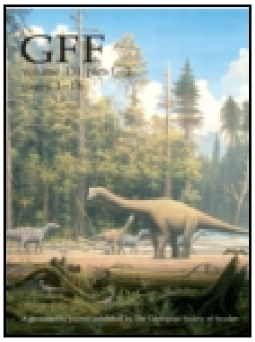

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Article

The sediments of the Floian GSSP: depositional history of the Ordovician succession at Mount Hunneberg, Västergötland, Sweden

SVEN EGENHOFF[1] and JÖRG MALETZ[2]

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Abstract: The succession at Mt. Hunneberg consists of intercalated siliciclastic mudstones and carbonates of Tremadocian to Floian age. Above an unconformity with underlying Furongian shales, siliciclastic mudstones with graptolites and overlying glauconite packstones of the upper Alum Shale Formation are exposed showing a sharp top contact to the carbonates of Bjørkåsholmen Formation. Above, the Tøyen Shale Formation consisting of siliciclastic mudstones and intercalated carbonate beds forms the stratigraphically youngest Ordovician unit at Mt. Hunneberg. The Tøyen Shale Formation is characterized by a lower marl- and carbonate-rich part, exclusively present in the southwest of Mt. Hunneberg, and an upper portion consisting of siliciclastic mudstones, extending from the *Tetragraptus phyllograptoides* graptolite Biozone on upwards. The siliciclastic mudstones of the Alum Shale Formation represent open shelf sediments reflecting sea-level highstands of two trans- and regressions. Overlying glauconite packstones indicate a transgression of *Adelograptus* zone age or younger. The Bjørkåsholmen Formation reflects a relative sea-level lowstand. The Tøyen Shale Formation records a deepening of the sedimentary environment during sea-level rise initially establishing offshore conditions, with the upper Tøyen Shale Formation siliciclastic mudstones indicating open shelf deposition. Abundant burrows throughout the succession reflect hospitable living conditions in the Mt. Hunneberg area, also during deposition of the Floian black shales. A pronounced decrease in thickness of the Hunneberg succession toward the northeast reflects erosion in the proximal compared to distal Hunneberg areas. The succession shows that alternating offshore to open shelf conditions is an ideal sedimentary environment to establish a Global Boundary Stratotype Section and Point with abundant and detailed biostratigraphic information.

Keywords: Mt. Hunneberg; Ordovician; sedimentology; depositional environment.

[1]*Department of Geosciences, Colorado State University, 322 Natural Resources Building, Fort Collins, CO 80523, USA; sven.egenhoff@colostate.edu*
[2]*Institut für Geologische Wissenschaften, Freie Universität Berlin, Malteser Str. 74-100 D-12249, Berlin, Germany*
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Introduction

Mt. Hunneberg in Västergötland is one of the table mountains that exhibit Lower Paleozoic (Cambrian to Silurian) sediments on top of the peneplained Precambrian basement in southern Sweden (Fig. 1). About 13–14-m-thick Ordovician succession in this area was only preserved due to an up to 100-m-thick dolerite sill protecting the siliciclastic mudstones and minor carbonates from predominantly pre-Quaternary erosional forces stripping most of Scandinavia from its sedimentary cover. Mt. Hunneberg also represents a special case regarding the Lower Ordovician (Tremadocian to Floian) facies distribution on the Baltic Shield: of all outcrops in Västergötland, it is the only one with high amounts of shales, while Mts. Kinnekulle and Billingen exhibit mostly carbonates (Jaanusson 1976, 1982) in this time interval. It thereby defines a prominent facies boundary between the "inner shelf carbonate" and the "deeper shelf shale" facies belts (so-called "confacies belts" of Jaanusson 1976). This facies boundary can be traced for many 100 km through Norway and Sweden into Poland (Jaanusson 1982).

Interestingly, Mt. Hunneberg has largely been left aside in studies focusing on the Lower Paleozoic in Sweden: while Tjernvik (1956) incorporated it into his detailed compilation of Lower Ordovician successions and its fossil (mainly trilobite) content, only Lindholm (1991a,b), Lindholm and Maletz (1989) and Maletz et al. (1996) focused on the paleontology of Mt. Hunneberg and described the graptolite faunas of the shales after several decades of virtually no studies since the original description of Törnquist (1901, 1904). However, Mt. Hunneberg shares the fate with many Lower Paleozoic successions in

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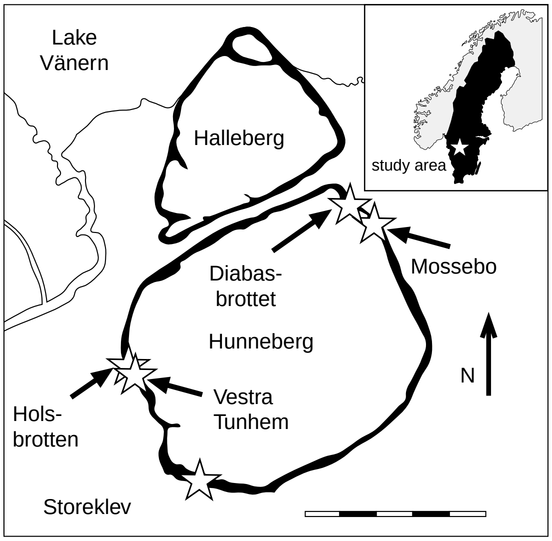

Fig. 1. Map of the Mt. Hunneberg areas with the five studied localities, Mossebo and Diabasbrottet in the NE, and Holsbrotten, Västra Tunhem and Storeklev in the SW.

Scandinavia. As most studies concentrated on the fossil faunas, namely trilobites, graptolites, conodonts and to a lesser degree brachiopods, the sedimentology of the strata was largely left untouched. This holds true especially for Mt. Hunneberg where exclusively paleontological investigations have been carried out to date, even though the area regained some interest when the Diabasbrottet section was proposed and selected as the stratotype of the Floian Stage of the Ordovician System (Maletz et al. 1996; Bergström et al. 2004). Earlier investigations discussed the lithostratigraphical succession at Mt. Hunneberg only in comparison to other areas in Västergötland (e.g. Hisinger 1797; Angelin 1854), but the general succession was already well understood through mapping in the 19th century (Sidenbladh 1870; Lindström 1887).

This study presents the first comprehensive account of the sedimentology of the Ordovician deposits at Mt. Hunneberg. It not only concentrates on the relatively thin carbonate beds (cf. Egenhoff & Maletz 2007) but also reconstructs the depositional environment of the shales that make up the bulk of the Tremadocian to Floian succession. As Mt. Hunneberg has been selected as the Global Boundary Stratotype Section and Point (GSSP) for the second stage of the Ordovician System (Maletz et al. 1995, 1996; Bergström et al. 2004), this study finally highlights the environmental conditions suitable for the preservation of relevant index fossils. These should be considered when selecting or revising GSSP's for Ordovician and Silurian chronostratigraphic units that rely on graptolite and conodont faunas.

Geological setting

During the Cambrian and Ordovician, Scandinavia formed the southern to southwestern (SW) edge of Baltica (Cocks & Torsvik 2002, 2005). The climate in this part of the paleocontinent during the Early Paleozoic changed dramatically as the plate moved northwards from about 30–60° south in the Cambrian to approximately 30° south during the Late Ordovician. While a cool to temperate water environment characterized Cambrian and Early to Middle Ordovician Sweden and Norway, Late Ordovician conditions gradually shifted toward tropical in the recent areas of Sweden and Norway as reflected in both faunas and sediments (cf. Stridsberg 1980; Cocks & Torsvik 2005). Regardless of climatic conditions, however, sedimentation rates remained low throughout Cambrian and Ordovician times on the cratonic part of the Baltic plate (Lindström 1971), while two foreland basins at the plate margins toward the Iapetus and Rheic oceans accumulated thick successions of predominantly siliciclastic sediments (Beier et al. 2000).

The relatively small Baltic plate was mostly covered by an epicontinental sea during the entire Early Paleozoic. Cambrian shallow-water siliciclastics gradually gave way to Early Ordovician carbonates paralleling the climatic change. The Scandinavian deep shelf environment, however, was dominated by fine-grained siliciclastic sedimentation throughout the Early Paleozoic (Lindström 1971; Egenhoff & Maletz 2007).

