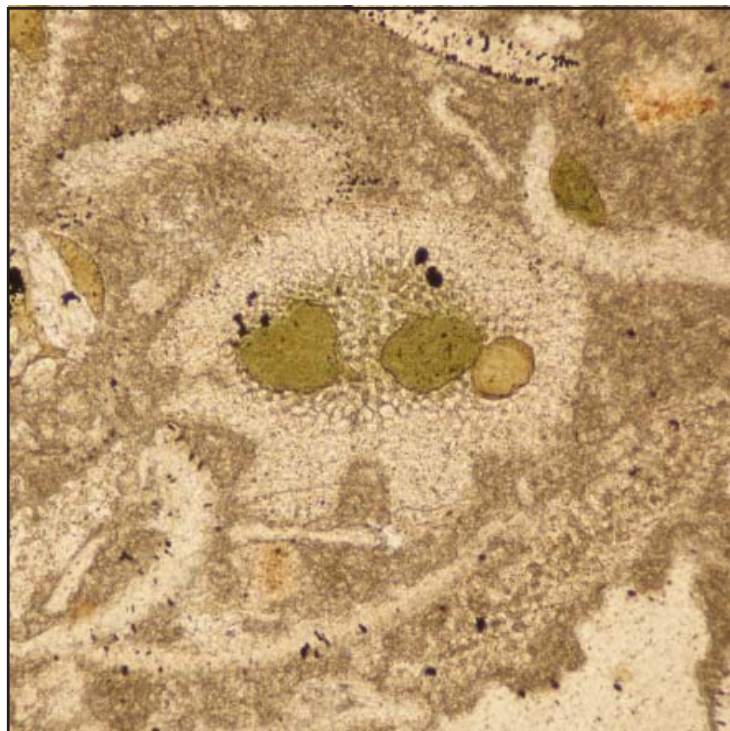


**From red to grey and back again:
A detailed study of the lower
Kundan (Middle Ordovician)
'Täljsten' interval and its
enclosing strata in Västergötland,
Sweden**

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Department of Earth- and Ecosystem Sciences
Division of Geology
Lund University
2010

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Cover picture: "Murray?" (no, it's just a somewhat piratey skeletal grain).

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Abstract: Lithologic and faunal characteristics of the anomalous lower Kundan (Darriwilian, Middle Ordovician) 'Täljsten' limestone interval and its enclosing strata have been studied at Kinnekulle (Västergötland, south-central Sweden). A 2.6 m thick rock succession has been sampled, resulting in thin-sections and acid-insoluble residues. Both lithology and fauna change markedly throughout the succession, as is visible at both macro- and microscopic level. Stratigraphically ascending, the lithology changes from red color in the Lanna Limestone to grey throughout most of the 'Täljsten' interval and then back to red again in the Holen Limestone. These changes are accompanied by a gradual transition from wacke- to packstones, and a reorganization of microfaunal components takes place in the 'Täljsten'. This faunal reorganization is most pronounced in the relative abundance of brachiopods and echinoderms. The former taxon first dominates among identified skeletal grains, but then notably declines in the lower half of the 'Täljsten', whereas the latter taxon increases and ultimately becomes dominant. Echinoderms are also abundant on a macroscopic scale in the 'Täljsten', in beds dominated by diploporite cystoids ('*Sphaeronites* beds'). A stabilization of faunal component relations is seen in the upper half of the 'Täljsten' and the superjacent Holen Limestone, where a new faunal association appears to have been established. These observations fit well with previous studies of the rock succession, and seem to be in concordance with prevailing views that the 'Täljsten' represents a regressive event.

Keywords: Täljsten, Lithology, Faunal changes, Lanna Limestone, Holen Limestone, Kinnekulle, Hällekis, Thorsberg, Ordovician, Sweden.

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Från rött till grått och tillbaka igen: En detaljerad studie av den mellanordoviciska (undre kunda) "täljstenen" och dess omgivande bergarter i Västergötland, Sverige.

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Sammanfattning: Fält-, mikroskop-, och litteraturstudier har utförts för att fastställa karakteristika rörande litologi och fauna i den mellanordoviciska (darriwilian, undre kunda), märkliga "täljstenen" (kalksten) och dess omgivande lager, som går i dagen vid Kinnekulle i Västergötland. En 2,6 m mäktig bergartssekvens har provtagits, resulterande i tunnslip och syraresistenta residualer. Både litologi och fauna genomgår anmärkningsvärda förändringar genom lagerföljden, vilket är synligt både på makro- och mikroskopisk nivå. Litologin förändras, i stratigrafiskt stigande ordning, från röda färger i lannakalkstenen till grått genom större delen av "täljstenen" och sedan åter till rött i holenkalkstenen. Samtidigt sker en gradvis förändring från wacke- till packstenar, medan en reorganisation av mikrofaunan sker i "täljstenen". Reorganisationen är tydligast gällande de relativa abundanserna av brachiopoder och echinodermer. Den förstnämnda djurgruppen dominerar först bland identifierade skeletala fragment, men uppvisar sedan en tydlig nedgång i den undre halvan av "täljstenen", samtidigt som den sistnämnda djurgruppen ökar och slutligen övertar den dominanta platsen. Makroskopiska echinodermer är också rikligt förekommande i "täljstenen", i lager dominerade av diploporida cystoidéer ("Sphaeronites-bäddar"). En stabilisering i faunan är skönjbar i de övre delarna av "täljstenen" samt i den överliggande holenkalkstenen, där faunan tycks ha antagit en ny sammansättning gällande olika djurgruppers relativa abundanser. Dessa observationer är samstämmiga med tidigare litologiska och faunistiska studier av bergartssekvensen och kan även tolkas som varande samstämmiga med de dominerande åsikterna, att "täljstenen" representerar en havsnivåsänkning.

Nyckelord: Täljsten, Lannakalkstenen, Holenkalkstenen, Kinnekulle, Hälleklis, Thorsberg, Mellanordovicium, Sverige.

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1 Introduction

This study aims to investigate the Middle Ordovician, so-called 'Täljsten' interval in Sweden. 'Täljsten' is the Swedish name for soapstone (or soaprock, steatite), but this particular rock interval is not to be confused with the metamorphic rock that a geologist would refer to as soapstone – it is a limestone, and the name has colloquial, non-formal, roots. Interrupting the reddish 'Orthoceratite limestones', the conspicuous 'Täljsten' is characterized mainly by its deviating grey color (Fig. 1). The fossil fauna of the 'Täljsten' seems to be just as peculiar as the lithology itself, and thus a large part of this study revolves around the fossil fauna connected to the studied rocks. Moreover, as will be described in closer detail throughout this thesis, the 'Täljsten' and its enclosing strata represent a very interesting chapter in the history of life.



Fig. 1. The studied and sampled strata in the Hällekis quarry, Västergötland, south-central Sweden, with the grey 'Täljsten' clearly visible along the approximate center of the photograph. Hammer (approximately 31 cm) for scale.

A succession some 2.6 m thick, containing the roughly 1.5 m thick 'Täljsten' interval, has been sampled and studied. The succession in its entirety is exposed in the abandoned Hällekis quarry at Kinnekulle, Västergötland, south-central Sweden (Fig. 2). Analogous strata are also exposed in the adjacent, active Thorsberg quarry, except for the lowermost part of the studied succession, which is below ground level.

In this thesis, efforts are made to characterize and describe variations in lithology and fossil grain composition throughout the studied succession, as recorded in sample materials. This allows for a more detailed interpretation of the environmental and depositional settings represented by the 'Täljsten' and its enclosing strata.

2 Materials & methods

2.1 Literature review

A multitude of publications, covering various relevant issues, were studied in preparation for – and throughout the course of – this study. The primary aim of this

exercise was to acquire a solid background knowledge on different aspects pertaining to the studied succession, and to compile an up-to-date review of the literature dealing with the 'Täljsten' interval, its enclosing strata, and correlative units.

2.2 Field studies

On location in Hällekis and in the nearby Thorsberg quarry, the strata were studied at a macroscopic level. These studies mainly resulted in a description of the *in situ* observations.

2.3 Thin-sections

Five standard petrographic thin-sections were prepared, from various levels throughout the studied succession. These were studied in detail under a petrographic microscope and interpreted according to methods described by Harwood (1988), Tucker (2001), and Flügel (2004). In addition, Adams *et al.* (1984) and Scholle & Ulmer-Scholle (2003) further aided in mineral and fossil identifications. Microfacies and various modal composition analyses were performed. The thin-section studies resulted in microfacies descriptions, rock classifications according to Dunham (1962 *sensu* Flügel 2004), and faunal composition determinations.

In order to classify the rocks, percentage of grains in relation to matrix was calculated for each thin-section, through point-counting. An automated microscope stage was used. Each count included 300 points and covered an area of approximately 1.5 cm² (total thin-section sample areas are approximately 6 cm² each). To enable assessment of grain-matrix relations also applicable on bulk rock samples, multiple hits per grain were allowed and subsequently counted. This means that large grains and endocasts (steinkerns) could be hit and counted multiple times. To minimize errant relative grain abundance assessments due to possible (and some suspected) grain concentration heterogeneities within thin-sections, all thin-sections were covered by two counts, each starting in opposing corners of the thin-section and moving in opposite directions. This proved to be superfluous in most thin-sections, but two of them were shown to harbor notable heterogeneous grain distributions. If nothing else, this test proved the reliability of the chosen point-counting technique. Mean values of paired count results were calculated, resulting in a total of 600 points counted and an area-coverage of approximately 3 cm² per thin-section.

In order to assess the faunal modal composition for the respective thin-sections, additional counts were performed, wherein skeletal grains were identified and counted. As above, each count included 300 hits, however, in order to get accurate modal composition data, multiple grain hits were not accepted this time. As different amounts of points were skipped due to matrix and/or multiple hits, the different counts covered varying area sizes. Eight grain categories, at different taxonomic levels, were used; Trilobita, Brachiopoda, Echi-

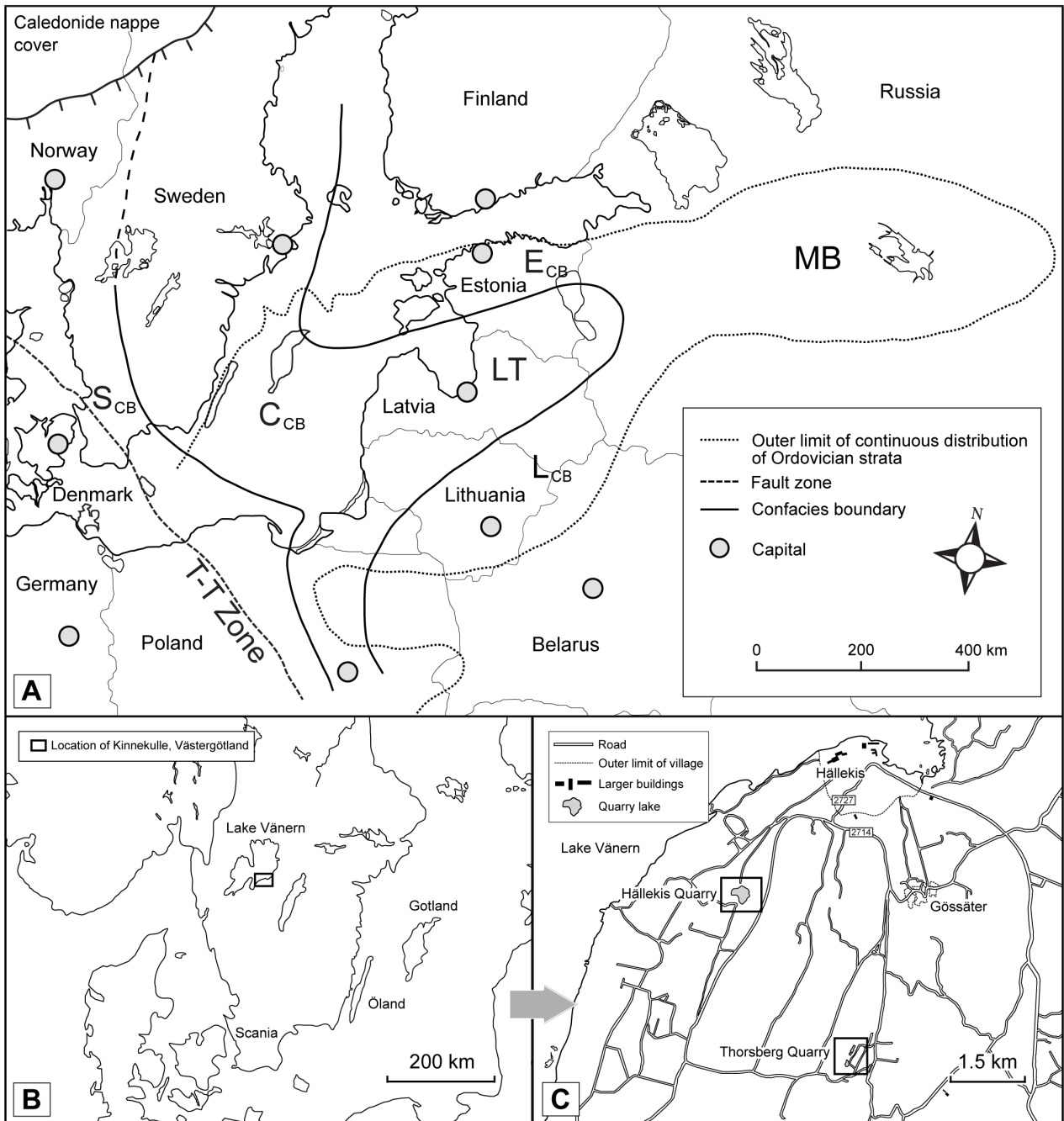


Fig. 2. **A.** Map of the Baltoscandian region, with the confacies belts (CB) defined. Abbreviations: C_{CB} – Central CB, E_{CB} – Estonian CB, L_{CB} – Lithuanian CB, LT – Livonian Tongue, MB – Moscow Basin, S_{CB} – Scanian CB. **B.** Map of southern Sweden, with the location of Kinnekulle. **C.** Map of the Kinnekulle area, with the locations of the Hällekis and Thorsberg quarries. Figure partly modified from Mellgren & Eriksson (in press).

