Geol. Mag. **143** (*1*), *2006, pp. 15–24. © 2006 Cambridge University Press*
doi:10.1017/S001675680500169X *Printed in the United Kingdom*

Evidence for rapid environmental changes in low latitudes during the Late Silurian Lau Event: the Burgen-1 drillcore, Gotland, Sweden

MIKAEL CALNER* & MÅRTEN J. ERIKSSON

GeoBiosphere Science Centre, Department of Geology, Lund University, Sölvegatan 12,
SE-223 62 Lund, Sweden

(*Received* 1 December 2004; *accepted* 20 June 2005)

Abstract – Erosional outliers are an important component of the Ludlow (Late Silurian) stratigraphy of Gotland, Sweden. However, due to the poor degree of exposure, outcrop studies have not revealed a detailed section from any of these outliers. The first complete stratigraphy of such an erosional remnant, the Burgen outlier, is presented here, based on the recently recovered Burgen-1 drillcore. Stratigraphical units encountered are, from oldest to youngest, the uppermost Hemse Group (> 35 m), Eke Formation (0.4 m), Burgsvik Formation (3.4 m) and the basal Hamra Formation (12 m preserved). Based on carbon stable isotopes and lithological correlation to nearby outcrops that are zoned by conodonts, it can be concluded that the most profound late Ludlow sedimentary changes took place shortly after the onset of the globally recognized Lau Event (δ^{13}C values reach 8.7 ‰ in the lower Hamra Formation). Sedimentary changes include development of discontinuity surfaces, widespread occurrence of an intraclastic conglomerate, increased microbial activity (*Rothpletzella* and *Wetheredella*), and influx of clastics to the basin. These changes are linked to substantial base-level changes during the event. A general comparison with the Prague basin suggests contemporaneous sedimentary changes on Baltica and on cratonic elements from peri-Gondwana during the event.

Keywords: Lau Event, stable isotopes, microbial, Silurian, Gotland, Baltica.

1. Introduction

The present geomorphology of Gotland (Fig. 1) is controlled primarily by the Silurian bedrock composition and secondarily by (sea and lake) base-level changes in the Baltic depression following the deglaciation of the Weichselian ice-sheet (e.g. Svensson, 1989). These factors have accentuated the topography into flat, low-lying farmland where argillaceous sedimentary rocks occur, and higher forested areas where more weathering resistant limestone occurs. Local occurrences of biohermal and biostromal rocks within the Hemse Group outcrop area have resisted complete erosion and now form elevated, isolated erosional remnants rooted on marls deposited in distal platform areas, such as the Linde, Lau and Burgen outliers (Fig. 1b). No previous studies have revealed the complete stratigraphy of any of these outliers. This is due to lack of continuous exposures because of natural geomorphological reasons, such as talus and earth accumulations along the lower flanks of outliers. Nonetheless, the temporal transitions from distal platform marls to shoal and reef complexes preserved in the outliers are critical for understanding at what relative rate reef complexes prograded and the platform expanded, and thus for elucidating the rate of relative sea-level change. Importantly, the transitions are crucial also from an event stratigraphical point of view since Silurian extinction events like the Mulde Event (Calner & Jeppsson, 2003) and the Lau Event (Jeppsson & Aldrige, 2000; Calner, 2005; this paper) are associated with intervals of major depositional changes in contemporaneous carbonate platforms.

The bioherm-rich Burgen outlier forms an elongated hill, *c.* 5.5 km long and less than 1 km wide, rising some 10–15 m above the surrounding flat-lying farmlands in the southeastern Hemse Group outcrop area (Fig. 1c). This paper describes in detail the stratigraphy of the Burgen-1 drillcore and documents anomalous carbonate platform development during the late Ludlow Lau Event.

2. The Lau Event

The cored interval includes one of the extinction events of the Silurian Period: the Lau Event (Jeppsson, 1987; Talent *et al.* 1993; Jeppsson & Aldridge, 2000; Calner, 2005). This event began in the latest part of the *Polygnathoides siluricus* conodont Chron (uppermost Hemse Group; Fig. 2) and is associated with a prominent carbon isotope excursion (CIE) reported from widespread locations such as Gotland (Samtleben, Munnecke & Bickert, 2000; this paper), Skåne in southernmost Sweden (Wigforss-Lange, 1999), Latvia, Estonia and Lithuania (Kaljo, Kiipli & Martma, 1997; Kaljo *et al.* 2003, 2004), Bohemia (Lehnert *et al.* 2003),

