the specimens. Most of them are cupped (see plate XIV, 3), especially the smaller ones with strong walls. Some of the larger (about 1 cm) ones are more elongated (see plate XIV, 1 – 2) than the smaller ones. Pole wards there are small notches on each side. On the larger specimens, irregular orientated pits can be observed. They occur at Solberga_3 only.

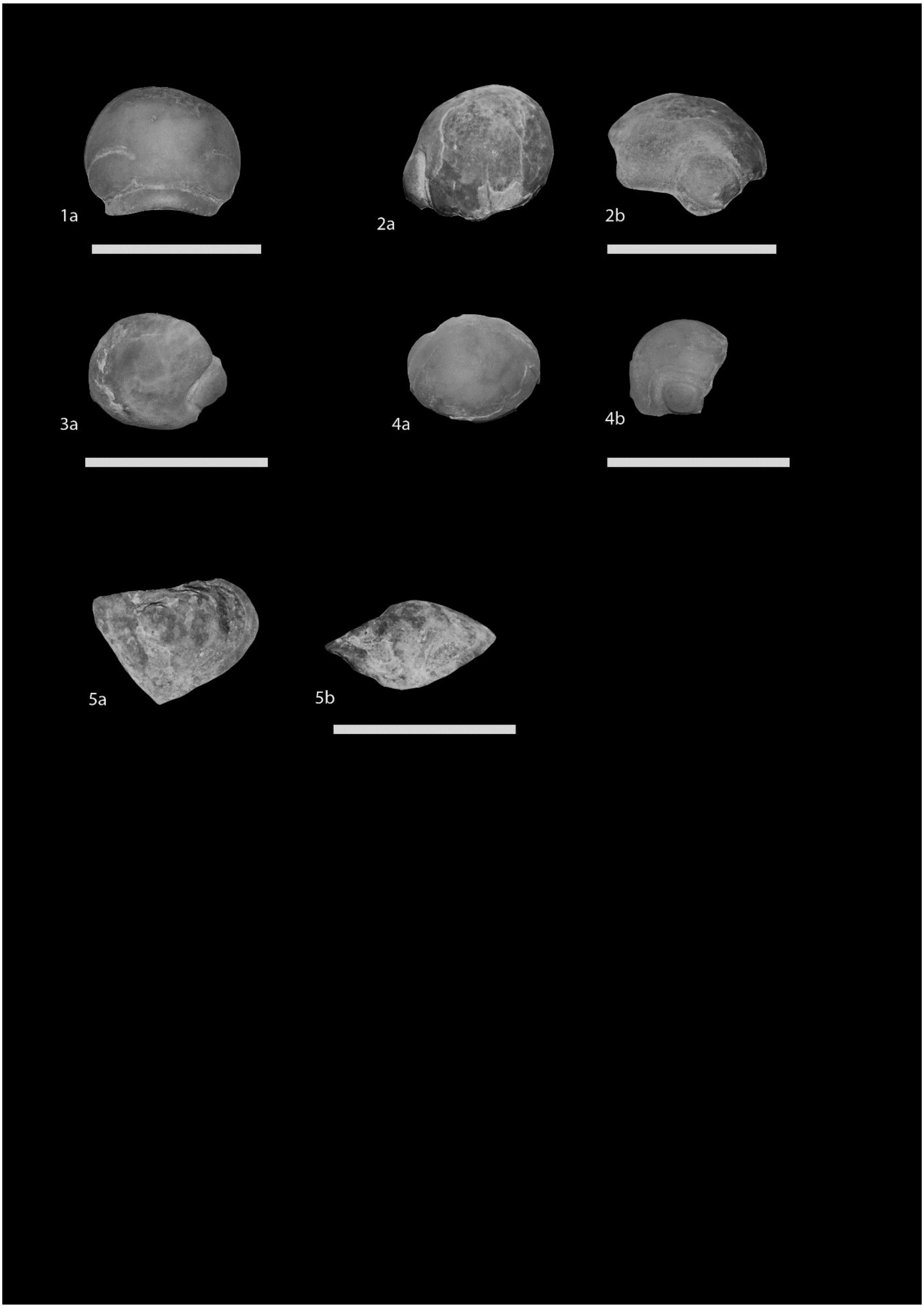


Plate XIII: Trilobites from Solberga_3: 1a: *Pompeckia regelini*, cranidia; 2 – 4: *Pompeckia minor*, cranidia from three different specimens; 5a – b: indet. Trilobite, cranidia; (scale is 1cm).