Stratigraphy

The Ordovician succession at Hunneberg is underlain by about 50 m of Cambrian strata, including ca. 24 m of Cambrian Series 2 sandstones referred to as the File Haidar Formation by Nielsen and Schovsbo (2011), but originally identified as the Eophytonsandstein (Linnarsson 1871a) or the Fucoid Sandstone (Lindström 1887) as well as a relatively incomplete succession of Cambrian Series 3 and Furongian shales and mudstones of the Alum Shale Formation (Andersson et al. 1985; Nielsen & Schovsbo 2006), about 25 m in thickness, but poorly exposed (Fig. 2). A hiatus separates the Cambrian from the overlying Lower Ordovician portion of the Alum Shale Formation (Tjernvik 1956). The latter interval is only a maximum of about 0.5 m thick (Fig. 3) and absent in some of the four studied localities. Even though the contact between these two black units is not easy to define in outcrop without the help of graptolites, the Ordovician portion contains glauconite (see below), is generally better cemented and is therefore harder than the underlying Cambrian shales. The Alum Shale Formation is overlain by the Bjørkåsholmen Formation representing the oldest carbonate unit in the succession. This only about 1-m-thick interval is prominent throughout Scandinavia and traceable from Öland through Västergötland into the Oslo Region of Norway (Egenhoff et al. 2010). The Tøyen Shale Formation overlies the Bjørkåsholmen Formation and forms the upper portion of the sedimentary succession at Mt. Hunneberg. It consists of dark shales, mudstones and marls with few intercalated nodular but laterally traceable carbonate beds. Its thickness varies significantly laterally across Mt. Hunneberg. While in the SW it is only between 6 and 8 m thick (Holsbrotten and Storeklev localities), the Tøyen Shale Formation shows thicknesses of more than 13 m in the northeast (NE) (Diabasbrottet and Mossebo localities; Maletz et al. 1996). The thickness variations are the result of the intrusion of an early Permian dolerite sill in different stratigraphic levels within the Paleozoic succession, thereby preserving more strata in the NE than in the SW of Mt. Hunneberg. The Permian dolerite sill now forms the cap of the succession at Mt. Hunneberg.

The Cambrian/Ordovician biostratigraphy

The biostratigraphy of the Cambrian and Ordovician strata is based on the presence and identification of trilobite, graptolite

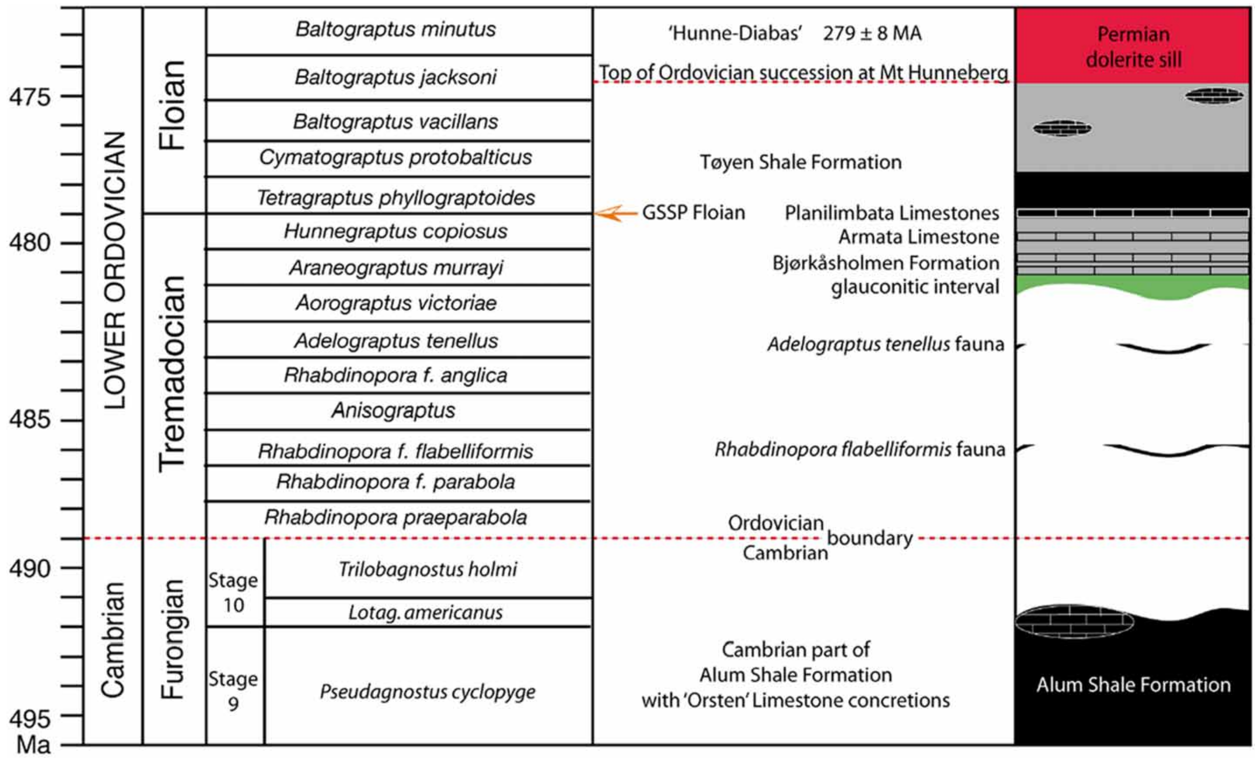

Fig. 2. Biostratigraphy of Mt. Hunneberg, based on various sources discussed in the text. Chronostratigraphy at http://www.stratigraphy.org. Cambrian stages and trilobite zones from Terfelt et al. (2008, 2011).

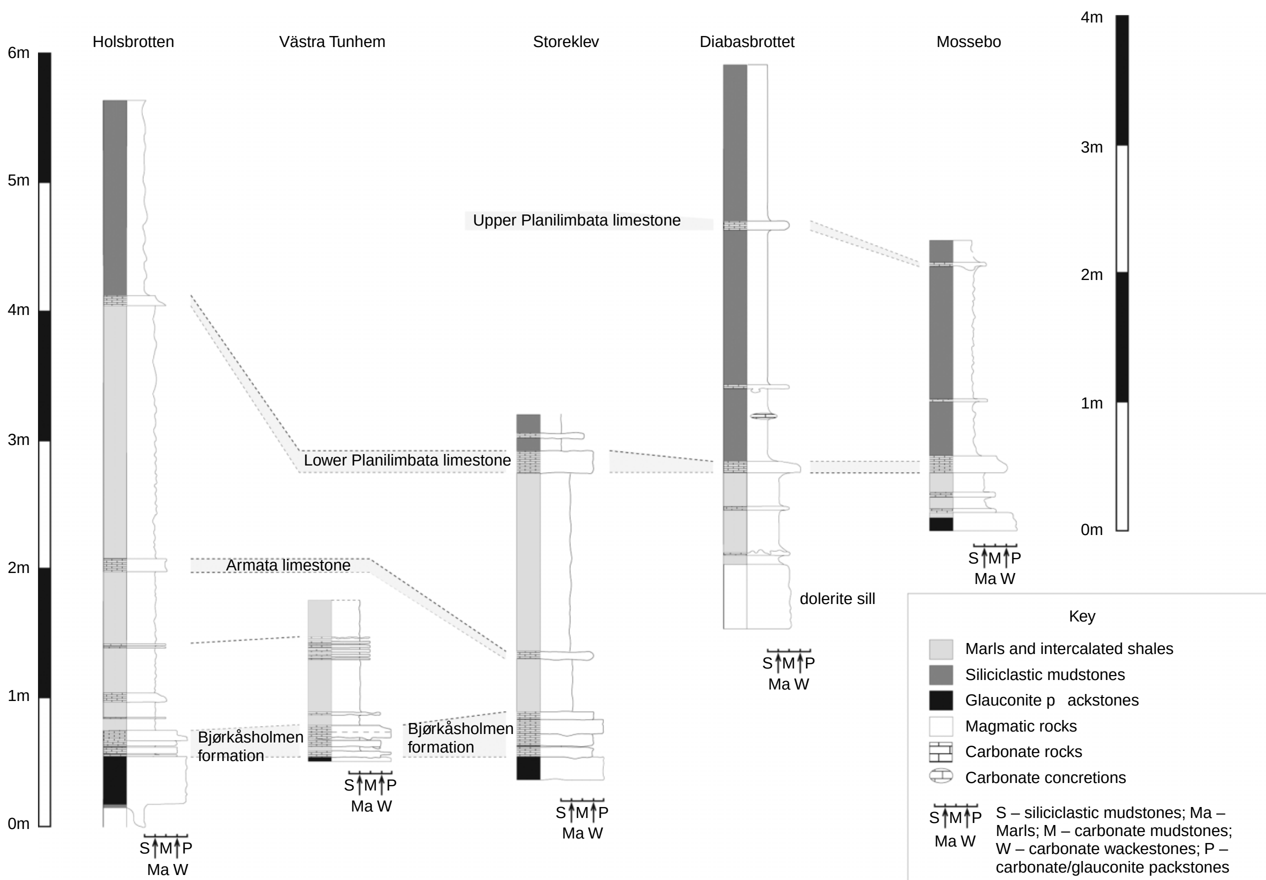

Fig. 3. Sections from the five studied localities, arranged from SW to NE. Correlation of the sections is based on detailed graptolite and conodont biostratigraphy (Maletz et al. 1996; Bergström et al. 2004; Egenhoff & Maletz 2007).

and conodont faunas in the various sediments. Fossils are often common and easily attained for dating the succession, except in the uppermost exposed strata consisting of fine-grained siliciclastics. These are strongly contact-metamorphosed and fossil faunas are difficult to obtain as the specimens are largely destroyed through growth of metamorphic minerals. The Cambrian succession has never been analysed in detail and, thus, is poorly known (see Westergård 1909, 1922).

