THESIS

SEDIMENTOLOGY OF AN UPPER ORDOVICIAN (LATE KATIAN-HIRNANTIAN) DEEP SHELF MUDSTONE EXPOSURE PRECEDING MASSIVE SEA LEVEL DROP - MOUNT ÅLLEBERG, VÄSTERGÖTLAND, SWEDEN

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ABSTRACT

SEDIMENTOLOGY OF AN UPPER ORDOVICIAN (LATE KATIAN-HIRNANTIAN) DEEP SHELF MUDSTONE EXPOSURE PRECEDING MASSIVE SEA LEVEL DROP - MOUNT ÅLLEBERG, VÄSTERGÖTLAND, SWEDEN

The deposition of siliciclastic mudstones in a passive margin deep shelf environment has not been explored well in literature. The upper Ordovician succession at Mt. Ålleberg, Västergötland (southern Sweden) is such a succession mirroring sedimentation on Baltica‘s deep shelf just prior to a catastrophic sea-level draw-down during the Hirnantian Ice Age. The here presented only exposed section is 6.3 meter thick and consists mostly of siliciclastic mudstones interspersed with carbonates. Siliciclastic mudstones are subdivided by dominant clast material and size into four facies, namely fine- to medium-grained (1), carbonate-rich (2), silt- to sand-rich (3), and bioclastic-rich (4). The carbonates are divided into two facies; a carbonate mud- to wackestone (facies 5) seen throughout the section and a lithoclastic fossiliferous carbonate rudstone (facies 6) only observed at the top of the section. Facies 6 carbonate rudstone clasts are poorly sorted and the matrix contains geopetal cement. The idealized succession coarsens upward from facies 1 to facies 5 and excludes facies 6; this idealized succession is observed only once in the section. Siliciclastic mudstones as well as one carbonate (facies 5) contain sediment features and trace fossils of round mud-filled burrows, randomly oriented shells, *Phycosiphon*-like fecal strings, and generally massive texture. Siliciclastic mudstones are observed with irregular, non-continuous, normally graded laminae.

The succession is interpreted as deposition on the low-inclined Baltica shelf reflecting a ramp-like setting mostly an outer shelf environment reaching into a mid-shelf setting. Sediment features and trace fossils are a result of bioturbating organisms and suggest the entire water column was at least suboxic to support benthic life. The irregular laminae observed in all mudstones are interpreted as storm

beds and counters the notion that the carbonate-siliciclastic transition is a product of storm wave base interaction. Rounded clasts in the carbonate rudstone (facies 6) reflect significant transport of those grains, likely from more proximal settings, and also indicate up-slope erosion. The geopetal cements are interpreted as indicating subaerial exposure following deposition. The exposure is likely the result of a glacioeustatic sea-level drop associated with the Gondwana glaciation during the late Hirnantian or at the Ordovician-Silurian boundary.

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INTRODUCTION

The deposition of siliciclastic mudstones on deep shelves in passive margin settings has not been widely explored to date (but see Egenhoff et al. 2015; Biddle et al. 2021). Previous studies focus on understanding the processes that lead to the deposition of siliciclastic mudstones (e.g. Schieber et al. 2007; Macquaker et al. 2010) and aimed at contrasting them with the long-held notion that siliciclastic mudstones (or “shales”) were deposited in an oxygen-free environment from suspension settling (e.g. Schieber 2003, and references therein). For many units, probably most of those preserved throughout geological history that has not been the case. The Upper Ordovician succession in Scandinavia is one point in case: while siliciclastic mudstones make up a significant amount of the sediments deposited, especially in southern Sweden, these siliciclastic mudstones were regarded as having been deposited by suspension (e.g. Jaanusson 1963) without really looking at them in detail. This assumption has led to misconceptions about their depositional style and the processes involved, and has also sent a false signal as to what processes operate in shale depositional systems located in passive margin settings.

The Scandinavian Upper Ordovician succession has for quite some time been extensively used to reconstruct sea-level changes associated with the Hirnantian Ice Age (e.g. Brenchley and Newall, 1980; Beier et al., 2000;), usually focusing on the geochemical signature of this significant climate shift and, to a lesser degree, on the sedimentological fingerprint of the carbonates that accompanies this catastrophic world-wide event. Looking in detail at the siliciclastic mudstones themselves that are directly underlying the Hirnantian carbonates and placing them into a basin framework has not been attempted to date. Nevertheless, such a study could shed some light on the sedimentary conditions that directly preceded the Hirnantian glaciation, and at the same time highlight deposition on a passive margin setting of a microcontinent that just entered a tropical environment (Cocks and Torsvik 2005).

This study therefore aims to explore the depositional conditions on the Scandinavian shelf just prior to and including the Hirnantian sea-level fall. The study area is focused on one specific and hitherto largely unstudied section at Mount Ålleberg in Västergötland (Fig. 1), southern-central Sweden.

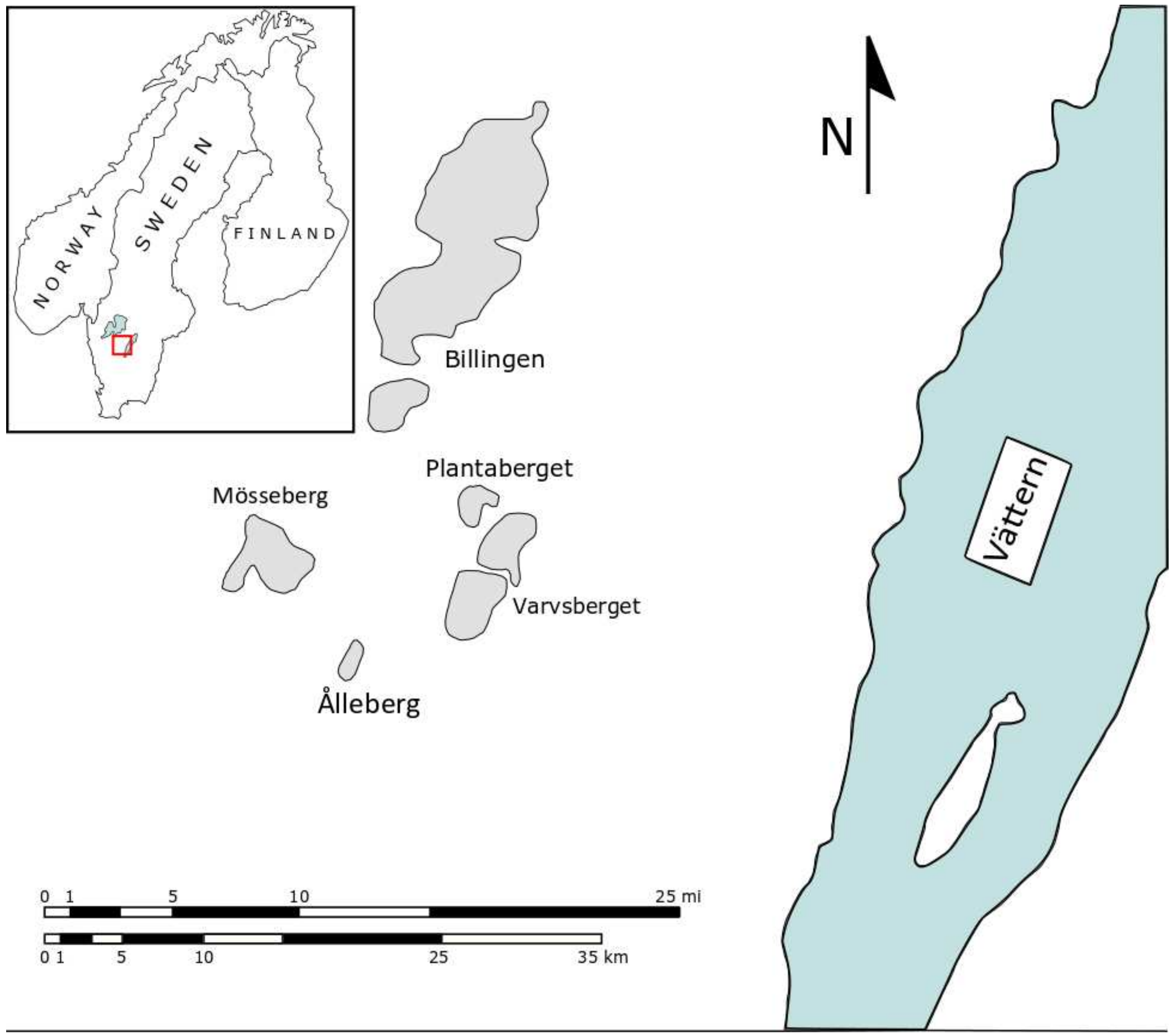

Figure 1. Location map of Västergötland, southern Sweden. Table mountains are labeled grey polygons in the center with Mount Ålleberg as the southernmost table mountain. Lake Vattern is to the east.

GEOLOGIC SETTING

During the early late Cambrian, the Baltica plate spanned between palaeolatitudes of 70° S and ~45° S (Cocks and Torsvik, 2002; their Fig. 5) with modern day southern Scandinavia being located on the northern margin of the microcontinent. In the Early Ordovician (Tremadocian), Baltica rotated 90° counter-clockwise and successively moved toward lower palaeolatitudes eventually passing the paleo-equator during the end-Ordovician (Torsvik and Rehnström 2003; Cocks and Torsvik, 2002; their Fig. 8). Since the early Cambrian, an active margin has been proposed running from the present-day Bergen area northwards along the entire length of Norway; during this time, what became southern Scandinavia (including Denmark) and parts of East Germany were bordering a passive margin (Cocks and Torsvik 2005). This changed, however, as Baltica had rotated, and a subduction zone developed at the southern margin in the Middle Ordovician (e.g., Beier et al. 2000), eventually leading to the docking of Avalonia with Baltica in the latest Upper Ordovician (Cocks and Torsvik 2005). It is likely that the Iapetus Ocean subduction during the end Ordovician and lower Silurian was directed westwards under the North American plate (Beier et al. 2000; Domeier 2016) as much of the Upper Ordovician succession exposed in the Oslo area does not reflect active margin sedimentation but rather resembles a passive margin (cf., Dalrymple and Narbonne, 1994; Navarro and Arnott, 2020).

