Sedimentary facies and fauna of the Late Silurian Bjärsjölagård Limestone Member (Klinta Formation), Skåne, Sweden

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Cover Picture: The Bjärsjölagård quarry in September 2005.

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Abstract: The late Ludlow Bjärsjölagård Limestone Member comprises a part of the Klinta Formation of the Öved-Ramsåsa Group in Skåne, southern Sweden. The ~25 m thick member was formed during the time of the globally known Lau Event and a major sea-level lowstand in the Baltic Basin. This study describes the sedimentary rocks, and their fossil fauna, of the Bjärsjölagård Limestone Member exposed in the Bjärsjölagård quarry, south-central Skåne. The investigation is based on fieldwork, during which three sections were measured and sampled. Complementary laboratory work included examination of 59 rock samples and 15 thin-sections. Both the lithology and fossils were recorded, and the ~6.5 m profiled stratigraphy could be subdivided into six depositional facies, of which two are of microbial origin. In order to investigate the palaeoecology, fossil elements on slab surfaces were counted in squares of specific areas. To enable correlations to sedimentary environments on a shelf, the skeletal composition was counted and plotted in a three-axis diagram. The bed geometry, depositional facies, and faunal content suggest a mixed carbonate-siliciclastic coastal setting. The fossils and the microbial facies indicate an open-marine lagoonal environment of normal salinity, possibly with fluctuations caused by fresh-water input. The major part of the succession contains normal Silurian ecological assemblages, commonly with several tiering levels, but the enclosing oncoid-rich units imply a stressed situation possibly related to the Lau Event. Based on available conodont- and carbon isotope data and a suggested sequence stratigraphical framework for the Bjärsjölagård Limestone Member, a high-resolution intrabasinal correlation between Skåne and Gotland is suggested.

Keywords: The Bjärsjölagård Limestone Member, Ludlow, sedimentary facies, faunal diversity, Lau Event, stratigraphical correlation, Skåne.

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Sedimentära facies och fauna från den sensiluriska Bjärsjölagårdkalkstenen inom Klintaformationen, Skåne, Sverige

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Sammanfattning: Bjärsjölagårdkalkstenen i Skåne, södra Sverige, är av sen ludlowålder och utgör en del av Klintaformationen inom Öved-Ramsåsagruppen. Denna kalksten bildades under tiden för den globalt kända Laukatastrofen och ett kraftigt havsnivåfall i den Baltiska bassängen. I denna studie beskrivs sedimentbergarter och dess fossila fauna från Bjärsjölagårdkalkstenen i det övergivna kalkbrottet i Bjärsjölagård. Till grund för undersökningen ligger fältarbete, under vilket tre sektioner uppmättes och provtogs. Litologi och fauna bestämdes vidare i labbet med hjälp av de 59 proverna och de 15 framtagna tunnslipen. Informationen låg till grund för en uppdelning av den ~6,5 m tjocka lagerföljden i sex olika depositionella facies. För att få statistisk information till den paleoekologiska tolkningen räknades antal fossil som kunde identifieras inom rutor av specifik storlek. Punkträkningar gjordes för att kunna jämföra den skeletala sammansättningen med en modell som beskriver dessas samband med olika sedimentära miljöer på en shelf. Lagrens geometri, faunainnehåll och depositionella facies indikerar en kustnära miljö på en mixad karbonat-siliciklastisk shelf. En tolkning av denna som en öppen marin lagun med generellt normal marin salinitet, möjligen med fluktuationer från inkommande färskvatten, indikeras av fauna och mikrobiella facies. Den största delen av stratigrafin i Bjärsjölagårdbrottet innehåller en normal silurisk marin fauna, men de två omgivande onkoidrika nivåerna tyder på en stressad miljö möjligen relaterad till Laukatastrofen. Baserat på tillgänglig conodont- och kolisotopdata samt ett upprättat sekvensstratigrafiskt ramverk har en korrelation mellan Skåne och Gotland föreslagits.

Nyckelord: Bjärsjölagårdkalkstenen, Ludlow, sedimentära facies, fauna diversitet, Laukatastrofen, stratigrafisk korrelation, Skåne.

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1. Introduction

The Silurian Earth (443.7–416.0 Ma; Gradstein et al. 2004) was characterised by global, contemporary changes in sediment composition and fauna (e.g. Jeppsson 1990; Jeppsson & Aldridge 2000). The changes have been explained by a theoretical oceanographic model presented by Jeppsson (1990, later revised and updated by Jeppsson 1993, 1998 and Cramer et al. 2005) in which a shift between two stable oceanic conditions causes a shorter, unstable interval, an event. Three of the recorded Silurian events are coupled with large anomalies in the stable isotope ratio of carbon; the most prominent of these is associated with the late Ludlow Lau Event (Fig. 1). This event caused a major ecological crisis in carbonate platforms (Calner 2005a) and extinctions among e.g. conodonts, polychaetes, and fish (Jeppsson & Aldridge 2000; Eriksson et al. 2004; Nilsson et al. 2005). The carbon isotope excursion (CIE) associated with the Lau Event has been recorded globally, including from Skåne, the southernmost province of Sweden (Fig. 2).

In Skåne the Silurian succession is the most complete in Scandinavia (Jeppsson & Laufeld 1986). Despite this, the Silurian strata have received little attention during the latest decades, largely because of few outcrops and extensive faulting, which complicate correlations (Larsson 1979; Jeppsson & Laufeld 1986). Hence, although geologists started to subdivide the known outcrops into different units as early as in the late 19th century (Eichstädt 1888; Grönwall 1897), it was not until the late 20th century that formal lithostratigraphical definitions and names were established within the Late Silurian Öved-Ramsåsa Group (Jeppsson & Laufeld 1986).

This study focuses on exposures of the late Ludlow Bjärsjölagård Limestone Member (Fig. 1) occurring in an old abandoned quarry at Bjärsjölagård, ~11 km NW of Sjöbo in south-central Skåne (Fig. 2). The locality has been known for a long time for its richness in fossils and its high abundance of oncoids (microbially coated grains). However, when Wigforss-Lange (1999) identified the CIE associated with the Lau Event, a new interest for the Bjärsjölagård Limestone Member arose. Moreover, the Baltic Basin, that Skåne was a part of, was exposed to a major sea-level lowstand during this time (Cherns 1982; Jeppsson et al. 1994; Calner & Eriksson 2006). The close relationship to the Lau Event and the sea-level lowstand makes the Bjärsjölagård Limestone Member of particular interest, and the outcrop in the Bjärsjölagård quarry has been the subject for this investigation.

The aim of this study has been to improve the knowledge about the Lau Event and the evolution of the Baltic Basin, by describing the Bjärsjölagård locality and correlating it to the better-known stratigraphy on Gotland. Thus, the sedimentary rocks and the faunal content have been described and the strata have been subdivided into different depositional facies. Subsequently a palaeoenvironmental interpretation has been made. Furthermore, the Bjärsjölagård Limestone Member has been correlated with Gotland by using available conodont- and carbon isotope data, as well as a suggested sequence stratigraphical framework.

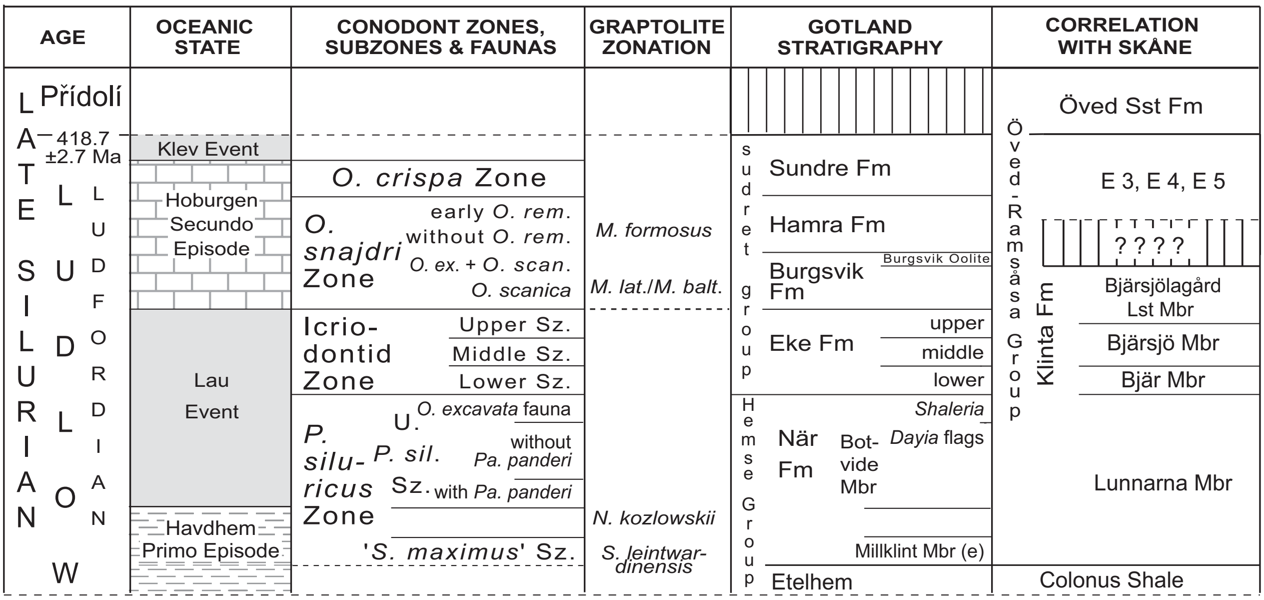

Fig. 1. Stratigraphical chart showing the oceanic states, conodont- and graptolite zonations, Gotland stratigraphy, and a correlation to the stratigraphy in Skåne within the Ludfordian Stage (modified from Jeppsson & Laufeld 1986 and Jeppsson et al. 2006a). For abbreviations, see references.

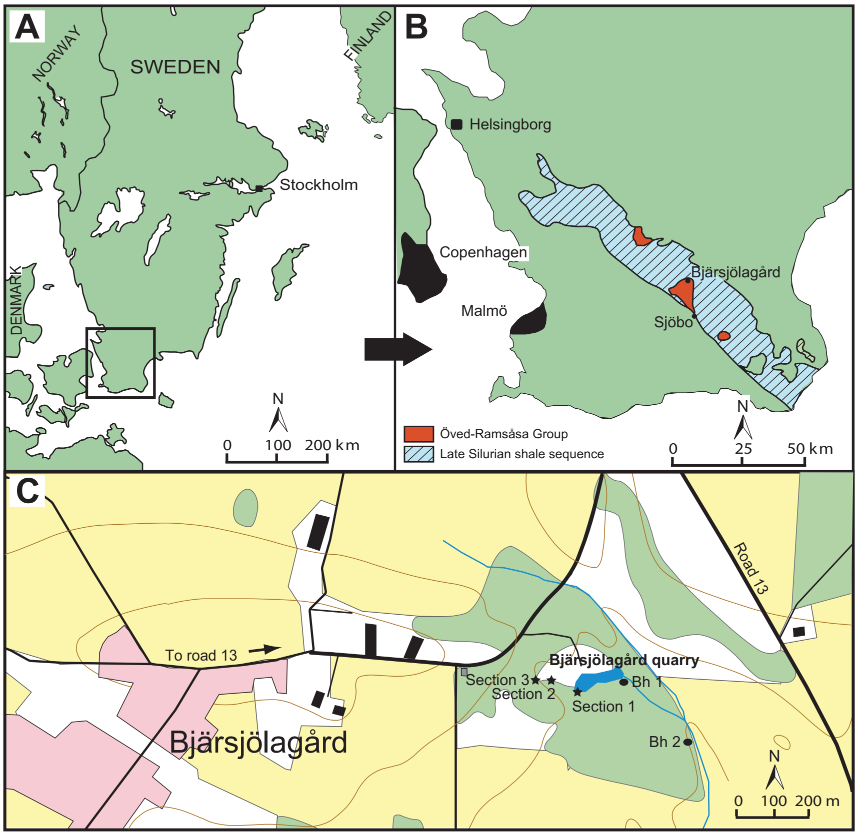

Fig. 2. Map showing the location of Bjärsjölagård in Skåne, Sweden. **A.** General map showing parts of Scandinavia. **B.** Map of Skåne with the position of Bjärsjölagård and the distribution of the Öved-Ramsåsa Group within the Vomb trough (modified from Jeppsson et al. 2006b). **C.** Map showing the location of the Bjärsjölagård quarry, the position of sections 1-3 and the drilling sites for the drill-cores Bh 1 and Bh 2 (modified from https://geoimager.lantmateriet.se/digibib/).