nodermata, Gastropoda, Ostracoda, Mollusca (i.e. Bivalvia, Cephalopoda, etc.), Other (harboring minor – often ambiguous – observed components, such as Acritarcha, Bryozoa, Foraminifera, etc.), and Unidentified (simply carrying unidentifiable bioclasts; Fig. 3). The size of the smallest identifiable grains varies somewhat between the thin-sections, but approximately 100 µm can be considered a general lower size limit. In each thin-section, an individual minimum size of identifiable grains was determined, based on the overall grain features of the specific thin-section. All

grains smaller than this minimum size were purposely omitted in the counts, in order not to bias the results (as some taxa are much easier than other to identify in smaller grains). Consistency and assurance in identification were prioritized – when in doubt, the Unidentified category was applied. Various control- and test-counts yielded no notable discrepancies regarding relative abundance patterns – thus, 300 grain identifications per thin-section were considered as being sufficient (cf. Flügel 2004, chapter 6).

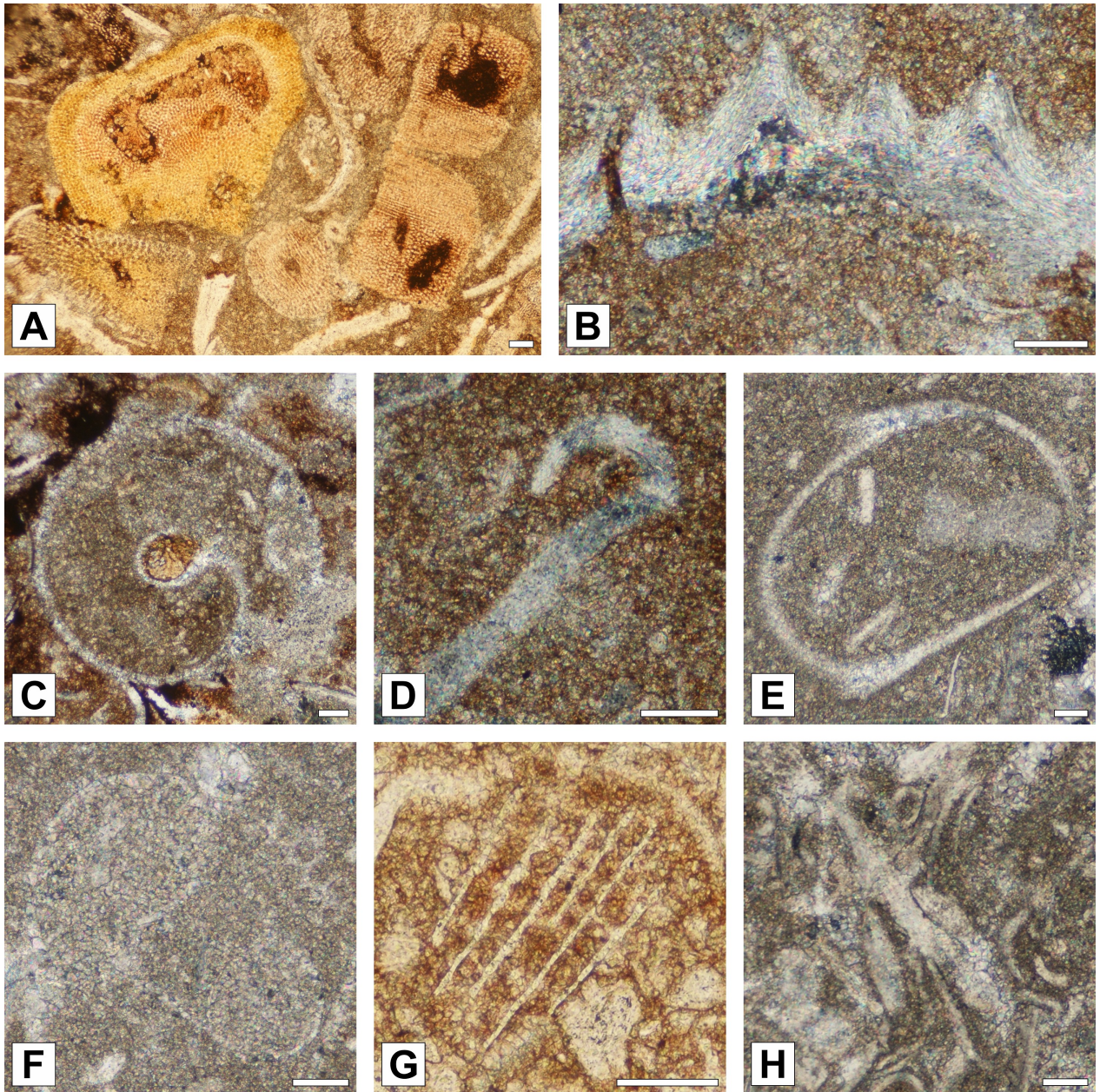


Fig. 3. Photomicrographs displaying examples of the different thin-section grain categories. Scale bar is 100 μm . **A.** A collection of Echinodermata grains, displaying characteristic stereom patterns and grain shapes. Less porous, lighter-colored brachiopod and trilobite grains are interspersed throughout (PPL; 'Rödarten', HÄ08-33). **B.** A typical grain identified as Brachiopoda, displaying a characteristic layered shell structure (XPL; 'Arkeologen', HÄ08-60). **C.** A typical grain identified as Gastropoda, displaying the characteristically coiled shell, which is recrystallized into fine-grained calcite spar (XPL; 'Rödarten', HÄ08-33). **D.** A typical grain identified as Trilobita, displaying characteristic light extinction and the unmistakable 'shepherd's crook' shape (XPL; 'Arkeologen', HÄ08-60). **E.** A rather favorably tilted grain identified as Ostracoda, displaying characteristically asymmetric shell valves (XPL; 'Likhall', HÄ07-13). **F.** A typical grain identified as Mollusca (XPL; 'Likhall', HÄ07-13). **G.** One of the few grains identified as Other, here interpreted as a fenestrate bryozoan (PPL; 'Arkeologen', HÄ08-60). **H.** A collection of grains typically categorized as Unidentified. Neither shape, texture, light extinction, nor birefringence confidently reveal their taxonomic affinity (XPL; 'Likhall', HÄ07-13).

2.4 Acid-insoluble sample residues

Previously prepared sample materials were kindly provided by Mats E. Eriksson. These comprise sample residues from the study of Mellgren & Eriksson (in press). The samples were taken from selected levels within the herein studied succession, then processed with acetic acid and buffered formic acid, and finally separated into different size and weight fractions. Conodonts were picked from the acid-insoluble residues, and the remaining material was made available for this exercise (for detailed information on laboratory methods, see Mellgren & Eriksson in press). The numerous sample residues were studied under a stereoscopic microscope (reflective light), and observations on fossil and mineral composition were noted and entered into a database (data courtesy of M.E. Eriksson). Five grain categories are discerned in the acid-insoluble residues; Brachiopoda, Gastropoda, Ostracoda, Echinodermata, and Other. Here, the Other category harbors both problematic and unidentified skeletal grains. Selected representative samples, highlighting variations throughout the studied succession, were photographed.

3 Geologic setting, stratigraphy, and previous studies

3.1 Palaeogeography and depositional setting

During the Middle Ordovician, the palaeocontinent Baltica was situated between southern temperate and subtropical realms, and steadily on a voyage northwards (Cocks & Torsvik 2006; Fig. 4). The palaeocontinent drifted at a fast rate, bringing it well into subtropical latitudes already by Late Ordovician times. Throughout the Ordovician, most of Baltica was covered by a relatively cold epicontinental sea of varying depth, overlying a rather featureless bottom topography (Nielsen 2004).

The Middle Ordovician of Sweden is characterized by condensed limestones, often in the form of red 'Orthoceratite Limestone', and argillaceous deposits such as marls, mudstones, and shales (e.g. Lindström 1963; Jaanusson 1972; 1976; Nielsen 2004; Tinn *et al.* 2006). Net sedimentation rates were low, and 1-9 mm per thousand years may be considered a reasonable estimate in the studied area (Nielsen 2004). Disconformities and hardgrounds are frequent, presumably due to alternating times of carbonate precipitation and dissolution/non-deposition (though, some authors have suggested times of sea-floor emergence as an underlying factor; e.g. Jaanusson 1961). Regionally, most rocks are poor in terrigenous materials (Lindström 1963; Jaanusson 1972, 1976; Nielsen 2004). This is not necessarily due to lack of relatively near-lying land masses at the time of deposition, but because the main sediment contributors were extensively peneplaned. As the Middle Ordovician of the Baltoscandian region

is characterized by low sedimentation rates and tectonic inactivity, documented sea-level variations likely represent eustasy (Nielsen 2004).

Sedimentologic and palaeontologic characteristics vary throughout the Baltoscandian region, giving rise to discernible facies zones, termed confacies belts (CB; Jaanusson 1972, 1976; Fig. 2A). These show a gentle and gradual shallowing in water depth, roughly from southwest to northeast, at the time of deposition. The herein studied succession, located in the boundary zone between the Central Baltoscandian CB and the Scanian CB, is thus considered to have been deposited in intermediate to moderately deep parts of the palaeo-basin. Opinions on the general water depths in this area differ quite a bit – estimations vary from depths within the photic zone to depths of hundreds of meters (e.g. Lindström 1963; Tinn & Meidla 2001; Tinn *et al.* 2006).



Fig. 4. The approximate location of Baltica during the lower Kundan, at approximately 466 Ma. The palaeocontinent was situated between southern temperate and subtropical realms. This paleogeographic reconstruction was made using the software *BugPlates* (courtesy of StatoilHydro), developed by Trond H. Torsvik (www.geodynamics.no).

3.2 The studied succession in closer detail

3.2.1 Stratigraphy and partitioning

The studied succession is part of the regional, so-called Lanna and Holen limestones, where the base of the 'Täljsten' marks the base of the Holen Limestone (e.g. Tinn & Meidla 2001; Tinn *et al.* 2006; Fig. 5). These limestones are variously described as (calcareous) calcilitites, wackestones, and packstones (e.g. Lindström 1963; Jaanusson 1972). The strata at Hällekis have a total thickness of about 27 m, of which the 'Täljsten' interval is approximately 1.5 m thick

3.2.2 General lithologic and palaeoenvironmental characteristics

The depositional setting of the studied limestones is generally described as a cool-water (deep) shelf basin (e.g. Dronov *et al.* 2001; Nielsen 2004). Lindström (1963) convincingly advocated a deep-water setting, without episodes of subaerial exposure. More specific details promoting this view include, for example, the extremely low rates of carbonate production, and lack of algal limestones and calcitic ooids (also, hard-ground beds display evidence of continuous submergence). Jaanusson (1972), when discussing water palaeotemperatures, noted that there are recent algae that can contribute to carbonate production, though their aragonitic composition suggests that they would not be preserved as fossils, and also that ooids are not always found in shallow water settings. The numerous hard-grounds found in the limestones show signs of alternating carbonate precipitation and dissolution events, indicating frequently fluctuating pH values through time (Lindström 1963). Alternating Eh (redox) conditions were also recurrent, with resulting chemical environments perhaps tied to the pH fluctuations (through H₂S formation, lowering pH). Reigning Eh conditions affect rock color, through influence on dominant iron compound formation (i.e. ferric and ferrous iron oxides).