---

*Author for correspondence: mikael.calner@geol.lu.se

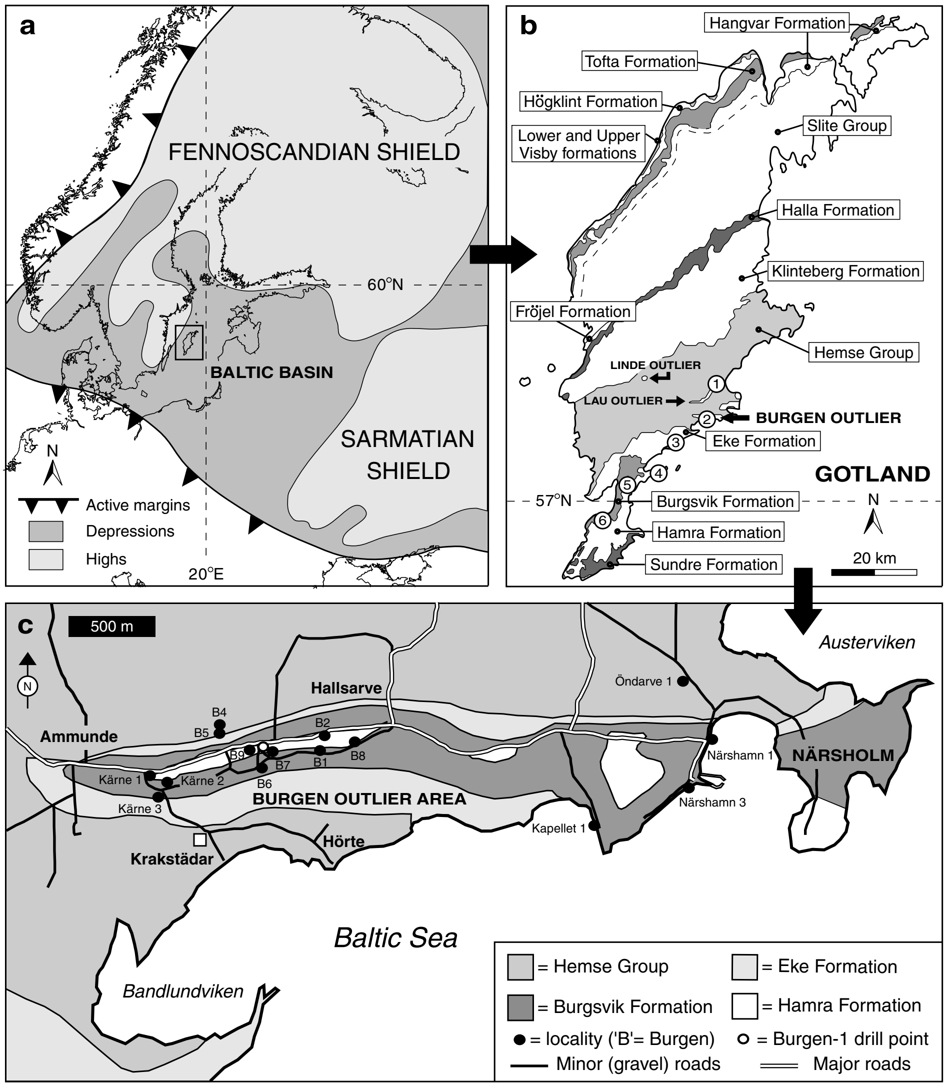

Figure 1. Map showing general setting, stratigraphy and localities. (a) Silurian palaeogeography on the Baltic craton. In the Late Silurian this basin was situated at tropical latitudes south of the equator. Note the location of Gotland within the square. Modified from Baarli, Johnson & Antoshkina (2003). (b) Stratigraphical units of Gotland and the location of the Burgen area in the southeasternmost parts of the Hemse Group outcrop area. Numbers refer to area (1) and drillcores (2–6) along the transect in Figure 3: (1) Botvide 1 locality, (2) Burgen-1 core, (3) Ronehamn-1 core, (4) Grötlingbo-1 core, (5) Uddvide-1 core, (6) Burgsvik-1 core. (c) The Burgen outlier area and the geographical position of the drilling site. The marked localities are those important for the stratigraphical subdivision of the outlier. The white square north of Krakstädar marks the location for the slab illustrated in Figure 5b.

Carnic Alps (Wenzel, 1997), Queensland (Andrew *et al.* 1994), and the United States (Saltzman, 2001). The CIE and the last appearance datum (LAD) of the zone fossil *P. siluricus* in the earliest part of the crisis hence facilitate identification of the event. The event caused extinctions and changes in community structures (Jeppsson & Aldridge, 2000, and references therein), and a reduction in the diversity of pentamerid brachiopods (Talent *et al.* 1993). Conodonts were severely affected and no platform-equipped taxon survived (Jeppsson & Aldridge, 2000). Initially, the Silurian biodiversity changes were explained in a key paper by Jeppsson (1990) as triggered by climate-driven changes in oceanic circulation. Thereafter, modified oceanographical models have been put forward to explain the Silurian events (Bickert *et al.* 1997; Cramer & Saltzman, 2005).

3. Properties of the core and methods

The Burgen-1 core has a diameter of 39 mm and reaches a depth of ~ 50 m below ground level at GPS O: 1667496 N: 6348342. Core recovery is estimated at better than 99 %. The core was studied by means of detailed facies logging. Field studies in natural outcrops and abandoned quarries within the area of the outlier (Fig. 1c) permitted correlation to the local stratigraphical units established by Hede (1925; see also Laufeld, 1974*a*). Sediment-petrographical studies of the core are based on 17 thin-sections (marked

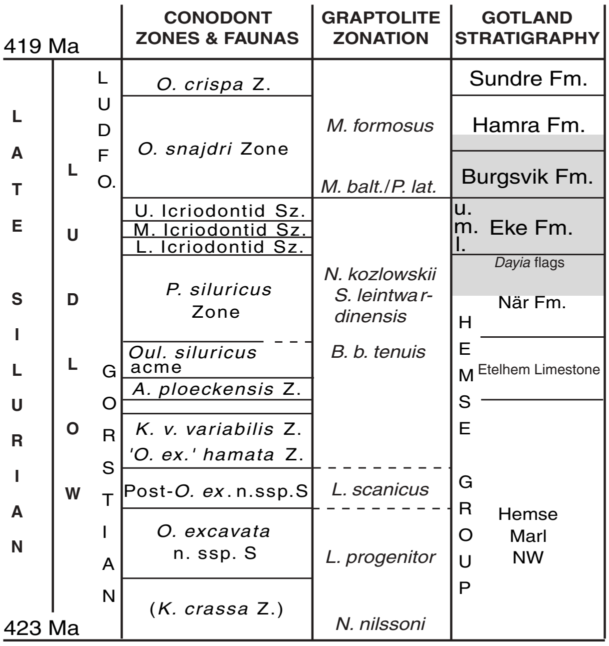

Figure 2. Stratigraphical framework of the late Ludlow of Gotland. Shaded area marks the cored interval. Conodont zonation from Jeppsson (in press) and references therein. Chronostratigraphical ages from Gradstein *et al.* (2004).

BU in figures and text) and polished cuttings (the core and samples from the core are stored at the GeoBiosphere Science Centre, Department of Geology, Lund University). All samples referred to are marked in the sedimentary log presented herein. In addition, 32 whole-rock samples were collected for carbon and oxygen stable isotopes (marked BUSI in figures and text). These were recovered by drilling, parallel to bedding, centimetre-long plugs of 3–5 mm diameter in the core. The micro-cores were ground in an agate mortar and between 200 and 300 μg were separated and roasted in vacuum at 400 °C. The sample was processed with a VG Prism Series II mass spectrometer attached to an Isocarb preparation system at the Department of Earth Sciences, University of Göteborg. For detailed descriptions of localities and drillcores mentioned, see Laufeld (1974*b*), Cherns (1983) and Calner, Jeppsson & Munnecke (2004*a*,*b*).

4. Stratigraphy and sedimentology of the Burgen-1 core

The Ludlow (Late Silurian) of Gotland was outlined by Hede (1925) and includes the Hemse Group, and the Eke, Burgsvik, Hamra and Sundre formations (Fig. 2). Based on several new drillings (Calner & Eriksson, 2004), a 40 km long transect that reveals the large-scale stratigraphical relationships for parts of these strata is presented herein (Fig. 3). In this section we first give a general description of the different units as they are known from outcrops. Thereafter, we outline in more detail their properties in the Burgen-1 core (Fig. 4).

