An interpretation of oncoid mass-occurrence during the Late Silurian Lau Event, Gotland, Sweden

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Cover Picture: An oncoid from Ronehamn, Gotland.

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Abstract: The geological significance of the microbial-formed oncoid is not as well understood as the recognized, analogous stromatolite but can, as well be used as an environmental indicator. In association with the larger Phanerozoic mass extinctions, a resurgence of microbialites as a disaster fauna is at present an accepted view. The same model, however, is under debate concerning whether or not it can be applied to *minor* extinction events such as the Lau Event, a coupled extinction-isotopic event recorded from Late Silurian. The Lau Event displays one of the largest positive carbon isotope excursions (CIE) during the entire Phanerozoic with detrimental effects on various marine fauna. The last appearance datum (LAD) of the conodont species *P. siluricus* in the uppermost Hemse Group on Gotland marks the commencement of the event and the superimposing Eke Formation is extremely rich in oncoids. To analyze the specific controlling determinants and the potential for oncoids as environmental indicators, I measured size and shape for over one hundred oncoids deriving from Gotland and Bjärsjölagård, Sweden. Thin sections and cross-sections of oncoids were produced and *Rothpletzella* was by far the most abundant calcimicrobe in oncoid cortex, often associated with *Wetheredella*. Results herein strengthen the theory of the mass abundant oncoids constituting an anachronistic facies. Furthermore, oncoid- shape and morphology are concluded herein to, with caution, be used as indicators of water energy which sets the deposition of the Eke Formation under a phase of transgression.

Keywords: Oncoids, Lau Event, Silurian, microbialites, Gotland, Bjärsjölagård, ecological crisis.

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En redogörelse för massförekomsten av onkoider associerad till Lau Event, en ekologisk kris från sen Silur

MARTIN QVARNSTRÖM

Sammanfattning: Den geologiska signifikansen av onkoider, mikrobialiter uppbyggda av calcifierande mikroorganismer, är varken lika studerad eller vedertagen som för de likartade stromatoliterna. I samband med de större fanerozoiska utdöenderna är ett uppsving av dessa mikrobialiter ett accepterat bevis för en krisfauna vilken utgör ett anarchronistiskt facies. Desto mer omdebatterad är möjligheten att applicera denna modell även på mindre utdöenden som Lau Event, ett *event* kopplat till ett udöende samt till en av de största kolisotop anomalierna under hela Fanerozoikum. Utdöendet av konodonten *P.siluricus* markerar eventets början och den överlagrande Eke Formationen är väldigt rik i onkoider. För att analysera biologisk determinism och onkoidernas potential som miljöindikatorer har storlek och form på över hundra onkoider analyserats från södra Gotland och Bjärsjölagård i centrala Skåne. Ett representativt urval gjordes för vidare analys i form av bland annat genomskärning, isotopprov och tunnslipsframställning. Resultaten styrker teorin att onkoiderna utgör en krisfauna. Genom studier av tunnslip visas *Rothpletzella* vara den dominerande mikroorganismen i onkoid-kortex. Fortsättningsvis, kontateras att onkoiders form och storlek är lämpliga parametrar för att istörre utsträckning användas som indikatorer för vattenenergi. Detta sätter depositionen av Eke Formationen under en fas av trangression.

Nyckelord: Onkoider, Lau Event, Silur, mikrobialiter, Gotland, Bjärsjölagård, ekologisk kris.

Ämnesinriktning: Berggrundsgeologi

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1 Introduction

1.1 Aim

This report describes and classifies a representative selection of the large number of oncoids that are found in the Silurian Eke Formation, southern Gotland and its analogue in Bjärsjölagård, Skåne. These formations are characterized by the, not so much investigated, ecological crisis Lau Event, which is associated with one of the greatest positive anomalies in the $\delta^{13}C$ record throughout the entire Phanerozoic (e.g. Samtleben et al., 2000; Lehnert et al., 2007a). By setting the microbial activity and its driving mechanisms in a regional and global context, this report help to improve the recent progress in the overall understanding of the Lau Event. To better understand climate changes and extinctions throughout the past is not only interesting in a geological history aspect. It is also important for understanding the present and future climate changes and their possible ecological consequences. New arrays of research is currently emerging in this field, such as, using calcifying cyanobacteria as a tool for precipitate calcite to decrease the anthropogenic polluted CO_2 (e.g. Jansson & Northen, 2010).

1.2 Oncoids (history, classification, and significance)

1.2.1 Historical view and significance

The geological significance of cyanobacteria and stromatolites is well known and has for long been a resource for paleo-climatological and environmental reconstructions of the past as well as for basin analysis (e.g. Peryt, 1981; Young & Long, 1976). In basin analysis stromatolites are used in both intra- and interbasin correlations and can also be used as proxy for water-depth (Young & Long, 1976). However, not as employed to these kinds of analyses are oncoids, another product of encrusting organisms, often calcifying cyanobacteria. Oncoids are coated grains, most often, formed by a bio- or lithoclastic nucleus with an enclosing micritic, laminated cortex (Flügel, 2004). The term oncolite is applied to a limestone in which oncoids exceed 50 % of rock volume. Oncolite is, thus, not a term referred to an individual grain. Equally a limestone containing oncoids, but less than 50% of rock volume shall be referred to as an oncoidal limestone.

Heim (1916) introduced the term oncoid for the first time. However, uncertainties of origin of oncoids under the major part of the 20th century led to a large confusion concerning their classification, as well as their geological significance (Peryt, 1981). A general division exists since the latter half of the 20th century, when two different groups of oncoids were distinguished by their differences in microstructure. These two groups are the spongiostromate and the porostromate oncoids, the latter mainly represented by the *Girvanella* genus (Peryt, 1981). Some authors prefer the division of non-skeletal and skeletal oncoids proposed by Riding (1977) but this is a direct analogue to the above mentioned classification (Flügel, 2004). Suggestions have also been made for several other classifications based on morphology or size (e.g., Dahanayake, 1977) but these classifications have not been fully accepted by the scientific community (Peryt, 1981; Flügel, 2004). However, Logan et al. (1964) adapted a morphological classification that has, to some degree been used both for recent and for ancient oncoids (e.g. Ratcliffe, 1988; Peryt, 1981; Flügel, 2004).

Throughout the whole Phanerozoic, oncoids were formed in different ecological assemblages and settings (Peryt 1981). Recent oncoids are present in fresh, brackish, as well as in marine environments with various organisms forming them (such as cyanobacteria, foraminifers, different algae and microproblematica) depending on their environmental tolerance. Oncoids in association to present great reefs, such as in Bahamas or at Bermuda, often do not exhibit a clear lamination since their growth structures are frequently destroyed (Flügel, 2004). Due to high environmental tolerance oncoid-forming microbes can also occupy niches with low level of biodiversity like settings of high salinity (e.g. Elicki et al., 2002; Arp et al., 2003). Peryt (1981) suggests a majority of marine oncoids from Cambrian to the Jurassic to be porostromate, in particular *Girvanella*, and lacustrine oncoids to be spongiostromate. In the same article, he further describes a switch of spongiostromate completely replacing porostromates in marine settings. This could support and perhaps explain the outcome of recent freshwater oncoids being a closer analogue to ancient marine oncoids (Monty, 1972).

1.2.2 Oncoids in unstable ecological conditions

As Sheehan et al. (2004) suggested, based on studies throughout the Phanerozoic, a resurgence of microbialites such as stromatolites and oncoids might provide a local or more expanded regional warning sign of an arising ecological crisis. This pattern of anachronistic periods was given acceptance in the late Ordovician mass extinction (Sheehan et al., 2004) as well as for the Frasnian-Famennian extinction, (Whalen et al., 2002) previously somewhat described (e.g. Wood, 1999). However, these anachronistic periods were not given any further attention but for the five major extinctions until Calner (2005a) launched the same theory for the less immense, Late Silurian, Lau Event. He showed evidence of less abounded grazing and infaunal activity in Eke- and Burgsvik formations along with a high abundance of oncoids and stromatolites.

To investigate the reason of microbial presence in the form of oncoids it is necessary to be familiar with their environmental determinants. These are summarized by Flügel (2004) and divided into physical, chemical and biological determinants. The physical factors are water temperature, water energy, quantity of light for photosynthesis, and underlying substrate.

Salinity, pH, water chemistry and dissolved gases are explained as the chemical factors. As for the biological determinants, nutrients, competitors and predators need to be taken into account when understanding the presence of oncoids.