The uppermost identifiable Cambrian strata at Mt. Hunneberg contain among less biostratigraphically relevant trilobites, the important taxon *Peltura minor*. Westergård (1909) discussed the succession at Nygård and identified the trilobites *Peltura scarabaeoides* and *Sphaerophthalmus alatus* in the topmost layer, but later provided an updated succession (Westergård 1922, pp. 73–76) and revised the taxa. His list includes *P. minor*, *Peltura acutidens, Sphaerophthalmus major* and *Ctenopyge tumida* in the uppermost Cambrian layers at Nygård. Tjernvik (1956) referred the trilobites at Mt. Hunneberg to the *P. minor* Biozone. Terfelt et al. (2008) revised the trilobite biostratigraphy of southern Scandinavia and provided a quite different trilobite biostratigraphy, eliminating the well-known *Peltura* and *Acerocare* zones of the upper Cambrian still used by Ahlberg (2003). Terfelt et al. (2011) showed the biostratigraphic range of *P. minor* to cover the interval of the *Lotagnostus americanus* Biozone of the lower Furongian, while the presence of *C. tumida* suggests more precisely an early *L. americanus* Biozone age for the fauna. Thus, a considerable part of the Furongian (upper Cambrian) is definitely missing.

The Lower Ordovician (Tremadocian) has first been identified by the graptolite *Adelograptus tenellus*, the type locality of which is Nygård on the western slope of Mt. Hunneberg (see Linnarsson 1871b; Moberg 1892; Maletz & Erdtmann 1987). The exact level of occurrence of the species in the succession was uncertain, but specimens of *A. tenellus* have been discovered at the base of the Ordovician succession. Also fragments of *Rhabdinopora flabelliformis* were recovered by Maletz (1987, fig. 13) from a similar level in the Västra Tunhem section, but the species was first mentioned by Linnarsson (1869) and discussed by Westergård (1909). Westergård (1909, p. 34) mentioned the occurrence of *R. flabelliformis* (as *Dictyonema flabelliforme*) and *A. tenellus* (as *Dichograptus tenellus*) directly in contact with the "Pelturalaget."

The overlying limestones of the Bjørkåsholmen Formation (see Egenhoff et al. 2010) were first mentioned by Angelin (1854) as "Regio Ceratopygarum" and later identified as the Ceratopyge Limestone based on the common occurrence of the trilobite *Ceratopyge forficula* (see Tjernvik 1956; Ebbestad 1998). The fauna consists largely of trilobites, but a number of articulate and inarticulate brachiopods are also present. The conodonts belong to the *Paltodus deltifer* Biozone (Löfgren 1993; Maletz et al. 1996) at Storeklev, but have not been investigated in the other localities.

The basal Tøyen Shale Formation succession includes limestones and shales with a variable composition of faunas, mainly graptolites and some phosphatic brachiopods in the shales and trilobites and conodonts in the limestone layers. The upper interval does not bear limestone layers, but occasionally large limestone concretions similar to the upper Cambrian "Orsten limestones." The interval can be referred to the Floian and is cut by the overlying dolerite sill. The conodonts identify the basal Floian interval with the *Paroistodus proteus* and the overlying *Prioniodus elegans* conodont zones (Löfgren 1993). The oldest graptolite faunas belong to the *Hunnegraptus copiosus* Biozone (Lindholm 1991a,b). They have first been recorded by Tjernvik (1956) at Storeklev and identified as "undescribed dichograptids." Egenhoff and Maletz (2007) documented the faunas from the Holsbrotten (Västra Tunhem) section. The interval is correlated with the *Ekeraspis armata* trilobite Biozone (Tjernvik 1956; Maletz et al. 1996).

The Diabasbrottet section is best known for its graptolite succession and became the GSSP for the Floian Stage of the Middle Ordovician Series (Maletz et al. 1996; Bergström et al. 2004). The fauna was first described in detail by Törnquist (1901, 1904), but a biostratigraphic scheme did not exist until Egenhoff and Maletz (2007) discussed the bio-sequence stratigraphy of the graptolitic succession of the section. The succession includes the *Tetragraptus phyllograptoides*, *Cymatograptus protobalticus* and *Baltograptus vacillans* Biozones. The faunas of the uppermost interval may belong to the "*Baltograptus deflexus*" Biozone of Toro and Maletz (2007) or the *Baltograptus* sp. cf. *B. deflexus* Biozone of Maletz and Ahlberg (2011) as it includes *Baltograptus jacksoni* Rushton, 2011 [= *Baltograptus* sp. cf. *B. deflexus* in Toro and Maletz (2007) and Toro et al. (2011)]. It is here identified as the *B. jacksoni* Biozone (Fig. 2). Younger Floian to Dapingian graptolite successions are described in Maletz and Ahlberg (2011) from the Lerhamn drillcore of Scania, southern Sweden, but are also present at Mt. Kinnekulle in Västergötland (Lindholm 1992).

At Mt. Hunneberg the succession is capped by the overlying dolerite sill and the uppermost shales are contact metamorphosed and graptolites difficult to identify. The conodonts of the succession are referred to a number of subzones of the *P. proteus* conodont zone, but conodonts are mainly present in the limestones and a precise correlation into the shaly facies with the graptolites is not always possible. Specimens of *Prioniodus* sp. cf. *P. elegans* in shales above the "Upper Planilimbata Limestone" (see Tjernvik 1956; Maletz et al. 1996) are used as an indication of the *P. elegans* zone. Trilobites in the limestones belong to the *E. armata* and *Megistaspis planilimbata* trilobite zone, but fragmented trilobite material from limestone concretions in the uppermost part of the Tøyen Shale Formation may belong to the *Megistaspis estonica* trilobite zone (Maletz et al. 1996).

Sedimentology

The succession at Hunneberg is heavily thermally overprinted by the Permian sill and shows a considerable contact aureole at its base. The "dolerite" sill forms a 60–100-m-thick protective cap on top of the Lower Paleozoic succession (Törnebohm 1877; Svedmark 1878; Mulder 1971). The contact metamorphism from these intrusions affected all levels of the Ordovician succession, but especially the exposed upper parts of the Tøyen Shale Formation throughout the Hunneberg area (Tjernvik 1956; Maletz et al. 1996) and caps the sediments at different levels in the various localities (see Sidenbladh 1870, fig. 2). In general, the contact is within the Tøyen Shale Formation in the southern region of Mt. Hunneberg, but is in the upper Cambrian at Mount Halleberg to the north, where it may be as low as the *Agnostus pisiformis* agnostoid zone (Maletz 1987, locality Svallklev). A thin dike originating from the overlying sill is injected parallel to the bedding in the Diabasbrottet section at the level of the Bjørkåsholmen Formation (Maletz et al. 1996, fig. 4) and has been discussed already by Sidenbladh (1870, fig. 10, Lilla Mossebo = Diabasbrottet). The sedimentary facies are mostly still recognizable and will be presented below. Throughout Mt. Hunneberg the carbonate rocks are more heavily affected by the thermal overprint than the siliciclastics mudstones of the Alum and Tøyen Shale Formations. Carbonate units are generally strongly recrystallized, and selected grains as well as matrix have been preferentially replaced or changed through thermally induced mineral growth. Even when this makes facies identification in places problematic, this study discusses the original facies also in heavily overprinted samples in order to use the data for the reconstruction of a depositional model. The unit descriptions and interpretations are presented here in stratigraphic order from the base of the Ordovician System to its top occurrence directly below the overlying Permian sill.

Cambrian–Ordovician contact

The contact between the Cambrian black shales and the overlying Ordovician sediments is sharp throughout the Mt. Hunneberg area, but in places difficult to define in outcrop because both sediments overlying and underlying the contact are dark, even though the Tremadocian unit appears to be slightly harder. A significant hiatus exists at this contact spanning at least the *P. scarabaeoides* and *Acerocare* trilobite Biozones of Ahlberg (1998) or the *Trilobagnostus holmi* Biozone of Terfelt et al. (2011) and Ahlberg and Terfelt (2012), and likely the basal Ordovician *R. flabelliformis praeparabola* to *R. flabelliformis parabola* graptolite Biozones (e.g. Maletz 1998), so approximately 6 million years (Fig. 2). In the Holsbrotten and Västra Tunhem localities (Fig. 1), the Cambrian–Ordovician contact shows a wavy appearance (Fig. 4A) and in places Cambrian mudstones of the *Lotagnostus holmi* Biozone have been truncated by overlying Ordovician glauconite-bearing sediments that along an erosional surface cut several decimeters deep into the Cambrian mudstones. The top of the Cambrian succession is locally characterized by mudcracks (Fig. 4B) that are only preserved within the depressions.

