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|---|---|---|---|---|---|---|

# Development of Facies and C/O-Isotopes in Transects through the Ludlow of Gotland: Evidence for Global and Local Influences on a Shallow-marine Environment

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## CONTENTS

## SUMMARY

The Silurian of Gotland is characterized by repeated changes in depositional facies development. The deposition of uniform sequences of micritic limestones and marls was interrupted four times by the growth of reef complexes and the formation of expanded carbonate platforms. Coinciding with these, often abrupt, facies changes extinction events occurred which predominantly affected nektonic and planktonic organisms. Ratios of carbon- and oxygen-isotopes covary with the facies development. Periods in which the deposition of limestone-marl alternations prevailed are characterized by relatively low C- and O-isotope values. During periods of enhanced reef growth isotope values are high. For these changes, Bickert et al. (1997) assume climatic changes between humid "H-periods", with estuarine circulation systems and eutrophic surface waters with decreased salinity in marginal seas, and arid "A-periods", with an antiestuarine circulation and oligotrophic, stronger saline surface waters.

In order to separate local and regional influences on the isotopic development from the global trend, the interactions between facies formation and isotope record have to be clarified. For this purpose, the patterns of isotope values in the upper part of the Silurian sequence on Gotland (upper Wenlock - upper Ludlow) has been determined and stratigraphically correlated along four transects through different facies areas. Facies formation during this time interval was investigated by differentiation and mapping of twelve facies complexes in the southern part of Gotland. These include shelf areas, reef complexes with patch reefs and biostromes, backreef facies, and marginal-marine deposits. The good correspondence between the carbon-isotope records of the four transects suggests that local environmental conditions in the different facies areas did not influence the $\delta^{13}C$ values. Therefore, a supra-regional or even global mechanism for the C-isotope variations is likely.

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In contrast to carbon isotopes, the oxygen-isotope values of the four transects generally show parallel trends, but higher variabilities and in parts distinctly deviating developments with a trend to more negative values. These are interpreted as an effect of local warming in small shallow-water areas which developed during arid periods in reef complexes and backreef areas.

The boundaries between A-periods and H-periods, as defined by $\delta^{13}C$ values, which are interpreted as isochrones, can be mapped. From the upper Homerian to the Pridolian six parastratigraphic isotope zones are defined which only partly match the stratigraphic division of Hede (1942, 1960). The isotope stratigraphy results in an improved correlation between the shallow and marginal-marine areas in the eastern part of Gotland and the uniform shelf areas at the west coast of the island.

Furthermore, a detailed relationship between the development of carbon and oxygen isotope ratios, the carbonate facies formation, and the succession of palaeontological events could be observed. At the transition from H-periods to A-periods, major extinction events occurred prior to the first increase of $\delta^{13}C$ and $\delta^{18}O$ values. Extinction events affected conodonts, graptolites, acritarchs, chitinozoans, and vertebrates and resulted in impoverished nektonic and planktonic communities. The reef-building benthos was less affected. Parallel to a first slight increase of isotope values, facies began to change, and reefs developed in suitable locations. The subsequent rapid increase of C- and O-isotope values occurred contemporarily with strong facies changes and a short-term drop of sea-level. Oligotrophic conditions in the later stages of A-periods led to strong reef growth and to an expansion of carbonate platforms.

The transitions from A-periods to H-periods were more gradual. The $\delta^{13}C$ values decreased slowly, but reef growth continued. Later the reefs retreated and were covered by the prograding depositional facies of shelf areas. The diversity of planktonic and nektonic communities increased again.

The close relationship between facies formation, palaeontological events and isotope records in the Silurian suggests common steering mechanisms but gives no indication of the causes for the repeated extincion events related to H-period/A-period transitions. Especially the observation, that strong extinctions occurred prior to changes of isotope values and facies, points to causes that left no signals in the geological record. Hypothetical causes like collapse of trophical nets, anoxias, or cooling events are not evident in the sediment record or do not fit into the regular succession of period transitions.

# 1 INTRODUCTION

## 1.1 Purpose of the study

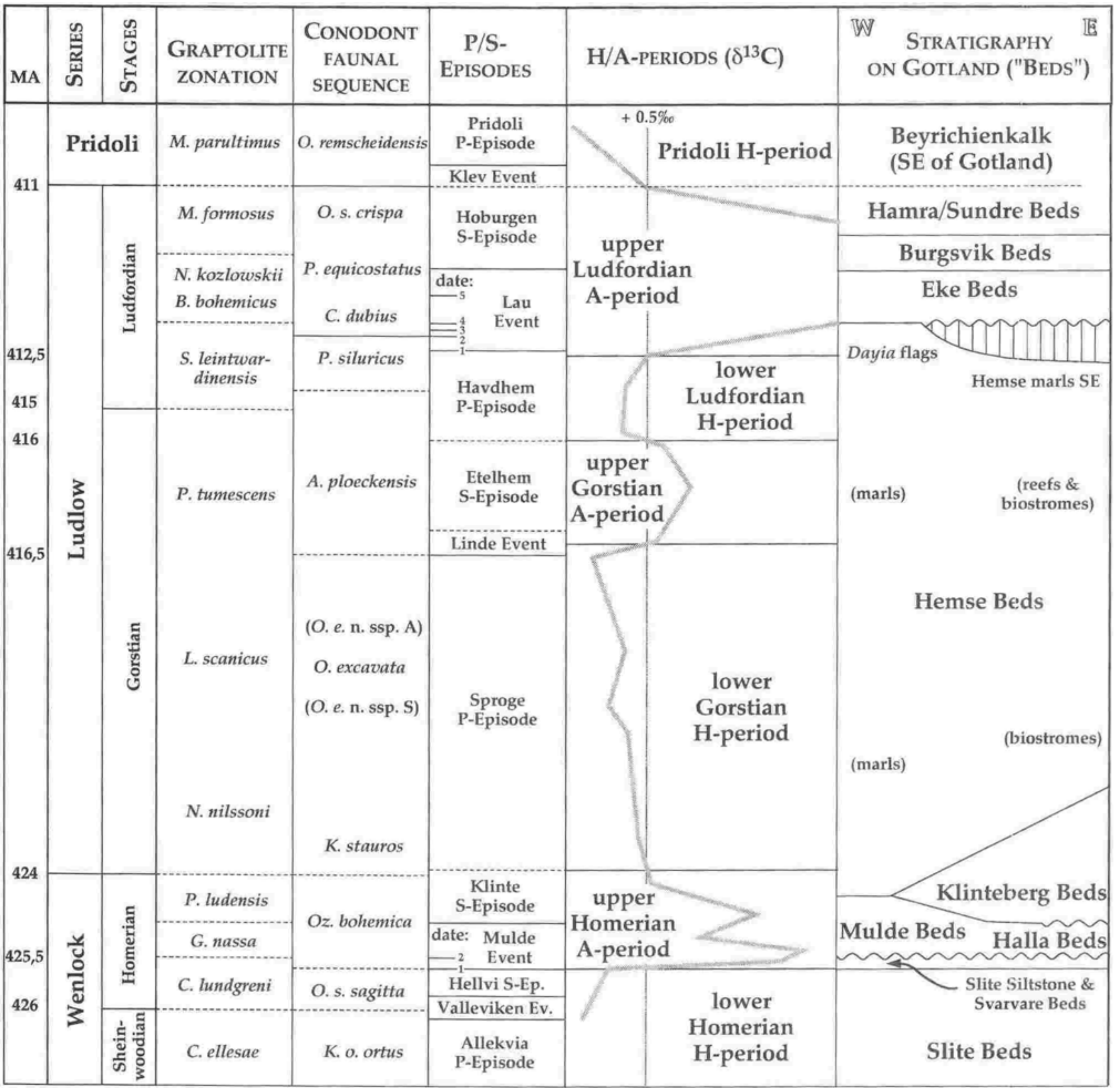
Changes in facies formation within Silurian sedimentary sequences are commonly attributed to sea level fluctuations (Johnson et al. 1981, 1991, Loydell 1998), and these fluctuations are often interpreted as causes of bio-events, i.e. rapid changes or collapse of fossil communities (Schönlaub 1986, Kaljo et al. 1995). Similar facies developments in distant regions are explained by corresponding variations in water depth which allow the reconstruction of a global sea level curve (McKerrow 1979, Johnson et al. 1991, Johnson 1996). For this purpose, individual curves from different areas are combined, and their general conformity is taken as a global signal.

On the other hand, climatic changes connected with varying freshwater input and changes in shallow ocean circulation pattern (estuarine vs. anti-estuarine) are discussed as causes for the facies development in Silurian carbonate sequences (Jeppsson 1990, Samtleben et al. 1996, Bickert et al. 1997). Regional facies formations are considered less important, based on the observation that corresponding carbon and oxygen isotope records are related to different successions in distant regions (e.g., Corfield et al. 1992, Talent et al. 1993, Kaljo et al. 1997, 1998, Azmy et al. 1998). However, to fit these different facies sequences into global conceptual models, it is necessary to separate local and regional influences on the isotopic development from the supra-regional trend, and therefore the interactions between facies formation and the isotope record must be clarified. Furthermore, for comparison of the isotopic record in different facies areas an exact stratigraphic correlation of isotope samples is required. For this purpose, in shallow marine sequences with spatially and temporally changing ratios between allochthonous sediment accumulation and autochthonous carbonate formation, (facies-)mapping is necessary.

The Silurian of Gotland is characterized by a pronounced isotopic development, with strong variations in $\delta^{18}O$ and $\delta^{13}C$ values associated with repeated changes in facies formation. The deposition of uniform sequences of micritic limestones and marls was interrupted four times by the growth of reef complexes and the formation of expanded carbonate platforms. Additionally, the strata show distinct lateral facies transitions from open-marine shelf areas in western Gotland to marginal marine deposits in the eastern part of the island. This offers an opportunity for comparison of the isotopic developments in several transects crossing contemporaneous, but different facies areas in order to identify and subtract the local/regional influences from the supra-regional or global isotopic record.

Purpose of this study is

- to determine the influences of local and regional factors on isotope ratios by comparison of C/O-isotope curves in different facies areas in order to separate them from the primary global isotope development;
- to use the isotopic record (mainly $\delta^{13}C$) as a parastratigraphic tool for the correlation of strata and facies areas on Gotland;
- to search for weak isotopic events with $\delta^{13}C$ amplitudes of less than 1‰, applying the obtainable precision in the determination of isotope values of ± 0.4‰, and to trace them through different facies areas;
- to investigate the time relations between isotope developments, facies formations, and palaeontological events in order to clarify the possible causal connections;
- finally, to use detailed isotope curves independent of local



| MA | Series | Stages | Graptolite zonation | Conodont faunal sequence | P/S-Episodes | H/A-periods (δ13C) | W Stratigraphy on Gotland ("Beds") E |
|---|---|---|---|---|---|---|---|
| | Pridoli | | *M. parultimus* | *O. remscheidensis* | Pridoli P-Episode<br>Klev Event | + 0.5‰<br>Pridoli H-period | Beyrichienkalk (SE of Gotland) |
| 411 | Ludlow | Ludfordian | *M. formosus* | *O. s. crispa* | Hoburgen S-Episode | upper Ludfordian A-period | Hamra/Sundre Beds |
| | | | *N. kozlowskii*<br>*B. bohemicus* | *P. equicostatus*<br>*C. dubius* | date: 5 4 3 2 1 Lau Event | | Burgsvik Beds<br>Eke Beds |
| 412,5 | | | *S. leintwar-dinensis* | *P. siluricus* | Havdhem P-Episode | lower Ludfordian H-period | *Dayia* flags<br>Hemse marls SE |
| 415<br>416<br>416,5 | | Gorstian | *P. tumescens* | *A. ploeckensis* | Etelhem S-Episode<br>Linde Event | upper Gorstian A-period | (marls) (reefs & biostromes) |
| | | | *L. scanicus*<br>*N. nilssoni* | (*O. e.* n. ssp. A)<br>*O. excavata*<br>(*O. e.* n. ssp. S)<br>*K. stauros* | Sproge P-Episode | lower Gorstian H-period | Hemse Beds<br>(biostromes)<br>(marls) |
| 424 | Wenlock | Homerian | *P. ludensis* | *Oz. bohemica* | Klinte S-Episode | upper Homerian A-period | Klinteberg Beds |
| | | | *G. nassa* | | date: Mulde 2 1 Event | | Mulde Beds Halla Beds |
| 425,5 | | | *C. lundgreni* | *O. s. sagitta* | Hellvi S-Ep. | lower Homerian H-period | Slite Siltstone & Svarvare Beds |
| 426 | | Shein-woodian | *C. ellesae* | *K. o. ortus* | Valleviken Ev.<br>Allekvia P-Episode | | Slite Beds |

Tab. 1. Synoptic presentation of the stratigraphic frame (Harland et al. 1990), biostratigraphic zonation (Jaeger 1991, Koren et al. 1996), conodont faunal sequence and P/S Episodes (Jeppsson 1990 - 1998), H/A-periods (this study), and topostratigraphy (Hede 1921 - 1960) on southern Gotland.

and/or regional influences for reconstructions of palaeoceanography and -climate in the Silurian in order to help in the detection of causes and steering mechanisms of facies formation and palaeontological events.

### 1.2 Previous research

The Silurian sequence on Gotland is about 450 m thick and was subdivided by Hede (1921) into 13 topostratigraphical units. The boundaries were defined largely by changes in lithology, and partly by index fossils or by discontinuity surfaces. The repeated changes between units dominated by limestone-marl alternations and others dominated by reef formation have been interpreted as the result of changing water depths connected with a general regression during the Silurian (e.g., Laufeld & Bassett 1981, Riding 1981) that was interrupted several times by periods of transgression (Bassett et al. 1989, among others). Accordingly, the shoreline should have advanced gradually to the southeast, running generally SW-NE, parallel to the present-day strike of the strata and to reconstructed Silurian facies belts (e.g. Brood 1976, Steel & de Coo 1977).

Jeppsson (1987) observed a close correlation between the temporal facies development on Gotland and significant cyclic changes in the conodont fauna. Sequences dominated by limestone-marl alternations representing an open shelf area are characterized by rich and diverse conodont assemblages, whereas periods of increased reef formation and expanded carbonate platforms exhibit a sparse and low-diversity conodont fauna. The shifts from highly diverse to impoverished faunas were abrupt and associated with general - often global - extinction events (KALJO et al. 1995) that also affected other groups of organisms, e.g., graptolites and acritarchs.

Based on these observations, JEPPSSON (1990) proposed a model for Silurian oceanographic cycles. He assumed changes between time intervals characterized by humid tropical climates and relatively cool high latitudes ("Primo Episodes") and time intervals with arid tropical climates and relatively warm high latitudes ("Secundo Episodes"). As a driving force for the oceanographic cycles, the formation of deep ocean water was proposed. During "P Episodes" cold, dense, oxygen-rich water was formed in high latitudes, whereas during "S Episodes" warmer surface temperatures reduced the ventilation of the deep oceans, and euxinic conditions developed.

Investigations of stable carbon and oxygen isotopes in brachiopod shells (SAMTLEBEN et al. 1996, WENZEL & JOACHIMSKI 1996, BICKERT et al. 1997) have shown that temporal changes in the depositional facies of the Silurian on Gotland were caused by changes in oceanographic circulation, precipitation and turbidity. The C and O isotopes show, in principle, parallel curves with repeated fluctuations between periods with high and low values. The oxygen isotope values are interpreted primarily to reflect palaeosalinity (SAMTLEBEN et al. 1996, BICKERT et al. 1997). Changes in these isotope values were caused by varying fresh water input rather than by temperature changes, because calculated temperatures would exceed the thermal limits for marine invertebrates. The carbon-isotope record is assumed to reflect changes in ocean circulation, with advection of $^{13}C$-rich surface water during periods of arid climate, and upwelling of $^{13}C$-depleted deep water during humid periods (BICKERT et al. 1997).

The reconstruction of corresponding oceanographic conditions (SAMTLEBEN et al. 1996, BICKERT et al. 1997) reveals a humid tropical climate during times with low isotope values ("H-periods"), with increased terrigenous input and an estuarine circulation on the shelves, resulting in upwelling of $^{13}C$-depleted, $CO_2$-rich deep water. Periods with high isotope values ("A-periods") are characterized by arid tropical climates with an anti-estuarine circulation on the shelves and advection of $^{13}C$-rich surface water. Oligotrophic conditions favoured the benthic carbonate production of sessile organisms and resulted in the formation of extended reefs and carbonate platforms. These periods of intensified carbonate production represent obviously relatively short interruptions of the "normal" marl-dominated sedimentation during longer-ranging humid climates (BICKERT et al. 1997). Thus, the palaeoceanographic and climatic conditions of the Silurian are considered to be the controlling factors for facies development. In contrast, changes in sea level obviously were of minor importance. They were not the cause, but the result of variations in carbonate accumulation (SAMTLEBEN et al. 1996). The reconstruction of oceanographic conditions during A- and H-periods (BICKERT et al. 1997) exhibits some similarities - but not a complete correspondence - to the palaeoceanographic model that JEPPSSON (1990) reconstructed for P and S Episodes based on observations of conodont faunas (see above).

Whereas during the various A-periods the amplitudes of the isotope variations show significant differences, the general courses of isotope curves and facies changes are very similar - up to breaks in sedimentation due to short-term sea-level fluctuations - indicating a conditional regularity. The question remains whether also a temporal regularity of isotopic and facies development exists.

## 2 STUDY AREA, MATERIAL, AND METHODS

In this study, the younger part of the Silurian sequence on Gotland from the upper Wenlock (upper Slite Beds) to the upper Ludlow (Hamra/Sundre Beds) was investigated (Tab. 1). The biostratigraphic classification follows largely the results of conodont investigations by JEPPSSON (1994, 1998) and JEPPSSON et al. (1994) which are correlated with the graptolite zonations of JAEGER (1991) and KOREN et al. (1996) (cp. JEPPSSON 1998). Problems and discrepancies in biostratigraphic correlation, however, could not be clarified by our investigations. The same holds for the absolute dating of the strata according to Harland et al. (1990) or Tucker & McKerrow (1995).

For the facies division of the upper Silurian sequence twelve facies complexes were distinguished and mapped at a scale of 1:100.000. Typical rock samples from the different facies complexes were investigated in the laboratory by means of thin sections, etched cross sections, SEM investigations, and geochemical analyses. Mapping of the facies areas was carried out, however, exclusively by field observations and based on characteristics of the rock formation, bedding structures, and fossil communities (Tab. 2).

For the determination of the C/O-isotope values, brachiopod samples were taken from four NW/SE transects through different facies areas (Fig. 1, 2). Altogether, samples from 192 localities have been analysed (including 32 samples from previous studies, SAMTLEBEN et al. 1996; Appendix 1). Most data points depicted in the isotope curves (see below) represent mean values of three or more specimens (157 localities).The samples were arranged stratigraphically and correlated, initially by means of the topostratigraphic division by HEDE (1921) (Tab. 1) and the geological maps of MUNTHE (1921) and HEDE (1925-29). For this study, a biostratigraphic arrangement of the samples based on conodonts was not precise enough due to the relatively low number of stratigraphically classified localities on Gotland. Therefore, the sample localities of each, several-kilometres-wide, transect had to be arranged geometrically, based on dip, strike, and elevation. Due to the unfolded and uniformly dipping nature of the strata, this applies well to the western side of Gotland where uniform sequences of argillaceous limestones and marls occur. On the eastern side of the island, however, the arrangement is considerably less certain due to abundant and rapid facies changes and to multiple gaps in the geological record. Here, the stratigraphic positions of samples were determined by means of sketch mapping, i.e. by ap-

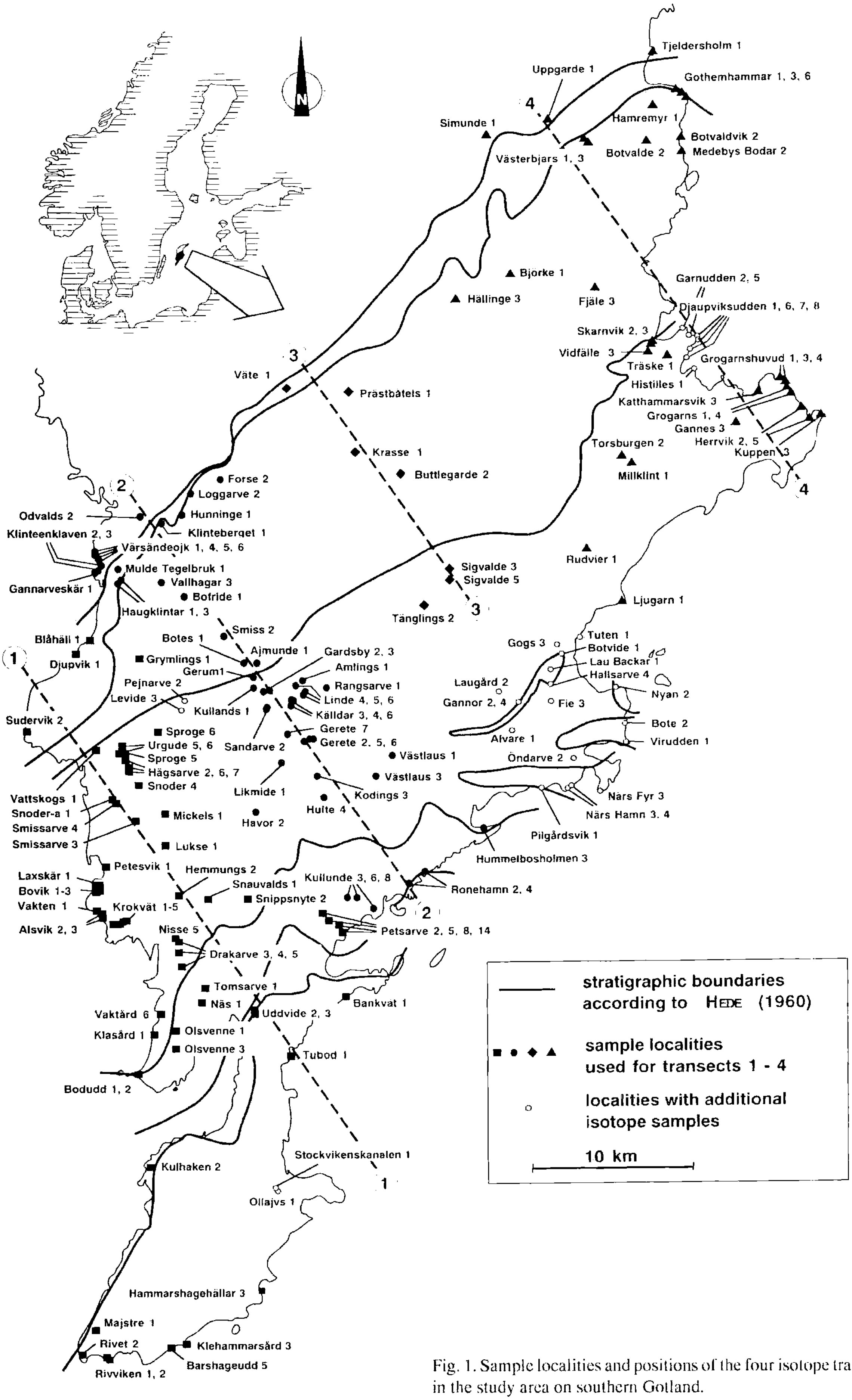


Fig. 1. Sample localities and positions of the four isotope transects in the study area on southern Gotland.

proximation of thicknesses, geometric relations, and facies connections to neighbouring localities.

In several instances, the positions of certain samples did not allow direct stratigraphic correlations between the four transects. In these cases, the constructed sections were correlated using the carbon-isotope values. The $\delta^{13}C$ values are assumed to reflect supra-regional, possibly even global climatic conditions and changes (SAMTLEBEN et al. 1996, BICKERT et al. 1997). Thus, in this study they are used to distinguish different isotope periods. As a reference point the base of the Linde Event (JEPPSSON 1993) was taken because it is prominent in every section (cp. Tab. 1, Fig. 3).

The registration of the sample localities follows the scheme for reference localities of LAUFELD (1974b). The coordinates and the descriptions of new localities are given in the Appendix 2 of the present article. The preparation of brachiopod samples and the isotope analyses follow the methods described in BICKERT et al. (1997) and SAMTLEBEN et al. (1996, in press).

Comparison of analyses from various Silurian brachiopods revealed taxa-dependent fractionation effects in strophomenids and most pentamerids which result in deviating isotope values. For the present study, only spiriferids, rhynchonellids, orthids, and occasionally *Gypidula galeata* (pentamerid) are used. If possible, samples were taken exclusively from the widely distributed species group of *Atrypa "reticularis"*. In autochthonous assemblages of specimens which lived contemporarily and are preserved without diagenetical alteration, original values of carbon and oxygen isotopes can be evaluated with a reliability of ± 0.4‰ (SAMTLEBEN et al. in press). Whole rock samples have not been used for isotope analyses as their values represent mixtures of various primary and secondary signals.

