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# Carbonate platform evolution and conodont stratigraphy during the middle Silurian Mulde Event, Gotland, Sweden

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**Abstract** – Evidence from sedimentology and conodont biostratigraphy is used to reinterpret the mid-Homerian (Late Wenlock) succession on Gotland, Sweden. A new conodont zonation includes from below: the *Ozarkodina bohemica longa* Zone (including five subzones), the *Kockelella ortus absidata* Zone and the *Ctenognathodus murchisoni* Zone (two taxa are named, *Ozarkodina bohemica longa* and *Pseudooneotodus linguicornis*). These new zones are integrated with facies in order to correlate strata and infer the major depositional environments and the controls on deposition during the mid-Homerian Mulde Event. Reef-associated and skeletal carbonate deposition predominated before and after the event, i.e. during the uppermost *O. s. sagitta* Zone and, again, in the *C. murchisoni* Zone. These periods are characterized by the expansion of reefs and shoal facies across marls in the topmost Slite Group on eastern Gotland and in the lower parts of the Klinteberg Formation on western Gotland, respectively. The intervening *O. b. longa* and *K. o. absidata* zones are initially characterized by rapid facies changes, including siliciclastic deposition, and later stabilisation of a carbonate depositional system. The composition of sediments and depositional rates are closely related to the creation and destruction of accommodation space and reflects a classical case of depositional bias of the carbonate and siliciclastic depositional systems. Based on coastline migration, stratal boundaries, and the stratigraphic position of major reef belts, several facies associations can be fitted into a sequence stratigraphic model for platform evolution. A highstand systems tract (HST) situation prevailed prior to, and during the early part of the event; the upper Slite Group including the lower Fröjel Formation. This HST was characterized by prolific skeletal production and regional reef development except for during the latest stage when carbonate production declined at the onset of the Mulde Event. Platform growth was inhibited during a following regressive systems tract (RST) when regional siliciclastic deposition predominated; the Gannarve Member. The subsequent lowstand resulted in regional emersion and karstification, i.e. a complete termination of the platform. The post-extinction transgressive systems tract (TST) is exclusively composed of non-skeletal carbonates; the Bara Member of the Halla Formation. Re-occurrence of reefs and a prolific skeletal production marks platform recovery during a second HST; the remaining Halla and the lower Klinteberg formations. Integration of high-resolution biostratigraphy and sequence stratigraphy reveals that the major physical control on platform evolution was a 5th order eustatic sea-level change during an early part of the Mulde Event, and that the bulk of the strata accumulated when the platform aggraded and prograded during the highstand systems tracts. Thus, Silurian oceanic events and associated sea-level changes had profound impact on the neritic carbonate system. The Gotland-based middle and late Homerian sea-level curve shows two rapid regressions, both leading to truncation of highstand systems tracts. The first lowstand occurred at the very end of the *C. lundgreni* Chron, and the second at the end of the *Co.*? *ludensis* Chron. The intervening interval was characterized by stillstand or possibly slow transgression.

Keywords: carbonate platforms, Conodonta, mass extinctions, sequence stratigraphy, Silurian.

## 1. Introduction

The nearly complete extinction of the graptoloid graptolites at the closing of the *Cyrtograptus lundgreni* Chron was the first recognized effect of one of the major Silurian extinction events. For a long time the event was believed to affect 'only' the graptolites. Recently however, this 'big crisis', '*lundgreni* event' or $C_1$ has been identified as only one of the major physical and biological changes during a perhaps 350–380 kyr long period of time – the Mulde Event – although all identified extinctions were concentrated to three datum points during the first 60–65 kyr of the event (Jeppsson, 1993; Jeppsson, Aldridge & Dorning, 1995; Jeppsson, 1998; Calner, Kluessendorf & Mikulic, 2001; Jeppsson & Calner, 2003). The graptolite extinction has now been identified globally (Jaeger, 1991; Koren' & Urbanek, 1994; Jeppsson & Calner, 2003). Similarly, a positive $\delta^{13}C$ excursion was widespread (Samtleben *et al.* 2000; Salzman 2001; Jeppsson & Calner, 2003).

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In this paper, the sedimentary and biostratigraphic sequences are described in order to provide the detailed data base needed for integration of sequence and event stratigraphy during the middle Homerian. Thus, the large-scale sedimentary (environmental) changes in the neritic carbonate system during the Mulde Event are documented (MC). A new detailed conodont zonation is introduced and ties to the current graptolite zonation are identified in order to enable global correlation (LJ). Therefore we present a detailed assessment of mid-late Homerian facies change on Gotland, using the highest stratigraphic resolution currently available.

### 1.a. Geological setting

The classical carbonate platform deposits of Gotland were formed at tropical latitudes during latest Llandovery-Ludlow time (cf. Scotese, 1997). The thin succession of strata [c. 500 m based on calculations of the maximum thickness of each member, Hede (1960), but closer to 600 m based on new such calculations] accumulated in very shallow water during *c*. 19 Ma (based on data in Harland *et al*. 1990). The many emersion surfaces and the limited thickness suggest that tectonically driven creation of accommodation space was limited. Still, major biostratigraphic gaps are absent on western Gotland. Seismostratigraphic data (Flodén, 1980) and lack of major slope breccias or turbidites towards the basin indicate that the Gotland succession represents stacked homoclinal carbonate ramps (*sensu* Read, 1982, see also Read, 1985). However, truncation during emergence of the platform followed by transgression appears to have changed the depositional profile and the platform break considerably at certain times; e.g. in the mid-Homerian when the ramp appeared to exhibit a distal steepening (this paper).

The local facies pattern is often complex but on a regional scale three major depositional situations may be resolved; slope and basin, shoal and reefal areas, and back-reef platform interiors (Samtleben, Munnecke & Bickert, 2000). The more argillaceous slope and basin deposits are exposed on the western and southwestern sides of the island and pass gradually into shallow water facies towards the E and NE. Similarly, widespread unconformities are well developed mainly on the more proximal, eastern side of the island (Samtleben *et al*. 1996, Fig. 2a,b; Calner, 2002). Bioherms and biostromes occur in several facies associations throughout the interval (Manten, 1971; Riding, 1981; Kano, 1994), notably also in the distal slope to basin environment (Stel, 1978; Nield, 1982; Calner, Sandström & Mõtus, 2000).

Siliciclastic background sedimentation rate was continuously high along the deeper parts of the platform during Late Wenlock-Early Ludlow and detrital clay and silt make up 30–40% of micritic limestones. Influx of sand-sized siliciclastics is evident at only two levels, viz., the mid-Homerian Fröjel Fm (Calner, 1999) and the Late Ludfordian Burgsvik Fm (Stel & de Coo, 1977; Long, 1993). The basin-regional silt belt discussed by Calner (1999) and herein was deposited close to the onset of the early Caledonian collisional event, dated at *c*. 425 Ma (Torsvik *et al*. 1996). According to Kaljo, Nestor & Einasto (1991), positive movements in the Scandinavian Caledonides determined the siliciclastic influx to the basin. However, the abundance of strained quartz grains, detrital mica, and presence of metamorphic rock fragments indicate that the source area for coarser siliciclastics in the Gotland area, at least in the Late Ludfordian, was the Precambrian shield of eastern Sweden (Long, 1993).

### 1.b. Methods

More than 100 localities within the uppermost Slite Group, Halla Fm, and the lower Klinteberg Fm were sampled for this study (see Fig. 1 for those mentioned below). Detailed descriptions and references to localities are provided in the following sources: Laufeld (1974*b*); the catalogue of Jeppsson & Jerre (in manuscript, copy available at the Allekvia Fieldstation, Gotland); Calner (1999), Calner & Säll, (1999) and appendix herein. Data concerning individual localities can be received from the authors upon request.

Temporal and spatial sedimentary trends were deciphered by facies mapping along five transects orientated more or less downdip (Fig. 1e). All transects start in the *Ozarkodina s. sagitta* Zone (the uppermost Slite Group) and pass through the *O. bohemica longa*, *Kockelella ortus absidata* and *Ctenognathodus murchisoni* zones (the Fröjel, Halla and lowermost Klinteberg formations, Fig. 2). The biostratigraphical data presented are based on a selection of these localities. Other localities can be closely tied to these (Fig. 3).

The sedimentological analyses include the study of *c*. 80 thin sections, several hundred polished slabs, and 16 samples examined using scanning electron microscopy (SEM). The SEM samples were cut perpendicular to bedding, polished and etched for 20 seconds in 0.1 M hydrochloric acid. The amount of insoluble material was measured through dissolution of 2.5 g of crushed rock (out of *c*. 20 g homogenised) in 25% HCl before the insoluble residue was weighed. In the studied limestone-marl alternations, insoluble/$CaCO_3$ relations were for consistency measured from the central parts of the limestone nodules. It should be noted that this method results in lower values of insolubles as compared to a whole rock analysis. However, the latter would require crushing and homogenizing *c*. 10 kg per sample. The result shows the *trend* in siliciclastic deposition. All textural terms follow those in the system developed for limestones by Dunham (1962, as revised by Embry & Klovan, 1972).

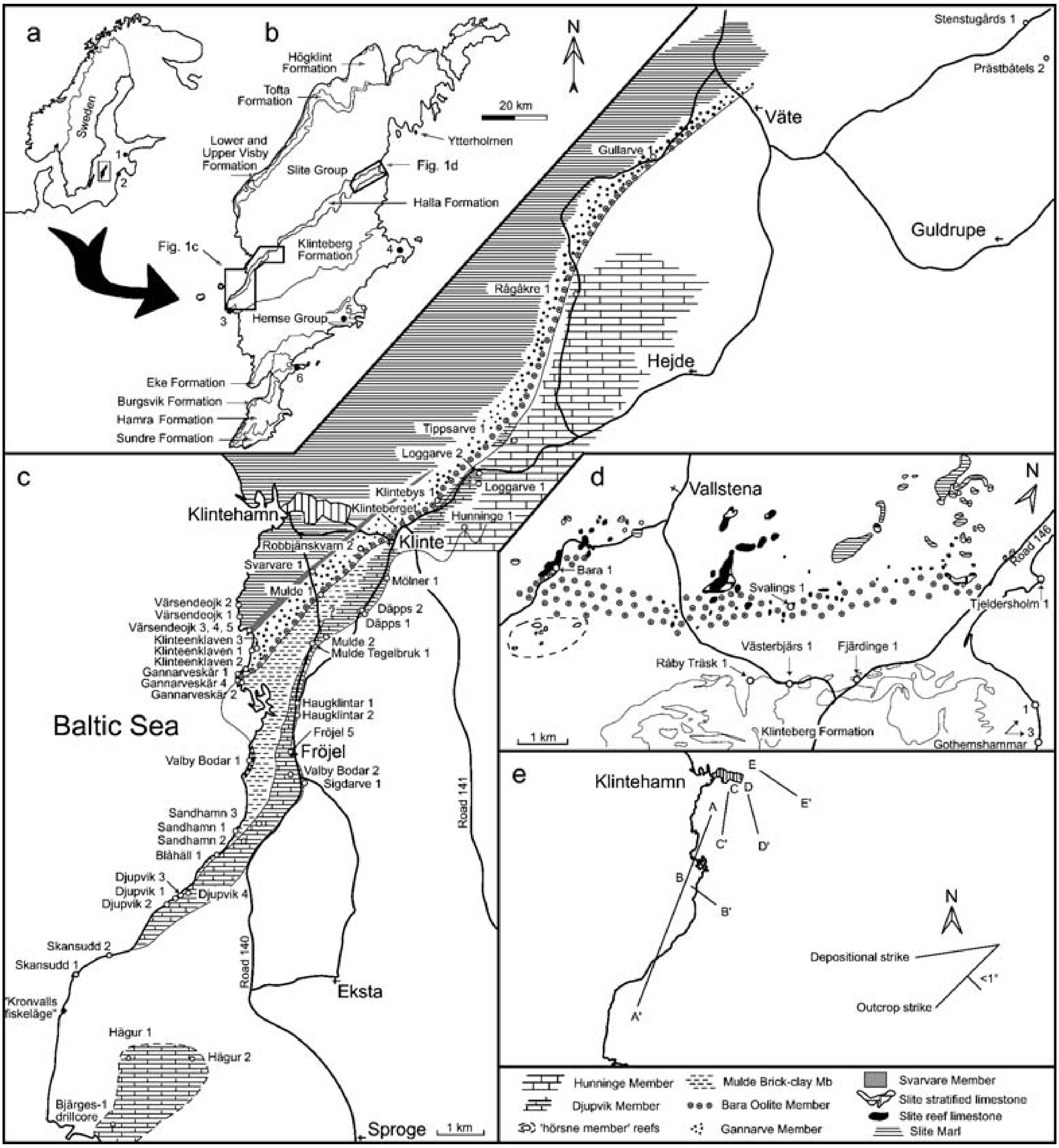


Figure 1. Location of the investigated areas and the herein discussed localities. (a) The geographic position of Gotland. The Baltic drillcores Ohesaare and Priekule are marked as 1 and 2, respectively. (b) The distribution of the Slite Group, the Halla and Klinteberg formations, and the two major outcrop areas dealt with; the Klintehamn area on western Gotland and the Vallstena area on eastern Gotland. The numbers indicate the position of drillcores; (3) Bjärges-1, (4) Östergarn-1, (5) När-1, (6) Grötlingbo-1. (c) Outcrop distribution of stratigraphic units and selected localities in the Klintehamn area. (d) Outcrop distribution and selected localities in the Vallstena area (modified from Calner & Säll, 1999). (e) Position and orientation of the five transects discussed in the text.

The conodont sampling (LJ) started long before sedimentological sampling (MC). However, reference material from old samples has been valuable for critical correlation between zonal and facies boundaries. Similarly, some samples collected for sedimentological analysis have, after study, been dissolved for conodonts (except for *c*. 0.2 kg kept for reference). The conodont extraction technique has been described in detail (Jeppsson & Anehus, 1995, 1999; Jeppsson, Anehus & Fredholm, 1999).

#### 1.c. Mid-late Homerian stratigraphy of Gotland

Major stratigraphic revisions have recently been accomplished within the mid-late Homerian of Gotland. The Fröjel Fm of the topmost Slite Group was defined

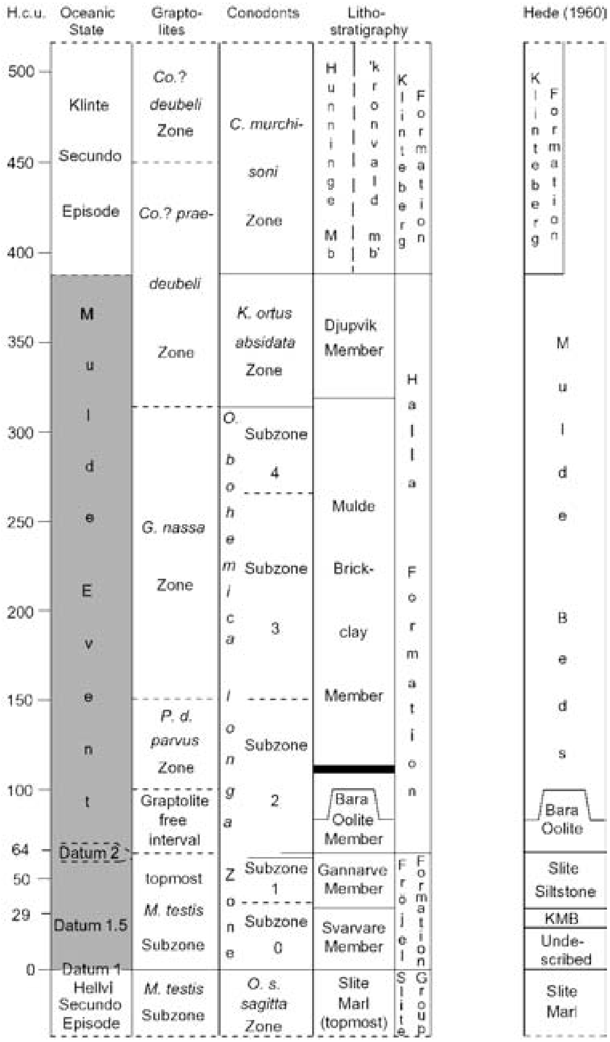


Figure 2. Revised stratigraphic framework of the Late Wenlock of Gotland. The left margin shows the Homerian chronal unit scale (H.c.u.) of Jeppsson & Calner (2003). The right column shows the subdivision of Hede (1960). KMB is an abbreviation for 'Kalksandstenens Märgliga Bottenlager' (Hede, 1917; 'the marly bottom layer of the carbonate sandstone'). The black bar in Subzone 2 of the *O. b. longa* Zone indicates the stratigraphic position of the Grötlingbo Bentonite. This is a 0.10–0.38 m thick, basin-regional marker, identified in the När-1, Grötlingbo-1, Ohesaare, and Priekule drillcores. Extensive silicification below it forms indirect evidence for its presence on western Gotland.

and analysed by Calner (1999). The unconformably overlying Halla Fm was revised by Jeppsson & Calner (2003) to incorporate two additional members in its distal parts, viz., the Mulde and Djupvik members. The term 'Mulde Marl' (*sensu* Hede, 1960), frequently as Mulde Beds, was discarded. In addition, two new units of the lower Klinteberg Fm in the westernmost outcrop area were distinguished; the Hunninge and 'kronvald' members. The new stratigraphical nomenclature and the distribution of the discussed members are shown in Figures 2 and 3a. The new conodont zonation is used to identify the stratigraphic position of different members and their boundaries.

In order to increase the stratigraphic resolution for the mid-late Homerian, a numerical time-scale was constructed by Jeppsson & Calner (2003). Graphic correlation between the När-1 core from Gotland and highly condensed strata of the Gräfenwarth section in Thüringia (Jaeger, 1991) demonstrates that the rate of sedimentation was approximately stable in the latter area. Hence, a Homerian timescale could be based on that section. It was chosen so that each millimetre of sediment in that section corresponds to one Homerian chronal unit (H.c.u.). This scale quantifies the general pattern that, where measured, the first and the last Homerian graptolite zones are several times as thick as the other. A preliminary calibration indicated that one H.c.u. equals about one kyr; hence, the average sedimentation rate is 1 mm $a^{-1}$. Biostratigraphic correlation, utilizing graptolites and conodonts, made it possible to apply this scale to the mid-late Homerian of Gotland. The H.c.u. scale is herein utilized to give the proportions of the different stages of platform development, including sequence stratigraphy, and their relationship to the Mulde Event (Jeppsson, 1997*b*; see section 4).

## 2. A new mid-late Homerian conodont zonation

The first Silurian conodont zonation, based on the Cellon section in Austria (Walliser, 1964), was later supplemented with an *Ozarkodina b. bohemica* Zone (Aldridge & Schönlaub, 1989). Recent changes in the Wenlock part of this zonation reached up to the *O. s. sagitta* Zone, which is coeval with the main part of the *C. lundgreni* Zone (Walliser, 1964; Jeppsson, 1997*c*). In the following section, the succeeding part of the conodont zonation is revised in a similar way.