Since the Cambrian (e.g. Álvaro et al. 2010) and throughout the Ordovician (Lindström 1971), southern Scandinavia was covered by an epicontinental sea with fluctuating sea-level accounting for much of its depositional architecture (Nielsen 2004). Overall, sedimentation rates were very low, reported values are in the range of 1 millimeter per thousand years (Lindström 1971) considering non-decompacted strata. Based on all Lower Paleozoic outcrops preserved by the Quaternary ice age the general facies distribution in much of southern Scandinavia shows coarse siliciclastics in nearshore environments that transition into carbonates on the shelf, and siliciclastic mudstones in deep shelf areas

(Egenhoff and Maletz, 2007; Álvaro et al. 2010). Climatic conditions are not clear during the Lower Paleozoic of Scandinavia. However, the low carbonate sedimentation rates, and the majorly temperate to in places sub-tropical position of Baltica argues for dominantly temperate climatic conditions that are only turning truly tropical in uppermost Upper Ordovician sediments influenced by the Hirnantian glaciation (e.g. Stridsberg 1980).

METHODS

Section measurements and field sample collections were performed in 2000 on the northern face of Mount Ålleberg; the section was measured at centimeter-scale detail, noting changes in lithology, fossil content/distribution, grain size trends, burrowing intensity, or other significant textural changes. Much of this table mountain is covered in trees and brush making complete, uncovered exposures a rare occurrence. Thirty-one nearly continuous, oriented samples were taken from the section despite the heavily weathered conditions of the outcrop; samples were later prepared to a standard thickness of 30 micrometers for carbonates and 20 - 25 micrometers for the shales to allow for more detailed observations of internal structure. Thin section observations were performed in cross polarized and plane polarized light on a Nikon Eclipse Ci Microscope with accompanying Nikon DS-Fi2 microscope camera for capturing microphotographs; some plate microphotographs were taken on a Leica DM 2700P with a Leica MC170 HD digital camera. Microscope observations were compared with field measurements, observations, and notes to further refine the section into the final section presented in this study.

SEDIMENTOLOGY

The succession at Ålleberg is here subdivided into 6 facies which are siliciclastic fine- to medium-grained mudstone (facies 1), carbonate-rich siliciclastic mudstone (facies 2), silt- to sand-rich siliciclastic mudstone (facies 3), bioclastic-rich siliciclastic mudstone (facies 4), massive carbonate mud- to wackestone (facies 5), and lithoclastic fossiliferous carbonate rudstone (facies 6); four of these facies are dominantly siliciclastic in composition, and two are carbonates. Each of these facies will be described in detail below along with an interpretation of depositional processes based on their characteristics and, if present, dominant sedimentary structures.

Facies 1 - Siliciclastic fine- to medium-grained mudstone

The siliciclastic fine- to medium-grained mudstone consists of a matrix of mud and clay-size siliciclastics making up 85-90% of this facies (Fig. 2A); nevertheless, despite the siliciclastic material, about 20-30 vol% (visual estimation) of the matrix is composed of very fine-grained to crystalline carbonate. The matrix often shows massive or weakly defined thin beds of mudstones that are less than a millimeter to several centimeters in thickness; if visible, grains in this facies are medium- to coarse-grained silt and sub-angular to well-rounded. These silt grains float randomly in the matrix and consist of poorly-sorted carbonate, quartz, feldspar, and elongate mica flakes, the latter ones aligned sub-parallel to parallel to bedding. The grain size of this fraction seems to cover much of the range of coarse silt sizes. In places, beds of facies 1 show sub-millimeter-thick accumulations of coarse-grained siltstone forming laminae of laterally varying thickness, extending a few millimeters or less laterally (Fig. 2B). Throughout this facies, mud-rich thin beds of sub-millimeter thickness occur that consist of the same fine- to medium-grained matrix without any outsized siltstone grains (Fig. 2C); they may or may not extend laterally for more than a few millimeters or centimeters, though. Rarely, thin beds showing normal grading from coarse- to fine-silt and clay are present throughout this facies (Fig. 2D).

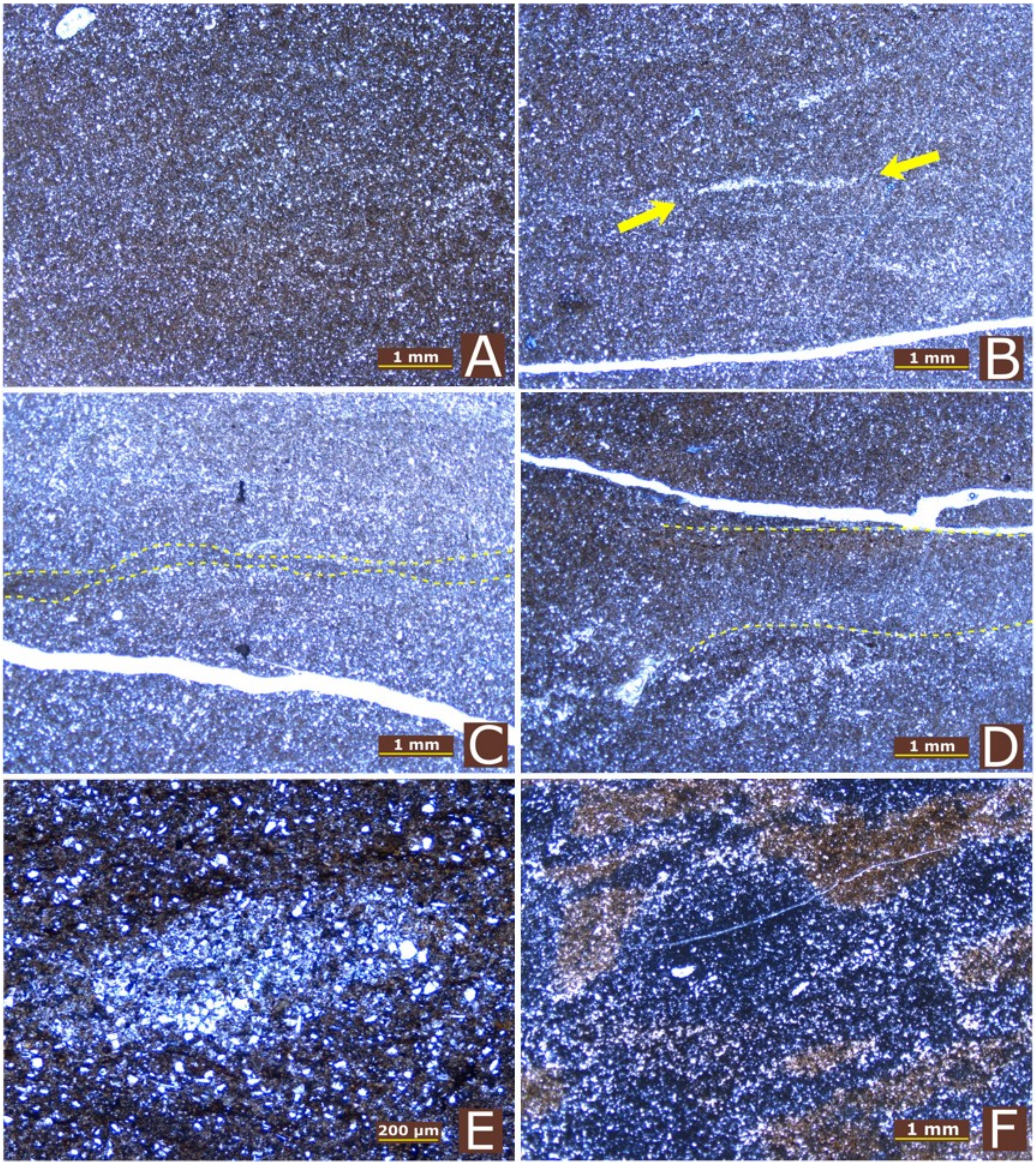

Figure 2. A) PPL (planar polarized light) view of Facies 1 siliciclastic fine- to medium-grained mudstone; silt grains are distributed randomly throughout the matrix with no other discernible features. **B)** PPL view of Facies 1; sub-millimeter-thick non-continuous, irregular siltstone lamina (arrows) are present in places. **C)** PPL view of Facies 1; irregular, fine-grained lamina outlined by yellow lines; the lamina is mostly devoid of silt grains. **D)** PPL view of Facies 1; non-continuous, irregular, normally graded beds outlined in yellow; silt content is high at the base and successively decreases upward; finer grains appear brown at the top of the bed. **E)** PPL view of Facies 1; about one millimeter in diameter roundish to oval feature with a high concentration of outsized silt grains; the feature lacks a distinct outline. **F)** PPL view of Facies 2 carbonate-rich siliciclastic mudstone; fine-grained matrix mixed with randomly distributed outsized silt and sand grains.