4.a. Uppermost Hemse Group

4.a.1. General description

The upper Hemse Group (the När Formation) is a homogeneous, graptolitiferous unit composed of slightly dolomitic calcareous mudstone with thin intercalations of limestone (Hede, 1919, 1927, 1942). The topmost part of the unit forms an approximately decimetre-thick bed across Gotland, very rich in the brachiopod *Dayia navicula*, which Munthe (1910, p. 1409) referred to as 'an uncommonly good type-bed'. The top of the Hemse Group is a discontinuity surface at least from the Botvide area in the northeast to the subsurface of the Ronehamn area in the southwest. During this study the discontinuity surface was identified *c.* 1.2 km southwest of the drilling point (loose blocks from a temporary well just west of the intersection of the roads to Hörte and Krakstädar, Fig. 1c). Here, the blackened discontinuity surface is penetrated by borings (Fig. 5b) as well as by a solution pipe. The surface is

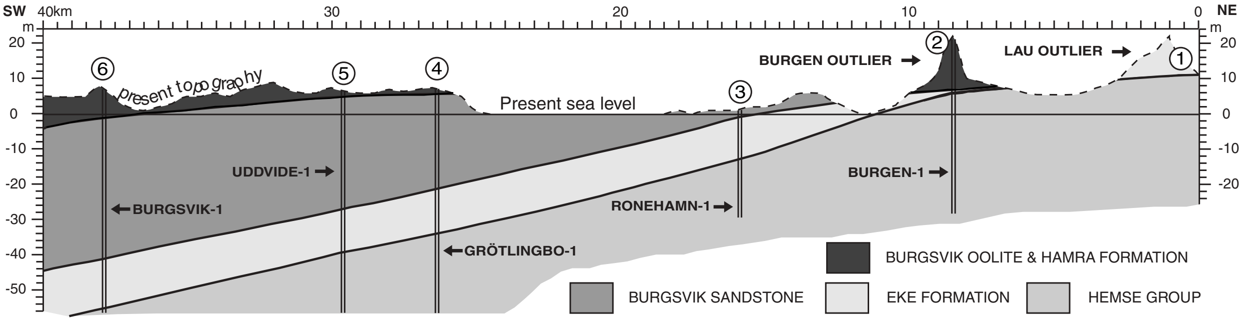

Figure 3. Transect showing the large-scale stratigraphical relationship in the Ludlow of southern Gotland. Note the substantial thinning of the Eke Formation across the Burgen outlier area. Note also that the two members of the Burgsvik Formation, the Burgsvik Sandstone and the Burgsvik Oolite, are distinguished in the figure (see sections 4.c.1 and 5), and that the Burgsvik Sandstone has its main subcrop (and outcrop) area on the southern peninsula and decreases in thickness towards the northeast. The top of the Burgsvik Sandstone and the top of the Eke Formation coalesce towards the Burgen outlier and are interpreted as being amalgamated in the Burgen-1 core. Hence, the Burgsvik Formation in the Burgen outlier is interpreted to correlate with the Burgsvik Oolite on southern Gotland (see text). See Figure 1 for location and orientation of the transect.

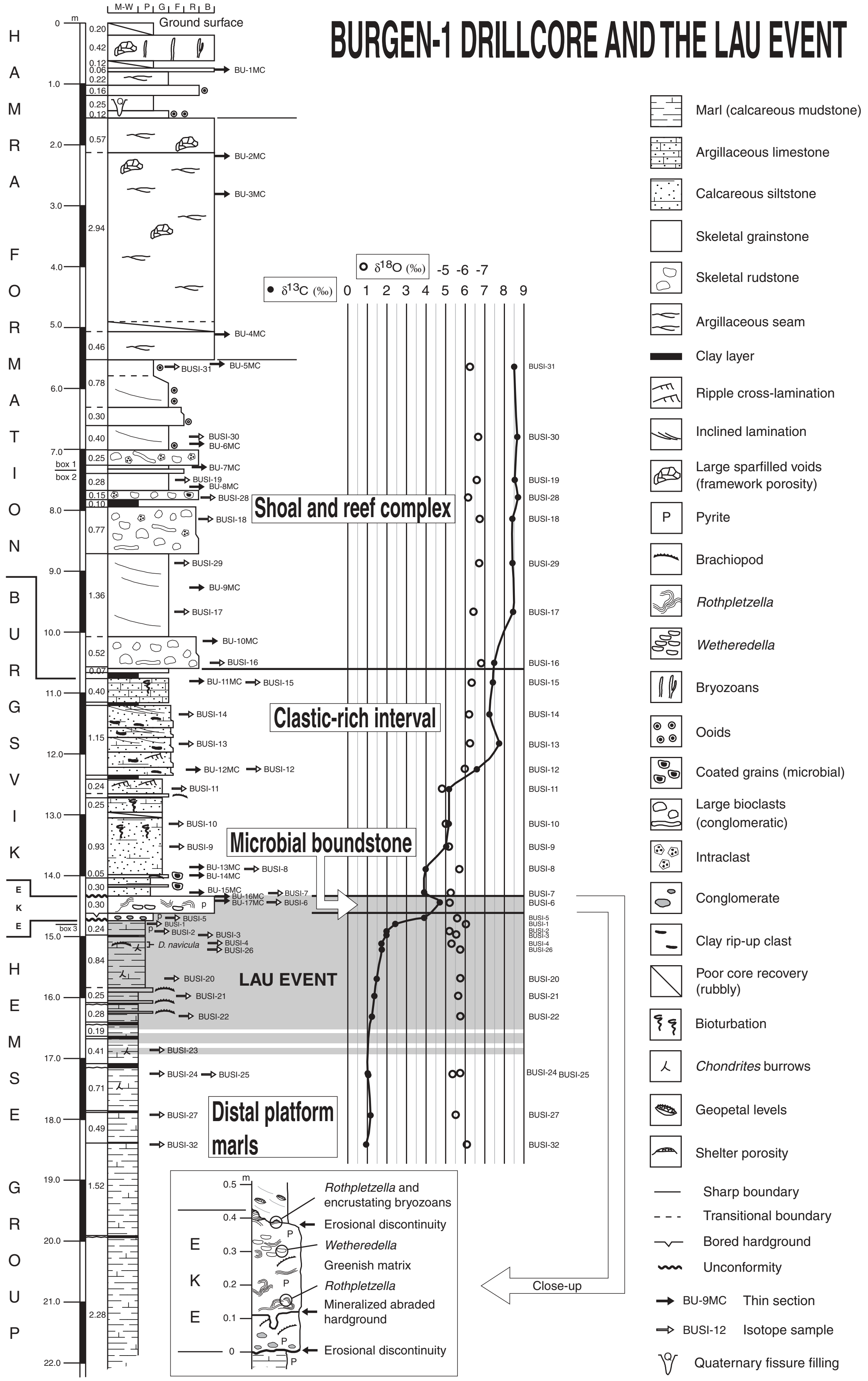

Figure 4. For legend see facing page.