### 2.a. The *Ozarkodina bohemica longa* Zone

*Ozarkodina bohemica* has scattered occurrences as early as in the early Wenlock (Aldridge, 1985; Jeppsson, 1997*c*, p. 101). Therefore, the lower boundary of the *O. b. bohemica* Zone has hitherto been taken either where that species became widespread in the mid-Homerian, or somewhat lower, where *O. s. sagitta* became extinct, at Datum 1 of the Mulde Event. The *O. b. bohemica* Zone, as used hitherto, corresponds to several graptolite zones, and does not reflect the major changes that took place among the conodonts, that is, its characters are those of a superzone. Utilizing these changes in full results in a conodont zonation with a precision similar to that of the most detailed graptolite zonation. Further, the zone needs to be re-named since Homerian populations are taxonomically distinct from *O. b. bohemica*. Here, the *O. b. longa* Zone is limited to an interval below the new *K. o. absidata* Zone (Fig. 2).

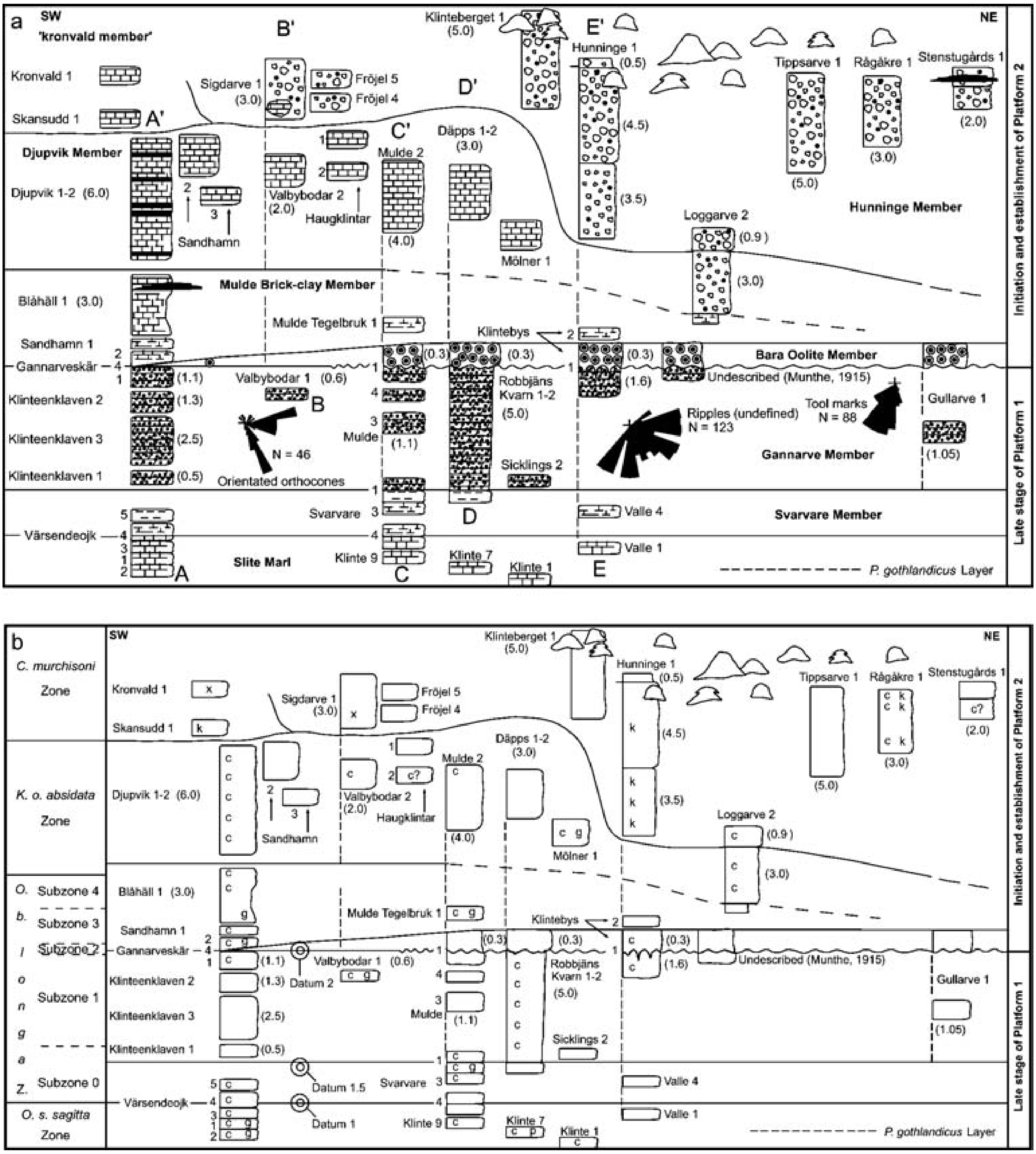

Figure 3. Temporal and spatial arrangement of the main lithofacies groups as mapped along transects A-A'–E-E' and biostratigraphic data set. (a) Main facies groups: The numbers within brackets indicate the outcropping stratal thickness at individual localities. The total thickness of different members can not be judged from the distance between the enclosing lines. Where thickness data are lacking, the outcropping section is one metre or less, e.g. surface exposures. The exposed thickness of the Gannarve Mb at Klintebys 1 and Gullarve 1 is based on Munthe (1915) and Sivhed (1976), respectively. These outcrops are today only poorly exposed. Palaeocurrent data from Calner (1999). See Figure 5 for a legend and section 4 for a discussion and interpretation of this figure. (b) Dataset for the new conodont biostratigraphy and the stratigraphic levels for datum 1, 1.5 and 2 of the Mulde Event. Note that extinctions took place within different systems tracts (cf. Fig. 12c). c – conodont collections including zone fossils; g – graptolite collections; p – *Pentamerus gothlandicus*; k – *K. o. absidata* in the lower part of the *C. murchisoni* Zone; x – selected large collections lacking both *K. o. absidata* and *C. murchisoni*.

The lower boundary is drawn at the distinct boundary marked by significant extinctions (see Fig. 2) and other conodont faunal changes at Datum 1. Such faunal changes are expected everywhere, although specific changes have been local or regional. On western Gotland a diverse fauna with *Panderodus* as the most frequent genus was replaced by a low-diversity fauna, strongly dominated by *Oz*. *excavata*.

The basal interval of the *O. b. bohemica* Zone lacks both *O. s. sagitta* and *O. b. longa* forming an interregnum. This is here included as Subzone 0 (zero) in the *O. b. longa* Zone, because collections from the interregnum are similar to those of the succeeding Subzone 1. At least on Gotland, the presence of *Walliserodus*, *Panderodus panderi*, and rare *Pseudooneotodus linguicornis* below Datum 1.5 in low frequency separates the lower and main part of Subzone 0 from its topmost part. The rest of the *O. b. longa* Zone can be subdivided into four subzones. Subzone 1 is strongly dominated by ramiform elements, in most collections *O. excavata*, like in the preceding Subzone 0 – the main difference is the presence of *O. b. longa*. In Subzone 2, coniforms dominate strongly, especially the genera *Pseudooneotodus* and *Panderodus* (only *P. equicostatus*, except at the base). In Subzone 3 ramiforms, especially *O. excavata*, have regained dominance. Subzone 4 has a more balanced conodont fauna.

Subzone 0 has been identified (see Fig. 3b) at Värsendeojk 5 and Svarvare 3; Subzone 1 at Gannarveskär 2, 4 (up to −0.04 m), Robbjänskvarn 1 and 2; Subzone 2 at Gannarveskär 4, 2, Klintebys 1, Bara 1 (through the oolite), and in the När-1 drillcore at 230.30–230.25 m; Subzone 3 at Sandhamn 1, Mulde Tegelbruk 1 and in the När-1 drillcore at 210.23–210.09 m, and Subzone 4 at Blåhäll 1 up to just above the biostrome (see Fig. 5 in Calner, Sandström & Mõtus, 2000). The correlation of these with the graptolite zonation is shown in Fig. 2 (for further data, see Jeppsson & Calner, 2003). See section 6 for records outside of Gotland of *O. b. longa* and this zone.

#### 2.b. The *Kockelella ortus absidata* Zone

Localities with *K. o. absidata* n. ssp. are limited to a narrow strip from Skansudd 1 to Rågåkre 1, possibly onwards to Stenstugårds 1, except for Hägur 1 and 2. These are found in a window south of this strip (Fig. 1c, Table 1). *K. o. absidata* is present in a variety of lithofacies, ranging from skeletal mud- and wackestones and marls in the SW, into rudstones and floatstones at Hunninge 1, and possibly into algal grainstones at Stenstugårds 1. In contrast, *K. o. absidata* is absent from all collections both from older strata – the Gannarve Mb, Bara Mb and the major part of the Mulde Mb (good collections from Mulde Tegelbruk 1 and Blåhäll 1) – and younger strata (large collections from Kronvald 1, Sudervik 1, 2, 3, and Bodbacke 1). That is, the minor lithological changes evident in the distal marls along the coast, e.g. an upward increase of carbonate content (through e.g. Sandhamn 1, Blåhäll 1, Djupvik 1–2, Sudervik 1–3, Bodbacke 1) did not cause its sudden appearance and disappearance. This pattern of presence and absence makes *K. o. absidata* useful for erection of a new zone. Its probable correlation with the graptolite zonation is illustrated in Figure 2 (see Jeppsson & Calner, 2003, for further data).

In the main part of the *K. o. absidata* Zone, and the lower *C. murchisoni* Zone, a collection of 100 or a few 100's of specimens is usually enough to get a specimen of *K. o. absidata* or at least a couple of fragments which can be identified as from a robust *Kockelella*. Since *K. o. absidata* is the only robust *Kockelella* known from this interval on Gotland, these are herein accepted as evidence for inclusion in either of these zones. The lowermost find of *K. o. absidata* in such a frequency is from Djupvik 1 at –1.05/–0.95 m. In both the very large collection G94-8LJ from –1.52/–1.47 m from Djupvik and in G94-77LJ from the 'top marker bed' (Calner, Sandström & Mõtus, 2000) at Blåhäll 1, just above the biostrome, there is a juvenile sp (Pa) element of *K. ortus* cf. *absidata*. The frequency is in the order of, or below, one per thousand. *P. unicostatus* is the most frequent coniform taxon in the Djupvik 1 sample but rare in that from Blåhäll 1. Neither species were found in the similar-sized collection just below, from the uppermost bed of the biostrome (top of the 'upper limestone-dominated unit' of Calner, Sandström & Mõtus (2000). Probably, the reappearance of *P. unicostatus* can be used as an ancillary indicator in the same way as in the mid-Sheinwoodian. The latter re-appearance is found on Gotland and in several cores and sections being studied by colleagues. Several of the originally proposed zonal indicators (Walliser, 1964) have frequencies in or below the per thousand range on Gotland (e.g. *K. patula* and *O. s. sagitta*) and in similar shallow platform areas. Thus, the base of the *K. o. absidata* Zone is here drawn below the record of *K. ortus* cf. *absidata* at Blåhäll 1.

The known occurrences of *K. o. absidata* on Gotland are listed in Table 1 as are the other conodont species found in that interval. In most samples *P. equicostatus* is the most frequent species with coniform elements throughout the Mulde Event. Among recent taxa, it is well known that closely related species may compete for the same ecological niche. This may result in exclusion of one of them. Alternatively, if their preferential niches do not overlap completely, the result may be that both are present but that their critical differences will increase in order to use their part of the niche better. Two contrasting patterns in the distribution of closely related Silurian conodonts have previously been interpreted as due to niche sharing (Jeppsson, 1997*a*). In particular environments the taxon with more gracile teeth is being most frequent and represented by all growth stages and the bigger taxon only by its largest individuals. Alternatively, in other intervals and environments the bigger taxon was best represented, grew large and was represented by all growth stages. During the Mulde Event, *P. equicostatus* had the latter role and other species of *Panderodus*,

Table 1. Samples from sections and exposures with *K. o. absidata* both from the *K. o. absidata* and *C. murchisoni zones*

| Localities, levels and samples | | | *K. o. absidata* | | | | | | Other taxa | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | sp | oz | ne | hi | pl+ ke | tr | *Pa. uni.* | *Oz. c.* | *Oz. ex.* | *Oz. b.l.* | *Oul. sil.* n. ssp. | *Cten. mu.* | "*Oz.*" Aldr. | *Pa. eq.* | *Ps. bic.* | *Ps. beck.* | *Bel.* | *Dec.* | *Da. obl.* | *Pa. serr.* |
| Stenstugårds 1 | | G85-39LJ | | | cf.1 | cf.1 | | | | x | x | x | 6 | | | 8 | | | | | | |
| Rågåkre 1 | +2.60/+2.70 | G94-63LJ | 3 | 3 | 2 | 6 | | 1 | x | x | x | x | x | 7 | 7 | 3 | | x | | | | |
| | +2.53/+2.60 | G85-42LJ | | | | 3 | 1? | | 2 | x | x | x | 5 | 1? | | 8 | | 9 | | | | |
| | 0.00/+0.05 | G85-41LJ | | | | | | | cf.x | x | x | x | 3 | 1 | 6 | 1 | | 4 | | | | |
| Loggarve 2 | +0.2/+0.3 | G90-126LJ | | | | | | | | x | x | 8 | | cf.4 | | x | | | | | | |
| | +0.00/+0.05 | G82-25LJ | | | | | | | | 2 | 5 | | | 2 | | 2 | | | | | | |
| | | G85-31LJ | 1 | | | | 2 | | | 1 | x | x | x | | 1 | x | | | 1 | 5 | 1 | 1 |
| | −0.10/−0.05 | G84-24LJ | | | | | | | | 1 | 6 | 2 | 4 | 1 | | 4 | | | | | | |
| | −0.87/−0.80 | G82-23LJ | | | | | | | | 1 | x | 3 | 1 | | 4 | 1 | | | | | cf.1 | |
| | −1.80/−1.72 | G82-22LJ | 1 | | | | | | | | 7 | cf.1 | | | | | | | | | | |
| | −2.05/−1.98 | G82-21LJ | | | | | | | | 1 | x | cf.1 | 1 | | | 3 | | | | | | |
| Loggarve 1 | | G77-22LJ | 2 | | | 2 | | | | | x | 2 | 1 | | | 5 | | 2 | | | | |
| | | G77-21LJ | | | 1 | | | | | 3 | x | x | 8 | | 8 | x | | x | | 5 | 1 | |
| Hunninge 1 | +5.27/+5.42 | G93-920LJ | | | | | | | | 6 | x | x | 2 | | | x | | | 1 | | 3 | 1 |
| | +2.00/+2.13 | G93-919LJ | 2 | | | 1 | | | | 5 | 9 | 1 | 2 | | | 4 | | | | | | |
| | −0.65/−0.13 | G93-918LJ | 1 | 1 | | 1 | | | | x | x | x | x | | | x | | | | | | |
| | −2.02/−1.95 | G93-917LJ | | | | | | | | x | x | x | x | | | x | | | | | | |
| | −2.07/−2.02 | G93-916LJ | | 1 | 2 | 1 | 2 | | | x | x | x | x | | 2 | x | | | | | | |
| | −3.50/−3.20 | G93-915LJ | | | | 5 | 5 | 1 | | x | x | x | x | | | x | | | | | | |
| Mölner 1 | | G71-36LJ | | | | | | | | 1 | x | 7 | | | | x | | | | | | |
| | | ES166/1965AM | | 1 | | | | | | | | | | | | 1 | | | | | | |
| Mulde 2 | | G99-3MCc | 3 | 1 | | | 2 | 1? | x | x | x | x | x | | | x | | 9 | | | | |
| | | G96-5LJ | | | | | | | 1 | | x | x | 4 | | | 1 | 1 | x | | 5 | 1 | |
| Haugklintar 2 | | G70-31LJ | | 1? | | | | | 1? | 3 | x | | 1 | | | cf.5 | | | | | | |
| Valby bodar 2 | | G93-967LJ | 1 | | | 1 | 2 | | 2? | x | x | 3 | x | | | x | | 7 | | | | |
| Blåhäll 1 | +0.88/+1.00 | G94-77LJ | 2 | | | 1 | | | 1 | 1 | x | x | 3 | | | x | 5 | x | | 1 | 1 | |
| Djupvik 4 | SE of the road | G84-20LJ | 1 | | 1? | | | | x | x | x | | 8 | 1? | | x | 1 | 3 | | 1 | | |
| Djupvik 3 | top | G84-19LJ | 1 | | | 1 | 1 | | x | 3 | x | 1 | 1? | | | x | 1 | 3 | | 6 | | |
| | *c.* 3.9 m below top | G84-18LJ | 1 | 1 | 1 | 1 | 2 | | x | | x | 1 | 3? | | | x | 1 | 1 | | 7 | | |
| Djupvik 1, 2 | +2.24 | G70-28LJ | 0 | | | | 1? | | x | 2 | x | x | x? | | 4 | x | | x | | 5 | 1 | |
| | +2.05/+2.10 | G85-34LJ | 1 | 1 | 3 | 4 | 2 | 1 | x | 3 | x | x | x | | | x | | | | 3 | 1 | |
| | +1.07/+1.20 | G70-27LJ | 1? | | | 1 | | 1 | x | | x | | 2 | | | x | | | | x | | |
| | +0.0/+0.2 | G70-25LJ | | 1 | | | | | | | x | | | | | 3 | | | | | | |
| | +0.0/+0.2 | G84-21LJ | 1 | | 3 | 2 | | 1 | x | | x | | 2 | | | x | | 1 | | 7 | 1 | |
| | −1.05/−0.95 | G70-26LJ | 1 | | | | | | 2 | | x | 2 | 2? | | | | 3 | 1 | | 1 | | |
| | −1.52/−1.47 | G94-8LJ | | | | | | | x | | x | x | x | | 2 | 8 | 6 | x | 3 | x | 1 | |
| | −2.05/−1.95 | G70-29LJ | | | | | | | | | 5 | | | | | 1 | | 2 | | | | |
| Skansudd 2 | | G87-425LJ | 1? | 1? | | 1? | | | | 1 | x | x | x | | | x | | x | | 2 | | |
| Skansudd 1 | | G87-424LJ | 2 | 2 | 2 | 2 | 2 | | | | x | x | 9 | | | x | | 6 | | 5 | 2 | |
| Hägur 1 | | G81-59LJ | 3 | | | 1 | 2 | 1 | 8 | 6 | x | 2 | x | | | x | | 2 | | 1 | | |
| Hägur 2 | | G94-78LJ | 1 | | | | | 1? | x | x | x | | 7 | | | x | x | x | | x | | |

Presence of a particular species is marked with an 'x', except when less than 10 specimens have been found. The localities are arranged from SW to NE; that is, except wihin a locality, samples are not in age order. Sample ES166 was collected and processed by Anders Martinsson. Other taxa from left: *Panderodus unicostatus*, *Ozarkodina confluens*, *O. excavata*, *O. bohemica longa*, *Oulodus siluricus* n. ssp., *Ctenognathodus murchisoni*, '*Ozarkodina*' n. sp. of Aldridge 1985, *Panderodus equicostatus*, *Pseudooneotodus bicornis*, *Ps. beckmanni*, *Belodella* sp., *Decoriconus*, *Dapsilodus oqliquicostatus*, and *Panderodus serratus.*

if present, are represented only by small (juvenile) specimens. In such cases, comparison of juvenile specimens is taxonomically important to exclude the possibility that juvenile characters are mistaken for a taxonomic separation. Identification of *P. serratus* is based solely on the serrated element and, hence, a few specimens of the other elements are probably counted among those referred to *P. unicostatus*. Principally, contamination cannot be excluded for finds of single or a couple of specimens like those of *Panderodus* aff. *greenlandensis* (the form found in the 'mid-Ludlow' eastern Hemse limestones) and *Ozarkodina* cf. *wimani*. However, elements and taxa more frequent in potentially contaminating collections, are not found. Hence, it is more probable that these specimens really are indigenous.