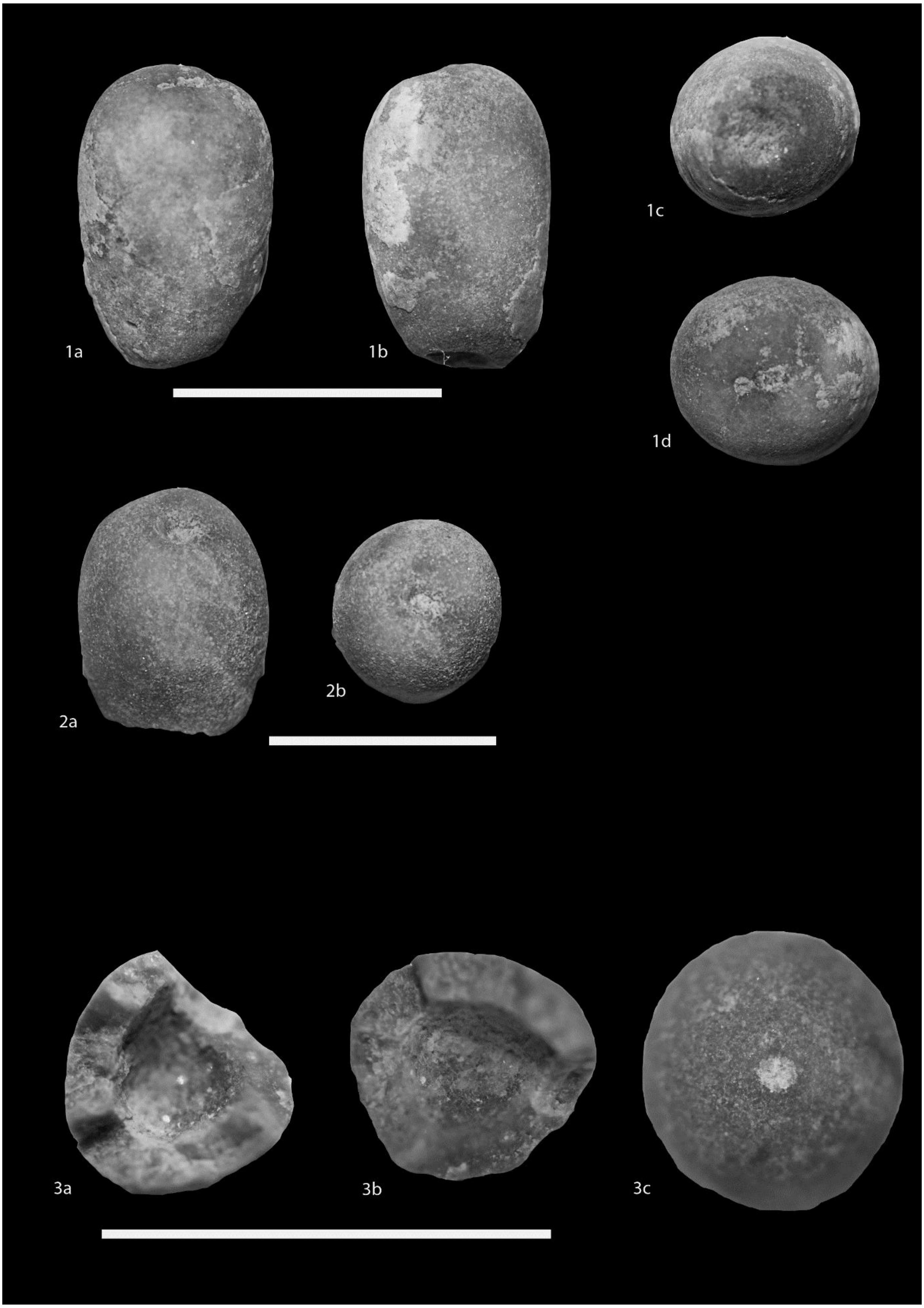


Plate XIV: Fossils of unknown origin from Solberga_3; 1a – b: lateral view, 1c – d: apical view with notches, large form (> 1cm); 2a: lateral view, 2b: apical view, large form; 3: small form, 3a – 3b: broken specimen, inside view: with cavity and strong walls; 3c: apical view with notch; (scale is 1cm).

Thin sections: Osmundsberget and Solberga_3

Osmundsberget: The following thin sections are taken from Osmundsberget 7 but they represent all five sites from Osmundsberget. It is a reddish to greenish wackestone-packstone, containing numerous fossils from pelmatozoan body parts, shells and Tabulata (figure 36) by a micritic matrix.

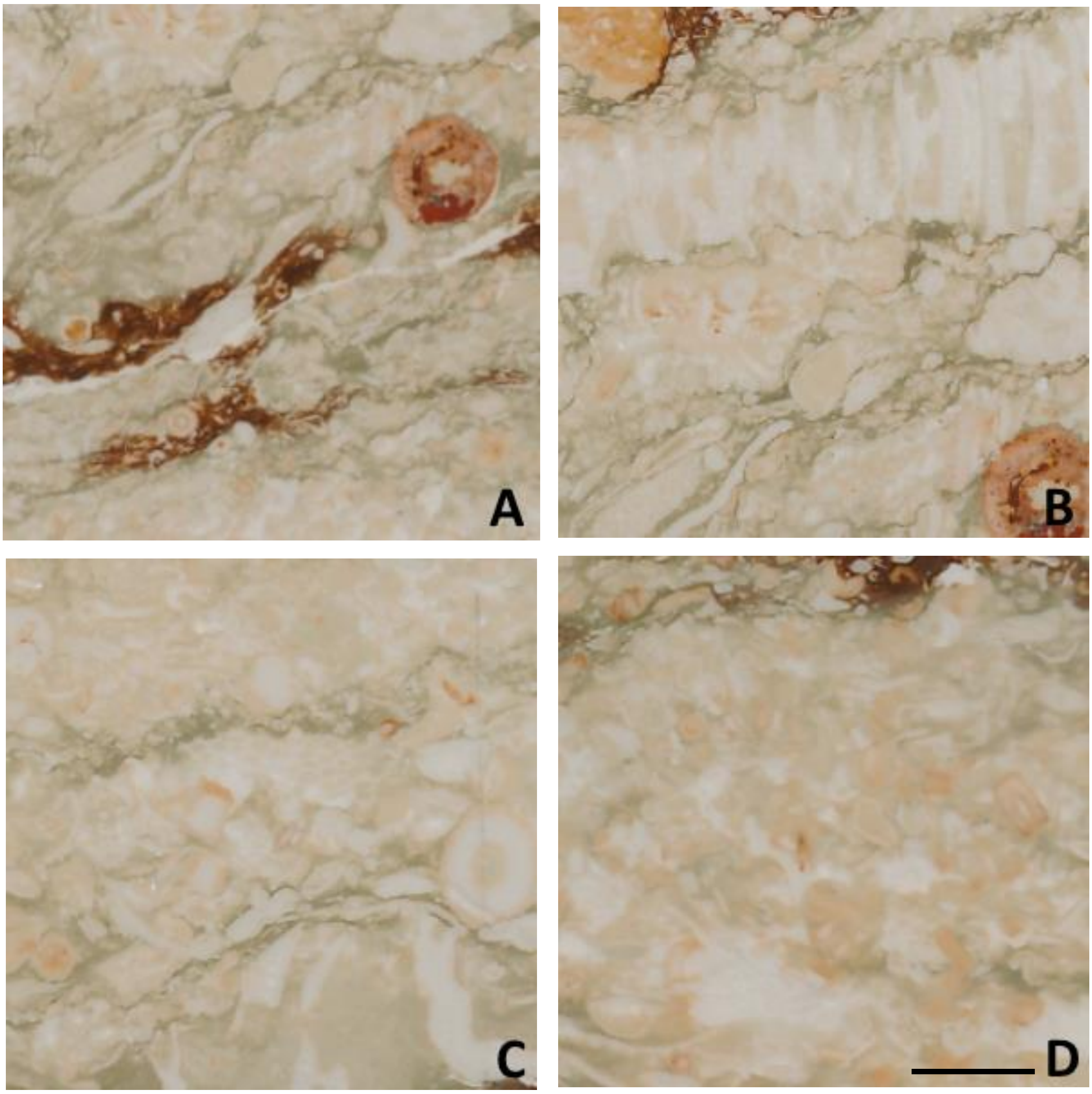


Figure 36: Thin sections from OB7; reddish – greenish packstone; A: pelmatozoan parts are dominating; B: tabulatan structures, the tabulae are recognizable; C-D: Pelmatozoan parts and bryozoan fragment; the micritic matrix is, as well as the larger grains, reddish or greenish colored; (scale is 5mm).

Solberga_3: The following thin sections are from the site Solberga_3 (figure 39). According to the classification of Dunham (Dunham, 1962), they are classified as wackestones. The dominant fossils are bryozoans but shellparts from brachiopods or mollusks, trilobites or ostracods can be found as well. Pelmatozoan parts are very rare.

Pocket B, Jutjärn

Section 1: base – 50 cm, figure 37 and 38

Section 1 of pocket B of Jutjärn contains trilobite segments, predominantly cranidia. At the very base and left of it *Palaeoporella* can be found (see figure 39). There is no preferred orientation of the cranidia. On the right side, the pocket is flanked by a typical limestone, associated to the flank facies (thin section in figure 43, B). It is classified as a grainstone (classification due to Dunham), consisting of disarticulated pelmatozoan segments.

Figure 37: Right: Section 1, base to 50 cm; lots of trilobite cranidia con be found, but they show no preferred orientation. Core limestone (reddish) with *Palaeoporella* are found at the very base and on the left side; typical pelmatozoan limestone of the flank facies are located on the right side.

