

Upper Ordovician stratigraphy of the Stora Sutarve core (Gotland, Sweden) and a high-resolution assessment of the Hirnantian Isotope Carbon Excursion (HICE)

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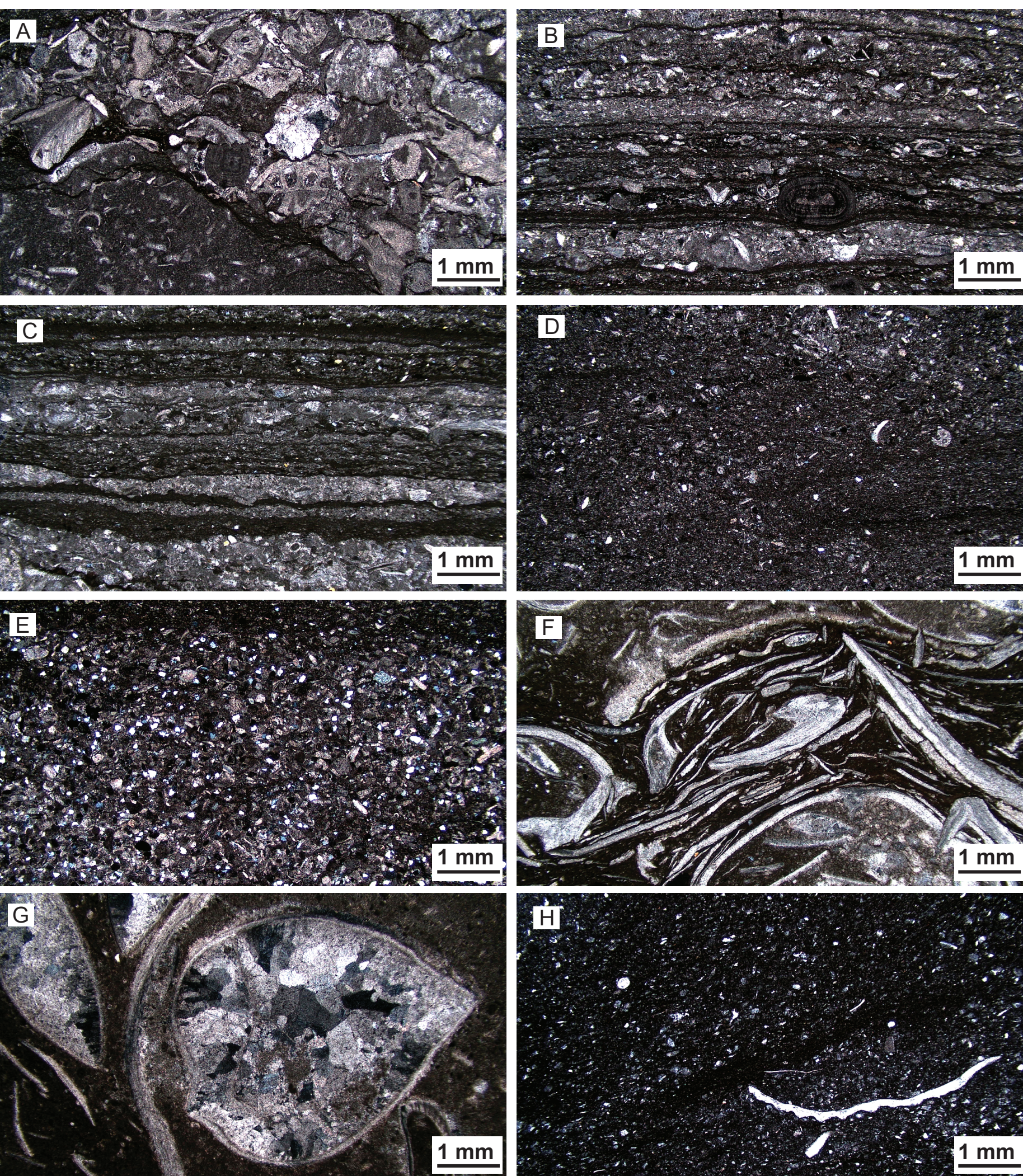
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The Hirnantian and the HICE

The Hirnantian Isotope Carbon Excursion (HICE) is a major anomaly in Earth's global carbon cycle at the end of the Ordovician time period, at ca 445 Ma. The anomaly is intimately associated with substantial cooling of the global climate and expansion of continental ice-sheets on the supercontinent Gondwana, paradoxically in higher $p\text{CO}_2$ levels than present day. The expanding ice-sheets caused major sea-level falls and the extinction of many marine species. During the deglaciation, widespread anoxia was induced by the glacio-eustasy, causing a second pulse of extinction. The two pulses together constitute the second largest extinction event in Earth history – the Late Ordovician Mass Extinction (LOME). Among the changing fauna are the characteristic *Hirnantia* brachiopod fauna who thrived in the cool climate. This fauna went extinct in the second pulse and was subsequently replaced by the post-glacial Edgewood-Cathay fauna. Much uncertainty remains about cause and effect and timing of as the as the geological record is particularly fragmented.