2. Geological setting and stratigraphical framework

2.1 Silurian palaeogeography and tectonic evolution of the Baltic Basin

In the late Ordovician and throughout the Silurian the majority of landmass, including the Fennoscandian Shield, was situated in the southern hemisphere (Fig. 3). In the late Ordovician to early Silurian the micro-continent Avalonia closed in on Baltica from the southwest. The collision led to a reduction of the Tornquist Sea by subduction of the ocean floor (Torsvik et al. 1996; Baarli et al. 2003). During the Silurian Baltica collided with Laurentia, creating an active margin also to the west (Fig. 4). This led to the early stages of the Scandian Orogeny and the closure of the Iapetus Ocean (Torsvik et al. 1996).

In the Silurian Baltica was partly covered by an epicontinental sea (Baarli et al. 2003). An area of this sea is commonly referred to as the Baltic Basin (Fig. 4); which covered parts of present day Denmark, Sweden, Poland, and the East Baltic States and tapered off towards Ukraine. Along the marginal parts of this basin a laterally extensive carbonate platform system had developed, whereas formation of shale dominated in the deeper central parts. Skåne, the region of interest herein, was situated at the southern margin of the Fennoscandian Shield (Fig. 4) and was part of a wide shelf area from Cambrian to early Silurian times (Wigforss-Lange 2006). When the Tornquist Sea, between Avalonia and Baltica, diminished due to the subduction in the southwest (Torsvik et al. 1996; Baarli et al. 2003), Skåne instead became part of a foreland basin. This tectonic evolution is evident from a significant increase in subsidence- and sedimentation rates (Poprawa et al. 1999).

The Wenlock and Ludlow strata from the basin show a regressive trend, eventually leading to a termination of marine deposition. Instead a progradation of continental sandstone began around the time of the Silurian-Devonian boundary (Bassett et al. 1989). This long-term sea-level fall is overprinted several times by more rapid pulses of regressive-transgressive cycles. During the late Ludlow a lowstand has been recorded as an extensive stratigraphical gap in Estonia (Jeppsson et al. 1994) and as erosion surfaces and palaeokarst on Gotland (Cherns 1982; Calner & Eriksson 2006). In Skåne no corresponding record of a distinct, rapid sea level drop has been identified.

2.2 Silurian stratigraphy of Skåne

The major tectonic Tornquist Zone traverses Skåne in a northwest-southeast direction; this has lead to extensive faulting complicating stratigraphical correlations. The development of horst and graben systems in the Mesozoic has scattered the exposures of Silurian rocks, but the majority are situated within the Vomb trough in the central parts of the province (Fig. 2B; Larsson 1979). The Silurian sedimentary deposits in Skåne constitute a regressive succession where deeply formed graptolitic shale is overlain by shallow marine limestone and sandstone (e.g. Jeppsson & Laufeld 1986; Baarli et al. 2003).

The Silurian of Skåne is traditionally subdivided into four units: in stratigraphically ascending order, the Rastrites Shale, Cyrtograptus Shale, Colonus Shale, and the Öved-Ramsåsa Group (e.g. Larsson 1979;

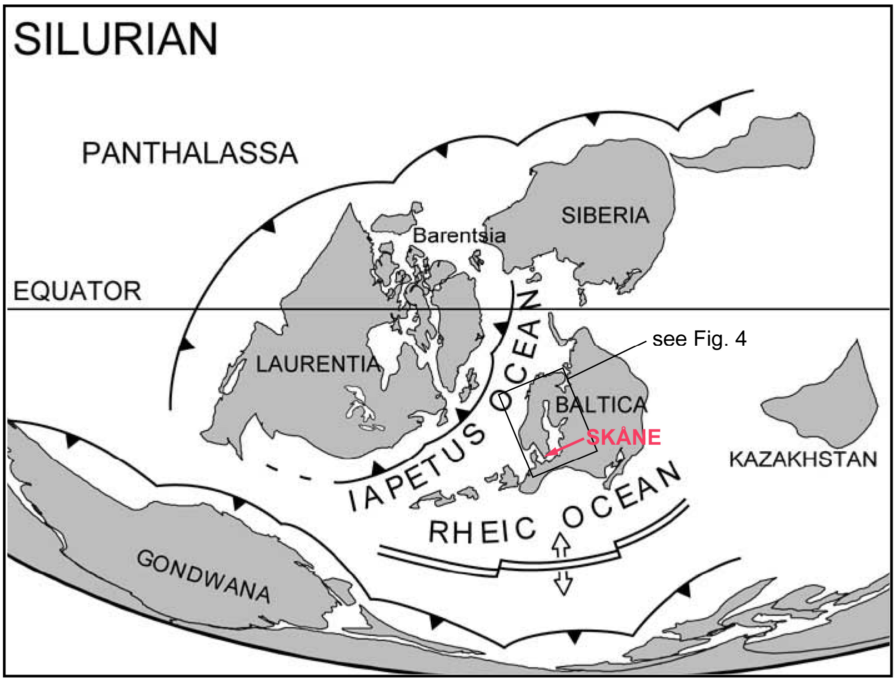

Fig. 3. Palaeomap showing the distribution of the continents during the Silurian, the position of Skåne is marked with red (modified from http://www.scotese.com).

Jeppsson & Laufeld 1986). The three older units are composed of grey shale and siltstone with a fossil fauna characterised by graptolites. The Öved-Ramsåsa Group, in contrast, has a varied lithology and a more diverse fauna (Jeppsson & Laufeld 1986). The Öved-Ramsåsa Group is of Ludlow (Ludfordian stage) to Přídolí age and represents the youngest Palaeozoic strata exposed in Sweden. The group has been subdivided into the Klinta Formation and the overlying Öved Sandstone Formation (Fig. 1; Jeppsson & Laufeld 1986). Three areas with major outcrops from these formations are known in Skåne; viz. the Bjärsjölagård-Övedskloster, the Ramsåsa, and the Ringsjö areas (Fig. 2B; Jeppsson & Laufeld 1986).

The Klinta Formation, with its lowermost parts assigned to the *Polygnathoides siluricus* conodont Biozone, includes four named members and yet unnamed intervals (Fig. 1; Jeppsson & Laufeld 1986). The lowermost parts are dominated by, often fissile, mudstone with incorporated siltstone and limestone beds. The uppermost parts of the formation are composed of the ~25 m thick Bjärsjölagård Limestone Member (Jeppsson & Laufeld 1986), with good exposures occurring in the Bjärsjölagård quarry, and a thin unnamed part (comprising Eichstädt's (1888) units 3-5; Fig. 1). By contrast to the enclosing lithosomes the Bjärsjölagård Limestone Member is dominated by limestone, but mudstone also occurs (Jeppsson & Laufeld 1986). The fossils characterising the member primarily include oncoids, corals, crinoids, brachiopods, and bryozoans (Wigforss-Lange 1999). The overlying Öved Sandstone Formation of Přídolí age (Fig. 1), is mostly composed of grey sandstone and shale (Jeppsson & Laufeld 1986). This unit can be seen as a portent of the progradation of the Old Red Sandstone (Bassett et al. 1989).

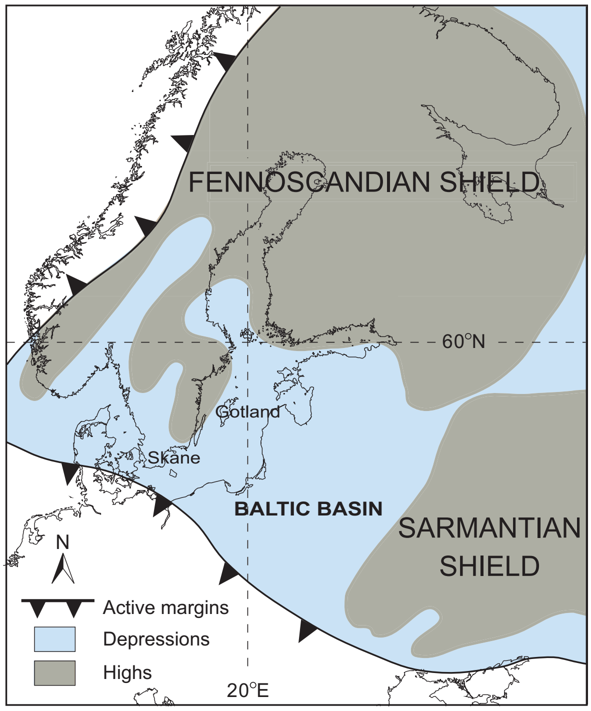

Fig. 4. Palaeomap showing the Baltic Basin area during the Silurian (modified from Baarli et al. 2003).

3. Material and methods

This study is based on fieldwork carried out in the limestone quarry at Bjärsjölagård (Fig. 2). Three sections were measured and 59 samples collected for lithofacies and faunal diversity determination. The samples are of various size, include bulk samples, and were taken at irregularly spaced intervals depending on rock type or specific aim of interest (Figs. 5-7). A total of ~80 polished slabs were investigated under a binocular light microscope. The textural classification follows Dunham (1962), as revised by Embry & Klovan (1971). For petrographical studies 15 thin-sections were prepared and examined with a petrographical microscope. The carbonate petrographical terminology used was obtained from Tucker (2001) and Flügel (2004).

To investigate the palaeoecology and tiering levels of the fossil assemblages in the sections, fossil elements were counted on the surfaces of six slabs. The counting was carried out in squares of 25 cm^2 or 12.25 cm^2, depending on sample size, and all fossils observed within this area were recorded. The results were plotted as pie-diagrams (Figs. 5-7, note that the pie-diagrams based on the smaller squares are marked with an asterix) showing the relative frequency (in percent) of the fossil groups identified in the different samples.

In order to enable correlations between skeletal composition and sedimentary shelf environments (cf. Watkins 1996), point-counting was carried out on eight polished slabs. The taxa were subdivided into three groups, one consisting of brachiopods, molluscs and arthropods, one of corals and bryozoans, and one of echinoderms, slightly modified from Watkins' (1996) model. These groups reflect major and environmentally controlled faunal associations on Silurian shelves (Watkins 1996). Skeletal elements larger than 0.5 mm belonging to these groups were counted; uncertain elements were not included in the analysis. Observations were made under a binocular light microscope, using a plastic scale with points spaced at 1 mm intervals. The number of points counted varies between 65 up to a maximum of 300 depending on the amount of skeletal grains. The abundance of each fossil group was calculated as percentage of the total points and plotted in a three-axis diagram.

