# ERLANGER GEOLOGISCHE ABHANDLUNGEN

**Gegründet von Prof. Bruno von Freyberg**

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**International Symposium on**

# Early Palaeozoic Palaeogeography and Palaeoclimate

September 1-3, 2004
Erlangen, Germany

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# Contents


Welcome ........................................................................ 5

Map of Erlangen ................................................................ 7

General Programme ............................................................ 8

Scientific Programme .......................................................... 9

Poster Presentations .......................................................... 14

Abstracts ........................................................................ 17

Field Guides .................................................................... 81

Participants ..................................................................... 153

Authors Index .................................................................. 156


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STAEDTLER STIFTUNG

IUGS UNESCO IGCP Project 503 ORDOVICIAN PALAEOGEOGRAPHY AND PALAEOCLIMATE

GEOLOGISCHE VEREINIGUNG e.V.

Friedrich-Alexander-Universität Erlangen-Nürnberg

Kitzmann Unser Erlanger Bier seit 1712

# Preface for the International Symposium "Early Palaeozoic Palaeogeography and Palaeoclimate"

During the past few years, knowledge about the Early Palaeozoic has increased markedly, and it is now known that the conditions during this time were much more variable than previously assumed. Progress has resulted from the integration of tectonical, stratigraphical, palaeoclimatological, palaeomagnetic, palaeontological, and geochemical evidence. Pronounced changes in environmental conditions are recorded, for example, in several distinct short-lived C- and O-isotope excursions that are globally recognised (including the isotope excursion of the Late Ordovician glaciation), with amplitudes of $\delta^{13}C$ values of up to 10‰. The causes and the steering mechanisms of these excursions are recently a matter of intense debate. It is also known that during the Ordovician radiation with the establishment of the Palaeozoic Evolutionary Fauna, the marine diversity has increased dramatically, including vastly increased morphological diversity. Knowledge of development of biodiversity is very precise for several groups of organisms, especially the graptolites, trilobites, and brachiopods, which have been studied in great detail for two centuries. However, for other groups, including chitinozoans, acritarchs, radiolarians, vertebrates, and land plants the data sets are still underrepresented, and their complete diversity spectrum is far from understood. The radiation subsequent to the end-Ordovician mass extinction characteristically is represented by development from surviving members of this Palaeozoic Evolutionary Fauna and did not result in the appearance of a plethora of new forms. This style of recovery in the Silurian, with the same levels of familial and generic diversity and ecologic complexity as in the Ordovician, demonstrates the robustness and stability of the Palaeozoic Evolutionary Fauna.

Currently, the possible causes of the Ordovician biodiversification, the end-Ordovician extinction, and the subsequent Silurian radiation are investigated especially with respect to palaeogeographic and climatic changes. Our symposium aims at discussing those and related topics, but will also serve as the Opening Meeting for the new IGCP project n° 503 "Ordovician Palaeogeography and Palaeoclimate", the successor project of the successful IGCP project n 410 "The Great Ordovician Biodiversification Event" (1997– 2002). After three days of indoor presentations in Erlangen, a field meeting the famous outcrops of southern Sweden will take place. Visits to the GSSP of the base of the Upper Ordovician at Fågelsång, the Ordovician of the island of Öland, and the Silurian succession of the island of Gotland are planned.

We hope that the meetings will provide a forum for palaeontologists, sedimentologists, geochemists, and climate modellers for fruitful exchange and discussion of their results and ideas.

Axel Munnecke & Thomas Servais

# Organising Committee

International Scientific Committee

*D.A.T. Harper* .................. *Copenhagen, Denmark*
*Li Jun* .................. *Nanjing, China*
*A. Munnecke* .................. *Erlangen, Germany*
*A.W. Owen* .................. *Glasgow, Scotland, UK*
*F. Paris* .................. *Rennes, France*
*P. Sheehan* .................. *Milwaukee, USA*
*T. Servais* .................. *Lille, France*
*Chen Xu* .................. *Nanjing, China*

Local Organising Committee
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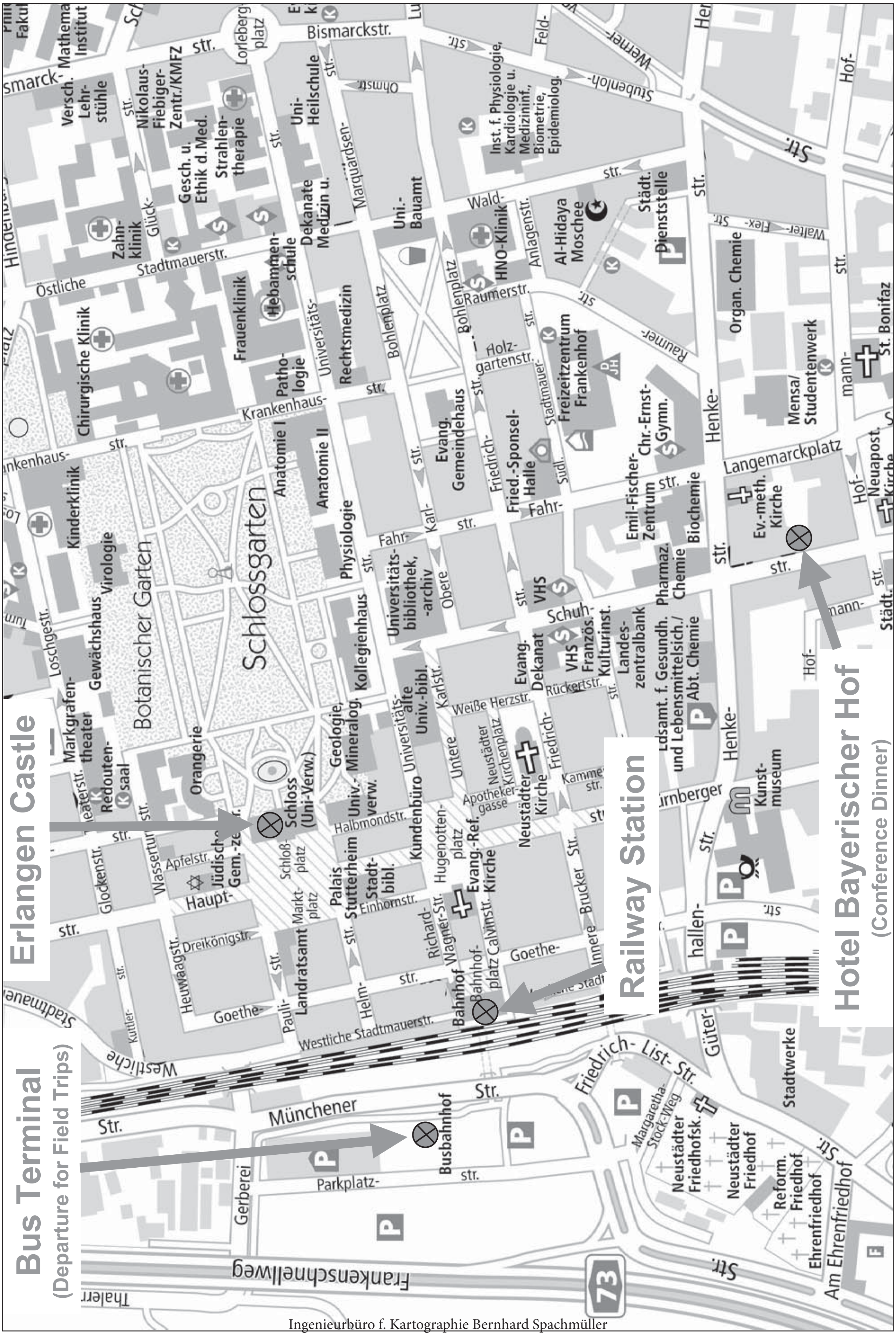


Ingenieurbüro f. Kartographie Bernhard Spachmüller

# General Programme

## Wednesday, September 1st

| | |
|---|---|
| 09h00 – 09h30 | Welcome |
| 09h30 – 10h15 | Invited lecture: PARIS & Webby |
| 10h15 – 10h45 | *Coffee & Poster* |
| 10h45 – 11h30 | Invited lecture: BICKERT et al. |
| 11h30 – 11h50 | Cramer & Saltzmann |
| 11h50 – 12h10 | Kaljo et al. |
| 12h10 – 12h30 | Joachimski et al. |
| 12h30 – 12h45 | *Group Photograph* |
| 12h45 – 14h00 | *Lunch* |
| 14h00 – 14h20 | Alvaro et al. |
| 14h20 – 14h40 | Villas et al. |
| 14h40 – 15h00 | Brenchley et al. |
| 15h00 – 15h20 | Armstrong et al. |
| 15h20 – 15h40 | Le Heron et al. |
| 15h40 – 16h00 | Moreau et al. |
| 16h00 – 16h20 | *Tea & Poster* |
| 16h20 – 16h40 | Albanesi & Voldman |
| 16h40 – 17h00 | Cherns et al. |
| 17h00 – 17h20 | Li & Kershaw |
| 17h20 – 17h40 | Calner et al. |
| 17h40 – 17h50 | Königshof et al. |
| 18h00 – 18h30 | Business meeting IGCP 503 |
| 18h30 – 20h30 | *Guided Tour through Erlangen* |

## Thursday, September 2nd

| | |
|---|---|
| 08h15 – 09h00 | Invited lecture: COCKS |
| 09h00 – 09h20 | Schulz et al. |
| 09h20 – 09h40 | Su & Shi |
| 09h40 – 10h00 | Lubnina |
| 10h00 – 10h20 | *Coffee & Poster* |
| 10h20 – 11h05 | Invited lecture: SCOTESE |
| 11h05 – 11h25 | Bassett et al. |
| 11h25 – 11h45 | Rong & Harper. |
| 11h45 – 12h05 | Servais et al. |
| 12h05 – 13h15 | *Lunch* |
| 13h15 – 19h15 | *Palaeontological Excursion: Solnhofen Museum* |
| 20h00 – 23h00 | *Conference Dinner* |

## Friday, September 3rd

| | |
|---|---|
| 08h30 – 09h00 | Invited lecture: MICHEELS et al. |
| 09h00 – 09h20 | Herrmann & Patzkowsky |
| 09h20 – 09h40 | Fortey & Cocks |
| 09h40 – 10h10 | Invited lecture: FRANÇOIS |
| 10h10 – 10h30 | *Coffee & Poster* |
| 10h30 – 10h50 | Achab et al. |
| 10h50 – 11h10 | Li & Yan |
| 11h10 – 11h30 | Esprit et al. |
| 11h30 – 11h50 | Harper & Tychsen |
| 11h50 – 12h10 | Owen |
| 12h10 – 12h30 | Tolmacheva |
| 12h30 – 14h00 | *Lunch* |
| 14h00 – 14h20 | Lefebvre & Esprit |
| 14h20 – 14h40 | Rozhnov |
| 14h40 – 15h00 | Fatka & Brocke |
| 15h00 – 15h20 | Dubinina & Ryazantsev |
| 15h20 – 15h40 | Zigaite |
| 15h40 – 16h00 | Bogolepova & Siveter |
| 16h00 – 16h20 | *Tea & Poster* |
| 16h20 – 16h50 | Dronov & Popov |
| 16h50 – 17h10 | Lehnert et al. |
| 17h10 – 17h30 | Díaz-Martínez & Grahn |
| 17h30 – 17h50 | Chen et al. |
| 17h50 – 18h20 | Invited lecture: SCOTESE |
| 18h30 – 18h45 | CLOSING CEREMONY |
| 19h00 – 20h30 | *Brewery Visit* |

## Saturday, September 4th

| | |
|---|---|
| 08h00 | Departure for field trip. |

# Scientific Programme

**Tuesday, August 31st**

*16h00 – 22h00* *Registration and fix posters*

*18h00 – 22h00* *Icebreaker Party (hall on the first floor of the Castle)*

**Wednesday, September 1st**

**OPENING SESSION**

*09h00 – 09h30* Welcome

*09h30 – 10h15* Invited lecture F. PARIS & B.D. Webby: *Aims, achievements and lessons learnt from six years of IGCP project n° 410*

*10h15 – 10h45* *Coffee & Poster*

**SESSION 1: ISOTOPE GEOCHEMISTRY AND INTERPRETATION**

**(Chairman: Peter Sheehan)**

*10h45 – 11h30* Invited lecture: T. BICKERT et al.: *Application of brachiopod carbon and oxygen isotopes for Paleozoic climate reconstruction: Examples from the Silurian of Gotland*

*11h30 – 11h50* B.D. Cramer & M.R. Saltzmann: *Glaciation, $CO_2$, and organic carbon burial in the early Silurian (Wenlock)*

*11h50 – 12h10* D. Kaljo et al.: *Ordovician carbon isotope trend based on Baltoscandian data: some aspects of composition and environmental interpretation*

*12h10 – 12h30* M. Joachimski et al.: *Does the oxygen isotope composition of Palaeozoic brachiopods reflect palaeoenvironmental conditions? A critical reappraisal*

*12h30 – 12h45* *Group Photograph*

*12h45 – 14h00* *Lunch*

**SESSION 2: END-ORDOVICIAN GLACIATION AND SEA-LEVEL CHANGES**

**(Chairman: Richard Fortey)**

*14h00 – 14h20* J.J. Álvaro et al.: *Hirnantian valley-glacier sedimentation in the eastern Anti-Atlas, Morocco*

*14h20 – 14h40* E. Villas et al.: *Modelling the Hirnantian eustatic fall and its related Gondwanan ice-sheet growth time*

*14h40 – 15h00* P.J. Brenchley et al.: *Karstified limestones in a submarine channel record end-Ordovician glacio-eustatic sea level fluctuations*

*15h00 – 15h20* H.A. Armstrong et al.: *Hirnantian deglaciation: a high latitude perspective from Palaeo-Tethys*

*15h20 – 15h40* D.P. Le Heron et al.: *Defining the maximum extent of the Hirnantian ice sheet in Morocco*

*15h40 – 16h00* J. Moreau et al.: *Ice-proximal sedimentary records of the Late Ordovician glacial cycles*

*16h00 – 16h20* *Tea & Poster*

**SESSION 3: OPEN SESSION I**

**(Chairman: Chen Xu)**

*16h20 – 16h40* G.L. Albanesi & G.G. Voldman: *Ordovician paleothermometry of the Argentine Precordillera based on Conodont Color Alteration Index*

*16h40 – 17h00* L. Cherns et al.: *Late Ordovician cool water bryozoan mud mounds from Lybia*

*17h00 – 17h20* Li Yue & S. Kershaw: *Reef reconstruction after extinction events of the Latest Ordovician in the Yangtze Platform, South China*

*17h20 – 17h40* M. Calner et al.: *Correlation of the middle Silurian graptolite crisis and coeval laminated sediments across the Baltic Shield and East European Platform*

*17h40 – 17h50* P. Königshof et al.: *"Devonian land-sea interaction: Evolution of ecosystems and climate" (DEVEC) – the new IGCP Project 499*

**OPENING SESSION OF IGCP 503**

*18h00 – 18h30* Business meeting IGCP 503

*18h30 – 20h30* *Guided tour through Erlangen*

**Thursday, September 2nd**

**SESSION 4: EARLY PALAEOZOIC PALAEOGEOGRAPHY**

**(Chairman: David Harper)**

| | |
|---|---|
| *08h15 – 09h00* | Invited lecture: L.R.M. COCKS: *Ordovician geography: probabilities and problems* |
| *09h00 – 09h20* | B. Schulz et al.: *New zircon ages and isotope data from the Austroalpine Cambrian to Silurian magmatic record and the consequences to models of north-Gondwanan terrane configuration* |
| *09h20 – 09h40* | Su Wenbo & Shi Xiaoying: *K-bentonites and progressive flysch succession around Ordovician-Silurian transition in South China: New evidences for accretion of Cathaysia to Yangtze Block and break-up of Gondwanaland* |
| *09h40 – 10h00* | N. Lubnina: *Ordovician palaeogeographical reconstruction of Baltica: palaeomagnetic data* |
| *10h00 – 10h20* | *Coffee & Poster* |

**SESSION 5: EARLY PALAEOZOIC PALAEOBIOGEOGRAPHY**

**(Chairman: Alan Owen)**

| | |
|---|---|
| *10h20 – 11h05* | Invited lecture: C.R. SCOTESE: *Early Paleozoic plate tectonics, paleogeography, and paleoclimate* |
| *11h05 – 11h25* | M.G. Bassett et al.: *Biogeographical assessment of Early to Mid Ordovician benthic faunas of north-central Iran* |
| *11h25 – 11h45* | Rong Jia-Yu & D.A.T Harper: *A Middle Ordovician silicified brachiopod fauna from Guiyang, South China and its palaeobiogeographical significance* |
| *11h45 – 12h05* | T. Servais et al.: *Are some fossils better than others for inferring palaeogeography? An old question revisited* |
| *12h05 – 13h15* | *Lunch* |
| *13h15 – 19h15* | *Palaeontological Excursion: Solnhofen Museum* |
| *20h00 – 23h00* | *Conference Dinner* |

**Friday, September 3rd**

**SESSION 6: EARLY PALAEOZOIC CLIMATE AND CLIMATE MODELLING**

**(Chairman: Michael Joachimski)**

| | |
|---|---|
| *8h30 – 9h00* | Invited lecture: A. MICHEELS et al.: *Palaeoclimate modelling studies for the Late Miocene and for the Neoproterozoic* |
| *9h00 – 9h20* | A.D. Herrmann & M.E. Patzkowsky: *Late Ordovician ocean-climate system and paleobiogeography* |
| *9h20 – 9h40* | R. Fortey & L.R.M. Cocks: *A late Ordovician global warming event?* |
| *9h40 – 10h10* | Invited lecture: L. FRANÇOIS: *Modelling atmospheric $CO_2$ changes at geological timescales* |
| *10h10 – 10h30* | *Coffee & Poster* |

**SESSION 7: EARLY PALAEOZOIC BIODIVERSITY TRENDS**

**(Chairman: Florentin Paris)**

| | |
|---|---|
| *10h30 – 10h50* | A. Achab et al.: *Patterns and driving factors of the chitinozoan diversification during the Ordovician* |
| *10h50 – 11h10* | Li Jun & Yan Kui: *The Ordovician acritarch assemblage from Meitan Formation, Tongzi, South China: Biostratigraphy and biodiversity* |
| *11h10 – 11h30* | N. Esprit et al.: *Radiation of bivalves during the Ordovician: morphological quantification of peri-Gondwanan faunas* |
| *11h30 – 11h50* | D.A.T. Harper & A. Tychsen: *The Orthida: Disparity, diversity and distributional dynamics in a Palaeozoic brachiopod clade* |
| *11h50 – 12h10* | A.W. Owen: *Trilobite diversity in Avalonia prior to the end Ordovician extinction - the peak before the trough* |
| *12h10 – 12h30* | T.Y. Tolmacheva: *Fossil assemblages from radiolarites of Central Kazakhstan – a key for the reconstruction of the pelagic ecosystem* |
| *12h30 – 14h00* | *Lunch* |

**SESSION 8: EARLY PALAEOZOIC PALAEOECOLOGY AND PALAEOBIOGEOGRAPHY**

**(Chairman: Rong Jia-Yu)**

*14h00 – 14h20* B. Lefebvre & N. Esprit: *Palaeoecology and palaeobiogeography of Cambro-Ordovician stylophoran echinoderms*

*14h20 – 14h40* S.V. Rozhnov: *Palaeogeography and the origin of higher taxa of echinoderms in the Early Palaeozoic*

*14h40 – 15h00* O. Fatka & R. Brocke: *Changes in Darriwilian acritarch and prasinophyte assemblages of the Yangtze Platform (South China) and the Barrandian area (Czech Republic)*

*15h00 – 15h20* S.V. Dubinina & A.V. Ryazantsev: *Ordovician conodonts in different palaeogeographical environments of the southern Urals*

*15h20 – 15h40* Z. Zigaite: *Endemic thelodonts (Agnatha) of the Silurian of Central Asia and Siberian Platform*

*15h40 – 16h00* O.K. Bogolepova & D.J. Siveter: *The myodocope ostracode Entomozoe from the early Silurian of Severnaya Zemlya, Russian Arctic: biostratigraphical and palaeogeographical significance*

*16h00 – 16h20* *Tea & Poster*

**SESSION 9: OPEN SESSION II**

**(Chairman: T. Servais)**

*16h20 – 16h50* A.V. Dronov & L.E. Popov: *Traces of frost action in the Obolus-Sand: the evidence for subglacial climate in the mid Cambrian to early Ordovician (Tremadocian) of the East Baltic*

*16h50 – 17h10* O. Lehnert et al.: *The oldest record of hydrothermal vent communities: intracratonic sites formed in the early stage (Tremadocian) of the Prague Basin*

*17h10 – 17h30* E. Díaz-Martínez & Y. Grahn: *Ordovician-Silurian boundary near La Paz (Bolivia): stratigraphy, sedimentology, chitinozoan biostratigraphy and regional palaeogeographic implications*

*17h30 – 17h50* Chen Xu et al.: *Consistency of the faunal replacement and environmental change through Ordovician and Silurian transition in South China*

*17h50 – 18h20* Invited lecture: C.R. SCOTESE: *Early Paleozoic paleoclimatic simulations: data and model comparisons*

*18h30 – 18h45* CLOSING CEREMONY

*19h00 – 20h30* *Brewery Visit (Kitzmann)*

**Saturday, September 4th**

*08h00* Departure for the field trip to Fågelsång, Öland, and Gotland (departure and arrival point is the Erlangen Bus Terminal)

# Poster Presentations

Antoshkina, A.I.: *Late Silurian reef biota in the northwestern Salair: Application to Silurian geography*

Bagnoli, G., Ribecai, R. & Albani, R.: *Changes in some acritarch genera across the Volkhov/Kunda boundary on Öland (Sweden)*

Blanchon, M., Raevskaya, E., Servais, T. & Vecoli, M.: *The Cambro-Ordovician acritarch Vulcanisphaera*

Couto, H., Sodré-Borges, F., Roger, G., Gutiérrez-Marco, J.C.: *The Ordovician of the Valongo Anticline (Portugal)*

Dahlqvist, P., Calner, M., Bergström, S.M. & Harper, D.A.T.: *The Upper Ordovician-Lower Silurian stratigraphic succession in the Caledonian foreland basin of central Sweden: relationship to the Hirnantian glacial interval*

Ernst, A. & Suttner, T.: *Bryozoa from the Pin Formation (Upper Ordovician – Lower Silurian) in the Tethyan Zone of the Indian Himalayas*

Fan Juanxuan & Chen Xu: *Late Ordovician graptolite extinction and biogeography of graptolites in the Yangtze region*

Fan Juanxuan & Zhang Yuandong: *SinoCor 3.0, a biostratigraphic program for graphic correlation*

Ghobadipour, M., Popov, L.E., Lehnert, O., Hairapetian, V. & Hosseini, M.: *Emergence of the Palaeozoic Evolutionary Fauna in the early Ordovician of the Alborz Range, northeastern Iran*

Gubanov, A.P. & Bogolepova, O.K.: *The earliest record of a colour pattern in molluscs*

Hints, O. & Eriksson, M.E.: *Early diversification of jaw-bearing polychaetes*

Jankauskas, T. & Gritite, J.: *Acritarch assemblages of the Ordovician and Silurian deposits in Lithuania*

Jendryka-Fuglewicz, B.: *Cambrian brachiopods from near the Teisseyre-Tornquist Line in Poland and their implications for palaeogeography*

Kershaw, S. & Young, G.A.: *Internal banding in Palaeozoic stromatoporoids and colonial corals: Classification and controls of formation*

Kiipli, T., Kiipli, E. & Kallaste, T.: *Record of Ordovician and Silurian volcanism in Estonian sections – prospect of research*

Lee, S.-b., Lefebvre, B. & Choi, D.K.: *Tremadocian stylophoran echinoderms from the Taebaeksan Basin, Korea*

Manda, S.: *Early Silurian cephalopod migrations to the Prague Basin (Perunica micro-plate, Bohemia)*

Mergl, M.: *The earliest brachiopod-bryozoan dominant community in North Gondwana: a case from Late Arenigian of the Barrandian, Bohemia*

Nardin, E. & Levebvre, B.: *Palaeogeography and biodiversity of Cambro-Ordovician echinoderms*

Nolvak, J.: *Ordovician chitinozoan distribution in the different areas of Baltoskandia*

Nützel, A., Lehnert, O. & Frida, J.: *Major changes in gastropod larval strategies during the Early Ordovician*

Ortega, G., Albanesi, G.L. & Frigerio, S.E.: *Early Darriwilian graptolite and conodont biofacies in the Los Azules Formation, Cerro Viejo section, Central Precordillera, Argentina*

Podhalanska, T.: *New data on the Ordovician ichnofossils from the Koszalin – Chojnice Region (Pomerania, NW Poland) – palaeogeographic implication*

Raevskaya, E., Le Hérissé, A. & Steemans, P.: *Quantitative distribution and evolution of palynomorphs associated with kukersite deposits in the Middle-Upper Ordovician of the East-European Platform*

Stricanne, L., Munnecke, A., Pross, J. & Servais, T.: *Development of acritarch communities across the late Silurian positive* $\delta^{13}C$ *excursion – data from Gotland, Sweden*

Trotter, J.A., Eggins, S.M., McCulloch, M.T., Barnes, C.R., Nicoll, R.S., Nowlan, G.S. & McCracken, A.D: *Sr isotopic and Mg cycling in Early Palaeozoic seawater: Implications for tectonic and climatic processes*

Vaida, M., Veliciu, S. & Verniers, J.: *Basin analysis: a punctual example in the South of Romania*

Vaida, M., Verniers, J. & Seghedi, A.: *The biostratigraphy of new chitinozoans from the South of Romania*

Vandenbroucke, T.R.A., Van Nieuwenhove, N. & Verniers, J.: *Towards an Upper Ordovician chitinozoan biozonation on Avalonia? Research on historical type areas and other UK key sections*

Vanmeirhaeghe, J., Van Noten, K., Van Grootel, G. & Verniers, J.: *Chitinozoans from the Upper Ordovician of the Fauquez area (Brabant Massif, Belgium)*

Vecoli, M., Al-Ruwaili, M., & Le Hérissé, A.: *Palaeobiological and palaeoenvironmental significance of cryptospores and acritarchs from the Llanvirn of Saudi Arabia*

Vennin, E., Álvaro, J.J., Villas, E. & Destombes, J.: *High-latitude bryozoan-dominated communities as a major carbonate factory on mixed carbonate-siliciclastic platforms of the late Ordovician northern Gondwana*

Vyhlasová, Z.: *Ordovician conulariid diversity in the periGondwana and Baltica regions – a summary with a special view to the Ordovician of Barrandian*

Wheeley, J.R., Cherns, L. & Wright, P.: *The Ordovician Baltic epeiric sea – taphonomy and early diagenesis of its carbonate sediments*

Woo, J. & Chough, S.K.: *Depositional environments and sequence stratigraphy of the Jigunsan Formation (Middle Ordovician), Taebaeksan Basin, Mideast Korea*

Wrona, R.: *Gondwanan provenance of the Lysogóry block (Holy Cross Mountains, Poland) supported by Upper Ordovician chitinozoans from the Pobroszyn section*

Xu Honggen & Yu Guohua: *Brief introduction of the Ordovician and Silurian in Northwest Zhejiang*

Zuykov, M.A. & Harper, D.A.T: *Platystrophia-like brachiopods: their potential use in biostratigraphy, palaeoecology and palaeogeography.*

# Patterns and driving factors of the chitinozoan diversification during the Ordovician

A. ACHAB[1], F. PARIS[2], J. NÕLVAK[3], and E. ASSELIN[4]

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[4]Centre géoscientifique de Québec, Natural Resources Canada, Geolological Survey of Canada, GSC-Québec, 880 chemin Ste-Foy, Qc, G1S 2L2

Oral Presentation

Ordovician chitinozoans have been fairly well documented from Gondwana, Baltica and Laurentia. Data from these palaeoplates have contributed to more than ⅔ of the global chitinozoan database established for the IGCP 410 project.

Notwithstanding the bias caused by irregular sampling through time and space, the regional chitinozoan diversity curves and their related parameters (normal total diversity, origination, extinction rates and turnover ratios) have permitted to document and to compare the changes undergone by chitinozoans at low, intermediate and high latitudes during the Ordovician.

In general, chitinozoan diversity is moderate (10 to 30 species per time-slice, i.e. usually less than 10 species per million years). However, this specific diversity is slightly higher in low latitude regions (Laurentia) than in high latitude ones (North Gondwana). Conversely, chitinozoan abundance is greater in high-latitude regions, where it may reach several thousand of specimens per gram of rock, than in low-latitude regions where the most productive samples have yielded no more than a few hundred specimens per gram of rock. Because of the Ordovician provincialism, which seems partly related to the dispersion of the main palaeoplates, three regional biozonations broadly reflecting the main Ordovician palaeoclimatic belts have been recognized.

A continuous diversification is observed in the three regions from the Early to the Middle Ordovician with the first maximum peak reached during the Darriwilian. A progressive decrease in diversity marks the Late Ordovician, with the minimum diversity being attained during the Late Ordovician coincident with the Hirnantian glaciation. In these three regions, this decrease is marked, however, by a short-lived diversification event in the middle part of the Ashgill. Other signals expressed by the curves are diachronous and seem to be related to features specific to each paleoplate (e.g. paleolatitude, local sea level variation, tectonics etc.). For example, the first occurrence of chitinozoans in North Gondwana has been recorded in the early Tremadocian, while in Laurentia it has been reported from the upper Tremadocian. Maximum diversity occurs in the upper Darriwilian in North Gondwana, while in Baltica it spans the late Darriwilian-early Caradoc interval and it peaks in the middle-late Caradoc in Laurentia. On the other hand, the decrease in diversity seems to have begun earlier and more drastically in Laurentia than in Baltica and North Gondwana.

Because of their pelagic mode of distribution, chitinozoans are usually associated with graptolites. However, if one compares the diversity curves available for the graptolites from low (Australasia), middle (Baltica) and higher latitude regions (Avalonia), no obvious relationships have been observed with the exception of the latest Ordovician drop in diversity. Although no paleolatitudinal trend was reported among graptolite diversity features, it is worth mentioning that contrary to the chitinozoans, the graptolite diversity is at a maximum earlier (early Arenig) in low latitude than in higher latitude (late Arenig - early Caradoc); the decrease in graptolite diversity is also observed earlier in high latitude regions.

# Ordovician paleothermometry of the Argentine Precordillera based on Conodont Color Alteration Index

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Oral Presentation

The present study aims to record and interpret paleotemperatures in Ordovician rocks of the Argentine Precordillera. Paleotemperatures are estimated by using the conodont color alteration index (CAI) method. The present work is one of the first to use this method at a regional and local scale in Argentine basins, and it is based on conodont collections deposited in the Museum of Paleontology of the National University of Córdoba, Argentina. Most conodonts were recovered from carbonate rocks by means of conventional acid etching techniques, and the color alteration and preservational characteristics were assessed by direct comparison with a set of standard reference conodont elements kindly provided by Dr. Anita Harris. CAI values of conodonts from numerous localities were plotted on a geological map of the Precordillera. Distributional patterns of paleotemperatures indicate a gradual increase toward the West and South, as well as the presence of several local anomalies caused by mafic intrusions. CAI patterns allow us to identify two paleothermometric domains: the diacaizone and the ancaizone. The diacaizone approximately corresponds to the Eastern and Central Precordillera, where overburden effects are the main cause of elevated paleotemperatures. The ancaizone, which corresponds to the Western Precordillera, shows paleotemperatures representing a very low grade metamorphism. Apparently, the thermal peak of this metamorphism occurred during a late Silurian – early Devonian event related to the obduction of the Famatinian ophiolites. Local anomalies are analysed within the evolving geotectonic context of the Precordillera. A case study from the Villicum Range, Eastern Precordillera, shows a particular congruence between theoretical and field results, suggesting that the thickness of phantom units represented by intra-Ordovician and Silurian unconformities is in the order of meters.

# Hirnantian valley-glacier sedimentation in the eastern Anti-Atlas, Morocco

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Oral Presentation

Although the Late Ordovician palaeogeographical reconstructions of the glacial episode show an ice-sheet centre located near central Africa, the peripheral extension of its palaeo-northern ice front remains unresolved. In Mauritania, terrestrial glacigenic deposits are prevalent in the southern Hoggar and Hodh areas, while glacimarine deposits are dominant in northern Hoggar and Adrar. Subsurface data from the northern Sahara basins show a third palaeogeographical domain absent in Mauritania, where glacially related marine muds reach several hundred of metres in thickness (Ghienne & Deynoux, 1998). As a result, between the well-defined subaerial glaciation of the southern Sahara and the glacimarine deposits of south-western Europe exists an enormous gap of glacial landforms, in which the palaeogeographical models suppose the absence of continental ice-sheet deposits by erosion or non-sedimentation. Modelling the behaviour of the Late Ordovician North Gondwana Ice Sheet requires an integration of the deglaciation history of both the European and North-African platforms, in which the valley-glacier and fjord deposition reported here from the Moroccan Anti-Atlas represents the northernmost prolongation of the Gondwanaland Ice Sheet, and can be considered as the hinge for comparison of both major palaeogeographical regions.

The Hirnantian sedimentary succession of the Alnif area (eastern Anti-Atlas) contains two glacigenic stratigraphical units named here the Alnif and Tamekhtart Members. The Alnif (subaerial) diamictite contains several glacial landforms, in particular flute (up to 3.5 km long) and associated end (De Geer-like) moraines, and gives the first sedimentary evidence of a grounded ice tongue northwards of the south-Saharian ice sheet. The glacial retreat from the Alnif palaeo-valley took place in a stepwise manner, with deposition of at least six moraines during halts in the recession. The overlying Tamekhtart glacimarine diamictite consists of chaotic beds directly onlapping a scarp inherited of the palaeo-valley after moraine erosion, finely laminated siltstones and claystones, and homogeneous claystones supporting isolated silt to granule dropstones filling the fjord depression.

The Alnif valley glacier, on the scale of 180 m deep, up to 1.5 km wide, and mapped along 10 km, incised into Ashgillian to Caradocian sedimentary rocks. This incision represents a relative sea-level fall greater than those previously reported from other palaeo-continents, although it is close to the supposed maximum sea-level lowering estimated for the Quaternary glaciations. The reason why other subaerial diamictites are probably still unrecognized in the Anti-Atlas could be related to their special geometries, if they are preferentially preserved as infilling of narrow valley glaciers.

The glacigenic unconformity located at the Alnif valley glacier (the base of the Upper Formation of the Second-Bani Group) corresponds to the greater Hirnantian ice-sheet extent on the northern peripheral extension of the Gondwanaland Ice Sheet. The final melting of the ice lobes and the succeeding glacimarine Tamekhtart sedimentation covered the entire Anti-Atlas basin forming a widespread onlapping geometry indicating a long-term transgression coeval with the final ice-lobe recession.

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## Late Silurian reef biota in the northwestern Salair: application to Silurian geography

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Poster Presentation

The Salair Ridge is a fragment of the mosaic structure of the Altaj-Sayan folded area (southwestern Siberia). The Silurian of this region is poorly known and poorly exposed. Silurian formations in the Salair region that are represented in composite sections have diverse Llandovery-Ludlow faunas. Much more work is to be done on the known sections to clarify their correlation and faunas. Essential new biota associations have been made from Silurian massive reefal limestones of subsurface data and the former Limestone quarry in the Vetokhino Square of the Zalesovo region in the northwestern Salair. The sequence under study was corresponded to the Potapovka and Baskuskan formations (geological service data of Kharin, 1967). Now, according to Elkin et al. (2003), the Potapovka Formation is the latest Telychian-Pridoli and the Baskuskan Formation – late Telychian in age. It is established that main frame builders of boundstones equally with common Silurian reef organisms (rugose corals, bryazoans, etc.) and calcareous algae (*Solenopora*, Codiaceae) were distinctive metazoans such as sphinctozoan aphrosalpingid sponge (*Aphrosalpinx*, *Palaeoshada*), and ?hydroids, *Fistulella* in association with very distinctive consortium of microbial taxa (such as *Girvanella*, *Renalcis*, *Wetheredella*, *Rothpletzella*, *Ludlovia*, *Sphaerina*). Strikingly similar reef biota communities of Ludlow age were described from sites in the Urals for the first time (Antoshkina 1979, 1994, 2003). The Ludlow reefs were rigid organic structures that grew at a passive platform margin of Baltica towards of the Paleo-Uralian Ocean. Reef paleolandscape elements – reef core, reef platform, and slopes and the typical association of reef rocks – boundstones, bioclastic and rudstone-breccias are distinguished in the Vetokhino massive limestone formation. This fact allows to determine the Vetokhino organic structure as a reef that formed in open sea conditions with active hydrodynamics. Some researchers believe that after the Early Caledonian Orogeny, the Salair island arc was a shelf margin of Siberia in the Paleo-Asian ocean. Other authors suggest that Salair island arc system existed in the Paleo-Asian ocean up to the Carboniferous. By occurring in the Urals and Salair, the distinctive microbial-sponge-hydroid biota establish an ancient biogeographic relationship between eastern East-European and southeastern Siberian cratons (in modern co-ordinate) in the Late Silurian. The fact of reef growth on the margin of platform shelves suggests a marine connection to communities evolving along the margins of the Uralian Seaway during the Late Silurian. However, the well-known paleogeographic reconstructions by Scotese and McKerrow (1990), Torsvik et al. (1996), Scotese (1997, 2000), etc. do not support this idea. There seem to be two explanations for this problem: 1. Position of the Siberian paleocontinent in the Middle Paleozoic, offered by these authors, is greatly erroneous. The ancient craton should be located near its present orientation, but was shifted by them along its Altaj-Sayan folded area towards the equatorial latitudes. 2. The accretion of the Salair island arc to Siberia is not connected with the Early Caledonian Orogeny and an arc's migration during Silurian can be discussed.

