

Rapporter och meddelanden 121

The Dynamic Silurian Earth

Subcommision on Silurian Stratigraphy
Field Meeting 2005

Field guide and Abstracts

Mats E. Eriksson & Mikael Calner (eds.)



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The Dynamic Silurian Earth

**Subcommision on Silurian Stratigraphy
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Edited by Mats E. Eriksson & Mikael Calner

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Cover photo: Photograph showing the rocky shores at Sjaustrehammarn (Hemse Group), eastern Gotland in July 2004. All photographs in this volume by Mikael Calner, except Figure 4.

Logotype: The Dynamic Silurian Earth logotype was made by Mats E. Eriksson and Sara Richardson. The illustration shows a scolecodont modified from Bergman (1989) and Eriksson et al. (2004). It represents the first right maxilla of the paulinitid *Kettnerites (Aeolus) sisyphi klasaardensis* from Gotland.

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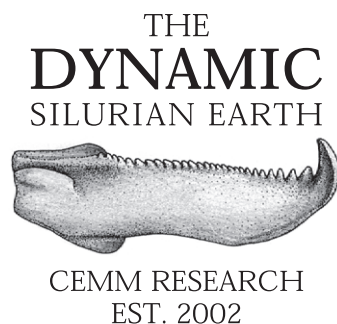
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Preface

In 2004 the Subcommittee on Silurian Stratigraphy (SSS) chose the island of Gotland, Sweden, as the site for the Silurian Field Meeting 2005. The view of the Silurian as a time of stable greenhouse environmental conditions has been successively challenged during the last decade. A wealth of recent biological and geochemical data suggests that this time interval was characterised by recurrent anomalies in the ocean-atmosphere system coupled with extinctions among marine faunas. The major positive $\delta^{13}\text{C}$ isotopic excursions indicate that the global carbon cycle went through considerable changes and more frequently so than during any other period of the Phanerozoic. For these reasons, the theme of the meeting – as indicated by its name ‘*The Dynamic Silurian Earth*’ – is the global environmental changes that are associated with this period of time in Earth history. The field trips highlight such signatures encapsulated in the well preserved carbonate platforms that form the bedrock of Gotland. It is obviously impossible to cover all aspects of the geology of Gotland in this combined field guide and abstract volume. Therefore we aimed at presenting an overview of the geology with particular emphasis on aspects that are closely linked to the focus of the meeting.

Lund, May 4th 2005

Mats E. Eriksson and Mikael Calner
(Editors)



The Baltic basin and the Silurian strata of Gotland, Sweden

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The Baltic Basin

The sedimentary fill of the intra- to pericratonic Baltic Basin can be subdivided into three major stratigraphical successions separated by prominent unconformities. These successions correspond to three phases of tectonic evolution affecting the Baltic craton, the Caledonian, Variscan, and Alpine tectonic stages, respectively (Poprawa et al. 1999). Only the former, which corresponds to the Vendian–lowermost Devonian basin fill, is discussed below. The gross architecture of this fill is a wedge that reaches a thickness exceeding 4,500 m along the south-western peri-Tornquist part of the basin. Its erosional cratonward limit is just north of Gotland and the Estonian mainland (Martinsson 1958, Flodén 1980, Poprawa et al. 1999).

The sedimentary strata of Gotland, together with outcrops and erosional outliers in southern and central Sweden, and the strata of the East Baltic area, show that the Baltic Basin at times covered vast areas of the craton – from the present-day Caledonian front across southern Sweden and the Baltic Sea, and further across the East Baltic area and south-eastwards to Ukraine. The basin sits on a Precambrian crystalline basement that formed a deeply weathered and peneplaned surface across the Baltic Shield prior to the Early Cambrian first order transgression. Following extension in the Precambrian and subsequent 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 collision event resulted in a change in tectonic regime, from a passive margin to a flexural foreland basin (Poprawa et al. 1999). The most profound tectonic changes, however, are associated with the western margin of Baltica. This part suffered substantial crustal shortening and eastward migration of thrust sheets during the collision of the Scotland–Greenland complex and western Norway during the final closure of the Iapetus Ocean and the development of the Laurussian supercontinent (Fortey & Cocks 2003). The lower Palaeozoic sedimentary fill of the Baltic Basin reflects well the combined effects of the tectonic evolution described above and the contemporaneous drift of Baltica from high southern latitudes in the Cambrian to equatorial latitudes in the Silurian. In the northern parts of the basin, of interest here, the Early Cambrian is characterized by terrigenous sands (arkoses and quartz arenites) eroded from the deeply weathered craton and deposited in extensive shallow seas. The moderate thickness and uniform facies of the succeeding mid-Cambrian and Furongian (late Cambrian) Alum shales and Ordovician cool-water carbonates (Ortoceratite Limestone) are consistent with a slowly subsiding and sediment-starved basin with maximum depositional depths of, at most, a few hundred metres. The appearance of calcareous oolites and corals in Late Ordovician outcrops of southern Sweden are consistent with that Baltica by this time approached lower latitudes. As Baltica rotated counter-clockwise and drifted into the tropics in the Silurian (Torsvik et al. 1996, Cocks & Torsvik 2002) the basin transformed into a partly dysoxic shale basin (graptolite-facies) with extensive carbonate platforms along the margins (conodont-facies). The bedrock of Gotland is an erosional remnant of this extensive platform complex. Towards the north-east from Gotland, in the East Baltic area, the limestone is partly dolomitised, and hiatuses are more extensive than on Gotland (Jeppsson et al. 1994). Devonian terrigenous strata rest unconformably on the Silurian platform carbonates just south of Gotland (Flodén 1980).

In the Silurian, the Baltic basin faced the broad Rheic Ocean and rifted Gondwanan terranes to the south (Figs. 1 and 2). The carbonate platforms of Gotland are therefore excellent sensors for changes in the contemporaneous oceans.



Fig. 1. Global Silurian palaeogeography. Note the position of Gotland at the southern margin of Baltica.

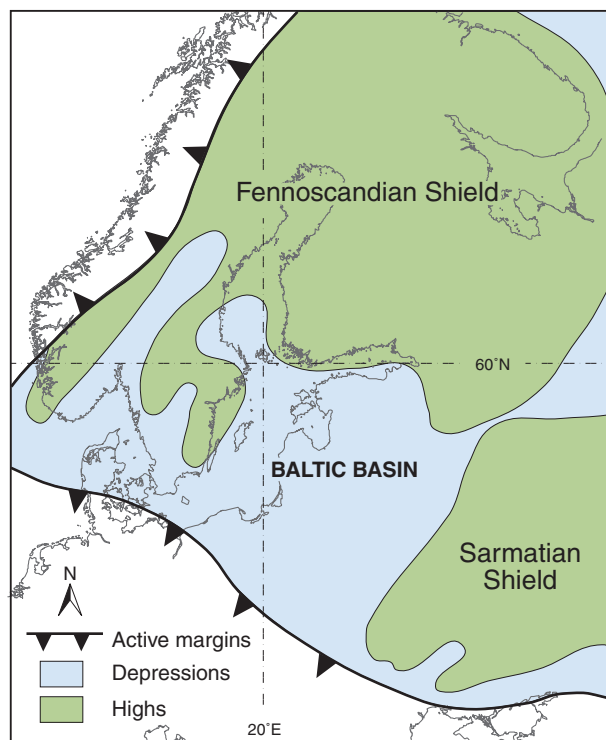


Fig. 2. Silurian paleogeography of Scandinavia and the East Baltic (after Baarli et al. 2003).

The Silurian of Gotland

The research history of the geology of Gotland dates back to the 18th century, and the world-famous naturalist Carl von Linné (1707–1778) can be considered as one of the pioneers in exploring the geology of the island. During his trip to Gotland in 1741 he was astonished by the abundance of fossils and their excellent preservation. In the 19th and earliest 20th centuries investigations particularly focused on fossil assemblages and numerous monographic papers on various fossil groups were published. In addition, the large-scale stratigraphical relationships of the strata were a target for analysis. The first comprehensive study of the

The Silurian Bedrock of
GOTLAND

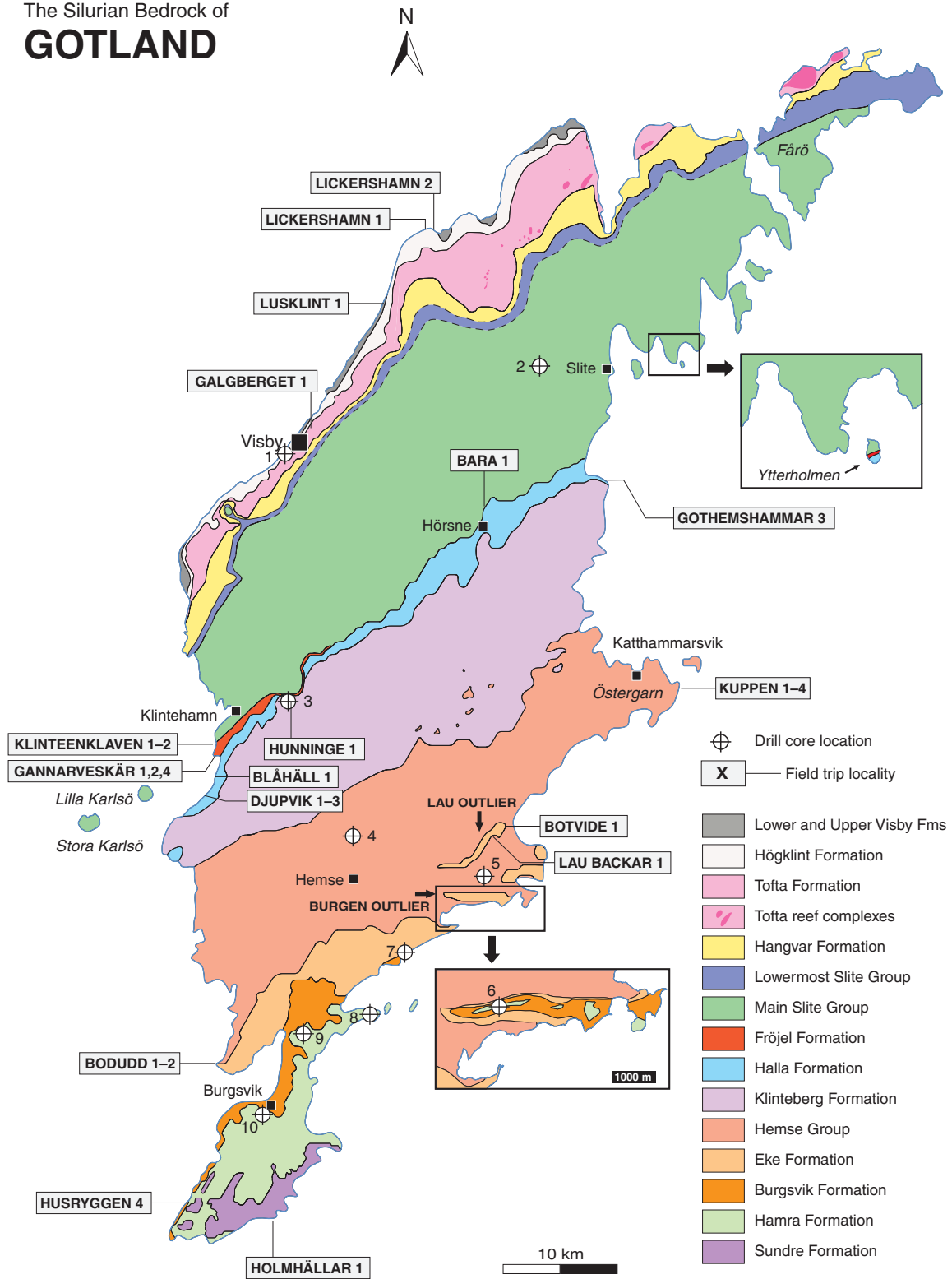


Fig. 3. Geological map of Gotland showing the major, mappable stratigraphical units and the field trip localities. Data from Hede (1921, 1960), Calner (1999), Calner & Jeppsson (2003), Calner et al. (2004a), and Jeppsson (2005a). Position of core drillings; Visby boring (1), File Haidar boring (2), Hunninge-1 (3), Linde-1 (4), När-1 (5), Burgen-1 (6), Ronehamn-1 (7), Grötlingbo-1 (8), Uddvide-1 (9), Burgsvik boring (10).

geology and stratigraphy of Gotland was published in a series of in-depth map descriptions produced by J.E. Hede and co-workers and published by the Geological Survey of Sweden (SGU) between the 1920's and the 1940's (see summary in Hede 1960). Studies of the Gotland geology have thereafter relied heavily on Hede's subdivision of the succession into thirteen topostratigraphical units, referred to as *Beds*, from oldest to youngest: Lower Visby, Upper Visby, Högklint, Tofta, Slite, Halla, Mulde, Klinteberg, Hemse, Eke, Burgsvik, Hamra, and Sundre (for details, see Hede 1960, Laufeld 1974a, Calner et al. 2004b). This framework has successively been revised and refined, particularly during the last two decades, and the current stratigraphical subdivision is shown in Figure 3.

The exposed strata range in age from the latest Llandovery through Ludlow, i.e. representing c. 10 million years (My, timescale from Gradstein et al. 2004). Depending on where measurements are done, the succession is c. 500–700 m thick, the higher number represents the sum of maximum thickness for individual time intervals. The large-scale stratigraphy is easily comprehensible with the oldest strata in the north-west and successively younger strata towards the south-east. Although the dip generally is minor, less than 1° towards the south-east, it may vary substantially locally, particularly adjacent to reef complexes. Except for the obvious down-dip facies change, there is also a prominent transition in facies along the erosional strike, from north-east to south-west. Open marine shelf facies, generally developed as monotonous alternations of argillaceous limestone and marl, dominate in the south-western parts of outcrop belts, whereas contemporaneous sediments towards north-east are more coarse-grained and variegated and show sedimentary structures typical for a shallow-water origin.

The strata show very little late diagenetic alteration, and tectonic imprint is rare and restricted to minor faults with limited vertical or lateral displacement. Moreover, the conodont colour alteration index (CAI) is very low (Fig. 4, Jeppsson 1983). This has resulted in excellently preserved fossil faunas, notably including calcareous micro- and nannofossils previously unknown in Silurian rocks (Munnecke et al. 1999, 2000). The orientation of the contemporary coastlines of Gotland, show that the preservation of the island itself is partly inherited from larger-scale tectonic zones. One of these is the Loftahammar–Linköping Shear Zone that cuts across the southern peninsula of Gotland (Sundblad et al. 1998). The lateral stratigraphical dislocations on southern Gotland are most probably related to tectonic movements along this zone.

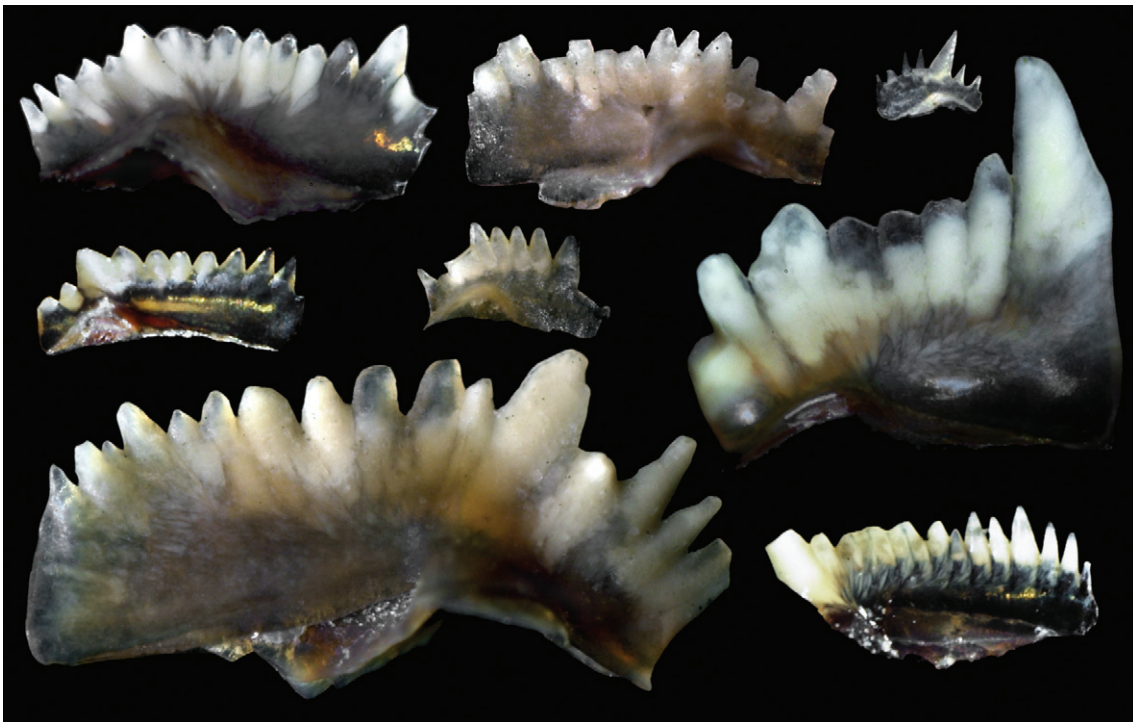


Fig. 4. Well preserved specimens of the conodont *Kockella ortus absidata*, sp (Pa) elements, $\times 30$, from the Late Wenlock of Gotland. For further details see legend to Figure 17 in Calner & Jeppsson (2003). Photographs by courtesy of Jonas Brane, Scanphoto.

Despite the relatively small size of Gotland (c. 3 000 km²) the island has numerous easily accessible outcrops along the coast as well as in inland buffs, ditches, and quarries that are either abandoned or still in production. The subsurface stratigraphy of the island, however, has for a long time primarily been known from only five borings: the Burgsvik (Hede 1919a), Visby (Hedström 1923), File Haidar (Thorslund & Westergård 1938), and När-1 and Grötlingbo-1 borings (Snäll 1977). Additional shallow borings on southern Gotland were examined by Pusch (1969). More recently, M. Calner co-ordinated new drillings and cores have been recovered from parts of the Wenlock and Ludlow: Hunninge-1, Linde-1, Burgen-1, Ronehamn-1, and Uddvide-1. Drill core locations are shown in Figure 3 (GPS-coordinates are given in Calner et al. 2004b).

Major depositional environments

From a genetic point of view the strata of Gotland reflect a series of stacked carbonate platform generations. The cyclical and forestepping development of barrier reef complexes, unconformities, and general facies trends, suggest that the strata can be subdivided into some ten depositional sequences, meaning that individual cycles were approximately 1 million years long (cf. Gradstein et al. 2004, Calner et al. 2004b). These cycles (depositional sequences) do not correspond with the subdivision of formations or groups in use, although their boundaries may coincide. New drill core data show that from the incipient transgressive surface to the development of prograding reef complexes, the platforms generally are some tens of metres thick although a great variation is evident depending on palaeogeographical position on the platform. The platforms are separated by variably pronounced stratigraphical discontinuities (interpreted as sequence boundaries) and poorly to moderately developed palaeokarst or other evidence for subaerial exposure is associated with several of these, e.g. within the middle Slite Group (Laufeld & Martinsson 1981), at the top of the Slite Group (Calner 2002), top Klinteberg Formation (Eriksson 2004), lower and middle Hemse Group (Keeling & Kershaw 1994), within the lower Eke Formation (Cherns 1982), and within the uppermost Sunde 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 brief in time or beyond biostratigraphical resolution on Gotland but increase substantially in magnitude in Estonian outcrops (cf. Jeppsson et al. 1994). The minor dip of the strata indicates that individual platforms were of ramp type. However, the intermittent development of extensive stromatoporoid-coral reef barriers (Hadding 1941, Manten 1971, Flodén et al. 2001, Bjerkéus & Eriksson 2001) indicates that ramps developed steeper gradients with time, and transformed into distally steepening ramps, or mature-stage, rimmed shelves.

In the context of carbonate platform models, three major depositional environments and their characteristic resulting lithofacies association can be distinguished in the Gotland succession. Although variation in lithofacies may locally be considerable, these prominent associations can generally be identified with little problem (modified from Calner et al. 2004b, see also Samtleben et al. 2000).

Peritidal, lagoonal, and back-reef areas

The Gotland back-reef facies chiefly consist of light-brownish, strongly bioturbated mudstone and wackestone. In areas with slightly higher water energy, thin-bedded, fine- to medium-grained grainstone and packstone were laid down, and local abraded hardgrounds can be observed. The sediments deposited in extremely shallow settings are characterised by rapid, commonly bed-by-bed, alternations of different rock types. Desiccation cracks, fenestrae, and ripple marks are good indicators of very shallow conditions. The fossil content varies substantially from one bed to another. Some beds are barren whereas others show a remarkable abundance of e.g. gastropods, bivalves, and rhynchonellid brachiopods occurring in low diversity (Fig. 5). Oncolites may be very common and the individual oncoids frequently show irregular cortices due to periods of stationary growth. Deposition took place in calm, sheltered areas behind the reef fringe. Transgressive peritidal units may be composed of ooids and micro-oncoids. Such deposits of any considerable thickness are limited to two stratigraphical intervals, the Late Wenlock (Bara Oolite Member) and the Late Ludlow (Burgsvik Oolite, Fig. 6) (see Calner & Säll 1999, Groves & Calner 2004).

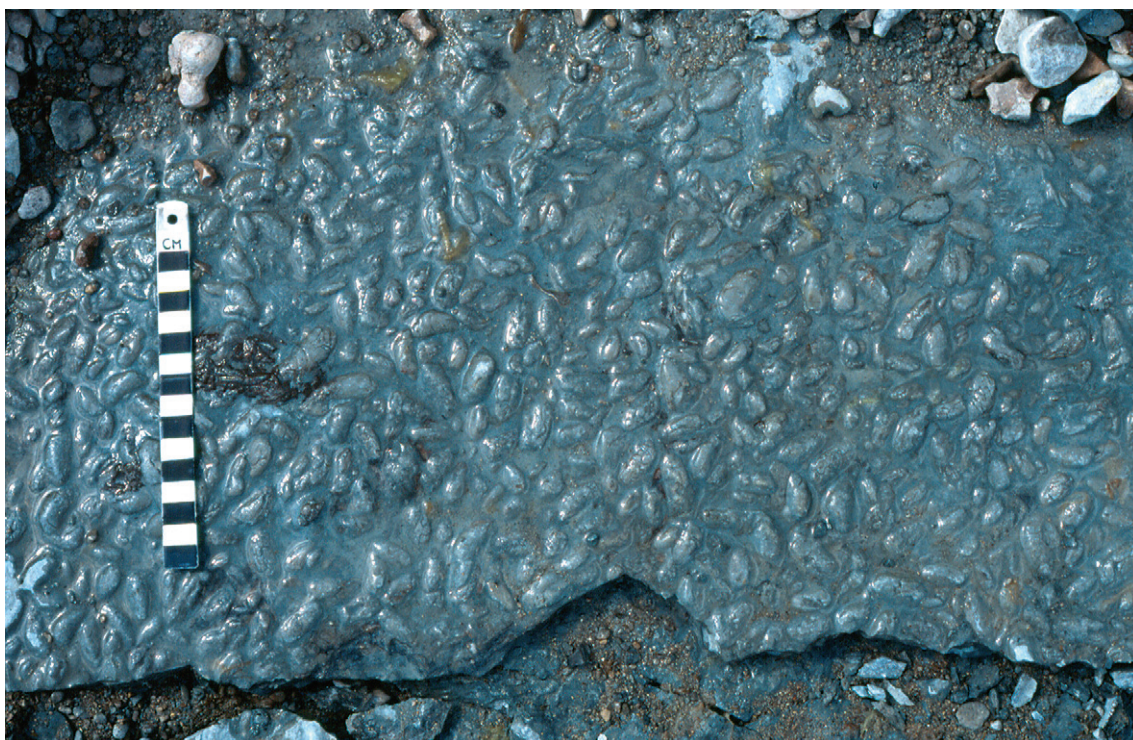


Fig. 5. Monospecific bivalve accumulation from marginal marine strata just south of Gothemshammar 1.

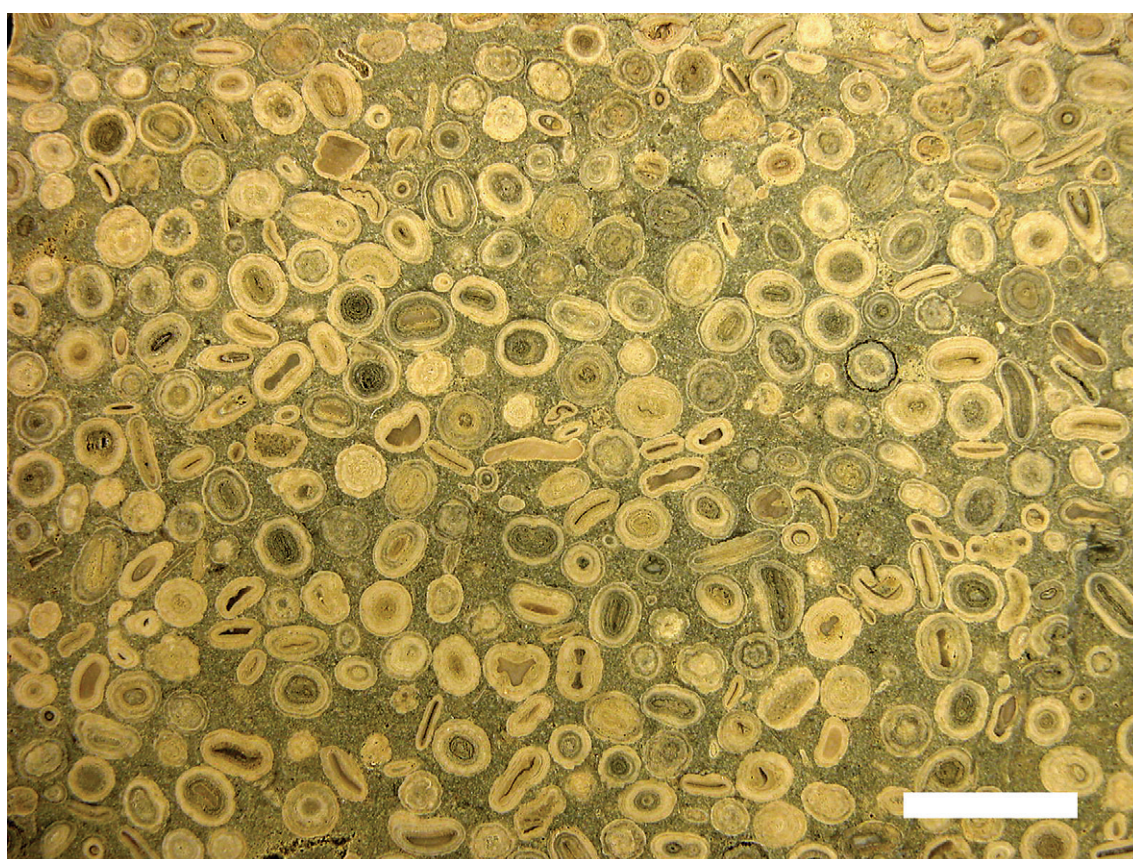


Fig. 6. Polished rudstone slab with coated spheroidal grains from a transgressive peritidal setting (the basal Burgsvik Oolite at Valar 2). Scale bar = 1 cm.

Biohermal, biostromal, and shoal areas

Stromatoporoid-coral reef complexes and related coarse-grained skeletal float- and rudstone reef flank deposits characterise the biohermal, biostromal and shoal areas. Patch-reefs, normally less than 100 m in diameter dominate basinward and grade into biostromes towards shallower environments (usually towards north-east). The patch-reefs were built predominantly by stromatoporoids and tabulate corals, but algae, pelmatozoans, bryozoans, and rugose corals are common associated faunal elements. The size, composition, and structure of a single reef can vary considerably as a consequence of local environmental conditions. Patch-reefs in the Höglint Formation are for example up to 150 m wide and up to 35 metres thick (Watts & Riding 2000). Most reefs are preserved as pale boundstones, frequently with a micritic matrix. Reef cores are often preserved as sea-stacks, a common component of the present coastal areas of Gotland (Fig. 7). The variable inter-reef strata may consist of a wide range of facies spanning from cross-bedded skeletal or pelmatozoan grainstone to fine-grained rocks such as skeletal mud- and wackestone. Areas with biostromes, which are well developed on eastern Gotland, can cover areas of more than 100 km². Individual biostromes were built mainly by densely growing, stacked and interlocking stromatoporoids (Kershaw & Keeling 1994) that commonly are tilted or transported and rounded. Sedimentary matrix deposited in between the stromatoporoids is commonly preserved as grainstone. Repeated interruption of the reef growth can be observed by frequent truncation surfaces. At places, very large reef bodies are truncated and wave-abraded, showing clear-cut truncations of stromatoporoids exceeding one metre in diameter (see Eriksson 2004). Coral biostromes locally grew also at greater depths in distal platform settings, forming thin and up to several hundreds of metres long ‘carpets’ (Calner et al. 2000, see also Nield 1982).

Shoal grainstone is commonly associated with biohermal and biostromal complexes. Trough cross-bedded crinoidal grainstone is a very common component of the Gotland strata, locally forming several metres thick aggrading or prograding successions (Fig. 8).



Fig. 7. Photograph showing an eroded reef area. The weathering resistant reef cores are preserved as several metres high sea-stacks ('raukar'). Uppermost Slite Group at the islet of Ytterholmen, north-eastern Gotland.



Fig. 8. Trough cross-bedded crinoidal grainstone from the lower Klinteberg Formation at Klinteberget (Late Wenlock). This is a common lithofacies in the Silurian of Gotland.

Slope and basin areas

Argillaceous skeletal limestones and marls with a mud-wackestone texture dominate seaward of reef barriers or below the storm wave-base (Fig. 9). Thin packstone-grainstone tempestites and shell coquinas generally punctuate these strata. They are often developed as monotonous limestone-marl alternations showing the typical “differential diagenesis”, i.e. early-cemented limestones and compacted marls (Munnecke 1997,



Fig. 9. Argillaceous distal platform skeletal mudstone and marl at the Blåhäll 1 locality. Late Wenlock Halla Formation, Mulde Brick-clay Member.

Munnecke & Samtleben 1996). 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. Bedding plane associations of stromatoporoids, halysitids, and heliolitids are common at some localities.

In addition to these three prominent types of depositional environments, a fourth environment, genetically unrelated to the platforms, is represented by the volumetrically less important siliciclastics, i.e. the mud-, silt-, and sandstone 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 these units contain a marine fauna, although strongly impoverished in certain intervals (e.g. Stel & de Coo 1977). The siliciclastic material was derived from western source areas (Karlsson 2005). Cross-bedding, flute marks, tool marks, ripple marks, and hummocky cross-stratification indicate periods of rapid deposition.

Bentonites occur in the När-1, Grötlingbo-1, and Hunninge-1 cores but are as yet only known from outcrops in the Llandovery and Wenlock interval. At least some of them caused beautifully silicified fossils (e.g. Laufeld & Jeppsson 1976, Stridsberg 1985, Liljedahl 1984, 1991, 1994, Cherns & Wright 2000). The bentonites have been used for studies of bolide-impact frequency (Schmitz et al. 1994), radiometric dating (Odin et al. 1986), long distance correlations (Batchelor & Jeppsson 1994, 1999), as well as for intra-basinal high-resolution correlations (Jeppsson & Männik 1993, Jeppsson & Calner 2003, Calner et al. 2004d, Calner et al. 2005 in this volume).

Biostratigraphy of Gotland

Lennart Jeppsson, Mats E. Eriksson & Mikael Calner

The biostratigraphy of Gotland (Fig. 10) is based chiefly on conodonts but several other fossil groups have contributed to the detailed scheme. The different fossil groups and how these have been used in biostratigraphy are outlined below.

Macrofossils. Most of the historical stratigraphical work was based on macrofossils and parts of these results still remain the most precise ones available, e.g. the laterally extensive *Riphidium tenuistriatum*, *Pentamerus gothlandicus*, and *Phaulactis* biohorizons. Moreover, the disappearance of the rugose coral *Paleocyclus porpita* at the top of the Lower Visby Formation has long been a characteristic biomarker (Hede 1921).

Graptolites. Graptolites occur in argillaceous strata deposited in slope and basin areas although they are generally rare. The following graptolite zonal indicators have hitherto been identified (stratigraphical position and genus names are modernised): *Monograptus* cf. *riccartonensis* in the Högklint Formation, unit b (Skoglund 1979), *Pristiograptus dubius latus* in the Högklint Formation, unit c? (Skoglund 1979), *Gothograptus nassa* with *P. dubius* in a lower part of the Halla Formation (Holm 1890, Jaeger 1981), *Colonograptus? praedeubeli* high up in the Halla Formation (Jaeger 1981, pers. comm.), *Saetograptus chimaera* in the Hemse Marl NW (Hede 1919b, 1942, Jaeger 1981), and *Bohemograptus bohemicus* in the När Formation (Hede 1919b, 1942). Many stratigraphically important graptolites have been recovered when processing samples for conodonts: *Retiolites textor* in the Slite Group (det. Jaeger, see Jeppsson 1997c for details), *G. kozłowski* (det. Kozłowska-Dawidziuk) in the topmost Slite Marl, *P. d. parvus* (det. Koren') just above the Bara Oolite Member of the Halla Formation, *Co.? praedeubeli* at several localities in the upper Halla Formation (det. Jaeger, see Jeppsson & Calner 2003 for a discussion of the three latter records), and *M. haupti* low in the När Formation (det. Jaeger, see Jeppsson & Aldridge 2000). As yet unpublished records include the following one: David Loydell has recently identified a fragment of *Cyrtograptus bohemicus* in the Upper Visby Formation (low in unit c, sample from 9.28/9.33 m above the reference level at Ireviken 3).

Graptolite identifications in the När-1 and Grötlingbo-1 cores by Jaeger (1991) and Calner et al. (2004d), respectively, can be correlated with the exposed succession. All these graptolite finds are important for correlations between the Silurian conodont and graptolite zonations (e.g. Jeppsson 1997c, Jeppsson & Calner 2003, Fig. 10).