Facies 1 is dark grey in outcrop and brown to red-brown in thin section. The contacts to the overlying facies 2 is gradational, and no contact to the underlying beds is exposed. There is very little fossil debris present in this facies estimated to be less than 0.5 vol%; the debris consists mostly of isolated bioclasts that are generally composed of quartz. They are sub-millimeter to millimeter in size, and if elongate oriented parallel to bedding; otherwise, their orientation is random. This facies also shows sub-millimeter to millimeter-size roundish features that are characterized by higher amounts of silt-size grains than the matrix and show irregular to fuzzy indistinct outlines (Fig. 2E). *Phycosiphon* isp. (cf. Egenhoff and Fishman 2013; but see Schieber et al. 2021) is present throughout this facies. In one place, a cluster of sub-rounded coarse silt-size grains is observed within the fine-grained matrix.

Interpretation

This facies consists to a large degree of matrix which is interpreted to have been brought into the depositional environment by both bed-load processes and suspension (e.g., Schieber et al. 2020). The matrix is generally highly bioturbated and does not preserve any sedimentary structures; however, the siltstone laminae that are present in places are here interpreted as lags. These lags are envisioned to be deposited by currents only depositing its coarse silt fraction and not its finer-grained load. The presence of both, fine as well as coarse grain sizes reflects the fluctuating energetic conditions during deposition of this facies with the siltstone laminae indicating relatively high-energy events. The lowest energy deposition is mirrored by the fine-grained mudstone laminae of which generally only remnants remain; these remnants have been generally partly destroyed by burrowing. The fine grain size of these low-energy and fine-grained laminae most likely shows deposition from suspension (e.g. Egenhoff and Fishman 2013); however, because they do not constitute a large percentage of the preserved rock, suspension may not have contributed much to the deposition of this facies. The fact that the matrix is coarser-grained than the suspension-derived material makes it likely that it was deposited by energy levels slightly higher than the fine-grained thin beds of this facies. Based on the experiments of Yawar and Schieber (2017), only fine-grained silt will reflect deposition from suspension settling, yet the grains distributed randomly throughout the matrix are coarse- to medium-size silt. The fact that they are marginally to well-rounded indicates that they have been deposited by bed load processes that would allow for abrasion of the grains. It therefore seems probable that these grains were originally deposited from currents concentrating them in lags during high-energy events; subsequent burrowing dispersed those grains throughout the matrix. While rare, the presence of silt grain clusters suggests that microbial mats were present in this or an adjacent siliciclastic mudstone environment (cf. Schieber 2004). These clusters are envisioned to originate from gas accumulating below a microbial mat. Once sufficient gas is present it rips out a piece of the mat together with the silt grains sticking to it. The mat fragment and the silt grains get transported and deposited; however, in this case the mat degraded completely, and only the silt grain clusters are left indicating that a microbial mat must once have been there.

The depositional environment must have been well oxygenated during deposition. This is indicated by the thorough burrowing of the sediment obliterating most sedimentary structures, the presence of roundish structures filled preferentially with silt and interpreted as burrow cross sections as well as ubiquitous fecal strings. The fact that the burrows are generally filled with slightly coarser-grained sediment than the matrix throughout this facies suggesting that they were open when filled, and the silt grains were shed into the structure during a slightly higher-energy event than the one forming the matrix. A likely oxic environment is also indicated by the absence of pyrite in this facies, even diagenetic pyrite is missing. It is suspected here that the Fe for forming pyrite must have been missing during and shortly after deposition; however, the abundance of calcite in the matrix interpreted from the presence of carbonate cement suggests that Ca was readily available, either from depositional carbonate mud, or as Ca ions in the pore water, or both. The fact that bioclasts of calcite-bearing organisms, e.g. shell parts, are currently composed of quartz indicates that this rock experienced a calcite to quartz replacement during its diagenetic history.

Facies 2 – Carbonate-rich siliciclastic mudstone

This facies consists of a fine-grained matrix with about 7.5 vol% of medium- to coarse-grained silt and very fine-grained sand that is randomly distributed throughout the matrix (Fig. 2F). The silt grains consist mostly of quartz and some carbonate (predominantly calcite). The grains are angular to sub-rounded, and the quartz grains show an overall better rounding than the carbonates. The quartz and carbonate grains are not well sorted and comprise the entire spectrum of medium- to coarse silt. The matrix consists of both siliciclastic components that are fine silt- or clay-size, and carbonate, which is likely mostly calcite. The carbonate is completely recrystallized so it forms a groundmass of crystalline carbonate within the matrix. The rock is generally massive in nature, however, it locally shows poorly-developed, laterally pinching-out laminae composed of coarse-grained silt; this facies also exhibits local remnants of horizontal bedding expressed in sub-millimeter thick clay-rich and carbonate-rich laminae. Facies 2 is black in outcrop and has an irregular speckled brownish to black appearance in thin section; this is the facies that has been referred to as “speckled mudstones” by several Swedish geologists (e.g., Jaanusson 1963; Kielan-Jaworowska et al. 1991). The contact to underlying facies 1 deposits is unclear; however, the contact to the overlying facies 3 sediments is sharp. Biogenic grains in this facies are bioclasts that are sub-millimeter to several millimeter in size, and make up 1-2 vol% of this facies. They are generally rounded, recrystallized, and show one or two generations of carbonate cement, and in places a generation of microcrystalline quartz overgrown by carbonate cement. Fecal strings of the type *Phycosiphon incertum* are present throughout these rocks. The bioclasts are arranged at various angles to bedding. Locally, poorly-developed phosphate concretions that are several millimeters in diameter occur parallel to bedding.

Interpretation

The mix of medium- to coarse-grained silt and very fine-grained sand that is randomly distributed in the fine-grained matrix indicates that the energy level to deposit this facies may have been at times significantly higher than suggested by the fine-grained matrix. It is interpreted here that the silt and sand grains have been originally deposited in laminae as lag deposits by currents; some of the lags are still present in the rock, but most silt and sand grains have been dragged and distributed throughout the fine-grained matrix by burrowing organisms. From the places where it is preserved it is evident that this facies was originally arranged into siliciclastic mudstone and carbonate-rich laminae. This and the presence of siltstone lags indicates that this facies was deposited by fluctuating energy conditions and received sediment from carbonate and siliciclastic-dominated sources. The source of the quartz silt and sand grains was most likely from the exposed basement of the Scandinavian Shield. The carbonate grains probably originated from an adjacent carbonate facies belt located further up on the shelf. The different sources for these two grain populations would also explain the different textures of the respective grains: sub-rounded to rounded quartz grains reflect a longer transport path than the generally sub-angular to moderately rounded carbonate grains which were derived from closer to the depositional site.

The few bioclastic grains indicate that life was present either in this or an adjacent sedimentary environment; nevertheless, the presence of bioclasts in this facies also indicates that these organisms have been fragmented subsequent to their demise. Similar to the siltstone lags this suggests an at times relatively high energy level in this facies in order to transport these relatively large bioclastic grains. Some amount of transport and abrasion is also reflected in the rounding of the bioclastic particles. The presence of *Phycosiphon incertum* (Egenhoff and Fishman 2013) in this facies as well as the various angles at which elongate bioclasts are found suggests at least some amount of burrowing in this facies and hence likely dysoxic and not anoxic conditions during deposition.

Facies 3 – Silt- to sand-rich siliciclastic mudstone

This facies consists of an intimate mix of carbonate and quartz (and minor plagioclase) silt to very fine-grained sand grains forming rocks of overall massive appearance (Fig. 3A). Quartz and minor amounts of plagioclase make up between 10 and 30 vol% of the rock, with carbonate grains and crystals between 15 and 30 vol% (visual estimation). The quartz grains are sub- to well-rounded while the carbonate grains display a wider range and are angular to well-rounded. Both carbonate and quartz grains are moderately well sorted and seem to be matrix/groundmass-supported. Rocks of facies 3 do not display grading or show sedimentary structures; however, where the amount of quartz/plagioclase surpasses 25 vol% the grains are arranged in diffuse laminae parallel to bedding that are less than one to several millimeters thick (Fig. 3B). The groundmass consists of clay-size components, some organic matter, and carbonate cement. The color of this facies is dark brown to dark grey in outcrop, and medium brown in thin section. The contact to over- and underlying facies can be sharp or gradational; this facies is underlain by the carbonate-rich siliciclastic mudstones of facies 2, and overlain by the mud- to wackestones of facies 5. In places, bioclasts occur in this facies, are sub-millimeter to about 2 millimeters in length and either aligned parallel to bedding or oriented at a clear angle to bedding. Some of the bioclasts show distinct rounding, most of them seem to be broken and abraded. Some distinct roundish burrows occur in this facies and are up to a millimeter in diameter. They are generally filled with matrix material and show siliciclastic mudstones around their perimeter. *Phycosiphon incertum* is common in this facies. Much of the matrix/groundmass consists of calcite cement, and some of the quartz grains also show an outer rim of calcitic cements.

