The Silurian of Gotland - Part I: Review of the stratigraphic framework, event stratigraphy, and stable carbon and oxygen isotope development

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1. INTRODUCTION

In the past 15 years our picture of the Silurian has changed dramatically. Based on palaeontological, geochemical, and sedimentological investigations, it is now known that the conditions during the Silurian were much more variable than previously assumed. The island of Gotland, Sweden, has played a very important role in these investigations. For the purpose of the IGCP 503 Field Meeting 2004, this paper reviews the current stratigraphic framework of Gotland, and how its strata and biotas reflect concurrent events (event stratigraphy), relative sea-level changes (sequence stratigraphy), and stable carbon and oxygen isotope evolution (chemostratigraphy). The combined database well illustrates the interaction of oceanographic, climatic, and biotic changes at low latitudes during the Silurian radiation.

MC is responsible for the sedimentological and sequence stratigraphic data, and conclusions based thereupon, LJ for biostratigraphic chapters and discussions of episodes and events ('the Jeppsson model'), and AM for isotopic data and discussions of the Bickert et al. model. However, we have all tried to use all the data available and read and helped to improve all of the text, making it as integrated as is possible.

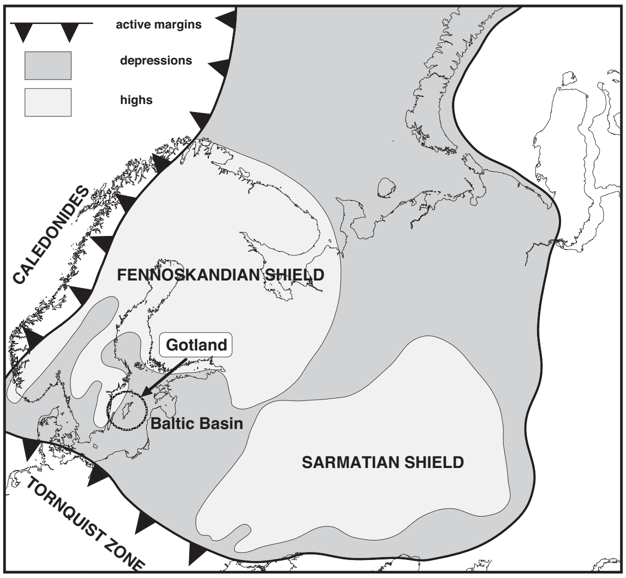

Fig. 1. Silurian Baltica showing principal shield areas and basins (redrawn after Baarli et al. 2003). Note the active margins in the NW and SW.

1.1 The Baltic Basin

The low-latitude carbonate platform strata of Gotland formed in the Baltic Basin. This intra- to pericratonic basin developed on the southern margin of the Baltic Shield and the East European platform (Fig. 1). Following extension and later tectonic quiescence in the earliest Palaeozoic, the south-western margin of the Baltic Shield was active from the latest Ordovician when the Avalonia Composite Terrane was amalgamated to Baltica (Pharaoh 1999). Subsidence curves show that this collisional event resulted in a change in tectonic regime – from a passive margin to a foreland basin (Poprawa et al. 1999). This is reflected by the more than 3 000 m thick Silurian deposits in Poland. During the Silurian, the western margin of Baltica was strongly affected by the collision of the Scotland/Greenland complex and western Norway (at ca 425 Ma), resulting in the early Scandian Orogeny (Torsvik et al. 1996) and eastward migration of thrust sheets. The strata on Gotland thus formed on the comparably protected and slowly subsiding craton-attached shelves between a two-armed foreland basin system (Fig. 1). This is reflected by a comparably thin cover of Lower Palaeozoic strata below Gotland; the crystalline basement is situated 378.4 m below sea level at Visby (Hedström 1923). The northern erosional limit of Silurian sedimentary cover within the basin is situated just north of Gotland and the Estonian mainland (Martinsson 1958; Flodén 1980), showing a successive depositional offlap towards the south. The Silurian subsurface below the Baltic Sea is fairly well known from numerous seismic stratigraphic survey lines (e.g. Flodén 1980; Flodén et al. 2001; Bjerkéus & Eriksson 2001).

1.2 Gotland

The Silurian bedrock of Gotland is an erosional remnant of an extensive carbonate platform complex that evolved along the margins of the Baltic Basin, from the western parts of the present-day Baltic Sea across the East Baltic and further southeast to Ukraine. The island is relatively small

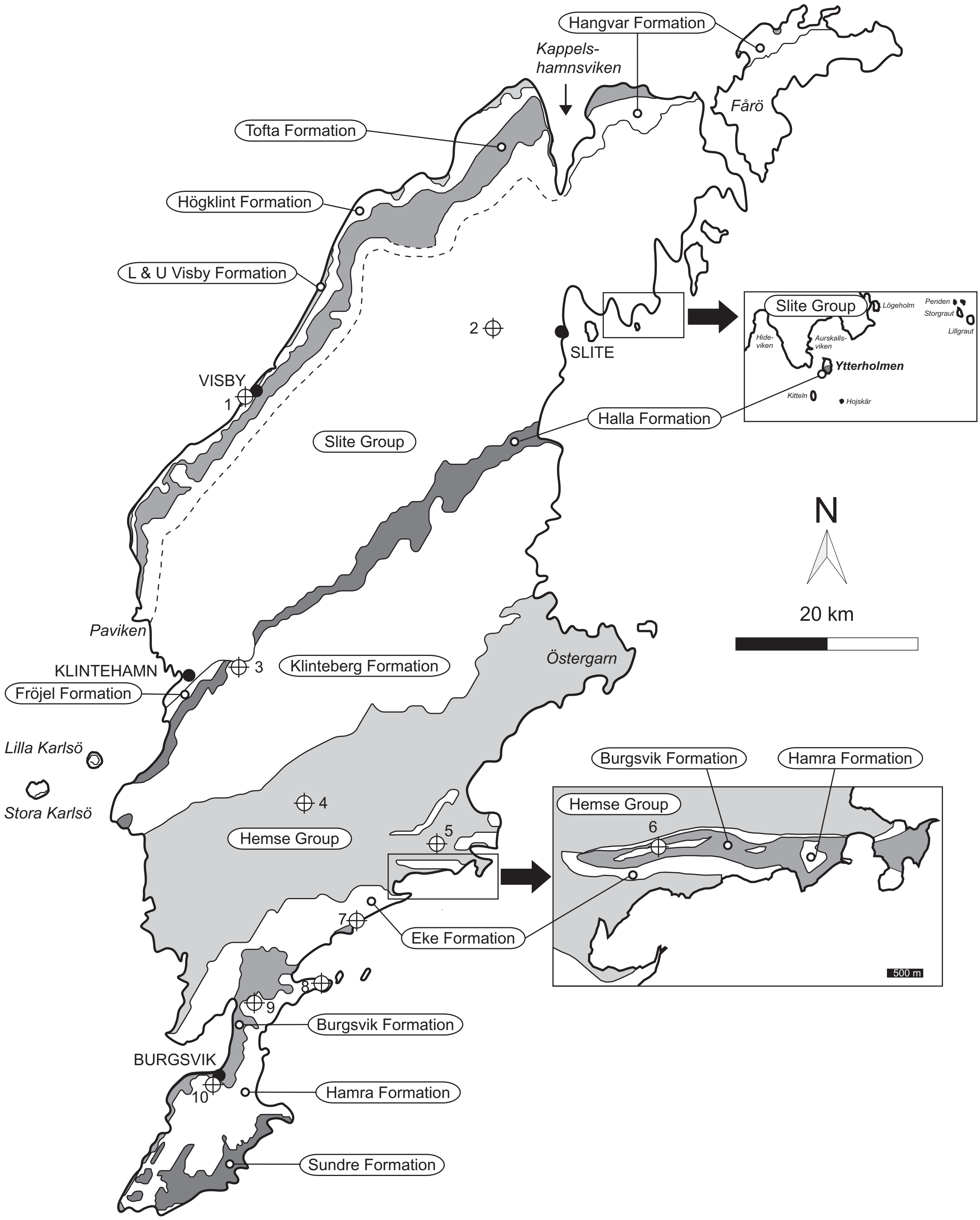

Fig. 2. A new geological map of Gotland (completed by LJ & MC), and position of borings; Visby boring (1), File Haidar boring (2), Hunninge-1 (3), Linde-1 (4), När-1 (5), Burgen-1 (6), Ronehamn-1 (7), Grötlingbo-1 (8), Uddvide-1 (9), Burgsvik boring (10). This preliminary map is chiefly based on Jeppsson & Calner (2003) and conodont data from Jeppsson (in manuscript; in prep.).

(ca 3 000 km^2), and outcrops are easily accessible along the coasts, in inland cliffs, ditches, and in still productive and abandoned quarries. The research history of the bedrock geology and fossils of Gotland goes back to the 18th century. Early studies focused primarily on the excellently preserved fossil biota and to resolve the large-scale stratigraphic relationships of the strata. The first comprehensive study of the geology and stratigraphy of Gotland was published in a series of detailed map descriptions published by the Swedish Geological Survey between the 1920's and the 1940's (summarised in Hede 1960 and refined by Laufeld 1974a, b).

The strata exposed on Gotland range in age from the latest Llandovery through Ludlow, i.e. encompassing ca 10 Ma of the Silurian System according to the ICS (2002) time scale. The entire succession is ca 500-700 m thick depending on were measurements are taken, the higher number is the sum of the maximum thickness for each interval.