Lower Ordovician part of Alum Shale Formation

The upper part of the Alum Shale Formation, formerly termed "*Dictyonema* Shale," is a relatively thin unit at Mt. Hunneberg, forming in part trough-filling sediment packages with thicknesses between 0 and 51 cm (Fig. 4A). While black in outcrop and, therefore, visually indistinguishable from the underlying shales, the unit consists mainly of interbedded glauconite packstones (Fig. 5A) and millimeter-thick carbonate mudstone, marl and siliciclastic mudstone laminae. The glauconite packstone comprises centimeter-thick beds and laminae of glauconite with sharp bases containing carbonate mud and cement in interstitial pore spaces, and rarely strongly recrystallized shell fragments. Individual laminae can have well-defined lenticular geometries. Thicker beds show denser packing of glauconite grains, especially at the very top. The interbedded marls and siliciclastic mudstones can be either massive or show faint to well-developed irregular horizontal laminations that in places bend around individual incorporated glauconite grains. The siliciclastic mudstones locally contain graptolites (*Rhabdinopora* sp. or *A. tenellus*), usually found at the base of the depression fill directly above the erosional surface separating Furongian and Lower Ordovician strata (Maletz 1987; Maletz & Erdtmann 1987), but both taxa never occur together within single laminae or thin beds.

Bjørkåsholmen Formation

The Bjørkåsholmen Formation (formerly termed Ceratopyge Limestone) consists of generally four mostly centimeter- to several decimeter-thick carbonate beds with one-to-two intercalated carbonate-rich siliciclastic mudstone laminae on top of the lowermost carbonate beds, each of them often not more than a centimeter in thickness. The carbonate beds are characterized by mudstones, wackestones and packstones. Each individual bed generally shows a sharp erosional contact at the base, which is overlain by either a centimeter-thick shell lag packstone of irregular thickness (Fig. 5B), or a several centimeter-thick unit of carbonate wackestones or mudstones (Fig. 5C). Individual beds display distinct normal grading when only centimeters thick, or, when thicker and more commonly, they consist of several stacked normally graded units.

The thickness and the internal stacking patterns vary slightly laterally not only over the distance of just a few kilometers within the Bjørkåsholmen Formation between Holsbrotten and Storeklev (Fig. 1), but also over some tens of meters between Holsbrotten and Västra Tunhem. Although in Västra Tunhem

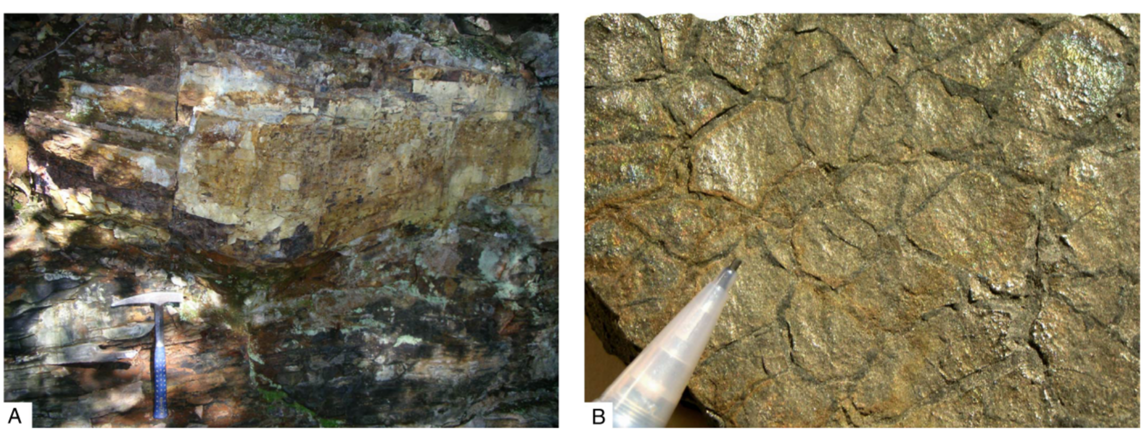

Fig. 4. **A**. Erosional truncation of Lower Ordovician siliciclastic mudstones and glauconite packstones (upper Alum Shale Formation) into underlying shales of the Upper Cambrian part of the Alum Shale Formation. Hammer for scale. **B**. Mudcracks from the top of the Cambrian Alum Shale Formation underlying the Lower Ordovician succession; Västra Tunhem locality, pencil for scale.

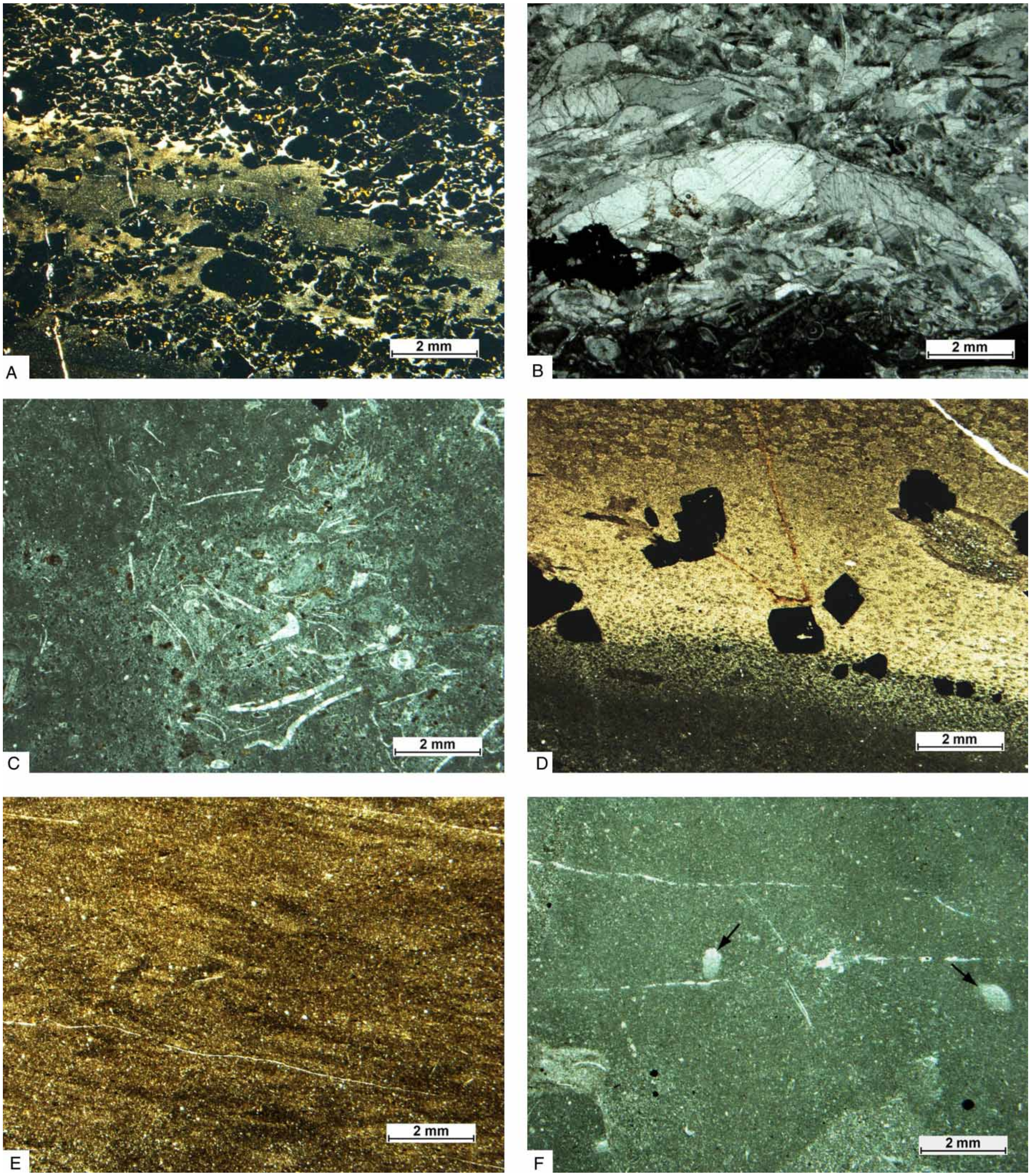

Fig. 5. **A**. Glauconite packstone with millimeter-thick laminae of carbonate mudstone to marl; upper Alum Shale Formation, Västra Tunhem locality. **B**. Brachiopod-trilobite packstone with large shelter pore; Bjørkåsholmen Formation, Storeklev locality. **C**. Carbonate wackestone with patchy accumulation of mostly trilobite debris; Bjørkåsholmen Formation, Diabasbrottet locality. **D**. Carbonate mudstone to marl from lower part of Tøyen Shale Formation, *H. copiosus* Biozone, Västra Tunhem locality. **E**. Siliciclastic mudstones from upper part of the Tøyen Shale Formation; note intense bioturbation that has destroyed all original sedimentary structures; Diabasbrottet locality. **F**. Carbonate mud- to wackestone with burrows (black arrows) that are partly filled with carbonate mud and partly with cement; *Armata* limestone, Diabasbrottet locality.

the Bjørkåsholmen Formation is only 0.245-m thick, it reaches 0.35 m in the Storeklev locality, so generally increases in thickness toward the NE. While the amount and thickness of intercalated shaly limestones between carbonate beds varies from section to section (Fig. 3), the thickest bed containing the highest amount of coarse packstone facies generally occurs toward the top of the unit. The Bjørkåsholmen Formation therefore shows an increase in overall grain size upsection succeeded by a thin normal grading within the uppermost bed marking the top of the unit.