As discussed in section 6, at least one other *Kockelella* lineage was coeval with *K. o. absidata* and may be present on Gotland. Further, a specimen of *K. variabilis* is present in the collection from Sudervik 1. This specimen differs from those in potentially contaminating samples, and hence, seems not to be a contamination. Hence, a third lineage of *Kockelella* is present just above the Homerian range of *K. o. absidata*, and, considering its distinctness, is expected to have existed as a separate lineage also during that chron.

The *K. o. absidata* Zone has now been identified on Gotland and in Oklahoma by J. Barrick and L. Jeppsson (see discussion of *K. o. absidata* in section 6). Identification in cores and in areas where only smaller collections are available may be helped by ancillary indicators, e. g. the increase in diversity, both generally and in *Panderodus*. The co-occurrence with *O. b. longa* may be useful if separation of *K. o. ortus* and *K. o. absidata* is uncertain.

### 2.c. The *Ctenognathodus murchisoni* Zone

This zone was named from Estonia (Viira, 1982). The very characteristic conodont fauna in the upper part of this zone includes *O. confluens densidentata*, *Ctenognathodus murchisoni*, *O. bohemica longa*, *O. roopaensis*, and other robust taxa but only very rare coniforms. The base of the zone is at least 1.55 m below the top of the Halla Fm as drawn at Gothemshammar 2 and 3 by Hede (1928, p. 54–55). The zone ranges through the exposed lowermost Klinteberg Fm there and has been traced south-westwards in a narrow belt with finds of it at Västerbjärs 1, Råby Träsk 1, Godrings 4, Båtels 1, Hällinge 2, and Hästings 1. *Ctenognathodus murchisoni* is present in the lowermost part of this zone, but not the highly distinct form of *O. c. densidentata*, e.g. at Gothemshammar 2, Vänge 1, Tass 1, Rågåkre 1, Loggarve 2, and Hunninge 1. Instead, a much less distinct form is present. Together, the conodont collections at hand indicate a gradation from this form via intermediate ones to the highly distinct one. *K. o. absidata* ranges into this part of the zone on western Gotland at Loggarve 2, Rågåkre 1 and Hunninge 1 (Table 1). There, the general faunal composition is also less distinct, and both *O. excavata* and *Panderodus* occur. *C. murchisoni* is not found further southwestwards. On Gotland, species of *Ctenognathodus* are, with few exceptions, found in the platform interiors (the pure limestone areas on the geological maps). Thus, it is more probable that the absence of *C. murchisoni* in the more distal marl facies is due to unfavourable environments rather than to a major gap in the sequence of collections. Thus, the ancestral form to *O. c. densidentata* is found at Sigdarve 1 where both *C. murchisoni* and *K. o. absidata* are absent, indicating that the latter disappeared before the typical *O. c. densidentata* replaced the older form. *O. c. densidentata* is also found in USA (Helfrich, 1975). In its typical form, that taxon is often a better zonal indicator since it is highly distinct, more widespread, and more frequent.

Above the *C. murchisoni* Zone follows at least two faunas without *O. bohemica*, before the true *O. b. bohemica* is briefly present, coeval with the *N. nilssoni* graptolite Zone (Walliser, 1964). That subspecies is known from Gotland, Bohemia and Cellon (Jeppsson, 1997*c*).

## 3. Facies descriptions

The coastal exposures south of Klintehamn on western Gotland (Fig. 1c) are the only sites in the Baltic basin where the mid-late Homerian succession is complete in outcrop (Calner, 2002). From Mulde 1 and northeastwards along the outcrop strike, a hiatus successively increases in magnitude (Calner, 1999) to exposures on Saaremaa, Estonia, where the mid-Homerian is lacking (Nestor & Nestor, 1991). In the Klintehamn area, about 40 m of strata crop out between Värsendeojk 4 and Bodbacke 1 (Fig. 1c). These strata reflect deposition of both carbonate and fine siliciclastics, the latter mainly detrital clay and silt together with small amounts of sand. Below, facies changes are described across the palaeo-platform margin as depicted by Calner, Sandström & Mõtus (2000). Transects A-A' and E-E' include the best successions of exposures and show the largest proximality differences, and are for this reason highlighted (Fig. 3). Comparisons to the eastern parts of the mid-late Homerian outcrop-belt (Fig. 1d) are made where appropriate.

### 3.a. Slite marl and reef limestone

The *O. s. sagitta* Zone continues above the cross-Gotland *Pentamerus gothlandicus* Layer of Hede (1927*a*, p. 29–31; Jeppsson 1997*c*; Calner, 1999) through the few metres of the uppermost Slite Marl in the west (at Värsendeojk 1–3; transect A-A'). The Slite Marl is a diagenetically enhanced alternation of thin bedded, nodular to continuous, slightly argillaceous limestones and more recessive marls, all generally of skeletal wackestone texture, with subordinate intercalations of mud- and packstone. Brachiopod, crinoid and trilobite grains dominate the skeletal composition. The sediments are well bioturbated. Micro-stratigraphic relationships show that there was at least two generations of ichnofabrics. 1) A mottled, endichnial 'background' fabric – common also in the distal parts of the overlying Halla Fm. 2) Centimetre thick traces, possibly *Thalassinoides*, are preserved endichnially or as epichnial ridges (cf. Martinsson, 1970). Stromatoporoids and tabulate corals of different low, domical morphotypes are common, generally 1–2 dm in diameter, and only rarely with sediment inclusions or ragged margins (cf. Kershaw & Riding, 1978; Kershaw, 1984). Bed thickness and nodule size decrease slightly through the last decimetres of the Slite Marl (at Värsendeojk 3 and 4; an *O. s. sagitta* Zone fauna is recorded at the former locality, although no zone fossil has been extracted).

The coeval reef platform on eastern Gotland, the youngest Slite reef generation (Slite 'g' of Jeppsson, Viira & Männik, 1994), is exposed from Slite (e.g. Slitebrottet 4) southwards to Tjäldersholm 1 and Bara 1. This platform shows considerable palaeorelief and has a low dip towards ESE (see section 3.b.2). The reefs have a preserved thickness of *c.* 12 m at Bogeklint (Hede, 1928, p. 30) but probably exceed 20 meters in the Bara 1 area. This reef tract forms a stratigraphically well-defined level not only on Gotland but also in the northern parts of the Baltic basin (Klaamann & Einasto, 1982).

The lateral relationship of the Slite Marl on western Gotland and the reef tract in the eastern part of the outcrop-belt clearly indicate a depositional setting of the marl far seaward of the reef belt. The sediments, their contained fauna, as well as the intense bioturbation, indicate a well-oxygenated sea floor, below, but probably close to, storm wave-base. This facies type is common on the distal platform throughout the major part of Wenlock and Ludlow.

### 3.b. The Fröjel Formation

The Fröjel Fm (Calner, 1999) conformably overlies the Slite Marl. This is the only Wenlock unit on Gotland that is rich in coarser siliciclastics. It is 9–11 m thick in its southern outcrops but thins out towards NE. This is partly due to erosion during the sea-level lowstand at the end of the *C. lundgreni* Zone. Coeval strata in the När-1 drillcore, *c.* 25 km to the southeast, are 4.28 m thick (Jeppsson & Calner, 2003).

#### *3.b.1. Svarvare Mudstone Member*

The Svarvare Mb of the Fröjel Fm is about 2–3 m thick, occurs in all transects, and is referable to Subzone 0 of the *O. b. longa* Zone (dated at Värsendeojk 5, Svarvare 1 and 3). Its lower, sharp contact (at Värsendeojk 4 and Svarvare 4) coincides with Datum 1 of the Mulde Event (Jeppsson & Calner, 2003). Thin-bedded, dark grey, highly argillaceous mud- and wackestones dominate in the lower parts, grading upwards into siliciclastic mudstones. The uppermost, still darker 0.25 m (at Svarvare 1) differs strongly from the older parts. It contains >90% of insoluble material in the clay and silt fraction and is rich in graptolites (a low diversity fauna was reported by Hede, 1942, Bergman, 1980).

The member differs fundamentally from the underlying Slite Marl in its dark colour, sparse bioturbation, and the lack of stromatoporoids, tabulate corals, and regularly alternating marls and limestone. The depositional setting was, based on facies and fauna, open marine below the effective wave-base, i.e. it may not have been much different from that of the topmost Slite Marl. There are several indications that the Svarvare Mb is not a regressive deposit (compare overlying strata). The dark colour, the frequent graptolites, the increased frequency of conodonts, and the relative high phosphorus content instead indicate slight condensation (Calner, 1999). Datum 1 of the Mulde Event is found at the base of the Svarvare Mb and Datum 1.5 *c.* four decimetres below its top.

#### *3.b.2. Gannarve Member*

The less fossiliferous Gannarve Mb conformably overlies the Svarvare Mb. The basal few decimetres at Svarvare 1 are referable to Subzone 0 of the *O. b. longa* Zone. The main part of the member belongs to Subzone 1 of the same zone; identified at Mulde 1, Gannarveskär 1 and Robbjänskvarn 1–2. The topmost 4 cm of the member (at Gannarveskär 4) belong to Subzone 2 of the same zone. The Gannarve Mb consists of 7–8 metres of silty limestones, mixed carbonate-siliciclastic mud-, silt- and, locally, fine sandstones (e.g. in one of A. Hadding's thin-sections from Klintebys 1). Dark grey, laminated mud- and siltstones, occasionally with graptolites, dominate in the lower parts (Fig. 4a). The middle and upper parts shows abundant wave and current ripples, planar laminations, and hummocky cross stratification (Fig. 4b,c). Towards its proximal part (Transect E-E') the grain size is somewhat coarser and the member is truncated by a low-relief epikarstic unconformity (Calner, 2002). This unconformity is coeval with the Slite Rocky Shoreline Unconformity on eastern Gotland (Calner & Säll, 1999). The latter truncates the topmost reef tract of the Slite Group and has a preserved erosional relief

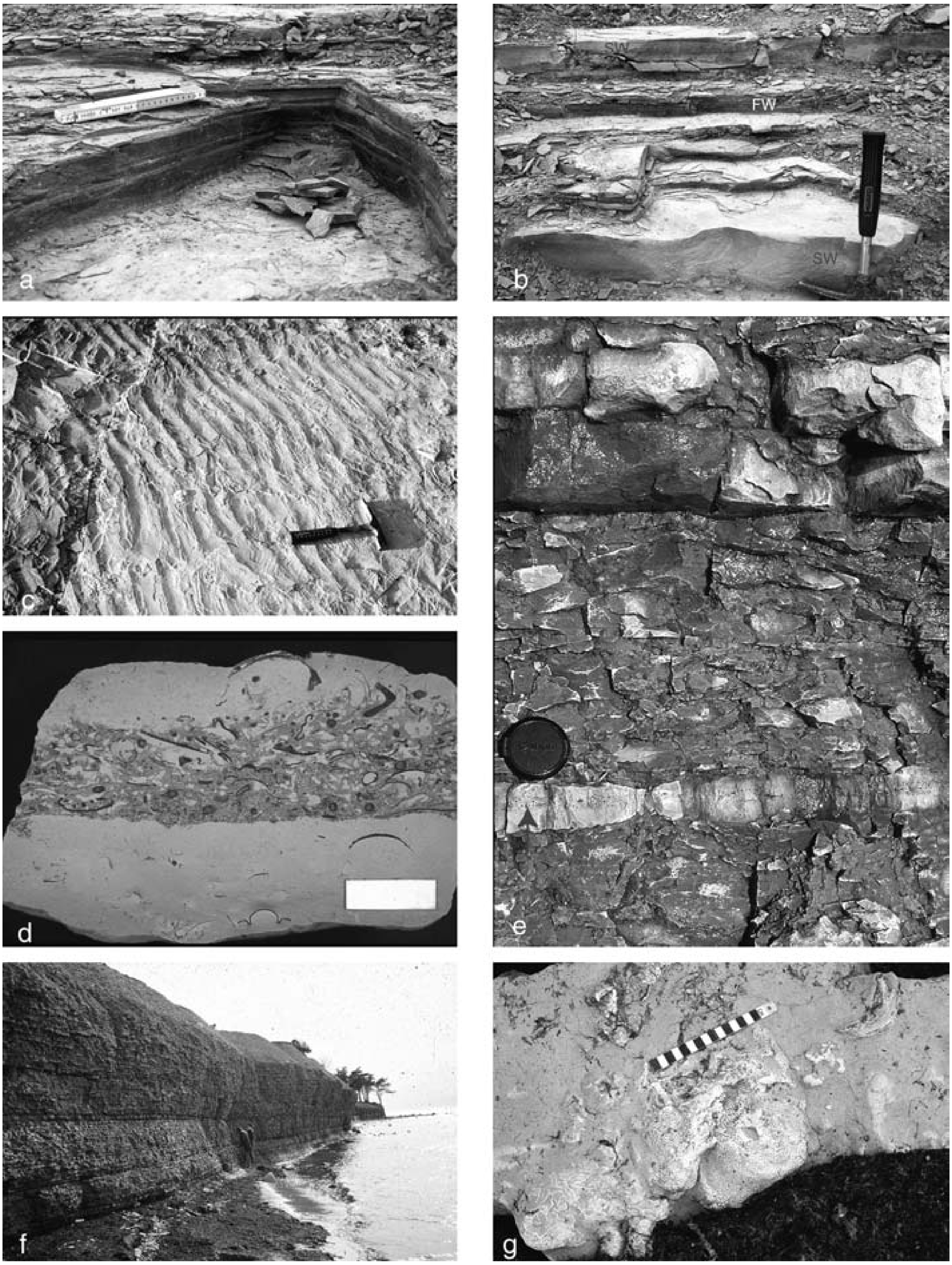


Figure 4. Photographs of selected localities and slabs. (a) Conspicuously parallel laminated, argillaceous siltstones from offshore current deposition. Frequent graptolites were recovered from this level (unpublished material of MC). Lower Gannarve Mb, lowermost Klinteenklaven 3, *O. b. longa* Zone, Subzone 1. (b) Thin to medium bedded storm deposited siltstone beds (SW) interbedded with softer and argillaceous fair-weather mudstones (FW). This is approximately two metres above the strata shown in 4a. Lower Gannarve Mb at Klinteenklaven 3, *O. b. longa* Zone, Subzone 1. (c) Wave-induced, slightly bifurcating ripples in calcareous siltstone. Upper Gannarve Mb at Valby Bodar 1, *O. b. longa* Zone, Subzone 1. (d) Thin packstone tempestite in polished slab from Blåhäll 1. Note sharp base and gradational upper boundary. Scale bar 1 cm. (e) Argillaceous wackestones interbedded with poorly consolidated siliciclastic mudstones and marls. The lens-cap (50 mm) rests on the bed shown in Figure 4d. Uppermost part of the mudstone dominated unit at Blåhäll 1. Mulde Mb, *O. b. longa* Zone, Subzone 4 (see also Fig. 6). (f) Aggradational to slightly progradational succession of argillaceous wackestones and marls at Djupvik 1. Djupvik Mb, *K. o. absidata* Zone (photo courtesy of S. Stridsberg). (g) Bedding plane association of halysitids, heliolitids and stromatoporoids from the lower parts of Djupvik 1. Scale bar in cm.

of 5.76 m at Svalings 1 and at least 16 m at Bara 1 (Fig. 1d). The unconformity is also coeval with the basin-regional seismostratigraphic discontinuity surface $S_4$ of Flodén (1980; see Calner & Säll, 1999). About 50 km east of Slite, the uneven unconformity has a dip of about 12° towards the south sector. It is interpreted to become conformable *c.* 8.5–10 km south of its appearance (Maria Eriksson, pers. comm. 1999, based on transect 9307). Such a major unconformity changed the depositional profile considerably. It denotes a major seaward advance of the shoreline during a brief interval at the end of the *C. lundgreni* Chron (Calner, 1999). A tidal flat locally fringed this lowstand shoreline (e.g. at Klintebys 1, Calner, 2002). The relation of the unconformity to Datum 2 of the Mulde Event is discussed by Jeppsson & Calner (2003).

Except for a small outcrop on Ytterholmen (cf. Hede, 1928, p. 40–41), the only remains of a former presence of the Gannarve Mb on eastern Gotland are as ooid nuclei in the basal Bara Mb at Svalings 1 and Bara 1 (Calner & Säll, 1999, and below). The siliciclastic belt is further traceable in the subsurface to Bjärges-1 south of the outcrops, Östergarn-1 on eastern Gotland, and to the Ohesaare core (160.0–157.35 m) on southernmost Saaremaa (for references, a measured profile and a detailed analysis of the Fröjel Fm, see Calner, 1999).

### 3.c. The Halla Formation

#### *3.c.1. Bara Oolite Member*

The Bara Mb is a linear, mainly oolitic, sedimentary body traceable across Gotland. On western Gotland it overlies epikarst of the Fröjel Fm except that the boundary is conformable in transect A-A' and no data exist from transect B-B'. The member is 0.04 m thick at Gannarveskär 4, 0.3 m at Mulde 1, 0.5 m at Robbjänskvarn 2, and 0.3 m at Klintebys 1 (Fig. 5). The cortex of coated grains at these localities consists mainly of algae. Thus, micro-oncoids predominate on western Gotland whereas the member is dominated by ooids on eastern Gotland (Calner & Säll, 1999). Repeated corrosion on grains and cements, a fitted grain fabric and numerous small-scale discontinuity surfaces at Klintebys 1 indicate that deposition was frequently interrupted (Calner, 2002). The upper surface of the oncolite at Klintebys 1 displays large-scale wave ripples with a mean crest direction at N48°E (Munthe, 1915; Bergman, 1979).

On eastern Gotland, the oolite rests unconformably on the Slite Rocky Shoreline Unconformity (see section 3.b.2.). Thus the sea-level drop that promoted deposition of the shoaling upward Gannarve Mb, *c.* 30 km towards the SW, was at least as large as the erosional relief on eastern Gotland, i.e. 16 m. The Bara Mb coarsens upward, comprising thin- and crossbedded, pure oolite grainstones and oolitic skeletal/peloidal grainstones, reaching a maximum preserved thickness of 5 m (at Bara 1; Manten, 1971). Three different oolite micro-facies were interpreted as representing both mobile bar and mixed bar/lagoonal deposits (Calner & Säll, 1999). Siltstone, as ooid nuclei, is common in the lowermost 1–2 cm of the oolite at Svalings 1, indicating proximity to possible by-pass pathways for the Gannarve Mb sediments (Calner & Säll, 1999).