The strata show no major late diagenetic alteration, and tectonic disturbances are rare and restricted to minor faults with limited vertical and/or lateral displacement. The excellent preservation is shown by, e.g., the conodont colour (very low CAI; Jeppsson 1983), and by the discovery of calcareous micro- and nannofossils that are previously unknown in rocks of this age (Munnecke et al. 1999, 2000). Studying the orientation of the present-day coastlines of Gotland, it is evident that the preservation of the island itself is partly inherited from larger-scale tectonic zones. The strata dip less than 1° towards the southeast, although this may vary substantially on a local scale, especially in the vicinity of major reef complexes. On a broad scale, the stratigraphy is easily comprehensible, with the oldest strata in the northwest of the island and successively younger strata towards the southeast (Fig. 2). The strata show a distinct facies transition southwestward along the erosional strike. Argillaceous limestones and marls of an open marine shelf facies dominate on western Gotland, whereas toward the NE contemporaneous sediments of shallower facies were deposited. This clearly shows that the palaeo-contour lines cannot have run SW-NE as proposed, e.g., by Bassett et al. (1989) but must have had a more E-W or ENE-WSW direction (cf. figure 6 in Baarli et al. 2003).

The Silurian subsurface stratigraphy of onshore Gotland is not known in detail. Apart from borings conducted by OPAB (Oil Prospecting AB) or quarry operators, often unavailable or inadequately described for the research community, these rocks have primarily been known from five borings (Fig. 2); the Burgsvik boring (Hede 1919), Visby (Hedström 1923), File Haidar (Thorslund and Westergård 1938), and the När-1 and Grötlingbo-1 borings (Snäll 1977). Additional shallow borings on southern Gotland were examined by Pusch (1969). At present, the cores still preserved are variably sampled and, due to their wide spatial distribution, of limited value for detailed stratigraphic analysis. For this reason, new cores have recently been recovered from parts of the Wenlock and Ludlow (co-ordinated by M. Calner), namely Hunninge-1 (42 m; GPS N: 6364427 O: 1647619), Linde-1 (102 m; GPS N: 6353227 O: 1654476), Burgen-1 (50 m; GPS N: 6348342 GPS O: 1667496), Ronehamn-1 (30 m; GPS N: 6342406 O: 1663083), and Uddvide-1 (70 m; GPS N: 6333020 O: 1653025)(Fig.2).

The present geomorphology of Gotland is the result of Quaternary glacial erosion and repeated post-glacial sea-level change. These processes have accentuated the topography into flat low-lying farmlands where argillaceous sedimentary rocks occur and somewhat higher, forested areas where more weathering resistant limestone occur.

1.2.1 Carbonate platforms of Gotland

Carbonate platforms are marine ecosystems that are born, developed, and, for various reasons, eventually die (Bosellini 1989). The strata on Gotland reflect a series of stacked carbonate platform generations. Individual platform 'life cycles' do not correspond with the subdivision of formations and/or groups in use, although their boundaries may coincide. The minor dips indicate that individual platforms were of ramp type. However, intermittent development of extensive stromatoporoid-coral reef barriers (Hadding 1941; Manten 1971; Flodén et al. 2001; Bjerkéus & Eriksson 2001) indicates that these ramps developed steeper gradients with time, and transformed into distally steepening ramps, or even rimmed shelfs, in their mature stages. Individual platform generations are generally some tens of metres thick – from the incipient transgressive surface to the development of prograding reef complexes – and separated by variably pronounced stratigraphic discontinuities. Poorly to moderately developed palaeokarst or other evidence for subaerial exposure is associated with several of these discontinuities, e.g., within the middle Slite Group (Laufeld & Martinsson 1981), at the top of the Slite Group (Calner 2002), top Klinteberg Formation (Eriksson, in press), lower and middle Hemse Group (Keeling & Kershaw 1994), within the lower Eke Formation (Cherns 1982), and within the uppermost Sundre Formation (Kano 1989). A few of these discontinuities have been traced in seismic lines across the east Baltic Sea to Estonia (Flodén 1980; see also Calner & Säll 1999). The related hiatuses are very short ranging or beyond biostratigraphic resolution on Gotland but increase substantially in magnitude in Estonian outcrops (cf. Jeppsson et al. 1994). However, despite the indications for Silurian subaerial exposure, especially in the shallower facies areas on the eastern part of the island, it must be assumed that at the end of the Silurian, a sedimentary cover (of unknown thickness) protected the whole succession. A Pridoli coastline south of Gotland (Bassett et al. 1989) is improbable because the "young" carbonates would have been affected by strong erosion and karstification.

1.2.2 Depositional environments

A detailed description of the facies complexes occurring on southern Gotland is given in Samtleben et al. (2000), who distinguished 12 different facies. The variation in lithofacies may locally be considerable. On a broad scale, however, three major depositional environments may be resolved, each with different lithofacies associations. These are:

1) *Slope and basin areas*. Argillaceous skeletal limestones and marls with a mud-wackestone texture and thin shell coquinas dominate seaward of reef barriers and/or below the storm wave-base. These strata are often developed as limestone-marl alternations showing the typical "differential diagenesis", i.e. early-cemented limestones and compacted marls (Munnecke & Samtleben 1996). Fragments of brachiopods, trilobites, and ostracods dominate the skeletal composition. However, Cherns & Wright (2000) have shown that a massive early diagenetic dissolution of originally aragonitic-shelled organisms (e.g. molluscs) has taken place resulting in a strong bias in the preserved fauna, except where early silicification due to weathering of bentonites has silicified such shells (Laufeld & Jeppsson 1976). Bioturbation was generally abundant, e.g. as cm-wide burrows or as *Chondrites*-like mottling. Detrital clays are volumetrically important and form a substantial part of this association. The abundance of interbedded skeletal pack- and grainstone beds increases with increasing proximality.

2) *Biohermal, biostromal, and shoal areas*. These areas are characterised by stromatoporoid-coral reef complexes, related coarse-grained skeletal float- and rudstone reef flank deposits and well sorted crinoidal/peloidal grainstones. Basinward, patch-reefs normally less than 100 m in diameter dominate whereas toward shallower environments (generally toward the NE) these bioherms grade into biostromes. The patch-reefs were built mainly by stromatoporoids and tabulate corals. Crinoids, bryozoans, and rugose corals are common. The reefs on Gotland are mostly composed of pale boundstones, often with a micritic matrix. The colour varies from greenish to brownish-reddish. However, depending on the local environmental conditions, the composition, size, and structure of single reefs can vary considerably. Inter-reef strata may vary in composition from traction deposits such as cross-bedded skeletal and/or crinoidal grainstones, to very fine-grained mud- and wackestones. The biostromal areas, which are developed on eastern Gotland, can cover areas of more than 100 km^2 (Kershaw 1990; see Calner et al. 2004a, this volume). The biostromes were built mainly by stromatoporoids, which grew densely stacked and interlocking (Kershaw & Keeling 1994). Often, the stromatoporids are tilted, or transported and rounded. The sedimentary matrix between the colonial organisms normally is a grainstone. Truncation surfaces are common indicating high-energy, shallow-water environments, and repeated interruptions of reef growth.

3) *Back-reef and lagoonal areas*. The back-reef facies on Gotland comprises mostly light-brownish, strongly bioturbated mudstones and wackestones, with varying contents of benthic organisms from an impoverished marine fauna. In parts, oncolites are very common. Individual oncoids often show irregular cortices due to periods of stationary growth. The sediments were deposited in sheltered, calm areas behind the reef fringe. In places were the water energy was higher, thin-bedded, fine- to medium-grained grainstones and packstones were deposited, and occasional abraded hardgrounds are observed. In extremely shallow environments, the sediments are characterised by rapid alternations of different rock types, often from bed to bed. Ripple marks and desiccation cracks indicate very shallow water conditions. Correspondingly, the fossil content changes abruptly. Many beds are devoid of fossils whereas others show extremely high abundances of, e.g., rhynchonellid brachiopods, bivalves, or gastropods, but generally with a very low diversity.

A fourth environment, genetically unrelated to the platforms, is represented by the volumetrically less important mud-, silt-, and sandstones that prograded into the Gotland area twice, in the Late Wenlock (Fröjel Formation), and in the Late Ludlow (Burgsvik Sandstone of the Burgsvik Formation). Both units contain a marine fauna, although in certain intervals strongly impoverished (e.g. Stel & de Coo 1977). The siliciclastic material was derived from western source areas. Sedimentary structures like cross bedding, flute marks, tool marks, ripple marks and hummocky cross stratification indicate periods of rapid deposition.

Bentonites are a scientifically very important component of the strata. Several are found through the successions of the När-1 and Grötlingbo-1 cores but are in outcrops as yet only known in the Llandovery and the Wenlock. At least some of them caused beautifully silicified fossils (Laufeld & Jeppsson 1976; Stridsberg, 1985; Liljedahl 1991; Cherns & Wright 2000). The bentonites are also important for the Silurian radiometric time scale (Odin et al. 1986) and have been used in studies of the global bolide-impact frequency (Schmitz et al. 1994). They have been fingerprinted as an aid for long distance correlations (Batchelor & Jeppsson 1994, 1999), and have been used for intra-basinal high-resolution correlations Jeppsson & Männik 1993; Jeppsson & Calner 2003; Calner et al. 2004b).

1.2.3 Sequence stratigraphy

Sequence stratigraphy is the study of stratal relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by unconformities. Sequence stratigraphical concepts have evolved tremendously over the years, and more recently they have been modified for ancient carbonate basins, which respond to relative sea-level change in a fundamentally different way from their siliciclastic counterparts. Since the early 1980's, sedimentologists and stratigraphers have conducted basin analysis by utilizing sequence stratigraphical concepts, considering relative sea-level changes to be the primary control on the facies architecture of basin fills and on the stacking pattern of depositional systems such as carbonate platforms. Unfortunately, global eustatic sea level changes are strongly invoked in sequence stratigraphy, despite the fact that true sea level change is not required to form depositional sequences (Burgess 2001). In stacked carbonate sequences, such as those on Gotland, the influence of a changing sea level can be unambiguously identified only if subtidal successions are capped by subaerial exposure surfaces (Burgess 2001), proven, e.g., by carbonate cements precipitated from freshwater. However, many features previously thought to be typical of freshwater diagenesis are now also known to originate during shallow marine burial diagenesis (Melim et al. 1995, 2002), and subaerial exposure surfaces often are difficult to distinguish from submarine hardgrounds.