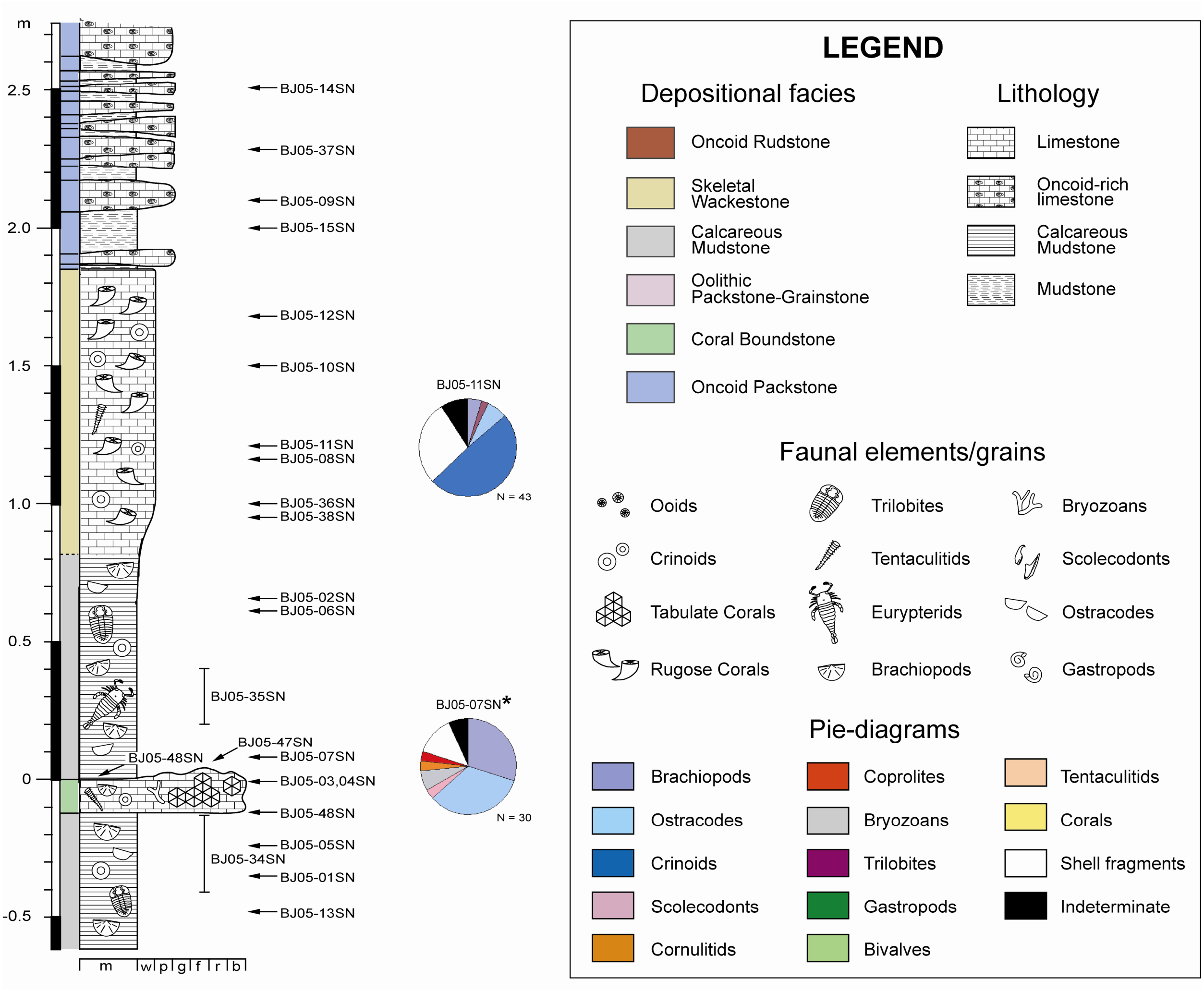

Fig. 5. The profiled stratigraphy at Section 1 and fossil assemblage pie-diagrams, counting made in the smaller square is indicated by an asterix.

4. Results

The quarrying at Bjärsjölagård has created good exposures stretching a few hundred meters in, predominantly, NW-SE and SW-NE directions. A groundwater lake has made the SW-NE wall inaccessible; therefore all investigations were made along the NW-SE trending wall, which comprises up to ~7 m high sections (Fig. 2). Three sections were measured and sampled, and the resulting profiles are presented in Figs. 5-7. sections 1 and 2 are separated by ~50 m in which both faulting and a dolorite dyke are present. Sections 2 and 3 are, however, more closely located, at ~15 m distance. A correlation between the measured sections was made in the field by tracing marker beds and estimating vertical displacements caused by the minor faults present (the correlation of the sections is further discussed in 5.1). In total the sections comprise ~14 m of strata, together representing ~6.5 m stratigraphy, which is dominated by argillaceous limestone and calcareous mudstone. The most argillaceous beds interfinger along the outcrop, while less matrix-rich beds have a greater lateral consistency. The upper parts of the sections are dominated by matrix-free and cemented, cross-stratified oncoid-rich limestone beds (Figs. 8, 9). In the bottommost part of the strata another oncoid-rich unit is exposed (Fig. 9C).

4.1 Depositional facies

The lithofacies occurring in the outcrop are limestone and calcareous mudstone, with an unusually high abundance of microbial and non-skeletal microfacies. The textural classification led to a subdivision of the lithofacies into six main depositional facies; oncoid rudstone, skeletal wackestone, calcareous mudstone, oolithic packstone-grainstone, coral boundstone, and oncoid packstone, which are described in detail below.

4.1.1 Oncoid Rudstone Facies

The oncoid rudstone facies represent the bottommost part of the strata (Fig. 9C) and comprises medium to thick beds (cf. Tucker 2001) separated by cm-thick beds of laminated mudstone (Fig. 7). The limestone, is due to the high abundance of oncoids (>50 %), defined as oncolite (Flügel 2004). The oncoids varies in size from micro (<2 mm) to macro (>10 mm) but they are commonly meso-oncoids (2–10 mm). The oncoid shape is dependent on the nucleus shape; shell fragments and other biotic grains create non-spherical, irregularly formed oncoids. Nuclei of complete shells can have cement infilling. The cortex varies in size, but is commonly thicker than the size of the nucleus (see Fig. 10A, B for basic terminology). Both spongiostromate oncoids, characterised by a micritic, clotted composition, and porostromate oncoids, with recognisable structural remains from microbes (e.g. *Girvanella*), are present in this facies. Micritic layers and *Girvanella* also co-occur. The oncoids are mostly poorly laminated, but lamination of type C and R arrangement (Fig. 10; cf. Flügel 2004, fig. 4.15), can be observed. Spherical or sub-spherical ooids of both normal and superficial type are locally present (Fig. 11A). The laminae are radial and radial-concentric; some of the radial-concentric ooids have micritic laminae incorporated (cf. Flügel 2004). A recrystallisation of the original micrite and cement has occurred, commonly displaying an inequigranular hypidiotopic fabric (Fig. 11A; cf. Flügel 2004, fig. 7.20).

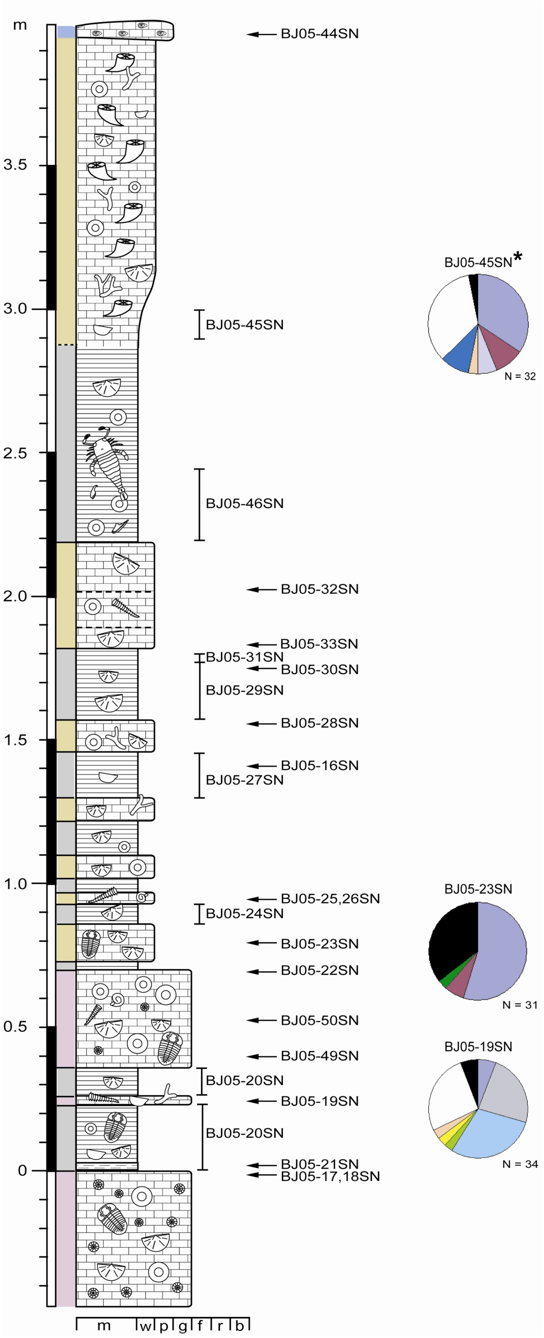

Fig. 6. The profiled stratigraphy at Section 2 and fossil assemblage pie-diagrams, counting made in the smaller square is indicated by an asterix, for legend see Fig. 5.

In addition to the oncoids and ooids, a few shell fragments and bryozoans (e.g. *Ptilodyctia lanceolata*) occur.

4.1.2 Skeletal Wackestone Facies

The skeletal wackestone facies occurs as thin to thick beds that commonly pinch out laterally, interfingering with the calcareous mudstone facies (Figs. 5-7). The beds can split along argillaceous levels creating a more stratified, occasionally almost shaly, appearance. This facies contains calcifying cyanobacteria, most of which can be assigned to *Girvanella*. The microbialites (cf. Riding 2000) often enclose grains, creating oncoids with coatings normally thicker at one side (Fig. 11B). The original micrite has undergone aggrading neomorphism, creating coarser crystals. The siliciclastic contents include a small amount of mica and quartz in a varied, locally high, amount.

The samples examined from this facies bear little signs of transport with generally whole fossils without preferred orientations. The most common fossils, as shown by the pie-diagrams (Figs. 5, 6), are brachiopods and crinoids. Other fossils recorded include trilobites, tentaculitids, bryozoans, scolecodonts, and sponges. Solitary rugose corals, with lengths ranging up to ~10 cm (Fig. 8E), occur in great abundance in a specific interval (at approximately 0.9–1.85 m in Section 1, 2.9–3.9 m in Section 2, and 3.3–3.8 m in Section 3; Figs. 5-7). This depositional facies contains variations in the fauna that seem to reflect successive assemblages within the facies. The studied thin-sections reveal bioturbation including burrows and micrite envelopes.

4.1.3 Calcareous Mudstone Facies

The calcareous mudstone facies consists of mudstone with varying calcium carbonate contents. The facies normally appears as shale with laminae varying from thin to thick. The original micrite has been recrystallised through aggrading neomorphism. Coarser siliciclastic material present includes quartz and mica in small amounts.

The sparse fossil content shows no preferred orientation and no or little sign of transport. The investigated samples reflect a generally low diversity benthic fauna with few epifaunal components. The element counting shows that the overall most common fossils in this facies are brachiopods and ostracodes (Figs. 5, 7). Trilobites, fragments of crinoids and scolecodonts are generally found. Bivalves, tentaculitids, cornularids, bryozoans, and fragments of eurypterids occur in small amounts (Figs. 5-7). Bioturbation is normally sparse but can at some levels be seen as incorporated patches of packstone.