Interpretation

The quartz grains that are abundant in this facies are interpreted to originate from the exposed Baltica Shield (cf. Cocks and Torsvik 2005) and were likely brought into the depositional environment by rivers, and then by marine processes shed onto the deep shelf. The long transport path that these grains underwent is reflected in their sub- to well-rounded nature which contrasts with the often not as well rounded carbonate grains. Although these two grain types have similar grain sizes only the carbonate grains are interpreted to have originated nearby. This is indicated by grains that are still

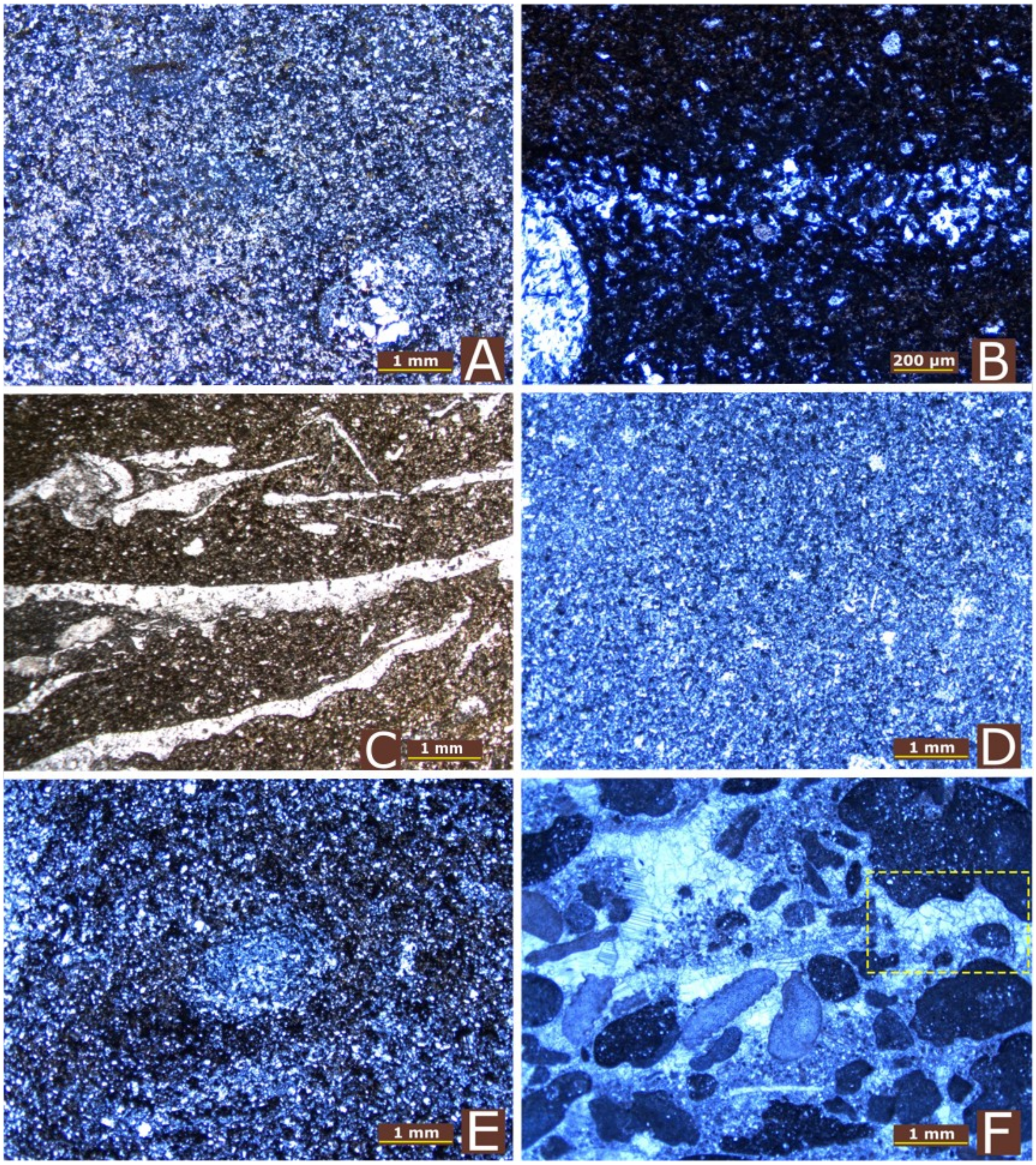

Figure 3. A) PPL (plane polarized light) view of Facies 3 silt- to sand-rich siliciclastic mudstone; silt and sand grains are thoroughly mixed with carbonate grains producing a massive texture; minor carbonate recrystallization is present in the lower right corner near the scale. **B)** PPL view of Facies 3; diffuse quartz lamina in center frame with recrystallized carbonate in the lower left. **C)** PPL view of facies 4 bioclastic-rich siliciclastic mudstone; strongly recrystallized bioclastic material floating in matrix sub-parallel or randomly oriented to bedding **D)** PPL view of Facies 5 massive carbonate mud- to wackestone; outsized angular carbonate grains float in a matrix of largely recrystallized carbonate mud and clay-sized siliciclastics. **E)** PPL view of Facies 5; roundish burrow cross-section with distinct outer rim of darker siliciclastic mudstone filled with matrix material. **F)** PPL view of Facies 6 lithoclastic fossiliferous carbonate rudstone; outsized coarse sand- to pebble-sized lithoclasts in fine-grained sand to silt matrix. Pore spaces contain small blocky carbonate crystals above fine-grained in-fill (highlighted in yellow).

angular reflecting little transport; however, some of them have been transported quite some distance because they are well-rounded. It is likely that the quartz grains were deposited by some kind of high-energy event such as storms; this high-energy sedimentation is still reflected in silt- and sand-rich portions of this facies where silt/sand grains form laminae which likely represent lag deposits of the largest grains the respective current could carry and would then deposit.

The grains stand in significant contrast to the fine-grained matrix the rock is embedded in when looking at depositional energy. It has been shown by flume experiments (Schieber et al. 2007; Schieber and Southard 2009) that fine grains, even when transported as floccules, separate from silt grains because of their different densities. Therefore, it is assumed that the silt and sand grains in this facies have been mixed in with the clay-rich matrix post-deposition by burrowing. A post-depositional origin of the grain size distribution can still be seen in the uneven texture of the silt- and sandstone laminae in this facies: this is interpreted to be caused by organisms burrowing through the laminae (Egenhoff and Fishman 2013). This “diffuse bioturbation” is indicated by elongate particles that are not arranged parallel to bedding and were likely dislocated by burrowing organisms, and the uneven arrangement of silt and sand grains in silt-/sandstone laminae whose original depositional texture was disturbed by bioturbation. The intense burrowing resulted in an overall massive nature of the rock, also interpreted as an activity of organisms right after deposition.

It is assumed that energy conditions fluctuated during deposition of this facies. These fluctuations are not only recorded in the discrepancy between matrix and grains but also in the silt and sand population itself; both smaller and larger quartz grains are present in the rock thereby indicating energy fluctuations during deposition of the grains. This is not uncommon for storms as those events can be stronger or weaker and produce stronger and weaker currents accordingly (Kreisa, 1981; Aigner, 1985). These currents would then transport larger or smaller grains to the depositional site. Not only the silt and sand grains but also the bioclasts indicate high-energy influence on deposition. These currents also likely contributed to the fragmentation and abrasion that these grains show. Accumulations of carbonate debris are interpreted as lags similar to the siltstone laminae because of their particle size which is larger than all other grains in this facies. The fact that they are arranged parallel to bedding also indicates deposition from a flow. When many bioclasts are arranged along the same bedding plane this facies shows a transition to the bioclastic-rich mudstones of facies 4. The burrows and fecal strings indicate at least suboxic but maybe even oxic bottom water conditions at the time of depositions. While the sedimentology of this rock is complex, its diagenesis seems to be confined to carbonate cement covering and partly replacing the outer margins of quartz grains as well as filling existing primary porosity with carbonate cement.

Facies 4 – Bioclastic-rich siliciclastic mudstone

The bioclastic-rich siliciclastic mudstones consist of mostly biogenic and bioclastic particles as well as siliciclastic grains in a siliciclastic mudstone matrix (Fig. 3C). Thin beds of this facies are up to about one centimeter thick but vary in thickness laterally, and may even pinch out. The biogenes are strongly recrystallized brachiopod shells as well as some crinoid ossicles; some of the brachiopods are still complete with two matching shells and are filled with carbonate cement. Isolated shells in this facies can be up to 1.5 centimeters long and all elongate grains are arranged parallel or sub-parallel to bedding. The crinoid particles are often broken but in places preserve their original internal structure. The bioclasts are recrystallized, generally consist of multiple carbonate crystals and are sub-millimeter to several millimeters in size. Bioclasts and biogenes together make up between 15 and 30% of the rock volume (visual estimation). A second group of particles are the siliciclastic and carbonate grains randomly dispersed in the matrix. They are dominantly quartz, calcite, and some plagioclase; the quartz accounts for 5-7 vol%, the plagioclase less than 0.5 vol%, and the calcite for 15-20 vol% of the rock (visual estimation). The matrix consists of clay intermixed with carbonate (calcite) and organic matter. This facies is massive and devoid of sedimentary structures. In outcrop, the rocks are dark gray to very dark brownish-black whereas in thin section that appear as medium brown to beige. Contact to over- and underlying facies are either sharp or difficult to define. This facies is generally intercalated into facies 3 silt- to sand-rich siliciclastic mudstones, and in places underlain by facies 5 carbonate mud- to wackestones. Distinct burrow outlines are absent in this facies; nevertheless, the fine-grained matrix shows *Phycosiphon incertum* fecal strings. This facies contains minor amounts of pyrite present as sub-millimeter crystals in the matrix as well as carbonate cements forming rims around detrital quartz grains.

Interpretation

Facies 4 is interpreted to represent deposition under overall high energy conditions which is reflected in the size of the biogenic grains. As they are partly broken they must have been moved prior to deposition. The locally sharp bases of the rudstones are here interpreted as erosive; it is envisioned that the storm during its peak first scoured the seafloor and formed the sharp erosional base. Subsequently, likely while losing some energy the storm concentrated the biogenic and bioclastic particles as lags. The fine-grained matrix, in contrast, was probably deposited when the storm had already calmed down significantly, and this fine-grained siliciclastic mud settled between the carbonate particles. The similarity between the matrix in these sediments and the matrix of over- and underlying strata makes it at times impossible to see a clear basal or top contact.