A detailed sequence stratigraphic framework for the Silurian of Gotland remains to be established. However, a few comments on the relationships between the exposed strata and relative sea level change can be made. Pure limestone units, especially those including reefs, enclosed

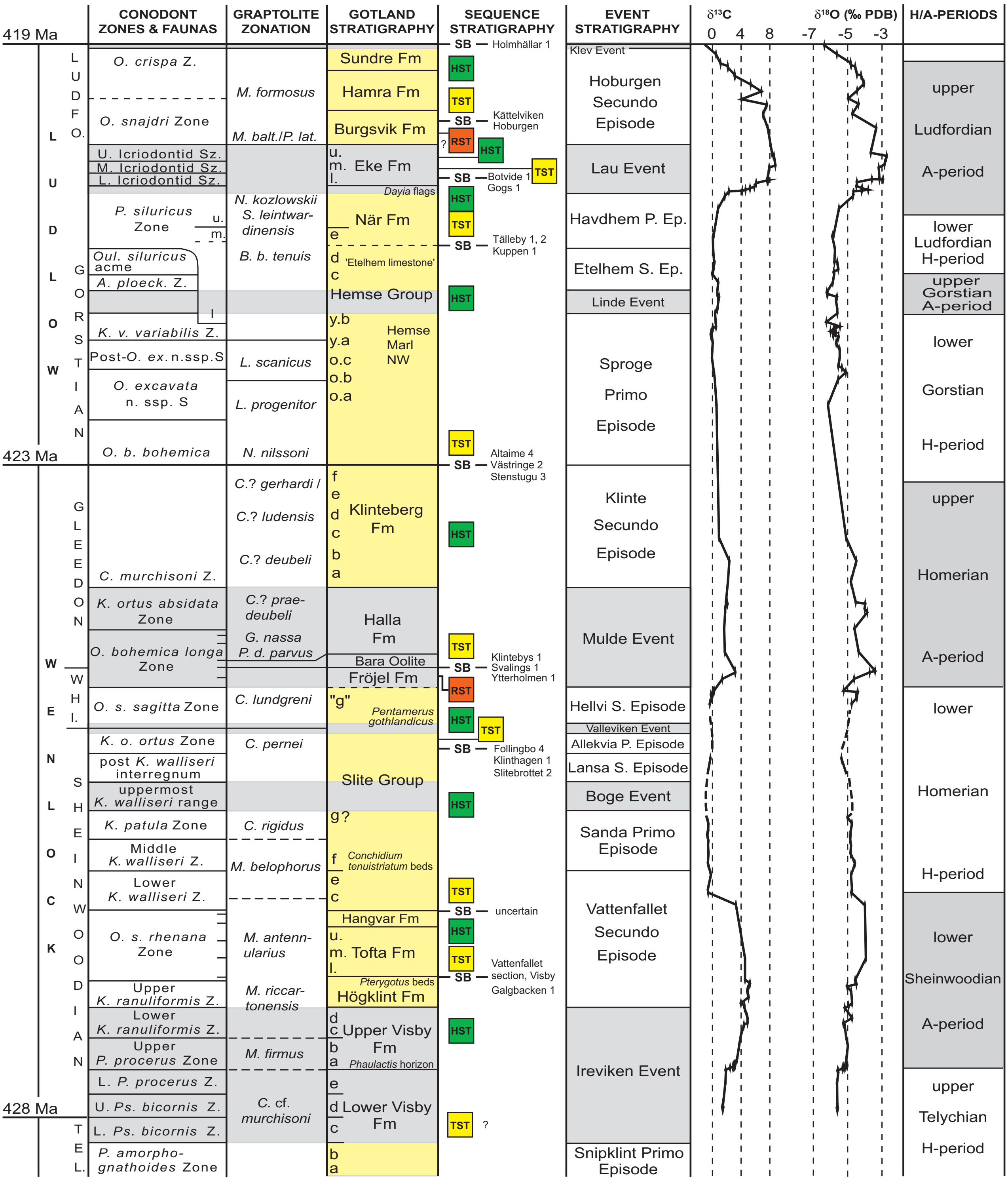

Fig. 3. Stratigraphic framework showing conodont zones and faunas and their relationship to graptolite biostratigraphy, stratigraphic units on Gotland, and a provisional sequence stratigraphic framework for the exposed strata. Also shown is the episodes and events of Jeppsson (1998) and Jeppsson & Aldridge (2000), and development of stable carbon isotopes and H/A-periods of Bickert et al. (1997), Samtleben et al. (2000), and Munnecke et al. (2003). The figure is partly based on stratigraphic data from Jeppsson (1997c) and Jeppsson (in manuscript), Calner (1999), and Calner & Jeppsson (2003).

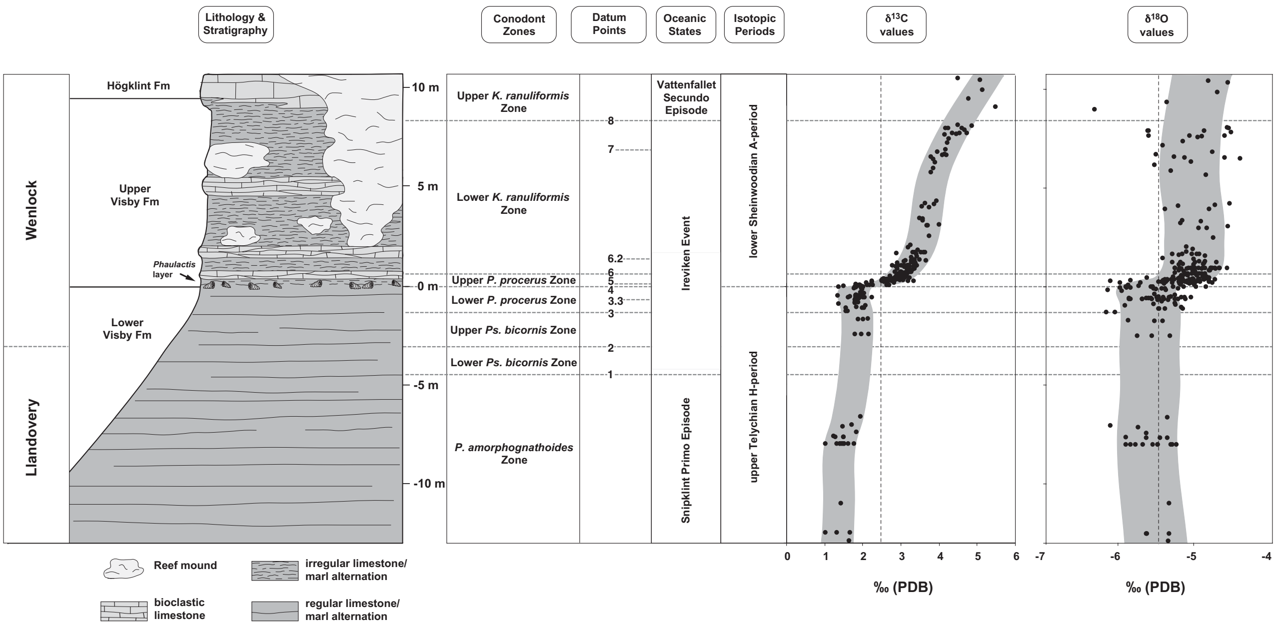

Fig. 4. Combined diagram of schematic weathering profile of the Lower and Upper Visby Formation (after Samtleben & Munnecke 1999), conodont zonation and extinction datum points (after Jeppsson et al. 1994; Aldridge et al. 1993; Jeppsson, 1997a, c), and δ18O and δ13C values (compiled from 9 localities, Munnecke et al. 2003).

in marls are surprisingly often taken as an indication of sea level lowering, because only the local (regressive) facies succession is considered. The discrimination of *depositional depth* and *true sea level change* is therefore of major importance in carbonate basins. Carbonate and siliciclastic basins respond fundamentally different to relative sea-level change. The different responses are inherited from the basic fact that siliciclastics are transported *to* the basin whereas carbonates form *in situ*, i.e., *within* the basin. In contrast to the siliciclastic depositional system, carbonate platforms produce and deposit most of their sediments during highstand situations (Schlager et al. 1994). This is primarily due to the increased areal extent of platform flooding and the associated increase in space available for skeletal carbonate production. This is well illustrated on Gotland. Here, the expansion and thickening of reef complexes across distal platform marls imply that reef barriers formed during relative highstand of sea-level (Calner & Jeppsson 2003). Such substantial progradation of reef complexes onto argillaceous limestone and marl deposited in deeper, distal settings can be seen e.g. in the Lower Wenlock north of Visby and in the Late Wenlock of the Klintehamn area. Further, substantial falling stage or lowstand deposits are rare in the majority of intracratonic carbonate platform successions, and also on Gotland. This is partly due to the comparably modest relief of carbonate basins. The siliciclastic-rich Gannarve Member (Fröjel Formation) on western Gotland (section 2.3.1) is an example of such deposits (Calner 1999).