#### *3.c.2. Mulde Brick-clay Member*

The highly argillaceous Mulde Mb is accessible at four places along the coast (Transect A-A') and at one inland locality (Transect C-C'). It is most argillaceous in its lower and middle parts and rapidly thins out towards the NE (cf. Hede, 1927a). The lowermost 0.2–0.3 m consists of nodular, argillaceous wackestones with large brachiopod fragments (e.g. *Leptaena* sp.) interbedded with softer marls (at Gannarveskär 2).

Stratigraphically somewhat higher up, the strata lacks diagenetically enhanced nodular bedding and consists of thin bedded, blocky and only slightly calcareous clay/mudstones (at Sandhamn 1). In contrast, resistant grainstone interbeds are common at the classical but now no longer accessible Mulde Tegelbruk 1 locality (Hede, 1921, 1927*b*, 1960, locality 31). These strata show frequent coarse intraclasts of greenish lime mudstone, shelter porosity and geopetal structures. The more argillaceous beds hold a diverse, extremely abundant, well preserved open marine shelly fauna. A drilling there, early this century, penetrated five metres of Mulde Mb without reaching the underlying Bara Mb (cf. Hede, 1927*b*, p. 19). This, together with observations by MC, indicates a thickness of slightly less than 10 m for the Mulde Mb along transect B-B'.

The Mulde Mb is best exposed at Blåhäll 1, a 3 m high shore-cliff (Figs 4d,e, 6). Exposures in between are poor but the base may be *c.* 2 m above the strata at Sandhamn 1. At Blåhäll 1, nodular to more continuous beds of argillaceous wackestones alternate with marls and siliciclastic mudstones. More or less bioturbated packstone beds, *c.* 1–2 cm thick, occur rarely throughout the section denoting subordinate, weak current deposition. Near the top, a thin, halysitid-heliolitid autobiostrome is traceable laterally for the length of the outcrop, *c.* 450 m (Calner, Sandström & Mõtus, 2000).

#### *3.c.3. Djupvik Member*

The thickness is estimated to be roughly 10 m along the western coast, thinning out northeastwards, and the combined thickness of the Mulde and Djupvik members is thus about 20 metres. This should be compared to the estimated 22 m in the När-1 drillcore (Jeppsson & Calner, 2003, Fig. 2). At the type locality Djupvik 1 (2.9 km NE of Skansudd 1; Fig. 4f),

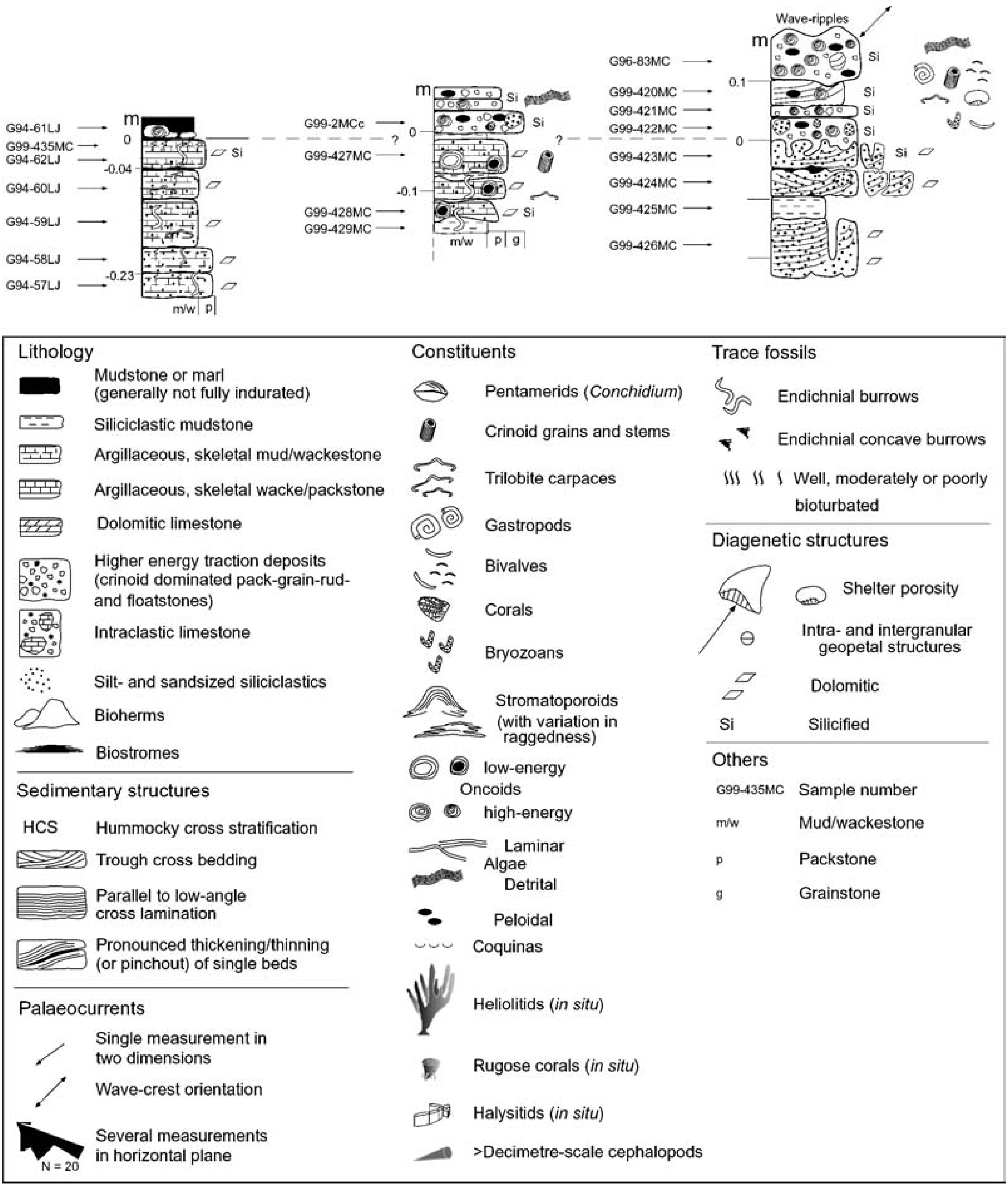


Figure 5. Transitional successions of the Slite Group (Fröjel Formation, Gannarve Mb) and Halla Formation (Bara Mb) at Gannarveskär 4 (left), Mulde 1 (middle), and at Klintebys 1 (right). The dashed line marks the base of the Bara Fm at Gannarveskär 4 and Klintebys 1. *O. b. longa* Zone, subzones 1 and 2.

about six metres of well bioturbated, aggradational to slightly progradational skeletal wackestones and marls crop out. The limestone beds are light bluish grey, nodular to continuous and generally some 3–5 centimetres in thickness. The slightly thinner, highly argillaceous marls display compaction features. Primary depositional texture includes rare thin tempestites. Skeletal grains are disarticulated and generally from brachiopods and trilobites. Large epibenthic metazoans are represented by stromatoporoids and

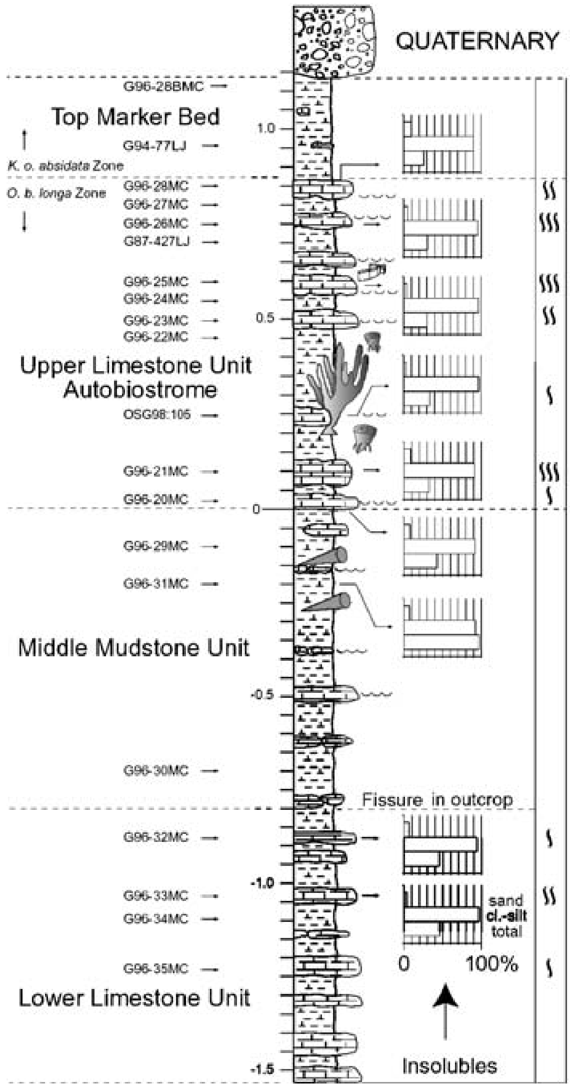


Figure 6. Sedimentary profile from Blåhäll 1. The profile shows aggrading to slightly prograding highstand marls deposited seaward of the platform margin (modified from Calner, Sandström & Mõtus, 2000). Note the zonal boundary between the *O. b. longa* Zone, Subzone 4 and the *K. o. absidata* Zone.

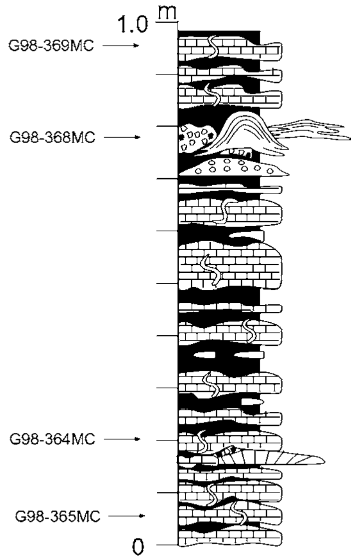


Figure 7. Sedimentary profile at the Valby Bodar 2 roadcut (Djupvik Mb). Note abundant stromatoporoids and heliolitids, and inclusions of grainstone facies.

various tabulate corals, e.g. *Halysites* sp. and *Heliolites* sp. (Fig. 4g). These are in growth position, low to highly dome-shaped, and are draped by overlying marls. Eight bentonites, none more than 5 cm thick, crop out at Djupvik 1 (Odin *et al*. 1986; Batchelor & Jeppsson, 1999). None of these bentonites have yet been identified at localities NE of Djupvik 1 where outcrops are scarce, less fresh and smaller.

This member generally becomes less argillaceous and contains an increasing number of tempestites towards the NE. It forms a steep slope in the topography, cropping out where roads are crossing the slope. This topographic correlation is confirmed by the presence of the *K. o. absidata* Zone (Table 1). The facies is closely similar to that at Djupvik but slightly less argillaceous and extensively bioturbated *c*. 5 km NE of Skansudd 1 (at Sandhamn 2 and 3). Although some current deposition can be inferred, depositional texture is not clearly visible. The facies is still generally a well bioturbated skeletal wackestone facies, although with subordinate intercalations of thin pack/grainstone tempestites 7 km NE of Skansudd 1 (Valby Bodar 2; transect B-B' in Fig. 7). Stromatoporoids grew as low to high domical morphotypes with only rare sediment inclusions and occasionally an encrusting bryozoan epifauna. Heliolitids with low/flat forms and halysitids occur. One metre of a similar burrowed wackestone facies, but with only rare stromatoporoids, is exposed 1400 m further towards the NE (at Haugklintar 2).

The steep slope, east and topographically above road 140, 9.1 km NE of Skansudd 1 is also formed by the Djupvik Mb. Below the slope, a middle part of the Mulde Mb has previously been exposed at Mulde Tegelbruk 1. Sediments of Blåhäll age would be expected within the intervening strata, which are not exposed at these localities. The base of the Djupvik Mb may be as high up as in the lowest part of the steep slope, at road level. A well exposed profile through the Djupvik Mb is accessible about 200 m further to the NE at Mulde 2. Here, the facies is comparable to that at Valby Bodar 2 although less argillaceous and with frequent sharp based packstone tempestites.

12.5 km NE of Skansudd 1, the Djupvik Mb disappears laterally into the lower or middle parts of the hill Klinteberget (just NE of Mölner 1). At the Loggarve 2 road-cut (Figs 8b,c, 9), 3 km further to the NE, *K. o. absidata* was not found in the lowermost 0.7 m of argillaceous strata, although the sample is small. Based on the lithology this part of the section is assigned to the Mulde Mb. The overlying 1.85 m of crossbedded and occasionally normally graded skeletal pack- and grainstone belongs to the Djupvik Mb.

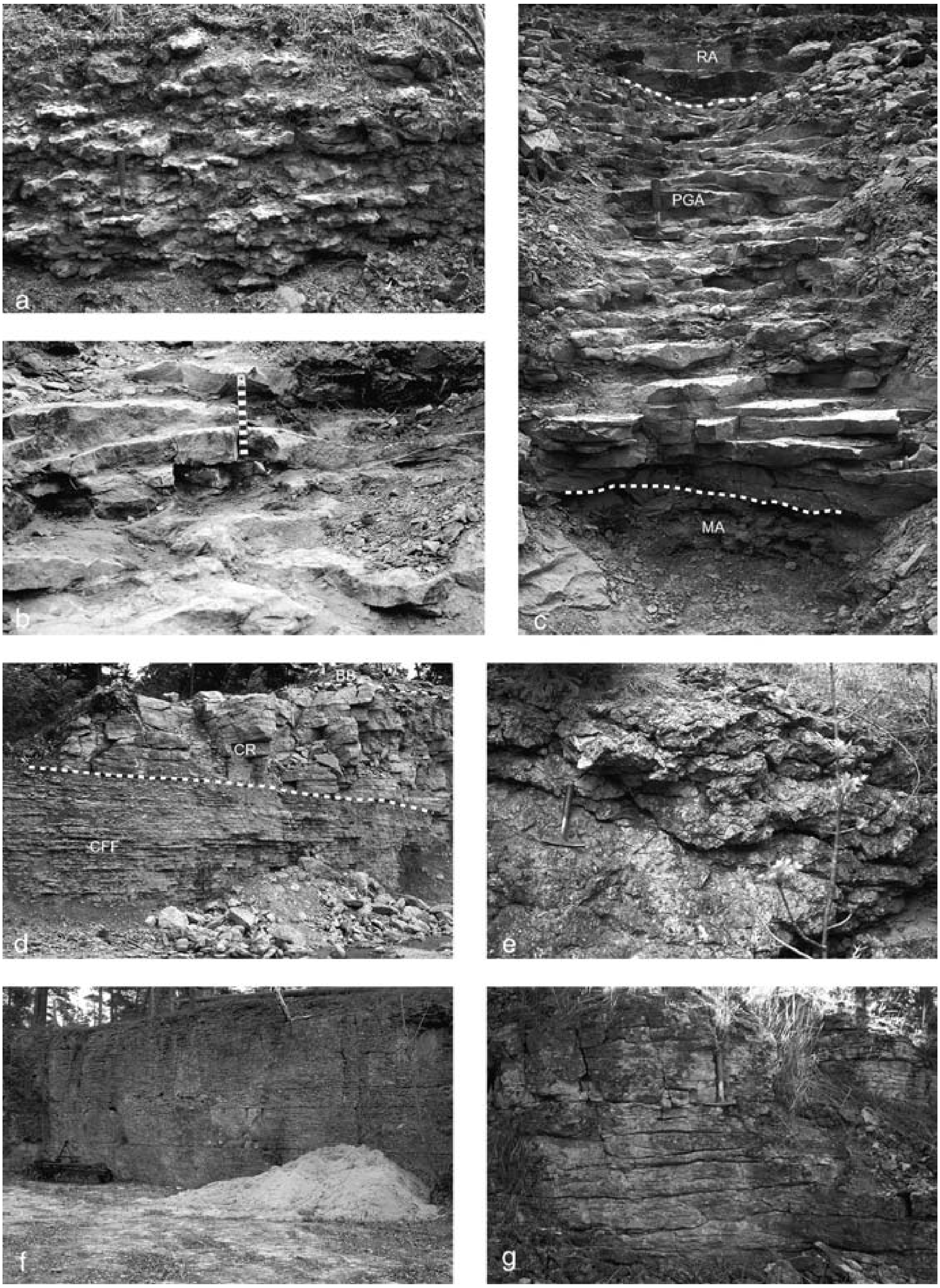


Figure 8. Photographs of selected localities. (a) Irregularly bedded wacke- and packstones interbedded with marls. Much of the irregularity is due to extensive bioturbation and early diagenesis. Hammer for scale. Däpps 1 (Djupvik Mb). (b) Close-up of the middle parts of the section shown in Figure 8c, displaying complex bedding, inferred hummocky cross stratification, in crinoid grainstones. Loggarve 2. Scale bar in centimetres. (c) Excavated section showing a progradational succession from marls and siliciclastic mudstones (mudstone association – MA), to a crossbedded crinoid pack- and grainstone association (PGA). This association is sharply capped by a crinoid grain- and rudstone association (RA) at the top. Hammer for scale. Loggarve 2; see Fig. 9 for a measured profile. (d) Progradational succession through coarse crinoid floatstone facies (CFF) to coarse crinoidal rudstones (CR). The succession is capped by a bryozoan boundstone (BB). The section is 8.4 m high. Hunninge 1, Hunninge Mb, *C. murchisoni* Zone. (e) Small bioherm in the uppermost part of the section at Hunninge 1. Hammer for scale. (f) Thick (5–6 m) aggradational succession through crinoidal grain- and rudstones. Tippsarve 1 (Hunninge Mb). (g) Retrogradational succession through crossbedded crinoid grain- and rudstones. Hammer for scale. Rågåkre 1, Hunninge Mb, *C. murchisoni* Zone (see Fig. 10 for a measured profile).