The same types of grains occur throughout the Bjørkåsholmen Formation with trilobite debris being most frequent and brachiopod shells being a close second. In the packstones, both of these grain types frequently form shelter pores (Fig. 5B). Other fossil components include ostracods and rare bryozoan fragments. In places, glauconite grains occur usually toward the top of the succession and in small quantities ($<5\%$ of the rock within a single bed).

Tøyen Shale Formation

The Tøyen Shale Formation at Mt. Hunneberg is composed of dark carbonate and siliciclastic mudstones, previously all described as "shales" (e.g. Maletz et al. 1996), and several distinct carbonate intercalations informally termed "*Armata*" limestones and lower and upper "*Planilimbata*" limestones, named after trilobite species occurring in these beds (Tjernvik 1956). In the lower part of the Tøyen Shale Formation, the succession is made up of intercalated millimeter- to centimeter-thick carbonate mudstone and marl beds (Fig. 5D) with generally only some millimeter-thick siliciclastic mudstone layers. One 0.5-cm-thick layer within these carbonate-rich beds contains *H. copiosus* (Maletz 1987; Maletz et al. 1996), and these carbonate- and marl-rich units occur exclusively in the SW part of Mt. Hunneberg. In the upper portion of the Tøyen Shale Formation, starting in the *T. phyllograptoides* graptolite Biozone (cf. Egenhoff & Maletz 2007) that occurs in all studied sections of Mt. Hunneberg, only siliciclastic mudstones occur (Fig. 5E) reflecting an overall fining-upward of the entire Tøyen Shale succession.

The carbonate mudstones and marls within the formerly termed "shale" portions of this unit (*H. copiosus* Biozone) consist mostly of very fine-grained carbonate mud and marls, in places with millimeter- to sub-millimeter-sized shell fragments randomly dispersed within the matrix, and preferentially accumulated at the base on individual beds. The siliciclastic mudstones consist of siliciclastic silt- and clay-sized material, with generally $<5\%$ bioclastic carbonate debris. Grains occurring in the siliciclastic mudstones of the Tøyen Shale Formation include well-rounded to sub-rounded silt-sized quartz, trilobite debris, brachiopod shells, as well as some biogenic particles of unknown origin. Graptolites occur as flattened specimens of entire colonies or rhabdosome debris. All components generally "float" in the fine-grained matrix, but in places the carbonate particles can form grain-supported lenses and layers, generally with a muddy matrix that can be up to 1 mm thick. Elongate grains such as shells are generally randomly arranged with respect to bedding and show inclinations of almost any angle. The mudstones are intensely bioturbated, and in places *Chondrites* and pyritized bedding-parallel burrows are well preserved. The Tøyen Shale Formation shows only faint bedding mostly accentuated through the limestone intercalations even though also the shales themselves exhibit some irregular bedding planes throughout. Diagenetic overprint is relatively strong in the shales reflected in phosphatization of some shells and strong recrystalization of all carbonate components.

The carbonate units intercalated into the Tøyen Formation consist mainly of carbonate mud-rich lithologies. The lowest one informally referred to as "*Armata* limestone" shows a distinct normal grading. It consists of a lower mud- to wackestone unit, about 3–4-cm thick, which is overlained by two marl beds, each, 2–3-cm thick separated by an indistinct siliciclastic mudstone lamina. All contacts are bioturbated and diagenetically overprinted. However, the basal contact of the "*Armata*" limestone is irregular wavy, but sharp. Grain types in the "*Armata* limestone" are biogenic, and sub-millimeter-sized bioclasts and trilobite remains are common, whereas bryozoans occur only rarely in this unit. All biogenic components are arranged at random angles to bedding. In places, the carbonate matrix shows roundish to oval burrows with diameters between less than a millimeter and several millimeters. These burrows are either filled with carbonate mud at the base and sparite at the top (Fig. 5F), or are entirely filled with carbonate cement. Organic material is absent in the carbonate beds. The two "*Planilimbata*" limestones, both located stratigraphically above the "*Armata* limestone," are overall finer grained than the "*Armata*" and Bjørkåsholmen Formation units. Both consist nearly exclusively of carbonate mudstone and can in places contain significant amounts of siliciclastic mud. In the Diabasbrottet locality, glauconite grains are locally interdispersed in the carbonate mud. Trilobite remains and a few ostracod shell fragments are the only other grain types that occasionally occur in these mudstones. These are oriented at random angles in the carbonate or marlstone matrix. The two "*Planilimbata* limestones" are also characterized by millimeter- and sub-millimeter diameter tube-like burrows that occur in places, the larger ones partly filled with carbonate mud and partly with sparite in their upper parts. Both lower and upper boundaries of these units are sharp and generally overprinted by diagenesis.

Depositional history of Mt. Hunneberg

The Hunneberg area shows a very complex history during Early Ordovician times and experienced environmental change from subaerial exposure to deposition on the deep shelf below storm wave base. The near absence of sand- and silt-sized siliciclastic sediments in combination with the very reduced thickness of the Tremadocian succession argues for only minor detrital input from land into the basin and therefore, most likely, low topographic relief on the Scandinavian craton forming the hinterland of the Ordovician shelf. The absence of carbonate grain types indicative of tropical conditions such as reef-building corals, ooids or peloids suggests relatively cool-water conditions during sedimentation (cf. James & Clarke 1997). However, the abundance of micrite indicates that local climate was rather temperate to maybe subtropical during deposition, which is in overall agreement with paleogeographic reconstructions for Baltica in the Early Ordovician (Cocks & Torsvik 2005).

At the onset of the Ordovician, the Hunneberg area was subaerially exposed as indicated by mudcracks locally forming the top of the *L. americanus* Alum Shale Formation mudstones (Figs. 4B, 6). This exposure most likely lasted at least 6 million years as the uppermost Cambrian *T. holmi* agnostoid Biozone is entirely missing (Fig. 2) at Mt. Hunneberg. The first relative highstand of sea level during the Early Ordovician must have established offshore conditions in the Hunneberg area (Fig. 6), which is still reflected in the only millimeter-thick siliciclastic mudstone layers containing abundant fragments of *R. flabelliformis* colonies. However, during the successive sea-level fall, most of the initial Ordovician transgressive and highstand sediments were eroded, and only thin remnants were