At this stage, the cyclic development of barrier reef complexes, unconformities (including subaerial exposure surfaces), and general facies trends permit establishing only a provisional sequence stratigraphic framework (Fig. 3). Based on onshore mapping (Manten 1971) and offshore seismic reflection studies (Flodén et al. 2001; Bjerkéus & Eriksson 2001), ca 10 more or less well developed barrier reef complexes evolved during Wenlock–Ludlow time. If the ICS time scale is applied, individual cycles range over ca 1 Ma. If utilising barrier reefs as indicators of highstand systems tracts, this would indicate that the strata on Gotland correspond to about ten more or less developed depositional sequences. The successive dislocation of reef complexes towards the basin-centre implies a forestepping sequence stacking, i.e. that lateral infilling of the basin was important, and thus the creation of accommodation space (subsidence rate) was limited.

2. GENERAL LITHOLOGY AND A REVISED BIOSTRATIGRAPHIC FRAMEWORK

Traditionally, studies on Gotland geology rely heavily on the stratigraphic framework of Hede (1921, 1925, 1960) who, based on many seasons of careful mapping, subdivided the succession into thirteen formations and groups, from oldest to youngest: Lower Visby, Upper Visby, Högklint, Tofta, Slite, Halla, Mulde, Klinteberg, Hemse, Eke, Burgsvik, Hamra, and Sundre. This framework has successively been refined and revised. Based on large conodont collections, a detailed conodont zonation and stratigraphic subdivision is now possible, e.g. for the late Telychian – early Homerian (Jeppsson 1997c; in prep.), middle Homerian (Calner & Jeppsson 2003), Gorstian – early Ludfordian (Jeppsson & Aldridge 2000; Jeppsson, in prep.), and for the late Ludfordian – early Pridoli (Jeppsson, in manuscript; in prep.); data below are from these sources unless references are given. The stratigraphic resolution of conodont zones in carbonate strata is comparable to that of the most detailed graptolite zonation in shale successions. An updated and substantially constrained stratigraphic framework is soon to be published and the most important changes are reviewed below and illustrated in Figures 2 and 3.

2.1 Lower and Upper Visby formations

2.1.1 Lithology

The Lower and Upper Visby formations form the oldest outcropping units on Gotland. These two formations are developed as a prograding limestone-marl alternation. The exposed part of the Lower Visby Formation consists of up to 12 m (at Lusklint 1) of fossil-poor, regular alternations of 2-5 cm thick, wavy-bedded to nodular argillaceous limestones (predominantly mudstones) and roughly 10 cm thick marls. The base is not exposed. The carbonate contents of the marls scatter around 20%, those of the limestones around 70% (Munnecke 1997). In some areas, up to 1 m thick *Halysites*-biostromes are observed. Thin layers of brachiopod and bryozoan debris are intercalated irregularly. The sequence was deposited below storm wave base and below the photic zone in a distal shelf environment. There are three distinct bentonites in the Lower Visby Formation: the Lusklint, the Storbrut (very thin), and the Ireviken bentonites (Batchelor & Jeppsson 1994).

The Upper Visby Formation is up to 12 m thick. Bedding is not as regular as in the Lower Visby Formation. The limestone-marl ratio increases, and detritic limestones (wacke- to grainstones) become more abundant, especially in the upper part of the formation. Erosional surfaces, ripple marks, and calcareous algae point to increased water energy and a depositional environment within the photic zone. Carbonate content is considerably higher than in the Lower Visby Formation, averaging 80% for limestones and 40% for marls (Munnecke 1997). The abundance of brachiopods, bryozoans, crinoids, tabulate corals, and stromatoporoids increases. The Upper Visby Formation contains numerous reef-mounds, ranging in size from a few decimetres to many metres. The main reef builders are tabulate corals, but also stromatoporoids and rugose corals.

2.1.2 Biostratigraphy

Conodonts show that Hede's (1921) definition of the boundary between the Lower and Upper Visby Formations coincides with a faunally important boundary, Datum 4 of the Ireviken Event (now identified globally). This datum coincides with a pronounced increase of $\delta^{13}C$ values and a distinct lithological boundary that is identifiable in the field (Fig. 4). There are four important criteria for a correct identification of the boundary: 1) In places where active erosion is moderate, the Lower Visby Formation weathers to a clay-covered slope. In contrast, due to the higher carbonate content the Upper Visby Formation weathers to a vertical wall. 2) *Palaeocyclus porpita*, the button coral, is limited to the Lower Visby Formation, and ranges to its top. 3) *Phaulactis angusta* (Lonsdale), det. Keith Mitchell 1990, a very large solitary rugose coral, had a mass occurrence in the basal bed of the Upper Visby Formation and this marker-horizon can be traced along a distance of over 50 km (Mitchell 1990; Samtleben et al. 1996; Jeppsson 1997a, c; see Plate 1 in Munnecke et al. 2003). 4) A thin layer of pyrite marks the exact boundary; where it is within a limestone bed, the pyrite may be seen as a sparse line of specular pyrite crystals, whereas it has weathered to a rust layer in marls. Previous confusion and reports of fossils on the 'wrong side of the boundary' are due to inconsistent use of Hede's definition, even in the geological map descriptions. The only exception hitherto is a single report of *P. porpita* in the Upper Visby Formation (Sheehan 1977).

Conodont correlations with the type locality show that the Llandovery-Wenlock boundary coincides with Datum 2 of the Ireviken Event (Jeppsson 1997c). Therefore, at Lusklint 1 for instance, up to ca 10.1 m of the Llandovery is exposed on Gotland.

2.2 Högklint, Tofta, and Hangvar formations

2.2.1 Lithology

The up to ca 35 m (Hede 1960) thick Högklint Formation is well exposed along the NE coast of Gotland, and the spectacular patch-reefs along that coast belong to this formation. The unit is a reef-complex, composed of large patch-reefs and inter-reef limestone (Hede 1940; 1960; Manten 1971; Riding & Watts 1991; Watts & Riding 2000). The most abundant reef-builders are stromatoporoids, along with tabulate corals, calcareous algae, and cyanobacteria. The formation can be subdivided into four subunits (a-d). The two lower units include large bioherms, while the upper parts (upper b and c) are dominated by biostromes. The top of subunit c is an unconformity, only locally overlain by subunit d.

The Tofta Formation is at least ca 15 m thick and bounded by unconformities throughout much of the outcrop area. It consists of thin to thick bedded limestone rich in oncoids (calcifying cyanobacteria and problematica), and reflects deposition in a restricted, marginal marine environment (Hede 1940, Riding & Watts 1991).

A new formation, the Hangvar Formation, is to be introduced between the Tofta Formation and Slite Group (Figs. 2, 3). It similarly includes marls as far SW as near Paviken (previously Slite Marl), limestones S to NE of Visby (previously Slite Beds, units a and b) and north-eastwards across Fårö (previously Högklint Beds). A distinct reef generation occurs within this interval, low in the Hangvar Formation, or possibly in the upper Tofta (the spectacular sea stacks on northern Fårö probably represents this formation). The combined thickness of the Tofta and Hangvar Formations exceeds 20 m.

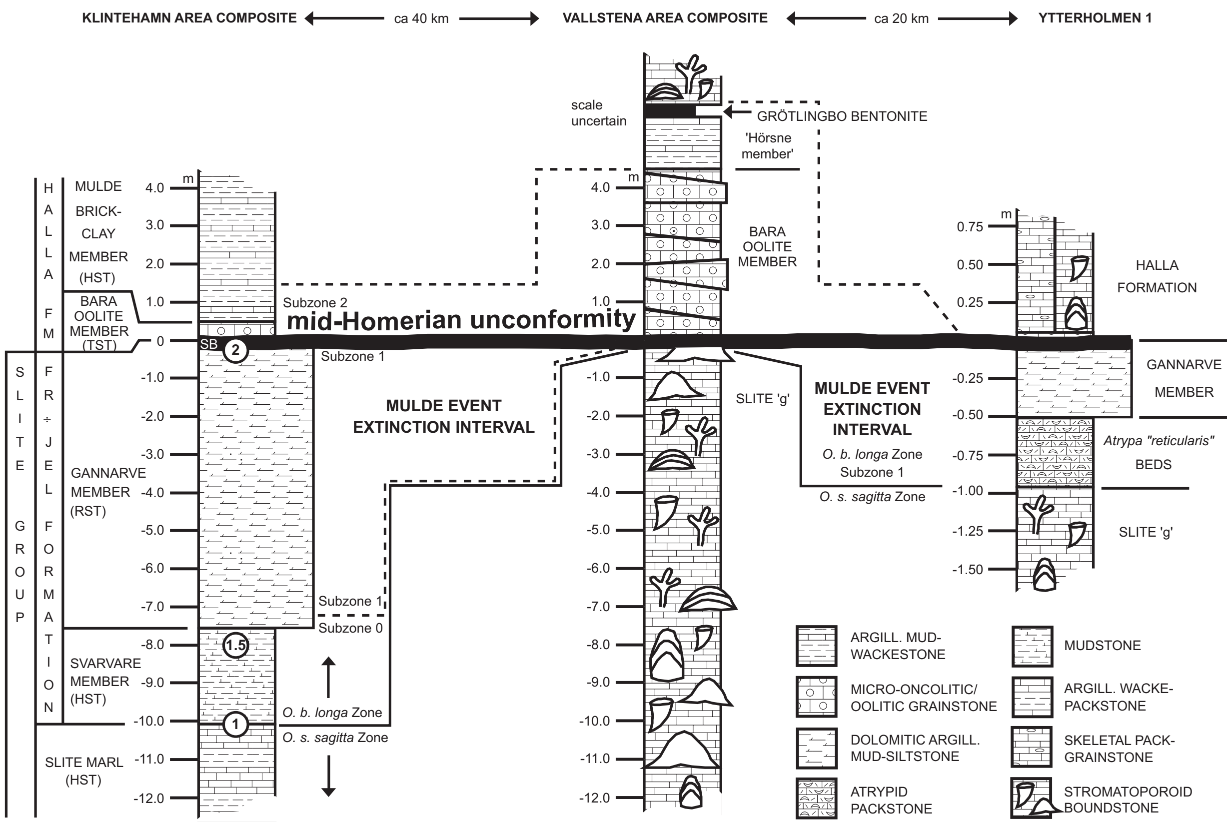

Fig. 5. General facies associations and stratigraphic correlation of the Slite Group–Halla Formation across Gotland. Thickness data and sequence stratigraphic subdivision in the Klintehamn area composite are from Calner (1999). The numbers 1, 1.5 and 2 in the Klintehamn composite profile indicate the three datum planes (points of extinction) of the Mulde Event identified by Jeppsson & Calner (2003). SB = sequence boundary, HST = highstand systems tract, RST = regressive systems tract, TST = transgressive systems tract. From Calner et al. (2004).