## 3 RESULTS

### 3.1 **Facies Complexes** (Tab. 2, Fig. 2)

The facies complexes observed on Gotland are in good accordance with the standard facies belts of WILSON (1975). However, due to the regional geological and palaeogeographical situation in the Baltic area, and due to the palaeobiological evolution in the Silurian, some deviations occur with respect to both single rock types and whole facies areas. Most of the topostratigraphic units (Beds) of HEDE (1925-29) show a facies change from marginal marine deposits and reef complexes in the NE towards open marine, distal shelf sediments in the SW (Fig. 2). The subunits of LAUFELD (1974a), identified for stratigraphic subdivision, largely represent facies groups. Their boundaries are heterochronous and cannot be traced over long distances.

#### 3.1.1 Distal shelf

The distal shelf facies is characterized by regular alternations of micritic limestones and marls, consisting predominantly of mudstones and wackestones (Pl. 2/1). Grainstones are nearly absent. In general, the micritic limestones are developed as beds with wavy bedding surfaces, or as nodules embedded in marls. These typical bedding features were produced diagenetically in the shallow burial by aragonite dissolution within the soft sediment and calcite precipitation within the limestone beds and/or nodules (MUNNECKE & SAMTLEBEN 1996, MUNNECKE et al. 1997). The sediment material of the distal shelf was imported, mostly as very fine-grained constituents in suspension, from adjacent shallower shelf areas and/or carbonate platforms. Due to a strong input of terrigenous material the carbonate content of the sediments is relatively low compared with other facies complexes on Gotland (see below).

Fossils are not very abundant in sediments of the distal shelf facies. Trilobites, ostracods, pelecypods, and a sparse brachiopod fauna, autochthonous and often preserved in life position, form the main part of the benthic association. Occasionally, single rugose and tabulate corals occur. In some beds orthoceratids are common, irregularly distributed and without an orientation due to the absence of bottom currents. Large specimens (Ø ≥ 10 cm) are preserved only with their lower part. The corrosion of the upper part indicates a slow and possibly pulsatory sedimentation. In some areas, horizontal (*Chondrites*-like) and vertical traces are abundant.

The sediments of the distal shelf point to an accumulation below storm wave base and, indicated by the lack of algae, below the photic zone. Only weak currents reached episodically the bottom, so reworking of bioclastic material is almost absent. As the sediments on Gotland are not tectonically affected, the palaeodepth can be estimated by topographic relations between contemporaneous rock formations in different facies areas, for example between the distal-shelf facies at Sudervik and the reef facies at Klinteberget. Due to these relations and under the assumption that rocks of the reef area underwent no stronger compaction than limestone-marl alternations, the water depth of the distal shelf is estimated at about 50 m maximum.

#### 3.1.2 Distal shelf with *Dayia navicula*

The *Dayia navicula* flags represent a special sediment formation within the distal shelf facies described above. Developed only in the upper Hemse Beds, mainly in the western part of Gotland, they consist of gray, silty, and well bedded limestones and marls (mudstones, wackestones, packstones) containing up to 50 % quartz, detritic dolomite, and mica in a calcitic matrix. Calcareous bioclastic debris is rare. The sediments are not bioturbated and are characterized by a fine horizontal lamination which causes the even bedding planes. The detrital grains (quartz, dolomite, mica) are well sorted and aligned in thin parallel layers indicating eolian input rather than hydrodynamic transport. Indications for reworking or bottom currents have not been observed.

Fossils are very rare. Occasionally, some trilobites and orthoceratids have been observed. In several beds the small brachiopod *Dayia navicula* occurs, sometimes in large numbers (clusters). Possibly this species lived in a pseudoplanktonic mode, attached to drifting organisms (e.g.,

| | *Davia* flags | distal shelf | proximal shelf | shelf with oncolites | reef complexes | biostromes | faros | shoal areas | backreef areas | backreef flats | marginal-marine areas | foreshore sandstones |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mudstones | 2 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1* |
| wackestones/floatstones | 1 | 1 | 2 | 2 | 1 | 0 | 0 | 0 | 2 | 0 | 1 | |
| packstones/rudstones | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | |
| grainstones/rudstones | 0 | 0 | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2* |
| boundstones | 0 | 0 | 1 | 0 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | |
| predominantly light coloured | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | |
| predominantly gray coloured | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| terrigenous material | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| limestone/marl alternations | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| continuous beds | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| discontinuous beds | 0 | 0 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 1 | 2 |
| plane-parallel lamination | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| flaser lamination | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| cross bedding / current ripples | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 2 | 0 | 1 | 0 | 1 |
| small scale wave ripples | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| large scale wave ripples | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| bioturbation | 0 | 1 | 2 | 1 | 0 | 0 | 0 | | 2 | 2 | 1 | 1 |
| horizontal trace fossils | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 2 | 2 | 1 | 1 |
| vertical trace fossils/burrows | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| sorting | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 2 |
| roundness of components | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 1 |
| conglomerates | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| intraclasts | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 2 | 1 | 1 |
| tidal channels | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| loferites | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | | 0 |
| desiccation cracks | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| hard grounds | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| abrasion surfaces/truncations | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 1 | 0 |
| algal laminations | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| encrusting algae | 0 | 0 | 1 | 2 | 1 | 1 | 0 | 0 | 2 | 1 | 1 | 0 |
| oncoids | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 |
| stromatolitic formations | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| fossils abundant | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| fossils rare | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 2 |
| brachiopods autochthonous | 0 | 2 | 1 | 2 | 2 | 2 | 2 | 0 | 2 | 0 | 2 | 1 |
| brachiopods allochthonous | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 0 | 2 | 1 | 1 |
| brachiopod fauna diverse | 0 | 2 | 2 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| brachiopod fauna restricted | 2 | 0 | 0 | 0 | 2 | 2 | 2 | 0 | 2 | 2 | 2 | 1 |
| *Pentamerus/Kirkidium* -assemblage | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 0 | 0 |
| *Davia navicula* -assemblage | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| stromatopores | 0 | 0 | 1 | 0 | 2 | 2 | 2 | 0 | 1 | 1 | 1 | 0 |
| tabulate & rugose corals | 0 | 1 | 2 | 0 | 2 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| bryozoans/coenitids | 0 | 0 | 1 | 0 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 0 |
| crinoids | 0 | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| orthoceratids | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| bivalves/gastropods | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 2 | 1 | 0 |
| trilobites | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| graptolites | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| occurrence in H-periods | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| occurrence in A-periods | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 |

Tab. 2. Sedimentological and palaeontological characteristics of facies complexes in the upper Silurian on Gotland (explanation of numbers: 2 = frequent and typical, 1 = common to occasionally occurring, 0 = absent or very rare; empty field = no observation).

orthoceratids). A sparse endobenthic fauna is documented by thin vertical and dendritic ichnofossils which, however, do not disturb the horizontal lamination.

### 3.1.3 Proximal shelf

The proximal shelf facies is characterized by alternations of grey limestones and marls that consist mostly of wackestones, but also of mudstones, packstones, and grainstones. Most limestone beds have an irregular flat-lentiform appearance and wedge out rapidly within a few metres (Pl. 2/2). Part of the bedding features are produced diagenetically by dissolution and reprecipitation processes. However, primary changes of composition and lithology were much more important than in the distal shelf facies. The water depth in the proximal shelf area was probably low. The occurrence of grainstones and reworked intraclasts indicate a depositional environment above storm wave base. Sparse occurrences of oncoidal crusts indicate occasional deposition within the photic zone. Erosional discontinuity surfaces and tidal channels indicate, at least in part, a sedimentation under subtidal conditions. Hard ground formation - although rarely observed - points to breaks in sedimentation, and possibly to erosion. However, no indications of subaerial exposure have been found.

The sediments of the proximal shelf facies are fossil-rich and contain an abundant and diverse fully marine fauna dominated by brachiopods, stromatopores, and tabulate corals. Besides these, trilobites, ostracodes, bryozoans, crinoid debris, pelecypods, and gastropods occur. Colonies of stromatopores and tabulate corals are normally preserved in autochthonous position, but partly tilted. Brachiopods, bryozoans, and molluscs show a parautochthonous occurrence. Often they are transported and sometimes broken, but they are only seldomly rounded due to a transport over longer distances (Pl. 3/1-2). Crinoid debris is imported mainly from nearby reefs and carbonate platforms. The sediments of the proximal shelf facies are in general intensively bioturbated. Besides *Rhizocorallium*- and *Chondrites*-like burrows, a great number of other types of burrows and tracks are observed. Intense bioturbation is responsible for the dominance of wackestones in this facies complex.

The proximal shelves were areas of intensive carbonate production. A portion of the sediment material, however, was imported from adjacent platforms. In periods of extensive reef growth and expansion of carbonate platforms, the proximal shelf areas also expanded basinward due to likewise increased carbonate production and deposition. Under less favourable conditions for carbonate production they retreated with a certain time lag. In separate transects, therefore, facies shifts affecting proximal shelves were often not contemporaneous with changes in isotope values, but exhibit phase differences.

### 3.1.4 Proximal shelf with oncolites

This facies is developed only in the Eke Beds (Pl. 2/3). The sediment consists of thinly bedded, grey, argillaceous and micritic limestones, mostly wackestones and packstones, and marls. They contain a diverse and abundant fully marine brachiopod fauna. The specimens are preserved either in life position or overturned, sometimes disarticulated. The shells are not broken or rounded indicating absence of reworking and extensive transport. Additionally, trilobites, ostracods, gastropods, orthoceratids, rugose corals, and bryozoans occur. In contrast to the "normal" proximal shelf, crinoid debris is rare, and colonies of tabulate corals and stromatopores are absent. Most fossils are encrusted more or less intensively by algae (*Girvanella*, *Rothpletzella*) forming oncoids (Pl. 5/3). The oncoids, ranging in size up to a few centimetres, show a typical cauliflower-like morphology (Pl. 3/4).

In sediment sequences of this facies complex, oncolitic layers alternate irregularly with limestones and marls of the "normal" proximal shelf type, indicating that both facies are deposited under similar conditions, i.e., in subtidal environments above storm wave base and within the photic zone. The conspicuous differences of the oncolitic shelf sediments compared to the 'normal' proximal shelf might be caused by sea-level fluctuations in the Ludfordian (see below) which resulted in the development of a sheltered shallow-marine environment, favouring the growth of both a diverse brachiopod fauna and encrusting algae.

### 3.1.5 Reef complexes

This facies complex consists to a large degree of reefs, autochthonous carbonate buildups which were formed mainly by the growth of colony-forming sessile organisms and by trapping and/or binding of suspended carbonate material. The diameter of the reefs is normally less than 100 m. They are surrounded by fans of reef debris which wedge out rapidly and grade laterally into shoal and backreef sediments (see below). Although reef bodies are volumetrically of secondary importance compared to reef debris and shoal sediments, they are characteristic for this facies complex since they represent the dominant carbonate production areas. Therefore, these areas are mapped uniformly as "reef complexes".

Depending on local conditions, the composition, construction, form, and size of single reefs vary considerably even in closely neighbouring areas. They were built mainly

Plate 1 Facies and C/O-isotopes in transects through the Ludlow of Gotland. Exposures in different facies areas

Fig. 1. Large, massive patch reef complex in the Hamra/Sundre Beds, built mainly by stromatopore reef-limestones, interrupted and surrounded by reef debris and bedded coarse bioclastic limestones. The reef developed above foreshore sandstones of the Burgsvik Beds (foreground) during a period of increasing water depth. Subsequently, it was covered by crinoidal limestone of the Sundre Beds. Storburg, Hoburgen peninsula. Height of the cliff ca. 30 m.

Fig. 2. Part of a large reef mound in the Klinteberg Beds. It consists of several metres large, lenticular bodies of crinoidal bafflestones and floatstones, with indistinct horizontal stratification. Hunninge quarry, E of Klintehamn.

Fig. 3. Stromatopore biostrome in the Hemse Beds. In the lower part, the stromatopores show laminar or low domical forms and are mostly preserved in life position. Higher up, they develop increasingly high domical and bulbous forms; they are often preserved in tilted position, and sometimes rounded due to reworking. The biostrome is overlain by coarse bioclastic limestones truncated by an abrasion-level surface. This succession indicates increasing water energy. Kuppen, Östergarn peninsula. Height of the wall 4 m.

Fig. 4. Crossbedded, coarse crinoidal limestone of the Hamra/Sundre Beds, forming a small shoal area (not mapped) north of the reefs at Hoburgen. Gervalds, Hoburgen peninsula. Height of the wall 1.8 m (hammer for scale).

Plate 1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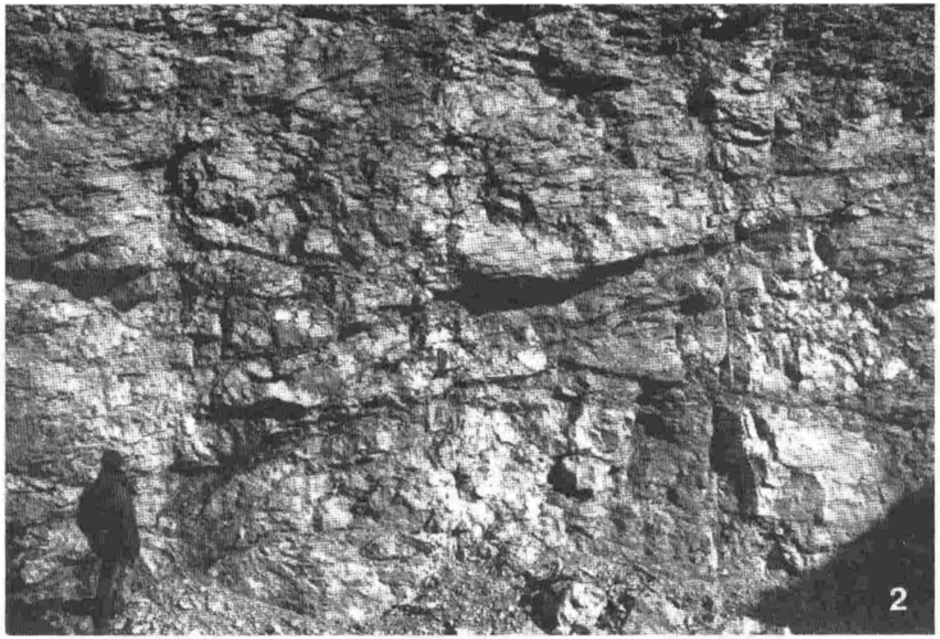
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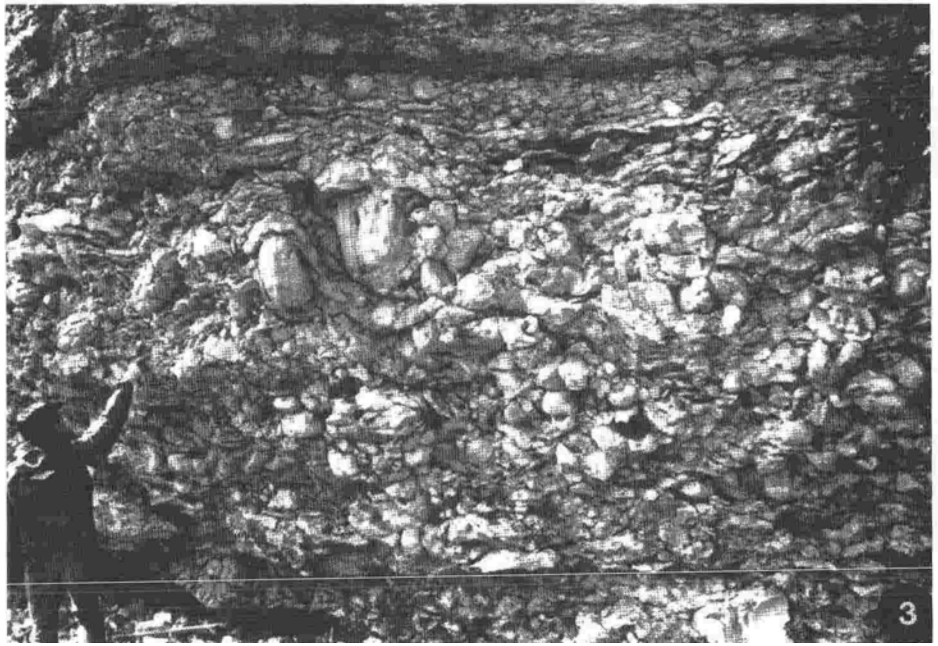
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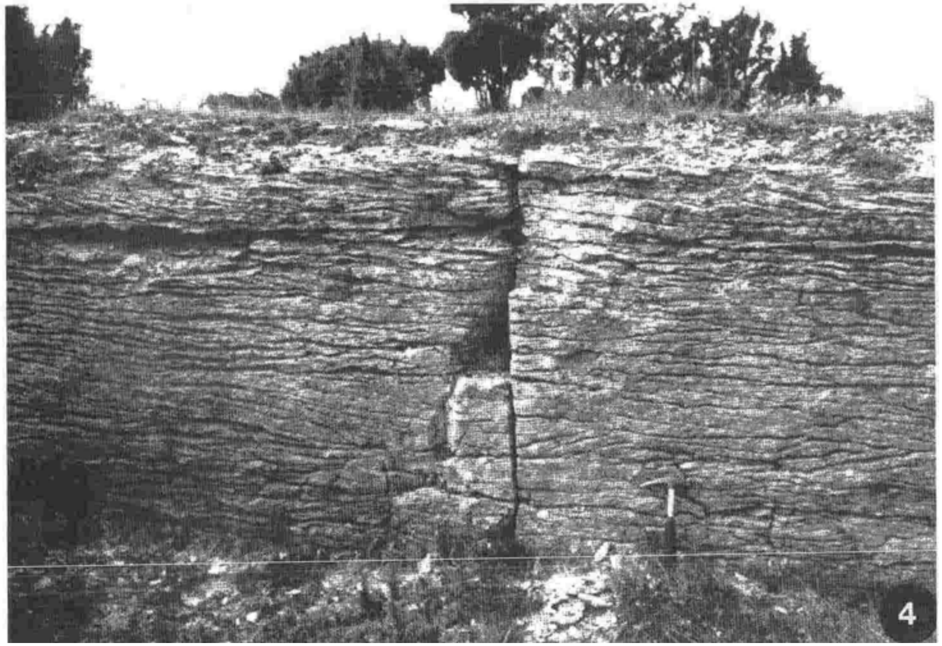
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by tabulate corals and stromatopores. Additionally, crinoids, rugose corals, bryozoans, and algae participated in reef formation. Reef growth often began in relatively deep water under calm conditions, possibly below the photic zone. Normally, the pioneers were tabulate corals which settled in dense groups at suitable sites and formed initial reef mounds (Pl. 5/1). At other localities, reef mounds and reefs were built by sediment trapping of narrowly spaced crinoids (Pl. 4/1). Reef mounds had no rigid framework and were only slightly elevated above the sea floor, however, they were often the base of succeeding large patch reefs (Pl. 1/1). These were built mainly by densely growing stromatopores forming a rigid framework. Patch reefs sometimes attained elevations of more than 10 m above the sea floor and grew into the agitated zone near the sea surface. In advanced stages of reef growth algae (*Solenopora*, *Rothpletzella*, *Hedstroemia*) became increasingly important as reef-binders encrusting reef-building colonies and forming tight connections. At the sea surface, patch reefs sometimes grew together forming extended biostromal platforms (see below). Occasionally, some reefs were subaerially exposed (FRYKMAN 1985).

Besides crinoids, bryozoans, and colonies of stromatopores and corals, the reef communities were rather poor in benthic fossils. The impoverished but normal marine brachiopod fauna contains smooth-shelled spiriferids (*Didymothyris*, *Lissatrypa*), very few strophomenids (*Leptaena*) and abundant pentamerids (*Conchidium*, *Kirkidium*) which settled as dense clusters in small niches within the central parts of the reefs (Pl. 4/4). Trilobites were rare, gastropods and bivalves nearly absent. Orthoceratids, in places rather abundant, were often represented by specialized morphotypes (e.g., *Gomphoceras*, *Ascoceras*).

Reefs on Gotland are composed of grey and light coloured boundstones, often with a micritic matrix. In reef mounds micritic and bioclastic material has been trapped in stalk-shaped or fence-like skeletons of tabulate corals (Pl. 5/1-2) or between the colonies of the first reef-forming organisms. Dominant rock types in patch reefs that have been formed above the seafloor are mostly light-coloured bindstones and framestones, usually with a greenish matrix. Reef rocks are massive without stratification and form low convex elevations on the ground surface. The reef cores are surrounded by and interlocked with coarse-grained limestones (rudstones, floatstones) which form an enveloping talus of reef debris. They consist mainly of bioclasts of reef organisms. The components are only slightly sorted, frequently broken, but they are seldomly rounded, and often well preserved (Pl. 4/3, 7). These rocks are mostly thickly bedded and without distinct stratification. A major part of bedded limestones within reefs are pure crinoidal limestones. Crinoids settled especially on reef flanks. Their roots helped to stabilize the bioclastic scree and often initiated the growth of lateral reef bodies.

### 3.1.6 Biostromes

This facies complex comprises bank-forming, laterally extensive reefs that grew in shallow water depths limiting vertical growth. On Gotland, biostromes cover areas exceeding 100 km$^2$. They frequently originated from the merging of patch reefs which stopped growing at the water surface. Therefore, biostromes and patch reefs are often transitional and cannot be easily separated in the field, especially if only surface exposures are present. Nevertheless, the origin of biostromes in more agitated shallow waters resulted in typical bedded structures and lithologies which distinguish them from patch reefs and reef mounds.

The ecological reef proper was built preponderantly by stromatopores which grew densely stacked and interlocking (KERSHAW 1993, 1994, KEELING & KERSHAW 1994). Frequently, the stromatopores are tilted or transported and rounded. In some banks, nearly globular colonies occur that obviously have been tumbled by water movement during growth, giving these banks the characteristics of very coarse conglomerates (Pl. 1/3). The sediment between the colonies varies. In sheltered places it is micrite; in places with stronger water movement it consists of pure grainstones. Characteristical for biostromes that have grown at the water surface are signs of episodical interruption of reef growth,

Plate 2 Facies and C/O-isotopes in transects through the Ludlow of Gotland. Exposures in different facies areas

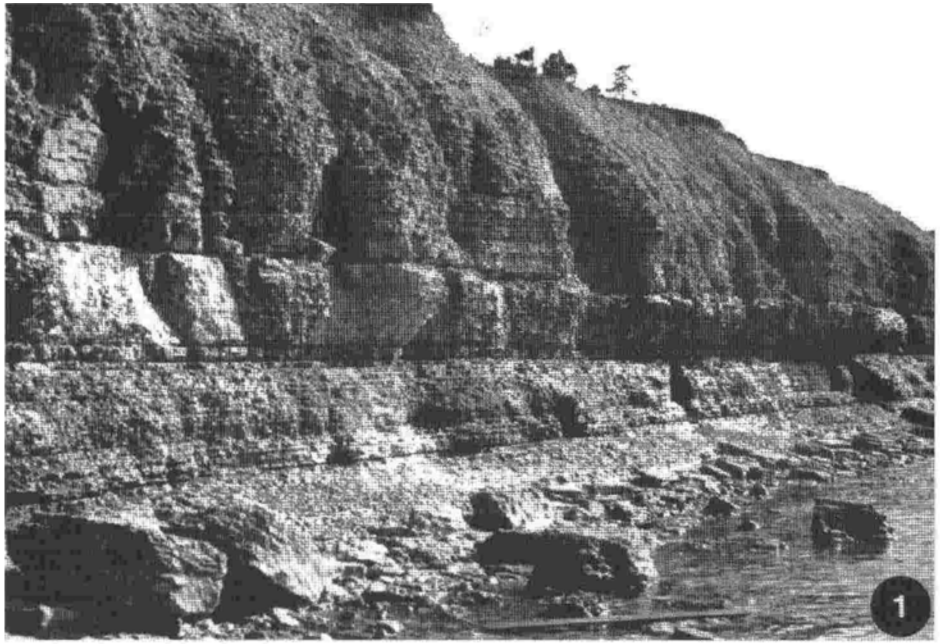
Fig. 1. Limestone-marl alternation of the Mulde Beds. The regular character of this facies is caused by sedimentation under calm conditions in a distal shelf environment. The conspicuous joints result from clay-rich horizons, interpreted as bentonites. Djupviks Fiskeläge, SW of Fröjel. Height of the wall 5.5 m.

Fig. 2. Limestone-marl alternation of the Klinteberg Beds. The fossil-rich sediments consist of bioclastic limestones and marls deposited in a proximal shelf environment. The agitated sedimentation area is reflected by the irregular bedding structures as well as by the fact that most layers wedge out within a few metres. The strata are overlain by thickly bedded, coarse debris limestones of the nearby reefs. Hunninge quarry. Height of the section 6 m.

