Palaeogeography, Palaeoclimatology, Palaeoecology 457 (2016) 304–322

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

# End-Wenlock terminal Mulde carbon isotope excursion in Gotland, Sweden: Integration of stratigraphy and taphonomy for correlations across restricted facies and specialized faunas

Emilia Jarochowska [a,*], Oskar Bremer [b], Daniel Heidlas [a], Stephanie Pröpster [a], Thijs R.A. Vandenbroucke [c,d], Axel Munnecke [a]

[a] GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, University of Erlangen-Nuremberg, Loewenichstr. 28, 91054 Erlangen, Germany
[b] Subdepartment of Evolution and Development, Department of Organismal Biology, Uppsala University, Norbyvägen 18A, SE-752 36 Uppsala, Sweden
[c] Department of Geology, Ghent University, Krijgslaan 281-S8, B-9000 Ghent, Belgium
[d] Evo-Eco-Paléo UMR 8198, Université de Lille, Avenue Paul Langevin, Bâtiment SN5, 59655 Villeneuve d'Ascq Cedex, France

ARTICLE INFO

*Article history:*
Received 24 April 2016
Received in revised form 12 June 2016
Accepted 19 June 2016
Available online 22 June 2016

*Keywords:*
Vertebrate
Fish
Conodont
Palynomorph
Taphonomy
Deformation

ABSTRACT

The decline of the upper peak of the Homerian Mulde carbon isotope excursion (CIE) is used in low- to mid-paleolatitudes as a marker for the Wenlock/Ludlow boundary, which is otherwise difficult to constrain in carbonate successions. In the Midland Platform (England) the CIE ends just below the boundary or ranges through it, whereas in Baltic sections it has been placed substantially below the inferred base of the Ludlow Stage. Difficulties in correlating the Baltic sections are caused by widespread development of lagoons and sabkhas with specialized conodont and vertebrate faunas. We describe here a lagoonal section from Gothemshammar, eastern Gotland (Sweden), spanning the entire upper peak of the Mulde CIE. Based on integrated conodont, $\delta^{13}C_{carb}$ and sequence stratigraphy, a hardground present at the lowering limb of the CIE is correlated with a sequence boundary present across the Baltic Basin, in the Midland Platform, and the southern shelf of Laurentia. This sequence boundary corresponds to a global eustatic regression and can serve as a correlative horizon in restricted facies with depauperate or specialized fauna. The Wenlock-Ludlow boundary is placed in the transgressive strata overlying this boundary. Species richness and abundance of thelodonts, anaspids, and osteostracans at Gothemshammar represent one of the first diversity peaks of vertebrates in the Silurian. Associated conodonts are characteristic for late Wenlock marginal-marine environments and distinguished by large, robust elements. We quantitatively assess the conodont assemblages to evaluate to which degree the overrepresentation of large elements in these facies is produced by taphonomic processes. The taphonomic alteration differs between species and facies, but is lowest for the shallow-water specialist *Ctenognathodus murchisoni*. Regardless, the use of this species as an index taxon is discouraged based on its strong facies affinity. Instead, the integrated approach proposed here indicates that the Wenlock/Ludlow boundary is situated lower in the Baltic sections than previously identified.


## 1. Introduction

Upper Wenlock stratigraphy and the position of the Wenlock/Ludlow boundary in carbonate successions remain elusive for paleoecological reasons: during the late Homerian the tropical epicontinental carbonate platforms of Baltica and Laurentia developed vast expanses of shallow restricted flats, populated by specialized faunas disparate from their open-marine counterparts. These epeiric basins saw an unprecedented diversity of early vertebrates (Märss, 1989; Turner, 1999; Sansom, 2008) and specialized conodont assemblages (Viira, 1982a; Barrick, 1997; Viira and Einasto, 2003; von Bitter et al., 2007; Jarochowska et al., 2016). Late Ordovician and early Silurian vertebrate faunas from the Baltic Basin and other areas generally show low diversities and are mainly represented by thelodonts (e.g. Märss, 1989; Turner, 1999). However, towards the Wenlock/Ludlow boundary diverse faunas containing many thelodont, osteostracan, and anaspid taxa have been found in several areas of the Baltic Basin (Fredholm, 1990; Blom et al., 2002; Märss et al., 2007, 2014). This diversity peak is more or less contemporaneous in both the Eastern Baltic region and Gotland (Sweden), but equally diverse faunas have been reported from younger sediments of the East Baltic (Blom et al., 2002; Märss et al., 2007, 2014). Thelodonts seem to have spread across a wide range of environments (Märss et al., 2007), but facies associations of