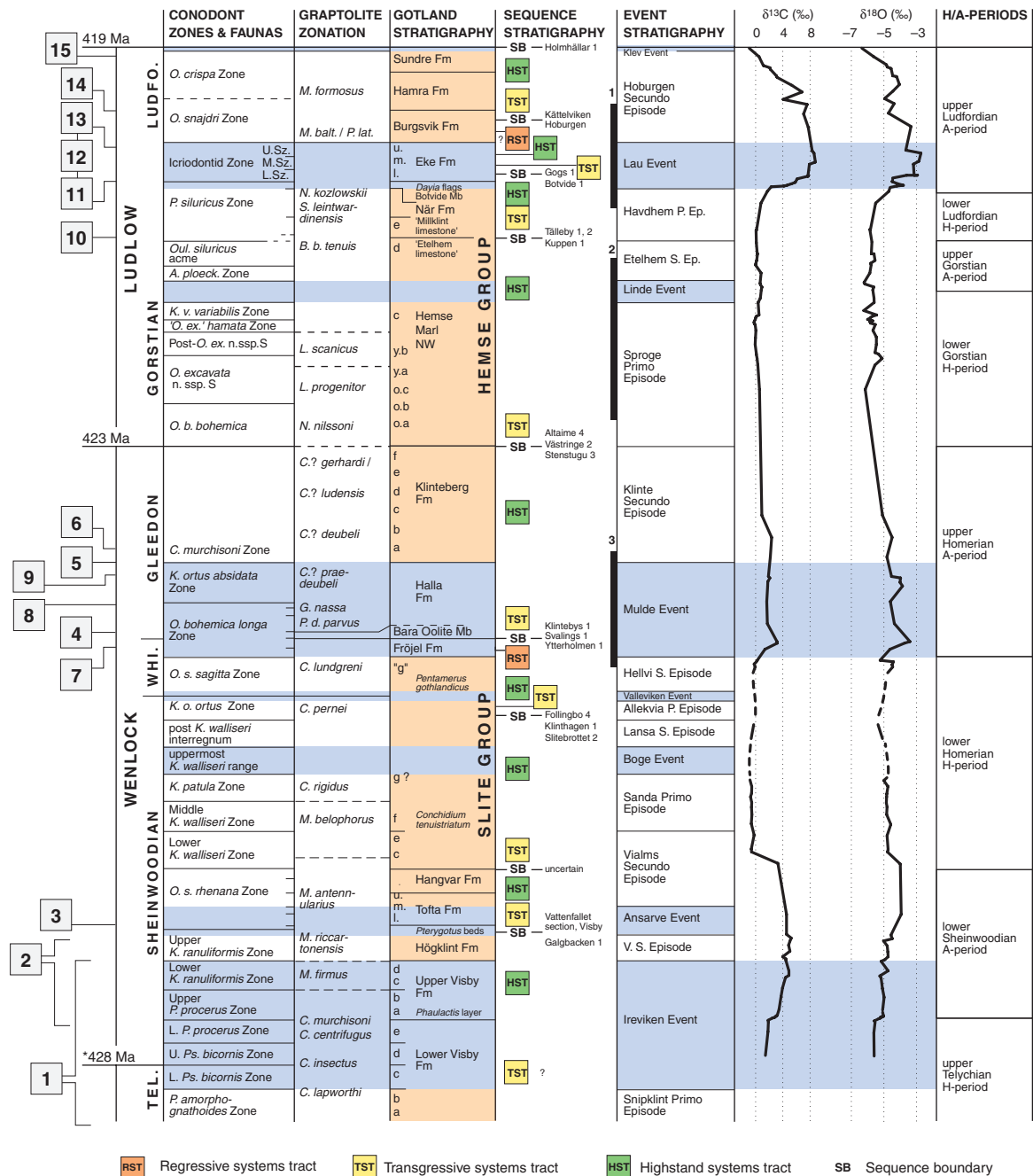


Fig. 10. Stratigraphical framework of Gotland. The diagram shows conodont zones and faunas and their relationship to graptolite biostratigraphy, stratigraphical units on Gotland, and to a tentative sequence stratigraphical framework for the exposed strata. The episodes and events follow Jeppsson (1998, 2005c) and Jeppsson & Aldridge (2000). Carbon and oxygen stable isotope curves and Humid and Arid periods (H/A-periods) are modified from Bickert et al. (1997), Samtleben et al. (2000), and Munnecke et al. (2003). The vertical black bars 1–3 denote the approximate stratigraphical range of the recently recovered Uddvide-1, Burgen-1 and Ronehamn-1 cores (1), the Linde-1 core (2), and the Hunninge-1 core (3). The figure is partly based on stratigraphical data from Jeppsson (1997c), Jeppsson (in press), Calner (1999), and Calner & Jeppsson (2003). Note that scattered, extremely rare *P. siluricus* occur at least as far down as the topmost *K. v. variabilis* Zone, both on Gotland and elsewhere. * = cf. new radiometric ages discussed for the Llandovery-Wenlock boundary at the locality Lusklint 1 (stop 1 in the locality guide). The numbers 1–15 refer to field trip localities.

Ostracodes, chitinozoans, fish, and scolecodonts. Martinsson (1967) used beyrichiid ostracodes to correlate strata both across Gotland and with other areas on Baltica and Avalonia. For example, his correlation of what is now known as the När Formation (Jeppsson in press) with the Upper Leintwardine Formation in Britain is still the most exact of that interval. Laufeld (1974a) described the sequence of chitinozoan faunas although he did not establish a formal zonation. Now, when such zonation exists (e.g. Nestor 1994, Nestor & Einasto 1997, Verniers et al. 1995) many of the zones can be identified based on Laufeld's locality data. Using fish scales, Fredholm (1988a, b) could correlate strata across Gotland and further to Estonia. For example, her identification of the *Phlebolepis ornata* fauna both on eastern Gotland and in the *Kockelella variabilis variabilis* s. str. Zone in the Linde area is still the most precise correlation of those shallow water strata on eastern Gotland. Sequences of polychaete faunas from Gotland have biostratigraphical potential although no formal zonation has yet been established (for a summary see Eriksson et al. 2004). Hints & Eriksson (2004) made some preliminary correlations between strata on Gotland and Saaremaa, Estonia.

Conodonts. Some zonal indices were identified early: *Polygnathoides siluricus* (Martinsson 1967, p. 372, Jeppsson 1975), *Pterospathus procerus* (Jeppsson 1979), and *Ozarkodina crispa* (Jeppsson 1982). *Ancoradella ploeckensis* has also been reported (Fåhraeus 1969). However, the illustrated fragment from the locality Linde 1 seems to derive from a *Kockelella* of the *K. variabilis* group. Because many stratigraphically important conodont taxa are rare on Gotland, extraction of adequately large collections is needed (mostly 30–100 kg/sample) but time-consuming. A detailed zonation has gradually been developed and has now been tested during many years, both on Gotland and, more importantly, on literature data and through restudy of major type collections. This has shown that the zonal scheme can function as the standard conodont zonation, nearly all latest Telychian to the early Homeric chrons have been identified in other sequences on Baltica, Avalonia, Laurentia, and Gondwanaland (Jeppsson 1997c). Known co-occurrences of conodonts and graptolites have been used to correlate the two zonations. The middle Homeric part followed Calner & Jeppsson (2003) and Jeppsson & Calner (2003), and the mid-Ludfordian part follows Jeppsson (in press, three zones are delimited, 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, Fig. 11). For a brief summary of the rest of the Ludlow, see Jeppsson & Aldridge (2000).

CONODONT ZONES AND SUBZONES	CONODONT FAUNAS	GRAPTOLITES	OCEANIC STATE (SEVERITY)	LITHOSTRATIGRAPHY	SEDIMENTS		THICKNESS metres		
					NE (proximal)	SW (distal)	NE	SW	
<i>O. snajdri</i> Zone (lower part)	moderate diversity	<i>Pm. latilobus</i>	Hoburgen Secundo Episode	Hamra Fm (lower part)	oncolitic lst., marl		Hamra + Sundre c.100 (88–124)		
				Burgsvik Fm	oolite sandstone		29.83? 47.22		
ICRIODONTID ZONE	Upper Icriodontid Subzone	im-poverished fauna	LAU EVENT (6.2)	upper Eke	oncolitic lst. + marl	oncolitic mudstone	10?		
	Middle Icriodontid Subzone			low diversity with <i>P. equicostatus</i>	middle Eke	oncolitic lst. + marls	oncolitic mudstone, rare lst. beds	L+M+U Eke 31.3? 13.90	
	Lower Icriodontid Subzone			low diversity	lower Eke	oncolitic marl oncolitic crinoid lst.	dolomitic mudstone, rare lst. beds	>10	2.55
<i>P. siluricus</i> ZONE	<i>O. excavata</i> fauna	rapid stepwise extinctions	(4)	HEMSE GROUP	<i>Shaleria coquinas</i> mudstone		0.21		
	Upper <i>P. siluricus</i> Subzone				När Fm Botvide Member	<i>Dayia coquinas</i> , dolomitic lst. and marl		<i>Dayia coquinas</i> , dolomitic mudst., rare lst. beds	2.1
<i>P. siluricus</i> Zone	Main part of the Zone	very diverse; platform conodonts	Havdhem Primo Episode	main part of the När Fm Millklint Lst. Mbr	crinoid lst.	lst. marl alt.	mudstone, marl, rare lst. beds	30+ 65+ Hense c. 200 (250?)	

Fig. 11. Stratigraphy of the Lau Event interval (after Jeppsson in press).

The currently used zonation is shown in Figure 10. Note that the Gorstian conodont faunal succession on western Gotland is closely similar to that in Cellon studied by Walliser (1964, an errata sheet from him and direct comparisons with his collections). What probably is *K. crassa* has now been identified across Gotland, partly co-occurring with the *Erika* fauna mentioned by Jeppsson & Aldridge (2000).

Kockelella v. variabilis s. str. is the very compact form represented by the holotype. The form illustrated by Serpagli & Corradino (1999) is younger than *K. v. variabilis* s. str. except that they co-occur in one collection without intermediates, thus they seem to belong to distinct species. Forms resembling *O. snajdri* and *O. crispa* occur through most of the Ludlow and the bases of their corresponding zones must therefore be defined by other criteria than FADs. The base of the *O. snajdri* Zone is at the return of a diverse fauna after the low-diversity, strongly unbalanced fauna of the Upper Icriodontid Zone. The base of the *O. crispa* Zone can probably be taken at the succeeding reappearance *O. crispa*.

Oceanic and climatic cycles

Lennart Jeppsson

The successively improved Silurian conodont zonation has revealed many large scale changes during a period previously believed to have been stable in terms of environmental conditions. An empirical model connected all known changes during two Silurian cycles to a single cause: transitions between different oceanic states (Jeppsson 1990, see also Cramer et al. 2005 in this volume). The model (Fig. 12) describes two oceanic states (primo and secundo episodes) with initially stable conditions, and how these gradually became destabilised. 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. Moreover, primo episodes are associated with low and stable, slowly increasing $\delta^{13}\text{C}$ ratios, whereas secundo episodes are associated with initially high, slowly decreasing $\delta^{13}\text{C}$ ratios (Talent et al. 1993, Samtleben et al. 1996, 2000, Wenzel & Joachimski 1996, Wenzel 1997, Saltzman 2001, Cramer & Saltzman 2005). Events – brief intervals with unstable oceanic conditions – can develop after the end of an episode, causing transient faunal changes and extinctions, as well as sedimentary and prominent isotopic effects. The model describes four potential kinds of events with different characters (Jeppsson 1998). The model is useful also in the field, predicting where a more detailed collecting effort should reveal unknown events. Minor primo-secundo events had mainly transient faunal effects and cannot be detected by comparing faunas from before and after the event. Their lithological effects, however, were typical although less widespread (Jeppsson 1993, 1998, 2005c, Aldridge et al. 1993, Jeppsson et al. 1995, Jeppsson & Aldridge 2000).

Finding the cause of an event requires high stratigraphical resolution. A five-fold increase in the resolution and precision of the three major event intervals has now been achieved (Jeppsson 1997c, Calner & Jeppsson 2003). High-resolution stratigraphy has revealed that conodont extinctions during these events were stepwise (Jeppsson 1997a, c, 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 of conodonts, chiefly the response of surviving taxa, permitting comparison of the severity of different events and datum points (Jeppsson 1998). By contrast, extinction percentages are not fully comparable since the biota at the start of separate events or at the onset of separate datum points differ from each other. Extinctions were interpreted as being caused by brief severe drops in primary planktic productivity, causing starvation among planktic larvae (Jeppsson 1990).

Of the eight events hitherto identified in the Silurian of Gotland (Jeppsson 1993, 1998, 2005c, Aldridge et al. 1993, Jeppsson et al. 1995, Jeppsson & Aldridge 2000), three had strong permanent faunal, sedimentary, and long-lasting $\delta^{13}\text{C}$ effects. These three events have already been detected in over 50 areas from Alaska to Australia using conodonts, graptolites, and stable isotopes (see below, updated from Calner et al. 2004b). The effects of the remaining five events seem to have been weaker, preventing easy identification.

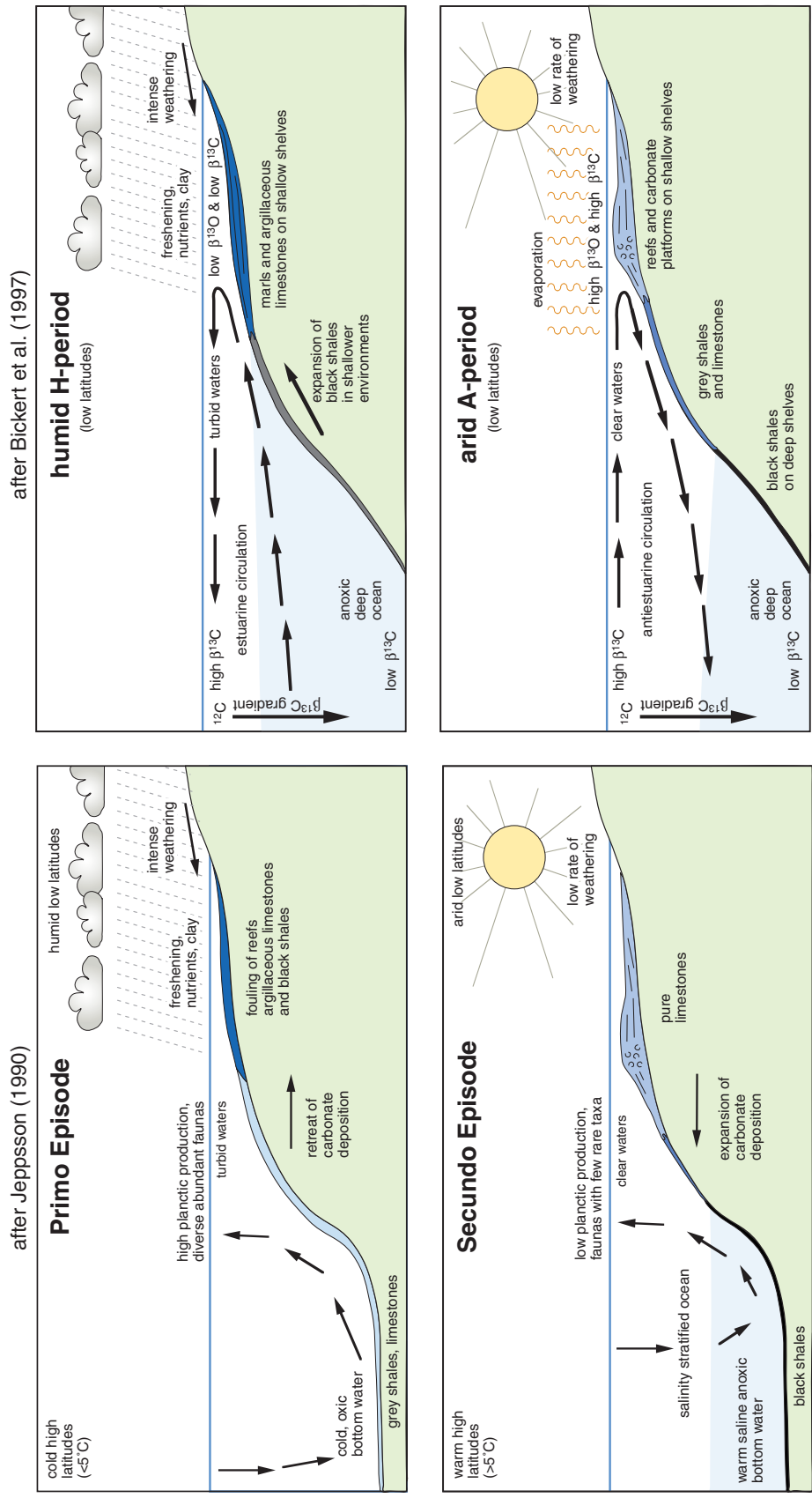


Fig. 12. Palaeoceanographic-climatic model of alternating humid and arid periods in the Silurian (simplified after Jeppsson 1990 and Bickert et al. 1997). Bickert et al. (1997) have modified the Jeppsson model with respect to isotope geochemistry and oceanic circulation and restricted their model to low latitudes.

The Ireviken Primo-Secundo Event

On Gotland, the Ireviken Event started in the upper part of the Lower Visby Formation and ended near the top of the Upper Visby Formation. Like the Mulde and Lau events, described below, this event reached a severity of 6.2, the highest point on the severity scale yet defined (Jeppsson 1998). It lasted for c. 0.2 My but nearly all extinctions took place during the first 0.1 My (Jeppsson 1997a). Conodont extinctions were stepwise and most steps have been identified globally (Jeppsson 1997a, c). Datum points 2 and 4 had the strongest effects. The total effects on the fauna were large, e.g. 80% of the globally known conodont species disappeared (Jeppsson 1998), and over 50% of the trilobites on Gotland (Ramsköld 1985b) at or very close to Datum 2. Extinctions have also been identified among graptolites, brachiopods, corals, ostracodes, and polychaetes (Eriksson 2005 in this volume). Conditions during this and other primo-secundo events deteriorated stepwise whereas the recovery at the end of the event was rapid. Like in many other areas, marls dominated before the event and reef boundstone and associated sediments after the event, due to carbonate platform progradation. $\delta^{13}\text{C}$ values begin to increase near Datum 4 (Talent et al. 1993, Samtleben et al. 1996, Cramer & Saltzman 2005).

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 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 (Urbanek 1970, fig. 6, 1993) = the *lundgreni* Event (Koren' 1991)]. The event lasted c. 0.35 My but nearly all extinctions took place during the first 0.06 My (during datum points 1, 1.5, and 2). The identified changes include: two extinctions (Datum points 1 and 1.5), a $\delta^{13}\text{C}$ increase of c. 3.8‰ (Calner et al. 2005 in this volume), 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. Most of the graptolite species perished well before Datum 2, probably at Datum 1 (cf. Porębska et al. 2004), like most of the expiring conodonts did. Literature data indicate extinctions among chitinozoans (Nestor 1994, cf. the redating of the presumed *G. nassa* in the Ohesaare core by Jeppsson & Calner 2003) and shelly faunas (e.g. Hede 1921, p. 51–52), but as yet these have not been fully studied. Datum 2 reached 6.2 on the severity scale. The relationship between the event and sequence stratigraphy, as well as anomalies in carbonate production during the event, has more recently been discussed (Calner 1999, 2002, 2005b, Calner & Säll 1999, Calner et al. 2000, 2004a, Calner & Jeppsson 2003, Jeppsson & Calner 2003, see also Calner et al. 2005 in this volume). Biological and physical changes have also been recorded from Britain (Jeppsson et al. 1995), Bohemia (Kříž 1992, p. 16, Kříž et al. 1993, Jeppsson et al. 1995), Estonia (Nestor 1997), Poland (Porębska et al. 2004), Nevada (Berry 1998), Arctic Canada (Lenz & Kozłowska-Dawidziuk 2001), and preliminarily in the central USA (Mikulic & Kluessendorf 1999, Calner et al. 2001). 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).

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 (Fig. 11). It caused extinctions and other faunal changes among acritarchs, chitinozoans, corals, brachiopods, ostracodes, trilobites, tentaculitids, graptolites, conodonts, and fishes. In addition, c. 30% of the polychaetes appears to have gone extinct (Eriksson et al. 2004). A loss, globally, of at least 30 to 50% of the species seems probable. Among conodonts, no platform-equipped taxa survived and the zone fossil *Polygnathoides siluricus* became extinct during the early part of the event. 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, in a similar way as during the Ireviken and Mulde events. The number of datum points and their exact position has not yet been identified with precision. The many changes during the event permit high-resolution correlations, based on conodonts, $\delta^{13}\text{C}$, and lithology changes. The substantial increase of microbially mediated facies in strata formed during and immedi-

ately after the event has recently been interpreted as a potential marine ecosystem response to the Lau Event (Calner 2005a, b).

A positive $\delta^{13}\text{C}$ excursion started at the beginning of the event, increased through it, and culminated near its end, its amplitude is up to 10.54‰ on Gotland (Jeppsson et al. unpublished data). This excursion has been identified – with varying amplitudes on Gotland (Samtleben et al. 1996, 2000, Calner & Eriksson in press), 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), and in Oklahoma (Saltzman 2001).

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).

Field Meeting Localities



Old gutnian house with a roof of *Cladium mariscus*.

Locality descriptions

Lennart Jeppsson, Mikael Calner & Mats E. Eriksson

Here we provide descriptions to all localities of the Dynamic Silurian Earth field trip. The descriptions are based on numerous sources, including Laufeld (1974b) and Calner et al. (2004b, c). Note that all papers quoted under the heading ‘references’ are not listed in the main reference list of this volume. They are included to illustrate the vast number of scientific studies conducted at individual localities. An asterisk (*) indicates the work providing the original description of the locality. Both stratigraphical and taxonomical nomenclature have been updated as far as possible, i.e. a report of *Monograptus dubius* from a Slite Siltstone locality would be listed as *Pristograptus dubius* from the Gannarve Member of the Fröjel Formation. If a fossil record in the quoted source is indicated to be the first/last appearance, this is given as follows: extinct (LAD), disappeared (lad), appeared (FAD), or reappeared (fad). Coordinates are given in accordance with the Swedish National Grid, unless otherwise specified.

Stop 1. Lusklint 1

640855 165567, c. 2.08 km WNW of Lummelunda church. Topographic map 66C Tingstäde. Geological map SGU Aa 183 Visby and Lummelunda. The locality encompasses the southernmost reef and the exposure south thereof at Lusklint (Fig. 13). Park in the north-western corner of the big raised beach pit above the cliff, c. 600 m south of Lusklint. Follow the path above the cliff northwards into the forest, c. 40 m beyond the pit where a path branches off (not marked on the map) and descends northwards onto the shore. The locality starts where the travertine cover has eroded away. A section was cleaned about 10 m south of the old pine which grows far down on the slope, c. 150 m north of where the path ends.



Fig. 13. View along the coast at Lusklint with prominent patch-reefs of the Höglint Formation seen in the background. The Lusklint 1 section, encompassing the Lower and Upper Visby formations, is in the steep slope in the foreground.

Reference level. The base of the Lusklint Bentonite c. 8.28 m above sea level (the lower one of the three bentonites, see below).

Stratigraphy and facies. See Figure 14. The Llandovery–Wenlock boundary in distal carbonate platform environments. The Lower Visby Fm, units a–e, and the Upper Visby Fm, units a–d. Approximately 10.1 m of the Llandovery is exposed and the Lower Visby Fm, unit a, the oldest strata exposed on Gotland, has only been identified above sea level here and along the shore to about 2.5 km to the south. There are four important criteria for a correct identification of the boundary between the Lower and Upper Visby formations: 1) In places where active erosion is moderate, the Lower Visby Formation weathers to a clay-covered slope. By 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*, a large solitary rugose coral, had a mass occurrence in the basal bed of the Upper Visby Fm (see Munnecke et al. 2003, plate 1). 4) A thin layer of pyrite marks the exact boundary.

The Lower Visby Fm consists of 1–5 cm thick beds of argillaceous limestone, often markedly concretionary and locally partly amalgamated. These limestone beds are interbedded with soft, sticky marl. There are three distinct bentonites in the Lower Visby Fm (Fig. 14): the Lusklint, the very thin Storbrut, and the often layered Ireviken bentonites (Batchelor & Jeppsson 1994). The bentonites permit a detailed correlation of exposures along the coast, and samples from other sections can therefore easily be correlated with the Lusklint 1 locality to form a composite. Hence, data from other localities are included below. The Lusklint Bentonite has been identified also in Estonia (Jeppsson & Männik 1993). In the Upper Visby Fm, the beds are thicker, up to 10–15 cm, and marl interbeds are thinner or absent. Bentonite-like clay beds occur also in the Upper Visby Fm and these have previously been interpreted as bentonites. However, when followed laterally along outcrops they change stratigraphical position and caution should be taken when interpreting these beds.

Most of the condont zones have been identified globally where sampling has been dense enough (Jeppsson 1997c).

Age. The Ireviken Bentonite has earlier been dated at 430.5 ± 6 Ma (2s) on biotite (Odin et al. 1986). Ulf Söderlund (Lund University) has two radiometric ages with a much higher precision using different methods (not yet published): 433.2 ± 1.6 Ma (2s) by using the U-Pb (TIMS) method on multi-grain zircon fractions, and 427.9 ± 0.9 Ma (2s) by using Ar-Ar on biotite and employing a decay constant of 5.543×10^{-10} for the ^{40}K (Steiger & Jäger 1977). The Ar-Ar age becomes indistinguishable (434.1 ± 0.9 Ma, 2s) from the U-Pb result, if using a total ^{40}K decay constant of 5.463×10^{-10} , derived by combining activity data of Endt & Van der Leun (1973) with modern values of physical constants (cf. Min et al. 2000). Additional U-Pb and Ar-Ar isotopic work is planned for reducing uncertainties to about ± 0.5 Ma (2s). The Ireviken Bentonite is c. 0.14 m above the base of the Wenlock and with an average rate of sedimentation of about 1 m per 20 000 years (Jeppsson 1987), the resulting radiometric age needs no adjustment to be relevant for the beginning of the Wenlock.

Oceanic effects. Lusklint 1 is the locality where the datum points of the Ireviken Event have been identified with the highest precision (see Fig. 14). The Lower Visby Fm was identified as deposited in Benthic Assemblage Zone 4 (Gray et al. 1974), hence, lithological changes are minor in this part of the basin. However, the limestone–marl ratio dropped at or near Datum 1. Furthermore, the changes at Datum 4 (= the Lower Visby/Upper Visby boundary), noted above, have been identified in numerous localities. Datum points 2, 3 and 4 are particularly easy to identify globally with conodonts (Jeppsson 1997c). As shown in the faunal lists below, most major clades are likely to be useful to identify one or more of these datum points.

Fauna. Thirty-two beds have been sampled for extracting shelly fossils in order to identify precise range ends. Note that not all groups mentioned below have been studied at Lusklint 1 but in coeval strata at nearby localities.

Beyrichiid ostracodes. Martinsson (1962, 1967) found profound differences between the Lower and Upper Visby faunas. LADs in the Lower Visby Fm include: *Apatobolbina simplicidorsata*, *Leptobolbina hypnooides*, *Barymetopon infantile*, *Noviportia simpliciuscula*, and *Beyrichia hirsuta*. Only *Craspedobolbina juguligera*, *C. unculifera*, and *Beyrichia halliana* occur in both formations and *Apatobolbina tricuspadata* and *Beyrichia bicuspis* appeared in the Upper Visby Fm. Ewa Säll (unpublished thesis, Lund University) studied the locality Ireviken 3 and found that *A. simplicidorsata*, *L. hypnooides*, and probably also *N. simpliciuscula* became extinct at Datum 4. *Beyrichia hirsuta* was only found 0.45/0.55 m above the Ireviken Bentonite and the level of its LAD is uncertain. In addition, Säll identified *A. gutnica* in the Lower Visby Fm.

Brachiopods. Except where noted, the lists below are from Bassett & Cocks (1974), and based on literature, museum, and their collections.

LADs in the Lower Visby Fm include: *Hesperorthis davidsoni*, *Eoplectodonta transversalis*, *Amphistrophia whittardi*, *Costistricklandia lirata lirata*, and *Eospirifer marklini*. Copper (2004) added *Gotatrypa hedei* (LAD in unit b) and Hoel (2005) added *Pentlandina tartana* and *Eoamphistrophia whittardi*. The *Dicoelosia* reported from Lower Visby Fm might be either *D. alticlava* or *D. verneuiliiana*, which occurs in the Upper Visby Fm (if different taxa: LAD for the former and FAD for the latter.)

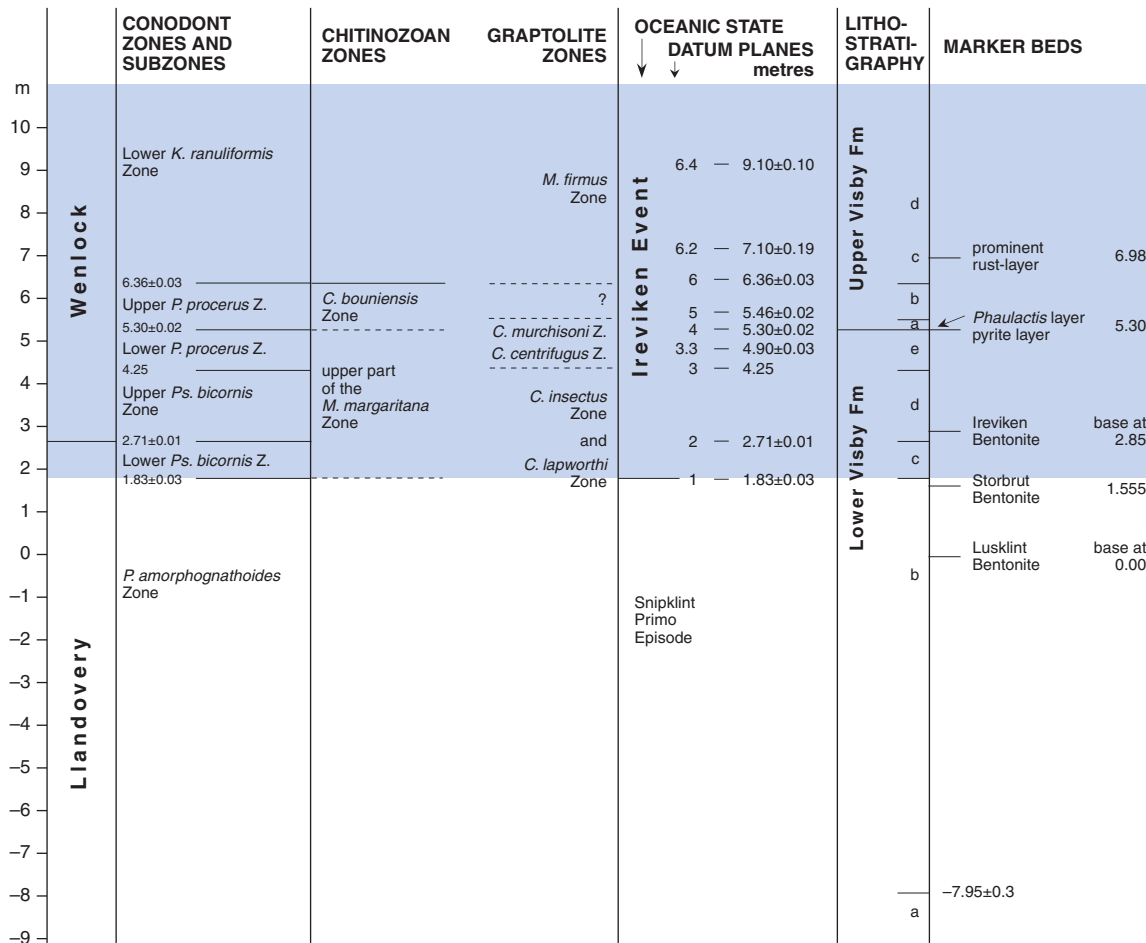


Fig. 14. Stratigraphical framework and event stratigraphy of the Lusklint 1 section. Correlations with the chitinozoan zonation herein are based on data from Leasows, the Llandovery/Wenlock stratotype section. Those data include conodont records (Mabillard & Aldridge 1983), updating of them (Aldridge et al. 1993), identification of the new conodont zonation there (Jeppsson 1997c), and a revision of the chitinozoan taxonomy and zonation (Mullins & Aldridge 2004). In short, Mullins & Aldridge found that the upper part of the *margaritana* Zone spans the epoch boundary and identified the zone, above the epoch boundary in samples yielding conodont faunas of the Upper *Ps. bicornis*, the Lower *P. procerus* and the Upper *P. procerus* zones. The preceding Lower *Ps. bicornis* Zone is thinner than the two *P. procerus* on Gotland and the beginning of the upper part of the *margaritana* Zone is hence probably at or below its base; and the base of that chitinozoan zone is down in the *P. amorphognathoides* Zone. The *margaritana* Zone is coeval with the *insectus*, *centrifugus* and most of the *murchisoni* zones. At least the base of the *Cingulichitina bouniensis* Zone, the succeeding chitinozoan zone, is in the upper *Cyrtograptus murchisoni* Zone (Mullins & Loydell 2001). *Cingulichitina bouniensis* is found with the Upper *P. procerus* Zone at both Leasows and in the Aizpute core-41 (Mullins & Aldridge 2004, Loydell et al. 2003). Further, *Conochitina acuminata* became extinct at or near Datum 3 at Ireviken 3 (Nestor et al. 2002, see the Lusklint description herein). That chitinozoan species range to the top of the *insectus* graptolite Zone in the Bawny River section; Mullins & Loydell 2001). However, published conclusions regarding the correlation of the conodont, chitinozoan and graptolite zonations are partly conflicting. Settling the correct correlation will require analyses of confidence intervals (cf. Marshall 1990, 1995) for both own and literature data, especially regarding taxa that are too rare to be found in every sample between FAD and LAD, and taking the number of specimens in account for better represented taxa (Jeppsson 2005b).

FADs in the Upper Visby Fm include: *Platystrophia jaaniensis*, *Resserella basalis*, *Plectotreta lindstroemi*, *Eodictyonella capewellii*, *Eoplectodonta duvalii*, *Aegiria grayi*, *Brachyprion* sp., *Valdaria testudo*, *Rhychotreta cuneata*, *Ferganella borealis*, *Microsphaeridiorhyncus? nucula*, and *Eospirifer radiatus*. Copper (2004) added *Atrypa gotha*, *Xanthea scabiosa*, *Plectatrypa abbreviata*, and *Endrea tubulosa*. Hoel (2005) added *Strophonella euglypha* and *Leptaena rhomboidalis* (FAD high in Upper Visby Fm). Taxa with both FAD and LAD in the Upper Visby Fm include: *Skenidioides acutum*, *Streptis grayii*, and *Liljevallia gotlandica* (error in Bassett & Cocks 1974, table 1).