Fig. 3. Oncoid-rich argillaceous limestones of the Eke Beds. The nuclei of the oncoids, up to 4 cm large, consist mainly of brachiopods, small rugose corals, and cephalopods. The observation that these organisms also occur with very thin or even without oncolitic crusts indicates a formation of the oncoids within the same environment. Bodudd, När peninsula. Surface exposure at the shore (hammer for scale).

Fig. 4. *Favosites*-reef mound of the Hemse Beds. This reef mound is built exclusively by round colonies of *Favosites* sp. which form a flat lenticular reef assemblage with a diameter of ca. 2 m. It is surrounded by thinly bedded argillaceous limestones of a marginal-marine facies area. Garnudden, NE of Kräklingbo (hammer for scale).

Plate 2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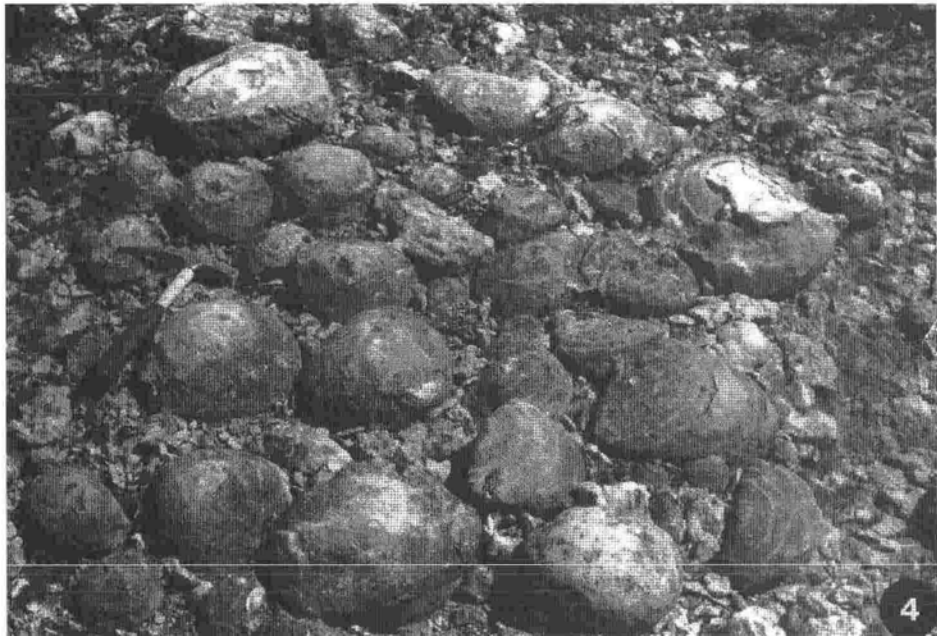
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erosion, and reworking. Topping of stromatopore colonies, planar abrasion surfaces, and channel cuttings are rather frequent. Beds of reef debris are intercalated with banks of colonies grown in situ. They consist largely of more or less coarse conglomerates formed by the accumulation of rubble-like rounded bioclasts, predominantly stromatopores (Pl. 4/6). Sparitic crinoidal limestones also occur due to dense settlements of crinoids in these shallow-water biotopes. They pass over to extensive shoals in the vicinity of the biostromes.

Generally, the fossil assemblages of biostromes show low diversities. Besides stromatopores, only *Favosites* played a major role as reef builder; other tabulate corals were almost absent. Stock-forming rugose corals and *Syringopora* exhibit intergrowth with stromatopore colonies and may have lived as commensals of the stromatopores (KERSHAW 1987). Smooth-shelled brachiopods (e.g. *Lissatrypa*, Pl. 4/5) and pentamerids settled in small niches.

### 3.1.7 Faros (shallow atolls)

Faros originated from biostromes, so, both have many rock types in common. However, the shape of a faro differs strongly from that of a biostrome (MANTEN 1971, KANO 1989), thus, they are classified here as a separate reef type. The characteristic form of a faro is that of an atoll-like semicircle with a diameter of 0.5-1 km and with distally dipping biostromal surfaces. Conspicuous vertical fissures, up to 0.5 m wide, cut radially and concentrically through these reef rings. They have been opened and refilled with sediment material repeatedly during growth of the reefs. Reef materials and sedimentary structures indicate that, during the formation of the faros near the sea surface, periods of intense reef growth under relatively calm conditions alternated with periods of stronger water movement and reef destruction. The interior areas of the reefs formed lagoons which were presumably filled with soft sediments, but on Gotland these have always been largely removed by erosion.

The reefs proper are composed of dense stromatopore framestones and/or bindstones and crinoidal bafflestones (Pl. 4/1) which in most cases have a micritic matrix. As in the top part of patch reefs, algal bafflestones occur which are formed predominantly by Solenoporaceae (Pl. 4/2). The reef rocks alternate with micritic or sparitic crinoidal limestones and coarse, occasionally conglomeratic grainstones that contain angular bioclasts, mostly from stromatopores.

On Gotland, faros occur only in the upper part of the Hamra/Sundre Beds. They are situated on the southeastern margin of an extended stromatopore biostrome and form semicircles open to the NW developed during an interval of gradual sea-level rise. It is presently not known whether there are patch reefs below the faros which formed elevations on the sea floor and, growing upward in competition with the sea-level rise, gradually modified into these atoll-like reef forms.

### 3.1.8 Shoals

Shoals are composed predominantly of light-coloured, medium- to fine-grained bedded grainstones. They consist of bioclasts of bryozoans and crinoids, ooids and peloids that are transported, washed and well sorted (Pl. 4/8). Frequently, beds show cross-stratification (Pl. 1/4) and large parallel-running oscillation ripple marks on the surfaces. Locally, allochthonous accumulations of large bivalves (*Megalomus* sp.) or brachiopod valves occur. The specimens are well preserved indicating short transports. Part of the beds contain predominantly vertical burrows. In some places fine-grained limestones show loferitic fenestral structures and/or algal laminations.

Plate 3 Facies and C/O-isotopes in transects through the Ludlow of Gotland. Bedding planes from different facies areas

Fig. 1. Argillaceous limestone of the Slite Beds. The abundance and diversity of the fossil assemblage (mainly gastropods, trilobites, ostracodes, brachiopods) as well as numerous traces indicate strong biological activity in a proximal shelf environment. Some of the fossils show orientation due to currents. The generally excellent preservation, however, indicates a parautochthonous embedding of the fossil association. Slite quarry. Width of the figure 15 cm.

Fig. 2. Bedding surface of a limestone in a proximal shelf facies area of the Hemse Beds. Parautochthonous assemblage of brachiopods, bryozoans, small tabulate corals, ostracods, trilobite and crinoid debris. Nyan, När peninsula. Width of the figure 11 cm.

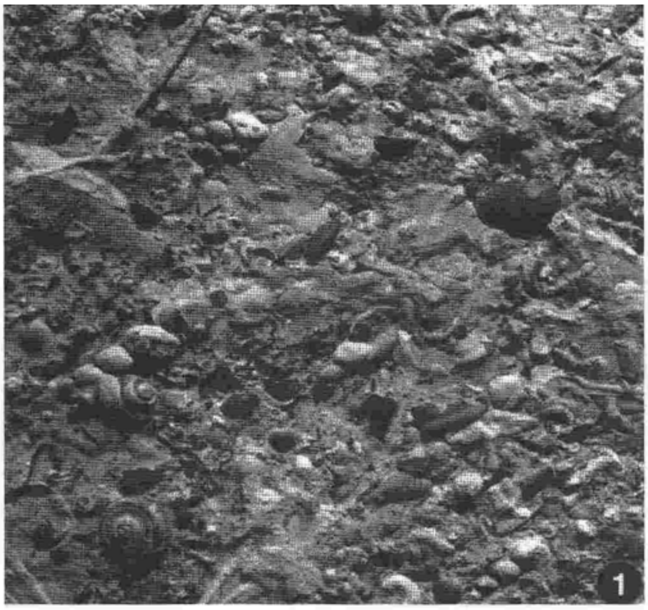
Fig. 3. Oncolitic crinoidal limestone of the Hamra/Sundre Beds. Bedding plane of a limestone in the backreef facies with rugose corals and parts of crinoids, deposited in close proximity to nearby reefs. Some of the fossils are encrusted by oncolitic algae. NW of Vamlingbo, Hoburgen peninsula. Width of the figure 16 cm.

Fig. 4. Oncolitic limestone of the Eke Beds. Bedding surface from a proximal shelf area with relatively large cauliflower-like oncoids ("*Sphaerocodium*"), additionally brachiopods and bryozoans. Ronehamn. Width of the figure 24 cm.

Fig. 5. Foreshore sandstone of the Burgsvik Beds. The sole bed shows vertical burrows, horizontal traces, and the imprint of a starfish (*Palaeasterina*). Husryggen, Hoburgen peninsula. Width of the figure 20 cm.

Fig. 6. Argillaceous limestone of the Halla Beds. The low-diversity assemblage of abundant brachiopods (*Microsphaeridiorhynchus nucula*, *Delthyris elevata*) and branching bryozoans indicates extreme ecological conditions in a marginal-marine environment. Gothemhammar. Width of the figure 8 cm.

Plate 3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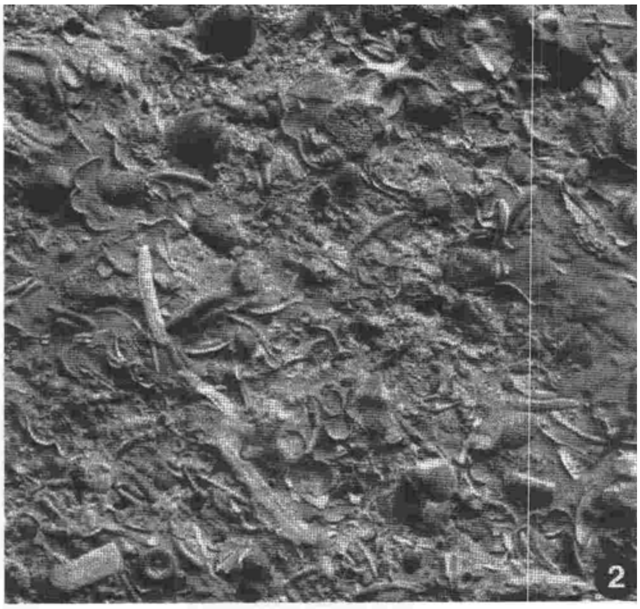
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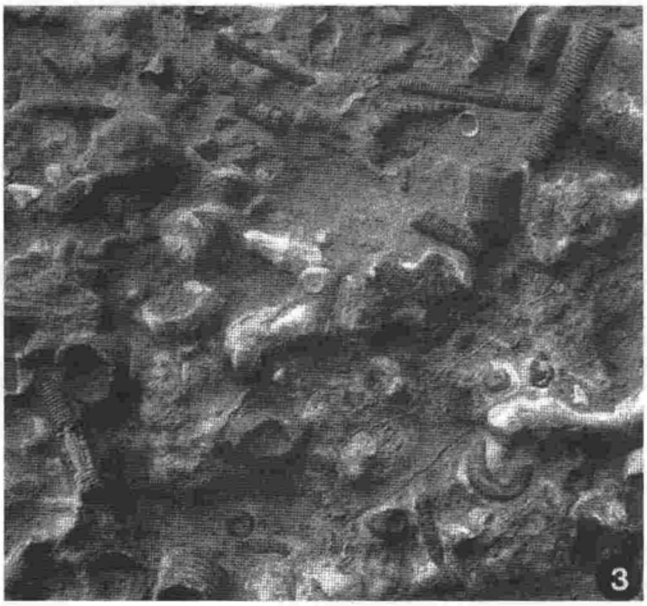
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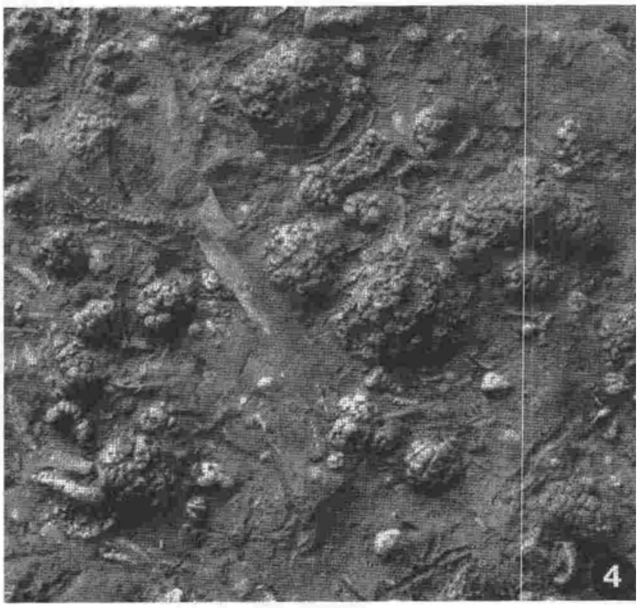
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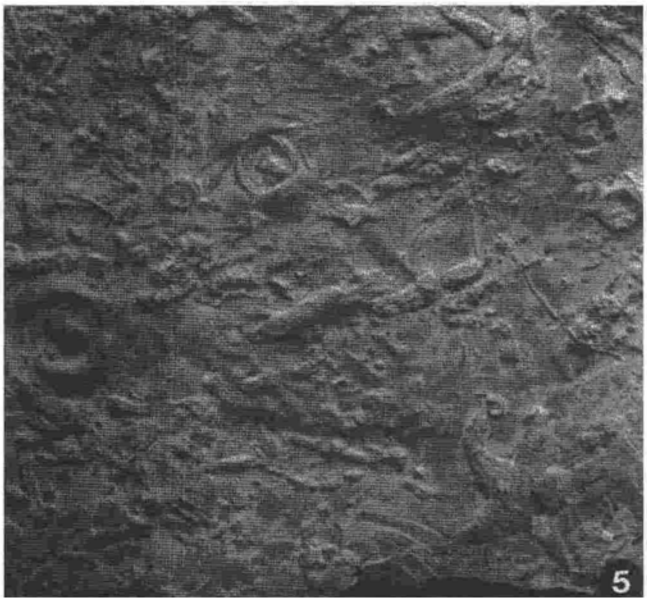
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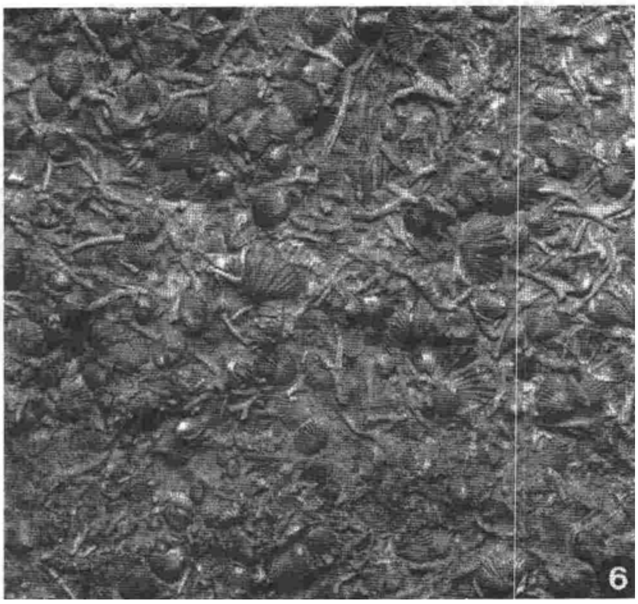
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The water depth is indicated by sedimentary structures. For example, SUNDQUIST (1982b) reconstructed the formation of large wave ripple-marks in a shoal area of the Hemse Beds at a water depth of about 10 m or less. On the other hand, fenestral structures and algal laminations point to intertidal conditions.

Shoals occur on carbonate platforms and intergrade laterally with reefs and reef debris. They covered extended areas in the vicinity of reef complexes and formed a sea floor of mobile carbonate sands. During calm intervals, an open marine fauna settled on and in these sands indicated by assemblages of brachiopods and bivalves. Sometimes, stromatopores, tabulate corals, and bryozoans could grow and build small reef mounds or thin biostromes. Although shoal sediments form a major portion of the rocks on carbonate platforms, in this study they are rarely mapped as distinct facies areas. They are mostly included in reef complexes and biostromes.

### 3.1.9 Backreef areas

This facies complex comprises predominantly micritic limestones that accumulated in the enclosed, sheltered and calm environment on the lee sides of patch-reef complexes. The sediments consist of light brown mudstones, fine-grained packstones, and intensively bioturbated wackestones. They contain small fossils and bioclasts which are rarely rounded. A large number of the shells have algal coatings (Pl. 3/3), and oncoids form a significant portion of the sediments (Pl. 5/5). On the contrary, terrigenous material is very rare.

The fossil content in backreef complexes varies. In some localities very fossil-rich sediments occur. The fauna reflects a restricted marine environment. Stromatopores, tabulate and rugose corals are rather abundant in places, but built only very small reef mounds. Bryozoans and crinoids are not abundant, but can be observed regularly. The autochthonous brachiopod fauna is impoverished and consists mainly of rhynchonellids (*Microsphaeridiorhynchus*, *Sphaerirhynchia*, *Stegerhynchus*) and small spiriferids (*Howellella*, *Delthyris*). Gastropods and bivalves (e.g., *Ilionia*) are common while trilobites are rare. Ostracods occur in some places in great abundance with predominantly smooth-shelled forms.

The sediments of the backreef facies accumulated in a shallow, light-penetrated environment without strong water movement behind reef complexes. It covered large areas on the carbonate platforms of the Klinteberg and the Hamra/Sundre Beds. Conspicuously, in both series the initially high proportions of oncoids decrease distinctly in the upper parts. There is no explanation for this change.

Plate 4 Facies and C/O-isotopes in transects through the Ludlow of Gotland. Cross sections and thin sections of typical lithologies from different facies complexes

Fig. 1. Crinoidal bafflestone from a faro in the Hamra/Sundre Beds (vertical view). The closely spaced crinoids and their roots have trapped micritic and fine-grained bioclastic material and, thus, are embedded in life position. Holmhällar, Hoburgen peninsula (hammer for scale).

Fig. 2. Solenoporacean bafflestone from a faro in the Hamra/Sundre Beds. This detail shows irregularly branching solenoporacean algae (bright) which have trapped micritic and fine-grained bioclastic material. Holmhällar, Hoburgen peninsula. Thin section, width of the figure 8 cm.

Fig. 3. Crinoidal rudstone from a faro in the Hamra/Sundre Beds. The low degree of sorting and the angular shape of the embedded large components (parts of stromatopores and corals) are typical for debris limestones deposited within reefs. Hammarshagehällar, Hoburgen peninsula. Etched cross section, width of the figure 7.5 cm.

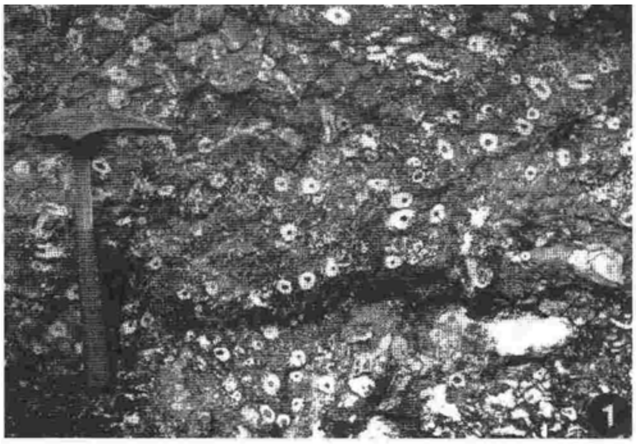
Fig. 4. Pentamerid limestone from a patch reef in the Klinteberg Beds. Specimens of *Conchidium biloculare* are characteristic reef dwellers and form, closely crowded, brachiopod banks in the upper part of the reef. The specimens are thin-shelled and embedded in life position. Lilla Snögrinde quarry, SE of Klintehamn. Etched section parallel to the reef surface, width of the figure 8 cm.

Fig. 5. Brachiopod-crinoidal rudstone from a biostrome in the Hemse Beds. Among brachiopods, *Lissatrypa sulcata* is one of the few reef dwellers on Gotland. The shells are preserved completely indicating that they are embedded in (par)autochthonous position. Kuppen, Östergarn peninsula. Thin section, width of the figure 4 cm.

Fig. 6. Stromatopore-conglomerate with grainstone-matrix from a biostrome in the Hemse Beds. In spite of the short distance from the source area (the reef), the stromatopore bioclasts are well rounded into pebbles indicating the high energy environment typical for biostromes. Kuppen, Östergarn peninsula. Etched cross section, width of the figure 8 cm.

Fig. 7. Bryozoan-crinoidal rudstone from a reef complex in the Klinteberg Beds. The bioclasts are well preserved and not rounded. This little sorted sediment was deposited close to the growing reef under relatively calm conditions. Some components are encrusted by oncolitic algae. (Solution seams in center of section). Old quarry at the Klinteberg. Thin section, width of the figure 4 cm.

Fig. 8. Crinoidal grainstone from a shoal area of the Hemse Beds. This well sorted sediment consists mainly of crinoid debris and peloids. The crossbedded fabric is partially interrupted by stylolites. Gannberg, S of Katthammarsvik. Thin section, width of the figure 4 cm.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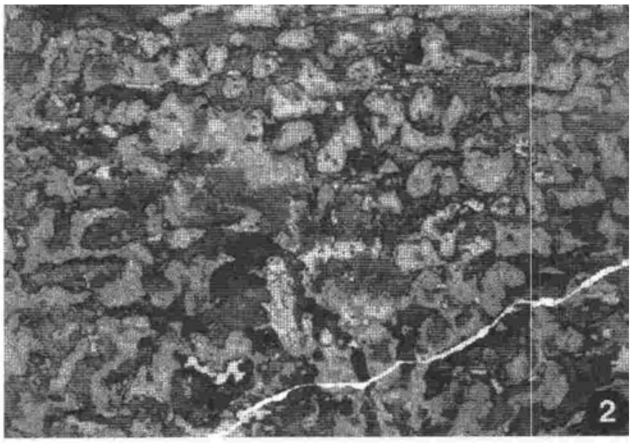
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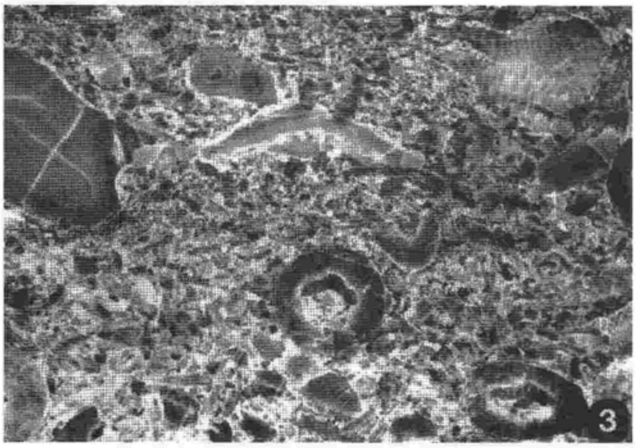
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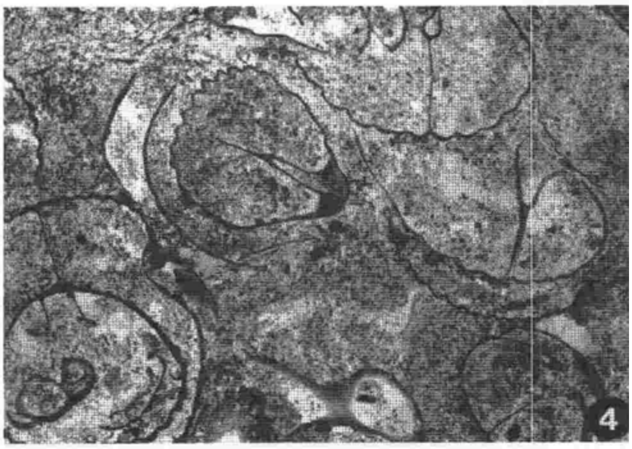
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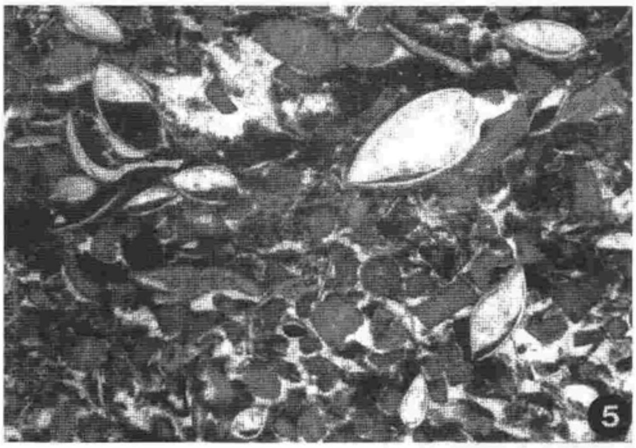
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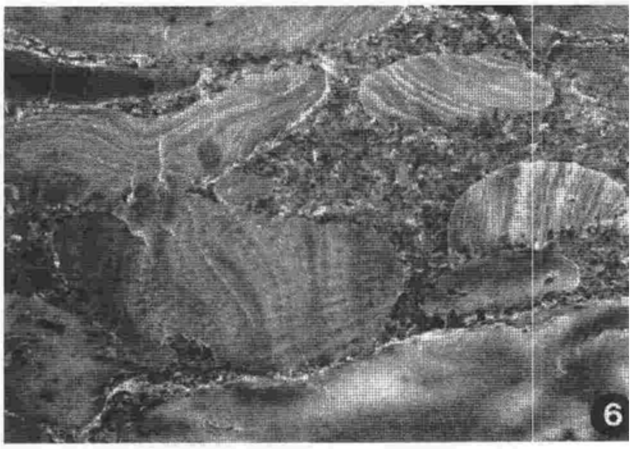
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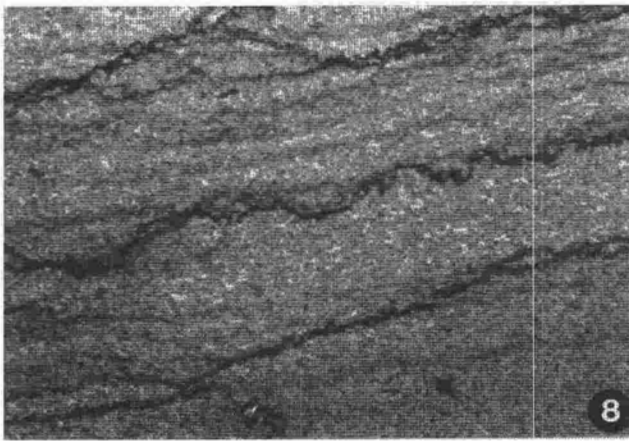
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### 3.1.10 Backreef flats

This facies is a special type within the backreef area of the Klinteberg Beds. It consists of light coloured, fine- to medium-grained grainstones and packstones that are well sorted and thinly bedded. The bedding structures are largely destroyed by vertical burrows and horizontal grazing tracks which produced irregular bedding surfaces full of pits and holes. The components of these sediments are small bioclasts and intraclasts. Oncoids are rare, but many bioclasts possess oncoidal coatings.