## Hirnantian deglaciation: a high latitude perspective from Palaeo-Tethys

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Oral Presentation

At the present day the presence of permanent ice is controlled by high latitude summer insolation modulated by obliquity (43kyr) forcing; eccentricity is not significant as a direct cycle of seasonal insolation change. Was this the case during the late Ordovician? The Hirnantian "hot" black shale member of the Batra Formation, Jordan was deposited in a high latitude anoxic basin that preserved an early deglacial record of TOC and carbon isotope ratios from organic matter ($\delta^{13}C_{org}$). Spectral analysis indicates cycles in the TOC data, a proxy for palaeoproductivity, have a period of 35,556 yrs, close to the predicted 36,000 yr Ordovician obliquity timescale. $\delta^{13}C_{org}$ values show a rising trend of -31 to -29‰, similar in magnitude but opposite in trend to those from low palaeolatitude. In the absence of changes in the source materials this variance could be explained if the $\delta^{13}C$ of dissolved $CO_2$ were elevated to levels similar to those predicted from low palaeolatitude carbon isotope ratios from carbonates ($\delta^{13}C_{carb}$). A hypothesis that cannot be tested in the Jordan section. Alternately, if $\delta^{13}C_{org}$ was primarily controlled by concentration of [$CO_2$(aq)], as some believe is the case for the modern high Southern Ocean, then [$CO_2$(aq)] in high palaeolatitude Palaeo-Tethys waters was falling during early deglaciation, probably in response to increased bioproductivity.

This work supports the hypothesis that obliquity-forced seasonal variations in high latitude insolation affected the melting dynamics of the ice sheet during early deglaciation which in turn, through the biosphere, effected drawdown of $CO_{2(atm)}$. During early deglaciation high latitude Palaeo-Tethys was a net sink of carbon, a situation that lasted for at least 100 kyrs. If global $CO_{2(atm)}$ levels were to rise in line with a return of greenhouse conditions the $CO_{2(atm)}$ must have been sourced from low-mid palaeolatitudes.

## Changes in some acritarch genera across the Volkhov/Kunda boundary on Öland (Sweden)

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Poster Presentation

The Lower to Middle Ordovician *Orthoceras* Limestone is a condensed carbonate sequence that accumulated on the East European Platform. The *Orthoceras* Limestones of Horns Udde and Horns Udde Quarry on the island of Öland (Sweden) have been investigated in great detail for acritarch, conodont and chitinozoan studies. These microfossils are abundant, well preserved, and are co-occurring in the same samples.

The acritarch taxonomy has been carefully examined and also intraspecific changes have been studied and documented, and compared with other sections from Öland. The succession of the acritarch species has been compared with available data on conodont biostratigraphy and biofacies, and sea-level changes.

The Horns Udde microflora spanning the Volkhov/Kunda boundary is dominated by representatives of the genus *Baltisphaeridium*, but other genera such as *Liliosphaeridium* and *Peteinosphaeridium* exhibit relevant evolutionary developments, and characterize the Volkhov/Kunda transition.

In the interval corresponding to the base of Darriwilian, with the beginning of a transgression, several species with a short stratigraphical range are present.

The following interval, spanning the Volkhov/Kunda boundary is characterized by the relative abundance of longer ranging species of *Peteinosphaeridium* and *Liliosphaeridium*.

In the higher part of the section *Peteinosphaeridium* and *Liliosphaeridium* are reduced, and several species make their last occurrence. In this interval a shift in conodont biofacies indicates a fast regressive episode. It is interesting to note that the biofacies conodont change is delayed compared to the disappearance of several acritarch taxa and appearance of new ones.

The changes in acritarch association are compared with the changes in chitinozoan succession as well.

# Biogeographical assessment of Early to Mid Ordovician benthic faunas of north-central Iran

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Oral Presentation

In plate-tectonic reconstructions Iran is interpreted as an assemblage of several peri-Gondwanan terranes, but existing data are not sufficient to define their positions in relation to the Gondwanan margin and other peri-Gondwanan terranes. Preliminary analysis of new collections of Early to Mid Ordovician faunas from the Derenjal Mountains of the Tabas region (Central Iranian plate) and the Simeh-Kuh Section near Damgham (Alborz plate) shows that in both regions shallow marine environments of BA2 were dominated by a low diversity *Protambonites* brachiopod assemblage. This fauna is known also from Armorica and Perunica and can be considered as essentially West Gondwanan, but it also occurs on the Uralian Margin of Baltica in the early Arenig. In the Tabas Region *Protambonites* is accompanied by *Tritoechia*, together with mostly cosmopolitan orthides (e.g. *Apheoorthis* and *Archaeorthis*) and syntrophiides. The accompanying trilobite fauna is of low diversity, but the occurrence of *Tungtzuella* sp., otherwise known from South China, is of particular interest. The lower part of the Darriwilian interval contains a low diversity brachiopod fauna of mostly endopunctate orthides and a new genus of polytichioids, associated with a trilobite assemblage dominated by *Paraszechuanella*. Notwithstanding previous reports, the upper Darriwilian contains abundant *Neseuretus* and *Birmanites*, which are considered as characteristic mostly of East Gondwana. Associated brachiopod faunas contain the orthide *Nicolella* which is also known from approximately contemporaneous deposits of Burma (Siburnasu) and South Tien Shan but appears in West peri-Gondwana only in the Late Ordovician. Other components of the assemblage include endopunctate orthides, plectambonitoids and the strophomenoids *Longvillia* and, possibly *Dirafinesquina*. Tremadoc to Arenig faunas of Alborz contain, among other trilobites, *Dikelocephalus* and *Taihungshania*, and the brachiopods *Yangtzeella* suggesting affinity with South China and the Tauride terrane. A diverse echinoderm fauna includes glyptosphaeritid and sphaeronitid diploporans together with echinosphaeronitid, caryocystid and hemicosmitid rombiferans with mixed Baltic and West Gondwanan signatures, but affinity of the Middle Ordovician echinoderm faunas with West peri-Gondwana is more evident. The Alborz terrane was most probably separated from mainland Gondwana and located in temperate latitudes, occupying an intermediate position between South China and the Tauride terrane during the Early to Mid Ordovician. In general, a Baltic affinity is more evident for the Early Ordovician faunas of Alborz, but this weakened significantly by the Mid Ordovician. Early to Mid Ordovician benthic faunas of the Central Iranian plate are more strictly Gondwanan with some affinity to South China, but affinity to contemporaneous fauna of Sibumasu becomes evident by the end of the Mid Ordovician.

## Application of brachiopod carbon and oxygen isotopes for Paleozoic climate reconstruction: Examples from the Silurian of Gotland

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Oral Presentation

Stable carbon and oxygen isotopes in biogenic calcites are common tools for reconstructing past environmental conditions. For the Paleozoic, brachiopods are thought to be the most reliable recorders of stable carbon and oxygen isotopes because they are widespread in marine carbonate sediments, they are assumed to secrete shell material at or near isotopic equilibrium with the surrounding seawater, and their shells consist primarily of low-magnesian calcite most resistant to diagenetic alteration. However, restrictions for isotope interpretations result from species-dependend disequilibria observed for several brachiopod orders (e.g., strophomenida, pentamerida), and from kinetic isotope fractionation during calcite precipitation from seawater. Brachiopods sampled within a single stratum or even within a taphozoenosis exhibit a significant range of isotope values. Furthermore, even if those effects are considered, isotope measurements are difficult to interpret in terms of paleoenviromental changes, since the fractionation of those isotopes each relies on more than one environmental parameter.

Here, we present the application of brachiopod carbon and oxygen isotopes from the Swedish island of Gotland for the reconstruction of Silurian paleoclimatic changes. In a combined approach using sedimentological, paleontologcial, and geochemical data, we interpret the repeated drastic changes of carbonate facies succession, extinctions, and stable isotope development in terms of climate variability and ocean circulation changes. The relative timing of positive isotope excursions, mass extinctions, and facies development is shown to be typical not only for the Silurian (Wenlock and Ludlow), but also for similar events in the late Ordovician, the late Cambrian, and, with some reservations, in the Proterozoic. A paleoclimatic model postulated for the Silurian of Gotland may, therefore, be applicable also for the older events.

## The Cambro-Ordovician acritarch *Vulcanisphaera*

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Poster Presentation

The acritarch genus *Vulcanisphaera* Deunff, 1961, and its type species *V. africana* were first described from Cambro-Ordovician sequences of the Algerian Sahara. A first detailed revision of the genus, with a description of three new species of the Tremadocian of Shropsire, England, was provided by Rasul (1976). Additional species were subsequently described from different other areas, including Spain, France, Poland, and Canada.

The revision of the literature shows that over 30 species have been attributed to the genus. The revision of the data available in previously published papers, together with the reinvestigation of large populations of *Vulcanisphaera* from the type-localities in Algeria and England, allow a new classification concept and a revision of the biostratigraphy and the palaeobiogeography of the genus.

The revision indicates that *Vulcanisphaera* shows a large intraspecific variability. From the 31 species described in literature, 11 can not be maintained within the genus. Three morphotypes can easily be distinguished and could be retained as species: *Vulcanisphaera africana*, *V. capillata*, and *V. simplex*. The 17 remaining taxa previously described as species could be classified as infraspecific taxa. At the generic level, *Vulcanisphaera* is clearly distinguished from other acritarch genera, although some relations exist with the genera *Cristallinium* Vanguestaine, 1978, and *Timofeevia* Vanguestaine, 1978.

In terms of biostratigraphy, the species attributed to the genus *Vulcanisphaera* described from the Precambrian clearly do not belong to the genus. The first *Vulcanisphaera* species appear in the Middle Cambrian, indicating a First Appearance Datum (FAD) in the *Pardoxides paradoxissimus* trilobite Biozone in eastern Newfoundland.

However, *Vulcanisphaera* is rare in the Middle Cambrian, and the genus only becomes very abundant in the Upper Cambrian. It reaches its highest morphological variability in the latest Cambrian and during the Tremadocian.
Palaeogeographically, as most acritarch genera of the Cambrian-Ordovician transition, the genus shows a cosmopolitan distribution, occurring from high latitudes in the southern hemisphere to lower, near-equatorial latitudes worldwide.

# The myodocope ostracode *Entomozoe* from the early Silurian of Severnaya Zemlya, Russian Arctic: biostratigraphical and palaeogeographical significance

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Oral Presentation

The myodocope ostracod *Entomozoe* aff. *Entomozoe tuberosa* (Jones, 1861) has been identified from strata of early Silurian Llandovery Series age from October Revolution Island, Severnaya Zemlya in the Russian Arctic. *Entomozoe* was previously known only from Scotland (*E. tuberosa*), Greenland (*E.* aff. *tuberosa*;), and South China (*E.* cf. *tuberosa*). The new find signifies that *Entomozoe* has biostratigraphical and palaeogeographical significance: all occurrences are from late Llandovery sediments deposited in tropical to subtropical palaeolatitudes.
The islands of the Severnaya Zemlya Archipelago are located in the Kara Sea, north of the Taimyr Peninsula of central Siberia. In 1999, the SWEDARCTIC international expedition visited Severnaya Zemlya to study its stratigraphy, palaeontology, structural geology, and palaeomagnetism. Collections were made in the Sredninskaya Formation, composed of limestones with alternating shales, siltstones and dolomites exposed in the middle reaches of the Ushakova River in the central part of October Revolution Island. The locality yields graptolites indicating a mid Telychian (late *cripsus* – *griestoniensis*) age for the strata (Bogolepova *et al*. 2000).
The Silurian ostracodes from Severnaya Zemlya are known to consist of various leperditiocopes, palaeocopes and podocopes (Abushik 1982), but myodocope ostracods have not been previously reported from the area. *Entomozoe* is an early and rare Llandovery myodocope ostracod. Occurrence of the genus in Scotland (Siveter & Vannier 1990), South China (Siveter *et al*. 1991) and North Greenland (Siveter & Lane 1999), as in Severnaya Zemlya, is confined to the late Llandovery Telychian Stage.
The myodocope ostracods occur in carbonate nodules with common graptolites, brachiopods, cephalopods, gastropods, and rare bivalves, machaeridians and algae. Notwithstanding the occurrence of graptolites and probable pelagic cephalopods, the facies and fauna imply a relatively shallow shelf setting dominated by epibenthonic forms. Similar, low diversity graptolite faunas dominated by *Stimulograptus*, with subordinate *Streptograptus*, have been described from shelf environments in Wales (Loydell & Cave 1993). The shelf setting of the Russian material is consistent with the previous occurrences of *Entomozoe* and with the idea that this early Silurian myodocope was probably benthonic.
The known global distribution of *Entomozoe* reflects low palaeolatitudes. The Severnaya Zemlya Archipelago together with the northern part of Taimyr represent the North Kara Terrane, a microcontinent that collided with central Taimyr (today part of Siberia) during late Palaeozoic times. During the Silurian, North Kara was located at low latitudes, perhaps separate from the nearby Baltica and Laurentia; Scotland and Greenland formed a part of the eastern margin of Laurentia; south China was at similar latitudes but distant. This palaeogeography is based on a range of geological data such as facies patterns and faunal distributions, and is supported by palaeomagnetic data (Metelkin *et al*. 2000). The occurrence of *Entomozoe* in Severnaya Zemlya provides additional evidence of proximity between North Kara and Laurentia and provides a possible option for "island hopping" further east to the south China plate.
Field work on Severnaya Zemlya was funded by the Swedish Polar Research Secretariat. This is an INTAS – NEMLOR (Northern Eurasian Margin & Lomonosov Ridge) contribution.

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# Karstified limestones in a submarine channel record end-Ordovician glacio-eustatic sea level fluctuations

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Oral Presentation

The late Ordovician glaciation of Godwanaland induced major global sea-level changes. The major regression at the start of glaciation and flooding at its demise are particularly significant as they correspond to the two phases of the end Ordovician mass extinction. Globally the sea-level changes are accompanied by major shifts in marine carbon and oxygen isotope values with a single positive isotope excursion commencing at the Rawtheyan-Hirnantian boundary and declining in the mid-Hirnantian.

The shelf sequence on the eastern margin of the Welsh Basin (UK) records early Hirnantian sea-level fall with a widespread erosion surface and channels that incise deeply into shelf mudstones. Above the erosion surface are marine sandstones deposited during the subsequent transgression. In one channel, at Meifod in Powys, Central Wales there is a more complex fill that includes a significant unit of limestone below the main sandstone body. The channel is about 370m wide and cuts at least 27m into the shelf mudstones. The sediments that form the initial, 8m of the channel-fill are sandy bioclastic packstones and grainstones with a fauna dominated by transported bryozoans. Oolitic intraclasts and phosphate nodules also occur. The limestones occur as a series of localised domes and pillars with vertical and overhanging margins. There is no evidence that these are constructional features as they are solely composed of detritus and are topped by a highly irregular corrosion surface. This is overlain by a micritic encrustation containing an *in-situ* fauna of encrusting bryozoans, cystoids, crinoids and clusters of brachiopods. We suggest that the limestones were lithified, karstified and then during the subsequently flooding colonised by a marine fauna. As transgression progressed the karstic surface was buried beneath a shallow marine sandstone cover. Constraints on the interpretation of the events within the Hirnantian channel are provided by comparison of the isotopic compositions of carbonate material with the global isotopic record. Somewhat surprisingly much of the limestone within the channel has Rawtheyan rather than Hirnantian isotopic values, suggesting to us that the detrital carbonate had been eroded from a Rawtheyan source elsewhere on the shelf. The sandstones above the karstic surface on the limestones record typically elevated Hirnantian isotopic values.

The Meifod succession reveals a particularly detailed record of end Ordovician sea-level change and enables an estimation of the magnitude of successive changes. These results are important because they constrain the magnitude and sequence of glacio-eustatic sea-level change which might be related to latest Ordovician biotic change.

# Correlation of the middle Silurian graptolite crisis and coeval laminated sediments across the Baltic Shield and East European Platform

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Oral Presentation

The near-total extinction of the graptolites at the end of the *Cyrtograptus lundgreni* Chron in the Late Wenlock (middle Silurian) forms part of a global extinction-radiation event much resembling more well-known Lower Palaeozoic marine faunal crises. The event records a 95 per cent extinction among graptolites (Lenz & Kozłowska-Dawidziuk 2001) = the 'Big Crises' of Jaeger (1991), the '*lundgreni* Event' of Koren´ (1991), or a part of the Mulde Event of Jeppsson & Calner (2003). The event also coincides with a positive $\delta^{13}C$ excursion from remote locations (Kaljo et al. 1997; Zimmerman et al. 2000; Kozłowska-Dawidziuk et al. 2000; Samtleben et al. 2000; Saltzman 2001), implying that this might have been a significant oceanographic-climatic turnover.

New biostratigraphic data from distal epicontinental strata of the Grötlingbo-1 core, southern Gotland (Sweden), constrain the extinction interval to within less than a 3.58 m thick interval without graptolites, which is between the last occurrence of *Monograptus flemingii* and the first occurrence of *Gothograptus nassa*. The 0.38 m thick Grötlingbo Bentonite occurs within the upper part of this interval. This bentonite post-dates the extinctions and its base is 2.83 m above the youngest find of *M. flemingii*. The non-graptolitic interval below the bentonite includes a 0.8 m thick unit of conspicuously laminated, calcareous mudrock.

The investigated interval also contains a rich acritarch succession. The frequency of acritarchs varies depending on stratigraphic interval. The part of the core yielding *M. flemingii* is characterised by a quite abundant acritarch assemblage that is poorly diversified and dominated by the genus *Leiofusa*. Contrary, the interval with no graptolite fauna includes a very poor, low frequency acritarch assemblage, with the same dominant genus. The same trend, both in diversity and frequency, is observed in the Bartoszyce core (Masiak & Kozłowska-Dawidziuk 2000), although here, the dominant species of *Leiofusa* is different.

The graptolite and acritarch successions in Grötlingbo-1 core show strong similarities to the Bartoszyce core in the East European Platform of Poland. The coincidence of the extinction event and barren, laminated basin facies, similarly, occurs in the Bartoszyce core and is previously known also from the Riga Formation (Ancia Member) in Latvia. Therefore, laminated basin facies was a widespread extinction-related phenomenon across the Baltic Shield and East European Platform.

The Grötlingbo-1 core further serves as an important link between the laminated basin facies and the carbonate platforms that fringed the basin coastlines. The corresponding time interval in outcrops and the Hunninge-1 core of central Gotland, and in the Ruhnu (500) core off Estonia (Põldvere 2003), includes a basin-regional unconformity overlain by oolitic strata and the Grötlingbo Bentonite. Thus, the brief but conspicuous interval with widespread laminated basin facies correlates with pronounced environmental changes also in the more proximal carbonate platforms.

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# Consistency of the faunal replacement and environmental change through Ordovician and Silurian transition in South China

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Oral Presentation

Patterns of graptolite species turnover during the latest Ordovician mass extinction have been studied based on four continuous Ashgillian to earliest Llandovery sections together with data from more than 30 other published sections. Graphic correlation among these sections reveals that the mass extinction was gradual or stepwise and began with a major extinction event spanned near the top of *Tangyagraptus typicus* Subzone to the middle of the *Normalograptus extraordinarius* Biozone. A secondary, more minor pulse of extinction took place late in the upper *Normalograptus persculptus* Biozone. The Ordovician DDO graptolite fauna was completely replaced at the end of Ordovician and a new Silurian normalograptid fauna occurred from the base of the *Akidograptus ascensus* Biozone. A *Hirnantia* brachiopod fauna associated with trilobite *Dalmanitina* and other shelly faunas usually occur from the lower *N. extraordinarius* Biozone to the lower *N. persculptus* Biozone in the Yangtze region, in particular from the Upper Yangtze region. However, the *Hirnantia* fauna became extinct before the end of the *N. persculptus* Biozone. An early Rhuddanian *Alispira* brachiopod fauna replaced the *Hirnantia* fauna in near shore, shallower water environmental conditions of southwestern margin of the Yangtze Platform.

The change of lithofacies and biofacies through the Ordovician and Silurian transition on the Yangtze Platform is consistent with the stepwise mass extinctions, recovery events, global sea-level changes, and regional palaeogeographic configurations. Facies patterns through three intervals, late-mid Ashgill, Hirnantian, and early Rhuddanian, indicate that black shale occupied most of the Yangtze Platform region during the late-mid Ashgill and early Rhuddanian, while the Hirnantian developed more diverse facies types. The black shale was replaced by carbonate facies during the Hirnantian coincident with a global sea-level low stand. The early Rhuddanian pattern of biofacies is a result of global sea-level rise, which may be synchronized with a recovery bioevent of graptolites after Hirnantian mass extinction.

# Late Ordovician cool water bryozoan mud mounds from Libya

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Oral Presentation

Upper Ordovician bryozoan mud mounds are identified from subsurface well material and seismic data of the Jifarah Formation of Tripolitania, NW Libya. These limestones form part of a much wider, high latitude belt of cool water carbonates across several hundred kilometres through NE Spain, Morocco, Algeria and western Libya, which lay on the NW margin of Gondwanaland. In the mud mounds, the diverse bryozoan assemblage includes delicate and robust branching, encrusting and nodular bryozoan growth forms. The mounds lack organic framework and microbial fabrics; limestones have mudstone/wackestone matrices and a floatstone texture. Regional geophysical data suggest rapid thickness changes between wells, where mud mounds in complexes up to 100m thick had some topographic relief over the surrounding muddy sea floor. In North Africa, glacial advances have been dated from Caradoc – Lower Silurian, although widespread glacial deposits are mostly dated as Hirnantian. The Jifarah limestones have been interpreted as developing during an early Ashgill period of warmer climates that preceded glaciation, when coral - stromatoporoid reefs formed at low latitudes in areas of Laurentia and Baltica. The Jifarah limestones are overlain by glaciomarine shales of Hirnantian age. Contemporaneous bryozoan mounds in NE Spain were interpreted as outer-ramp features; they became exposed during Hirnantian regression, and are also overlain by Hirnantian glaciomarine shales. It is proposed here that analogues of the Jifarah bryozoan mounds are represented from the Quaternary of the Great Australian Bight by cool-water bryozoan mud mounds, which apparently flourished at depths of 80-200m during the last glacial lowstand, associated with ocean current upwelling. Well data and seismic images indicate that these mounds form elongate features up to 10km across the slope, in mound complexes that form part of a much wider slope-parallel zone across several hundred kilometres. This comparison suggests that the Jifarah mounds may have developed in slope/outer ramp environments at an early Ashgill lowstand, and in cool climates. Late Caradoc and Ashgill stromatactis mud mounds of the Kullsberg and Boda limestones in Sweden may provide further evidence of cool water mound growth at times of regional or wider lowstand.

# Ordovican geography: probabilities and problems

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Oral Presentation

Terrane positioning is best achieved through combining the separate disciplines of palaeomagnetics (which can only determine palaeolatitudes and rotations), palaeobiogeography (which can demonstrate closeness and distancing of terranes) and, to a lesser extent, sediment distributions (which can help towards latitudinal positioning. The relative positions of the three large terranes in today's North Atlantic area, Laurentia (most of North America), Baltica (most of northern Europe), and Gondwana (which included South America, Africa, peninsular India, Antarctica, Australia and more) are reasonably well-known. The medium-sized terrane of Avalonia is also well-constrained, moving as it did from being an integral part of Gondwana at the start of the Ordovician, across the Iapetus Ocean, and docking with Baltica as the Ordovician ended. All of these were in the southern hemisphere, although Laurentia straddled the palaeoequator. The large terrane of Siberia (which consisted of much, but not all, of today's Siberia) is known to have been inverted, in relation to today's orientation, and much of it was in northern latitudes during the Ordovician; however, its distance from Baltica is unknown at the beginning of the period, although probably relatively close by Ordovician-Silurian boundary times. Most of the northern hemisphere was occupied by the vast Panthalassic Ocean. Some of the most difficult questions are posed by the many terranes, some of which were substantial, which may or may not have been either integral parts of, or immediately adjacent to, the vast Gondwana superterrane. The Armorican Terrane assemblage (ATA), which covered much of southern Europe, including France and the Iberian Peninsula, includes faunas indicating that it was

probably an integral part of Gondwana during the whole Ordovician. However, the relationships between the ATA and the various parts of Sardinia, the Perunica (Bohemia) Terrane, Apulia, the Hellenic Terrane, and the two terranes (Pontides and Taurides) which today make up Turkey are arguable. Comparably, the Middle Eastern Sanand, Lut, Alborz, Afghan and Karakorum Terranes have yielded variable amounts of evidence, much of it slim, which makes their Ordovician positions uncertain. Today further east, the Ordovician positions of the North China, South China, Sibumasu and Annamia (Indo-China) terranes are also debateable, although faunal evidence indicates that the South China and Sibumasu terranes were not far away from each other during at least the late Ordovician. Even more contentious is the immense area of Central Asia today: all workers are agreed that a large number of Ordovician terranes, possibly as many as twenty, are represented there; however, their relative positions and relationships both with each other and with the large terranes in the Ordovician are not agreed. To today's west of Gondwana, the various terranes making up Argentina are now better-known, although the geological history of the Precordillera Terrane is in dispute; however, the central America area has several Lower Palaeozoic terranes whose Ordovician identities and positionings are very poorly constrained.

# The Ordovician of the Valongo Anticline (Portugal)

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Poster Pesentation

The Valongo Anticline, near Oporto, is situated in the Central Iberian Zone of the Iberian Massif, lying in the axial part of the Variscan Fold. The Ordovician rocks discordantly overlie folded metasedimentary rocks of the Schist-Greywacke Complex, interpreted to be of Precambrian? and/or Cambrian age.

The Ordovician sequence above the unconformity starts with shelf deposits represented by alternances of fine and coarse grained sediments of the Santa Justa Formation (Arenigian), which includes massive quartzites that correlates with the "Armorican Quartzite" facies so widely distributed in southwestern Europe. The Arenigian alternances are composed mainly of banded arenitic, siltitic and pelitic beds. We emphasize the occurrence of exhalative-sedimentary intercalations ("black layers") and of distal volcanogenic prints in the metasediments. Organic matter is represented by migrabetumes and fusinitizated fragments which sometimes have a graphitoïd texture. Sporadic occurrence of some transported algal and bryozoan remains also suggest that these black intercalations of carbonaceous fine-grained black sediments were related with episodic development of anoxic conditions. Towards the top of Santa Justa Formation, a lingulid shell bed consisting in a phosphate-rich layer allows direct correlation with the same horizon recorded in other places of the Iberian Peninsula, France, Morocco and Serbia, and suggest the proximity to the coastline of northern Gondwana by the early Middle Ordovician.

In the Valongo Formation (Upper Arenigian to Lower Dobrotivian) the record of diploporid echinoderms is discrete comparatively with their great abundance in Spain, which may be related with the preference of these echinoderms for a shallow and softer substratum, conditions only present in the inner parts of the Central-Iberian platform. Relatively deeper environments are also indicated by some cheirurid and trinucleid trilobites (*Dionide, Valongia, Protolloydolithus*) which are typical or exclusive from the Valongo Formation.

The Ordovician sequence of the Valongo Anticline ends with the Sobrido Formation, that lies disconformably on the Middle Ordovician shales and consists of Kosovian (Hirnantian) quartzites and glaciomarine diamictites.

# Glaciation, $CO_2$, and organic carbon burial in the early Silurian (Wenlock)

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Oral Presentation

The Llandovery-Wenlock boundary interval marks a major turning point in the middle Paleozoic. The late Ordovician glacial epoch, which may have begun as early as the Caradoc, continued into the early Silurian. Recent advances in South American stratigraphy are beginning to indicate that the bulk of glaciation was coming to a close by the late Llandovery.

The Llandovery-Wenlock boundary is also coincident with a major biotic crisis known as the Ireviken Event where roughly eighty percent of all conodont species became extinct. A similar fate was shared by many marine organisms including trilobites, graptolites, and acritarchs. A pronounced shift in the carbon isotope ratio of marine carbonates began during this protracted extinction event and lasted much of the early Wenlock (Sheinwoodian). The Llandovery-Wenlock boundary interval is also marked by a change in carbonate deposition from clastic/marl dominated lithologies to clean carbonate deposition throughout the tropics. Interpretations of these coincident changes in biology, chemistry, and lithology that occurred during this interval of the Silurian have produced several contrasting oceanographic models. However, the causal connections between glaciation and the Silurian global carbon cycle remain a matter of debate. In particular, the location and timing of organic carbon burial have been difficult to define.

In an effort to determine if the coincident increase in carbonate production and carbon isotope values observed elsewhere is a global pattern, carbon isotope ($\delta^{13}C_{carb}$) stratigraphy was carried out on three geographically widespread, well dated marine carbonate successions from the mid-continent of North America. The Ireviken Excursion is recorded in Tennessee, Ohio and Iowa. Carbon isotope values begin at +2.5‰ at the base of the Maddox Member of the Wayne Formation in central Tennessee and increase to +3.9‰ before decreasing back to a baseline of +1‰ halfway through the Maddox Member. In a core from Eastern Iowa, carbon isotope values begin at +1‰ at the base of the Scotch Grove Formation. The Ireviken Excursion is recorded in a rapid shift to +4.5‰ with heavy values continuing into the Gower Formation. A quarry from Western Ohio exposes the Brassfield and Dayton Formations with values beginning at +2.3‰ at the base of the Dayton but only reaching a high of +3.4‰. In each of the three sections an unconformity occurs immediately prior to the Ireviken Excursion, consistent with the rise in $\delta^{13}C$ and clean carbonate deposition tracking post-glacial transgression.

In order to investigate changes in Silurian climate, paired $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ analyses were carried out on the section from Tennessee. The results of this study indicate that a positive shift in $\delta^{13}C_{carb}$ coincided with a minimum in $\delta^{13}C_{org}$ (-30.11‰). This suggests that a period of rising $pCO_2$ was also characterized by enhanced organic carbon burial, which supports a model in which the site of deep water formation switched to low latitudes during the post-glacial early Wenlock period.

# The Upper Ordovician-Lower Silurian stratigraphic succession in the Caledonian foreland basin of central Sweden: relationship to the Hirnantian glacial interval

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Poster Presentation

The Upper Ordovician-Lower Silurian sedimentary rocks in Jämtland, central Sweden, form part of the Caledonian foreland basin-fill. This is an area relatively isolated from the nearest Ordovician-Silurian outcrops in Scandinavia. As a consequence and due to previous limited biostratigraphic control, these strata have previously not been adequately placed in the context of global changes related to the Hirnantian glacial interval and have received little attention in related discussions. The most recent analyses have, however, integrated detailed studies on sedimentology with conodont biostratigraphy and brachiopod faunas and the results are presented herein.

Stratigraphic summary

A major part of the upper Caradoc to upper Ashgill succession in Jämtland is characterised by continuous and uniform deposition of clay and silt over wide areas, now forming the Kogsta Siltstone. The uppermost few metres of this unit yield shelly faunas suggesting a Rawtheyan-Hirnantian age. Overlying strata are much more complex stratigraphically, including erosional surfaces and complex lateral facies relationships between the Ede Quartzite in the west and the Kyrkås Quartzite in the east.

In the west, a major syn-sedimentary erosional surface, with at least one metre of relief locally, forms the boundary between the Kogsta Siltstone and the Ede Quartzite. Lower parts of the latter unit consist of medium to thick-bedded quartzites capped by a discontinuity surface. Above this discontinuity the unit consists of a basal favositid biostrome overlain by thin bedded, calcareous sandstones, skeletal limestones and intensely bioturbated shales. The presence of the conodont species *Kockelella*? *manitoulinensis* and *Pranognathus tenuis* in this upper part establishes for the first time the previously controversial age of early-mid Aeronian for the upper Ede Quartzite. Brachiopods from this upper part also suggest a mid-Aeronian age for the strata. Hence, a significant time gap separates the lower part of the Ede Quartzite (or less likely the uppermost Kogsta Siltstone) and the upper Ede Quartzite, and the Rhuddanian and perhaps parts of the Hirnantian, are missing. The Ede Quartzite, which represents the end of terrigenous deposition in this part of the basin is overlain by the Berge Limestone, a fine-grained micritic limestone. A conodont sample from the base of this unit yields a similar fauna as that in the upper Ede Quartzite.

By comparison, the eastern part of the basin shows a markedly different development. As indicated by brachiopods and trilobites, coarse clastics (the Kyrkås Quartzite) entered the basin during the Rawtheyan-Hirnantian transition and two Late Ordovician depositional sequences separated by a transgressive surface were developed. The presence of the brachiopods *Dalmanella testudinaria*, *Eostropheodonta hirnantensis*, and ?*Kinnella kielanae* and the trilobites *Dalmanitina* (*Mucronaspis*) *mucronata* and *Brongniartella platynota* a few meters above this transgressive surface constrain the age of the upper sequence to the Hirnantian. Graptolites of the *Normalograptus persculptus* Biozone are found only some metres above this level. The two sequences indicate two late Ordovician regressive events in this part of the basin. Due to post-Ordovician erosion, these are the youngest preserved sediments in the eastern part of the study area.

Conclusion

The new results constrain the stratigraphic position of the O-S boundary to within less than a three metres thick interval and thereby improve, significantly, the timing of facies changes within the Jämtland basin complexes. The new data show that a substantial downward shift in coastal onlap and hiatus development overlap in time with the glacial interval, suggesting that the interaction of allocyclic controls such as glacio-eustasy and climate change were the overriding controls on deposition.

# Ordovician-Silurian boundary near La Paz (Bolivia): stratigraphy, sedimentology, chitinozoan biostratigraphy and regional palaeogeographic implications

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Oral Presentation

The Ordovician-Silurian transition along the Eastern Cordillera of Bolivia north and east of La Paz is characterized by a conspicuous diamictite-bearing unit (Cancañiri Formation) which overlies several different upper Ordovician units (Amutara, San Benito and Tokochi formations), and underlies the shales of the Silurian Uncía Formation. Near the pass of La Cumbre, 20 km NE of La Paz and at an altitude of about 4850 m, the road from La Paz to Coroico offers a continuous outcrop of the Cancañiri Formation, and allows to corroborate its stratigraphic relationships and to test some ideas and interpretations previously proposed for these units.

A detailed stratigraphic section including facies analysis and sampling for petrology and chitinozoan biostratigraphy allowed for a thorough interpretation of sedimentary processes and environments involved during its deposition, and to reassess and constrain the age of this unit. Intermediate to distal turbidites and dark shales indicate a deep marine environment, with interbedded mud flows, debris flows, slumps and large slided slabs providing evidence for sediment instability and resedimentation.

The chitinozoan assemblage present in the Cancañiri Formation includes *Belonechitina* sp., *Conochitina* sp., and *Cyathochitina* sp. B Paris 1981. Despite its poor preservation, this newly discovered assemblage indicates a middle to late Llandovery age, which settles the long maintained discussion on the age of this unit, at least for this part of the Peru-Bolivia basin. The resedimented character of the deposit explains the Ordovician fauna previously described in the Cancañiri Formation, which must be considered as recycled from underlying units. Evidence for glaciation, in the form of glacially faceted and striated clasts, as well as large granitoid boulders within the resedimented materials, indicate local glaciation of the source area, and may be interpreted as recycled from former glacigenic deposits. The evidence found in the Cancañiri Formation corroborates glaciation of the source area most probably prior to the late Llandovery (Telychian), but does not allow to confirm the precise age of the glaciation in this part of Gondwana. A similar chitinozoan assemblage has been recently found in equivalent diamictite-bearing units from adjacent Early Paleozoic intracratonic basins in South America (Amazonas, Parnaiba, Chaco-Paraná), and from the southern end of the Peru-Bolivia basin, suggesting an Aeronian to early Telychian age for all of them. In the case of central and western Bolivia, tectonic deformation and the resulting relief along the active margin of western Gondwana may be respectively identified as the origin for the instability and local glaciation. The new data imply that the Ordovician-Silurian boundary was not preserved in the area around La Paz, and that an erosional hiatus (disconformity with variable regional significance) is present between different Ordovician units (Caradoc quartzites and shales of the Amutara Formation in the case of La Cumbre) and the Cancañiri Formation. The euxinic black shales of the Tokochi Formation, in the central Altiplano and Eastern Cordillera of Bolivia, would therefore represent the youngest Ordovician unit in the region, and more research should be focused on it.

# Traces of frost action in the *Obolus*-Sand: the evidence for subglacial climate in the mid Cambrian to early Ordovician (Tremadocian) of the East Baltic

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Oral Presentation

The Middle Cambrian to Early Ordovician (Tremadocian) shallow marine siliciclastic deposits of the East Baltic known as *Obolus*-Sands demonstrates remnants of beach and bar systems as well as discontinuity surfaces developed during periods of the sea level low stand and subaerial exposition of sediments. Various features suggesting frost action during their formation can be seen in the natural and artificial outcrops. Most of the observed structures most likely had been caused by seasonal freezing, but existence of collapse structures may suggest that permafrost developed during a pronounced subaerial exposition of sediments in the periods of regression. The best preserved ice wedge casts, can be observed in tunnels on the east side of the Syas River near the village of Rebrovo, east of St Petersburg. They are apparently singenetic to the deposition of the uppermost Sablinka Formation. However, collapse occurred during transgression at the beginning of the Late Cambrian (*Agnostus pissiformis* to *Leptoplastus* biozones) at the initial stages of deposition of the Ladoga Formation. The collapse structures reported from the Cambrian deposits of Sweden (e.g. 'Bratterfors plugs' from Västergötland and 'funnel grabens' from Skåne) were formed within the same time interval and could also be a result of transgression of the sea onto the shore affected by permafrost.

According to the latest palaeogeographic reconstructions Baltica in the Mid to Late Cambrian was geographically inverted with Caledonian margin facing north and occupying latitudes of more then 40°, whereas the Uralian margin faced the North African part of Gondwana at somewhat more then 60° south. Even if assume that position of the geographical pole in the Cambrian was somewhat different from the palaeomagnetic pole and Baltica was shifted up to 10° south, Scandinavia still maintained geographical position slightly more then 50° south. Development of ice wedges about a size of 'Bratterfors plugs' suggests an existence of severe periglacial environment at these latitudes with mean annual temperature below -6° C. The appearance of extensive permafrost with a development of ice wedges in temperate latitudes between 40° and 50° could be regarded as a strong evidence for existence of extensive ice shield covered southern part of Baltica. A substantial sea level rise at the transgressive phase of the Black Mountain Event could be caused by degradation of the Baltic ice shield at the beginning of the Ordovician resulted from a rapid northward drift of the continent at that time.