3.2.3 Fossil fauna

The macrofossil content of the studied succession is often described as poor, though some beds can be fossiliferous (Lindström 1963; Paul & Bockelie 1983). As can be expected from the informal name attached to the red limestones, they are characterized by conspicuous nautiloid cephalopods. Other relatively common macrofossils include trilobites (predominantly asaphids) and brachiopods (both inarticulate and articulate). Typical microfossils include echinoderms, trilobites, brachiopods, gastropods, ostracods, and conodonts. Examples of more fossil-rich beds, are the conspicuous '*Sphaeronites* beds' in the 'Täljsten', which are entirely dominated by abundant diploporite cystoids (*Sphaeronites* sp.; Paul & Bockelie 1983).

3.2.4 The 'Täljsten' interval

It has been repeatedly suggested that the 'Täljsten' interval represents a shallowing event. Dronov *et al.* (2001) interpreted the sequence of lithologies throughout the Lanna and Holen limestones as reflecting a shallowing event in a deeper shelf environment, with a transgression taking place towards the top of the 'Täljsten' interval. They also tied the event to lithologies in other regional localities (see below). Tinn & Meidla (2001) interpreted ostracod species variations occurring throughout the studied succession as a possible result of a regressive event, with indications of a relatively high-energy environment in the 'Täljsten'. Their conclusion regarding the general water depth in the area, is that the ostracod fauna possibly represents

the uppermost aphotic zone. Based on conodont species dynamics, Mellgren & Eriksson (in press) also came to the conclusion that a shallowing event has taken place. According to their data, a regression was likely initiated in the lower parts of the 'Arkeologen' bed. The lower half of the 'Täljsten' then displays a gradual shallowing, climaxing around the 'Blymåkka' bed (and from thereon cystoid presence increases, while conodont quantities decrease). A transgression follows towards the top of the 'Täljsten', as is inferred by certain conodont species in the uppermost part of the interval. Mellgren & Eriksson (in press) also noted that the boundary between 'Likhall' and 'Flora' may represent a depositional break.

On a more general note, the time around the Volkhov-Kunda boundary is associated with a series of sea-level drops in the Baltoscandian region, estimated to a maximum of 30-40 m (Dronov 2004). Nielsen (2004) described the base of the Kundan as representing a major lowstand, followed by an even more prominent lowstand around the base of the *A. raniceps* Zone (compare with results from Mellgren & Eriksson in press, above). These lowstands resulted in, for example, lithologic changes in Sweden, and in large unconformities in Estonia.

Paul & Bockelie (1984) noted a strong preferred orientation in cephalopod shells in some beds, consistently indicating currents from the north (though, generally there is no preferred shell orientation in the studied succession, according to Schmitz *et al.* 2001). Paul & Bockelie (1984) also noted that cystoid fossils display time-averaging, as younger specimens are found attached onto older ones showing evidence of already being dead for some time before attachment (of the younger).

The 'Täljsten' interval is correlated to other distinctive rock units within the Baltoscandian Basin, and also in other palaeocontinents (Dronov *et al.* 2001; Mellgren & Eriksson in press). In the closest geographic vicinity, the 'Täljsten' has been recorded on Mount Billingen, and further to the southeast in the Degerhamn quarry, Öland (both localities in Sweden). Regionally, the 'Täljsten' has been identified in the 'Tartu drill core' from southeast Estonia. Some individual 'Täljsten' beds can be traced among different localities – for example, '*Sphaeronites* beds' have been observed on Öland (Stouge 2001). Towards the northeast, the interval grades into the iron ooid-rich 'Lower Oolite Bed', which corresponds to the Sillaoru Formation in north Estonia and the lower part of the Obukhovo Formation in northwestern Russia (Dronov *et al.* 2001). In Latvia, the Šakyna Formation is correlated to the 'Täljsten' (Nielsen 2004). Some contemporaneous strata in other parts of the world also show anomalous lithologies (e.g. the Chinese 'mini-mounds' mentioned by Schmitz *et al.* 2008).

3.2.5 Extraterrestrial component

The studied succession is unusually rich in extraterres-

trial matter (e.g. Schmitz *et al.* 2001, 2003, 2008). Findings of more than 50 fossil meteorites and elevated levels of extraterrestrial chromite, together with other signals, reveal an elevated influx of extraterrestrial matter just before, during, and slightly after the time of the 'Täljsten' deposition. An influx peak is apparent in the 'Arkeologen' bed. Higher concentration of extraterrestrial matter due to changes in sedimentation rates were ruled out by Schmitz *et al.* (2003, 2008), though some concentration may have been induced by sediment winnowing due to bottom currents (Schmitz *et al.* 2001).

Various analyses have shown that the meteorites (and the extraterrestrial chromite grains) have their origin in a disruption of a parent-body at about 470 Ma, which gave rise to the so-called L-type chondrites (Schmitz *et al.* 2001, 2003, 2008). Furthermore, there seems to be a global increase in impact craters around this time. Today, about 20% of the meteorites reaching Earth actually seem to derive from the same parent-body as the ones found in these Middle Ordovician strata.

3.3 The Great Ordovician Biodiversification Event and the studied succession

The Ordovician Period was characterized by extensive faunal diversification (e.g. Webby *et al.* 2004; Rasmussen *et al.* 2007; Schmitz *et al.* 2008; Servais *et al.* 2009). Following the well-known Cambrian explosion, diversity at the order, family, and genus levels increased markedly during a relatively brief time-span (about 25 Ma) in the Ordovician. Most metazoan groups underwent rapid evolution, both concerning complexity and mode of life. This has been termed the Great Ordovician Biodiversification Event (GOBE). A notable result was that trilobite-dominated shelf ecosystems of the Cambrian Evolutionary Fauna were largely replaced by filter-feeding benthos – brachiopods in particular – and various burrowers of the Palaeozoic Evolutionary Fauna (e.g. Sepkoski 1981; Webby *et al.* 2004).

Several hypotheses as to why the diversification took place have been proposed. Plausible causes mostly involve various favorable environmental conditions (Servais *et al.* 2009). A relatively warm global climate, accounted to high CO₂ levels, is considered as being beneficial to life in general. A tectonic plate distribution with many separate continents combined with generally high sea-levels, resulting in large shelf areas available for colonization, likely promoted (endemic) speciation. Large-scale volcanism together with an increase in phyto- and zooplankton, providing nutrients and broadening trophic systems, are also considered as being of importance. It is not farfetched to assume that a combination of these factors jointly promoted diversification (and, naturally, many scientists believe this to be the case). Additionally, Schmitz *et al.* (2008) argued that an increased flux of meteor-

ites may have stimulated the diversification process – relatively small-scale disturbances seem to have this effect.

On a global scale, a multitude of taxa showed remarkable increase in diversity around the Arenig-Llanvirn boundary, approximately 466 Ma (e.g. Webby *et al.* 2004; Schmitz *et al.* 2008). Thus, the diversification coincided with the interval embraced in the studied succession, although it should be noted that global, precise age-correlations between local as well as regional biodiversity curves may be difficult to make.

Tinn & Meidla (2001) documented an ostracod diversification occurring around the Volkhov-Kunda boundary and in the lower Kundan, at Hällekis. Their samples cover the entire Lanna and Holen limestones, and the 'Täljsten' and its adjacent strata show the highest species diversity (and include some short-ranging taxa). Tinn *et al.* (2007) observed a similar ostracod diversification, at the Gullhögen quarry of Mount Billingen (also in Västergötland), and noted that nine new taxa appeared in the 'Täljsten'. Moreover, similar results were described by Tinn *et al.* (2006), using samples from many localities in the Baltoscandian region.

Mellgren & Eriksson (in press) conducted thorough studies of the conodont fauna at Hällekis. The lower parts of the succession show both increasing species diversity and abundance. Species diversity peaks in the 'Täljsten', whereas abundances decline. About halfway through the 'Täljsten', a decline in species diversity was also observed, coinciding with the lowest abundances. Mellgren & Eriksson (in press) correlated this to the time of maximum regression. The upper part of the succession displays a return to pre-'Täljsten' environmental conditions, though some differences in conodont species composition are apparent.

Paul & Bockelie (1983) documented speciation among diploporite cystoids throughout the studied succession, although it should be noted that only two species (*Sphaeronites minor* and *S. pomum*, with only the former being found in lower parts of the succession) were observed – albeit in very large numbers. Rasmussen *et al.* (2007) recorded a brachiopod diversification spike in strata of this age in the Eastern Baltic region. Diversity reached its peak during the transgression corresponding to the upper half of the studied succession. This was discussed also by Schmitz *et al.* (2008), noting high extinction and origination levels.

4 Results

4.1 Field studies

Close visual inspection was performed at both the Hällekis and the Thorsberg quarries. The strata at these localities are easily correlated. The red 'Orthoceratite limestones' clearly dominate the quarries, with colors varying from deep brownish-red, through green and yellow hues, to light grey. Variegation is often apparent – more so in some levels than others – but the

overall color impression is a rusty light red tone. The 'Täljsten' interval is often easily discerned in the exposed strata, and superficially gives an impression of being rather homogeneously light grey in color. In some sections, however, large parts of the interval may display a greenish tint. The general thickness of the 'Täljsten' is roughly 1.5 m at both localities, though the grey interval thickness and boundary sharpness vary to some extent – in places, the color shifts between the 'Täljsten' and enclosing strata display a more gradual fashion, but often the boundaries are rather sharply defined. The underlying red 'Arkeologen' limestone is not vertically exposed in the active Thorsberg quarry, as it presently constitutes the quarry ground level (a few sawed slabs exempted).

At both quarries, *Sphaeronites* sp. cystoid echinoderms become increasingly abundant a few decimeters above the base of the 'Täljsten'. In the Hällekis quarry, the most obvious cystoid presence occurs near the top of the grey part of the 'Täljsten' interval, in a rather conspicuous '*Sphaeronites* bed' (corresponding to the uppermost 'Fjällbotten' quarry unit; Fig. 6). Cystoids also occur lower in stratigraphy, but the rough vertical quarry surfaces, together with variable weathering, provide some difficulties in studying the exposed beds in more detail.



Fig. 6. A conspicuous '*Sphaeronites* bed', dominated by diploporite cystoids, in the Hällekis quarry. The traditional quarry units visible in the photograph are, in stratigraphically ascending order, 'Fjällbotten' and 'Likhall' (the compass is placed on the quarry unit boundary, approximately along the center of the photograph). Compare with Fig. 7.

The freshly-sawed strata at Thorsberg, on the other hand, provides excellent surface exposures to study. There, *Sphaeronites* presence becomes increasingly visible approximately 60 cm above the base of the 'Täljsten' (around the 'Gråkartan'-'Blymåkka' boundary), and a rather weakly developed '*Sphaeronites* bed' is found at approximately 80 cm (within 'Fjällbotten'). Following upwards are two particularly distinct such beds, at approximately 95 and 115 cm from the 'Täljsten' base (in the upper parts of 'Fjällbotten' and 'Likhall', respectively). The most pronounced '*Sphaeronites* bed' seems to be the one at approximately 95 cm (Fig. 7). There seems to be an increase in general cys-

toid size (with individual diameters ranging from approximately 1 to 4 cm) upwards in the 'Täljsten', and the largest specimens were found in the bed at 115 cm. These observations, measurements and relative '*Sphaeronites* bed' distances correlate rather well with the results of Paul & Bockelie (1983). Quarried slabs exposing '*Sphaeronites* bed' surfaces were available for detailed study. The *Sphaeronites* dominance is unmistakable – one is certainly hard-pressed to find other macrofossils in these beds!

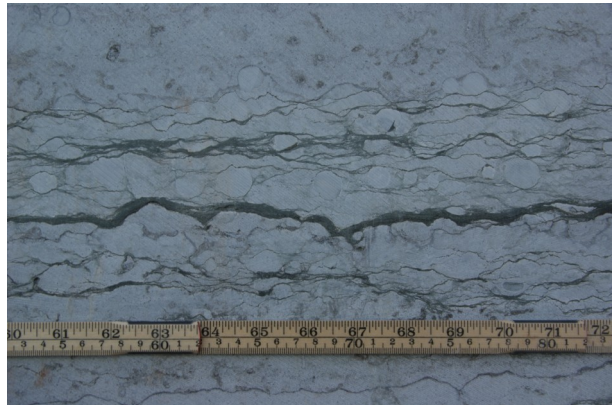


Fig. 7. A '*Sphaeronites* bed' in the Thorsberg quarry. The traditional quarry units visible in the photograph are, in stratigraphically ascending order, 'Fjällbotten' and 'Likhall' (the boundary between the quarry units is along the conspicuous, dark bed level, approximately centered in the photograph). Compare with Fig. 6.