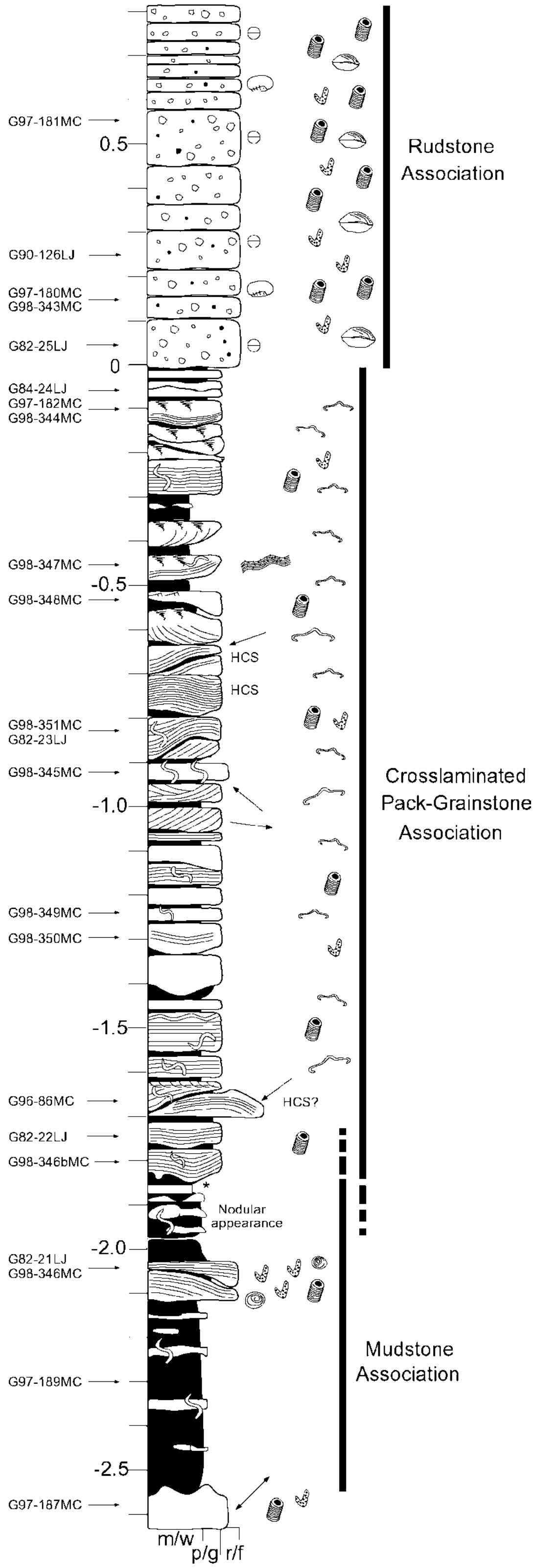


Figure 9. Sedimentary profile showing the Loggarve 2 roadcut. The three subdivisions represent, from the bottom, the Mulde, Djupvik, and the Hunninge members. Facies are interpreted as reflecting progradation of crinoid shoal facies across a storm-dominated, proximal platform slope. The asterisk indicates a distinct horizon useful as an ancillary reference level, 1.80–1.88 m below the boundary ['plastic clay' of Jeppsson & Jerre (unpublished)]. See also photographs in Fig. 8b,c.

It is here sharply overlain by coarse, crinoid grain- to rudstone facies of the Hunninge Mb. Upper bedding planes in the Djupvik part of the section show abundant horizontal epichnial grooves, a few centimetres long and about one centimetre deep. Endichnial traces filled with a greenish micrite/clay occur throughout the entire section. The abundant trace fossils indicate a prolific infaunal activity between episodes of high-energy deposition.

### *3.c.4. 'hörsne' and 'gothemshammar' members*

On eastern Gotland, 'hörsne member', *c.* 5 m of the middle Halla Fm (Laufeld, 1974*a*), consists of small bioherms and associated biodetrital inter-reef sediments, best exposed at Hörsne 1–6. Biostratigraphy suggests correlation with the Mulde and parts of the Djupvik members in the SW (Martinsson, 1967; Jeppsson & Calner, 2003). This and the following name are here used informally and are therefore written in lower case.

The 'gothemshammar mb' corresponds to the upper unit of the Halla Fm recognized by Hede (1928; unit *c* of Laufeld, 1974*a*). The member consists of about ten metres of strata (cf. Munnecke, 1997). Abundant bivalve shell lags are characteristic for the lower parts of the member which also includes a 0.4 m thick, rippled skeletal rudstone unit of progradational character, inferably a channel deposit (just north of Gothemshammar 1). The uppermost *c.* 3 m of the member consists of thin-bedded, extensively bioturbated oncolitic wacke- and packstones arranged as a limestone-marl alternation. Oncoids are several centimetres across and irregular due to periods of stationary growth. Based on facies and stratigraphic relationships, the member is interpreted as representing aggradational back-reef lagoonal environments with local channel deposition.

Hede (1928) drew the lower boundary of the Klinteberg Fm at Gothemshammar 3 at a polished unconformity surface, with abundant truncated oncoids (Hede, 1928). Here, the basal part of that formation consists of a thin transgressive marl followed by bioturbated oncoid wacke- to packstones rich in gastropods, bivalves and brachiopods i.e. a similar facies to that of the uppermost Halla Fm (see Hede, 1928; Frykman, 1989). The only major facies change was that mentioned above, *c.* 3 m lower down. Similarly, the conodont fauna collected at 1.55–1.35 m (G92-381LJ) below the unconformity represents the *C. murchisoni* Zone, including *C. murchisoni* and *O. c. densidentata*. It is not older than that in the basal Klinteberg Fm on western Gotland. The unconformity has only been recognized locally and does not serve to separate the formations in other outcrops and a future revision *c.* 3 m downward seems warranted.

### 3.d. The lower Klinteberg Formation

#### 3.d.1. ‘kronvald member’

Strata belonging to the ‘kronvald mb’ crop out along the coast from Skansudd 1 and southwards to Hammarudd. The carbonate content is higher than in the Djupvik Mb. As a result, bedding is more pronounced, lacking the typical nodular to wavy bedded character of the Djupvik Mb. Also the interbedded marl is better lithified than in that member at Djupvik 1, and falls apart in centimetre-thick beds. More data need to be accumulated before the ‘kronvald mb’ is formally defined.

#### 3.d.2. Hunninge Member

The Hunninge Mb is well exposed in several outcrops from Fröjel to Rågåkre 1 and refers to a unit chiefly composed of crinodal allochthonous debris, deposited in a high-energy environment. Except for at Sigdarve 1, the conodont faunas from this member are referable to the overlap interval with both *K. o. absidata* and *C. murchisoni* (Fig. 3b, Table 1). In the southwesternmost localities studied (Sigdarve 1, $>3$ m exposed, and Fröjel 5, $<1$ m exposed) the Hunninge Mb consists of thinly nodular bedded, peloidal pack- to grainstones, rich in well-rounded, pebble-sized intraclasts of crinoid wackestones. The Djupvik-Hunninge boundary is likely to occur in the middle part of the poorly exposed section at Fröjel 5. The lack of *K. o. absidata* at Sigdarve 1 indicates a clearly younger age for these strata than for those at Skansudd 1 and Hunninge 1. Strata of the latter age are expected to occur somewhere below the road at Sigdarve 1. The present topography indicates that these strata are easily weathered and, for this reason, argillaceous. Thus, the exposed strata resulted from highstand shedding from a contemporary, adjacent platform margin, into deeper waters. The present steep topography immediately NE of Sigdarve 1 (Fig. 3) shows palaeo-seaward inclination of reef-builders and is likely to reflect this platform margin. The lack of *C. murchisoni* at Sigdarve 1 probably reflects an unsuitable facies for that species.

The Hunninge 1 quarry (transect E-E’) exposes three walls, each about 8.5 m high, and together exceeding 700 $m^2$. Although the new quarry floor measures only c. $30 \times 30$ m, correlation between the walls is difficult because of the complex facies architecture. Frykman (1989) investigated a smaller section west of the new quarry. He described three facies, viz., peloid-rich wackestone, crinoid grainstone and biohermal facies (his facies B, C, and D).

The north-eastern quarry wall, approximately 50 m NE of Frykman’s section, contains a progradational, coarse-grained interval which may be subdivided into three distinct facies associations (Fig. 8d). The lowermost unit is a limestone-marl alternation of floatstones. The more resistant beds vary from (2-)5–6(-20) cm, decreasing in thickness in the uppermost metre. They have a coarse matrix dominated by disarticulated skeletal grains, gastropods, trilobites, club-like bryozoans and larger fragments (some few mm to cm) of mainly brachiopods (e.g. *Conchidium conchidium*), bryozoans, crinoids and rounded, abraded clasts of stromatoporoids. Intragranular geopetal structures of lime mud are common. The intercalated marls are thinner and contain similar coarse bioclastic material. Large, overturned tabulate corals are found in similar facies in the south-eastern quarry wall. Geopetal structures and fabric show that bedding planes in that wall, dipping more than 20° N, represent the primary depositional dip. Sediment dispersal, as estimated from trough structures and depositional dips, was roughly from SE or S, towards N.

The lower floatstone unit is sharply overlain by cross-bedded to massive crinoid, pebbly rudstones dominated by crinoid stalks, bryozoans and stromatoporoid grains, the latter being coarsest (2–10 mm). In the SE and SW walls, this facies includes abundant overturned and abraded stromatoporoids. Intergranular lime mud geopetals are common throughout the rudstone facies.

The rudstones are overlain irregularly by bryozoan boundstones with a greenish, lime mud matrix. Well-preserved, non-abraded brachiopods and club-like bryozoans are abundant, whereas gastropods and disarticulated trilobite cuticles are sparse. A yellowish-white lime mud occurs abundantly as intragranular geopetal fillings. These are discordant relative to the bedding planes, in places indicating a depositional dip of at least 15°.

On the top and immediately SE of the quarry, Quaternary deposits have been removed to admit further quarrying. Here, and west of the quarry, biohermal facies dominated by stromatoporoids and tabulate corals occurs (Fig. 8e). Crossbedded crinoid rudstones fill out some of the interbiohermal depressions.

The Hunninge Mb continues northeastwards and is exposed in abandoned quarries 16.5 km (Tippsarve 1) and *c.* 20 km (Rågåkre 1) NE of Skansudd 1. At least six metres of aggradational, thin bedded crinoid rudstones containing large overturned stromatoporoids (Fig. 8 f) are exposed at Tippsarve 1. At Rågåkre 1, the succession starts with a thin shale horizon *c.* 0.12 m below the present quarry floor (Fig. 10). Apart from abundant graptolites (*P. dubius*) and subordinate tiny brachiopods, the shale is extremely rich in scolecodonts (Calner & Eriksson, 2002). The quarry floor itself displays prominent wave ripples with a mean crest orientation of N60° E (Bergman, 1979) in a bryozoan pack-grainstone. Abundant horizontal exichnial trace fossils occur on the trough surfaces. This surface is overlain by c. 2.5 m of crinoid-bryozoan grainstones, typical for the Hunninge Mb (Figs. 8g, 10). Individual bedsets are roughly decimetre

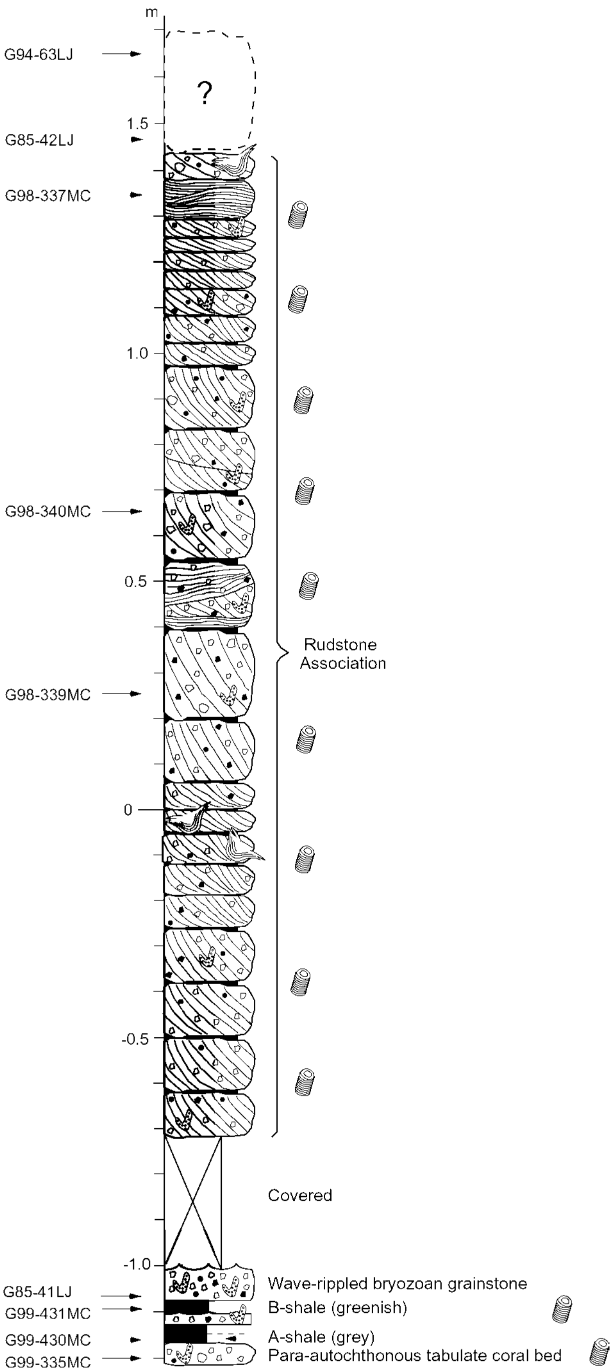


Figure 10. Sedimentary profile from the Rågåkre 1 quarry showing a homogenous facies association of crinoidal grain- and rudstones. The condensed A-shale in the lowermost part includes frequent graptolites (Calner & Eriksson, 2002).

thick with erosive bases and coarsely spaced internal lamination/bedding forming crossbedding or undulating stratification. Beds generally pinch out laterally over a few decimetres. Framework grains are generally well sorted, current aligned and range in size from fine to coarse sand. Intercalations of laminated, peloidal packstone, some few centimetres thick, occur at a few levels and as well-rounded intraclasts in the crinoid facies.

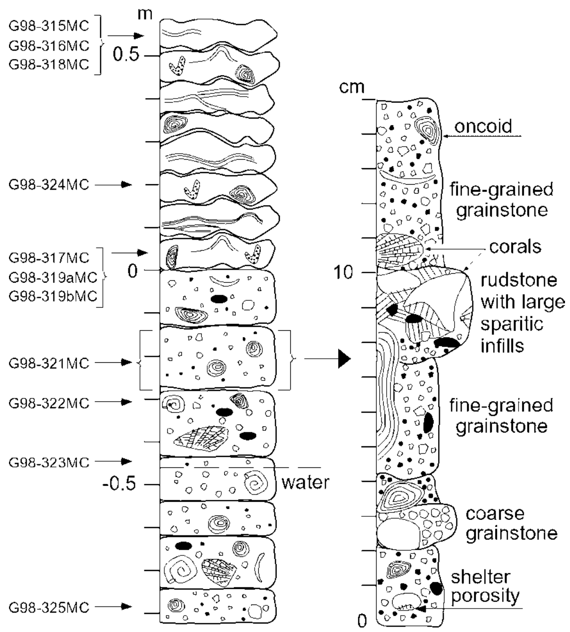


Figure 11. Sedimentary profile with two different algal facies from the Stenstugårds 1 quarry (*K. o. absidata* Zone). Note in the detail of bed G98-321MC that outcrop bedding does not coincide with microfacies alternations. The section forms part of a sheet-like, tabular sedimentary body.

Topographical correlation further NE is not feasible. However, *K. o.* cf. *absidata* is present at the abandoned quarry at Stenstugårds 1, more than 30 km NE of Skansudd 1. Hence, this sequence is described with the Hunninge Mb until temporal and spatial facies variations are better known. In the northwestern wall of the northeastern pond, the lower parts of the quarry section consist of thin-bedded, skeletal grain- to rudstones with abundant well rounded oncoids, about 1–3 cm in cross-section. These are thickly coated, generally enclosing well-rounded, abraded grains or clasts, and only rarely display signs of stationary growth. The grain-rudstones are texturally mature with grain sizes mainly within the sand interval. Grains are extensively micritised and consist mainly of crinoid fragments, although reworked algae and bryozoan also occur. Each bedset consists of alternations of distinct microfacies denoting pulsating current deposition and a later diagenetic origin for the bedding (Fig. 11). Fabric characteristics indicate cross-lamination in a few beds. The grainstones are overlain (probably conformably) by wavy bedded algal limestones forming a thin biostrome. The biostromes matrix consists of a fine-grained greenish wackestone and crinoid debris dominates among the grains. The algal components of the biostrome are laminar to rounded.

## 4. Discussion

### 4.a. Interpretation of facies

The temporal and spatial platform architecture and the major depositional environments are revealed by

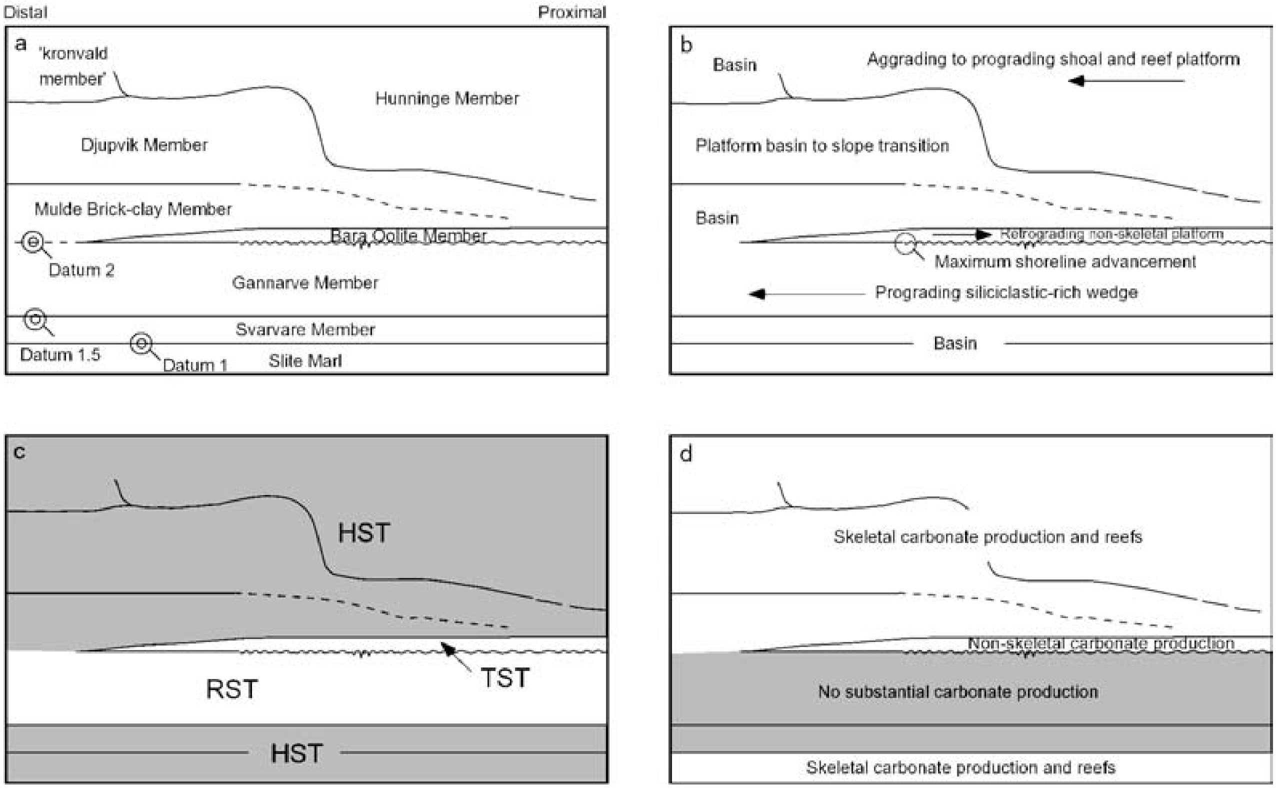


Figure 12. Synthesis of Fig. 3, showing (a) the distribution of the members and the Mulde Event datum planes, (b) the main carbonate platform depositional environments, (c) the inferred sequence stratigraphic framework (modified from Calner, 1999; HST – highstand systems tract (shaded areas), RST – regressive systems tract, TST – transgressive systems tract), and, (d) the observed changes in the mode of carbonate production. Note that non-skeletal carbonates occur as post-extinction sediments. The temporal and spatial arrangement of facies is interpreted as reflecting platform margin response to a 5th order sea-level change (see text).

facies mapping along downdip oriented transects when combined with the sequence of zones (Fig. 3, 12a–d). On a large scale the investigated interval is interpreted as two stacked generations of platforms, separated by the profound mid-Homerian unconformity (Fig. 3). The Slite marl and reef limestone and the Fröjel Fm represent the late stage and the termination stage of the lower platform, respectively. Thus, initial platform stress is coeval with Datum 1 of the Mulde Event and is marked by an abrupt decline in carbonate production and deposition. Datum 1 of the Mulde Event cased the first extinctions during the Mulde Event, too. Seismostratigraphy offshore Gotland (section 3.b.2.), as well as palaeotopography and epikarst onshore, clearly show that this platform was finally terminated by subaerial exposure following the mid-Homerian eustatic lowstand (see below). The onlap of the Halla Fm onto the resulting palaeotopography (Calner & Säll, 1999) and the succeeding seaward expansion of reefs in the Klinteberg Fm show that these formations represent the initiation and successive development of a new platform, respectively (Fig. 3).