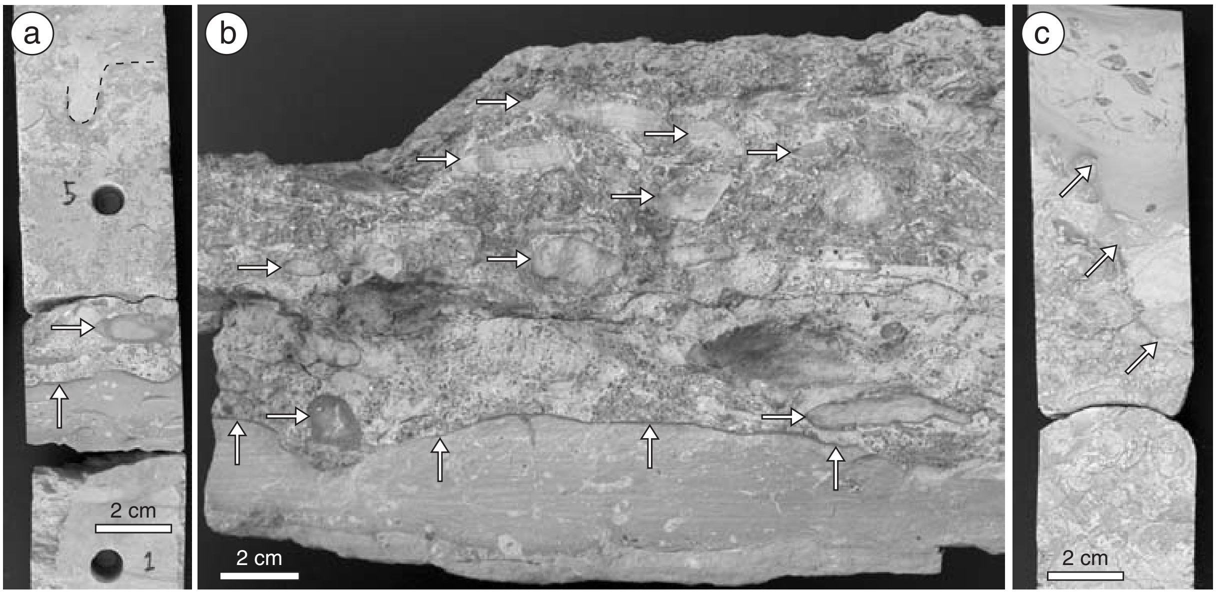

Figure 5. Stratigraphical boundaries. (a) The Hemse–Eke boundary in the Burgen-1 core (vertical arrow). Note black rim along the discontinuity surface and around the clast (horizontal arrow). A bored hardground occurs in the lower Eke (dashed line). (b) Slab with the blackened Hemse–Eke boundary surface (vertical arrows) from 1.2 km southwest of the drilling point. Abundant clasts, more or less blackened, of Hemse origin occur above the boundary (horizontal arrows). Note the *c.* 1 cm deep borehole penetrating the erosional surface (between the two central vertical arrows). (c) The Eke-Burgsvik boundary in the Burgen-1 core (arrowed). Note the steep relief of the microbial boundstone (Eke Formation) and the draping by terrigenous mudstone (Burgsvik Formation). Geopetal- and spar-filled brachiopods occur in the latter.

overlain by a decimetre-thick monomict paraconglomerate with pyritic packstone matrix rich in fragments from brachiopods, trilobites and crinoids. The majority of clasts are subrounded and aligned close to horizontal with their a-axes (Fig. 5b). Encrustation of bryozoans is evident on at least one clast (cf. similar results from Botvide 1 by Cherns, 1983). Loose flat clasts from this locality include abundant *D. navicula* and also *Shaleria* aff. *ornatella* brachiopods.

4.a.2. *Burgen-1 drillcore*

The upper 35 m of the Hemse Group that was cored is dominated by alternations of thin-bedded dark grey-green marlstone (argillaceous wackestone) and fine-grained, nodular or layered light-grey skeletal wackestone. Bioturbation is fairly common and most striking is the abundance of *Chondrites*, which occurs frequently within limited intervals. Poorly consolidated clay layers occur throughout the upper Hemse Group and they increase in frequency and thickness upwards through the unit (Fig. 4). In the uppermost *c.* 1.3 m, bioturbation decreases, revealing sedimentary structures dominated by planar lamination and ripple cross-lamination. These structures are recurrently interrupted by thin shell coquinas. Only one brachiopod that provisionally can be identified as *D. navicula* was found in the uppermost metre of the Hemse Group.

The top of the Hemse Group is a discontinuity surface occurring in a pyrite-rich zone. The surface is overlain by rounded clasts of upper Hemse lithology (Fig. 5a). As in other areas, the discontinuity surface itself, as well as individual clasts, has a dark rim.

The carbon isotope excursion, and thus the Lau Event, starts approximately 1.8 m below the top of the Hemse Group in the Burgen-1 drillcore (Fig. 4).

4.b. Eke Formation

4.b.1. *General description*

The Eke Formation exhibits fundamentally different facies southwest and northeast of the Burgen outlier. To the southwest, in the subsurface, the formation is a more or less stratiform (Fig. 3) and progradational unit of marls, packstone and grainstone exceptionally rich

---

Figure 4. Sedimentary and stable isotopic data from the upper part of the Burgen-1 core. The start of the Lau Event is near the onset of the carbon isotope excursion (oxygen isotopes do not reveal useful information in this sense) some 1.8 m below the upper unconformable boundary of the Hemse Group. More data is necessary to pinpoint the onset of the excursion more exactly. High values of carbon isotopes continue well into the lower Hamra Formation in the Burgen-1 core and the peak is not identifiable within the sampled interval. This differs from the isotope curve in Samtleben *et al.* (2000, fig. 3), which also shows high carbon isotope values into the Hamra Formation but a peak within the Eke Formation.