In addition to the cystoids, cephalopods are the most conspicuous macroscopic fossils at both localities. In the Thorsberg quarry, a few freshly-sawed, hollow cephalopod shells displayed some dark fluid coming from them, shown by Worm Andersen & Buchardt (2001) to be oil. Trilobite body parts, preferentially pygidia of varying sizes, are also common throughout the studied succession. Some fossil shell cavities show an apparent stepwise infilling of sediments and calcite crystals, perhaps a testament to the generally low sedimentation rate. The infill material contacts may act as geopetal indicators, and varying tilting relative to the rock bedding may indicate that some reworking has taken place through time. This was noted also by Paul & Bockelie (1983). In the Hällekis quarry, putative crinoid holdfasts were observed in the 'Täljsten'. Pelmatozoan stem fragments were also observed, but their stratigraphic origin is slightly uncertain (they were found in weathered grey limestone masses, probably of 'Täljsten' origin).

Numerous bed levels, often clearly visible at both localities, are interpreted as hardgrounds. Other beds, such as some '*Sphaeronites* beds', appear to have been at least somewhat lithified before continued deposition. A number of beds also show vertical and horizontal streaks and shapes of varying sizes and colors, interpreted as animal burrows. Accumulations of darker materials, presumably concentrated siliciclastic clays, occur in some beds in the 'Täljsten'. Also of interest,

are some rather conspicuous dark green-colored bands, presumably stained by glauconite (a hydrous K-Fe-Al-Si mineral; Adams *et al.* 1984; Flügel 2004). These occur in both the red and grey strata, and are especially prominent in some 'Täljsten' exposures. Glauconite is also believed to be responsible for tinting parts of the 'Täljsten', as described above.

4.2 Thin-section microfacies analyses

All samples display a lime-dominated, muddy matrix laden with skeletal grains (allochems). Some thin-sections have sparry areas, perhaps as a result of infilling of hollows or (partial) hardground formation. Stratigraphically ascending, an increase in relative amount of grains (compared to matrix) is clearly visible. The studied succession thus passes from wacke- to packstone in textural composition.

The state of skeletal grain preservation varies between the different thin-sections, and sometimes even within different parts of a thin-section. In general, the state of preservation deteriorates throughout the succession, and maximum grain size increases. The shells of molluscs (both the Gastropoda and Mollusca categories) are more or less always substituted by calcite spar (henceforth, unless the explicit terms Gastropoda and Mollusca are used, the term mollusc and its varieties refers to molluscs in general). Some other grains, preferentially larger trilobite fragments, are also substituted by calcite spar, especially in the 'Likhall' bed (sample HÄ07-13). The degree of bioturbation varies throughout the sampled levels, though it is generally perceived as more extensive in higherlying strata. Shell-borings are frequent throughout all samples.

In some thin-sections, there is evidence of authigenic mineralization inside shells and carapaces, resulting in endocasts of various colors. The most abundant minerals seem to be glauconite and various iron compounds (e.g. hematite and goethite/limonite). Below follows detailed descriptions of the thin-sections, in stratigraphically ascending order. Accompanying descriptions of skeletal grain compositions are provided in Chapter 4.4.1.

4.2.1 'Arkeologen' (HÄ08-60)

This thin-section is light beige-red to rusty brownish-red in color (Fig. 8A). The matrix is micrite-like, with some slight variations in finer textures. It is relatively evenly, but generally not very densely, laden with skeletal grains. Mean skeletal grain size is estimated to approximately 200 µm, with sizes ranging up to approximately 2 mm. There seems to be no porosity to speak of. Some (relatively) large-scale features are visible. A bleak beige, roughly circular shape is visible towards one end, covering about one-tenth of the thin-section. A red-to-brown-variegated, oblong streak is also visible, cutting diagonally across most of the thin-section lengthwise. Along the length of the streak, its boundaries become increasingly sharply defined, and increasingly surrounded by lighter-colored material.

The streak ends in a rounded shape with mottled rims. Some darker-colored flow patterns are apparent within the streak. The sediments in the described features are seemingly of the same composition and texture as that of the surrounding rock, thus differing only in color. Bioturbation is rather extensive throughout the thin-section – some areas display conspicuous swirling motion, accompanied by streamlined grain concentrations.

The general state of grain preservation is fair to good, regarding extent of fragmentation and retention of grain edge definitions (i.e. lacking micritization, signs of dissolution, etc.). Gastropods (some rather well-preserved) are readily visible at a superficial level, as are echinoderm and trilobite parts, and ostracod and brachiopod valves. Mollusc shells are consistently replaced by calcite spar. Some other grains also display such recrystallization, albeit often only partially, and preferentially in larger grains. Partial infilling of coarser calcite is present in some gastropod shells. Borings, varying in effect and extent, are present in some shells.

The rock in this sample is clearly matrix-supported. Grain concentration displays some variations, though generally it is intermediate, with quite some space between grains. Point-counting reveals a rock composition with approximately 63% matrix (Fig. 9). According to the Dunham classification system, it is classified as a wackestone. A fitting microfacies name is skeletal wackestone.

Remarks. – The circular feature described is reminiscent of that of animal burrowing action. However, this is opposed by the fact that some grains seem to cut the rims of the shape – but that detail may just indicate rather soft substrate burrowing. The streak-shape is definitely interpreted as being a result of burrowing, as it is very sharply defined and it cuts grains (perhaps it was made after some substrate lithification had taken place). The lighter-colored matrix in connection to these features is likely a result of microlocal anaerobic/anoxic conditions, perhaps as a result of detritus accumulation and accompanying metabolism. Recrystallization of (preferentially aragonitic) shells is generally interpreted as being relatively early, as is indicated by some later (mostly rather minute) dissolution features along shell surfaces. Most gastropods – at least among less fragmented, favorably oriented specimens – seem to carry oblong shell shapes ('*Turritella* sp. in miniature'). A majority of the recognizable echinoderm grains are various forms of pelmatozoan appendages (but most echinoderm grains are shapeless, unidentifiable stereom masses). One of the more interesting problematic fossils is present in this sample (Fig. 10A). It is remarkably reminiscent of a tabulate coral (cf. Flügel 2004, pp. 510-511, plate 83:11). Information on the first tabulate coral appearance in Sweden has not been found, though in Estonia they are not reported until the late Caradoc (Mõtus 1997).

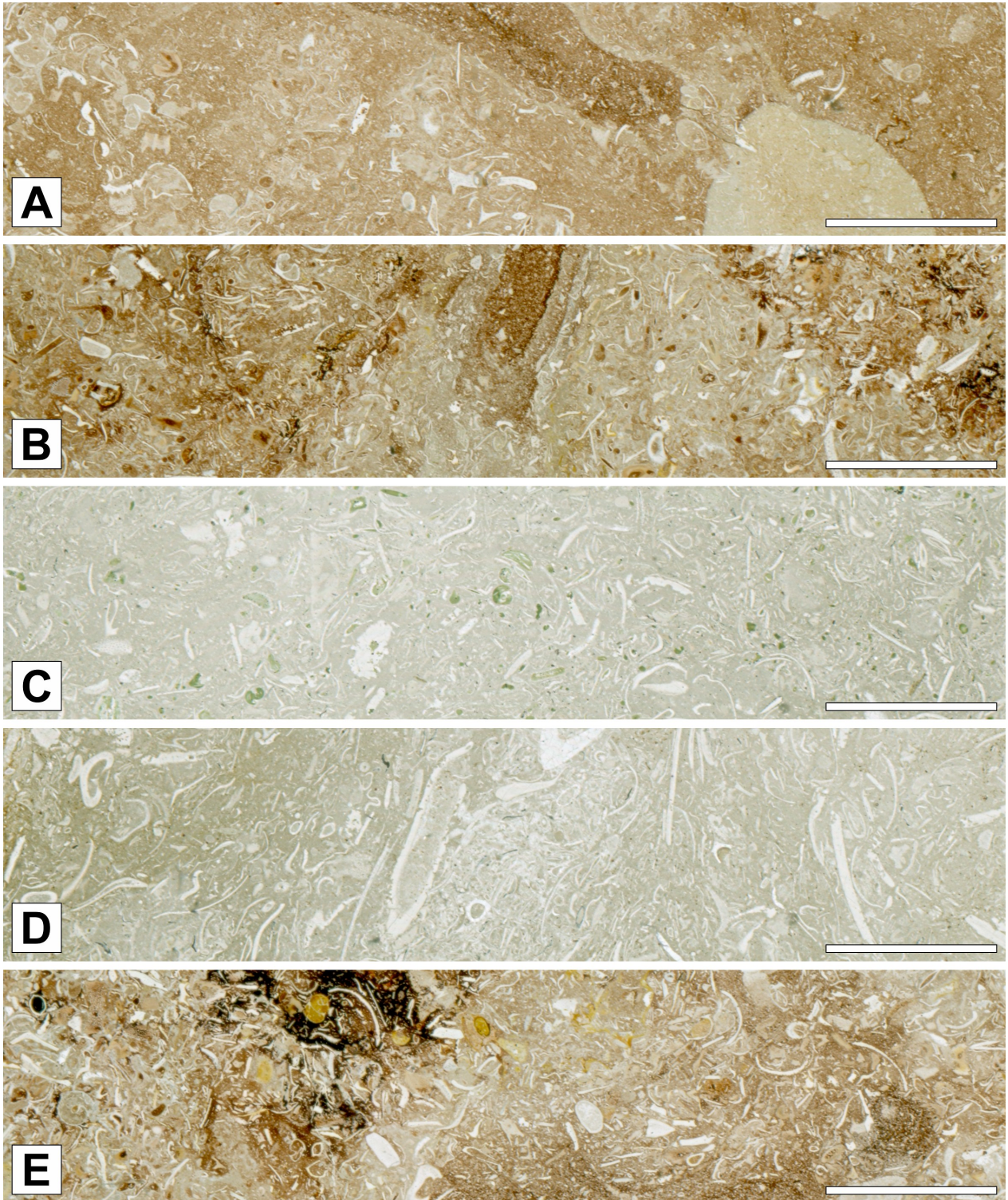


Fig. 8. Photographs displaying characteristic portions of the thin-sections (original images courtesy of Sanna Holm). Scale bar is 0.5 cm. Note that magnification is the same in all images, to allow for more straightforward comparisons between samples. **A.** 'Arkeologen' (HÄ08-60). Note the dark-colored feature protruding from the top center of the image, and the light-colored, spherical feature towards the lower right. Both features are interpreted as burrows. **B.** 'Golvsten' (HÄ07-2). Note the tube-like feature in the top center of the image. It is interpreted as a burrow. **C.** 'Gråkartan' (HÄ07-7). Note the numerous greenish speckles. These are interpreted as authigenic glauconite, which has filled hollows and produced endocasts. **D.** 'Likhall' (HÄ07-13). Note the heterogeneous grain distribution, and the abundance of larger grains. **E.** 'Rödkartan' (HÄ08-33). Note the golden-yellow endocasts, in and around the dark feature slightly left of the top center of the image. The endocasts are presumably colored by goethite/limonite, and the dark feature is interpreted as a burrow.

4.2.2 'Golvsten' (HÄ07-2)

This thin-section generally is light beige in color (Fig. 8B). Towards one short end, there is some more pronounced reddish-brown mottling, strewn with small black stains. As in the preceding sample, the matrix is micrite-like. Parts of the thin-section display a slightly coarser calcite interspersed in the matrix, perhaps best described as microspar (henceforth, the likes will be described as such). Compared to the preceding sample, this thin-section shows an obvious increase in skeletal grain abundance. Mean skeletal grain size is estimated to approximately 300 μm , with sizes ranging up to approximately 4 mm. Porosity is absent. The most pronounced larger-scale feature is a black-rimmed ring-shape (approximately 0.25 cm^2), situated towards one corner. Its rim is more or less opaque in both plane-polarized light (PPL) and cross-polarized light (XPL). Roughly in the middle of the thin-section, a beige-to-reddish-brown-variegated streak-/tube-shape cuts into the matrix from one of the long sides. Sediment partitioning in the streak gives an almost three-dimensional impression of having filled a tubular hollow. The streak is surrounded by seemingly rearranged skeletal grains, and a rim of lighter-colored matrix (compare with description and remarks above). Cutting laterally across some parts of the thin-section, are also what looks like submillimeter-sized brittle cracks, all arranged in roughly the same direction. Some (preferentially vertical) movement is implied along parts of the cracks (cut grains are not traceable on both sides). Bioturbation appears to be thorough in this thin-section.