Figure 38: Beneath: *Palaeoporella* limestone from the base of the pocket; typical micritic core limestone, spherical to elongated structures are *Palaeoporella*

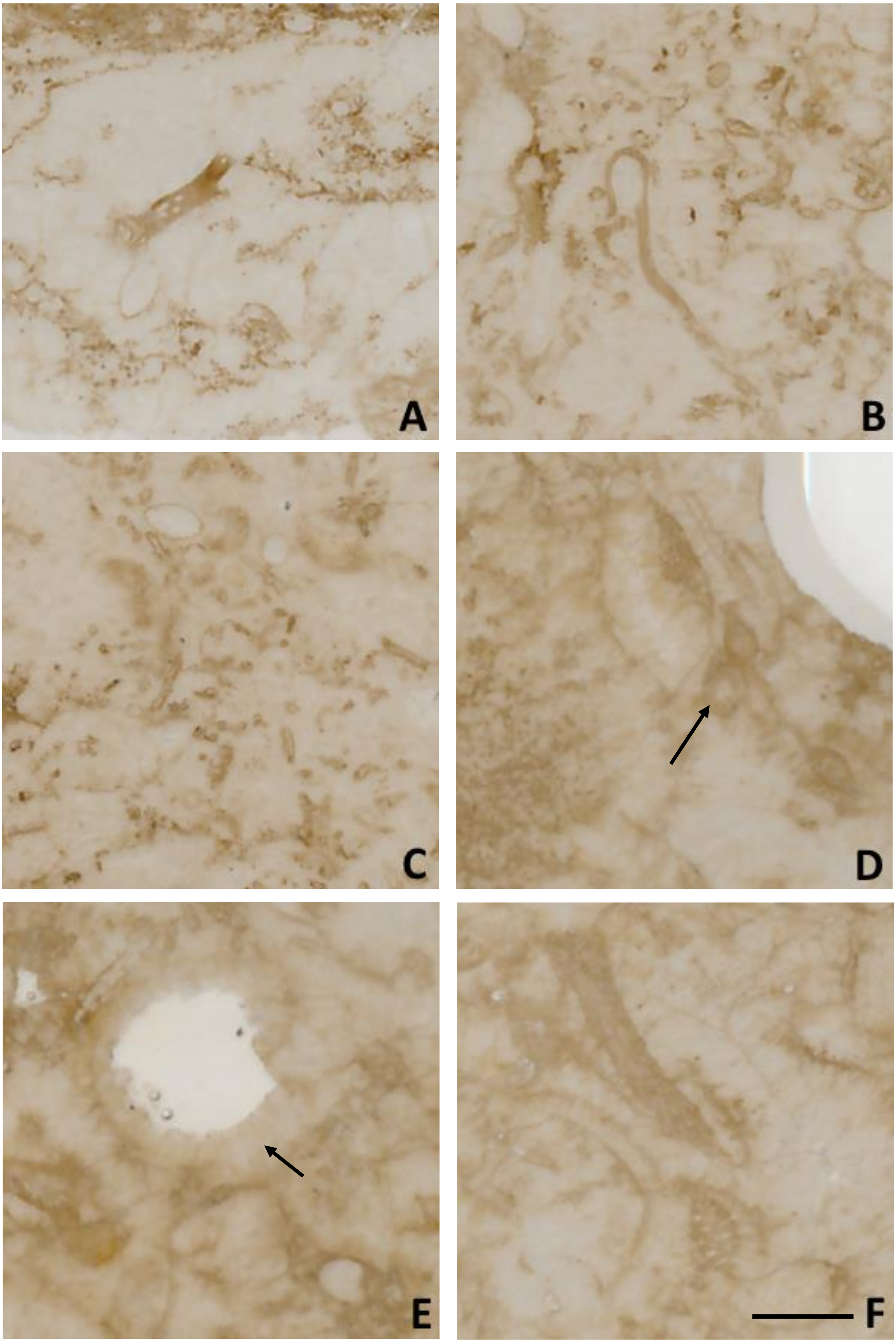


Figure 39: Thin sections from Solberga_3, wackestone; A: fragments of bryozoans and ostracodes; B: trilobite fragment; C: ostracode; D: tube-like structures of algae (marked by arrow); E; spheroidal structure (see Problematica); F: bryozoan fragments (scale is 5mm).

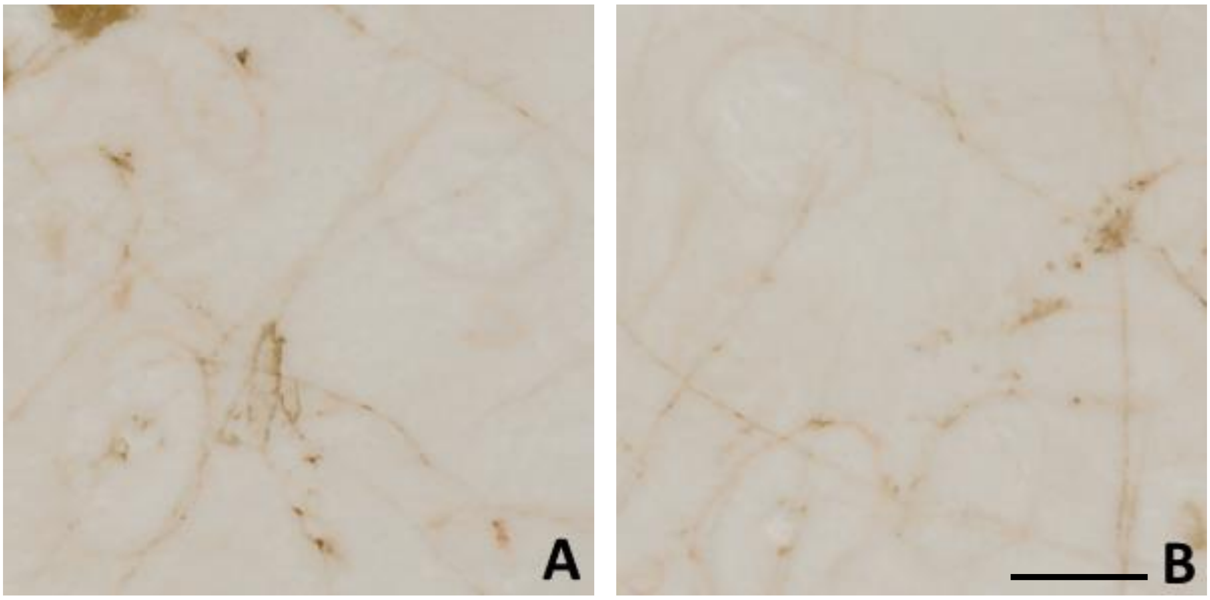


Figure 40: A and B: mudstone with *Palaeoporella* (spherical structures); (scale is 5mm).

The thin sections shown in figure 40 are taken from the base and show a typical mudstone, with less features, except from some concentric structures. Those structures are *Palaeoporella*. There are no trilobite body parts in the thin sections shown.

Section 2: 50 cm - 200 cm, figure 41 and 42

Like the first section, this section is dominated by trilobite cranidia with no predominant orientation. It is a small duct (figure 41), flanked on the left side by a typical core limestone, but without *Palaeoporella*, and a pelmatozoan limestone on the right side. The duct-shaped pocket extends to the left side. Here, trilobite cranidia can be found again. Figure 42 shows a well preserved trilobite cranidia and the reddish limestone. Thin sections are shown in figure 43. A lot of trilobite parts can be seen, supported by a micritic matrix.