2.2.2 Biostratigraphy

Establishing and applying a sequence of subzones of the *O. s. rhenana* Zone solves the old problem regarding the relation between the Högklint and the Tofta Formations. The previously assumed large gap between Högklint c and Slite c on Fårö and parts of main Gotland does not exist. The true Högklint Formation is found in a narrow strip along the coast, north-eastwards as far as Kappelshamnsviken (Fig. 2), only. The Tofta Formation ranges from marls in the SW (previously mapped as Slite Marl) and limestone northeast thereof (all the strata previously included in the Tofta), reaching across Kappelshamnsviken as far as to Fårö (previously included in the Högklint Beds). Lower, middle and upper parts of the Tofta Formation can be separated as far as they are exposed. Tofta is rich in algal limestone, and at least parts of the strata now identified seems to be so too, e.g. oncolites appeared between strata identified as upper Högklint and lower Tofta, respectively, at a recently identified section on the western shore of Kappelshamnsviken.

These conodont-based stratigraphic revisions also remove the discrepancy in the chitinozoan ranges on Gotland and in East Baltic cores (Nestor & Einasto 1997), and the chitinozoan zonation of Nestor (1994) can now be recognised on Gotland and correlated with the conodont zonation.

2.3 Slite Group and the Halla and Klinteberg formations

2.3.1 Lithology

The Slite Group is exposed over a large area on northern mainland Gotland and on Fårö (Fig. 2). It is a complex and lithologically highly variable unit. The lower part, some 20 m thick (Hede 1960) is dominated by relatively pure limestone along most of the strike. This is followed by more limestones and above that, marls across Gotland. The uppermost formation of the Slite Group is the Fröjel Formation (Calner 1999). This formation is 9-11 m thick in the Klintehamn area and 0.5 m thick on NE Gotland (Ytterholmen). The formation is absent between these areas, but its former presence here is revealed by a residue micro-conglomerate in the basal centimetres of the overlying Halla Formation (see below). In the Klintehamn type area, the formation is subdivided into two members. The Svarvare Member is a 2-3 m thick, slightly calcareous mudstone that differs fundamentally from the underlying Slite Marl in its dark colour, comparably sparse bioturbation, and the lack of stromatoporoids, tabulate corals, and regularly alternating marls and limestone. This member includes an interval with an abundant but low-diversity graptolite fauna. The overlying Gannarve Member is characterised by shallowing associated with storm-dominated deposition of fine (silt-fine sand) siliciclastics across the platform. This member shows a rapid facies transition from laminated mudstone and siltstone, locally with graptolites, in its lower parts to hummocky cross-stratified strata, and eventually to intertidal epikarst at the upper boundary, where it is unconformable with overlying sediments (Calner 1999; 2002). The upper boundary of the Slite Group is a basin-regional unconformity that truncates different units along strike; the Fröjel Formation in the southwest (Klintehamn area and the Hunninge-1 core) and northeast (Ytterholmen), as well as between these areas; the Slite "g" or the *Atrypa "reticularis"* Beds depending on the extent of erosion (Fig. 5; Calner et al. 2004).

The Halla Formation rests on the mid-Homerian unconformity, and reflects the initiation of a new platform generation. The basal Bara Oolite Member is a transgressive peloidal oolite or micro-oncolitic grainstone formed in the shallow subtidal to intertidal environment. The unit is exposed in a narrow belt across most of the island, thinning from ca 4.5 m on east-central Gotland (Bara area) to ca 0.3-0.5 m in the Klintehamn area on west-central Gotland, where it pinches out. On eastern Gotland, the oolite is overlain by argillaceous limestone with small reefs and back-reef lagoonal, oncoidal packstone. Coeval strata on western Gotland were formed in deeper water and consist of argillaceous limestone and marl.

The Klinteberg Formation is a ca 70 m (Hede 1960) thick unit predominantly composed of crinoidal limestone and, especially in its upper parts, biohermal and biostromal limestone (Frykman 1989). Several metres thick, crossbedded units of crinoidal pack-, and grainstone are common throughout this unit. On eastern and central Gotland, the top of the formation is a conspicuously smooth unconformity with abundant clear-cut stromatoporoids, some of them more than one metre in diameter (Eriksson, in press). This unconformity is situated a few metres below the traditional stratigraphic level for the top of the Klinteberg Formation (Hede 1929).

2.3.2 Biostratigraphy

Conodont biostratigraphy permits splitting the Slite Group into at least 5 faunally and lithologically distinct formations. The Homerian succession of Gotland starts high in the Slite Group, that is, with the youngest Slite limestone and reef generation in the east (unit "g" of Jeppsson et al. 1994), and in the upper Slite Marl in the west. Revisions and refinements of the uppermost Slite – lowermost Klinteberg stratigraphy have been published by Calner & Jeppsson (2003), and Calner et al. (2004).

The overlying Halla Formation now includes also parts of the former Mulde Formation, a name introduced by van Hoepen (1910). Hede (1925) restricted it to strata on western Gotland, and extended it to include some immediately older and younger strata. Jeppsson & Calner (2003) divided his Mulde into three members: the Mulde Brick-clay Member, the Djupvik Member, and the informally named 'kronvald member', the latter forming a lateral facies equivalent to the more proximal parts of the Klinteberg Formation (cf. the map of Hede 1921). The former two members form distal equivalents to parts of the Halla Formation and therefore were included in that formation. For data on these and adjacent units, see Hede (1927a, b), Calner (1999), Calner & Säll (1999), Calner et al. (2000), and, in particular, Jeppsson & Calner (2003) and Calner & Jeppsson (2003).

The lowermost Klinteberg Formation includes a highly characteristic conodont fauna, the *C. murchisoni* Zone. The topmost Klinteberg includes another highly characteristic conodont fauna, with *Erika* cf. *divaricata*. Both faunas have hitherto been traced from eastern shore exposures to 5 km or less from the western coast. The faunas of the strata in between the *C. murchisoni* and *E.* cf. *divaricata* faunas, i.e. the major part of the Klinteberg Formation, are less well characterised, but each of the two distinct faunas refute the suggestion that the Wenlock-Ludlow boundary cut obliquely across the Klinteberg Formation (Bassett 1976, p. 216).

2.4 Hemse Group and the Eke, Burgsvik, Hamra and Sundre formations

2.4.1 Lithology

The Ludlow sequence of southern Gotland includes a wealth of rapidly changing lithofacies spanning from marlstone deposited below storm wave-base to oolites and stromatolites of intertidal origin, as well as local karst development and flat-pebble conglomerates.

The Hemse Group rests unconformably on the Klinteberg Formation, at least in central and eastern Gotland. On a broad scale, the western parts of the outcrop belt are dominated by marl and argillaceous limestone whereas shallow platform carbonates dominate the eastern parts. The eastern area is characterised by well exposed, stacked biostromes dominated by stromatoporoids (Kershaw & Keeling 1994; Samtleben et al. 2000; Sandström & Kershaw 2002). The När Formation (= the upper Hemse Group) consists of argillaceous, often laminated limestones and marls in the west and central parts of the outcrop belt and crinoidal limestone and reefs in the east (the Millklint Limestone of Hede, 1929). In the laminated deposits benthic fossils are nearly absent, except for coquinas with *Dayia navicula* (brachiopod), for which a pseudoplanktonic mode of life is discussed (Samtleben et al. 2000). The lamination and the very sparse occurrence of benthic fossils indicate unfavourable (probably anoxic or dysoxic?) bottom water conditions. The upper boundary of the Hemse Group is a discontinuity surface throughout the central and eastern parts of the outcrop belt.

he Eke Formation shows substantial changes in thickness and facies across its outcrop area. In the southwestern parts (Uddvide-1 and Ronehamn-1 cores), the formation is remarkably homogenous with regard to facies and thickness (ca 12.0-12.5 m thick) and composed of a shoaling succession of oncoid-rich wacke-, pack-, and grainstones, interbedded with marls. The oncoids generally have thick cortices, variable shapes, and co-occur with a diverse marine benthic fauna. In the Uddvide-1 drillcore, the lowermost part of the unit is composed of argillaceous crinoidal wackestone lacking oncoids. In the area of the Burgen outlier (Burgen-1 core), the formation thins substantially (Calner & Eriksson, in prep.). In the northeasternmost parts of the outcrop area, the Eke Formation consists of argillaceous biohermal accumulations and coarse-grained crinoidal grainstones and rudstones. Here, the lower parts of the formation exhibit karst features and stromatolites (Cherns 1982).