# Ordovician conodonts in different paleogeographical environments of the Southern Urals

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Oral Presentation

Among complexes of the Ordovician convergent margin investigated in the Southern Urals structure, the Guberlinskaya ensimatic island arc complexes and those formed in basins located on both sides of this arc, are distinguished. A marginal basin was located between the Ordovician Guberlinskaya arc and passive margin of the Eastern European craton; another basin – to the east of this arc. Later, since Early Devonian, the part of the second basin was enclosed between waning Ordovician arc and nascent Magnitogorsk ensimatic island arc. In modern structure these complexes are present in Sakmara allochthon and at the boundary of Prisakmara-Voznesensk and Western-Magnitogorsk zones.

Complexes of the marginal basin cover the Tremadoc-Ashgill stratigraphic range. At the Tremadoc level (i.e., Kidryasovskaya Formation) a significant volume is occupied by arkoses formed due to a transportation of terrigenous material from a platfom margin. Facies changes are expressed in presence of shallow-water coarse-grained rocks with shelly fossils and more deep-water

clayish rocks with graptolites. Tuffaceous sandstones and aleurolites predominated at the Arenig-Llanvirn level, are facially replaced by cherty tephroites in the Llanvirn-Ashgill. Tuffaceous rocks of this type (i.e., Kuraganskaya Formation) mark a slope and bottom of the volcanic arc faced to a continental margin; cherty tephroites - arc bottom and forearc trough.

As established on conodonts, complexes of basins located to the east of the Ordovician arc, cover the Arenig-Ashgill stratigraphic range. Redeposited Late Tremadoc *Loxodus bransoni* Furnish has been found as well. This type is traced in a system of nappes where different elements of the paleobasin are juxtaposed. Nappes belong to the structure of an accretionary prism in front of a Devonian Magnitogorsk arc. They are represented by a chert/basalt complex (i.e., Polyakovskaya Formation), which is the upper member of the ophiolite association.

The island arc complex of this basin is represented by Guberlinskaya and Bauluskaya formations. Tuffites, acid and mixed composition tuffs, basalt and rhyolite flows predominate in a section of Guberlinskaya Formation. Conodonts in a section of this Formation belong basically to the Middle Ordovician. These are: *Pygodus serra* (Hadding), *Periodon aculeatus* Hadding, *Eoplacognathus robustus* Bergstrom, *Dapsilodus mutatus* (Branson et Mehl), *Protopanderodus varicostatus* (Sweet et Bergstrom). Acid and basic effusive rocks and minor component of andesites represent Bauluskaya Formation. Series of massive sulfide ore deposits are connected with these rocks in the Mednogorsk area. In the middle part of the section, above ore bodies, where acid and basic effusive rocks are replaced by basaltoids, cherts, jaspers, and cherty/hematite shales are present. The latter yield the Late Caradoc-Ashgill *Hamarodus brevirameus* (Walliser), *Protopanderodus liripipus* Kennedy et al., *Periodon grandis* (Ethington), *Scabbardella altipes* (Henningsmoen), *Belodina confluens* Sweet. Upsection, in Blyava quarry, basalts contain beds of carbonaceous shales with Llandovery graptolites. The Ordovician arc complexes are traced into Tagil Zone.

Guberlinskaya arc waning and arc jump to the east was accompanied by spreading in the basin located between these arcs. It has created conditions for a collision of a dying arc and the platform margin. In the Late Devonian this process coincided with the formation of nappes and high-pressure metamorphites.

## Bryozoa from the Pin Formation (Upper Ordovician – Lower Silurian) in the Tethyan Zone of the Indian Himalayas

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Poster Presentation

The Pin Formation consists of a 280 m thick sequence, from which the lower part (90-220 m) has been dated as the Upper Ordovician (*A. ordovicicus* Zone) and the upper part (220-280 m) as the Lower Silurian. The age is provided by conodonts occurring in the sequence from 90 to 220 m. The uppermost part could be dated by coeval conodont bearing beds from a closely located site at Mikkim.

Micro facial analyse points to shallow marine environment. Three distinct sedimentation cycles are distinguished in the Pin Formation. The middle part of the Formation contains reefal structures built by stromatoporoids and corals. Other fauna is represented by brachiopods, bryozoans, corals, echinoderms, molluscs, tentaculites and trilobites. The glaciation and global cooling phase during late Rawtheyan to Hirnantian cannot be identified through fossils (and sediments); it may be represented by a hiatus between Cycle 2 and 3 (220 m).

Bryozoa appear in the lower part of the Pin Formation becoming most abundant and diverse in the middle part regarded as Caradocian (?) to Ashgillian in age (140-220 m). They seem to be lacking in the Silurian part (220-280 m) of the section. Bryozoans are represented by all main stenolaemate orders. The most abundant and diverse group are bifoliate cryptostomes from which different species of genera *Phaenopora*, *Insignia*, *Pseudopachydictya*, *Graptodictya* and *Pseudostictoporella* were found in the middle part of the Pin Formation. Trepostome bryozoans are less abundant represented by few species of genera *Eridotrypa*, *Monotrypa* and *Monticulipora*. Two phylloporinid bryozoans, *Enallopora* and *Pesnastylus*, occur in the Pin Formation. The latter one is known with the single species from the Upper Silurian of Australia and Lower Silurian of Kazakhstan. Cystoporid bryozoans are represented by the genus *Ceramopora*. Some few species of rhabdomesid bryozoans were also found in this fauna. The cyclostome species *Kukersella borealis* (Bassler 1911) found at the level of 190 m is cosmopolite for Upper Ordovician.

The investigated bryozoan fauna confirms mainly to the Upper Ordovician age dating provided by other groups. However, some distinct Silurian elements occur too. This fauna displays paleobiogeographic connections to Australia and Siberia.

# Radiation of bivalves during the Ordovician: morphological quantification of peri-Gondwanan faunas

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Oral Presentation

Bivalve molluscs underwent a major radiation in Early Palaeozoic times, with no more than 5 genera reported in Early and Middle Cambrian and near 150 in the Ordovician period [1]. This «great Ordovician biodiversification event» has been documented by several uni- or bi-variate analyses focusing on taxonomic diversity [2, 3, 4 & 5], and has been studied by only descriptive approach regarding morphological disparity [2, 3, 5 & 6]. No multivariate analysis have been yet used to assess morphological evolution of this molluscan class. The aim of this work is to establish a multivariate morphospace of Ordovician bivalves relating their fast evolution of disparity during this period.
From this point of view, each genus reported in the Ordovician has been here described according to different morphological statements of qualitative characters (e.g. dentition, ligament, valve shape, ornamentation, shell microstructure, soft parts scars, etc). Each state of character is then encoded and included in a matrix, which is computed by multivariate analysis (PCO). This produce principal components which define the morphospace axes in which bivalve genera are ordinated according to similarities in morphologies.
Then, the spatiotemporal settings of these faunas is compared with evolution and occupation of their morphospace:
*In Early Ordovician times, the majority of bivalves are endobenthic or semi-endobenthic (mainly Paleotaxodonts, Heteroconchs, few Pteriomorphs). They seem to be restricted to siliciclastic environments on peri-Gondwanan shelves (from low to high latitudes of Gondwana, Avalonia).
*In Middle Ordovician times, under intrinsic impulse (e.g. development of gill grade for cardiolariids –Paleotaxodont forms–), epibenthic and semi-endobenthic faunas start to expand. If Paleotaxodonts and Heteroconchs are still abundant, Pteriomorphs increase in diversity, and morphological disparity follows.
*In Upper Ordovician, and after a fast morphological diversification, these faunas colonize other palaeocontinents (Laurentia, Baltica, Siberia) and prevail there in more warm and carbonate environments (extrinsic factors). Simultaneously, taxonomic diversity decrease on peri-Gondwanan margins.

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# Late Ordovician graptolite extinction and biogeography of graptolites in the Yangtze region

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Poser Presentation

The present work is mainly based on four continuous Ashgillian to earliest Llandovery sections together with data from more than 30 other published sections from South China. The studied sections represent relatively shallow-water and deeper-water belts in the Yangtze region. We have combined the species range data from these sections into a single graptolite composite standard sequence (GCSS) using Shaw's (1964) graphic correlation technique (see Fan, 2001). As is common in graphic correlation analyses, the stratigraphic scale of the GCSS is a function of the scale of the reference section, the Wangjiawan North section. A temporal scale for graptolite zones in the Ordovician and Silurian developed by Cooper and Sadler (in press) and Melchin et al. (in press) was adopted and the GCSS ranges were plotted against this temporal scale.

The new GCSS reveals that the mass extinction was gradual or stepwise and began with a major extinction event that spanned an interval from near the top of *Tangyagraptus typicus* Subzone to the middle of the *Normalograptus extraordinarius-N. ojsuensis* Zone. A secondary, more minor pulse of extinction (minor extinction) took place late in the interval of the upper *Normalograptus persculptus* Zone. This result coincides with a binary cluster analysis of the four sections, especially the GSSP candidate section of the Hirnantian Stage, the Wangjiawan North section, which indicates two separate faunal turnover near the base of the *N. extraordinarius-N. ojsuensis* Zone and the top of *N. persculptus* Zone.

Using temporally scaled range data, species diversities, extinction and origination rates can be calculated more precisely. According to the species-area relationship method, we can calculate that if the area of the Yangtze Sea were reduced to 50%, the diversity will drop down to 19%. But actually, in the Yangtze region, during the major extinction event, less than 50% reduction of the area of the epicontinental sea was gone with 75% reduction of graptolitic species. So, the deterioration of the environment, such as the cooling of the seawater and the accompanying changes of the quality of the seawater (e. g., the upward movement of dysaerobic and anaerobic water), can result in at least 56% declining of the species diversity.

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# SinoCor 3.0, a biostratigraphic program for graphic correlation

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Poster Presentation

As a method for quantitative biostratigraphic analysis, graphic correlation has been widely applied in biostratigraphic analysis (Sweet, 1984; Sweet and Tolbert, 1997; Kleffner, 1989,1995; Cooper and Lindholm, 1990; Cooper, 1992; Zhang and Chen, 1994; Zhang, 1995; Carter *et al*., 1995; Grubb and Finney, 1995; Klapper and Kirchgasser; Macleod, 1995; Mann and Lane, 1995; Melnyk, 1995; Finney *et al*. 1996; Fan *et al*., 2002). SinoCor is strictly designed in accordance with the principles of graphic correlation and therefore can be effectively used in stratigraphic analysis of fossiliferous sections of any age.

In order to enhance the function and capacity of SinoCor 3.0, the authors began to design the new version of SinoCor from early 2004. It is written in Visual Basic programming language and designed for Microsoft Windows. SinoCor 3.0 adopts interactive graphical interface and can deal with almost unlimited dataset, which is only depended on how fast the user's computer is.

1. What is new in SinoCor 3.0?

- SinoCor 3.0 was designed under Windows 2000 circumstance and can also run under Windows 9x, Me, XP etc.
- The processing ability of SinoCor 3.0 enhances greatly. It can deal with almost unlimited dataset, which is mainly depended on how fast the user's

computer is.

- SinoCor 3.0 supports dogleg fit method as well as linear fit method.
- SinoCor 3.0 is more convenient to use. Its graphic interface is similar with that of some popular software such as Microsoft Word. All the functions can be obtained using mouse.
- The output function has been greatly enhanced. Users can output results to any printer supported by Windows.
- All the steps during the compounding are restored and users can back to any previous step.
- The result can be output to Microsoft Excel as data or to Corel Draw as figures.

**2. System requirement**

- Intel Pentium II processor or equivalent
- 64MB of RAM
- 20M hard disk space
- 65,000-color (High Color/16-bit) video display card
- printer supported by Windows
- MS Windows 95 or higher version

**3. Acquisition**

SinoCor 3.0 was designed and programmed for scientific purpose. Anyone that wants to have a copy please contacts the present authors, fanjuanxuan@yahoo.com and ydzhang@jlonline.com. It will also be put on the new website of International Subcommission on Ordovician, www.ordovician.org.cn.

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# Changes in Darriwilian acritarch and prasinophyte assemblages of the Yangtze Platform (South China) and the Barrandian area (Czech Republic)

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Oral Presentation

Sediments of the Upper Dawan and Shizipu formations (Yangtze Platform, South China) and of the Sárka Formation (Barrandian area, Czech Republic) are characterized by different fossil groups, including common and well diversified assemblages of organic walled microfossils (OWM), such as acritarchs, prasinophytes and chitinozoans. During the Lower and Middle Ordovician both areas were located in different parts of peri-Gondwana. A position from intermediate to low palaeolatitudes has been documented for the Yangtze Platform while a placement of the Barrandian area is supposed to correspond to high southern palaeolatitudes. Succesions in both areas are well dated by graptolites (Barrandian area) and/or by graptolites and conodonts (South China), respectively.
However, the composition of OWM assemblages throughout the transition from the Lower to the Middle Ordovician shows very similar patterns of diversification and evolution in both peri-Gondwanan sectors. An example of comparable trends in the development of acritarch and prasinophyte assemblages has been recently established within the Middle Ordovician sequence, namely above the base of the Darriwilian Stage. This stratigraphic interval is characterized by a global transgressive event (CHEN & BERGSTROM 1997).

Changes in acritarch and prasinophyte assemblages.

BROCKE et al. (2000) distinguished four acritarch assemblages (designated as assemblages *A* to *D*) within upper Arenigian – lower Llanvirnian sequences on the Yangtze Platform. The older assemblages *A*, *B*, and also the younger assemblage *D* are highly diversified, whereas the assemblage *C* (= *U. austrodentatus* graptolite biozone and corresponding to the base of the Darriwilian Stage) is characterized by a common occurrence of large representatives of the prasinophyte genus *Leiospharidia* associated with poorly to moderately diversified acritarchs.
Comparable results regarding diversification trends in acritarch and prasinophyte assemblages have been also documented from the Barrandian sections by FATKA (2003 - locality Praha - Cervenývrch and FATKA et al.,

1996 - locality Rokycany – Drahous).
Study of changes in acritarch and prasinophyte assemblages during transgressive-regressive pulses in moderately deep to deeper water enable to explain fluctuations in diversity and productivity of the primary producers.

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## A late Ordovician global warming event?

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Oral Presentation

The attention focussed upon the latest Ordovician Hirnantian glacial event has deflected attention away from an important pre-Hirnantian climatic fluctuation. Changes in pre-Hirnantian facies distributions, endemic faunas, and migration of key trilobite and brachiopod taxa all point to a phase of global warming. On the Gondwana continent the event is marked by a short-lived, but practically universal interval of bryozoan limestone deposition interrupting previously clastic formations. Movement pole-wards of previously palaeoequatorial taxa (known in earlier strata from China and the Far East), including hammatocnemid trilobites and *Paraphillipsinella*, is consistent with the same climatic change. A few trilobite taxa, such as the cheirurid *Heliomera* from the Cystoid Limestone of Spain, apparently crossed to Gondwana from Laurentia at the same time. On the Yangtze Platform in China the same climatic phase induces a most unusual endemic evolution of graptolites such as *Tangyagraptus*, presumably adapted to elevated temperatures. In Baltica/Avalonia the distinctive and richly fossiliferous Boda Limestone and its equivalents appears to equate with the same event. Other carbonate mudmounds marking the event are known from Ireland, England, Estonia and as far eastwards as eastern Siberia. The interval marks a peak in strophomenoid brachiopod diversity. Laurentian endemic platform coral faunas, and a diverse succession of Midcontinent conodont faunas are probably the result of unusually elevated temperatures on that palaeocontinent. This positive climatic excursion invariably predates the latest Ordovician deterioration.

## Modelling atmospheric $CO_2$ changes at geological timescales

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Oral Presentation

Temporal variations of atmospheric $CO_2$ at geological timescales ($\Delta t > 0.1$ my) can be described with simple geochemical box models. Such models couple the major biogeochemical cycles, such as those of carbon, calcium, magnesium, sulphur, etc. They contain a representation of the climate system, either through simple parametric relationships (Berner and Kothavala, 2001), energy balance models (François and Walker, 1992) or even general circulation models (Donnadieu et al., 2004). They thus allow taking into account the feedbacks between climate and geochemical processes. The core of these models is the description of continental weathering, which is a function of surface temperature, runoff, soil $pCO_2$ and rock type. Recent work has emphasized, for instance, the important role of basaltic rocks in the evolution of atmospheric $CO_2$ and climate over Earth's history (Dessert et al., 2001).
In this talk, the general characteristics of geochemical box-models will be described, together with the hypotheses on which they rest. Some results will illustrate the use of these models for calculating long-term evolution of atmospheric $CO_2$ and climate over Cenozoic or Phanerozoic times, as well as for studying shorter geological events, such as the impact of basaltic trap emplacement and biological crisis on the carbon cycle and climate at the K-T boundary (Dessert et al., 2001), the Permo-Triassic boundary (Grard et al., in preparation) and in relation with snowball Earth episodes (Goddéris et al., 2003).

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## Emergence of the Palaeozoic Evolutionary Fauna in the early Ordovician of the Alborz Range, northeastern Iran

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Poster Presentation

The Simeh-Kuh section northwest of Damghan (eastern Alborz Range) provides a nearly continuous record of environmental and faunal changes from the Upper Cambrian through the Middle Ordovician. The Upper Cambrian bioclastic carbonates of the Mila Formation formed in shallow water. They are comprised mostly of *Billingsella* coquina beds and echinoderm limestones which accumulated in some high energy environments. Carbonate sedimentation ceased by the end of the Cambrian and started again after rapid subsidence with deposition well below storm wave base in the basal Ordovician. The Tremadocian interval of the lower Lashkarak Formation is represented by fine clastics with a characteristic deep water trilobite fauna dominated by *Schumardia* and agnostides, but including also *Apatokephalus*, *Asaphellus, Dikelocephalus, Asaphopsis,* and *Psilocephalia*. Shallow water brachiopod faunas dominated by the billingsellid *Protambonites* and orthides are only preserved in some slump deposits and silty limestone beds most likely representing tempestites.

The lower Arenig boundary is well defined by the appearance of *Tetragraptus* and *Didymograptus,* and a characteristic trilobite assemblage including *Taihungshania miqueli*, *Paramegalaspis*, *Asaphellus*, and *Basilicus* (*Basiliella*). In the Lashkarak Formation, most Arenig deposits formed in storm dominated environment slightly below storm wave base. The background sedimentation is characterized by silt and clay. Beds of fine grained sand within the *Prioniodus elegans* Biozone and bioclastic limestones in the predominantly carbonatic sequence are representing proximal tempestites. The transition to a storm dominated carbonate sedimentation is marked by the sudden appearance of the obolid *Thysanotus* and the associated lingulate brachiopod assemblage known also from Baltica (South Urals, Poland and Estonia) and Perunica. It is regarded as an opportunistic fauna taking advantage of a rapidly changing environment. With the onset of carbonate deposition during the uppermost *Prioniodus elegans* or *Oepikodus evae* biozones, benthic faunal assemblages acquire typical features of the Palaeozoic Evolutionary Fauna. The importance of trilobites declines dramatically, whereas rhynchonelliform brachiopods become predominant. The early appearance of bryozoans and ostracodes in the upper *P. elegans* Biozone and the diversification of echinoderms are also remarkable. Taxa of the cold water group are clearly dominating the upper Tremadoc and Arenig conodont faunas which are "contaminated" by only a few elements of the temperate water group. The faunal composition typical for the Balto-Scandic province is well comparable to other cold water peri-Gondwana areas and far less diverse than on Baltica.

The series of events preceeding the emergence of benthic assemblages dominated by the Palaeozoic Evolutionary Fauna strongly resembles the succession of Baltica. On both plates, the development of storm dominated environments following a pronounced sea level rise is connected with the invasion of the *Thysanotus* brachiopod assemblage and an onset of carbonate sedimentation formed in temperate water environments at higher latitudes. However, Lower Ordovician trilobites of the Alborz terrane retain strong Gondwanan signatures and the Arenig rhynchonelliformean brachiopod assemblage includes *Yangtzeella* known from South China and the Turkish Taurides. Thus, the observed similarity presumably reflects a similar paleogeographic position in latitudes between 40 and 50 degrees south. It most likely displays a general pattern in environmental and faunal turnover occurring in higher latitudes of the southern hemisphere between Baltica and East Gondwana during early Ordovician times.

# The earliest record of a colour pattern in molluscs

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Poster Presentation

Unique preservation of the oldest colour pattern (? 490 Ma) of a molluscan shell, and the first record in monoplacophorans, are reported from the borehole that penetrated the Early Ordovician (Tremadocian) sediments in the Pechora Basin of Arctic Russia. The unusual preservation reflects low subsidence temperatures and minimal tectonic deformation, possibly due to close association of the fossil-bearing strata to the solid metamorphosed Precambrian basement. A colour pattern in the form of radial stripes coincides with the pattern of multiple muscle attachments to the shell which obviously influenced the mantle margin responsible for the shell formation and pigment deposition. We assume that this type of colour pattern is one of the most ancient to have appeared in molluscan evolution.

# The Orthida: Disparity, diversity and distributional dynamics in a Palaeozoic brachiopod clade

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Oral Presentation

The orthides were one of the most diverse, numerically-abundant and successful groups of Palaeozoic benthos, appearing first in the early Cambrian and disappearing around the Permian-Triassic boundary. The two suborders, the orthidines (impunctates) and dalmanellidines (punctates) appeared sequentially during the Cambrian and Ordovician, respectively, diversifying into deeper-water and carbonate environments during the Ordovician and Silurian in a step-wise manner. The overall morphological disparity of the group peaked during the Caradoc; although the orthidines developed much greater disparity during the mid Ordovician, already in the late Ordovician, the dalmanellidines were a focus for increasing disparity and morphological innovation. Although the orthidines developed their greatest disparity during the mid Ordovician, the overall morphological disparity of the Orthida peaked during the Caradoc, where the dalmanellidines were a focus for increasing disparity and morphological innovation. The Ordovician radiations within the order are related to dispersed plate configurations during the earlier Ordovician and the capitalization of sparsely populated ecospace in the later Ordovician. A revised global diversity curve for the order displays a distinctive two-phase pattern. First, a near isometric increase in biodiversity during the mid Cambrian to early Caradoc was then followed by a latest Caradoc to late Permian interval of exponential decline. The radiation was rapid and correlation between absolute geological time and generic diversity reveals a linear trend, peaking during the late Caradoc. The interval of decline, however, models an almost exponential decay curve, gathering momentum at the Hirnantian extinction event and interrupted only by a minor diversity increase during the early Devonian. The early Palaeozoic radiation possibly conforms to a logistic model although the paucity of Cambrian data inhibits information on the early part of the curve. The later stages of the Palaeozoic decay curve may reflect the persistence of several cosmopolitan and eurytopic taxa continuing after the last major diversifications during the Devonian. Conversely the early history of the group may provide proxies for changing environmental conditions and palaeogeographic configurations in Early Palaeozoic oceans.

# Late Ordovician ocean-climate system and paleobiogeography

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Oral Presentation

The Ordovician was a time of extensive diversification and radiation of marine life. The end of the Ordovician is marked by a major mass extinction that is generally attributed to environmental perturbations associated with an extensive yet short-lived glaciation. The understanding of the climate dynamics during this crucial time period for the evolution of life is still fragmental.

We used an atmospheric general circulation model (AGCM) and an ocean general circulation model (OGCM) to study the climate system in the Caradoc (~454 Ma) and the Ashgill (~545 Ma). Specifically, we investigated the response to changes in paleogeography, atmospheric $pCO_2$, solar insolation cycles (obliquity), poleward ocean heat transport, and sea level. We also used a 3-dimensional ice sheet model to explore the necessary boundary conditions for ice sheet formation.

The AGCM results indicate that, assuming that $pCO_2$ did not fall below 8x PAL (a minimum value for this time period), a drop in $pCO_2$ and the paleogeographic evolution can only be regarded as preconditioning factors in the glaciation. In order for ice sheets to form, other factors must have changed such as a drop in sea level from its

generally high Late Ordovician levels and/or a reduction in poleward ocean heat transport.
In all OGCM simulations, a drop in sea level led to a reduction in poleward ocean heat transport. This indicates a possible positive feedback that could have led to enhanced global cooling in response to pre-glaciation sea level drop. Continental drift could explain the observed global cooling trend in the Late Ordovician through a combined reduction in poleward ocean heat transport and increased ice-albedo effect. The ocean-climate system was also dominated by strong latitudinal temperature gradients and vigorous horizontal and vertical ocean circulation.
Finally, we compared the paleobiogeography of different taxonomic groups to the results of the climate models. The spatial distribution of Caradocian marine organisms is consistent with climatic and oceanographic gradients inferred from coupled ocean-climate models. The paleobiogeographic data thus provide an important evaluation of the global ocean-climate models and lead to a more robust inference of the early Late Ordovician global ecosystem.

# Early diversification of jaw-bearing polychaetes

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Poster Presentation

Polychaete annelids have been playing an important role in marine ecosystems already since the Early Palaeozoic. The jaw-bearing forms of the Order Eunicida, for which the fossil record is most complete due to their differentiated jaws – the scolecodonts, appeared in the latest Cambrian. However, their main diversification falls into the Early and Middle Ordovician during which many typical Palaeozoic families and genera first appeared. Another important diversification episode occurred when Palaeozoic faunas were replaced by Mesozoic and modern ones, but this is still very poorly documented.
Ordovician scolecodonts have been reported from many different regions of the world. However, except for North America and northern Europe the data available are too limited to allow any detailed analyses of diversity patterns and palaeobiogeography. The outdated parataxonomical treatment further complicates the situation since many old names are of little use without careful revisions of type collections and re-sampling of type localities.
Comparison of polychaete faunas from Laurentia and Baltica indicates that most Ordovician species were restricted to one continent, although few examples of inter-continental distribution have also been documented. Most genera, however, were common to both regions though in some cases their appearance has been diachronous. The few records from other continents also indicate worldwide distribution of many Ordovician genera. Thus, the genus-level data can be taken as so far the best approximation of the diversification history of jawed polychaetes. Currently altogether some 50 apparatus-based polychaete genera are known from the Ordovician Period.
The Early Ordovician record of polychaetes is still poorly documented. Although a recent discovery from Estonia indicates occurrence of more genera than reported earlier, the frequency and diversity seem to have been still very low during the Early Ordovician. Moreover, only forms with primitive placognath/ctenognath type jaw apparatus are known from that period, some of which related to xanioprionids and conjungaspids and the enigmatic *Lunoprionella*.
During the early Middle Ordovician the first more advanced forms, including those with labidognath/ctenognath apparatuses are recorded. Although the diversity remains relatively low until the early Darriwilian, it seems evident that already by the earliest Middle Ordovician the main polychaete lineages had become differentiated.
A major increase in species diversity and abundance, as well as a rapid increase in the number of genera are recorded in the Darriwilian and the earliest Late Ordovician. This interval marks the first appearance of most of the genera that become common in younger strata. Therefore the recorded genus-level diversity remains rather stable through the Late Ordovician. Also, since the majority of Ordovician genera range into the Silurian, there is no major drop in genus level diversity of jaw-bearing polychaetes at the Ordovician-Silurian boundary.
To further assess the early diversification of jaw-bearing polychaetes it is essential to go down to species level and obtain systematically collected and monographically treated material from other regions/continents and from the intervals that are still poorly covered, like the Early and early Middle Ordovician.

## Acritarch assemblages of the Ordovician and Silurian deposits in Lithuania

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Poster Presentation

Some samples from the Upper Ordovician and Lower Silurian deposits in the well Ledai-179 (Lithuania) have been collected and examined. Ashgilian acritarchs have been identified at the depth 800.6 m (Saldaus Formation, *Glyptograptus persculptus* graptolite zone): *Baltisphaeridium longispinosum*, *B. constrictum*, *B. brevifilicum*, *B. perclarum*, *Orthosphaeridium rectangulare*, *Ordovicidium chondrododora*, *Diexallophasis* ex gr. *sanpetrensis*, *Hogclintia digitatum,* and others. Llandoverian acritarchs have been obtained from depth of 790.3 m and 778.5 m and contains numerous *Multiplicisferidium frondi*, *Cimbosphaeridium pilaris*, *Diexallophasis denticulata*, *Solisphaeridium nanum*, *Domasia elongata*, *D. trispiniosa*, *Deunffia monospinosa*, and others. Wenlockian acritarchs established in depth of 771 m and 758.2 m. Ludlovian acritarchs presents in the interval of 941.6 - 989 m in core material of well Shiupiliai-69. Pridolian acritarch assemblage recorded in core Bebirva-109 (interval 925.5 - 964.4 m).

## Cambrian brachiopods from near the Teisseyre-Tornquist Line in Poland and their implications for palaeogeography

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Poster Presentation

The results of my investigation on Cambrian brachiopods of Poland are based on many years of work on them, and on comparative analyses with collections gathered in the natural history museums in Great Britain, Sweden and Norway.

Baltic Depression, Podlasie Depression and Lublin Slope are situated within the Polish part of the East-European Craton (EEC). Brachiopods from 25 boreholes from this area were studied. On the other side of the Teissyre-Tornquist Line, the investigations were conducted in the Holy Cross Mountains, and lately in the Upper Silesia Massif. The analysis of fossils from the Holy Cross Mountains were mostly done on materials from outcrops.

The Cambrian is represented by siliciclastic facies, mainly sandstones and mudstones intercalated with claystones. Complete sequences of Cambrian strata occur here and the collected fossils represent the entire Cambrian. Inarticulate brachiopods are quite common but the clastic facies are not very favourable for good preservation of their delicate shells. Mostly the specimens are preserved as external or internal moulds.

The described brachiopods from the Polish part of the EEC are grouped in three distinct faunal assemblages typical of each Cambrian Series: Lower, Middle and Upper and are strictly correlated with the facies present. Their optimum occurrence is related to mudstone and siltstone strata of the upper Holmia Zone and lower part of the *Eccaparadoxides oelandicus* Superzone. The oldest species (middle Holmia zone) belong to *Micromitra* and *Mickwitzia*. The dominant brachiopod group in the Lower Cambrian is composed of several species of the genus *Westonia* (not *Lingulella*). Very characteristic shells of botsfordids are present, 'acrotretids' have remained scarce, and calcareous species are absent. In the Middle Cambrian 'acrotretids' are most frequent and speciated. Species of '*Acrotreta*' are accompanied with shells of *Acrothele*. Among linguloids *Lingulella ferruginea* Salter is very common.

The Upper Cambrian deposits known from the Baltic Depression are very thin and brachiopods there are scarce and not speciated. Only in limestones of the *Parabolina spinulosa* Zone frequent recrystalized shells of *Orusia lenticularis* (Wahlenberg) commonly form coquina layers.

Overall 29 species are recognised, among them 19 are common with Scandinavia. It proves there were direct connections between these two areas and their association with the same faunal province. Toward E and SE less and less brachiopod species and shells occur in spite of fact that on Lublin Slope the thickest series of craton-type Cambrian are developed.

In the Holy Cross Mountains**,** Cambrian sediments are over 3000 m thick. On the base of facial development and tectonics two regions of Cambrian are distinguished: the southern Kielce Region where the Lower and Middle Cambrian deposits occur and the northern Łysogóry Region where only the Upper Cambrian is documented. 21 brachiopod species are recognised there. They form three faunal assemblages, as in the Polish part of the EEC, but their taxonomic content differ, including only few common species: *Mickwitzia* cf. *monilifera* (Linnarsson), *Obolella rotundata* Kiaer and *Westonia bottnica* (Wiman) in the Lower Cambrian, *Acrothele granulata* Linnarsson in the Middle Cambrian, and *Orusia* cf. *lenticularis* (Wahlenberg), *Lingulella ferruginea* Salter in the Upper Cambrian. The last two species are widely distributed within the Acado-Baltic faunal province. The remaining species from the Holy Cross Mountains are known from Wales, Atlantic Coast of Canada and the Mediterranean (Spain and Morocco) or are endemics. Scarcity of obolids and lack of botsfordids (both groups common in the EEC) is noticeable. Presence of taxons with calcareous shells, *Trematobolus sp.* in the Protolenus Zone and *Trematobolus pristinus* (Matthew) in the Eccaparadoxides oelandicus Superzone indicate connection of the Holy Cross Mountais with Avalonian part of Gondwana. At the same time the fauna of the Protolenus Zone from the EEC is less diverse and the thin sediments reflect shallowing facies. In Scandinavia stratigraphic breaks is present at the junctions of the Lower Cambrian and Middle Cambrian with exception to this found in the Baltic. The Alum Shale Formation of the later Middle Cambrian (Ptychagnostus gibbus Zone) contains beds and lenses of bitominous limestone locally developed as the *Acrothele granulata* Conglomerat. In the Holy Cross Mountains *A. granulata* in the sandstone facies occurs, other species here are endemic forms, and the Pepper Mountains Shale Formation has nothing in common with the Scandinavian Alum Shales.

The Upper Cambrian is thick and the brachiopods include abundant *Lingulella davisii* M' Coy, typical for Welsh Ffestiniog Flags. Morphology of *Orusia* cf. *lenticularis* (Wahlenberg) occuring in sandstone facies is different than in the EEC. The only common 'acrotretid' is the endemic '*Acrotreta*' *multa* Orłowski.

The faunal and facial differences, as well as the differences in the stratigraphical sections justify establishing a new subprovince within Acado-Baltic Province: the Holy Cross Mountains Subprovince. It shows greater resemblance to the Avalonian part of the Gondwana. This is more pronounces in the Middle than in the Lower Cambrian, and is especially striking in the Upper Cambrian. The differences reflect different environmental conditions on both sides of the TTL. The question is: are they caused by palaeogeographical separation of the HCM area from the nearby Baltica?

# Does the oxygen isotope composition of Palaeozoic brachiopods reflect palaeoenvironmental conditions? a critical reappraisal

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Oral Presentation

Brachiopod shells have been extensively used to unravel the oxygen isotope history of past oceans and to reconstruct oceanic palaeotemperature variations. The applicability of the oxygen isotope composition of Palaeozoic brachiopod calcite as a palaeotemperature proxy is hampered by the tendency of Palaeozoic brachiopods to show lower $\delta^{18}O$ values with increasing age. This trend was explained by Veizer et al. (1999) to reflect a secular decrease in $\delta^{18}O$ of sea water. In order to verify this long-term decline, the $\delta^{18}O$ of Palaeozoic conodont apatite was investigated.

Oxygen isotope ratios of Early Devonian, Middle Devonian, Late Carboniferous as well as Early and Late Permian brachiopod calcite are in thermodynamic equilibrium with those of contemporaneous conodont apatite and give comparable and realistic palaeotemperatures. However, Late Devonian brachiopods are significantly depleted in $^{18}O$ in comparison to conodonts. Palaeotemperatures calculated from $\delta^{18}O$ values of Frasnian brachiopods range from 30 to 40° C, whereas $\delta^{18}O$ values of conodonts translate into more realistic palaeotemperatures of 27 to 32° C (assuming $\delta^{18}O_{seawater}$ = –1 ‰ V-SMOW for an ice-free world). A similar pattern can be observed in the Silurian and Ordovician. $\delta^{18}O$ values of Silurian brachiopods translate into unrealistic palaeotemperatures of 24 to 40° C in comparison to 26 to 32° C calculated from $\delta^{18}O$ of coeval conodont apatite. $\delta^{18}O$ values of Caradocian brachiopods yield palaeotemperatures of 32 to 36° C while those calculated from conodont $\delta^{18}O$ range from 24 to 30°C.

Lower $\delta^{18}O$ values of brachiopods can not result from diagenetic alteration since only well-preserved shells were used for oxygen isotope analysis. In addition, different life habitats of benthic brachiopods and nectobenthic or nectonic conodonts cannot explain the difference in reconstructed palaeotemperatures. Furthermore, conodonts and brachiopods investigated in this study were partly collected from the same horizons and therefore no major differences in salinity/$\delta^{18}O$ of ambient sea water are expected. Lastly, it is questionable whether the observed offset can be explained by non-equilibrium fractionation. Brachiopods are generally assumed to precipitate calcite in near-isotopic equilibrium with ambient sea water. However, Auclair et al. (2003) observed a kinetic isotope fractionation effect for the modern brachiopod *Terebratalia transversa* that results in significantly depleted $\delta^{18}O$ values of shell calcite relative to expected equilibrium values. Although we are currently unable to give a satisfactory explanation for the discrepancy in $\delta^{18}O$ of early Palaeozoic calcite and apatite, we argue that Ordovician to Devonian conodonts record palaeotemperatures more faithfully than coeval brachiopods. Most important, the oxygen isotope record of conodont apatite does not support the hypothesis of a secular change in the oxygen isotope composition of sea water.

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## Ordovician carbon isotope trend based on Baltoscandian data: some aspects of composition and environmental interpretation

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Oral Presentation

Carbon isotopes are nowadays increasingly applied in the Ordovician stratigraphy and palaeoclimatology. Most of the publications are devoted to the upper Ordovician, Hirnantian in particular, and only recently two papers read by Ainsaar and colleagues at the last WOGOGOB meeting reported the first middle Ordovician carbon isotope data. Application of carbon isotopes as a tool for stratigraphic correlation and dating of rock sequences is in principle a simple method, where success depends mainly on how complete and detailed is the standard trend used as a base for comparisons. Different environmental interpretations are more speculative and uncertain although some good progress has been achieved in isotope palaeoclimatology and palaeo-oceanology.

A more or less complete carbon isotope trend for the late Ordovician has been ascertained based on the studies carried out mainly in Baltica and Laurentia, but also elsewhere (a summary of published and our new data will be demonstrated). There remain some small gaps (e.g. at the Ordovician Silurian boundary) or debates about dating of the end-Ordovician isotope shift. The pre-Caradoc Ordovician trend shows at least one (Darriwilian) clear positive shift, but the older part of the curve still needs additional data for overcoming the indistinctness caused by hiatuses and slow sedimentation. Excluding the Tremadocian and Hunnebergian clastic rocks (occupying 10 Ma of time) we do believe that the general pattern of the carbon isotope changes can well serve as a stratigraphic tool for the remaining 30 Ma. It should be stressed that it is the shape of the curve that is most important, not so much the actual values of the $\delta^{13}C$, because the latter may depend to some extent on the facies characteristics of the rocks measured.