The sediments of this facies are fossil-rich and contain a conspicuously diverse gastropod fauna. The likewise significant bivalves consist predominately of alate forms which lived on the sediment surface. Orthoceratids and trilobites are allochthonous and often crushed. The same holds for the low-diversity brachiopod fauna which is similar to those of the adjacent backreef areas. It consists mostly of disarticulated valves, often rounded and/or thinly coated. In addition, small rugose corals, a few tabulate corals, and stromatopores occur, but they did not build reefs or reef buds. In places, accumulations of branched bryozoans and *Coenites* are observed that show only slight breakage indicating minimal transport. They obviously settled on the sea floor during calm intervals.

The backreef-flat facies represents sediments that have been reworked, transported, and redeposited in agitated water. They accumulated at some distance from the sheltering reefs or in shallow water on bank areas.

### 3.1.11 Marginal-marine facies

This facies complex is characterized by rapid alternations of different rock types and fossil contents, often from bed to bed. The lithology ranges from grey, thinly bedded or flaggy mudstones to light-coloured, coarse grainstones which can also be conglomeratic. Predominant components are strongly crushed bioclasts, peloids and fecal pellets. In places, stromatolitic (Pl. 5/8) or biostrome-like formations or small reef mounds occur. Some of the sedimentary structures indicate very shallow water or even emersion. These include desiccation cracks and small oscillation ripple marks which exhibit different direction patterns within short vertical and horizontal distances. Abraded hard grounds and topped stromatopores indicate abrasion.

Corresponding to the lithologies, the fossil content changes frequently and abruptly. Dense accumulations and autochthonous assemblages of brachiopods are often present in high abundance, but they rarely comprise more than three species of a restricted fauna. Predominantly rhynchonellids

Plate 5 Facies and C/O-isotopes in transects through the Ludlow of Gotland. Cross sections and thin sections of typical lithologies from different facies complexes

Fig. 1. *Halysites*-bafflestone from a reef mound in the Slite Beds. Very well preserved debris of reef-dwelling organisms (mainly bryozoans and crinoids) embedded in a micritic matrix between the palisades of the tabulate chain coral *Halysites*. Spillings, W of Slite. Thin section, width of the figure 4 cm.

Fig. 2. Bryozoan-crinoidal floatstone from a reef mound in the Slite Beds. Parts of reef-dwelling organisms (mainly bryozoans, tabulate corals, crinoids, gastropods) embedded in a micritic matrix. Spillings, W of Slite. Thin section, width of the figure 4 cm.

Fig. 3. Oncolitic brachiopod rudstone of the Eke Beds. Shells of the abundant and diverse brachiopod fauna have been coated by algae in a proximal shelf environment. Indistinct stratification of the fine-grained sediment, low degree of sorting of components, and good preservation of non-encrusted shells indicate a parautochthonous accumulation. Näs. Etched cross section, width of the figure 6.5 cm.

Fig. 4. Oncolitic oolite (rudstone with grainstone-matrix) of the Burgsvik Beds. Oolitic limestones were deposited in a shallow water environment above the Burgsvik Sandstone. Bioclasts (mostly debris of molluscs) with oncoidal coatings were embedded in the sediment. Uddvide quarry, S of Grötlingbo. Thin section, width of the figure 3 cm.

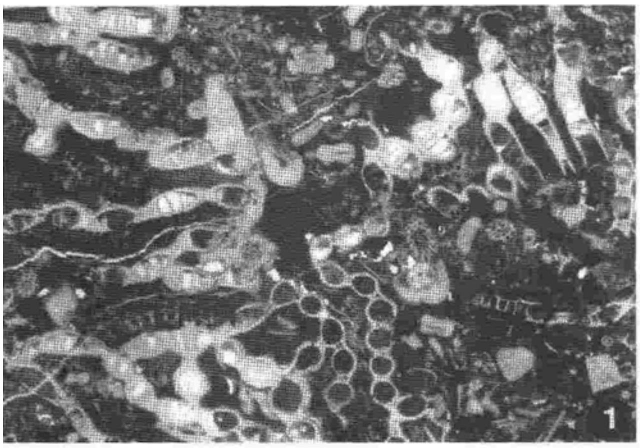
Fig.5. Oncolitic rudstone of the Hamra/Sundre Beds. The oncolitic limestones of the lowermost Hamra/Sundre Beds developed from the oolitic sediments of the topmost Burgsvik Beds (Pl. 5/4) by the gradual increase of algal crusts. The large, encrusted bioclasts are mostly parts of bryozoans. Kettelvik, Hoburgen peninsula. Etched section, width of the figure 8 cm.

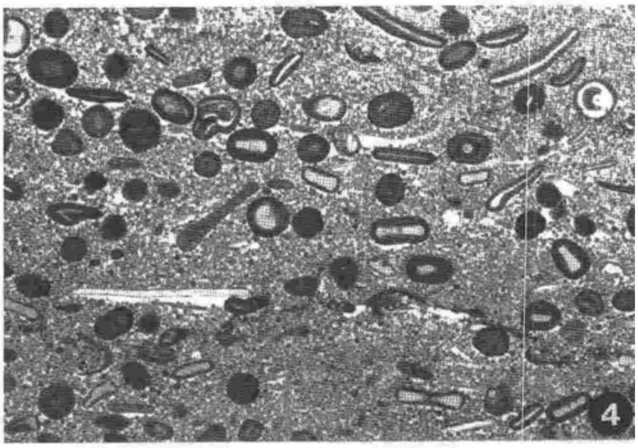
Fig. 6. Dasycladacean floatstone of the Hemse Beds. The intensively bioturbated and pelleted, fine-grained sediment of the marginal-marine environment contains bioclasts of mollusks and ostracods, and dasycladacean algae (recrystallized). The bivalve *Ilionia prisca* (right above), preserved in life position, is a typical inhabitant of this milieu. Grogarnshuvud, Östergarn peninsula. Thin section, width of the figure 4 cm.

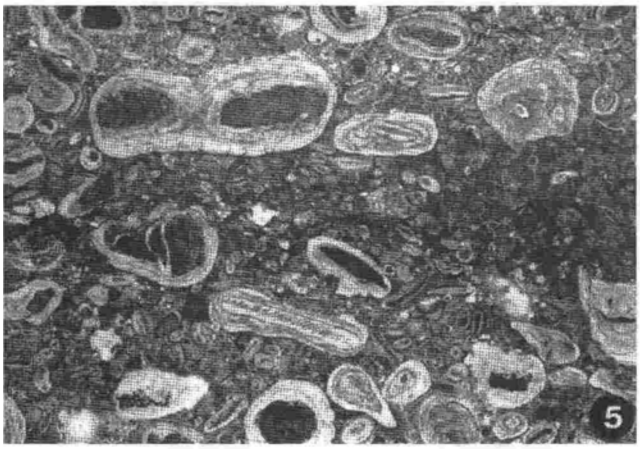
Fig. 7. Bivalve coquina (rudstone) of the Halla Beds. Assemblage of isolated valves, exclusively of *Palaeoneilo* sp., closely packed by water movement in a marginal-marine environment. Some of the valves show thin oncolitic crusts. Gothemhammar. Thin section, width of the figure 5 cm.

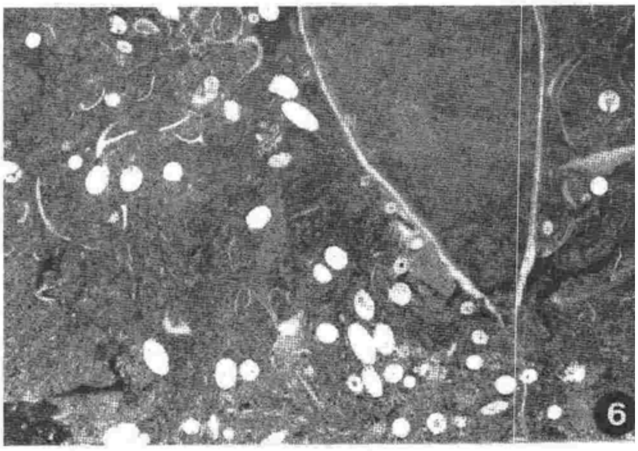
Fig. 8. Stromatolitic bafflestone of the Halla Beds. The finger-like stromatolites developed from large oncolites, wich, probably due to their increasing size and weight, could not be turned round by the water movements of that marginal-marine site. Besides algae, stromatopores and bryozoans joined in the formation of the stromatolites. Gothemhammar. Etched cross section, width of the figure 5 cm.

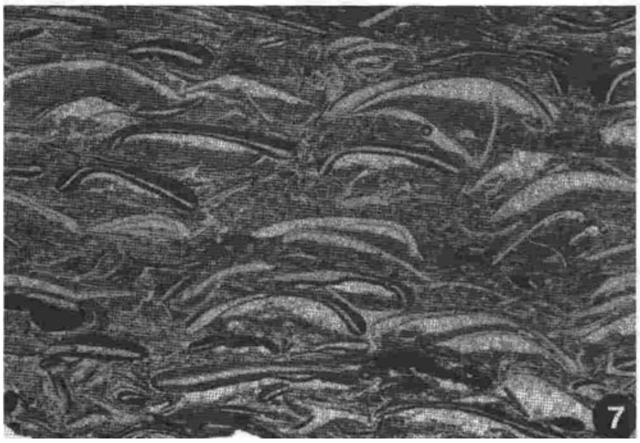
## Plate 5

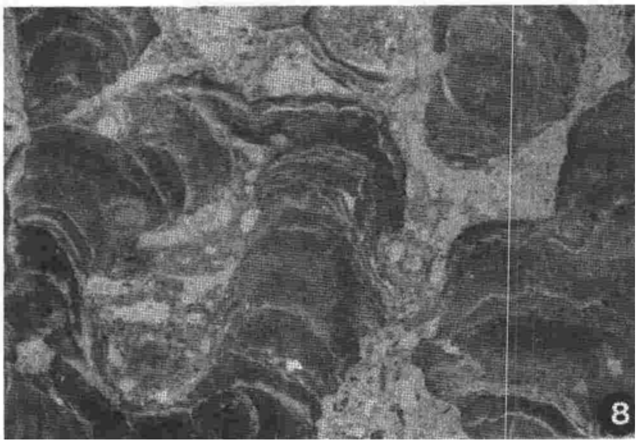












(*Microsphaeridiorhynchus*, *Sphaerirhynchia*, *Stegerhynchus*), small spiriferids (*Howellella*, *Delthyris*) or *Chonetes* (cp. Pl. 3/6) occur. Assemblages of intact branching bryozoans are common. Bivalves occur in coquinas (Pl. 5/7) as well as in dense autochthonous associations in vertical life position (e.g. *Ilionia prisca*, Pl. 5/6). Gastropods with various shapes and sizes can also be abundant. The occurrence of numerous oriented orthoceratids on bedding planes of a strongly bioturbated wackestone sequence in the Hemse Beds on eastern Gotland indicates stranding in an extremely shallow lagoonal environment (SUNDQUIST 1982a). The majority of these specimens are encrusted by stromatopores, bryozoans, or *Aulopora*. Micritic sediments may contain, in addition to abundant ostracodes, broken dasycladacean thalli (Pl. 5/6). Some limestone beds are intensively bioturbated. Others contain *Chondrites*-like burrows or grazing tracks (e.g. *Rhizocorallium*).

In obviously sheltered areas, stromatopores and *Favosites* could thrive, became frequent and reached relatively large sizes, resulting in biostrome-like beds. A unique type of small reef mound has been observed that does not occur in other facies areas. Dense assemblages of round colonies, exclusively of *Favosites* sp., form flat reef pillows with diameters of 1-2 m in thin beds of gray, argillaceous limestones (Pl. 2/4).

Due to the extreme shallow environment the depositional and ecological conditions were unstable and changing. Deviations from normal salinity may have resulted in hypersaline as well as in brackish milieus.

Marginal-marine facies areas are found exclusively in the eastern part of Gotland. Their geographic position is similar to that of the backreef flats (Fig. 2). The large variability in lithology and fossil content of this facies previously described by HEDE (1928, 1929) has been used by LAUFELD (1974a) for the identification and separation of stratigraphic subunits in the Halla Beds (unit c), Klinteberg Beds (unit a), and Hemse Beds (units b, c in parts). But these subunits cannot be traced very far to the SW because they interfinger with sediments of the backreef facies or are covered by biostromes. Lithologies and geographic situation of the marginal-marine facies do not indicate proximity to a coast, but suggest remoteness and seclusion from the open marine environment.

### 3.1.12 Shallow-marine sandstones

In contrast to the facies complexes described above, sandstones are more dependent on geological processes in the source area of the terrigenous material than on oceanographic conditions in the deposition area.

Sandstones occur on Gotland in the upper Wenlock (Slite Siltstone) and the upper Ludlow (Burgsvik Sandstone). They are light grey, silty to fine-grained, well sorted sandstones with a calcitic matrix. They form thin, flaggy to very thick (> 1 m) beds with different types of stratification. Besides horizontal parallel lamination they show small-scale cross-bedding, often associated with parting lineation and/or small ripple marks on the bedding planes, and medium to large festoon cross-bedding in channel cuttings. In thickly bedded sandstones of the Burgsvik Beds load casting is observed which has intensively deformed the lower bedding planes. Channel cuttings, erosional disconformities, and slumping structures interrupt the stratification. Consequently, sediment beds with accumulations of intraclasts are common. Besides vertical burrows, various kinds of traces, grazing tracks, and imprints of resting animals (e.g., *Palaeasterina*, *Cruziana*, Burgsvik Sandstone) are observed on bedding planes, and document the activities of a vagile benthic fauna in this environment (Pl. 3/5).

The fossil content is variable but generally scarce. Allochthonous assemblages are predominant containing well preserved complete shells and isolated valves which indicate short transports. But locally, bioclasts are abundant, resulting in grainstone-like biodetritic quartz sandstones. Brachiopod assemblages have low diversities and are composed of species of restricted-marine character. Drifted orthoceratids and parts of trilobites (*Homalonotus*, Burgsvik Sandstone) are observed in places. Occasionally, alate bivalves (*Pteronitella*) have accumulated as shell lags.

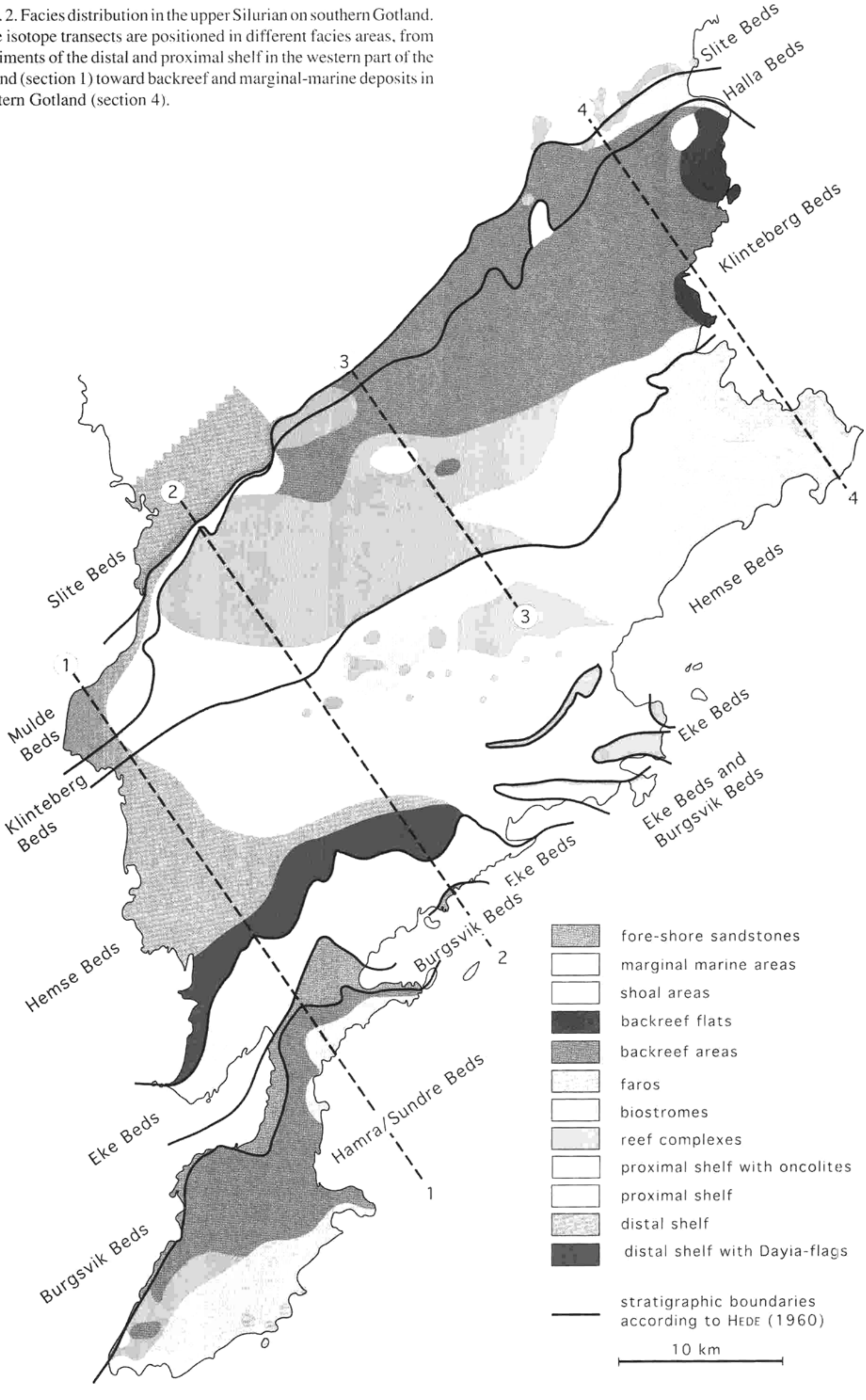
The sandstone beds are commonly separated by layers of dark grey, laminated argillaceous clay, sometimes resulting in sandstone-marl alternations in which graptolites may occur (Slite Siltstone).

Stratification structures of the two sandstone sequences, signs of erosion and reworking, and the association of trails and burrows indicate sedimentation in shallow subtidal milieus. Only the lower part of the Slite Siltstone was deposited at greater water depth. Marly clays and silty wackestones accumulated below wave base. Storm events transported coarser material into the basin and deposited crossbedded, finegrained sandstones. Decreasing water depths resulted in a gradual increase of sandstones with shallow-water characteristics.

## 3.2 Isotope stratigraphy

Generally, the reconstructed $\delta^{18}O$ and $\delta^{13}C$ curves exhibit subparallel courses (Fig. 3A) with a few exceptions that may even show antiparallel courses. On a broad time scale (cp. Fig. 6) the curve of the $\delta^{13}C$ values shows a typical saw-tooth appearance. A rapid increase of the values is followed by gradual decrease. Although the beginning of an A-period (see Previous research) might be seen at the first slight rise of the $\delta^{13}C$ values, the boundary was defined uniformly at +0.5‰ according to the isotope pattern in the upper Silurian (Homerian - Ludfordian) on Gotland. This definition offers the opportunity to determine boundaries even in those transects that contain only a few data points, and to subdivide the gradual decrease of isotope values commonly observed in the transition from A- to H-periods. The subdivision, especially the limiting value at +0.5‰, is purely pragmatic. In other time periods it could be defined at other values as not the absolute value is decisive but the course of the isotope curve. For example, the distinct H-period in the upper Llandovery (Lower Visby Beds) on Gotland shows $\delta^{13}C$ values of about +2‰ which in the Ludlow would be charac-

Fig. 2. Facies distribution in the upper Silurian on southern Gotland. The isotope transects are positioned in different facies areas, from sediments of the distal and proximal shelf in the western part of the island (section 1) toward backreef and marginal-marine deposits in eastern Gotland (section 4).



teristic for an A-period. The transition to the subsequent A-period in the lower Wenlock (Upper Visby Beds) is marked by a rapid increase of about 3‰ (SAMTLEBEN et al. 1996).

The boundaries between A- and H-periods (Fig. 3A) defined by the $\delta^{13}C$ values can be seen as isochrones. Due to the unfolded nature and the rather uniform dip of the strata, these boundaries can be figured in a map (Fig. 4). The result is in partial agreement with the stratigraphic boundaries of HEDE (1942, 1960). Some significant differences, however, do occur. In the lower part of the sequence, at the base of the Halla and Mulde Beds, the boundaries show a good correspondence. The upper Mulde Beds are correlated with the lower Klinteberg Beds. The boundary between the Klinteberg Beds and the Hemse Beds which is based on facies changes is strongly diachronous and inconsistent with the isotope period boundaries (Fig. 4). This results from the fact that the relatively continuous shelf sedimentation in the western part of Gotland changed into thicker but discontinuously accumulated deposits on the eastern side. This holds also for the upper Gorstian A-period (Fig. 3, 4) which is represented as a few metres of limestones and marls on W-Gotland, but is developed by rather thick and extended reef complexes and biostromes on E-Gotland. In the upper Ludlow, in the Eke and Hamra/Sundre Beds, the topostratigraphic boundaries of HEDE and the isotope-stage boundaries are again parallel to each other.

## 3.3 Facies development and palaeontological events during the isotope periods in the upper Silurian on Gotland

(Tab. 1; Figs. 2 - 5)

### 3.3.1 Lower Homerian H-period

The investigated sequence of strata begins in the upper Wenlock (lower Homerian), in the upper part of the Slite Beds. In a proximal shelf area, south of an ancient carbonate platform that existed since the lower Wenlock fossil-rich wackestones and packstones accumulated. These sediments grade to the SW into micritic limestone-marl alternations of a distal shelf area. Facies and conodont fauna correspond to the Allekvia Primo Episode (JEPPSSON et al. 1995). The negative $\delta^{13}C$ values indicate a marked H-period (lower Homerian H-period). At the top of this sequence, in the eastern part of Gotland, isolated reefs began to grow. Brachiopods in these reefs reveal slightly elevated C-isotope values, but still within the range typical for H-periods (e.g. Simunde 1: $\delta^{13}C = +0.1$‰).

At the west coast of Gotland, the distal shelf sediments of the uppermost Slite Beds show negative $\delta^{13}C$ values and, therefore, are also placed in the lower Homerian H-period. They are overlain by condensed argillaceous or silty clays of the hemipelagic Svarvare Beds (CALNER 1999a) which contain locally abundant graptolites. As conodonts, graptolites and chitinozoans show strong reductions of species numbers already at the base of the Svarvare Beds, JEPPSSON (1998) placed here the beginning (datum 1) of the Mulde Secundo-Secundo Event which marks the change from the Hellvi S-Episode to the succeeding Klinte S-Episode (Tab. 1).

