Earth-Science Reviews 151 (2015) 288–350

Contents lists available at ScienceDirect

Earth-Science Reviews

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

Invited review

# The regressive Early-Mid Cambrian 'Hawke Bay Event' in Baltoscandia: Epeirogenic uplift in concert with eustasy

Arne Thorshøj Nielsen [a,*], Niels Hemmingsen Schovsbo [b]

[a] Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, DK-1350 Kbh K, Denmark
[b] Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Kbh K, Denmark

ARTICLE INFO

*Article history:*
Received 15 May 2015
Received in revised form 29 September 2015
Accepted 30 September 2015
Available online 22 October 2015

*Keywords:*
Middle Cambrian
Sea-level
Biostratigraphy
Chronostratigraphy
Sequence stratigraphy
Palaeogeography
Isostasy
Baltica

ABSTRACT

The lower Middle Cambrian of Scandinavia is reviewed and subjected to sequence stratigraphical analysis. Sequences are defined as transgressive–regressive depositional units bounded by maximum regressive surfaces and their correlative conformities. The lower Middle Cambrian forms part of a 2nd order sequence, labelled Cambrian Supersequence 3 (CS-3). It is bounded at the base by a regional unconformity ascribed to the so-called Hawke Bay Event, the focus of this paper. CS-3 comprises at least four 3rd order sequences, but the upper part above the *Triplagnostus gibbus* Zone has not been analysed as yet and the upper supersequence boundary remains undefined for the time being. The oldest sequence of CS-3 is seemingly of Early Cambrian age. There are numerous T/R cycles in the *Acadoparadoxides oelandicus* Superzone, here ranked as subsequences (4th order sequences), but a classification as 3rd order cycles of some of these is possible, thereby increasing the number of prospective sequences in CS-3. The high frequency sea-level fluctuations are reminiscent of glacioeustasy and the early Mid Cambrian possibly represents a c. 5 Ma long glacial interval with overall low global sea-level and frequent sea-level changes.

The Hawke Bay Event, as identified in Scandinavia, primarily reflects an extensive and long-lasting epeirogenic uplift of western Baltica, and using the term *event* is a misnomer. The uplift is informally referred to as the Hawke Bay uplift. However, the initial rapid uplift in the latest Early Cambrian coincided with ≥100 m eustatic lowering of the sea-level, leading to simultaneous regression in the East Baltic area and elsewhere. This forced regression is assumed representing the Hawke Bay Event s.str. In Estonia–Latvia–Lithuania, the unconformity separating the Kibartian and Deimenian regional stages signals the Hawke Bay regression. The Hawke Bay uplift gradually and differentially subsided during the early Mid Cambrian, starting in the Öland–Gotland area, and the collapse then slowly progressed westwards and southwestwards. Subsidence also advanced from western Norway and eastwards whereas the western margin of Baltica apparently remained uplifted throughout the late Mid Cambrian to earliest Ordovician. In central Scandinavia, the last traces of the Hawke Bay uplift eventually disappeared during the *Acidusus atavus* Chron. As a result the Hawke Bay unconformity represents a greater hiatus in central and southernmost Scandinavia where the uplift persisted for a longer time (locally up to c. 6 Ma), causing long-lasting non-deposition associated with minor erosion. The epeirogenic uplift is inferred to have been triggered by stress-induced isostasy linked to major plate-tectonic adjustments, possibly the onset of subduction in the adjacent Iapetus Ocean or cessation of the Timanide collision, or both.

A series of palaeogeographical maps is constructed for the Middle Cambrian of Scandinavia and adjacent countries. Subcrop and onlap maps of the Hawke Bay unconformity, as well as isopach maps for Middle Cambrian formations are also shown. The elongate land area that straddled the axis of the Scandinavian Peninsula during the Early Cambrian disappeared after subsidence of the Hawke Bay uplift and a new basin configuration was established. This had an overall gentle westwardly sloping sea floor delimited by a broad uplift along the western Baltica margin that formed a submarine sill from the medial Mid Cambrian and onwards. The sill, which eventually disappeared in the later part of the Tremadocian, restricted exchange of water masses and the deeper parts of the epicontinental sea became characterized by dysoxic and anoxic conditions. The resulting organic-rich deposit is referred to as Alum Shale.

The sea-level rose eustatically after the terminal Early Cambrian Hawke Bay lowstand (in a strict sense) to reach a temporary highstand during the later part of the *A. oelandicus* Superchron. It then fell abruptly again at the end of the *A. oelandicus* Superchron and remained low in the earliest part of the *Paradoxides paradoxissimus* Superchron. Overall, on a 2nd order scale, the sea-level remained low during the early Mid Cambrian and as a result, the clastic supply was relatively high. The principal sediment supply was from the east; initially minor amounts of clastics

* Corresponding author.
*E-mail addresses:* arnet@snm.ku.dk (A.T. Nielsen), nsc@geus.dk (N.H. Schovsbo).

http://dx.doi.org/10.1016/j.earscirev.2015.09.012
0012-8252/

were also supplied from the uplifted parts of Scandinavia but overall erosion of the uplifted area was limited, probably due to the extremely flat topography. The high clastic influx from the east resulted in progradation, progressively shifting the coastline westwards. Eventually it reached a position roughly corresponding to the present-day east coast of mainland Sweden.