The Burgsvik Formation is the only coarse grained siliciclastic lithosome in the Ludlow of Gotland. Hede (1921) subdivided the Burgsvik Formation into the Burgsvik Sandstone and an overlying Burgsvik Oolite. Only the middle and upper parts of the formation are well exposed in coastal exposures and abandoned quarries on southernmost Gotland. The entire stratigraphy of the formation, including the lower parts, is today only represented in the Uddvide-1 core. In this core, the Burgsvik Sandstone is 31.12 m thick and consists of three primary lithofacies. The lower unit consists of dark shale and mudstone with rare fossils. The middle unit consists primarily of massive to laminated siltstone with abundant dewatering structures. The upper unit consists of 1-2 m thick bedsets of massive to laminated sandstone. Correlation to nearby exposures shows that the lamination in the upper member is related to large scale hummocky cross stratification. The conspicuous upper boundary of the Burgsvik Sandstone can be traced in outcrops and in the subsurface for ca 25 km, from Hoburgen to the area of Uddvide. The boundary is generally sharp and planar erosive but, in places, slightly irregular. This surface is overlain by the Burgsvik Oolite, which especially in the upper part is an oncolite rudstone with ooid-grainstone matrix. As with the Eke Formation, the Burgsvik Sandstone thins markedly towards the northeast. A west-east transect across southern Gotland shows the large-scale facies relationship, including two sandstone wedges separated by argillaceous platform carbonates.

The basal Hamra Formation consists of algal limestone with small bioherms. Bioherms and crinoidal limestones comprise the bulk of the formation.

The ca 10 m thick Sundre Formation is built by thick-bedded, coarse-grained crinoidal grainstones and massive stromatoporoid reef limestones.

2.4.2 Biostratigraphy

The Hemse Group can also be subdivided using conodonts (Jeppsson, in prep.). The Ludfordian uppermost Hemse – Burgsvik sequence on Gotland includes more substantial and more rapid facies changes than most older and younger intervals. A revised conodont zonation includes three zones, the *P. siluricus*, the Icriodontid, and the *O. snajdri* zones, and four subzones, the Upper *P. siluricus* Subzone, the Lower, Middle and Upper Icriodontid subzones (Jeppsson, in prep.). It permits the first high-resolution correlations across the island, and a more detailed stratigraphic subdivision of the strata. The Millklint Limestone, the main (unnamed), and the Botvide members of the När Formation (new formation, the upper part of the Hemse Group), the lower, middle, and upper Eke Formation, and the Burgsvik Formation are distinguished, resulting in a considerable increase in stratigraphic precision. Calculations based chiefly on biostratigraphic data from the När and Burgsvik cores, and the Vamlingbo drilling (Munthe 1921), indicate that the Ludlow strata on western Gotland are between 337 and 425 m thick instead of the 215 m given hitherto (Jeppsson, in prep.). New larger conodont collections from the Hamra and Sundre Formations indicate that a better stratigraphy of that interval is feasible and that the succession reaches at least to the top of the Ludlow.

3. EVENT STRATIGRAPHY AND STABLE ISOTOPES

3.1 Event stratigraphy

Event stratigraphy and its relation to changing oceanographic conditions is a topic that attracts much scientific attention today. This stratigraphical approach utilizes patterns of biotic extinction, innovation, and recovery among different lineages of taxa to delineate the architecture of biological extinctions. Although the majority of the major Phanerozoic extinction events are close in time to eustatic sea-level change (Hallam & Wignall 1999), extinctions do not correlate with the formation of sequence boundaries in individual basins, simply because different basins have different tectonic histories that may mask or enhance sea-level change. Nevertheless, it has been common to follow sequence stratigraphical concepts and identify sequence boundaries as important levels for past extinctions. The risk of pigeon-holing is obvious since stratigraphic resolution has often been far too low for identifying true ends of taxa, e.g. due to the Signor-Lipps effect, or as a result of sampling errors. The collection size and sampling density are of fundamental importance for a reliable stratigraphy.

3.1.1 Oceanic and climatic cycles

As recent as in 1991, Boucot concluded that no mass extinction had occurred during the Silurian. This (incorrect) conclusion was due to inadequate precision even in the best correlations of Silurian carbonate sequences – where most known taxa are found. The successively improved conodont zonation remedied this situation, and the first Silurian events were found.

An empirical model connected all of the then known changes during two Silurian cycles to a single cause;

transitions in oceanic state (Jeppsson 1990). The model describes two possible oceanic states with initially stable oceanic conditions, and how these gradually became destabilised. Among the many characteristics of the episodes it may be mentioned that secundo episodes were characterised by a more arid climate at low latitudes favouring the expansion of reefs and associated sediments throughout the tropics whereas the more humid climate during primo episodes resulted in increased transport of terrigenous material to the sea, favouring argillaceous limestone deposition. Some general characteristics of the oceanic model are summarised in Fig. 6.

The differences between primo and secundo episodes were so large that stable carbon isotope differences were also predicted (Jeppsson 1990). Since the publication of this model it has become clear that primo episodes are associated with low stable isotope ratios while secundo episodes are associated with high stable isotope ratios and isotopic excursions (Talent et al. 1993; Samtleben et al. 1996, 2000; Wenzel & Joachimski 1996; Wenzel 1997; Saltzman 2001; see chapter 3.2).

Events – brief intervals with unstable oceanic conditions – can develop after the end of an episode, causing both transient faunal changes and extinctions (even mass extinctions), as well as sedimentary and isotopic effects. Most importantly, this model can be tested: it predicted then unknown effects, e.g. where to search for Lazarus taxa. Some indications were found quickly (Jeppsson 1997) and confirmed with larger collections (see figure 3 in Jeppsson 1998). The model describes four potential kinds of events with different characters (Jeppsson 1998a). Two kinds of events were known then during the Wenlock and Ludlow, and a secundo-primo event has since been found (Jeppsson & Aldridge 2000) but the search for an example of primo-primo events continues. This part of the model has been very useful in the field, predicting where a more detailed collecting effort should reveal unknown events. Most of the minor events had only, or mainly, transient faunal effects, and can not be detected by comparing faunas from before and after the event. Their lithological effects were however, typical (and revealed their existence) although less widespread (Jeppsson 1993, 1998; Aldridge et al. 1993; Jeppsson et al. 1995; Jeppsson & Aldridge 2000).

Three major Silurian events were detected (Jeppsson 1993). In addition to faunal and sedimentological changes, these also resulted in higher $\delta^{13}C$ values (see chapter 3.2). These three events have already been detected in over 50 areas using conodonts, graptolites, and stable isotopes, from Alaska to Australia.

Finding the cause of an event must start with studying the sequence of changes during the event. This requires a much higher stratigraphic resolution for the event interval than needed to find the event. A five fold increase in the resolution and precision of the intervals containing the three major events has now been achieved (Jeppsson 1997c; in manuscripts; Calner & Jeppsson 2003). High-resolution stratigraphy has revealed that conodont extinctions during these events were stepwise (Jeppsson 1997a, c, in prep.; Jeppsson & Calner 2003). The 1990 model did not permit detailed interpretations of the changes during the events. The later incorporation of Milankovitch effects remedied this (Jeppsson 1997a). A severity scale for Silurian events has been based on the faunal composition, chiefly the response of surviving taxa, permitting comparison of the severity (as felt by the conodonts) of different events and datum points (Jeppsson 1998). In contrast, extinction percentages are not fully comparable since the biota at the start of two events or at the onset of two datum points differ from each other. Faunal and sea level changes, as well as the sedimentary succession during the events fit well with predictions based on the oceanic model. Extinctions were caused by brief severe drops in primary planktic productivity, causing starvation among planktic larvae (Jeppsson 1990).

3.1.2 The Ireviken Primo-Secundo Event

On Gotland, the start of this event is recorded in the upper part of the Lower Visby Formation, with its end near the top of the Upper Visby Formation. Like the Mulde and Lau events (reviewed below), this event reached a severity of 6.2, the highest point on the severity scale yet defined (Jeppsson 1998). It lasted ca 0.2 Ma but nearly all extinctions took place during the first 0.1 Ma (Jeppsson 1997a). Conodont extinctions during the Ireviken Event were stepwise and literature data have permitted most steps to be identified globally (Jeppsson 1997a, c). Datum points 2 and 4 had the strongest effects. The rare literature data with a similar precision and resolution of other major clades show the same pattern. The total effects on the fauna were large, e.g. 80 % of the globally known conodont species disappeared (the highest percentage perished at Datum 2; Jeppsson 1998), and over 50 % of the trilobites on Gotland (Ramsköld 1985) at or very close to Datum 2. If other major clades turn out to have been hit similarly, the extinction percentage would be comparable with the weaker ones of the so called 5 big mass extinctions. The fact that the Ireviken Event remained unknown until recently illustrates well the previous state of the correlation of Silurian carbonates. Extinctions have hitherto been identified among conodonts, graptolites, brachiopods, corals, ostracodes, and polychaetes. As expected from the model, conditions during this (and other) primo-secundo event deteriorated stepwise whereas the recovery at the end of the event was fast.

This part of the sequence on Gotland is deposited in deeper water than most other parts (Gray et al. 1974), and no spectacular sequence of sedimentary changes has been identified there. Like in many other areas, marls dominated before the event and reef boundstone and associated sediments after the event. $\delta^{13}C$ values begin to increase during the Ireviken Event, marking the onset of the early Sheinwoodian (basal Wenlock) positive carbon isotope excursion (Talent et al. 1993; Samtleben et al. 1996; Bickert et al. 1997; Munnecke et al. 2003; Cramer & Saltzman, submitted).