1.2.3 Affinities of *Rothpletzella*, *Wetheredella* and *Girvanella*

The genus *Rothpletzella*: The type species was first described from Gotland as *Sphaerocodium gotlandica* by Rothpletz in 1908 and later revised to *R. gotlandica* by Wood (1947). It is described as an encrusting, threadlike organism that is closely attached to a foreign body or closely tangled without a nucleus (Wood, 1947). A division is made between the type species, *R. gotlandica* and another species, *R. munthei* by the latter having somewhat smaller threads (20-25 μm in diameter compared to 30-35 μm in *R. gotlandica*) and thinner walls, typically 2-3 μm. Riding, (1991b) regarded the genus as a "microproblematica" since no present analogues indicate it being neither cyanobacteria nor green algae. Microproblematica is a classification which includes microfossils with no clear modern analogues or evidence for other classification leading to uncertainty of systematic status (Flügel, 2004).

The genus *Wheteredella*: The type species is named *W. silurica* by Wood (1947). Wood describes them as subcircular nodules, 10 μm in diameter, with an encrusting habit, often associated with *Spongiostroma*, *Girvanella* or *Rothpletzella*. Uncertainties of affinity have led to many propositions of related genera (Feng et al., 2010), including foraminifera (Wood, 1947), green alga (cf. in Feng et al., 2010), cyanobacteria (Copper, 1976) and microproblematica (e.g. Riding, 1991b).

The genus *Girvanella*: The type species, *Girvanella problematica*, was described and named from the Girvan district in Ayshire, Scotland by Nicholson and Etheridge (1878). It is an encrusting organism composed of uniform sized, sinuous tubes with thin micritic walls. Tube thickness show a large variation in size of somewhat 10 to 100 μm in diameter (e.g. Feng et al., 2010) and *Girvanella* appears in sediment as single tubes to larger clusters, more than a centimeter across (Danielli, 1981). Preservation of initial porostromate structure can differ from good to lack of recognition within a single oncoid, (Wood, 1947) which can lead to confusion in classification. Concerning affinity, *Girvanella* has been regarded as foraminifera, sponge and green alga (Riding, 1975b) but is considered by many as an analogue to present cyanobacteria (e.g. Lauritzen & Worsley, 1974; Riding, 1977). It differs from *Rothpletzella* by the latter having chambered and thereby not uniform tubes.

1.3 Geological setting and stratigraphy

The oncoids treated herein are associated with the Late Ludlow Lau Event. To set their abundance in a useful perspective to the extinction event, understanding of the environment in which they were deposited is important.

1.3.1 Paleobaltica

Silurian outcrops are widely spread throughout Scandinavia from Máhkarávju in the very north of Norway to Skåne in south and also neighboring deposits occurs in Denmark (Bassett, 1985) and in the East Baltic area. The sedimentation took place in a shallow-marine basin situated on the Baltic paleocontinent, defined in west by the emerging of the early Scandian Orogeny and in the southwest by the ongoing collision with Avalonia (Torsvik et al., 1996). The basin was located on low latitudes, south of the equator with a tropical climate, favoring carbonate production. The deposits appear as massive bioherms and bedded limestones along the basin margins and shales in the deeper parts of the basin. Southwards, the intracratonic basin is transitional into a foreland basin, which is characterized by successively increased subsidence and sedimentation towards the south (e.g. Poprawa et al., 1999; Erlström et al., 2006). As a result, 3000 m thick Silurian deposits are to be found in Poland (Calner et al., 2004b). Gotland was well protected from the branched foreland basin system, and the area had initially low terrestrial sediment input as the adjacent foreland basins acted as deep sediment traps (Calner et al. 2004b). The low subsidence rate is marked by the crystalline basement being less than 400 below sea level in the central parts of Gotland (Calner et al., 2004).

1.3.2 The Eke Formation, Gotland

The Eke Formation is a thin division which superimposes the uppermost Hemse Group, (Hede 1921, 1925b), and which outcrops in an area from Ronehamn in northeast to Näsudden in southwest. It displays distinct lateral thickness- and facies variations (e.g., Hede, 1925; Jeppsson, 2005; Calner & Eriksson, 2006; Eriksson and Calner, 2007) with the Burgen outlier marking a slope break of the paleoplatform (Eriksson & Calner, 2007). The northern part, including the Lau outlier, is estimated to a thickness of 10 m (Eriksson & Calner, 2007 after Munthe, 1902) and is heterogeneous in terms of depositional environment (Eriksson and Calner 2007). The basal parts also show a hiatus marked by a basal flat-pebble conglomerate originating from the underlying Hemse group, based on the presence of the small brachiopod *D. navicula* in the clasts (Calner, 2005a). The lower part of the Eke Formation also displays palaeokarst, another erosional evidence (Cherns, 1982; Eriksson & Calner, 2007). Characteristic is also the abundant presence of oncoids which encrusting microbials being early described as new genera by Rothpletz and Whetered (1890 and 1893, respectively) but no documents are today available (Wood 1947). Later, Wood (1947) revised the new genera and renamed them to *Rothpletzella* and *Wheteredella*.

The proximal shelf facies that appears throughout the formation is mainly represented by beds of micritic wackestone, packstone and marl (Samtleben et al., 2000; Stel & de Coo 1977). Large *in*
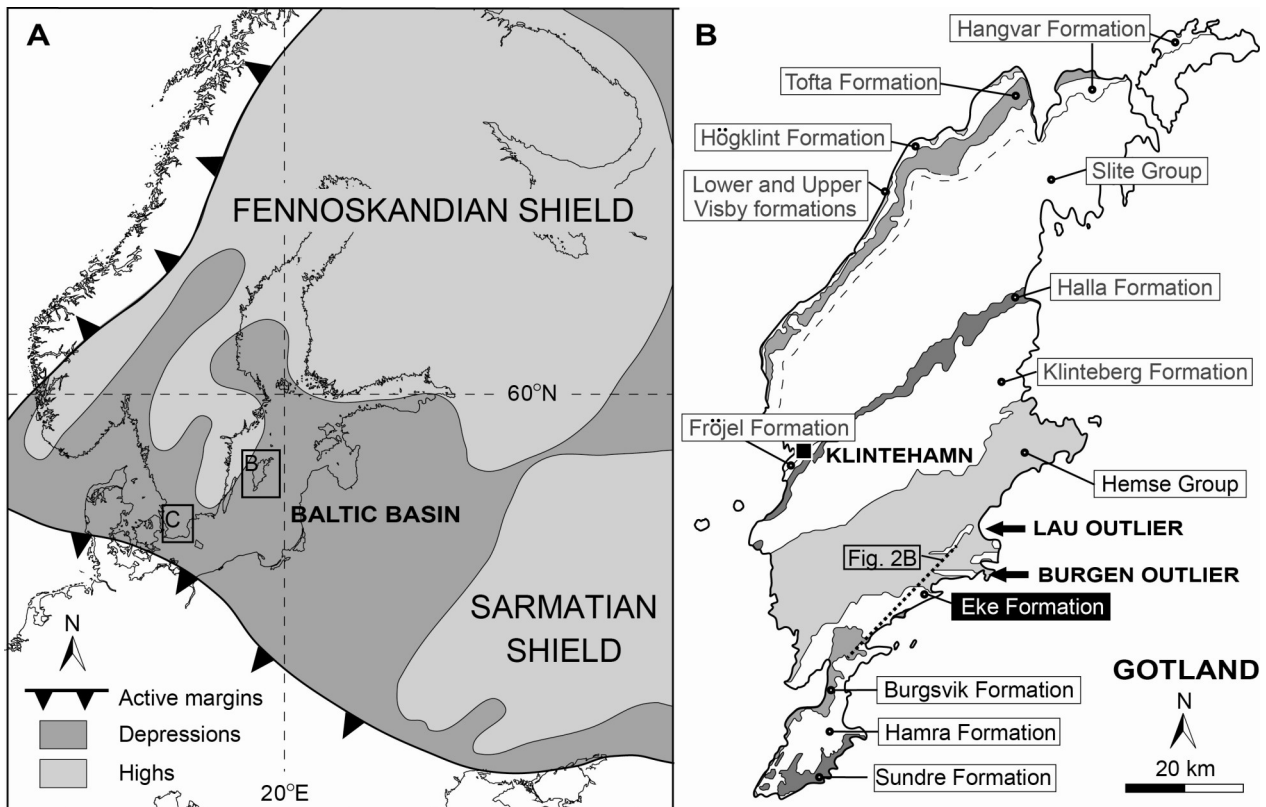
Fig. 1. Location of Gotland and Bjärsjölagård. A. Paleogeography of the Baltic Basin during the Silurian with Gotland and Skåne marked by squares, (modified from Baarli et al., 2003). B. Gotland with stratigraphic units. Marked transect is presented in Fig. 2b, (modified from Calner, 2005a). C. Skåne and location of the Öved-Ramåsa Group and the Late Silurian shales in the Vomb Through, (redrawn from Jeppsson et al., 2007).
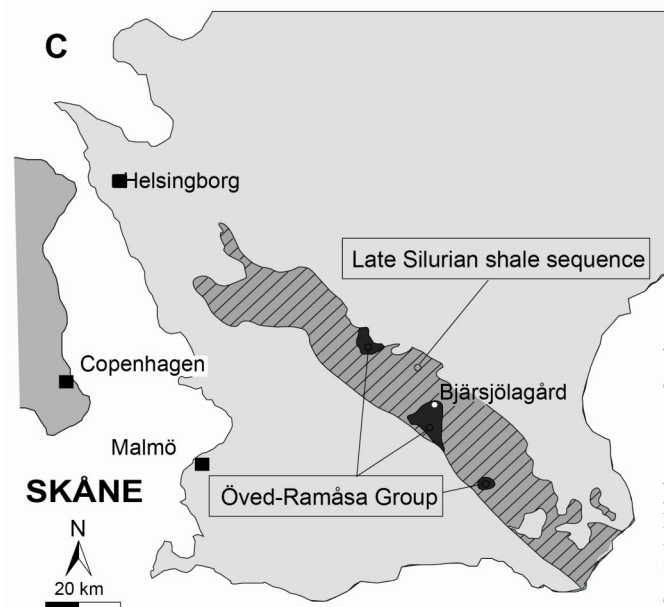
situ grown oncoids are (commonly) so abundant that they form oncolites. Samtleben et al. (2000) describes an alteration between oncoidal layers and "usual" related proximal shelf facies suggesting smaller sea-level fluctuations during the Ludfordian. The Hemse Group, underlying the Eke Formation and the Hamra Sundre formations, overlying the Burgsvik Formation display major reef complex growth (cf. Fig 2A). In contrast the Burgsvik Formation is composed of more terrigenous material forming silt- and sandstones with