The general state of grain preservation varies from poor to rather good. Some grains display a fuzzy rusty-reddish rim, reminiscent of micritization. Filled hollows display some brown-colored (sometimes better described as 'dark amber') material, showing roughly the same color in both PPL and XPL. Echinoderms, generally yellow-beige-colored, are conspicuous. Trilobite parts and brachiopod and ostracod valves are also readily visible, as are molluscs, though gastropods are generally fragmented. Again, molluscs display recrystallization into calcite spar, as do some other, often relatively large, grains. A few gastropods display complete shell dissolution, and are only identified by the distinct shapes of their endocasts. Some skeletal grains show extensive signs of boring activity, with jagged surfaces and vertical holes – sometimes even rather large grains are completely pierced.

The rock in this sample is neither clearly matrix-, nor grain-supported. Grain concentration is mostly very high – often with grain surface contact – though some variations in grain concentration are apparent. Point-counting reveals a rock composition with approximately 42% matrix (Fig. 9). According to the Dunham classification system, it is classified as a packstone. A fitting microfacies name is skeletal pack/wackestone.

Remarks. – Microspar indicates diagenetic influence

on the original matrix. The above described ring-shaped feature is interpreted as a burrow made in a sublithified substrate, later to have its rims partly dissolved and infilled with some dark, unidentifiable material (oil/organics?). The streak-shape is reminiscent of the bottom part of a *Diplocraterion* ichnofossil viewed from the rock surface down. Brownish and yellowish materials are assumed to be colored by various iron compounds, such as hematite and/or goethite/limonite. According to Jaanusson (1972), the micrite-like coatings on grains are iron oxide. A majority of the recognizable echinoderm grains are pelmatozoan appendages.

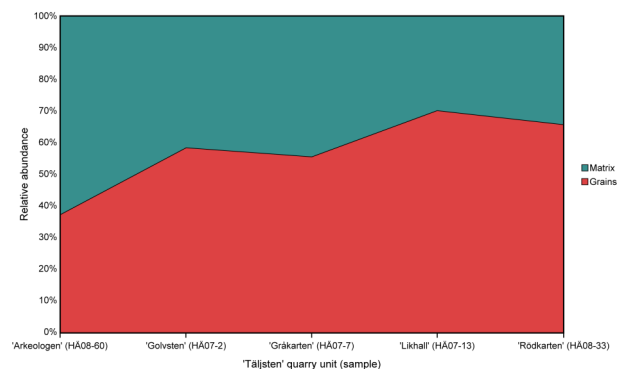


Fig. 9. Variations in grain-matrix relations throughout the studied succession. Stratigraphically ascending, the relative amount of skeletal grains increases, with some fluctuations. A slight matrix decrease is apparent in the topmost thin-section.

4.2.3 'Gråkartan' (HÄ07-7)

This thin-section is rather homogeneously light grey in color, and strewn with green mineral speckles (Fig. 8C). The matrix is fine-grained and homogenous (again, micrite-like). Skeletal grains are abundant, and the relative amount of larger grains seems to have decreased slightly compared to the preceding thin-section. Mean skeletal grain size is estimated to approximately 300 μm , with sizes ranging up to approximately 4 mm. There is no visible porosity. This thin-section lacks obvious larger-scale features – a few bleak, rusty-orange mottlings are visible as wisps through the matrix, some with faint brittle cracks in their centers. Very small (approximately 10-50 μm) aggregates containing dark, anhedral mineral grains are found on some skeletal grains throughout the thin-section. The aggregates are opaque in both PPL and XPL, and appear black under reflective light. Additionally, whitish-light-blue (both in PPL and XPL), sub-hedral crystals (generally around 50 μm in size) are found throughout the thin-section. Bioturbation has disturbed and sometimes aligned grains.

The general state of grain preservation is fair. A green mineral – light olive-green to light brownish-green in PPL, dark green in XPL – fills many fossil body cavities, producing some sharply defined endocasts. At a superficial level, relatively large shell

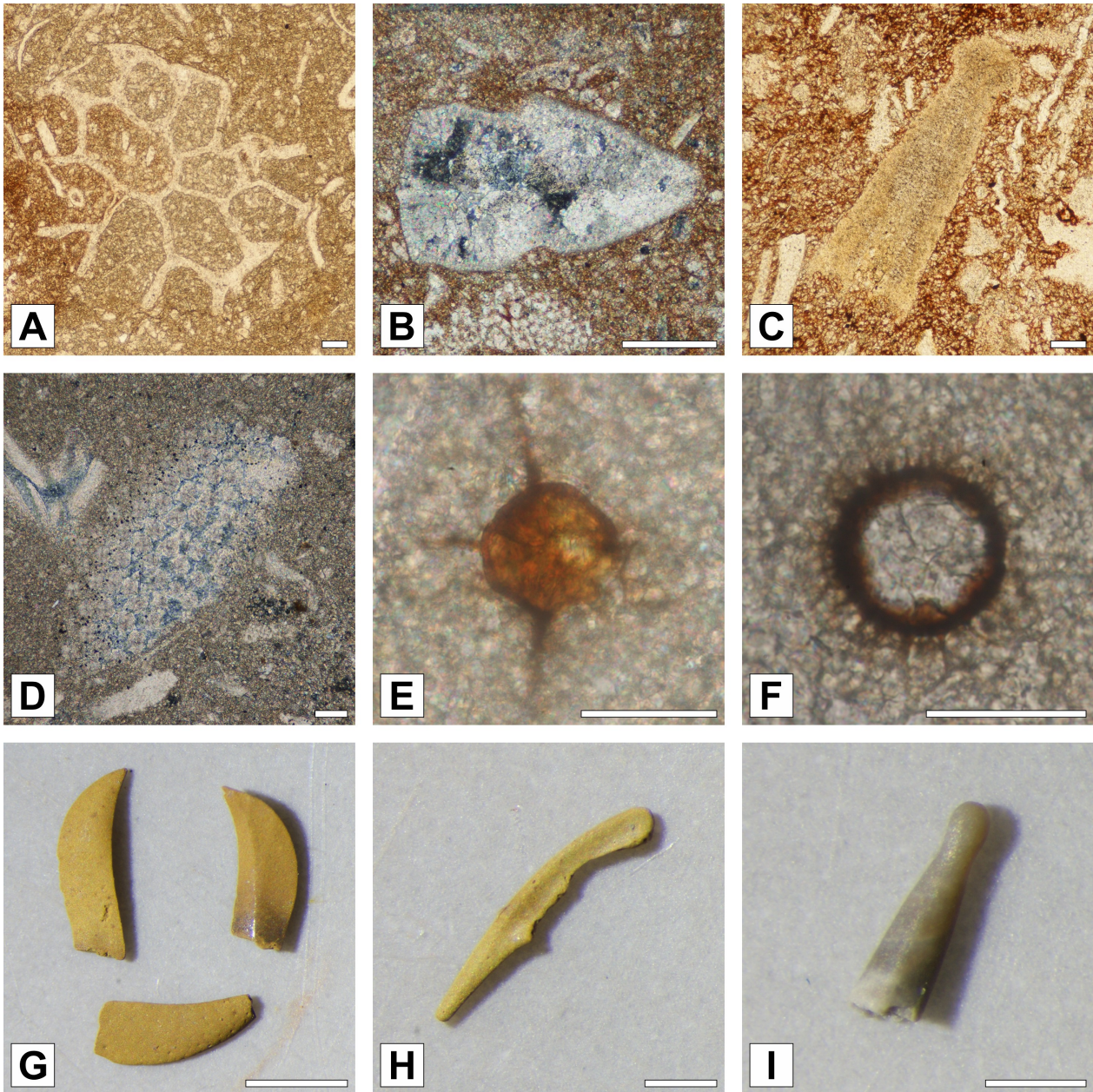


Fig. 10. Photomicrographs displaying examples of some odd and/or problematic grains, both from thin-sections and acid-insoluble residues. **A.** A specimen remarkably similar to a tabulate coral. Scale bar is 100 μm (PPL; 'Arkeologen', HÄ08-60). **B.** A calcite-filled specimen with an enigmatic shape. Scale bar is 100 μm (XPL; 'Arkeologen', HÄ08-60). **C.** A possible echinoderm spine. Such objects also occur in the acid-insoluble residues (compare with Fig. 10I). Scale bar is 100 μm (PPL; 'Rödarten', HÄ08-33). **D.** A grain reminiscent of a pseudopunctate brachiopod shell. Scale bar is 100 μm (XPL; 'Gråarten', HÄ07-7). **E.** A putative polygonomorph acritarch. Scale bar is 50 μm (XPL; 'Likhall', HÄ07-13). **F.** A putative sphaeromorph acritarch. Scale bar is 50 μm (PPL; 'Likhall', HÄ07-13). **G.** These knife-like endocasts are common in the residues, but their affinity is uncertain. Perhaps they are trilobite parts (compare with tips on some thoracic pleura, for example). Note the punctate pattern in the lowermost specimen. Scale bar is 1 mm (reflective light; 'Mumma', HÄ08-31). **H.** Endocasts similar to this one are numerous in the residues, with some variations in shape and size. One specimen side (here, to the right) always appears to be broken along a suture-like surface. These grains may represent trilobite librigena. Scale bar is 1 mm (reflective light; 'Mumma', HÄ08-31). **I.** These objects are common in the residues. The body is a flattened cylinder, and the bulb at the top varies between specimens, regarding size and tilt (compare with Fig. 10C). Scale bar is 1 mm (reflective light; 'Botten', HÄ07-4).

valves (of various taxa) and trilobite parts are most conspicuous. Echinoderms also constitute a clearly visible component, together with gastropods. Mollusc shells are recrystallized into calcite spar. This is also visible in some other taxa, and various hollows are filled with rather coarse calcite crystals. Sometimes calcitization occludes the grain origin, hindering identification. Shell surface dissolution is apparent to various extent throughout the thin-section. Boring activity is visible, but not as pronounced as in 'Golvsten'.

The rock in this sample is neither clearly matrix-, nor grain-supported, as some heterogeneities are apparent. Grain concentration is mostly rather high, though generally with some space between grain surfaces. Point-counting reveals a heterogeneous rock composition with approximately 45% matrix (Fig. 9). According to the Dunham classification system, it may be classified as either a wacke- or a packstone, depending on interpretation. A fitting microfacies name is skeletal pack/wackestone.

Remarks. – The conspicuous greenish mineral is interpreted as authigenic glauconite. The opaque mineral grains are simply interpreted as some kind of metal (further identification is difficult, due to lack of identifiable features). The whitish crystals are reminiscent of dolomite. A majority of the recognizable echinoderm grains are pelmatozoan appendages.

4.2.4 'Likhall' (HÄ07-13)

This thin-section is light grey and shows an apparent large-scaled swirling motion, concentrating and orienting grains towards one corner, which entails a heterogeneous grain distribution (Fig. 8D). The matrix is very fine-grained and micrite-like. Skeletal grains are very abundant, harboring the largest grains of all thin-sections. Mean skeletal grain size is estimated to approximately 400 μm , with sizes ranging up to approximately 5 mm. Again, porosity is lacking. In one corner of this thin-section, there is a rather large area displaying rusty-reddish mottling, with swirling motions and grain concentration towards the edges. Part of the thin-section displays a gradual transition into an increasingly coarser, sparry calcite matrix. Bioturbation is extensive and easily seen at a superficial level. Some infilled grains appear to display at least some reworking.

The general state of grain preservation is poor, with many grains displaying significant fragmentation and coarse (partial or full) calcite recrystallization. Additionally, many grains show various degrees of dissolution and assimilation into the matrix. On the other hand, relatively undisturbed parts of the thin-section contain rather well-preserved grains (such as, for example, articulated bivalves and brachiopods). Relatively large shell fragments of various taxa, preferentially trilobites, are readily visible at a superficial level. Mollusc shells are consistently recrystallized into fine-grained calcite. Shell-borings are visible, even at a superficial level, but vary in extent in differ-

ent parts of the thin-section.

The rock in this sample appears to be mostly grain-supported, though some grain concentration heterogeneities are present. General grain concentration is high, very often with grain-to-grain contact. Point-counting reveals a heterogeneous rock composition with approximately 30% matrix (Fig. 9). According to the Dunham classification system, it is classified as a packstone. A fitting microfacies name is skeletal packstone.