The main positive excursions of the $\delta^{13}C$ values are as follows (in brackets Baltoscandian data, published and new ones): mid-Darriwilian (1.9‰), mid-Caradoc (2.2‰), 1st late Caradoc (1.9‰), 2nd late Caradoc (2.4‰), early (2.5‰) and mid-Ashgill (2.0‰), Hirnantian (4–7‰). By intensity of the carbon cycling the post-Hunnebergian Ordovician is subdivided into a long (24 Ma) low variability period (the $\delta^{13}C$ values vary close but mainly below 1‰) with a single mid-Darriwilian shift at 464 Ma. The second increasingly variable period (10 Ma) began with the mid-Caradoc excursion at 454 Ma and ended with the major Hirnantian excursion. This change of intensity seems to have a profound palaeoclimatological sense and is marked also by sedimentological and palaeontological features. On this background several environmental events such as relatively cool-water beginning of the sequence enriched by glauconite and/or iron oxydes, levels with organic matter (kukersite, black shale) accumulations, micritic limestones, alternation of arid/humid episodes, glaciation and general warming are commented in the context of stable isotope changes.

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# Internal banding in Palaeozoic stromatoporoids and colonial corals: classification and controls of formation

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Poster Presentation

Palaeozoic corals and stromatoporoids exhibit a variety of internal banding phenomena, many of which have been commonly interpreted as annual growth bands. We evaluate bands through analysis of colonial corals and stromatoporoids from three stratigraphic intervals: Upper Ordovician of Manitoba Canada, Llandovery–Wenlock, and Ludlow of Gotland, Sweden. Banding features are divided into four categories: (1) absence of banding; (2) density banding formed by variation in density or form of elements; (3) growth-interruption banding indicating growth cessation and regeneration; and (4) post-mortem banding caused by compaction or diagenesis. For discrimination of band types, it is essential to examine internal structures and skeletal margins in thin sections or acetate peels.

Species vary considerably in degree and type of banding; each has a distinct pattern of variation. We propose criteria to determine if banding is consistent with seasonally-induced growth variation: (1) consistency in band character and thickness; (2) continuity of skeletal growth; (3) marginal features; and (4) evidence of diagenetic alteration. Density bands in tabulate and rugose corals probably represent annual growth variations, but results for stromatoporoids are more ambiguous; although stromatoporoids commonly show banding, unequivocal density banding is poorly developed and, growth interruption generated most stromatoporoid banding. Cerioid rugose and tabulate corals possess the thickest density bands; the thinnest bands are in stromatoporoids and heliolitid tabulates.

# Record of Ordovician and Silurian volcanism in Estonian sections – prospect of research

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Poster Presentation

In Estonian Ordovician and Silurian carbonate rocks volcanic ash beds are represented by thin clay- or feldspar-rich interbeds with common thickness of few centimetres. At Early Palaeozoic this area was 600–2000 km apart from potential volcanic sources at plate margins. Consequently each of these ash beds has wide distribution over the ancient shelf sea, and represents very large eruptions. These ash beds can be used as perfect time markers in correlation of sections. For proving correlations, study of immobile trace elements in bulk samples (Kiipli et al. 2001), composition of pyroclastic sanidine (Kiipli and Kallaste, 2002) and biotite (Kiipli et al. 2002) is useful. When mapped over large areas, ash beds can be used to point directions to the source volcanoes and to get information of main wind directions. Assemblage of authigenic minerals (illite-smectite, K-feldspar, kaolinite, chlorite-smectite) formed from the volcanic ash reflects, besides other parameters, also sedimentary environment in shallow marine shelf sea.

Number of altered volcanic ash beds in Estonia occurring at particular stratigraphical levels is following: Ludfordian–1, Homerian–3, Sheinwoodian–26, Telychian–40, Aeronian–2, Rhuddanian–1, Ashgillian–4, Caradocian–25.

Using Zr/Ti ratio as fractionation index three following to each other magmatic cycles can be distinguished in Caradoc. Formation of new volcanic sources or additional magma intrusions into the existing magma chamber can explaine these cycles. Finds of rare phenocrystals, e. g. almandine garnet, in Caradocian volcanic ashes of Estonia and in massive volcanics from Lake District area in England point to the volcanoes in the island arc near the Avalonia microcontinent (Kiipli and Kallaste, 2003).

Trace element composition of 40 Telychian volcanic ashes points to at least two different volcanic sources being active at the same time. One of these magma types is characterised by high Zr and Nb contents, other by high Ti, Sr and P contents.

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# "Devonian land-sea interaction: Evolution of ecosystems and climate" (DEVEC) – the new IGCP Project 499

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Oral Presentation

During the last two decades research on the Devonian period had been included in some of the successful IGCP projects, e.g., in IGCP 216 "Global biological events in Earth history" (lead by O.H. Walliser), IGCP 335 "Biotic recoveries from mass extinctions" (lead by D.H. Erwin and E.G. Kauffman), and IGCP 421 "North Gondwanan Mid-Palaeozoic bioevent / biogeography patterns in relation to crustal dynamics" (lead by R. Feist and J.A. Talent). In these projects, however, the main focus was on the "marine side", i.e., plaeobiological/palaeontological, sedimentological, facial, and other aspects mainly concentrated on areas more of less "well under water". Therefore, an interesting field of investigations has not much been considered: The transition zone between land and sea plus their continuation in both, landward and seaward directions. Of course, IGCP Project 328 "Palaeozoic microvertebrate biochronology and global marine / non-marine correlation" (lead by A. Blieck and S. Turner) dealt with this zone, but focus was exclusively on fish remains and preferably their potential in biostratigraphical use and subsequent correlation. The recently accepted new IGCP Project 499 "Devonian land-sea interaction: Evolution of ecosystems and climate" (DEVEC) aims a broader view of this transitional zone which will be one of the main aspects of the project. But not only the processes within this (limited) area on or immediately near the former continents shall be studied – adjacent areas on the shelves reaching even reef structures that built up in a fair distance from the coast will have to be investigated by the participants of the new project. Especially the interactions between continental/coastal – shallow-water siliciclastics – outer shelf to even reefal settings are to be considered; the evolution of "continental/near-continent areas" may turn out to play a key role influencing all other facies including further details about palaeoecosystems and the Devonian palaeoclimate.

In the following paragraphs the outline of the new project is briefly summarized.

The Devonian was a critical period with respect to the diversification of early terrestrial ecosystems. The geotectonic setting was characterized by the switch from the post-Caledonian to the pre-Variscan situation. Plant life on land evolved from tiny tracheophytes to trees of considerable size in combination with a global increase in terrestrial biomass, and vertebrates started to conquer the land. Extensive shallow marine areas and continental lowlands with a wide range of different habitats existed which are preserved in a large number of basins all around the world. Climate change finally led from greenhouse to icehouse conditions towards the end of the Devonian. Both, rapid evolution of terrestrial ecosystems and climate change had a pronounced influence on sedimentation and biodiversity not only in the terrestrial but also in the marine realm ("Devonian Change"). A major goal of the project will be to focus on controls and interactions of the respective facies parameters in different paleogeographic settings in order to refine the global picture by international co-operation in a number of case studies. Geoscientific co-operation will include a variety of disciplines, such as sedimentology, paleontology, stratigraphy, paleoclimatology, paleogeography, geochemistry, paleooceanography, and structural geology.

The rapid evolution of early life on land and its interaction

with sedimentary processes, climate, and paleogeography, both on land and in marine settings, will be covered by studies in different terrestrial and marine facies. Increasing colonization of the land by plants in combination with soil-forming processes and changing runoff led to major changes of sediment input into the marine system. On the other hand, sediment input and climate are major controls for carbonate production and reef development. The study of responses and interactions thus needs detailed characterization of facies and high-resolution correlation which can only be provided by a refined stratigraphy including biostratigraphy, lithostratigraphy, chronostratigraphy, etc. Characterization of facies and correlation of stratigraphic units is especially difficult in marine-terrestrial transitions and will be an important focus of the project. Resolution of sea-level changes will be enhanced by recognition and exact correlation of their effects which may be hidden just in these transitions. On the background of the global geotectonic situation (paleogeography s.l.), this will be an important prerequisite for a better discrimination of eustatic, climatic, and biotic controls, both on regional and global scale.
The focus of the project concerns the interrelated evolution of terrestrial and marine paleoecosystems with respect to biotic and abiotic factors in space and time. Studies will include individual paleoecosystems and their components as well as their paleobiogeographic distribution. Biotic and abiotic factors of paleoecosystems are controlled by both, earthbound and extraterrestrial triggers causing either cyclicity and/or distinct events. Thus in turn, such studies may give a clue to underlying causes of global changes. The project will include sedimentologic and climatic controls of reef development and distribution as well as diversity, and paleoecology of reef building organisms throughout the Devonian, because the Middle to Late Devonian was a peak in reef development with reefs spreading into latitudes as high as 45-60 degrees. On the other hand, accomodation space for Early Devonian reefs was greatly reduced due to major input of sediment from the continents in combination with sea-level lowstand(s). A marked decline in reef development towards the end of the Devonian was probably caused by climatic deterioration.
The integrative kind of research which is needed for the success of the project can only be carried out by a worldwide network of research groups representing different disciplines. Such a network can now be based on core groups successfully participating in the recently terminated IGCP 421. Furthermore, the project will extend the results of the former IGCP 328. It will actively interlink with IGCP 491 which is mainly centered around vertebrate research. IGCP 499, however, will concentrate on the correlation and interaction of different ecosystems in a more general way. Special attention will be paid to coupling effects between the terrestrial and marine realm. Co-operation will also put forward with the new IGCP Project 497 "The Rheic Ocean: its origin, evolution and correlatives". Furthermore, an active network is represented by the members of the "Subcommission on Devonian Stratigraphy" (SDS). These existing networks will be integrated and thus providing the necessary base for an improved understanding of the Devonian period. A number of the respective colleagues and working groups have already agreed to contribute to the proposed project (see list of participants on the website).

## Tremadocian stylophoran echinoderms from the Taebaeksan Basin, Korea

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Poster Presentation

Abundant and diverse isolated remains of cornute and mitrate stylophorans are reported from the late Tremadocian (*Asaphellus* Zone) of the Tumugol Formation of Korea. Cornute skeletal elements represent an assemblage of marginals and brachials, suggesting the occurrence of at least four different species, very likely of cothurnocystid affinities. Mitrate remains include numerous isolated adorals, marginals and brachials of peltocystidans. Isolated peltocystid adorals from Korea had been previously described as *Anatifopsis cocaban* and *A. truncata* but interpreted as cirriped elements (Kobayashi, 1960) or problematica (Choi and Kim, 1989).
In this study, several morphometric analyses of kirkocystid adorals have been undertaken to explore the morphological diversity displayed by Korean adorals, and to compare their morphologies with those of other kirkocystids documented elsewhere. Main results of morphometric analyses are: (1) the distinction of three morphotypes within adorals of Gondwanan kirkocystids ("*Anatifopsis*", "*Balanocystites*", and "*escandei*" morphotypes); (2) the identification as *Anatifopsis* sp. of two Korean specimens corresponding to the "*Anatifopsis*" morphotype; and (3) the assignment of most Korean adorals, comparable in morphology to those already described as *A. cocaban* but clearly distinct from all

other kirkocystid adorals, to a new genus *Taebaekocystis*. Anatomy of peltocystids and kirkocystids is re-investigated and several internal structures are evidenced (e.g. palmar complex). Finally, a cladistic analysis shows that peltocystids from the Tumugol Formation are intermediate in morphology between primitive Peltocystida (*Peltocystis*) and Kirkocystidae.
In summary, this study expands the knowledge of peltocystid mitrates and evidences more diverse mitrate stylophoran fauna in the early Ordovician time.

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## The oldest record of hydrothermal vent communities: intracratonic sites formed in the early stage (Tremadocian) of the Prague Basin

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Oral Presentation

Based on data from filament-rich jaspers, Little & Thorseth (2002) showed evidence for bacteriogenic Fe-oxide precipitation at low temperature deep-sea hydrothermal vent sites since the early Ordovician. The record of 490 Ma of clearly biogenic filaments in jaspers linked to Fe-oxidizing bacteria is usually connected with vent systems at mid-ocean ridges and spreading centres in back-arc basins. However, the oldest record of fossil communities from hydrothermal sites was up to date a low diverse association from Silurian massive sulphide deposits in the southern Ural Mountains (Little et al. 1997). In contrast to the economically interesting sulphidic deposits, the vent communities in the Prague Basin are of intracratonic origin connected with acidic to intermediate volcanism around volcanic centers and along fault systems.
In the western part of the basin near Rokycany-Holoubkov there is a unique record of stromatolitic deposits preserved as iron ores. The occurrence of a silicified receptaculitid fits with our interpretation of shallow water conditions. Cuts and polished slabs of iron ores show a high variety of morphologies from biolaminitic structures to stacked hemispheroids. There are extraordinary levels with microstromatolites growing on top of each other and forming small "reef structures" of approximately 3 cm in diameter. Similar microstromatolites are known from Neoproterozoic carbonates from Siberia. Of course, the Barrandean iron stromatolites formed under extreme environmental conditions, an influence of volcanic activity and hydrothermal solutions. We propose that mainly microorganisms, rather than chemical precipitation, generated the formation of the stromatolitic succession.
In general, stromatolites represent a dominant feature of Precambrian and Cambrian warm and shallow-water environments, later they are described mainly from restricted environments. This fits with the situation in the shallow western part of the early Prague Basin. No index fossils are known from the stromatolitic successions reflecting unfavourable life conditions, but causing problems for a detailed age control. However, the sites are Tremadocian in age based on the stratigraphic framework. The ore units represents shallow-water deposits within the Trenice Formation. This is supported by fossil assemblages from the underlying (Trenice) conglomerate and from the overlying greywackes.

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# Defining the maximum extent of the Hirnantian ice sheet in Morocco

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Oral Presentation

The Lower Palaeozoic inliers of the Moroccan Hercynides (Meseta) and of the High Atlas contain large exposures of uppermost Ordovician sediments. Deposition of these rocks was coeval with the growth and decay of the major North and West African ice sheet during the Hirnantian. The uncertain relationship between the inliers has meant that the late Ordovician evolution of the Northern Morocco has remained poorly understood. In this paper, we present a palaeogeographic reconstruction and, on the basis of sedimentological data, define the maximum extent of the ice sheet in Morocco.

In the central High Atlas, Hirnantian sediments display an ice-proximal character, and comprise massive sandstones and sandy diamictites that are interpreted as glacially-derived mass flow deposits, separated by siltstones and bedded sandstones that reflect quiescent interglacial sedimentation. These sediments occur within a chaotic, folded package of 40-50 m thickness that bears internal truncation surfaces. These structures imply multiple phases of syn-sedimentary deformation and are interpreted as glaciotectonic structures. Overlying Silurian strata are unaffected. The association of streamlined subglacial bedforms (roches moutonées) with these deformation structures indicates that the High Atlas was occupied by ice. Northward, in the Rehamna inlier, the presence of soft-sediment deformation and downwardly injected sedimentary dykes suggests that the ice sheet continued into the southern Meseta.

In the Massif Central and Coastal Meseta, a succession of sandy diamictites is sharply overlain by two, stacked successions of thickening upward, parallel laminated and ripple cross-laminated, well sorted sandstones that were shed from the south or west. The latter sediments are undeformed and are interpreted to record the build out of shelf-edge deltas during maximum glacio-eustatic lowstands. Although these sediments would have been expected to provide a stable substrate during ice sheet advance, the absence of soft-sediment striated surfaces and ice proximal facies imply that the ice front never reached these areas. Northward, in the Tazzeka Massif, a thick turbidite-dominated succession (>300 m) is preserved. It records several glacial cycles in a very ice-distal slope setting with poor evidence of true glaciogenic sedimentation.

# Palaeoecology and palaeobiogeography of Cambro-Ordovician stylophoran echinoderms

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Oral Presentation

Stylophorans (Cornuta, Mitrata) are a class of asymmetrical, free-living (unattached), arm-bearing Palaeozoic echinoderms, closely related to asterozoans and crinoids (Ubaghs 1961, Nichols 1972, David *et al*. 2000). In Cambro-Ordovician times, stylophorans frequently formed relatively dense populations on soft substrates. Palaeoenvironmental and palaeobiogeographical distributional characteristics of Cambro-Ordovician stylophorans both support their interpretation as psychrospheric faunas. Although they are known since the Early Mid Cambrian, stylophorans underwent a major radiation in the Upper Cambrian - Early Ordovician time interval. This diversification is well-documented in shallow to deep environments of cold to temperate seas of different high-latitude peri-Gondwanan regions (e.g. Montagne Noire, Morocco, Shropshire), but also, exclusively in deep environments, in several low-latitude regions (e.g. Australia, Korea, western North America). In Middle Ordovician times (Fennian to Llandeilian), palaeobiogeographical distribution of stylophorans appears to be restricted to high-latitude peri-Gondwanan regions (e.g. Bohemia, Brittany, Morocco). In contrast, during the Late Ordovician, stylophorans progressively extend to, and diversify in deep environments in the periphery of lower latitude regions (e.g. Australia, Baltica, eastern North America, Siberia). This palaeogeographical extension of stylophorans is particularly well-documented in the Upper Ordovician of eastern North America, where it coincides with a major shift in sedimentation and faunal assemblages, both probably correlated to a great transgression event (Patskowsky & Holland 1993). Interestingly, a similar «invasive» pattern is observed in the Upper Ordovician of eastern Laurentia for many other «cold» Gondwanan groups (e.g. bivalves, cryptolithinid trilobites; Shaw 1991, Cope & Babin 1999).

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# The Ordovician acritarch assemblage from Meitan Formation, Tongzi, South China: biostratigraphy and biodiversity

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Oral Presentation

Five palynologic assemblage zones have been recognized from the Meitan Formation of the Honghuayuan section in Tongzi, Guizhou Province. Assemblage Zone I, in the *D. eobifidus* graptolite biozone, is poor in both acritarch diversity and abundance. The acritarch diversity of Assemblage Zone II in the *C. deflexus*-lower *A. suecicus* graptolite biozone is rather high. This assemblage is characterized by the appearance of *Acanthodiacrodium tasselii*, *Ampullula erchunensis*, *Arbusculidium filamentosum*, *Athabascaella playfordi*, *Cristallimium dentatum*, and *Tongzia meitana,* and is dominated by *Polygonium*. Assemblage Zone III, in the upper *A. suecicus* graptolite biozone, is characterized by the dominance of *Stelliferidium*. Acritarch diversity within Assemblage Zone IV, which occurs in the *U. austrodentatus* graptolite biozone, is closely consonant with that of Assemblage

Zone III. The relative abundance of *Polygonium* decreases but that of *Peteinosphaeridium* spp. becomes greater in this acritarch Assemblage Zone. Assemblage Zone V, recorded in the *U. austrodentatus* graptolite biozone, is dominated by *Leiosphaeridia* and *Polygonium*.
The acritarch assemblage recovered from the Meitan Formation from Tongzi shows close affinities to those reported from apparently coeval localities in central and southwest Europe, North Africa, the Middle East, South Asia, South America, and eastern Newfoundland, Canada. The Pre-Gondwana typical taxa *Coryphidium* and *Striatotheca* are found in all assemblages of the Meitan Formation in Tongzi. The Yangzte Platform belongs to pre-Gondwana acritarch province.
The FADs of *Ampullula erchunensis*, *Arkonia*, *Dicrodiacrodium*, and *Leprotolypa evexa* in the Meitan Formation are earlier than recorded from other localities.
Acritarch diversity in the Meitan Formation in Tongzi increases rapidly, and reaches a maximum in the *A. suecicusi* graptolite biozone. Acritarch diversity trends within the South China Plate provide some useful insights about Ordovician biotic radiation.
The distribution of acritarchs is seemingly affected by palaeoenvironment change. There is a correspondence between the generalized trend of acritarch diversity and the facies association curve for the same interval at Honghuayuan.
Vertical fluctuations in relative abundances of acritarchs appear to be related to changes in depositional facies. High relative abundances of *Leiosphaeridia* and *Striatotheca* indicate lower sea level, and high relative abundances of *Baltisphaeridium*, *Polygonium*, *Peteinosphaeridium*, the Galeata, and diacromorph group indicates higher sea level.
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# Reef reconstruction after extinction events of the Latest Ordovician in the Yangtze Platform, South China

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Oral Presentation

Early Silurian reef reconstruction on the Yangtze Platform, in the northern part of the South China Block, is preceded by a combination of regional and global processes. During most of Ashgill time (Late Ordovician), the area was dominated by Wufeng Formation deep water graptolitic black shales. Reefs largely disappeared in the middle of the Ashgill Stage, from the northwestern margin of Cathyasian Land (southeastern South China Block), in advance of the Late Ordovician glaciation and mass extinction, due to regional sea-level changes and regional uplift, unrelated to the mass extinction itself. Late Ordovician microbial mudmound occurrence is also found in the western margin of the Yangtze Platform, its age corresponding to the *Dicellograptus complexus* graptolite biozone of pre-extinction time. On the Yangtze Platform, a thin, non-reef-bearing carbonate, the Kuanyinchiao Formation (= Nancheng Formation in some sites), thickness generally no more than 1 m, occurs near several landmasses as a result of Hirnantian regression. Reappearance of the earliest Silurian carbonates consisting of rare skeletal lenses in the upper part of Lungmachi Formation, are correlated to the *acensus* graptolite biozone, early Rhuddanian of Shiqian, northeastern Guizhou, near Qianzhong Land. Carbonate sediments gradually developed into beds rich in brachiopods and crinoids in the lower part of Xiangshuyuan Formation, middle Rhuddanian. In the middle part of Xiangshuyuan Formation, biostromes, containing abundant and high diversity benthic faunas such as corals, crinoids and brachiopods, show beginnings of reconstruction of reef facies. Substantial reef recovery occurred in the upper part of Xiangshuyuan Formation, lower Aeronian, as small patch reefs and biostromes. During the late Aeronian, carbonate sediments, especially reefs and reef-related facies, expanded on the upper Yangtze Platform, and radiation of reefs occurred in Ningqiang Formation, upper Telychian. The long period of reef recovery, taking several million years, remains difficult to explain, because redistribution of any refugia faunas would be expected to take place soon after the extinction. Reefs and reef-related facies subsequently declined after Telychian time due to regional uplift of the major portion of the Yangtze Platform. Carbonate facies are therefore uncommon in South China during the rest of Silurian time.

# Ordovician palaeogeographical reconstruction of Baltica: palaeomagnetic data

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Oral Presentation

At the present day the position of Baltica during Early-Middle Ordovician time is still discussed. Based on the Scandinavian data mainly, the northern margin of Baltica was reconstructed at 40°S during Early-Middle Ordovician. However, palaeomagnetic data for of the Uralian shelf zone of Baltica (Eletsk zone) and sequences of the continental slope (Lemva zone) testify for more low-latitude position of Baltica (Tectonic history of the Polar Urals, 2001). According to the palaeomagnetic data for the Early-Middle Ordovician sequences form the St. Petersburg area, Baltica was located at 20°S (Lubnina & Zaitsev, 2004). New paleomagnetic data for the Upper Ordovician rocks is evidence the position of Baltica at 30°S (Lubnina, 2004). Summarised all new palaeomagnetic data the position of Baltica during Ordovician time have been reconstructed.

For the palaeomagnetic analysis Early-Middle Ordovician sedimentary rocks from St. Petersburg area, Late Ordovician rocks from Podolia, Ukraine and Late Cambrian-Early Ordovician rocks from the Uralian margin of Baltica, the Polar Urals have been sampled. All these rocks were carried out the palaeomagnetic treatments. More than 400 oriented samples were collected. Measurements were made at the palaeomagnetic laboratories of the Institute of Physics of the Earth (Moscow, Russia), Paris Institute of Physics of the Earth (France), and the Russian Scientific Research Geological Institute (VSEGEI, St. Petersburg, Russia), using cryogenics (SQUID) and JR-4, JR-5a spinner magnetometers. Characteristic high-temperature components were separated by detailed laboratory measurements. The primary origins of whose proving by conglomerate test (Lemva zone) and fold, conglomerate and reversal tests (Eletsk zone).

According to the palaeomagnetic and literary data, during Early Ordovician time Baltica moved to tropical southern latitudes, where its W-SW parts occupied the extreme south (up to 30°S). At the Late Tremadoc - Arenig along the Uralian margin of Baltica was formed active continental margin, to the west of which the Lemva deep-sea basin was generated. Palaeomagnetic data suggest the location of the Uralian margin of Baltica at 10°S, and the Lemva zone in near-equatorial latitudes. During the maximal rifting, width of this zone was more than 500 kms (Tectonic history.., 2001). Probably, at this time the Lemva zone was clockwise rotated about Baltica. Probably, this latitudinal difference was the result of forming the first oceanic basin of the PalaeoUrals to the east from the Lemva zone (Ruzhentsev, 1998). During Late Ordovician Baltica was located at 30°S.

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# Early Silurian cephalopod migrations to the Prague Basin (Perunica micro-plate, Bohemia)

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Poster Presentation

Silurian transgression event caused the graptolite shale sedimentation on the north Gondwanan shelf. The early Silurian cephalopod radiation followed latest Ordovician extinction at the tropical carbonate platforms of the Laurentia and Baltica where characteristic Silurian cephalopod clades originated. The environment above the black shale biofacies in the Prague Basin was only suitable for the specialised cephalopods *Discinocaris* and *Plectocaris* with longicone shells closed by opercula. As the graptolite shale biofacies was progressively replaced by carbonate sedimentation the cephalopod migrated and colonised to new niches continued in the peri-Gondwana.

The pelagic cephalopod assemblage appears in the Prague Basin in the latest Llandovery, and its diversity and density continually increases up to the early Ludlow. At the Llandovery-Wenlock boundary coiled nautiloid *Phragmoceras* occurs in the black shale environment, and documents first nektobenthic cephalopod migration to the Prague Basin. Since the late Wenlock the cephalopods are frequently more common than the graptolites.

The Prague Basin volcanic archipelago shallow slopes were since the late Aeronian colonised by benthic communities. First few cephalopod migrants of the Baltic-Avalonian origin (*Dawsonoceras*, *Peismoceras*, *Trubiferoceras* a.o.) occur in the early Sheinwoodian but the first prominent radiation of the cephalopod migrants started in the early Homerian. All Silurian cephalopod orders except actinocerids are presented. The cephalopod limestone biofacies originated within the shale biofacies where surface currents ventilated normally anoxic bottom since the late Wenlock. In the cephalopod limestone biofacies the pelagic and nektobenthic cephalopods with longicone shells are accompanied by a few nautiloids. The cephalopod radiation continued in the early Ludlow. The second cephalopod migration and adaptive radiation is connected with development of the isolated carbonate platforms in the early Ludfordian. The increase of the cephalopod diversity and the adaptations of the migrants to the cephalopod limestone biofacies are evident trends during the Wenlock and early Ludlow.

The current activity caused the ecosystem recovery after the late Ordovician glaciation and the later graptolite shale sedimentation after the early Silurian transgression. The peri-Gondwanan cephalopod fauna usually consist of the pelagic and nektonic cephalopods and a few nektobenthic nautiloids. The origin of highly diversified cephalopod assemblages in the Prague Basin is related to the position of the Perunican micro-plate north of the peri-Gondwana in the Rheic Ocean within the reach of the South Tropical Current. The relation between the graptolite extinctions and cephalopod migrations and radiations and appearance of the cephalopod limestone biofacies are prominent features of the early Silurian recovery. The cephalopod fauna documents faunal links between Baltica (Podoli, Gotland), Avalonia (Wales), Laurentia, and the Prague Basin.

# The earliest brachiopod-bryozoan dominant community in North Gondwana: a case from Late Arenigian of the Barrandian, Bohemia

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Poster Presentation

In North Gondwana, the bryozoan-brachipod-pelmatozoan (BBP) communities are spread from the Middle Ordovician with the maximum in the early Ashgill. There are rare and only local occurrences in the older Ordovician stages contrary to other low-latitude palaeocontinents (Baltica, Laurentia). In North Gondwana, the BBP communities are typically known from the late Caradoc to middle Ashgill shallow shelves of the Iberian Peninsula, Montagne Noire of South France, Sardinia, the Carnic Alps, the Anti-Atlas and the Ghadamis Basin of Lybia, and from shallow-water volcanoclastic accumulations of the Armorican Massif.

In the Barrandian area of Bohemia, the communities of the BBP type are known in areally restricted sites in the Letná, Zahořany, Bohdalec, and the Králův Dvůr formations (Beroun to Ashgill). The most famous is the „*Polyteichus*“ biofacies of Late Caradoc (Bohdalec Formation). There, the BBP communities originated on coeval tectonic rising zones.

In the Barrandian, the earliest communities that may be referred to the BBP communities are known in upper part of the Klabava Formation (Late Arenig). The foramtion consists of several depth-related lithofacies. The shallow lithofacies of rewashed volcanic tuffs bears a low-diversity *Nocturnellia* community bordered NW margin of the basin. It is dominated by a small dalmanellid *Nocturnellia nocturna* locally associated by moderately diverse fauna of siliceous sponges, trepostomate bryozoans, bellerophontid *Modestospira* and other fauna.

The most diversified fauna is known in nearby areas of ancient rocky coast, present in abandoned iron ore open mine near Ejpovice (SW part of the basin). The hematite oolite lens with abundant small chert pebbles yielded a remarkably rich fauna. This consists of massive, ramose and discoid trepostomate bryozoans (three undescribed species), encrusting bryozoan-like *Berenicea vetera*, orthid brachiopods *Nereidella pribyli*, *Nocturnellia nocturna, Poramborthis* sp. and *Protohesperonomiella* sp., hyperstrophic gastropod *Mimospira helmhackeri*, trilobite *Pseudopetigurus hoffmani*, a small conulariid, and large organophophatic brachiopods *Orbithele rimosa, Lithobolus plebeius* and *Elkanisca lineola*. All fossils are preserved in thin spongolite intercalation inside the larger oolite lense. The fossil accumulation is a taphocoenose, with shells trapped into the mat of detached and decayed sponges at the sea bottom. The absence of pelmatozoans is outstanding, but this group is unknown in the Klabava Formation. The taphocoenose represent the original benthic community of any sheltered crevice or cave of the nearby

rocky coast. Fossils attached to cliffs of ancient coast are known some 100-200 m apart. There, a thin stromatolite mat, with uncrusting *Berenicea vetera* and discoidal small tremapostomate bryozoan were found. Other encrusting mats and zoaria of bryozoan-like *Berenicea vetera* and *Marcusodictyon* sp. are know from abraded surface of the cliff, boulders, and pebbles in infillings of cliff and adjacent sediments.
The presence of the bryozoan dominant fossil association indicates that (1) origin of later BBP North Gondwanan communities can be sought in shallow temperate part of North Gondwana, and (2) the oldest BBP North Gondwanan communities are also of Arenig age, similar to BBP communities in low-latitude palaeocontinents.

# Palaeoclimate modelling studies for the Late Miocene and for the Neoproterozoic

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Oral Presentation

We commonly use climate models to analyse the present-day climate and the future climate change, but they also allow us to identify and to understand the relevant processes of past climates. Exemplarily for palaeoclimate modelling we present here the application of (1) the model ECHAM4/ML to the Late Miocene (Tortonian, ~10 Ma), and (2) the model Planet Simulator to the Neoproterozoic (~850 Ma).
Late Miocene proxy data suggest a generally warmer and more humid climate than today, and particularly the Miocene meridional temperature gradient is weaker as compared to nowadays. In order to simulate the Late Miocene climate, we use the highly complex atmospheric general circulation model (AGCM) ECHAM4 coupled to a mixed-layer ocean model (ML). For our Tortonian model simulation we consider a lower palaeorography, a weaker palaeocean heat transport, and an appropriate palaeovegetation. On the global scale, the Tortonian simulation demonstrates a slightly warmer (+0.6°C) and more humid climate (+36 mm/a) as compared to a present-day control experiment. Primarily the high latitudes are warmer (up to +4°C) in the Tortonian simulation, and accordingly the polar sea ice cover and the meridional temperature gradient are reduced as compared to today. A quantitative comparison indicates that the Tortonian simulation agrees quite good with terrestrial proxy data, but the model tends to be too cool in the high latitudes. Thus, we understand the Late Miocene climate just partly and further studies are demanded.
In contrast to the warm Miocene, the Neoproterozoic (~850 Ma) was a cold episode during which the earth is assumed to have been largely ice-covered, but the degree of the Neoproterozoic glaciation is controversially discussed: A 'snowball earth' versus a 'slushball earth'. Referring to this debate, we perform a series of sensitivity experiments with the earth model of intermediate complexity (EMIC) Planet Simulator. Our preliminary results indicate that it is possible to maintain a global ice cover, but the model must be strongly forced at the initial setup. For the 'snowball earth'-scenario, the global average temperature is below –55°C. In addition to the 'snowball earth'-simulation we initialise the Planet Simulator with more moderate boundary conditions (e.g. the initial sea ice extension varies between 50° and 90°N/S) as compared to the 'snowball earth'-run. In these 'slushball earth'-scenarios the sea ice margin extends from the poles towards 30°N/S, but the equatorial regions remain ice-free. Basically, our Planet Simulator sensitivity experiments support the hypothesis of a 'slushball earth' rather more than this of a 'snowball earth'.

## Ice-proximal sedimentary records of the Late Ordovician glacial cycles

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Oral Presentation

During the latest Ordovician (Hirnantian), western Gondwana was covered by an extensive ice sheet, the front of which fluctuated throughout the present-day North and West Africa. Field survey and 3D seismic interpretations on the Late Ordovician glacial sediments in the western Murzuq Basin (Libya) enable the sequence stratigraphy and architecture of an ice-proximal succession to be characterised. Five ice-related depositional sequences are identified. They are separated by erosional unconformities of subglacial origin.
Subglacial unconformities are inferred by the presence of highly deformed sandstones including intraformational striated surfaces and plurikilometre-scale streamlined bedforms visible on aerial or satellite images. These subglacial unconformities are gently dipping concave-up erosional surfaces, 5 to 15 km in width, up to 200 m in depth, which form up to 50 km long palaeovalleys. Geological mapping indicates that, due to different ice-flow orientations through time, the several generations of glacial valleys create a complex architecture of nested valleys and associated terraces. Depositional sequences are made up of a succession of glaciomarine, deltaic, estuarine or fluvial deposits recording glacial recession (transgressive) and highstand conditions. In the two upper depositional sequences, the backstep of successive outwash fans indicates that ice recession occurred during an overall post-glacial transgression.
The depositional sequences which comprise a succession of seismic-scale, unconformity-bound, ice-related depositional units, are climatically controlled and represent major glacial cycles throughout the north-gondwanian shelf. Therefore, the whole succession preserves a record of the evolution of the Late Ordovician ice sheet. The two first phases are dated as basal Hirnantian (chitinozoans) and represent the first occurrence of ice into the Murzuq Basin. A significant flooding is then recorded, indicating a major retreat of the ice fronts and a long-lasting interglacial phase before a third glacial advance of subordinate extent. The fourth phase is considered as the most important one in the area and, probably, by comparison with studies in ice-distal areas, in the whole North Gondwana. The subsequent ice-sheet recession comprises a number of subcycles. The last (fifth) glacial cycle was of limited extent as the ice did not re-advance further than the present day 25°N parallel. Overlying sediments record the post-glacial evolution prior to the deposition of Silurian shales.

## Palaeogeography and biodiversity of Cambro-Ordovician echinoderms.

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Poster Presentation

In recent years, palaeobiogeographical aspects and biodiversity patterns (diversity, disparity) of the Cambro-Ordovician radiation of metazoans have been extensively investigated (Miller, 1997). However, most studies focused on the same three groups of marine invertebrates (articulate brachiopods, molluscs, and trilobites), whereas other significant components of Early Palaeozoic biota, such as echinoderms, remained largely neglected. (Harper & Mac Niocaill, 2002; Novack-Gottshall & Miller, 2003). Preliminary studies on the ecology of Cambro-Ordovician echinoderms have suggested relatively different diversification patterns in Laurentia (Guensburg & Sprinkle 2001) and on the northern Gondwanan margin (Lefebvre & Fatka 2003).
A comprehensive database including all records of Early Palaeozoic echinoderms has been built, so as to provide, for the first time, a global pattern of taxonomic diversity for this phylum in Cambro-Ordovician times. This global pattern of echinoderm diversity has been compared both with local diversity trends evidenced in selected regions of three palaeocontinents (Baltica, Gondwana, Laurentia), and with biodiversity patterns observed for several classes and/or major clades of echinoderms (e.g. asterozoans, blastozoans, crinoids, edrioasteroids, stylophorans). Finally, global and local diversity trends described for echinoderms have been compared with those reported for other marine invertebrates.

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# Ordovician chitinozoan distribution in the different areas of Baltoscandia

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Poster Presentation

Chitinozoan species can be used to evaluate the fluctuation through time of the biodiversity of the still unknown metazoan group producing these microfossils, if one accepts the statements that the status of species (received by majority of experts) is regarded as representative of a true species, and their final count has not been achieved yet. The dataset of more than 5300 samples from Baltoscandia from the first occurrence of the group in the Tremadocian to the Ordovician-Silurian boundary is used for documenting the biodiversity. The total diversity, the origination and extinction rates as well as the turnover ratios are calculated for the 19 time-slices proposed by Webby et al. 2004. The distribution of chitinozoans from the eleven different areas of Baltoscandia (North-, West- and South Estonia, Russia (St Petersburg District), Latvia, Lithuania, Poland, Belarus, Ukraine, Norway, Sweden) is calculated separately, and the list of Ordovician chitinozoans summarizes the data of 157 species of 26 genera. Detailed data of chitinozoan quickly evolved assemblages from these regions has been relatively successfully used (see Nõlvak & Grahn 1993 for a general review) despite some complications in correlation of beds caused by (1) the differentiation of the sequence into five main composite belts, (2) unfavorable preservational conditions (barren active water sediments, dolomitization, thermal heath flow, marine redbeds or carbonate mounds etc.), (3) the differences in sampling and their size. In Baltoscandia it is difficult to obtain reliable data from largerly dominated bedded limestone samples with weight less than 300-400 grams. Their abundance usually ranges from small number of specimens to several tens of specimens per gram of rock. Specifically to the East Baltic sections in some portions in Upper Ordovician there are possibilities to adopt more detailed subdivision, e.g. in the time-slices 5b-5c. In the Lower Ordovician the situation reveals reverse: the time-slices 1c-2c are difficult to separate, which pronounces the "normal" scarcity in the early chitinozoan assemblages due to the noticeable stratigraphical gaps.