Figure 41: Right: section 2, 50 cm – 200 cm; small duct (20 cm – 40 cm), fossil content dominated by trilobite cranidia with no preferred orientation; marked out on the right side by the flank facies limestone

Figure 42: Beneath: detail, showing a well preserved trilobite cranium, orientated convex up

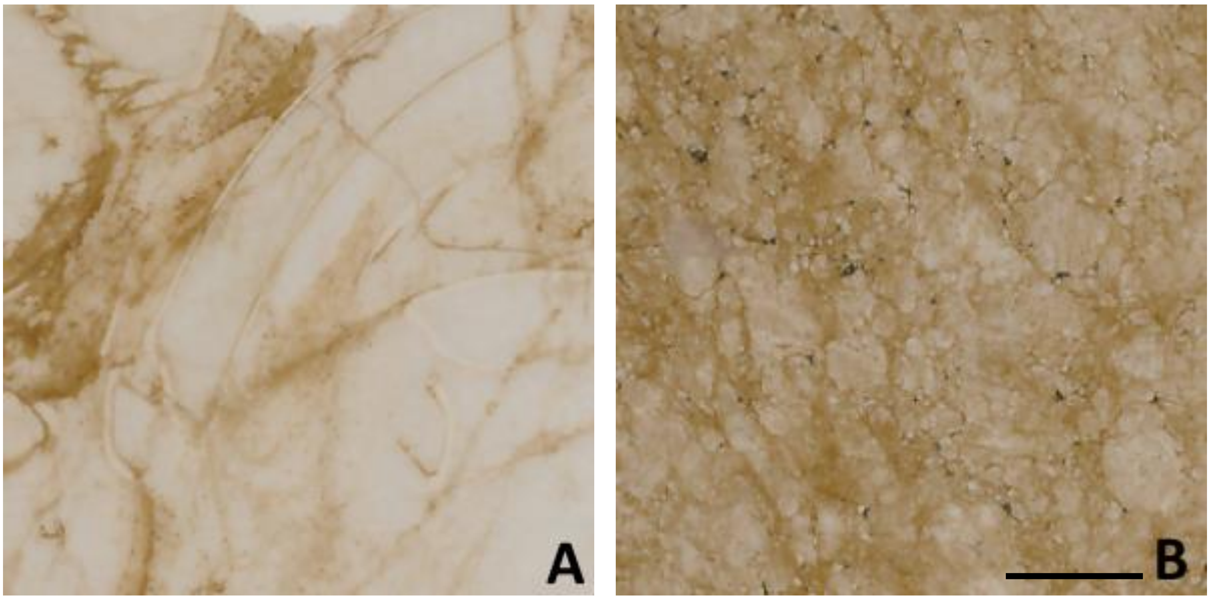


Figure 43: Thin sections from section 2 of PB; A: mudstone-wackestone dominated by trilobite cranidia in random orientation; B: grainstone representing a typical flank facies dominated by pelmatozan fragments; (scale is 5mm).

Section 3: top of pocket

Section 3 is the uppermost part of the pocket. While at section 1 and 2 the pocket has the shape of a small duct, not more than 20 to 40 cm in extension, the pocket widens up to 100 cm, but narrows at the upper end. It is difficult to investigate that part and some climbing is necessary. The in-field measuring of the orientation of the trilobite cranidia as well as the measurements from a rock sample (see figure 44) taken from that part show a trend to a convex-down orientation.

Figure 44: Polished rock sample from section 3 (uppermost part); most of the trilobite cranidia are orientated convex-down; (scale is 1cm).

Discussion

The total taxa proportion (see figure 15) shows a dominance of brachiopods at all sites. At Osmundsberget, other taxa than brachiopods and Anthozoa (Rugosa and Tabulata) are rare in number or completely absent. Solberga_3 shows a very low number of Rugosa and Tabulata are missing at all. However, Mollusca (gastropods, bivalves and less cephalopods), are common. Due to some findings of bivalve and trilobite fragments at Osmundsberget, it is supposed that those taxa occurred at these sites but today they are very rare because of dissolution processes (see erosive marks on Rugosa, plate V - VII). Gastropod and bivalve shells seem to be more sensitive to dissolution than the hard parts from brachiopods or Rugosa / Tabulata. Focusing on the Rugosa, the erosive marks could be an evidence of enhanced dissolving processes. The same holds true for trilobite shells. Another reason for the lack of trilobites could be the selective trapping and binding (Suzukii & Bergström, 1999) of smaller parts from algae mats and the accumulation of the larger trilobite parts in pockets. Including the disarticulation behavior of brachiopods and bivalves, where bivalves tend to disarticulate and brachiopods of the order Atrypida (and further rhynchonellids) are more likely to be found in an articulated state (Brett & Baird, 1986), correlates with the majority of the found bivalves and atrypids at Osmundsberget. The articulated, in situ orientated bivalves found at Solberga_3 indicate a fast burial. Unfortunately no data of the ratio of pedicle to brachial valves from brachiopods were taken. In general, the brachial valve tends more to fragment than the pedicle valve, even without lateral transport (Noble & Logan, 1981). Due to the sedimentary features (marly – limestone) at Osmundsberget, it is supposed to be of deeper water origin. This is supported by the work of Hansen et al., 2010 and the occurrence of *Diplotrypa* (bryozoan), indicating a deeper, quiet bottom environment but still above storm wave base. Focusing on the orientation of the fossils, none is recognizable at the sites of Osmundsberget (compared to the bivalves found at Solberga_3). According to Brett and Baird, 1986, the Osmundsberget sites can be classified as low energy (see sediment: marly limestone) with low to intermediate sedimentation rates (1 -10 cm / 10^3yr). The sedimentation rate is estimated from disarticulated parts and the erosive marks observed on rugosan corals. The well preserved and abundant specimens from various taxa, some of them in life orientation (bivalves) indicate a fast burial scenario for Solberga_3. Hold to the assumption of a reef mound habitat with higher environmental energy, a fast burial seems reasonable. This could explain the state of preservation in contrast to the surrounding core limestone.

The three sites of OB4 (bed 1 – 3) look as if they became more and more similar to OB_8 according to their taxa distribution. The cluster analysis (see figure 19) shows the similarity of the three sites of OB4 and OB_8. Interpreting the results from the NMDS, OB4 and OB_8 are close to each other on coordinate 1 values. Bed 1 to 3 show slightly different coordinate 1 values but are aligned straight in coordinate 2 values. It can be observed, that the uppermost Boda reef structures became more like Jonstorp Formation strata in respect to its sedimentary features. Figure 15 reflects this trend in the taxonomic composition. The results from the NMDS (figure 17) can therefore be interpreted as the coordinate 1 reflecting the sea level with a lowering to higher coordinate 1 values. Solberga_3 with a high coordinate 1 value fits well to its supposed reef top environment closer to the water surface than the intermound facies of the Jonstorp Formation beds. It has to be mentioned that water depth alone is not a significant environmental value. More important are the various effects that come along with such as the availability of light (phototrophic organisms), water currents, temperature and sediment type (see Sheehan, 1979). Noticeable are the different positions of OB_8 and OB_7. Both are supposed to be strata assigned to the Jonstorp Formation. OB7 has a relatively low number of Rugosa and is placed, as seen in the cluster analysis as the results from NMDS and PCO near Solberga_3. This can be explained by the dominance of E. rhombica and Br_15 at both sites. Figure 45 shows the results from NMDS excluding the data from Solberga_3. OB_7 and OB_8 are closer on coordinate 2. The position of the three beds at OB4 and OB8 is relatively unaffected. Like before, the coordinate 1 axis could be interpreted as the water depth with deep water at the left (OB7) and more shallow water at the right. On the other hand, the coordinate 2 axis could be reflecting a water depth gradient too. These results should be seen with precaution and the exclusion of Solberga_3 is recommended for comparison of the sites of Osmundsberget.