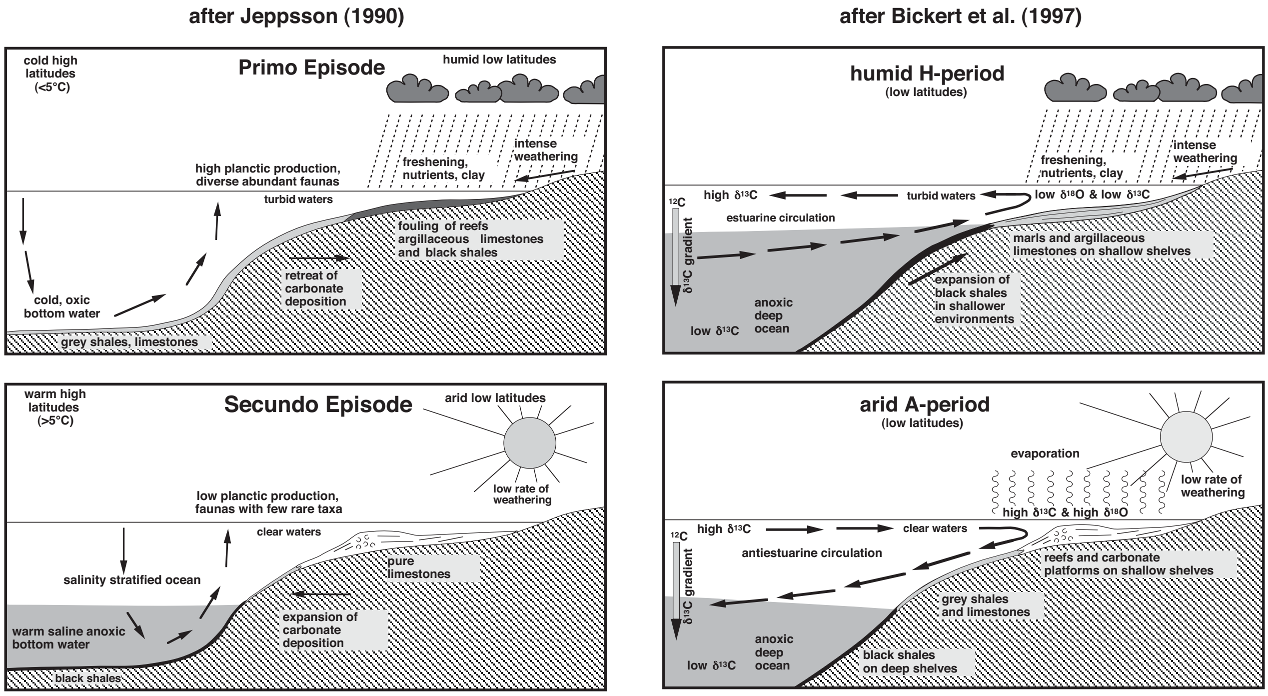

Fig. 6. Palaeoceanographic/climatic model of humid and arid periods in the Silurian, simplified after Jeppsson (1990) (left) and Bickert et al. (1997) (right). Bickert et al. (1997) have modified the Jeppsson model with respect to isotope geochemistry and oceanic circulation and restricted their model to low latitudes.

3.1.3 The Mulde Secundo-Secundo Event

On Gotland, the start of the Mulde Event is recorded at the base of the Fröjel Formation and the end at the top of the Halla Formation. The following brief review is partly based on Jeppsson & Calner (2003) unless indicated: Major graptolite extinctions during the middle Homerian (Late Wenlock) were observed and discussed before any other effect of a Silurian event had been described (Jaeger 1959). Historically, the Wenlock/Ludlow boundary had been placed at the point where the last of the doomed graptolites disappeared. The Wenlock /Ludlow boundary in graptolite facies was taken at this level until graptolite finds in the type area showed that the Wenlock Limestone Formation belonged in a younger zone. Laufeld et al. (1975, p. 220) found that the evidence available at that time indicated 'a world-wide event of great ecologic significance'… 'a regression caused by glaciation'. Application of the model of oceanic and atmospheric changes (Jeppsson 1990) showed that this interval is an oceanic event, the Mulde Secundo-Secundo Event (Jeppsson 1993; Jeppsson et al. 1995). The event started with Datum 1 (Jeppsson 1997b, 1998), and not at the extinction of the last of those taxa that characterize the *Cyrtograptus lundgreni* Zone [Datum 2 = 'the big crisis' (Jaeger 1959, 1991) = the C_1 (figure 6 in Urbanek 1970, 1993) = the *lundgreni* Event (Koren´ 1991) etc.]. This correction, for the first time, tied extinctions among benthic taxa to this event. The event lasted ca 0.35 Ma but nearly all extinctions took place during the first 0.06 Ma (during datum points 1, 1.5, and 2). Graphic correlation using graptolites and conodonts has provided a high-resolution timescale for correlating from coastal to deep oceanic sections and, thereby, also a detailed record of the sequence of changes during the Mulde Event (Jeppsson & Calner 2003). The identified sequence of changes includes, in order of the onset: two extinctions (Datum points 1 and 1.5), a $\delta^{13}C$ increase of ca 3‰ (Samtleben et al. 2000), the onset, maximum, and end of a sea level fall and rise of at least 16 m during 30 kyr, a third extinction (Datum 2), a disaster fauna, and a protracted faunal recovery. Published detailed records indicate that most of the graptolite species perished well before Datum 2, probably at Datum 1, like most of the expiring conodonts did. Literature data indicate considerable extinctions among chitinozoans (Nestor 1994, fig. 20/4) and shelly faunas (e.g. Hede 1921, p. 51-52), but as yet these have not been fully studied. Datum 2 reached a severity of 6.2 on the severity scale. As predicted by the model (Jeppsson 1998), conditions during this secundo-secundo event reached the low point quickly and then improved slowly during the main part of the event. The first two extinction steps and the first lithological and isotopic changes predated the onset of sea level change, falsifying a popular explanation for many events, that sea level changes caused the mass extinctions. The major sea level drop was hence "only" another effect of the oceanic disturbance, not the cause of the extinctions. A minimum amplitude of the drop (16 m) was measured, and the maximum amplitude and approximate duration (in the order of 30 ka) calculated; these fit well and only with a glaciation (previously, Silurian sea level cycles had usually been drawn as smooth curves with a 'wave length' in the order of 0.5 to several Ma.). Temporal resolution is now high enough to permit some comparison with Quaternary glaciations.

In addition to the global identification of extinctions of the last of the expiring graptolites at Datum 2 in graptolite successions, biological and physical effects of the Mulde Event have now been identified in shallower successions on Gotland (Jeppsson et al. 1995; Calner 1999; 2002; Calner & Säll 1999; Calner et al. 2000; Calner & Jeppsson 2003; Jeppsson & Calner 2003; Calner et al. 2004), Britain (Jeppsson et al. 1995), Bohemia (Kríz 1992:16; Kríz et al. 1993; Jeppsson et al. 1995), Estonia (Nestor 1997), Nevada (Berry 1998), Arctic Canada (Lenz & Kozlowska-Dawidziuk 2001), and preliminarily in the central USA (Mikulic & Kluessendorf 1999; Calner et al. 2001). Previously described local effects can now thereby be placed into a broader context. In addition to loss of biota and sedimentary changes, major stable isotope perturbations beginning during the Mulde Event have been widely recorded (Samtleben et al. 1996, 2000; Kaljo et al. 1997; Zimmerman et al. 2000; Saltzman 2001).

3.1.4 The Lau Primo-Secundo Event

On Gotland, the start of the Lau Event is recorded at the base of the Botvide Member (När Formation), and the end at the top of the Eke Formation. The Lau Event caused considerable extinctions and other faunal changes. Effects have hitherto been found in acritarchs, chitinozoans, corals, polychaetes, brachiopods, ostracodes, trilobites, tentaculites, graptolites, conodonts, and fishes. Imprecise knowledge of range-ends hampers calculation of extinction metrics but a loss, globally, of at least 30 to 50 % of the species seems probable. Among conodonts, no platform-equipped taxon survived. The community structure changed also, and low diversity conodont faunas strongly dominated by a single taxon developed during the most severe part of the event, similar to the Ireviken and Mulde events. As during other events studied in some detail, extinctions were stepped. The number of datum points and their exact position has not yet been identified with enough precision. The many changes during the event permit high-resolution correlations, based on conodonts, $\delta^{13}C$, and lithology changes. Across a wide range of different facies the locally typical sediment production was replaced by formation of other, often more unusual sediments. This continued into the immediate post-event time.

Jeppsson & Aldridge (2000) reported the event on Gotland, in the Welsh Borderland, Austria (based on data in Walliser 1964), Poland (data in Urbanek 1993, 1997), and New South Wales (data in Talent et al. (1993). The zone fossil *Polygnathoides siluricus* became extinct during the early part of the event, identifying the event globally and facilitating the identification of the interval of interest for isotope sampling and other studies.

A positive $\delta^{13}C$ excursion started at the beginning of the event, increased through it, and culminated near its end; its amplitude is up to 9‰ on Gotland. This excursion has been identified – with varying amplitudes - on Gotland (Samtleben et al. 1996; 2000), in Skåne (Wigforss-Lange 1999), Latvia (Kaljo et al. 1997), Bohemia (Lehnert et al. 2003), in the Carnic Alps (Wenzel 1997), in Queensland (Talent et al. 1993), Oklahoma (Saltzman 2001), and probably in Nevada (Saltzman 2001) – the biostratigraphy quoted fits better with the Linde Event but that needs to be confirmed.