wrinkle structures (Calner, 2005a) in addition to oolites and oncoids.

1.3.3 Bjärsjölagård, Skåne

Along the road 13 in central Skåne, 12 kilometers north of Sjöbo, parts of the 25 m thick Bjärsjölagård Limestone Member (Wigforss-Lange, 1999) outcrops in the Bjärsjölagård quarry. It consists, in the area studied, of oncoid-rich beds which overlay more eroded beds with higher clay content. The member is dated to Whitcliffian, Late Ludlow and forms a part of the Klinta Formation which, in turn, constitutes the Öved-Ramåsa Group along with the Öved Sandstone Member. The Öved-Ramåsa Group contains shallower facies in opposite to the antecedent grey graptolitic shales of the Silurian in Skåne. The shallowing upward facies indicates an infill of the basin.

1.4 The Lau-Event and associated $\delta^{13}C$ anomaly

The ecological crisis associated with the Lau Event began just before the last appearance datum (LAD) of

the conodont *Polygnathoides siluricus* in the commencement of the late Ludfordian (Jeppsson & Aldridge, 2000). It spans from the base of the Botvide Member, När Formation, and was believed to end at the summit of the Eke Formation. Through high resolution carbon isotope chemostratigraphy and by the maintained presence of anachronistic facies it is more likely extending to the top of the overlaying Burgsvik Formation (cf. Calner, 2005b; Fig. 2). Along with the Ireviken and Mulde events, the Lau Event is considered to be one of the three larger, coupled extinction-isotopic events during the Silurian, and well-registered in the Gotlandic stratigraphy (e.g. Jeppsson and Aldridge, 2000; Calner et al. 2004b; Calner 2008). Detrimental effects of the event have been proved in conodont fauna, where no platform equipped taxon survived (Jeppson & Aldrige, 2000) as well as in vertebrates (e.g. Eriksson et al., 2009), brachiopods, acritarcs, chitinozoans, corals, polychaetes, ostracodes, trilobites, tentaculites and graptolites (Calner et al., 2004b). Since the effects on conodonts were so severe and that they are easy to correlate globally between continents they are seen as key fossils. The start of the event, associated with the rising limb is perfectly correlated with the LAD of the conodont species *P. siluricus* (Jeppsson, 2005).

The driving forces behind the comparably small Silurian extinction events are not fully understood but they have been suggested to be a consequence of oceanic cycles, creating an alternation between two stable environmental conditions. Jeppson (1990) introduced a model based on differences in bottom seawater ventilation causing P- and S episodes. The former explained to be an episode of humid lower latitudes and cooler higher latitudes and the latter an episode of more arid lower latitudes and somewhat warmer high latitudes. Based on this model, Samtleben et al. (1996) suggested the input from freshwater to be a more important source causing the low oxygen isotope ratios and an organic carbon burial as an explanation for $\delta^{13}C$ fluctuations. Bickert et al. (1997) launched a somewhat different two-phase model suggesting an alteration between H (humid) and A (arid) periods in an otherwise stable climatic condition. The late Silurian being a period of generally stable climate has however been questioned (e.g. Loydell, 2007).

The carbon isotope excursion (CIE) associated with the Lau Event is registered in Skåne (Wigforss-Lange, 1999), Gotland (e.g. Samtelben et al., 1995), East Baltic area (Kaljo et al., 1997), Australia (Jeppsson et al., 2006), North America (e.g. Talent et al., 1993) and in the Prague basin (Lehnert et al., 2006). This anomaly in the carbon cycle is one of the greatest in the Phanerozoic history with, for example, values measured to +11.2 ‰ PDB (Pee Dee Belemnite, standard used for $\delta^{13}C$ measurements) in Bjärsjölagård (Wigforss-Lange, 1999). On Gotland it reaches from the uppermost *P. siluricus* zone to the O. crispa zone in the magnitude from about 0.5 ‰ PDB, in the När Formation to 9 ‰ PDB in the Eke Formation (Calner et al., 2004). Together with fossil correspondence, the correlation between the $\delta^{13}C$ anomalies from the different continents is the main evidence of the Lau Event being a global event.

2 Material and methods

This dissertation is a study based on description and analyzes of collected material. It was supplemented by an initial literature study consisting of books and articles in scientific journals dealing with oncoid-formation and extinction events. To understand the ancient determinants of microbial growth, an important aspect was the finding of modern analogues and studies treating both modern and ancient types.