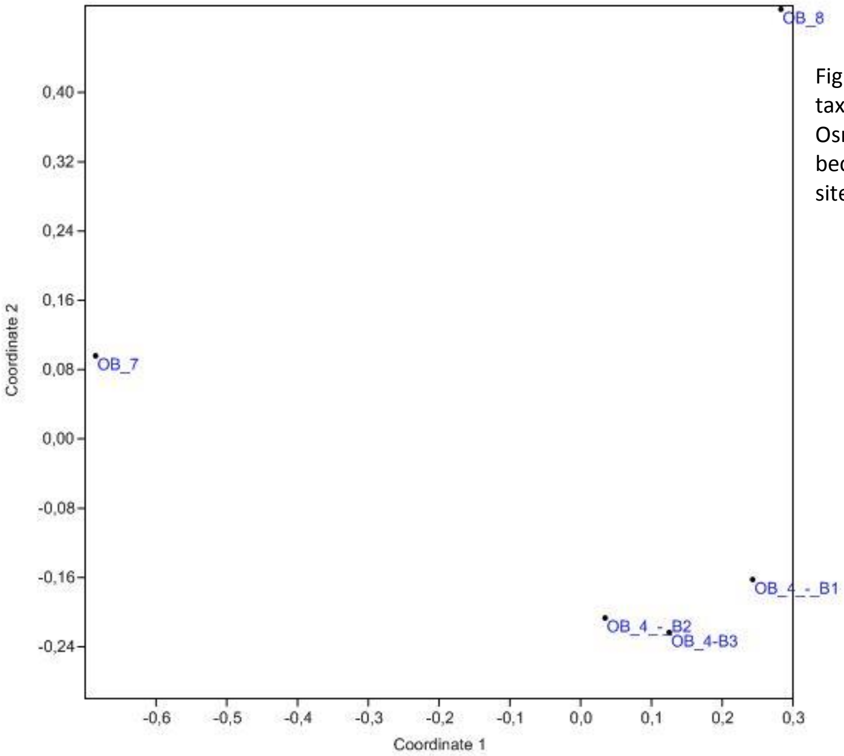


Figure 45: NMDS including data from all taxa from all five sites at Osmundsberget; Solberga_3 is excluded because of better comparison of those sites.

The brachiopods are the most abundant and diverse group of all taxa discussed and analyzed in this study. According to Sheenan, 1979, the most abundant species from the reef core also occur in this work are *Eoplectodonta, Cliftonia* and *Eostropheodonta luna*. *Cliftonia* and *E. luna* are not known from Solberga_3 but *Eoplectodonta* is one of the most abundant brachiopod taxon at all sites. The flank is dominated by *Eospirigerina*, *Nicolella oswaldi*, *Sulevorthis*, *Eoplectodonta* and *Christiania*. Except from *Christiania* all of them occur at OB4. *N. oswaldi* is missing at OB4_B1. According to that findings, the beds of OB4 are more related to flank deposits but the missing of *Christiania* as a taxon related to the flank is interesting. Having a look at the strophomenids according to Cocks, 2005 and the list of abundant to rare species (Cocks, 2005) show some unexpected results. From the four species assigned as abundant (*L. bergstroemi, C. dalarnensis, L. longae* and *E. rhombica*) only *E. rhombica* and *C. dalarnensis* are abundant (more than 10 specimens) in the collected material. From the rare species, *T. bella* is fairly common at Solberga_3. *Craspedelia sp*. occur at OB4 only. According to Cocks (2005), the affinity to the genus *Craspedelia* is not confirmed and it is possible, that this is a new genus, endemic to Boda (Cocks, 2005). Like the specimens described in Cocks, 2005, the found specimens from this work are articulated too, so the interior is not accessible and therefore the definite identification difficult. Like Sheenan (1979), Cocks assigned *L. bergstroemi* and *E. rhombica* as the only strophomenids known from the reef core mound. Additional strophomenid taxa found at Solberga_3, assumed as an atypical mud mound environment, are *T. bella, L. candelabra* and one unidentified specimen. Compared to the very diverse brachiopod fauna of Taimyr (Cocks & Modzalevskaya, 1997), where most of the collected specimens belong to two atrypid species only, the same is observable at the Jonstorp Formation sites OB7 and OB8 with the two *Eospirigerina* forms. Only seven brachiopod genera are congeneric between Taimyr (site 4, 4a and 4b due to Cocks & Modzalevskaya, 1997) and the investigated sites in this study.

Where the sites OB8 and the three beds of OB4 look very similar to each other on the high taxonomic level (see figure 15), they differ strongly in their composition of brachiopod orders. Focusing on that, OB8 and OB7 are very similar, with dominating atrypids. The predominant amount of strophomenids at Solberga_3 is referable to the relatively high number of specimens of the genera *Trondonema* and *Eoplectodonta*. There is an observable shift in brachiopod diversity. The most diverse site is OB4_B1 (17 species), followed by OB4_B2 (16 species). OB4_B3 shows the same diversity as OB7 and OB8 with 12 found species. Interpreting the results from the abundance plots, it seems that bed 2 and 3 show a very similar genus composition, with *Sulevorthis* and *Eoplectodonta* among the most abundant taxa. The specimen numbers from *Holorhynchus* taken from Shiino and Suzuki (2014) could not be assigned to an exact site. They distinguish between two beds, where the beds 1 and 2 - according to this work - were pooled together. The identification of the specimens of *D. testudinarius* from bed 3 of OB4 is not confirmed. Some of them could be assigned to the genus *Hirnantia*. Both genera are associated with the Hirnantian and distinct elements of the *Hirnantia* deep water community (Cocks & Price, 1975). At OB4_B1 pentamerids and atrypids are dominant, along with *Eoplectodonta*. Regarding to the evenness index, bed 1 and 2 are very similar (0,59 and 0,54). Bed 3 has the highest evenness value of 0,80. The Jonstorp Formation sites OB7 and OB8 show low evenness indices of 0,34 and 0,4. Both sites are dominated by one of the two atrypid species, whereby the other atrypid species is very rare or completely missing. This could indicate a switch of these two forms. As said before, those two species are separated due to their different shell morphology and it is not clear, whether they are in fact two separate species or just an intraspecies variety. Solberga_3 has similar evenness values as bed 1 and 2 of OB4, with *Eoplectodonta* as the dominant element. Having a look at the results from the NMDS (figure 46), showing Solberga_3 close to OB7. Like before, it is recommended to exclude the site Solberga_3 and focus on the Osmundsberget sites. Figure 46 shows the NMDS results with brachiopod data only without Solberga_3.