Sediment sequences, fossil occurrences, and isotope values of the lower Homerian in the western part of Gotland do not fit with those of the eastern part. On the western side, the $\delta^{13}C$ values are inconsistent with the identification of the Hellvi S-Episode (JEPPSSON 1998). A continuation of the Allekvia P-Episode into the lower part of the Svarvare Beds corresponds to the facies development and is more consistent with the isotope data.

### 3.3.2 Upper Homerian A-period

The small reefs of the lower Homerian H-period in eastern Gotland were covered by light-coloured limestones of a shoal facies which are characterized by high C-isotope values (e.g. *Atrypa reticularis*-Beds at Uppgarde 1: $\delta^{13}C = +2.3$‰) and demonstrate the shift into the upper Homerian A-period. This isotope period corresponds to the Hellvi S-Episode of JEPPSSON et al. (1995) which shows only a relatively slight faunal change compared with the preceding P-Episode. The sedimentation terminated in this region with a sea-level fall (- 16 m), leading to emersion of the reefs and partial erosion of the *Atrypa reticularis*-Beds (CALNER & JEPPSON 1999). The discontinuity surface is overlain by the shallow marine Bara Oolite, a shoal sediment at the base of the Halla Beds (CALNER & SÄLL 1999).

In western Gotland, the Svarvare Beds (see above) are overlain by the Slite Siltstone (Gannarve Member, CALNER 1999b) which, according to grain sizes and sedimentary structures, indicates a gradual shallowing upward. It yields strongly increasing C-isotope values (e.g. Klinteentklaven 4: $\delta^{13}C = +1.4$‰, Klinteentklaven 2: $\delta^{13}C = +3.2$‰) and was deposited at the beginning of the upper Homerian A-period. In the central part of the island the Slite Silstone is topped by a discontinuity surface (near Klintebys) which corresponds to that on top of the *Atrypa reticularis*-Beds in the east. The Bara Oolite is also found above a discontinuity here (HEDE 1927a).

At the west coast the Slite Siltstone changes rapidly into the Mulde Beds which are developed as proximal and distal shelf sediments. No gap or discontinuity is observed between the two series. At this boundary a strong extinction event occurred that notably affected the graptolites (JAEGER 1991). Most species disappeared from the sediment sequences world-wide. This event coincides with the top of the *Cyrtograptus lundgreni* Zone and represents datum 2 of the Mulde Event (JEPPSSON et al. 1998) which, besides the Svarvare Beds and Slite Siltstone, also comprises the lower part of the Mulde Beds.

In the central part of Gotland, reefs of the Halla Beds are developed above the Bara Oolite. Their high C-isotope values (e.g., Väte 1: $\delta^{13}C = +3.4$‰) indicate a continuation of the upper Homerian A-period. To the east, they border a backreef facies which grades into a marginal-marine environment with low-diversity assemblages of brachiopods (Pl. 3/6) and bivalves and, in the upper part, conspicuous oncoidal and stromatolitic formations (e.g., Gothemhammar, Pl. 5/8). The top of the Halla Beds formed as an abraded hard ground is overlain by marginal-marine sediments of the Klinteberg Beds.

The Mulde Beds in the western part of Gotland are

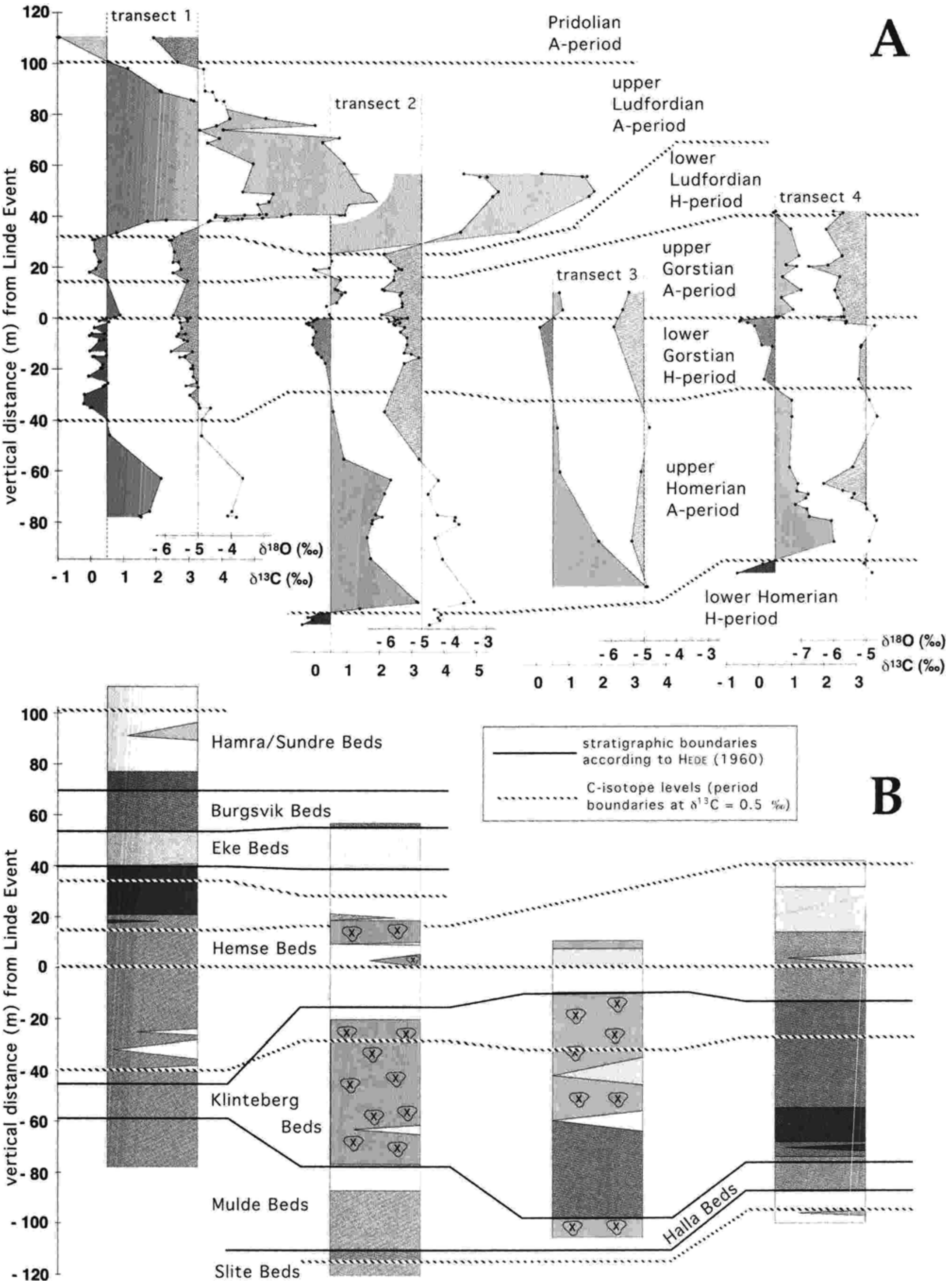


Fig. 3A. Developments of C- and O-isotope values in transects 1 - 4; stratigraphic correlation by means of C-isotope values (green = H-periods, red = A-periods). 3B: Schematic presentation of facies formation in the sample localities on transects 1 - 4. Explanation of the colours see Fig. 2.

assigned to the *Gothograptus nassa* Zone. They yield $\delta^{13}C$ values (1.5-1.8‰) which correspond to the upper Homerian A-period. The Mulde Beds contain an impoverished, monotonous conodont fauna. In contrast, the brachiopod associations comprise a wide variety of species in the proximal shelf facies (e.g., Haugklintar 1, Däpps 2) as well as in the distal shelf area (e.g., Blåhäll 1, Mulde Tegelbruk 1, Djupvik 1). The regular limestone-marl alternation of the distal shelf facies in the middle part of the Mulde Beds (Pl. 2/1) passes to the northeast into sediments of a proximal shelf area with increasing intercalations of bioclastic packstones and grainstones. In this facies, crinoidal reef mounds grew in a calm water environment (Hunninge 1, Pl. 1/2) and gradually gave way to the small patch reefs, surrounded by shoal sediments, of the Klinteberg Beds (FRYKMAN 1989). Although these reefs were elevated only a few metres above the surrounding sea floor they formed a sheltering barrier for an extended area to the northeast. Here, under calm conditions, a uniform oncoidal backreef facies with a restricted-marine fauna developed. In contrast, at the east coast of Gotland, in areas with very low water depths, the sediments have been frequently reworked.

In the southwest, a wide proximal shelf area was attached to the reef complex of the Klinteberg Beds which passes into sediments of a distal shelf. The transition from reef facies to proximal shelf, although exhibiting only minor differences in altitudes (≤ 10 m), occurred in most cases within short distances. In contrast to that, the facies areas of the proximal and the distal shelves were intensively interfingering and show very gradual transitions.

By means of corresponding C-isotope values, localities in different facies areas that formerly have been assigned to different stratigraphic units, now can be correlated. For example, the locality Sudervik 2 in the distal shelf area that has previously been assigned to the Mulde Beds (HEDE 1927b) can be correlated with the reef and reef debris of the locality Klinteberg 1. Both localities have $\delta^{13}C$ values of +2.1‰ and exhibit the rise of the C-isotope values in the lower Klinteberg Beds (*Pristiograptus ludensis* Zone). The reefs of the Klinteberg complex yielded relatively high $\delta^{18}O$ values which points to an increased salinity within this part of the carbonate platform (SAMTLEBEN et al. 1996). The lower Klinteberg Beds correspond to the Klinte Secundo Episode (JEPPSSON et al. 1995).

### 3.3.3 Lower Gorstian H-period

Despite the relatively few and isolated sample localities it is obvious that the C-isotope values decreased in the upper Klinteberg Beds. In the western part of Gotland, the O isotopes also show a decline during this time, pointing to a gradual change of the oceanographic conditions. In the backreef and shallow water areas in the eastern part of the island the O isotopes show varying values, presumably because local factors strongly influenced temperature, evaporation and salinity. Near the Wenlock/Ludlow boundary which cannot be determined biostratigraphically on Gotland a C-isotope value of +0.5‰ marks the beginning of the lower Gorstian H-period. This corresponds largely with the Sproge Primo Episode (JEPPSSON 1998). Its lower part comprises the *Neodiversograptus nilssoni* Zone of the lower Ludlow and contains, especially in the shelf-facies area of SW Gotland, typical conodont associations with *Erika divaricata* and later *Kockelella stauros* (JEPPSSON 1998). The gradual decrease of $\delta^{13}C$ values, presumably correlated with changes to a more humid climate and antiestuarine circulation, initially was not connected with an alteration of facies distribution on Gotland. Although the entire reef complex began to retreat to the east, extensive biostromes developed in the eastern part of the island, covering reef complexes and backreef deposits. Presumably, the origin of these biostromes resulted from the growth of the carbonate platform to the sea surface. Since upward growth was no longer possible, the persisting production of carbonate material in the biostromes resulted in an expansion of the carbonate platform to the southeast.

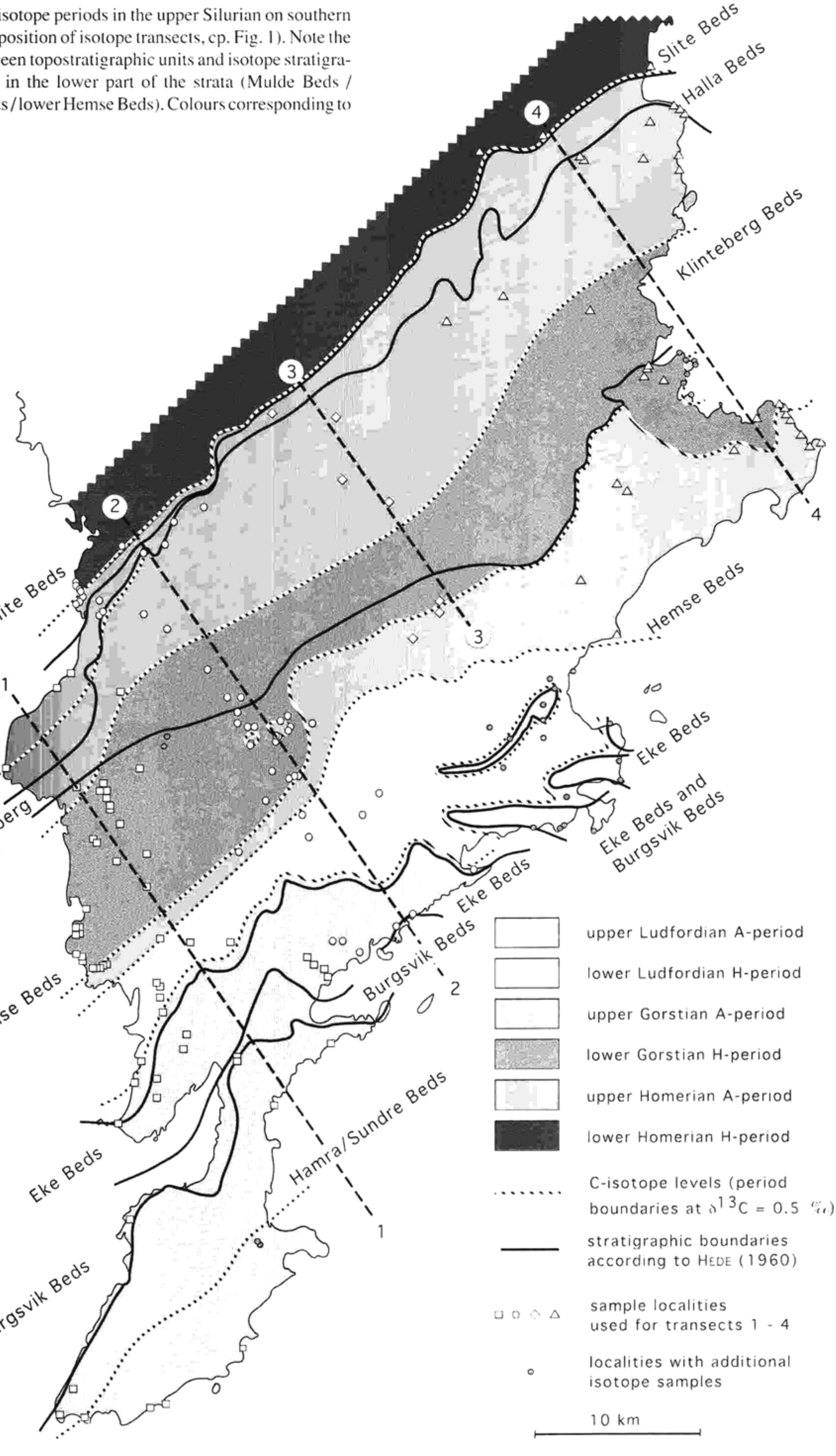
In the southwestern area of Gotland, the distal shelf facies persisted. The sedimentary sequence which is mapped as Hemse Beds (HEDE 1927b) is assigned to the *Lobograptus scanicus* Zone and contains conodont associations with *Ozarkodina excavata* n. ssp. S in the lower, and *O. excavata* n. ssp. A in the upper parts (JEPPSSON et al. 1994). The C-isotope values are variable but consistently low and partly negative (-0.2 ‰ to +0.4‰) corresponding to the lower Gorstian H-period. In addition, low $\delta^{18}O$ values are observed which are likewise typical for H-periods.

In the upper part of the Sproge Primo Episode the oceanographic conditions of the H-period prevailed, and sediments of a proximal shelf facies covered the reef formations of the Klinteberg Beds to the northeast. The strata of this facies contain *O. excavata* n. ssp. A in a diverse open-marine fauna and extend to 6 km NE of Etelhem (e.g., Sigvalde 3: $\delta^{13}C = +0.1‰$). On the east coast of Gotland, various sediments of a marginal-marine facies were deposited. They contain a low-diversity fauna and show characteristics of deposition in very shallow water. These sediments yield the same low C-isotope values (Skarnvik 3: $\delta^{13}C = +0.1‰$ - Grogarnshuvud 3: $\delta^{13}C = -0.5‰$) as the proximal shelf facies in the west and are therefore regarded as being of similar age. There is no lateral connection exposed between these two facies areas. They are separated by the progradation of the Klinteberg Beds to the southeast (Figs. 2, 5) which probably formed a rocky shore during deposition of the lower Hemse Beds (*N. nilssoni* /*L. scanicus* Zone) (HEDE 1929).

### 3.3.4 Upper Gorstian A-period

In the uppermost part of the *scanicus* Zone, reefs developed in the central part of Gotland surrounded by reef debris and shoal sediments. These grade to the northeast into extended stromatopore biostromes. They correlate with an increase in $\delta^{13}C$ of up to 1‰ and show the rapid reaction of facies to a shift of the oceanographic circulation and the change of the climate to more arid conditions at the onset of the relatively insignificant upper Gorstian A-period. As in

Fig. 4. Map of isotope periods in the upper Silurian on southern Gotland (1 - 4: position of isotope transects, cp. Fig. 1). Note the mismatch between topostratigraphic units and isotope stratigraphy especially in the lower part of the strata (Mulde Beds / Klinteberg Beds / lower Hemse Beds). Colours corresponding to Fig. 3A.



the uppermost Slite Beds (see above), isolated reefs began to grow distinctly below $\delta^{13}C$ values of +0.5‰ (e.g., Sandarve 2b: $\delta^{13}C$ = -0.1‰). The increase of the $\delta^{13}C$ values corresponds to the Linde Event which marks the beginning of the Etelhem Secundo Episode with sediments containing conodont associations with *Ancoradella ploeckensis* (Jeppsson 1998). In the shelf area of southwestern Gotland the upper Gorstian A-period can only be identified by means of isotope analyses. For example, wackestones of a proximal shelf facies near Hemse (Havor 2: $\delta^{13}C$ = +0.7‰) and limestone-marl alternations of the distal shelf at the west coast (e.g., Krokvät 1: $\delta^{13}C$ = +0.9‰) can be assigned to this period. The outcrop width of these sediments of about 1 km corresponds to a thickness of little more than 5 m which strongly differs from the about 15 m thick reef complexes in central Gotland.

At the east coast of Gotland, extensive biostromes developed that grew in very shallow water. On the peninsula Östergarn, the increase of C-isotope values at the beginning of the upper Gorstian A-period is observed within sediments of the marginal-marine facies (e.g., Grogarnshuvud 3: $\delta^{13}C$ = -0.5‰, Grogarnshuvud 4: $\delta^{13}C$ = +0.6‰). After the isotope values reached relatively high levels indicating the shift of the oceanographic circulation, the facies changed to stromatopore marls and then to a biostrome (e.g., Grogarns 4: $\delta^{13}C$ = +1.1‰).

To the southwest, in the interior of the island, stromatopore biostromes of this period rest on biostromal formations of the Klinteberg Beds. Both are separated by an uneven discontinuity surface that corresponds to a stratigraphic gap in the *L. scanicus* Zone and presumably represents a rocky shore during that time interval (Hede 1929; see p. 22). Conspicuously, the O-isotope values in the reefs of the upper Gorstian A-period remained at a rather low level and did not increase as in the other A-periods. In the biostromes on the east coast of Gotland the $\delta^{18}O$ values even show a distinct decline compared to the sediments of the lower Gorstian H-period below.

### 3.3.5 Lower Ludfordian H-period

The succeeding lower Ludfordian H-period corresponds to the Havdhem Primo Episode which is assigned biostratigraphically to the *Saetograptus leintwardinensis* Zone, and by means of conodonts to the *Polygnathoides siluricus* Zone (Jeppsson 1998). During this period, the growth of reefs stopped and sediments of the shelf facies advanced to the east. Isolated, higher elevated reefs on the south side of the carbonate platform persisted for some time during this H-period and were surrounded by sediments of the proximal shelf facies. Following Hede (1927b), these sediments are called "Hemse Marl SE" (Laufeld 1974a). They are characterized by highly diverse fossil associations with brachiopods, conodonts, ostracods, and vertebrates.

During this time, in western Gotland sediments of the distal shelf propagated to the east and changed slowly into the *Dayia*-flag facies. This facies differs from the distal shelf facies by its high amount (about 50%) of silt grains of quartz and dolomite The brachiopod assemblages consist mainly of the small species *Dayia navicula*. Facies and fossil content of the *Dayia*-flags indicate extreme conditions for the benthos community, far from a normal environment of an H-period. The large amount of probably wind-driven terrigenous material indicates a climatic shift accompanied by a change in the wind system.

### 3.3.6 Upper Ludfordian A-period

In the upper 10 m of the *Dayia*-flags the C-isotope values begin to increase towards the upper Ludfordian A-period (e.g., Vaktård 6: $\delta^{13}C$ = +0.1‰, Klasård 1: $\delta^{13}C$ = +0.8‰) accompanied by a change in facies. The upper part of this transition has been studied in detail in the southwest of Gotland (Boddud 1). Intercalated in the *Dayia*-flags are grey argillaceous limestones with an increasingly diverse brachiopod fauna. They show rapidly increasing $\delta^{13}C$ values, from +2.3‰ to +5.8‰ in the uppermost 1.7 m. The boundary to the overlying Eke Beds is marked by the first occurrence of oncolites. Here, the $\delta^{13}C$ values are around +6.0‰.

While in the SW of Gotland this rapid but continuous increase of the $\delta^{13}C$ values is observed, a hiatus exists in the eastern part of the island, related to an abrasion surface (Cherns 1983). The hiatus can be identified by intervals between the C-isotope values (e.g., Nyan 2: $\delta^{13}C$ = +0.6 -> +4.6‰; Gannor 2 - 4: $\delta^{13}C$ = +0.6 -> +5.6‰). At the locality Nyan 2 a karstic surface occurs above the hiatus indicating a period of subaerial exposition (Cherns 1982).

The increase of the $\delta^{13}C$ values corresponds to the Lau P-S Event (Jeppsson 1993). This interval marks the top of the *P. siluricus* Zone and comprises a sequence of five extinction events in conodonts, graptolites, chitinozoans, and fishes. The earliest extinction event occurred within the *Dayia*-flags and coincides with the initial increase of $\delta^{13}C$ values. The second event, located within the upper few metres of the *Dayia*-flags in the western and within the hiatus in the eastern part of Gotland, is associated with the disappearence of *P. siluricus*. The third to fifth events occur within the Eke Beds which Jeppsson (1998) attributes completely to the Lau Event.

In southwestern and central Gotland, the Eke Beds consist of a proximal shelf facies exhibiting an impoverished conodont fauna, but a rather diverse brachiopod fauna. In this aspect, the Eke Beds are similar to the proximal shelf facies of the Mulde Beds (see above). However, it is remarkable that, with the exception of *Gypidula galeata*, the pentamerids disappear at this event. Therefore, the Lau Event probably corresponds to the Pentamerid Event of Talent et al. (1993). It is not clear, however, to which of the five datums it coincides, since the precedingly deposited upper Hemse Beds exhibit an ecologically restricted brachiopod fauna.