In general, (1) in the above listed different regions great similarities appear in the faunal logs, and in the order and levels of fluctuations (originations, extinctions); (2) regional differences do not exceed 10% of all taxa within the same time-slice; (3) this gives a good ground for the workable biozonation schemes in Middle and Upper Ordovician. Some problems appear in practical application of the chitinozoan zones. In first approximation the defining of range zones was comfortable; both zonal boundaries were fixed and clear according to the data available (Nõlvak & Grahn 1993). However, in some sections the earlier data about known ranges of important species may be out of date, and earlier criteria of the zonal boundaries should be redefined.

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# Major changes in gastropod larval strategies during the Early Ordovician

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Poster Presentation

Minute steinkerns of molluscs commonly dominate Cambro-Ordovician small shelly assemblages. These assemblages indicate a major change in size and shape of early ontogenetic mollusc shells (protoconchs) across the Cambrian/Ordovician boundary. Based on new material and the published record, a fundamental faunal turnover and a drastic change in the overall shapes and morphologies across the Cambro-Ordovician boundary can be recognized. This turnover is suggested by the extinction of typical Cambrian small shelly molluscs and the origination of several gastropod clades with a characteristic early ontogeny.

Although the systematic and phylogenetic significance of these minute steinkern faunas is limited, size and shape of the internal molds give direct evidence for ontogenetic strategies (i.e. the amount of yolk) during this important time interval. Characteristic Cambrian, limpet shaped or coiled molluscs (e.g. *Aldanella, Anarbarella, Latouchella*) have relatively large, undifferentiated initial parts which indicate lecitotrophic ontogeny. In the early Ordovician, various forms of gastropod larval shells appear for the first time. Many of these protoconchs have a loosely coiled first whorl (see also Dzik 1994), and the size of their initial part suggests planktotrophic larval development. At the same time larger protoconchs are present which indicate lecitotrophic development. This shows that planktotrophy and nonplanktotrophy occurred at the same time during the Ordovician while planktotrophy cannot be substantiated for Cambrian molluscs. The acquirement of planktotrophy formed a major step for the evolution of the molluscs with far reaching consequences for larval dispersal. Gastropod protoconchs from Ordovician small shelly assemblages have a multitude of shapes and many of them are indeed openly coiled. This variation reflects the tremendous radiation of the Gastropoda during the Ordovician. The openly coiled form of protoconchs was still dominant during the Silurian but subsequently removed from the fossil record so that this once dominant morphology is unknown from the Mesozoic (Nützel and Frýda 2003).

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# Early Darriwilian graptolite and conodont biofacies in the Los Azules Formation, Cerro Viejo section, Central Precordillera, Argentina

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Poster Presentation

The Middle-Upper Ordovician Los Azules Formation is part of a transgressive rock complex overlying the San Juan Limestone in the Central Precordillera of western Argentina. The type area of this formation is located on the western flank of the Cerro Viejo at Huaco, San Juan Province. The formation consists of three members: a lower claystone and K-bentonite member, a middle member of basal micaceous sandstones and siltstones, and an upper calcareous siltstone and limestone member. Graptolites and conodonts are the dominant faunal elements but palynomorphs, phyllocarids, inarticulate brachiopods, ostracodes, machaeridians, and trilobites are also present. The presence of guide fossils allows for the identification of the *Undulograptus dentatus, Holmograptus lentus, Pterograptus elegans, Hustedograptus teretiusculus,* and *Climacograptus bicornis* graptolite zones, and the *Lenodus* *variabilis, Eoplacognathus suecicus, Pygodus serra,* and *Amorphognatus tvaerensis* conodont zones, which span the interval of the Darriwilian (Da2) to Gisbornian (Gi2) stages of the Australian chronostratigraphic scale. The contacts between the members coincide with two stratigraphic gaps. The lower hiatus is within the Darriwilian (probably Da3) as suggested by the absence of the *Diplograptus? decoratus* Zone (*Nicholsonograptus fasciculatus* Baltic Zone) and part of the *E. suecicus* Zone. The upper hiatus, corresponding to the Gisbornian (Gi1) is recognized by the absence of the *Nemagraptus gracilis* Zone, and the *Pygodus anserinus* and lower part of the *A. tvaerensis* zones. The *U. dentatus* Zone ranges through the lower 9 m of the the lower member. It contains a rich graptolite assemblage, including *Parisograptus caduceus, Glossograptus* sp., *Paraglossograptus tentaculatus, P. tricornis, Cryptograptus antennarius, Arienigraptus zhejiangensis, A. angulatus, Arienigraptus* sp., *Undulograptus austrodentatus, U. dentatus, U. primus, U. sinicus, U.* sp. cf. *U. cumbrensis*, *U.* sp. cf. *U. dicellograptoides,* and frequent dichograptids and sigmagraptids. The appearance of the *Archiclimacograptus* and *Hustedograptus* genera marks the overlying *H. lentus* Zone, although the eponymous species was not recorded. The major part of the preceding fauna remains unchanged. *Archiclimacograptus angulatus, Archiclimacograptus* sp., *Haddingograptus oliveri, "Climacograptus" pungens,* and *Cryptograptus schaeferi* appear within this interval. *Bergstroemograptus crawfordi* is recorded in the upper part of the biozone, just 30 cm before the appearance of the *P. elegans* fauna. This species is associated to *A. angulatus, A. marathonensis, C. schaeferi, "C." pungens*, *H. oliveri,* and isograptids. Most of the lower *H. lentus* Zone graptolite assemblage disappears at this level. *B. crowfordi* is associated with the first record of the conodont *Polonodus magnum*, just below the appearance of the *Pygodus anitae*, which indicates the upper part of the *E. suecicus* Zone. Despite the absence of diagnostic Da3 graptolites within this interval, a sudden change in faunal composition suggests either the presence of strata corresponding to the uppermost Da2 or a part of the Da3. The Pacific Province graptolite faunas of the lower member are similar to those from Australia and Laurentia, and are characteristic of deep water environments of the isograptid biofacies. Associated conodont species include *Bryantodina* aff. *typicalis, Drepanodus arcuatus, Drepanodus robustus, Drepanoistodus* spp., *Paroistodus horridus, Periodon aculeatus, Protopanderodus gradatus,* and *Spinodus spinatus* which span the *L. variabilis - E. suecicus* zonal boundary, and *Polonodus magnum,* which marks the presence of the *E. suecicus* Zone in the upper part of this member. Conodont diversity at the top of the San Juan Limestone is about 25 species. After the abrupt environmental change caused by the drowning of the carbonate platform, the conodont diversity dramatically drops to about 10 species in the lower member of the Los Azules Formation. These forms correspond to the pelagic biotope of conodont communities, which are restricted to cold waters of the deep-slope environments.

# Trilobite diversity in Avalonia prior to the end Ordovician extinction – the peak before the trough.

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Oral Presentation

The trilobite biodiversity curve for Avalonia differs markedly from the global and other regional patterns in having the peak of diversity immediately prior to the Hirnantian extinction event rather than in the Caradoc or even earlier. This reflects both the very wide spectrum of biofacies represented in this part of the succession in Avalonia and the immigration of taxa resulting from the closure of the Iapetus and Tornquist oceans. Detailed analysis of the faunas demonstrates that Avalonia exemplifies the many factors involved in provincial breakdown and their influence on biodiversity. Furthermore, it emphasises the need to understand the palaeoenvironmental context within which such changes took place.
Nearly 80 trilobite genera are known from the Rawtheyan of Avalonia with half of these making their first appearance on this microcontinent in that or the preceding Cautleyan stage. The wide environmental spectrum reflected in the rock record not only includes the return of the deepest water (cyclopygid-atheloptic) biofacies but also marks the first recorded development in Avalonia of the pure carbonate illaenid-cheirurid association. The latter may reflect the drift of the microcontinent towards tropical latitudes and hence the appearance of a faunal association that was first established in low latitude Laurentia much earlier in the Ordovician. Half of the new taxa were restricted to this carbonate environment including several genera of cheirurids and lichids. Recruitment into this and other shelf environments was from several palaeoplates, but the largest cohort (over half of the genera) had its origins in Laurentia although some of these also had occurrences in Baltica in the late Caradoc and early Ashgill. The Rawtheyan sampled diversity is more than twice that of any part of the Caradoc

and, setting aside the 'new' pure carbonate environment, indicates that provincial breakdown resulted from the insinuation of immigrant taxa into existing communities across the shelf rather than any substantial replacement of the established incumbents. The peak of diversity in the Rawtheyan makes the climatically triggered Hirnantian extinction all the more dramatic in Avalonia.

## Aims, achievements and lessons learnt from six years of IGCP project n° 410

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Oral Presentation

The main goal of IGCP project n° 410 from 1997 was to provide a global and quantified evaluation of the Great Ordovician Biodiversification Event based on the fossil record. Other aims were: 1) to develop a globally integrated time scale using graptolites, conodonts, and other zonal fossils, wide-ranging bioevents and graphic correlation; 2) to analyse onshore-offshore biofacies profiles across palaeolatitudes; 3) to identify patterns of biotic response to climatic change; 4) to depict extrinsic factors (e.g., plate movements, sea level change, volcanic activity), which possibly favoured the major biodiversification; and 5) to compare the organic-matter assemblages of economically important oil shales. In terms of societal benefits the project work was expected to: 1) identify possible causes of pre-industrial biodiversity change (i.e., "lesson from the past"); 2) assist in support of scientists from developing countries; and 3) increase awareness of the oil-shale deposits. To achieve all these ambitious tasks, seven regional teams and a global clade team were formed to collect the numerous data. Meetings and field excursions were held in China, Korea, Mongolia, Russia, the Czech Republic, France, USA, Australia and Brazil. Financial support allowed a number of scientists from developing countries to attend the activities. Some 200 Ordovician experts from 38 different countries participated in IGCP n° 410.

In terms of the original aims, the study of the oil shales made little progress. Also, opportunities to input all relevant biodiversity data in a web-based global relational database were not adopted by all workers, and in processing their biotal data, some workers did not attempt to interpret the effects of bathymetry or palaeolatitudes on their particular diversity patterns. Nevertheless, a number of fossil groups were shown to exhibit overall patterns of diversity increase to a maximum near the end of the Middle Ordovician and decline well before the Hirnantian glaciation. Other significant scientific advances include: 1) elaboration of a refined, 19 time-slice, subdivision of the Ordovician System, using ties between graptolite/conodont/ chitinozoan biozones, calibrated to radiometric data; 2) important progress towards defining a global sea level curve using records from the Baltic and N America; 3) development of global or regional databases for many fossil groups; and 4) assessment of the regional and global rate of diversity changes through time (biodiversity curves). The success of the project was largely due to the goodwill and cooperation of Ordovician specialists worldwide; they enthusiastically embraced most aspects of the work. We employed a good management structure, close linkages (e.g., Ordovician Subcommission and IGCP related groups) and networking, disseminating details of work programs as widely as possible (via the website, email, and other news sources). The project produced some 1000 relevant publications, including monographs, field guides, and an authoritative, 484-page book on the "Great Ordovician Biodiversification Event". The coverage, content and quality of the IGCP n° 410 publications is testimony to the success of the project. We expect participants in successor IGCP n° 503 to establish new initiatives and directions, but we hope they will also take over some of the programs we left unfinished. In particular, it would be nice to have the Ordovician oil-shale deposits properly evaluated on a worldwide basis.

# New data on the Ordovician ichnofossils from the Koszalin – Chojnice Region (Pomerania, NW Poland) – palaeogeographic implication

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Poster Presentation

For the first time, well–preserved ichnofossil assemblage comprising other than the coprolite Tomaculum problematicum Groom ichnospecies, have been discovered in the tectonically disturbed Ordovician rocks drilled by deep boreholes in Koszalin – Chojnice Region in Pomerania (NW Poland). This area is a narrow band situated between the SW margin of the East Europen Craton to the NE and the Variscan belts to the SW. The Ordovician deposits are tectonically deformed, dipping from 20° to 90°, but are not metamorphosed.

The uppermost Llanwirn – Lower Caradoc succession is composed mainly of grey, brownish and green–greyish mudstones and silty mudstones as well as of grey, partly dolomitic siltstones. The Ordovician of the Koszalin – Chojnice Zone contains graptolites of teretiuscus, gracilis, multidens and clingani biozones.

The most rich and well-preserved ichnofaunas have been found in Skibno 1 profile. They are present in brownish–grey, greenish–grey and reddish mudstones and silty mudstones.

The strata of greyish-green fine-grained sediment of the Upper Llanvirn contain several examples of tracemakers activity represented mainly by fodinichnia (feeding–dwelling burrows of benthic organisms) of low–energy environment. This includes of mobile deposit-feeder *Planolites* isp., and, most characteristic of oxygen–deficient environment, *Chondrites* isp.

In greyish–brown and reddish–brown mudstone and silty mudstone of Caradoc (multidens biozone) *Chondrites* isp. are not present anymore. Besides examples of fodinichnia represented by *Planolites* isp. and *Palaeophycus* isp. a few examples of domichnia (dwelling burrows of benthic organisms) appear. This includes forms of cylindical shape ?*Cylindrichnus* isp. and ?*Bergaueria* isp. These trace fossils were made probably by suspension-feeders in shallower, more oxygenated and more agitated environment.

Grand trace fossils (domichnia) produced probably by suspension-feeders have been also found in Caradocian deposits of Chojnice 5 and Jamno IG-2 profiles. In Miastko 1 profile and in one, newly drilled core the examples of the mobile tracemaker *Planolites* isp. has been stated.

Faecal pellets Tomaculum problematicum (Groom) are present throughout the Ordovician profile; a few giant examples have been found in the Caradocian reddish mudstones of the Skibno 1 profile.

Trace fossils assemblage just described differs in some cases from this of Rügen Island and other regions of Avalonia. The typical deep–water Nereites–ichnofacies with typical graphoglyptids is not identified. This assemblage indicates rather shallower and better oxygenated environment especially in the upper part of the Ordovician.

The new data obtained from the Ordovician deposits of the Koszalin – Chojnice Zone give cause for the controversial discussion concerning the palaeoenvironmental and palaeogeographic connections of this area with the other regions of Avalonia and Baltica.

# Quantitative distribution and evolution of palynomorphs associated with kukersite deposits in the Middle-Upper Ordovician of the East-European Platform

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Poster Presentation

Middle-Upper Ordovician Kukersite-type deposits occur in an area of about 100 000 square kilometers of the eastern part of Baltic basin, and they constitute important hydrocarbon source rocks for the region, exploited since the beginning of the last century. These organic-rich shales are dominated by a concentration of *Gleocapsomorpha prisca* Zallesky, 1917, for which the biological affinity (based on optical and geochemical characteristics) remains under discussion. Periodic blooms of this colonial marine microorganism were related to environmental changes, what was also influencing the diversity of associated phytoplankton communities. The present palynological study is focused on the qualitative and quantitative evolution of palynomorph distribution, below, within and above the kukersite-beds in the Alekseevka Quarry section (St.-Petersburg region). Here, 3 m of the Mednikovo Formation, consisting of bluish-grey marlstone, and 6 m of the overlying Solets Formation, represented by four productive kukersite beds intercalated with clay, yellowish-grey limestone with kerogen and clayey limestone, have been sampled. The sequence, embracing the Middle – Upper Ordovician transition (the Ukhaku and the Kukruse Stages respectively), corresponds to the interval of the *Glyptograptus teretiusculus* – *Nemagraptus gracilis* graptolite Zones.

In the upper part of the Mednikovo Formation "normal" phytoplankton community, comprising more than 25 different taxa belonging to *Baltisphaeridium*, *Leiofusa*, *Leiosphaeridia*, *Micrhystridium*, *Ordovicidium*, *Pachysphaeridium*, *Peteinosphaeridium*, *Polygonium,* and *Veryhachium* becomes dominated by *Gleocapsomorpha prisca* (92%). Then, in the kukersite beds at the base of the Solets Formation, palynomorph assemblage is characterised by almost a monospecific association with more than 99,5 % of *G. prisca*. Very few specimens of *Leiosphaeridia*, *Micrhystridium*, or small finely ornamented *Baltisphaeridium* are present in palynological slides made from kukersite. In the overlying sediments, however, together with *G. prisca* still in a remarkable quantity of 60-70 %, all previously identified acritarch species occur again.

*G. prisca* is clearly major contributor of kerogen-rich deposits of the kukersites. Its accumulation is probably not a result of selective preservation, because of accompanying acritarchs in the kukersites beds association, but due to particular paleoenvironmental and depositional conditions, related to sea-level changes in Baltica and/or higher salinity situations as suggested elsewhere.

## A Middle Ordovician silicified brachiopod fauna from Guiyang, South China and its palaeobiogeographical significance

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Oral Presentation

A new silicified brachiopod fauna from the Kuniutan Formation (Darriwilian) at Wudang, Guiyang, central Guizhou, South China contains abundant *Yangtzeella, Orthambonites,* and *Leptellina*, along with common *Parisorthis*, *Saucrorthis*, rare *Anomalorthis*?, *Hemipronites*?, *Leptestia*? and significantly, *Aporthophyla*. Sparse trilobites, gastropods, crinoids and nautiloids are associated with the brachiopods. This shelly fauna is assigned to shallow-water, Benthic Assemblage 3. The first record of *Aporthophyla* in South China is significant since this genus has been regarded as one of the key taxa of the Toquima-Table Head Province (marginal North America, Kolyma and western Norway) during the Mid Ordovician, and indicates a link between South China and the latter province, where the *Aporthophyla* fauna is more typically developed. However, based on this study, the various assemblages bearing *Aporthophyla* may be different in nature, composition and diversity and may have different background palaeobiogeographical signatures. This association is characterized by 1) the absence of many other typical elements of the *Aporthophyla* fauna, 2) the presence of *Orthambonites* and *Hemipronites*?, suggesting some relationships between South China and the Baltic Platform during the Mid Ordovician and 3) the occurrence of some endemic taxa (*Yangtzeella*, *Saucrorthis* and *Parisorthis*). The assemblages containing *Aporthophyla* in South China, Qaidam, Malaysia (Sibumasu), Australia, and probably Tibet are clearly different biogeographically from those associated with the Toquima-Table Head and the high-latitude Celtic provinces.

## Palaeogeography and the origin of higher taxa of echinoderms in the Early Palaeozoic

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Oral Presentation

New higher taxa appear in geological history always suddenly, with already well formed body plans, and usually without demonstration of intermediate forms and supposed ancestors. For many of them is characteristic, that their ancestors lived in another region than that in which the first representatives of a new taxon appeared. In some cases this may be due with incompleteness of palaeontological record. However in most cases the sudden appearance of new body plans resulted from special mechanism of their formation, such as paedomorphosis (retention of the ancestral juvenile characters in the descendant adult) or other kinds of heterochrony (change in timing or rate of developmental events relative to the same events in the ancestors). In such cases the ancestral morphology may be reconstructed from ontogeny data and aberration of adult forms. In the Ordovician Baltic basin numerous echinoderm taxa which first appeared here have heterochronic, mostly paedomorphic traits. Appearance of these characters might be facilitated by the delay in individual development of benthic animals larva. This delay was possibly connected to the increase of their planktonic stage duration while cruising across large open ocean spaces between continents. Benthic animal larvae getting in the oceanic currents decay if they do not find suitable place for attachment. Under condition of suitable change of configuration, mutual disposition of continents or islands and directions of oceanic currents, some larvae, capable of especially long existence in plankton, reach the other shore of the ocean and attach. Extreme duration of planktonic stage favours numerous manifestations of paedomorphosis and other heterochronies. This very mechanism of a new body plan formation could be suggested for the Silurian-Devonian crinoid superfamily Pisocrinacea. Morphology, ontogeny, and stratigraphic distribution convincingly show that Pisocrinacea originated from Homocrinacea in the Early Silurian by paedomorphosis. The Baltic basin

was the center of origin and spreading of Pisocrinacea. At the same time ancestral Homocrinacea are known only in North America. That is why it may be suggested that the Pisocrinacea originated from the Homocrinacea during getting over of the Iapetus ocean from Laurentia to Baltica at the beginning of the Silurian. By this time the Iapetus became considerably narrower, and the larvae of numerous benthic animals could cross it, though over a long period of time. Crossing of this ocean by larvae of one of the homocrinid members led to a delay in skeleton formation and to acceleration of maturity after attachment of larvae in the Baltic basin. As a result a new body plan which characterized the Pisocrinacea appeared, firstly in the framework of the genus *Pisocrinus*. One of the *Pisocrinus* subgenera and its descendant genus *Parapisocrinus* might immigrate by reverse currents to the North American basins and achieved there high species diversity and abundance, particularly in shallow waters. In the Baltics, Urals, Tien-Shan, and Australia *Pisocrinus* gave rise to some new genera among which new forms with multiple arms appeared during the Devonian. The superfamily Allagecrinacea with multiple arms further originate from these genera by paedomorphosis. Notably, the ancestral Pisocrinacea inhabited only in Eurasia and Australia basins, and the earliest Allagecrinacea descendants appeared in North America at the end of the Devonian. Later during the Mississippian some of them migrated to European and Asian basins. This suggest that extremely long crossing of waters barriers by benthic animal larvae while changing of oceanic currents may be an important and a rather usual factor in the origin of the new taxa.

# New zircon ages and isotope data from the Austroalpine Cambrian to Silurian magmatic record and the consequences to models of north-Gondwanan terrane configuration

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Oral Presentation

In the Austroalpine Basement to the south of the Tauern Window, distinct suites of metabasites occur with orthogneisses in the pre-Early-Ordovician units of the Northern-Defereggen-Petzeck- and the Defereggen Groups. Tholeiitic and alkaline within plate basalt type metabasites are associated with acid meta-porphyroids in the post-Early-Ordovician Thurntaler Phyllite Group. Pb-Pb single zircon evaporation protolith ages, whole-rock Ta/Yb-Th/Yb and oxygen, Sr, Nd isotope data define two principal magmatic evolution lines. An older evolution at elevated Th/Yb typical of subduction-related magmatism, started by 590 Ma N-MORB-type and 550 - 530 Ma volcanic arc basalt type metabasite suites which mainly involved depleted mantle sources. These remnants of an active margin are restricted to the pre-Ordovician Northern-Defereggen-Petzeck Group. The evolution of the active margin magmatism was completed by mainly crustal-source 470 - 450 Ma granitoids in both of the pre-Early-Ordovician units and by acid volcanics in the Thurntaler Phyllite Group. An other magmatic evolution line enclosing tholeiitic and 430 Ma alkaline within plate basalt type suites is characterized by an intraplate mantle metasomatism and enrichment trend along multicomponent sources. These former basalts occur as amphibolites in all Austroalpine lithostratigraphic units. The magmatic evolution lines can be related to a plate tectonic scenario which involved terranes aligned in the north-Gondwanan periphery. From the actual spatial position and polarity of the Austroalpine lithostratigraphic units, the progressively mature Neoproterozoic to Ordovician active margin should have been situated to the north, with southward-directed subduction of a Prototethys oceanic crust beneath the terrane assemblage. Early-Silurian alkali magmatism was related to subsequent Palaeo-Tethys opening and passive margin evolution to the south. Multicomponent sources of the alkali magmatites signal a mantle heterogeneity possibly induced by the precedent subduction. However, in the Austroalpine to the south of the Tauern Window no magmatic and metamorphic record of possible Early-Ordovician rifting and subsequent collision events has been found yet. There is no direct magmatic evidence of a Early-Palaeozoic convergent plate setting later than Ashgill until Variscan collision and metamorphism started at Carboniferous times.

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# Early Paleozoic Plate Tectonics, Paleo-geography and Paleoclimate

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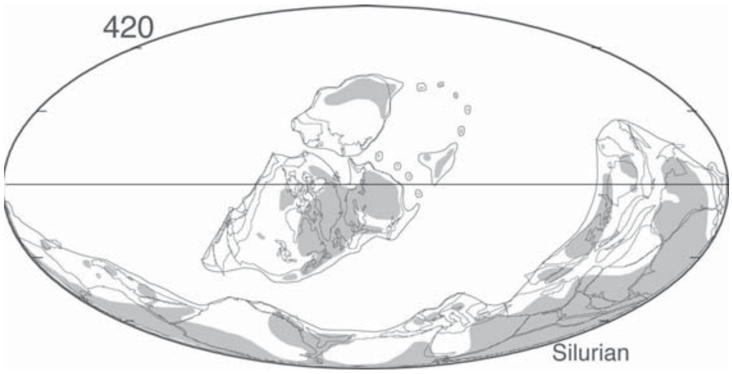
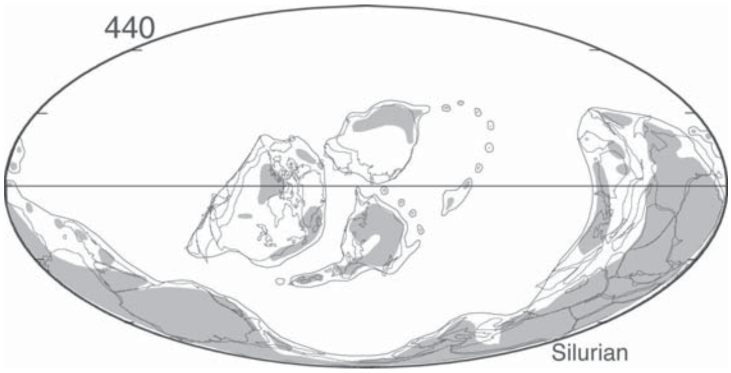
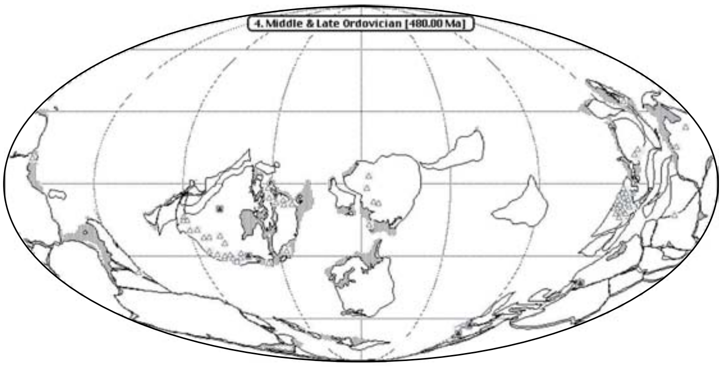
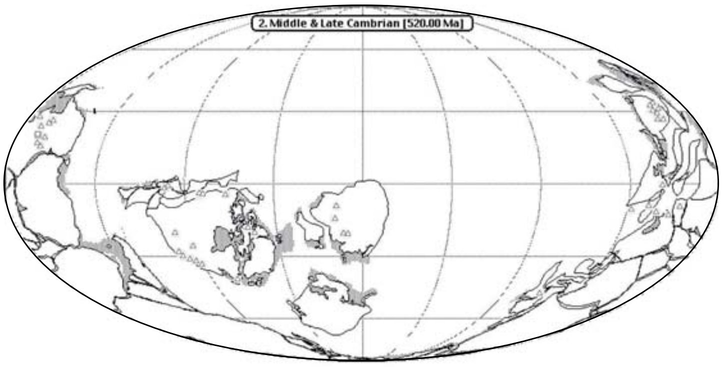
Oral Presentation

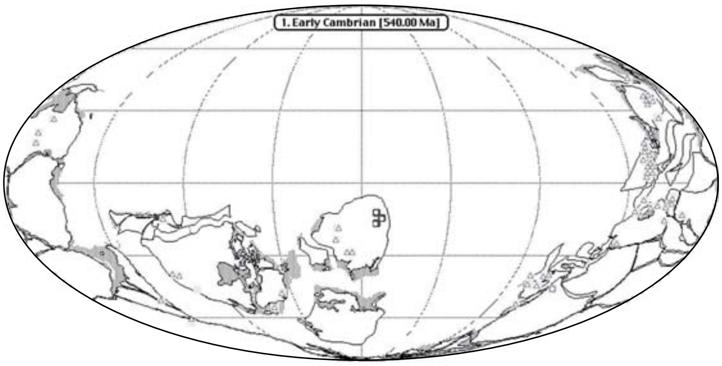
Ten paleoreconstructions are presented illustrating the plate tectonics, paleogeography and paleoclimate of the latest Precambrian and Early Paleozoic. The time intervals chosen include two maps for the latest Precambrian (600 Ma and 570 Ma), maps for the Early and Late Cambrian, four maps for the Ordovician (early Tremadoc, early Arenig, Llandeilo/Caradoc, and Ashgill), as well as paleoreconstructions for the Early and Middle Silurian. The plate tectonic reconstructions show the probable location of active plate boundaries (subduction zones, island arcs and mid-ocean ridges). The paleogeographic maps illustrate the distribution of deep oceans, shallow shelves, lowlands and mountainous areas for each time interval. There are two versions of each paleogeographic map. One map shows the extent of maximum flooding during a period of high eustatic sea level. The second map shows the paleogeography during a time of minimum sea level corresponding to a major sequence boundary. In the final set of maps, climatically sensitive lithofacies such as evaporites, calcretes, bauxites, and tillites are plotted on the paleoreconstructions. Climatic zones are mapped based on the distribution of these climatically sensitive lithofacies.



# Early Paleozoic Paleoclimatic simulations: data and model comparisons

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Oral Presentation

Computer models that are used to simulate paleoclimate, such as GCMs and FOAMs are expensive to run, use excessive amounts of computing time, and often give results that are in poor agreement with the geological record. GCMs are notorious for results that look more like the present-day than the geological past. Hot Houses climates, like the Cretaceous, have been especially difficult to simulate. Though the GCM simulations for Hot House climates can be improved by drastically increasing $CO_2$ levels or enhancing equator-to-pole oceanic transport, these adjustments often seem forced and ad-hoc. An alternate climate modeling technique has been developed by the author, called the Parametric Climate Model (PCM), that is inexpensive, can be run quickly on personal computers, and makes paleoclimatic predictions that are in better agreement with the rock record. The PCM is a non-dynamical climate model uses geological information describing past climates to set important boundary conditions for the paleoclimatic simulations. These boundary conditions include: the pole-to-equator temperature gradient, surface moisture, land cover, and the size and extent of the paleo-Hadley cell circulation.

Most of the computing time and expense of a GCM run is the result of the repetitive calculations required to “spin up” a dynamical simulation of the oceans and atmosphere. Only after running for a number of “model years” (often weeks of computing time) are the estimates considered accurate. In contrast, the PCM starts with boundary conditions that reflect our knowledge of past climates and consequently gives more geologically satisfying results.

To test the Parametric Climate Model, five paleoclimatic simulations were run for the: Late Precambrian (600 Ma), the Early Cambrian, the Early Ordovician, the latest Ordovician (Ashgill), and the Middle Silurian (Wenlock). Global temperatures, precipitation patterns, surface ocean currents and upwelling zones that were predicted by the PCM were compared with availabale GCM runs and with the distribution of lithologic indicators of climate such as evaporites, calcretes, bauxites, kaolinites, and tillites. A database of lithologic indicators of climate comprising more than 8000 entries for the Phanerozoic has been compiled by A.J. Boucot (Oregon) and Chen Xu (Nanjing).

# Are some fossils better than others for inferring palaeogeography? An old question revisited

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Oral Presentation

In their publication entitled “*Are some fossils better than others for inferring palaeogeography? The early Ordovician of the North Atlantic region as an example*”, Fortey and Mellish (1992) asked whether some fossils were better than others for inferring Ordovician palaeogeography. Planktic fossil groups (graptolites, acritarches, etc.) were considered not to ‘see’ a separation between Gondwana and Baltica, while trilobites and ostracodes provided evidence for this separation. Fortey and Mellish (1992) concluded that planktic fossils such as graptolites, chitinozoans and acritarchs were in general of low palaeogeographical value, while their seleced groups of benthic organisms such as trilobites, brachiopods, and ostracodes were more useful for biogeographical discrimination.

Fortey and Mellish's (1992) paper has resulted in an ongoing discussion on the relative merits of palaeobiogeographical indicators in the Ordovician (e.g. Servais and Fatka, 1997; Samuelsson et al., 2001). At the heart of this debate is the question of whether the planktic groups were so widely distributed as to be virtually cosmopolitan in the Ordovician world, or whether distinct areas of the Earth were characterized by distinct faunas and microfloras (as they are in modern oceans and during the Mesozoic) and if so, what controlled their distribution during the Early Palaeozoic.

In the present study we discuss the palaeogeographic distribution of graptolites, chitinozoans, and acritarchs in detail, and, together with the distribution of conodonts and some pelagic trilobites, plot the occurrences on different palaeogeographic reconstructions, including the maps of Cocks (2001).

It appears that the distribution scenarios between planktic and benthic fossil groups are often surprisingly very similar, and that planktic groups have a clear palaeogeographical signal. The major problem is to find, for every fossil group (benthic or planktic), the good biogeographic marker.

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# Development of acritarch communities across the late Silurian positive $\delta^{13}C$ excursion – data from Gotland, Sweden

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Poster Presentation

In the last decades, a rising amount of studies have underlined the potential of Palaeozoic acritarchs as accurate proxies for palaeoenvironmental reconstructions. In order to better understand the acritarch distribution in critical intervals, i.e. in times of strong climatic changes, a detailed palynological study has been carried out in the Ludlow (Upper Silurian) of Gotland (Sweden). The present work focuses on the distribution of acritarchs through a vertical profile from the Hemse to Hamra/Sundre Beds. In this time interval the strongest global positive $\delta^{13}C$ and $\delta^{18}O$ excursion of the entire Phanerozoic has been reported (Bickert et al., 1997; Samtleben et al., 2000). According to Bickert et al. (1997), the time of high isotope values corresponds to arid climate conditions in low latitudes, while the times of low values are attributed to humid conditions. Our results show a close connection of palynomorphs with the development of stable C and O isotopes. Not only the acritarchs, which most probably belong to the phytoplankton and, thus, are good indicators of surface water conditions, but all marine palynomorphs decline considerably in relative and absolute abundances during the isotope excursion. These results clearly indicate that the isotope excursion cannot be the result of increased marine phytoplankton productivity. Terrestrial spores, in contrast, strongly increase during the isotope excursion. Within the most common acritarchs, ornamentated genera (i.e., *Evittia*, *Percultisphaera*) are more common before the excursion, and decrease during the rise of the isotope values. Such genera have been previously reported in more distal environments in the Gorstian sediments of Gotland (Stricanne et al., 2004). Less-ornamentated acritarchs (i.e., *Micrhystridium*, *Veryhachium*) are more frequent during the excursion than before, and these genera have been attributed to proximal environments.

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# K-bentonites and progressive flysch succession around Ordovician- Silurian transition in South China: new evidences for accretion of Cathaysia to Yangtze Block and break-up of Gondwanaland

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Oral Presentation

The 'Cathaysian Oldland' or 'Cathaysian Block' has been taken as a significant tectonic unit in the southeast China for many years (Grabau, 1924). Determination of its relationship with the Yangtze Block and its geologic development in the Paleozoic has an important impact to the understanding of the tectonic evolution of south China. Several problems in this topic, however, still remain to be solved. These problems include: whether or not existed such a Land in Paleozoic, where is the exact boundary between the two units, and what was the accretion process.

Recently, a number of K-bentonite beds have been recognized in the Ordovician-Silurian transition (Ashgillian ~ Early Llandovery) in the Yangtze Block, south China. A preliminary analyses on geochemical composition of the K-bentonites has suggested a parental magma origin of trachyandesite to rhyodacite with some rhyolite in general, which came from volcanic-arc (VA) and syn-collision (syn-COL) to intra-plate (WP) tectonic settings. A regional correlation of these K-bentonite beds has indicated that they have clearly potential of increasing southeastward both in thickness and grain-size. These characters suggest that the original volcanic ash may come from southeast part of the present south China.

In addition, along the southeast margin of the Yangtze Block, typical flysch successions have also been identified both from the Zhoujiaxi Group (early Llandovery) and Tianmashan Formation (Ashgillian) in the southern part of Hunan Province, south China. Geochemical analysis on the silicate minerals has suggested that the flysch successions were deposited in the basin on a passive continental margin. Field observations on the paleo-currents, cross-beddings, ripple marks as well as flute marks, all suggest that the detrital components must have been transferred from the southeast part of the present south China, in good agreement with the conclusion drawn from the analysis of the K-bentonites. Furthermore, the flysch successions both in Tianmashan Formation and Zhoujiaxi Group clearly show a northwestward progradation in space and time during the Ordovician-Silurian transition.

Based on the present study and also the former works, we would like to conclude that there did exist the Cathaysia Land or Cathaysia Block beside the Yangtze block in south China during Early Paleozoic. Both the K-bentonites and flysch successions could be regarded as the products in responding distantly of the area to the continuous northwestward collision and accretion process of the Cathaysia Block to the Yangtze Block. The west boundary of the Cathaysian block, however, probably located along the suggested Early Paleozoic suture (Wang et al, 1987; Yang et al, 1995). According to the present study, we also hold that the accretion of the Cathaysia to Yangtze Block may be related to the initial break-up of the Gondwanaland. At this time, the south China blocks were largely at the low latitude adjacent the Gondwanaland (McKerrow and Scotese, 1990; Fang et al, 1990; Wu et al, 1999; Zhang et el, 2004).