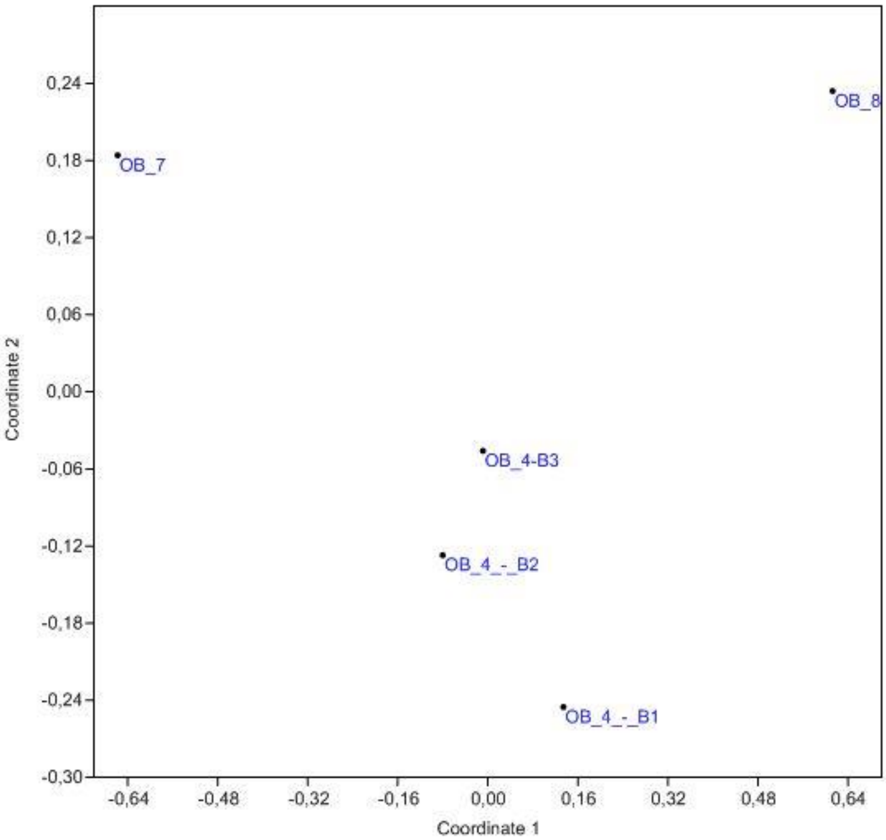


Figure 46: results from the NMDS including data from brachiopods excluding the site Solberga_3.

The NMDS was done several times, and this result is the most likely one (6 of 10). The interpretation on this is the ongoing deepening. OB7 and OB8 are at the top of the coordinate 2 axis but still on different sides of the coordinate 1 axis. In respect to the abundance analysis, showing that the taxa composition is quite different of these two sites, it is not surprisingly, but the factor of the taxonomic differences is still unknown.

The results from the cluster analysis are the same as with the data including all taxa.

Including the results from brachiopods only, they show an affinity between the sites of OB8 and OB4. This is supported by the data from the proportion of higher taxonomic groups (see figure 15) and the results from the ecospace analysis (see figure 16). The proportion of the brachiopod order show different results. It shows a high similarity of OB7 and OB8, dominated by atrypids but of different taxa / forms.

Rugosa and Tabulata are common at the sites from Osmundsberget but rare at Solberga_3 and Tabulata are missing. Tabulata occur at the reef flank or the intermound facies only and no findings of them are recorded from the reef core. Rugosa are rare in the core as well, but can be found. This lack of tabulate corals and the low number of Rugosa support the assumption that Solberga_3 was located at the top of the mound. The proportion of Rugosa / Tabulata is almost the same for all sites of Osmundsberget. At any site of Osmundsberget, the erosive marks of Rugosa can be found, indicating a very similar environment to all sites (see taphonomy and sediment). Looking at the tabulatans only, the taxonomic composition are different at each site, but OB7 stands out. Two taxa only are known. The dominant taxon is *Halysites*, for example at OB8. The habitus analysis of Tabulata shows the similarity of those both sites again, but with dome-like structures found at OB8. The NMDS (figure 33) and cluster analysis (figure 35) based on the data from Rugosa and Tabulata show again that OB8 and OB4 are close.

The Mollusca are important at Solberga_3. The lack of specimens from this taxa at Osmundsberget is attributed to dissolving processes (see erosive marks of Rugosa). At Solberga_3 the finding of three bivalves close together with articulated valves tell about the deposition. Due to Brett and Baird, 1986, articulated bivalve shells are an indication of fast burial. The preservation state at this site is extraordinary, including several taxa. Beside bivalves, many gastropods can be found.

Bryozoans occur at any investigated site with several growth forms. At Solberga_3 all found bryozoans are of a fine, fragile habit. They are very abundant and it is supposed to be a bryozoan limestone. Noticeable is the occurrence of *Diplotrypa* at the sites of OB4_B1 and B3. Specimens from OB7 are not confirmed.

Like the mollusks, trilobites can be found at Solberga_3 in a well preserved condition. Their low abundance and poor preservation at the sites of Osmundsberget is explained by dissolving or selective (trapping, see Suzukii & Bergström, 1999) processes. Most of the trilobites found at the Solberga site have eyes. This indicate a non-pocket origin for Solberga_3 because most of the pockets originated from a cave are dominated by eyeless forms (Suzukii & Bergström, 1999). The specimens found at the pocket PB at Jutjärn belong to a few taxa, probably to one taxon only. It seems to be a typical, dominated by one taxon-only, pocket (Suzukii & Bergström, 1999).

The most interesting fossils found at Solberga_3 are those abundant spherical structures. No definite assignment could be made and no structures like this can be found in the literature of this region or in collection material. An inorganic origin is excluded, because of those “apical” notches. Due to their shape and the cavity, they could be algae or more likely calcareous sponges. If they are in fact sponges, this is one of the rare places of the Boda Limestone Formation, where sponges can be found as macrofossils and in such abundance.

Conclusion

The sites OB4, bed 1 to 3, OB7 and OB8 are very similar to each other regarding their depositional environment, which is likely to be deeper water. The preservation of the fossils and the corrosion features shown by rugosan corals support that assumption. The three beds of OB4 are close together at any NMDS and similar to their higher taxonomic composition, ecospace model and brachiopod orders. On most NMDS plots the samples OB4 and OB8 are close on one coordinate axis, with OB7 apart. The three beds of OB4 are interpreted as the uppermost Boda reef, developing gradually into flank facies. This is supported by the occurrence of *Eospirigerina*, *Nicolella oswaldi*, *Sulevorthis* and *Eoplectodonta*. They occur at OB7 and OB8 too, in addition to Christiania, but the brachiopod order composition (dominated by atrypids at those sites) is different. The distinctness of OB4 and the sites OB7 and OB8 is shown by the values of evenness and the Tabulata / Rugosa-proportion. Figure 46 illustrate the most likely scenario with an ongoing sea level rise, where the uppermost reef mound become more like the mound flank and the deeper intermound facies, represented by OB7 and OB8. The coordinate 2 axis is here interpreted as a rising sea level towards higher coordinate 2 values. It is interpreted as a short transgression event, drowning the Boda reefs followed by a regression event (Upper Boda Member (coquinas) and dripstones at several sites). The data taken from brachiopods seem to be the most reliable. They are very abundant and most of them could be identified to at least the genus level.