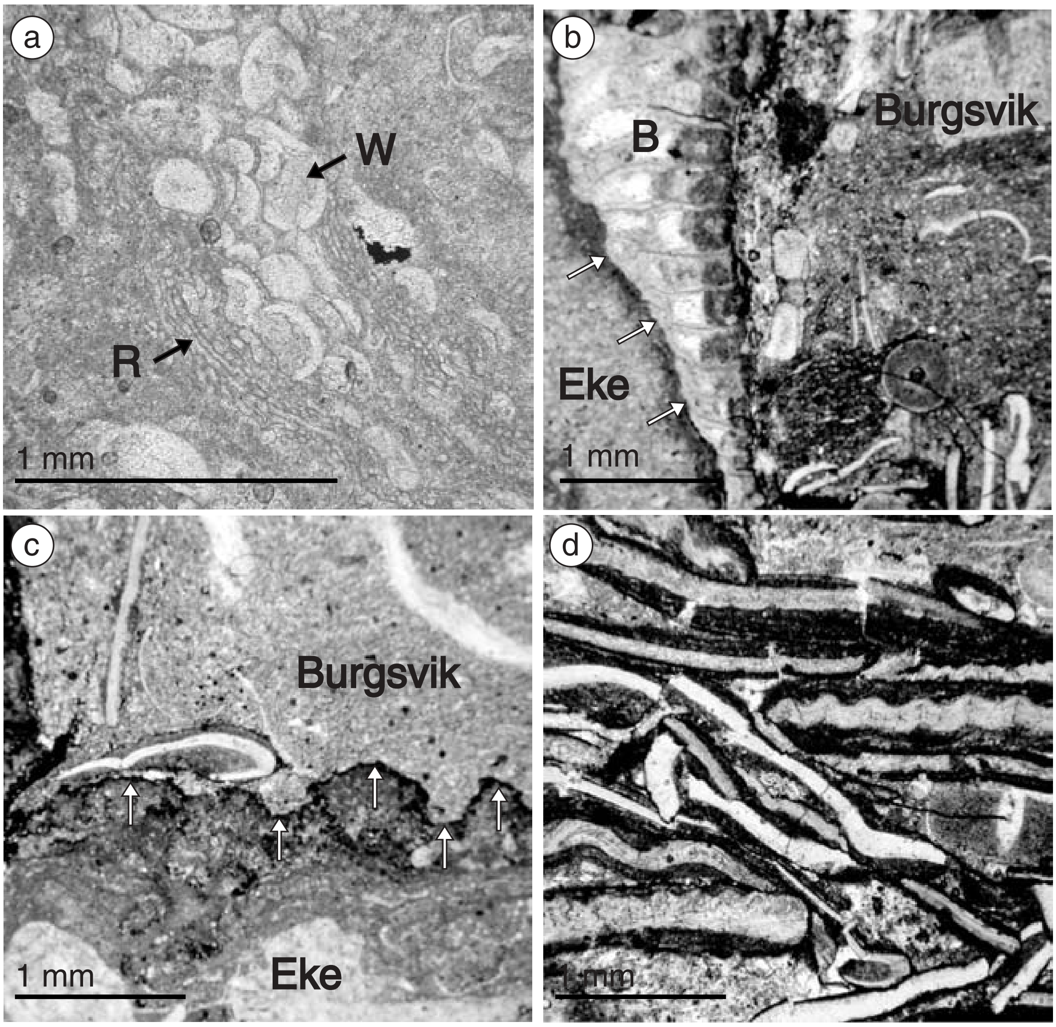

Figure 6. Photomicrographs of rocks from the Burgen-1 drillcore. (a) Intergrowth of *Rothpletzella* tubes (R) and *Wetheredella* (W) in the uppermost part of the Eke Formation (BU17-MC). (b) Bryozoan (B) encrusting the upper, ragged Eke (left) boundary (arrowed, BU16-MC). (c) The upper boundary of the Eke Formation (arrowed) showing micro-topography on microbial boundstone (BU16-MC). (d) Coquina from *c.* 0.30 m above the Eke–Burgsvik boundary. Note fitted fabric and the dark microbial coatings around fragments (BU14-MC).

in oncoids (e.g. of ‘cauliflower-type’). The thickness varies from 12.5 m in the Ronehamn-1 core to *c.* 14 m in the Uddvide-1 and Burgsvik-1 (Hede, 1921) cores. In contrast, in the Lau outlier, to the north of the Burgen outlier, the Eke Formation is represented by *c.* 10 m of cross-bedded crinoidal packstone and grainstone and small matrix-rich mounds, containing small stromatoporoids, corals and algae (Manten, 1971). Strata in the Lau outlier yield abundant stromatolites with flat, domal, and/or columnar growth forms. These generally reach only a few centimetres in height and grew as isolated or laterally interconnected colonies. Although they in part are related to karst, they are frequently found together with *in situ* branch-formed heliolitid corals, brachiopods and abundant crinoidal debris, indicating formation under normal-marine, subtidal conditions (Calner, 2005). The exposed lower part of the Eke Formation is karstified in the Lau outlier (Cherns, 1982). We believe this karst penetrates through the entire Eke Formation in the area, and the upper boundary of the unit is interpreted as a sequence boundary (Eriksson & Calner, unpub. data).

4.b.2. Burgen-1 drillcore

In the core, the Eke Formation is 0.4 m thick, that is, considerably thinner than to the southwest and to the northeast of the outlier (Fig. 3). The lowermost part is a fine-grained crinoidal packstone, having a greenish matrix including delicate fragments of brachiopods and trilobites. A bored hardground occurs 0.07 m above the Hemse–Eke boundary (Fig. 5a). The topmost *c.* 0.3 m, that is, the major part of the formation, is a microbial boundstone dominated by *Rothpletzella* and *Wetheredella* (see Riding & Fan, 2001, p. 804 for relationship to *Sphaerocodium gotlandicum*; Fig. 6a). Matrix consists of wackestone with occasional silt-sized quartz grains and fragments from brachiopods and crinoids (BU17-MC). Repeated intergrowth of *Rothpletzella* and encrusting bryozoans characterizes the topmost centimetres of the formation (Fig. 6b).

The upper boundary of the Eke Formation has a relief of *c.* 0.1 m (Fig. 5c). The immediate boundary surface is ragged and shows minor dissolution features (Fig. 6c), and is locally covered by a very thin lamina enriched in eluviated silt-grade quartz grains. This microfacies also fills fissures between microbial Eke strata and an encrusting bryozoan colony, as well as a microfracture in the topmost Eke Formation. The overlying very finely laminated mudstone drapes the topography (Fig. 5c).

4.c. Burgsvik Formation

4.c.1. General description

The Burgsvik Formation (Hede, 1921; Stel & de Coo, 1977; Long, 1993) includes the Burgsvik Sandstone and the overlying Burgsvik Oolite (Hede, 1921). The former unit, which is *c.* 37 m thick in the Burgsvik-1 core (Hede, 1919) and *c.* 30 m thick in the Uddvide-1 core, is composed of mud-, silt- and sandstone. The Burgsvik Oolite is composed of oolites or oncoidal rudstone with a grainstone matrix. The boundary between the Burgsvik Sandstone and Burgsvik Oolite is well exposed along a distance of *c.* 25 km along the western coast of the southern peninsula. At these localities, the uppermost parts of the sandstone are generally composed of thick bedsets of massive to hummocky cross-stratified strata. The thickness and sedimentary structures of the sandstone reflect deposition below fair-weather wave-base while the overlying oolite has a basal winnowed lag of abraded bioclasts and shows peritidal signatures. This boundary is interpreted as a major flooding surface (Calner, Jeppsson & Munnecke, 2004*b*, fig. 5/1).