Remarks. – Sparry calcite may indicate that this thin-section is part of a hardground complex. The broad variation in grain preservation, e.g. states of dissolution and assimilation, perhaps also indicates enhanced time-averaging due to decreased – or even ceased – carbonate/lime deposition, adding to the former suspicion. The observed dissolution and assimilation of grains indicate that all taxa contribute extensively to the formation of lime mud, but the underlying processes are most likely taxonomically discriminative. Thus, they are bound to have taphonomic implications on relative grain abundances (alas, further discussions on this topic are beyond the scope of this thesis). Again, a majority of recognizable echinoderm grains are pelmatozoan appendages. Some of the more interesting problematic fossils are present in this thin-section. One is an approximately 50 μm sized brownish object, enclosed by a dark brown membrane, and perhaps best described as a polygonomorph acritarch (Fig. 10E). It appears to have a weakly developed hexa- or perhaps octahedral shape. Three rather long, cilia-like appendages protrude from the sides, in what appears to be a systematic manner. One end displays a rupture in the enclosing membrane. Adjacent to this rupture, a fourth appendage is suggested. A similar object, of approximately the same size and general color, has a roughly circular body with numerous short, cilia-like protrusions extending from its membrane (Fig. 10F). The center of the object is filled with carbonate, displaying some color grading towards the membrane, suggesting a spherical shape. Fittingly, the object is best described as a sphaeromorph acritarch. A few similar objects, in varying state of preservation, are found throughout this thin-section, but – curiously – none have been unambiguously recorded in the other thin-sections.

4.2.5 'Rödarten' (HÄ08-33)

This thin-section is rather varied in color (Fig. 8E). The matrix varies from light beige to light rusty-brown distributed in wispy patterns. The matrix of the rock is micrite-like, but rather extensively interspersed with microspar. Skeletal grains are generally abundant and evenly scattered. Mean skeletal grain size is estimated to approximately 200 μm , with sizes ranging up to approximately 2 mm. As before, there is no porosity to speak of. The most prominent large-scale feature is an approximately 0.75 cm^2 sized rusty-red to almost black

drop-shape, relatively sharply defined towards the host rock, and seemingly disturbing and cutting surrounding grains. It is speckled with golden-yellow-colored endocasts. At the top of the drop apex, a flow-like pattern of the same golden-yellow color is visible. Other dark-colored (varying from rusty-red to light brown), indistinctly shaped features are spread throughout the thin-section. Bioturbation appears to be extensive.

The general state of fossil preservation is poor (with a few exceptions). Partially dissolved and assimilated grains are frequent. Most of the herein identified taxa are readily visible at a superficial level, partly owing to the golden-yellow endocasts. Borings are present in some shells, though they are not an obvious feature in this thin-section.

The rock in this sample appears to be mostly grain-supported. General grain concentration is very high, often with grain-to-grain contact. Point-counting reveals a rock composition with approximately 34% matrix (Fig. 9). According to the Dunham classification system, it is classified as a packstone. A fitting microfacies name is skeletal packstone.

Remarks. – Both the microspar and the dissolved/assimilated grains signal diagenetic effects. The drop-shape is interpreted as a burrow. The other dark features are also interpreted as burrows, though their indistinct shapes indicate origins in softer substrate. Golden-yellow endocasts and features are believed to be colored by some iron compound, likely goethite/limonite. A majority of the recognizable echinoderm grains are pelmatozoan appendages. One problematic fossil, frequently recurring also in the acid-insoluble residues, was found in this thin-section (Fig. 10C). It is a bowling pin-shaped object, approximately 0.8 mm long, sharing some characteristics with echinoderm fragments (but lacking a sharply defined stereom structure).

4.3 Characteristics of the acid-insoluble residues

Following is a description, in stratigraphically ascending sample order, of the lithologic and fossil characteristics, and their variations, taking place throughout the acid-insoluble residues (henceforth, simply referred to as residues; Fig. 11). There are often rather striking differences between samples, with regards to, for example, color and mineral abundance. Note that conodonts had been picked from the residues and that problematic fossils are numerous. Accompanying descriptions of skeletal grain compositions are provided in Chapter 4.4.2.

The 'Arkeologen' samples are dominated by rusty red grains, generally in the 0.1-0.5 mm size range (Fig. 11A). The general grain size increases somewhat when ascending through the stratigraphy. Mineral grains, such as glauconite and pyrite, are either rare or absent in most of the 'Arkeologen' samples. The abundance of fossil grains varies, though it generally increases up-

wards through the succession. Brachiopod fragments clearly constitute the majority of the skeletal grains in all the 'Arkeologen' samples, whereas other fossils generally are rather rare. Except for the brachiopods, rusty red gastropod endocasts are the only other numerically notable constituents (though other taxa are also present). The general state of fossil preservation is rather poor, as endocasts lack finer details.

In 'Golvsten', there is an increased presence of golden-yellow grains, and pyrite grains are abundant in sample HÄ07-3 (Figs. 11B and 11C). Other than that, the 'Golvsten' residues are closely similar to those of 'Arkeologen'.

By comparison, 'Botten' displays some notable differences (Figs. 11D and 11E). The dominant color has changed to light grey, as typical for the 'Täljsten', though grain size is similar to those of the preceding residues. Glauconite is abundant in sample HÄ07-6, whereas pyrite is generally rare. A few amorphous chert/quartz grains are present. As are some platy/tabular, mostly hyaline, and rather soft crystal aggregates (tentatively identified as barite, BaSO₄, through SEM investigation; Fig. 11D). The fossil grain abundance is generally rather high. Gastropods show a marked increase in abundance, as do other fossil taxa, notably ostracods and echinoderms. Most endocasts variably appear to be siliceous and/or phosphatic, or glauconitic, but many display a mixture of infilling materials. Many endocasts may best be described as being filled by unidentified argillaceous materials. These mineralizations promote preservation of more fragile taxa, such as echinoderms. The general state of fossil preservation is fair to rather good.

The general features of 'Gråkartan' are similar to those of 'Botten', except for an increased presence of the platy/tabular mineral (and to some extent also chert/quartz; Fig. 11F). Glauconite is abundant in sample HÄ07-8.

'Blymåkka' also shares most of its characteristics with the two preceding samples, though fossil abundance seems to have decreased, whereas glauconite is moderately abundant. 'Fjällbotten' is similar, but the fossil abundance is low in sample HÄ07-12.

'Likhall' displays a renewed increase in fossil abundance, though the general state of preservation has declined to being rather poor. The relative amount of the platy/tabular mineral also appears to increase somewhat, and euhedral grains are conspicuously present in sample HÄ07-13, together with pyrite. Glauconite abundance is moderate. General features are otherwise similar to those of the preceding samples.

'Flora' displays some notable differences in overall color (Fig. 11G). The grey grains are interspersed by abundant, conspicuous golden-yellow endocasts, presumably colored by goethite/limonite. This material appears to have had a positive impact on the general state of preservation, and many skeletal grains show fine surface details. Gastropods are obviously numerically dominant, together with problematic fossils (e.g. Figs. 10G and 10H). Mineral grains appear to be rare.

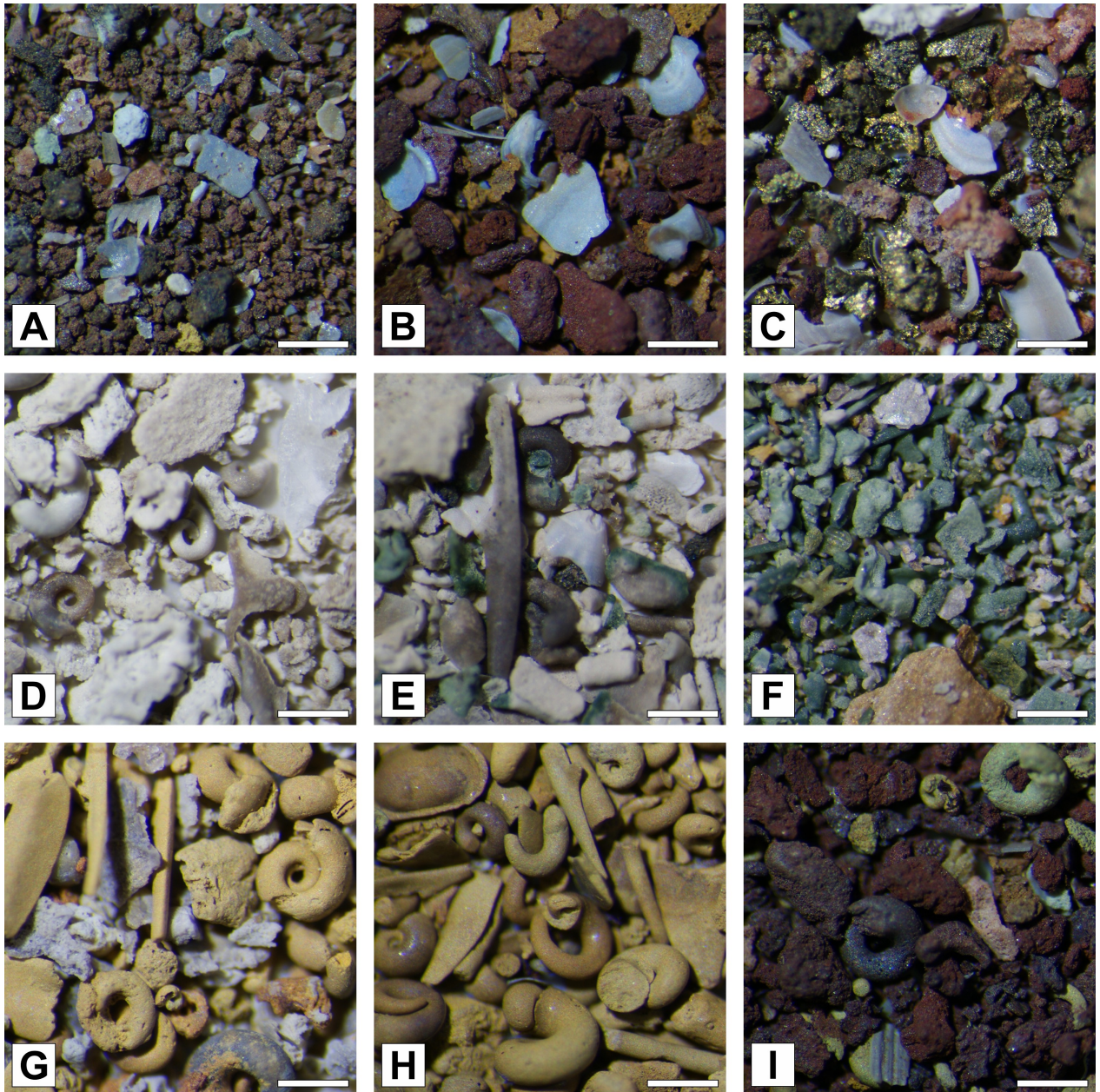


Fig. 11. Photomicrographs highlighting the varying features of the acid-insoluble sample residues. Scale bar is 0.5 mm. Note that magnification is the same in all images, to allow for more straightforward comparisons between samples, and that conodonts have been picked from the samples. HF and LF refer to liquid separated heavy and light fractions, respectively. **A.** 'Arkeologen'. Note the small grain size, as compared to most other samples (HÄ08-Ark1). **B.** 'Golvsten'. Brachiopods clearly dominate the skeletal grains (HÄ07-2; HF). **C.** 'Golvsten'. Pyrite is abundant (HÄ07-3; HF). **D.** 'Botten'. Note the whitish mineral grain in the top right, tentatively identified as barite, BaSO_4 . Such mineral grains become rather abundant in the upper half of the 'Täljsten' (HÄ07-4; HF). **E.** 'Botten'. Endocasts display varying infill materials (HÄ07-6; HF). **F.** 'Gråkartan'. Glauconite is abundant (HÄ07-8; LF). **G.** 'Flora'. Gastropod endocasts are abundant (HÄ08-30). **H.** 'Mumma'. Gastropod endocasts are abundant, and fossil preservation is good (HÄ08-31). **I.** 'Rödkartan'. Fossil preservation has deteriorated markedly, compared to the subjacent 'Täljsten' samples (HÄ08-32).

'Mumma' has the same characteristics as 'Flora', though rusty red, generally rather large (approximately 0.5-1 mm), grains return in moderate amounts (Fig. 11H). In general, greyish residues appear to contain larger amounts of silty siliciclastic materials, which are rather absent in the reddish samples.

The 'Rödskarten' residues display a return to general pre-'Täljsten' appearance, though some golden-yellow endocasts are still present, and brachiopod presence is not as conspicuous as in the 'Arkeologen' samples (Fig. 11I). The state of preservation has again deteriorated.

4.4 Faunal composition studies

4.4.1 Thin-section skeletal grain point-counting

Following are descriptions of the faunal composition and its variations occurring throughout the thin-sections, based on skeletal grains present. Only identified grains are accounted for in these descriptions. Relative grain abundances are always in focus, as the various thin-sections yielded different amounts of identified grains. The Unidentified category comprises approximately 26% to 41% of the total numbers, being lowest in 'Golvsten' (sample HÄ07-2) and peaking in 'Likhall' (HÄ07-13). These amounts vary as a consequence of thin-section grain abundance and state of preservation. The relative difficulty/ease of identifying the various taxa through skeletal grains probably results in some skewing in the data, but this should not affect eventual trends. Trilobita is likely underrepresented, as many – perhaps even a majority – of the unidentified grains are suspected to belong to that category. Mollusca and Other might also be underrepresented, due to hesitance in identification. Some of the grains in the Mollusca category may belong to fragmented specimens of Gastropoda, as both categories display similar shapes and shell recrystallization. Point-counting results are presented as graphics in Figs. 12 and 13.