This study

The aim with the present study is to make a stratigraphic assessment of the Upper Ordovician succession of the recently recovered Stora Sutarve drillcore from southernmost Gotland. The Hirnantian of the nearby Grötlingbo drillcore has been studied with respect to biostratigraphy (Männik et al., 2015), but until now, no chemostratigraphic study of the Hirnantian has been undertaken from the Gotland area. This study presents the first integrated Upper Ordovician stratigraphy and chemostratigraphy, with an especially detailed account of the microfacies and carbon isotope chemostratigraphy of the Hirnantian Stage. Comparison is made to the Borensult and the Viki cores.



The Loka Formation

The figure above shows thin sections of the Loka Formation (the log in the figure to the top right). A) Reworked lithology with lithoclasts from the underlying formation (ranges from -0.19 to 0 m in the Loka Formation). B-C) Set of grainstone-packstone conspicuously laminated with organic-rich mud (ranges 0 to 0.33 m). D) Wackestone-packstone with streak of clay. E) Well-sorted quartz-rich packstone with streaks of organic-rich clay, almost approaching a calcareous siltstone (0.505 to 0.60 m). F) Brachiopod coquina of whole, articulated brachiopods and brachiopod skeletal fragments in an organic-rich matrix, G) is a whole *Brevilamnulella* in the coquina (ranges 0.60 to 0.68 m). H) Wackestone with mud-rich matrix (photo from ca 1.0 m). The muddier facies ranged from 0.68 m to ca 1.52 m, the carbonate content increase upwards. The most condensed dark mudrock is around 0.85 m.

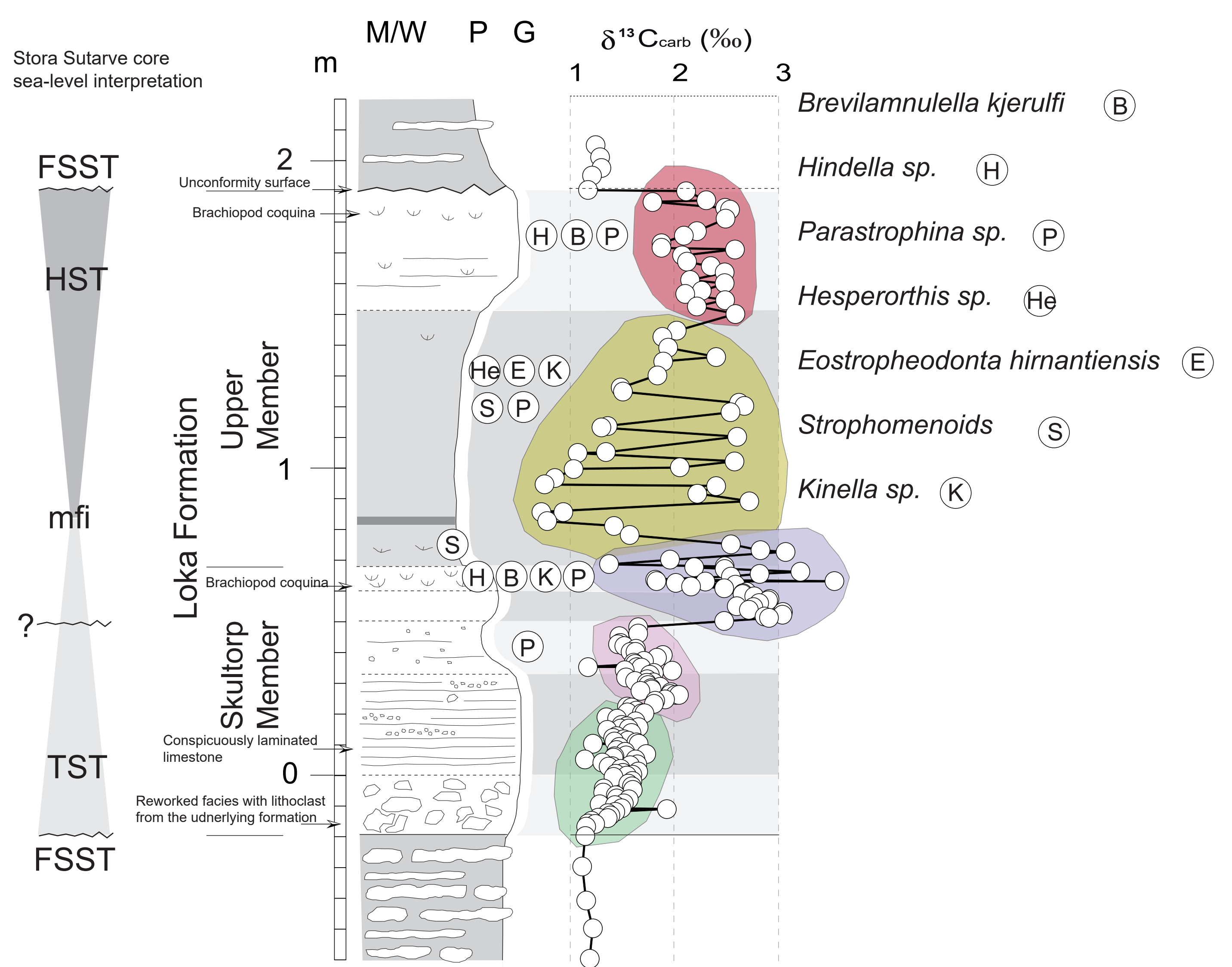
From 1.52 m to the top of the Loka Formation is a packstone-grainstone with a second coquina. The upper boundary of the formation is set at an unconformity.