Lateral thickness and/or facies changes are evident at a few levels. It is inferred that the truncation of the lower platform to some extent influenced the geometry of the Mulde Mb. As noted in section 3.b.2., the mid-Homerian unconformity has a considerable lateral extent. The rapid proximal thinning of the Mulde Mb, and its low carbonate content, may partly be an expression for the observed transgression across the shoreline position of the previous lowstand (cf. Fig. 12b). The succeeding interval with *K. o. absidata* (Table 1) permits correction of previous diachroneity and provides new insight to lateral facies changes over a distance of 30 km. The records of this taxon together with topographic correlations indicate a lateral transition from highly argillaceous skeletal mud- and wackestones at Djupvik 1, 2 and Skansudd 1, 2 into coarse-grained crinoid-dominated facies and small reefs at Hunninge 1, Loggarve 2, Tippsarve 1 and Rågåkre 2 and probably into the high-energy algal grainstones at Stenstugårds 1. This lateral transition is interpreted as reflecting a transition from the carbonate platform slope, into the shoal and reef area, and further into a high-energy back-reef environment, respectively. The area of coarse crinoid facies is notably large, indicating a wide shallow high-energy belt landward of an abrupt slope. The coeval oncoid wacke- and packstone facies further landward ('gothemshammar mb') similarly indicates low-energy lagoonal areas behind the reef- and high-energy belt. As on western Gotland, also these facies successions are aggradational to progradational, reflecting that carbonate production matched or exceeded creation of accommodation space. The appearance of *C. murchisoni* permits the conclusion that the unconformity at Gothemshammar 3 defines a shoreline position during the deposition of the Hunninge and 'kronvald' members. This should be compared to the situation at the end of the chron corresponding to the *O. b. longa* Subzone 1 when the shoreline was situated in the Klintehamn area (Calner, 2002).

#### 4.b. Mid-late Homerian sea-level and sequence stratigraphy

Much evidence accumulated during the last few years attests to an eustatic sea-level fall in the middle Homerian (e.g. Nestor & Nestor, 1991; Calner, 1999; Calner & Säll, 1999; Calner, 2002; see also references in Kaljo *et al*. 1995 and Loydell, 1998). The maximum lowstand has, based on East Baltic sections, previously been suggested to be in the 'early *nassa* time' (Nestor & Nestor, 1991, p. 58). However, new high-resolution biostratigraphic correlations within the Baltic basin re-date the lowstand with accuracy as to the very end of the *Cyrtograptus lundgreni* Chron (Jeppsson & Calner, 2003).

Limestone units, especially those holding reefs, enclosed in argillaceous strata are surprisingly often taken as an indication of sea level lowering, because only the local facies succession is considered. The suggestion that there are two regressive episodes with an intervening minor sea-level rise in the mid-late Homerian (Loydell, 1998, p. 462, partly based on the Gotland succession) appears to be an expression for such an outlook. The uppermost Slite Group and the Klinteberg Formation do constitute shallow water facies with abundant reefs, however, their thickness and strong seaward expansion across distal platform marls (Calner, Sandström & Mõtus, 2000), shows that they formed during periods when accommodation space was created. Thus, these strata only reflect a decrease in *depositional depth*, not in sea-level. Our previous works have pointed out a close relationship between a mid-Homerian eustatic event and the sedimentary succession on Gotland; e.g. substantial loss of accommodation space is evident from the graptolitiferous Svarvare Mb to the intertidal, epikarstic unconformity on the top of the Gannarve Mb (Calner, 1999; Calner & Jeppsson, 1999; Fig. 3a). Carbon and oxygen stable isotope curves (Samtleben, Munnecke & Bickert, 2000) do not show any major excursion across the base of the Svarvare Mb (Fig. 13). The oxygen curve shows a positive excursion first well into the lower half of the Gannarve Mb. These data add support to the interpretation of the Svarvare Mb as a highstand deposit (Calner, 1999) since $\delta^{18}$O otherwise fluctuates with depositional depth throughout the Wenlock-Ludlow succession on Gotland (Samtleben, Munnecke & Bickert, 2000). The temporal change from basin facies (Slite Marl and Svarvare Mb) to shoreline facies (Gannarve-Bara boundary) and further into reef proximal facies (Hunninge Mb) along transect E-E′ shows that the shoreline migrated substantially forth and back during the mid-Homerian. Seismostratigraphy suggests almost 10 km of coastal progradation during Subchron 1 of the *O. b. longa* Chron (section 3.b.2.). Since palaeorelief is preserved, an initially rapid transgression exceeding 16 m (Calner & Säll, 1999) must have occurred (cf. Johnson, Rong & Kershaw, 1998). The deepening is reflected in the Klintehamn area as a rapid change from the grainstones of the Bara Mb to the fossiliferous wackestones of the lowermost Mulde Mb. Thus, the transition from intertidal karst to argillaceous facies, deposited below the wave-base, occurs over a few decimetres along transect E-E'. The above data indicate that a high sea level was established already in the upper part of Subchron 2 of the *O. b. longa* Chron. The numerical time-scale (section 1.c.) further constrains the timing of regression and transgression considerably. The regression took place during the deposition of the Gannarve Mb. This represents the final *c*. 34 kyr of the *C. lundgreni* Chron. A new highstand was established after the deposition of the Bara Mb, that is, within *c*. 30 kyr, hence, this was a 5th order sea-level change (cf. Miall, 1990; Fig. 13), caused by continental glaciation (Calner & Jeppsson, 1999; Jeppsson & Calner, 2003).

Accommodation space was continuously created after the mid-Homerian lowstand, and carbonate production matched or exceeded that rate. Such a conclusion is supported by the aggradational (e.g. Djupvik 1, Tippsarve 1) to progradational (e.g. Loggarve 2, Hunninge 1, Gothemshammar 2–3) character of individual sections, the upward increase of $CaCO_3$ through the local Halla Fm on more distal parts on the platform, and by the subsequent seaward expansion of reefs (Calner, Sandström & Mõtus, 2000; Fig. 12a). It is further supported by decreased sediment accumulation in the distal basin from the *K. o. absidata* Zone and onwards (Jeppsson & Calner, 2003, Fig. 4). Thus, at that point, the main depocenter appears to have been located on the proximal slope of the platform. The Mulde and Djupvik members and their lateral equivalents, the 'hörsne' and 'gothemshammar' members are for the above reasons interpreted as highstand deposits. If a sea-level curve was based only on the depth changes recorded on eastern Gotland, without knowledge of the now identified palaeotopography (Calner & Säll, 1999), that curve would likely have excluded even a 'minor transgression'. This reinforces the importance of studying genetic relations of sedimentary bodies, not individual sections, if sea-level curves should have any accuracy.

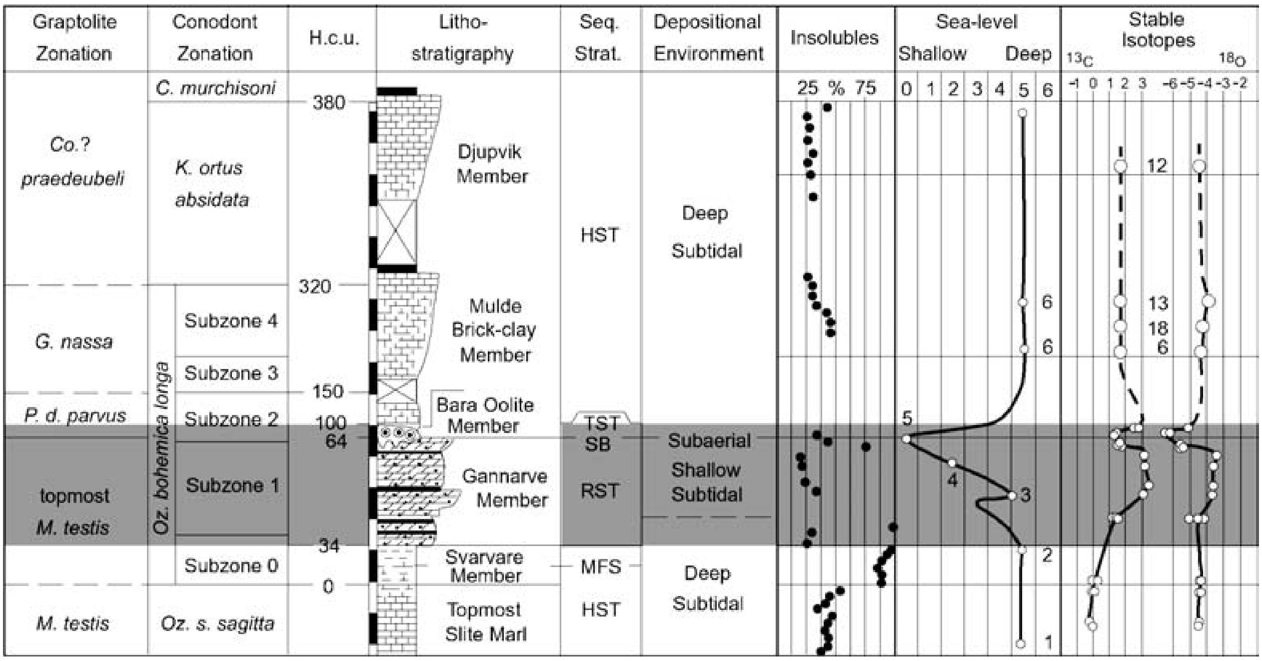


Figure 13. General facies characteristics of mid-late Homerian of western Gotland and a sea-level curve for this interval. The shaded band indicates the stratigraphic range for the regressive-transgressive cycle. Comments on the sea-level curve: 1. Brachiopod data included from Hurst (1975). 2. Sedimentary and faunal data from the Svarvare 1 locality. 3. See discussion in Jeppsson & Calner (2003). 4. Brachiopod data included from Gray, Laufeld & Boucot (1974). 5. Sedimentary and diagenetic data from the Klintebys 1 locality (Calner, 2002). 6. Brachiopod data are included from the Mulde Tegelbruk 1 and Blåhäll 1 localities (Spjeldnaes, 1984). The numbers at the top of the sea-level column refers to the Benthic Assemblage zones 1–6 (Boucot, 1975; Brett, Boucot & Jones, 1993), and thus, only indicate depositional depth, not sea-level (see also Musteikis & Kaminskas, 1996 for criticism as to the absolute depth of these zones in the Baltic basin). “0” marks subaerial exposure. Comments on the stable isotope curve : Data derive from brachiopod shells sampled and processed by C. Samtleben (Kiel), A. Munnecke (Tübingen), and co-workers (Samtleben, Munnecke & Bickert, 2000), except for the seven samples spanning the transition of the Gannarve and Bara members. These are whole-rock samples from Klintebys 1 (Calner, 2002). Larger circles represent several samples (the number is indicated). The scale bar to the left of the sedimentary profile is sectioned at two metre intervals.

The facies succession of the Klinteberg Formation, starting with the *C. murchisoni* Zone, contradicts major sea-level changes during the time of its deposition (Manten, 1971, p. 349). This is partly supported by lack of stratigraphically narrow excursions in stable isotope records through that succession (see the curves of Samtleben *et al*. 1996; Bickert *et al*. 1997; Samtleben, Munnecke & Bickert, 2000). There is no unequivocal evidence for renewed subaerial exposure during the deposition of the Klinteberg Fm. Previously reported internal sediments, interpreted as vadose silt, was confined to biohermal facies (Frykman, 1985, 1986) and, thus, does not necessarily indicate extensive platform emersion due to regression. During this interval, the platform aggraded and prograded, indicating that carbonate production largely matched or exceeded the creation of accommodation space. This space may have been inherited from tectonically driven subsidence of the basin rather than eustatic sea-level rise. Palaeotopography at the top of the Klinteberg Fm denotes renewed regression at or near the Wenlock – Ludlow boundary, i.e. at the top of the *Co*.? *ludensis* Zone (Jeppsson & Aldridge, 2000).

In summary, two rapid regressions are evident from the mid-late Homerian of Gotland. Both regressions are based on the *truncation* of highstand systems tracts, not on the presence of reefs or associated shallow water facies. The first regression occurred at the very end of the *C. lundgreni* Chron, and the second at the end of the *Co*.? *ludensis* Chron. The intervening interval was characterized by a rapid transgression initially, followed by a stillstand or possibly slow transgression. Thus, data from Gotland challenge the common opinion of a long-term Late Wenlock regression. A falling sea-level would most probably exceed the slow subsidence in epicontinental basins, and thus, would likely not give rise to such wide expansion of reef belts as seen on Gotland (cf. Fig. 2 in Calner, Sandström & Mõtus, 2000).

#### 4.c. Depositional bias during the Mulde Event

The shallow water carbonate and siliciclastic systems respond fundamentally different to relative sea-level change (Schlager, 1991). This response is inherited from the basic fact that siliciclastics are transported *to* the basin whereas carbonates form *in situ*, i.e. *within* the basin. As opposed to the siliciclastic depositional system, carbonate platforms produce and deposit most of their sediments during highstand situations (lowstand

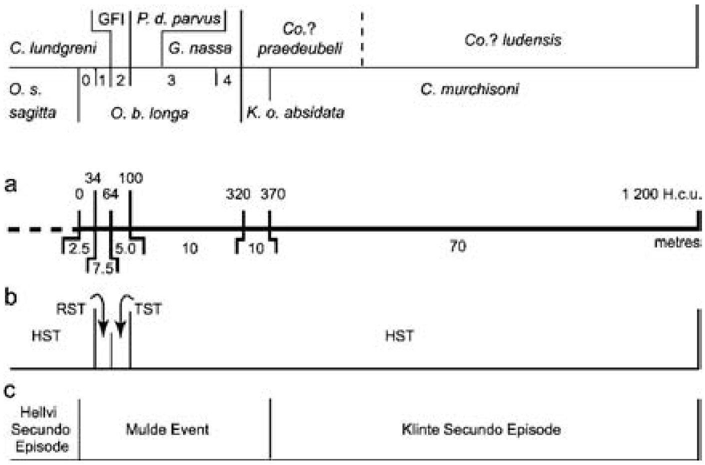


Figure 14. The stages of platform evolution tied to the graptolite and conodont stratigraphy (see Fig. 2). GFI = Graptolite Free Interval of Jeppsson & Calner (2003). The numerical time-scale is here applied to the succession, starting at the base of the Svarvare Mb. (a) Depositional rates calculated from stratal thickness per Homerian chronal unit (H.c.u.). The total maximum thickness is estimated at 105 m (based on data in Hede, 1960, Manten, 1971 and Calner, 1999). The 2.5 m thick Svarvare Mb accumulated during 34 H.c.u. whereas the regressive Gannarve Mb shows three times that rate (7.5 m during 30 H.c.u.); Bara Mb = 5 m during 36 H.c.u.; Mulde Mb = 10 m during 220 H.c.u.; Djupvik Mb = 10 m during 50 H.c.u.; Klinteberg Fm = 70 m during 830 H.c.u.). It is notable that the Djupvik Mb shows very high sedimentation rates compared to the Mulde Mb. This is interpreted to reflect rapid aggrading during highstand shedding. (b) The relative duration of systems tracts. It is evident that the platform aggraded and expanded during HST. The RST and the TST accumulated only about 15 metres of sediments. If the maximum thickness of different units between the *Pentamerus gothlandicus* Layer (upper *C. lundgreni* Zone) and the top of the *Co*.? *ludensis* Zone is considered it appears that 88 % of the sediments accumulated during highstand systems tracts, 7 % during the regressive systems tract (RST), and about 5 % during the transgressive systems tract (TST). The formation of a sequence boundary took only a fraction of this time-frame. (c) The relative duration of the Hellvi and Klinte secundo episodes and the Mulde Event.

*vs*. highstand shedding of Schlager, Reijmer & Droxler, 1994). This is primarily due to the increased areal extent of platform flooding and the associated increase in space available for skeletal carbonate production (Handford & Loucks, 1993; Schlager, Reijmer & Droxler, 1994; Tipper, 1997). Non-skeletal carbonates, on the other hand, are generally of transgressive character (e.g. Jenkyns & Wilson, 1999; Zempolich & Erba, 1999) or show affinity to highstand situations (Schlager, Reijmer & Droxler, 1994; however, note that these authors included the transgressive systems tract in a 'highstand situation'). With regard to the large-scale depositional trends, the situation on Gotland during the Mulde Event represents a classical case of depositional bias of the carbonate and siliciclastic systems (*sensu* Schlager, 1991; Fig. 12b,c). Coarser siliciclastics reached the basin during regression (Calner, 1999). As in many other areas, the superposition of oolites on karst and palaeotopography supports a transgressive affinity for non-skeletal carbonates also on Gotland (Calner & Säll, 1999; Calner, 2002). The major part of the *O. b. longa* Zone; i.e. the Fröjel Fm, the Bara Mb, and the major part of the Mulde Mb contain no reefs on Gotland (Calner, Sandström & Mõtus, 2000). The main part of the Fröjel Fm formed during the regression. However, apparently reefs neither did manage to re-establish during the ensuing transgression. Although the lower platform suffered emersion, the exact cause(s) for its termination is not possible to demonstrate unequivocally. The dark, dysoxic sediments of the Svarvare Mb contrast with the underlying Slite Marl and it is likely that the deviating characters of the former unit was inherited from the ceasing of carbonate production on the proximal platform. If so, a substantial drop in production preceded the onset of regression, which is marked by the overlying Gannarve Mb. In a similar way, the two first extinctions of the Mulde Event preceded onset of regression (Fig. 3b; Jeppsson & Calner, 2003). If the numerical time-scale is applied, the reef-devoid interval ranged in the order of 300 kyr (Fig. 2). This should be compared to the 0.5 to 2.5 kyr lag-phase of sub-recent reefs that experienced the Holocene transgression (Bosscher & Schlager, 1992).