The following taxa occur in both formations: *Isortis loveni*, *Visbyella visbyensis* LAD, *Dalejina phaseola* LAD, *Leangella segmentum*, *Coolinia pecten*, *Clorinda rotunda* LAD, *Sphaeirhynchia* spp. “*Rhynchonella*” *exigua* (questionably in the Upper Visby Fm) LAD, *Cyrtia exporrecta*, *Howellella elegans*. Copper (2004) added *Oglupes visbyensis* and *Zygatrypa exigua*, and Hoel (2005) added *Belimurina wisgoriensis*, *Katastrophomena* ?*penkillensis*, *Leptaena depressa visbyensis*, *L. sperion* (FAD high up in the Lower Visby Fm), *Leptaenoidea rugata* (FAD high up in the Lower Visby Fm), *Mesoleptostrophia filosa*, *Brachyprion semiglobobosa*, and *B. walmstedti* (LAD in the middle Upper Visby: Bassett & Cocks (1974) recorded different ranges for some of these taxa).

Pentlandina sp., ?*Camerella* sp., *Desquamatia* sp., and *Glassia obovata* occur in the Lower Visby Fm and above the Upper Visby Fm.

Conodonts. Every bed and interbed near most datum points has been collected for conodonts in order to identify the datum points with centimetre precision. **Datum 1**, at c. +1.81 m: *Nudibelodina sensitiva* LAD, *Pseudooneothodus tricornis* lad, *Ps. bicornis* fad, *Panderodus langkawiensis* lad, *Kockelella ranuliformis* fad. **Datum 2**, at +2.71 ± 0.01 m: *Apsidognathus walmsleyi* LAD, *Ozarkodina polinclinata* LAD, *Oulodus* sp. b LAD, *Pa. panderi* n. ssp. p LAD, *Pa. greenlandensis* LAD, *Pa. panderi* n. ssp. r FAD, *Pa. equicostatus* group fad. **Datum 3**, at +4.25 m: *Pterospathodus amorphognathoides* LAD. **Datum 3.3** at +4.90 ± 0.3 m: *Panderodus langkawiensis* LAD. **Datum 4**, at +5.30 ± 0.02 m: *Oulodus petilus* LAD, *Ozarkodina* n. sp. a LAD, *Pa. serratus*, lad, *Pa. panderi* n. ssp. r lad. **Datum 5**, at +5.46 ± 0.02 m: *Walliserodus* sp. b of Männik et al. (2002) LAD, *Ps. tricornis* LAD. **Datum 6**, at +6.36 ± 0.03 m: *Pt. procerus* LAD. **Datum 6.2**, at +7.10 ± 0.19 m, perhaps at the rust-layer at 6.98 m: *Pa. unicostatus* lad. **Datum 6.4**, at +9.10 ± 0.10 m: *Panderodus* n. sp. j FAD. *Walliserodus* sp. v of Männik et al. (2002) FAD at 10.2 m. As far as is now known, *Distomodius staurognathoides*, *Pa. unicostatus*, *Decoriconus*, *Ozarkodina excavata*, *Oulodus* sp., and *Ps. beckmanni*, persisted through the exposed interval. The frequency of most or all of the taxa changed during the event. Several taxa which otherwise are absent occur in low frequency in the centimetres just around datum points.

Conularids. Jerre (1993, 1994) found the Lower Visby Fm conularid fauna to be abundant and diverse: *Conularia sarae* LAD at the top of the Upper Visby Fm, *C. wimani* and *C. sp. a* LADs at Datum 4, *Pseudoconularia* aff. *P. scalaris* only occurs between Datum points 2 and 3. *Metaconularia aspersa*, and *M. sp. a* were also recorded. By contrast, the Upper Visby Fm yielded a poor conularid fauna including *C. sarae*, *M. aspersa*, and *M. sp. a*?

Chitinozoans. Laufeld’s (1974a) record at Ireviken 3 was taxonomically updated by Nestor (Nestor et al. 2002) and additional samples were processed. Below, LADs and FADs at Ireviken 3 are given relative to Datum 4 (= the Lower and Upper Visby boundary) in order to facilitate comparison with Lusklint 1. Data from the locality Vattenfallsprofilen 1 (Laufeld 1979a) improve the range ends: *Ancyrochitina ancyrea* FAD*, *A. ansarvensis*, *A. primitiva*, *A. vikiensis*, *Angiochitina longicollis* (LAD is close to halfway up in the Upper Visby Fm at Vattenfallsprofilen 1), *Calpichitina densa*, *Conochitina acuminata* (LAD somewhere between -2.6 and -1.3 m (Datum 3 is at c. -1.4 m), *C. claviformis*, *C. cf. flamma* FAD*, *C. cf. proboscifera*, *C. p. f. gracilis*, *C. p. f. truncata*, *C. visbyensis* FAD*, *C. cf. sp. 6* FAD*, *Eisenackitina causiata* FAD*, *E. doliliformis* FAD*, *Margachitina cf. margaritana*, *Plectochitina pachyderma* FAD*, and *Pterochitina macroptera*. *Conochitina acuminata* ranges to the top of the *insectus* graptolite Zone in the Bawny River section (Mullins & Loydell 2001). The majority of the chitinozoon taxa became extinct during the Ireviken Event (Nestor et al. 2002).

* = first find at c. 1.8 m above the Ireviken Bentonite. These taxa are rare (added by Nestor et al. 2002), however only smaller samples were processed below that level. The nearest of these samples was 0.45/0.55 m above the Lusklint Bentonite. Datum 1 is found in the unsampled interval in between these two samples.

Corals. Neuman & Kershaw (1991) noted that the following taxa are most typical for the Lower Visby Fm: the rugose corals *Palaeocyclus porpita* LAD at Datum 4, *Araeopoma prismaticum*, *Phaulactis kunthi*, *P. sp.*, *Cystiophyllum visbyense*, *C. tenue*, *Tryplasma cf. primum*, *Dinophyllum involutum* (rare), *Nanophyllum gotlandicum* (Johannessen pers. comm.), and the tabulates *Angopora hisingeri* (see Klaamann 1983). Young in an unpublished report listed ‘*Halysites catenularius*, *Heliolites interstinctus*, *H. sp.*, *Stelliporella* sp., *Catenipora* spp., *Aulopora* sp., and favositids’. The following taxa are most typical for the Upper Visby Fm: The rugose corals *Holophragma calceoloides*, *Dinophyllum involutum*, *Phaulactis cyathophylloides*, *P. irregularis*, *Araeopoma elongatum*, *Pilophyllum* n. sp. a (= *P. visbyense*, Arntzen unpubl. thesis), *P. n. sp. b* (= *centerradiatus*, Arntzen

unpubl. thesis), *Donacophyllum lindstroemi*, *Schlotheimophyllum patellatum*, *S. n. sp.* (= *S. furioso*, Søiland unpubl. thesis), *Tryplasma hedstroemi*, *Calostylis lindstroemi*, *Dokophyllum annulatum*, *D. hoegbomi*, *Prohexagonaria favia*, *Acervularia brevisseptata*, and *A. conglomerate*. Young in the same unpublished report listed the tabulates *Halysites* sp., *Catenipora* spp., *Stelliporella* sp., *Plasmopora calyculata*, *P. scita*, *Propora tabulata*. Johannessen (1993) redescribed the operculate coral *Goniophyllum p. pyramidale* as occurring in both the Lower and Upper Visby formations.

Polychaetes. Eriksson (1997, 2001) recorded *Oeononites latus*, *O. cf. wyszogradensis*, *Kozlowskiprion longicavernosus*, *Megaramphoprion magnus*, and possibly *O. wejstorpi*, *O. olavi*, and *O. eichwaldi*. See also Eriksson (2005 in this volume) for relative frequency changes during the Ireviken Event.

Stromatoporoids. Neuman & Kershaw (1991) listed *Densastroma pexisum* (by Kershaw 1984) and *Clathrodictyon simplex*, *Pseudolabechia hesslandi*, and *Stromatopora impexa* (by Mori 1968) from the Lower or Upper Visby formations.

Trilobites. Ramsköld (1985b) identified 16 species in the Lower Visby Fm at the locality Rönnskint 1. In one sample from unit b he found a scutellid, a bumastid?, *Warburgella?*, *Deiphon* sp., *Calymene frondosa?*, *Acernaspis pectinata*, *A. sp.* or spp., a small lichid, *Leonaspis* sp. nov., *Harpidella* sp. nov., *Youngiana* sp., and *Encrinurus* (*E.*) sp. nov. The latter three, and *Acernaspis quadrilineata*, *A. sororia*, and *'Bronteus' platyactin*, are limited to the Lower Visby Fm. At least half of the number of species disappeared between two samples, by conodonts dated as below and above Datum 2, respectively. *Encrinurus* (*E.*) *laevis* is the dominant trilobite throughout the Upper Visby Fm. It is restricted to that formation and so are *Hyrokybe? globiceps* and probably also *Dudleyaspis* (*D.*) *uncifera*. The Upper Visby fauna also includes *Warburgella?*, a proetid, *Calymene frondosa?*, a small lichid, and *Acernaspis pectinata*.

References. Hede 1940 refers in many places to Lundsclint as the southernmost place where sections are available. However, according to the topographical map, this name is found on a cliff c. 250 m north of the Lusklint 1 section, Jerre 1993, 1994, Jeppsson & Männik 1993, Jeppsson et al. 1994, Schmitz et al. 1994, Batchelor & Jeppsson 1994*, Eriksson 1996, 1997, 2001.

Stop 2. Lickershamn 2

6414600 1660492, c. 4080 m NNW of Stenkyrka church. Topographic map 66C Tingstäde. Geological map SGU Aa 183 Visby & Lummelunda. Stream section, from 100 m west of the bridge to the sea, c. 260 m north-west of the north-westernmost house at Lickershamn (Fig. 15). Lickershamn 2, together with Lusklint 1, form an excellent composite section for the Ireviken Event.



Fig. 15. Intercalated limestone and marl of the Upper Visby Formation and crinoidal pack-grainstone of the basal Höglint Formation at the Lickershamn 2 section.

Reference point. The bridge along the path.

Reference level. The boundary between the Upper Visby and Högklint formations (Laufeld 1974b). This boundary undulates slightly and, hence, centimetre precision field work must be based on the two eroded thin clay beds. The lower one, the *auxilliary reference level*, is c. 4.39 m below the formation boundary. The second thin clay layer is at +2.49 m. Measurement with a horizon instrument places the base of the Högklint Fm at +4.39 m, c. 8.4 m (corr.) a.s.l.

Stratigraphy. Early Sheinwoodian on north-western Gotland. Upper Visby Fm and Högklint Fm, units a (the crinoid limestone) and b (the succeeding marly limestone). Lower *K. ranuliformis* Zone to c. +1.95 m and Upper *K. ranuliformis* Zone. This section is more complete than that at the locality Vattenfallsprofilen 1 in Visby (cf. Jeppsson & Männik 1993).

Oceanic effects. The final interval of the Ireviken Event, including the two last datum points 7 and 8.

Beyrichiid ostracodes. In the Upper Visby Fm at the nearby locality Lickershamn 1, Martinsson (1962) identified *Craspedobolbina juguligera*, *C. unculifera*, *Beyrichia bicuspis*, and *B. halliana*. In the Högklint unit a at Lickershamn 2, he identified *Apatobolbina gutnica*, *C. unculifera*, and *B. halliana*, and in member b *Apatobolbina gutnica*(?), *C. ornulata*, *B. halliana*, and *B. hystricoides*.

Chitinozoans. In Högklint Fm, unit b Laufeld (1974a) identified *Ancyrochitina ancyrea*, *A. primitiva*, *Conochitina proboscifera*, *C. proboscifera* f. *truncata*, *Margachitina margaritana*, and *C. flamma* (only c. 20 m west of the bridge).

Conodonts. The fauna includes *Distomodus staurogathoides* LAD at 1.99 m, *Kockeella ranuliformis*, *Ozarkodina excavata*, *Oz. paraconfluens* fad at +1.5 m, *Oz. martinsoni* FAD at 4.7 m (due to the change in lithology), *Oulodus* sp., *Pseudooneothodus bicornis*, *Ps. beckmanni*, *Ps. boreensis*, *Panderodus equicostatus* group, *Pa. unicostatus* lad at c. 2.2 m, *Decoriconus*, *Panderodus* n. sp. j FAD at 1.3 m and LAD at 2.55 m, and *Wal-liserodus* sp. v of Männik et al. (2002) FAD at 0 m. **Datum 7**, c. +1.99 m and **Datum 8**, at c. 2.2 m.

Polychaetes. Bergman (1989, 1995) recorded *Kettnerites* (*K.*) *abraham abraham*, *Lanceolatites gracilis*, *K. (Aeolus) sisyphi sisyphi*, *K. (K.) martinsoni*, *K. (Aeolus) sisyphi*, *K. (A.) microdentatus*, *K. (K.) abraham* cf. *isaac*, and *Symmetropriion spatiosus*. Eriksson (1997, 1998, 2001) found *Oeononites latus*, *O. wejstorpi*, *O. olavi*, *O. eichwaldi*, *O. zappae*, *O. jennyensis*, *O. cf. wyszogrodensis*, *Kozlowskiipriion longicavernosus*, *Dubichaetaspis bergmani*, *Protarabellites staufferi*, *P. rectangularis*, and possibly “*Pararamphopriion*” cf. *nordicus*. In addition Eriksson et al. (2004) identified members of Kalloppriionidae, Moctyellidae, Skalenopriionidae, and Atraktopriionidae. See also Eriksson (2005 in this volume) for relative frequency changes during the Ireviken Event.

References. Hede 1940 p. 23 (contains a list of fossils from the Högklint Fm 13.15 m a.s.l.), Martinsson 1962 p. 47 (Martinsson’s locality Lickershamn II), Laufeld 1974a, b*, Larsson 1979, Le Hérissé 1988, 1989, Bergman 1989, 1995, 1998, Fredholm 1990, Le Hérissé & Gourvenec 1995, Eriksson 1996, 1997, 1998, 2001, Eriksson et al. 2004.

Lickershamn 1. 6414824 1660404, c. 4350 m NNW of Stenkyrka church. Maps: see Lickershamn 2. Cliff section c. 500 m north-west of the north-westernmost house at Lickershamn. Lickershamn 1 comprises the cliff north-west of the outlet of the stream and towards north-west to the giant sea stack Jungfrun (= The Virgin, Jungfruklint on the topographical map).

Reference point. The protruding part of the cliff c. 50 m SSE of Jungfrun.

Reference level. The base of the limestone bed above the eroded ‘bentonite’ bed c. 1.2 m above the base of the cliff.

Stratigraphy. Lower Visby Fm, unit e at sea level, Upper Visby Fm unit a with the *Phaulactis* Layer at 0.2 m a.s.l., unit b, and unit c with the Lower *K. ranuliformis* Zone sampled just above the reference level, and Högklint Fm, unit a.

Note. The *Phaulactis* Layer (basal Upper Visby Fm) is 0.1 m above the water level near the southern end of the section. A bed with small reefs is found c. 1 m above the *Phaulactis* Layer. This horizon is c. 0.8 m above sea level at Lickershamn 2.

References. Hede 1940 p. 10, p. 13, p. 28, Spjeldnaes 1959, p. 583, fig. 2, Martinsson 1962, p. 47 (Lickershamn I), Mori 1968, p. 22, Loc. 4 a, Laufeld 1974a, b*, Eriksson & Laufeld 1978, Riding 1981 (Jungfrun), Le Hérissé 1988, 1989, Le Hérissé & Gouvenec 1995, Mótus & Klaaman 1999.

Lickershamn 3. 6414955 1660143, c. 4560 m NNW of Stenkyrka church. Maps: see Lickershamn 2. The plateau on top of Stuklint, just north of the end of the path, c. 750 m north-west of the north-westernmost house at Lickershamn.

Stratigraphy. Högklint Fm, unit a, top.

References. Hede 1940, p. 28, Laufeld 1974a, b*, Le Hérisse 1988, 1989.

Stop 3. Galgberget 1

6394564 1649655, c. 1360 m north-east of the Visby Cathedral. Topographic map 66A Visby. Geological map SGU Aa 183 Visby & Lummelunda. Abandoned quarry c. 300 m ENE of the monument (the ‘Gallows’). Enter between the two flagpoles from road 149, keep to the right until you see the ‘Motorbana’, stop, and find a narrow path on your right leading towards the east, into the quarry. This section is the most widely quoted Högklint-Tofta boundary locality (Fig. 16).



Fig. 16. Cross bedded grainstone of the uppermost Högklint Formation and the unconformably overlying Tofta Formation at Galgberget 1. The hammer is placed on the unconformity.

Reference point. The protruding part of the south-west quarry wall.

Reference level. The Högklint-Tofta boundary (see Hede 1940, fig. 10, marked in the wall).

Stratigraphy. Early Sheinwoodian in a proximal setting (Högklint and Tofta formations). Note the unconformity between the formations. This discontinuity surface occurs in most outcrops exposing this interval (Hede 1940). At least two distinct conodont faunas are missing, indicating a hiatus at this boundary (Jeppsson 2005c).

The leperditiocopid-rich basal Tofta Fm, the Stajnkrogen Mbr of Riding & Watts (1991) contains Subzone 1s of the *O. s. rhenana* Zone (Jeppsson 1997c, 2005c). Although thin, this member is laterally extensive and the same distinct lithology occurs at least c. 5 km to the north (Riding & Watts 1991), with conodonts of the same subzone.

Oceanic effects. Jeppsson et al. (1993) interpreted the Högklint Fm through the lower Slite Group as an unusually long stable episode, the Vattenfallet Secundo Episode (cf. Jeppsson 1998). However, stratigraphical revisions have resulted in increased precision and revealed another event, the Ansarve Event (Jeppsson 2005c). Thus, the Vattenfallet Secundo Episode now includes two secundo episodes, separated by the Ansarve secundo-secundo Event (see Fig. 10). The discontinuity, the Stajnkrogen Mbr and probably also the succeeding Tofta, was formed during the Ansarve Event.

Beyrichiid ostracodes. Martinsson (1962) identified *Beyrichia halliana*, *B. ponderosa*, *B. bicuspis*, *B. hystericoides*, and *Bingeria zygophora*.

Conodonts. In the Stajnkrogen Mbr, *O. s. rhenana* dominates, followed by *Oz. martinsoni*. The frequencies of *Ctenognathodus* n. sp. i and *Panderodus equicostatus* are below 10% whereas that of *Kockelella ranuliformis* (a large form) is between one and a few percent. *Pseudooneothodus* cf. *bicornis* is rare.

Corals. Hede (1940) recorded the rugose coral *Acervularia ananas singularis* and Klaamann (1983) reported ‘unidentified favositids (*Favosites mirandus*)’ from the Tofta Fm.

Stromatoporoids. Neuman & Kershaw (1991) noted that *Actinodictyon tenue* and *Clathrodictyon kudriavzevi* had been found by Mori (1968).

References. Hede 1940, figs. 10, 14, 15, p. 32, Hede 1960, Loc. 4, pp. 55–56, Martinsson 1962, p. 48, Taugourdeau & Jekhowsky 1964, I.F.P. No. 4954, Mori 1968, p. 26, Loc. 25, p. 27, Loc. 34, Laufeld 1974a, b*, Bassett & Cocks 1974, p. 23, p. 29 (Galberget), Claesson 1979, Watkins 1979, 1992, Laufeld & Martinsson 1981, Jeppsson 1983, Sandford & Mosher 1985, 1994, Bergman 1989, Sivhed 1990, Neuman & Kershaw 1991, Riding & Watts 1991, Schmitz et al. 1994, Sandford & Mosher 1994.

Stop 4. Bara 1

6387900 1667569, c. 3300 m south-west of Vallstena church. Topographic map 66B Gothem. Geological map SGU Aa 169 Slite. Abandoned quarry, c. 575 m west of the Bara church ruin (Fig. 17).



Fig. 17. Bara 1 – the classical locality for the Bara Oolite Member (Halla Formation). The hill in the background is a large reef body of the uppermost Slite Group. The cross-bedded Bara Oolite in the foreground is younger than the reef but topographically below.

Stratigraphy and facies. Early Homeric and earliest Late Homeric in the proximal platform area on eastern Gotland. The reef boundstone of the uppermost Slite Group (Slite “g”) forms the hill. These strata belong to the *O. s. sagitta* Zone, although the zonal index has not been recorded at this locality. The younger Bara Oolite Mbr (type locality) of the Halla Fm is exposed along the lower flanks of the reef and these strata belong to the *O. b. longa* Zone, Subzone 2. This interval, which is just below the *P. parvus* graptolite Zone, lacks graptolites even in suitable lithologies (Jeppsson & Calner 2003). The stratigraphical relationships at this and nearby localities were interpreted as a rocky shoreline unconformity by Calner & Säll (1999, see also Fig. 18). The Bara Oolite is thinly bedded, light-coloured, cross-bedded, and well sorted. The major grain types are ooids in the fine to coarse sand fraction, skeletal grains (mainly brachiopods and bryozoans), peloids, and intraclasts.

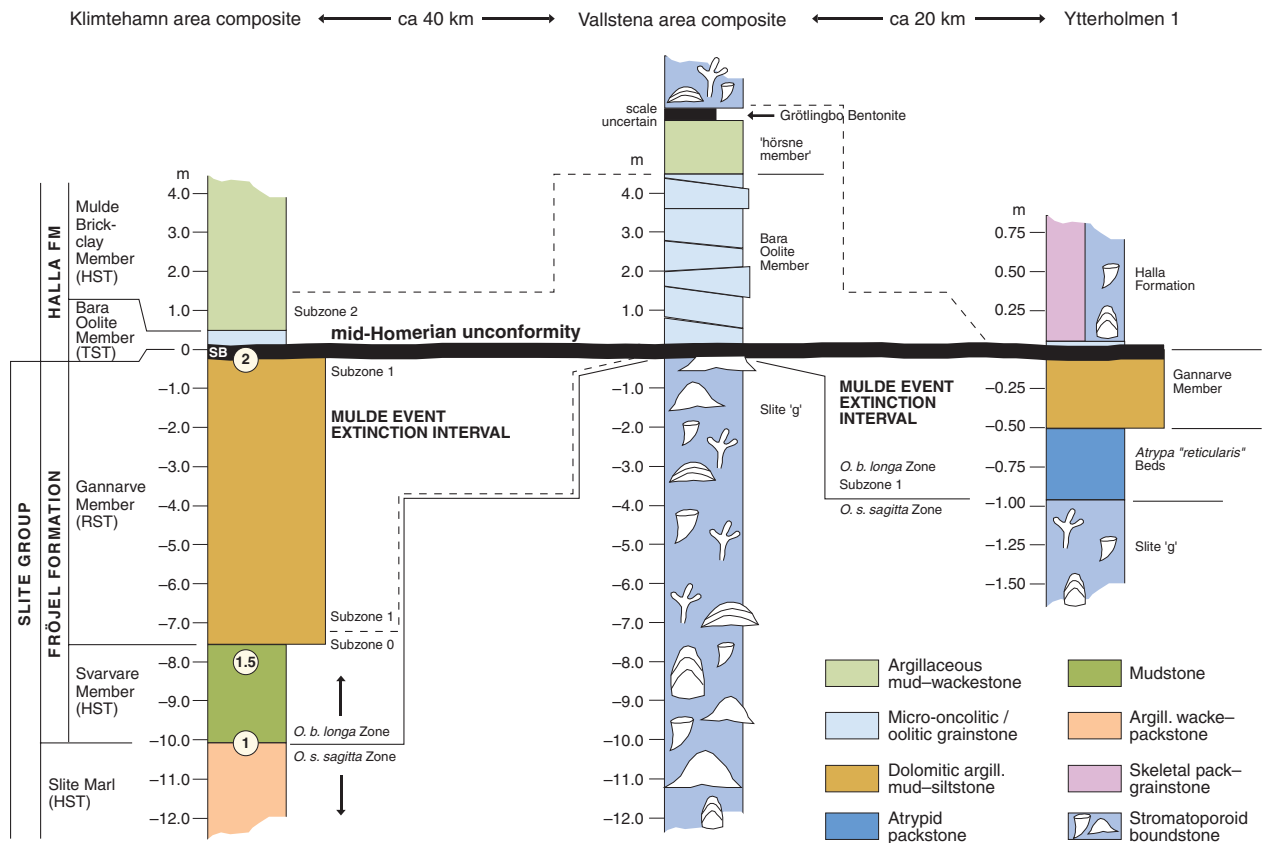


Fig. 18. Stratigraphical relationships along the Slite Group and Halla Formation boundary from the islet Ytterholmen in the north-east to the Klimtehamn area in the south-west. The Bara 1 locality belongs to the Vallstena area composite in the middle of the figure. Note the lack of the Fröjel Formation in this area. However, a microconglomerate derived from the Fröjel Formation in the lowermost centimetres of the Bara Oolite indicates its former presence here (Calner & Säll 1999, Figure originally from Calner et al. 2004a).

Oceanic effects. The strata seen at this locality formed just before and during the Mulde Event. Due to a brief hiatus points 2–5 below are not seen in this proximal setting. The sequence of changes is:

- 1) Formation of an extensive reef complex during the Hellvi Secundo Episode (the large reef forming the hill north of the quarry).
- 2) Start of the Mulde Event with Datum 1.
- 3) Formation of the Svarvare Member mudstones in distal platform areas, Datum 1.5.
- 4) Formation of the *Atrypa "reticularis"* Beds (Paul Copper has identified the atrypid in question as *Atrypa harknessi*) and the Gannarve Member siltstones during a substantial regression.
- 5) Maximum lowstand and Datum 2.
- 6) Rapid transgression and formation of the Bara Oolite (includes grains of the Gannarve Member in its basal part) during the faunally most severe interval of the Mulde Event. The conodont fauna of the oolite is dominated by coniforms, mostly *Panderodus equicostatus*. This fauna is found as far offshore as the corresponding interval (marl) in the När-1 core on southern Gotland (closely similar *P. equicostatus*-dominated faunas characterise the most severe parts of the Ireviken and Lau events).

Beyrichiid ostracodes. Martinsson (1962) found *Craspedobolbina* sp.

Conodonts. *Ozarkodina bohémica longa*, *O. excavata*, *O. cf. confluens*, *Oulodus* sp., *Panderodus equicostatus*, and *Pseudooneothodus beckmanni*.

Corals. Neuman & Kershaw (1991) listed (from the Slite? Group) *Schlotheimophyllum* n. sp. (= *S. corpulenta*, Søiland 1986 unpubl. thesis), *Acervularia ananas*, *A. brevisseptata* n. sp., and *Cystiophyllum* sp. Klamann (1983) identified the tabulates *Halysites junior* from the Bara Oolite, and *Paleofavosites pauculus*, and *P. asper* from Halla b.

Fish. Fredholm (1990) recorded *Loganiella grossi* in the Slite Group and *Thelodus schmidti* in the Halla Formation.

Note. In old collections and literature the name of this locality is often Bara Backe.

References. Hede 1928, pp. 45–46 (contains list of fossils), Hede 1960, Loc. 19, pp. 66–67, Martinsson 1962, p. 52, Laufeld 1974a, b*, Larsson 1979, Jeppsson 1982, 1983, Ramsköld 1983, Sanford & Mosher 1985, Jaanusson 1986 (Bara backe), Frykman 1989, Bergman 1989, Fredholm 1990, Sivhed 1990, Neuman & Kershaw 1991, Calner & Säll 1999, Calner & Jeppsson 2003, Jeppsson & Calner 2003, Calner et al. 2004a.

Stop 5. Gothemshammar 3

6390750 1679250, c. 5350 m north-east of Gothem church. Topographic map 66B Gothem. Geological map SGU Aa 169 Slite. Low coastal section where the road along the shore diverges.



Fig. 19. Irregularly bedded back-reef strata of the basal Klinteberg Formation at Gothemshammar 3. The boundary to the underlying Halla Formation (sensu Hede 1928) is at an abraded hardground just below the marl interval. The section is c. 1 m high.

Reference level. The early Late Homeric Halla–Klinteberg boundary (Fig. 19).

Stratigraphy and facies. Late Homeric on eastern Gotland. Halla Fm, 'gothemshammar member', and Klinteberg Fm, unit a, *Ctenognathodus murchisoni* Zone. Coastal exposure showing aggradational lagoonal oncolitic wacke- and packstone of the upper Halla and the basal Klinteberg formations. The strata are thin-bedded, often intensely bioturbated and arranged as a slightly progradational limestone-marl alternation. Oncoids are several centimetres across and often highly irregular due to periods of stationary growth. A polished and mineral-stained discontinuity surface (abraded hardground) with clear-cut oncolitic structures forms the boundary between the two formations (sensu Hede 1928). However, distinct faunal and lithological changes are found a few metres below this discontinuity surface. These changes are closer in time with the same formational boundary on western Gotland. A thin marl bed with abundant well preserved brachiopods immediately overlies the discontinuity surface.

Oceanic effects. Klinte Secundo Episode immediately after the end of the Mulde Event.

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported a brachiopod average of 1.51‰.

Fish. Fredholm (1990) recorded *Loganellia martinsoni* and *Thelodus schmidti* at –0.04/0.00 m and at 0.15/0.25 m.

Conodonts. *Ctenognathodus murchisoni* FAD at c. –1.5 m, *O. confluens densidentata* FAD at c. –1.8 m (a few 100 m to the west), *Ozarkodina bohémica longa*, ?*Erika*, *O. excavata*, *O. sp.*, *Panderodus*, *Pseudooneotodus beckmanni*, and *Ps. bicornis*.

Polychaetes. Bergman (1989) reported *Kettnerites (K.) bankvaetensis*, *K. (K.) cf. polonensis*, *K. (K.) cf. martinsoni*, *K. (K.) martinsoni*, and *K. (A.) sisyphi sisyphi*. Eriksson (2001) recorded *Ramphoprion gotlandensis* morphotype ?A.

References. Laufeld 1974a, b*, Hurst 1975b, Claesson 1979, Poulsen et al. 1982, Jeppsson 1983, Frykman 1989, Bergman 1989, Fredholm 1990, Sivhed 1990, p. 244, 250, Neuman & Kershaw 1991, Eriksson 2001, Jeppsson & Calner 2003, Calner & Jeppsson 2003.

Stop 6. Hunninge 1

6364282 1647535, c. 1575 m east of Klinte church. Topographic map 56C Klintehamn Geological map SGU Aa 160 Klintehamn. Quarry c. 720 m south-east of the transformer station south-east of Klintebys. For a detailed description of the old quarry, see Hede (1927a).

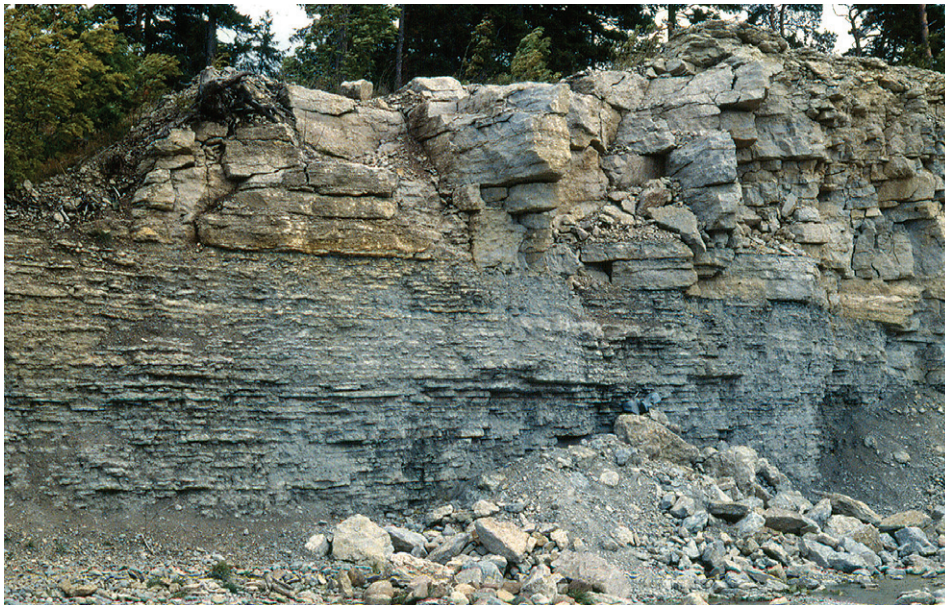


Fig. 20. Progradational reef-flank float- and rudstone of the lowermost Klinteberg Formation at Hunninge 1.

Reference point. The north-western part of the north-eastern wall in the new part of the quarry.

Reference level. The sharp contact, at the reference point, between the intercalated marl and limestone and the overlying limestone, c. 4 m above the quarry floor and 5.4 m below the top of the section (Fig. 20).

Stratigraphy and facies. Early Late Homerian on western Gotland. Klinteberg Fm, lowermost part. The north-eastern quarry wall displays a progradational, coarse-grained interval which may be subdivided into three distinct facies associations. The lowermost unit (below the reference level) is a limestone-marl alternation of floatstone. The more resistant beds have a coarse matrix dominated by disarticulated skeletal grains, gastropods, trilobites, club-like bryozoans and larger fragments of mainly brachiopods, bryozoans, crinoids and rounded, abraded clasts of stromatoporoids. The intercalated marls of this lower unit are thinner and contain similar coarse bioclastic material. Large, overturned tabulate corals are found in similar facies in the south-eastern quarry wall. Geopetal structures and fabric show that bedding planes in that wall, dipping more than 20°N, represent the primary depositional dip. The lower floatstone unit is sharply overlain by cross-bedded to massive crinoidal, pebbly rudstones dominated by crinoid stalks, bryozoans, and stromatoporoid grains. In the south-east and south-west walls, this facies includes abundant overturned and abraded stromatoporoids. The rudstone unit is overlain by bryozoan boundstone with a greenish, lime-mud matrix. Well-preserved, non-abraded brachiopods and club-like bryozoans are abundant. In addition, on the top and immediately south-east of the quarry biohermal facies dominated by stromatoporoids and tabulate corals occurs. Cross-bedded crinoid rudstones fill out some of the interbiohermal depressions.

Oceanic effects. Klinteberg Seundo Episode. Seaward expansion of the carbonate platform.

Brachiopods. *Conchidium biloculare* is frequent. It is characteristic for the Klinteberg Formation.