4.1.4 Oolithic Packstone-Grainstone Facies

The oolithic packstone-grainstone facies appears as laterally continuous, thin to thick beds, but a minor lateral change in thickness is noted and it can be assumed that this unit pinch out at a low angel. Many of the grains exhibit a thin microbial coating (Fig. 11C, D) and can therefore be considered as superficial micro-oncoids (<2 mm). Present microbials include calci-

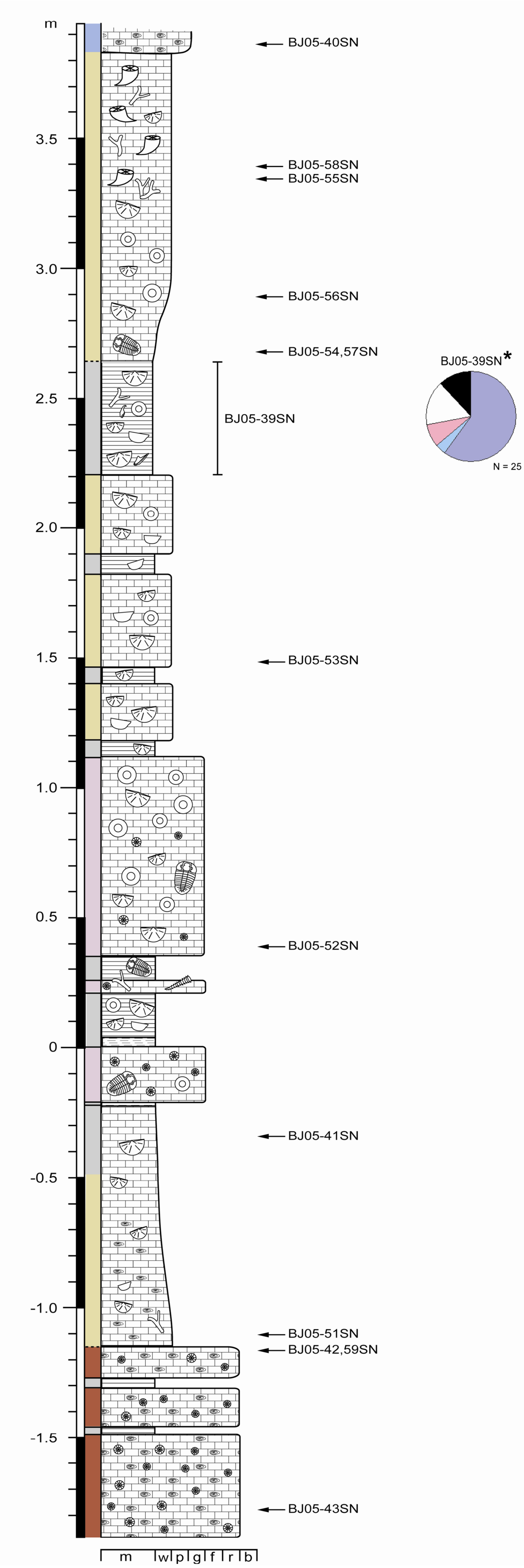

Fig. 7. The profiled stratigraphy at Section 3 and fossil assemblage pie-diagram with counting made in the smaller square, for legend see Fig. 5.

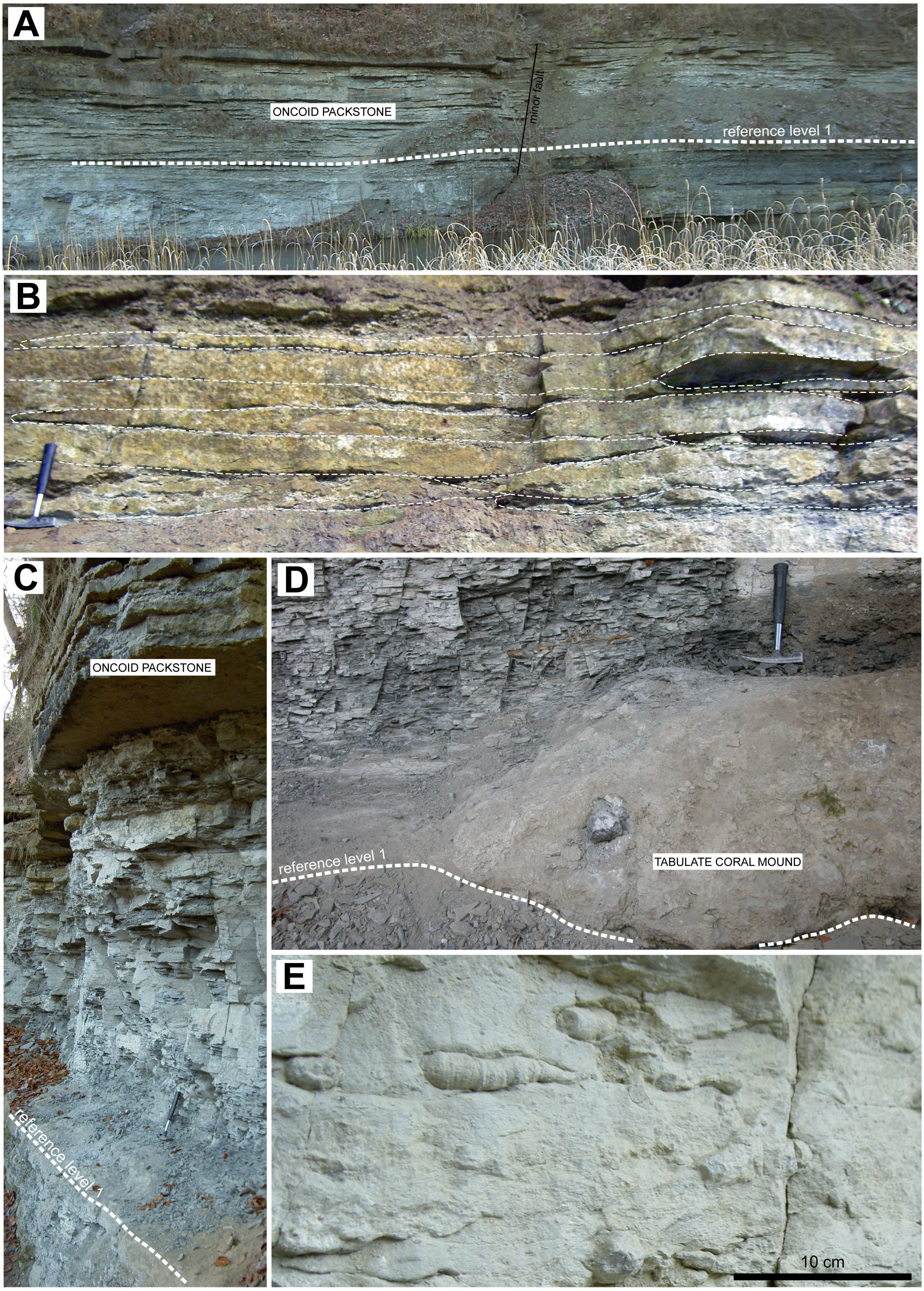

Fig. 8. Photographical plate with pictures taken at, or close to, Section 1. **A.** Reference level 1 and geometry of the oncoid packstone beds east of Section 1. A minor fault is indicated with thin black line. **B.** The oncoid packstone facies; the beds, with a clear pinch-out geometry, are indicated by dashed lines. Geological hammer for scale. **C.** Section 1 showing the oncoid packstone facies and reference level 1, hammer for scale. **D.** Reference level 1 with distinct tabulate coral mound on top of the reference surface (coral boundstone facies). Note that shale is overlying the mound. Hammer for scale. **E.** Rugose corals at the level within the skeletal wackestone facies abundant in these fossils.

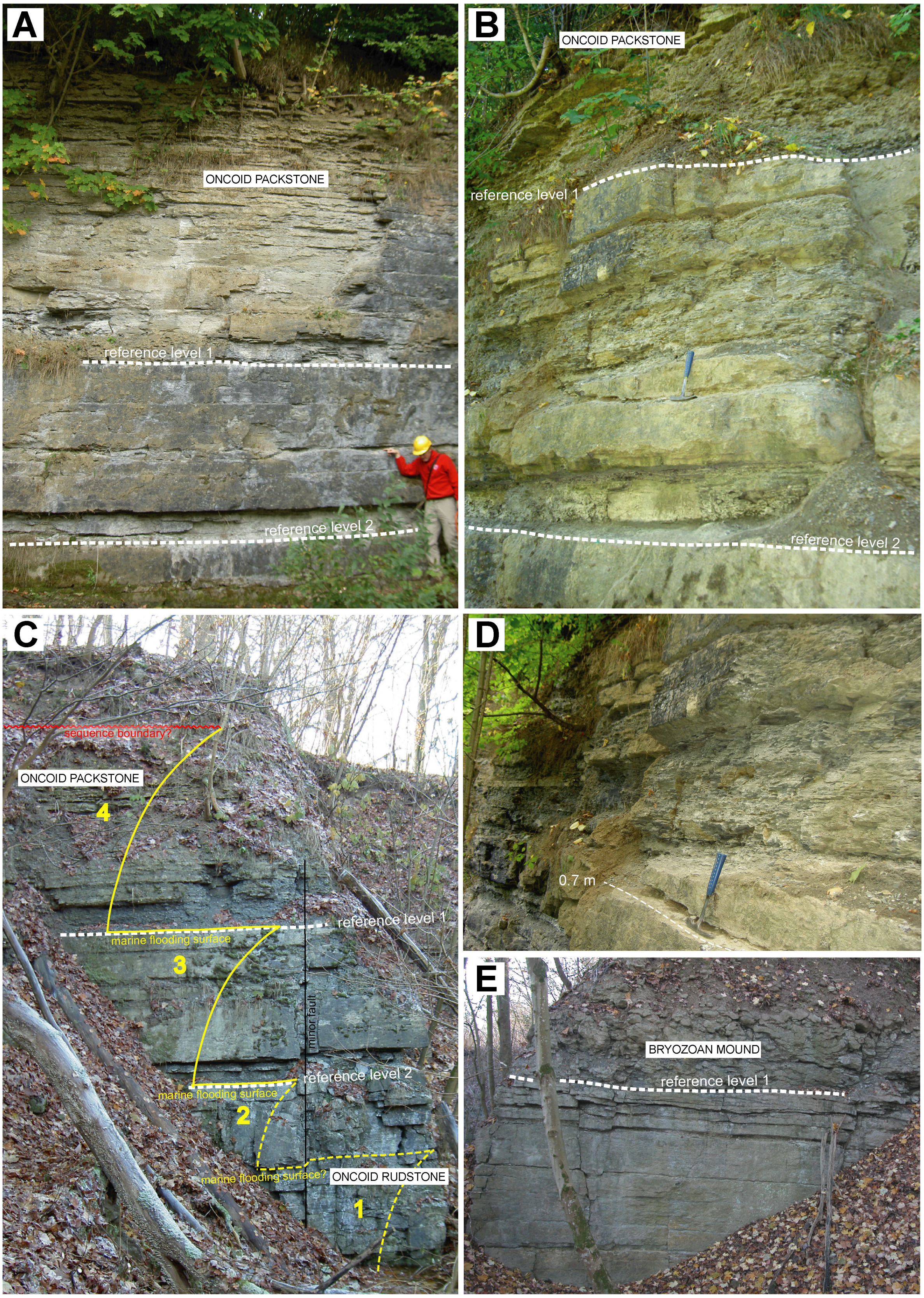

Fig. 9. Photographical plate with pictures taken at, or close to, sections 2 and 3. **A.** Southeast of Section 2, showing the oncoid packstone facies and reference levels 1 and 2. **B.** Section 2, showing the reference levels 1 and 2 and the oncoid packstone facies. Geological hammer for scale. **C.** Section 3, reference levels 1 and 2 and oncoid packstone- and rudstone facies are labelled. A minor fault is indicated with thin black line. The interpreted sequence stratigraphical framework is shown in yellow and in red for the suggested level for a sequence boundary. **D.** Section 2, level 0.7 m is shown with dashed line, note the hammer for scale. **E.** North of Section 3 showing reference level 1 with a large bryozoan mound on top.