Depositional rates (Fig. 14) were approximately three times higher during regression and influx of siliciclastics (Gannarve Mb) than during the preceding highstand systems tract (Svarvare Mb). High depositional rates continued during the transgressive systems tract (Bara Mb). The rate decreased substantially during the deposition of the Mulde Mb. This was possibly the combined result of the previous rapid shoreline retrogradation and the subsequent establishment of a high sea-level. A notable increase in depositional rate, coupled to an increase in $CaCO_3$ deposition, occurs in the *K. o. absidata* Zone. This is interpreted as a response to the approaching carbonate factory during the noted platform progradation.

Based on the numerical time-scale of Jeppsson & Calner (2003), it can be concluded that the vast majority of the mid-late Homerian succession was formed during highstand systems tracts (Fig. 14) and that carbonate production on the platform was closely related to the creation and destruction of accommodation space, although there was a comparably long lag-phase in reef re-establishment following the mid-Homerian lowstand (Figs 12b, 13).

## 5. Conclusions

The results of this investigation of the Mulde Event can be summarized as follows:

1. The temporal and spatial architecture of the Gotland carbonate platform during the Mulde Event is revealed by facies mapping along downdip-oriented transects when combined with the new conodont stratigraphy. Major environmental changes are associated to the event.
2. A new, more precise, mid-Homerian conodont zonation includes from below: the *Ozarkodina bohemica longa* Zone (including five subzones), the *Kockelella ortus absidata* Zone and the *Ctenognathodus murchisoni* Zone. It can be correlated with the current graptolite zonation.
3. The mid-late Homerian sedimentary succession on Gotland resulted from depositional bias of the carbonate and siliciclastic sedimentary systems. Changes were triggered by the Mulde Event. Reef-associated and skeletal carbonate deposition predominated during the *O. s. sagitta* Zone and, again, in the *C. murchisoni* Zone. These pre- and postevent periods are characterized by the expansion of reefs and shoal facies across marls in the topmost Slite Group on eastern Gotland and in the lower parts of the Klinteberg Fm on western Gotland, respectively. The aggrading and prograding characters of single sections indicate that carbonate production matched or exceeded relative sea-level rise. Initial platform stress is coeval with Datum 1 of the Mulde Event and marked by an abrupt decline in carbonate production and deposition. Datum 1 caused the first extinctions during this event, too. Siliciclastic strata were deposited during regression whereas epikarst and palaeotopography developed during the following brief lowstand, leading to complete platform termination. Non-skeletal carbonate deposition predominated during early transgression when reefs did not manage to re-establish.
4. The bulk of the sediments accumulated during highstand systems tracts, whereas only a minor part accumulated under higher depositional rates during the regressive and the transgressive systems tracts.
5. The Gotland-based Homerian sea-level curve shows two rapid regressions, both leading to truncation of highstand systems tracts; during the very latest *C. lundgreni* Chron and at or near the end of the Homerian, respectively. The time-scale of the former was that of a glaciation.
6. Major extinctions (at datum points 1 and 1.5) preceded that regression. Similarly, reef construction evidently ceased well before regression started. Hence, the regression could not have been the trigger. The regression was either a secondary effect of one or more of the initially triggered changes or, if the trigger delivered several successive beats, it may have resulted from a subsequent beat.
7. The Mulde Event had global effects. Effects have been documented in sediments, stable isotopes, faunas, and at all oceanic depths.

## 6. Taxonomy

*Pseudooneotodus linguicornis* Jeppsson, herein
Figure 15a–l

*Derivation of name*. From *lingua* (Latin) tongue, and *cornis* as used in the names of two other species of this genus.

*Holotype*. LO 8599T (Fig. 15e,f).

*Material*. Several hundreds of elements.

*Diagnosis*. A species of *Pseudooneotodus* with elements with a markedly elliptic cross section and a slightly recurved tip.

*Description*. The elements differ from those of related taxa in the posteriorly flattened cross section, from the tip to the edge of the basal cone. That edge is closer to the tip on the anterior side than on the flatter posterior side. Thus when an element is oriented in the slide with the tip up, the posterior side is more prominent than the anterior one.

*Stratigraphic range*. Widespread and relatively frequent from near the base of the *O. s. sagitta* Zone to the top of that zone, that is, up to Datum 1 of the Mulde Event. It survived that datum but was, at least on Gotland, rare up to Datum 1.5 of the Mulde Event, that is, up to only slightly below the top of Subzone 0 of the *O. b. longa* Zone (see section 2.a.).

*Geographic range*. In the literature this species has been known as *Ps*. n. sp. 1 and has been reported from eastern and western Gotland, the När core, Poland (Männik & Małkowski 1998), Australia (Jeppsson, 1997*c*, p. 103, based on a restudy of Bischoff's, 1996, collections). In addition, several colleagues have shown me as yet unpublished collections from this interval yielding this taxon, e.g. from Europe and America.

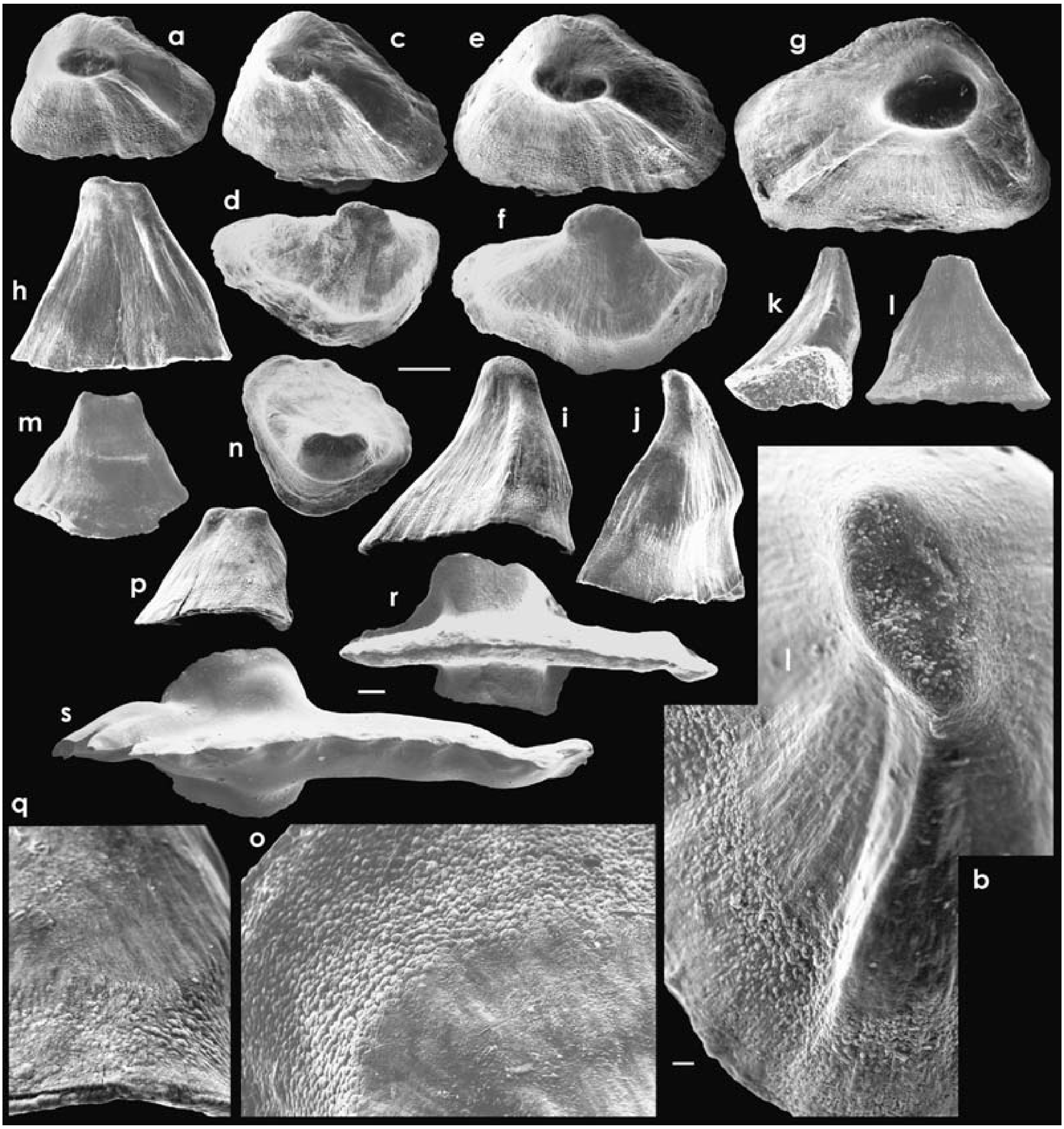


Figure 15. (a–l) Seven elements of *Pseudooneotodus linguicornis* n. sp. Jeppsson, from Värsendeojk 2, from sample G87-407LJ. (e and f) = Holotype, LO 8599T. (a, c, e, g) 'Microscope view', i. e., as seen when resting on the rim; LO 8597–8600. Their maximum diameters are 0.37, 0.41, 0.50, and 0.59 mm, respectively (sizes given in Figures 15–17 are measured directly in the microscope and having an uncertainty of mostly less then 0.01 mm). The position of the main costa separates what probably were right and left elements. (b) Detail of (a) showing the striated main part and granulated marginal zone. (d) and (f) 'Axial' view of the specimens in (c, e) to show the flatness of the posterior side (cf. 15j and 15k); this character is in 'microscope view' (upper row) only evident as a straight posterior margin (in 15c only if the lost lower left part is taken in account). (h) Posterior view; LO 8601t. (i) Obliquely lateral view to contrast the difference in the distance from the tip to the anterior and posterior margins, respectively; LO 8602t. (j) (=i) Oriented to emphasize the flatness of the posterior side. (k) Close to 'lateral microscope view', i.e. perpendicular to the side it is resting on; LO 8603t. (i) (=k) Posterior view. (m–q) Two elements of *Pseudooneotodus bicornis* from the same sample. (m) Oblique posterior view and (n) 'microscope' view of LO 8604t, (o) detail of parts of the striated top part and the granulated zone. (p) Posterior view and (q) detail of LO 8605t. (r) *Kockelella ortus absidata* same specimen as in Figure 17g. (s) *Ozarkodina bohemica longa* Jeppsson herein; same specimen as in Figure 16g. The two scale bars for coniforms and ramiforms, respectively, are 100 $\mu$m according to the SEM instrument; these differs slightly from the direct measurement due to a lower precision in the calibration of the SEM scale. Magnification c. X43 and X87, respectively. Scale bars for the details are *c*.10 $\mu$m.

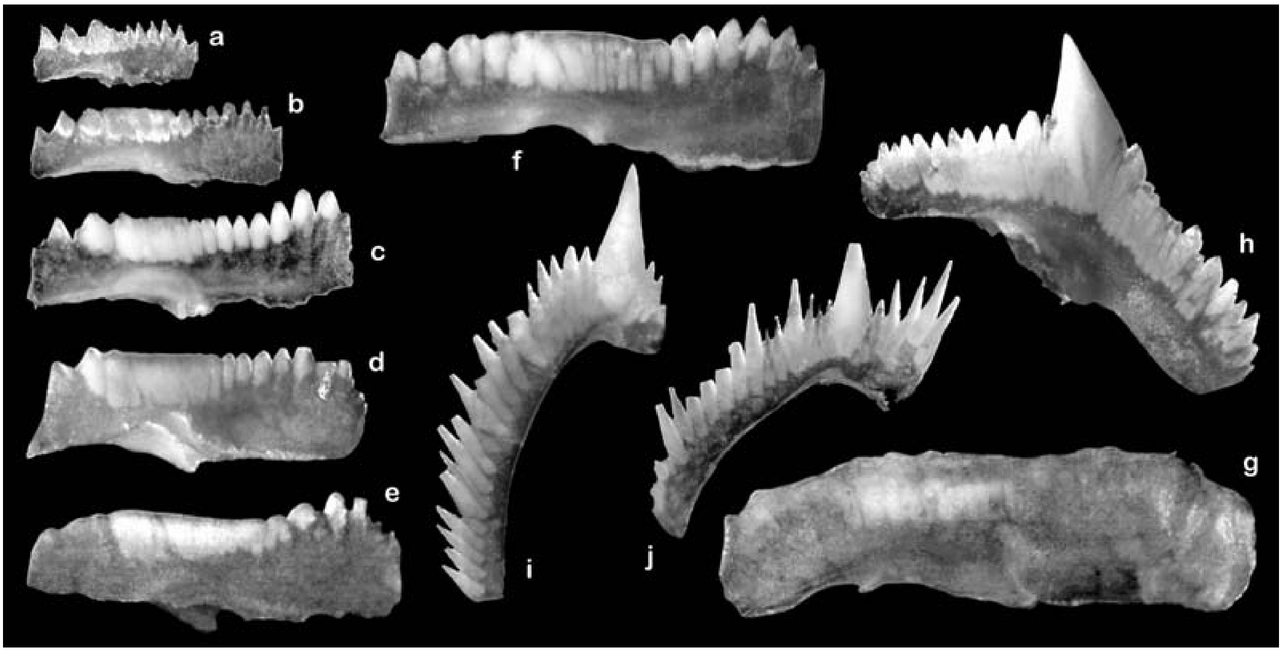


Figure 16. *Ozarkodina bohemica longa* n. ssp. 16a, b, c, f, h, i, and j from sample G77-28LJ from Möllbos 1. 16d, e, and g sp (Pa) elements from sample G92-379LJ from c. +1.25 – 1.50 m at Gothemshammar 3. All specimens 35x and photographed by Jonas Brane, Scanphoto. Later adjustement to black-and-white by us resulted in lower quality. Regarding length data, see legend to Figure 15. (a–g) Sp (Pa) elements forming a growth series. (a) A 0.44 mm long juvenile element with sharp-pointed denticle tips. LO 8242t. (b) A 0.67 mm long adult element with cusp and nearest denticle tips fused to a short ridge. LO 8243t. (c) A 0.87 mm long adult to mature element. LO 8244t. (d) A 0.90 mm long mature element with long ridge. The three anteriormost denticle tips lost post-mortem. LO 8245t. (e) A 1.00 mm long mature to gerontic element. LO 8246t. (f) A 1.17 mm long mature to gerontic element. Cusp and at least 10 denticle tips fused to a ridge, other tips short-tipped or more or less blunt. LO 8247T, holotype. (g) A 1.43 mm long gerontic element with all denticle tips fused to a slightly irregular edge. LO 8248t. (h) A 1.23 mm long mature to gerontic oz (Pb) element, inner view. LO 8249t. (i) A 1.29 mm long mature ne (M) element, inner view. LO 8250t. (j) A 1.05 mm long, mature pl or kl (Sb or Sd) element in inner view. The tip of the long process and of some of its denticles and cusp has been broken away post-mortem. LO 8251t.

*Discussion*. The origin of this species is yet unknown. The narrow-tipped form (Jeppsson, 1997*c*) is morphologically closest but it is not proven to be a distinct lineage. It was ecologically distinct enough to co-occur with at least the form of *Ps*. *bicornis* illustrated in Figure 15m–q. No intermediates are found, hence, separation is usually easy. However, the variation in *Ps*. *bicornis* is wide and correct identification of single specimens may require direct comparisons with good collections of both species.

*Ozarkodina bohemica longa* Jeppsson, herein
Figures 16, 15r

*Derivation of name*. From *longa* (Latin) alluding on that the sp (Pa) elements are longer than those of *O. b. bohemica*.

*Holotype*. LO 8247T, an sp (Pa) element (Fig. 16f).

*Material*. Several 100's of sp (Pa) elements. The lower preservation potential of the other elements results in somewhat fewer specimens.

*Diagnosis*. A subspecies of *Ozarkodina bohemica* with long, low sp (Pa) elements.

*Description*. All collections of *O*. *bohemica* include a considerable variation and further, there are often also some variation between collections.

*Sp (Pa) elements*. In *O*. *bohemica* the tip of the basal cavity is near its anterior end (Fig. 15b), hence the cusp is also markedly anterior of the middle of the widely expanded basal cavity. Typically, the proximal anterior denticles are narrow and slender (from root to tip) gradually increasing in width distally. Posterior denticles may be more irregular, both in the width of the roots, their development and point of origin. In average, in *O*. *b*. *longa* the maximum length/height ratio of the sp (Pa) element is markedly greater than that of *O*. *b*. *bohemica*. The posterior process has on average about 4 (-6) denticles in older populations of *O*. *b*. *longa*, about 6 in populations from the *O*. *c*. *densidentata* Zone, and (2-) 3 (-4, rarely more) in *O*. *b*. *bohemica*. The degree of fusion of the cusp and proximal denticles into a ridge varies from specimens in which all denticles have a distinct tip and a distinct white matter root, to those in which no individual tips, roots or root tips are visible in the proximal part of the sp element. The ridge crest often is aligned with a line through the very tips of the nearest free denticles. This difference is found already in juvenile specimens, although more denticles are incorporated with age. Further, it seems as if the frequency of specimens with distinct cusp and denticles decreases somewhat with age. The ridge crest may be straight or wavy but specimens with a distinct pointed tip on the cusp and proximal denticles are very rare in *O. b. longa* but frequent in *O. b. bohemica*.

*Stratigraphic range*. From the base of Subzone 1 of the *O. b. longa* Zone and through the *C. murchisoni* Zone (see section 2). Subspecific identification of older collections is yet not possible.

*Geographic range*. *O. b. longa* is widespread and most reports of *O. bohemica* and *O. b. bohemica* are in fact based on this subspecies. For example, it has been found in Estonia (Viira in Jeppsson, Viira & Männik, 1994), Britain, where at least those from the lower part of Much Wenlock Limestone are referable to *O. b. longa* (e.g. Aldridge, 1985, pl. 3.4 : 3), Oklahoma (Barrick & Klapper, 1976), and? Podolia (Drygant, 1986, as *S. s. rhenana*; see Jeppsson, 1997*c* for a discussion). The appearance in these areas marks the base of the *O. b. longa* Zone.

In contrast, confirmed records of true *O. b. bohemica* are limited to Bohemica, Urgude 2 on Gotland, and bed $15B_1$ at Cellon in Austria (see Jeppsson, 1997*c*). This rarity is probably not due to geographic restrictions but to a very short stratigraphic range during an interval with a low sea-level (Jeppsson & Aldridge, 2000), that is, a less wide distribution of sediments of that age, and probably also a rarity of exposures due to more easily eroded sediments.