Pocket B (PB) at Jutjärn seems to be a typical pocket, dominated by one trilobite taxon. The favored convex down orientation indicates a filling from the top with less currents.

The position of Solberga_3 as a mound top habitat is supported by the localization straight within a massive core limestone and the lack of Tabulata. The brachiopods occurring fit well into the description of mound core taxa (Cocks, 2005; Sheehan, 1979). In addition to those, a few more taxa like *Luhaia* and *Trondonema* could be added. The state of fossil preservation as well as the thin sections are indicative for a mound core facies. The in situ position of bivalves can be interpreted as a fast burial event. The environmental reconstruction is that of a bryozoan dominated habitat close to the mound top, affected by high environmental energy. The spheroidal structures, shown in plate XIV, could be some kind of calcareous sponges. This is more likely than algae due to their thick wall structure and their central cavity with two apical notches. The interpretation as a pocket for Solberga_3 seems unlikely: Various taxa with no dominance of one kind of trilobite, brachiopod or cephalopod (of which most pockets consist) can be found. There are indeed pockets with diverse faunas, but most of them are dominated by eyeless taxa (trilobites, ostracodes) (Suzukii & Bergström, 1999), which is not the case at Solberga_3.

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Appendix I

Brachiopoda data

Order	**Species**	**OB4_B1**	**OB4_B2**	**OB4_B3**	**OB7**	**OB8**	**Sol_3**
Orthida	Dicoelosia sp.	15	15	5	0	0	0
Atrypida	Br_2	27	10	11	1	87	0
Orthida	Sulevorthis lyckholmensis	17	27	21	13	21	0
Pentamerida	Parastrophinella sp	40	1	3	21	5	0
Orthida	Br_5	1	0	6	16	1	0
Orthida	Resserella pirguensis	3	1	4	1	26	7
Orthida	Br_7	7	4	0	0	0	0
Strophomenida	Bimuria popovi?	0	1	0	0	6	0
Orthida	Plaesiomys saxbyana	0	0	0	1	2	0
Orthida	Nicolella oswaldi	2	1	5	29	1	0
Strophomenida	Leptaena bergströmi	0	0	0	0	1	4
Atrypida	Br_15	0	12	0	157	0	25
Orthida	Barbarorthis foraminifera	0	0	0	4	14	0
Orthida	Br_17	1	0	0	9	1	0
Strophomenida	Eoplectodonta rhombica	19	17	13	59	6	39
Strophomenida	Craspedelia sp.	2	1	4	0	0	0
Strophomenida	Christiania dalarnensis	0	0	0	6	20	0
Pentamerida	Costilamnulella sp.?	19	1	0	0	0	1
Strophomenida	Eostropheodonta luna	1	0	0	2	1	0
Orthida	Laticrura sp.	10	0	0	1	1	0
Strophomenida	Trondonema bella	1	0	3	0	0	8
Orthotetida	Cliftonia sp.?	0	0	0	0	1	0
Strophomenida	Leptaena roomusoksi	1	0	0	0	0	0
Orthotetida	Coolinia dalmani	3	0	0	0	0	0
Orthida	Boreadorthis sp.	10	0	0	0	0	0
Orthida	Br_32	1	0	0	6	0	0
Strophomenida	Holtedahlina suedica	0	2	0	0	0	0
Billingsellida	Vellamo sp.	0	1	0	0	0	0
Pentamerida	Tscherskidium sp.	0	1	0	0	0	0
Orthida	Dalmanella testudinarius	0	0	11	0	0	0
Orthida	Drabovia sp.?	0	0	0	1	0	0
Strophomenida	Leangella longae	0	0	0	1	0	0
Pentamerida	Brevilamnulella sp?	0	0	0	0	0	13
Strophomenida	Br_40	0	0	0	0	0	1
Strophomenida	Luhaia candelabra	0	0	0	0	0	1
Lingulida	Pseudolingula quadrata	0	0	0	0	0	1
Orthida	Nicolella sp.	9	0	0	0	7	0
Orthida	Br_45	0	0	0	0	0	5
Orthida?	Br_46	0	0	0	0	1	0
Pentamerida	Holorhynchus giganteus	5	5	20	0	0	0

Appendix II

Rugosa and Tabulata data

Order	Species	OB4_B1	OB4_B2	OB4_B3	OB7	OB8	Sol_3
Stauriida	Grewingkia bilateralis	3	0	0	2	0	0
Stauriida	Grewingkia contaxta	12	2	6	0	5	3
Stauriida	Streptolasma prinum	6	4	2	2	5	0
Stauriida	Bodophyllum osmundense	28	7	10	4	12	0
Stauriida	Borelasma crassitangens	33	3	2	3	8	0
Heliolitida	Ta_1	9	3	7	0	1	0
Heliolitida	Ta_2	11	2	1	3	2	0
Lichenariida	Lichenaria sp.	22	2	10	0	3	0
Heliolitida	Halysites	7	3	7	7	10	0

Trilobita data

Order	Species	OB4_B1	OB4_B2	OB4_B3	OB7	OB8	Sol_3
Phacopida	Pompeckia minor	0	0	0	0	3	19
Proetida	Holotrachelus sp.	0	0	0	0	0	1
Phacopida	Pomeckia regelini	0	0	0	0	0	1
Phacopida	Amphilichas wahlenbergi	0	0	0	0	0	1
Phacopida	Amphilichas periformis	0	0	0	0	2	1
Corynexochida	Eobronteus sp.	0	0	0	0	0	1

Mollusca data

Order	Species	OB4_B1	OB4_B2	OB4_B3	OB7	OB8	Sol_3
	G_1	0	0	0	0	0	10
Murchisoniina	Lophospira sp.	0	0	0	0	0	1
Euomphalina	Holopea sp.	0	0	0	0	0	2
Bellerophontida	Bucania sp.	0	0	0	0	0	2
	G_5	0	0	0	0	0	19
	G_6	0	0	0	0	0	9
Pterioida	Ambonychinia ernugata	0	0	0	0	0	1
Acroida	Cyrtodonta sp	0	0	0	0	0	11
Modiomorphoida	Modiolopsis pygmaea	0	0	0	0	0	1
Pterioida	Ambonychinia extudima	0	0	0	0	0	1
Pterioida	Amphicoelia transplicata	0	0	0	0	0	1
	B_4	0	0	0	0	0	1