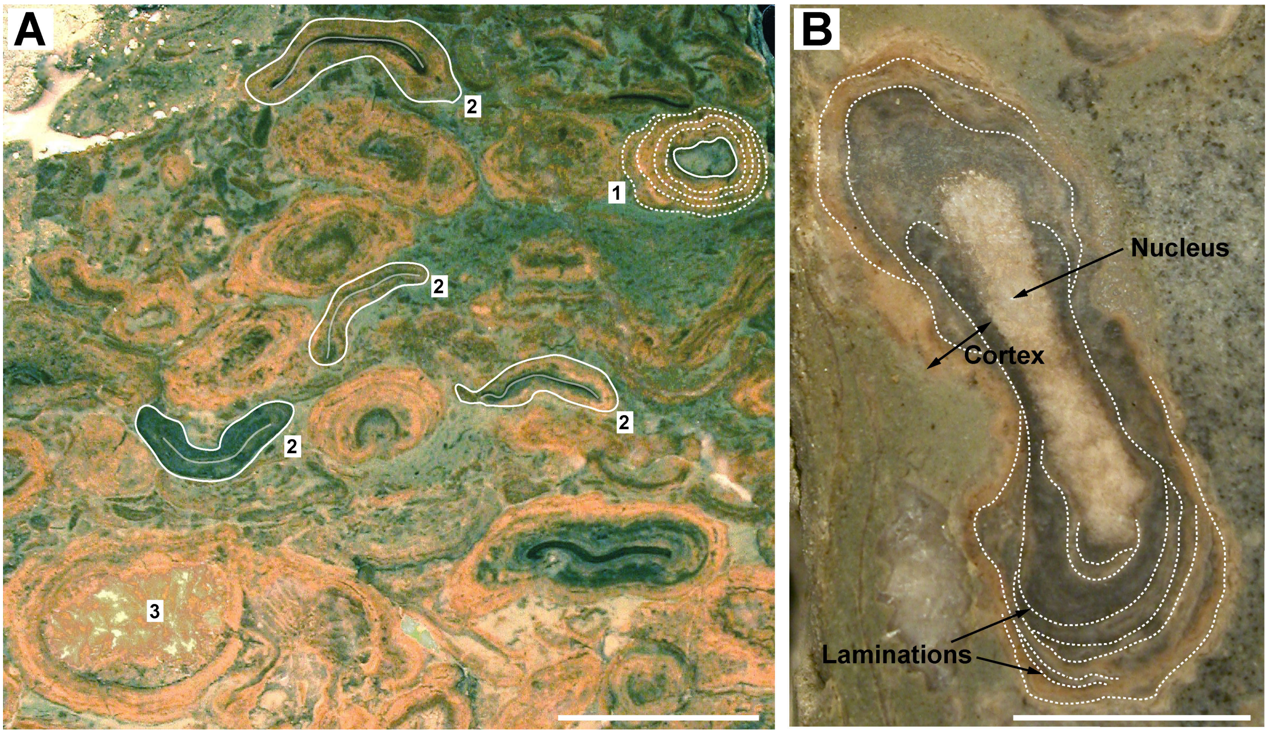

Fig. 10. Polished slabs from the two oncoid facies recorded in the Bjärsjölagård quarry. **A.** Slab from the oncoid rudstone facies showing: **1** typical oncoid with lamination in type C arrangement, **2** oncoids with irregular outer shape formed by irregular nucleus, **3** oncoid nucleus with cement infilling. Scale-bar 1.0 cm. **B.** Slab from the oncoid packstone facies showing basic oncoid terminology for an oncoid with lamination in type R arrangement. Scale-bar 0.5 cm.

fied cyanobacteria (e.g. *Girvanella*; Fig. 11E). The facies contains algae, commonly green but also a few specimens of red algae, and peloids in abundance. Single, and a small number of compound, spherical or sub-spherical ooids are locally abundant (Fig. 11D). They are usually of normal type with a radial-concentric structure of the laminae, but superficial ooids and radial structure also occur (cf. Flügel 2004). The original structure has undergone neomorphic processes that has led to crystal growth (Fig. 11D). A low-level dolomitisation can be interpreted from the presence of a small amount of dolomite crystals. The siliciclastic mineral content, that occasionally displays a preferred orientation, includes a few mica-grains and locally relatively large amounts of quartz.

This facies is rich in body fossils but with local variations in dominating group/s. The skeletal material is disarticulated and abraded from transport. Fossils identified include brachiopods, crinoids, tentaculitids, bryozoans, trilobites, corals, cornulitids, gastropods, and ostracodes (Figs. 6, 7). The pie-diagram (Fig. 6) indicates that bryozoans and ostracodes are most common, but the large amount of shell fragments is likely due to a high abundance also of brachiopods. The fossil assemblage reflected is of high diversity with tiering in several levels. Signs of bioturbation include grey, matrix-rich parts of endichnial borings.

4.1.5 Coral Boundstone Facies

The coral boundstone facies is only found in Section 1 directly above the reference level (Fig. 5). It is composed of one bed, varying from thin to medium in thickness, and on top of this there are small-scale, isolated mounds, ranging from less than 0.2 m up to approximately 1.0 m in diameter, creating an undulating surface (Fig. 8D). These mounds are built up by a framework of, ~10 cm high, tabulate corals. Smaller tabulate corals, a few centimetres in diameter, also form a significant component. Microbials, generally *Girvanella*, occur in a high abundance, often filling voids between the colonial skeletons of larger corals (Fig. 11F). The texture of the facies varies laterally. The bed acting as "foundation" for the mounds is more argillaceous and contains fewer fossils than the mounds. Detrital mica and quartz occur in small amounts.

The investigated samples from the mounds show that the fossil content is rich and reflects a diverse fauna with tiering from both in- to epifauna. The assemblages include solitary brachiopods and sessile suspension feeders such as stalked crinoids, colonial bryozoans, tabulate corals, and siliceous sponges. The fauna in the "foundation" bed is not as diverse and includes brachiopods, tentaculitids, and crinoids.

4.1.6 Oncoid Packstone Facies

The oncoid packstone facies is composed of thin to medium bedded oncoid-rich packstone alternating with generally thin mudstone layers (Figs. 5-7). It consists of cross-stratified bedsets with individual beds extend-

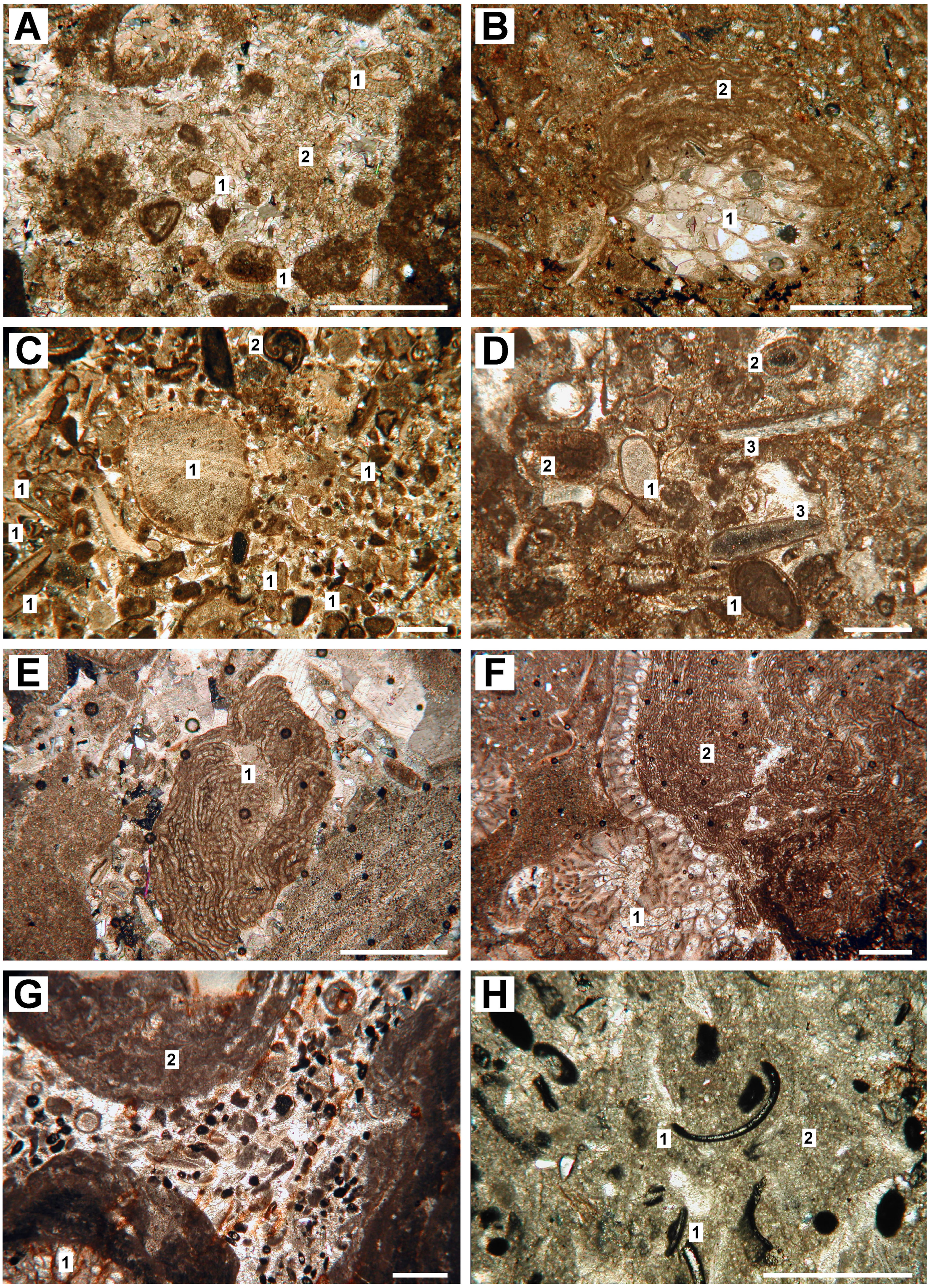

Fig. 11. Photomicrographs of studied thin-sections; the scale-bars are 0.5 mm. **A.** The oncoid rudstone facies, sample BJ05-43SN, showing **1** normal radial ooids, **2** recrystallised matrix (dolomite?). **B.** The skeletal wackestone facies, sample BJ05-28SN, showing an oncoid with a bryozoan nucleus (**1**) coated on one side by *Girvanella* (**2**). **C-E** The oolithic packstone-grainstone facies; **C.** from sample BJ05-22SN with a domination of crinoidal debris (**1**), a gastropod is marked with **2**; **D.** from sample BJ05-18SN showing **1** superficial ooids with radial-concentric structure **2** normal ooids with radial-concentric structure, the left is somewhat recrystallised **3** grains with distinct thin microbial coatings; **E.** from sample BJ05-22SN showing *Girvanella* (**1**) occurring alone. **F.** The coral boundstone facies, sample BJ05-04SN, showing tabulate coral (**1**) filled with *Girvanella* (**2**). **G, H.** The oncoid packstone facies, sample BJ05-09SN; **G. 1** bryozoan nucleus, **2** *Girvanella* cortex; **H. 1** indicates bioturbation preserved as small iron-peloids where the shape of the original shell can be clearly seen, **2** recrystallised matrix (dolomite?).

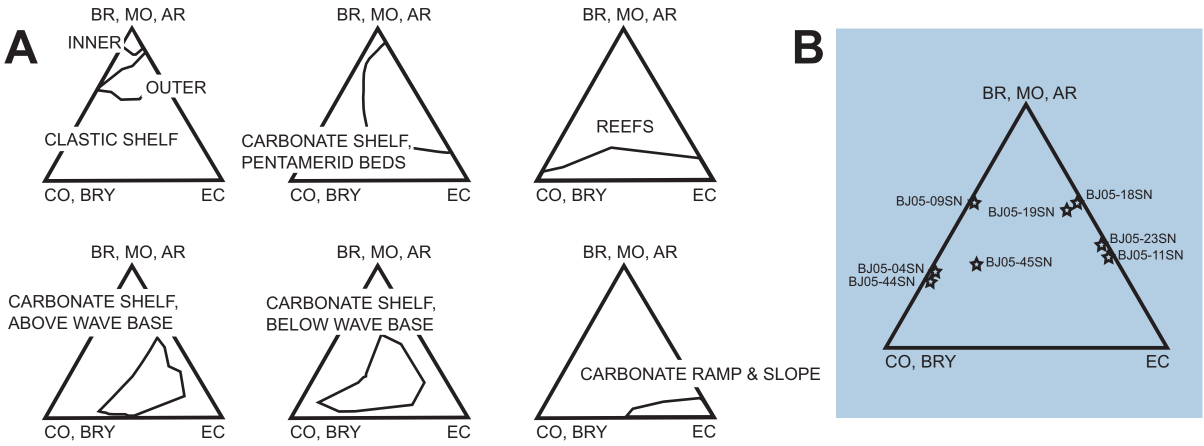

Fig. 12. **A.** A model for comparison between skeletal composition and sedimentary environments on a shelf (modified from Watkins 1996). For abbreviations, see text (section 3). **B.** The result of the point-counting plotted in a three-axis diagram.

ing laterally a few metres (approximately 3–5 m), pinching out in a low angle (Fig. 8B). The facies is more argillaceous in the lower parts but limestone beds rapidly increase and become dominant upwards. The oncoids present range in size from micro (<2 mm) to meso-oncoids (2–10 mm) with a domination of the latter. The cortex often displays a rough surface and a variation in thickness around the nucleus (Figs. 10B, 11G). Where lamination can be distinguished the oncoids can be subdivided into the geometric types C and R (Fig. 10; cf. Flügel 2004, fig. 4.15). Some grains are only coated on one side; calcified cyanobacteria (e.g. *Girvanella*) also occur separately. Disarticulated shells and bryozoans commonly constitute the nucleus of the oncoids, giving them an irregular appearance. Some whole shell fragments acting as nuclei are filled with matrix. The beds from this facies have undergone neomorphic processes. The most fine-grained mosaic (Fig. 11H) probably has its origin in micrite, which gives the facies a depositional packstone epithet. The recrystallised matrix and cement display an inequigranular hypidiotopic fabric (cf. Flügel 2004, fig. 7.20). The mineral content includes very small amounts of siliciclastic mica and quartz.