All slabs and free lying oncoids presented and discussed herein were provided from several localities on Gotland and from a visit in the quarry of Bjärsjölagård (Fig. 1). In total, size and shape was measured for over one hundred oncoids. A subset of oncoids was then selected based on variation in size and shape, for further investigation. Treatment in laboratory consisted of cutting of numerous samples from Gotland, 16 oncoids and four larger slabs, and a few comparing examples of Bjärsjölagård, four oncoids and one larger slab. The unsullied surfaces were furthermore polished with 1200 grit paper and subsequently scanned in 1200 dots per inches and examined under light microscope. Three polished slabs, two from Gotland and one from Bjärsjölagård were selected to produce thin sections. These thin sections were made at the Ceramic laboratory at the Geological Department in Lund. A two component epoxy was used in addition to attach the polished samples onto microscope glass slides which were grinded down to approximately 100 μm. Furthermore, a slab containing two large representative oncoids, with large micrite-containing nucleus and surrounding matrix, was drilled with a dental drill in 17 locations (Fig. 4I). The rock powder was sent to Geo-Zentrum Bayern in Erlangen, Germany, for analysis. The samples were subsequently reacted with 100% phosphoric acid (density >1.9; see Wachter and Hayes, 1985) at 75° C using a Kiel online preparation line connected to a ThermoFinnigan 252 masspectrometer. All values are reported in permil relative to the V-PDB by assigning a $\delta^{13}C$ value of +1.95% and an $\delta^{18}O$ value of -2.20% to NBS19. Reproducibility for carbon isotope analyses was monitored by replicate analysis of laboratory standards and was better than ±0.05% (1σ). Any limestone classification mentioned herein, follows Dunham (1968) and methods for oncoid description is largely based on Peryt (1981) and Flügel (2004). Regarding further oncoid classification the one developed by Logan et al. (1964) has been used for comparison but is not adapted in strict sense since it is not considered as more relevant than others.
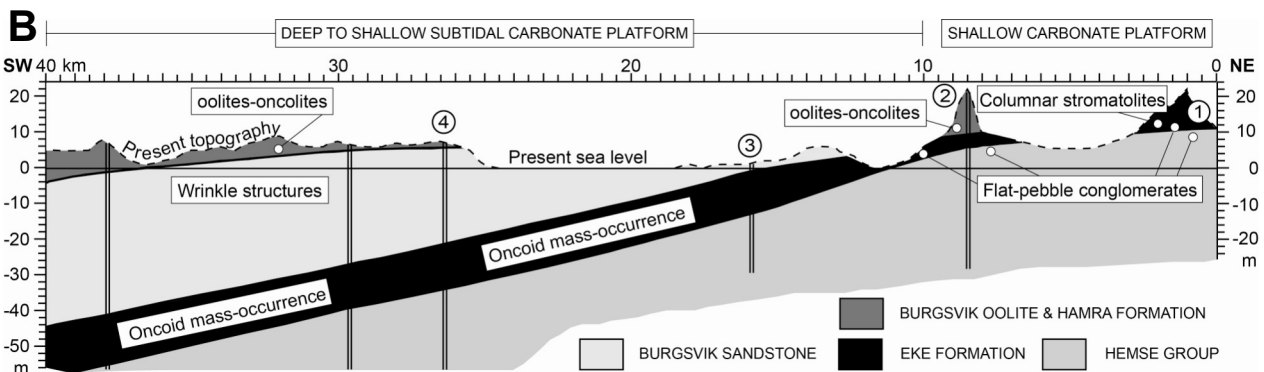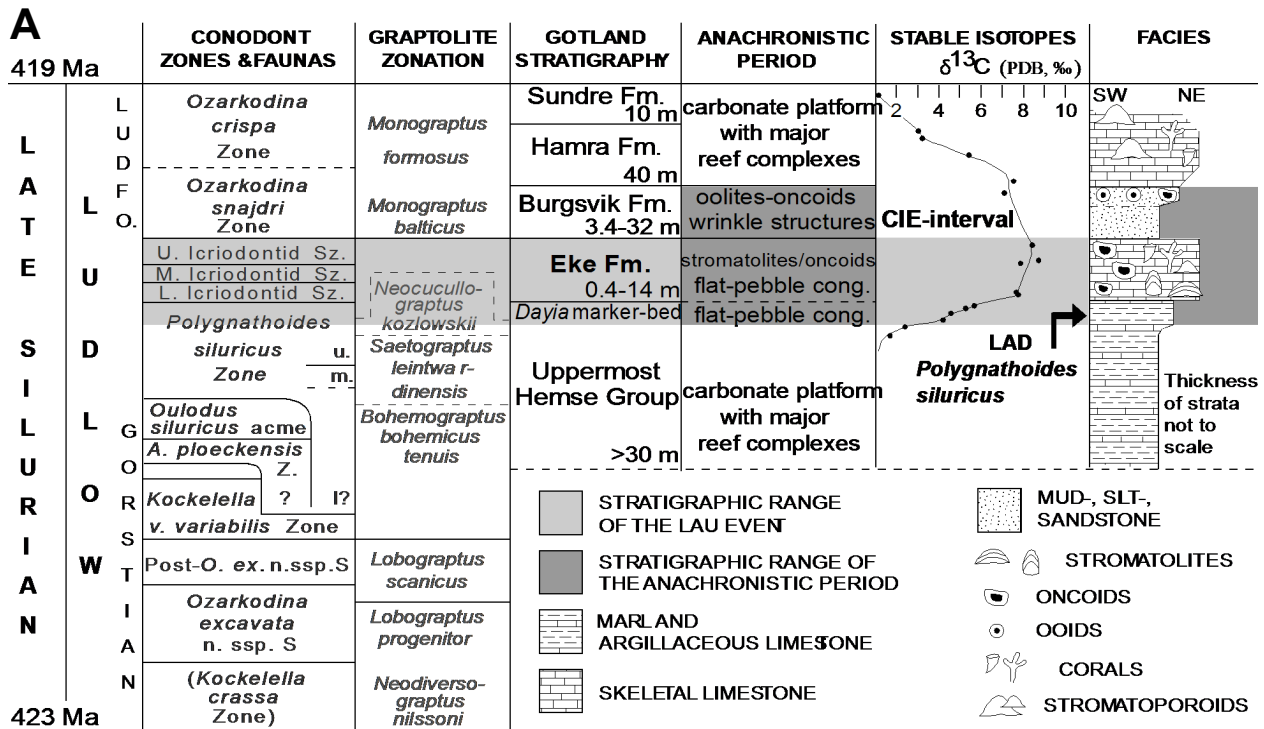
CONODONT ZONES &FAUNAS			GRAPHOLITE ZONATION	GOTLAND STRATIGRAPHY	ANACHRONISTIC PERIOD	STABLE ISOTOPES $\delta^{13}C$ (PDB, ‰)	FACIES

Fig. 2. Stratigraphy of Late Silurian, Gotland. A. Biostratigraphical framework in association to Lau Event. Note the span of the anachronistic facies which ends at the uppermost of the Burgsvik Formation, (modified from Calner, 2005a with carbon isotope excursion data from Samtleben et al., 2000.) B. Transect with stratigraphical units concerned and distribution of anachronistic facies. Note the lateral thinning of the Eke Formation, (modified from Calner., 2005).

3 Results

3.1 Oncoids

3.1.1 Surface, cortex and lamination

The surface and structure of many oncoids of Gotland are of "cauliflower" type, which visible in cross section reflects bulbous column lamination growth within cortex. These bulbous forms are, however, frequently concatenated close to nucleus and the columns are often separated by micrite infillings, light grey in color. The ratio cortex/nucleus is high in these oncoids and cortex is often thicker on one side, interpreted as upper side. Bjärsjölagård analogues are, in general, smaller with a lower cortex/nucleus ratio and the "cauliflower" structure is not as common as on Gotland. Instead the surfaces are often more concentric and regular and the major part of the oncoids are clo-

sely packed and vary from constructing oncolites and oncoidal pack/wackestones.

Lamination within cortex of the oncoids is throughout the study area micritic, but differs however somewhat in coloration between the localities. In broad-spectrum, the color variation is of yellow, beige, red or greyish nature. In Ronehamn (uppermost Eke) very reddish cortex occurs, implying oxidation or other iron related chemical processes. There are examples of multiple composed nucleuses within the same oncoid, along with possible concurrence and syngrowing of tabulate corals, such as *Syringopora*. Smaller fossil fragments, mainly consisting of ostracodes, bryozoans, trilobites (represented by "shepherd hooks") and fractured brachiopod shells occur within cortex. Also found are oncoids exhibiting a two generation cortex differed by lamination color change. (cf. Fig. 4B).
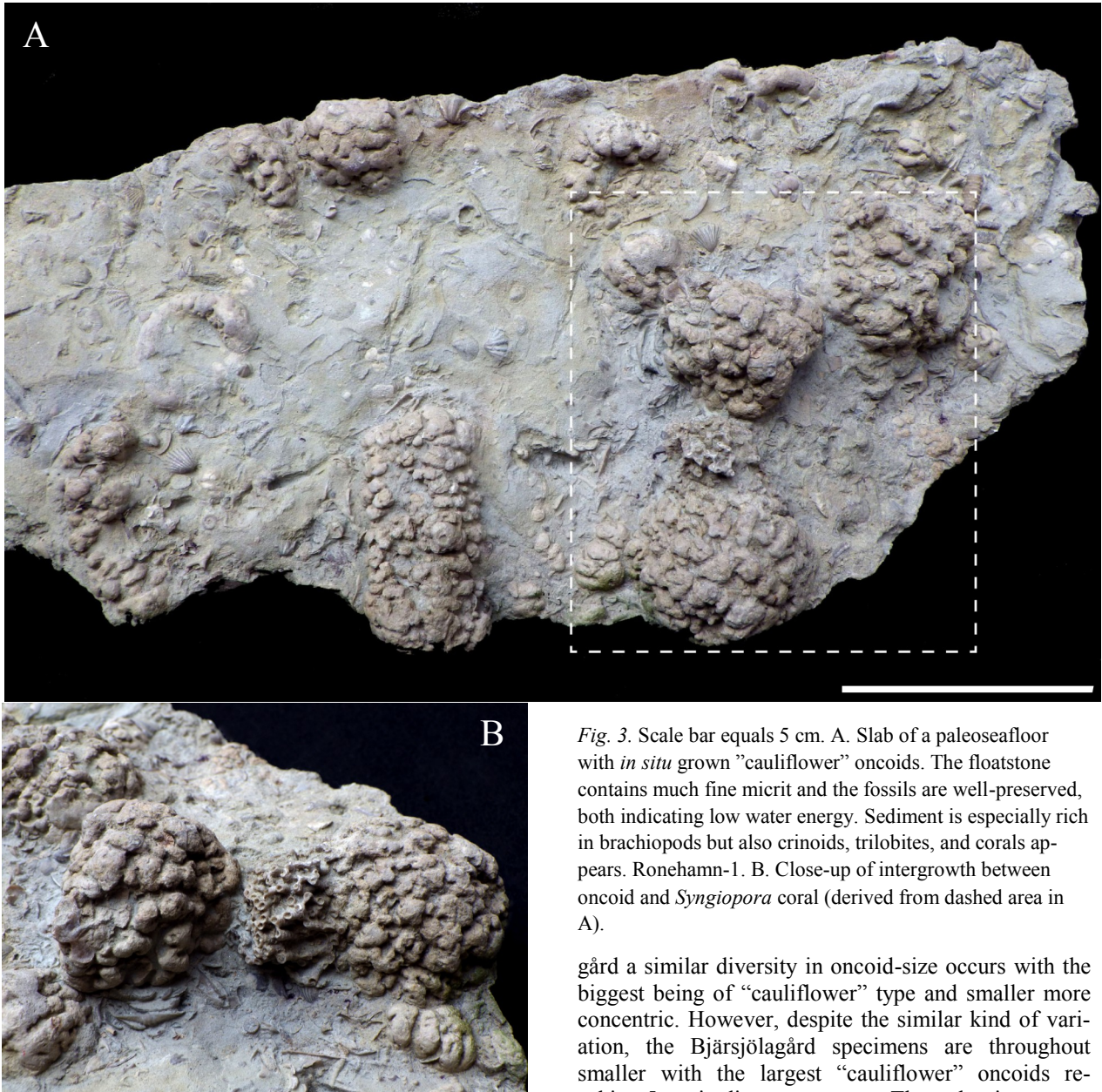
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Fig. 3. Scale bar equals 5 cm. A. Slab of a paleoseafloor with *in situ* grown "cauliflower" oncoids. The floatstone contains much fine micrit and the fossils are well-preserved, both indicating low water energy. Sediment is especially rich in brachiopods but also crinoids, trilobites, and corals appears. Ronehamn-1. B. Close-up of intergrowth between oncoid and *Syngiopora* coral (derived from dashed area in A).