In the 'Arkeologen' (HÄ08-60) thin-section, a total of 190 skeletal grains were identified. Brachiopoda is the largest taxonomic category of these, constituting approximately 40% of the preserved assemblage. Trilobita is the second largest category, closely followed by Echinodermata; each category constituting approximately 15-20% of the identifiable grains. Gastropoda and Ostracoda form some 10% each, whereas Mollusca is slightly less abundant with approximately 5%. The Other category is represented only by bryozoans (adding up to approximately 1% of the total).

'Golvsten' (HÄ07-2) yielded 222 identified grains. Some differences are seen in the relative abundances, as compared to the 'Arkeologen' thin-section. Most taxa decline at various rates, with the most notable exception being Echinodermata. The latter category almost doubles in relative grain abundance, and constitutes more than one-fourth of the total grains identified. Brachiopoda, though declining slightly, still

dominates, now constituting slightly more than one-third of the grains. Following are Trilobita and Gastropoda, each constituting 13% of the total (thus, the latter category has actually increased). Ostracoda declines slightly, whereas Mollusca now constitutes only slightly more than 1%. The Other category is again represented solely by bryozoans, forming almost 1% of the total grains identified.

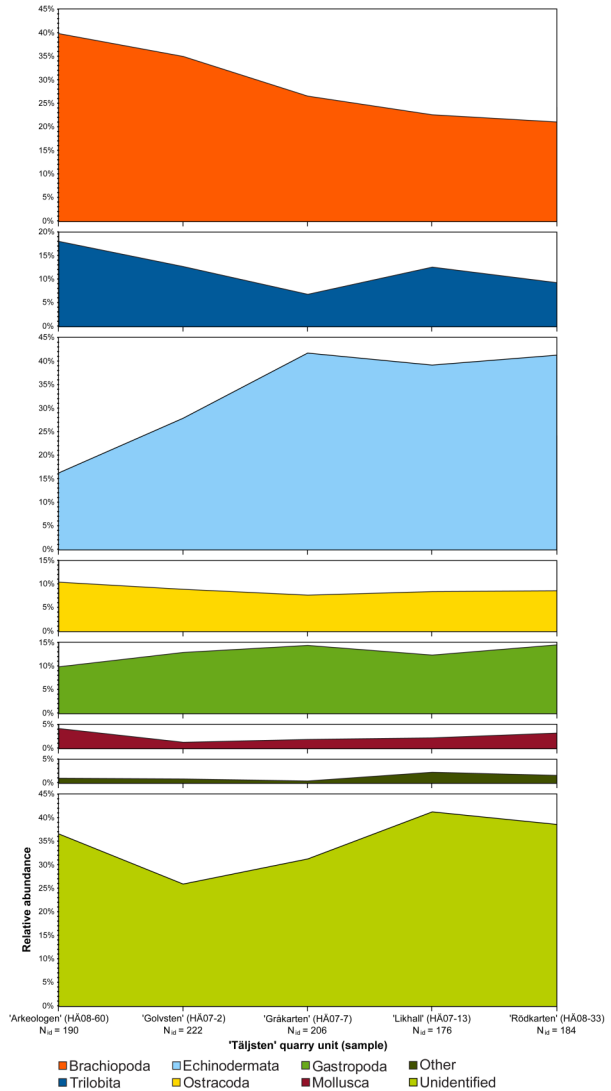


Fig. 12. Variations in relative skeletal grain abundance throughout the studied succession, based on thin-section point-counting data. The Unidentified category relative abundance was calculated using total counted grains ($N=300$), whereas all other categories were calculated using only identified grains (N_{id} , as indicated under each quarry unit name).

'Gråskarten' (HÄ07-7) yielded 206 identified grains. This thin-section shows roughly the same trend as the preceding one. Again, Echinodermata shows a continued, rather linear, increase. In this thin-section, the taxon actually dominates the identified grains, and constitutes slightly more than 40% of the total. At the other end of the spectrum, the Other category (again, only bryozoans) and Mollusca are only represented by approximately 0.5 and 2% of the identified grains,

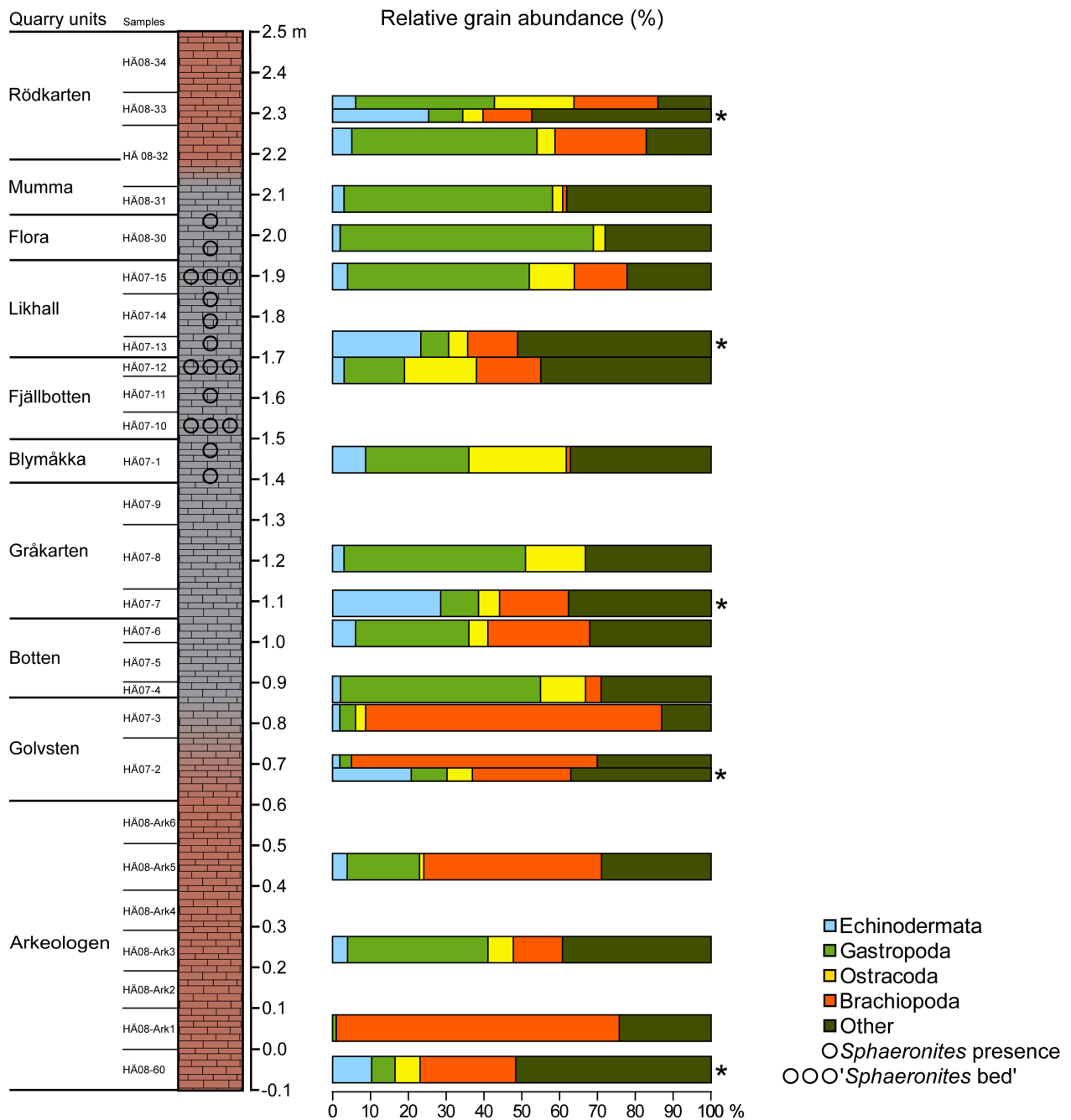


Fig. 13. Variations in faunal composition throughout the studied succession, based on residue and thin-section grain point-counting data (residue data courtesy of M.E. Eriksson). Abundance bars with asterisks (*) are based on thin-section data, adapted to the residue category partitioning (the Other category includes Mollusca, Other, Trilobita, and Unidentified). *Sphaeronites* presence and approximate position of '*Sphaeronites* beds' are indicated in the stratigraphic column, based on field observations.

respectively. Brachiopoda becomes the second most abundant taxon, comprising slightly more than one-fourth of the grains. Relations between the remaining taxa do not change significantly, except for Trilobita, which continues its decline and now constitutes less than 7% of the total. Thus, Gastropoda – being almost at 15% of the total – takes a clear third-place and Ostracoda (approximately 8%) takes fourth-place.

'Likhall' (HÄ07-13) yielded 176 identified grains. This level shows a decline in the three most abundant taxa, whereas the other ones change variably. The gen-

eral pattern is still maintained, though Trilobita exhibits a rather steep increase, and now constitutes almost 13% of the total. Thus, it is equal to Gastropoda. Still, Echinodermata dominates, constituting almost 40%. Following is Brachiopoda, declining towards being 20%, though the rate of decline has decreased as compared to rates between the preceding thin-sections. Ostracoda (approximately 9%) and Mollusca (approximately 2%) both display minute increase. The Other category also displays an increase, and now constitutes slightly more than 2% (and an interesting addition to

the bryozoans, is an acritarch).

'Rödkarten' (HÄ08-33) yielded 184 identified grains. Echinodermata displays a slight increase, and thus still dominates the grains. The decline of Brachiopoda has almost ceased. Ostracoda and Trilobita are now equal (at around 9%, with Trilobita being slightly more abundant). Gastropoda increases again, and is now represented by almost 15% of the total identified grains. Mollusca also sees some increase, and now constitutes slightly more than 3% of the total. The Other category is again represented by bryozoans, and constitutes less than 2% of the total identified grains.

4.4.2 Residue skeletal grain point-counting

Although they should have been dissolved in the acid treatments, even taxa originally bearing only aragonitic and/or calcareous hard parts are preserved in the residues, and often so in relatively fine detail. Most commonly, these specimens are preserved as endocasts, but permineralized skeletal parts also occur. Some variations in faunal composition are apparent when comparing the residues. Following are descriptions of the skeletal grain composition and its variations, arranged by category and decreasing initial relative abundance (with the exception of Other, which is described last). Point-counting results are presented in Fig. 13 (data courtesy of M.E. Eriksson).

In the lower part of the studied succession, from the lowermost 'Arkeologen' (HÄ08-Ark1) to uppermost 'Golvsten' (HÄ07-3), Brachiopoda generally dominates the residues. Only one sample (HÄ08-Ark3) deviates from this trend, with a rather equal dominance between Gastropoda and Other. Throughout 'Arkeologen', Brachiopoda's relative abundance fluctuates rather extensively, mostly in harmony with Gastropoda and Other. Brachiopoda first declines in the lower half of 'Arkeologen', but then increases again towards the base of the 'Täljsten' interval. From the lowermost 'Botten' (HÄ07-8) and upwards through the 'Täljsten', Brachiopoda generally constitutes a relatively minor grain component, though fluctuations can be seen (the taxon varies between approximately 0% and 17%). Fluctuations are again generally balanced by Gastropoda and Other, and in turn Ostracoda and Echinodermata. Brachiopoda is missing in the middle part of 'Gråkartan' (HÄ07-8), and is only a minute component in 'Blymåkka' (HÄ07-1). Thereafter, a general, but fluctuating, increase can be seen towards 'Rödkarten', but Brachiopoda never seems to retain its original place in the relative grain abundance hierarchy. Brachiopoda's relative abundance varies between 0% and 75% of the total in the various residues.

Gastropoda fluctuates broadly in relative abundance. The category starts out as a minimal component in the lowermost 'Arkeologen' (HÄ08-Ark1). An increase is visible in the lower parts of 'Arkeologen', followed by a decline towards the base of the 'Täljsten', mostly to the benefit of Brachiopoda. From the lower part of 'Golvsten' (HÄ07-2) and upwards,

Gastropoda generally increases, and becomes clearly dominant midway through 'Gråkartan' (HÄ07-8). Thereafter, the category declines again, mostly to the benefit of Other and Ostracoda, but in part also to Brachiopoda and Echinodermata. In the uppermost part of 'Likhall' (HÄ07-15), Gastropoda becomes (clearly) dominant again. A peak is seen in 'Flora' (HÄ08-30), followed by some decline towards the top of the succession, apparently to the benefit of all other categories except Other. Gastropoda's relative abundance varies between 1% and 67% of the total in the various residues.