4.c.2. Burgen-1 drillcore

The Burgsvik Sandstone is 3.4 m thick in the core. The basal *c.* 2 m are dominated by mudstone and calcareous and dolomitic siltstone (Fig. 4). Small-sized load structures and borings are common and thin shell coquinas occasionally occur. The two lowermost coquinas consist of coarse-grained grainstone dominated by fragments from brachiopods, bivalves and trilobites having dark (almost black on polished slabs) microbial coatings of uniform thickness (Fig. 6d). Well-rounded intraclast lags from wackestone and siltstone occur within these coquinas, as well as compaction features and fitted grain fabrics (BU-14MC; Fig. 6d). Several poorly consolidated clay layers with notably sharp bases occur within an interval between 12 and 13 m below ground surface. The lower three have millimetre thicknesses, while the topmost clay layer has a thickness of at least 0.06 m (incomplete core recovery?). Strata succeeding the uppermost clay layer (12.2 m below ground surface) are coarser-grained as well as more calcareous than strata in the lower part (Fig. 4). This upper part of the Burgsvik Formation is composed of calcareous siltstone/silty limestone (BU-12MC) or peloidal grainstone with only little quartz (BU-11MC), showing cross-lamination or inclined lamination. Rip-up clasts of greenish mud are common at the base of beds.

4.d. Hamra Formation

4.d.1. General description

The Hamra Formation is, in the major part of its outcrop area on the southern peninsula, composed of stratified, more or less marly, limestone, although reefal deposits are prominent in the southernmost parts. In the Burgen outlier, the boundary between the Burgsvik and Hamra formations has hitherto only been poorly defined (at Burgen 7 by Laufeld, 1974*b*; cf. Hede, 1925, p. 34). Here, the lower exposed Hamra Formation is dominated by oolitic and oncolitic cross-bedded shoal deposits with enclosed bioherms (well exposed at Burgen 8, an abandoned quarry).

4.d.2. Burgen-1 drillcore

The boundary between the Burgsvik and Hamra formations in the Burgen-1 core is herein placed at the top of 0.08 m thick, dark-grey shale that separates argillaceous limestone from pure limestone (Fig. 4). The lower part of the Hamra Formation is composed of thin- to thick-bedded crinoidal grainstone, oolitic-microoncolitic grainstone, and coarse-grained skeletal rudstone. The upper part of the formation is a microbial-bryozoan dominated bioherm.

5. Discussion and implications

On a broad basis, the Burgen-1 core succession can be subdivided into four facies groups, each corresponding to a lithostratigraphical unit (Fig. 4).

The upper Hemse Group is interpreted as being deposited below the effective wave base based on lithology, widespread occurrence and an absence of sedimentary structures. The laminated beds and the slight increase in carbonate content in the uppermost metre may indicate the onset of shallowing of the depositional environment, but could partly be a contemporaneous taphonomic effect due to decreased rates of infaunal activity (see Calner, 2005). The single find of a potential *D. navicula* indicates absence of the topmost Hemse marker bed in this central part of the Burgen outlier (Munthe (1902, fig. 3) reported *D. navicula* from a nearby locality). This and the conglomerate suggest erosion at the top of the Hemse Group. However, the lack of major deviations in our stable isotope curve across the Hemse–Eke boundary and the associated conglomerate contradicts a major hiatus at this level.

The overlying microbial boundstone (Eke Formation) indicates a shallow-water origin based on the basal conglomerate of rounded flat pebbles (cf. Myrow *et al*. 2004), abundance in *Rothpletzella* and *Wetheredella*, and dissolution features with encrustations of bryozoans (Fig. 6b). Thus, the transition from distal platform marl to microbial boundstone is very rapid, notably lacking transitional facies (Figs 4, 5a, b). Such abrupt shift in platform configuration differs markedly from the evolution of older platform generations on Gotland; the Late Wenlock Halla–Klinteberg platform and the early Ludlow lower Hemse platform (the Hunninge-1 drillcore and the Linde-1 drillcore, respectively). These comprise shallowing-upward successions, including several metres of transitional facies, that is, reflecting the successive progradation of carbonate platforms across argillaceous limestone deposited in deeper waters. Such 'normal progradation' reflects that the rate of carbonate production exceeds the rate at which accommodation space is being created. Contrary to this, the abrupt facies change across the Hemse–Eke boundary in the Burgen-1 core reflects a much more rapid seaward shift of reef complexes and shallow water facies and, hence, a more rapid relative regression. The karst dissolution in the Lau outlier (Cherns, 1982) is interpreted as a result of the subaerial exposure following this regression. Similarly, the conspicuous upper boundary of the Eke Formation in the core is therefore likely a consequence of the same period of subaerial exposure.

The Burgsvik Formation in the Burgen-1 core differs in several aspects from its expression on the southern peninsula: it is considerably thinner, it is more calcareous and it overlies a subaerially affected unconformity (top Eke Formation). As shown in Figure 3, the major flooding surface on top of the Burgsvik Sandstone and the top of the Eke Formation on southern Gotland coalescence towards the Burgen outlier and are interpreted as being amalgamated in the Burgen-1 core. The Burgsvik Formation in the Burgen-1 core hence corresponds to the Burgsvik Oolite on southern Gotland and was deposited during a post-lowstand relative transgression.

The Hamra Formation in the Burgen outlier can probably be assigned to a following highstand systems tract. Since reefs preferentially grow on submarine palaeohighs (Tucker & Wright, 1990, p. 204), the numerous reefs in the Burgen outlier may be the result of antecedent topography. Such a Silurian submarine palaeohigh in the present area for the Burgen outlier may be an additional cause for the substantial thinning of the Eke Formation across this area and by the 're-appearance' of about 10 m of the unit north thereof (Fig. 3). The topography may have been inherited from Upper Ordovician carbonate mounds, which in turn can reflect Cambrian–Precambrian palaeohighs (Sivhed *et al*. 2004).

5.a. Implications for the Lau Event

Due to the increased use of stable isotopes, Silurian faunal events have received successively more attention over the last 15 years. The environmental changes during these events, however, have received very little attention. Carbon stable isotopes reported herein and lithological correlation between the core and nearby outcrops zoned by conodonts (Jeppsson, in press) permit identification of the Lau Event in the Burgen-1 drillcore (Fig. 4). It is notable that the homogeneous and widespread pre-extinction strata (upper Hemse Group) shortly after the start of the event are succeeded by shallow-water platform facies and complex stratigraphical relationships. In the core, the strata that formed shortly after the onset of the CIE and the Lau Event include at least two discontinuity surfaces. These are at the top of the Hemse Group and at the top of the Eke Formation, respectively. The latter unconformity is coeval with the top of the Burgsvik Sandstone in a basinward direction (Fig. 3). It formed as a result of subaerial exposure of the platform following a period of siliciclastic influx to the basin. This implies that relative sea-level change was important during the event. By comparison, the Lau Event sedimentary interval has recently been related to a relative sea-level fall in the Prague basin (Lehnert *et al*. 2003) and in the marginal parts of the southeastern Baltic basin (Holy Cross Mountains, Central Poland: Kozłowski, 2003). In the Prague basin, the isotopic shift starts slightly before the last appearance datum (LAD) of *P. siluricus*, and less than 2 m above this LAD is a bed rich in *Dayia minor*, immediately followed by a sequence boundary related to erosion. The isotopic peak values in the Prague basin are some 1.5 m further above the sequence boundary, just below the first appearance datum (FAD) of *Ozarkodina snajdri* (see fig. 2 and references in Lehnert *et al*. 2003). On Gotland, the LAD of *P. siluricus* is just below the Hemse–Eke boundary at Botvide 1 in the Lau outlier (Jeppsson, in press) and the CIE starts just below this boundary in the core (Fig. 4). *Ozarkodina snajdri* has been reported at the Burgen 7 locality just southeast of the drilling site (Jeppsson, in press; B7 in Fig. 1c), a stratigraphical level that corresponds to the Hamra Formation in the core. However, the FAD of *O. snajdri* on Gotland is just above the flooding surface at the top of the Burgsvik Sandstone at Uddvide 2 (Jeppsson, in press), *c*. 21 km southwest of the drilling site. With our correlation, this would correspond to strata just above the unconformable top of the Eke Formation in the Burgen outlier (Fig. 3). Hence, although differences in depositional rates and amount of erosion render slight discrepancies, our data show that similar and inferably contemporaneous sea-level change occurred on Baltica and on peri-Gondwanan cratonic elements during the Lau Event. Further studies are, however, needed to elucidate the magnitude of the late Ludlow sea-level change associated with the Lau Event.