3.1.5 Other Wenlock and Ludlow events

Four more events during these epochs have hitherto been identified and named (Jeppsson 1993, 1998; Jeppsson et al. 1995; Jeppsson & Aldridge 2000). An unnamed probable secundo-secundo event spans the Högklint/Tofta boundary (Jeppsson in manuscript). A wellknown effect of the 'mid-Sheinwoodian' Boge Event was the extinction of the conodonts *Kockelella patula* and *K. walliseri*. The Valleviken Primo-Secundo Event spans the base of the Homerian (Jeppsson 1993; Jeppsson et. al. 1995). The *Pentamerus gothlandicus* Layer formed across the island close to, or during a part of this event. The Linde Primo-Secundo Event is found between the *K. v. variabilis* s. str. and *A. ploeckensis* zones (Jeppsson 1993; Jeppsson & Aldridge 2000). The Valleviken and Linde events caused the same kind of lithological changes (although less extensive) as the two known strong primo-secundo events, the Ireviken and Lau events. The Klev Secundo-Primo Event started during the latest Ludlow and ended at or possibly slightly after the beginning of the Pridoli (Jeppsson & Aldridge 2000). No high-resolution study has as yet been conducted on any of these events, hence they are still poorly known. These weaker events were probably also briefer than the three strong ones.

3.2. Stable C and O isotopes

Brachiopod shells are considered as the most reliable material for the determination of $\delta^{13}C$ and $\delta^{18}O$ values because they consist of diagenetically stable low-magnesium-calcite, and the shell is secreted in isotopic equilibrium with the ambient seawater (see discussion in Samtleben et al. 2001). Up to now, more than 2000 brachiopods from Gotland have been analysed for stable carbon and oxygen isotopes. Most of these results are published in Samtleben et al. (1996, 2000, 2001), Bickert et al. (1997), and Munnecke et al. (2003), to which the reader is referred. Here, a brief summary of these results and their interpretation is presented.

The Silurian succession on Gotland exhibits three major and one minor positive $\delta^{13}C$ and $\delta^{18}O$ excursions. At present, the three major excursions have been detected from other palaeo-continents indicating global steering mechanisms (Munnecke et al. 2003). The isotope excursions are closely correlated with lithological changes on Gotland (and also world-wide; summarised in Munnecke et al. 2003), and with the development of the conodont communities described above (Fig. 3). In general, times of high isotope values coincide with times of strongly enhanced reef and carbonate platform growth (Upper Visby to Hangvar Formation, Fröjel to Klinteberg Formation, parts of the Hemse Group, upper part of När to Sundre Formations), whereas times of low isotope values are characterised by argillaceous deposits, and strongly reduced reef growth (Lower Visby Formation, Slite Group, large parts of the Hemse Group). The isotope values, however, are not *directly* connected to the carbonate facies, because on Gotland contemporaneous deposits exhibit nearly identical $\delta^{13}C$ values regardless of the local depositional environment (Samtleben et al. 2000). Oxygen isotope values exhibit lower amplitudes but generally show a parallel trend to the $\delta^{13}C$ development, however, in extremely shallow environments on eastern Gotland they have been affected by local changes in temperature and salinity, and therefore show a higher variability than the $\delta^{13}C$ values.

The first excursion, with an increase from less than 2‰ to more than 5‰ in $\delta^{13}C$, occurs close to the Llandovery-Wenlock boundary. The onset of the isotope excursion coincides with the conodont extinction datum 4 (fig. 4), and the high values lasted from the Upper *P. procerus* Zone into the Lower *K. walliseri* Zone. The excursion is correlated with the lithological change from regular limestone-marl alternations of the Lower Visby Formation to the reefmound bearing Upper Visby Formation, and the reef- and/or algal-dominated Högklint and Hangvar Formations. The succeeding parts of the Slite Group are characterised by low isotope values ($\delta^{13}C \approx$ -0.5‰; Fig. 3).

In the uppermost Slite Group, $\delta^{13}C$ values increase again from values below 0‰ to more than 3‰ in the Fröjel Formation (Gannarve Mb). High but more or less continuously decreasing values are observed in the succeeding Halla and Klinteberg Formations. Thus, the excursion ranges from the *O. bohemica longa* Zone to the *C. murchisoni* Zone. Again, strong facies changes are associated with the isotope excursion. On western Gotland, the increase corresponds to the lithological change from the marly, graptolite-bearing Svarvare Member to the siltstones of the Gannarve Member deposited under high-energy conditions. On eastern Gotland, limestone-marl alternations of a proximal shelf environment ($\delta^{13}C \approx$-0.5‰) grade into patchreef-bearing strata, in parts overlain by the *Atrypa "reticularis"* Beds ($\delta^{13}C \approx$ +2.3‰). Both reefs and *A. "reticularis"* Beds of the Slite Group are truncated by a prominent unconformity (Fig. 5; Calner 1999, 2002; Calner et al. 2004). Above the unconformity, oolites of the Halla Formation were deposited. In the east, these are overlain by marginal marine and backreef deposits ($\delta^{13}C \approx$ +2.3‰). Up to now, no isotope values from brachiopods exist from the Bara Oolite.

The third $\delta^{13}C$ excursion is the weakest one of the four observed on Gotland (≈ 1‰ $\delta^{13}C$ amplitude). It is, however, also accompanied by facies changes, at least in central and eastern Gotland. Here, reefs and extended biostromes were built during this time interval, e.g. the famous stromatoporoid biostrome on the Kuppen peninsula (Kershaw 1990; Kershaw & Keeling 1994; Calner et al. 2004, this volume). On western Gotland, no facies shift is observed in the open marine shelf deposits.

The final $\delta^{13}C$ excursion on Gotland lasted from the uppermost *P. siluricus* Zone to the *O. crispa* Zone (Fig. 3), and represents – to our knowledge - the strongest positive excursion of the entire Phanerozoic. On western Gotland, isotope values increase continuously from about 0.5‰ $\delta^{13}C$ in the upper När Formation to nearly 9‰ in the Eke Formation. On eastern Gotland, the När-Eke formational boundary is associated to a mineralised hardground and the base-level for a somewhat younger palaeokarstic surface (Cherns 1982).

Generally, there is a good correlation between stable isotope development and the primo and secundo episodes (see section 3.1.1 above; Fig. 3). However, up to now, no isotope data exist from the Boge, Valleviken, and Klev-events on Gotland.

The interpretation of the isotope values is still a matter of intense debate. The fact that the excursions have been found on different palaeocontinents clearly excludes a diagenetic origin. However, both the shifts in $\delta^{13}C$ and in $\delta^{18}O$ are too high to be explained by common mechanisms like productivity and temperature changes, respectively. Furthermore, interpretation is hampered by the fact that true pelagic sediments (i.e. deposited on oceanic crust) of Palaeozoic age are generally subducted and, thus, conclusions on the pelagic realm are mostly based on outer shelf deposits. Shifts in $\delta^{13}C$ exceeding 2-3‰ cannot be explained by fractionation due to changes in oceanic productivity (see discussion in Bickert et al. 1997), and no indication of enhanced deposition of organic-rich deposits during the excursions large enough to account for the extreme amplitudes observed were known by Bickert et al. (1997) and Wenzel (1997). According to the model of Jeppsson (1990) a reduced pelagic production occurred during secundo episodes (times of arid climate). However, despite of the reduced productivity, in order for a secundo episode to end as described by the model, an increased deposition of organic material on the deep shelves is necessary (see discussion in Cramer & Saltzman subm.). At least one such event of enhanced deposition of organic-rich sediments has been identified (Jeppsson & Calner 2003). According to Cramer & Saltzman (subm.) such increased C_{org} deposition is responsible for the $\delta^{13}C$ excursion in the early Wenlock. However, Munnecke et al. (2003) noted that the fact that the Silurian $\delta^{13}C$ excursions are observed on various palaeo-continents, but with different absolute values and amplitudes (generally lower values, and lower amplitudes in deeper water environments) argues against deposition of organic matter as driving mechanism for the $\delta^{13}C$ development.

Also the interpretation of the $\delta^{18}O$ values is somewhat problematic. An interpretation in terms of temperature changes would result in temperature variations of up to 16°C which is unrealistic for tropical surface waters. Storage of ^{16}O in polar ice caps might have influenced the $\delta^{18}O$ composition of the acient sea-water however, up to now, no indications for major glaciations – al least in the late Silurian – have been found.

Based on isotopic results Bickert et al. (1997) have modified the oceanic model of Jeppsson (1990) with respect to stable isotope geochemistry and oceanic circulation (Fig. 6). Times of arid and humid climate are called A- and H-periods, respectively. This new nomenclature was used because (a) the onset of the climatic changes is seen slightly differently in Jeppsson (1990) and Bickert et al. (1997) (see Fig. 3), and (b) not every episode/event is documented by changing $\delta^{13}C$ values (Fig. 3). In their model, a shift between estuarine and anti-estuarine circulation in shallow seas, caused by precipitation changes, is the main driving mechanism (Fig. 6). Permanent euxinic conditions below the surface mixed layer of the ocean during the entire Silurian are predicted, resulting in a strong fractionation in $\delta^{13}C$ composition between surface and deep waters produced by the settlement and deposition of ^{12}C-rich organic material in deep-sea sediments. Today, a similar fractionation is observed in the Black Sea (Fry et al. 1991). The shift from humid (H-period) to arid climates (A-period) led to changes in ocean circulation. During A-periods the formation and downwelling of saline surface water caused an anti-estuarine circulation pattern in shallow seas, and O_2-rich but ^{12}C-depleted open ocean surface water reached the shelf areas, resulting in oxygenated deep shelf sediments observed during most A-periods. The low $\delta^{13}C$ values in the humid H-periods were produced by the upwelling of ^{12}C-rich deep water (Fig. 6). The development of the oxygen isotopes is in accordance with both the Jeppsson (1990) and the Bickert et al. (1997) model. In arid periods intense evaporation resulted in an increase in salinity, and thereby a stronger ^{18}O fractionation, and, thus, enhanced $\delta^{18}O$ values. In humid times, fresh water influx resulted in a lower salinity, and in lower $\delta^{18}O$ values.

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