The examination of thin sections and polished slabs show a wide difference in preservation of initial microbial morphology within laminae, ranging from well preserved to completely absent within a single oncoid. Even when primary tube forms are absent, the oncoid coatings conserve colored lamination.

3.1.2 Size
The oncoids collected from Gotland range from <1 to >10 cm in diameter. Of 60 samples from Bodudden1 (appendix) the dominating size is of 2 cm in diameter. The 50 samples originating from Petsarve1 (appendix) display two general sizes, one ranging from 1-2 cm and the other with a diameter of approximately 3 cm. At Ronehamn the main size of 20 collected oncoids are of 2-4 cm but oncoids bigger than 5 cm in diameter are found and thereby these oncoids are the largest among the samples. Within the sediments of Bjärsjöla-

gård a similar diversity in oncoid-size occurs with the biggest being of "cauliflower" type and smaller more concentric. However, despite the similar kind of variation, the Bjärsjölagård specimens are throughout smaller with the largest "cauliflower" oncoids reaching 5 cm in diameter at most. Through microscopy, micro-oncoids with a diameter of less than 2 mm are found in the thin section from Bjärsjölagård. Equal sized ones are found in the Eke Formation as well, primarily in facies with higher water energies such as shallow subtidal sediments (e.g. Burgen8, Öndarve1 and Petsarve3).

3.1.3 Shape and nucleus
The nuclei of the observed oncoids are most often of biotic origin, a bioclast, but appear occasionally as only micritic or completely absent. Brachiopods (such as *Leptaena*, *Ferganella borealis, Howellella elegans*), bryzoans, crinoids and molluscs all form nucleus. In comparison with adjacent fossil biota, no distinctive selection for nucleus forming bioclasts seems present. Some nucleus-forming bioclasts are filled with lighter micritic content than surrounding sediment, which
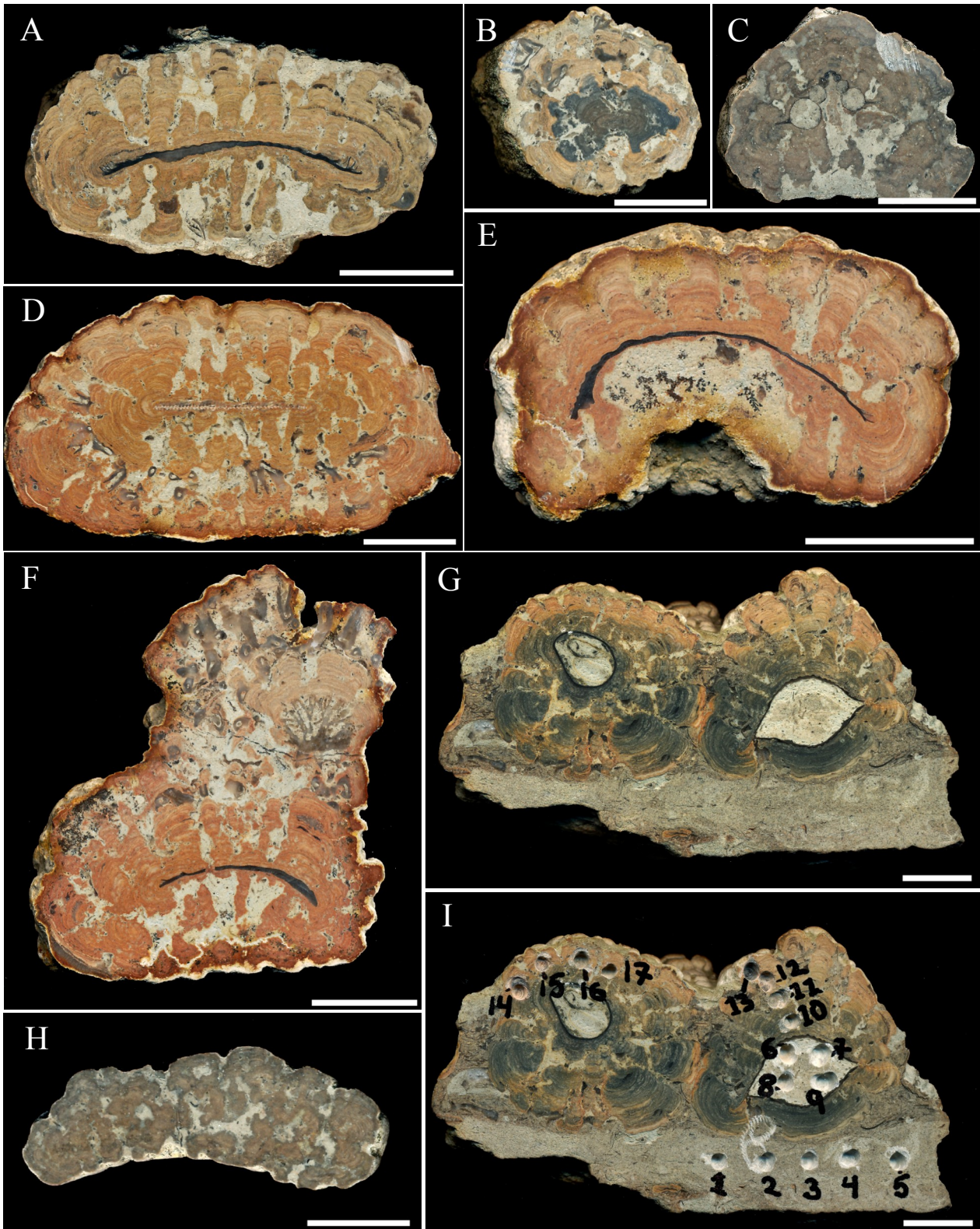
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Fig. 4. All scale bars equal 1 cm. "Cauliflower"-type oncoids exhibiting lobate lamination with micrite filling. A. Oncoid with brachiopod nucleus and central isolated lobate lamination structure in cortex. Ronehamn2. B."Bananaic" oncoid in short-axis cross section. Note the two phase cortex in which closer to nucleus appears dark grey and outerwards orange/red. Petsarve. C. Small, grey oncoid with a sparilly coiled gastopod as nucleus. Bodudd1. D. Redish oncoid with bryozoan nucleus. Note the sporadic tubular coral fragments which outborders a vague first cortex phase. Ronehamn2. E. The morphology of the nucleus forming brachiopod reflects oncoid shape, resulting in a cavity on the lower side. Ronehamn2. F. Oncoid with brachiopodshell nucleus overgrown by tabulate corals. Note the continued growth on the coral up to the right. Ronehamn2. G and I. Two *in situ* grown oncoids, overturned in a stormdeposit with marked drillholes for δ^{13}C analysis. Drillings marked in lighter micrite within nucleus (6-7), enclosing sediments (1-5) and in resistant oncoid cortex(10-17). Ronehamn1. H. "Bananaic" oncoid in longitudal through cutting. Bodudd1.

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Fig. 5. Scale bar equals 5 cm. Example of analogue "cauliflower" type oncoids from Bjärsjölagård. Compare size and structure with fig. 3.

may reflect transportation and reworking before or after encrustation by cyanobacteria.