The increased microbial activity on Gotland (e.g. the oncoids and stromatolites of the Eke Formation) and elsewhere in the basin (Wigforss-Lange, 1999) during the Lau Event is in agreement with the microbial resurgence associated with more severe extinction events of the Phanerozoic, such as in the latest Ordovician (Sheehan & Harris, 2004) and in the Frasnian–Famennian (Whalen *et al.* 2002). Based on the co-occurrence of the Lau Event extinctions (Jeppsson & Aldridge, 2000) and the increase of facies previously referred to as 'disaster forms' or anachronistic, it was recently shown by Calner (2005) that minor-scale events may also create taphonomic windows for the preservation of microbialites, and that the Eke and Burgsvik formations reflect a short-lived anachronistic period in the Late Silurian.

6. Conclusions

(1) The Burgen-1 core from the late Ludlow (Late Silurian) of Gotland for the first time enables a detailed study of one of the many outliers of the Hemse Group, and thereby enhances the stratigraphical framework of Gotland and for Silurian extinction events. On a local scale, the most salient stratigraphical feature is the considerable thinning of the Eke and Burgsvik formations across the outlier (0.4 and 3.4 m, respectively).

(2) It can be concluded that profound sedimentary changes took place shortly after the onset of the Lau Event. In the investigated core, the Late Ludlow CIE starts in the uppermost Hemse Group. Correlation between the core and nearby conodont-zoned sections shows that the onset of the CIE is just below the LAD of the conodont *P. siluricus*. The highest measured δ^{13}C values (*c.* 7.5–8.5 ‰) are related to transgression and possibly highstand of relative sea-level in the succeeding Burgsvik and Hamra formations.

(3) Carbon stable isotopes from the Burgen-1 core permit correlation with shelf carbonates of the peri-Gondwanan Prague basin. Although differences in depositional rates and amount of erosion render slight discrepancies, our data show that similar and inferably contemporaneous sea-level change occurred on Baltica and on peri-Gondwanan cratonic elements during the Lau Event.

Acknowledgements. We are grateful for the helpful reviews by Oliver Lehnert and Steve Kershaw. Birger Schmitz kindly arranged for the processing and running of stable isotope samples. The research of MC is financed by the Swedish National Research Council (VR). The fieldwork of MJE was funded by grants from the Johan Christian Mobergs fund (Lunds Geologiska Fältklubb) and by the Jakob A. Letterstedts travel fund.

References

Andrew,A. S., Hamilton,P. J., Mawson,R., Talent,J. A. & Whitford,D. J. 1994. Isotopic correlation tools in the mid-Paleozoic and their relation to extinction events. *APEA Journal* **34**, 268–77.

Baarli,B. G., Johnson,M. E. & Antoshkina,A. I. 2003. Silurian stratigraphy and palaeogeography of Baltica. In *Silurian Lands and Seas: Paleogeography outside of Laurentia* (eds E. Landing and M. E. Johnson), pp. 3–34. New York State Museum Bulletin 493.

Bickert,T., Pätzold,J., Samtleben,C. & Munnecke,A. 1997. Paleoenvironmental changes in the Silurian indicated by stable isotopes in brachiopod shells from Gotland, Sweden. *Geochimica et Cosmochimica Acta* **61**, 2717–30.

Calner,M. 2005. A Late Silurian extinction event and anachronistic period. *Geology* **33**, 305–8.

Calner,M. & Eriksson,M. 2004. Subsurface data on depositional facies and geometries from the Late Silurian of Gotland, Sweden. *GFF* **126**, 109.

Calner,M. & Jeppsson,L. 2003. Carbonate platform evolution and conodont stratigraphy during the middle Silurian Mulde Event, Gotland, Sweden. *Geological Magazine* **140**, 173–203.

Calner,M., Jeppsson,L. & Munnecke,A. 2004*a*. The Silurian of Gotland – Part I: Review of the stratigraphic framework, event stratigraphy, and stable carbon and oxygen isotope development. *Erlanger geologische Abhandlungen, Sonderband* **5**, 113–31.

Calner,M., Jeppsson,L. & Munnecke,A. 2004*b*. The Silurian of Gotland – Part II: Guide to the IGCP 503 field meeting 2004. *Erlanger geologische Abhandlungen, Sonderband* **5**, 133–51.

Cherns,L. 1982. Palaeokarst, tidal erosion surfaces and stromatolites in the Silurian Eke Formation of Gotland, Sweden. *Sedimentology* **29**, 819–33.

Cherns,L. 1983. The Hemse-Eke boundary: facies relationships in the Ludlow series of Gotland, Sweden. *Sveriges Geologiska Undersökning* **C800**, 1–45.

Cramer,B. D. & Saltzman,M. R. 2005. Sequestration of ^{12}C in the deep ocean during the early Wenlock (Silurian) positive carbon isotope excursion. *Palaeogeography, Palaeoclimatology, Palaeoecology* **219**, 333–49.

Gradstein,F. M., Ogg,J. G., Smith,A.G., Bleeker,W. & Lourens,L. J. 2004. A new geologic time scale, with special reference to Precambrian and Neogene. *Episodes* **27**, 82–100.

Hede,J. E. 1919. Djupborrningen vid Burgsvik på Gottland 1915. Paleontologiska-stratigrafiska resultat. *Sveriges Geologiska Undersökning* **C298**, 1–59.

Hede,J. E. 1921. Gottlands Silurstratigrafi. *Sveriges Geologiska Undersökning* **C305**, 1–100.