Besides oncoids this facies includes bryozoans, tabulate corals, trilobites, brachiopods, and crinoids. Bioturbation in skeletal grains by endolithic cyanobacteria (Golubic et al. 1981) is preserved as small iron-peloids (cf. Stockfors & Peel 2005). This feature, seen as µm-sized black dots, is locally very abundant (Fig. 11G, H).

4.2 Skeletal composition

Different depositional settings on a shallow-marine shelf are characterised by different faunal assemblages, and thus they have different skeletal compositions. Watkins (1996) created a model in which he connected particular skeletal compositions to their most common shelf settings (Fig. 12A; Watkins 1996). In order to compare the depositional facies of this study, described above, with the environments calculated in the model, eight samples from four of the facies were point-counted. The counting of the skeletal composition was based on a subdivision into three major faunal associations (slightly modified from Watkins 1996). The result was plotted on a three-axis diagram, shown in Fig. 12B. For a complete disquisition on the counted samples, see appendix.

Because the samples usually only contained elements from two of the three fossil groups the points generally ended up along the sides of the diagram. Samples BJ05-18SN and BJ05-19SN that belong to the oolithic packstone-grainstone facies plotted closely together in the diagram. From the skeletal wackestone facies three samples were counted (BJ05-11SN, BJ05-23SN, and BJ05-45SN), and ended up having a larger spread than the former two. The two samples BJ05-04SN and BJ05-44SN, representing the coral boundstone and the oncoid packstone facies, respectively, plotted close to each other and furthest towards the coral-bryozoan axis. Another sample from the oncoid packstone facies, BJ05-09SN, ended up closer to the brachiopod-mollusc-arthropod axis.

4.3 Faunal content and diversity

Faunal information was obtained from field observations, petrographical studies, and investigations of samples and slab surfaces under a binocular light microscope. The results are incorporated into the logs (Figs. 5-7) in order to indicate the general composition of the faunal assemblages occurring through the sections. For statistic information, elements were counted on sample surfaces and slabs. The results obtained are presented as faunal pie-diagrams in these figures.

The six depositional facies include fossils of both vagile and sessile organisms. The faunal assemblages present are of different composition and they display different degrees of tiering. Brachiopods comprise one of the most abundant fossil groups in all the described facies. The investigated samples show that *Atrypa* and *Howellella* are the most frequently occurring genera, but rare *Craniops* specimens have also been identified.

Another common fossil group present is the trilobites, e.g. members of the genus *Calymene*. Other solitary, vagile organisms present include locally abundant ostracodes (commonly *Hermannina* sp. but also *Beyrichia* sp.), rare bivalves (e.g. *Cardiola*), and a few cornularids. Scolecodonts, all belonging to the paulinitid genus *Kettnerites*, were observed, generally in the more argillaceous levels. Paulinitids were one of the most abundant and diverse Silurian polychaete families but also other representatives have been reported from Bjärsjölagård (Eriksson 2002; Eriksson et al. 2004). Observed tentaculitids, which were suspension feeding, more stationary organisms than the above, have been identified as belonging to two species; *Tentaculites hisingeri* and *Lonchidium scanicus*. For a detailed account of tentaculitid species in the Bjärsjölagård area, see Larsson (1979). Conodonts from Bjärsjölagård have been reported by Jeppsson (1974) and Jeppsson & Laufeld (1986), in which the strata from the quarry have been assigned to the *Ozarkodina wimani* fauna. The samples investigated by Jeppsson (1974) comprise five species, of which *O. scanica* occurred most frequently. Still unpublished conodont data of Jeppsson from the quarry are discussed in section 5.5.

Sessile organisms identified from the samples include bryozoans, locally in abundance, and much rarer, parts from siliceous sponges, and a few cornulitids. Further to the northwest from the measured sections a large bryozoan mound has been identified above reference level 1 (Fig. 9E). Crinoids are locally abundant and stems of both pentameric and holomeric types occur, in some specimens a symplexial articulation (cf. Donovan 1989, fig. 1) can be observed. The amount of crinoidal debris increase along the outcrop towards the northwest. Corals (both tabulate and rugose) occur to different extends, the greatest amounts are, however, restricted to specific intervals (Figs. 5-7).

For an historical review of works made until 1986 regarding the Bjärsjölagård Limestone Member and its fossil content, see Jeppsson & Laufeld (1986) and references therein.

5. Discussion

The facies and the faunal information described above enable an interpretation of the depositional environment (discussed in section 5.3). This is of specific interest since the strata formed during a time-interval related to an extensive ecological crisis, the Lau Event (section 5.4). The position of the rocks in Bjärsjölagård within the stratigraphy of Skåne (section 5.2) and its correlation to Gotland, and other parts of the world (section 5.5), is therefore central to increase our knowledge about this Silurian event. In addition, this period in time is coupled with major sea-level changes in the Baltic Basin, why an attempt at a sequence stratigraphical interpretation is made, in order to improve the understanding of the basin evolution (sections 5.6, 5.7).

5.1 Stratigraphical correlations within the quarry

The oncoid packstone facies is easily traced laterally in the quarry (Figs. 8, 9) and made correlations between the three sections upper parts unproblematic (Fig. 13A). Between sections 1 and 2 a dolorite dyke is present and faulting has occurred (creating a soil-talus), complicating the stratigraphical correlations. By following the marker beds (reference levels 1 and 2 in Figs. 8, 9) and estimating the vertical displacement associated with the fault, a further correlation between sections 1 and 2 was, however, achieved during the fieldwork. This was later confirmed by the established profiles that shows that the same succession of facies occur in all sections in the interval between the uppermost correlations (between 0– ~1.85 m in Section 1, ~2.2–3.9 m in Section 2, and ~2.2–3.8 m in Section 3; Figs. 5-7). Also between sections 2 and 3 minor faulting has occurred, but the close location of the profiles made their correlation uncomplicated. The reference level in Section 2 (i.e. reference level 2 in Figs. 8, 9) was easily found also in Section 3 because the same facies enclose it in both these sections. In addition a thin (2–3 cm), laterally extensive, very argillaceous layer (bentonite?) is present just above this reference level, which was used to confirm this lowermost correlation. The wackestone bed at ~2.0 m in Section 2, already correlated with the marker bed in Section 1 (representing reference level 1), was followed along the wall and the top of it was found at approximately the same height (~2.2 m) above the reference level (i.e. reference level 2) in Section 3.

5.2 Stratigraphical correlation with the Bh 2 drill-core

The complete Bjärsjölagård Limestone Member is only known from two drill-cores. Of these, the Bjärsjölagårdborrningen 1 (Bh 1), taken in the southeast part of the investigated quarry (Fig. 2C; Larsson 1979), lacks the uppermost parts exposed in the quarry. The entire member is only known from the Bjärsjölagårdborrningen 2 (Bh 2) drill-core, taken ca 175 m southeast of the quarry's groundwater lake (Fig. 2C; Larsson 1979). In this core the member can be subdivided into three distinct units. The lowermost (~17 m) and the uppermost (~4 m) units are composed of oncoid-rich limestone. The unit (~4 m) between these comprises mudstone and calcareous mudstone (cf. Wigforss-Lange 1999, fig. 4). The oncoid-rich uppermost limestone unit is well exposed and easily distinguished in the outcrop at Bjärsjölagård. Sampling from Section 3 disclosed that the lowermost oncoid-rich unit occurs also in the bottom of the quarry. This observation results in a good correlation between the exposures in the quarry and the drill-core (Fig. 13). Based on this observation it can be concluded that the thickness of the strata between the oncoid-rich limestone units change only insignificantly between the location for the Bh 2 drill-core and the quarry.

5.3 Depositional environment

The lithosomes enclosing the Bjärsjölagård Limestone Member are dominated by siliciclastic strata. Accordingly the deposits in the Bjärsjölagård quarry and the coeval strata at Klinta represent a time of increase in carbonate formation in this part of the basin. Carbonate sedimentation is controlled by many factors, e.g. temperature, salinity, water depth, and siliciclastic input, but can form anywhere in the world (Tucker 2001). The productivity though, is highest in warm, shallow, agitated waters of normal salinity, and thus the most extensive times of production are correlated with global sea-level highstands, increasing the area of shallow epicontinental seas, like the Silurian Baltic Basin. Despite the increase in calcium carbonate contents, the terrigenous component of the Bjärsjölagård Limestone Member is still considerable and the limestone beds are mostly argillaceous and interbedded with calcareous mudstone. Thus the setting can not be described as a classic carbonate platform; it is rather representative of a mixed carbonate-siliciclastic inner shelf environment, where the unusually high abundance of microbes implies an ecologically stressed situation (e.g. Schubert & Bottjer 1992; Whalen et al. 2002; Pruss et al. 2004). A mixed carbonate-siliciclastic setting is further supported by the analysis of the skeletal composition (Fig. 12B). According to the model (Fig. 12A; Watkins 1996), the typical siliciclastic shelf has a composition matching the percentages in the top-part of the triangle, and the environment with the highest carbonate productivity, i.e. reefs, is found in the bottom. In Bjärsjölagård all the point-counted samples end up in the middle of the triangle, indicating a mixed setting.

On a smaller scale, the strata are characterised by compositional heterogeneity, as the ~6.5 m of stratigraphy investigated are subdivided into as much as six depositional facies. These facies reflect a great variation in water-energy levels, from mudstone deposited in sheltered low-energy environments to lithologies poor in matrix, such as the packstone-grainstone and the rudstone, formed in high-energy environments. A heterogenic setting is also proposed by Fig. 12B, in which the skeletal composition shows a significant spread. Because there are no signs of the strata being particularly condensed, the depositional environment is interpreted as having been relatively easily shifting, something that can be indicative for settings at various depths. A deeper environment accountable for forming variable strata is e.g. the position close to the fair-weather wave-base on a homoclinal ramp, where even small-scale relative sea-level changes alter the facies formed. An interpretation of a deeper setting however lacks support from both the type of facies associations and fauna. In an explanation based on a generally shallow environment the depositional facies and energy levels are mostly dependent on small topographic differences instead of sea-level changes. A shallow depositional depth for the Bjärsjölagård Limestone Member is supported by several factors, including bed geometry, faunal contents and geometric distribution of fauna and facies. In the quarry the composition of the beds often vary laterally (e.g. the amount of crinoidal debris in the oolithic packstone-grainstone facies that seems to increase towards the northwest), and the calcareous mudstone facies and the wackestone facies beds interfinger over short distances; a deeper setting is likely to have a more pronounced lateral homogeneity. In further environmental interpretations two grain types, ooids and oncoids, are of particular importance.