The fact that quite a few brachiopods with fitted shells are present in facies 4 makes it likely that this storm event buried some of them alive. Fossils still having two fitted shells and filled with carbonate cement must have been closed when buried, and the organisms living in them were likely killed by the storm. Similar to facies 3, the siliciclastic and carbonate detrital grains (quartz, feldspar, and calcite) are interpreted to stem from two different sources; the quartz and feldspar originated most likely from the erosion of exposed Baltica basement and were subsequently transport into the sea, probably by rivers.

The carbonates, in contrast, were most likely formed in shallow water and taken up by the same event that deposited the siliciclastic grains, the shells and crinoids.

The massive nature of the matrix within this facies is likely a result of burrowing. Even though there are no distinct burrows in these rocks the position of some of the shells at an angle to bedding suggest bioturbation of the matrix; similarly, the presence of fecal strings also argues for some amount of organic life at the seafloor right after deposition of facies 4. The presence of fecal strings and the assumed presence of burrows indicates that the depositional environment must have been at least partly oxygenated in order to support organic life. The finely dispersed pyrite in the matrix, in contrast, most likely reflects anoxic conditions during diagenesis.

Facies 5 – Massive carbonate mud- to wackestone

The carbonate mud- to wackestones are composed of majorly recrystallized carbonate mud with a size between 5-20 microns, and varying amounts of clay-size siliciclastic mud particles (Fig. 3D); these two together are here considered to be the matrix of the sedimentary rock. Individual carbonate mud particles vary from angular to well-rounded. Sorting of the carbonate particles is moderate, and carbonate mud grains of different sizes are found next to each other in the same stratigraphic position. Quartz and plagioclase grains of up to several tens of micrometers in size also occur but make up less than 2% of the rock volume; they are generally well rounded. Up to several millimeter-long shell fragments and millimeter-sized crinoid particles make up about 1-2% of the rock volume; the shells are arranged randomly in the matrix. Overall, this facies is massive in nature and does not show grading or contain any sedimentary structures. It is brown in outcrop, and of the same color to in places red-brown in thin section. Contacts to this facies are sharp to in places gradational; over- and underlying rocks belong to all other facies. Cross-sections of burrows in this facies are common, often roundish and filled with the same material as the surrounding matrix (Fig. 3E); their diameters are generally between about 1 and 2 millimeters. Nevertheless, they have a distinct outer rim that consists of siliciclastic mudstone. In places, these burrows are also seen as elongate features in thin section. Some matrix grains show a rim of carbonate crystals at their outer margins that is a few micrometers in thickness.

Interpretation

The carbonate mud represents mostly low-energy conditions and likely reflects sedimentation from suspension (but see Schieber et al. 2013); however, the quartz and plagioclase grains in this facies are larger than the carbonate mud grains and therefore reflect slightly higher depositional energy. Because of their size it is unlikely that they have been deposited together with the carbonate matrix. They are therefore interpreted as having been sedimented as a separate entity within the carbonate mudstones, most likely in thin layers, and subsequent to deposition randomly distributed throughout this facies. The siliciclastic grains probably originate from exposed basement rocks in Sweden. It is likely that the high-energy events that brought in the siliciclastic grains correspond to river floods washing these grains far onto the shelf; or, alternatively, the mud might have been stored close to the delta that brought it into the marine realm and was subsequently reworked and transported to its final depositional site during storms (e.g. Traykovski et al 2000). It remains unclear if the organisms producing the biogenic carbonate particles were living in the environment itself or if these carbonate particles have been transported into the site of deposition after the demise of the organism. Their random orientation, nevertheless, suggests that bioturbation has displaced these particles after deposition. The intense burrowing is also reflected in the varying range of matrix grain size, and the presence of burrow cross sections with up to 2 millimeters of diameter. The abundance of burrows also indicates that the depositional environment of this facies was most likely well-ventilated, and clearly oxic. The carbonate rims on the edges of detrital siliciclastic grains are interpreted as being diagenetic.

Facies 6 – Lithoclastic fossiliferous carbonate rudstone

Facies 6 consists of millimeter- to centimeter-size clasts of mud-rich carbonates comprising mud-, wacke- and packstone facies. These lithoclasts are moderately to well-rounded and show a variety of shapes from elongate oval to U-shaped or irregular (Fig. 3F); the sorting of the particles is poor. The lithoclasts make up 30-35 vol% (visual estimation) of this facies. Another important grain type are biogenic and bioclastic particles that include crinoids, brachiopod shells, and green algae. These grains make up about 10-20 vol% (visual estimation) of this facies. They are generally well-rounded and roundish to elongate in shape. The matrix of this facies consists of majorly carbonate and some siliciclastic debris; the siliciclastic component is made up mainly of quartz with subordinate feldspars. The carbonate component is exclusively calcite grains. Siliciclastic grains are medium sand-size and carbonate grains range from medium to coarse sand. Both grain types are sub-angular to sub-rounded. Interstices between the grains are filled with either carbonate mud, or calcite cement. This facies occurs in one 30-50 cm-thick bed that shows a wavy appearance laterally. The facies appears to be massive, is devoid of sedimentary structures and does not show sorting or grading. The color of the rock is ivory to light grey in outcrop and thin section. The contact to over- and underlying facies is sharp and distinct. Facies 6 is underlain by facies 3 silt- to sand-rich siliciclastic mudstones, and overlying beds are covered but are likely fine-grained in nature. Biogenic and bioclastic grains in this facies are mostly broken; however, all pieces have been well rounded. Some of the crinoid particles show a syntaxial cement. No burrows are recognized in these rudstones. All cements are carbonate, some of them show up to millimeter-long crystals. They are preferentially developed on the underside of grains or in-between grains, and never on the top side of particles. Some of the pore spaces are filled with blocky cements.

Interpretation

The size of the clasts indicate a very high transport energy of the grains, and this high energy is also reflected in the rounding of the millimeter- to centimeter-size particles and the sharp base of this facies; the rounding reflects significant transport and abrasion, and the different lithologies that comprise the clasts indicates that a variety of different shelf positions got eroded and their clasts incorporated into this rudstone. The poor sorting may be a reflection of the 2D cut, and it may look different in 3D; however, it could also be that the depositing flows had fluctuating energies transporting and mixing grains of different grain sizes. Based entirely on the grain size it is assumed that the depositing flow transported the clasts as bed load as there are no sedimentary structures preserved in these rocks. However, as some of the clasts show algae still attached to likely hardened carbonate sediment the erosion must have impacted carbonate facies well up-slope in a well-lit part of the shelf that was characterized by algal growth. The sand-size siliciclastic debris is likely derived from the exposed parts of the Baltic shield and similar in origin to these clasts in mudstone facies. However, as the grains are not as well rounded as in other facies it is suggested that they come from a location that is closer to the depositional environment than the ones in the mudstones. The carbonate debris probably originated from up-shelf and its sub-angular to sub-rounded nature also suggests an origin in the relative vicinity to its place of deposition. Overall, the discrepancy between the size of the millimeter- to centimeter-size clasts and the sand-size fill in-between the grains indicates that the sand-size particles most likely got deposited in-between the large grains after those had been deposited. The carbonate mud that characterizes much of the intersticial space not occupied by either of those clasts and grains reflects even lower energy sedimentation. It therefore must have been infilling the pore spaces after the two grain types had been deposited. A large number of cements that characterize this facies are geopetal; this means that while these cements formed the pore space must have been filled with both air and water as is generally the case when an area is exposed (Longman 1980; Belkhedim et al., 2019). A diverse later diagenesis post-dating the formation of the geopetal cements characterizes these sediments and resulted in syntaxial and blocky cements.

FACIES ARCHITECTURE

The 6.5 m thick succession is dominated by various mudstone and carbonate facies in a series of five decimeter- to meter-scale coarsening-upward sediment packages (Fig. 4). These coarsening-upward packages show a generalized facies succession consisting of four, potentially five facies. If this “ideal” cycle is completely developed the base is made up of a carbonate-rich siliciclastic mudstone (facies 2) which shows a sharp contact to overlying silt- to sand-rich siliciclastic mudstone (facies 3). Facies 3 sediments may show intercalated shell lags of bioclastic-rich siliciclastic mudstone (facies 4); the top of this idealized cycle is formed by massive carbonate mud- to wackestone (facies 5). It is unclear if the fine- to medium-grained siliciclastic mudstone (facies 1) which is only exposed in the lowermost about half meter of the succession forms the basal part of this “ideal” cycle or not as it does not occur anywhere else in the section; however, meters 2.25 to 3.35 are covered, and it remains unclear which facies would be exposed there. Nevertheless, a complete "idealized cycle" is not observed within this succession.

The five coarsening-upward sediment packages show two thicker units from 0 - 1.6 m and 3.2 - 5.85 m and two only several decimeter-thick units in-between, as well as one top package that culminates in a 30 cm thick bed of lithoclastic fossiliferous carbonate rudstone (facies 6). Only the two meter-scale packages represent a nearly complete “cycle” while all smaller coarsening-upwards units are only showing a selection of the six facies.