Conodonts. Jeppsson (in Calner & Jeppsson 2003) found *Kockelella ortus absidata*, *Ozarkodina bohemia longa*, *O. confluens*, *O. excavata*, *Oulodus siluricus* n. ssp., ‘*Ozarkodina*’ n. sp. of Aldridge 1985, *Panderodus equicostatus*, *P. serratus*, *Dapsilodus obliquicostatus*, and *Belodella* sp.

Polychaetes. Bergman et al. (2004) recorded *Rhytiprion magnus*.

References. Hede 1927a, p. 42, (contains list of fossils), Munthe 1927a, p. 94, (the age of the old quarry – abandoned “some years ago” – etc.), Martinsson 1962, p. 53, Eisenack 1963a, p. 134, pl. 3, fig. 17, Eisenack 1964a, p. 310, Loc. 28, Manten 1971, p. 345, fig. 175, Laufeld 1974a, b*, Bassett & Cocks 1974 (under various Hunninge designations), Franzén 1974, Larsson 1979, Klaaman & Einasto 1982, Franzén-Bengtson 1983b, Jeppsson 1983, Odin et al. 1984, Frykman 1985, 1986, 1989, Le Hérissé 1988, 1989, Bergman 1989, Fredholm 1990, Môtus & Klaaman 1999, Bergman et al. 2004.

Stop 7. Klinteenklaven–Gannarveskär localities

All the localities are on Topographic map 6I Visby SO and Geological map SGU Aa 164 Hemse.

Description. The Early/Late Homeric boundary interval in distal platform areas on western Gotland. These low coastal exposures form the type sections for the Gannarve Member of the Fröjel Formation (Fig. 21). The lowermost parts of the overlying Halla Formation are exposed in the southernmost exposures at Gannarve. The Gannarve Member consists of light bluish-grey to brownish, silty and slightly dolomitic limestones and calcareous siltstones that alternate with darker, fissile mudstones and argillaceous siltstones. The more weathering resistant siltstones display current-oriented orthocones, rare shell lags and abundant primary sedimentary structures, e.g. current ripples and hummocky cross-stratification. The lower bedding planes of these beds are sharp to erosive and show abundant tool marks indicating transport from approximately north to south. Current ripples at the upper bedding planes show various palaeoflow-directions, generally from west to east. Intense horizontal bioturbation (epichnial grooves) is common on some upper bedding planes. The interbedded mudstones and fissile siltstones are massive or display planar lamination. The top of the Gannarve Member is conformable here, but is an epikarstic unconformity only a few kilometres further towards the north-east. The succession reflects deposition during alternating storm- and fair-weather conditions during progressive shallowing and siliciclastic input to distal platform environments.



Fig. 21. Alternating mixed carbonate-siliciclastic storm beds and fair-weather mud- and siltstones of the middle Gannarve Member (Fröjel Formation) at Klinteenklaven 3.

Oceanic effects. The Mulde Event. The sequence of changes studied here (Jeppsson & Calner 2003) is:

1. Siltstone due to the regression caused by the Gannarve Glaciation, a low diversity fauna – brachiopods, graptolites (the *flemingidubius* biozone of Porębska et al. 2004) and conodonts (strongly dominated by *Ozarkodina excavata*), increasing $\delta^{13}\text{C}$ (at Klinteenklaven 2 and Gannarveskär 1).

2. Maximum regression, a subaerial erosion surface in more proximal settings but not here. Rapidly increasing carbonate content towards the end of this interval. A slightly more diverse conodont fauna occurs at the end of this interval, probably due to relaxed competition during Datum 2 of the Mulde Event (at Gannarveskär 4).

3. Abrupt end of the glaciation, rapid transgression, formation of the Bara Oolite Mbr across Gotland. Laminated sediments further offshore. The conodont fauna is strongly dominated by coniforms, and among them by *Panderodus equicostatus*.

4. Marly limestone and marls at Gannarveskär 2 with a similar conodont fauna as in the Bara Oolite. Deposition of the c. 0.3 to 0.4 m thick Grötlingbo Bentonite (hitherto identified in cores from Gotland, an exposure on eastern Gotland, in Estonia and Latvia). Not seen here but evident in the strong silicification of some carbonate fossils.

Klinteenklaven 2. 636106 164253, c. 2180 m NNW of Fröjel church. Shoreline exposure c.100 m north of the southern side of the bay, just west of a locked gate (Fig. 22).



Fig. 22. Upper bedding plane of hummocky cross-stratified calcareous siltstone at Klinteenklaven 2 (Gannarve Member, Fröjel Formation). Crowbar for scale.

Reference level. A decimetre-thick siltstone bed, which displays large scale tangential cross-bedding at its northernmost extension. The bed crops out c. 30 m south-west of the gate, and is the second uppermost resistant bed accessible at the outcrop.

Stratigraphy. Slite Group, Fröjel Fm, Gannarve Mbr. At nearby localities this member has yielded conodonts of the *O. b. longa* Zone, Subzone 1, and graptolites of the uppermost *Cyrtograptus lundgreni* Zone.

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported a brachiopod average of 3.20‰.

References. Calner 1999* (includes a measured section), Calner & Jeppsson 2003, Jeppsson & Calner 2003.

Gannarveskär 1. 636100 164235, low cliff section along the western shore of Skäret. The locality includes the exposure from the north-east tip of the peninsula to the end of the exposures, c. 150 m to the SSW.

Reference level. The boundary between the pure siltstone and succeeding thin-bedded alternating lithologies near the top of the section, a surface with bored holes with rounded bottoms.

Stratigraphy. Slite Group, Fröjel Fm, Gannarve Mbr, *O. b. longa* Zone, Subzone 1. Mulde Event.

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported a brachiopod average of 3.15‰.

Conodonts. *Ozarkodina bohemica longa*, *O. excavata*, *O. cf. confluens*, *Oulodus* sp., *Panderodus equicostatus*, *Pseudooneothodus bicornis*, *Ps. beckmanni*, and *Dapsilodus*.

Brachiopods. Type locality for *Plagiorhyncha cordata* and *Streptochonetes cingulatus* (Lindström 1860).

Chitinozoans. At Robbjäns Kvarn 2, in the upper part of the Gannarve Mbr, Laufeld (1974a) found *Ancyrochitina cf. gutnica*, *Conochitina aff. elegans*, *C. pachycephala*, *Desmochitina muldiensis*, and *Gotlandochitina cf. uncinata*.

Note. The thin-bedded strata above the reference level are poorly exposed.

References. Lindström 1860, Kiesow 1888, p. 15 ("Skäret" bei Gannarfve), Westerberg 1895, p. 419, Hede 1927, p. 16, Bassett & Cocks 1974, p. 28 (Gannarfleskar), Ramsköld in Jaanusson 1986*, Calner 1999 (includes a measured section), Calner & Jeppsson 2003, Jeppsson & Calner 2003.

Gannarveskär 4. 636084 164231, 2.12 km north-west of Fröjel church. Section in a small excavated hole 10 m north of the northern shore of the small bay.

Stratigraphy. Slite Group, Fröjel Fm, Gannarve Mbr, and *O. b. longa* Zone, Subzone 1 extends up to 0.55 m below ground level. Halla Fm and Subzone 2.

Oceanic effects. Mulde Event. Graptolite finds from the area show that Datum 2 (= the *lundgreni* event as originally defined) of the Mulde Event, is within the strata exposed between Klinteenklaven 2 and Gannarveskär 2. Conodont data (see below) further indicate that this datum is within the topmost 4 cm of the Gannarve Mbr or at the upper boundary of this member (Jeppsson & Calner 2003).

Conodonts. The lower samples yielded *Ozarkodina bohemica longa*, *O. excavata*, *Oulodus* sp., *Panderodus equicostatus*, *Pseudooneothodus beckmanni*, *Ps. bicornis*, and *Dapsilodus*. A sample from the topmost four centimetres of the Gannarve Mbr contained *Ozarkodina bohemica longa*, *O. excavata*, *O. confluens*, *Oulodus cf. siluricus*, *Panderodus equicostatus*, *P. serratus* or *unicostatus* group, *P. panderi*, *Pseudooneothodus beckmanni*, *Ps. bicornis*, *Dapsilodus*, and *Decoriconus*. Regarding the succeeding Halla fauna see Gannarveskär 2, below.

References. Calner & Jeppsson 2003, Jeppsson & Calner 2003* (includes a measured section).

Gannarveskär 2. 636080 164234. Small exposure of argillaceous limestone at the shoreline of the small bight facing south-west on the western side of Skäret, 100 m south of Gannarveskär 1.

Stratigraphy. Halla Fm, Mulde Mbr, *O. b. longa* Zone, Subzone 2, *P. d. parvus* graptolite Zone.

Oceanic effects. Mulde Event.

Conodonts. *Ozarkodina bohemica longa*, *O. excavata*, *Oulodus* sp., *Panderodus equicostatus*, *Pseudooneothodus beckmanni*, *Ps. bicornis*, and *Decoricus*.

Graptolites. Koren' (in Jeppsson & Calner 2003) identified graptolite fragments, extracted with the conodonts, as *Pristiograptus dubius parvus*.

References. ?Kiesow 1888, p. 15 ("Skäret" bei Gannarfve), Bassett & Cocks 1974 (p. 28: Gannarfleskar), Ramsköld in Jaanusson 1986, Probably Liljedahl 1994, p. 33 (Gannarveskär), Jeppsson et al. 1995, Calner 1999*, Calner & Jeppsson 2003, Jeppsson & Calner 2003.

Stop 8. Blåhäll 1

6356759 1641910, c. 2940 m south-west of Fröjel church. Topographic map 56C Klintehamn. Geological map SGU Aa 164 Hemse. A c. 450 m long coastal cliff section, immediately south-west of the parish boundary at Blåhäll (Figs. 9 and 23).

Reference level. The lower surface of a protruding bed, c. 2 m above sea-level (Bergman 1989). It can be followed for at least 50–100 m.



Fig. 23. Close-up of argillaceous skeletal mud- and wackestone of distal platform origin. Blåhäll 1 locality (Mulde Brick-clay Member, Halla Formation). Lens cap for scale.

Stratigraphy and facies. Early Late Homeric on western Gotland. The Mulde Brick-clay Mbr of the Halla Fm, upper part, *O. b. longa* Zone, Subzone 4 and *K. o. absidata* Zone, lowermost part (topmost in the section), *G. nassa* graptolite Zone in the sense of Jaeger (1991). The very argillaceous strata at this locality reflect the transgression and maximum flooding following the middle Homeric lowstand. The section is composed of argillaceous skeletal mudstone, wackestone, and marl of distal platform origin (Fig. 24). More or less bioturbated packstone beds, c. 1–2 cm thick, occur rarely throughout the section inferring subordinate, weak current deposition. The benthic shelly fauna is exceptionally rich and includes frequent brachiopods and trilobites. A 0.3–0.5 m thick halysitid-heliolitid autobiostrume (bafflestone) is traceable throughout the outcrop (Calner et al. 2000, cf. Neuman & Kershaw 1991). This biostrome is both geographically and stratigraphically isolated on the seaward slope of the platform. It is dominated by the tabulate corals *Stelliporella* cf. *parvistella* and *Halysites laticatenatus*, and the rugose coral *Dokophyllum elegantulum*. The matrix of the biostrome is in places exceptionally rich in paleocopid and metacopid ostracodes.

Oceanic effects. Mulde Event, recovery stage as delimited by Jeppsson & Calner (2003).

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported brachiopod averages of 1.49‰ and, higher up, averages of 1.54‰.

Beyrichiid ostracodes. Martinsson (1962) identified *Craspedobolbina clavata* and *Beyrichia morifera*.

Chitinozoans. Laufeld (1974a) recorded *Anchyrochitina gutnica*, *Conochitina* aff. *elegans*, *C. pachycephala*, *C. tuba*, *C.* aff. *proboscifera*, and *Desmochitina muldiensis*.

Conodonts. Jeppsson (in Calner & Jeppsson 2003) found *Kockelella ortus absidata* FAD at +0.88/1.00 m, *Ozarkodina bohemia longa*, *O. confluens*, *O. excavata*, *Oulodus siluricus* n.ssp., *Panderodus equicostatus*, *P. unicosatus* fad, *Pseudooneothodus beckmanni*, *P. bicornis*, *Dapsilodus obliquicostatus*, and *Decoriconus*.

Corals. Neuman & Kershaw (1991) and Young (unpubl. report) recorded the rugose corals *Arachnophyllum purchisoni*, *Spongiophylloides grayi*, *Entelophyllum pseododianthus*, *Tryplasma vermiculare*, *Helminthidium mirum*, and the tabulates *Favosites gothlandicus*, *Heliolithes megastoma*, *H. interstinctus*, *H. farvistella*, *Plasmophora seita*, and *Propora tubulata*.

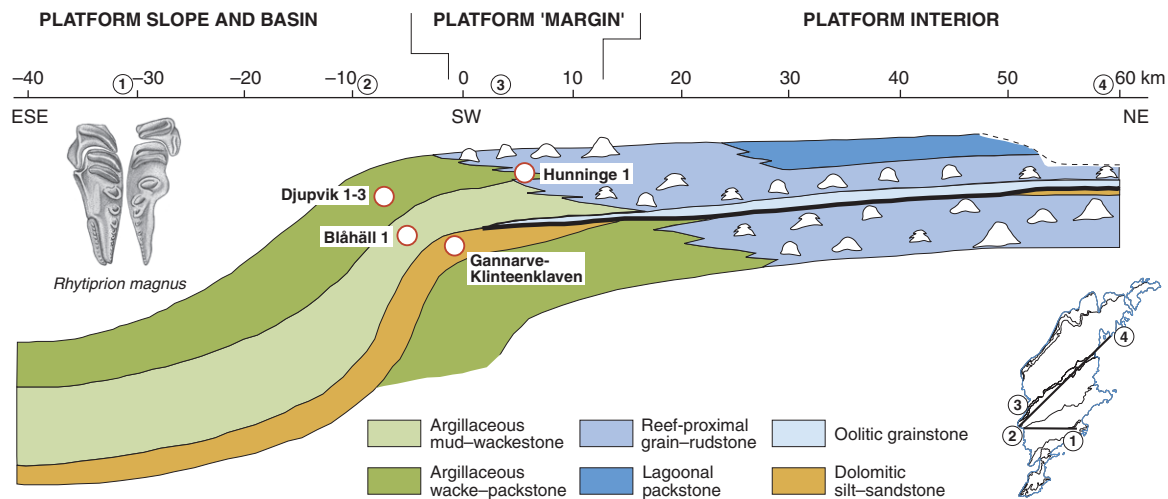


Fig. 24. Large-scale facies relationships during the Late Wenlock of Gotland (thicknesses not to scale). The palaeogeographical and inferred platform position of some of the Dynamic Silurian Earth field trip localities are plotted. The facies controlled polychaete *Rhytiprion magnus* (shown by its reconstructed jaw apparatus) was relatively abundant only in off-shore, low energy environments in which soft, fine-grained substrates formed below the effective wave base (Bergman et al. 2004). It is relatively common only in the distal Djupvik Member. Note the position of the Djupvik 1–3 localities seaward of the platform margin. The thick line represents a basin-regional unconformity (Calner 2002) that separates the Slite Group (below) from the Halla Formation (above), and which approximately corresponds to the top of the *Cyrtograptus lundgreni* graptolite Zone. The uppermost line corresponds to the *Colonograptus? praedeubeli* graptolite Zone. Numbers 1–4 refer to geographical areas and drillcores; 1 = När-1 drillcore, 2 = Bjärages-1 drilling, 3 = Klintehamn area, 4 = Ytterholmen. Illustration modified from Calner et al. (2000) and Bergman et al. (2004).

Graptolites. *Gotographus nassa* and *Pristiograptus dubius*.

Polychaetes. Bergman (1989) identified *Kettnerites (K.) martinsoni* var. *mulde*, *K. (Aeolus) sisyphi*, and Bergman et al. (2004) recorded *Rhytiprion magnus*.

Trilobites. Ramsköld (1985b) identified *Proteus concinnus*, *Warburgella* sp., *Harpidella elegantula*, *Encrinurus (E.) macrourus*, *Calymene* spp. *Dalmanites myops*, and a small lichenid.

Note. There are several Blåhäll on Gotland, at least three of which are found in the geological literature, e.g. “Blåhäll fiskeläger” of Johannessen (1993) is another locality (south of Stavsklint 1).

References. Hennig 1905, p. 16, Hede 1927b, p. 19, Hede 1942, Loc. 2 b, Martinsson 1962, p. 53, Laufeld 1974a, b*, Bassett & Cocks 1974 (St. Blåhäll), Claesson 1979, Larsson 1979, Poulsen et al. 1982, Klaaman & Einasto 1982, Jeppsson 1983, Spjeldnaes 1984, Ramsköld 1984, 1985a, b, 1986, Sanford & Mosher 1985, Le Hérisse 1988, 1989, Frykman 1989, Bergman 1989, Scrutton 1989 (Blahall), Fredholm 1990, Young & Scrutton 1991, Neuman & Kershaw 1991, Samtleben et al. 1996, Mótus & Klaaman 1999, Calner et al. 2000 (includes a measured section), Adrian et al. 2000, Munnecke et al. 2001, Jeppsson & Calner 2003, Calner & Jeppsson 2003, Bergman et al. 2004.

Stop 9. Djupvik 1

6355822 1641069, c. 4180 m south-west of Fröjel church. Topographic map 56C Klintehamn. Geological map SGUAA 164 Hemse. Coastal cliff section, c. 75 m south-west of the house north-west of the road, c. 275 m south-west of the harbour of Djauvik.

Reference level. There are four distinct bentonite horizons at the locality. The middle two are only 0.16 m apart. The lower of these is the reference level (Fig. 25).

Stratigraphy and facies. Early Late Homeric on western Gotland. Halla Fm, Djupvik Mbr, middle part, *K. o. absidata* Zone. The *G. nassa* graptolite Zone (in the restricted sense of Jaeger 1991). *Co.? praedeubeli* has been found in the succeeding strata but not here. Approximately six metres of well bioturbated, aggradational to slightly progradational skeletal wackestones and marls crop out at the locality. The limestone beds are light bluish grey, nodular to continuous and generally some 3–5 cm in thickness. The slightly thinner, highly argillaceous marls display compaction features. Primary depositional textures include rare



Fig. 25. Argillaceous and slightly progradational skeletal wacke- and packstone formed in distal platform settings. Four bentonites occur in the lower half of the c. 5 m high section. Note that the photograph is from Djupvik 2, just south of Djupvik 1. Djupvik Member, Halla Formation.

thin tempestites. Skeletal grains are disarticulated and generally derive from brachiopods and trilobites. Large epibenthic metazoans are represented by stromatoporoids and various tabulate corals, e.g. *Halsites* sp. and *Heliolites* sp. These are in growth position, low to highly dome-shaped, and are draped by overlying marls.

Oceanic effects. Near the end of the recovery phase of the Mulde Event.

Age. Odin et al. (1986) dated the two middle bentonites as 427.4 ± 6.0 Ma.

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported a brachiopod average of 1.79‰.

Beyrichiid ostracodes. Martinsson (1962) identified (*Craspedobolbina variolata*), *C.?* *percurrens*, *C. clavata*, *Beyrichia dactyloscopica*, and *B. morifera*.

Chitinozoans. Laufeld (1974a) recorded *Anchyrochitina gutnica*, *A. primitiva*, *Conochitina* aff. *elegans*, *C. pachycephala*, *C.* aff. *proboscifera*, *C.* sp., *Desmochitina muldiensis*, *Gotlandochitina cornuta*, *Linochitina cingulata*, and *L.* cf. *odiosa*.

Conodonts. Jeppsson (in Calner & Jeppsson 2003) identified *Kockelella ortus absidata*, *Ozarkodina bohemica longa*, *O. confluens*, *O. excavata*, *Oulodus siluricus* n. ssp., ‘*Ozarkodina*’ n. sp. of Aldridge (1985), *Panderodus equicostatus*, *P. unicastatus*, *Pseudooneothodus beckmanni*, *P. bicornis*, *Dapsilodus obliquicostatus*, *Decoriconus*, and *Belodella* sp.

Fish. Fredholm (1990) identified *Thelodus schmidti* at +0.00/0.16 m, and, at Djupvik 2, *Loganellia martinssoni* at -1.05/-0.95 m.

Polychaetes. Bergman (1989) recorded *Kettnerites* (*K.*) *martinssoni* var. *mulde* and *K. (A.) sisyphi sisyphi*, and Bergman et al. (2004) identified *Rhytiprion magnus*.

Stromatoporoids. Mori (1970) reported *Clathrodictyon djupvikense*, *Pycnodictyon densum*, *Actinostromella vaiverensis*, and *Densastroma* sp.

Note. Many old collections and published data may include material from Djupvik 2–4.

References. von Helmersen 1858, p. 9 (contains list of fossils), Holm 1890, p. 25, Hennig 1906, p. 25, Hede 1927b, p. 19, Hede 1942, Loc. 1 b, Boucot 1962, pl. 97, figs. 1–6, pl. 100, fig. 14, pl. 101, figs. 12–13, Martinsson 1962, p. 53, Eisenack 1964b, p. 310, Loc. 25, Mori 1970, p. 14, Loc. 68, Laufeld 1974a, b*, Larsson 1979, Laufeld & Martinsson 1981, Jeppsson 1982, 1983, 1989d, Odin et al. 1984, 1986, Cooper 1984, Stridsberg 1985 (old collections), Cavell & Baadsgaard 1986 (sample B-108), Baadsgaard 1988

(sample B-108), Le Hérisse 1988, 1989, Bergman 1989, Fredholm 1990, Sivhed 1990, Neuman & Kershaw 1991, Liljedahl 1994, Schmitz et al. 1994, Batchelor & Jeppsson 1999, Calner et al. 2000, Munnecke et al. 2001, Calner & Jeppsson 2003, Jeppsson & Calner 2003, Bergman et al. 2004.

Djupvik 3. 635577 164096, c. 4275 m south-west of Fröjel church. Topographic map 56C Klintehamn. Geological map SGU Aa 164 Hemse. A section of about 7.2 m of tilted strata is exposed from below the solitary house west of the road to the fault, about 50 m south-west of the house. Djupvik 1 starts beyond the fault.

Stratigraphy. Early Late Homeric. Halla Fm, Djupvik Mbr.

Fauna. The same as at Djupvik 1.

References. See “Note” on Djupvik 1 for possible older references, Bergman 1989*, Fredholm 1990.

Stop 10. Kuppen 1–4

All are on Topographic map 56D Ljugarn. Geological map SGU Aa 170 Katthammarvik.

Stratigraphy. Late Early Ludfordian biostromes and rocky shorelines of the Hemse Group, units d and e, on easternmost Gotland. The locally overlying crinoid limestone (although topographically beside) represents the Millklint Limestone = unit d.

Description. The Kuppen localities refer to several hundred of metres of well exposed coastal sections in the easternmost parts of the Östergarn peninsula on east-central Gotland (Fig. 26). The peninsula is characterized by several outliers composed of stacked biostromes and interbedded skeletal grainstone and packstone. The outliers have conspicuously planar tops. These surfaces most likely are inherited from prominent transgressive surfaces separating underlying reef tracts from overlying, now eroded, argillaceous limestone and marl.

Oceanic effects. The biostromes at Kuppen represent the Etelhem Secundo Episode and the overlying crinoid limestone the succeeding Havdhem Primo Episode.



Fig. 26. Thick stromatoporoid biostrome unconformably overlain by fine to coarse grained limestone. Kuppen 1. Hemse Group, unit d. Hammer for scale.

Kuppen 1. 6370598 1687580, c. 4170 m east of Östergarn church. Cliff section at the southernmost end of the cliff at the innermost part of the bight, c. 30 m north-west of the easternmost tip of Snabben. For a detailed description, see Hede (1929 and 1960).

Reference point. The central part of Fig. 28, Munthe 1910 (= Fig. 12, Hede 1929).

Reference level. The base of the bedded limestone unit.

Stratigraphy. Hemse Group, units d and e. *P. siluricus* Zone in the bedded limestone unit, the subzone with the conodont described as gen. et sp. indet. by Jeppsson (1983).

Conodonts. A sample from the bedded limestone yielded *Polygnathoides siluricus*, gen. et sp. indet. of Jeppsson (1983), *Corryssognathus dubius*, *Ozarkodina confluens*, *O. excavata*, *Panderodus* aff. *greenlandensis*, *P. unicostatus*, and *P. panderi*.

References. Munthe 1910, fig. 28, Hede 1929, fig. 12, p. 40, Hede 1960, Loc. 39 *pars*, p. 78, p. 79, Laufeld 1974a, b*, Laufeld et al. 1978, Larsson 1979, Riding 1981, Jeppsson 1982, 1983, Kershaw 1987a, 1990, Fredholm 1988a, b, Bergman 1989, Sivhed 1990, Neuman & Kershaw 1991, Keeling & Kershaw 1994.

Kuppen 2. 6370704 1687532, c. 4140 m east of Östergarn church. Map 56D Ljugarn. Cliff section, c. 110 m north-west of the easternmost tip of Snabben, c. 80 m WNW of Kuppen 1. For a detailed description, see Hede (1929 and 1960).

Reference point. The left part of Hede's Fig. 13.

Reference level. The boundary between the lowermost, thick unit and the 0.3 m thick unit. The reference level was marked in the section.

Stratigraphy. Hemse Group, unit d.

Stromatoporoids. Kano (1990) identified *Lophiostroma schmidtii*, *Pseudolabechia granulata*, *Plectostroma scaniense*, *Densastroma podolicum*, *Clathrodictyon mohicanum*, *C. convictum*, *Ecclimadictyon robustum*, *Stromatopora beckkeri*, *S. venukovi*, *S. sp.*, *Parallelostroma typicum*, *Syringostromella borealis*, and *Parallelopora ornata*.

References. Hede 1929, Fig. 13, p. 40, Hede 1960, Loc. 39 *pars*, p. 79, Laufeld 1974a, b*, Kershaw & Riding 1978, Riding 1981, Laufeld & Martinsson 1981, Kershaw 1981, 1987a, b, 1990, Jeppsson 1982, 1983, Fredholm 1988a, b, Le Hérissé 1988, 1989, Bergman 1989, Kano 1990, 1994, Neuman & Kershaw 1991, Keeling & Kershaw 1994.

Kuppen 3. (CJ 7556 6662), c. 4120 m east of Östergarn church. Map 56D Ljugarn. Cliff section c. 170 m north-west of easternmost tip of Snabben, c. 70 m north-west of Kuppen 2.

Reference point. Marked on the cliff in red paint.

Reference level. The erosion surface at the top of the lowest biostrome.

Stratigraphy. Hemse Group, unit d. *P. siluricus* Zone.

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported a brachiopod average of 0.88‰.

References. Kershaw 1987a, b, 1990, Neuman & Kershaw 1991.

Kuppen 4. (CJ 7548 6668), c. 4050 m east of Östergarn church. Map 56D Ljugarn. Cliff section c. 280 m north-west of easternmost tip of Snabben, c. 170 m north-west of Kuppen 2.

Reference point. Marked on the cliff in red paint.

Reference level. The base of the lowermost biostrome.

Stratigraphy. Hemse Group, unit d.

References. Kershaw 1987a, 1990, Neuman & Kershaw 1991.

Stop 11. Botvide 1

6355803 1671542, c. 2350 m north-east of Lau church. Topographic map 56D Ljugarn. Geological map SGU Aa 156 Ronehamn. A c. 3 m high roadside section west of the road, SSW of the southernmost house at Botvide.



Fig. 27. The unconformable boundary between the Hemse Group and the Eke Formation at Botvide 1. The centimetre scale bar rests on the boundary, which is developed as an abraded hardground. Note the poor sorting of the overlying conglomerate.

Reference point. At the highest point of the anticline.

Reference level. The Hemse-Eke boundary, marked by a basal Eke conglomerate (see below and Fig. 27). The position of this boundary undulates strongly, from 2.25 m above the bottom of the ditch at the highest point to only 0.5 m, 7 m further northwards.

Stratigraphy and facies. The middle Ludfordian on eastern Gotland. The exposed När Fm consists of interbedded limestone and marls. The contact between its main part and the Botvide Mbr at c. -2.15 m is no longer accessible without digging. The upper part of the Botvide Mbr was once referred to as the *Dayia* Flags (Munthe 1910) because of coquinas of the brachiopod *Dayia navicula* in some beds and its higher weathering resistance than subjacent beds (due to being dolomitic). This “*Dayia* Flags” lithology is found everywhere along the strike. The brachiopod *Shaleria* aff. *ornatella* (sensu Bassett & Cocks 1974) is relatively rare in the *Dayia* Flags. A minor hiatus is related to the Hemse-Eke boundary at this locality.

The Eke Fm starts with a thin basal conglomerate of Hemse Marl pebbles (Munthe 1902). This conglomerate occurs at all exposures on eastern and central Gotland. Phosphorite and glauconite coatings occur on the erosion surface, which has been ascribed to submarine weathering (Spjeldnaes 1950). The conglomerate is overlain by more or less oncoidal crinoid limestone of the Eke Fm. The bedding of the latter is disturbed and boulders and smaller grains of different lithology are mixed. Cherns (1982, 1983) interpreted this as the result of karst weathering.

Biostratigraphy. *Polygnathoides siluricus*, indicator of the *P. siluricus* Zone, is regularly present in collections from the main part of the När Fm, but extremely rare (c. 1/25 000 specimens) or episodic in the Botvide Mbr. It has been found at –1.40 m, but at –0.1 m at Malms 1. Correlations with Australia show that it survived to the top of the Botvide Mbr (Jeppsson et al. unpublished data). Hence, the whole Botvide Mbr belongs in the Upper *Po. siluricus* Subzone of the *Po. siluricus* Zone. The Eke Fm belongs in the Lower Icriodontid Subzone of the Icriodontid Zone (Jeppsson in press). The exposed strata have been correlated with what is now the Upper Leintwardine Fm in the Ludlow Type Area, based on the presence of *Neobeyrichia lauensis* and *N. scissa* (by Martinsson 1967) or the lowermost Lower Whitcliffe Fm.

Oceanic effects. The Lau Event. The sequence of changes is:

1. Strata below c. –2.15 m probably represent the Havdhem Primo Episode. The succeeding Botvide Mbr represents the early Lau Event, whereas the exposed Eke Fm represents the middle Lau Event.

2. Start of the event with Datum 1. As during other primo-secundo events, the conodont faunas initially remained essentially the same as during the preceding primo episode, although large collections reveal a few differences, e.g. *P. siluricus* became exceedingly rare.

3. Changes through the Botvide Mbr include extinctions and other faunal changes, increase in the dolomite content, and increased frequency of *Dayia* coquinas. Over 50% of the conodont taxa on Gotland became extinct or disappeared during this time. Most of these taxa had a frequency of c. 1% or less (several taxa <<1%), hence, the position of the succeeding datum points is not yet precisely known, except that the disappearance of *Pa. panderi recurvatus* near above –0.90 m is well established. Globally, all platform conodonts became extinct (*Polygnathoides* and *Kockelella*, the latter with at least two lineages, one found to the top of the Hemse) and so did two other widespread taxa, i.e. *Oulodus siluricus* and *Pa. gracilis*.

4. A global change on Gotland reflected as a change from *Dayia* coquinas to *Shaleria* aff. *ornatella* as the dominant brachiopod. Changes occur also in the conodont fauna and in $\delta^{13}\text{C}$ values.

5. Submarine erosion (Spjeldnaes 1950).

6. Deposition of Eke Fm, oncolitic and crinoid rich limestones with stromatolites.

7. A regression and the development of karst (Cherns 1982, 1983) during or after the deposition of the Eke Fm.

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported a brachiopod average of 1.45‰. Analyses by Anita Andrews (pers. comm.) of 69 micrite samples from –2.24 to +1.31 m indicate i.a. cyclical fluctuations around a rapidly increasing trend, from 1.49 to 4.3‰.

Fauna. Literature data indicate substantial macrofaunal differences between the main part of the När Fm and the Eke Fm.

Beyrichiid ostracodes. Martinsson (1962) identified *Sleia equestris*, *Lophoctenella* cf. *scanensis*, *Neobeyrichia scissa*, *N. lauensis*, and *Plicibeyrichia* aff. *ornatissima* in the Hemse Group.

Brachiopods. Lena Gustavsson (Lund University) has assembled the literature record from Botvide 1: *Dayia navicula*, *Shaleria* (*S.*) *ornatella*, *Isorthis canaliculata*, *Protochonetes striatellus*, by Hede 1960 (and earlier and later authors), and *Brachyprion* sp. by Hurst (1975). She found all these except *Brachyprion*, in a bulk sample from a marly layer in the uppermost decimetre of the Hemse. The sample yielded 1167 specimens on a 1-mm-screen. In addition she identified *Craniops implicata*, *Endrea ekenia*, *Howellella elegans*, cf. *Kirkidium knighti* LAD, *Mesopholidostrophia laevigata*, *Microsphaeridiorhyncus? nucula*, *Morinorhyncus? sp.* (possibly = *M. crispus*), *Nucleospira pisum*, *Ptychopleurella bouchardi* FAD, strophomenid indet. sp. (?= Hurst's *Brachyprion* sp.), *Strophonella euglypha*, and *Lepidoleptaena poulsenii*. Most of the taxa added by her were represented by only a few small specimens.

Chitinozoans. Laufeld (1974a) identified *Ancyrochitina* cf. *diabolus*, *A. primitiva* LAD at –0.5 m, *Angochitina ceratophora*, *A. crassispina*, *A. echinata*, *Conochitina lauensis*, *Desmochitina hemsiensis*, *D. squamosa*, *Sphaerochitina* sp., and *Linochitina convexa* in the Hemse Group, and *Angochitina elongata*, *Eisenackitina philipi*, and *Linochitina convexa* in the Eke Fm.

Conodonts. The following taxa had their LAD in the strata exposed at this locality: *Polygnathoides siluricus*, *Kockelella* aff. *ortus*, *K.* aff. *maenniki*, *K.* aff. *sardoa*, *K.* cf. *variabilis*, *Ozarkodina c. confluens*, *Oulodus s. siluricus*, *P. gracilis*, etc. Other taxa range higher: *Corrysognathus dubius* lad, *O. confluens* ssp. e, *O. excavata*, *Oul. excavata*, *Panderodus unicostatus*, *P. panderi* lad, *P.* aff. *serratus*, *Pseudooneothodus beckmanni*, *Decoriconus*, and *Belodella*.