* Corresponding author.
*E-mail address:* Emilia.Jarochowska@fau.de (E. Jarochowska).

http://dx.doi.org/10.1016/j.palaeo.2016.06.031
0031-0182/

anaspids and osteostracans indicate that these groups preferred lagoon and shoal areas (Märss and Einasto, 1978; Sansom, 2008; Märss et al., 2014). Sansom (2008) suggested that our understanding of early osteostracan evolution is largely obscured by the taphonomic bias resulting from their seemingly specific environmental preferences during the Silurian. Deposits of Llandovery and early Wenlock age in Gotland have only produced a handful of thelodont scales, and only a few fragments of anaspids and osteostracans have been reported from the upper Slite Group (Fredholm, 1990), slightly before the diversity peak mentioned before. Limited understanding of the stratigraphic distribution, dispersal patterns and ecology of these groups is partly due to their occurrence in restricted facies which yield little faunal indicators of age and environmental conditions.

The replacement of open-marine, high-diversity early Homerian conodont faunas with rare, specialized forms has been attributed to an 'extinction event' (e.g. Jeppsson and Calner, 2003; Cramer et al., 2012) and linked to perturbations in the carbon cycle, responsible for the Homerian 'Mulde' double-peaked carbon isotope excursion (e.g. Samtleben et al., 2000; Calner et al., 2004; Munnecke et al., 2010; Cramer et al., 2012). However, the conodont turnover of the time closely follows the transition from fully marine, platform-margin and slope facies to restricted, microbially-dominated, low-diversity intraplatform flats, to the point that individual highest occurrences fall at lithological and parasequence boundaries (Calner and Jeppsson, 2003; Viira and Einasto, 2003; Calner, 2005; Jarochowska et al., 2016). Such shallow facies dominated by the microbial carbonate factory are rich in hiatuses, often cryptic, and the paucity of fauna renders correlations almost impossible. These difficulties are reflected in the diversity of conodont zonations proposed for the middle Silurian (summarized in Corradini et al., 2015). What is more, specialist shallow-water conodonts are also poorly characterized morphologically and new taxa are commonly described based on small collections from isolated localities (e.g. Viira, 1983, 1994; Viira and Einasto, 2003; Jeppsson et al., 2006), or left in open nomenclature (e.g. Strömberg, 1997; Jarochowska et al., 2016). Peculiar morphologies of these specialist forms may result from sampling bias favoring normal-marine, easy to process lithologies (Lehnert et al., 2005), from adaptations to particular diet, or from taphonomic factors. In Devonian conodont biofacies, which have long been recognized and used for facies-specific zonations, shallow-water conodonts are typically the largest and most 'robust' (e.g. Sandberg and Dreesen, 1984; McGoff, 1991). Robustness is also invoked with respect to Wenlock lagoonal conodont faunas (Strömberg, 1997; Calner and Jeppsson, 2003). It has, however, not been investigated, to what extent is this the result of taphonomic factors, such as entrainment of small, gracile elements by waves (Broadhead et al., 1990; McGoff, 1991) or their fracturing during diagenesis (von Bitter and Purnell, 2005). This study has three aims: (1) integrate all environmental and paleontological information to identify clues which may be used in correlating upper Wenlock lagoonal, intra-platform successions with each other and with their open-marine counterparts, (2) characterize the early vertebrate communities thriving in such environments, and (3) to evaluate whether the high proportion of 'robust' conodonts results from taphonomic bias. To achieve this, an upper Wenlock lagoonal section is examined in the Swedish island of Gotland, the Silurian succession by far best documented in terms of carbonate platform development and stratigraphy (Samtleben et al., 2000; Calner and Jeppsson, 2003; Calner et al., 2004; Jeppsson et al., 2006; Cramer et al., 2012).