A single subtle facies-scale grain size trend is observed within the basal fine- to medium grained siliciclastic mudstone (facies 1) as "outsized" quartz and plagioclase grains increase slightly (≤ 5 vol%) from the base to the top of the facies. The most prominent facies change occurs between the uppermost unit of silt- to sand-rich siliciclastic mudstone (facies 3) and the top unit of lithoclastic fossiliferous carbonate rudstone (facies 6) which comprises the topmost coarsening-upward sediment

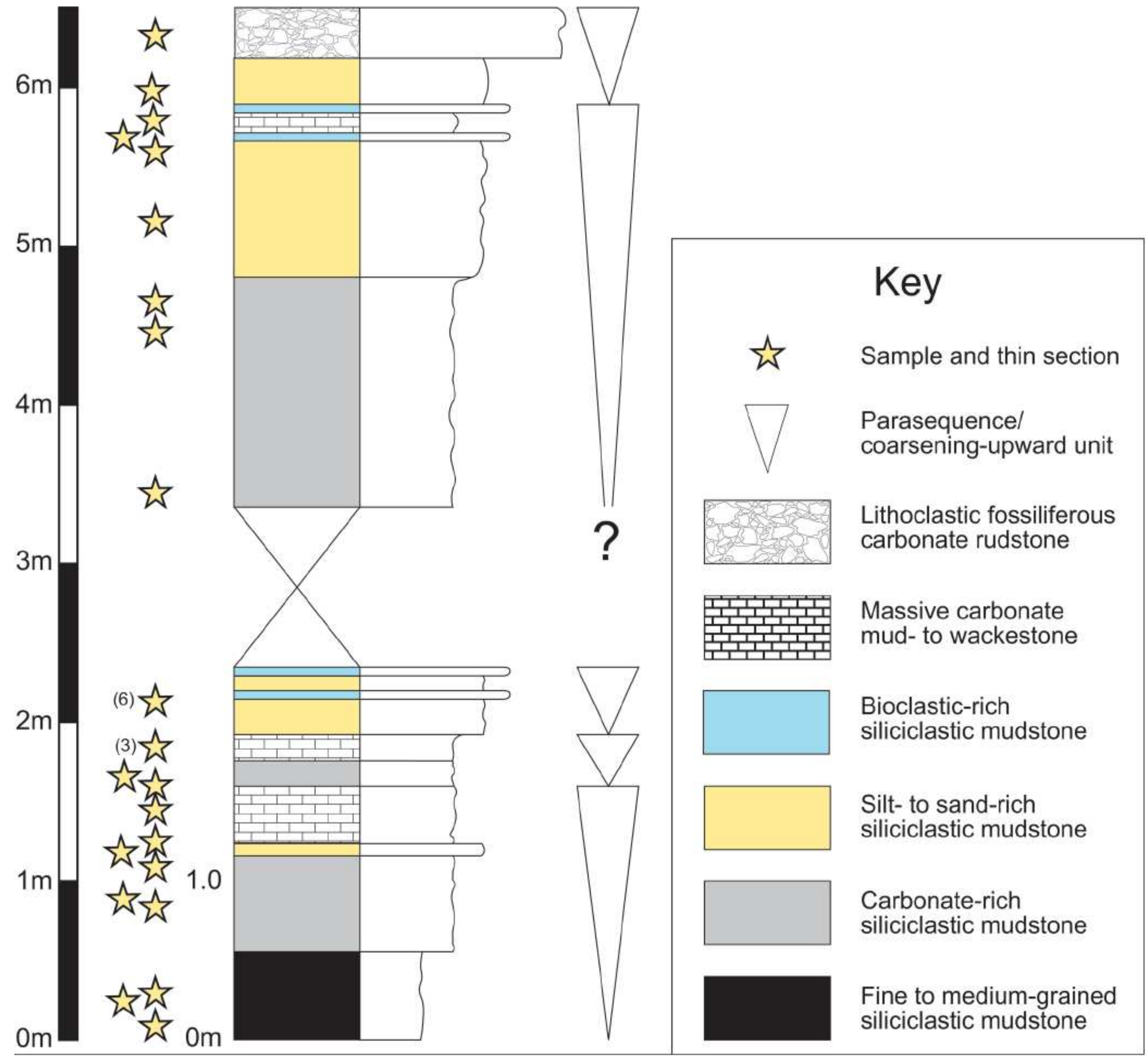

Figure 4. Section schematic of the 6.5 m exposure from Mt. Ålleberg, Sweden. Stars along the left side of the schematic indicate where in the section samples were collected. Numbers in parentheses near ~2 m show where samples are too close together to display individually. The "X" between ~ 2.3 m and 3.3 m indicates where the section was 'covered' in the field; this data gap also prevents parasequencing which is marked with a '?' on the parasequence column to indicate incompleteness.

package within the succession. The contact between the two is sharp and wavy and the carbonate rudstone is not observed elsewhere in the succession. The average grain size increases from the silt-sand transition in facies 3 up to the sand-pebble transition in facies 6; the carbonate rudstone also contains a crystalline calcite cement that is only developed on the bottom of grains, and neither coarse-grained sand nor crystalline calcite cement are observed in any of the other facies.

DEPOSITIONAL MODEL

The Upper Ordovician succession at Mt. Ålleberg shows a subdivision into two broad facies belts the proximal carbonates represented by the massive carbonate mud- to wackestones (facies 5), and the distal siliciclastic mudstones reflected in all other facies with lower numbers (facies 1 to 4). Facies 6 is interpreted to represent an exception to this otherwise consistent model and a drastic change in the sedimentological history of central Scandinavia and will be dealt with separately. It therefore does not form part of the transect shown in Figure 5.

The entire succession recorded in the Ålleberg section formed part of a shelf located at the southwestern margin of the Baltica microcontinent (Cocks and Torsvik 2005); nevertheless, none of the facies except facies 6 reflects deposition influenced by subaerial exposure and all facies were deposited in a subaqueous environment. This shelf was influenced by storms up to its most distal siliciclastic mudstone setting represented by facies 1. Nevertheless, the tempestites are mostly mixed in with the surrounding matrix in facies 1, 2, and 3, but are interpreted to have gotten generally thicker towards more proximal settings as the influence of storms got more prominent towards shallower water. Facies 4 beds, intercalated into facies 3 mudstones or occurring at the boundary to the carbonate facies belt are the only storm beds relatively well-preserved in the succession; the reasons for this are likely because the beds were thick enough and the grains large enough not to be entirely burrowed and easily mixed in with other sediments. The storms carried a mix of siliciclastic grains derived from the Baltica mainland and carbonate grains that originated from up-slope carbonate facies onto the deep shelf. The further away a facies was located from the coastline the less storm influence it experienced and silt content it has. While a significant amount of storm-derived silt grains are still present in facies 3, facies 2 sediments already show much less silt and thereby reveal their more distal position on this shelf.

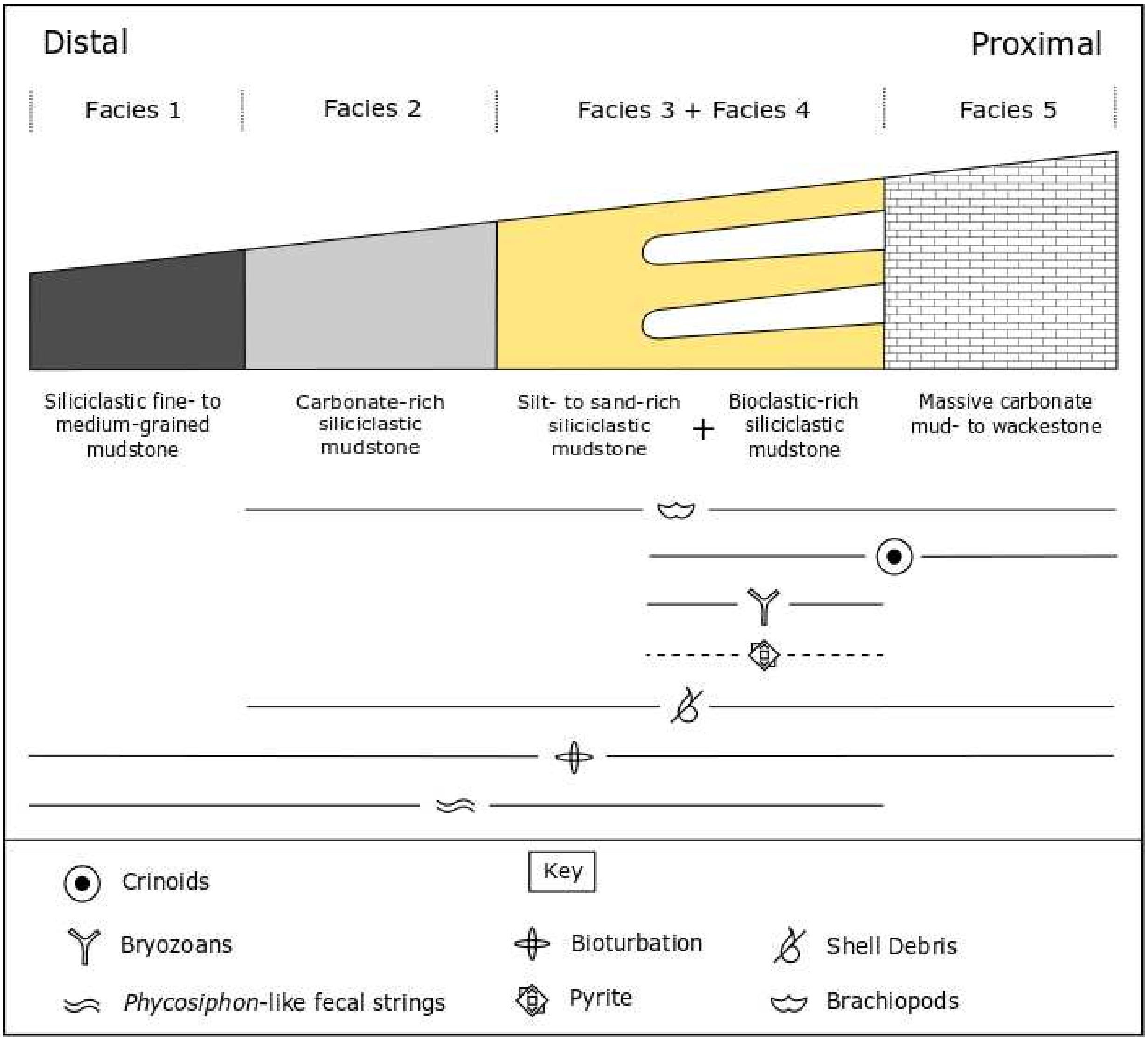

Figure 5. Depositional model for the Upper Ordovician exposure at Mt. Ålleberg. The depositional environment can be subdivided into four facies representing distinct depositional zones. The most proximal setting consists of carbonate mud- to wackestone as opposed to the other three more distal settings all consisting of various siliciclastic mudstones. All mudstone facies contain bioturbated sediment and Phycosiphon-like fecal strings; all but the most distal facies contain fossils and other biolclastic material. Facies 4 is represented by the white arms in the yellow Facies 3; the only facies with observable pyrite is Facies 4 and even then only in minor amounts.