The Eke Beds contain a high amount of homogeneously distributed oncoids with small rugose corals, orthoceratids, and brachiopods of the local fauna as nuclei. The oncoids were formed in a light-penetrated and calm shallow-water environment. This was different from the other shelf areas in

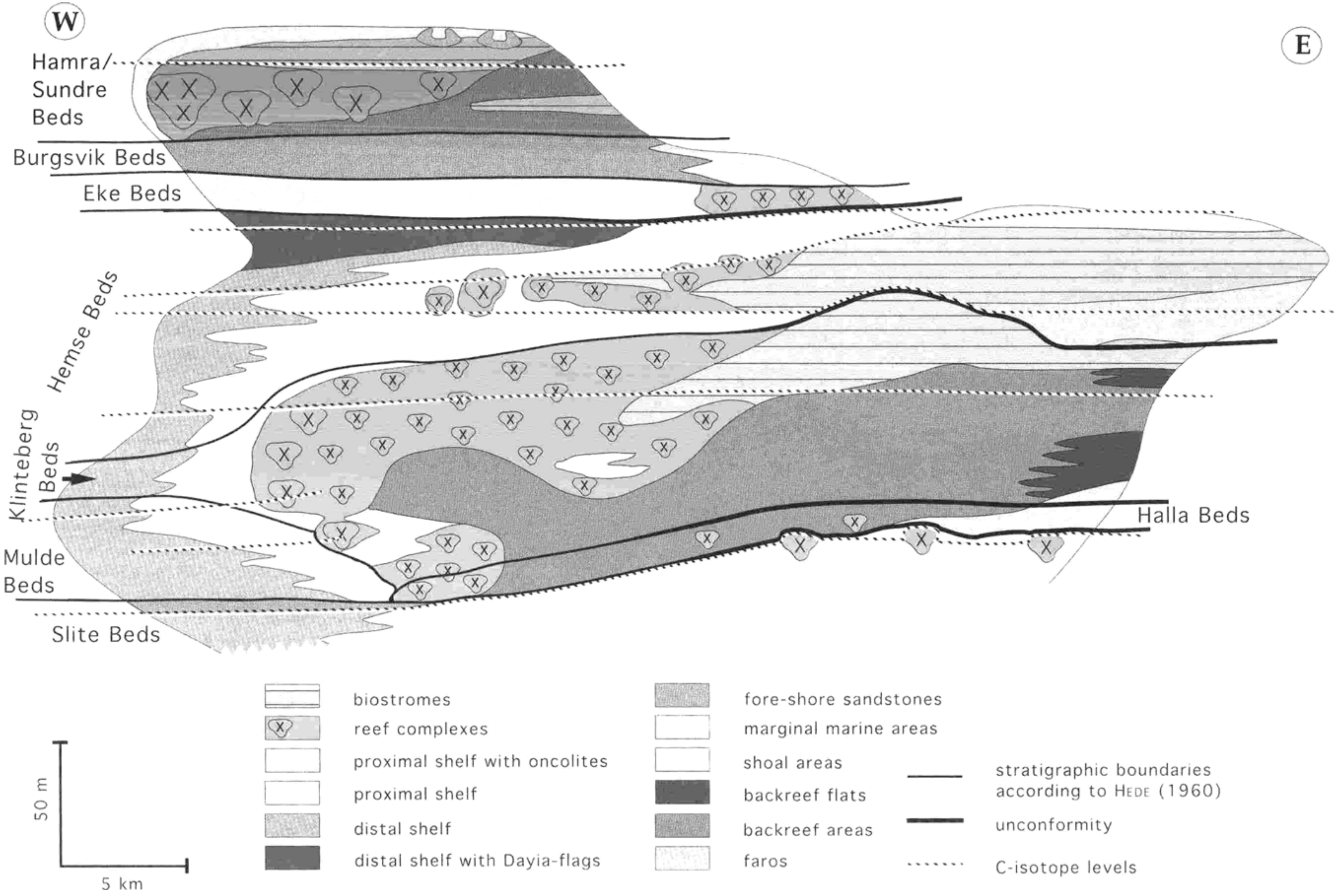


Fig. 5. Schematic section through the upper Silurian strata on southern Gotland (height : width = 100 : 1). It is important to note that the vertical order of this scheme is somewhat artificial due to the unfolded nature of the nearly horizontally lying strata. Often, younger strata are found some kilometres in SE direction (cp. Fig. 2) and not directly above the "underlying" deposits. This migration represents the ongoing filling of the Baltic Basin.

the Silurian of Gotland indicated by the scarcity of sessil colonizing organisms like stromatopores and tabulate corals. The $\delta^{13}C$ values in brachiopods of the Eke Beds are the highest in the Silurian of Gotland (e.g., Petsarve 8: $\delta^{13}C$ = +8.8‰, Kullunde 6: $\delta^{13}C$ = +8.6‰). The $\delta^{18}O$ values are also high (Petsarve 2, Kullunde 6: $\delta^{18}O$ = -2.7‰) similar to those of the upper Homerian A-period within the Klinteberg Beds.

To the east, the argillaceous, oncoid-bearing sediments of the proximal shelf facies grade into a reef area, consisting of brachiopod-rich reef mounds surrounded by bioclastic limestones and marls. The overlying Burgsvik Sandstone was deposited as a foreshore sediment in a tidal to shallow subtidal environment. The sandstone indicates a period of sea-level lowstand as well as a strong input of quartz sands. At the east coast of Gotland, the sandstone is replaced by limestones of a shoal facies. The normal marine brachiopod fauna, found only at a few localities of the Burgsvik Sandstone, exhibits very high $\delta^{13}C$ and $\delta^{18}O$ values (e.g., Kulhaken 2: $\delta^{13}C$ = +7.7‰ and $\delta^{18}O$ = -3.3‰). This indicates that the oceanographic circulation and the arid climatic conditions of this extreme A-period continued during the deposition of the Burgsvik Beds. At the top of the Burgsvik Sandstone, oolites were deposited which in the lower part have quartz grains, in the upper part calcareous shell fragments as nuclei for the ooids (Pl. 5/4). These oolites pass over into the oncolitic limestones of the Hamra/Sundre Beds which are overlain by bioclastic limestones and rather large patch reefs. This carbonate sequence was deposited during a period of increasing water depth. It borders to the SW with a limestone-marl sequences of a proximal shelf, and to the NE and E with extended back-reef areas with intercalated biostromes. Increasing water depth initiated the formation of faros on top of the biostromes. Frequent discontinuity surfaces and erosion marks indicate a growth of these reefs close to the seasurface. Concentric and radial fissures that were repeatedly opened and refilled indicate the increasing instability of these small atoll-like reefs due to their rapid vertical growth. The shelf facies sediments of the uppermost Hamra/Sundre Beds at the southern coast of Gotland document the termination of reef growth.

Jeppsson (1998) includes both, the Burgsvik Sandstone as well as the Hamra/Sundre Beds within the "Hoburgen Secundo Episode".

### 3.3.7 Pridolian H-period

The $\delta^{13}C$ values decrease gradually for the duration of reef growth. The low values in the shelf sediments on the south coast of Gotland (Klehammarsård 3: $\delta^{13}C$ = +0.5‰) indicate the boundary to the subsequent Pridolian H-period. At the seafloor south of Gotland limestones and limestone-marl sequences ("Beyrichienkalke") containing a typical Pridolian ostracod fauna crop out (Martinsson 1965, 1967). Low $\delta^{13}C$ values in brachiopods from ice-transported boulders of these beds in the Pleistocene of NW Germany (e.g. Schulau: $\delta^{13}C$ = -0.9‰) indicate that they were deposited under H-period conditions.

## 3.4 Generalized development of facies and sequence of events in the Silurian of Gotland

The facies in the Silurian of Gotland react in different ways to climatic changes (H/A-periods) as indicated by isotopes:

The distal shelf exhibits no differences in facies, although, it was widespread during H-periods and more restricted during A-periods. The proximal shelf reacted rapidly to oceanographic and consequent ecological changes. Increased colonization by sessil benthos during A-periods caused a high carbonate production and a rapid expansion of the shelf facies.

The formation of reefs was primarily connected to A-periods during which low influxes of terrigenous material created optimal conditions for the growth of reef-building organisms. The initial growth of reefs started at the very beginning of these periods, when the isotope values were just starting to rise. Isolated reefs developed in proximal shelf areas. They were surrounded by bioclastic and micritic, argillaceous sediments. A direct relationship between the initiation of reef growth and a rapid decrease in suspended terrigenous material, however, cannot be assumed.

The reef complexes generally survived transitions from A-periods to H-periods as long as the reef surfaces were spared from covering by terrigenous fine material owing to their exposure to water movement. Therefore, these complexes reacted with resistance to the unfavourable conditions of an H-period.

Biostromes developed due to the lateral growth of patch reefs. In most cases, these biostromes mark a special facies in the later stage of an A-period. They could also develop in shallow environments at the beginning of A-periods. In periods with increased input of terrigenous material (H-periods), the growth of biostromes near the water surface on carbonate platforms could continue as long as sedimentation did not cover and kill the reef-building colonies.

Due to the obviously calm conditions in the Silurian of Gotland, low reef heights were sufficient for the protection of backreef areas which expanded rapidly during A-periods. Like the patch reef complexes, the backreef areas could exist well into an H-period as long as they were exempted from the deposition of terrigenous material. Conspicuously, the early parts of A-periods are characterized by strong and widespread occurrences of oncoids, especially in the backreef facies. The formation of oncoids later decreased, and finally ceased at the transition to the subsequent H-period.

The marginal-marine facies was largely immune to the effects of oceanographic changes between A-periods and H-periods. Due to its characteristics related to local hydrographic, sedimentological and ecological conditions, even global environmental alterations are reflected in local patterns and remained without significance.

The stratigraphic sequence of the Silurian on Gotland is characterized by strong differences of the geological record in different facies areas. Whereas the distal shelf sediments, in a geological sense, were deposited rather continuously, carbonate platforms and shallow-water deposits accumulated episodically, each within rather short periods and interrupted by large hiatuses.

Although the relationships of isotope changes, palaeontological events and facies shifts vary between the four transects, a generalized succession of H/A-period transitions can be reconstructed. This is in accordance with the sequences of the middle Homerian (Mulde Event), the middle Gorstian (Linde Event), and the middle Ludfordian (Lau Event):

- Early extinction events, especially of conodonts, clearly precede any isotope or facies changes related to the H/A transition.
- Parallel to an initial slight increase in $\delta^{13}C$ and $\delta^{18}O$ values, facies began to change, and reef mounds as well as small patch reefs developed on suitable locations.
- A rapid increase in C- and O-isotope values occurred parallel to strong facies changes associated with a short-term drop of sealevel (ca. 10-20 m). In shallow-water areas in the eastern part of Gotland emersions and hiatuses occurred.
- Further extinction events affected conodonts, graptolites, acritarchs, chitinozoans, and vertebrates. The sessile benthos was less influenced.
- The again rising sealevel and the oceanographic-climatic conditions, especially the decrease in terrigenous input due to arid conditions, led to strong reef growth and to expansion of the carbonate platforms. Back reef and proximal shelf areas also became more extensive.
- In the final stage of this sequence the isotope values reached their peaks and began to decrease.

Changes related to A/H-period transitions obviously lasted for longer intervals and were more gradual:

- The slowly decreasing $\delta^{13}C$ values presumably were connected with changes in oceanographic and ecologic conditions as diminishing circulation, more humid climate, and stronger terrigenous input, but these were not directly associated with changes in facies formation. Reef growth continued, and patch reefs extended laterally forming biostromes.
- The $\delta^{18}O$ values exhibit irregular records in reef and restricted shallow water environments due to various local influences. On the contrary, in distal shelf areas the $\delta^{18}O$ values decreased steadily.
- Reef growth diminished gradually and, due to regional subsidence, the reefs retreated and were covered by shelf facies sediments.
- The diversity of planktonic and nektonic faunal associations increased, partly caused by the return of species that were previously pushed into other provinces, and partly by the adaptive radiation of new species.

## 4 DISCUSSION

The close relationship between facies development, palaeontological events and isotope records in the Silurian suggests common controlling mechanisms which result from local as well as global factors. While, in general, palaeoceanographic changes are assumed to be the main causes, the interpretations and models diverge substantially (e.g., Jeppsson 1987, 1990, 1998, Brenchley 1988, Brenchley et al. 1995, Wenzel & Joachimski 1996, Samtleben et al. 1996, Bickert et al. 1997, Kaljo et al. 1995, 1998). The results of the present study allow reconstructions of the oceanographic processes in the Silurian, because the comparison of C- and O-isotope records of the four transects, each with its own facies succession, facilitates the separation of local and global influences.

For comparison, the transects have been correlated according to their C-isotope variations (Fig. 3A) and transferred into the time domain by interpolating linearly between the few datums given in Tab. 1 (Harland et al. 1990). Following the suggestions of Bickert et al. (1997), a time interval of about 1.5 Ma has been schematically assigned to the A-periods in the upper Homerian and in the upper Ludfordian, and of 0.5 Ma to the less distinct upper Gorstian A-period (Fig. 6).

### 4.1 Carbon isotopes

Since the variations of C isotopes have been used as a stratigraphic tool, it is not surprising that the curves of the four transects vary in a nearly parallel way (Fig. 6). But notable is that the four C-isotope records actually match in their absolute values at any given age, within the precision of C-isotope analyses in brachiopod samples (±0.4‰, Samtleben et al. in press). An exception are the values between 425 and 424 Ma in the eastern profiles 3 and 4 which differ from the values in the western profiles 1 and 2 by about -1.5‰. The reason for the deviation in the eastern transects may be due to gaps in the geological record. The data coverage is also sparse and, hence, the stratigraphic resolution is not sufficient. The elsewhere excellent match of the C-isotope records of the four transects, even in the indistinct upper Gorstian A-period, suggests that local environmental conditions in the different facies areas did not influence the $\delta^{13}C$ values. Therefore, a supra-regional or even global mechanism for the C-isotope variation is likely.

A further argument for a supra-regional control of the C-isotope development is the similarity of records from other regions, although these records show somewhat differing amplitudes (Corfield et al. 1992, Azmy et al. 1998, Kaljo et al. 1997, 1998). In SW England and in Wales, C isotopes were analysed in whole rock samples from different facies at the Wenlock/Ludlow boundary (Corfield et al. 1992). All records show a similar decrease in $\delta^{13}C$ values, comparable to the C-isotope record observed in the Klinteberg Beds and lower Hemse Beds on Gotland.

Whole rock analyses from sediment cores of the Silurian in Estonia and Latvia provided a C-isotope record that exhibits three maxima corresponding to those of Gotland (Kaljo et al. 1997, 1998). For a comparison of the C-isotope records of both the Baltic states and Gotland, these authors calculated mean values within each graptolite zone. For Gotland, the values of brachiopods from Samtleben et al. (1996) and Wenzel & Joachimski (1996) were used. The resulting records are generally parallel, but rather smooth due to the low data coverage.

The fact that the C-isotope development in the Ludlow of Gotland (and elsewhere) is independent of facies differences, confirms the interpretation by Bickert et al. (1997) that the C-isotope variation is controlled by circulation changes related to global climatic changes. Because of permanent euxinic conditions below the surface water in the open ocean during the entire Silurian (Wilde et al. 1991), a strong C-isotope fractionation occurred between surface and deep water. This was caused by continuous removal of $^{12}C$ from surface waters by formation and export of organic matter to the subsurface, where it was trapped because of the stagnant ocean conditions. Today, a similar fractionation is observed in the Black Sea. The shift from humid to arid climates led to changes in ocean circulation. During humid periods, an estuarine circulation was caused by the influx of fresh water resulting in an upwelling of $CO_2$-enriched deep water with low $\delta^{13}C$ values to the shelf regions. The formation and downwelling of saline surface water in arid periods caused an anti-estuarine circulation pattern in shallow seas, and $O_2$-rich, but $^{12}C$-depleted surface water reached the shelves.

The interpretation of the C-isotope development in the Baltic Silurian by Kaljo et al. (1998) which also conforms to the view of Brenchley et al. (1995), differs from the interpretation by Bickert et al. (1997). Kaljo et al. (1998) explain the periods of high $\delta^{13}C$ values by increased upwelling of nutrient-rich deep water and a resulting increase in productivity in a formerly oligotrophic environment due to glacial climate conditions. Many groups of organisms that could not stand the change of ecological conditions became extinct. According to Kaljo et al. (1998) these periods were characterized by a low diversity but highly productive fauna, associated with a corresponding strong C-isotope fractionation in the water column. Changes in fresh-water supply are neglected in this scenario. The interpretation disregards the palaeontological evidence for high plankton productivity during low $\delta^{13}C$ periods (H-periods) and vice versa (Jeppsson 1990, 1997, 1998, Jeppsson et al. 1995). Furthermore, an increased upwelling of nutrient-rich deep water would have decreased the $\delta^{13}C$ values of the surface water, as is observed in today´s upwelling areas (c.p. Bickert & Wefer 1999). Additionally, even extremely high productivity would fall far short of creating the C-isotope fractionation of about 8‰ observed in the Lau Event. Finally, there are no indications for continental glaciation in the Ludlow which might have been associated with such a change in upwelling intensitiy.

### 4.2 Oxygen isotopes

In contrast to carbon isotopes, the O-isotope records of the four transects exhibit generally parallel, but in some intervals strongly differing patterns, as well as overall higher variabilities (Fig. 6). The O-isotope record of the western transect (1) is taken as reference because it is based mostly on shelf-facies deposits. From this it is clear that the $\delta^{18}O$ record in general is nearly parallel to the $\delta^{13}C$ record taking into account that in the Ludlow it shows an additional long-term trend to lower values as described and discussed by Bickert et al. (1997). The other transects show substiantially lower values in some intervals. These deviations are obviously related to shallow-water facies (cp. Fig. 3B). For example, during the upper Homerian A-period (425.5 - 424 Ma), the $\delta^{18}O$ values generally decrease from west to east. The values of the backreef flats at 424.5 Ma in transect 4 are about 2‰ lower than contemporaneous values in transect 1. A second example is given by the low value determined in a reef complex of the upper Klinteberg Beds at 424 Ma in transect 2 (Bofridel: $\delta^{18}O$ = -6.1‰). Further deviations to negative values are observed at the base and in the middle part of the upper Gorstian A-period in transects 2 and 4. Finally, the depression in the record within the Hamra/Sundre Beds in transect 1 (411.5 Ma) represents samples from a back reef facies (Fig. 3B, 6). On the contrary, transects 2, 3, and 4 exhibit similar $\delta^{18}O$ values to transect 1 when they are obtained from shelf-facies deposits.

The question arises which mechanisms are responsible for the local facies-dependent $\delta^{18}O$ excursions. Likely is a local warming on the order of several °C in spatially limited shallow-water areas due to intense solar radiation. This hypothesis is strongly supported by the fact that the $\delta^{18}O$ deviations were associated with periods of reef formation (A-periods) when extremely shallow-water environments occurred in the reef and backreef facies. However, these areas were not completely isolated from the open marine realm. Otherwise, the arid conditions would have caused an increase in salinity and thereby a stronger $^{18}O$ fractionation due to intense evaporation. Furthermore, a reduced influx of open-ocean water would have restricted ventilation and thus altered the C-isotope fractionation. Such deviations in C-isotope values did not occur in the four transects, as stated above. Therefore, the causes of the $\delta^{18}O$ anomalies are probably local temperature rises. The general coincidence of the $\delta^{18}O$ records of the four transects indicates that there has been a considerable amount of supra-regional control on the $\delta^{18}O$ changes in the Silurian of Gotland. These changes were caused by climatic variations in precipitation and evaporation (A-periods versus H-periods) (cp. Samtleben et al. 1996, Bickert et al. 1997). Reduced precipitation during A-periods resulted in higher salinity and therefore higher $\delta^{18}O$ values in the surface water. The corresponding reduction of terrigenous influx resulted in oligotrophic conditions and favoured reef growth.

A supra-regional control is likely even for the weak phase of reef formation in the upper Gorstian A-period (416.5-416 Ma) because the $\delta^{13}C$ maxima are observed in all four transects. However, it remains unknown why this period lasted only that short time, and why reefs developed in times without significant increases in O-isotope values. In the Silurian of Gotland, however, the $\delta^{18}O$ and $\delta^{13}C$ values show a good correlation, but the $\delta^{13}C$ variability exceeding that of $\delta^{18}O$ by a factor of 2.5 (Bickert et al. 1997). Since in the upper Gorstian A-period the $\delta^{13}C$ values are raised by only 1‰, the increase of $\delta^{18}O$ values during this period is assumed to be about 0.4‰. This value corresponds to the reliability of C and O isotope analyses in Silurian brachiopods from Gotland (Samtleben et al. in press) and is,

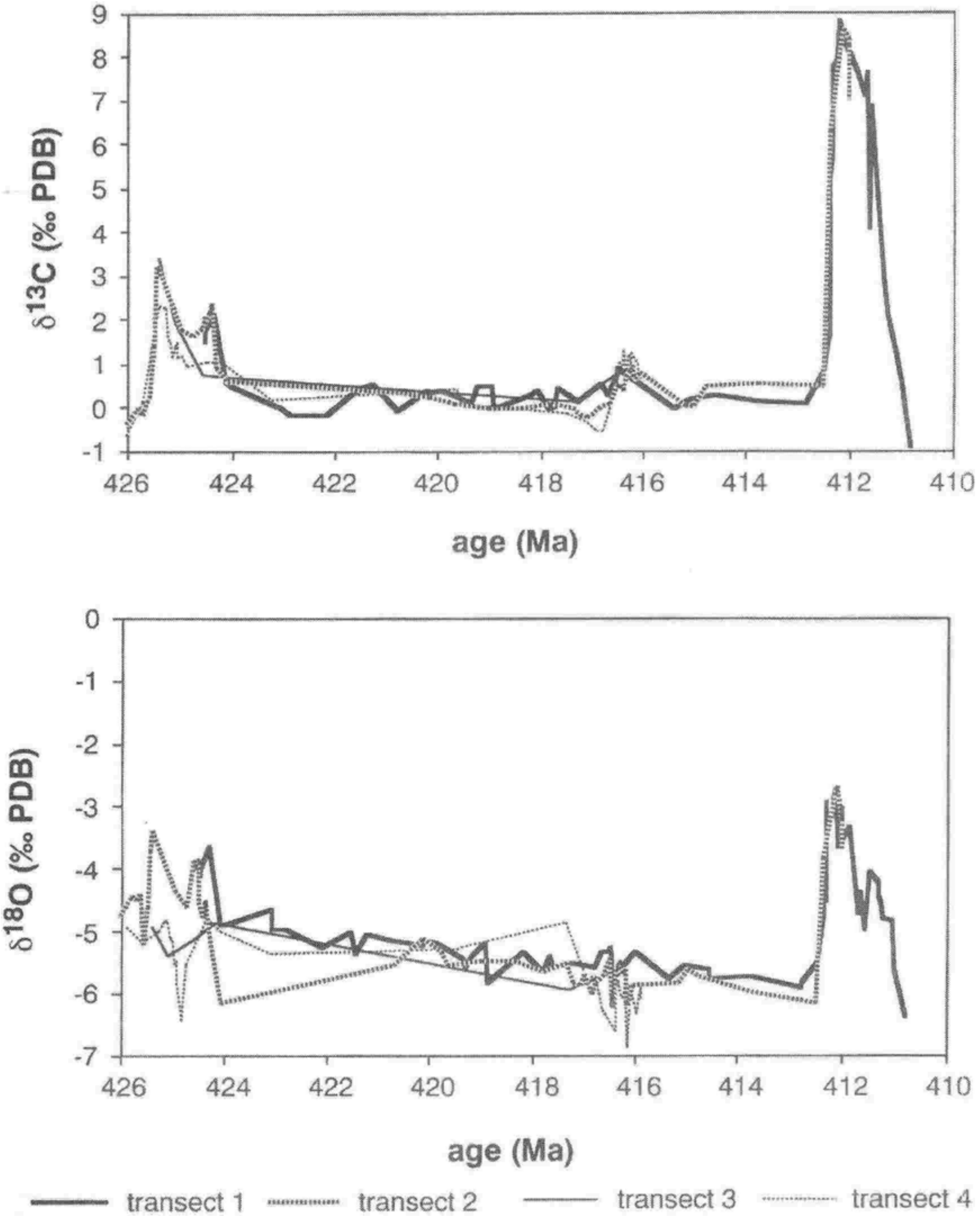


Fig. 6. Carbon- and oxygen-isotope records in the Ludlow of Gotland, plotted against age. Note the good correlation of the C-isotope curves of different facies areas. The O-isotopes show a subparallel course to the C-isotopes but a higher variability due to local temperature and salinity effects.

therefore, hidden in the short-term variability of the O-isotope record. An additional difficulty may be due to the fact that increasing salinity and increasing temperature result in both raised and lowered O-isotope values, respectively, which largely balance each other. This might have been the case at the onset of the upper Homerian and the upper Ludfordian A-periods. Here, the reef formation also began in times of relatively low $\delta^{18}O$ values.

### 4.3 Relationship between C-/O-isotope values, facies changes, and extinction events

The fact that extinction events in the Silurian of Gotland (Jeppsson 1987-1998, Kaljo et al. 1995) are generally associated with very rapid changes in isotope values and facies formations at the transitions from H-periods to A-periods confirms the existence of causal relationships between bioevents and palaeoceanographic changes. A possible explanation is drawn from the asymmetry of the isotope record:

The slowly decreasing isotope values during an H-period might indicate an intensification of the hydrologic cycle which led to an increasing imbalance and finally to a rapid turn over of the circulation system. The shift from estuarine to anti-estuarine circulation resulted in the change from eutrophic to extremly oligotrophic conditions in epicontinental seas. This abrupt change could have led to a breakdown of the ecosystem and the extinction of especially adapted taxa of the plankton and nekton (conodonts, graptolites, acritarchs, vertebrates).

In the Silurian of Gotland the first extinctions occurred in the very early phase of an H-period/A-period transition, i. e., prior to the increase of isotope values and much earlier than the sea-level drop connected with this transition. During the Ireviken Event at the Llandovery/Wenlock boundary (Jeppsson & Männik 1993) and in the transition during the Homerian (Slite Beds to Klinteberg Beds) conodont extinctions occurred prior to isotope changes and inferred climatic alterations (Jeppsson 1998). There are no indications in the geologic record for the causes of these early extinction events.

Climatic shifts between humid and arid periods and related patterns in sedimentation and bio-events were common features in the Middle Palaeozoic. McGhee et al. (1991) described from the Devonian of North America five cycles of varying terrigenous input to the Appalachian Basin within 45 million years. Similar to the H- and A-periods in the Silurian on Gotland, these cycles were connected to palaeontological events (extinctions, speciations) involving mostly ammonoids, brachiopods, and conodonts. These events coincided with global extinction events of ammonoids and are explained by global environmental changes, the exact causal connections being still unknown (House 1985). The durations of these cycles were of about the same order as the climatic periods in the Silurian.