Corals. The youngest two finds of halysitids (*Cystihalysites* sp.) on Gotland are from this locality, see Mötus & Sandström (in press).

Fish. Eva Nilsson (Lund University) has assembled and updated the literature records and studied further samples from this locality (LAD etc. based on her studies). Fredholm (1988a, b, 1989) reported *Archegonaspis lindstroemi* LAD at –0.1 m, *Andreolepis hedei* LAD at –0.1 m, *Thelodus parvidens*, *Gomphonchus sandelensis*, *Nostolepis striata* LAD at –0.1 m, *Lanarkia horrida* (FAD just below the LAD of *A. hedei* at Nyan 2), and a fragment of *Tremataspis* at –0.59/0.52 m. Eva Nilsson has also identified *Phlebolepis elegans* LAD at –0.1 m, *Thelodus carinatus* LAD at –0.1 m, and *Thelodus* sp. See also Nilsson et al. (2005 in this volume).

Polychaetes. Bergman (1989) identified *Kettnerites* (*K.*) cf. *polonensis*, *K.* (*K.*) cf. *burgensis*, *K.* (*K.*) *burgensis*, and *K.* (*K.*) *huberti*. Eriksson (2001) recorded *Megaramphrion magnus* and *Ramphoprion gotlandensis* morphotype D. In addition Eriksson et al. (2004) reported members of Polychaetaspidae, Kalloprionidae, Skalenopronidae, Atraktoprionidae, and Hadoprionidae. See also discussion of the polychaetes of the Lau Event in Eriksson et al. (2004).

Trilobites. Ramsköld (1985b) found *Encrinurus nasutus* (described in Ramsköld 1986), proetids, *Papillicalymene* spp., *Calymene?* sp., a small lichid and a bumastid, in the lower Eke Fm at the nearby locality Gannor 1 (same lithology and stratigraphical position).

References. Munthe 1902, p. 41, van Hoepen 1910, p. 50, Hede 1925, p. 45, Hede 1960, p. 80–81, Loc. 42, Martinsson 1962, p. 57, 1967, p. 370, Fähraeus 1969, p. 12, 14, Laufeld 1974a, b*, Jeppsson 1975, p. 10, 1982, 1983, Hurst 1975b, Larsson 1979, Laufeld & Martinsson 1981, Cherns 1982, 1983, Klaaman & Einasto 1982, Ramsköld 1986, Fredholm 1988a, b, Le Hérisse 1988, 1989, Bergman 1989, 1995, Sivhed 1990, Young & Scrutton 1991, Sanford & Mosher 1994, Jeppsson & Aldridge 2000, Eriksson 2001, Eriksson et al. 2004, Calner 2005a, b, Calner & Eriksson in press.

Botvide 2. 6355635 1671444, c. 2190 m north-east of Lau church. Topographic map 56D Ljugarn. Geological map SGU Aa 156 Ronehamn. Isolated south-east-facing cliffs, c. 90 m south-east of the triangulation point 17.36, and c. 120 m south of the windmill. Botvide 2 is up in the hill behind Botvide 1.

Stratigraphy. Eke Fm, lower part.

References. Munthe 1902, p. 41, Hede 1925, p. 45, footnote, Laufeld 1974a, b*, Sivhed 1990.

Stop 12. Lau Backar 1

6354887 1670849, c. 1250 m ENE of Lau church. Topographic map 56D Ljugarn. Geological map SGU Aa 156 Ronehamn. Exposures in former clay pits (Munthe 1925), now vernal pools, c. 1000 m south-west of the triangulation point near Botvide. Stop at the solitary house at the 90° bend of the private road. Walk WNW to the power-line pole. For a detailed description, see Hede 1960.

Stratigraphy. Late Ludfordian Eke Fm on eastern Gotland, type locality for the *Rhizophyllum* Limestone. Uppermost part of the Lower Icriodontid Subzone (Jeppsson in press).

Oceanic effects. Lau Event, slightly younger strata than those at Botvide 1, and coeval with those just below the appearance of oncoids at Bodudd 1.

$\delta^{13}\text{C}$. Brachiopod data range from c. 5.1 to 7.3‰ (Wenzel and Joachimski 1996, Samtleben et al. 2000) and micrite gave 6.6‰ (analyses by Anita Andrews pers. comm.). No stratigraphical level is given for any analysis but the values and their range agree well with the increase through a similar thickness of coeval strata at Bodudd 1.

Fauna. Lau Backar 1 is a famous locality for fossil collecting and records a diverse fauna, much of which was described a long time ago.

Beyrichiid ostracodes. Martinsson (1962) identified *Atilia calcarulata*, *Hamulinavis convexivelata*, *Cliniella* cf. *hysiniana*, *Garniella* sp. *Retisacculus commatatus*, *Sleia equestris*, *Hemsiella loensis*, *H. anterovelata*, *Lauella uncinata*, *Beyrichia globulifera*, *B. duplicicalcarata*, *Neobeyrichia ctenophora*, *Calcaribeyrichia bicalcarata*, *Plicibeyrichia* aff. *ornatissima*, *Gannibeyrichia biplicata*, and *Kolmodinia* cf. *grandis*.

Brachiopods. Lena Gustavsson (Lund University) has assembled and updated the literature records: Lindström 1860, 358–371, Munthe 1902, p. 249, p. 250, Hede 1921, p. 68–69, Hede 1925b, p. 46, Hede 1960, Bassett & Cocks 1974, Hurst 1975, Harper & Boucot 1978b, Copper 2004, Hoel in press). Her large bulk sample from here yielded 4375 specimens (LAD etc. are also based on her literature studies): *Craniops*

implicata, *Dayia navicula*, *Delthyris elevata*, *Endrea ekenia*, *Gypidula galeata*, *Hesperorthis gotlandica*, *Homeospira baylei*, *Howellella elegans*, *Isorthis canaliculata*, *Janius barrandi* LAD, cf. *Glassina laeviscula*, *Lepidol-
eptaena poulsenii*, *Leptostrophia filosa*, *Mesopholidostrophia laevigata* LAD, *Microsphaeridiorhynchus? nucula*, *Morinorhynchus? sp.* (?=*M. rubeli* Musteikis & Cocks 2004) FAD, *Nucleospira pisum*, *Protochonetes striatellus*, *Ptychopleurella bouchardi*, *Shaleria (Shaleria) ornatella*, *Striispirifer sp.* (?=*S. striolatus*, see below), *Strophonella euglypha*, *Sphaerirhynchia wilsoni* “*Dinorthis rigida*” LAD and Orthid indet. sp. The following records are only based on literature data and partly updated: *Discina sp.*, *Orbiculoidea pilidium* FAD and LAD, *Orbiculoidea rugata*, *Boucotinskia? elongata* FAD, *Dalejina hybrida*, *Eodictyonella capewelli*, *Didymothyris didyma*, *Ferganella diodontia*, *Rhynchonella sphaerica* LAD, *Rhynchotreta cuneata* LAD, *Salopina tubulata*, *Shaleria (Shaleriella) ezerensis*, *Striispirifer striolatus*, and *Whitfieldella nitida*.

Chitinozoans. Laufeld (1974a) identified *Angochitina echinata*, *A. elongata*, *Conochitina sp.*, *Desmochitina hemsiensis*, *Eisenackitina cf. lagenomorpha*, *E. philipi*, and *Linochitina convexa*.

Conodonts. *O. confluens* ssp. e, *O. excavata*, *Panderodus unicostatus*, *Ps. serratus*, *Pseudooneothodus beckmanni*, and *Belodella*.

Corals. Neuman & Kershaw (1991) listed the rugosans *Rhizophyllum gotlandicum*, *Holmophyllum holmi*, *Entelophyllum fasciculatum*, *E. lauense*, and *Thryplasma simplex*, and the tabulates *Aulopora* spp. *Stelliporella parvistella*, *Heliolites interstinctus*, *H. daintreei* (reported by G. Young unpubl.), and massive favositids. Furthermore, a loose fragment of a halysitid has been seen but was not collected. If *in situ* halysitids can be confirmed here, it would be the youngest halysitid record, perhaps not only on Gotland.

Fish. Eva Nilsson (Lund University) has assembled and updated the literature records and studied further samples from here. Compared to the pre-event strata the yield is very poor. Spjeldnaes (1950) reported *Lanarkia horrida*, *Thelodus parvidens*, *Gomphonchus sandelensis*, and *Nostolepis striata*. In addition Fredholm (1989) found *Thelodus* sp.

Polychaetes. Bergman (1989) recorded *Kettnerites (Aeolus) cf. sisyphi*.

Stromatoporoids. Mori (1970) identified *Lophiostroma schmidti*.

Trilobites. Ramsköld (1985b) identified *Encrinurus nasutus* (the most common trilobite at this locality), *Balizoma obtusus* (both in Ramsköld 1986), *Eophacops lauensis* (type locality, Ramsköld 1985a), proetids, *Ktenoura coniformis?* *Papillicalymene* spp. *Acastella* sp., a small lichid, and *Dudleyaspis* sp. or spp. (Ramsköld 1985b).

Other fossils. Hede (1960) listed *Fenestella* spp., *Ptilodictya lanceolata* and numerous other bryozoans, and the ostracode *Leperditia phaceolus*.

Note. The name-form Lauberg is often found in old collections.

References. Lindström 1860, pp. 358-371, Lindström 1882a, p. 27, Munthe 1902, p. 31 (contains list of fossils), Munthe 1902, p. 249, p. 250, Munthe 1910 (contains a detailed map also reproduced in Munthe et al. 1925, the exposure is located within the *Ancylus* ring beach marked on the map), Munthe 1925, p. 85, Munthe et al. 1925, Hede 1921, p. 69 (list of fossils), Hede 1925a, p. 46 (list of fossils), Hede 1960, Loc. 43 (list of fossils), Wedekind 1927, pp. 23, 24, 31, Spjeldnaes 1950, p. 211, pl. 1, Figs. 1-7 (short report on several groups of fossils), Boucot 1962, pl. 104, figs. 9-14, Martinsson 1962, p. 57, Taugourdeau & Jekhowsky 1964, I.F.P. No. 4961, Borg 1965, p. 20, pl. 1, fig. 3, pl. 3, figs. 3, 6, Laufeld 1973, 1974a, b*, Hurst 1974, 1975b, Bassett & Cocks 1974 e.g. pp. 24, 39, 49, 51 (incl. Lauberg), Hurst 1975, Brood 1975a, 1978, 1984 (Lauberg), Laufeld & Jeppsson, 1976, Harper & Boucot 1978b, Larsson 1979, Laufeld & Martinsson 1981, Cherns 1983, Ramsköld 1983, 1984, 1985a, b, 1986, Bergman 1989, Fredholm 1989, Sivhed 1990, Neuman & Kershaw 1991, Young & Scrutton 1991, Sandford & Mosher 1994, Wenzel & Joachimski 1996, Johannessen 1998, Adrian et al. 2000, Copper 2004, Hoel in press.

Stop 13. Bodudd 1

6329554 1644709, c. 6220 m south-west of Näs church. Topographic map 56B Hemse. Geological map SGU Aa 152 Burgsvik. Shore exposure north of the point at the south-west ‘corner’ of the Näs peninsula. There are some boat-houses not marked on the topographical map. Bodudd 1 is c. 50 m east of the northernmost house.

Reference point for the lower part of the section. The southernmost of the six large Precambrian boulders found within c. 10 m from the shore, c. 80-90 m north of the fishing huts at the end of the road. The second boulder is c. 10 m further northwards.

Reference level. The Hemse-Eke boundary (Laufeld 1974b), at the contact between the typical western Hemse and the rubbly weathering lower Eke strata. There has been some confusion regarding the identification of this level. Hence, a distinct layer is selected here as **auxiliary reference level for the lower part of the section:** The upper surface of the distinctly pale, 26 mm thick, hard (resounding when a handheld slab is struck by the hammer) dolomite layer, just south of the second boulder.

Reference point for the upper part of the section. The largest Precambrian boulder with lichens, c. 130 m S 56° W of the fishing huts (note that there are several nearly as big boulders further away).

Auxiliary reference level for the upper part of the section. The upper surface of the most distinct, laterally continuous layer 0.52 m below the first scattered small oncolites. The exposure of this surface reaches from north-east of the boulder and continues out into the sea. Two similar, but less distinct, beds are found at +0.20 and +0.35 m, respectively. The oncolite frequency increases rapidly upwards.

Stratigraphy and facies. Late Ludfordian on western Gotland. This is the most distal exposure of the Hemse-Eke boundary. Hemse Group, När Fm, Botvide Mbr. At least one typical *Dayia navicula* coquina bed (5–15 mm) is found c. 15–20 m south of the lower auxiliary reference level and in the direction of the dip. A thin limestone bed outcrops another 8 m away in the same direction. The fauna agrees well with the Upper *Po. siluricus* Subzone (Jeppsson in press).

Eke Fm, the boundary between the lower part and the middle part is below the FAD of *P. equicostatus* at +0.67/0.70 m above the upper auxiliary reference level, that is, at or very close to the appearance of the first oncoids. It is also the boundary between the Lower and the Middle subzones of the Icriodontid Zone (Jeppsson in press). As far as is known, sedimentation was continuous here, in contrast to at more proximal localities.

Oceanic effects. Lau Event. See the description of Botvide 1, except that no pre-event strata, no erosion surface, and no conglomerate have been found here.

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported brachiopod averages of 2.31, 4.19, 4.62, 5.25, and 5.84‰ in 1.7 m of the strata. Analyses by Anita Andrews (pers. comm.) of 47 whole rock samples indicate i.a. cyclical fluctuations around a rapidly increasing trend from +1.54‰ at 3.22 m below the upper auxiliary reference level, high up in the Botvide Mbr, to a maximum of 7.05‰ at +0.61 m, then dropped to 5.57‰ at the top of the section, at +1.16/1.20 m.

Chitinozoans. Laufeld (1974a) found *Ancyrochitina* cf. *diabolus*, *Angochitina ceratophora*, *A. crassispira*, *A. echinata*, *Conochitina lauensis*, *Eisenackitina philipi*, and *Linochitina erratic* in the *Dayia navicula* bed.

Conodonts. *K. aff. sardoa*, *Ozarkodina c. confluens*, *P. gracilis* LAD, *P. equicostatus* fad at the base of the middle Eke, *Corrysognathus dubius* lad, *O. excavata*, *Oul. excavata*, *Panderodus unicostatus*, *P. aff. serratus*, *Pseudooneothodus beckmanni*, and *Decoriconus*.

Fish. Fredholm (1988) identified *Lanarkia horrida*, *Thelodus carinatus*, *Gomphonchus sandelensis*, and *Nostolepis striata*. Further samples studied by Eva Nilsson (Lund University) yielded *Thelodus parvidens*.

Polychaetes. Bergman (1989) recorded *Kettnerites (Aeolus) sisiphy klasaardensis*, *K. (A.) cf. microdentatus*, *K. (K.) martinsoni*, *K. (K.) huberti*, and *Lanceolatites gracilis* var. *visby*. Eriksson (2001) identified *Ramphoprion gotlandensis*.

References. Munthe 1921, p. 25, p. 26, Laufeld 1974a, b*, c, 1979b, 1993, Larsson 1979, Jeppsson 1982, 1983, Cherns 1983, Ramsköld 1986, Fredholm 1988a, b, Bergman 1989, Eriksson 2001.

Bodudd 2. 6329417 1644750, c. 6300 m south-west of Näs church. Topographic map 56B Hemse. Geological map SGU Aa 152 Burgsvik. Shore exposure south-west of the field road, c. 750 m WNW of the triangulation point at Skåls. Bodudd 2 is located to the west of the tail of erratic boulders in the sea. Bodudd 2 is on the opposite side of the road from Bodudd 1.

Stratigraphy. Eke Fm, upper part. Upper Icriodontid Subzone (Jeppsson in press).

Oceanic effects. Late Lau Event, the most severe interval. The conodont fauna is strongly dominated by coniforms, and particularly by *Panderodus equicostatus* (like during the most severe parts of the Ireviken and Mulde events).

$\delta^{13}\text{C}$. Samtleben et al. (2000) reported a brachiopod average of 7.79‰.

Chitinozoans. Laufeld (1974a) identified *Ancyrochitina ceratophora*, *A. echinata*, *Desmochitina squamosa*, and *Eisenackitina philipi*.

Conodonts. The Upper Eke fauna includes *Panderodus equicostatus* group, *Pseudooneothodus beckmani*, *Decoriconus*, rare *Dapsilodus*, and rare ramiforms like *Icriodus*, *Ozarkodina excavata*, *Oz. cf. scanica*, and *Oulodus*. Even a normal sample of 30 kg yields only fragments of some of the more rare taxa.

Polychaetes. Bergman (1989) found *Kettnerites (K.) huberti* and *Lanceolatites gracilis*.

Note. The western end of the locality is located within a bird sanctuary (“Fågelskyddsområde”) and is not accessible between 15 March and 30 June.

References. Munthe 1921, p. 26, Laufeld 1974a, b*, Larsson 1979, Cherns 1983, Bergman 1989, Sivhed 1990, Samtleben et al. 1996.

Stop 14. Husryggen 4

631571 164281, c. 2110 m WNW of Sundre church. Topographic map 56A Hoburgen. Geological map SGU Aa 152 Burgsvik. Abandoned quarry approximately 10 m west of the road, south-west of a small road leading down to the beach, c. 850 m south of the house at Klasens.



Fig. 28. The unconformable boundary between the Burgsvik Sandstone and the Burgsvik Oolite at Husryggen 4. Note the coarse transgressive lag in the basal Burgsvik Oolite.

Reference level. The highest massively bedded sandstone bed below the first accumulation of *Pteronitella retroflexa* (Fig. 28).

Stratigraphy. Burgsvik Fm, uppermost part.

Oceanic effects. Hoburgen Seundo Episode.

Fauna. The Burgsvik includes a diverse bivalve-fauna including abundant *Pteronitella retroflexa*.

Reference. Stel & de Coö 1977*.

Stop 15. Holmhällar 1

6314268 1651201 c. 5670 m south-east of Vamlingbo church. Topographic map 56A Hoburgen. Geological map SGU Aa 152 Burgsvik. The sea stack area was mapped in detail by Manten (1971, his Enclosure 2). Another detailed map was published by Kano (1989).

Reference point. The coordinates given above refer to Manten's (1971) observation point No. 228 at the very characteristic sea stack SSE of the letter W in his map. It is recommended that Manten's numbered observation points in his detailed map are used as reference points in all serious studies at Holmhällar 1 (e.g. Holmhällar 1:228). Reference point 228 is located at the characteristic sea stack resembling an anvil with a hole through its central part. It is easily seen from the field road.

Reference level. The discontinuity mapped by Kano (1989) may serve as reference level.

Stratigraphy. Sundre Formation, just before the Klev Event. At least parts of the strata at the locality represent the *O. crispera* Zone. The youngest generation of reefs on Gotland consists of a line of semicircular or circular reefs, ≥ 500 m in diameter. These are faro reefs, today known from the Maldives (Samtleben et al. 2000). Kano (1990) traced a subaerial discontinuity surface with a considerable relief here. At least some strata here represent the very latest Ludlow, i.e. they are much younger than the uppermost Ludlow at the type area at Ludlow.

Oceanic effects. At least some of the strata here were deposited during the Hoburgen Secundo Episode, only slightly before the Klev Event (Jeppsson & Aldridge 2000).

Corals. Kano (1989) found (identified by B. Neuman) *Holmophyllum* sp. and *Tryplasma* sp.

Conodonts. *Ozarkodina crispera*, *Oz. reimscheidensis*, *Oz. confluens*, *Oulodus elegans*, *Oul. excavata*, *Panderodus equicostatus* group, *Pa. unicosatus*, and *Pseudooneothodus beckmanni*.

Polychaetes. Bergman (1989) recorded *Kettnerites* (*K.*) *polonensis* and *Langeites glaber*.

Stromatoporoids. Kano (1989) identified *Plectostroma scaniense*, *Parallelostroma typicum*, *Lophiostroma schmidti*, *Syringostromella borealis*, *Clathrodictyon mohicanum*, *C. convictum*, *Densastroma podolicum*, *Diplostroma yavorski*, *Plexodictyon katrinense*, and *C. sp.* The latter three are rare and were only found above the discontinuity.

References. Lindström 1890, p. 30, p. 33, p. 38, Hennig 1906, p. 44, Munthe 1921, figs. 73–75, p. 67, Jux 1957, pl. 3, Rutten 1958, figs. 16–18, Mori 1970 p. 30, Loc. 154, Manten 1971, pp. 181–189, 191–205, figs. 79–83, 86, 88, 90–91, Encl. 2, Laufeld 1974a, b*, Franzén 1974, 1983a, Laufeld et al. 1978, Larsson 1979, Laufeld & Bassett 1981, fig. 8, Laufeld & Martinsson 1981, Riding 1981, Zankl & Ziegler 1981, Jeppsson 1982, Ramsköld 1983, Le Hérisse 1988, 1989, Bergman 1989, Kano 1989 (detailed map), 1990, 1994, Fredholm 1989, Neuman & Kershaw 1991, Kershaw & Keeling 1994, Kershaw 1998, Jeppsson & Aldridge 2000.

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Abstracts

Reef biota migration between Alaska, the Urals, and Salair allows Late Silurian reconstruction

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During the Late Silurian, reefs with similar frame-building biotas formed along the margins of the Uralian Seaway in areas that include present-day south-eastern Alaska, the Ural Mountains, and the Salair Ridge in south-western Siberia. The Uralian reefs were rigid organic structures that grew at a passive platform margin and experienced periodic transport of reefal talus downslope. The Alaskan and Salairian reefs were originated in island arcs during phases of waning volcanism.

The unique feature of these Ludlovian reefs is the framework structures that were built by microbial communities associated with atypical Silurian reef-related metazoans. Sphinctozoan sponges (aphrosalpingids) and problematic hydroids – (*Fistulella*) are strongly linked in the reef framework with microbial organisms such as *Renalcis*, *Epiphyton*, *Girvanella*, *Ludlovia*, *Hecetaphyton*, and *Sphaerina*. Unique taxonomic compositions reflect different environmental conditions for reef development. The unusual but highly similar reef biotas imply that the paleo-Uralian sea during the Ludlow was partially enclosed, narrow, and subequatorial.

In the Paleo-Asian Ocean, the Salair island arc may have been welded to the Siberian continental margin after the Early Caledonian orogeny, but other evidence suggests Salair persisted as an arc system until the Carboniferous. The microbial-sponge-hydroid reefs in Salair suggest a marine connection to similar reef communities of the Urals and Alaska evolving along the margins of the Uralian Seaway during the Late Silurian. This suggests that, contrary to most paleogeographic reconstructions, the Siberian craton with respect to the East-European craton (paleocontinent Baltica) must have been located within equatorial latitudes near its present position in the mid-Paleozoic.

Beginnings of the Middle Paleozoic Crinoid Evolutionary Fauna: Anticosti Island, Quebec

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The transition from the Early to the Middle Paleozoic Crinoid Evolutionary Fauna (CEF) occurred nearly contemporaneously with the end-Ordovician extinction event. New crinoid faunas from the Ordovician–Silurian sections at Anticosti Island, Quebec, Canada, provide a new opportunity to examine the face-value fossil record of this macroevolutionary transition.

The Llandovery of Anticosti Island is a section of continuous (as nearly so as can be determined) sedimentation with a Rhuddanian through Telychian sediment stack totaling more than 500 m in stratigraphic thickness. The Llandovery of Anticosti Island records coral-stromatoporoid-microbial reef to offshore siliciclastic facies, presumably alternating due to eustatic sea-level change. Crinoid faunas are present in most facies. A total of 37 crinoid species assigned to 29 genera are recognized from the Llandovery of Anticosti Island, with 8 genera in the Rhuddanian, 10 genera in the Aeronian, and 20 genera in the Telychian. Six-

teen of the Anticosti crinoid genera are new, which increases the total Llandovery crinoids known globally by 24% (from 93 to 105).

Faunas from the Middle Paleozoic CEF were characteristically dominated by monobathrid camerate, cladid, and flexible crinoids rather than the diplobathrid camerate and disparid crinoid faunas of the Early Paleozoic CEF. On Anticosti Island, generic richness and specimen abundance face-value numbers display different trends. The abundance trend is more closely aligned with the global trend. This is believed to be both a function of facies present on Anticosti Island and the nearly complete Anticosti Llandovery record.

Table 1. Generic composition by clade for richness and specimen abundance for Llandovery crinoids from Anticosti Island.

	Diplobathrid Camerates	Monobathrid Camerates	Dendrocrine Cladids	Cyatocrine Cladids	Flexibles	Disparids
TELYCHIAN						
Percent Richness	20	20	15	10	15	20
Percent Abundance	18	57	6	1	9	9
AERONIAN						
Percent Richness	20	20	20	0	30	10
Percent Abundance	0	59	3	0	31	7
RHUDDANIAN						
Percent Richness	25	25	13	0	13	25
Percent Abundance	70	11	2	5	9	4

The Silurian of Novaya Zemlya: a report from the SWEDARCTIC Expedition 2004

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Novaya Zemlya is a narrow, c. 1000 km long, sinuous archipelago, that reaches from the Polar Urals of northern Russia north-eastwards to c. 77°N on the continental shelf. It is surrounded by the most important proven and potential hydrocarbon provinces in the Arctic (e.g. Barents Sea, Pechora Basin, West Siberian Basin and Kara Sea) thus being a unique area to study the deep subsurface geology of the nearby off-shore.

The Novaya Zemlya fold-and-thrust belt is regarded as the youngest (Cimmerian) segment of the Uralides (Korago et al. 2004). However, Palaeozoic ophiolite and associated island-arc rocks of the Polar Urals of the Uralide Orogen are not found further north in this domain. Interestingly, Novaya Zemlya with its trend back northwards and eastwards is apparently connected with the Taimyr fold-and-thrust belt of northern Siberia. Stratigraphic and palaeontological evidence (Abushik et al. 1997, Korago et al. 2004) have been presented for the close affinity of the northern part of Novaya Zemlya's North Island succession with Severnaya Zemlya.

In 2004, the SWEDARCTIC international expedition visited the southernmost part of Novaya Zemlya. It was the first western scientific expedition since the 1930s. The bedrock group had a wide range of expertise including structural geology and stratigraphy, sedimentology, palaeontology, igneous petrology, and isotope geochronology, with interests ranging from the Neoproterozoic to the late Palaeozoic (Gee 2005).

The Silurian of Novaya Zemlya is extensively developed and is represented by mainly marine deposits. The Lower Silurian is dominated by limestones, locally by sandstones which rest unconformably on the Ordovician strata in the central part, and graptolite shales in the north. The Upper Silurian is normally characterised by dark, muddy, fossiliferous limestones and graptolite shales. A considerable difference in lithologies

between the South and North islands is probably controlled by a change from shelf (in the south) to basin (in the north) environments. There are also thick sequences of terrigenous rocks reported from the western coast and the northernmost part of North Island (Bondarev 1964). They are apparently derived from a large uplifted area extending north-eastwards from the Kanin Peninsula to the Severnaya Zemlya Archipelago (Gee & Bogolepova in press). Faunas are rich and diverse, consisting of brachiopods, trilobites, gastropods, bryozoans, tabulate corals, stromatoporates, ostracods, graptolites, and conodonts. These allow the distinction of the majority of the Silurian stages, although problems in biostratigraphy and correlation remain.

The lecture will concentrate on the first results of the expedition with more details on the Silurian stratigraphy, facies distribution, palaeontology, and palaeogeography of this area.

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The Arctic Palaeo-Network (APN) – an invitation to join in

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Our project aims to establish a palaeontology database which will contain detailed information on Palaeozoic (initially on Early Palaeozoic) fossils and fossil localities along the Eurasia's northern margin, from Svalbard in the west to Chukotka in the east. The necessity of this work is strongly dictated by 1) the SWEDARCTIC international expeditions to Novaya Zemlya (2004), Severnaya Zemlya (2003, 2002 and 1999) and Taimyr (1998), during which a unique palaeontological material has been collected and stored in Uppsala, and 2) many of the Russian collections obtained from these areas (e.g. Novaya Zemlya) are lost or inaccessible for study.

Goals for international cooperation are:

- to established AP-network and an information exchange between the scientists in Sweden, Western Russia and Estonia,

- to evaluate the present status of existing palaeontological collections from the Arctic regions housed in West Russia, Estonia and Sweden,
- to archive palaeontological data (documentation of material, location, collector, holotypes, etc.) derived from unpublished fossil reports (geological surveys), published literature, as well as our own collections,
- to compile a relevant palaeontological bibliography, and
- to report on the importance and exceptional character of the existing collections.

The Arctic basin is the least known area on Earth. However, this region will be of vital importance for the European economy over the coming decades, due to already known large amounts of oil and gas in the Barents and Kara seas. Our long-term objective is to develop the Arctic database that will form the basis for testing existing hypotheses of the geological evolution of the northern Eurasian margin. This database, with complete palaeontological bibliography, should be an important tool for future geological investigations in these regions, as well as a useful tool for palaeontologists, biostratigraphers and palaeogeographers.

Our ambition is to involve other Nordic (Norway and Denmark) and Baltic countries and institutions in West Russia into this project, and to create a website, with the palaeontological dataset on-line.

We thank the Visby Programme (Swedish Institute) for the 2004 financial support of our initiative.

The motif of depositional sequences across a carbonate-to-clastic, active foreland: examples from the Silurian Appalachian Basin

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Silurian sedimentary successions display carbonate-to-siliciclastic depositional sequences of multiple temporal scales (10^5 to 10^6 years) across the Appalachian foreland basin in eastern Laurentia. Vertical facies off-sets mark major sequence stratigraphic surfaces: sequence boundaries, maximum starvation surfaces, and forced regression surfaces. Systems tracts between these basin-wide discontinuities exhibit consistent motifs. Seafloor erosion and availability of over-compacted substrates favored burrowed firm-grounds at sequence boundaries (or ET surfaces). Skeletal grainstone-rudstone facies typify transgressive systems tracts (TSTs) in shallow cratonic areas. TSTs become increasingly condensed down-ramp, typified by compound hardgrounds, glauconitic, nodular limestones, and thin, phosphatic nodule beds, but thicken and become increasingly sand-rich, eastward toward siliciclastic sources and are capped by ferruginous beds, including the well-known Clinton ironstones. Widespread horizons of skeletal buildup (e.g. coral-algal bioherms, thrombolites) typify maximum flooding zones due to the combination of deepening and clear water favoring rapid rates of upward growth. Highstand systems tracts (HSTs) are characterized by widespread (>1000 km cratonward) mud deposition. On the western side of the basin HSTs are dominated by wacke- to packstones, typically containing abundant shaly partings, which impart thin-bedded, rubbly to wavy/nodular weathering. Closer to siliciclastic sources HSTs become increasingly shale-rich and are readily differentiated from surrounding cleaner limestones. Siliciclastic grain-size increases eastward, producing HSTs that are dominated by alternations of mud, silt, and sand. Falling stage systems tracts (FSSTs) occur as sharply based, downstepping packages on both sides of the basin. On the carbonate-dominated flank these deposits are composed of highly abraded and fragmented skeletal material, which typically display distinctive parallel, swaly, or flaser-like lamination, indicative of shoreface deposition. On the clastic side of the basin the FSST is sand-dominated and forms a thick, coarse, clastic wedge that extends well out into the basin. In many cases these coarser clastics stand in sharp contrast to underlying shales (HST) and overlying shelly, mineralized sands (TST). In both cases FSSTs may show abundant soft-sediment deformation, indicative of seismites. The widely correlative sequences that dominate sedimentary successions in the Appalachian basin suggest a predominance of allocyclic processes modified locally by tectonic overprint.

High-resolution sequence stratigraphy of the Early Silurian (Llandovery–Wenlock) interval reveals patterns of active tectonism alternating with periods of relative quiescence. The quiescent times are typified by thin successions of mixed carbonates, shales and thin ironstone and phosphatic condensed beds (e.g. lower portion of Clinton Group, Aeronian to lower Telychian). The basin center and eastern shoreline display a pattern of eastward migration at these times. Conversely, times of active tectonic loading are characterized by westward migration of the foreland basin, accentuated erosion on the forebulge and a shift from carbonates to siliciclastic dominated sedimentary successions. The appearance of thin K-bentonites as well as probable seismites (widespread deformed horizons) corroborates interpretation of active tectonism during these times. Two such intervals are recognized: an early phase (Rhudannian) associated with the Medina-Tuscarora clastic wedge is interpreted as a final tectophase of the Taconic Orogeny. The later phase, during late Telychian through Wenlock time (upper Rose Hill-Keefer siliciclastics) marks the onset of the “Salinic” Orogeny.

Evidence for suppressed grazing and infaunal activity in shallow seas during the Late Silurian Lau Event, Gotland, Sweden

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The middle Ludfordian Lau Event is known as a faunal extinction event coupled to one of the largest stable carbon isotope excursions of the Phanerozoic. Natural outcrops, quarries, and recently recovered drill cores on Gotland enable study of contemporaneous depositional changes in a low latitude carbonate platform system across the entire stratigraphic range of the event. These studies reveal compositional changes in carbonate facies during the event and the sudden appearance of microbial facies otherwise rare on Gotland (Calner 2005a, b). The strata formed during and immediately after the event – the uppermost Hemse Group and the Eke, Burgsvik, and basal Hamra formations – include flat-pebble conglomerates, low-relief domical and columnar stromatolites, a mass-occurrence of oncoids, and subtidal wrinkle structures in normal marine environments. The latter structures have previously been suggested to be restricted to Proterozoic–Cambrian and Early Triassic times and are therefore regarded as anomalous for the Phanerozoic. The presence of the anomalous facies points to suppressed grazing and infaunal activity in shallow low-latitude seas during and shortly after the event. The co-occurrence of the Lau Event extinctions and the increase of so called ‘disaster forms’ implies that a short-lived anachronistic period occurred in the Late Silurian. Hence, although less devastating, the Lau Event is comparable to the end-Ordovician and end-Permian mass extinctions from a general ecological point of view. It should be noted that also the most important reef-builders in pre- and post-extinction strata, stromatoporoids, were rarer during the event and occurred predominantly as small forms during the extinction intervals. The sedimentary and ecological changes can be firmly tied to a high-resolution biostratigraphic framework and to the global Late Silurian positive carbon isotope excursion. Contemporaneous changes may therefore be searched for elsewhere in order to test the regional or global significance of the Late Silurian anachronistic period.