# Fossil assemblages from radiolarites of Central Kazakhstan – a key for the reconstruction of the pelagic ecosystem.

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Oral Presentation

The ribbon-banded cherts of the Burubaital Formation exposed west of Lake Balkhash in Central Kazakhstan represent the complete and detailed record of basinal sedimentary succession ranging in age from at least the late Cambrian to the early Caradoc (*Eoconodontus notchpeakensis-Pygodus anserinus* biozones). The condensed sediments accumulated during that time interval on the seafloor are completely made up of skeletons of radiolarians and sponges spicules with the minor input of fine clastic material. Basinal environment was inhabited by conodonts, graptolites, pterobranchs, linguloid brachiopods, and caryocaridid arthropods showing that richly diversified marine fauna existed in the open ocean far from the continental margins. Besides the listed fauna cherts of the Burubaital Formation contain numerous silicified bacteria and chitinous microspheres (0.3-0.05 mm in diameter) that are commonly found in clusters and supposed to be arthropod eggs.

Faunal remains buried in radiolarian oozes are preserved in the poorly opaque and semi-transparent cherts, which like amber keep traces of trophic interactions of organisms in the marine ecosystem. One of the examples of trophic interplay are the silicified bacteria fed on organic matter of pterobranchs and graptolites. Numerous faecal pellets composed of conodont elements and small fragments of cariocaridid shells found in cherts evidently indicate the existence of carnivorous macrozooplankton and nekton in the Early Paleozoic. The size of faecal pellets, number and taxonomic composition of conodont elements composing the pellets differs significantly. It is possible to distinguish two types of pellets produced by organisms different in the predation strategy. Conodont animals were possibly one of the predators that consumed juvenile conodonts as well as mesoplankton arthropods (0.5- 1 cm). Single pellet of these predators contains the remains of one individual. The significantly larger faecal pellets containing elements of more then one conodont animal (up to 150 conodont elements) possibly were produced by another predator. These large pellets also show that either conodont animals existed in cohorts of individuals of the same age or predator was consistent with the selection of preys by size and taxonomy.

The degree of fossils fragmentation and disintegration of faecal pellets in the cherts of the Burubaital Formation differs from bed to bed through the succession and is strongly connected with the color and textural characters of cherts, that in turn, depends on the physical-chemical conditions of the bottom and sediment water during sedimentation. The latter is possibly controlled by changes in paleooceanographical circulation patterns as well as in variations in net primary productivity. The most significant changes recorded in the cherts of the Burubaital Formation are confined to the base of *Oepikodus evae* Biozone. Faecal pellets became less abundant since then possibly due to increase in oxygenation of the bottom waters and related to it growth of radiolarian productivity.

## Sr isotopic and Mg cycling in Early Palaeozoic seawater: implications for tectonic and climatic processes

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Poster Presentation

Continental weathering, mantle degassing, and landmass distribution have long been recognized as major drivers of climate change. Resolving the relative contributions of these competing forces at short timescales is particularly challenging. This study attempts to recognize high-resolution fluctuations in Ordovician and Early Silurian seawater chemistry derived from minor element and isotopic compositions of conodont apatite, and thus deconvolve the relative shifts in the dominant processes operating during this period.

Temporal variations in Mg/Ca compositions of conodont apatite are correlated with established sea-level curves. Magnesium cycling in seawater is driven by the mass balance of hydrothermal activity, continental weathering, carbonate deposition and dolomitization (eustasy, pH and $CO_2$), and thus has implications for understanding palaeoclimate. An integrated approach utilizing high-resolution Mg/Ca and Sr isotopic compositions of Early Palaeozoic seawater, as inferred from conodont geochemistry, can help identify the major sources and sinks of Mg and Sr, and accordingly, better constrain tectonic, eustatic, and climate dynamics.

Conodont apatite was analyzed using high-resolution, in-situ, laser ablation micro-sampling techniques (ICPMS and MC-ICPMS) providing continuous compositional profiles of single conodont elements. Compositional heterogeneity can be significant hence the high spatial resolution afforded by laser micro-sampling can exclude diagenetic zones, thereby ensuring data integrity.

## Basin analysis: a punctual example in the South of Romania

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Poster Presentation

The Moesian Platform on the territory of Romania is divided by the Intramoesian Fault into two parts with different tectonics, the eastern part being considered to have more complicated tectonics and many stratigraphic gaps in comparison with its western part. The eastern part is separated from the North-Dobrogean Orogen by the Pecineaga Camena Fault, which allowed it to develop as an independent sedimentation basin. Based on palynological data, especially new chitinozoan assemblages, the age of sediments as well as some palaeogeograghic conditions of sedimentation for a borehole located in northern Moesia have been revised. Sedimentation rate in the basin was greater in the Cambrian than in the Ordovician, while in the Silurian it suddenly accelerated; thereafter, during the Devonian, it decreased rapidly to a constant level, this being a little bit less than during Devonian and Carboniferous times. Sediment burial curves show that subsidence was pronounced from Cambrian until Silurian times. The Devonian and Carboniferous are characterized by burial curve patterns with a more important linear trend than earlier. As for the thermal basinal regime during the Cambrian-Carboniferous span, an important observation is that high terrestrial heat flow values are inferred from the reconstructed temperature versus time model. The high heat flow and the organic matter content of some of the Silurian sediments permitted hydrocarbon generation with a TOC (total organic carbon) range of approximately 0.5 mg HC/g initial dry rock. The Silurian sediments are mostly represented by shelly-fauna with graptolites. The vitrinite reflectance versus depth curves exhibit values that provide additional consistent arguments for a high thermal regime. This interpretation is possibly supported by the present day oil resources that are exploited in the eastern part of the Moesian Platform where hydrocarbons are supposed to have migrated into carbonaceous Mesozoic reservoirs from deeper formations.

## The biostratigraphy of new chitinozoans from the South of Romania

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Poster Presentation

The south of Romania is occupied by the Moesian tectonic block. New chitinozoan assemblages are described for the sediments of its eastern part. They contain Wenlock and Ludlow as well as Pridoli/Lochkovian chitinozoans, most of them in a good state of preservation. the *Conochitina pachycephala* biozone and some characteristic species, *e.g. Conochitina tuba, C. claviformis,* were recognized in the samples from boreholes. Also identified were Pridoli chitinozoans such as *Urnochitina urna, Eisenackitina lagenomorpha, Eisenackitina filifera, and Bursachitina krizi, etc.* The biozones *Eisenackitina bohemica* and *Urochitina simplex* together with accompanying species such as *Cingulochitina plusquelleci, C. ervensis, C. serrata, Angochitina filosa, Bursachitina oviformis,* etc. were also described, these being characteristic for Lochkovian age. Macrofauna are also present in the study area. In the western part of the Moesian terrane, the facies of "shelly fauna" without graptolites is present while, in the eastern part, the facies of "shelly fauna" that contains graptolites occurs. The *lundgreni, nilssoni-scanicus, bohemicus* and *ultimus-formosus* graptolite zones were identified. The *Icriodus woschmidti* conodont zone was recognised in the eastern part as well as in the western part of Moesia (Iordan, 1971). Supposing that affinities are not clearly indicated for the Wenlock-Ludlow by the chitinozoans assemblage, because they are cosmopolitan specimens, there is evidence that shows a North Gondwanan affinity for this part of Moesia for the Pridoli/Lochkovian. Moreover, the Pridoli/Lochkovian affinities are similar to those from Podolia, Ukraine (Paris & Grahn, 1996). Otherwise, the same palaeogeographical affinities are demonstrated for Moesia in Bulgaria by some authors (Haydoutov & Yanev, 1997; Gutiérez-Marco et al., 2003).

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## Towards an Upper Ordovician chitinozoan biozonation on Avalonia? Research on historical type areas and other UK key sections.

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Poster Presentation

The recent study of the rich and diverse chitinozoan assemblages from the historical type area of the Ashgill Series in the Cautley District (Cumbria, Northern England) led to the recognition of several, both new as previously defined biozones, from bottom to top: the *Fungochitina fungiformis*, *Tanuchitina bergstroemi*?, *Conochitina rugata* (three Baltoscandian biozones), *Spinachitina fossensis*, *Bursachitina* sp. 1 n. sp. (two typical Avalonian biozones), *Ancyrochitina merga* (a Northern Gondwana biozone) and the *Belonechitina postrobusta* Zone (a global lower Silurian biozone). All biozones are well correlated with the graptolite (Rickards, 2002) and shelly fauna (Ingham, 1966) biozones described from the region. These data were already presented on several occasions (e.g. Vandenbroucke *et al.*, 2003), but are now consequently completed with data from other key sections in the U.K., such as the

Pus Gill section (Cross Fell Inlier, Cumbria, Northern England), which originally gave its name to the lowest stage of the Ashgill Series. The Baltoscandic *F. fungiformis* Zone (Nõlvak and Grahn, 1993) has been recognised in this section as well, thus quite easily allowing correlation between both sections, for the first time with a widely distributed planktonic fossil group. From the combined study of the sections, it is clear that the base of the Ashgill Series lies within the *F. fungiformis* Zone, rather than in the *T. bergstroemi* zone as previously written (thus, slightly lower in the chitinozoan biozonation).

In addition, the Baltoscandic chitinozoan zones mentioned above are now much better tied to the British chronostratigraphy, which has been and still is widely used in literature, although at present abandoned on a international level. Equally interesting, the occurrence of *Angochitina communis* in the Pus Gill section, below the FAD of *Fungochitina fungiformis*, is correlated with the topmost Onnian beds of the historical type Caradoc section in the Onny Valley (Shropshire, U.K.); this thus leaves the *F. fungiformis* bearing part of the Pus Gill Onnian absent from the type Caradoc area (see Jenkins, 1967). As far as we know, this is the first direct correlation between the two historical type areas.

Chitinozoan research in the Greenscoe section through the Kirkley Bank Formation in the Lake District (Dalton-in-Furness, Northern England) yielded abundant chitinozoans belonging to the *Fungochitina fungiformis* zone, stressing the usefulness of this biozone for correlation within Avalonia and between Avalonia and Baltica. The section also allows calibration with the *Amorphognathus superbus* conodont biozone (Smith, 1999).

The Caradoc succession between Fishgard and Cardigan (southwest Wales) has good potential to be correlated with the lower stratigraphical levels in Cautley and the Cross Fell inliers, according to preliminary chitinozoan results from 24 samples, the top ones tentatively assigned to the ?*Fungochitina fungiformis* and *Tanuchitina bergstroemi* zones. The samples were taken from graptolite slabs, collected during a recent BGS mapping project in the area (Williams *et al.*, 2003); the chitinozoan results will thus be tightly correlated with the graptolite data (*Diplograptus multidens*, *Dicranograptus clingani* and *Pleurograptus linearis* biozones).

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## Chitinozoans from the Upper Ordovician of the Fauquez area (Brabant Massif, Belgium)

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Poster Presentation

The biostratigraphy with chitinozoans of the Upper Ordovician rocks of the Fauquez area is studied in detail. The Chitinozoans of four recently defined formations, the Bornival, the Huet, the Fauquez and Madot Formations (Van Grootel *et al.,* 1997) are studied from 53 samples. Except for the Fauquez Formation, in which the *clingani* or *linearis* Graptolite Biozone was recognised (Maletz & Servais, 1998), the rocks are devoid of any graptolites or conodonts. The chitinozoans are poorly to moderately preserved but nevertheless several Baltoscandian biozones (Nõlvak & Grahn, 1993; Nõlvak, 1999) could be recognised. Also correlations with the Type Ashgill area (Vandenbroucke, in prep.) and the Belgian Condroz Inlier (Vanmeirhaeghe, in prep.) on Avalonia can be made.

The Bornival Formation, which is subdivided into three members, contains *Belonechitina robusta* and *Conochitina minnesotensis*, whereas *Lagenochitina baltica* was recovered from the second member. The presence of a few specimens of *Belonechitina hirsuta* is probaly due to reworking. The co-occurence of *B. robusta* and *L. baltica* indicates a Cheneyan or younger age. The Huet Formation contains *L. baltica, L . prussica,,* and *B. robusta*. These three species co-occur in Baltica in the late Caradoc and the early Ashgill. In the Fauquez Formation, these three species co-occur together with *Tanuchitina bergstroemi*?, indicating a late Caradoc to early Ashgill age, corroborated by the graptolite data. The Madot Formation contains the same chitinozoan assemblage. Trilobites, probably found in the Madot Formation (Richter & Richter, 1951) indicate an early Ashgill age. Martin & Rickards (1979) studied acritarchs in four samples in the Fauquez area and obtained a broad Caradoc to Llandovery age for the Madot Formation, not contradictory to our results.

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# Palaeobiological and palaeoenvironmental significance of cryptospores and acritarchs from the Llanvirn of Saudi Arabia

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Poster Presentation

Core samples and cuttings from the shallow drillcore QSIM-801 in the Qasim region of central Saudi Arabia were investigated palynologically. The studied interval corresponds to the Qasim and Saq formations, and yielded well preserved and abundant palynomorph assemblages comprising cryptospores, acritarchs, and chitinozoans. Palynological dating (acritarchs and chitinozoans) points to a late Arenig to Llanvirn age for the investigated interval, as confirmed also by graptolite data.

The lowermost cored levels, consisting of marine, shallow water, fine grained sandstones are palynologically dominated by rich and diversified cryptospore assemblages comprising permanent tetrads, diads, monads, and possibly cuticle-like phytoclasts. These findings confirm previous reports of palynological evidence for early land plants in Saudi Arabia and the interest and importance of this area for the study of the evolution of primitive vegetation.

Palynological assemblages from the upper part of the drillcore are richer in marine elements (acritarchs and chitinozoans), although recurrences of cryptospore-dominated levels indicate shoreline proximity throughout the sequence. The acritarchs are very well preserved and comprise few examples of previously unreported morphologies, probably belonging to new taxa.

The quantitative analysis of relative abundances and representativity of the main morphological groups of acritarchs and the calculation of t/m index are tentatively used to track changes in palaeoenvironmental conditions. Common occurrence of teratological forms, of cysts at various stages of maturity, and frequently observed local over-representation of specific form-groups (e.g., galeates, *Frankea*), are interpreted as evidence of highly stressed palaeoecological conditions, probably linked to coastal palaeoenvironmental dynamics. On the basis of this observations, we tentatively discuss the influence of fluctuations in hydrographic processes on acritarch cyst development.

# High-latitude bryozoan-dominated communities as a major carbonate factory on mixed carbonate-siliciclastic platforms of the late Ordovician northern Gondwana

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Poster Presentation

The northern Gondwana platforms were adequate to record an anomalous peak of carbonate productivity during Ashgill times. Carbonate sedimentation was then characterized by temperate- to cold-water reefal and non-reefal limestones, in which a robust skeletal carbonate factory was episodically resilient to poisoning by terrigenous input. The Ashgillian sedimentary succession of the Erfoud area (eastern Anti-Atlas) corresponds to the bryozoan-rich Khabt el Hajar Formation. The succession consists of two mixed (siliciclastic-carbonate) units bounded by marls in distal areas and by a major discontinuity in proximal areas. A preliminary biostratigraphical study, based on echinoderms (*Herpetocystis destombesi*), trilobites (*Brongniartella platynota maroccana*), and brachiopods (*Paucicrura catalanica)* allows us to propose a mid Ashgill age, at least for the marls and the upper mixed unit.

The Ashgill sediments of the Erfoud area are arranged into two depositional sequences, up to 70 thick, respectively topped by two major stratigraphic discontinuities. The first sequence commences with a lower transgressive systems tract (TST1) characterized by a gradual increase in carbonate content representing a mid-ramp system dominated by storm-induced processes. TST1 is capped by a laterally correlatable flooding surface indicated by the widespread distribution of carbonate production. The high stand systems tract (HST1) has recorded a progradational trend on the whole ramp with the development of a bryozoan-rich biofacies in a front-delta system.

The second depositional sequence clearly onlaps the erosive surface capping the last HST1 (D1). The transgression (TST2) is marked in the proximal area by a fine-grained carbonate sedimentation rich in echinoderms and bryozoans passing basinward into marls where *in situ* delicate-branching bryozoan clusters developed. The upper highstand systems tract (HST2) shows a new progradation of bryozoan-rich sediments capped by a sharp erosive unconformity (D2) that marks the contact with Silurian iron-rich crusts. Neither the Hirnantian nor the lower stages of the Silurian have been identified in these sections.

Two bryozoan-dominated biofacies and one bryonoderm biofacies occur within the above-reported mixed carbonate-siliciclastic units. These biofacies change in a proximal-distal transect through the platform. The distal biofacies in sequence 2 (TST2) is composed of *in situ* delicate-branching bryozoans that formed metre-scale clusters embedded in a marly substrate developed on outer-ramp environments. The proximal biofacies are the bryozoan and bryonoderm ones. The bryozoan biofacies is dominated by encrusting bryozoans and secondary robust-branching bryozoans developed in a front-delta system (sequences 1 and 2), where an epibenthic community, which colonized and stabilized the siliciclastic substrates, is commonly observed at the top of sand shoals and on abandoned marginal channels. The bryonoderm biofacies (sequence 1), dominated by thick crinoids and robust-branching bryozoans, developed in mid-ramp settings and corresponds to pelmatozoan-bryozoan meadows degraded by wave activity and input of siliciclastic material. Three main bryozoan morphotypes have been identified: encrusting forms, erect-rigid and robust-branching forms, and delicate-branching forms. Each of them occupies different depositional settings from shallow-ramp settings dominated by siliciclastic sedimentation, carbonate mid-ramp settings rich in echinoderms, and deep-ramp settings dominated by a marly sedimentation.

From a paleogeographic point of view, the middle-Ashgill Erfoud ramp is characterized by episodic exclusion of carbonate productivity in nearshore environments related to an active shoreline source of siliciclastic sediments. Only centimetre-scale bryozoan clusters developed in this part of the northern Gondwana platform, differing from the carbonate mud-mound complexes preserved in the Iberian Chains (Spain). Was the higher latitudinal position of the Moroccan platform directly responsible for the lack of reefal development?

This paper is a contribution to projects BTE2002-0118, Eclipse and IGCP 503.

# Modelling the Hirnantian eustatic fall and its related Gondwanan ice-sheet growth time

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Oral Presentation

Actualistic interpolations allow the inference of past glacial conditions by applying glacial isostatic adjustment (GIA) models. The processes and effects of the Hirnantian (latest Ordovician) glaciation can therefore be analysed by comparison with analogous Quaternary glaciation episodes. One of the main unresolved questions of the Hirnantian glaciation is its related eustatic fall, a key parameter, which is required to explain the associated major extinction event. Previous estimates of this sea-level drop have been advanced based on evidence of the subaerial exposure of pre-Hirnantian siliciclastic and carbonate platforms and their subsequent erosion and karstification. These analyses have usually been made in subtropical- and temperate-water platforms, postulating an eustatic drop of 50 to 100 m related to the Hirnantian sea-level draw-down (Brenchley & Newall, 1980).

New data from the Moroccan Anti-Atlas related to the relative-sea level drop associated with glacioeustacism and the isostatic depression driven by ice loading on the northernmost glaciated Gondwana (Alnif area; Álvaro et al., this volume) allow estimates to be made on the maximum ice volume accumulated, as well as on the growth rate of the ice sheet. A recorded valley-glacier incision of at least 180 m, eroding the pre-Hirnantian platform sediments of the Alnif area, is interpreted as a directly induced glacioeustatic draw-drown driven by the accumulation of the Hirnantian ice-sheet on high-latitude Gondwana. To estimate the eustatic drop in sea level in this area, it is necessary to add to the 180 m of erosion, the estimated bathymetry of the youngest Ashgill (pre-Hirnantian) marine sediments (the shales of the Upper-Ktaoua Formation that were deposited in offshore settings: ca. 60 m deep).

Recent palaeogeographical reconstructions depict the Hirnantian South Pole close to the Guinean Gulf surrounded by an ice cap that reached the southern Sahara, Saudi Arabia, South Africa, South America, and even the eastern Anti-Atlas in Morocco (Álvaro et al., this volume). As a result, a continuous polar ice sheet reaching southern latitudes of 60° (radius of ca. 3 300 km) can be postulated for the Hirnantian glaciation peak. According to the known relationships between radius (L) and volume (V) of Quaternary ice sheets (Paterson, 1972: $L = k\ V^{5/2}$), an Hirnantian ice-sheet volume of about 120 $10^6$ $km^3$ can be estimated, which would imply an eustatic drop of ca. 250 m. This estimate greatly increases the highest probable values proposed in previous-reported eustatic drops and fits well with the value envisaged in the Alnif case-study. The Hirnantian maximum ice-sheet volume and sea-level drop would have surpassed by nearly 25% the maximum Quaternary values, representing the largest-known Phanerozoic glaciation.

With our GIA model, the adjustment between the estimated curves of eustatic, isostatic and relative sea-level fluctuations observed in Alnif has only been possible for an ice-sheet growth time of the order of 10 000 years. Thus, a total glaciation time span of no more than 20 000 years is estimated, reducing considerably the previouslyreported time span of ca. 500 000 years. In the light of this new estimate, the primary causes that controlled the growth and decay of the Hirnantian ice cap must be re-evaluated. The extremely short time span of this glaciation and its huge sea-level change will permit a better understanding of the importance of its related extinction event.

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# Ordovician conulariid diversity in the periGondwana and Baltica regions – a summary with a special view to the Ordovician of Barrandian

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Poster Presentation

High biodiversity of the suborder *Conulariina* Miller and Gurley, 1896 is exhibited globally at the Middle-Upper Ordovician. In the contrast to the Cambrian from which no genera is described, first occurences of eight genera are documented from the Middle-Upper Ordovician of the periGondwana and Baltica regions.

The periGondwana is characterised by the cool-water EAP (*Exoconularia-Archaeoconularia-Pseudoconularia*) conulariid province (Van Iten – Brabcová, 2004) typical of following other species: *Anaconularia, Conularia, Conulariella, Eoconularia,* and *Metaconularia*. Host rocks of these generas are usually fine-grained sandstones and shales, exceptional preservation is in iron ores. All the forms are medium to big conulariids with well-developed sculpture. The genus *Conulariella*, typical for its rectangular cross-section and smooth transversal ribs is characteristic only for the Arenigian of Bohemia. The EAP Province includes France, Bohemia, Thuringia, Sardinia, Morroco, Turkey and, probably, Jordan.

The palaeocontinet Baltica is assigned to the warm-water CC (*Conularia* – *Climacoconus*) conularid province with following other representatives: *Archaeoconularia*, *Conularina*, *Ctenoconularia*, *Eoconularia*, *Exoconularia*, *Glyptoconularia*, *Metaconularia,* and *Pseudoconularia*. Host rocks are most often carbonates or cratonic basin shales. The CC province representatives are small to medium conulariid forms characteristic for its simple sculpture.

In the Prague Basin (Bohemia), all the Ordovician forms, except for the species *Conularia (Plectoconularia) proteica* Barrande, 1854; are not recorded in the younger stages. High specialization of the Ordovician species indicated by complicated sculpture did not allow to these form adapt to new climate conditions after the Hirnantian glaciation. Close similarities in morphology were studied at the species *Pseudoconularia grandissima, Exoconularia pyramidata, Anaconularia anomala* and *Conularia rugulosa* occuring in the Prague Basin (Bohemia), France and Morroco regions, and *Metaconularia bilineata* occuring in the Prague Basin (Bohemia) and Gotland (Sweden).

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# The Ordovician Baltic epeiric sea – taphonomy and early diagenesis of its carbonate sediments

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Poster Presentation

Shallow water carbonate sedimentation persisted in the Ordovician Baltoscandian epeiric sea from the Tremadocian. 'Cephalopod limestones' are the typical limestones preserved today in Jämtland, Östergötland, Västergötland, Öland (central-southern Sweden), Estonia, and Denmark. As well as these distinctive sequences, reefs and limestone-shale alternations are known from Norway, and carbonate mud mounds are documented from the Caradoc and Ashgill of Siljan District Sweden (Kullberg and Boda mounds), Gotland, the Baltic and Russia. This dynamic carbonate deposystem was the setting for much of Ordovician Baltoscandian biodiversification, yet the exact environmental controls on sedimentation, and particularly processes of early diagenesis are poorly understood. Developing a taphonomic and early diagenetic model is critical for fully appreciating the spatial and temporal trends of Ordovician biodiversification for Baltica, particularly for taphonomically vulnerable groups such as molluscs.

Research on the cephalopod limestone of Jämtland has revealed that these are largely a product of an extensive destructive taphonomic system, similar to that seen in Cenozoic temperate carbonates. Early diagenetic characteristics indicating extensive syndepositional dissolution include a calcite-biased bioclastic fraction, partly to completely dissolved shells, contrasts in preservation of originally aragonitic nautiloid cephalopods, pores overprinted by dissolution and the possible presence of pitted microspars. Evidence for bioturbation is ubiquitous and is closely related to early remobilisation of carbonate – a *Thalassinoides*/*Chondrites* suite is commonly documented, as is a finer scale sediment retexturing. 'Micritic' nodular limestones and 'diagenetic beds' are interpreted as features of early carbonate remobilisation and lithification. The micritic limestones are composed of extensively comminuted bioclasts, as well as micrite/ microspar cements displaying displacive clay cages. An aragonite mud precursor is a possibility, yet no obvious source is preserved (bearing in mind this is a 'calcite sea') that could have provided sufficiently large volumes to source diagenetic limestone; a skeletal source is more likely. The apparent slow accumulation rate for the cephalopod limestone can be interpreted as evidence for a diagenetically open system rather than low carbonate production.

This diagenetic regime has implications for the nature of biodiversity trends for molluscs. For example, the second major radiation of bivalves in the Upper Ordovician has been linked to the development of low latitude carbonate platforms on Baltica and Laurentia. However, the cephalopod limestone facies existed from the Tremadocian in Baltica, yet contains hardly any fossil record for bivalves among a normal marine fauna. Recently compiled bivalve data for Baltica shows that many of these bivalves are known from the Boda limestone mud mounds and siliciclastic facies elsewhere in Baltica that have a contrasting early diagenetic history compared to the cephalopod limestones. The paucity of bivalves then from cephalopod limestones is likely to be taphonomic rather than ecological and may well be obscuring the true timing and nature of bivalve radiation. Studies on the Silurian carbonates from Gotland have proven that early diagenetic dissolution of bivalves occurred on a previously unrecognised large scale for diversity and abundance; there is no reason to assume the case was any different in the Ordovician for bivalves (cephalopods and gastropods).

## Depositional environments and sequence stratigraphy of the Jigunsan Formation (Middle Ordovician), Taebaeksan Basin, Mideast Korea

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Poster Presentation

The Jigunsan Formation (Middle Ordovician) in the eastern Taebaeksan Basin, mideast Korea, is an extensive fine-grained deposit of mixed carbonate-siliciclastic platform that is correlated for long distances. This study focuses on the depositional processes and sequence stratigraphic implications of the siliciclastic-dominant mixed carbonate-siliciclastic succession. The deposits of the Jigunsan and the juxtaposed formations can be classified into eleven sedimentary facies and six successive facies associations.

Facies association (FA) 1 consists of a shallowing-upward successional assemblage of peloidal grainstone, crudely laminated lime mudstone, bioturbated wackestone, and finely laminated lime mudstone that occur in the upper part of the Makgol Formation. It represents low-energy peritidal environments. FA2 consists predominantly of dark gray mudstone alternating with crudely laminated lime mudstone, resulting from hemipeagic settling in deep subtidal to basinal environments. FA3 is characterized by frequent alternation of laminated calcisiltite and dark gray mudstone or greenish gray siltstone representing storm-influenced deep subtidal platform. FA4 consists of greenish gray siltstone, massive grainstone and limestone conglomerate and is interpreted as deposit of local slope environments in storm-influenced shallow subtidal platform. FA5 consists of greenish gray siltstone and massive pack-grainstone, reflecting shallow subtidal platform environments. FA6 consists mainly of massive pack-grainstone and oolitic grainstone, deposited in shallow subtidal platform and shoal.

The facies sequence reflects an overall development of carbonate platform that was inundated during initial transgression (lower part of FA1) in the early Darriwilian and formed deep subtidal to basinal environments where storm-induced density and turbidity currents prevailed (FA2, 3 and 4). During sea-level still-stand, shallow platform sediments (FA 5 and 6) prograded over the deep subtidal to basinal area. The initial inundation surface of the platform, where a peloidal grainstone bed overlies a paleosol horizon, is interpreted as a sequence boundary/ transgressive surface. The maximum flooding zone, representing a transition from transgression to regression, occurs in the upper part of facies association 2 which is characterized by a mudstone interval without carbonate sediment. According to biostratigraphic time scale, the entire sequence represents a cycle of third-order (3–10 Myr) sea-level rise and fall.

# Gondwanan provenance of the Łysogóry block (Holy Cross Mountains, Poland) supported by Upper Ordovician chitinozoans from the Pobroszyn section

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Poster Presentation

Chitinozoans have been discovered in the carbonate-phosphorite lithofacies assigned to the Ordovician Bukowiany Limestone Formation of the Pobroszyn section in the Łysogóry Terrane, Holy Cross Mountains, central Poland (Trela et al. 2001). This tectonostratigraphic unit is emplaced between the East European Craton (EEC) and Małopolska Massif in southern Poland, and together with the Pomerania unit in northern Poland belongs to a mosaic of exotic terranes separating the old Precambrian craton of Baltica from the Phanerozoic western Europe along the prominent tectonic suture - the Trans-European Suture Zone (TESZ). The Łysogóry Unit together with Małopolska Massif in the Holy Cross Mountains are the only units where the Ordovician rocks crop out at the EEC margin. Recovered chitinozoan species, including *Belonechitina capitata*, *B. micracantha*, *Conochitina primitiva*, *C.* cf. *dolosa*, *Cyathochitina campanulaeformis*, *Cy. calix*, *Cy. sebyensis*, *Desmochitina minor ovulum*, *D. m. amphorea*, *D. m. erinacea*, *D. m. minor*, *D. nodosa*, *D. lacaniella, D. acollarea*, *D. juglandiformis*, *D. rugosa*, *Eisenackitina rhenana*, *Euconochitina* sp., *Lagenochitina deunffi*, *Pistillachitina pistillifrons*, *P. elegans*, *P. capitata*, *Laufeldochitina stentor,* and *L. striata*, are restricted to the upper Llanvirn-lower Caradoc. The chitinozoan assemblages document standard zones of Baltoscandian domain (Nõlvak & Grahn 1993). The stratigraphic occurrence of this assemblage extend from *L. striata - stentor* Biozone up to *L. deunffi-dalbyensis* (Aseri to Nabala Baltoscandian stages) with subzones: *sebyensis, clavaherculi, tuberculata,* and *rhenana*. Some of the identified chitinozoans are regarded as biogeographically significant and are characteristic for high palaeolatitudes (Paris 1999), in particular the discovered index species *L. deunffi*. This chitinozoan palaeobiogeographic evidence, as well as lithological similarities between the investigated strata and their equivalents from Buçaco, Portugal (Central Iberian Terrane) indicate that the Łysogóry Unit could have been situated at fairly high latitudes before the Late Ordovician. These observations together with previous palaeontological, palaeomagnetic and geochronologic (Belka *et al.* 2002) results obtained from the older (Cambriana) strata, support a hypothesis that the Łysogóry Unit was a terrane derived from Gondwana and accreted before the Late Ordovician to the south-western margin of the East European Craton (Baltica).

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# Brief introduction of the Ordovician and Silurian in Northwest Zhejiang

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Poster Presentation

The Ordovician and Silurian in Northwest Zhejiang is a continuous marine succession, which can be divided into 2 litho-series approximately by the upper surface of Caradocian. The lower part is mainly composed of slope-basin sediments, and the upper of flyschs and flyschoids.

1. The lower series

The lower and middle part of Tremadocian is composed of argillaceous limestones, mudstones, and shales, in which some graptolite and trilobite fossils are found. The lithofacies then were replaced by neritic calcitic mudstones, which changed into red and grey knollenkalks at the end. The transgression in the afternoon of Early Ordovician brought on the famous graptolite shales in Northwest Zhejiang. It distributed from *D.(C.) deflexus* Zone to *N. gracillis* Zone in "JCY area" which was near a certain detached island, and a little longer inside the Zhe-Wan basin. The recession after the *N. gracillis* Zone resulted in great changes of lithofacies. Limestones containing cephalopoda and trilobite fossils of the upper part of Caradocian replaced the black shales. The litho-units of the series, which lasted around 50Ma and only formed hundreds of meter thick strata, can be traced in a large range. It indicates the steadiness of the local crustal block. However the "JCY detached island" and bentonites found at Hangnitang foreshowed the crustal activity. The SHRIMP age of zircons picked out from the bentonites is about 460Ma.

2. The upper series

After the finish of the low-speed aggradation, the high-speed progradation began in Ashgillian, and lasted to early Wenlock for about 15Ma. In such a short time thousands of meter thick strata composed of grey flyschs and flyschoids (interweaved red hue) formed, which records a high frequency of depositional changes. It obviously shows the crustal unsteadiness in that period. The flyschs were sediments of fluidified grain flows, while the flyschoids were mainly the result of tidal currents. The lithofacies and thickness vary in Northwest Zhejiang, mostly caused by synsedimentary. In the early Ashgillian flyschoids almost covered the whole Northwest Zhejiang, and flyschs, generally containing graptolite fossils, mainly sedimented in the northwest. At same time, the JCY area was a carbonate platform, on which an exented reef was built mainly by algae. Except these evidences of the crustal activity, even a slumping event was recorded as olistostromes in the JCY area. Though the regression in late Ashgillian was likely to be caused by the glacier event, there are no obvious phenomena indicating the cool climate. Around the boundary of the Ordovician and Silurian a brachiopod fauna (*Isorthis-Leptaena* fauna) spread over the Northwest Zhejiang, which is the latest bloom of brachiopods in the Early Paleozoic. In this fossil bed and the shales above some graptolite fossils (*N. persculptus* Zone and *A. ascensus* Zone) were found. In the upper part of the Llandovery, there are only 2 thin fossil beds mainly made up of brachiopods species. A set of very thick littoral sandstones, probably sedimented in early Wenlock, is the latest strata of the Early Paleozoic in Northwest Zhejiang. In these sandstones a 3-5 meter thick sedimentary tuff was found, which should have a great value on geotectology and stratigraphy.

Making a comprehensive survey on the whole Early Paleozoic, the sedimentary difference between the mentioned two series is the most obvious characteristic. We think the end of Caradocian is the period that Caledonian Movement started in Northwest Zhejiang.

# Endemic thelodonts (Agnatha) of the Silurian of Central Asia and the Siberian platform

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Oral Presentation

Unique material from outcrops of Central Asia (Tuva and North West Mongolia) and five subregions of the Siberian Platform were analysed. Material is stored in the Institute of Geology and Geography, Vilnius, Lithuania.

The Lower Silurian samples (Llandovery and Wenlock) of North West Mongolia and the Siberian Platform were examined and yielded numerous vertebrate microremains, as well as samples from the entire Silurian (Llandovery to Pridoli) of Central Tuva. All the thelodont micromaterial (dentine scales) were ascribed to three genera - *Angaralepis* Karatajute-Talimaa, 1997, *Loganellia* Turner, 1991, and *Talimaalepis* Zigaite, 2004, gen. nov.

*L. sibirica* (Karatajute-Talimaa, 1978) was found in the Llandovery series of North West Mongolia and the Siberian Platform. The case reflects the statement that these terranes were part of the unite Early Silurian palaeobasin (Fortey & Cocks, 2003). The *L. sibirica* biozone of the Lower and Middle Llandovery was distinguished in the region.

*L. tuvaensis* (Karatajute-Talimaa, 1978) is restricted to Silurian deposits of Central Tuva (Wenlock to Pridoli series). This fact points Tuva being situated more or less separate from the main Siberian palaeocraton (Fortey & Cocks, 2003). *L.* cf. *L. tuvaensis* is described in the Upper Silurian of North Greenland (Blom, 1999), which was a North East Laurentia, facing and approaching Siberian palaeocontinent in the Silurian time (Cocks & Torsvik, 2002). Such a finding may attribute to Early Palaeozoic continent relationship.

*Talimaalepis rimae* Zigaite 2004, gen. et sp. nov., first described in Llandovery series of Central Asia, joins the Early Silurian palaeobasins of the region, as it is common in North West Mongolia, the Siberian Platform and Tuva as well.

The abundance of endemic thelodont taxa in Silurian sections of the region, indicates it as a proper place for genesis and radiation of early thelodont species. This consideration refers to warm and productive basins, which existed on the Siberian palaeocontinent during its supposed crossing of the Equator during the Silurian (Cocks & Torsvik 2002).

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# *Platystrophia*-like brachiopods: their potential use in biostratigraphy, palaeoecology and palaeogeography

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Poster Presentation

Rhynchonelliformean brachiopods usually identified as *Platystrophia* (s.l.) belong to one of the most easily recognizable and widespread brachiopod groups in the Middle - Upper Ordovician and Early Silurian of Baltoscandia together with the Upper Ordovician of Laurentia. Moreover they are also reported from Avalonia and China. Only the Baltoscandian successions, however, contain the most complete record of the evolutionary history of *Platystrophia* (s.l.), corresponding to the whole known stratigraphic range of this genus. *Platystrophia* (s.l.) is thus also an important paleobiogeographical indicator of provincial affinity through time (Williams 1973) and moreover is useful for biostratigraphy. In particular, the Ordovician deposits of Lithuania (Lithuanian Confacies Belt) were subdivided by Paskevicius (2000) into twenty biostratigraphical units based on brachiopods; six of them were based on species of *Platystrophia* (s.l.). The biostratigraphical significance of platystrophiids in the North Estonian Confacies Belt (Estonia, St. Petersburg region, north-western Moscow basin) is also well established (Alichova 1953, 1960).

Unfortunately, most of the species within the '*Platystrophia*' plexus were defined on external morphology, whereas interiors and especially the morphology of dorsal cardinalia for most are inadequately known. A recent review of Baltoscandian, Avalonian and Laurentian *Platystrophia* (s.l.) has led to an improved understanding of their morphology, taxonomy, and systematics (Zuykov 2003, Zuykov & Egerquist in press, Zuykov & Harper in press). In the revised diagnosis of the genus, the term *Platystrophia* (s.s.) is confined to a large group of Arenig to Late Caradoc species from Baltoscandia and Avalonia, whereas the Ashgill and lower Silurian taxa from these regions and from Laurentia are assigned to three new genera.