Similarly, quiet-water deposition during fair weather is evident in all facies belts. This indicates that all facies have been deposited below fair-weather wave base (for an argument why fair-weather wave base can't be observed in the wave distribution in the recent Atlantic and Gulf of Mexico see Peters and Loss 2012) but, as the presence of tempestites indicate, above storm wave base. Based on the abundance of burrowing in all facies it is assumed that all environments have been at least sub-oxic during deposition. Nevertheless, a clear trend can be seen with burrowing getting scarcer and less diverse towards the offshore with a clear minimum in facies 1 only containing *Phycosiphon* isp.; this trend is similar to diversity trends from proximal to distal offshore settings in other basins (e.g. Williston basin, Egenhoff and Fishman 2013).

Relative sea-level fluctuated significantly during deposition of the Ålleberg strata, and resulted in a total of 5 coarsening-upward parasequences in this succession. It is likely that these sea-level changes were significant because the facies changed a few times back and forth between the several environments in the siliciclastic mudstone facies belt and the carbonate facies belt. This is not too surprising as the onset of Hirnantian glaciation in the Katian (Kiipli & Kiipli 2020) is thought to have influenced deposition worldwide and led to high-amplitude sea-level fluctuations also visible at Ålleberg. However, the duration of the cycles is unclear; it is assumed that they represent Milankovitch-type cycles because of the connection of this cycle type with glaciations (de Boer and Smith 1994) but this remains speculative without further biostratigraphic data.

The lithoclastic fossiliferous carbonate rudstone at the very top of the succession indicates a drastic sea-level fall that led to the exposure of the study area reflected in the presence of vadose cements in this unit. This exposure is preceded by a radical shift of facies basinwards that most likely exposed carbonate rocks that had already been deposited. They were subjected to a high-energy regime, eroded, and transported as large clasts downslope following gravity. The fossils in facies 6 are marine in origin but are most likely reworked from slightly older rocks of a nearshore environment that were eroded during the here recorded Hirnantian sea-level drop. It is unclear whether these clasts were transported in water or subaerially; nevertheless, it is likely that transport happened in a water-saturated setting because the water in the pore spaces helps supporting transport of the grains (e.g. Legros 2002; Marani et al. 2009). Therefore, while subaerial exposure may have helped with eroding the grains transport did most likely happen within the marine realm.

DISCUSSION

The Hirnantian sea-level drop at Mount Ålleberg

Facies 6 is interpreted to reflect the sea-level drop during the Hirnantian Ice Age, and how it affected the Mount Ålleberg area. While the succession showing this Hirnantian sea-level fall is at least 0.6 meters thick it is poorly exposed, and no sedimentological details could be collected in the field. The succession is also only characterized by one thin section in this study. It is therefore most likely that this thin section does not reflect the entire sedimentological history of the area but may emphasize just one part of the story. Nevertheless, it does indicate sub-aerial exposure of the Mount Ålleberg region during this sea-level fall.

The subaerial exposure is insofar important as it emphasizes the extent of this sea-level drop; while the Ålleberg area deposited mudstones and carbonates prior to the sea-level fall it was entirely exposed after sea-level receded. Taking into account both the results of this study and the very rough paleogeographic reconstructions of Baltica by Cocks and Torsvik (2005) for the Hirnantian it seems that this sea-level fall exposed the shallow and deep shelf over an area of several hundred kilometers in width (Kiipli and Kiipli 2020). It also indicates that carbonate rocks older than the end-Hirnantian sea-level fall were first eroded from the shelf during this sea-level drop, and subsequently exposed. Considering that most of the eroded rocks contain ample amounts of carbonate mud suggests that they originate from more distal, mud-rich settings on this shelf and not from the proximal realm.

All recent descriptions of the end-Ordovician sea-level fall identify several trans- and regression that can be related to this particular glaciation. Based on their own paleogeographic distribution, Kiipli and Kiipli (2020) argue for four major lowstands in the Baltic basin, each more pronounced and widely distributed than its predecessor. During the first two lowstands the Ålleberg area remained submerged by marine water as can be reconstructed from their mapping of the exposure; nevertheless, the third lowstand may have transformed the Ålleberg area into a marginal marine or even continental environment. The fourth lowstand, however, definitely sub-aerially exposed the area. It is therefore likely that the meniscus cements found in the facies 6 lithoclastic fossiliferous carbonate rudstone were formed during this last and most extreme lowstand of the Hirnantian glaciation.

Anoxic or sub-oxic?

The entire succession at Mount Ålleberg is intensely burrowed or characterized by fecal strings which are interpreted as products of organism interactions with the sediment. Dashtgard et al. (2015) have shown that bioturbation intensity decreases with oxygen saturation of the water column and is not only a mirror of oxygen levels above the sediment-water interface. Nevertheless, the presence of some burrowing and fecal strings in the Ålleberg section reflect some amount of benthic life during deposition. This, in turn, shows that oxygenation levels or oxygen saturation levels of the water during deposition have been at a sub-oxic and not an anoxic level. It furthermore shows that the entire passive margin shelf of Baltica, as much of it as is exposed in the Ålleberg succession, was likely oxygen-deprived as reflected in the low abundance of faunas but it wasn't completely anoxic during deposition of the Upper Ordovician succession.

The same is reflected in the only minor amounts of pyrite in these strata which seem to be exclusive to facies 4. In general, all dark and especially black shales contain abundant pyrite, up to nine generations (Fishman et al. 2019), and the pyrite is thought to be entirely diagenetic. The Ålleberg succession, however, does not contain much pyrite which is unusual for a dark-colored shale as even the Tøyen Shale in Scandinavia shows abundant pyrite throughout its different facies (Egenhoff et al. 2018). This low abundance of pyrite may be a function of a lack of iron to form pyrite, or simply a function of its constant overall well-oxygenated nature during deposition. Nevertheless, as diagenesis and burial will invariably lead to anoxic conditions in the sediment it remains unclear why only very small amounts of pyrite have been detected in this unit so far.

Storm Events in the Ålleberg succession

In this study, very different types of sedimentary rocks are interpreted to have been caused by storms; laminae consisting of silt and sand in facies 1, 2, and 3 as well as shell lags in facies 4 and partially facies 3; furthermore, outsized floating grains in facies 5 are interpreted as storm-derived because of the energy necessary to move them. Even though all of these sediments show a range of grain sizes and are in part made of different materials (calcite shells versus mostly quartz grains) they are envisioned to have been deposited by a similar process and just sourced their material from varying parts of the Ordovician shelf of Baltica.

The siltstone laminae in facies 1 are interpreted as representing high-energy deposition because their grain size is significantly larger than the one of the bulk of facies 1 sediments. The same holds true for siltstone laminae in facies 2 and 3. The fact that these laminae are not laterally continuous shows that they have been deposited by bed load and not by suspension settling. It is therefore likely that they originate from relatively high-energy events which were likely storms in this part of the shelf. This interpretation also indicates that even the deepest parts of the Baltica shelf represented by facies 1 was affected by storms and was therefore located above storm wave base.

Nevertheless, it is assumed that only a small portion of the storm beds originally present in this facies are preserved as such. Many of the grains brought in by storms are now outsized grains 'floating' in the fine-grained matrix. It is therefore likely that many if not most storm beds have been destroyed by bioturbation and the grains originally forming these storm beds are now distributed all across the matrix.

The bioclast-rich siliciclastic mudstones (facies 4) are also interpreted as storm deposits in this study, however, they are very different from the tempestites in facies 1; nevertheless, they resemble the classic storm deposits of Kreisa (1981) and Aigner (1985). The size of the bioclasts in this facies is much larger than all other grains and is therefore interpreted as deposited by a high-energy event. Their occurrence as shell lags swept together by such high-energy currents in an otherwise tranquil environment is what classifies them as most likely being a product of a storm. These storm deposits, however, also contain the grains that are characterizing the tempestites in facies 1. The question is therefore why there are shells in facies 4 in storm beds while the tempestites in facies 1 are devoid of these biogenic grain types.