5.3.1 Ooids

The origin of ooids is still uncertain, but the common view is that warm, very shallow, normally agitated waters, supersaturated with respect to $CaCO_3$, can lead to their precipitation (Simone 1981). Ooids, present in the oolithic packstone-grainstone facies and the oncoid rudstone facies (Fig. 11A, D), can therefore be valuable palaeoenvironmental indicators, but the transport possibility must be taken into consideration (Simone 1981). Because many other factors indicate that the depositional setting was shallow, the ooids present probably formed, if not here, in relatively close vicinity. Consequently the ooids can be used to suggest a depositional environment. Based on the morphological types (radial and radial concentric, some with micritic laminae incorporated) one interpretation is that they were formed in a relatively calm, shallow marine to lagoon-like environment varying from possibly brackish to restricted in salinity (cf. Flügel 2004, fig. 4.26).

5.3.2 Oncoids

Oncoids have generally been believed to indicate high energy, a simplification that does not hold. Today oncoids are believed to form in a range of settings, which can make them useful in palaeoenvironmental interpretations (Flügel 2004). Descriptions and categorisation (e.g. according to size, composition, and geometric types) are helpful in determining plausible environments. The Bjärsjölagård Limestone Member contains an unusual high abundance of microbial facies, which is most importantly indicative of stressed conditions (e.g. Schubert & Bottjer 1992; Whalen et al. 2002); this relationship is further discussed in section 5.7. The oncoids present are often large (meso to macro in size) with irregular outer margins (Fig. 11G), and sometimes with coating on only one side (Fig. 11B). These features all suggest at least periods of stationary growth in low-energy waters. This is further supported by the coexistence of many whole fossils, especially in the oncoid packstone facies. Both spongiostromate- and *Girvanella*-dominated oncoids occur. Peryt (1981) suggested a general situation in which spongiostromate oncoids mainly form in lacustrine and transi-

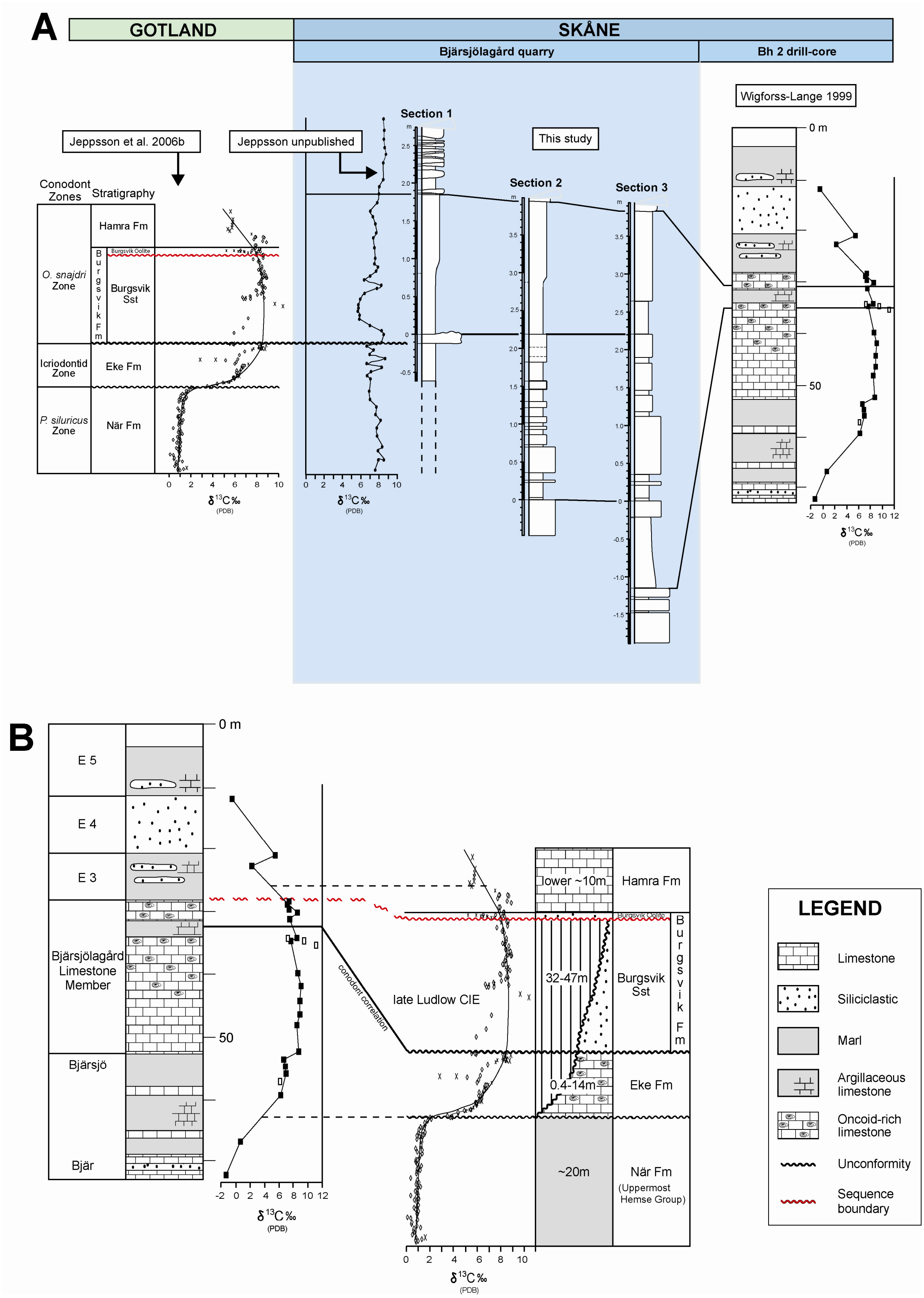

Fig. 13. Correlation between the studied interval in Skåne and coeval strata of Gotland. **A.** Correlation between the three studied sections, shown in the blue field, together with carbon isotope data from Jeppsson (unpublished). The sections are correlated, to the right, with the Bh 2 drill-core and the carbon isotope data from Wigforss-Lange (1999), and, to the left, with the Gotland stratigraphy and carbon isotope data from Jeppsson et al. (2006b, X=data from Gotland and ◊=data from Australia). Conodont data are from Jeppsson (pers. comm. 2005). **B.** An intrabasinal correlation between Skåne and Gotland based on conodont data from Jeppsson (pers. comm. 2005), carbon isotope data from Skåne (Wigforss-Lange 1999) and Gotland (Jeppsson et al. 2006b), correlation indicated with black dashed lines, and by suggested level for sequence boundary, correlation indicated with red line.

tional continental-marine environments and *Girvanella* oncoids during marine subtidal conditions. In a comparison between the types of oncoids present in Bjärsjölagård and a compilation of case studies in Flügel (2004, fig. 4.17) the "open-marine lagoon" depositional environment was most agreeable.

5.3.3 Salinity

The salinity levels in which the strata in Bjärsjölagård were formed have been discussed by Wigforss-Lange (1999), who noted that the oxygen isotope samples from the Bh 2 drill-core and the outcrop was depleted in the heavier ^{18}O-component (Wigforss-Lange 1999, table 1). Low values can be explained by diagenetic processes, such as recrystallisation, occurring in contact with meteoric or hydrothermal water (Hudson 1977), but also other explanations have been proposed to alter the composition (e.g. Qing & Veizer 1994). Wigforss-Lange (1999) suggested that the fluctuation to less depleted values was caused by restricted water circulation and evaporation creating increased salinity. A shallow environment with topographical differences can be expected to cause local differences in salinity, e.g. by evaporation in a temporarily constricted lagoon. The radial structure appearing in some of the ooids can be interpreted as forming in waters of elevated salinity (for references, see Simone 1981), which supports that view. However, several factors also conflict with an explanatory model for the $\delta^{18}O$ values based on elevated salinity. No cerebroid ooids, which in Klinta have been interpreted as a sign of unusually high salinity conditions (Wigforss-Lange 2006), have been found at Bjärsjölagård. Instead some of the ooids have possibly been formed in brackish conditions; this would rather suggest a coastal environment in which temporarily constricted lagoons could have a lowered salinity due to freshwater influx. Despite smaller local variations, the general conditions in the area are likely to have been normal marine. This is suggested by the fauna between the two oncoid-units, representing normal Silurian ecological assemblages, commonly with several tiering levels (Figs. 5-7). Especially the presence of corals (Fig. 8D, E) indicates that no unusual salinity levels had developed (Vennin et al. 2004). In addition, the fact that small-scale tabulate coral mounds (Fig. 8D), and a larger bryozoan mound (Fig. 9E), were able to build up suggests normal marine conditions in a shallow, low energy setting (e.g. Krainer 1995; Samankassou 2001; Krainer et al. 2003). Furthermore, even though the $\delta^{18}O$ values in Bjärsjölagård fluctuate (Wigforss-Lange 1999, fig. 4), the ^{18}O-component is never more abundant than in the normal Silurian $\delta^{18}O$ values around -6‰ (Popp et al. 1986), which would be expected if the salinity was unusually high. Instead many of the values range beyond the normal spectrum in the other end; they are more depleted in the heavy isotope. This is proposed to be caused by a combination of two factors; diagenetic processes and temporarily lowered salinity. If the suggested coastal setting is responsible for a fresh-water input this could have led to temporarily lowered salinity levels, and a dolomitisation originating in a mixing zone. The recrystallisation of the beds (evident from the studied thin-sections; Fig. 11) is thus likely to have occurred under the influence of meteoric water. Because the conditions are interpreted to generally being normal marine, the diagenetic process is suggested to be the main factor depleting the ^{18}O values, but fresh-water input can be responsible for creating the fluctuations.

5.4 Silurian oceanography and the late Ludlow Lau Event

During the Silurian a pattern of recurrent widespread contemporary changes in the stratigraphical record has been identified. These changes in sediment composition and fauna can be explained by a theoretical model, presented by Jeppsson (1990) and later revised and updated by Jeppsson (1993, 1998) and Cramer et al. (2005). The model is based on alternations between two different states in the ocean-atmosphere system. These states are referred to as primo and secundo episodes and primarily reflect different sources of the oceanic deep-water production. If the climate is dry at low latitudes and warm at high latitudes the main deep-water source would be salinity-dense surface water in mid-latitudes and the condition is described as a secundo episode. If the climate instead is more humid at low latitudes and colder at high latitudes, as today, the deep-water production originates from cold-dense surface water in polar areas and the result is referred to as a primo episode. These relatively long time intervals with stable conditions are interrupted by shorter, unstable intervals, or events. These occur when the oceanic circulation is disturbed and thereby turned on and off (Jeppsson & Aldridge 2000). The unstable conditions are interpreted as resulting in extinctions and faunal turnovers. The model predicts changes in the primary production and the burial of organic carbon, which should have an impact on the stable isotope ratios of carbon.

In the late Ludlow, by the time of deposition of the Bjärsjölagård Limestone Member, the Havdhem Primo and the Hoburgen Secundo episodes are separated by the comparably brief Lau Event (Fig. 1). This event is observed in the stratigraphical record as major ecological changes in carbonate platforms (Calner 2005a) and a varying rate of extinction among e.g. conodonts, polychaetes, and fish (Jeppsson & Aldridge 2000; Eriksson et al. 2004; Nilsson et al. 2005). The event is also characterised by one of the most prominent changes in the stable isotope ratio of carbon during the Phanerozoic. This globally known anomaly reaches $\delta^{13}C$ peak values of +12 ‰ in Australia (Andrew et al. 1994) and approximately +4 ‰ in the USA (Saltzman 2001) and the Czech Republic (Lehnert et al. 2003). In the Baltic Sea region peak values of +5.9 ‰ are recorded from the East Baltic area (Kaljo et al. 1997), ~+8.5 ‰ from Gotland (Samtleben et al. 1996; Jeppsson et al. 2006b; Calner & Eriksson 2006) and up to +11.2 ‰ from the Bjärsjölagård Limestone Member in Skåne (Wigforss-Lange 1999).