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Relative timing of anomalies in carbonate production, biodiversity, and stable carbon isotopes in the middle Silurian of the Baltic Shield and the East European Platform

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The middle Homeric coupled carbon isotope excursion and extinction event (Mulde Event/lundgreni Extinction Event) are known from sedimentary successions on widely separated cratons. This brief time interval evidently was related to a significant anomaly in the global carbon reservoir and a wide variety of environmental changes at different latitudes. An integrated analysis of carbonate platform evolution, biodiversity changes, and carbon stable isotope trends is presently conducted in order to unravel the architecture of this global perturbation. This is done in the Baltic Basin along an intrabasinal transect, from ultra-shallow marginal marine carbonate platform settings to the deep parts of the basin.

As a part of this project, the Hunninge-1 core was recovered from the Hunninge 1 quarry in the Klintehamn area in 2004. This core provides the first continuous succession of strata through the middle Homeric of Gotland – corresponding to the uppermost Slite Marl, Fröjel, Halla, and the basal Klinteberg formations. Due to a suite of characteristic carbonate facies and a prominent middle Homeric unconformity (traceable for more than 250 km), the core succession is correlated with conodont-zoned outcrops across Gotland. In the core, the Grötlingbo Bentonite (in the upper Bara Oolite Member of the Halla Formation) together with the middle Homeric carbon isotope excursion (CIE), permits precise correlation also to the Grötlingbo-1 core on southern Gotland, and to the Ruhnu (500), Ohesaare, and Priekule cores in the East Baltic. A new detailed graptolite zonation of this interval in the Grötlingbo-1 core permits further correlation to the Bartoszyce core in the East European Platform of Poland. The combined data set allows middle Homeric ‘graptolite facies’ to be precisely correlated with shallow-water ‘conodont facies’ and the event can thereby be monitored and compared with other Palaeozoic crises.

The transect reveals the relative timing of biodiversity and frequency changes among graptolites, acritarchs, and conodonts. Furthermore, it can be demonstrated that faunal changes in these planktonic and nektonic groups relate to anoxia in the deeper parts of the basin (laminated strata) and to substantial anomalies in carbonate production and sequence stratigraphy in contemporaneous carbonate platforms. Thus, the correlation provide evidence for that all environments from the shoreline to the deep basin was affected indicating a high complexity of the crisis. Based on whole-rock samples from the Hunninge-1 core, the CIE starts just below the middle Homeric regional unconformity. The highest values and the peak (at 3.8‰) are associated with the immediately overlying basal transgressive strata and a shift from dominantly skeletal to non-skeletal carbonate production in the shallow parts of the basin. Carbon isotope values from the Grötlingbo-1 core increase within a faunally impoverished (no graptolites) conspicuously laminated interval and peak (at 2.4‰) at the top of this interval. This provides new evidence that laminated strata in the deep part of the basin (Grötlingbo-1, Priekule, and Bartoszyce cores) were related to a rapid transgression that caused a basin-wide anoxic event. A correlation scheme will be presented and discussed.

The upper Silurian Sardinian “Ockerkalk”

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Sardinia is a segment of the European Hercynian collisional chain which was affected by strong deformation, metamorphism and intense magmatic activity. Silurian rocks are exposed discontinuously in southern Sardinia. The situation in the south-eastern part is quite distinct from that in the south-western part of the island and these sequences remind of the Silurian exposed in Thuringia and in Bohemia respectively. The mutual relation between these areas is still unclear, but they probably represent two different terranes put together by the Hercynian orogeny.

The most complete middle Palaeozoic sequence of the whole island belongs to the Gerrei Tectonic Unit of south-east Sardinia. Here the Silurian and early Devonian is represented by the classical Thuringian facies triad: “Lower Graptolitic Shales” (LGS) – “Ockerkalk” (OK) – “Upper Graptolitic Shales” (UGS). It should be noted that informal names are still in use for the Silurian–Devonian units of this area.

The Ockerkalk is a blue-grey argillaceous limestone that gets an ochre colour (so the name) through weathering and has a typical irregular flaser texture. It is almost always characterised by a high pyrite content, also evident in the conodont heavy fraction. The thickness of this unit is about 25 m, but local variation is probable, as well as a slight reduction of thickness from east to west.

Crinoidal stems and loboliths, as well as rare cephalopods, are the only macrofossils clearly visible in the outcrops. The lobolith-horizon with the giant pelagic crinoid *Scyphocrinites*, well known across the S/D boundary along the northern Gondwana margin, occurs in the upper part of this unit at the base of the *Oz. el. detortus* Zone. Trace fossils and very small solitary corals are also reported. Microbrachiopods and phyllocarid gnathal lobes are occasionally found in the conodont heavy fractions.

Microbiofacies analysis reveals fine micritic limestones with a fossil content (ostracodes, brachiopods, thin-shelled bivalves, trilobite and echinoderm fragments, gastropods, sponge spiculae) scattered in the matrix and only locally concentrated in millimetric shell-lags of disarticulated debris. Lamination is visible in the matrix of some samples, as well as geopetal structures and bioturbation fabric. The sedimentary environment is quiet and pelagic below normal wave-base and with bioclastic input variable in time and probably in space, especially in the crinoidal fraction.

A rich conodont fauna is reported from several sections and outcrops. The twenty-six conodont taxa, belonging to twelve genera, reported from this limestone document eight conodont zones (*Oz. exc. hamata*, *A. ploeckensis*, *Pol. siluricus*, *Pe. latialata*, *Oz. snajdri*, *Oz. crispa*, *Oz. remscheidensis* and *Oul. el. detortus*), suggesting an early Ludlow-top Přídolí age for this unit. Therefore, according to graptolite data from the overlying Upper Graptolitic Shales, the Silurian–Devonian boundary in south-east Sardinia is more or less coincident with the OK-UGS boundary.

A unified Silurian oceanographic model: past, present, and future

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The presence of at least four major positive carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) excursions as well as several of the most severe extinction events of conodonts and graptolites in the Paleozoic, have prompted the development of numerous oceanographic and climatic models to account for the apparently unstable conditions during the Silurian. Unfortunately, the Silurian has long been considered an “interval of climatic stability within a greenhouse episode”. This conclusion has been shown to be rather erroneous in the past decade as carbon isotope stratigraphy has proliferated, demonstrating that the Silurian was the single most volatile system in the Phanerozoic in terms of perturbations to the global ocean–atmosphere–system and the global carbon cycle. As a result, several oceanographic models have recently come to the forefront of Silurian climate research. Several of these models are in close agreement however their proposed connections between oceanography, climate, lithology, and biology have remained heretofore difficult to combine.

As a result of the proliferation of detailed carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) stratigraphy during the past few years, several important conclusions can now be made regarding the timing of global Silurian events, permitting several predictions of the previous models to be ruled out, and a viable single model to be developed. After careful comparison of the different models against each other and against all available isotopic, biostratigraphic, and sedimentological data, we have developed a predictive model that combines aspects of Witzke (1987), Jeppsson (1990), Bickert et al. (1997), and Cramer & Saltzman (2005). The connections between the various models only became apparent with the aid of extremely high-resolution correlation between global sections, both bio- and chemostratigraphic, which allowed a truly global oceanographic picture of the Silurian to be developed.

According to the oceanographic model we have developed, alternations between cold and warm climate states significantly altered global oceanography by switching the site of deep water formation from high to low latitudes. The extreme transgression of Silurian cratons during third order sea-level fluctuations provided extensive areas for the formation of saline bottom water to be downwelled off of the cratons. This downwelling saline water, combined with warming at the poles, acted to switch deep ocean circulation from a thermohaline to a halothermal mode, effectively disconnecting epicontinental seas from the deep ocean reservoir of nutrients and light carbon (^{12}C), and promoting the expansion of carbonate platform environments during eustatic highstands.

The three previous models have been successfully combined, providing a common ground from which Silurian oceanographic investigation can progress. However, the process of combining the models has highlighted a few important unanswered questions regarding Silurian oceanography. In particular the oxygenation state of the deep ocean during the non-excursion intervals is an area that requires further investigation. At present, the utility of this Silurian oceanographic model has also been demonstrated in the Devonian as well as the Ordovician. Hopefully, further detailed research in other parts of the timescale will reveal important additions or alterations that will constrain more precisely the arguments contained in the model.

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Revised Telychian – Sheinwoodian stratigraphy of North America: chemostratigraphic correlation across the Laurentian craton

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Silurian strata were among the first to be intensely studied in North America, with the classical New York (Niagaran) sections of the northern Appalachian Basin serving as the basis for correlations farther west. Over the past five years, a detailed carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) data-set has been produced from sections across the Laurentian craton, demonstrating several important miscorrelations of Silurian strata. The most severe of which is present in the classical New York sequence. Our data indicate that the Irondequoit, Rochester, Decew, Gasport, and Goat Island formations are all Sheinwoodian (early Wenlock) in age. This is in stark contrast to previous investigations that have concluded this interval of New York strata represents all of the Wenlock and much of the Ludlow.

The presence of two major positive carbon isotope ($\delta^{13}\text{C}_{\text{carb}}$) excursions, entirely within the Wenlock (Ireviken and Mulde excursions), provide a unique Paleozoic opportunity to use chemostratigraphy for high-resolution correlation of middle Silurian strata similar to work done in the Cenozoic. The well-studied Ireviken Excursion begins immediately above the Llandovery–Wenlock boundary, and has now been documented in Nevada, Oklahoma, Iowa, Tennessee, Ohio, and New York.

An oceanographic model for the Silurian has correctly predicted the character of the strata containing the Ireviken Excursion in different depositional environments throughout North America. Application of this model to the revised stratigraphy of the Appalachian Basin provides considerable insight into the oceanographic and sedimentological development of lower Silurian strata throughout the Laurentian craton. In particular, the location and timing of organic carbon burial during the early Wenlock has been difficult to define. Our data allow for the first time the ability to precisely correlate Appalachian Basin stratigraphy with global sections during the Ireviken Excursion, demonstrating an important prediction of the model and an important feature of Silurian stratigraphy. Namely, that organic carbon burial during the major positive carbon isotope excursions in the Silurian took place in the deep ocean and the deepest of intra-cratonic basins, while shelf and platforms settings experienced prolific reef growth and an expansion of carbonate platform environments.

Early Silurian carbonate platform development in the Caledonian foreland basin, central Sweden

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Early, but not earliest, Silurian strata of the Caledonian foreland basin in Jämtland, central Sweden, rest on an unconformity representing a stratigraphic gap corresponding to at least the Rhuddanian Stage. Onset of sedimentation is dated to early–mid Aeronian by the biostratigraphically important conodonts *Pranognathus tenuis*, *Kockelella? manitoulinensis*, and *Pranognathus siluricus*. The underlying truncated Upper Ordovician strata include a thick unit of fine-grained siliciclastics, which are terminated by a cross-bedded quartzite that marks the Hirnantian glacio-eustatic regression and lowstand. In contrast, the post-Rhuddanian Lower Silurian is characterised by the regional expansion of a carbonate platform. The change from a siliciclastic-dominated shelf to a carbonate-dominated shelf is consistent with a mid Aeronian reef recovery in other areas at similar latitude and with a climatic change from icehouse to greenhouse conditions. The carbonate platform succession is 50–75 m thick in Jämtland and consists of micritic limestone, mostly with a mud-wackestone texture, and subordinate grainstone and packstone. The various platform biota included rugose and tabulate corals (locally mound-forming), stromatoporoids, brachiopods, crinoids, bryozoans, ostracods, gastropods, orthocones, and conodonts, i.e. typical faunal elements of an open marine Silurian carbonate platform. The extensive hiatus below the platform indicates that at that time, this might have been an area characterised by a tectonic uplift rate that exceeded the rate of the post-glacial eustatic rise.

The carbonate platform succession is overlain by the Osmundsberg K-bentonite (locally 0.55 m thick) and black shales. The latter mark the drowning of the platform and termination of the carbonate deposition. Graptolites from the lowermost part of the shale sequence date the drowning event to the early Telychian *turriculatus* Zone. The Osmundsberg K-bentonite is of regional stratigraphic importance as it is found in Sweden, Estonia, Norway, and probably in Scotland, Northern Ireland and Denmark. Previous studies indicate that these areas were not far from a substantial source of subduction-related volcanism. The drowning of the carbonate platform and development of a deep-water shale basin demonstrate that a period of substantial subsidence of the Caledonian foreland basin started in the Early Telychian. This was probably related to large scale tectonism as Laurentia and Baltica converged. In conclusion, the initiation and the demise of the Early Silurian carbonate platform in this part of the Caledonian foreland basin were controlled by the interplay of climate warming and its sea level effect and regional tectonics.

Silurian phytoplankton associations, palaeoenvironments, event stratigraphy and palaeoclimates

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The latest Ordovician to Silurian depositional sequences following the late Ordovician glacial events show marked changes in phytoplankton composition that may be related to changing global climate as well as changing relative sea level. The Silurian acritarchs, prasinophytes and chitinozoans show a broad latitudinal distribution in both tropical and temperate areas. Within these areas, there are marked variations in abundance and composition of acritarch assemblages across shelf seas and in oceanic areas related to marine water

mass characteristics, comparable in many ways to modern dinoflagellate cyst distribution. During the early Rhuddanian, the phytoplankton associations are globally of remarkably low diversity. Diversity rises in the late Rhuddanian, with a marked increase in diversity in the mid Aeronian. Significantly higher acritarch and chitinozoan species diversity is characteristic of the Telychian, with many originations and some extinctions linked to the Llandovery–Wenlock Ireviken Event. Acritarch diversity is moderate during the late Sheinwoodian, Homerian and Gorstian with variations in assemblage composition linked to alternating wet dry climate cycles. During the Late Silurian, phytoplankton associations are of moderate species diversity, with an increased tendency for a single genus, including *Cymbosphaeridium* and *Visbysphaera*, to form a significant part of marine palynological assemblages.

Faunal turnovers of vagrant benthos (Polychaeta) during the Silurian Ireviken Event on Gotland, Sweden

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The Llandovery–Wenlock Ireviken Event had a strong impact on the contemporary fossil faunas and facies development. Shut-down in primary productivity coupled with oceanic overturns caused stepwise faunal extinctions and ecosystem breakdowns. The conodont faunas suffered great taxonomic losses (>80% of the globally known species disappeared, most of which became extinct) but also other common groups, such as trilobites (>50% of the species on Gotland disappeared), ostracodes, chitinozoans, corals, and graptolites were affected during this event. Compared to the now available detailed data on the presumably nektonic conodonts, similar information about the vagrant benthos is limited.

Jawed polychaetes formed a substantial part of the benthonic communities in Silurian seas, as revealed by the abundance and diversity of scolecodonts (polychaete jaws) preserved in the Gotland strata. High-resolution sampling from pre-event strata of the Snipklint Primo Episode, through the Ireviken Event, and the post-event Vattenfallet Secundo Episode strata has yielded extensive collections of well-preserved scolecodonts. Genus-level, relative frequency data were calculated on >13 000 counted specimens (generally the first maxillae) from 40 samples. The resulting patterns reveal dramatic turnovers during the Ireviken Event. Particularly between datum points 4 and 6.2 the faunas are almost inverted as compared to those in younger and older strata expressed as unusually low frequencies of *Oeononites* and *Kozlowskiprion* (both of Polychaetaspidae) coupled with amplified frequencies of *Atraktoprion* (Atraktoprionidae) and *Mochtyella* (Mochtyellidae) and allied placognaths. The former two genera, which generally form >50% of the faunas in the studied interval, comprise <10% between datum points 4 and 6.2. In addition to the relative frequency changes, at least two paulinitid taxa (*Kettnerites* (*K.*) *versabilis* and the Visby variety of *Lanceolatites gracilis*), one ramphoprionid (*Megaramphoprion magnus*), one kalloprionid (*Kalloprion* sp.), and one *Oeononites* species disappear. That is, at least 20% of the hitherto identified taxa became extinct or disappeared during the event. Planned taxonomic work is expected to rise that percentage. Some lineages show range gaps similar to those of certain conodont taxa – they disappear during the Ireviken Event and reappear in the Sheinwoodian Slite Group.

The results indicate that conditions at datum points 2 and 4 most severely affected the polychaete faunas, thus reinforcing the importance particularly of the latter datum, which corresponds to the boundary between the Lower and Upper Visby formations. Not only was datum 4 among those with the strongest effects on conodonts but many other taxonomic groups were also affected, including the extinction of the characteristic, small rugose coral *Paleocyclus porpita*. Also $\delta^{13}\text{C}$ values began to increase approximately by this time. This datum is distinct also in the field, it is marked by a rusty pyrite layer followed by a few cm thick, laterally extensive bed with the solitary rugose coral *Phaulactis* in mass-occurrence.

Because the Ireviken Event affected the polychaete faunas of Gotland, detailed data on this metazoan group will aid in interpreting the nature of the event and how different taxonomic groups with variable modes of life responded.

The scolecodont smorgasbord of Gotland — an entombed guide to extinct polychaetes

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In the latest Llandovery to latest Ludlow succession of Gotland, Sweden, scolecodonts, or polychaete jaws, comprise one of the most common microfossil groups. Their abundance can reach thousands of specimens per kg rock and the well-preserved specimens provide evidence of the diverse polychaete faunas that once prospered in this shallow sea. Polychaete research was pioneered by Hinde (1882), who described some 40, mostly single-element-based, species and varieties from the Sheinwoodian Högklint Formation and Slite Group of the Visby area. It is, however, during the last three decades that research has been most intense (for summary, see Eriksson et al. 2004). Several years of microfossil sampling has produced extensive collections of scolecodonts allowing a deep insight into Silurian polychaete faunas. Approximately 50% of the Gotland taxa have been formally named and described and the number of occurring species seems to be of the order of one hundred. These belong to no less than 28 genera and a dozen families based on multi-element taxonomy. During the last few years it has become increasingly clear that the sequences of polychaete faunas of Gotland have biostratigraphic potential although no formal zonation has yet been established. Moreover, the resistant properties (even to hydrofluoric acid) of scolecodonts and their occurrence in strata formed in different environmental settings can aid in resolving the stratigraphic bias between the deeper water ‘graptolite facies’ and shallower water ‘conodont facies’. Both long-ranging taxa, ranging through the entire succession and beyond, and short-ranging taxa and morphotypes occur. Diversity and temporal distribution patterns related to facies reveal eurytopic as well as stenotopic taxa. Many families and genera were widespread during the Silurian and have been identified also in other regions, particularly in Baltica outside Gotland and in Laurentia. Albeit data from higher paleolatitudes are meager some congeneric taxa have been recognized also from such regions. We are only beginning to see the potential of this intriguing group of microfossil that clearly merits further attention.

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Updating of the Sardinian Ockerkalk (Upper Silurian) conodont biostratigraphy by means of graphic correlation

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The Upper Silurian of south-eastern Sardinia is represented by the Ockerkalk, an argillaceous limestone with a blue-grey colour weathering into ochre (wherfrom the name Ockerkalk) and a typical irregular flaser texture. This unit is about 25 m thick. The only macrofossils visible in the outcrops are crinoid stems, rare cephalopods and loboliths. On a microscopic scale ostracods, thin shelled bivalves, brachiopods, gastropods, trilobite fragments, crinoids, small cephalopods, and sponge spiculae are also found. A detailed biostratigraphy of the Ockerkalk is possible thanks to an abundant conodont fauna: twenty-six taxa reported from this limestone document eight conodont zones and suggest an early Ludlow to late Přídolí age for this unit. To obtain an accurate conodont range chart and precise correlations between the sections, the graphic correlation method was used considering data from eight sections, of which two contain a repeated part. This method (Shaw 1964) is a technique based on a Cartesian coordinate system and is used to correlate time-equivalent sections by plotting them two-by-two on the perpendicular axes of a graph. One section is chosen as the standard reference, normally the thickest, non-tectonised section containing the largest fossil database. Each section is correlated with that reference section. The fossil range data in common between the two sections plot in the field of the graph. The correlation line representing the point-by-point time-equivalence of the sections is drawn in a way as to cause minimum change of known ranges. After each correlation, data from the correlated section are projected onto the standard reference section thus composing a composite section or 'composite' for the region. In this study, the Silius section was selected as reference since it is the thickest and most complete section of the region. The resulting composite standard developed in this study allows a subdivision of the Upper Silurian Ockerkalk into 24.7 CSU (composite standard units) derived from the Silius section (Serpagli et al. 1998). It provides a much higher resolution than the traditionally used conodont zonation. The bases of the conodont zones are situated at 1.5 CSU (*A. ploeckensis*), 3.2 CSU (*Pol. siluricus*) 7.7 CSU (*Pe. latialata* i.z.), 10.0 CSU (*Oz. snajdri* i.z.), 11.3 CSU (*Oz. crispa*), 13.9 CSU (*Oz. remscheidensis* i.z.) and 17.3 CSU (*Oul. elegans detortus*).

Correlation of the Sardinian composite standard with the Cellon section (Walliser 1964) in the Carnic Alps, the Klouk section (Jeppsson 1988) in Bohemia and the worldwide Composite Standard by Kleffner (pers. comm.) shows that *Oul. elegans detortus* appears much earlier in Sardinia compared to the other regions. This earlier appearance has some implications on the global conodont biostratigraphy.

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The Late Silurian Lau Event and brachiopods from Gotland, Sweden

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In the Jeppsson (1990) model, two kinds of stable oceanic “episodes” are separated by short-lived “events”. Events caused extinctions, faunal and sedimentary changes and isotopic effects. The globally known Late Silurian Lau Event is associated with one of the largest positive carbon isotope excursions of the Phanerozoic. On Gotland, the Lau Event spans the Botvide Mbr (uppermost När Fm, upper Hemse Group) and the Eke Fm. Conodonts responded heavily, more than 50% of the taxa became extinct or disappeared. During the later part of the event the conodont fauna became dominated by a single taxon.

In total, 64 brachiopod species have been found before, during and after the event. 42 of these have a record before the event. However, only 18 of them are found in the immediate pre-event fauna in the När Fm. During the event, diversity did not drop (the maximum diversity is reached in the upper part of the lower Eke Fm) but the faunal composition changed considerably.

Atrypa (*A.*) *sowerbyi* and cf. *Kirkidium knighti* became extinct at the beginning of the event, and *Jonesea grayi*, disappeared from Gotland. *Endrea ekenia* and *Ptychopleurella bouchardi* appeared slightly later. Next (in the lowermost Eke Fm), two lingulid taxa disappeared, while *A. (A.) alata*, *Navispira pusilla* and *Boucotinskia sulcata* appeared. At least nine Lazarus taxa also reappeared in the lowermost Eke Fm. During the intermediate part of the event, further Lazarus taxa returned and brachiopods flourished at Lau Backar 1, where at least 35 brachiopod species have been recorded. Of them, only six appeared during the event. By the end of the intermediate part of the event, two more taxa, *Janius barrandi* and *E. ekenia*, became extinct and *Dinorthis rigida* and *Mesopholidostrophia laevigata* disappeared from Gotland. During the later part of the event no taxa are proven extinct, except for at the Eke–Burgsvik boundary, where lithology as well changed considerably. Out of the 42 pre-event taxa, 25 survived the event. Among taxa that first appeared during the event, at least *N. pusilla* and *B. sulcata* also survived. After the event especially the atrypids radiated rapidly.

Only nine or ten taxa have more or less continuous ranges through the event. Nevertheless, several of these suffered from adverse conditions. *Isorthis canaliculata*, *Protochonetes striatellus* and *Microsphaeridiorhynchus? nucula* show distinct Lilliput effects, and the pentamerids may also have been affected.

A comparison with published faunas from some other Silurian sequences, on Baltica and outside, showed a similar re-organisation pattern as on Gotland. Lastly, the herein extended ranges of *Pt. bouchardi*, *Me. laevigata*, *Strophonella euglypha*, *E. ekenia*, and *Nucleospira pisum*, as well as the identification of cf. *K. knighti* at Botvide 1, reflect the importance of large collections.

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Relationship of Silurian sea-level fluctuations to oceanic episodes and events

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Different ways to recognize sea-level fluctuations are reviewed that relate to recurrent patterns perceived to be of global extent in the Silurian System. The concept that marine benthic associations correspond to bottom-dwelling communities at different water depths led to the earliest derivations of sea-level curves based on brachiopods from the Lower Silurian. Other methods to trace sea-level trends rely on pelagic graptolites and nektonic conodonts. A physical approach to gauging Silurian sea-level changes uses unconformities related to the erosion and burial of rocky shorelines as distinct markers. Changes in absolute water depth have a one-to-one correspondence to the topographic relief transgressed by marine deposits. Yet another physical approach seeks to correlate glacial deposits with global low-stands in sea level. Chemostratigraphy advances this approach by testing for oxygen and carbon isotopes through carbonate sequences.

Eight major high-stands separated by seven major low-stands in sea level have been proposed by this author as the general pattern that emerges from study of the Silurian System on a continent-to-continent basis. Some emendations to the pattern are necessary to incorporate additional, widespread trends. Five major and one minor high-stand are recognized in the Lower Silurian (Llandovery and Wenlock series) and three major high-stands are attributed to the Upper Silurian (Ludlow and Přídolí series). Three reasonably constrained episodes of glaciation correspond to prominent draw-downs recorded in the Lower Silurian. Topographic relief measured at various unconformities in the Lower Silurian reflect sea-level changes on the order of 30 m to 70 m. The maximum paleorelief found to be flooded in the Upper Silurian is 30 m.

Some of the terminology applied to oceanic episodes and events is needlessly arcane, but key trends are clear when the relationship with sea-level fluctuations is tested against a tight biostratigraphic framework. The Sandvika Event correlates with a drop in sea level between the second and third high stand recorded in the Llandovery Series. An unnamed secundo-primo event relates to the draw-down between the third and fourth high-stand in the Llandovery Series. The Ireviken Event corresponds to a drop in sea level recorded near the base of the Wenlock. The Boge Event equates with a minor draw-down superimposed on the fifth high-stand from the Sheinwoodian Stage. The Mulde Event, in part, seems to fit with a precise low stand in the Lower Homerian Stage. The Linde Event corresponds to the low between the sixth and seventh peak in sea level from the Ludlow Series and the Klev Event fits the low between the seventh and eighth high-stand in the transition between the Ludlow and Přídolí series. The Lau Event, however, contradicts this pattern by overlapping with the seventh high-stand in sea level. As yet, no oceanic event has been formally named for the interval corresponding to the draw-down between the first and second peaks in sea level recorded in the Lower Llandovery Series which is equated with a glacial deposit. In a contradictory way, an equal number of secundo and primo episodes correspond to six out of eight high-stands in sea level.

Dating of Silurian rocks: views about bio- and/or carbon isotope stratigraphy

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Isotopic methods have gained an eminent position in the Silurian palaeoclimatology, palaeoceanology and stratigraphy. The success in carbon isotope stratigraphy has been promising. Most likely reliable results will be achieved depending mainly on how complete and detailed a standard trend used as a basis for comparisons is. Of course, correct biostratigraphic dating of sections and samples is crucial for obtaining good results.

The following positive carbon isotope excursions have been established in the Silurian (dating in terms of graptolite biozonation according to Kaljo et al. 1998 and Kaljo & Martma 2000): the early Aeronian (in the *D. triangulatus* Biozone), early Sheinwoodian (peak in the *M. riccartonensis* Biozone or slightly above it) and middle-late Homerian (main peak in the *M. ludensis* Biozone, with one or two smaller shifts below the main shift) excursions, and the most prominent one in the Phanerozoic – the middle Ludfordian shift. The last excursion has been correlated with the *N. kozlowskii* Biozone, but conodonts provide a direct dating – the last occurrences of *Polygnathoides siluricus* below the main shift and the appearance of *Ozarkodina wimani* and *O. crispa* above the excursion (Martma et al. 2005).

These excursions could serve as a tool for dating and correlation of sections, especially of those with scarce biostratigraphical criteria. But the above dating of peaks represents only our view, while also several more or less diverging datings have been suggested (e.g. Schmidt et al. 2002, Lehnert et al. 2003). These suggestions will be discussed in our report and our point of view will be motivated. In conclusion, some levels useful for the correlation of the Silurian of Gotland and East Baltic will be proposed.

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Substrate relationships in Palaeozoic stromatoporoids and corals

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The traditional view of growth of stromatoporoid sponges and corals is that individuals began by settling on a hard object (e.g. shell fragment), then grew across neighbouring substrate, which was often soft argillaceous calcareous muds. In some cases they may have settled directly on soft muds. In nearly all examples, the base was assumed to have been in complete contact with substrate throughout life, with lateral growth more important than vertical growth. Common cryptic faunas on stromatoporoid and coral bases were assumed to be facilitated by scouring of sediment, or storm-induced movement across uneven substrates, creating secondary cavities. Ragged margins of stromatoporoids were assumed to have formed by episodic sedimentation killing topographically lower flanking portions of the skeleton, with recovery over the new sediment surface.

Reassessment of these assumptions was stimulated by recognition of original growth cavities in Devonian stromatoporoids in the Canning Basin, Australia, proved by downward-growing cryptic organisms and geopetal cements beneath stromatoporoid bases. Cavities were formed by the stromatoporoid skeleton arching over sections of substrate, touching the sediment in only a few places, in stabilised stromatoporoids, thin laminar outgrowths can extend laterally for up to 1 m, without touching substrate. Original growth cavities seem to be common in Devonian stromatoporoids, their preservation assisted by the large amounts of early marine cement known in Devonian rocks. However, the same seems not true for Silurian corals and stromatoporoids. Original cavities are recognised in some cases, and may be more common, but there is less early cement to prevent compactional closing of cavities, and quite likely the response to substrate was not developed to the same extent as in the Devonian. The likely reasons why stromatoporoids grew above their substrates include a response to sedimentation or a desire to keep away from potentially tissue-clogging sediment for efficient lateral growth. Therefore, while the formation of ragged margins cannot be always assumed to be due to direct deposition, the preservation of delicate laminar outgrowths are good indicators of low energy conditions while they grew and were subsequently buried.

Ca-carbonate dissolution in the East Baltic deep shelf in the Ashgill and Llandovery (Ordovician–Silurian)

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Claystone, calcareous claystone and marlstone represent the East Baltic deep shelf sediments of the Ordovician–Silurian. Limestone covered the shallow shelf. The offshore diminishing of carbonate could be related either to a) the boundary of mechanical input, i.e. calcite particles were too large to be carried far offshore, b) the weakness of ‘carbonate factory’ to supply the wide shelf, c) absence of pelagic carbonate-secreting organisms or, d) the offshore dissolution of Ca-carbonate. According to the rule of granulometric differentiation lime mud must have reached the deep shelf as well as the terrigenous mud. In reality the Baltic deep shelf sediments do not contain calcite, only a small amount of dolomite, up to 10%, is present. This presumes calcite dissolution. The variation of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios in vertical section was taken

as proxy for transgressions–regressions and water depth. The calcite dissolution depth corresponded to the depth of the Aizpute core site in the mid Llandovery. In the late Llandovery the calcite was disappeared in the Viki core, situated higher in the shelf slope and at shallower water depth than the Aizpute core in mid-Llandovery. In the Ashgill the boundary of total calcite dissolution supposedly shifted closer to the shelf edge, the general trend of calcite decreases offshore but was nevertheless traceable.

The pH decrease with depth caused the calcite dissolution in deeper waters. The relatively low pH was evidenced by deep water metabentonites consisting of kaolinite and illite-smectite, in contrary to shallower water non-kaolinitic metabentonites. Kaolinite in the metabentonites was characteristic of the mid- and late-Llandovery. The pH of the deep shelf bottom waters was low enough to dissolve calcite, but not dolomite. The pH, corresponding to the boundary of calcite dissolution, was determined by the closeness of the warm, anoxic, and saline ocean deep waters. These anoxic waters washed the deepest part of the Baltic shelf near the Teisseyre-Törnquist Line during most of the Palaeozoic resulting in dark clayey sediments. Some hints on the carbonate chemistry of the anoxic basin could come from upwelling waters of the mid-Llandovery (Kiipli et al. 2004). Dolomites of the deep shelf Heinaste Member, the lowermost Raikküla stage, reveal a negative excursion in carbon isotope, of about 2‰. Uplifted waters contained a lot of organic matter-derived light inorganic carbon causing the isotope shift. The upwelling waters, supposedly, favoured precipitation of dolomite of the Heinaste Member, as sulphate reduction in anoxic waters diminished the inhibiting effect of sulphate ion.

The calcite distribution pattern shows that calcite dissolution took place in the Baltic deep shelf. The depth at which calcite dissolved varied depending on Ca-carbonate production and seawater pH. On the one hand the ocean deep water was anoxic but on the other hand the atmospheric $p\text{CO}_2$, involving primary bioproductivity of surface waters, modeled the pH profile.

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Correlation of Silurian bentonites based on the composition of sanidine phenocrysts

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Volcanic ash interbeds (altered to bentonites in old rocks) are potentially perfect time markers in geological sections. Sedimentary sections often contain a number of bentonites and therefore a problem arises as how to identify the bentonite bed formed from a particular volcanic eruption. Random preservation of thin ash beds due to variable wind directions, sedimentary dynamics and drilling quality causes additional complications.

We have worked out a method for identification of bentonites by the composition of sanidine (K,Na)AlSi₃O₈ phenocrysts using X-ray diffractometry (XRD) measurements of 201 reflection (Kiipli & Kallaste 2002). Sanidine, occurring in many volcanic rocks, is a primary crystal formed in a magma chamber before the eruption. Silurian bentonites in Estonia contain sanidine with various content of sodium component (20–47 mol%) being often very specific ($\pm 1\%$) to a particular ash bed.

Advantages of the method compared to others:

- Magmatic sanidine reveals primary chemical signal from the magma chamber environment. This is a remarkable advantage compared to the analysis of bulk bentonite, which have lost most primary chemical

features during crystallization of amorphous volcanic ash in sedimentary environments.

- XRD measurements of 20–1 sanidine reflection represent the average composition of sanidine in a sample. This is a difference (an advantage?) compared to the analysis of sanidine composition by electron microprobe. A large number of microprobe measurements are needed to achieve statistical average. Restrictions to the applicability of the method:
- In many bentonites XRD reveals wide sanidine reflections, which are similar for all these beds and are therefore difficult to use for single bentonite identification. To work out diagnostic features of sanidine in beds of this type, electron microprobe may have greater potential.
- In slightly metamorphosed sections (e.g. Garntangen and Vollen in the Oslo region, Laesa and Olea on Bornholm) XRD measurements do not reveal sanidine reflections. Supposedly, sanidine has been recrystallized into the K- and Na-rich end members of the solid solution. Perhaps electron microprobe analysis of phenocrysts is still effective. According to our experience XRD measurements of sanidine can be used in Estonian, Latvian and Lithuanian sections. Sanidine was recorded also in Gotland bentonites (Snäll 1977).