The most common shapes are spherical to subspherical, discoidal, elongate or "bananaic" varying primarily as a function of size and nucleus. Well preserved bryzoan nucleus attends to control oncoid shape resulting in a characteristic "bananaic" shape. Larger brachiopod specimens are occasionally even detectable without having to cut the specimen. Large spherical oncoids, especially those from Ronehamn, displays hollow undersides and large cortexes on one side, interpreted as upper side.

3.2 Oncoid-forming calcimicrobes
Two genera of encrusting calcimicrobes are with certainty found in the oncoids, by which *Rothpletzella* is by far most abundant. The chambered initial tube forms are found in isolation or in clusters with tabulates in juxtaposition. Tube size of *Rotpletzella* is normally 20-30 µm in diameter but chambers up to 50 µm wide appears in thin sections. Wall thickness is generally in the size dimension of 5-10 µm. In *Rotpletzella* oncoids, which appears red in through-cutting, a strong alteration between red and light grey laminae is often present. The former often have poor preservation and in cases where tube-structure is not visible, lithification is strong. These areas are much more resistant to drilling than surrounding sediment. Some smaller but vague tube forms of 10 µm appear but whether or not these are of *Girvanella* origin, or simply smaller *Rothpletzella* tabulates was not possible to determine.

Hemispherical to spherical *Wetheredella* chambers are found isolated and imbedded by large clusters of *Rothpletzella* or together in small colonies. Normal size is of 50-100 µm in diameter. As for *Rothpletzella* the preservation rate of *Wetheredella* differs and occasionally determination of genus is not possible. Troubling resembling forms are in many cases consi-

dered to be small micritic infillings or fractions of fossils only coincidentally shaped as *Wetheredella*.

3.3 Associated facies
All samples analyzed herein derive from sedimentary facies associated with a shallow marine depositional environment in a protected intracratonic setting. The oncoids were formed above and below the effective wave base, resulting in different shape, size, cortex, surface and lamination. Also the general fossil assemblages, including the nucleus-forming fossils, reflect variation in species composition and preservation rate between the localities. To investigate whether or not the oncoids can act as environmental indicators, the overall view must be studied in a broad sense.

3.3.1 Bjärsjölagård
In the section at Bjärsjölagård quarry, ca. 2.5 m above ground, a mass abundance of oncoids occurs in an oncoidal packstone composed of 0.1-0.2 m thick limestone beds which are interbedded by thin argillaceous layers. There is a brief thinning of the beds laterally. Micro-oncoids, less than 2 mm in diameter are abundant but average size is around 2 cm and as mentioned, oncoid-size does not exceed 5 cm. The largest oncoids are to be found in the eroded sediments towards the lake shore, a few meters from the section. Visible through microscopy, surrounding matrix is a micritic, very fine-grained packstone composed of crinoid fractions, isolated microbial tabulates, ostracodes, trilobite fragments and micro-oncoids only 0.1-0.2 cm in diameter. In addition to the oncoids, macrofossils such as mollusks, brachiopods, tabulate corals, crinoids are present. The underlying sequence, which commencement is below ground level, is muddier and less erosional resistant, resulting by overhanging of the oncolite. It contains trilobites, brachiopods and a mass abundance of crinoids. Laterally, the two sequences are cut by a SE-NW vertical through cutting of thin calcite precipitation but not surprisingly, no major signs of tectonically actions are found.

3.3.2 Gotland
As indicated herein, the Eke Formation on Gotland displays a lateral change in composition as a consequence of relative position within the platform (e.g., Fig. 4; Calner, 2005a). The most proximal facies display a well protected environment which, laterally, towards the slope develops into higher water energies marked in the sediment by grainstones with low or none mud content (Eriksson & Calner, 2007). The fore-reef facies contain siliciclastic material which decreases in grain size into terrigenous muds towards the distal parts of the platform. The shallow subtidal and the deeper subtidal sediments differ in fossil assemblages, grain size and characteristic oncoids. The deeper subtidal facies is associated with a micritic sedimentation including well-preserved, non-orientated and not fractioned macrofossils as trilobites, brachiopods, mollusks, crinoids and big "cauliflower" *in situ* grown
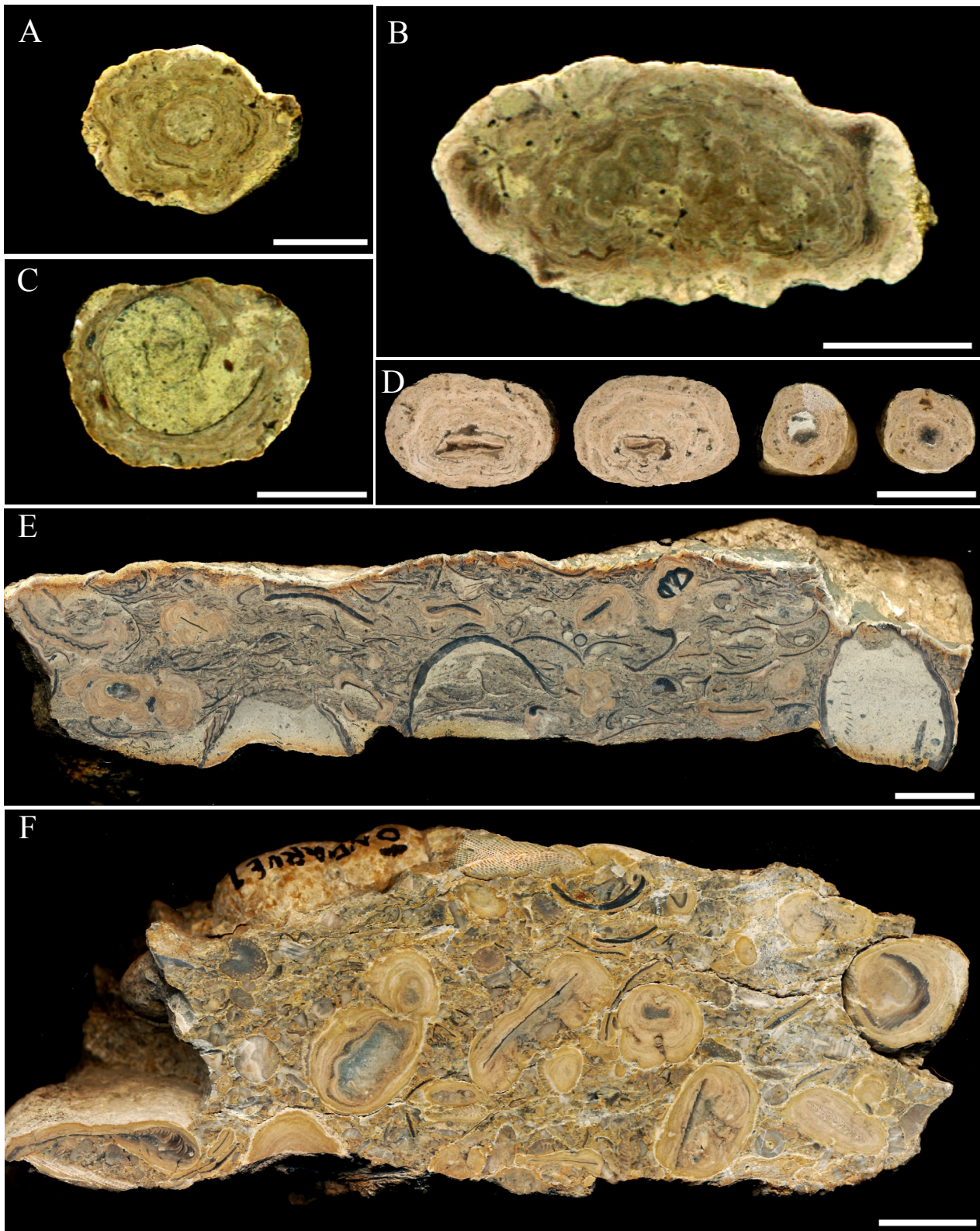
Fig. 6. All scale bars equal 1 cm. Rounded and subrounded oncoids with rolling or partially rolling during growth. A-C. On-coids, yellowish to grey/brownish in color. Note the lobate growth patterns (B) which does not indicate constant rolling during growth. Nucleus in C consits of a longitudinal through cutting of a gastropod. Bjärsjölagård. D. Beige, very rounded oncoids. Burgsvik. E. Oncoidal packstone/rudstone with oncoids of low cortex/nucleus ratio. Non-fractioned shells seems to completely lack microbial coatings. Note the light micrite conserved within brachiopod shells on lower part of picture. Petsarve. F. Coarse oncoidal rudstone with rounded oncoids with concentric lamination. Rolling during growth is evident and deposition is without specific orientation. Öndarve1.