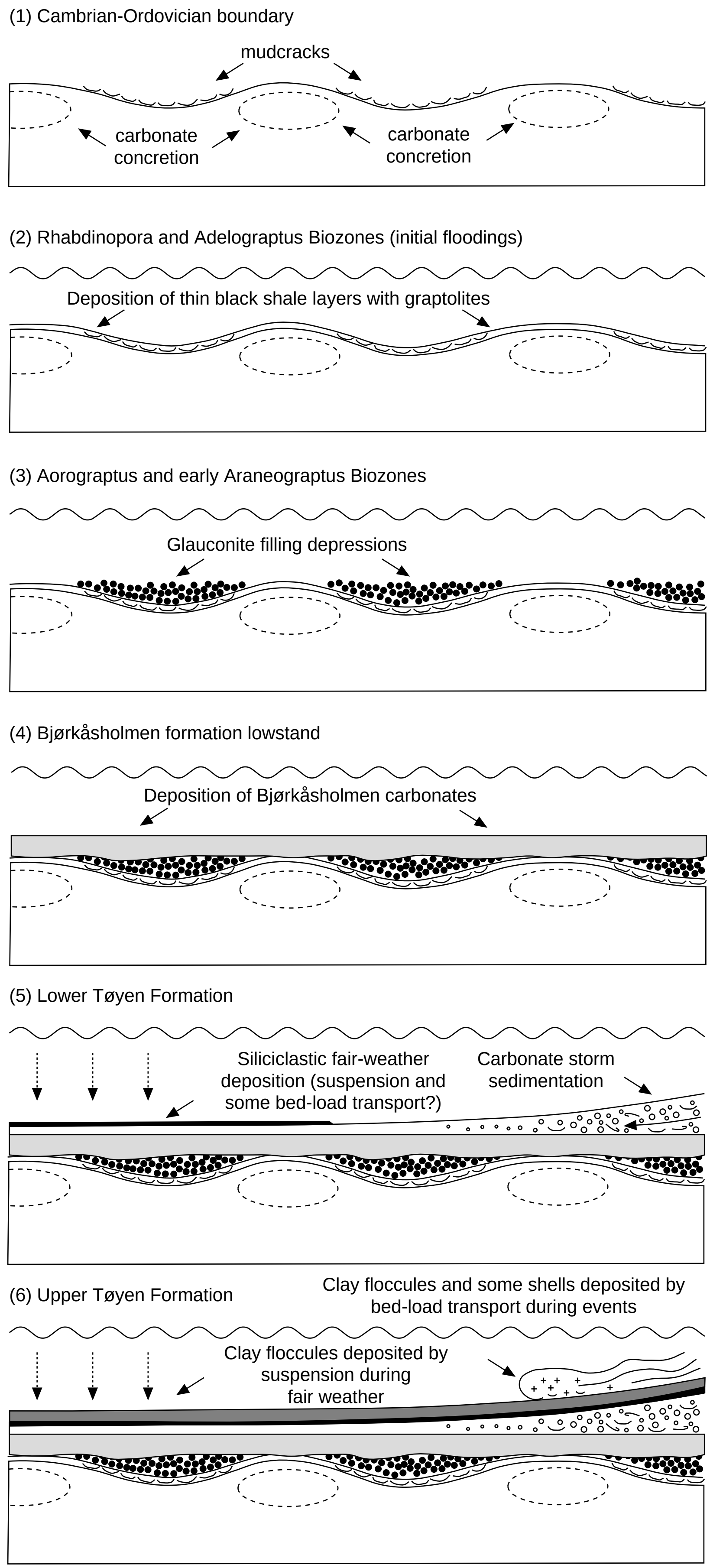

Fig. 6. Depositional history of Mt. Hunneberg in six steps: (1) mudcracks formed in depressions within Alum Shale Formation sediments around Cambrian–Ordovician boundary times; (2) two flooding events deposited each a layer of siliciclastic mudstones both containing graptolites (*Rhabdinopora* and *Adelograptus*), these sediments are exclusively preserved within the depressions; (3) a transgression is reflected in glauconite deposition preferentially preserved within the depressions; pre-Bjørkåsholmen times, for exact timing of *Araneograptus* and *Aorograptus* graptolite Biozones compare to Fig. 2; (4) a subsequent lowstand of sea level results in deposition of the Bjørkåsholmen Formation carbonates; (5) sea level rises at the onset of deposition of the Tøyen Shale Formation supplying both carbonates and shales to the Mt. Hunneberg region that is located in an offshore position; (6) during upper Tøyen Shale Formation times, the Mt. Hunneberg area had deepened to an open shelf environment where fair-weather siliciclastic mudstones and tempestite shell debris was deposited.

preserved preferentially in the decimeter-scale depressions within the Late Cambrian Alum Shale Formation. Similarly, transgressive and highstand sediments deposited during a second fluctuation of sea level during *A. tenellus* times (middle Tremadocian) were again best preserved within the depressions in Cambrian Alum Shale Formation deposits (Fig. 6). A subsequent strong transgression of either *Adelograptus* age or younger must have deposited significant amounts of glauconite (Figs. 5A, 6), likely throughout the study area, as it escaped erosion forming a succession of about 0.5 m or less thick in, for example, the localities of Holsbrotten, Västra Tunhem and Storeklev.

The Bjørkåsholmen and overlying Tøyen Shale Formations display the depositional transect well that governed sedimentation during Tremadocian and Floian times at Mt. Hunneberg (Fig. 7; cf. Egenhoff & Maletz 2007): the carbonates represent the shallower portion of the system, mostly mid ramp to outer ramp offshore deposition, and the siliciclastic mudstones show sedimentation on the open shelf, likely below storm wave base (nomenclature of MacEachern et al. 1999; MacEachern & Gingras 2007). The mid ramp carbonate strata consist of wacke- to packstones with intercalated mudstones, and the outer ramp deposits comprise mostly fine-grained carbonate mudstones with some wackestones (Burchette & Wright 1992).

The Bjørkåsholmen Formation limestones resting directly on top of the Ordovician part of the Alum Shale Formation reflect deposition primarily in a mid-to-outer ramp environment. This unit, consisting nearly exclusively of shallow offshore carbonate mudstones to packstones that represent tempestites (Egenhoff & Maletz 2007), reflects several trans- and regressions, each transgression indicated by a siliciclastic mudstone lamina, and the regressions and sea-level lowstands by carbonate beds. The lack of siliciclastic mudstones in the central and upper portion of the Bjørkåsholmen Formation in combination with an overall more grain-rich character of the limestone beds suggests that most likely no or only very thin transgressive mudstones had been deposited during late Bjørkåsholmen times. If any mudstones had been deposited they must have been eroded during subsequent regressions and lowstands. This is, for example, indicated in the Västra Tunhem locality by the sharp erosional incision that can be up to a decimeter deep of the uppermost thick Bjørkåsholmen carbonate bed into the underlying siliciclastic mudstones (Fig. 3).

The transition between the Bjørkåsholmen Formation and the overlying Tøyen Shale Formation is marked by a sharp transgressive surface across which water depth increased, but the environment stayed within the offshore realm. Deposition was characterized by alternating siliciclastic mudstone deposition reflecting fair-weather conditions, and centimeter-thick normally graded and mud-rich carbonates to marls representing storm beds (Fig. 6). Throughout deposition of the Tøyen Shale Formation, however, the amount of siliciclastic mudstone in the succession successively increased, and from the *Tetragraptus approximatus* Biozone on deposition of mostly clay- and silt-rich siliciclastic sediment in the Hunneberg area reflects an overall deepening of the environment. However, during the late Tremadocian *H. copiosus* Biozone, a some millimeter-thick layer of siliciclastic mudstones established open shelf conditions at Mt. Hunneberg for a short time period, reflecting the maximum flooding during sea-level highstand preserved in both the localities of Storeklev and Holsbrotten. The switch from a setting with significant and regular carbonate input, mostly in the form of tempestite carbonate mud and shell lags, to an environment with only rare influx of carbonate debris, probably only during extreme storms (*T. approximatus* Biozone and younger; Fig. 6), likely reflects the transition from offshore to open shelf conditions.

The depositional processes for most of the Tøyen Shale Formation siliciclastic mudstones remain unclear because ubiquitous intense bioturbation has destroyed nearly all of the original structures of the sediment. However, some millimeter-thick intercalated shell lags indicate that bed-load transport played a role in depositing these fine-grained siliciclastic rocks. Sedimentation of the siliciclastic mudstones in a generally tranquil deep shelf setting, however, makes suspension deposition of at least a part of the siliciclastic mudstones likely (Egenhoff & Maletz 2007) even though some of the mud may have also been deposited as floccules by bed load transport (Fig. 6; cf. Schieber et al. 2007). Nevertheless, the intense bioturbation responsible for destroying the internal structure of much of the sediment reflects hospitable living conditions on the sea floor during deposition. These living conditions must have continued some millimeters to centimeters below the sediment–water interface as indicated by individual burrows that extend this far down into the sediment.