Ash beds with similar sanidine composition can occur repeatedly in a section, therefore, for final identification of a particular bed, all available beds must be analysed and graphically correlated.

In Silurian sections of Estonia bentonites from 73 different eruptions have been identified, most of them (40) concentrated in the Telychian. From the total of 73 bentonites, 38 can be perfectly identified by sanidine composition.

High resolution bentonite-based correlations from relatively shallow sea (Viki) to the deep sea (Ohesaare and Aizpute) sections allow detailed and well constrained correlation of conodont and graptolite biostratigraphy in the Telychian, also including the Llandovery–Wenlock boundary.

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Retiolitid evolution and the *lundgreni* Extinction Event

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Retiolitid evolutionary history was relatively short: only twenty million years, from the Llandovery through the Ludlow. During this time, significant changes in rhabdosome construction occurred, reflecting colony changes. There were considerable differences in evolutionary development of retiolitid faunas before and after the *lundgreni* Event. The oldest retiolitids had complex rhabdosomes with short siculae and large thecae, sometimes ended by a nematularium. Smooth or striated bandages are their characteristic ultrastructural features. They represent so-called L-colonies with large rhabdosomes and up to 80 pairs of thecae that increase in size slightly distally. They originated in the Aeronian and continued as long-ranging faunas, perhaps indicating relatively stable environmental conditions.

Significant changes in retiolitids occurred in the *lundgreni* Biozone. By this time they reached their maximum diversity, with long siculae and smaller thecae, and some of which are ended by an appendix. Most groups possessed pustulose bandages. The *lundgreni* Extinction Event marked the end of the biozone

and killed almost all graptolites. Fortunately retiolitids survived and they represent a final type of growth colony with a clearly limited number of thecae (*Gothograptus nassa* and similar forms). After the event, the retiolitids existed for only about five million years, during which they again became diverse and developed new characters of rhabdosomes. However, retiolitid rhabdosomes were never large again. Great reduction in both number (fewer than 15 pairs) and volume of thecae, and in skeletal elements occurred in all post-event groups. Contrary to the thecal size decrease, a distinctive increase of sicula length is observed in the new retiolitids. For example, the smallest colony, represented by *Neogothograptus alatiformis* (2.5 mm long) with only two pairs of thecae (zooids) possessed a sicula probably 2 mm long. The youngest retiolitids representing S-colonies with small rhabdosomes and long siculae appeared in the late Homeric and range through the Ludlow. The longest Llandovery species possessed about 40 times more thecal pairs than the smallest Ludlow retiolitids. At the same time the ratio of the sicula to rhabdosome length in a mature S-colony rhabdosome is 1:0.8, whereas in L-colonies it is 1:0.008. The volume of individual thecae in S-colonies was approximately one-quarter of that in the L-colonies, whereas their sicula was about twice the length of that in L-colonies. Thus in extreme cases, the S-colony siculozooid would be twice as long as L-colony siculozooid whereas zooids would have been one-quarter of those in some L-colonies.

Another significant aspect of retiolitid evolution is the reduction of rhabdosome elements, which are composed mostly of bandaged lists. The reduction is rarely observed in some older groups, but is particularly common in the post-*lundgreni* Event faunas. The youngest and most reduced rhabdosomes are known only from the Polish part of the East European Platform: *Semiplectograptus urbaneki* and *Plectodinemagraptus gracilis* as well as some recently described *Holoretiolites helenaewitoldi*. They represent significant successive stages in the reduction of the ancora sleeve.

The *lundgreni* Extinction Event: paleontological and geochemical data from Arctic Canada

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The *lundgreni* Extinction Event (LEE) in which 90–95% of the graptolite species were extirpated is now well known globally, and its record is well documented in Arctic Canada where well-exposed sections yield rich faunas of superbly preserved graptolites and radiolarians. There, as in other regions globally, the LEE appears to differ from other mass extinctions in its near-total restriction to planktonic animals such as graptolites and radiolarians. Following a general global pattern, the *lundgreni* Biozone with its approximately 50 species (more than 40 in Arctic Canada) that developed during a period of transgression or highstand was reduced to two species during the LEE. The extinction appears to have been relatively abrupt, and coincided with a stillstand or possibly with a rapid shallowing. The brief post-extinction survival period (the *nassa-dubius* Interval Biozone, a short period of perhaps no more than 10s to 100s of thousands of years) was followed by rapid evolutionary diversification of the graptolites during the *praedeubeli-deubeli* Biozone, apparently coinciding with renewed transgression.

Radiolarians are diverse and abundant throughout the *lundgreni* Biozone but are sparse to absent directly following the LEE and are not found in any abundance again until the top of the *ludensis* Biozone, uppermost Homeric. Thus they were strongly affected during the LEE, with extinctions occurring at both the species and genus level. Their absence may in part be related to preservation and in part to a facies change associated with the observed shoaling in the uppermost Homeric. The sparseness of post-extinction radiolarian data creates difficulties in determining the rapidity of radiolarian species turnover.

Acritarch frequency throughout the entire investigated interval is extremely low, and only in one level in the *lundgreni* Biozone so-called “giant acritarchs” were observed. Sphaereomorph acritarchs and amorphous organic matter are moderately common in the *lundgreni* Biozone, but their abundance is reduced in post-LEE strata, although some fluctuation is observed through the upper Homerian. The presence of dark yellow and light brown-colored organic matter indicates that the absence of acritarchs is not due to reworking or thermal degradation but is, instead, suggestive of palaeoecological control.

At Rookery Creek, Cornwallis Island, a complete record of graptolite, radiolarian and palynologic data is accompanied by geochemical data. $\delta^{13}\text{C}_{\text{organic}}$ data show a bifurcated positive excursion associated with the extinction and post extinction events. The maximum peak of the excursion (a shift of +3.3‰) is roughly coincident with the LEE, occurring within 1 meter of the last occurrence of *lundgreni* Biozone taxa. A correlative bifurcated positive excursion of $\delta^{13}\text{C}_{\text{organic}}$ is also noted at Abbott River, Cornwallis Island, and Twilight Creek, Bathurst Island with the lower fork of the peak also coincident with the LEE.

Graptolite fossil record as a principal tool in reconstruction of the Lower Silurian sedimentary succession of the Hlinsko Zone, NE Bohemian Massif, Czech Republic

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Heavily tectonized and poorly exposed, epizonal and contact metamorphic black siliceous slates and silicites of the Mrákotín Formation have been known as the only fossiliferous rocks in the Hlinsko Zone, situated in the north-eastern interior of the Variscan Bohemian Massif. The majority of graptolite zones, so far recognized in the Llandovery succession of the classical Barrandian area of central Bohemia, have been identified in the Hlinsko Zone by means of large graptolite material collected from bulk sampling of loose boulders and a few outcrops. Early Llandovery (Rhuddanian) *C. vesiculosus* Biozone, *D. triangulatus*, *D. pectinatus*, ?*M. simulans*, *P. leptotheca*, and *L. convolutus* biozones of middle Llandovery (Aeronian) age, and *R. linnaei*, *S. turriculatus*, *S. crispus*, *M. griestoniensis*, *T. tullbergi*, and *O. spiralis* biozones of the late Llandovery (Telychian) age were identified in loose boulders. Late Telychian *T. tullbergi* and *O. spiralis* biozones were found in situ, in an abandoned quarry. No Wenlockian taxa occur among 84 graptolite species that we have recorded in the black-shale succession of the Hlinsko Zone. The original sedimentary succession of the Mrákotín Formation has been reconstructed in particular by means of detailed biostratigraphic correlation with graptolite successions in the Barrandian area, Thuringia and other well understood areas outside the Bohemian Massif. There is no apparent difference between the graptolite fauna of the Hlinsko Zone and that one of the Barrandian area. However, lithological successions of these two areas are different. Barren greenish mudstone beds intercalate black graptolitic shales of the late Llandovery Litohlavy Formation in the Barrandian area. They are missing in the Hlinsko Zone where the whole known Llandovery sequence is composed of silicified black shales. It is assumed that the Mrákotín Formation of the Hlinsko Zone was not deposited in the same basin as coeval formations of the Barrandian area.

Warm waters in the cooler oceans of the latest Ordovician glacial phase, Yangtze Platform, South China Block

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During the Hirnantian, the Yangtze Platform was situated in the western part of the South China Block (SCB) before its later rotation, and was situated in middle–low palaeolatitudes of the southern hemisphere in the north-east side of peri-Gondwana. It is part of the Kosov Faunal Province as indicated by the *Hirnantia* fauna. Sedimentary evidence shows domination by cool ventilated marine water from its offshore ramp and shelf. Hirnantian shallow water carbonate facies (Kuanyinchiao Bed) overlie earlier Ashgill graptolitic black shales (Wufeng Formation) due to marine regression. In the Yangtze Platform, however, we have found local areas of intertidal to nearshore facies that lack typical high diversity *Hirnantia* fauna. Some warm-water features (radial oolites, peloids, diverse solitary rugose corals and other benthic shelly fauna) occur commonly in some limited shallow areas, forming grainstones and packstones. Although interglacial episodes within the Hirnantian glaciation could be responsible for these features, their limited occurrence within the interior of the platform leads us to interpret the deposits as indicating that cold-water currents from the south-eastern high latitudes were partly excluded from the near shore area of the Yangtze Platform. The landmass of the eastern SCB in the Hirnantian epoch, prevented access to some areas of the cold marine water masses that flowed from higher latitudes of Gondwana, the result was persistence of warm-water shallow marine facies in some areas.

Isolated Llandovery graptolites from Baltica

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During the processing of samples for chitinozoans for our integrated biostratigraphical work, various graptolites have been chemically isolated from the enclosing rocks. This presentation will focus on upper Telychian monograptoids, including several species not previously known from isolated material, for example *Streptograptus kaljoi* and *S. nodifer*. Some remarkable thecal morphologies will be shown. We will emphasize the difficulty of erecting a generic diagnosis for *Streptograptus* and will compare our material with that described recently from lower in the Llandovery of Sweden. Our new work is in press in *Palaeontology*.

Environmental and biotic changes of the subtropical isolated carbonate platforms during the Kozlowskii and Lau events (Prague Basin, Silurian, Ludlow)

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The early Palaeozoic Prague Basin represents a rift type basin located at the northern margin of peri-Gondwana on the Perunica microplate, which shifted during the Silurian across the subtropical zone. Carbonate sedimentation extends during early Ludfordian lowstand and continued up to the early Přídolí transgression. The isolated carbonate platforms, forming the specific carbonate system without organic overgrowths, include variable settings reflecting palaeo-tectonic position and eustatic oscillations. The prominent Ludfordian change in facies and fauna is between the *N. kozlowskii* and the *M. latilobus* zones.

The extension of the cephalopod limestones and trilobite shale biofacies over the elevations during deepening and high-stand characterized the *N. kozlowskii* Zone. The widely distributed *Cardiola alata* Community and rare cephalopods reflect stable, but cooler surface currents overflowing the elevations. Restricted communities with *Cheiropteria* (lower slope) and *Dayia* (upper slope) reflect rapid decrease in current activity connected with deepening in the latest *N. kozlowskii* Zone terminated by the Kozlowskii Event.

Spectacular crinoidal-brachiopod, brachiopod-trilobite and cephalopod limestones in the *M. latilobus* Zone overlie the erosive surface sequence boundary with gap in sedimentation (early *M. latilobus* Zone). A more complete sequence on a distal slope exhibits continual shallowing during the early *M. latilobus* Zone and subsequent lowstand in the late *M. latilobus* Zone. The expansion of cephalopod limestone during the *M. latilobus* Zone finished in the *M. fragmentalis* Zone and reflects increasing current activity.

The Kozlowskii extinction event correlates with a short-term deepening and low current activity in the latest *N. kozlowskii* Zone. The extinction affected pelagic as well as benthic faunas, especially ostracods, graptolites, bivalves, and cephalopods. The extinction is followed by a rapid recovery during the *M. latilobus* Zone shallowing and lowstand. The shallow-water, rich benthic communities contain local taxa and common immigrants occupying variable environments at submarine topographic elevations. The morphology of some animals changes rapidly, e.g. ancestors rarely occur below unconformity surfaces and descendants commonly occur above (stocks of the *Atrypoides linguata*-*A. modesta* a.o.). Radiation of exotic immigrants, mostly of Laurentian origin, is documented among trilobites, cephalopods and crinoids. Some immigrants go extinct just below the latest Ludlow *M. fragmentalis* Zone (brachiopods, trilobites), whereas others successfully evolve up to the Ludlow–Přídolí, or Silurian–Devonian boundary (cephalopods).

The short duration of the Kozlowskii Event is prominent among Ludfordian extinction events (base of the *B. bohemicus*, *N. kozlowskii*, *M. fragmentalis* zones). Faunal turnover at the event is connected with rapid eustatic oscillations and changing ocean current system. The Kozlowskii Event is synchronous with the facies change and correlates with the beginning of the positive carbon isotope excursion (Lau Event), while the maximum isotope peak of the Lau Event occurs within the faunal stasis of the *M. latilobus* Zone. The succession of the extinctions, facies change and isotope shift differs from those reported from Gotland due to its position in the higher latitudes.

Widespread soft-sediment deformation horizons in Silurian strata of the Appalachian basin: distal signature of orogeny

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The Silurian Period has typically been considered a tectonically quiescent time, however, there is growing evidence from eastern North America that the Silurian was much more dynamic than previously considered. Silurian strata of the Appalachian Basin and Cincinnati Arch contain multiple discrete intervals of soft-sediment deformation separated by thick successions of strata that show little to no evidence of disruption. Distribution patterns of these deformed intervals appear to be non-random. Deformed beds are preferentially clustered within falling stage systems tracts (FSSTs) of 3rd-order depositional sequences. Such periods of regression are marked by increased sedimentation rates, previous researchers concluded that these deformed beds are simply the result of sediment loading. Nevertheless, recent detailed sedimentology and stratigraphic mapping of many Silurian deformed beds in eastern North America demonstrates that these event beds are extremely widespread and that their component sediment layers were not deformed during initial deposition, but later, during shallow burial, owing to the effects of shaking induced by large-scale earthquakes, i.e. they are seismites.

Silurian deformed beds display a range of sedimentary features that supply information about the environment and timing of deformation. The deformed strata themselves are typically composed of shales, overlain by laminated siltstone to fine-grained sandstones (laminites). The shale typically shows little evidence of bioturbation, those burrows that are present are sharply defined indicating formation in firm muds. The overlying laminites commonly contain hummocky to swaley cross-bedding, suggesting lower shoreface deposition. The laminite beds display sole marks (e.g. scratches, prods, and flutes) suggesting deposition on firm, over-compacted mud substrate that were stable, even during deposition of uneven sediment loads. Thus, the contacts between the mud and the overlying laminite bed are very sharp, an interface that is poised at instability given the inherent thixotropic properties of the mud.

Observation of the deformation structures (ball-and-pillows, mudstone diapirs, etc.) suggests that mobilization of thixotropic mud caused deformation of the surrounding sediments during gel to sol transitions. In the gel state the muds were cohesive enough to record sole marks and to support the load of overlying silts/sands. However, during episodes of seismic shaking muds flowed upward as diapirs, evacuating from the lower part of a deforming interval of strata to be redeposited on top. Truncation of the upper surfaces of deformed intervals indicates that deformation occurred near the sediment–water interface.

The regular distribution of deformation prone facies within many Silurian depositional sequences (in the FSSTs) was regulated by eustatic fluctuations. Thrust induced loading of the cratonic margin resulted in re-activation of basement faults well in to the cratonic interior, proving the triggering mechanisms to produce wide spread soft-sediment deformation. The record of deformed intervals within Silurian strata of the Appalachian Basin, together with evidence of periods of increased siliciclastic influx and probable K-bentonite horizons provides a meter of intensity and timing of pulses of tectonism marking the final (late) tectophase of the Taconic orogeny in the Rhuddanian and the short-lived Salinic orogeny during the Telychian to late Wenlock.

Carbon isotope stratigraphy of the Rhuddanian to Lower Telychian (Early Silurian) of Cornwallis Island, Arctic Canada

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Samples were collected for analysis of carbon isotopes from the organic matter and carbonate fractions of the Cape Phillips Formation on Cornwallis Islands in Arctic Canada. Within the Llandovery succession the $\delta^{13}\text{C}_{\text{org}}$ signal shows a series of oscillations, mostly over a range of variation of $\pm 1\text{--}3\text{‰}$. The timing of these oscillations shows a striking degree of qualitative coincidence with the sea level changes in several published eustatic curves, as well as with the local sea level changes as interpreted from lithostratigraphic and fossil evidence. Positive $\delta^{13}\text{C}_{\text{org}}$ shifts coincide with proposed times of low sea level (lower and upper Aeronian) and negative shifts with times of higher sea level (upper Rhuddanian, mid-Aeronian and lower Telychian). The most striking of the positive shifts occurs in the upper Aeronian, *sedgwickii* Zone-equivalent strata. In addition to being a time of eustatic fall the late Aeronian has been identified as a time of high extinction rates in the graptolites, and it also coincides with the Sandvika Event, an interval of conodont extinction suggested to be related to a change in climate state.

Both the early and late Aeronian times of sea level fall have been correlated with episodes of glacial expansion in South America, although some of the published sea level curves suggest that sea levels fell to somewhat lower levels in late Aeronian than in the early Aeronian. In addition to the sea level changes, it is expected that glacial events should lead to episodes of change in climate and ocean circulation. However, the timing and duration of the late Aeronian excursion event and its relationship to global episodes of reef development and deposition of organic-rich mudrocks in deep-water successions do not appear to match well with the predictions of models that relate positive $\delta^{13}\text{C}$ excursions with changes in global productivity or changes in global climate state. However, the event does correlate very well with an episode of widespread exposure of carbonate shelf successions, which supports the hypothesis that an increase in the rate of carbonate platform weathering during sea level fall was an important contributing factor to the C-isotope shift.

If the larger scale $\delta^{13}\text{C}_{\text{org}}$ excursions and the smaller ones can both be related to variations in rates of erosion resulting from sea level changes, then C-isotope curves may prove to be a useful proxy for determining the timing and relative magnitude of eustatic fluctuations through this time interval.

Stable isotope (C, O) stratigraphy in the Silurian of Gotland: bulk rock and brachiopod data compared

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Generally, the Silurian is characterised by at least 5 short-lived positive $\delta^{13}\text{C}$ excursions, most of which have been detected on a world wide scale. The Silurian deposits on Gotland are famous for their abundant and well-preserved fossils, including brachiopods. Among calcitic fossils, brachiopods are generally assumed to be the most reliable recorder of the isotopic composition of ancient sea water. Up to now, we have analysed the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ composition of the secondary shell layer of more than 2100 diagenetically unaltered bra-

chirodps from more than 300 localities on Gotland. Additionally, the isotopic composition of 128 bulk rock samples (limestones and marls) has been determined. The analytical precision based upon duplicate analyses of individual samples for both brachiopods and rock samples is generally below 0.05‰. The standard deviation, based on measurements of several contemporaneous samples, however, is different for brachiopods and micritic rock samples. **Stable isotope data from autochthonous brachiopod assemblages are highly reliable** with a mean standard deviation of 0.17‰ and 0.14‰ for carbon and oxygen isotopes, respectively. In contrast to the oxygen isotopes, carbon isotopes from brachiopods are not affected by the local facies development on Gotland. Therefore, their $\delta^{13}\text{C}$ values can be used as a parastratigraphic tool, especially in times of changing isotope values.

In contrast to brachiopods, which do not occur in every layer, especially in drill cores, micritic whole rock analysis allows a much higher stratigraphic resolution. Recent carbonate muds, however, consist of variable mixtures of aragonite, high-Mg-calcite (HMC) and low-Mg-calcite (LMC) – polymorphs with different fractionation factors when precipitating from dissolved bicarbonate. These mineralogically heterogeneous muds are then turned into LMC limestones during diagenesis. It is generally accepted that due to the low amount of carbon compared to oxygen in pore water, $\delta^{18}\text{O}$ values are more prone to diagenesis than carbon isotopes, and should not be used to answer palaeoenvironmental or stratigraphic questions. In contrast, $\delta^{13}\text{C}$ data from whole rocks are widely used although little is known about the relation in the isotopic composition between diagenetically unaltered brachiopod samples and whole rock samples in contemporaneous strata. Bulk rock $\delta^{13}\text{C}$ data from Gotland show a similar isotopic development compared to brachiopod data, and the three major isotope excursions in the lower Sheinwoodian, late Homeric, and late Ludfordian are clearly recognisable. The standard deviation from several contemporaneous samples compared to brachiopod data, however, is much larger with 0.44‰ for limestones and 0.33‰ for marl samples. Minor isotope excursions with less than 1‰ as, for example, the one seen in brachiopod data from the late Gorstian, therefore might be overlooked by using whole rock data.

$\delta^{13}\text{C}$ record across the Ludlow Lau Event: new data from mid palaeolatitudes of northern peri-Gondwana (Prague Basin, Czech Republic)

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During the late Silurian the Prague Basin was located in mid southern latitudes. In contrast to palaeocontinents positioned in tropical and subtropical latitudes like Baltica, no reefs were developed, which is in accordance with the predicted cooler water. The Prague Basin represents a relatively restricted and shallow rift basin with a complex tectonic history. In close vicinity to the volcanic centres, which are located at the intersections of WSW–ENE and NNW–SSE striking fault zones, the several hundred metres of Silurian rocks are interrupted several times by volcanoclastic deposits. The deposits of the Ludlow Kopanina Formation investigated in the key section of the present study have been deposited on the slope-to-basin transition near the Kosov volcanic centre. The sediments are developed as an alternation of dark, partly laminated limestones and marls with an increase of the limestone–marl ratio in the upper part of the succession. A pronounced positive carbon isotope excursion starts in the *Neocullograptus kozlowkii* graptolite and late *Polygnathoides siluricus* conodont zone. The maximum of the shift is observed in the lower part of an interval characterised by the *Ananaspis fecunda*–*Cyrthia postera* community. The maximum values scatter around 8‰, which represent the highest values reported from the Prague Basin so far. In low latitudes, often a decrease of $\delta^{13}\text{C}$ values

towards deeper water settings is reported. In contrast, in the present study the $\delta^{13}\text{C}$ values of about 8‰ are much higher than those recorded from the contemporaneous shallow-water sections studied in the classical Mušlovka and Požáry (GSSP) Quarries. The most reasonable explanation is the presence of gaps in the shallow-water sections of the tectonically and volcanically highly active basin caused by a prominent sea-level drop leading to volcanic and tectonic elevations and to strongly reduced sedimentation of the cephalopod limestone biofacies as well as to erosion, solution or karstification in certain areas.

A manuscript treating our new data across the Lau Event in the Prague Basin has already been compiled by O. Lehnert, J. Frýda, W. Buggisch, A. Munnecke, A. Nützel, J. Kříž, and Š. Manda, and represents a contribution to IGCP 503 “Early Palaeozoic Palaeogeography and Palaeoclimate”.

Extinctions and faunal turnovers of early vertebrates during the Late Silurian Lau Event, Gotland, Sweden

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The Late Ludlow (Late Silurian) Lau Event is one of the major oceanic events first identified on Gotland. It is associated with one of the largest stable carbon isotope excursions recorded in the Phanerozoic, as well as rapid, conspicuous changes in lithology and extinctions and faunal turnovers among various groups of fossils. In this study, the early vertebrate (fish) faunas were studied over the Lau Event interval. Particularly isolated scales occur abundantly in the Gotland succession. They were extracted using buffered acid digestion techniques. Twenty-six samples from the upper Hemse Group through the Hamra Formation yielded over 2500 scales, representing six different vertebrate groups: actinopterygians, heterostracans, anaspids, osteostracans, acanthodians, and thelodonts. In addition, tesseræ plates, dental elements, and two species (Gen. indet. sp. A and B) of unknown affinity were recorded.

The diverse and abundant pre-event fauna is dominated by acanthodians and includes *Paralogania martinsoni*, *Phlebolepis elegans*, *Archegonaspis lindstroemi*, *Andreolepis hedei*, *Thelodus carinatus*, *T. parvidens*, *Gomphonchus sandelensis*, and *Nostolepis striata*. It is succeeded by a low-diversity, low abundance event fauna. Five of the eight species (63%) occurring in the pre-event strata go extinct during the event: *Pa. martinsoni* had its LAD during the very beginning of the event whereas *Ar. lindstroemi*, *An. hedei*, *Ph. elegans*, and *T. carinatus* disappear slightly later, high up in the Upper *P. siluricus* conodont Subzone (slightly below the top of the Botvide Member, Hemse Group). Some taxa have their FADs during the event interval. *Thelodus* sp. and *Paralogania?* sp. appeared early during the event whereas *Pa. ludlowiensis* first appeared during the late phase of the event, the Upper Icriodontid conodont Subzone (upper Eke). Moreover, *Lanarkia horrida* and *Thelodonti* sp. A occur exclusively in collections from the event. In addition to the species vanishing, five taxa show range gaps (Lazarus gaps) in the event interval. Diversity and abundance increase considerably in the thelodont-dominated post-event strata (the Burgsvik and Hamra formations) with the FADs of *Poracanthodes porosus*, *Septentrionia mucronata*, *Th. sculptilis*, *Tahulalepis elongituberculata*, *Osteostraci?* indet., type A, and *Osteostraci?* indet., type B.

Patterns similar to that found on Gotland can be noted in the fish faunas also in other regions (cf. Märss 1992), inferring that the pronounced effects on the vertebrate faunas were not exclusive to Gotland and that vertebrates will be a useful tool to identify this event elsewhere.

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Sea level fluctuations and forced regressions in the Silurian basin in the Precordillera of western Argentina

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In the Precordillera of western Argentina, Silurian deposits occur as part of a sedimentary succession that extends from the Upper Ordovician Hirnantian Stage to the Lower Devonian and that is bounded at the base by the glaci-eustatic erosional unconformity, related to the Hirnantian glacial event, and at the top by the Chánica tectonic phase. In this sequence, four regressive para-sequences are recognized belonging to the La Chilca Formation (Hirnantian to lower Wenlock), Los Espejos Formation (middle? Wenlock to Lochkovian), Talacasto Formation (Lochkovian to lower Emsian), and Punta Negra Formation (lower Emsian-Eifelian?), all of them are separated by para-conformities (flooding surfaces). Silurian strata are widely distributed in the Central Precordillera, but they are scarce in the Eastern Precordillera, and reports of their occurrence in the Western Precordillera are dubious because of the lack of diagnostic fossils and isotopic data. The classical Silurian succession, as displayed in the Central Precordillera in the San Juan River area, is represented by the Tucunuco Group, which includes the lower La Chilca Formation (Hirnantian to lower Wenlock) and the upper Los Espejos Formation (middle-upper Wenlock–Ludlow to Lochkovian). To the north in the Jáchal River area and to the south at La Dehesa creek the Silurian succession is represented by the Tambolar Formation, a correlative facies of the Tucunuco Group. This reflects east (proximal) to west (distal) facies changes, and the depositional system exhibits fine-gained sequences to the south and to the west.

At the base, the Tucunuco Group and its equivalent Tambolar Formation are bounded by a regional glaci-eustatic erosional unconformity related to the Hirnantian glacial event, and are topped by a flooding surface (para-conformity) that is overlain by the Lower Devonian mudstones of the Talacasto Formation. The para-conformities (flooding surfaces) separating the four (Silurian and Devonian) regressive para-sequences are interpreted as records of episodic subsidence events related to an extensional regime acting as a tectono-sedimentary control of basin geometry and infilling. Evidence of the extensional events includes: 1) a thickening-coarsening upward succession, in each para-sequence, 2) the occurrence of slumps in the middle and upper part of the Los Espejos Formation, 3) the geometry of infilling, and 4) the marked north to south and east to west facies changes. Additional evidence is the absence of Silurian strata in the Western Precordillera, the stratigraphic succession of which differs completely from that of the Central Precordillera, and the fault-boundary separating the Precordillera from the basement rocks of the Western Pampeanas Ranges. It is apparent from this evidence that Silurian, as well as Devonian, strata of the Precordillera were not deposited in a foreland basin as proposed by others, but, instead, were deposited only in extensional basins.

Silurian graptolite biostratigraphy of the Galicia–Trás-os-Montes Zone (Spain and Portugal)

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The Galicia–Trás-os-Montes Zone (GTMZ) includes a number of allochthonous terranes stacked upon a relative autochthon considered to represent the continental margin of Gondwana. These oceanic, ophiolitic and exotic continental terranes were emplaced during the early stages of the Variscan orogeny and are exposed today in the north-west of the Iberian Peninsula as dismembered and relatively thin megaklippen of mafic and ultramafic rocks, forming the so-called Allochthonous Complexes. The relative autochthon of all these units is a very thick (>4,000 m) metasedimentary succession, known as “Schistose Domain” or “Para-Autochthonous Thrust Complex”, which was superimposed on the Central Iberian Zone (CIZ).

The age of the metasediments from the “Schistose Domain” remained uncertain for a long time, being preferentially assigned to the Silurian owing to the discovery of graptolites in scarce localities placed within the traditional boundaries of the GTMZ. However, a detailed stratigraphy of these successions never was adequately established, due to the difficulties imposed by the high structural complexity and metamorphism displayed by the main outcrops.

Recent palynological and U-Pb single datings of the Río Baio Thrust Sheet, east of the Cabo Ortegal Complex, propose a main Ordovician age and a large allochthonous interpretation for the lithostratigraphic units involved in the “Schistose Domain”. Their suggestion implies that all the localities with Silurian graptolites previously reported within the GTMZ may occur right below the “Schistose Domain” basal thrust, belonging in fact to the normal succession of the CIZ.

In order to elucidate the discrepancies of the last interpretation, we have reviewed all the Silurian graptolite data occurring within the traditional boundaries of the GTMZ. Reappraisal of the thirty localities was achieved by restudying the original graptolite collections from some previous authors, direct sampling on many places, or even by the discovery of new fossiliferous localities both in Portugal and Spain. Our biostratigraphic overview shows that the general Silurian sequence is of relatively small thickness, being composed of 15–20 m of shales and black cherts (lydites) bearing late Rhuddanian to mid-Telychian graptolites, locally preceded by a basal quartzite (?early Rhuddanian), which are followed by about 50 m of black shales, locally micaceous and rich in carbonaceous nodules, ranging from late Telychian to early Ludfordian in age according to their graptolite assemblages. The succession ends with unfossiliferous shales of unknown thickness (?>100 m) that may intercalate some lenticular limestones of probably late Silurian to early Devonian ages.

The present results, although preliminary, improved very much the knowledge of the Silurian sequence at a regional scale. Its frequently misinterpreted, rather anomalous facies of enormous thickness, must be the consequence of underestimation of the tectonic overprint in the south-west part of the GTMZ. This has led, for instance, to the erroneous consideration of some very thick shale lithosomes with intercalations of lydites occurring in apparently multiple stratigraphical positions, that certainly correspond to structural repetitions of a single and close interval yielding Llandovery graptolites of the *Coronograptus cyphus*, *Demirastrites triangulatus*, *Lituigraptus convolutus*, and *Spirograptus guerichi* biozones, as occurring in apparently multiple stratigraphical positions. The abundance of lydites in the Silurian of the GTMZ sharply contrasts with their rarity in other areas of the northern CIZ or WALZ (West Austrian–Leonese Zone). The Silurian in these

adjacent zones is still very imperfectly known. Otherwise the reappraised graptolite localities not only lie in the peripheral rim of the GTMZ, but also in areas cartographically placed well within those units recently reinterpreted as Ordovician. From a palaeogeographic point of view, the Silurian rocks of the GTMZ display a moderate “Mediterranean character” similar to that exhibited by the successions of Moncorvo and Truchas, thus supporting the parautochthonous nature formerly assigned to the “Schistose Domain”.

New data on lower Ludlow (Gorstian) graptolites and graptolite biostratigraphy of the Prague Basin (Barrandian, Czech Republic)

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Silurian graptolites have been studied since the mid-19th century in the Barrandian area by J. Barrande and J. Perner. Systematic research on Ludlow graptolites then culminated between 1942 and 1952 (several papers by B. Bouček and A. Přibyl). Despite minor communications published in the 80’s and in the 90’s the Ludlowian graptolite fauna and graptolite biostratigraphy of the Prague Basin have been in need of modern revision.

The majority of the earlier studied localities of the Kopanina Formation (Ludlow) have been situated in the limestone-dominated, rather shallow-water, central and eastern parts of the Prague Basin, between Prague and south-western periphery of Beroun. There the graptolite faunas, however, are less common and less diversified than those in deeper, shale-dominated and so far overlooked south-western part of the Basin (west, south and south-west of Kosov near Beroun).

The present study involved bed by bed sampling of two shaly, graptolite rich sections near the villages Vseradice and Bykos, south of Beroun, c. 35 km south-west of Prague. There the early Ludlow (Gorstian) part of the Kopanina Formation is largely developed in the form of muddy calcareous shales with intercalated limestone nodules. An abundant and diversified graptolite fauna is accompanied by flattened nautiloid shells, rare bivalves, crinoids, and ostracods.

The Ludlow succession starts with the *nilsoni-uncinatus* Biozone. Its base is characterized by the first occurrence of *Neodiversograptus nilsoni*, accompanied by the appearance of *Monograptus uncinatus*, *Colonograptus colonus*, *C. roemeri*, and *Bohemograptus bohemicus*. Also *Pristiograptus dubius*, *Plectograptus macilentus* and *Spinograptus spinosus* are common.

The lower boundary of the following *progenitor* Biozone is defined by the appearance of the index graptolite *Lobograptus progenitor*. There is a prominent overlap with *N.nilsoni* and *M.uncinatus* which both disappear from the fossil record well above the base of the *progenitor* Biozone. Along with common occurrence of the zonal index species the *progenitor* Biozone assemblage is composed of *Monoclimacis micropoma*, *P. dubius*, *C. colonus*, *C. roemeri*, *B. bohemicus*, *Sp. spinosus*, *Sp. münchi*, *Pl. macilentus*, and *Holoretolites* cf. *mancki*.