Hede,J. E. 1925. Berggrunden (Silursystemet). In *Gotlands geologi. En översikt* (eds H. Munthe, J. E. Hede and L. von Post), pp. 13–30. *Sveriges Geologiska Undersökning* **C331**.

Hede,J. E. 1927. Berggrunden (Silursystemet). In *Beskrivning till kartbladet Hemse* (eds H. Munthe, J. E. Hede and G. Lundqvist), pp. 15–56. *Sveriges Geologiska Undersökning* **Aa164**.

HEDE, J. E. 1942. On the correlation of the Silurian of Gotland. *Meddelanden från Lunds Geologisk-Mineralogiska institution* **101**, 1–25.

JEPPSSON, L. 1987. Lithological and conodont distributional evidence for episodes of anomalous oceanic conditions during the Silurian. In *Palaeobiology of conodonts* (ed. R. J. Aldridge), pp. 129–45. British Micropaleontological Society Series.

JEPPSSON, L. 1990. An oceanic model for lithological and faunal changes tested on the Silurian record. *Journal of the Geological Society, London* **147**, 663–74.

JEPPSSON, L. In press. Conodont-based revisions of the Late Ludfordian on Gotland. *GFF* **128**.

JEPPSSON, L. & ALDRIDGE, R. J. 2000. Ludlow (late Silurian) oceanic episodes and events. *Journal of the Geological Society, London* **157**, 1137–48.

KALJO, D., BRAZAUSKAS, A., KAMINSKAS, D., MARTMA, T. & MUSTEIKIS, P. 2004. The Ludfordian carbon isotope excursion in the Vidukle core, Lithuania, its relations with the Lau Oceanic Event and environmental background in NW Baltica. *Berichte Institut für Erdwissenschaften Karl-Franzens-Universität Graz* **8**, 60–2. European Society for Isotope Research, Isotope Workshop Volume, 7th workshop, Karl-Franzens University & Landesmuseum Joanneum.

KALJO, D., KIIPLI, T. & MARTMA, T. 1997. Correlation of carbon isotope event markers through the Wenlock–Pridoli sequence at Ohesaare (Estonia) and Priekule (Latvia). *Palaeogeography, Palaeoclimatology, Palaeoecology* **132**, 211–23.

KALJO, D., MARTMA, T., MÄNNIK, P. & VIIRA, V. 2003. Implications of Gondwana glaciations in the Baltic late Ordovician and Silurian and a carbon isotopic test of environmental cyclicity. *Bulletin de la Société géologique de France* **174**, 59–66.

KOZŁOWSKI, W. 2003. Age, sedimentary environment and palaeogeographical position of the Late Silurian oolitic beds in the Holy Cross Mountains (Central Poland). *Acta Geologica Polonica* **53**, 341–57.

LAUFELD, S. 1974*a*. Silurian Chitinozoa from Gotland. *Fossils and Strata* **5**, 1–130.

LAUFELD, S. 1974*b*. Reference localities for palaeontology and geology in the Silurian of Gotland. *Sveriges Geologiska Undersökning* **C705**, 1–172.

LEHNERT, O., FRÝDA, J., BUGGISCH, W. & MANDA, S. 2003. A first report of the Ludlow Lau Event from the Prague Basin (Barrandian, Czech Republic). In *INSUGEO serie Correlación Geológica* **18** (eds G. Ortega and G. F. Aceñolaza), pp. 139–44.

LONG, D. G. F. 1993. The Burgsvik Beds, an Upper Silurian storm generated sand ridge complex in southern Gotland, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* **115**, 299–309.

MANTEN, A. A. 1971. Silurian reefs of Gotland. *Developments in Sedimentology* **13**. Amsterdam: Elsevier, 539 pp.

MUNTHE, H. 1902. Stratigrafiska studier öfver Gotlands silurlager. *Sveriges Geologiska Undersökning* **C192**, 1–55.

MUNTHE, H. 1910. On the sequence of strata within the southern Gotland. *Geologiska Föreningens i Stockholm Förhandlingar* **32**, 1397–1453.

MYROW, P. M., TICE, L., ARCHULETA, B., CLARK, B., TAYLOR, J. F. & RIPPERDAN, R. L. 2004. Flat-pebble conglomerate: its multiple origins and relationships to metre-scale depositional cycles. *Sedimentology* **51**, 973–96.

RIDING, R. & FAN, J. 2001. Ordovician calcified algae and cyanobacteria, northern Tarim basin subsurface, China. *Palaeontology* **44**, 783–810.

SALTZMAN, M. R. 2001. Silurian δ^{13}C stratigraphy; a view from North America. *Geology* **29**, 671–4.

SAMTLEBEN, C., MUNNECKE, A. & BICKERT, T. 2000. Development of facies and C/O-isotopes in transects through the Ludlow of Gotland: Evidence for global and local influences on a shallow-marine environment. *Facies* **43**, 1–38.

SHEEHAN, P. M. & HARRIS, M. T. 2004. Microbialite resurgence after the Late Ordovician extinction. *Nature* **430**, 75–7.

SIVHED, U., ERLSTRÖM, M., BOJESEN-KOEFOD, J. A. & LÖFGREN, A. 2004. Upper Ordovician carbonate mounds on Gotland, central Baltic Sea: Distribution, composition and reservoir characteristics. *Journal of Petroleum Geology* **27**, 115–40.

STEL, J. H. & DE COO, J. C. M. 1977. The Silurian Upper Burgsvik and Lower Hamra-Sundre Beds, Gotland. *Scripta Geologica* **44**, 1–43.

SVENSSON, N. O. 1989. Late Weichselian and early Holocene shore displacement in the central Baltic, based on stratigraphical and morphological records from eastern Småland and Gotland, Sweden. *Lundqua Thesis* **25**, Lund University, Department of Quaternary Geology, pp. 195.

TALENT, J. A., MAWSON, R., ANDREW, A. S., HAMILTON, P. J. & WHITFORD, D. J. 1993. Middle Palaeozoic extinction events: Faunal and isotopic data. *Palaeogeography, Palaeoclimatology, Palaeoecology* **104**, 139–52.

TUCKER, M. E. & WRIGHT, V. P. 1990. *Carbonate sedimentology*. Blackwell Science, 482 pp.

WENZEL, B. 1997. Isotopenstratigraphische Untersuchungen an silurischen Abfolgen und deren paläozeanographische Interpretation. *Erlanger geologische Abhandlungen* **129**, 1–117.

WHALEN, M. T., DAY, J., EBERLI, G. P. & HOMEWOOD, P. W. 2002. Microbial carbonates as indicators of environmental change and biotic crises in carbonate systems: examples from the Late Devonian, Alberta basin, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* **181**, 127–51.

WIGFORSS-LANGE, J. 1999. Carbon isotope δ^{13}C enrichment in Upper Silurian (Withcliffian) marine calcareous rocks in Scania, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* **121**, 273–9.