Despite uncertainties in the determination of absolute ages, it can be assumed that the durations of the climatic cycles in the middle Palaeozoic varied between less than four to about seven million years. Obviously, these cycles did not depend on a strict periodicity. Thus, astronomical forcing as a driving mechanism is excluded. It is more likely that long-term oceanographic and climatic processes led to unstable conditions, causing abrupt changes and subsequent relapse to the previous mode. The various physical, chemical, and biological processes within these cycles interfered with one another. Reciprocal effects influenced intensity and duration of the cycles. The basic driving mechanisms, however, remain unknown.

## 5 CONCLUSIONS

- The detailed evaluation of isotope data in brachiopod shells from the upper Silurian of Gotland allowed the establishment of a high-resolution isotope stratigraphy for various Ludlowian facies successions. To some extent, stratigraphic correlations could be established more precisely than by using conodont assemblages.
- Within the upper Gorstian (middle part of the Hemse Beds) a relatively weak, but distinct A-period following the Linde Event could be distinguished and mapped within different facies areas.
- The isotope records of four parallel transects exhibit a saw-tooth pattern with a steep rise at the beginning of A-periods and a subsequent gradual decrease towards the end of H-periods. The comparison of facies successions and isotope records along the four transects reveals corresponding carbon-isotope developments independent of lateral changes in facies. On the other hand, O-istopes exhibit influences of local environmental conditions.
- For the oceanographic-climatic periods a general and regular development of facies, isotopes, and palaeontological events was established. The new results confirm previous interpretations by Samtleben et al. (1996) and Bickert et al. (1997) that isotope variations and facies development are related to changes in oceanographic conditions. Periods of low isotope values (H-periods) are indicative of humid climate and estuarine circulation in epicontinental seas. Periods of high isotope values (A-periods) are connected with arid conditions and anti-estuarine circulation.
- The interpretation of the variations in facies and isotope ratios as being caused by changes in the oceanographic system does not identify a control mechanism for the repeated extincion events related to the H-period/A-period transitions. In particular, the observation that early bio-events occurred prior to changes of isotope values and facies points to causes that left no observable signals in the geological record.

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# Appendix 1: Isotope Data

## Transect 1

| Locality | beds | coordinates | | m above Linde Event | mean values δ13C | δ18O | number of specimens | facies |
|---|---|---|---|---|---|---|---|---|
| Blåhäll 1a | MB | 635676 | 164191 | -78.0 | 1.54 | -3.84 | 18 | distal shelf |
| Blåhäll 1b | MB | 635676 | 164191 | -77.0 | 1.49 | -4.10 | 13 | distal shelf |
| Djupvik 1 | MB | 635582 | 164107 | -75.8 | 1.79 | -3.97 | 12 | distal shelf |
| Sudervik 2 | MB | 635110 | 163794 | -62.8 | 2.14 | -3.63 | 5 | distal shelf |
| Vattskogs 1 | HeB | 635000 | 164210 | -46.0 | 0.59 | -4.89 | 3 | distal shelf |
| Grymlings 1 | KB | 635566 | 164505 | -40.0 | 0.50 | -4.89 | 4 | proximal shelf |
| Urgude 6 | HeB | 635010 | 164365 | -35.2 | 0.00 | -4.62 | 2 | proximal shelf |
| Urgude 5 | HeB | 634980 | 164360 | -35.0 | 0.04 | -4.94 | 4 | proximal shelf |
| Sproge 5 | HeB | 634980 | 164385 | -33.8 | -0.20 | -4.97 | 1 | proximal shelf |
| Hägsarve 6 | HeB | 634920 | 164400 | -30.0 | -0.18 | -5.25 | 2 | proximal shelf |
| Hägsarve 7 | HeB | 634888 | 164414 | -27.0 | 0.39 | -4.99 | 3 | distal shelf |
| Sproge 6 | HeB | 635108 | 164600 | -26.5 | 0.44 | -5.36 | 3 | proximal shelf |
| Hägsarve 2 | HeB | 634861 | 164415 | -25.3 | 0.52 | -5.03 | 3 | proximal shelf |
| Snoder-a 1 | HeB | 634675 | 164308 | -22.7 | -0.06 | -5.15 | 3 | distal shelf |
| Smissarve 4 | HeB | 634647 | 164342 | -19.5 | 0.36 | -5.21 | 3 | distal shelf |
| Snoder 4 | HeB | 634781 | 164466 | -19.5 | 0.32 | -5.14 | 6 | distal shelf |
| Petesvik 1a | HeB | 634258 | 164270 | -18.2 | 0.38 | -5.16 | 3 | distal shelf |
| Laxskär 1 a | HeB | 634140 | 164210 | -15.3 | 0.13 | -5.41 | 5 | distal shelf |
| Laxskär 1 b | HeB | 634140 | 164210 | -15.0 | 0.07 | -5.55 | 8 | distal shelf |
| Bovik 1 | HeB | 634131 | 164225 | -14.5 | 0.49 | -5.38 | 5 | distal shelf |
| Bovik 3 | HeB | 634088 | 164206 | -13.0 | 0.47 | -5.17 | 3 | distal shelf |
| Bovik 2 | HeB | 634091 | 164227 | -12.8 | -0.01 | -5.81 | 3 | distal shelf |
| Smissarve 3 | HeB | 634534 | 164457 | -9.0 | 0.27 | -5.32 | 3 | proximal shelf |
| Vakten 1 | HeB | 633985 | 164218 | -8.3 | 0.41 | -5.42 | 2 | distal shelf |
| Alsvik 4 | HeB | 633960 | 164255 | -7.0 | -0.02 | -5.64 | 3 | distal shelf |
| Mickels 1 | HeB | 634590 | 164641 | -6.3 | 0.05 | -5.38 | 3 | distal shelf |
| Alsvik 3 | HeB | 633940 | 164255 | -6.0 | 0.43 | -5.58 | 3 | distal shelf |
| Lukse 1 | HeB | 634388 | 164650 | -4.0 | 0.12 | -5.50 | 3 | distal shelf |
| Krokvät 5 | HeB | 633883 | 164320 | -1.5 | 0.55 | -5.55 | 3 | distal shelf |
| Krokvät 4 | HeB | 633892 | 164337 | -1.0 | 0.27 | -5.31 | 2 | distal shelf |
| Krokvät 3 | HeB | 633900 | 164353 | -0.3 | 0.49 | -5.32 | 5 | distal shelf |
| Krokvät 2 | HeB | 633909 | 164378 | 0.4 | 0.74 | -5.23 | 6 | distal shelf |
| Krokvät 1 | HeB | 633920 | 164395 | 1.0 | 0.91 | -5.74 | 4 | distal shelf |
| Hemmungs 2 | HeB | 634064 | 164733 | 15.0 | 0.51 | -5.32 | 5 | distal shelf |
| Nisse 5 | HeB | 633808 | 164710 | 18.0 | -0.02 | -5.76 | 3* | dist. shelf + D-flags |
| Snauvalds 1 | HeB | 634050 | 164900 | 19.5 | 0.17 | -5.52 | 5 | distal shelf |
| Drakarve 3 | HeB | 633710 | 164720 | 22.0 | 0.30 | -5.59 | 3* | dist. shelf + D-flags |
| Drakarve 5 | HeB | 633780 | 164730 | 22.0 | 0.26 | -5.75 | 2* | dist. shelf + D-flags |
| Drakarve 4 | HeB | 633632 | 164736 | 26.0 | 0.13 | -5.72 | 1 | dist. shelf + D-flags |
| Snippsnyte 2 | HeB | 634059 | 165145 | 30.5 | 0.07 | -5.87 | 2 | dist. shelf + D-flags |
| Vaktård 6 | HeB | 633333 | 164627 | 30.5 | 0.14 | -5.80 | 1* | dist. shelf + D-flags |
| Klasård 1 | HeB | 633190 | 164580 | 33.5 | 0.80 | -5.48 | 3* | dist. shelf + D-flags |
| Olsvenne 1 | HeB | 633217 | 164705 | 37.8 | 1.74 | -4.67 | 2* | dist. shelf + D-flags |
| Bodudd 1 | HeB | 632958 | 164468 | 38.3 | 2.31 | -4.63 | 3 | dist. shelf + D-flags |
| Bodudd 1 | HeB | 632958 | 164468 | 38.6 | 4.19 | -4.17 | 2 | dist. shelf + D-flags |
| Bodudd 1 | HeB | 632958 | 164468 | 38.8 | 4.62 | -3.78 | 3 | dist. shelf + D-flags |
| Bodudd 1 | HeB | 632958 | 164468 | 39.3 | 5.25 | -4.13 | 3 | dist. shelf + D-flags |
| Bodudd 1 | HeB | 632958 | 164468 | 40.0 | 5.84 | -4.47 | 3 | dist. shelf + D-flags |
| Olsvenne 3 | EB | 633108 | 164709 | 40.5 | 6.10 | -4.45 | 3 | proximal shelf |
| Bodudd 2 | EB | 632942 | 164475 | 40.8 | 7.79 | -3.57 | 3 | prox. shelf + oncol. |
| Näs 1 | EB | 633399 | 164866 | 40.8 | 7.64 | -2.91 | 5 | prox. shelf + oncol. |
| Tomsarve 1 | EB | 633479 | 164889 | 40.8 | 7.71 | -3.12 | 5 | prox. shelf + oncol. |
| Petsarve 5 | EB | 633920 | 165675 | 44.8 | 7.91 | -3.16 | 4 | prox. shelf + oncol. |
| Petsarve 8 | EB | 633891 | 165720 | 45.8 | 8.80 | -2.83 | 4 | prox. shelf + oncol. |
| Petsarve 2 | EB | 633960 | 165633 | 48.8 | 8.60 | -2.70 | 4 | prox. shelf + oncol. |
| Petsarve 14 | EB | 633840 | 165759 | 49.8 | 8.34 | -3.63 | 4 | prox. shelf + oncol. |
| Kulhaken 2 | BS | 632355 | 164531 | 60.8 | 7.74 | -3.32 | 3 | fore-shore sandst. |
| Uddvide 3 | BS | 633338 | 165194 | 68.8 | 7.08 | -4.70 | 3 | fore-shore sandst. |
| Uddvide 2 | HSB | 633354 | 165203 | 70.8 | 7.60 | -4.34 | 6 | backreef area |
| Bankvät 1 | HSB | 633436 | 165773 | 73.8 | 4.06 | -4.94 | 3 | backreef area |
| Tubod 1 | HSB | 633061 | 165434 | 75.8 | 6.86 | -4.43 | 4 | backreef area |
| Rivet 2 | HSB | 631200 | 164123 | 78.3 | 5.35 | -4.03 | 3 | proximal shelf |
| Rivviken 2 | HSB | 631177 | 164265 | 85.3 | 3.16 | -4.20 | 5 | proximal shelf |
| Majstre 1 | HSB | 631341 | 164180 | 85.8 | 3.07 | -4.43 | 3 | proximal shelf |
| Rivviken 1 | HSB | 631150 | 164296 | 88.8 | 2.17 | -4.54 | 2 | proximal shelf |
| Hammarshagehällar 3 | HSB | 631575 | 165247 | 89.3 | 2.13 | -4.77 | 4 | biostrome |
| Barshageudd 5 | HSB | 631220 | 164665 | 97.8 | 1.14 | -4.82 | 6 | proximal shelf |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Klehammarsård 3 | HSB | 631250 | 164765 | 100.8 | 0.52 | -5.61 | 7 | proximal shelf |
| Beyrichienkalk. Schulau. Pleistocene erratic boulder | | | | 110.0 | -0.92 | -6.34 | 5 | ? proximal shelf |

**Transect 2**

| Locality | beds | coordinates | | m above Linde Event | mean values | | number of specimens | facies |
|---|---|---|---|---|---|---|---|---|
| | | | | | δ13C | δ18O | | |
| Odvalds 2 | SB | 636445 | 164500 | -120.5 | -0.36 | -4.75 | 5 | distal shelf |
| Värsändeojk 6 | SB | 636220 | 164235 | -118.5 | -0.05 | -4.43 | 2 | distal shelf |
| Värsändeojk 1 | SB | 636208 | 164238 | -117.5 | -0.20 | -4.48 | 2 | distal shelf |
| Värsändeojk 4 | SB | 636195 | 164257 | -116.5 | 0.13 | -4.39 | 2 | distal shelf |
| Värsändeojk 5 | SB | 636190 | 164257 | -116.0 | 0.24 | -5.21 | ** | distal shelf |
| Klinteenklaven 4 | SB | 636148 | 164263 | -114.0 | 1.39 | -4.60 | 3 | fore-shore sandst. |
| Klinteenklaven 2 | SB | 636106 | 164253 | -112.0 | 3.20 | -3.69 | 2 | fore-shore sandst. |
| Gannarveskär 1 | SB | 636100 | 164235 | -111.5 | 3.15 | -3.38 | 2 | fore-shore sandst. |
| Mulde Tegelbruk 1 | MB | 636124 | 164380 | -94.5 | 1.75 | -4.34 | 6 | distal shelf |
| Hunninge 1 | KB | 636445 | 164760 | -86.5 | 1.64 | -4.58 | 12 | proximal shelf |
| Haugklintar 1 | MB | 636025 | 164372 | -81.0 | 1.79 | -3.84 | 3 | proximal shelf |
| Haugklintar 3 | MB | 636060 | 164387 | -79.5 | 1.80 | -3.99 | 4 | proximal shelf |
| Loggarve 2 | MB | 636597 | 164819 | -78.0 | 2.10 | -3.95 | 3 | proximal shelf |
| Loggarve 2 | KB | 636597 | 164819 | -77.5 | 1.90 | -4.51 | 5 | proximal shelf |
| Klinteberget 1 | KB | 636435 | 164621 | -69.0 | 2.17 | -4.79 | 3 | reef complex |
| Forse 2 | KB | 636680 | 165020 | -63.5 | 2.37 | -4.47 | 3 | shoal area |
| Vallhagar 3 | KB | 636024 | 164636 | -55.5 | 0.92 | -5.07 | 4 | reef complex |
| Bofride 1 | KB | 635942 | 164777 | -37.0 | 0.58 | -6.13 | 4 | reef complex |
| Botes 1 | KB | 635529 | 165160 | -18.0 | 0.34 | -5.53 | 3 | proximal shelf |
| Smiss 2 | KB | 635700 | 165040 | -15.5 | 0.23 | -5.09 | 2 | proximal shelf |
| Ajmunde 1 | HeB | 635530 | 165242 | -14.0 | 0.12 | -5.32 | 6 | proximal shelf |
| Gerum 1 | HeB | 635435 | 165215 | -13.5 | 0.09 | -5.52 | 3 | proximal shelf |
| Kullands 1 | HeB | 635370 | 165207 | -10.5 | -0.05 | -5.44 | 10 | proximal shelf |
| Gardsby 3 | HeB | 635348 | 165275 | -8.0 | -0.02 | -5.44 | 2 | proximal shelf |
| Gardsby 2 | HeB | 635363 | 165317 | -5.5 | 0.06 | -5.65 | 10 | proximal shelf |
| Sandarve 2 | HeB | 635275 | 165304 | -3.5 | -0.05 | -5.51 | 2 | reef complex |
| Gerete 7 | HeB | 635082 | 165424 | -3.0 | -0.16 | -5.81 | 2 | proximal shelf |
| Amlings 1 | HeB | 635420 | 165530 | -2.5 | -0.23 | -5.84 | 3 | proximal shelf |
| Källdar 3 | HeB | 635267 | 165436 | -2.0 | -0.16 | -5.66 | 2 | proximal shelf |
| Gerete 2 | HeB | 635042 | 165530 | -1.5 | -0.02 | -5.98 | 3 | proximal shelf |
| Gerete 5 | HeB | 635055 | 165560 | -1.0 | 0.01 | -5.81 | 3 | proximal shelf |
| Likmide 1 | HeB | 634911 | 165371 | -0.5 | 0.08 | -5.72 | 5 | proximal shelf |
| Gerete 6 | HeB | 635057 | 165569 | 0.0 | 0.51 | -5.42 | 5 | proximal shelf |
| Sandarve 2 | HeB | 635275 | 165304 | 1.5 | 0.47 | -6.22 | 2 | reef complex |
| Källdar 4 | HeB | 635300 | 165438 | 4.5 | 0.39 | -5.58 | 3 | reef complex |
| Havor 2 | HeB | 634590 | 165210 | 6.0 | 0.70 | -5.58 | 8 | proximal shelf |
| Rangsarve 1 | HeB | 635378 | 165676 | 9.0 | 0.85 | -5.66 | 3 | proximal shelf |
| Rangsarve 1 | HeB | 635378 | 165676 | 10.0 | 0.96 | -5.60 | 4 | biostrome |
| Linde 4 | HeB | 635362 | 165530 | 11.0 | 0.73 | -6.14 | 4 | reef complex |
| Linde 5 | HeB | 635322 | 165500 | 11.5 | 0.66 | -6.19 | 4 | reef complex |
| Källdar 6 | HeB | 635320 | 165447 | 15.0 | 0.82 | -5.85 | 7 | reef complex |
| Linde 6 | HeB | 635391 | 165486 | 18.5 | 0.05 | -5.80 | 3 | reef complex |
| Kodings 3 | HeB | 634813 | 165598 | 19.0 | 0.00 | -5.60 | 3 | proximal shelf |
| Hulte 4 | HeB | 634680 | 165650 | 19.5 | 0.48 | -5.70 | 3 | distal shelf |
| Västlaus 1 | HeB | 634960 | 166072 | 22.0 | 0.55 | -5.95 | 3 | proximal shelf |
| Västlaus 3 | HeB | 634810 | 165977 | 25.0 | 0.51 | -6.15 | 2 | proximal shelf |
| Hummelbosholm 3 | HeB | 634495 | 166608 | 34.0 | 6.27 | -3.79 | 4 | proximal shelf |
| Kullunde 3 | EB | 634060 | 165796 | 47.8 | 8.45 | -2.81 | 4 | prox. shelf + oncol. |
| Kullunde 6 | EB | 634054 | 165859 | 49.8 | 8.59 | -2.65 | 4 | prox. shelf + oncol. |
| Kullunde 8 | EB | 633987 | 165953 | 55.8 | 8.38 | -3.20 | 4 | prox. shelf + oncol. |
| Ronehamn 2 | EB | 634145 | 166190 | 55.8 | 8.23 | -2.99 | 3 | prox. shelf + oncol. |
| Ronehamn 4 | BS | 634225 | 166287 | 56.8 | 6.98 | -3.70 | 2 | fore-shore sandst. |

**Transect 3**

| Locality | beds | coordinates | | m above Linde Event | mean values | | number of specimens | facies |
|---|---|---|---|---|---|---|---|---|
| | | | | | δ13C | δ18O | | |
| Väte 1 | HaB | 637264 | 165427 | -105.5 | 3.43 | -4.90 | 4 | reef complex |
| Prästbåtels 1 | KB | 637235 | 165818 | -87.5 | 1.93 | -5.38 | 3 | backreef area |
| Krasse 1 | KB | 636865 | 165860 | -60.5 | 0.74 | -5.08 | 1 | shoal area |
| Buttlegarde 2 | KB | 636729 | 166140 | -43.0 | 0.67 | -4.83 | 1 | biostrome |
| Sigvalde 3 | HeB | 636125 | 166458 | -3.5 | 0.11 | -5.92 | 5 | proximal shelf |
| Sigvalde 5 | HeB | 636052 | 166454 | 3.0 | 0.81 | -5.64 | 10 | biostrome |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tänglings 2 | HeB | 635890 | 166283 | 10.0 | **0.72** | **-5.46** | **3** | reef complex |

**transect 4**

| **Locality** | **beds** | **coordinates** | | **m above Linde Event** | **mean values** | | **number of specimens** | **facies** |
|---|---|---|---|---|---|---|---|---|
| | | | | | **δ13C** | **δ18O** | | |
| Tjeldersholm 1 | SB | 639362 | 167744 | -100.0 | **-0.64** | **-4.81** | **8** | proximal shelf |
| Simunde 1 | SB | 638863 | 166703 | -97.0 | **0.14** | **-5.07** | **4** | reef complex |
| Uppgarde 1 | SB | 638940 | 167083 | -88.0 | **2.32** | **-4.89** | **4** | shoal area |
| Gothemhammar 6 | HaB | 639118 | 167852 | -80.0 | **2.28** | **-4.69** | **16** | marginal marine |
| Gothemhammar 1 | HaB | 639104 | 167884 | -78.0 | **1.58** | **-4.74** | **4** | marginal marine |
| Gothemhammar 3 | KB | 639075 | 167925 | -75.0 | **1.51** | **-4.98** | **10** | marginal marine |
| Västerbjärs 1 | KB | 638830 | 167316 | -73.5 | **1.15** | **-5.02** | **2** | backreef area |
| Botvalde 2 | KB | 638822 | 167700 | -71.0 | **1.43** | **-5.43** | **3** | backreef flats |
| Västerbjärs 3 | KB | 638817 | 167335 | -69.5 | **1.53** | **-5.35** | **1** | backreef area |
| Hamremyr 1 | KB | 639040 | 167754 | -68.0 | **1.15** | **-5.72** | **4** | backreef flats |
| Botvaldvik 2 | KB | 638830 | 167912 | -65.0 | **1.22** | **-6.31** | **3** | backreef flats |
| Medebys Bodar 2 | KB | 638740 | 167915 | -59.0 | **0.97** | **-5.42** | **5** | backreef flats |
| Björke 1 | KB | 637988 | 166832 | -39.0 | **1.03** | **-4.65** | **4** | backreef area |
| Hällinge 3 | KB | 637825 | 166483 | -32.3 | **1.05** | **-4.89** | **4** | backreef area |
| Fjäle 3 | KB | 637895 | 167382 | -24.5 | **0.19** | **-5.24** | **3** | backreef area |
| Skarnvik 2 | HeB | 637545 | 167715 | -11.3 | **0.44** | **-5.18** | **5** | marginal marine |
| Skarnvik 3 | HeB | 637540 | 167730 | -11.0 | **0.10** | **-5.15** | **3** | marginal marine |
| Vidfälle 2 | HeB | 637485 | 167700 | -3.5 | **-0.12** | **-4.73** | **3** | marginal marine |
| Katthammarsvik 3 | HeB | 637245 | 168377 | -2.0 | **-0.31** | **-5.63** | **4** | marginal marine |
| Träske 1 | HeB | 637455 | 167835 | -1.5 | **-0.56** | **-5.61** | **2** | marginal marine |
| Grogarnshuvud 3 | HeB | 637300 | 168527 | -1.0 | **-0.54** | **-6.14** | **5** | marginal marine |
| Grogarnshuvud 1 | HeB | 637294 | 168536 | 0.0 | **0.53** | **-6.50** | **4** | marginal marine |
| Grogarnshuvud 4 | HeB | 637290 | 168540 | 0.3 | **0.63** | **-5.69** | **18** | marginal marine |
| Grogarns 1 | HeB | 637273 | 168545 | 0.5 | **0.59** | **-5.76** | **1** | marginal marine |
| Grogarns 4 | HeB | 637228 | 168581 | 3.0 | **1.06** | **-5.67** | **5** | biostrome |
| Herrvik 5 | HeB | 637137 | 168625 | 8.0 | **0.73** | **-5.89** | **4** | marginal marine |
| Herrvik 2 | HeB | 637048 | 168678 | 10.5 | **1.32** | **-5.95** | **5** | marginal marine |
| Rudvier 1 a | HeB | 636260 | 167312 | 16.0 | **0.74** | **-5.81** | **3** | biostrome/shoal |
| Rudvier 1 b | HeB | 636260 | 167312 | 20.0 | **1.19** | **-6.76** | **3** | biostrome/shoal |
| Kuppen 3 | HeB | 637070 | 168753 | 21.0 | **0.88** | **-6.18** | **5** | biostrome |
| Ljugarn 1 | HeB | 635912 | 167533 | 24.0 | **1.26** | **-5.73** | **8** | biostrome |
| Gannes 3 | HeB | 637045 | 168257 | 34.5 | **1.02** | **-6.21** | **4** | shoal area |
| Millklint 1 | HeB | 636784 | 167601 | 41.0 | **0.45** | **-5.71** | **3** | shoal area |
| Torsburgen 2 | HeB | 636833 | 167540 | 41.5 | **0.53** | **-6.01** | **6** | shoal area |

**additional samples (alphabetical order)**

| **Locality** | **beds** | **coordinates** | | **m above Linde Event** | **mean values** | | **number of specimens** | **facies** |
|---|---|---|---|---|---|---|---|---|
| | | | | | **δ13C** | **δ18O** | | |
| Alvare 1 | HeB | 635100 | 166850 | - | **0.37** | **-5.90** | **12** | proximal shelf |
| Bote 2 | EB | 635150 | 167540 | - | **6.18** | **-4.23** | **5** | reef/shoal |
| Botvide 1 | HeB | 635578 | 167156 | - | **1.45** | **-5.55** | **3*** | prox. shelf + D-flags |
| Djaupviksudden 6 | HeB | 637432 | 167925 | - | **-0.08** | **-5.85** | **4** | biostrome |
| Djaupviksudden 7 | HeB | 637535 | 167986 | - | **1.09** | **-6.05** | **5** | biostrome |
| Djaupviksudden 8 | HeB | 637548 | 167982 | - | **0.93** | **-6.04** | **4** | marginal marine |
| Djaupviksudden 1 | HeB | 637493 | 167952 | - | **-0.08** | **-5.44** | **5** | marginal marine |
| Fie 3 | HeB | 635294 | 167097 | - | **0.43** | **-6.24** | **2** | proximal shelf |
| Gannor 2 | HeB | 635285 | 166888 | - | **0.57** | **-5.94** | **4** | proximal shelf |
| Gannor 4 | EB | 635295 | 166885 | - | **5.60** | **-4.88** | **3** | reef complex |
| Garnudden 5 | HeB | 637557 | 167938 | - | **1.08** | **-5.93** | **5** | biostrome |
| Garnudden 2 | HeB | 637600 | 167900 | - | **0.26** | **-5.49** | **5** | marginal marine |
| Gogs 3 | HeB | 635640 | 167130 | - | **0.57** | **-5.84** | **6** | proximal shelf |
| Hallsarve 4 | HeB | 635405 | 167096 | - | **4.70** | **-4.11** | **3** | proximal shelf |
| Histilles 1 | HeB | 637360 | 167960 | - | **0.64** | **-6.01** | **1** | biostrome |
| Lau Backar 1 | EB | 635489 | 167085 | - | **5.47** | **-4.38** | **5** | reef complex |
| Levide 3 | HeB | 635246 | 164760 | - | **0.23** | **-5.09** | **3** | proximal shelf |
| När Fyr 3 | HSB | 634720 | 167400 | - | **8.64** | **-2.97** | **2** | biostrome |
| Närs Hamn 4 | BS | 634738 | 167183 | - | **8.68** | **-2.75** | **5** | shoal area |
| Närs Hamn 3 | BS | 634770 | 167218 | - | **8.47** | **-2.62** | **5** | shoal area |
| Nyan 2 | HeB | 635367 | 167489 | - | **0.55** | **-5.45** | **5** | prox. shelf + D-flags |
| Nyan 2 | EB | 635367 | 167489 | - | **4.61** | **-4.11** | **5** | reef complex |
| Ollajvs 1 | HSB | 632197 | 165300 | - | **1.48** | **-5.64** | **1** | backreef area |
| Öndarve 2 | HeB | 634930 | 167226 | - | **5.11** | **-4.09** | **3** | proximal shelf |
| Pejnarve 2 | HeB | 635320 | 164782 | - | **0.54** | **-5.26** | **1** | proximal shelf |
| Pilgårdsvik 1 A | EB | 634740 | 167035 | - | **8.24** | **-4.39** | **2** | proximal shelf |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pilgårdsvik 1 B | EB | 634740 | 167035 | - | **7.66** | **-3.85** | **7** | proximal shelf |
| Stockvikenskanal 1 | HSB | 632222 | 165287 | - | **1.91** | **-6.33** | **4** | backreef area |
| Tuten 1 | HeB | 635702 | 167280 | - | **0.49** | **-6.00** | **3** | proximal shelf |
| Virudden 1 | EB | 635037 | 167548 | - | **8.47** | **-4.70** | **3** | reef complex |

* number of *Dayianavicula* samples; each sample from 10-20 specimens;
** no brachiopod sample obtained; analysis from micritic limestone.