Sea-level changes had a significant impact on depositional patterns in the Tøyen Shale Formation (Egenhoff & Maletz 2007). During times of lower sea level, the frequent influx of carbonate material during storm events formed stacked tempestite mud-, wacke- and packstones amalgamated into distinct carbonate beds traceable over large distances through Mt. Hunneberg (Fig. 3). The influence of currents and/or wave action is still indicated in the grain-rich carbonate lithologies within these beds by the convex-up orientation of many of the shells (Fig. 5B). The sea-level lowstands during deposition of the Tøyen Shale Formation, however, were not as pronounced as the Bjørkåsholmen Formation lowstand (cf. Egenhoff et al. 2010). Their successive finer-grained nature and thinner-bedded expression upsection indicates more and more distal conditions of carbonate deposition during the Tøyen Shale Formation lowstands. This reflects the overriding transgressive trend that

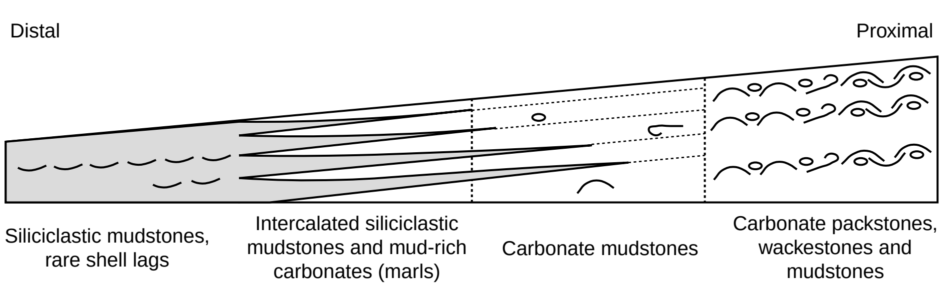

Fig. 7. Generalized proximal to distal transect highlighting deposition at Mt. Hunneberg. The low-angle depositional profile is subdivided into four facies zones with the siliciclastic mudstones occupying the most distal portion of the shelf. Not to scale.

parallels a change in facies of the embedding siliciclastic mudstones. The thin nature of the distinct limestone beds into the lower Tøyen Shale Formation and the fact that each of the "*Armata*" and "*Planilimbata*" limestones are represented by a single several centimeters-thick carbonate bed indicate that all of these lowstand deposits represent only a single drawdown of sea level in contrast to the Bjørkåsholmen Formation that consists of a series of lowstands.

Sedimentation most likely continued in the Hunneberg area far beyond the preserved exposure reaching up into the Lower Ordovician (Floian) *B. vacillans* Biozone (Egenhoff & Maletz 2007). The missing part of the succession was probably most similar to the Tøyen Shale Formation in the Oslo Region (cf. Owen et al. 1990). However, the proximity of Mt. Hunneberg to the mostly carbonate-producing ramp environments of Billingen-Falbygden and Kinnekulle makes it most likely that the Hunneberg succession was slightly more carbonate rich with carbonate grains and mud shed especially during lowstands than the time-equivalent exposures in the Oslo Region to the west and surroundings.

Discussion

Facies

The mudcracks at the base of the Ordovician succession are exclusively preserved within decimeter-deep depressions cut into the upper Cambrian Alum Shale Formation in several of the Hunneberg localities. They represent the most convincing argument that the Hunneberg area was subaerially exposed during Cambrian–Ordovician boundary times. When exposing an irregular land surface it is generally more likely that rainwater accumulated exclusively within the depressions, which subsequently dried out leaving the mudcracks behind. It is therefore most probable that the mudcracks are originally only present within the depressions and, similar to modern puddles do not extend far up the flanks and onto the adjacent crests. Within the depressions they were also best protected from erosion during later transgressions that would mostly infill the depressions but not erode much of their sedimentary content.

The several centimeter- to decimeter-thick carbonate beds of the Bjørkåsholmen Formation, "*Armata*" and "*Planilimata*" limestones are interpreted as individual lowstands in this study and not as individual tempestite deposits even though they show the thicknesses and maximum grain sizes of tempestites recognized in many other areas (e.g. Triassic Muschelkalk, Aigner 1985). For example, the Bjørkåsholmen Formation limestones frequently show an arrangement of facies into several normally graded centimeter-scale units (Egenhoff et al. 2010). These are indeed typical for waning energy conditions during tempestite sedimentation (Kreisa 1981). However, several of these normally graded units and intercalated fine-grained carbonate mudstones within a single bed suggest that each individual bed consists of multiple tempestite events and therefore rather reflects deposition during a longer lasting period allowing sedimentation during several storms, than just one storm event. While this holds true mostly for the Bjørkåsholmen Formation, the same depositional processes are also assumed for both the "*Armata*" and the "*Planilimbata*" limestones despite their in places relatively structureless appearance. At least the "*Armata*" limestone consists of several carbonate and siliciclastic mudstone beds that each by itself may represent one or more storm events and intermittent fair-weather sedimentation. Nevertheless, as a whole the unit does represent a longer lasting basinward shift of carbonate facies belts compared to the over- and underlying siliciclastic mudstones.

It is herein assumed that the Tøyen Shale Formation was deposited in an offshore to open shelf environment that was not anoxic but rather well ventilated and home to a diverse fauna as reflected in the content of shell fragments and burrows within this unit. This is in contrast to the often still upheld notion that black shales are deposited in relatively deep and tranquil basins and – especially when containing abundant graptolites such as the Tøyen Shale Formation – largely anoxic settings (e.g. Tyson 1987). Even though, the Tøyen Shale Formation sediments are highly bioturbated, less than a millimeter-thick laminae of shell fragments aligned along bedding planes most likely represent lag deposits from currents or waves sorting sediment even in this distal setting. While there are no indications whether unidirectional or bidirectional flows produced these lags, these relatively coarse-grained deposits show that most probably either storm waves or storm-induced currents were still influencing sedimentation on the outer shelf at Mt. Hunneberg during Tøyen Shale Formation times. The preserved lags were presumably not the only ones formed but rather represent the few that escaped destruction by bioturbation. Therefore, the frequency of storms was likely much higher even during deposition of the siliciclastic mudstones of the upper Tøyen Shale Formation than reflected in the abundance of lag deposits. It is likely that if these lags were caused by currents, these brought in oxygenated water from shallow shelf areas, or if caused by waves, then mixing of the water column also increased the oxygen content of bottom-near waters. The abundance of burrows in the Tøyen Shale Formation destroying nearly all sedimentary structures, however, argues for a constantly well-oxygenated environment and not for episodically recharging of oxygen during storms. It is therefore likely that the Tøyen Shale Formation represents an oxic environment despite its dark color and the abundance of graptolites in these rocks.

Vertical and lateral trends

Worldwide, sea level seems to have been overall high during the early and middle Tremadocian (Ross & Ross 1992; Egenhoff 2000; Nielsen 2004). This is in agreement with low-energy open shelf siliciclastic mudstones and glauconitic sediment being deposited during this stratigraphic interval at Mt. Hunneberg. However, these mudstones and glauconite packstones do not record constant or fairly constant sedimentation during early to middle Tremadocian times, but rather episodic preservation of only very few graptolite species such as *R. flabelliformis* and *A. tenellus* (Maletz & Erdtmann 1987; Maletz et al. 1996) in thin mudstone layers overlain by glauconite-bearing strata, mostly in small depressions (Fig. 6). Graptolite biostratigraphy indicates that significant hiatuses separate individual mudstone layers, and that both most likely reflect transgressive pulses and/or maximum flooding. Hiatuses in stacks of deep shelf mudstones associated with glauconite as observed at Mt. Hunneberg are often difficult to recognize, and this represents a stratigraphic and sedimentological problem also for lower to middle Tremadocian successions in Västergötland and parts of Öland (Jaanusson 1982).

Two possible scenarios can be made responsible for producing widespread hiatuses as observed in the lower to middle

Tremadocian in Scandinavia: (1) the missing portions of the succession were removed during one or several sea-level falls, either by exposure during the lowstands, or by subsequent transgressions eroding previously deposited falling-stage systems tracts and lowstand deposits (cf. Plint 1988), or (2) the succession underwent submarine erosion as suggested by some authors (cf. Moore et al. 1978).

The top of the Cambrian succession is characterized by distinct mudcracks (Fig. 4A) indicating exposure of the Mt. Hunneberg area during the transition from the Latest Cambrian to the Early Ordovician. Sea level must have been low enough at times to expose larger portions of the Baltoscandian platform, including the Hunneberg area. It therefore seems more likely that the hiatuses in the directly overlying succession were formed by erosion caused by sea-level fluctuations than by large-scale submarine erosion, the latter being more common in the pelagic realm produced by turbidites and contourites (Moore et al. 1978). Local tectonic uplift, however, may have helped creating the observed hiatuses, especially as synsedimentary tectonics are proposed for the time of deposition of the Bjørkåsholmen Formation likely caused by compressional movements related to a collision of an island arc with Baltica (cf. Greiling & Garfunkel 2007; Egenhoff et al. 2010).

The Hunneberg succession shows a distinct increase in thickness from the NE to the SW. This thickness increase is exclusively noted in the siliciclastic mudstone portion of the succession while the carbonate units do not unanimously follow the same trend. The thicker siliciclastic mudstones most likely reflect a proximal–distal relationship as the paleo-coastline ran approximately WNW–ESE to northwest–southeast (NW–SE) in the study area (Cocks & Torsvik 2005). In the Mt. Hunneberg sections, the bulk of the siliciclastic mudstones represents the regressive portion of third-order cycles as the maximum flooding surfaces indicated by graptolites tend to be located close to the carbonate beds representing the previous lowstand sediments (Egenhoff & Maletz 2007). Therefore, the erosion of siliciclastic mudstones must have been taken place during the regressive portion of the cycles, most likely just prior to the deposition of the overlying carbonate lowstand beds such as the "*Armata*" and "*Planilimbata*" limestones. This view is corroborated by the fact that erosional scours are present, for example, at the base and internally within the Bjørkåsholmen Formation limestone beds that represent another lowstand carbonate unit. However, both depositional energy and erosional power must have significantly decreased over a lateral distance of just a few kilometers downramp between the NE and SW portion of Mt. Hunneberg. This is not only reflected in the greater thickness of the siliciclastic mudstones, but also in the pinching out of the upper "*Planilimbata*" limestone from the Mossebo and Diabasbrottet localities in the NE to Storeklev and Holsbrotten in the SW (Maletz et al. 1996). It is therefore most likely that the thickness and facies variations are related to erosion during falling sea level, and facies variations between a more carbonate-rich and a more mudstone-dominated facies zone in the Hunneberg area during Tøyen Shale Formation times.