In addition to the initial Hawke Bay regression (s.str,) in the latest Early Cambrian significant forced regressions occurred at the end of the *Acadoparadoxides pinus–Pentagnostus praecurrens* Chron (here named the Faludden Lowstand) and in the *T. gibbus* Chron (the Mid-gibbus Lowstand). Several unnamed sea-level lowerings also occurred in the *A. pinus–P. praecurrens* Chron. A rapid, major sea-level rise at the beginning of the *A. pinus–P. praecurrens* Chron, estimated at c. 60–70 m, is named the Oelandicus Drowning. Fast sea-level rises at the start and in the middle of the *T. gibbus* Chron are referred to as the Forsemölla and Exsulans drownings, respectively. From the middle of the *T. gibbus* Chron onwards into the *A. atavus* Chron there was a major sea-level rise (Atavus Highstand). This latter rise is estimated at c. 100 m and for the first time the sea-level became as high or higher than it was just prior to the Hawke Bay regression. The associated transgression shifted the coastline some 500–700 km eastwards and from then onwards, extreme clastic starvation prevailed in the epicontinental sea covering Scandinavia. Simultaneously, the mid-shelf became a net sedimentary bypass zone, either due to regular outboard transport of sediment during storms or due to recurrent erosive events associated with sea-level lowstands.

Two Mid Cambrian depositional phases are recognized, termed Depositional Phases 3 and 4. Depositional Phase 3 encompasses the transient increase in sedimentary supply during the early Mid Cambrian sea-level lowstand, whereas DP4 covers the strongly starved conditions and widespread dysoxia from the *A. atavus* Chron onwards associated with high sea-level. A gradual expansion of the oxygen minimum zone during the Mid Cambrian developed independently of the rising sea-level and is suggestive of a stratified water column, presumably created by silled basin conditions. It is likely, however, that the general 'background' oxygen level in the oceans also was low, perhaps due to sluggish global circulation in a greenhouse world.

Two new regional stages, the Bödan and Almbackenian, are introduced for the Middle Cambrian *A. oelandicus* and *P. paradoxissimus* superzones of Scandinavia, respectively. The base of the Middle Cambrian *Timofeevia lancare* acritarch assemblage zone is located within the upper part of the *A. pinus–P. praecurrens* trilobite Zone. The *T. gibbus* trilobite Zone is informally subdivided into a lower *Paradoxides jemtlandicus* subzone and an upper *Bailiaspis dalmani* subzone.



**Contents**

1. Introduction . . . 290
2. Geological and depositional setting . . . 290
   2.1. Depositional Phase 3 (DP3; early Mid Cambrian): transient increase in clastic supply and onset of oxygen shortage . . . 295
   2.2. Depositional Phase 4 (DP4; medial-late Mid Cambrian): sedimentary starvation and widespread dysoxia . . . 299
3. Stratigraphic framework . . . 301
   3.1. Lithostratigraphy . . . 301
   3.2. Biostratigraphy . . . 301
      3.2.1. Trilobite zonation . . . 301
      3.2.2. Acritarch zonation . . . 302
   3.3. Chronostratigraphy . . . 303
      3.3.1. The Bödan Stage (new) . . . 306
      3.3.2. The Almbackenian Stage (new) . . . 306
4. Sequence stratigraphy . . . 308
   4.1. Approach and terminology . . . 308
   4.2. Central Baltic area . . . 309
      4.2.1. Grötlingbo (southern Gotland) . . . 309
      4.2.2. När (eastern Gotland) . . . 309
      4.2.3. File Haidar (northern Gotland) . . . 309
      4.2.4. Hamnudden (Gotska Sandön) . . . 310
      4.2.5. Finngrundet and Västra Banken (Bothnian Sea) . . . 310
      4.2.6. Öland . . . 311
   4.3. Scania with remarks on Bornholm . . . 311
   4.4. Östergötland . . . 312
   4.5. Närke . . . 313
   4.6. Västergötland . . . 313
   4.7. Mjøsa district . . . 313
5. Comparison with other areas . . . 315
   5.1. Digermul, Finnmark . . . 315
   5.2. Northernmost Scandinavia . . . 316
   5.3. Jämtland and southernmost Västerbotten . . . 317
      5.3.1. Lower Allochthon, Tåsjön-Ormsjön area . . . 317
      5.3.2. Parautochthon, Storsjön area . . . 317
      5.3.3. Autochthon . . . 318
   5.4. Vassbo-Guttusjö, Dalarna . . . 319
   5.5. Southern Norway . . . 319
      5.5.1. Autochthon . . . 319