## 2. Geological setting

The investigated section (φ N 57°36′33.46″; λ E 18°47′46.32″) is located on the NE coast of the island of Gotland, E Sweden (Figs. 1–2). This area is part of a low-latitude carbonate platform, which stretched across the southern margin of the paleocontinent of Baltica during the early Paleozoic. The Silurian succession in Gotland spans the uppermost Llandovery through Ludlow (Calner et al., 2004). The strata dip towards the southeast and range from off-platform, deeper-water facies across the western coast to restricted, intra-platform facies in the east. In this eastern facies belt the middle Silurian deposits are poorly exposed, and, consequently, poorly studied. The section is located ca. 0.5 km WNW of the first of a series of coastal outcrops characterized as Gothemshammar 1–8 (Hede, 1928; Laufeld, 1974a) and corresponds (with an overlap) to strata immediately below those exposed at Gothemshammar 1. The interval has been made available for investigation by recent coastal erosion (Fig. 2). The new exposure is designated Gothemshammar 9, in order to distinguish it from previously described sections and preserve the stratigraphic order of numbering. The exposed interval is situated slightly below the boundary between the Halla and Klinteberg formations, placed by Hede (1928) at a hardground surface at Gothemshammar 1. The position of this boundary is revised further in the present study.

The Halla Fm. in eastern Gotland consists, from bottom to top, of the Bara Oolite Mb. and the informally defined 'Hörsne' and 'Gothemshammar' members (Calner and Jeppsson, 2003). The 'Gothemshammar mb' is formed by oncoidal packstones interpreted as back-reef, lagoonal deposits Across the paleo-basinward transect,

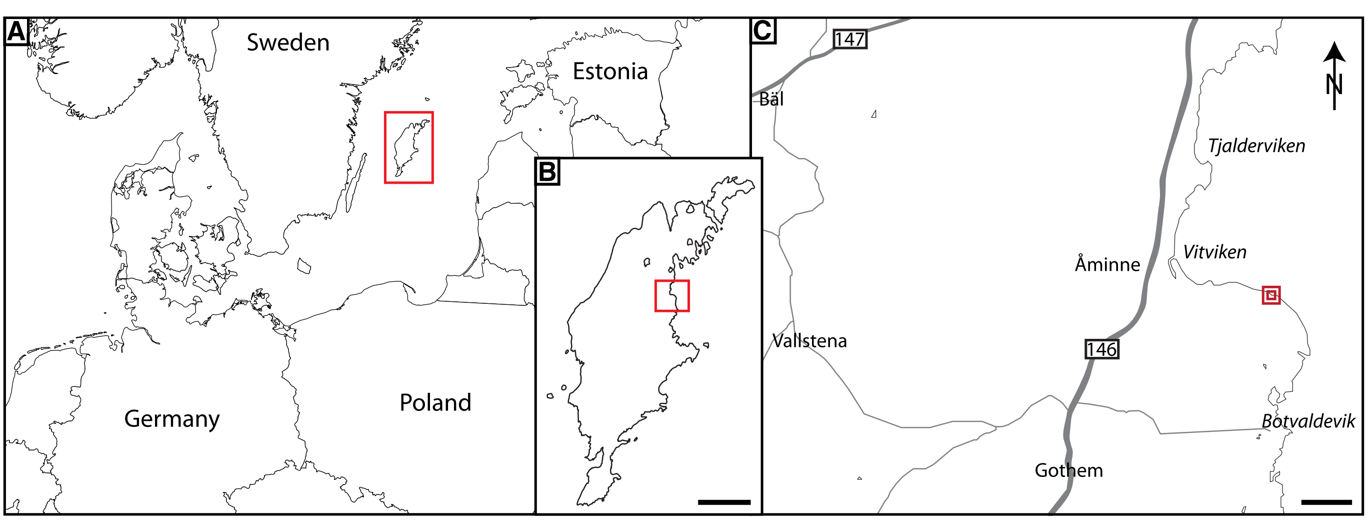


**Fig. 1.** Map of the Gothemshammar 9 locality in Gotland, Sweden. A) Political map with Gotland marked in red. B) Position of the section in NE Gotland. Scale bar equals 20 km. C) Red square marks the position of the studied section at the coast. Scale bar equals 1 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)