Each individual carbonate bed within the Bjørkåsholmen Formation has been interpreted as being caused by a single fluctuation within the Milankovitch band for both the Öland sections toward the east, and the outcrops around Oslo in the NW (Egenhoff et al. 2010). Adopting this interpretation for Mt. Hunneberg, the Bjørkåsholmen succession would show four of these precession cycles, which is significantly less than observed in both Öland and Oslo where 7–9 and around 11 are exposed, respectively. One possible explanation for this would be following the interpretation put forward by Egenhoff et al. (2010). The Bjørkåsholmen Formation does not record time-equivalent sedimentation in the form of a carbonate sheet covering entire Scandinavia, but rather represents carbonate wedges stepping down the ramp profile during third-order sea-level fall, and carbonate wedges showing retrogradational stacking during the subsequent sea-level rise. The retrogradational parasequences in both Öland and the Oslo Region contain significant amounts of glauconite, which is not observed in the Bjørkåsholmen Formation at Mt. Hunneberg. It seems therefore most likely that the four carbonate beds just represent a portion of the downstepping carbonate wedges from the falling limb of the sea-level curve. The retrograding wedges recording the subsequent sea-level rise, in contrast, were either not deposited in the Hunneberg area or eroded during the third-order transgression. The postulated erosion during the transgression following deposition of the Bjørkåsholmen Formation probably also removed a portion of the carbonate wedges deposited during the sea-level drop. This is indicated by the low number of progradational parasequences at Mt. Hunneberg in comparison to Oslo and Öland. Furthermore, the Oslo sections that represent a further distal setting on this Ordovician ramp than the Mt. Hunneberg area show shallow marine shoreface sediments during the peak Bjørkåsholmen lowstand. As Mt. Hunneberg is lacking these sediments or any signs of time-equivalent subaerial exposure, it is most likely that such sediments were also removed during the transgression that initiated deposition of the overlying Tøyen Shale Formation.

Mt. Hunneberg as a GSSP for the Floian stage

The Diabasbrottet section at Mt. Hunneberg was officially selected as the GSSP for the Floian or the second stage of the Ordovician System (Bergström et al. 2004). Therefore, the Mt. Hunneberg succession represents an excellent opportunity to evaluate which sedimentary environments are especially suitable for defining such a GSSP as they contain the crucial fossil content that forms the basis for a detailed biostratigraphy. Both conodonts and graptolites are used in the study to argue for the Swedish Mt. Hunneberg section versus a Newfoundland section on the Cow Head Peninsula (e.g. Williams et al. 1994; Maletz et al. 1996); however, the first appearance datum of *T. approximatus*, a graptolite and not a conodont, is considered as the defining species in this particular case.

Within the Mt. Hunneberg succession, graptolites occur at several levels, but mostly within the Tøyen Shale Formation originally considered to be entirely a shale except for some minor carbonate intercalations. However, its lower part equivalent to the *H. copiosus* Biozone (Maletz et al. 1996) consists of marl and carbonate mudstones with millimeter-thick shale caps that are generally devoid of graptolites with some exceptions (see Maletz 1987). Within this interval, only one half a centimeter-thick bed contains abundant *H. copiosus* and shows siliciclastic mudstones with graptolites entirely lacking carbonates. This level is interpreted to represent a maximum flooding event (Egenhoff & Maletz 2007). Siliciclastic mudstones containing rich graptolite faunas, however, only occur again right with the onset of the *T. approximatus* siliciclastic mudstones at the very base of the GSSP boundary. The critical facies for establishing a GSSP based on graptolites is therefore the occurrence of siliciclastic mudstones. Nevertheless, these mudstones do not represent an anoxic environment but are characterized by abundant burrowing co-occurring with the graptolites. It is therefore most likely that these sediments represent an oxic to in places dysoxic environment, probably located below storm wave base but within reach of storm-induced currents. Such open shelf conditions are necessary for graptolites to thrive and also to be preserved within the bottom sediments. In contrast, simple offshore deposits still containing significant amounts of carbonate derived from the shallow shelf seem not to possess the characteristics to preserve sufficient graptolitic material for biostratigraphic sampling. Nevertheless, conodonts are known in significant amounts only from the offshore carbonate storm layers. Therefore, an alternation of carbonate storm beds and open shelf siliciclastic mudstone environments seems to be ideal for containing both of the indicative index fossils that define GSSPs in the Ordovician and Silurian.

Conclusions

(1) The Ordovician part of the Hunneberg succession overlies a hiatus of around 6 million years that records subaerial exposure of the area indicated by the presence of mudcracks. Subsequent deposition of the Lower Ordovician portion of the Alum Shale Formation consists of siliciclastic mudstones with graptolites and overlying irregular glauconite beds. The mudstones and their fossil content record two distinct trans- and regressions during the *R. flabelliformis* and *A. tenellus* Biozones, both preserved as highly condensed units. These two cycles most likely show only parts of the transgressive and highstand sediments, and are mostly preserved within decimeter-deep depressions within the underlying Cambrian Alum Shale Formation. The glauconite-rich sediments reflect transgressive conditions and occur within the depressions, but may also form up to 0.5-m-thick deposits outside the depressions in some localities at Mt. Hunneberg.

(2) The upper Tremadocian Bjørkåsholmen Formation consists of four carbonate mud-, wacke- and packstone beds with in places minor intercalated shales. These carbonates represent stacked shallow offshore storm deposits, and each of the beds records one short-term sea-level fluctuation during the Bjørkåsholmen lowstand, probably reflecting precessional cycles within the Milankovitch band.

(3) The uppermost Tremadocian to Floian Tøyen Shale Formation is characterized by siliciclastic mudstones and intercalated carbonate beds. The succession shows an overall fining upward with intercalations of siliciclastic mudstones and carbonate mudstone/marl beds from its base to the *T. approximatus* Biozone, and a transition into mostly siliciclastic mudstones from there until the top of the exposed succession. The siliciclastic mudstones with the carbonate mudstone/marl intercalations in the lower part of the Tøyen Shale Formation reflect offshore deposition, most likely above storm wave base. In this environment, the fine-grained siliciclastic sediments represent fair-weather tranquil conditions, and the carbonate mudstones that in places show normal grading individual tempestite beds. The top portion of the Tøyen Shale Formation, in contrast, reflects open shelf deposition with very few intercalated carbonate beds presumably deposited from storm-induced currents. The entire succession also shows several carbonate intercalations such as the "*Armata*" and "*Planilimbata*" limestones. These units represent lowstands and proximal offshore sedimentary conditions where several tempestite beds would amalgamate to form distinct and laterally traceable carbonate beds. The abundance of burrows throughout both, the carbonates and the siliciclastic mudstones, argues for well-oxygenated conditions throughout deposition of the Tøyen Shale Formation.

(4) The decrease in thickness of the Tøyen Shale Formation succession toward the NE within Hunneberg was likely caused by more intense erosion of mudstone lithologies in the Diabasbrottet and Mossebo areas. The erosion probably took place during falling sea level and a decrease of accommodation space prior to the deposition of lowstand carbonate units. Similarly, a pinching out of lowstand carbonate units toward the SW within the upper part of the Floian succession at Hunneberg is interpreted as reflecting a lateral transition from an offshore to an open shelf setting within the study area.

(5) The Hunneberg locality represents the GSSP for the Floian or the second stage of the Ordovician System (Bergström et al. 2004). This study shows that for Ordovician and Silurian GSSPs where graptolites play a major role, an alternating open shelf and offshore setting may be ideal to tie in deeper water occurring graptolites with conodonts that seem to be restricted mostly to offshore carbonate settings. However, the carbonate-rich character of the lower Tøyen Shale Formation siliciclastic mudstones at Mt. Hunneberg may allow to even encounter conodonts within the lithologies hitherto recorded as "graptolitic shales" that make up a far larger part of the succession than the few isolated carbonate lowstand beds (cf. Maletz et al. 1996). It is therefore suggested here that the Tøyen Shale Formation should be searched for conodonts in order to further enhance the biostratigraphic resolution of this and possibly other GSSPs in similar facies.

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