Appendix III

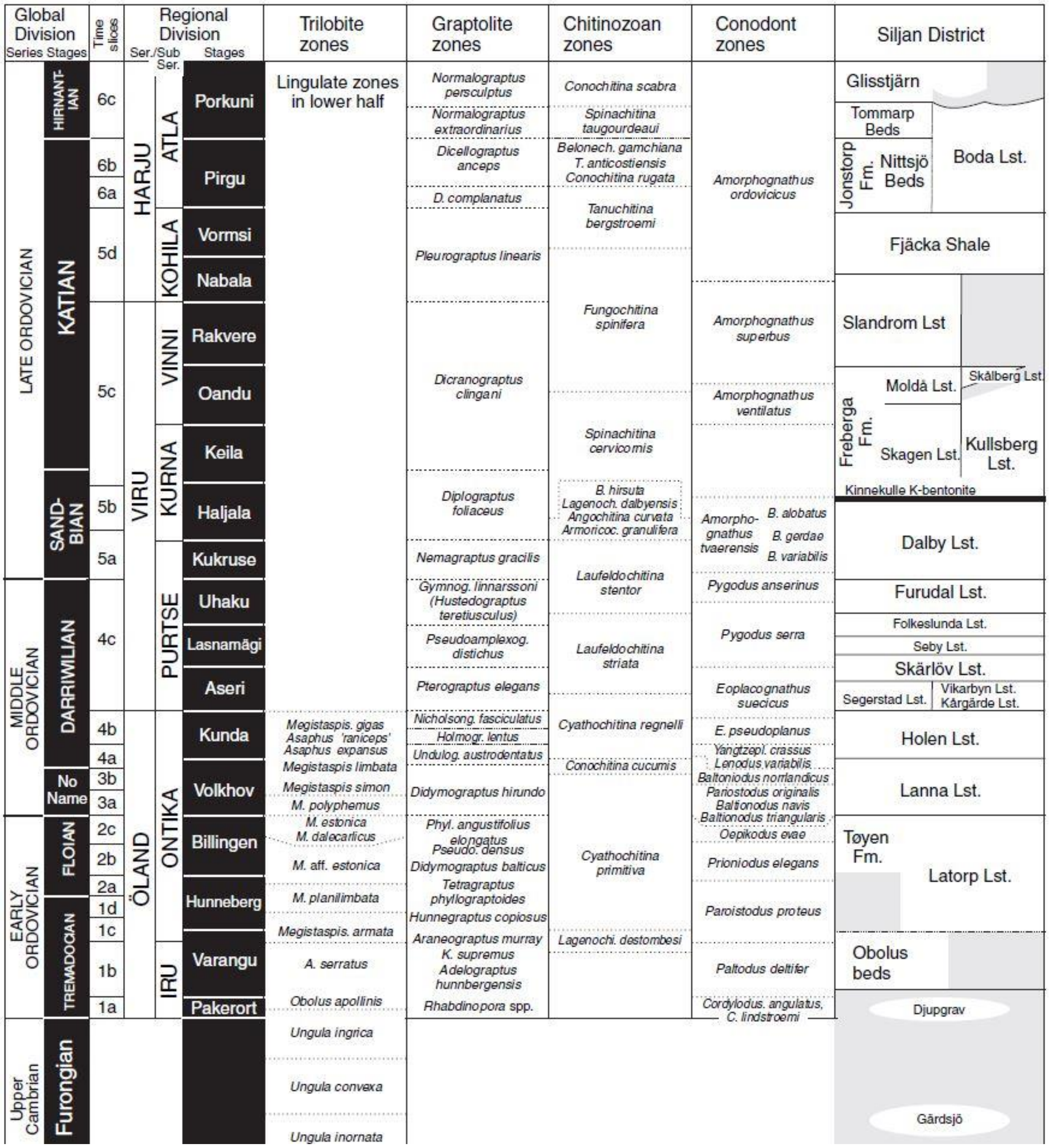

Figure 47: Ordovician global and regional division, including trilobite, graptolite, chitionzoan, conodont zonation and the various limestone formations from the Siljan district. From Ebbestad et al., 2007.

Zusammenfassung:

Die Boda mud mounds der Boda Limestone Formation aus der Region Dalarna, Schweden, entwickelten sich im späten Katium (spätes Ordovizium) und ihr Auftreten wird mit dem Boda-Event, einer Zeit starker klimatischer Veränderungen, in Verbindung gebracht. Sie zeichnen sich durch eine sehr gute Fossilerhaltung aus verschiedensten Faziesbereichen der mounds aus. Mithilfe der Fauna wurden Schichten aus Osmundsberget, welche sich am Übergang vom Katium ins Hirnantium befinden, untersucht. Diese Schichten sind von Interesse, da das Wachstum der mud mounds zu dieser Zeit aufhörte und die Gründe dafür und dem damit einhergehenden Absterben dieser Strukturen noch immer nicht vollständig verstanden sind. Es gibt zwei mögliche Erklärungen dafür: Infolge einer globalen Regression, ausgelöst durch die Vereisung des Südpoles, fielen die Riffstrukturen trocken. Diese Ansicht wird gestützt durch das Upper Boda Member, welches über den Schichten in Osmundsberget liegt. Das Upper Boda Member umfasst Schichten von massiven Kalk und Brachiopoden-Coquinas, welche als Ablagerungen von Sturmereignissen interpretiert werden. An verschiedenen Stellen in der Region finden sich Tropfsteine, welche sich in Hohlräumen gebildet haben und als klares Anzeichen für ein nicht marines Environment interpretiert werden. Sowohl die Brachiopoden-Coquinas als auch die Tropfsteinfunde weisen auf ein Austrocknen der Riffe hin infolge einer Regression, welche in Zusammenhang mit dem HICE-Event (Hirnantian Isotope Carbon Excursion) aus dem Hirnantium gebracht wird. Eine entgegengesetzte Erklärung geht von einem kurzzeitigen Transgressions-Event im ausgehenden Katium aus. Dieser Meeresspiegelanstieg führte dazu, dass die mud mounds mit dem Wachstum nicht mehr mithalten konnten und schlussendlich „ertranken“. Die Schichten des späten Katiums, welche noch den mud mounds zugeordnet werden, weisen Sedimenteigenschaften auf, welche auf tieferes Wasser hindeuten. Das Vorkommen der Bryozoengattung *Diplotrypa* spricht ebenfalls für ein Meeresspiegelanstieg. Diese Arbeit untersucht verschiedene mud mound Bereiche – Kern, Flanke und intermound Fazies – auf deren Fossilinhalt, basierend auf quantitativen Daten. Diese Daten stammen aus gesammeltem Material von sechs Schichten aus Solberga und Osmundsberget. Für die Auswertung und Interpretation der Daten wurden non-metrical multidimensional scaling (NMDS), principal coordinates analysis (PCO), Diversitätsanalysen und Ecospace-Analysen verwendet. Über 1500 Exemplare von fast 70 Arten wurden gesammelt und möglichst genau bestimmt. Der Großteil der Daten stammt von Brachiopoden, Rugosa und Tabulata. Mithilfe dieser Daten wurde versucht zu klären, welches der oben genannten Szenarien für das Verschwinden der Boda mud mounds auf Basis der Untersuchung der Fauna am wahrscheinlichsten zutrifft. Drei der besammelten und untersuchten Schichten stammen von bekannten mound Bereichen: eine Fundstelle aus Solberga kann dem mound Kern zugeordnet werden, während zwei Schichten aus Osmundsberget den tieferen Schichten der Jonstorp Formation (intermound Fazies) entsprechen. Diese wurden mit drei Schichten, welche sich am Übergang vom Katium ins Hirnantium befinden, im Hinblick auf deren Fossilbestand verglichen. Die Ergebnisse sowohl aus der NMDS als auch aus der Faunenzusammensetzung zeigen, dass die drei Schichten aus dem späten Katium jenen der Jonstorp Formation immer ähnlicher werden. Dies wird durch das Auftreten des Taxons *Diplotrypa* (Bryozoa) unterstützt. Die Faunenanalyse unterstützt somit ein kurzzeitiges Transgressions-Event am Ende des Katiums als Ursache für das Absterben der mud mounds.

Curriculum Vitae

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School education

1995 – 1999: Volkschule Altenstadt

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