Materials and methods

The Stora Sutarve drillcore was drilled near Hamra on southernmost Gotland (coordinates Sweref 99 N 6320673 E 699981; Fig. 2) by the Geological Survey of Sweden in 2018. Coring was stopped at -564.95 m in the Cambrian Faludden Sandstone and the core thus includes the entire Ordovician and most of the Silurian succession of the Baltoscandian Basin.

For the present study 34.5 m of the core from core boxes 81-86 were studied. This interval of the core was documented in terms of general lithology and stratigraphic changes. More than 30 pieces of the core were subsequently split and polished for overall analysis of microfacies textures. From these slabs, a total of 22 thin sections were produced at the Flügel Lab in Erlangen and provided by Oliver Lehnert.

A total of 391 whole-rock carbon isotope samples were collected from the core using a handheld micro-drill. Of the 391 samples, 189 samples were collected from the Loka Formation with the aim to sample as many carbonate microfacies as possible and make a high-resolution assessment of the HICE. A few samples were deliberately collected from the cement of spar-filled bioclasts and lithoclasts to evaluate the offset in $\delta^{13}\text{C}$. All the isotope analyses were carried out in the Stable Isotope Lab in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, China.



The HICE curve

Five broader trends are observed in the HICE. A steady increase (marked in green) associated with the reworked facies and the conspicuously laminated limestone. A slightly decreasing trend (marked in pink) continues. A substantial offset to peak values (marked in blue) continues, associated with an increased quartz content, although the strata do not seem unconformable as observed in the core. A peak plateau (marked in yellow) continues throughout the muddier facies, with substantial fluctuation which is interpreted as diagenetic effects. A stable plateau (marked in red) associated with a more carbonate-rich facies continues. The HICE is truncated at the upper unconformity and thus the falling limb is not preserved.

The Hirnantian brachiopod fauna

Several brachiopods of both the *Hirnantia* and the Edgewood-Cathay faunas have been identified in the Loka Formation. *Hindella* of the *Hirnantia* fauna and *Brevilamnulella kjerulfi* of the succeeding Edgewood-Cathay fauna do not, as would be supposed, occur consecutively. Instead they co-occur, in the coquina and throughout the uppermost limestone including the second coquina. Notably the lowermost identified brachiopod in the Stora Sutarve core is *Parastrophina* of the post-glacial Edgewood-Cathay fauna.

The Hirnantian sea-level

The sea-level of the Stora Sutarve core has been interpreted as one transgression-regression cycle bounded by two glacially induced hiatuses at the base and top. The condensed mudrock represented the maximum flooding interval. The offset between subunit C-D potentially represent a transgressive ravinement surface.

Summary

Several $\delta^{13}\text{C}$ excursions have been identified in the core; LSNICE, GICE, Moe excursion, HICE and possibly Late Aeronian ICE. The Hirnantian Loka Formation constitutes the Skultorp Member and the Upper Member in the core. Brachiopods of the *Hirnantia* and the Edgewood-Cathay faunas have been identified within the Loka Formation. The specific genera of the two faunas co-occur, and do not appear consecutively as would be supposed. The HICE of the Loka Formation includes a slowly increasing rising limb, a peak and plateau, which is truncated at an unconformity at the formation's upper boundary. A conspicuous offset in the HICE occurs during the transition from rising limb to peak $\delta^{13}\text{C}$ values, however no hiatus is obvious in the core. The Hirnantian Loka Formation in the core is interpreted as one cycle of transgression-regression bounded by hiatuses in the lower and upper boundary of the formation, inferably glacially induced.