We report results of the analysis of species diversity of *Platystrophia*-like brachiopod genera through the Ordovician and Silurian and provide an outline of their stratigraphical and geographical distribution together with a new phylogenetic scheme. We support Schuchert & Cooper's (1932) proposed biphyletic origin of the *Platystrophia*-like taxa: "The American forms arising out of the stock that gave rise to *Plectorthis* and the European forms independently out of some unknown stock." However, ancestry of both lineages is uncertain and needs further evaluation. Our revision suggests that *Platystrophia* s.s. is no longer a cosmopolitan taxon (cf. Williams & Harper 2000, p. 775), but its distribution is limited to the shallow-water biofacies of the Baltoscandian and Avalonian palaeobasins. Baltoscandia is defined as a major center of diversification and subsequent dispersion of the genus during the Ordovician. Many are short-lived species potentially useful as a basis for the biostratigraphical zonal schemes in the shallow-water sequences of the Baltoscandian basin. Brachiopod shells from the East Baltic are not affected by any significant alteration and usually have well-preserved shell structures. Baltic *Platystrophia*-like brachiopods represent a homogenous group ranging through nearly all Middle and Upper Ordovician and are thus ideal for isotopic investigation.

# Guide to some classical Ordovician and Cambrian localities in the Fågelsång area, Scania, southern Sweden

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## Introduction

One of the most well-known outcrop areas of Ordovician rocks in Baltoscandia is near the settlement of Fågelsång about 8 km east of Lund in south-central Scania (Skåne). In scattered outcrops in the valleys of the Sularp Brook and the Fågelsång (Rögle) Brook there are more than 50 recorded exposures of fossiliferous Ordovician and Cambrian strata. The geology of these rocks have been studied for more than 250 years. The succession consists mainly of deeper-water shales and mudstones deposited in a foreland basin not far from the southern margin of the Baltic plate. Carbonate units, although important paleontologically, are very subordinate in the Ordovician succession, being represented in outcrops by only two units, the Early Ordovician (Tremadocian) Bjørkåsholmen Formation (formerly *Ceratopyge* Limestone) and the early Middle Ordovician (Darriwilian) Komstad Limestone. In addition, there are limestone nodules in the Middle-Upper Ordovician Almelund Shale. A thin Upper Ordovician limestone, the Skagen Limestone, is known only from drillings. Most of the Middle and Upper Cambrian succession, which is poorly exposed and best known from drillings, consists of shales and mudstones (Westergård, 1942, 1944; Axheimer and Ahlberg, 2003), the only relatively prominent limestone unit being the Middle Cambrian Andrarum Limestone. There are also richly fossiliferous limestone nodules in the Upper Cambrian shales.

The dominant fine-clastic lithology in the Fågelsång succession differs markedly from the calcareous lithology in the coeval shallower-water platform deposits in the more central portions of Baltoscandia, such as in the Province of Västergötland and on the Island of Öland. On the other hand, the Scanian fine-clastic Ordovician sequence is in important respects similar to that in the Oslo Region, south-eastern Norway. This regional facies differentiation across Baltoscandia has served as a basis for the recognition of so-called confacies belts (Jaanusson, 1976). Such individual facies belts (Fig. 1) are characterized by regional similarities in both lithology and fauna and they evidently represent specialized conditions in the depositional environment.

Although many of the old outcrops in the Fågelsång area are now covered or destroyed and hence not available for study, the Ordovician and Cambrian successions can be pieced together based on existing exposures combined with several drill-cores. For the Ordovician, the principal drillings include the Fågelsång core (Hede, 1951), the Koängen core (Nilsson, 1977), and two cores drilled at the Lindegård farm 0.5 km north of the Sularp Brook (Glimberg, 1961; Nilsson, 1980). The Almbacken core (Axheimer and Ahlberg, 2003) has provided important data on the unexposed upper Lower and Middle Cambrian succession in the Fågelsång area, and a core drilled 300 m south of Södra Sandby church (Westergård, 1942, 1944) has yielded substantial information about the Middle Cambrian-Lower Ordovician (Tremadocian) sequence.

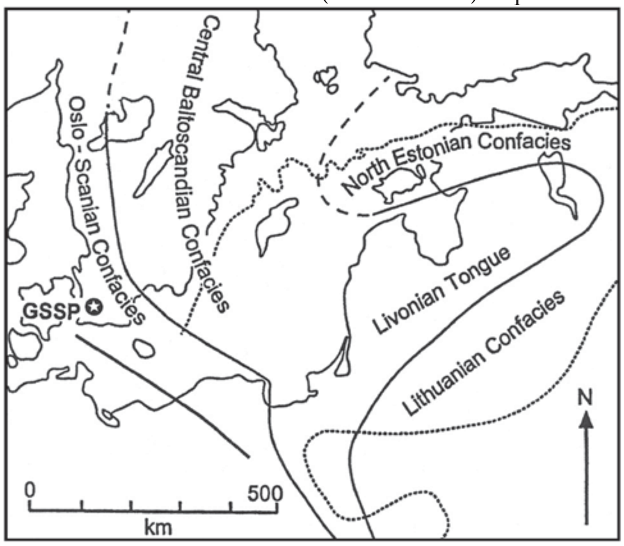


Fig. 1. Geographic location of the Fågelsång Upper Ordovician GSSP in terms of the Baltoscandian confacies belts. (Slightly modified after Jaanusson, 1995).

Most of this succession is stratigraphically condensed as shown by the fact that the remarkably complete Ordovician sequence has a total thickness of only about 145 m. An instructive illustration of this stratigraphic condensation is provided by the thickness of the graptolite zones between the early Middle Ordovician Komstad Limestone and the top of the Upper Ordovician *Dicranograptus clingani* Zone in the partly overlapping Fågelsång and Koängen cores:

*Dicranograptus clingani* Zone................................*12.75 m*
*Diplograptus foliaceus* (formerly *Diplograptus multidens*) Zone........................................................................*30.46 m*
*Nemagraptus gracilis* Zone.......................................*6.74 m*
*Hustedograptus teretiusculus* Zone..........................*6.95 m*
Transition beds ........................................................*1.80 m*
*Didymograptus murchisoni* Zone (including the *Pterograptus elegans* and *Didymograptus clavulus* Zones of Hede (1951) ..........................................................*14.10 m*

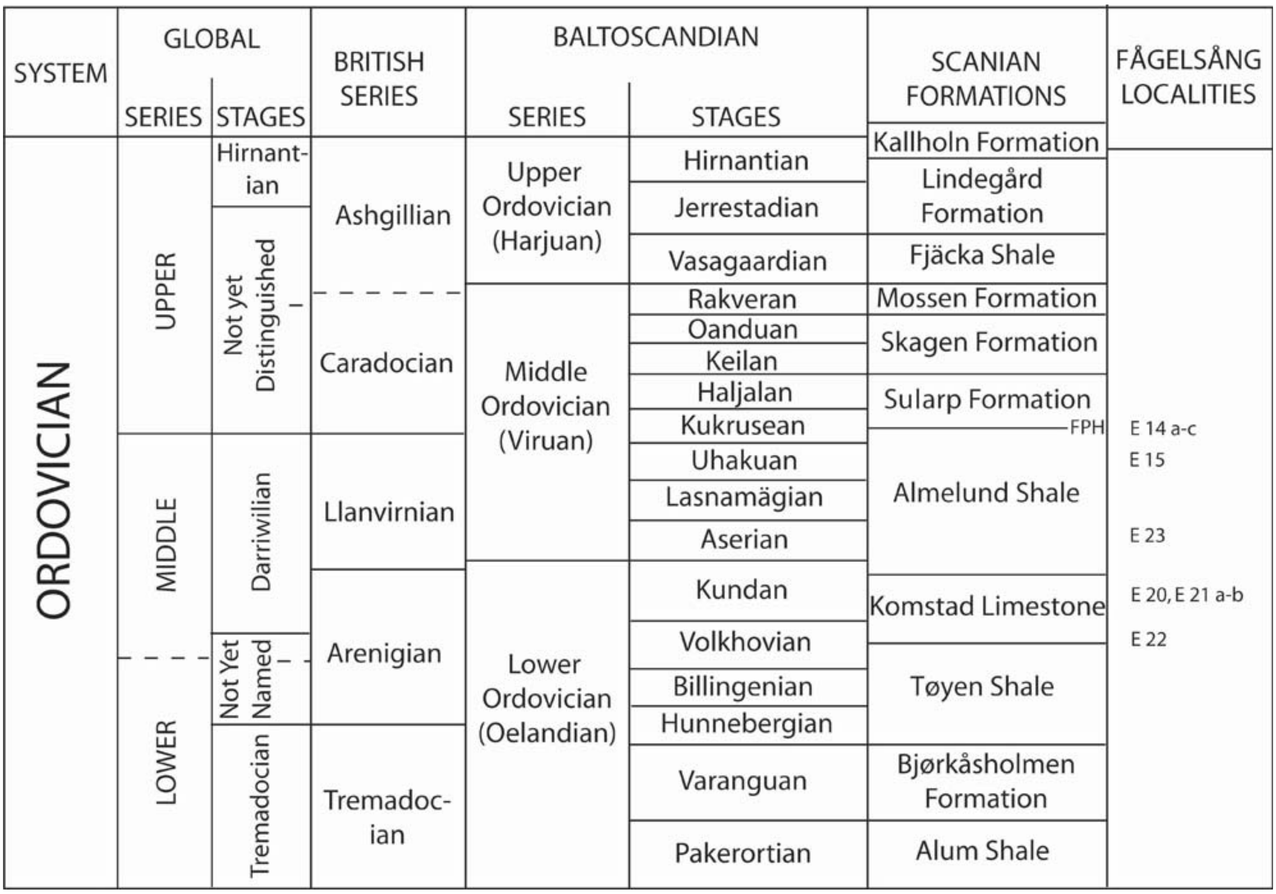


Fig. 2. Chronostratigraphic and lithostratigraphic classification of the Ordovician sequence in Scania and stratigraphic position of the outcrops discussed herein. Local stratigraphic gaps and a couple of lithostratigraphic units with a very restricted geographic distribution are not shown. FPH denotes the Fågelsång Phosphorite that marks the boundary between the Almelund Shale and the Sularp Formation.

*Didymograptus 'bifidus'* (*?artus*) Zone....................*2.17 m*
Total about *75 m*

The Middle and Upper Cambrian succession is extremely condensed but stratigraphically virtually complete as shown by the drillings at Södra Sandby and Almbacken. The sequence consists of dark-grey to black, organic-rich mudstones and shale (alum shale) with lenses and beds of dark-grey limestone. The limestone intercalations and concretions are in Swedish often referred to as *orsten*. In the Fågelsång area the Middle Cambrian (including the *Agnostus pisiformis* Zone) is about 41.5 m thick, and the Upper Cambrian (Furongian Series) is about 50 m. The Middle Cambrian Andrarum Limestone is about 1.20 m thick in the Södra Sandby drill-core and 1.55 m thick in the Almbacken drill-core (Westergård, 1944; Axheimer and Ahlberg, 2003).

The Fågelsång Ordovician succession is unique in Baltoscandia in having a virtually complete succession of graptolite zones, and this graptolite zone sequence has long served as a standard for national and international biostratigraphic comparisons. Being located close to Lund, this sequence has since the 1700s been studied by many generations of geologists from Lund University as well as by field trip groups and scientists from elsewhere in Sweden and abroad. Pioneer Ordovician investigations carried out by, among others, Stobaeus (1734), Wahlenberg (1818), Hisinger (1837, 1840), Törnquist (1865,1875), and Linnarsson (1875, 1879) were followed by more detailed studies by Moberg (e.g. 1910) and his students, especially Strandmark (1902), Olin (1906), Westergård (1909), Hadding (1913), Funkquist (1919), and Ekström (1937). Later investigations include Hede (1951), Nilsson (1953, 1977, 1980), Lindström (1953, 1955), Glimberg (1961), Bergström and Nilsson (1974), Nielsen (1995), Bergström et al. (1995, 1997, 1999, 2000, 2002), and Stouge and Nielsen (2003). For a summary of the current lithostratigraphic and chronostratigraphic classification of the Ordovician succession, see Fig. 2.

In recent years, the Fågelsång sequence has attracted particular international attention because an important part of it has been designated the GSSP for the base of the global Upper Ordovician Series. After a decision in 1996 by the International Subcommission on Ordovician Stratigraphy (ISOS) that the base of the Upper Ordovician shall be the level of first appearance of the morphologically distinctive and geographically widespread graptolite *Nemagraptus gracilis* (Fig. 7), a Subcommission Working Group conducted a world-wide search for a suitable GSSP for this important boundary. After extensive assessments

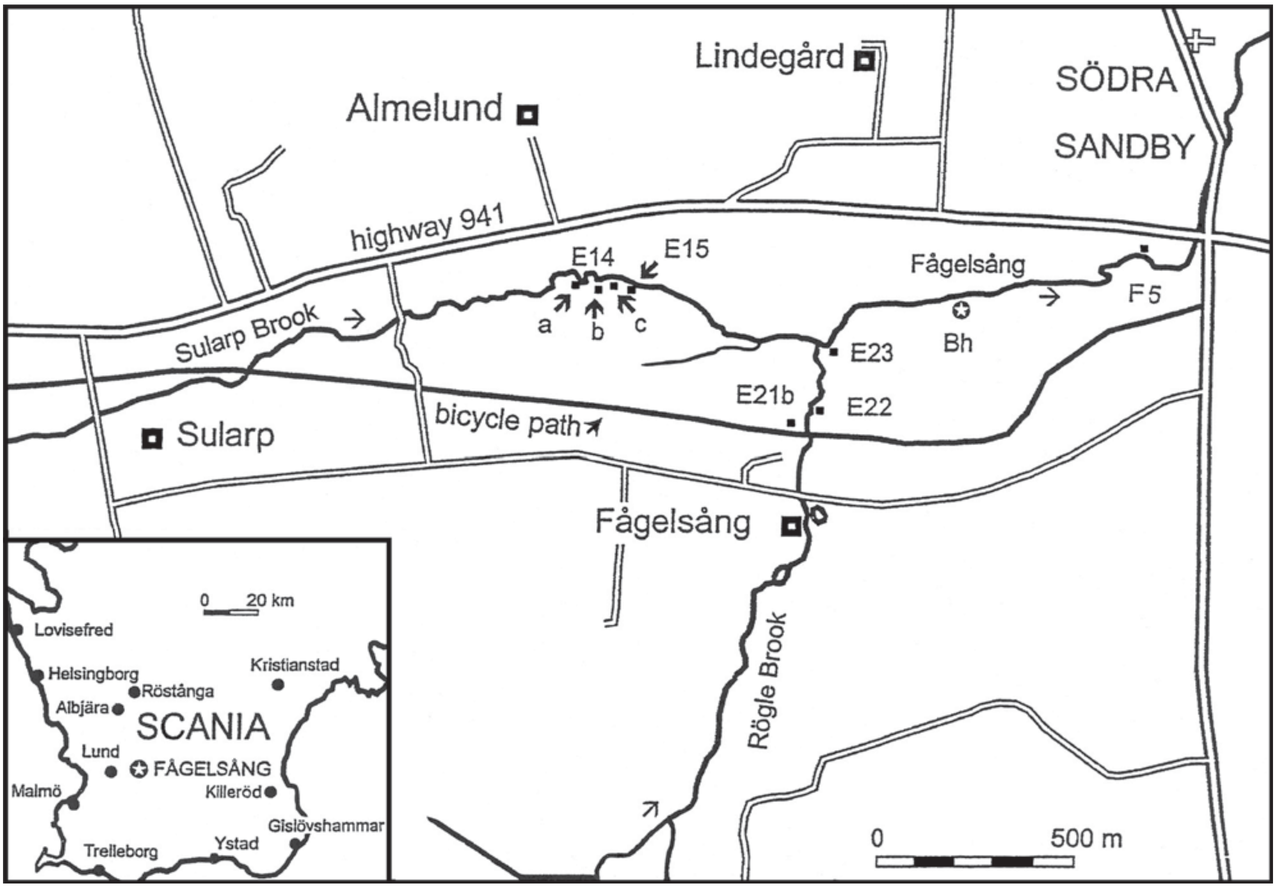


Fig. 3. Sketch-map of the Fågelsång area showing location of important outcrops of Ordovician (E localities) and Cambrian (F5 locality) strata. The GSSP of the Upper Ordovician Series is at the E14b locality.

in the field and much discussion, three sections emerged as principal GSSP candidates, namely that at Calera, Alabama that at Dawangou in northwestern China (Tarim), and that at Fågelsång. After further investigations and discussions, it was concluded that all things considered, the Fågelsång outcrops at locality E14 are the best sections currently known anywhere in the world for this boundary; they have excellent biostratigraphic control based on graptolites, conodonts, and chitinozoans, are easily accessible, and are unlikely to be destroyed by human activities in the future. This locality was approved by the ISOS as GSSP in 2001, and this decision was formally ratified by the International Commission on Stratigraphy in 2002. Dedication ceremonies with unveiling of an information sign and hammering of a "golden spike" into the shale wall at the boundary level took place in May, 2003 with participation of geologists from more than a dozen countries.

## Description of Ordovician localities

Several of the classical, and most important, Ordovician localities in the Fågelsång area are easily reached by following a public footpath running northward from the parking area just west of the Fågelsång settlement along the west side of the Fågelsång (Rögle) Brook to the Sularp Brook (Fig. 3). The following localities are situated near this footpath, as well as along the Sularp Brook (locality designations after Moberg, 1910) and can conveniently be visited in the order described below.

### *Localities E20 and E21a–b*

A short distance north of the former railroad, and just west of the footpath from the Fågelsång parking area, there are three, long disused and partly water-filled, small quarries exposing the early Middle Ordovician Komstad Limestone (Fig. 3). The Komstad Limestone is the only prominent limestone unit in the otherwise shale-dominated Fågelsång Ordovician succession, and it reflects a period of shallowing of the depositional environment. Because a coeval regression can be recognized in many other successions round the world, it is likely that this shallowing event is not due to local uplift but rather represents a period of negative eustatic sea level change. This regression is known internationally as the Whiterock regression.

For centuries and up to about 1860, these small quarries furnished limestone that was used locally as building and tombstone material. Because of faulting, estimates of the total thickness of the Komstad Limestone at this site are uncertain but it is of the order of 7–8 m (Stouge and Nielsen, 2003). Although some beds are moderately fossiliferous, fossils are not easily collected these days without excavations. However, collecting during more than 150 years has resulted in the recovery of a diverse fauna that is dominated

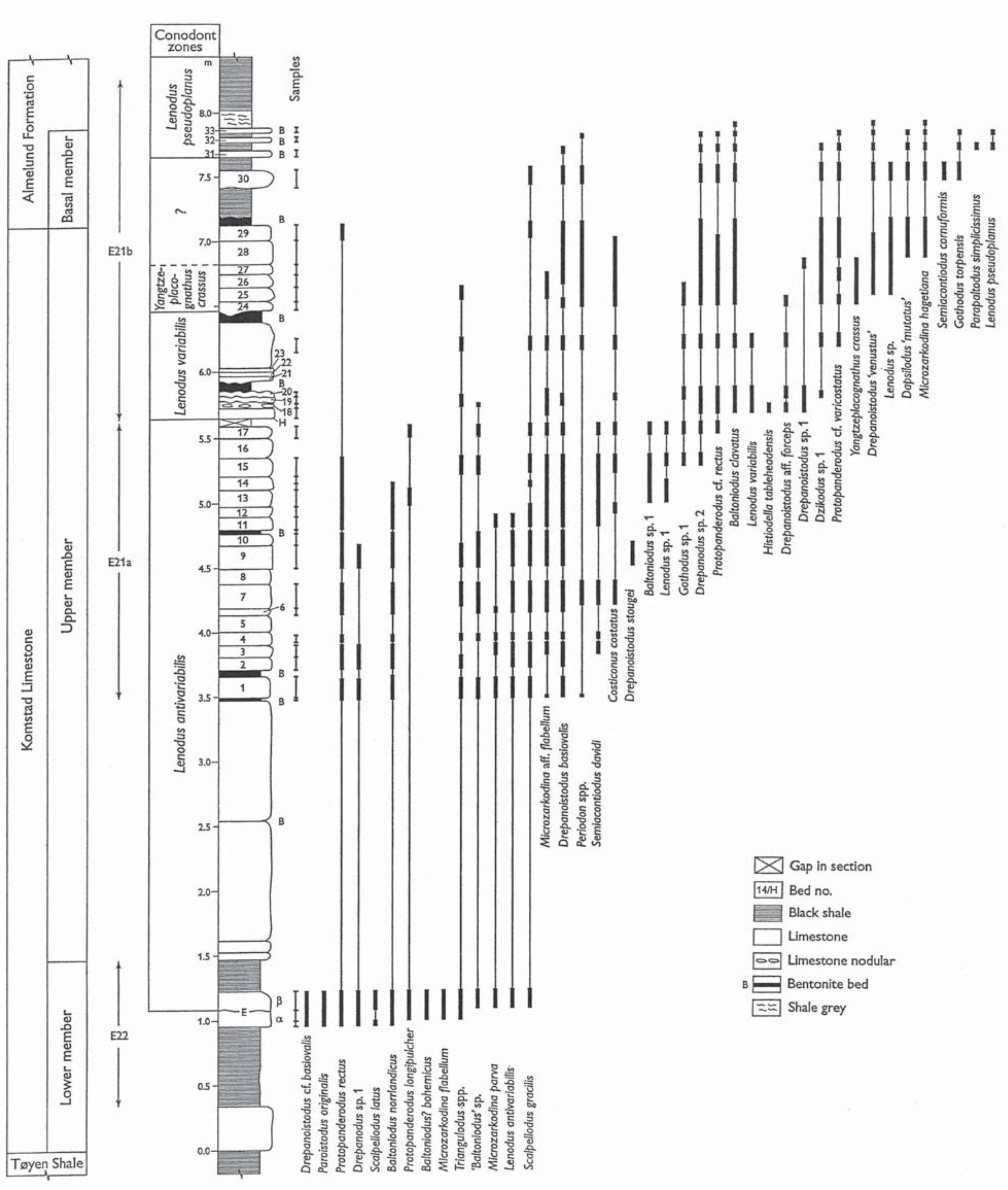


Fig. 4. Stratigraphic column showing lithologic succession and conodont distribution through the early Darriwilian (early Middle Ordovician) Komstad Limestone at Fågelsång. Also shown are the stratigraphic ranges of the E21a, E21b and E22 outcrops. The type stratum of the interesting graptolite *Pseudophyllograptus cor* (Strandmark) is the shale bed just above limestone bed E near the base of the Komstad Limestone. (Figure slightly modified from Stouge and Nielsen, 2003).

by trilobites (more than 20 species), but also includes conodonts (about 40 species), cephalopods, brachiopods, and ostracodes. The trilobites attracted particular attention when the quarries were in operation and the site is the type locality of several species, including some described by Angelin in his classic Palaeontologia Svecica (1851) and Palaeontologia Scandinavica (1854). Stouge and Nielsen (2003) recently summarized the known range of trilobites and conodonts in the Komstad Limestone in these outcrops (Fig. 4). The succession represents the *Megistaspis limbata*, *Asaphus expansus*, and *Asaphus raniceps* Trilobite Zones, and the *Lenodus antivariabilis, Lenodus variabilis*, and *Yangtzeplacognathus crassus* Conodont Zones. In terms of global series classification, the Komstad Limestone is of early Middle Ordovician (Darriwilian) age. It is also referred to the upper Volkhovian and lower Kundan Stages in the Baltoscandic classification.

*Locality E22*

On the east side of the Fågelsång (Rögle) Brook about 100 m north of the former railway there is a small outcrop of a 0.24 m thick bed of limestone overlain and underlain by shale. This is apparently the lowermost exposed part of the Komstad Limestone (Fig. 4) or/and the uppermost part of the underlying Tøyen Shale. The shale has yielded graptolites of the *Didymograptus hirundo* Zone. The shale bed just above the limestone bed E is of special interest in that it is the type stratum (Strandmark, 1902) of the morphologically peculiar and geographically widespread graptolite *Pseudophyllograptus cor* (Strandmark) (Fig. 5). The type material of this species was re-described by Cooper and Lindholm (1985).

*Locality E23*

This outcrop is an approximately 5 m high shale section in the south bank of the Sularp Brook a few tens of m east of the mouth of the Fågelsång (Rögle) Brook (Fig. 3). Although not as well exposed as in the past, this is the best outcrop of the lower part of the Almelund Shale (formerly Upper *Didymograptus* Shale) in the Fågelsång area and it has been studied by several authors since Törnquist (1865), especially by Ekström (1937). The diverse graptolite fauna includes, among others, *Pterograptus elegans, Phyllograptus? glossograptoides,* and *Didymograptus murchisoni* and indicates the *D. murchisoni* Zone, or in another, more recent, zone classification (Maletz, 1998) the *Pt. elegans* Zone (Darriwilian Stage).

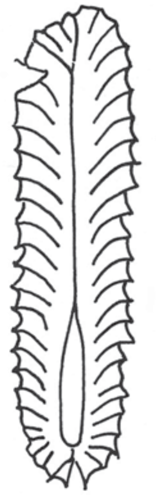

Fig. 5. Outline drawing of the graptolite *Pseudophyllograptus cor.* Redrawn from Cooper and Lindholm (1985, fig. 3:G). Length of specimen 21 mm.

*Localities E14a–c and E15*

These four outcrops are 4-5 m high natural cliff sections along the south side of the Sularp Brook, 0.4-0.5 km west of the mouth of the Fågelsång (Rögle) Brook (Fig. 3). The most convenient route to these sections is by a footpath that runs westward from near the mouth of the latter brook along the south bank of the Sularp Brook. An alternative route is walking southward from highway 941 across the cultivated field and the meadows in the Sularp Brook Valley just north of the brook but parts of the latter are swampy and carry tall and dense vegetation in the summertime. These sections may also be reached by walking northward across the cultivated fields from the former railroad bank (now bicycle path) near the Fågelsång settlement but this should obviously be avoided during the growing season.

There is little doubt that the E14-E15 outcrops (Fig. 6) are the most well-known, and most intensely studied, sections in the Fågelsång area. The E14b outcrop is the

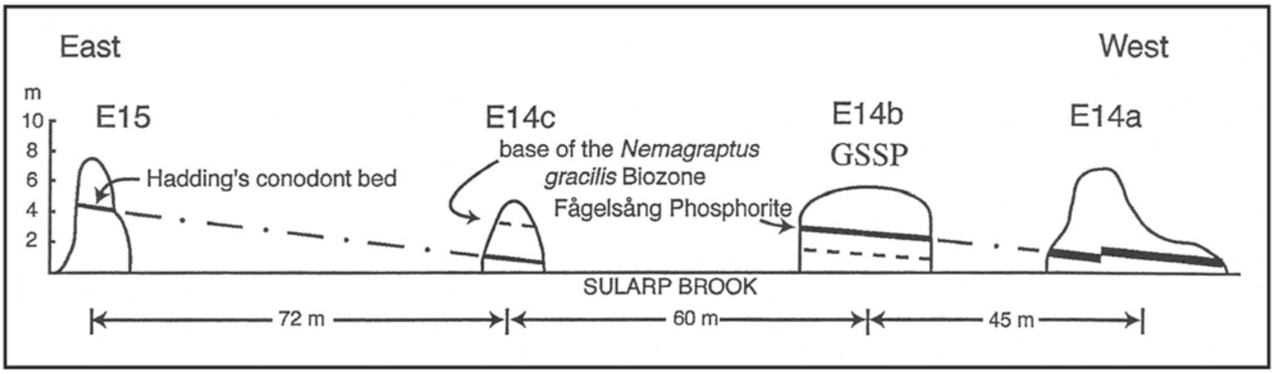


Fig. 6. East-west cross section showing the relations between the E14a-c and E15 outcrops along the Sularp Brook. Note the position of the Fågelsång Phosphorite that marks the boundary between the Sularp Formation and the Almelund Shale. Also note the level of the base of the *Nemagraptus gracilis* Zone that at the E14b GSSP marks the base of the global Upper Ordovician Series.

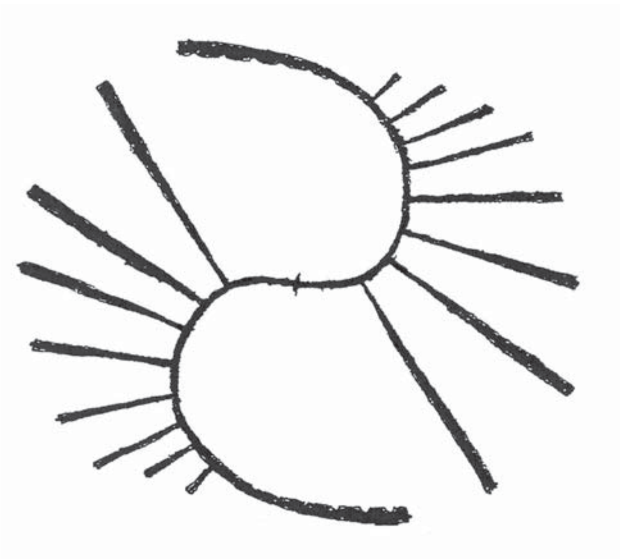

Fig. 7. The graptolite *Nemagraptus gracilis* (Hall), the first appearance of which at the locality E14b marks the base of the global Upper Ordovician Series.

GSSP of the base of the global Upper Ordovician Series, the level of which is now marked by a "golden spike" in the shale wall. The beds dip slightly to the south-west and the sections overlap so a total of about 13 m vertical succession is exposed. The exposed rocks are a lithologically rather monotonous succession of dark-grey to black shale and mudstone with occasional large (up to 1 m in diameter) concretions of impure limestone. There are also a few, with one exception quite thin, beds of phosphorite and several K-bentonite beds (especially at E14a).

These K-bentonites represent the lower part of one of the most extensive complexes of early Paleozoic K-bentonites known anywhere in the world that in the Koängen drill-core includes more than 150 individual beds (Bergström and Nilsson, 1974). Unfortunately, the E14a K-bentonite beds have not yielded isotopically dateable minerals. The lower portion of the shale succession from the top of the Komstad Limestone up to the prominent phosphorite bed (named the Fågelsång Phosphorite by Bergström et al., 2000), is referred to the Almelund Shale (Bergström et al., 2002). The strata above the phosphorite represent the lowermost part of the Sularp Formation (Fig. 2).

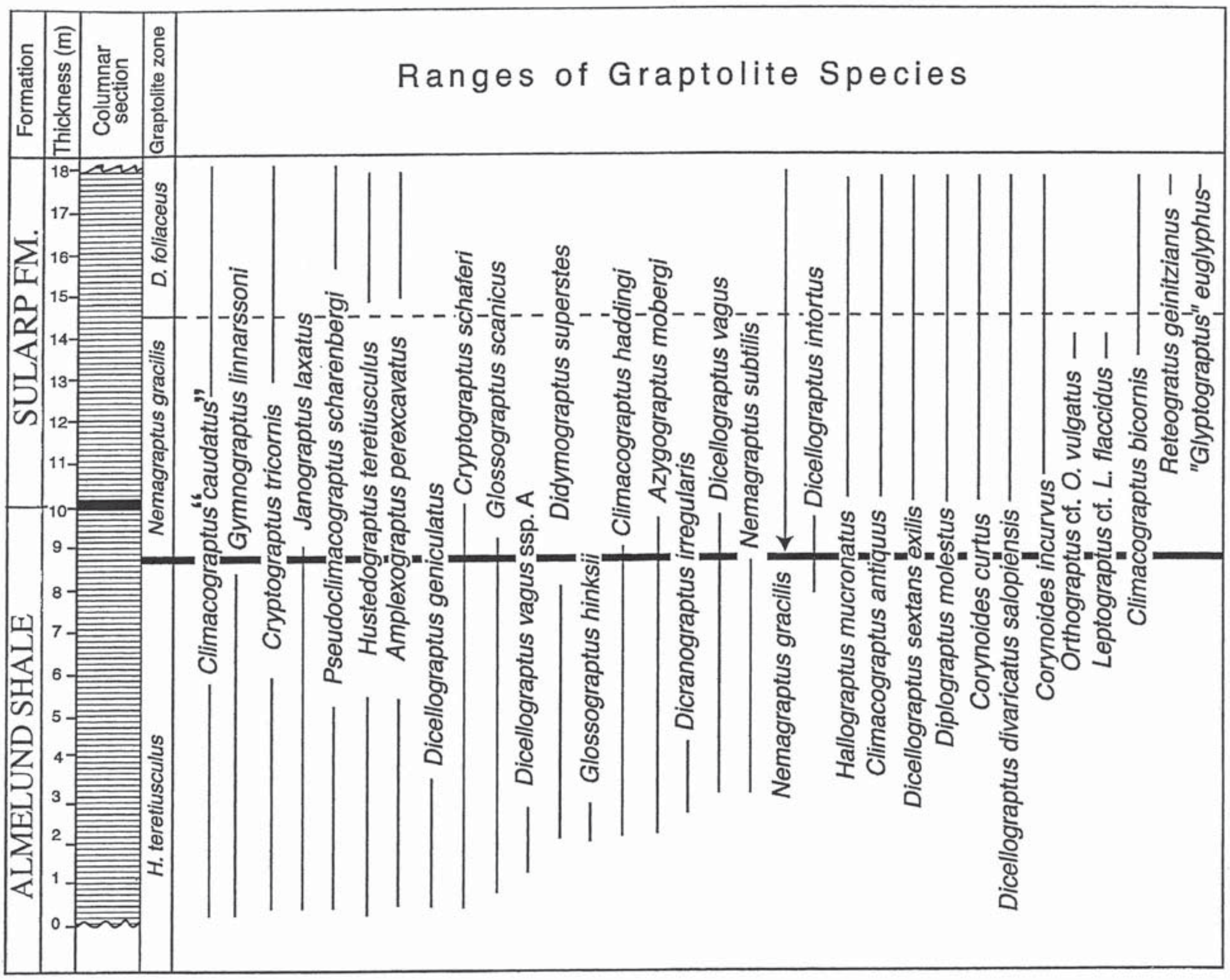


Fig. 8. Known ranges of important graptolites in the upper *Hustedograptus teretiusculus, Nemagraptus gracilis*, and lower *Diplograptus foliaceus* Zones in the Fågelsång area. Based on Hede (1951), Nilsson (1977), and Pålsson (2001). Recent study shows that the Fågelsång graptolite identified as *Climacograptus caudatus* by Hadding (1913) and other workers is an undescribed new species. Note the position of the base of the *Nemagraptus gracilis* Zone about 1.4 m below the Fågelsång Phosphorite (marked by a bold black line). (Slightly modified from Bergström et al., 2000).

Graptolites are moderately abundant in the shales throughout the succession and they are frequently quite well-preserved. These fossils have been collected from these outcrops for more than two centuries, and the type locality of the widespread zone index *Hustedograptus teretiusculus* is at this site. As early as 1865, Törnquist published the first illustrated Baltoscandian record of *Nemagraptus gracilis* based on specimens from these outcrops. This was only the second record from Europe of this species (Fig. 7), which was originally described from New York State by Hall (1847). The classical study of graptolites from these outcrops is that by Hadding (1913), and the graptolites of the corresponding interval in the Fågelsång and Koängen drill-cores have been investigated by Hede (1951) and Nilsson (1977), respectively. However, recent restudies by Pålsson (2001) and S. Finney suggest that some of the previous records are in need of re-assessment. The distribution of selected graptolites, based on both outcrops and drill-cores, is summarized in Fig. 8.

Two graptolite zones are recognized in the succession at the E14–E15 outcrops, the lower one being the *Hustedograptus teretiusculus* Zone and the upper one the *Nemagraptus gracilis* Zone (Fig. 8). Comparison with drill-cores indicates that virtually the entire thickness of these zones is exposed at these localities. Until recent studies, the base of the latter zone was taken to coincide with the Fågelsång Phosphorite, which is an important lithostratigraphic marker bed in this region. However, restudy of core specimens, as well as reinvestigation of the outcrops, show that the first appearance of *N. gracilis*, which defines the base of the *N. gracilis* Zone and the base of the global Upper Ordovician Series, is somewhat lower stratigraphically, namely about 1.4 m below the phosphorite bed. This level is best accessible at E14b and this is the GSSP outcrop with the 'golden spike'. It should be noted that specimens of the index fossil *N. gracilis* are relatively rare below the phosphorite bed but much more common above this bed at the E14a outcrop.

The graptolite fauna of the *Hustedograptus teretiusculus* Zone is quite distinctive and includes, among others, early dicranograptids (*Dicranograptus irregularis*), early dicellograptids (*Dicellograptus geniculatus, D. vagus*), and early nemagraptids (*N. subtilis*) along with *Hustedograptus teretiusculus, Glossograptus scanicus, Gymnograptus linnarssoni*, and *Janograptus laxatus*. The graptolite fauna of the overlying *Nemagraptus gracilis* Zone includes, among others, *N. gracilis* (a probable descendant of *N. subtilis*), *Dicellograptus divaricatus salopiensis, D. sextans exilis, Diplograptus molestus, Corynoides curtus*, and *Hallograptus mucronatus.* Higher parts of the *N. gracilis* Zone have yielded *Climacograptus bicornis* and large biserial taxa, such as *Orthograptus* cf. *vulgatus*. In other parts of the world (China, North America) this interval would be classified as the *C. bicornis* Zone.