5.5 The Bjärsjölagård Limestone Member and the Lau Event

The major anomaly in the $\delta^{13}C$ values has made it possible to identify the Lau Event in several parts of the world. Wigforss-Lange (1999) identified this positive excursion in Skåne at the Bjärsjölagård and Klinta areas. The anomaly is constrained to the Bjärsjö and Bjärsjölagård Limestone members and reaches its peak value, +11.2 ‰, in a stromatolite-sample from the outcrop at Bjärsjölagård (Wigforss-Lange 1999). Still unpublished conodont data confirm that the strata in the quarry and the anomaly are associated with the Lau Event (Jeppsson pers. comm. 2005). Conodont collections from Section 1 in this paper reveal that the strata in the Bjärsjölagård quarry are contemporary with the uppermost part of the Eke, and the Burgsvik formations on Gotland (Fig. 13). Up to the base of the limestone bed underlying the reference level in Section 1 (Figs. 8, 9) the conodont fauna is of low diversity and dominated by a single species; *Ozarkodina scanica*. This level is ascribed to the Upper Icriodontid Subzone (Figs. 1, 13). In the limestone marker bed (-0.12–0 m in Section 1; Fig. 5) the fauna changes and becomes diverse and the upper parts of the sections are instead to be ascribed to the *O. snajdri* Zone (Figs. 1, 13; Jeppsson pers. comm. 2005).

An intrabasinal correlation between Skåne and Gotland can also be made based on the carbon isotope curves (Fig. 13B). Both curves show a major increase of $\delta^{13}C$ values, the onset of the late Ludlow carbon isotope excursion (CIE), a time of more stable high values (a plateau), and finally a decrease, the CIE conclusion. Since changes in carbon isotope values can be considered as simultaneous, the beginning and the end of the CIE can be correlated. In Fig. 13B the conodont correlation, established by Jeppsson (pers. comm. 2005), is also incorporated. This shows that after the onset of the CIE, the succession in Skåne contains an interval within the Icriodontid Zone with high stable $\delta^{13}C$ plateau values that is not present on Gotland.

The Bjärsjölagård Limestone Member and its contemporary deposits in Klinta are distinguished from other Silurian strata in Skåne by their abundance of limestone beds. In these deposits oncoids are present, especially at Bjärsjölagård where they show a mass-occurrence in two units separated by mudstone (cf. Wigforss-Lange 1999, fig. 4). The formation of microbial carbonates is controlled by both biotic and abiotic factors and this has made extensive occurrences of microbialites, as in Bjärsjölagård, unusual in Silurian strata. Earlier, in the Precambrian and the earliest Phanerozoic, microbial mats were common due to e.g. low activity from grazing organisms. When metazoans radiated and grazing organisms became widespread it restricted the growth of microbialites (Schubert & Bottjer 1992). Though, at times of declining metazoan activity, i.e. mass extinction events, microbial carbonates seems to temporary have recovered and increased in productivity (Schubert & Bottjer 1992; Riding 2005). Calner (2005a) suggested that increases of microbialites not only can be related to the major five extinction events of the Phanerozoic, but also to events that taxonomically were less devastating. This conclusion is based on studies on Gotland, where oncoids and stromatolites become abundant in strata formed during the Lau Event. Another important factor controlling microbial carbonate formation is the saturation state of $CaCO_3$ in the water; a high saturation state favours microbialites (Riding 2000, 2005). When these two factors have reinforced one another, i.e. when the metazoan diversity has declined and the saturation state is high, the effect has been the greatest (Riding 2005).

The increase in calcium carbonate formation at Bjärsjölagård and Klinta compared to the rest of the Silurian strata in Skåne is likely due to the regressive trend in the area, which created a warm, shallow sea, ideal for generating limestone deposits. The time interval around 420 Ma is also coincident with a peak in the calculated seawater saturation ratio (Riding 2005; Riding & Liang 2005), which can be considered as another positive feedback for such deposits to form. The ooids, co-existing with oncoids in the oncoid rudstone facies, are a sign of the waters at Bjärsjölagård having been supersaturated in $CaCO_3$. Therefore, at Bjärsjölagård it is probable that both the environmental factor and the coincident with the Lau Event are parts of the explanation for the oncoid mass occurrence. These two factors and which of them that bears the greatest responsibility for the extensive microbial carbonate formations during this time interval are debated (Calner 2005b). In this case the stress caused by the Lau Event is probably the overriding control; otherwise such microbial deposits would likely have been formed also at times not directly correlated with the event.

5.6 Sea-level changes and the use of sequence stratigraphy in Bjärsjölagård

The sedimentary environments and thereby the type of facies deposited are affected by several factors. In the formation of carbonate sediments the position of the relative sea-level is the key aspect. This is a complex feature controlled by many processes, of which climate and tectonics are considered the major two (Coe 2003). The changes in sea-level can be regional, e.g. caused by an increase in subsidence rate, as during the Silurian in the part of the Baltic Basin where Skåne was situated, or global (i.e. eustatic), e.g. due to the closure of the Iapetus Ocean. Sea-level changes can also be subdivided into five different orders depending on the time-scale at which they operate (Miall 1997; Coe 2003). The global sea-level curve is based on first-order alternations (~50–200 Myr), caused by the continental drift creating long-term changes. Times of extensive formation of limestone can generally be related to highstands in this curve, e.g. in the Ordovician and the Cretaceous. In basins, second- and third-order alternations (~0.2–50 Myr) are more directly responsible for the resulting sedimentary architecture. Changes within these magnitudes create depositional sequences separated by unconformities and their correlative conformities. The depositional sequences consists of sedimentary facies, commonly appearing in a specific and predictable pattern, reflecting different stages, systems tracts, in a relative sea-level curve (Fig. 14). The four systems tracts (falling stage systems tract, lowstand systems tract, transgressive systems tract, and highstand systems tract) are all separated by stratigraphically important surfaces, helpful in the subdivision. Sea-level changes of the fourth- and fifth-order (~10–200 kyr) are responsible for metre-scale cycles seen in the sediments referred to as parasequences. These constitute beds in shallowing-upwards successions of varying thicknesses (decimetres to tens of metres), separated by marine flooding surfaces. Their formation is often ascribed to Milankovitch cycles, especially in carbonate basins (Tucker 2001). Parasequences thus represent short-term, sea-level changes that superimpose the more long-term changes represented by the four different systems tracts (Fig. 14). Due to the prediction possibility, sequence stratigraphy is a tool useful in describing the evolution of a basin.

The Baltic Basin covered a wide area, and different parts evolved differently depending on depth and position in relation to the active margins (Fig. 4). Regardless of this, evidence for a few correlated sea-level changes, of the magnitude and rapidity required to outpace subsidence, has been identified in different parts of the basin. One of these took place during the late Ludlow and is marked by unconformities in Estonia (Jeppsson et al. 1994) and on Gotland (Cherns 1982; Calner & Eriksson 2006). This time interval is in Skåne represented by the Bjärsjölagård Limestone Member and its enclosing lithosomes (Fig. 1), but in these strata no clear erosional surface or hiatus has yet been identified. An identification of a sequence boundary (SB), which is representative of a major sea-level fall, within this time interval would enable better parallels to be drawn between Skåne and other areas and thus give a more complete picture of the evolution of the Baltic Basin.

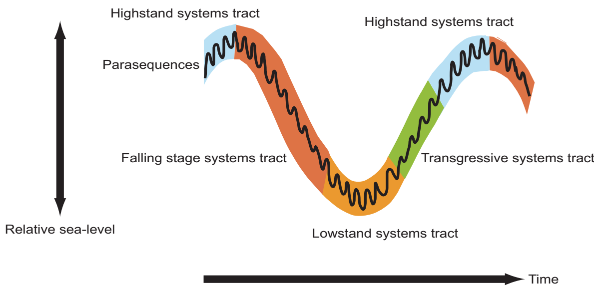

Fig. 14. Basic sequence stratigraphical terminology (after Coe 2003).

5.7 A sequence stratigraphical framework for the Bjärsjölagård Limestone Member

The profiled stratigraphy from the Bjärsjölagård quarry is ~6.5 m; consequently it is evidence for short-term sea-level changes (fourth- and fifth order) that primarily can be expected. In the sediments such changes are seen as parasequences interrupted by marine flooding surfaces. In Bjärsjölagård there are parts of possibly four parasequences present. Two levels, coincidental with the two reference levels, are interpreted as marine flooding surfaces. These are seen as calcareous mudstone distinctly overlying sediments with much higher calcium carbonate - and skeletal grain contents (Fig. 9A-C). In addition, the level above the lowermost oncoid-rich unit probably represents a marine flooding surface (Fig. 9C). Such an interpretation is supported by the distinct transition to a more argillaceous unit seen in the Bh 2 drill-core (Fig. 13), but this is not clearly evident in the field. Two, or probably three, complete parasequences are, however, generally not enough for determining what type of stacking pattern they form part of. For an idea on the direction of the sea-levels at a larger scale, the enclosing stratigraphy known from the Bh 2 drill-core (Fig. 13) also has to be taken into consideration. This shows that the Bjärsjölagård Limestone Member is characterised by high limestone contents with a successive increase of microbial facies, which suggests that it represents a relative regression within a falling stage systems tract. The more argillaceous unit in the upper part of the member, exposed in the quarry, is probably a phenomenon depending on local conditions. A sequence boundary forms when the relative sea-level drops and areas therefore become subaerially exposed. On Gotland a SB, coincident with the late Ludlow CIEs decline, is found at the bottom of the Burgsvik Oolite (Fig. 13; Calner & Eriksson 2006). These types of major sea-level lowstands are laterally extensive, and a correlative SB can be expected in Skåne, that was a part of the same palaeobasin. Since the sea-level fall is interpreted as being a consequence of a substantial forced regression the SB can also be expected to be time-equal. Because the SB identified on Gotland coincides with a decrease in the stable isotope ratio of carbon, which also is considered simultaneous, the SB in Skåne can be predicted to occur where the $\delta^{13}C$ values starts to decline towards normal values. The SB is therefore correlated with the Bjärsjölagård Limestone Member-E 3 boundary, not yet identified in the field (Fig. 13). This correlation is based on the decreasing of $\delta^{13}C$ values, starting in the E 3 unit, and that the level coincides with a change to a more argillaceous, possibly transgressive unit. Such a transition is not only evident from the Bh 2 drill-core; it is also indicated by the vegetation-covered top surface of the quarry, indicating the former presence of easily eroded mudstone, coeval with the boundary.

6. Conclusions

The results in this study led to the following conclusions:

- The strata exposed in Bjärsjölagård could be subdivided into six depositional facies; oncoid rudstone, skeletal wackestone, calcareous mudstone, oolithic packstone-grainstone, coral boundstone, and oncoid packstone.
- The lithological and faunal information suggest a coastal environment on a mixed carbonate-siliciclastic shelf. The setting is interpreted as an open-marine lagoon of generally normal salinity, possibly with fluctuations caused by fresh-water input.
- The major part of the stratigraphy exposed in the Bjärsjölagård quarry contains fossils that reflect normal Silurian ecological assemblages with tiering in several levels. The two enclosing oncoid-rich units imply an ecologically stressed situation possibly related to the Lau Event.
- An intrabasinal correlation between Skåne and Gotland has been made based on available conodont- and carbon isotope data and a suggested sequence stratigraphical framework. This correlation implicates that the regression coeval with the CIE onset on Gotland, occurred later in Skåne (a coincident that probably is depth-related).

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Appendix

Table showing the point-counted samples, their depositional facies, and the number of counted points.

Sample number	Depositional facies	Number of counted points
BJ05-11SN	Skeletal wackestone	65
BJ05-23SN	Skeletal wackestone	300
BJ05-45SN	Skeletal wackestone	300
BJ05-18SN	Oolithic packstone-grainstone	85
BJ05-19SN	Oolithic packstone-grainstone	156
BJ05-04SN	Coral boundstone	174
BJ05-09SN	Oncoid packstone	170
BJ05-44SN	Oncoid packstone	300

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