The easiest explanation for this discrepancy in the make-up of grain types forming the storm beds is distance from shore coupled with dissolved oxygen in the water column (Dashtgard et al. 2015) and thereby living conditions on this Ordovician shelf during deposition. Based on most shelf transects in literature (e.g. summaries in James and Dalrymple, 2010) it seems like the bioclasts are much more frequent in more proximal strata while slightly deeper on this shelf their frequency diminishes. This shelf trend, frequent throughout all geological ages (James and Dalrymple, 2010), would also explain the presence of shells in facies 4 interpreted as having been deposited in a more proximal location than facies 1. It also shows that most likely not many brachiopods or crinoids lived this far down on the shelf profile in comparison to the more proximal facies 4 environment. Alternatively, the non-uniformity of storm beds across the section of Mt. Ålleberg can be explained by a storm's waning effective energy with increasing water depth. Moving from a proximal setting to a more distal setting we would expect to see maximum grain size, tempestite thickness, and tempestite lateral extent decrease as the water depth increases (Kreisa, 1981). Following this interpretation the difference in biogenic grain abundance could be seen as an aspect of storm reworking generally decreasing towards the offshore and hence not moving and sweeping together shell material during this process (e.g., Kreisa, 1981; Aigner, 1985; Midtgaard 1996; Dumas and Arnott 2006).

Despite reworking through intense bioturbation, the storm events observed in multiple facies contain sedimentary structures that do not reflect a single set of depositional conditions. Siltstone laminae found in a fine-grained matrix are most likely deposited from currents during a relatively high-energy event, likely a relatively low-energy storm. The lowest-energy deposition, however, is recorded through suspension settling in the form of fine-grained mudstone laminae. Furthermore, outsized grains from facies 2 and 3 consisting of coarse- to medium-silt size, being too large for suspension, are marginally- to well-rounded and must have been transported some distance via bedload processes to account for such abrasion (Yawar & Schieber 2017). The shell lags in facies 4 contain abundant fine-grained siliciclastic mud which is the same as the surrounding matrix; this makes the upper contacts difficult or impossible to define, and the overprint by bioturbation doesn't help. It is therefore not always easy to put a clear line between potential suspension sediments that were deposited in-between events, and bed-load deposits consisting of coarse grains but showing a fine-grained matrix that is identical to the suspension deposits.

The carbonate-siliciclastic mudstone transition

The transition from carbonates to siliciclastic mudstones in the Ålleberg succession is mostly seen as a lithofacies boundary and does not constitute the position of the storm wave base as in many of the classical examples (e.g., Burchette and Wright 1992). This facies transition is also not quite as abrupt as sketched in published examples; all the Ålleberg facies are dark in color, and all of them, including the carbonates, contain some amount of siliciclastic mud that is responsible for the color of the rock. The siliciclastic mudstones of facies 2 and 3 show abundant carbonate in their matrix. This shows that carbonate is transported far beyond this facies boundary and siliciclastic mudstone in turn is deposited quite a bit above the same boundary. This lithological boundary is therefore not static but seems to continuously move up and down the shelf profile.

The other aspect is that, similar to the upper Bakken shale in North Dakota, US, storm deposits are found on the shelf below the carbonate-siliciclastic mudstone transition (Borcovsky et al. 2017). This clearly shows that this lithofacies boundary cannot be equivalent to storm wave base even though it is tempting to assume so because of the lithological and color contrast. Nevertheless, the assumption that the carbonate-siliciclastic mudstone transition reflects storm wave base stems from the idea that siliciclastic mudstones were deposited exclusively from suspension in a quiet-water, non-oxygenated setting (e.g., O'Brian and Slatt 1990; but see Schieber 2003). Therefore, the carbonate-siliciclastic mudstone transition was interpreted to reflect the boundary between some burrowing in a still oxygenated environment to no burrowing in an anoxic setting, an assumption that got questioned by finding numerous trace fossils and fecal strings in siliciclastic mudstones deposited distally from this boundary (e.g., Macquaker and Gawthorpe 1993; Schieber 2003; Egenhoff and Fishman 2013; Borcovsky et al. 2017; Biddle et al. 2021). With this assumption questioned the search for a lithologic expression of storm wave base is now on again – and it must lie somewhere within the siliciclastic mudstone depositional realm. However, storm wave base may not be reflected or reflected well in the Mount Ålleberg succession.

Sediment input from the Baltica microcontinent

All facies contain some amount of silt-size quartz grains, and quartz is still visible in facies 1 sediments here interpreted to constitute the most distal facies belt. This contribution assumes that the quartz grains originated from the Baltica microcontinent but did not specify the processes that transported the quartz to the site of deposition. It seems adequate to assume that the quartz originated from Baltica; during the end-Ordovician, Baltica was an isolated micro-continent and while Laurentia was approaching from the west it had not yet reached a close vicinity to Baltica (Cocks and Torsvik 2005). That the origin of the quartz must have been the Baltic Shield is also reflected in the abundance of these grains in different facies in the Ålleberg section; quartz gets rarer the further distal a facies got deposited indicating that the origin of the quartz was likely the Baltica microcontinent. Nevertheless, two general modes of transportation are envisioned to deliver the quartz grains onto this shelf environment; sediment input by wind (e.g., Tsoar and Pye 1987), or transport of quartz grains by water as assumed for most quartz grains in siliciclastic mudstones, and also reproduced by experiments (e.g., Yawar and Schieber 2017).

Quartz grain transport by wind is a common process by which silt grain content is explained in rocks where quartz is not a frequent rock constituent, e.g. carbonates (e.g., Brooks et al. 2003). All quartz grains are generally well rounded. This textural characteristic is common of both eolian (Whalley et al. 1982) as well as marine siltstones so does not favor one over the other process responsible for silt transport. Wind can transport silt grains many thousands of kilometers from their origin which is seen on satellite images of dust storms that carry quartz from the Sahara desert out over the Atlantic Ocean (Goudie and Middleton 2001). While such a scenario would explain the silt content in the Ålleberg mudstones it does not clarify why there is a clear decrease in quartz content from proximal to distal. Such a grain size trend would, on the contrary, favor a water-transport of quartz; the quartz grains derived from the Baltica microcontinent are brought onto the shelf and then distributed by marine forces. As these forces get weaker the further away an environment is from the coast it is less likely that any grains including quartz get transported towards distal shelf settings. This decrease in energy therefore explains the observed distribution of quartz grains in the Ålleberg succession. Additionally, a transport of the silt grains by water indicates that Baltica still shed quartz, likely eroded from its basement rocks onto its shelves even though its relief was thought to be extremely low (Cocks and Torsvik 2005). No outcrops are preserved showing such an environment where quartz grains could have originated; nevertheless, these quartz silt grains indicate the presence of at least one delta during the Upper Ordovician on Baltica.

CONCLUSION

(1) The Upper Ordovician succession at Mt. Ålleberg is a 6.3 meter outcrop consisting primarily of a variety of siliciclastic mudstones (facies 1 to 4) with an intermittent massive carbonate mud- to wackestone (facies 5). The siliciclastic mudstones can be distinguished by the dominant clasts floating within the matrix and are divided into fine- to medium grained (facies 1), carbonate-rich (facies 2), silt - to sand-rich (facies 3), and bioclastic-rich (facies 4). Only the uppermost facies is formed by a lithoclastic fossiliferous carbonate rudstone (facies 6).

(2) The section consists of a series of five decimeter- to meter-scale coarsening-upward sediment packages. These coarsening-upward packages would potentially show the carbonate-rich siliciclastic mudstone (facies 2) at its base which has a sharp contact to overlying silt- to sand-rich siliciclastic mudstone (facies 3). Facies 3 sediments may contain intercalated shell lags of bioclastic-rich siliciclastic mudstone (facies 4); the top of this idealized cycle is formed by massive carbonate mud- to wackestone (facies 5). The fine- to medium-grained siliciclastic mudstone (facies 1) may form the base of these coarsening-upward packages, however, it only occurs once in the succession and its exact position therefore remains enigmatic.

(3) The general depositional environment at Mt. Ålleberg is a carbonate shelf with a ramp-like geometry where most of the succession developed as siliciclastic mudstones in a distal outer shelf setting with the exception of facies 5. Despite facies 5 showing the most proximal setting its environment is still interpreted as mid-shelf (ramp) based on mud content, clast size, and reworking. Facies 4 is the most proximal mudstone and an intermediate between the mid and outer shelf (ramp) environments and is produced by storm reworking at that transition concentrating bioclastic grains. A general trend in the depositional model shows progressively decreasing clast size and storm bed thickness with increasing depth down the shelf/ramp profile. Facies 6 is not considered part of the depositional model as it most

likely reflects a worldwide glacioeustatic event not associated with the rest of the succession at Mount Ålleberg.

(4) All facies, except for facies 6 in the succession at Mt. Ålleberg have pervasive burrowing and bioturbation throughout the entire shelf/ramp setting. The environment must therefore have been oxygenated throughout most of the water column and was at least sub-oxic in the most distal setting that showed deposition of the siliciclastic mudstone (facies 1). This is reflected in the pervasive burrowing or presence of fecal strings throughout the succession, and also in overall lack of pyrite; however, the availability of iron also limits the production of pyrite and can't be ruled out as a controlling variable.

(5) The carbonate-siliciclastic mudstone transition was previously thought to be associated with storm wave base (e.g., Burchette and Wright 1992); however, storm deposits are observed even within the most distal mudstone setting. Therefore, the carbonate-siliciclastic transition is not a response to storm wave base and must be the product of another mechanism. The carbonate and siliciclastic grains also reflect different transport distances; siliciclastic grains are generally more rounded than carbonates and are interpreted as transported from the Baltica microcontinent via fluvial, marine, and eolian processes.

(6) Facies 6 is not included in the depositional model because it reflects a unique event in geologic time. The carbonate rudstone is interpreted as the result of erosional processes transporting clasts from more proximal settings as they are subaerially exposed after a massive sea-level drop. This sea-level drop is most likely a result of the Gondwana glaciation at the Ordovician-Silurian boundary.

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