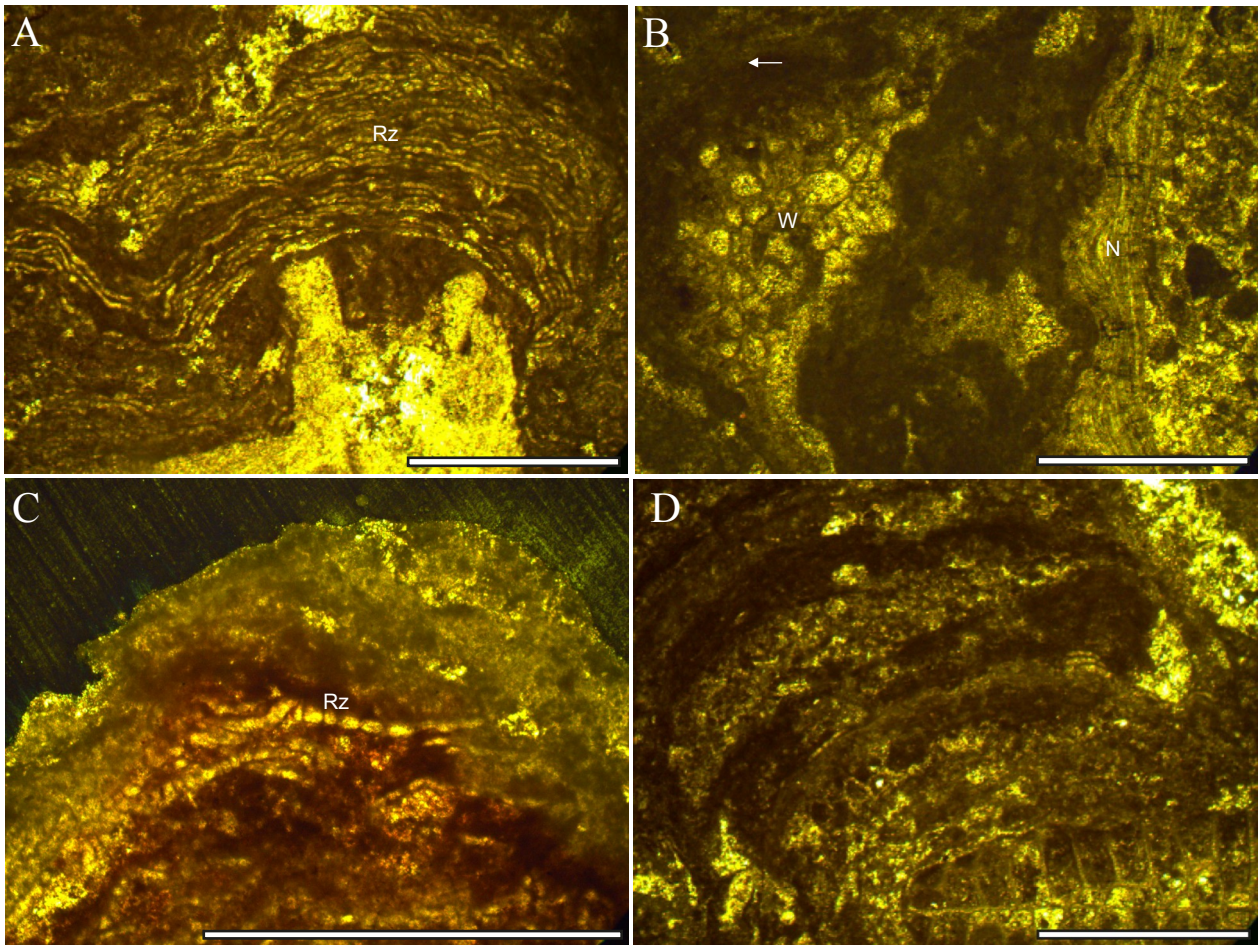*Fig 7.* Calcimicrobes in thin section. All scale bars equal 500 µm. A. Cluster of *Rothpletzella* (Rz) arranged hemispherical around nucleus. Gotland. B Brachiopod nucleus (N) and a cluster of *Wetheredella* (W). Bjärsjölagård. C. Single tube of typical *Rothpletzella* origin. Note the very distinct chambers which differs *Rothpletzella* from *Girvanella*. D. Thin section of a "Bananaic" oncoid with bryozoan nucleus and bulbous lamination towards upper right. Note the color alternation in laminae and the absence of initial calcimirobe structure.

oncoids. In contrast oncoids inhabiting slighter shallower waters tend to be transported and turned during storm events even though their morphology also reflects growth under low water energy. A significant morphology difference is seen in oncoids originating from the shallow subtidal above the wave base, having a concentric lamination reflecting rolling during growth.

3.3.3 δ^{13}C values

The 17 values from the δ^{13}C drilling (Fig. 4I) are presented in appendix. Measures 1-5, taken in enclosing matrix, gave a mean value of 7.91‰ PDB with a standard deviation of ± 0.04. Values obtained from drilling in oncoid cortex (measures 10-17) displays slighter higher values, 8.44 ± 0.04‰ PDB. The lowest δ^{13}C values was obtained in the lighter micrite within nucleus, 6.14 ± 0.00‰ PDB.

4 Discussion

4.1 Calcimicrobes

The genera *Rothpletzella* and *Wetheredella* are the only recognised oncoid-forming microbes visible in the thin sections investigated. *Girvanella* was expected to be found in the samples, as it is the most abundant oncoid-forming microbe throughout the Phanerozoic (e.g. Peryt, 1981) and even considered as a possible major source for the origin of lime mud, especially during early Paleozoic (Pratt, 2001). Previous studies also imply an association and possible concurrence between *Rothpletzella* and *Girvanella* within oncoids (e.g. Bingham-Koslowski, 2010). Possible explanations of *Girvanella* not being detected are either a complete absence, a really low abundance in the formations (i.e. low detection probability) or simply that initial tubes are absent due to a poor preservation. Smaller, less than 20 µm wide and less well-preserved tubes than the other *Rothpletzella* were found in the thin sections. It implies the latter as a probable explanation since *Girvanella* tubes are commonly of 10-40 µm in size (Danielli, 1981). Whether or not *Rothplet-*

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zella has a greater possibility of preservation than *Girvanella* is unknown. Certain, however, is that preservation is a complicating factor in oncoid classification. For example, oncoids appearing to have a spongiostromate fabric can actually, inversely, be of porostromatic origin (Peryt, 1981; Flügel, 2004). Also the oncoid forming microbes from Gotland have been the topic for origin and genus discussions much because of preservation state (summarized in Wood, 1947). Much may be explained by that, within a single oncoid, preservation can range from good to very poor.

Rothpletzella is both found as juxtaposed encrusting tabulates and likewise dispersed and disorientated in oncoid cortex. Former somewhat discussed by Feng et al. (2010) is the possibility of colonization of oncoid forming microbes from deeper water depth with lower light concurrence to shallower parts of the carbonate platform during ecological unstable periods. Nevertheless, the authors later reject this possibility in the same case study. It seems, however, like this could be a probable succession of the microbial community treated herein. Not sufficiently studies to conclude the succession with confidence has been done within project but it is nevertheless an interesting field for further studies. Through determination of microbial facies in strata formed before, during and after the event in both shallow and contemporary deeper waters, it may be possible to determine migration from deeper to shallower settings and thereby define more closely the colonization of calcimicrobes.

Not as abundant as *Rothpletzella* but present in all samples is *Wetheredella*. The genus has, similar to *Rothpletzella* an uncertainty regarding its classification. It seems reasonable as Feng et al. (2010) suggest that a classification has no purpose since evidence and confidence of affinity is too poor. Thereby, it is considered being a microproblematica. The same authors reasons in the same way regarding *Rothpletzella* even if Riding (1991) positions it in the phylum of Cyanophyta. Since *Rothpletzella* resemble much the chambered forms of *Cyanophyceae* it is also considered herein as a cyanobacteria.