## Appendix 2: New Localities

**Alsvik 4**, 3960 164255, ca. 6800 m WSW of Hablingbo church. Top. map 56B Hemse (5I Hoburgen NO & 5J Hemse NV). Geol map Aa 164 Hemse.
Low shore exposure, 400 m north of the field road ending at the central part of the bay.
Hemse Beds, lower Gorstian H-period.

**Björke 1**, 7988 166832, ca. 2000 m E of Ganthem church. Top. map 66B Gothem. Geol. map Aa 170 Katthammarsvik.
Exposure in the ditch on the northern side of the road from Ganthem to Norrlanda, 800 m W of the small road to Björke.
Klinteberg Beds, upper Homerian A-period.

**Bote 2**, 35150 167540, 5150 m E of När church. Top. map 56D Ljugarn. Geol. map Aa 156 Ronehamn.
Shore exposure at the eastern coast of the peninsula Hammaren, just south of the huts of Hammarnäs Fiskeläge (not marked on the topographical map).
Eke Beds, upper Ludfordian A-period.

**Botvalde 2**, 638822 167700, 2500 m NE of Gothem church. Top. map 66B Gothem. Geol. map Aa 169 Slite.
Exposure in new (1999) E-W running ditch, E of the road to Gajrvide; 150 m S of the junction with the road from Botvalde to Botvaldvik.
Klinteberg Beds, upper Homerian A-period.

**Bovik 2**, 634091 164227, ca. 6600 m WSW of Hablingbo church. Top. map 56B Hemse (5I Hoburgen NO & 5J Hemse NV). Geol. map Aa 164 Hemse.
Small shore exposure on the southern side of the Bovik. Bearing to the windmill near Petes=35°, to the hut on Laxskär=340°.
Hemse Beds. Hemse Marl, northwestern part, lower Gorstian H-period.

**Bovik 3**, 634088 164206, ca. 6800 m WSW of Hablingbo church. Top. map 56B Hemse (5I Hoburgen NO & 5J Hemse NV). Geol. map Aa 164 Hemse.
Shallow shore exposure on the southern side of the Bovik, 550 m S of the hut on the peninsula Laxskär (bearing to the hut on Laxskär=03°).
Hemse Beds, Hemse Marl, northwestern part. lower Gorstian H-period.

**Djaupviksudden 6**, 637432 167925, 5050 m NE of Kräklingbo church. Top. map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Low shore exposure in the small bay, about 250 m NE of the point where the way from Träske to the shore bends to the NE.
Hemse Beds, lower Gorstian H-period.

**Djaupviksudden 7**, 637535 167986, 5950 m ESE of Anga church. Top. map 66B Gothem. Geol. map Aa 170 Katthammarsvik.
Low shore exposure, about 50 m S of the triangulation point at Hammarudden.
Hemse Beds, upper Gorstian A-period.

**Djaupviksudden 8**, 5900 m ESE of Anga church. Top map 66B Gothem. Geol. map Aa 170 Katthammarsvik.
Small exposure of bedded limestones at the shore, about 100 m NW of the triangulation point at Hammarudden.
Hemse Beds, upper Gorstian A-period.

**Drakarve 3**, 633710 164720, ca. 6600 m W of Grötlingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Irrigation pond NE of Nisseviken; excavated material on the southern side.
Hemse Beds, lower Ludfordian H-period.

**Drakarve 4**, 633632 164736, 6500 m W of Grötlingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Temporary excavation at a pylon just N of the road from Nisseviken to Drakarve, 890 m W of the junction with the small road to Drakarve.
Hemse Beds, lower Ludfordian H-period.

**Drakarve 5**, 633780 164730, 6600 m WNW of Grötlingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Small exposures in shallow ditch parallel to a power line running in NNW-SSE direction (not marked in the topographical map; edition 1987). 100-200 m N of the road from Nisseviken to the road no. 140 at Burge.
Hemse Beds, lower Ludfordian H-period.

**Gannor 4**, 635295 166885, 1600 m SSE of Lau church. Top. map 56D Ljugarn. Geol. map Aa 156 Ronehamn.
Exposure in small. dry drainage ditch N of Lau Kanal (Närkån).
(Locality named „45-2 Gannor“ in SAMTLEBEN et al. 1996.)
Eke Beds, upper Ludfordian A-period.

**Gardsby 3**, 635348 165275. 2500 W of Linde church. Top. map. 56C Klintehamn. Geol. map Aa 164 Hemse.
300 m SSW of Gardsby; exposure in NW-SE running ditch crossing the field road from Gardsby to SSW (not marked in the topographical map); 20-70 m SE of the bridge.
Hemse Beds, lower Gorstian H-period.

**Garnudden 5**, 637557 167938, 5500 m E of Anga church. Top map 66B Gothem. Geol. map Aa 170 Katthammarsvik.
Shore exposure on the west side of the small bay, about 500 m SSE of the triangulation point at Hammarudden.
Hemse Beds, upper Gorstian A-period.

**Gerete 5**, 635055 165560, 2850 m S of Linde church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Exposure in the large, E-W running drainage ditch, ca. 100 m E of the place, where the brook from Linde flows into the large ditch; excavated material on the northern side.
Hemse Beds, lower Gorstian H-period.

**Gerete 6**, 635057 165569, 2850 m S of Linde church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Exposure in the large, E-W running drainage ditch, ca. 180 m E of the place, where the brook from Linde flows into the large ditch; excavated material on the southern side.
Hemse Beds, close to the boundary lower Gorstian H-period/upper Gorstian A-period.

**Gerete 7**, 635082 165424, 1400 m SE of Fardhem church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Excavated material from drainage ditch 0-50 m S of the bridge at the end of the field road 550 m ENE of the house at Gerete.
Hemse Beds, lower Gorstian H-period.

**Gerum 1**, 635435 165215, 500m S of Gerum church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Loose material in shallow ditch just W of the road from Gerum to Fardhem; from the little wood N of the farm Uddvide right to the farm (ca. 100 m N-S).
Hemse Beds, lower Gorstian H-period.

**Gogs 3**, 635640 167130, 3600 m SSE of Alskog church. Top. map 56D Ljugarn. Geol. map Aa 156 Ronehamn.
Loose material from the northern field balk 0-100 m W of the road N of Lausbackar, 450 m N of the road junction at Goks.
Hemse Beds, upper part. close to the boundary lower Ludfordian H-period/ upper Ludfordian A-period.

**Grogarns 4**, 637228 168581. ca. 3050 m NE of Östergarn church. Top. map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Skerry-like exposure on the rubble covered bar running from the shore into the sea (Skånerevet). ca. 100 m distant from the shore line.
Hemse Beds. upper Gorstian A-period.

**Grogarnshuvud 3**, 637300 168527. 3200 m NE of Östergarn church. Top. map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Exposure on the shore platform; ca. 150 m NE of the triangulation point (31.8) at Grogarnshuvud.
Hemse Beds. lower Gorstian H-period.

**Grogarnshuvud 4**, 637290 168540, 3170 m NE of Östergarn church. Top.

map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Shore exposure, mainly to the E of the huge boulders on the beach, NE of the northeasternmost part of the hill, and ca. 280 m E of the triangulation point at Grogarnshuvud.
(Locality named "39-1 Grogarnshuvud B" in Samtleben et al. 1996.)
Hemse Beds, upper Gorstian A-period.

**Hägsarve 6**, 634920 164400, 3950 m NW of Silte church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Exposure in shallow ditch on the W-side of the road just N of Hägsarve.
Hemse Beds, Hemse Marl. northwestern part, lower Gorstian H-period.

**Hägsarve 7**, 634888 164414, 3550 m NW of Silte church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Excavated material from ditch E of the road at the junction with the way to Botrajvs.
Hemse Beds, Hemse Marl. northwestern part, lower Gorstian H-period.

**Hällinge 3**, 637825 166483, 2500 m NE of Sjonhem church. Top. map 66B Gothem. Geol. map Aa 170 Katthammarsvik.
Material from temporary excavation for an electric power line on the northern side of the E-W running road, 530 m W of the junction with the road from Dalhem to Kräklingbo.
Klinteberg Beds, upper Homerian A-period.

**Hallsarve 4**, 635405 167096, 1200 m ESE of Lau church. Top. map 56D Ljugarn. Geol. map Aa 156 Ronehamn.
Exposure in the embankment on the W-side of the road E of Laus Backar. 150 m SW of the junction with the road from Nyan.
Hemse Beds and Eke Beds, upper Ludfordian A-period.

**Hammarshagehällar 3**, 631575 165247, 3600 m S of Hamra church. Top. map 56A Hoburgen. Geol. map Aa 152 Burgsvik.
Material from huge boulders in the jetty on the southern side of the entrance of Vändburg fishing harbour (the harbour is not marked on the topographical map. edition 1987). The boulders were quarried in the area of the new harbour basin.
Sundre Beds, upper Ludfordian A-period.

**Hamremyr 1**, 639040 167754, 4000 m NE of Gothem church. Top. map 66B Gothem. Geol. map Aa 169 Slite.
Temporary (1999) surface exposure and excavated material E of the straight way which runs from the road Magnuse - Botvalde träsk towards NNE through the wood; exactly 1000 m NNe of the road junction.
Klinteberg Beds, upper Homerian A-period.

**Havor 2**, 634590 165210, 3650 m SW of Hemse church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Excavated material on the northern side of a pond, 900 m ENE of Stora Havor.
Hemse Beds, upper Gorstian A-period.

**Hemmungs 2**, 634064 164733, 2500 m SSW of Hablingbo church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Exposure in ditch on the eastern side of the road, just S of the crossing at Kyrkeby.
Hemse Beds, close to the boundary upper Gorstian A-period/lower Ludfordian H-period.

**Herrvik 5**, 637137 168625, 3000 m ENE of Östergarn church. Top. map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Shore exposure, 870 m NW of the lighthouse of Herrvik harbour.
Hemse Beds, upper Gorstian A-period.

**Histilles 1**, 637360 167960, 5100 m ENE of Kräklingbo church. Top. map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Shore exposure on the north side of the peninsula NE of Histilles.
Hemse Beds, upper Gorstian A-period.

**Hulte 4**, 634680 165650, 2000 m SE of Hemse church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Excavated material on the northern and the western side of the large pond. S of the road from Hemse to Rone.
Hemse Beds, lower Ludfordian H-period.

**Hummelbosholm 3**, 634495 166608, 6850 m E of Rone church. Top. map 56B Hemse. Geol. map Aa 156 Ronehamn.
Small shore exposure on the northwestern side of the small peninsula N of the former fishing hamlet of Hummelbosholm.
Hemse Beds, upper Ludfordian A-period.

**Katthammarsvik 3**, 637245 168377, 2100 m NNE of Östergarn church. Top. map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Shore exposure on the eastern side of the bight
Katthammarsvik, ca. 600 m N of the southern house at Vassmunds.
Hemse Beds, lower Gorstian H-period.

**Klehammarsård 3**, 631250 164765, 3700 m SE of Sundre church. Top. map 56A Hoburgen. Geol. map Aa 152 Burgsvik.
Loose material collected on the shore platform at the southern side of the peninsula Klehammarsård, obviously wave-eroded from the south-eastern nearby offshore area.
Sundre Beds, probably younger, close to the boundary upper Ludfordian A-period/Pridolian H-period.

**Klinteenklaven 4**, 636148 164263, 2500 m NNW of Fröjel church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Shore exposure, about 50 m N of the small spit in the middle of the bay.
Slite Beds. Slite Siltstone. upper Homerian A-period.

**Krokvät 2**, 633909 164378, 6050 m SW of Hablingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Ditch exposure and excavated material. collected 50-300 m SW of the bridge at Krokvät 1.
Hemse Beds, upper Gorstian A-period.

**Krokvät 3**, 633900 164353, 6300 m SW of Hablingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Ditch exposure and excavated material. samples 0-100 m NE of a small bridge (not marked on the topo-graphical map 1:50000), ca. 470 m SW of Krokvät 1.
Hemse Beds, close to the boundary lower Gorstian H-period/upper Gorstian A-period.

**Krokvät 4**, 633892 164337, 6450 m SW of Hablingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Ditch exposure and excavated material, 0-250 m SW of a small bridge (not marked on the top. map 1:5000), ca. 470 m SW of Krokvät 1. Krokvät 4 ends at the slight bend in the direction of the ditch.
Hemse Beds, lower Gorstian H-period.

**Krokvät 5**, 633883 164320, 6650 m SW of Hablingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Ditch exposure and excavated material SW of Krokvät, 250-500 m SW of a small bridge (not marked on the top. map 1:5000), ca. 470 m SW of Krokvät 1.
Hemse Beds., close to the boundary lower Gorstian H-period/upper Gorstian A-period.

**Kulhaken 2**, 632355 164531, 5500 m NNW of Vamlingbo church. Top. map 56A Hoburgen. Geol. map Aa 152 Burgsvik.
Material from boulders in an outcrop at the shore. The boulders may come also from an old open quarry closely behind this place.
Burgsvik Beds, upper Ludfordian A-period.

**Lau gård 2**, 635365 166753, 2300 m WSW of Lau church. Top. map 56D Ljugarn. Geol. map Aa 156 Ronehamn.
Exposure in the large drainage ditch on the southern side of the road, 130 m E of the drive to the farm Lau gård.
Hemse Beds, lower Ludfordian H-period.

**Linde 4**, 635362 165530, 230 m N of Linde church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Small exposures halfway up in shallow valley on the eastern side of Lindeberget.
Hemse Beds. upper Gorstian A-period.

**Linde 5**, 635322 165500, 280 m WSW of Linde church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Exposure in the embankment on the western side of the road from Linde to Fardem.
Hemse Beds. upper Gorstian A-period.

**Linde 6**, 635391 165486, 630 m NW of Linde church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Cliff exposure of stromatoporoid reef in the northern slope of Lindeberget, just W of the small ancient stronghold.
Hemse Beds, lower Ludfordian H-period.

**Närs Fyr 3**, 634720 167400, 5700 m SE of När church. Top. map 56B Hemse. Geol. map Aa 156 Ronehamn.
Small exposure on the shore, 300 m ESE of the lighthouse.
Hamra Beds, upper Ludfordian A-period.

**Närs Hamn 4**, 634738 167183, 4400 m SSE of När church. Top. map 56B Hemse. Geol. map Aa 156 Ronehamn.
Shore exposure 840 m SW of Närshamn harbour (southern quay), 1850 m W of the lighthouse on Närsholmen. The outcrop area is marked by two huge erratic boulders on the shore platform.
Burgsvik Beds, upper Ludfordian A-period.

**Nisse 5**, 633808 164710, 6750 m WNW of Grötlingbo church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Excavated material from the construction of a power line pylon, 450 m N of the road which runs from Nisseviken to the road no. 140; 2900 m W of the road junction at point 17.98. At this locality the power line (not marked on the topographical map; edition 1987) bends to the NW.
Hemse Beds, lower Ludfordian H-period.

**Odvalds 2**, 636435 164494, 1100 m WNW of Klinte church. Top. map 56C Klintehamn. Geol. map Aa 160 Klintehamn.
Excavated material (1994) from a ditch on the east side of the Klintehamn school's sports field.
(Locality named "23-1 Klintehamn" in SAMTLEBEN et al. 1996.)
Slite Beds, lower Homerian H-period.

**Petesvik 1 a**, 634258 164270, 5850 m W of Hablingbo church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Exposure on the eastern shore of Petesvik; bearing to the hut on Laxskär=207°. bearing to the windmill of Petes =126°. This locality is within **Petesvik 1** in the catalogue!
Hemse Beds, lower Gorstian H-period.

**Rivet 2**, 631200 164123, 4300 m SW of Sundre church. Top. map 56A Hoburgen. Geol. map Aa 152 Burgsvik.
Shore exposure, ca. 600 m S of Storburg.
(Locality named "50-1 S Hoburgen" in SAMTLEBEN et al. 1996.)
Hamra Beds. upper Ludfordian A-period.

**Rivviken 1**, 631150 164296, 3500 m SSW of Sundre church. Top. map 56A Hoburgen. Geol. map Aa 152 Burgsvik.
Large shore exposure on the western side of the peninsula Udden which forms the eastern border of Rivviken. At low water several tens of square meters with bedding planes are exposed.
Hamra/Sundre Beds. upper Ludfordian A-period.

**Rivviken 2**, 631177 164265, 3470 m SE of Sundre church. Top. map 56A Hoburgen. Geol. map Aa 152 Burgsvik.
Small shore exposure on the western side of the peninsula Udden which forms the eastern border of Rivviken, ca. 100 m SE of the place where the path from Digrans reaches the shore.
Hamra/Sundre Beds, upper Ludfordian A-period.

**Ronehamn 4**, 634225 166287, 4900 m SE of Rone church. Top. map 56B Hemse. Geol. map Aa 156 Ronehamn.
Ditch exposure and excavated material in the wood, ca. 100 m NE of the easternmost houses of Hus Fiskeläge. NE of Ronehamn harbour.
Burgsvik Beds, upper Ludfordian A-period.

**Simunde 1**, 638863 166703, 2000 m SE of Källunge church. Top. map 66B Gothem. Geol. map Aa 169 Slite.
Small hill (3-4 m high) S of the road from Bara to Källunge; exposure of reef rock material on the embankment of the road.
Slite Beds, lower Homerian H-period.

**Smissarve 3**, 634534 164457, 2550 m W of Silte church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Exposure in ditch on the northern side of the road which runs from Siglajvs (SW of Silte) to the coast, 1400 m SW of the junction with the road no. 140.
Hemse Beds, lower Gorstian H-period.

**Smissarve 4**, 634647 164342, 3400m W of Silte church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Exposure in ditch crossing the field road (not marked on the topographical map) which runs from the road to Kvarnåkershamn to the Snoder-a.
Hemse Beds, lower Gorstian H-period.

**Snippsnyte 2**, 634059 165145, 1000 m NW of Havdhem church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Ditch on the northeastern side of the road from Hablingbo to Havdhem, 550 m SE of Snippsnyte.
Hemse Beds. lower Ludfordian H-period.

**Snoder-a 1**, 634675 164308, 3600m W of Silte church. Top. map 56B Hemse. Geol. map. Aa164 Hemse.
Excavated material on both sides of the northern branch of the Snoder-a, ca. 100-200 m W of the point of branching.
Hemse Beds, lower Gorstian H-period.

**Sproge 6**, 635108 164600, 1250 m NE of Sproge church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Excavated material from new shallow pond (not marked on the topographical map. edition 1987) ca. 100 m W of the field road from Sproge to Levide, at the southwestern edge of the small wood.
Hemse Beds, lower Gorstian H-period.

**Urgude 5**, 634980 164360, 1600m W of Sproge church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Loose material from the field balk ca. 100 m S of the E-W running road from Sproge to Kruse.
Hemse Beds, lower Gorstian H-period.

**Urgude 6**, 635010 164365, 1550m W of Sproge church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Loose material from the field balk ca. 0-100 m N of the E-W running road from Sproge to Kruse.
Hemse Beds, lower Gorstian H-period.

**Vaktård 6**, 633333 164627. 2700 m WSW of Näs church. Top. map 56B Hemse. Geol. map Aa 152 Burgsvik.
Loose material excavated during the construction of a power line (ditch now refilled). 0-300 m S of the E-W running way to Vaktården, 450 m SE of the house at Vaktården.
Hemse Beds, lower Ludfordian H-period.

**Värsändeojk 6**, 636220 164235, 4000 m WSW of Klinte church. Top. map 56C Klintehamn. Geol. map Aa 160 Klintehamn.
Bedding surfaces exposed on the shore and in the sea, accessible at low water. Follow the road towards N by Värsändeojk 1 about 100 m.
Slite Beds, Slite Marl, lower Homerian H-period.

**Västerbjärs 3**, 638817 167335, 2100 m NW of Gothem church. Top. map 66B Gothem. Geol. map Aa 169 Slite.
Exposure in the ditch on the southern side of the road to Hörsne, 200 m SW of the road junction at Västerbjärs (point 16.68).
Klinteberg Beds, upper Homerian A-period.

**Västlaus 3**, 634810 165977, 2500 m NNE of Rone church. Top. map 56B Hemse. Geol. map Aa 164 Hemse.
Small exposures in the S-N running main drainage ditch of the Ronemyr. just W of the field road to Rone.
Hemse Beds, lower Ludfordian H-period.

**Vattskogs 1**, 635000 164210, 3100m W of Sproge church. Top. map 56C Klintehamn. Geol. map Aa 164 Hemse.
Loose material on the path from the "Barnkoloni" Mattsarve to the SW, obviously excavated during the construction of a power line (ditch now refilled); 370 m S of the easternmost house at Vattskogs.
Hemse Beds, close to the boundary upper Homerian A-period/lower Gorstian H-period.

**Vidvälle 2**, 637485 167700, 3350 m SE of Anga church. Top. map 56D Ljugarn. Geol. map Aa 170 Katthammarsvik.
Excavated material from a shallow ditch in the wood, just W of the private field road to the Skarnvik, 370 m N of the road from Kräklingbo to St. Hammars.
Hemse Beds, lower Gorstian H-period.

**Virudden 1**, 635037 167548, 5400 m ESE of När church. Top. map 56D Ljugarn. Geol. map Aa 156 Ljugarn.
Small shore exposure on the southeastern spit of the peninsula Hammaren, 400 m SSE of Djaupdy Fiskeläge.
Eke Beds, upper Ludfordian A-period.