*Discussion*. Specimens illustrated as "*Spathognathodus tillmani*" by Helfrich, 1975) is evidently an *O. bohemica*. The type collection also include "*S. primus multidentatus*", a synonym of *O. c. densidentata*, hence, it is coeval with *O. b. longa*. However, the name *O. tillmani* is not used here for the following reasons. The holotype is illustrated in 'lateral microscope view', that is, in an oblique lateral-aboral view. In such a view a specimen look lower than it is. However, it, and most other illustrated specimens, look short and high like *O. bohemica*. There is no information about the denticle roots, hence, the inclination of the denticles, their degree of overgrowth etc. are unknown. Such characters are critical for unambiguous separation of many of the over 50 species of *Ozarkodina* now described. Last, the description is on microfiche, and as such not recognized by the International Code of Zoological Nomenclature. It might be argued that the two characters (total length and relative length of the two processes; Helfrich p. 31, printed on paper as required) stated to separate these elements from those of '*S. s. bohemica*' constitute a 'description'. However, that comparison is not with the type material of *O. b. bohemica* but with a collection that is considerably older, geographically far away from the type locality and not referable to *O. b. bohemica*.

Although the length/height relation is here considered important in separation of *O. b. longa*, future work may establish other characters as more fundamental. Similarly, a good description based on topotype material and coeval translucent North American material may recover the name *O. tillmani* from the group of nomina dubia, provided that the formalistic objection against microfiche can be circumvented.

*Kockelella ortus absidata* Barrick & Klapper 1976
Figures 17, 15s

*Kockelella absidata* Barrick & Klapper 1976, p. 73, Pl. 2, figs. 15–16.

*Material*. See Table 1.

*Emended diagnosis*. A subspecies of *K. ortus* (Walliser, 1964) with short, compact, high, blade-like sp (Pa) elements with the proximal denticle on the posterior process included in the blade, i.e. partly fused with the cusp. Elements with very well developed basal cavity lips.

*Description and comparison of material from Gotland*. Number of denticles on the sp (Pa) element varies somewhat. Most specimens are very short and high with 2 (-3) posterior and about 6 anterior denticles. Other specimens are lower and somewhat longer with more denticles – up to 4–5 on the posterior process and 8–11 (-14?, see below) on the anterior process. *K. o. absidata* differs from both temporal forms of *K. o. ortus* found on Gotland (see Jeppsson, 1997*c*) in its very well developed basal cavity lips. Those of *K. o. ortus* are about as inconspicuous as in coeval *O. excavata* whereas those of *K. o. absidata* protrude like those of *O. bohemica longa* but are much more robust (thicker) and more arched or folded. In *K. o. ortus* the posterior denticles are rounded in cross section, are not or only slightly fused, and that process is low, two or more times as long as it is high, and deflected obliquely outwards. In *K. o. absidata* the posterior process is often only about as long as it is high, straight or directed obliquely inwards or outwards. The denticles are compressed like those of the anterior process and fused. These changes result in that the posterior process is integrated with the cusp and the anterior process, forming a strong blade. One consequence is a better preservation potential – sp elements with both distal ends intact are only occasionally encountered in *K. o. ortus* but typical in available collections of *K. o. absidata*. Other changes, too, serve to increase the strength of the tooth, e.g. the anteriormost denticle may be broader and higher than those behind it. About a dozen sp elements from 9 localities indicate a temporal change in their

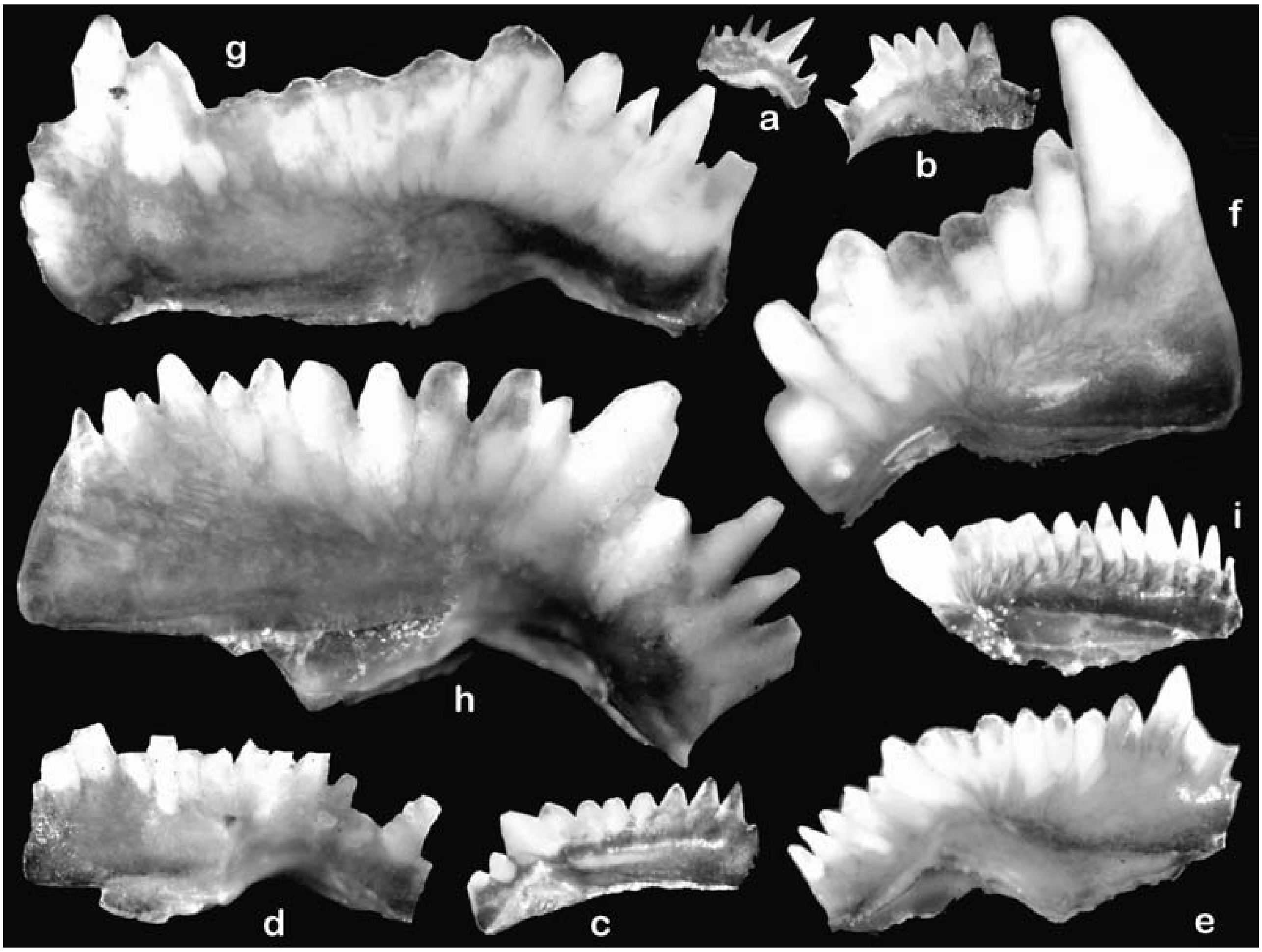


Figure 17. (a–h) A growth series of sp (Pa) elements of *Kockelella ortus absidata*. Short and long elements of the early and the late populations. All specimens in inner lateral view (perpendicular to the blade) except for 17a, which is in slightly oblique view, as is evident from the basal cavity lip. All specimens are complete except that most or all of the basal filling is absent in some specimens, that a few denticle tips are broken post-mortem yielding sharp edges (straight lines and angular corners in the figures, e.g. the posteriormost large denticle on 17c and the cusp in *K*. cf. *stauros*). Similarly, the very distalmost part of the posterior process is lost in 17d. All specimens 35x and photographed by Jonas Brane, Scanphoto, however treated afterwards like those in Figure 16. Regarding length data, see legend to Figure 15. Note the characteristic *Kockelella* pattern of more or less oblique white streaks and elongated spots below the denticle roots, especially the proximal anterior roots (e.g. in 17f, g, h, and i; i = *K*. cf. *stauros*). Together the specimens illustrate some of the ontogenetic and phenotypic changes through life. Juvenile specimens (16a, b, and c) have lustrous surface (unless etched or worn post-mortem), sharp slender cusp and denticles, and short denticle roots well separated from each other. From adult to gerontic the lustrous surface gradually became dull and the roots became more or less fused. Regeneration of cusp and denticle tips after breakage resulted first in blunt hyaline tips (e.g. proximal anterior denticles of 17f, g), gradually becoming unevenly white (cusp of 17f) and finally invisible except for the bluntness and sometimes the offset in the margins (the two middle denticles on the posterior process of 17h). Often regeneration produced a two-rooted denticle tip from two former denticles (or cusp + proximal denticle as on 17f). (a) Early juvenile, 0.31 mm long specimen from sample G81-59LJ from Hägur 1. LO 8233t. (b) Juvenile specimen, 0.60 mm long, from sample G84-20LJ from Djupvik 4. Processes complete but the anteriormost denticle and most of the cusp has been lost post-mortem. LO 8234t. (c) Subadult specimen, 0.79 mm long, the low form of the older population from sample G85-34LJ from +2.05–2.10 m at Djupvik 2. Note overgrown denticles below the cusp on the posterior process, that the proximal anterior denticles have two roots indicating prior fusion, and that the next denticle is overgrown. Compare denticle spacing with that in the juvenile specimen in fig. 17a. LO 8235t. (d) Adult specimen, 1.10 mm long, the low form of the older population from sample 84-19LJ from Djupvik 3. LO 8236t. (e) Adult specimen, 1.25 mm long, the high form of the older population from sample G70-26LJ from –1.05 to −0.95 m at Djupvik 2. Most of the basal body preserved. LO 8237t. (f) Mature specimen, 1.29 mm long, the high form of the younger population from sample G85-31LJ from the topmost Halla Fm at Loggarve 2. LO 8238t. (g) Gerontic specimen, 1.93 mm long, the long form of the younger population from sample G-87-424LJ from Skansudd 1. LO 8239t. (h) Gerontic specimen, 2.07 mm long, the high form of the older population from sample G93-967LJ from Valby Bodar 2. Note the dull surface, the more or less fused denticle roots, the blunt, repeatedly broken and more or less irregularly regenerated denticle tips compared with the illustrated juvenile to adult specimens. LO 8240t. (i) *Kockelella* cf. *stauros*, adult, 1.01 mm long fragment of a sp (Pa) element, from sample G70-28LJ from +2.24 m at Djupvik 1. LO 8241t.

morphology. In the *K. o. absidata* Zone especially, the short high form of the sp element is relatively highly built and frequently has slender, somewhat radiating denticles (that is, distally on the processes the denticles are increasingly inclined). This form is found at Djupvik 1, 3, Valby Bodar 2, and probably at Hägur 1. In the *C. murchisoni* Zone, sp elements are markedly more robust, usually with nearly aligned, sturdy denticles. The cusp is broad and pointed and, in adult specimens, the anteriormost denticle can be markedly bigger than the rest, especially in the short form. The latter form is found at Rågåkre 1, Loggarve 2, Hunninge 1 and Skansudd 1 (Fig. 1b).

No major difference in the oz (Pb) elements to those of *K. o. ortus* is known now.

Ne (M) elements have an inner basal cavity lip with a strong fold. The lip is much better developed than that of *K. o. ortus*. Length of process varies from 3 (4?) denticles to 7. Base of cusp strengthened by thickening on inside. In *K. o. ortus* it is strongly flattened throughout.

Hi (Sc) elements have an inner basal cavity lip forming a wide sheet with rounded inner lower margin. There is a rather pronounced angle between the processes.

Pl, ke and tr (other S) elements are similarly strengthened around the cusp base. Thus, the inner basal cavity lip is developed as a marked fold.

*Comparisons*. Compared with Ludlow forms of *K. ortus* (and closely related species of *Kockelella*) the closest form is found in the 'post-*Oz. excavata* n. ssp. S fauna' of Jeppsson (1998). Like the Gotland populations of both *K. o. ortus* and *K. o. absidata*, this form is robust and probably was the top predator among the conodonts. It differs from *K. o. absidata* in that an extra denticle is often developed on the oral side of one of the basal cavity lips and in some other minor details. This form may either be a younger subspecies of *K. ortus* or a younger population of *K. o. absidata*. In preceding Ludlow interval, the position as the most robust form was chiefly held by *Ancoradella*? n. sp. and *K. stauros* n. ssp. whereas *K. ortus* or a closely related species is represented by rare small individuals. Similar complications are found after the post-*Oz. excavata* fauna. Exactly the same pattern of rarity and size differentiation as an alternative to complete absence due to competitive exclusion has been described for taxa of *Panderodus* in the latest Llandovery and earliest Ludlow (Jeppsson, 1997*c*).

The single fragmentary juvenile sp (Pa) element with 14 denticles on the posterior process mentioned above (only the posterior process + parts of the basal cavity lips are preserved; Fig. 17i) closely resembles those of *K. stauros*. *K. s. stauros* was partly coeval with *K. o. absidata*. Hence, considering the discussion of early Ludlow competition above, it seems possible that *K. stauros* was absent because *K. o. absidata* had the upper hand in the sampled area, except for this fragment.

*Discussion*. As a result of comparisons of collections and discussions with Barrick, collections from Oklahoma, older than the *O. b. longa* Zone, are referred to *K. o. ortus* although these in some aspects are intermediate. The anterior process of the sp (Pa) elements is slightly curved inwards in both Oklahoman and Gutnian specimens of *K. o. ortus* and the proximal posterior denticle is not fused to the cusp, at least in most specimens; this is evidently one of the best characters of this subspecies. However, the Oklahoman sp (Pa) elements resemble *K. o. absidata* in the short posterior process. A parsimonious conclusion is that *K. o. absidata* descended from the Oklahoman or a related population of *K. o. ortus* that found a refugia somewhere during Datum 1 of the Mulde Event whereas the Gutnian population of *K. o. ortus* became extinct.

*Occurrence*. Gotland (Table 1) and Oklahoma (Barrick & Klapper, 1976; see discussion above).

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## Appendix: New localities

Localities are found on Top. map 56C Klintehamn (6I Visby SO) and Geol. map Aa 164 Hemse, unless noted.

Fröjel 5, 635924 164255, *c*. 50 m N of Fröjel church. At the wooden stair in the steep slope between the old road and the churchyard. Strata *in situ* are accessible below the soil cover.

Klinteberg Fm, lowermost part.

Gannarveskär 4, 636084 164231 (CJ 2978 6018), 2.12 km NW Fröjel church. Section in a small hole dug by hand, 10 m N the northern shore of the small bay, just inside a large rose bush (on the shore line deposits) *c*. 70 m S the concrete building. Reference level: A 0.25 m hard unit is with sharp contacts underlain (at *c*. 0.55 m below ground level) by soft siltstone and overlain by soft clay with a layer of concretionary limestone. The latter contact is used as the reference level.

Fröjel Fm, Gannarve Mb (below the reference level), Halla Fm, Bara Mb and Mulde Mb.

Hägur 2, 635164 164086 (CJ 2759 5012), 4.45 km between SW and WSW Eksta church. Exposure in the road ditch E the road junction 900 m SSE Bäne.

Halla Fm, topmost, or Klinteberg Fm, lowermost.

Hästings 1 637141 165912 (CJ 4730 6945), 2.05 km ENE Guldrupe church. Top. map 6 J Roma SV. Geol. map Aa 160 Klintehamn. Exposure in the northwestern road ditch, 0.5 m E the garden entrance to the house with a veranda, 175 m SE “Ringkors” (‘Celtic’ cross; a medieval monument).

Klinteberg Fm.

Klinteenklaven 3, 6361455 1642657, *c*. 2450 m NNW of Fröjel church. Abandoned quarry 20 m E of the intersection between the unpaved road along the coast and the smaller road towards the SE.

Fröjel Fm, Gannarve Mb, upper part of lower half.

Kronvald 1, 635331 163840 (CJ 2530 5300), *c*. 6400 m W Eksta church. Shoreline exposure 400 m N the road junction at Kronvald, where the paved road passes inside a grove of pine trees (an unpaved road passes on the seaside of the grove).

Klinteberg Fm, ‘kronvald mb’.

Sandhamn 1, 635732 164232 (CJ 2950 5670), *c*. 2240 m SSW Fröjel church. A small road leads down on the shore, 90 m S where the road along the shore from Djauvik by St. Blåhäll turns 90° inland. The small road leads down to some mooring channels in which the bedrock is available below a thin layer of sand.

Halla Fm, Mulde Mb.

Sandhamn 2, 635706 164245, *c*. 2400 m SSW of Fröjel church. Road cut immediately S of the road where it makes a strong bend up through the steep slope. *c*. 2 m of sediments is accessible under a thin soil cover.

Halla Fm, Djupvik Mb, upper part.

Sandhamn 3, 635747 164281, *c*. 2125 m SSW of Fröjel church. Road cut immediately S and about halfway up the steep slope. *c*. 1 m of sediments is accessible under a thin soil cover.

Halla Fm, Djupvik Mb, upper part.

Skansudd 1, 635387 163853 (CJ 2598 5352), 6.25 km W Eksta church. Exposure in a mooring rill in the small bay N Skansudd, 100 m NW the ruin.

Klinteberg Fm, 'kronvald mb'.

Skansudd 2, 635433 163925 (CJ 2627 5393), *c*. 5520 m E Eksta church. An about 200 m long shore-line exposure. The southern end is *c*. 575 m W the road junction, 160 m NE Vavle.

Klinteberg Fm, 'kronvald mb'.

Sudervik 2, 635135 163801 (CJ 2476 5105), *c*. 7180 m WSW (W) Eksta church. Shore line exposure, 1.60 km S the road junction at Kronvald. There are some groves of pine and spruce trees on the sea side of the road here.

Klinteberg Fm, 'kronvald mb'.

Sudervik 3, 635042 163801 (CJ 2467 5015), *c*. 7560 m WSW Eksta church. Large surface exposure on the tip of Hammarudd.

Klinteberg Fm, 'kronvald mb'.

Valbybodar 2, 635857 164358 (CJ 3090 5781), 570 m S Fröjel church. Geol. map Aa 160 Klintehamn. Northern roadside section, 200 m W road 140 and Sigdarve.

Halla Fm, Djupvik Mb.

Valle 4, 636517 164582, *c*. 1150 m N of Klinte church. Geol. map Aa 160 Klintehamn. Ditch excavation immediately E of the N–S trending road, in the centre of its slight westward curve *c*. 110 m NNE of the long building marked on the topo. map at Valle.

Fröjel Fm, Svarvare Mb.

Vänge 1, 637364 166133 (CJ 4968 7154), 2.33 km ESE Viklau church. Top. map 56C Klintehamn (6 J Roma SV). Geol. map Aa 160 Klintehamn. Exposure in the large ditch, 170 m WSW the milestone, *c*. 30 m N the confluence of the ditch from S and that from E.

Klinteberg Fm.

Värsendeojk 3, 636200 164252 (CJ 3009 6132), 3.98 km SW Klinte church. Geol. map Aa 160 Klintehamn. Surface exposure in the sea, in the northernmost part of the small bay, a few m outside the grass. A field road (not marked on the map) leads down to the shore (and a couple of boats) just NW of the point where the NE-directed road (to road 140) branches off from the coastal road.

Slite Group, Slite Marl, topmost. [Lindsträm 1861, p. 343 (Djupviken nedanför Stenstugu, Steinstugu i Fröjel); Hede 1942, Loc. 2a; Jaanusson 1986 (Djupviken etc.; the quote of *M. ludensis* must be an error)].