4.2 Disaster forms, anachronistic facies

The presence of microbialites in carbonate platforms as disaster forms in association with an ecological crisis and its aftermath is a somewhat accepted view today (e.g. Whalen et al., 2002). This presence is especially evident in the bigger mass extinctions known from the Phanerozoic (e.g. the late Ordovician and the Frasnian-Famennian mass extinctions; Sheehan et al., 2004; Whalen et al., 2002). Parallels are drawn to minor extinction although other researchers, conversely, suggests that the saturation of carbon dioxide is a more determining factor of microbial increase (e.g. Riding 2005 comment to Calner, 2005a; Feng et al., 2010). In line with the carbon dioxide hypothesis, Dean and Eggleston (1984) described a recent example of industrial impacts on a lake and the resulting flourish of cyanobacteria as a response to anthropogenic change in carbon saturation and salinity. These were certainly factors determining cyanobacte-

rial growth, but no regards were taken to faunal changes except the disappearance of Charophytes. A possible hypothesis could be that the oncoids were a secondary product of the water chemistry and salinity changes but more directly affected by the disappearance of competitors and/or predators. However, a case study is always required since external factors can differently express and favour determinants of microbiological colonization in general and oncoid formation in specific. As for the Lau Event, the immense oncoid occurrence in the Eke Formation together with its basal conglomerate and the wrinkle-structures in the Burgsvik Sandstone (Calner, 2005a; Calner 2005b) all suggest it being a result of a disaster fauna. Regarding the oncoids, their appearance is so sudden after the commencement of the event immediate in association with the rising limb of the CIE (the commencement of the carbon isotope excursion), thus, calcimirobes being either opportunists occupying the novel vacant niches or simply favoured through a decreased grazing rate. The two outlined possibilities are hence both being based on consequences of biological determining factors.

4.3 Oncoids as environmental indicators

Ratcliffe (1988) distinguish three types of oncoids appearing (vic. Logan et al. 1964) in strata of Wenlock age in England. His C-type oncoid (cf. Logan et al., 1964) is described as having irregular surfaces with top-grown laminae, thus, being *in situ* formed. The explanation and description matches well the "cauliflower" type from the Eke Formation in Gotland and analogues from Bjärsjölagård. My interpretation is the same, there seems without doubt that these "cauliflower" forms are generated from an *in situ* growth. Smaller oncoids with more regular forms and concentric lamination, more similar to Ratcliffe's A-type, are in contrast grown under conditions of higher water energy with a constant or partial rolling as a consequence. Oncoid shape can, thus, to some degree also be used as an indicator of water energy and not only of slow sedimentation rates which is already proposed (e.g. Peryt, 1981). However, caution must be taken though earlier incorrect hypothesis proposing that an appearance of oncoids generally should indicate high water energies (Peryt, 1981). It should also be mentioned that of the oncoids studied herein, intermediates between the "Cauliflower" forms and the very concentric ones occurred in various kind. I do not catalogue these as Ratcliffe (B-type) but they are without doubt a consequence of environments with water energy variation. Another complicating factor is that since oncoid shape is mainly regulated by water energy, wave-protected environments might display the same oncoid structures as forms grown on subtidal outer shelf. So to construct a correct interpretation of facies, caution must be taken to associated fossils, mud content etcetera.

Oncoids displaying hollow undersides are all of *in situ* grown "cauliflower" type. These cavities are a

frequent phenomenon that in some cases may reflect a disintegration of plant stems that acted as nucleus during growth (Flügel, 2004). In this particular case the hollow parts often reaches the skeletal nuclei whilst other sides have much larger cortex, all evidences for *in situ* growth and cavities shaped where light is absent. However, oncoids found in growth position also seem to form depressions on their upper side. It is however, interpreted rather as being a consequence of nucleus shape rather than a consequence of overturning or a morphology made for micrite-trapping. Surface depression can, thus, be located on either upper or lower side of *in situ* grown oncoids depending on the initial deposition of nucleus-forming bioclast.

Variation in matrix composition and origin, especially comparison between nucleus and the enclosing sediments, can somewhat give hints in a chronological aspect. A light micrite is for example more pure in the aspect of containing less siliciclastic material. Sampled oncoids processing a lighter micritic filling within nucleus than the surrounding matrix reflects thereby a transportation before or after microbial colonization. This is common in oncoids grown in quiet water condition but later re-arranged to storm deposits but the feature appears as well in oncoids with concentric lamination formed in constant higher water energies.

The different localities on Gotland discussed herein cover the Eke Formation from the lowermost part to the uppermost part. Oncoid formation in the uppermost parts of the formation (Ronehamn) reflect a somewhat deeper water setting than oncoids from example oncoids from Bodudd1. Thereby, it seems reasonable that the Eke Formation was deposited under a period of a minor transgression, in the degree of tens of meters. The basal Eke marked by conglomerates and paleokarst (Cherns, 1982; Eriksson & Calner, 2007) indicates equally that some sort of transgression is needed for the deposition of shallow and deeper subtidal sediments.

4.4 The Lau Event and CIE

Obtained δ^{13}C values match well the general evolution of the CIE recorded on Gotland since the slab measured derives from Ronhamn1 and represent, thus, the very upper part of the Eke Formation. Values deriving from oncoid cortex approach, as a result, the peak value obtained from the Eke Formation which is close to 9 ‰ PDB (Jeppsson et al., 2007). Also notable, is the somewhat lower values obtained in the light micrite within nucleus. These are more than 2 ‰ inferior compared to both oncoid cortex and enclosing matrix. It reinforces the interpretation that the lighter micrite was transported within nucleus before encrusted by calcimirobes since the calcification is in equilibrium with water composition.

The driving forces responsible for the extinction and the carbon isotope excursion are despite the models proposed during the latest decades, nevertheless unknown. Loydell (2007) summarize

possibilities for positive excursions during the Silurian pointing out carbonate weathering as a result from glaciations as the most probable. Other possible explanations are an increase in primary production as a function of a preferred uptake of the lighter ^{12}C isotope, massive carbon burial which would lock high quantities of ^{12}C from the carbon cycle and change of gas exchange rates between ocean and atmosphere by temperature and overall climate change. Despite the uncertainties, the explanation to the isotope anomaly is most likely to be more complex than just a single solution. Glaciations seem very possible. Primary production might also been increased by a mass abundance of calcimicrobes which amplified the excursion.

5 Conclusions

1) Oncoids deriving from the Eke Formation show different morphologies depending on paleo-bathymetry, even though the microbes forming them are throughout the same, *Rothpletzella* and *Wetheredella*. When formed in the shallow subtidal zone on the outer part of the carbonate shelf, with or without occasional storm deposits, big *in situ* grown "cauliflower" oncoids appear. In the shallow subtidal zone on the outer side of the platform, however, rounded smaller oncoids are to be found. The same reasoning applies for oncoids sampled at Bjärsjöla-gård.

2) The origin of the abundant oncoids in, mainly, the Eke Formation on Gotland and in the Bjärsjöla-gård Limestone is most likely due to a massive colonization of the ecologically more tolerant cyanobacteria (and microproblematica), which can be referred to as a disaster fauna. The presence of this fauna, being an indicator of changes in biological conditions, thereby favors the theory of an anachronistic facies associated with the Lau Event. Thereby, neither a relative increase caused by a disappearance of other species in the sediment nor a water chemistry variation by saturation of carbon dioxide is considered as major causes.

3) Most likely, an important reason behind the amplification of the positive δ^{13}C anomaly associated with the Lau Event is an increased primary production by the primitive ecological assemblage, *inter alia* forming oncoids and stromatolites. A possibility is that, before the event, the calcimirobes were restricted to larger water depth with lower light-concurrence for photosynthesis. In association to the extinction and lower concurrence or predation rate, however, they inhabited in the shallow marine setting and flourished as opportunists.

4) It seems most likely that during the deposition of the Eke Formation, the Baltic Basin was under phase of short-term transgression. It is indicated by larger oncoids deriving from the upper strata compared to the lowermost oncoids. It is also strengthened by the erosional relics found as conglomerates and palaeo-karst in the base of the Eke Formation and the supraimposing, shallow deposited sandstones.

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8 Appendix

8.1 Localities, Gotland

Bodudd1, 6329554 1644709, lower part of the Eke Formation.

Burgen8, 634840 166857, Burgsvik beds.

Petsarve4, 6338901 1657130, upper part of the Eke Formation.

Ronehamn1, 6341678 1662386, upper part of the Eke Formation.

Ronehamn2, 6341444 1661942, uppermost part of the Eke Formation.

Öndarve1, 634917 167234, base of the Eke Formation.

8.2 Locality in the Bjärsjölagård quarry

Bjärsjölagård quarry, 5543530, 01342276, Bjärsjöla-gård Limestone.

8.3 Values of isotope analyzes

Table 1. Results from isotope analysis. Sample numbers equals drillhole locations in fig. 4I.

Sample	δ13C*	Location
1	7.82	Matrix
2	8.12	Matrix
3	7.93	Matrix
4	7.87	Matrix
5	7.75	Matrix
6	6.03	Nucleus
7	6.29	Nucleus
8	6.40	Nucleus
9	5.83	Nucleus
10	8.33	Cortex
11	8.45	Cortex
12	8.52	Cortex
13	8.41	Cortex
14	8.37	Cortex
15	8.41	Cortex
16	8.53	Cortex
17	8.46	Cortex
	* Mean permil V-PDB	

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