The first appearance of the spinose saetograptid *Saetograptus fritschi* indicates the beginning of the *fritschi* Biozone with a rich assemblage containing *S. fritschi*, *S. chimaera*, *S. cf. leintwardinensis primus*, *P. dubius*, *C. colonus*, *Mcl. micropoma*, *Pseudomonoclimacis* sp. 1., *B. bohemicus*, *L. progenitor*, ?*L. simplex*, *Crinitograptus crinitus*, *Cr. operculatus*, *Pl. macilentus*, and *Holoretolites* cf. *mancki*.

Organic carbon isotope record and the state of mid-Palaeozoic ocean – example from the Góry Bardzkie (Sudetes, Gondwanan Europe)

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Silurian–Lower Devonian oceanic sediments in the Góry Bardzkie Mountains form part of an accretionary prism of Early Carboniferous age. These deposits occur as a stratigraphically condensed (70 m thick), tripartite succession, which is composed of the Lower Graptolitic Shale, Green Shale and Upper Graptolitic Shale. Lithologically, the succession consists of black radiolarian cherts, black and light siliceous shales and shales containing numerous phosphorite concretions.

During the Early Palaeozoic, the Góry Bardzkie Mts were situated north of the Armorica terrane assemblage within the southern Rheic Ocean. During the Early Silurian (Lower Graptolitic Shale) this area was affected by a stable upwelling system that developed in the subpolar divergence zone of the Southern Hemisphere. During the Late Silurian (Green Shale), the upwelling system moved northwards and became part of an oligotrophic, tropical ocean typified by nearly stagnant, salinarily stratified waters. With the latest Silurian–Early Devonian (Upper Graptolitic Shale), climatic cooling resulted in an intensified circulation that was only episodically interrupted by stratified water conditions.

Stable organic carbon isotopes, principal and trace elements, and REE were determined in 95 samples spanning the uppermost Ordovician through Lower Devonian succession in the Góry Bardzkie. Each sample was characterized in terms of sedimentological and palaeoecological constraints, and assigned to the graptolite zonation. The carbon isotope curve obtained follows essentially the shape of that derived for inorganic carbon from coeval, epicratonic records in tropical areas. As compared with organic-carbon isotopic curves from those areas, the Góry Bardzkie record is more complete and of a higher stratigraphic resolution. The measured values of $\delta^{13}\text{C}$ range from -31.5 to -25.5‰ (PDB), with maximum anomalies within 1.3 – 4.5‰ .

The most negative values (-31.5 to -30.0‰) correspond to the black shales of the mid and late Sheinwoodian and Gorstian. These, together with other geochemical indicators, suggest that these shales record a high mesotrophic ocean that was typified by moderate circulation, short-term stratification and rising sea level (global transgression). The low values of the heavier organic C isotopes appear typical of biochemical and physical products of the naturally anoxic system of the Silurian ocean during phases of climatic amelioration. The Llandovery black radiolarites and Lochkovian–Pragian black shales yielded less negative ranges (-30.6 to -29.3‰), and correlate with a mesotrophic, highly dysoxic ocean developed in a cooler climate and experiencing a stronger and deeper convection.

The positive excursions of $\delta^{13}\text{C}$ appear characteristic for periods of low eustatic sea level and the deposition of light colored shales, poor in organic matter (OM). The most positive values of $\delta^{13}\text{C}$ (-28.2 to -25.5‰) correlate with the development of a stratified, suboxic and oligotrophic ocean during probably the warmest and driest time of the entire Silurian (upper Ludlovian–lower Přídolí Green Shale). The smaller positive values of $\delta^{13}\text{C}$ correspond to glacial periods and related lowstands in the sea level, accompanied by intense circulation, enhanced bottom-current activity and the weakly mesotrophic ecosystem of the photic zone during the Late Ordovician (-28.8 to -27.4‰) and the early Sheinwoodian of the early Wenlock (-28.8 to -28.4‰). The late Wenlock anomaly ($+4.5\text{‰}$), recorded in light colored, bioturbated mudstones (*predeubeli-gerhardi* time) can also be related to a eustatic fall. Still positive, but the weakest excursions ($+1.7\text{‰}$ and 1.8‰ , respectively) are associated with the *lundgreni* event (early Homerian) and *transgrediens* event (S/D). The development of these excursions was caused by the eutrophication of the photic zone, and outpaced extinction and continued through survival time.

The documented correlations of the most negative $\delta^{13}\text{C}$ with black-shale deposition and sea-level highstands and of the positive anomalies with light shale deposition and lowstands, are opposite to those recorded from the Late Palaeozoic and Mesozoic. This reversal appears to be related to the mass availability of isotopically heavier OM since the Devonian.

Carbonate depositional environments, sea level change and exceptional preservation in the Much Wenlock Limestone Formation (Silurian) of Dudley, England

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The Much Wenlock Limestone Formation of the Dudley inliers, West Midlands, contains one of the richest known Silurian marine biotas, both the high diversity and exquisite quality of preservation are unusual compared with the outcrops elsewhere on the Midland Platform. Detailed comparisons between outcrop and museum collections have allowed for the determination of five faunal-lithological associations, the identification of numerous horizons of exceptional skeletal preservation and the interpretation of the formation, and its fossil biota, as a single third order sequence stratigraphic cycle of sea level change.

The principal factor in the establishment and preservation of such a rich biota within the Dudley inliers appears to be related to the mid-platform position of the West Midlands and its consequent impact upon sedimentation rates, turbidity and bathymetry-related factors. On the scale of a third-order cycle of sea level change the members of the Much Wenlock Limestone Formation show marked variations in background terrigenous sedimentation rates, resulting in minimal terrigenous input during the transgressive systems tract and increasingly high levels of sedimentation associated with the highstand systems tract. Accordingly, the Lower Quarried Limestone and basal Nodular Beds members represent periods of reduced terrigenous sedimentation, while the upper Nodular Beds and Upper Quarried Limestone members represent a period of enhanced terrigenous sedimentation. Furthermore, owing to lesser water depths than at the platform margin, carbonate production was established earlier, during the early transgressive systems tract, leading to the development of thick-bedded oncolite limestones that are exclusive to the Lower Quarried Limestone Member of the West Midlands.

Superimposed upon the third-order changes in the background rate of terrigenous sedimentation is the ability of storms to redistribute terrigenous sediment locally. About SWB, minimal storm activity resulted in sediment starvation and allowed for the development of hardgrounds. Close to FWWB, high levels of storm activity flushed mud into deeper waters, resulting in the development of shifting crinoidal sands. When associated with minor transgressive events these developed into firmgrounds and hardgrounds. Between these extremes of storm activity, conditions appear to have been ideal for the sequestering of terrigenous sediment resulting in a dominantly soft muddy substrate with frequently turbid waters.

Variations in terrigenous sedimentation rates, brought about by sea level change at a variety of scales, are also critical in explaining the high preservation potential. The articulated preservation of taxa such as pelmatozoan echinoderms and trilobites typically resulted from either rapid burial by obrution deposits close to FWWB, or smothering by storm-sequestered muds in slightly deeper-water settings. Such intervals of exceptional preservation are most commonly associated with flooding surfaces that reduced the likelihood of reworking once rapid burial had taken place.

The establishment of a sequence stratigraphic framework for the upper Wenlock Series (Homerian) of the Midland Platform, England

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The Homerian Stage of the Wenlock Series type area situated along the Wenlock Edge escarpment, Shropshire, is characterised by a single upward-shallowing sequence. This begins at the base of the Farley Member (Coalbrookdale Formation) and terminates at the top of the Much Wenlock Limestone Formation. This sequence contains at least four distinct lithofacies: previous workers have considered all but the uppermost crinoidal grainstone lithofacies to be laterally discontinuous, and have further shown the Much Wenlock Limestone Formation to be regionally diachronous, the unit youngs from east to west, particularly at the base. Consequently, correlation across the Midland Platform at resolutions below that of the established graptolite biozones is at present problematic.

Based upon the establishment of a detailed third-order sequence stratigraphic framework for the contemporaneous strata of the West Midlands regions, it has been shown that the Much Wenlock Limestone Formation alone contains 13 identifiable upward-shallowing sequences (parasequences). The relationship between these parasequences along with their bounding surfaces allow for the identification and correlation of early and late stages of the transgressive and highstand systems tracts and associated sequence boundaries across the West Midlands region.

Using the knowledge gained from the strata of the West Midlands, preliminary fieldwork in the type area has started to identify similarly distributed parasequences. In particular, the current biostratigraphical framework indicates that the Much Wenlock Limestone Formation at Wenlock Edge is contemporaneous only with the upper half of the Nodular Beds Member and the entirety of the Upper Quarried Limestone Member. This broadly represents a transition from below SWB to about FWWB, interrupted by 2 minor flooding surfaces, an overall upward-shallowing sequence. Thus, the formation at Wenlock Edge appears to display similar characteristics, both in terms of lithological change, thickness and distribution of minor flooding surface, to much of the late highstand systems tract as developed within the West Midlands. Furthermore, contained within the underlying Farley Member, are additional parasequences, these appear to be broadly similar to the remainder of the highstand systems tract and much of the transgressive systems tract as developed in the West Midlands, both in terms of their thickness and aggradational to retrogradational geometries.

Further investigations are required to fully establish the synchronicity of sea level change between the West Midlands, Wenlock Edge and the rest of the Midland Platform. However, the initial comparisons are encouraging and suggest that there is great potential for the development of a platform-wide sequence stratigraphic framework that should greatly improve regional correlation.

The use of computational fluid dynamics in reconstructing the hydrodynamic properties of graptolites

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Graptolites are some of the most commonly preserved Silurian planktonic organisms. By analogy with modern plankton, they should carry significant palaeoceanographic information about the dynamic nature of the Silurian oceans. However, realising this potential has proved problematic for two reasons. First, it is difficult

to resolve the lateral and vertical distribution of particular species, second, the interpretation of graptolite functional morphology is rendered problematic by their lack of close modern analogues or homologues.

Physical modelling of graptolites has explained some aspects of their hydrodynamic behaviour, such as their orientation relative to currents (Rickards et al. 1998) and their rate of response to new directions of water flow (Rantell 2001). However, this technique is slow and laborious and the accuracy of the physical models limits the level of detail that can usefully be studied. Computational fluid dynamics (CFD) are routinely used in engineering applications in order to overcome these limitations. Iterative solutions to the equations of flow are generated for small volumes of water and the results of each solution passed down-flow to the next set of volumes whose iterative solutions are then modified and passed on in turn. CFD models of graptolites have been generated and the results tested against the known outcomes of physical models. Three-dimensional models of graptolites, drawn to real scale are exposed to computed fluid flow from a variety of orientations. Cross-checks with physical modelling show that these iterative computational solutions produce verifiable results. Virtual graptolites can be modified at will and exposed to a range of current velocities. Results suggest that major improvements in our understanding of graptolite functional morphology will result from further use of this novel technique.

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Late Ordovician C and Sr isotope stratigraphy from central Nevada: paleoceanographic implications

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We present an integrated $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and sequence stratigraphic analysis in central Nevada (Antelope-Monitor Range composite) to investigate the timing and causes of the transition to a Late Ordovician–Silurian icehouse climate. A $^{87}\text{Sr}/^{86}\text{Sr}$ drop of ~ 0.0008 is recorded in the uppermost Antelope Valley Limestone and lowermost Copenhagen Formation. The drop, which occurred over a time interval of ~ 5 – 6 myr in the middle to late Whiterockian (end Darriwilian), is comparable in magnitude to the well-known Late Cenozoic rise that occurred over a much longer time period during the Neogene. Sr isotope values reach a steady baseline and change little for the remainder of the Late Ordovician. $\delta^{13}\text{C}$ values are steady through the Whiterockian–Mohawkian transition interval, but record a significant positive excursion in the upper part of the Copenhagen Formation in the Chatfieldian Stage (mid-Caradoc). This isotopic shift, which is well-documented on a global scale, was closely followed by relative sea level drop during deposition of the prominent Eureka Quartzite. $\delta^{13}\text{C}$ values appear to remain steady during the Cincinnati until the anomalous Hirnantian excursion, which was previously documented in the Hanson Creek Formation by Finney et al. (1999) and Kump et al. (1999). Sr isotopes do not change during the Hirnantian, but begin to shift towards more radiogenic values in the early Llandovery (Shields et al. 2003).

The abrupt Sr drop in the late Whiterockian–Mohawkian corresponds to the transition between pure shallow-water limestones of the Antelope Valley and the clastic-dominated Copenhagen–Eureka interval. This falls within the Sauk–Tippicanoe sequence boundary zone, and also overlaps in time with the Taconic orogeny in eastern Laurentia. It appears that any regional input of radiogenic Sr from cratonal rocks during

sea level drop was overwhelmed by input from young volcanic rocks. The rapid erosion of juvenile volcanics associated with the beginning stages of the Taconic orogeny in eastern Laurentia provide a possible source for lowering oceanic $^{87}\text{Sr}/^{86}\text{Sr}$. K-bentonites do occur in the Appalachians in the late Whiterockian–early Mohawkian interval, reaching their peak in the Mid-Mohawkian as the Sr isotope curve stabilizes at lower values. The Chatfieldian $\delta^{13}\text{C}$ excursion that follows signals enhanced organic carbon burial, which may have lowered atmospheric $p\text{CO}_2$ to levels near the threshold for ice buildup in the Ordovician greenhouse. Sr isotopes appear steady through the remainder of the Ordovician, perhaps buffered by a combination of carbonate weathering and continued high input from young volcanics.

Renewed transgression marks the base of the Hanson Creek Formation above the Eureka quartzite interval and a highstand of sea level characterizes much of the Cincinnati. C isotopes show an abrupt peak in the Hirnantian, likely due to enhanced organic burial in the deep ocean. Again, Sr isotopes do not change in step with $\delta^{13}\text{C}$, but lag the event before rising during the Llandovery.

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The Ordovician–Silurian boundary in Australasia – an update

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Established and possible sections that span the Ordovician–Silurian boundary in Australasia are confined to the Lachlan Orogen in the south-east of the Australian Plate (for a recent comprehensive summary of the Lachlan Orogen see Gray & Foster 2004). The best documented section to date is that at Darraweit Guim in central Victoria, north of Melbourne, where there are graptolites representative of the latest Ordovician and earliest Silurian zones (Vandenberg et al. 1984).

Near Forbes in the central west of New South Wales, about 300 km west of Sydney, Sherwin (1973) suggested that the Cotton Formation spans the Ordovician–Silurian boundary because of a contained graptolite fauna that extended from Late Ordovician (Bolindian) to Early Silurian (Late Llandovery). Webby et al. (1981) questioned the stratigraphic continuity of the formation on the basis of discontinuous outcrop and the absence of several graptolite zones, especially between the end of the Ordovician and the late Llandovery. Sherwin (1976) later reported an early Llandovery *cyphus-gregarius* zone assemblage from the Cotton Formation, reducing the number of unrecorded zones. The Cotton Formation consists for the most part of well bedded quartz rich siltstone with minor cherty beds that are more common in the lower part of the formation. Sandstone is a minor component more common in the middle part of the formation, possibly near to the Ordovician–Silurian boundary, in this respect resembling the section at Darraweit Guim. Flaky intraformational conglomerates are rare and more typical of the Ordovician section of the Cotton Formation. Their

distribution is suggestive of channel fill deposits (Krynén et al. 1990). *Normalograptus normalis* is abundant near the top of the lower part of the formation and could be latest Ordovician or early Silurian in age. Unequivocal evidence for the *ascensus-vesiculosus* zones is wanting.

In the Mudoonen Range east of Yass, about 220 km south-west of Sydney, Ordovician shales grade into a dominantly lithic quartz arenite unit, the Mudoonen Sandstone, at about the Eastonian–Bolindian boundary. The Mudoonen Sandstone is overlain with a slight angular unconformity by the (Late) Wenlock Hawkins Volcanics. The upper age limit of the Mudoonen Sandstone could thus be as young as Llandovery, implying that it straddles the Ordovician–Silurian boundary, but unequivocal internal evidence for a post Ordovician upper limit is presently wanting (Sherwin & Strusz 2002).

In the Goulburn district, about 150 km south-west of Sydney, there is also a transition from shales to sandstone in the Late Ordovician Bendoc Group, the latest Ordovician graptolites being of early Bolindian age. Late Llandovery graptolites have long been known from this area (Naylor 1936), supplemented by more recent finds of mid Llandovery assemblages, but it is uncertain whether or not these Ordovician and Silurian assemblages are part of a continuous sequence. Recent mapping by the Geological Survey has confirmed previous opinions that the early Palaeozoic strata east of Goulburn are complexly folded and faulted. The shales with Llandovery graptolites are all in fault bounded slices.

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Facies development, depositional settings and sequence stratigraphy across the Ordovician-Silurian boundary: a record from the Barrandian area of Bohemia, Czech Republic

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Upper Ordovician and lower Silurian formations of the Barrandian area are distinguished by weakly tectonized, almost uninterrupted and fossiliferous sedimentary successions deposited under mid- to outer-shelf or shelf-edge settings and controlled by remote Gondwanan glaciation and subsequent, long-persisting post-glacial anoxia. High-resolution graptolite stratigraphy enabled a detailed correlation among 42 surface sections and boreholes, and linked sedimentary record, graptoloid faunal dynamics, organic-content fluctuations and spectral gamma-ray curves. A combined record of relative sea-level changes inspired the subdivision of local Hirnantian and Llandovery succession into four third-order sequences (units 1–4).

Pre-Hirnantian Ashgillian is shaly, marked by deep-shelf benthic fauna and scattered graptolites. Early Hirnantian graptolite *N. ojsuensis* is locally common below the first of two levels of glacio-marine diamictites. Subsequent onset of mid-shelf storm sandstones indicates a pronounced glacio-eustatic sea-level draw-down. During the subsequent sea-level rise, the sea bottom got below the storm wave base and no sand was deposited in the transgressive systems tract (TST) of the Unit 1 sequence. The middle Hirnantian shale-dominated succession was deposited in mid-outer shelf conditions, well below the storm wave base. Unit 1 is terminated by a prominent erosional unconformity and a sequence boundary. Unit 2 begins with conglomerates and coarse, inner-shelf storm sandstones indicating major, late Hirnantian sea-level lowstand. Higher up in the sandstone package hummocky cross-stratification is common. The subsequent relative sea-level rise is marked by a gradual retreat of storm sandstones in favor of mud sediment. The TST culminates with calcareous mudstone dated by *Hirnantia* fauna and *N. persculptus*. Still above, heavily burrowed mudstone indicates a condensed, firm bottom horizon topped by a supposed maximum flooding surface. This is directly overlain by a black shale (TOC c. 2%) with basal Silurian graptolites of the *ascensus* Biozone – a HST of Unit 2. Unit 2 terminates with a more or less prominent unconformity, recognized after a pronounced gap in sedimentation and an abrupt facies change. A sequence boundary is capped by condensed black laminites of Unit 3, with clastic laminae deposited from collapsed suspension clouds transported by a current. Higher up the sequence, gamma-ray activity strongly increased and then culminated together with TOCs of 6–7% in late Rhuddanian to early-middle Aeronian. Although a maximum flooding surface has not been identified, black shales of the *leptotheca* and lower *convolutus* zones may be considered as HST deposits of Unit 3. A new relative sea-level drawdown commenced with the upper *convolutus* Zone. It is marked by an increased amount of silt, decreased TOCs, pale mudstone beds and local nondeposition. Despite further short-term sea-level fluctuations, the *sedgwickii*, *linnaei* and lower *turriculatus* zones represent a LST of Unit 4. The subsequent rise in sea-level continued up to the *spiralis* Zone. Barrandian data suggest that early Silurian rises correlate with high-diversity graptolite faunas, and sea-level falls largely correlate with graptoloid mass extinctions. In the Barrandian, black shales with TOCs over 4% persisted from the upper *acuminatus* Zone, with some interruptions in the *convolutus*, early *sedgwickii*, *linnaei* and lower *turriculatus* zones, for about 15 m.y. This pattern is very different from that described for shelfal palaeodepressions across North Africa and suggests that a steady upwelling system triggered primary organic production in the north-western periphery of Gondwana.

Middle Telychian (Llandovery) graptolites of North-African intracratonic basins and coeval graptolite fauna of the peri-Gondwanan Europe: biostratigraphical correlation and palaeogeographical implication

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A low-diversity but stratigraphically and palaeobiogeographically important graptoloid association comprising *Metaclimacograptus flamandi* (Legrand), *Parapetalolithus meridionalis* (Legrand) and *Torquigraptus australis* Storch was identified in the core samples of wells A1-66 and A1-43 in the Ghadames Basin of Libya. The former two species have been originally recovered from Algeria. All three taxa are common and widespread in the middle Telychian strata of Spain (Central Iberian Zone and Western Iberian Cordillera) and France (Brittany). In European sections, the species are associated with other, moderately diverse graptoloid faunas, which enable a more precise and worldwide biostratigraphic correlation of Saharan boreholes and surface sections. The present faunal association indicates middle Telychian age (upper *crispus*, *griestoniensis* and lowermost *crenulata/tullbergi* biozones) of the strata and suggests close palaeobiogeographical links between North African pericratonic basins and Armorican shelves. *M. flamandi* has not been found outside this NW-Gondwanan realm.

Silurian cephalopods on Gotland

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The Silurian cephalopod fauna of Gotland is unique, both regarding the number of species and the superb state of preservation of the specimens. There is only one area known with similar richness in cephalopod taxa, and that is the Barrandian area in the Czech Republic. The Barrandian fauna was studied and very well described and illustrated by Joachim Barrande in the 19th century.

The first papers regarding the Gotland cephalopod fauna were published in the 18th century when German naturalists described fossil fragments from erratic boulders found in Germany. During the 19th century more research on cephalopods was conducted and in 1867 Lindström made a list of 14 species. In 1885 this list had increased to 30 species and in 1888 to 37 species. In 1890 Lindström described 16 new species, mainly ascoceratides, and thus 53 species were known in 1900. Hedström made a magnificent monograph of phragmocerids in 1917 and 32 new species were described and added to the faunal list. In the late 20th century Mutvei and Stridsberg described 12 additional species, rising the total number to 97 species. Furthermore, in the beginning of the 20th century Holm prepared a paper in which he described numerous new cephalopods from Gotland. Unfortunately he only managed to fulfill eleven excellent plates, but no text, before he died.

Naturally a number of the historical species have subsequently been revised, but the list of 97 species still is largely valid and gives an idea of the diverse Silurian cephalopod fauna on Gotland. However, there is still a great number of undescribed species, represented by beautifully preserved and prepared specimens, in the collections of the Swedish Museum of Natural History in Stockholm (SMNH). These specimens were collected mainly in the late 19th century, particularly by Gustav Lindström, who like Holm, did not have time to finish his work before he passed away in 1901.

Among the undescribed material at the SMNH there are species of trochocerids and other groups, never

reported from Gotland. Furthermore, there is quite a number of orthocone cephalopods, with less characteristic morphologies than many of the described convolute or evolute taxa from Gotland.

Calibration of the chitinozoan and graptolite biozonations and the chronostratigraphy of the Silurian: a summary

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Ten years ago, a global chitinozoan biozonation, with seventeen biozones, was proposed for the Silurian (Verniers et al. 1995). Since then, further progress has been made in calibrating the chitinozoan biozonation with the graptolite biozonation and the chronostratigraphy and a summary is presented here.

The base of the Silurian at the GSSP locality at Dob's Linn has been restudied (Verniers et al. 2003) and the results of recent work in Scania, which has correlated the Rhuddanian chitinozoan and graptolite biozones, will be presented at this symposium by Verniers and others. The chitinozoans from the basal Aeronian and Telychian at their GSSP localities in Trefawr, Wales, and Cefn Cerig, Wales, respectively, were studied by De Permentier (1999, see also Verniers & De Permentier 2002). At the GSSP locality, the base of the Aeronian occurs at least 41 m above the base of the *maennili* chitinozoan Biozone, at a level high in the *cyphus* graptolite Biozone. The *alargada* chitinozoan Biozone is present 9 m above the base of the Aeronian and this corresponds to a level within the *magnus* graptolite Biozone. The base of the *dolioliformis* chitinozoan Biozone is placed high in the Aeronian and high in the *sedgwickii* graptolite Biozone in the type area according to Geng Liangyu & Wang (1997) and low in the *sedgwickii* graptolite Biozone according to Verniers & De Permentier (2002). The base of the *longicollis* chitinozoan Biozone correlates with the base of the *spiralis* Biozone in Latvia (Loydell et al. 2003, Loydell & Nestor in press). The base of the *margaritana* chitinozoan Biozone does not correlate with the base of the Wenlock, but occurs in the uppermost Llandovery at the GSSP locality at Hughley Brook, England (Mullins & Aldridge 2004). Where calibration with the graptolite biozonation has been possible, the base of the *margaritana* Biozone has been first recorded near the base of the *insectus* graptolite Biozone in Wales (Mullins 2000, Mullins & Loydell 2001) and within the upper part of the *spiralis* graptolite Biozone in Latvia (Loydell & Nestor in press). The Wenlock graptolite and chitinozoan biozones were calibrated in the type area of the graptolite biozonation (Rhyader, Wales) by Verniers (1999). The base of the *cingulata* chitinozoan Biozone coincides with the base of the *belophorus* graptolite Biozone, the base of the *pachycephala* chitinozoan Biozone occurs near the boundary of the *rigidus* and the *perneri* graptolite biozones and the base of the *lycoperdoides* chitinozoan Biozone is situated near the boundary of the *praedeubeli* and *deubeli* graptolite biozones. The Ludlow and Přídolí chitinozoan biozones were defined in the respective type areas and are thus well constrained chronostratigraphically (Verniers et al. 1995).

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Chitinozoan biozonation at the Ordovician–Silurian transition in Dob's Linn (Scotland, U.K.) and Lönstorp (Scania, Sweden)

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A detailed logging and sampling for chitinozoans in the GSSP of the Ordovician–Silurian boundary at Dob's Linn (Scotland, U.K.) allowed to draw a detailed 10.5 m thick stratigraphical log and to locate exactly the stratigraphical position of chitinozoan samples. The many bentonite beds, pyrite rich levels and some fine siltstone beds were used as marker beds to locate the GSSP. The graptolite biozonation established by Williams (1982, 1983), Williams and Ingham (1989) and revised by Melchin & Williams (2000), Melchin (2001, 2003) and (Melchin et al. 2003) proved the presence of the *persculptus*, *ascensus*, *acuminatus* and *vesiculosus* biozones. The position of the GSSP had not to be changed after this revision of the graptolites and remains fixed at 1.60 m above the base of the Birkhill Formation.

The chitinozoan assemblages extracted from 45 samples are often poor in specimens, poorly preserved and moderately diversified. It allows, however, a biozonation accurately calibrated with the GSSP and the graptolite biozonation. The chitinozoan *Ancyrochitina ellesbayensis* is found in three samples from 0.12 m below until 0.06 m above the GSSP. The species has been observed in the Anticosti (Canada) in the upper half of the Laframboise Member, above the bioherm level of the Ellesbay Formation. This allows correlation of the GSSP in Dob's Linn to the previous candidate section of the Ordovician–Silurian boundary in Canada, where graptolite finds are rare. Higher up the *laevaensis* biozone is recognized in samples 0.45 m to 0.75 m above the GSSP, in the basal *ascensus* biozone. The *Belonechitina aspera* biozone is found in samples 3.1 to 3.5 m above the GSSP, in the top part of the *acuminatus* biozone.

To calibrate more exactly the chitinozoan biozonation versus the graptolite biozonation around the Or-

dovician–Silurian boundary, another chitinozoan study was undertaken in the Lönstorp borehole in Scania (southern Sweden), drilled by one of the authors (A.N.). A detailed and well documented graptolite biozonation could be established in two other boreholes in Scania (Koren' et al. 2003). They recognised a new latest Ordovician (Hirnantian) post-*persculptus* and pre-*ascensus* subzone. The Lönstorp borehole studied by Koren' et al. (2003) for graptolites was sampled for chitinozoans. The intervals under interest are between 60 and 77.3 m depth, with the Ordovician–Silurian boundary at –74.9 m. It comprises the *vesiculosus* zone (60–69.7 m), *acuminatus* zone (69.7–74.3 m), *ascensus* zone (74.3–74.9 m), *minor/avitus s.s.* zone (lacking the *persculptus* zone) (74.9–76.5 m), and the *persculptus s.s.* zone (76.5–77.3 m). The chitinozoans from 35 samples in these intervals are rather well preserved (light to dark brown). The assemblages are dominated by Ancyrochitinae with often broken appendices and rich in *Cyathochitina*. The rare *Spinachitina* allow correlation with other sections. The chitinozoan biozonation from both areas will be compared with Scania, Avalonia, Bohemia, northern Gondwana and Laurentia.

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Hirnantian–Llandovery (uppermost Ordovician–lowermost Silurian) carbon isotope ($\delta^{13}\text{C}$) stratigraphy from Anticosti Island, Quebec: implications for oceanography, glaciation, and organic carbon burial

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Changing climate and oceanography during the Late Ordovician (Hirnantian), led to multiple episodes of Gondwanan glaciation and resulted in two phases of mass extinction. A large positive carbon isotope excursion (up to +7‰) has been documented from many Hirnantian sections worldwide and shown to be a global perturbation of the carbon cycle. The Hirnantian carbon isotope ($\delta^{13}\text{C}$) excursion has now been doc-

umented in new high-resolution carbonate and organic-matter carbon isotope ($\delta^{13}\text{C}$) data from Anticosti Island, Quebec, with values as high as +4.7‰ in carbonates and -25.3‰ in organic-matter. The excursion is recorded in the uppermost Lousy Cove and the Laframboise Members of the Ellis Bay Formation, from a tidal flat exposure near Point Laframboise on the western end of Anticosti Island. Previous conodont, chitinozoan, and brachiopod biostratigraphic work has demonstrated that the Ellis Bay Formation is Hirnantian. The relatively unaltered Upper Ordovician through Lower Silurian carbonate sequence on Anticosti Island records the Hirnantian excursion in both carbonate and organic matter isotopes, and allows for a unique opportunity to examine an interval of major climatic, oceanographic, and biological change in Earth's history.

Our data reveal that peak $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{org}}$ values are not coincident, and that the heaviest $\delta^{13}\text{C}_{\text{org}}$ values occur prior to the heaviest $\delta^{13}\text{C}_{\text{carb}}$ values. These paired carbonate and organic-matter carbon isotope data suggest that atmospheric $p\text{CO}_2$ was declining and reached its lowest levels prior to the $\delta^{13}\text{C}_{\text{carb}}$ peak. High $p\text{CO}_2$ was coincident with high $\delta^{13}\text{C}_{\text{carb}}$ values, and falls again after the $\delta^{13}\text{C}_{\text{carb}}$ excursion. The excursion has been previously attributed to increased burial of organic carbon (i.e. black shales) due to increased marine productivity. While this is a likely mechanism, the excursion appears to have occurred during an interval of clean carbonate deposition in epeiric seas, not black shale deposition. Continental margin and shelf black shale deposition (e.g. Vinini Creek, Polk Creek Shale) took place in the upper Richmondian (Rawtheyan) (*D. ornatus/P. pacificus* graptolite zones) prior to the $\delta^{13}\text{C}_{\text{carb}}$ excursion. Sedimentological and biological evidence are consistent with the heaviest values of the excursion having been recorded during a sea-level highstand (interglacial), rather than glaciation. In this scenario, strong thermo-haline circulation occurred prior to and after the peak of the excursion and led to development of black shales in shelf settings. The excursion is attributed to either enhanced preservation in the deep oceans during formation of warm, saline bottom waters in an interglacial, or to higher productivity in more open ocean settings beyond the craton.

New early vertebrate data from the Lower Silurian of central Asia and south Siberia

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Endemic early vertebrates occur in the Lower Silurian of central Asia and five subregions of the southern part of the Siberian platform. Outcrop material from the Lower Silurian (Llandovery and Wenlock) of north-west Mongolia, central Tuva and south Siberia yields numerous thelodont and acanthodian microremains. Two endemic genera of thelodonts, as well as two endemic genera of acanthodians, were identified in the Lower Silurian of the region (Karatajute-Talimaa 1997, Karatajute-Talimaa & Meredith Smith 2003, Zigaite 2004). The acanthodians are extremely abundant in the Lower Silurian of the Siberian platform where they form almost pure 'bone beds'. Two early acanthodian genera are common in the region. *Lenacanthus* Karatajute-Talimaa & Meredith Smith, 2003 and its only species *L. priscus* Karatajute-Talimaa & Meredith Smith, 2003, is restricted to shallow shelf facies of the Siberian platform, although absent in lagoonal, beach and submarine – deltaic facies. By contrast, *Tchunacanthus* Karatajute-Talimaa & Meredith Smith, 2003 is widespread in each of the facies mentioned above (including bar belt facies) of south Siberia, Tuva (Karatajute-Talimaa & Ratanov 2002) and north-west Mongolia (Karatajute-Talimaa et al. 1990).

All the thelodont micromaterial is ascribed to four genera: *Angaralepis* Karatajute-Talimaa, 1997, *Loganellia* Turner, 1991, *Paralogania* Karatajute-Talimaa, 1997, and *Talimaalepis* Zigaite, 2004. *A. moskalenkoae* is found in the Siberian platform only, whereas *L. tuvaensis* (Karatajute-Talimaa 1978) is restricted to Wenlock deposits of central Tuva. *Angaralepis* and *Loganellia* are common in shallow water sediments such as shallow shelf, marine delta and brackish lagoon facies, whereas *Talimaalepis* is present both in shallow and deeper shelf sediments. *Talimaalepis rimae* Zigaite 2004, first described from the Llandovery Series of central

Asia, is common in north-west Mongolia, the Siberian platform as well as Tuva. A probable new species of *Paralogania* (or even a new thelodont genus) is present in the Upper Llandovery–Wenlock molasse – type sediments of north-west Mongolia. The facies is rich in benthic faunas including the endemic *Tuvaella* brachiopods (Minjin 2001).

The abundance and richness of endemic species in the region indicate that it was a suitable place for genesis and radiation of the earliest vertebrates (Blieck & Janvier 1993). Numerous thelodont and acanthodian taxa in the Silurian sections of this region are indicative of warm and productive basins, which existed in the Siberian palaeocontinent during its inferred journey across the Equator during the Silurian (Cocks & Torsvik 2002).

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