Ostracoda varies broadly in relative abundance. Throughout most of 'Arkeologen' and the lowermost 'Täljsten' interval, the category is generally missing, but it constitutes a minor component in two samples (HÄ08-Ark3 and HÄ08-Ark5). From the upper part of 'Golvsten' (HÄ07-3), Ostracoda increases in relative abundance, peaking in 'Blymåkka' (HÄ07-1). Thereafter, a decline is visible, in turn followed by a new increase in lowermost 'Rödkarten' (HÄ08-32). Ostracoda's relative abundance varies between 0% and 26% of the total in the various residues.

Echinodermata constitutes a small component throughout all the samples. The category is missing in the lowermost 'Arkeologen' (HÄ08-Ark1), but thereafter it is present, with some fluctuations. A peak is seen in 'Blymåkka' (HÄ07-1). Echinodermata's relative abundance varies between 0% and 9% of the total in the various residues.

Generally, the Other category is a rather stable and visible grain component, but in some levels – namely lower 'Arkeologen' (HÄ08-Ark3), uppermost 'Botten' (HÄ07-6), 'Blymåkka' (HÄ07-1), and uppermost 'Fjällbotten' (HÄ07-12) – it constitutes the dominant category. A minimum is found in upper 'Golvsten' (HÄ07-3). Other's relative abundance varies between 13% and 45% of the total in the various residues.

5 Discussion

5.1 Observed environmental signals – the rocks and the fauna tell their story

First and foremost, one cannot help but notice the color variations in the studied succession (Fig. 1). The red coloring is most likely related to precipitation of iron oxides (e.g. hematite) in relatively well-oxygenated waters, whereas the grey coloring can perhaps be interpreted as a result of less oxygen-rich conditions (for more detailed discussions, see e.g. Lindström 1963; Jaanusson 1972). There is no fundamental reason to believe that there are lesser amounts of iron in the grey limestone – it just represents different Eh conditions (i.e. reducing conditions). The grey color of the 'Täljsten' could be a result of increased amounts of organic matter. This would be a likely consequence of shallowing and, perhaps, changes in currents could

also contribute. The golden-yellow material in some endocasts, seen in both thin-sections and residues, is believed to be stained by goethite/limonite. As was noted by Lindström (1963), the various iron compounds unfortunately reveal little about overall depositional environment and water depth.

Pyrite is visibly present in most residues, although the relative amounts vary greatly. The presence of pyrite may indicate organic-rich and/or euxinic (i.e. dys-/anoxic and/or stagnant) conditions, promoting anaerobic metabolism (Flügel 2004). Because the pyrite occurs here as amorphous grains, and no pyritized fossils were recorded, it is interpreted as being of diagenetic origin. According to Jaanusson (1972), pyrite is most common in the grey limestones in Baltoscandia. This may further support the grey lithology's reducing conditions (as ferric iron supposedly is more easily reduced in the rocks, but it also depends on how early the pyrite was formed). No clear pattern of pyrite abundance was seen in the studied succession.

The glauconite present in some samples is interpreted as being authigenic, because the mineral fills cavities in fossil shells and replaces skeletal parts (this had an obvious positive impact on the preservation/taphonomy of some fossils). The presence of authigenic glauconite is generally considered to indicate a relatively shallow marine setting with slow rates of sedimentation, with glauconite crusts (as described in the field observations) indicating times of non-deposition (Adams *et al.* 1984; Flügel 2004). In modern oceans, glauconite is most abundant in mid-shelf to upper slope environments, at depths from 50 to 300 m, and occurs down to approximately 500 m. As convincingly shown by Chafetz & Reid (2000), however, glauconite should not be considered a solid depth signal by its own, as some glauconite-rich Cambrian-Ordovician rocks indicate both tidal zone settings and rapid sedimentation. Glauconite may indicate eutrophic environments (Flügel 2004).

The observed general lithologies and textures fit into a variety of depositional environments in different facies models, so depth is not easily inferred from lithology alone. When lithologies are combined with their faunal content, most often they fit into a deep shelf environment (e.g. Standard Microfacies Type 9 of Flügel 2004). This appears reasonable when compared to other authors' conclusions regarding these strata (see chapters 3.2.2 and 3.2.4), but it should be noted that most facies models are more or less standardized for warm-water (i.e. tropical) carbonate environments. Thus, they may be (very) inaccurate when applied to cold-water carbonate environments, as represented by the Baltoscandian 'Orthoceratite limestones'.

Shallowing could result in lateral transposition of the confacies belt lithologies. Ascending through the studied succession, the lithologies are actually increasingly reminiscent of those of the more eastern CB:s' characteristics (cf. Jaanusson 1972). As Kinnekulle is located in a CB boundary zone, the depositional envi-

ronment would likely show rather swift reaction to fluctuating water depths. If not an effect of decreased carbonate deposition, the transition from wacke- to packstones could suggest increasing water energy levels throughout the studied succession. Such lithologic sequence may be expected from shallowing, as the latter could result in increased winnowing of bottom sediments and removal of matrix. 'Likhall' (HÄ07-13) could thus represent the most high-energy environment resolved in the thin-sections. Curiously, the top-most thin-section (HÄ08-33) does not seem to show clear signals of a return to a lower-energy environment – only a slight increase in matrix was observed – as 'Rödarten' is generally assumed to represent a return to deeper waters.

The fauna includes stenohaline taxa (such as echinoderms), supporting a fully marine setting with reasonably stable water chemistry. The remarkable 'Sphaeronites beds' are rather enigmatic. One can only suppose that they represent environmental conditions somehow particularly beneficial for cystoids (unless it is a taphonomic concentration effect).

The lack of identified algae and other positively light-dependent organisms corroborate previously described views that the sediments were deposited below the photic zone (which is generally estimated to be within the upper 200 m in modern oceans).

5.2 The faunal composition and its variations – observations and interpretations

Though perhaps obvious, it should be stressed that the relative abundance of grains should not be confused with actual numbers of individuals, as different taxa produce different amounts of skeletal debris. For example, today as before, only one continuously growing shell is produced throughout a gastropod's lifetime. By sharp contrast, a trilobite produced considerably more skeletal parts throughout a lifetime, both as a result of bearing a multisclerite exoskeleton, and by undergoing multiple ecdysis events (i.e. molting). Adding to this is the fact that all taxa have different preservation potential (and varying preservation potentials are present within taxa). Moreover, throughout the studied succession, there is varying degree of bioturbation and accompanying disarticulation and fragmentation. Sometimes it is even difficult to prove that grains are autochthonous. These are just some examples of natural factors influencing fossil associations, that may bias results and interpretations. Keeping this in mind, here follows the discussion on the faunal data.

Data from both the thin-sections and the residues indicate that a faunal reorganization occurs in the studied succession. The acid processes used in the production of the residues are obviously disadvantageous for some fossil taxa that are clearly present in the thin-sections (though a clear advantage of the former materials is that they allow for three-dimensional studies of preserved fossils). Thus, these taxa are – expectedly –

underrepresented or absent in the residues, entailing some discrepancies between thin-section and residue grain modal compositions (this is especially obvious regarding echinoderms and trilobites). However, overall faunal trends are similar when comparing the two sets of samples.

The most obvious pattern in the thin-sections relates to brachiopods and echinoderms. Brachiopod abundance declines throughout the studied succession, though slightly less towards the top of the succession. This is also seen in the residues, where an increase is even seen in the uppermost samples. Echinoderms appear to constitute an opposite to the former taxon in the thin-sections, and at the top of the studied succession the two taxa's grain proportions are roughly inverted, as compared to the bottom (in the residues, echinoderm presence is too small to allow for any meaningful discussion). A similar, but less conspicuous, trend may exist in the relative abundance of trilobites and gastropods, and some patterns seem to correspond between echinoderms, gastropods, and trilobites. Ostracods constitute a very stable component throughout the studied thin-sections, while the taxon displays rather large fluctuations in the residues (likely due to a combination of varying preservation potential and higher sample resolution in the latter samples). The remaining thin-section categories are too small to allow for any meaningful discussions, and the Other category of the residues mostly contains unidentifiable grains. Regardless of category, it may be best to refrain from trying to interpret anything significant from smaller fluctuations recorded in the sample materials.

The fact that roughly the same variations in faunal composition are apparent in both thin-sections and residues (where comparisons are allowed) supports a faunal reorganization event. Also, echinoderm presence becomes highly conspicuous on a macroscopic scale in the '*Sphaeronites* beds' of the 'Täljsten', and adds to the pattern observed in the thin-sections. Pinpointing the cause of this inferred faunal reorganization may of course be difficult, but considering the growing evidence of a contemporaneous shallowing event, a connection appears plausible. Environmental changes caused by a regression can be regarded as disturbance, likely to result in ecological instability. For example, Botquelen *et al.* (2006) showed that fluctuations in relative abundance of dominant taxa may be an expected result of sea-level fluctuations. Trends such as those observed regarding brachiopods and echinoderms (and, perhaps, trilobites and gastropods) may also be expected, as taxa with similar modes of life compete (Botquelen *et al.* 2006). Similarly, life mode may explain why some taxa appear to be more affected by the environmental perturbations than others. Tiering levels might play an important role in the case of the echinoderms and brachiopods.

Judging by the trends seen in the lower parts of the succession, the faunal reorganization appears to have been rather rapid (assuming that the rate of deposition was relatively constant). Contrarily, the fauna does not

seem to show any obvious return to pre-'Täljsten' conditions towards the top of the succession (compare with lithology discussions above), though there are signs of stabilization in the brachiopod-echinoderm relationship in the thin-sections (and perhaps a slight brachiopod recovery is visible in the residues). It would be interesting to perform additional studies on a stratigraphically longer interval, to see what happens above and below the studied succession (it would also be interesting to see if similar faunal reorganization is seen in contemporaneous strata at other localities, or in a more definite way in the macroscopic fauna). Regardless of the ultimate fate of the various taxa, this asymmetric pattern of faunal reorganization – rapid change, followed by stabilization and (possibly) a slow return to previous faunal associations – may be an expected result of a regression-transgression cycle, as environmental stress is more severe during the regression phase (e.g. Rollins *et al.* 1979). It should be noted that distinct such patterns are mostly expected in shallower settings, as environmental gradients are more pronounced there.

Interestingly, Rozhnov (2001, 2004) described an echinoderm increase and subsequent community dominance in the Baltic basin during the Volkhovian. Many of these echinoderm communities disappeared in the early Kundan, most likely as a result of shallowing. So, perhaps the echinoderm increase observed in the Kinnekulle strata is a natural continuation of the one seen further east – as Kinnekulle was situated in deeper parts of the Baltoscandian palaeobasin, it would not be an inconceivable result of shallowing, as echinoderms would gradually colonize waters of fitting depth (compare with CB discussions above). Whatever the reason, the echinoderm increase can perhaps simply be viewed as being part of radiations connected to the GOBE.

6 Conclusions

There certainly seems to be some kind of event associated with the 'Täljsten' interval. The lithology is obviously affected in color, as clearly seen even on a macroscopic scale. This study documented an increase in grain concentration (i.e. a transition from wacke- to packstones) throughout the studied succession, accompanied by an apparent reorganization of the microfauna in the lower half of the succession. The initially dominant brachiopods (and other taxa) gradually give way to echinoderms, resulting in that the latter taxon eventually becomes (increasingly) dominant, with regards to relative skeletal grain abundance. Contemporaneously, diploporite cystoids become dominant in the preserved macrofauna. A stabilization in the microfaunal composition follows in the upper half of the succession, where a new, echinoderm-dominated association appears to have been established.

As has been proposed by many authors, a regression-transgression cycle seems to have taken place around the 'Täljsten' interval. The regression is suppos-

edly represented by roughly the lower half of the studied succession and appears to have culminated in the 'Täljsten', whereas the upper half of the succession represents a subsequent transgression. The results from this study might be explained by such an event, and perhaps even underscore the event itself. The faunal reorganization in the lower half of the succession can be interpreted as having been induced by the regression, whereas the following transgression is not (clearly) resolved. The observed increase in grain concentration may be a result of increased energy levels, and as such may support the view that a regression took place.

The notion of a new faunal composition in strata superjacent to the 'Täljsten' is in concordance at least with the results of Mellgren & Eriksson (in press), who described a contemporaneous reorganization among conodonts. Similar results may be interpreted regarding ostracods, when studying data from e.g. Tinn & Meidla (2001).

When viewed in light of the GOBE and the increased influx of extraterrestrial matter, one can conclude that the studied succession spans a time of significant environmental and faunal events on a larger scale. Continued detailed studies of the Kinnekulle limestones may perhaps broaden the picture of the events represented by the 'Täljsten' and its enclosing strata, in a local, regional, and maybe even global, perspective.

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