A biostratigraphically important component of the fauna is conodonts that occur sparsely on shale surfaces and more commonly in the 2-cm limestone bed just beneath the Fågelsång Phosphorite, and in a thin phosphorite bed (Hadding's conodont bed in Bergström et al., 2000) about 4.25 m above the base of the E15 outcrop. Conodonts were first described from these outcrops by Hadding (1913), and his taxa were later revised by Lindström (1955). Recent work (Bergström et al., 2000) has led to the establishment of a conodont biostratigraphy through the boundary interval. The *Pygodus serra/Pygodus anserinus* Conodont Zone boundary, a key horizon in global correlation, is about 5 m below the Fågelsång Phosporite and 3.6 m below the base

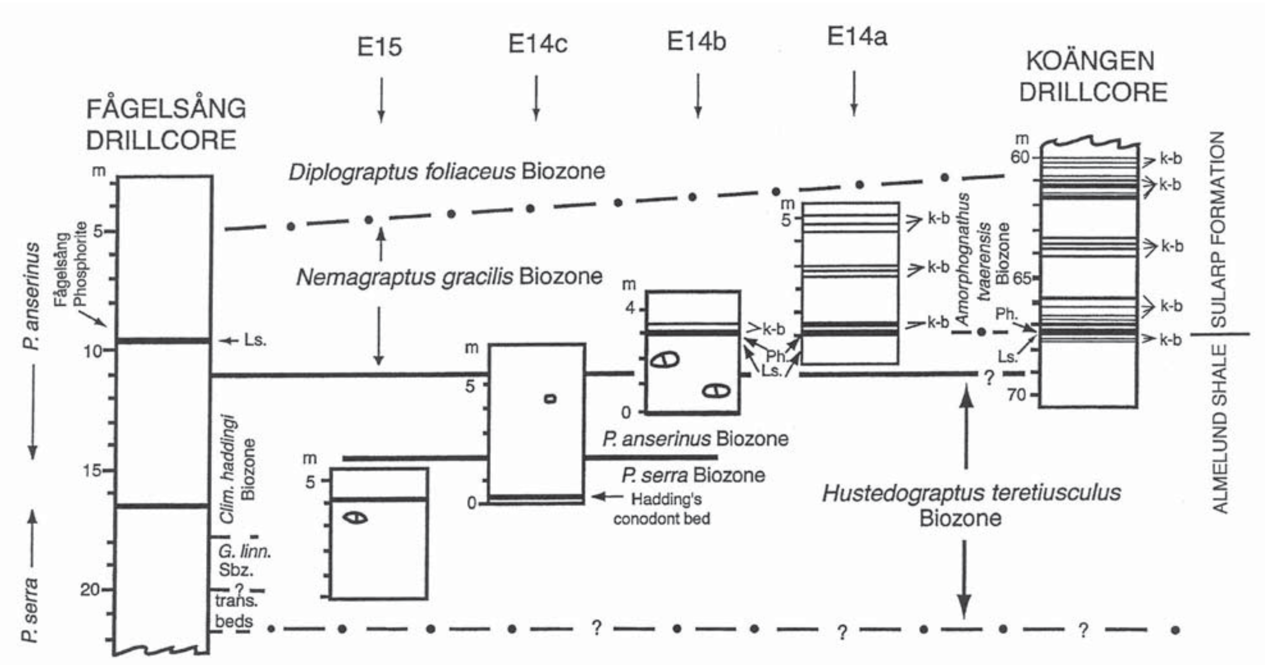


Fig. 9. Diagram showing relations between the successions of graptolite and conodont zones in the upper Almelund Shale and lower Sularp Formation in two drill-cores and the E14a–c and E15 outcrops. K-b refers to K-bentonite beds; Ls., limestone bed; *G. linn.* SbZ., *Gymnograptus linnarssoni* Subzone of Hede (1951). (Modified from Bergström et al., 2000).

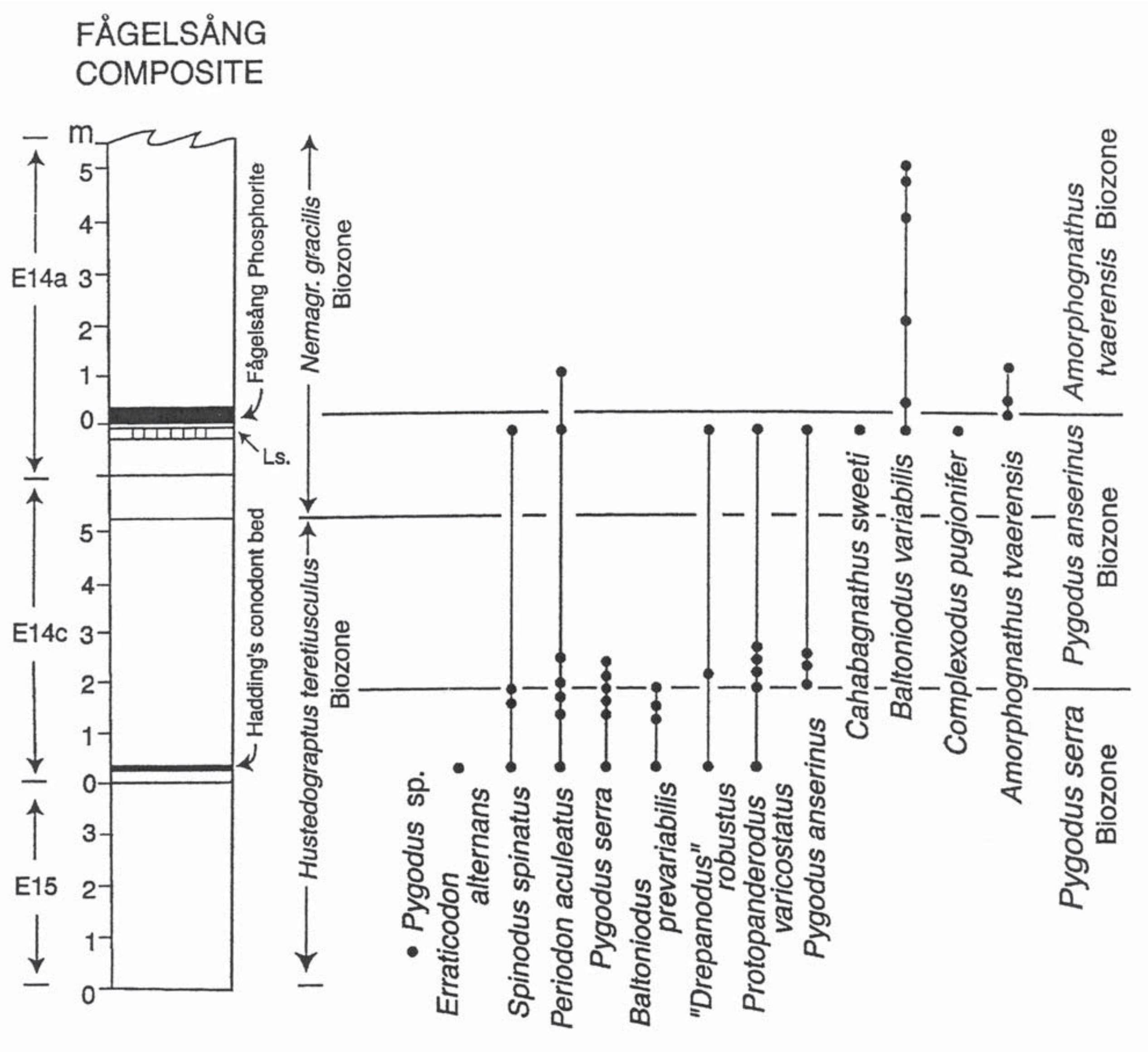


Fig. 10. Known ranges of important conodonts in, and conodont and graptolite zone classification of, the upper Almelund Shale and lower Sularp Formation at the E14a, E14c, and E15 localities. Note the position of the *Pygodus serra/Pygodus anserinus* Zone boundary about 5 m below the Fågelsång Phosphorite, and about 3.6 m below the base of the *Nemagraptus gracilis* Zone. At the E14b GSSP the latter marks the base of the global Upper Ordovician Series. (Modified from Bergström et al., 2000).

of the *N. gracilis* Zone. This level is readily accessible about 2 m above the base the E14c outcrop (Fig. 9). Relatively sparse but biostratigraphically diagnostic conodonts of the *Amorphognathus tvaerensis* Zone, including several specimens of the zone index, have been found on shale bedding-planes just above the Fågelsång Phosphorite. For a summary of the known ranges of important conodont species in these sections, see Fig. 10.

Chitinozoans are common and relatively well preserved in the E14b sequence. A preliminary study (Bergström et al., 2000) indicated that the base of the *N. gracilis* Zone, and the base of the Upper Ordovician, is within the *Laufeldochitina stentor* Chitinozoan Zone. In a more detailed study, as yet only published briefly in an abstract, Vandenbroucke et al. (2003) recognized three chitinozoan zones in the GSSP section. It is expected that also these microfossils will prove very useful for the recognition of the base of the global Upper Ordovician Series.

## Description of Cambrian localities

Most of the Cambrian succession is not exposed in the Fågelsång area and is known only from drill-cores, the most informative ones being the Södra Sandby drilling (Westergård, 1942, 1944) and the Almbacken drilling (Axheimer and Ahlberg, 2003). A very comprehensive outcrop of the Lower Cambrian sandstone succession is the Hardeberga Quarry, which is located about 2.5 km south-west of the Fågelsång settlement.

*Localities F5 and F6*

Upper Cambrian strata are exposed along the north bank of the Sularp Brook at Södra Sandby in the easternmost part of the Fågelsång area (locality F5 of Moberg, 1910, p. 72; locality 5 of Westergård, 1922, fig. 8). The section was described in detail by Moberg and Möller (1898) and consists of about 2 m of alum shales with concretionary limestone (orsten) lenses. The lower part of the exposed section contains the trilobites *Acerocare ecorne* (abundant) and *Parabolina acanthura*, which indicate the uppermost Subzone of the *Acerocare* Zone (uppermost Cambrian). The middle and upper parts of the outcrop are poorly fossiliferous and have yielded only a few indeterminate trilobite fragments. This outcrop is the type locality for both *A. ecorne* and *P. acanthura* that were first described by Angelin (1854).

The lower part of the *Acerocare* Zone (either the *Peltura transiens* Subzone or the *P. costata* Subzone) was previously exposed in a small stream about 50 m southeast of the F5 locality. This outcrop (locality F6 of Moberg, 1910) is now covered or destroyed but has in the past yielded *Acerocarina granulata* and the fairly widespread *Parabolina heres heres.*

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# Ordovician siliciclastics and carbonates of Öland, Sweden

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## INTRODUCTION

The Baltic Basin (also known as the Baltic syneclise) is a large intracratonic basin at the western margin of the East European Craton (Fig. 1). The Baltic Shield slope, the Latvian Saddle and Byelorussian anticlise are respectively the northern, eastern and southeastern limits of the Baltic Basin. The exact boundaries of the Baltic Basin are not well defined, but generally lie where the crystalline basement is buried at depths greater than 0.5–0.8 km. However, the southwest margin of the Baltic Basin is clearly defined by the Trans-European Suture Zone (TESZ; Fig. 1). The Baltic Basin contains a maximum preserved sediment thickness of about 8.000 m of predominantly late Proterozoic (Vendian) to Phanerozoic strata. The sediments are almost entirely shallow marine or terrestrial deposits. The basin is a proven petroleum province and contains several producing hydrocarbon fields with Lower Cambrian sandstones and Upper Ordovician carbonate reefs as reservoirs.
Precambrian crystalline rocks underlie the basin and were peneplained before the beginning of the Cambrian. Erosional remains are preserved in a few areas indicating that a once coherent sedimentary blanket extending from Russia to the front of the Scandinavian Caledonides existed (Fig. 2).


Figure 1: The Baltic Basin.

Sedimentation commenced with the deposition of clastic sediments i.e. quartzitic sandstones, with a thickness that exceeds 100 m only at the margin of the East European Craton. This sandstone appears to be mainly Lower to lower Middle Cambrian and varies in thickness from approximately 10 to 600 m. The 100–140 m thick sandstone at the top of the Lower – Middle Cambrian is the main hydrocarbon-bearing reservoir of the Baltic region. It contains trace fossils as well as some rare inarticulate brachiopods, but at the top of the Lower Cambrian thin silty and glauconitic or calcareous beds accumulated and olenellid trilobites are the most important fossil remains.
The Middle Cambrian may reach a thickness of a few tens of metres. Several hiatuses occur and in some areas it is totally missing. The dominant sediments are silt and fine sand (which may be glauconitic clay), several limestone beds and thin rubbly condensation layers with phosphoritic and glauconitic crusts. Towards the top, s black shale facies invades from the west. Compared with the Lower Cambrian and with the Upper Cambrian the fauna is rich and varied. It mainly comprises trilobites, among them a number of large paradoxidids and many species of the blind agnostids. There are also several species of inarticulate brachiopods.
The entire Upper Cambrian consists of black shale. The succession is almost complete in several areas, although there is evidence of prolonged phases with no sedimentation. There are 6 main trilobite zones, each divided into subzones. Each zone is recognisable by its trilobite fauna, which may be as rich in individuals as it is poor in number of species. Lenses exist of strongly bituminous limestone that may consist almost entirely of the remains of a single olenid or agnostid. The beds were formed in quiet waters. Cross bedding and bioturbation are not seen. The thickness reaches a a maximum of a few tens of metres. Very slow sedimentation was combined with the enrichment of bitumen and trace elements, such as vanadium and uranium.
At the transition to the lower-most Ordovician, the sedimentation of the organic-rich mud underwent a definite change. The bituminous limestone gradually vanishes, and laminae of greensand or quartz sand appear in some places. In the Ordovician up to 10 m of deeper marine siltstone and shale (the Alum Shale and Djupvik formations) were deposited during several transgressive-regressive cycles in a wide epeiric sea.
A final early Early Ordovician regression led to the deposition of siltstone, and then carbonate sedimentation began. The fauna changes rather abruptly. The olenids

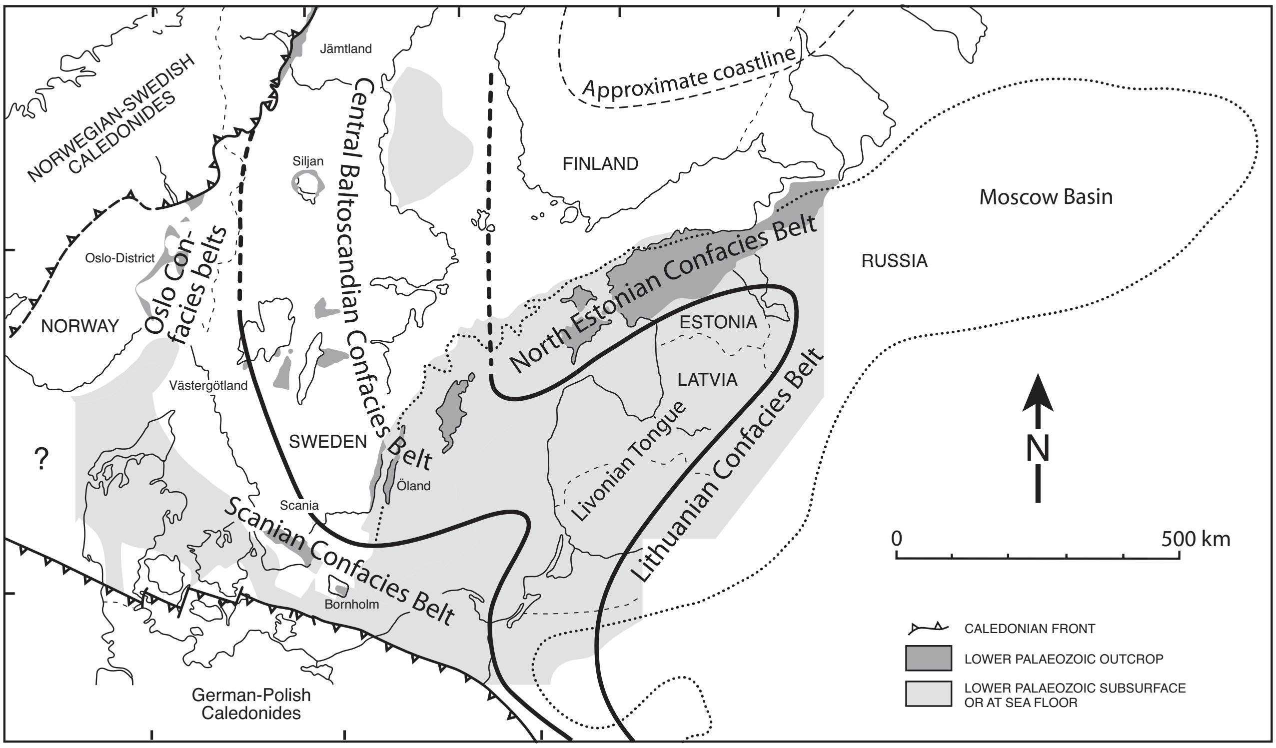


Figure 2: The Baltic Basin and confacies of Jaanusson (1976; modified from Nielsen 1995).

all but disappear. In their place dendroid graptolites, principally species of *Rhabdinopora,* inarticulate brachiopods and conodonts become common in the basin. The upper part of the Tremadoc contains a trilobite fauna that is characterised by *Ceratopyge forficula*. This upper part becomes calcareous and thus is the first representative of the succession of bedded limestones so characteristic of the Ordovician of the Baltic Shield.
The Ordovician may be about 100 m thick. Its lower and middle sections consist of a cool to temperate water limestone that is known as the '*Orthoceras* Limestone'. It is made up of beds a few tens of millimetres thick, which are separated by thin, irregular marly partings or by discontinuity surfaces with some kind of stain e.g. yellow from goethite, green from glauconite, or dark red from haematite. The limestone is mostly very fine-grained bioclastic limestone with no other internal structures apart from a great deal of bioturbation. Particularly in the lower part, the fauna is poor in species and consists mainly of arthropods. Higher up, disarticulated echinoderm fragments contributed to the sediment, and cephalopods appear in the macrofauna. Sessile benthos are rare or absent in the lowermost Ordovician. Conodonts are abundant throughout the Lower Ordovician and frequencies of 1.000 spms/1.000 g of rock are normal.
In the Middle and Upper Ordovician the deposits are largely composed of three separate facies: the deep water black bituminous shale in the west, the limestone, marl and clay in the central part and the shallow shelf carbonate rocks in the east. Later in the Ordovician the Baltic Basin underwent subsidence (Taconic movements) during which the facies became more varied and the fossil diversity more extensive. Ordovician deep-water fine-clastic sediments accumulated in a fore-reef setting with reef-like build-ups and back-reef sediments accumulating in the shallow water environment. This pattern continued until the end of the Silurian, but was interrupted by the short lived Hirnantian glaciation. The reef-like structures re-entered the basin after the glaciation ended.
The Silurian deposits consist of limestone and shale. The composition of the formations change with increased distance from the platform margin. Shaley deposits with graptolites predominate in the south and the south-west and grade into marl and limestone towards the east. The succession is only relatively complete in the south-central and south-eastern part of the East European Craton. The classical Silurian succession is exposed on the Isle of Gotland, where it is 400–500 m thick. The sediments comprise marl and biogenic limestone, the latter is partially developed as reef. The fauna is as rich and varied. There is evidence particularly in the upper part of phases of shallow-water sandy sedimentation.
The later part of the Silurian witnessed a gradual withdrawal of the sea from the East European Craton. This late Silurian to Devonian uplift occurred along the Caledonian margin of the basin (Scandian phase of the Caledonian Orogeny). Marine to non-marine clastic sediments accumulated in a fore-deep basin that developed on the south-west flank of the Baltic Basin. Most of the deformation of the margin of the Baltic Basin in the form of thrust faulting and folding occurred during this orogeny.

## ORDOVICIAN OF THE BALTIC BASIN

Ordovician strata – predominantly carbonates - are preserved and widely exposed in the north-east to south-

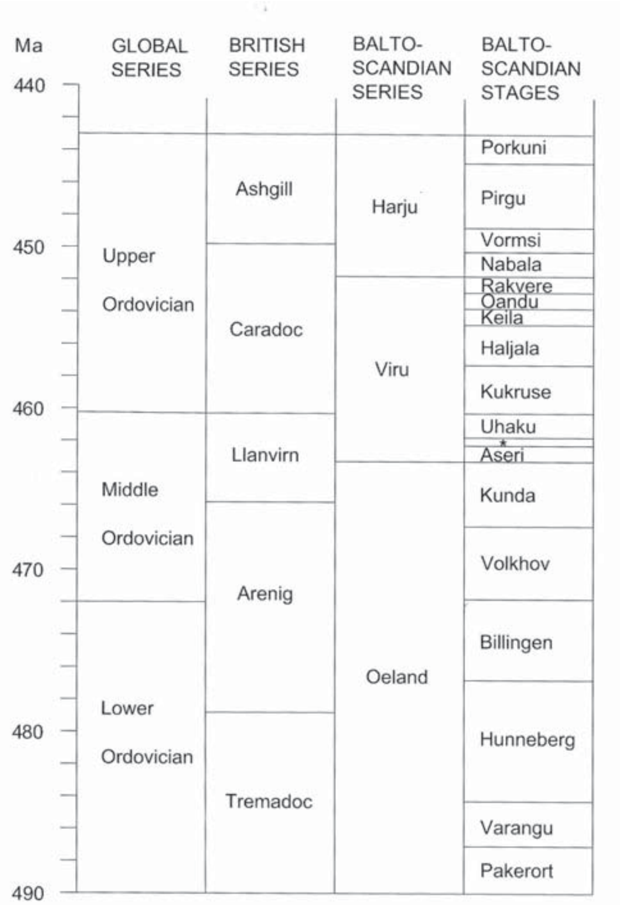


Figure 3: Chronostratigraphy of the Baltiscandian region (modified from Männil & Meidla 1994 and Webby *et al*. 2004).

west trending edge or crest on the north-west side of the Baltic Basin or the southern slopes of the Baltic Shield. The exposures extend from southern Öland towards the north-east and are virtually continuous from the North Estonian coastline and into western Russia. These exposures present the best Cambrian to Ordovician succession of sedimentary rocks in Baltoscandia.

A number of K-bentonite beds occur in the Baltic Basin and these are of remarkable correlative importance (Bergström *et al*. 1995). Within the Baltic Basin various lithofacies are arranged in belts, which are characterised by comparatively stable complexes of litho- and biofacies. Männil (1966) applied the term 'facies zone' to delineate the complex litho- and biofacies and Jaanusson (1976) called these 'Confacies belts' (Fig. 2). In general they reflect differences in depth, but their actual nature are much more complicated than just a simple depth zonation (Jaanusson 1973).

## CHRONOSTRATIGRAPHY

Trilobites are the obvious marker fossils of the Ordovician of the Baltic Basin. They were widely distributed and occur in a fairly precise succession, but outside the basin very few of the Baltic genera and species are present. Cephalopods and brachiopods are other groups of useful index fossils for part of the succession.

The classical Ordovician stratigraphy is based mainly on graptolites, and as graptolites are mostly scarse or absent in the Baltic Basin facies, a set of major divisions (Series, Stages) have come into use. This division is independent of other schemes and cannot be precisely correlated with the global scheme. Schmidt (1881) initially distinguished six series in the Ordovician. Öpik (1930) used a four-fold subdivision of the Ordovician System and referred those to *Obolus*,-, conodont-, *Asaphus*, *Chasmops*- and *Isotelus*-Series. Later, these series named after the type areas, and Iru, Tallinn, Viru and Harju Series came into use. Kaljo *et al*. (1958) combined the Iru and Tallinn Series into the new Oeland Series. Hence, the Ordovician of Baltoscandia is referred to the Oeland, Viru and Harju Series with seven sub-series and 18 stages (Männil & Meidla 1994).

The regional chronostratigraphical time scale (Männil & Meidla 1994) (Fig. 3) is used in this guide but reference to the international timescale (Webby *et al*. 2004) is made, wherever necessary.

### Oeland Series

The Oeland Series (Kaljo *et al*. 1958) refers to the Lower Ordovician of the region (*sensu* Raymond 1916). The Oeland Series corresponds to the Lower and *pars* Middle Ordovician of the international time scale (of Webby *et al*. 2004; Fig. 3).

The series includes the succession from the base of the Ordovician System to the top of the Kunda Stage, which corresponds to the *Didymograptus artus* Zone. The name of the series originates from Öland, which is chosen as the type area for the Lower Ordovician Series (Kaljo *et al*. 1958; Männil & Meidla 1994; Stouge *et al*. 1995).

## ORDOVICIAN SUCCESSION OF ÖLAND

Öland is approximately 150 kilometers long and 15 kilometers wide (Fig. 4). Inland, it consists of a plain with thin vegetation, and is called Alvar.

Öland is situated at the western margin of the Baltic Basin. Cambrian and Lower – Middle Ordovician sediments overlie the Precambrian basement with a slightly eastward dip. The slight eastward dip on the western flank of the Baltic Basin led to a structure where the oldest formations are exposed in the west-facing sea-cliffs and inland scarps along the Sound of Kalmar. The oldest beds on the island belong to the uppermost Lower Cambrian sandstones in the west and the youngest beds are the Middle Ordovician lower Dalby Limestone in the east. However, the '*Orthoceras*' limestone covers most of the island and the inland plain or Alvaret consists essentially of a single bed of limestone. The Ordovician succession continues from the land and disappears eastwards with a very gentle dip under the sea. Some of succession can be reconstructed from erratic boulders, which were transported westwards and deposited on the island by differential movement of the Pleistocene land ice.

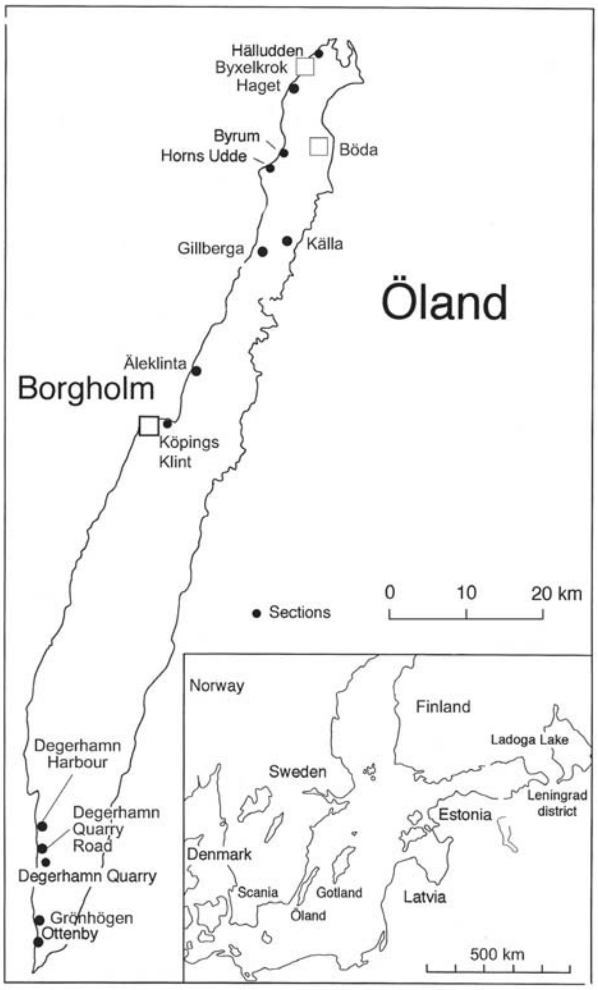


Figure 4: Öland and the localities (= black dots) mentioned in the text.

On Öland, the Ordovician is approximately 41 m thick (Böda Hamn well); the Lower Ordovician is around 17 m thick and the Middle Ordovician is about 24 m thick.

## The base of the Ordovician

The Cambrian–Ordovician transition on Öland is developed as a hiatus. The hiatus is situated within the Alum Shale Formation and the base of the Ordovician is recognised by the appearance of *Rhabdinopora flabelliforme*. The hiatus comprises the uppermost Upper Cambrian trilobite subzones and two graptolite subzones of the Pakerort Stage (Westergård 1922, 1944). On the northern part of the island the black shale facies of the Alum shale Formation is very thin or it is completely absent (Westergård 1922). The hiatus comprises the Middle and most of the Upper Cambrian and parts of the Lower Ordovician.
In the north, the oldest Lower Ordovician strata are developed as a conglomerate, known as the '*Obolus*' conglomerate (Westergård 1947). It is named after the brachiopod *Obolus apollinis*, which is present in the conglomerate and corresponds to the *Rhabdinopora flabelliforme typica* Subzone.

## ORDOVICIAN FORMATIONS OF ÖLAND

The stratigraphic terminology of Öland evolved from the first field impressions i.e. using distinctive colours (red-green-grey) and applying fossil names, mainly from trilobites and cephalopods, to the units. Later, a topostratigraphic approach was applied. Topostratigraphic units are combinations of litho- and faunal characteristics. The application of lithostratigraphic units *sensu stricto* (i.e. defined on the basis of a stratotype and given a geographic name) has begun (van Wamel 1974; Stouge & Bagnoli 1990), but it is not yet completed on Öland (Stouge in prep.).

## ALUM SHALE FORMATION

*Previous names*. – Olenid shale, *Dictyonema* Shale and *Ceratopyge* Shale (*pars*).
The Alum Shale Formation consists of bituminous black shale with bituminous limestone nodules (called antraconites - or 'orsten' in Swedish), which locally can become extremely large (2 x 1 mtrs). Sedimentation of the unit began in the Middle Cambrian and the facies persisted with interruptions into the Lower Ordovician. The uppermost black shales of the Alum Shale Formation described here were previously called the *Ceratopyge* Shale, but this black shale cannot lithologically be distinguished from the underlying black shales of the Alum Shale and thus it is now allocated to the Alum Shale Formation.
The Ordovician part of the Alum Shale Formation is referred to the Pakerort and Varangu stages of the Oeland Series. It is well exposed on south Öland, where it becomes up to 8 m thick at Ottenby, but decreases in thickness northwards (Westergård 1947). On northern Öland and north of Horns Udde it is absent and an extensive hiatus ranging down to the Middle Cambrian is developed.
The fossils include graptolites and the *Rhabdinopora flabelliforme* and *Bryograptus kjerulfi* graptolite zones are recorded. *Clonograptus heres* and a few phosphate shelled brachiopods i.e. *Broeggeria salteri* and *Nanorthis*? *cristianiae* are found in the uppermost part of the unit. Conodonts occur at certain levels, and also in the antraconites from which *Cordylodus proavus* and *Cordylodus angulatus* are recorded (Lindström 1971; van Wamel 1974).

## DJUPVIK FORMATION

*Previous name*. - *Ceratopyge* Shale (*pars*), member Dk1.
The unit consists of glauconite-bearing silt- and sandstone with small limestone lenses. The unit can be interbedded with grey bituminous and laminated shale of the Alum Shale facies. In the south it is barely 35 cm thick, but it becomes up to 1.5 m thick on the northern part of the Island. The fauna includes the brachiopod *Broeggeria salteri* and the trilobite *Shumardia*.
The Djupvik Formation, as it is applied here, does not follow the original definition given by van Wamel (1974), who included Middle and Upper Cambrian and Lower Ordovician black shales of the Alum Shale Formation in

the Djupvik Formation. Here the formation is only used for the Lower Ordovician strata as indicated above.

## KÖPINGSKLINT FORMATION

*Previous names*. - *Ceratopyge* Limestone, Lower *Planilimbata* Limestone; Latorp Limestone (*pars*). It is equivalent to the Bjørkåsholmen Formation in the Oslo Region, Norway.

The Köpingsklint Formation includes red-brown, violet or green lime mudstone and wackestone with abundant glauconite and pyrite and with interbeds of glauconite silt- and sandstone. Recrystallised limestone is common within the formation at certain levels. Glauconite grains are the most frequently occuring allochems. The Köpingsklint Formation (van Wamel 1974) is 0.85 m thick at the type location but becomes thicker on southern Öland. Several beds, if traced laterally, display great variation with respect to thickness and lack of persistence within the formation.

The Köpingsklint Formation differs from the underlying Djupvik Formation by the predominance of limestone in the former and the predominance of terrigeneous clastics in the latter. It differs from the overlying Bruddesta Formation by having a high glauconite content.

Van Wamel subdivided the formation into three informal members; these are difficult to trace laterally and hence are not used here.

The Köpingsklint Limestone is referred to the Hunnebergian and early Billingenian substages of the Latorp Stage (Tjernvik 1956; van Wamel 1974). The lower part of the unit belongs to the *Apatocephalus serratus* trilobite Zone (Tjernvik 1956) and the conodonts (van Wamel 1974; Bagnoli *et al*. 1988) are referred to the *Paltodus deltifer* Zone of Lindström (1971). The upper part of the formation comprises the *Megastaspis armata* and the *M. planilimbata* trilobite zones (Tjernvik 1956). The conodonts represent the *Paroistodus proteus* Zone and the *Prioniodus elegans* conodont Zone is recorded from the uppermost part of the formation (van Wamel 1974; Bagnoli *et al*. 1988). The uppermost of the formation also include the basal (transgressive) part of the *Oepikodus evae* conodont Zone.

The Tremadoc–Arenig Series boundary is placed within the *Paroistodus proteus* Zone (Maletz *et al*. 1996) and on Öland the boundary is recorded within the upper third of the Köpingsklint Formation. A hiatus is often developed at the boundary.

## BRUDDESTA FORMATION

*Previous names*. - *Planilimbata* Limestone (*pars*), *Limbata* Limestone (*pars*) and Lanna Limestone (*pars*).

The unit consists of red to brown to light-grey, slightly marly, fossiliferous limestone with many disconformitites. Marl beds are common, except in the upper section. Remains of fossils are the most frequently occurring allochems.

On northern Öland and at about half way up the Bruddesta Formation a rock-interval occurs with intensively red-brown coloured limestone. In this interval disconformities with frequent amphora-shaped borings are present. Below these disconformities and around the trace fossils brownish yellow (goethitisation) zones are found. This interval occurs throughout the area and is called 'Blommiga Bladet' (= the 'Flowery Sheet').

The Bruddesta Formation is referred to the Billingenian Substage of the Latorp Stage and to the lower Volkhov Stage (Tjernvik 1956; van Wamel 1974; Bagnoli & Stouge 1997). The lower part of the formation belongs to the *M. dalecarlicus* trilobite Zone (Tjernvik 1956) and the conodonts (van Wamel 1974; Bagnoli *et al*. 1988; Bagnoli & Stouge 1997) are referred to the *Oepikodus evae* Zone of Lindström (1971). The upper part of the formation comprises the *Megistaspis polyphemus* trilobite zone (Tjernvik 1956) and the '*Baltoniodus*' *triangularis* and *Baltoniodus navis* conodont zones (van Wamel 1974; Bagnoli *et al*. 1988; Bagnoli & Stouge 1997; Löfgren 2000).

## HORNS UDDE FORMATION

*Previous name*. – *Limbata* Limestone; Lanna Limestone.

The formation consists of greenish red, or green and red variegated highly fossiliferous and haematitic limestone (wackestone and grainstone). It is interspersed by innumerable (stylotitic) disconformities and remains of fossils are the most frequently occurring allochems. Orthoceratids are relatively abundant, glauconite grains may occur. Most fossil fragments are impregnated with glauconite, goethite or haematite. Haematite is present throughout the Horns Udde Formation concentrated sedimentarily and secondarily. On northern Öland an approximately 10 cm. thick intensively red-brown coloured interval exists; it is called 'Blodlaget' ( = the Bloody layer') and is found in the basal portion of the formation. On southern Öland a similar horizon is present but is situated in the upper part of the formation.

The Horns Udde Formation is uniformly developed on Öland, both in the vertical and lateral sense; its total thickness varies between 1.55 and 1.65 m.

The macrofauna from the Horns Udde Formation is not well known. It is tentatively referred to the *Megistaspis polyphemus* Zone of the Volkhov Stage. The conodont fauna however is very distinct and Lindström (1971) named it the *Paroistodus originalis* (acme) Zone.

## FORMATION A+B

*Previous names*. - *Limbata* Limestone, Lanna Limestone, *Lepidurus* Limestone,

Volkhov Stage, *Asaphus* Limestone, Hjorthamn Limestone, Holen Limestone.

*Remarks*. – Stouge & Bagnoli (1990) introduced Formations A and B and considered the units as potential formations. Subsequent fieldwork reveals that it is better to combine the two units into one. Bohlin (1949) introduced the Hjorthamn Limestone for a narrow part of the succession on northern Öland.

Formation A+B (= to be named the Gillberga formation) includes grey to green lime mudstone and wackestone with abundant glauconite and some pyrite. Interbeds of glauconite silt- and sand are common. Fe-ooids may occur within the formation and two distinct levels (a lower ooid and an upper ooid) can be distinguished in the unit on northern Öland. A dark grey to black, organic-rich, thin shale occurs in the formation. Glauconite grains are the most frequently occuring allochems. Phosphatisation is a common feature in the formation.

On southern Öland red haematite impregnated horizons characterise the upper part of the formation. A key horizon or 'Sphaeronites Bed' forms the upper part of the formation on southern Öland.

Formation A+B is very fossiliferous. Within the formation many fossils display disrupted orientation, which suggests that the fauna has been transported by storms (Bohlin 1949).

Trilobites are the characteristic faunal elements and *Megistaspis limbata*, *Asaphus expansus* and *Asaphus* '*raniceps*' (Late Volkhov to early Kunda i.e. Valastean Substage) are recognised in the unit. Brachiopods may also be well-represented in this unit. The conodonts are referred to the *Baltoniodus norrlandicus*, *Lenodus antivariabilis*, *Lenodus variabilis* and *Yangtzeplacognathus crassus* zones (Stouge & Bagnoli 1990; Löfgren 2000).

The green limestone in the formation is very rich in organic shelled fossils and graptolites. Acritarchs and chitinozoans have also been recorded from several levels within the formation.

FORMATION C

*Previous names*. - *Asaphus* Limestone, Holen Limestone.

The formation consists of light grey, yellow to pink wackestone with scattered glauconite and grains of phosphorite. It is interspersed with innumerable disconformities and stylolites. Fossil remains are the most frequently occurring allochems. Trilobites and orthoceratids occur frequently and glauconite grains may occur.

Fossils from Formation C have have not been investigated systematically. The trilobite fauna includes *Asaphus* '*raniceps*' (Bohlin 1949 p. 566) indicating that the formation may belong to the Valastean Substage of the Kundan Stage.

Conodonts are abundant (Löfgren 2000) and are referred to *Lenodus kielcensis* Zone (Stouge unpublished).

## FORMATION D

*Previous names*. – *Asaphus* Limestone (*pars*), '*Vaginatum*' Limestone, '*Obtusicauda*' Limestone, '*Gigas*' Limestone, Holen Limestone.

The unit consists of grey, yellow to red fossiliferous limestones. Marly intercalations are commonly present. Trilobite remains are the most frequently occurring allochems. In Formation D, red haematite impregnation of the limestone and haematite surrounding the fossils is common.

Formation D is referred to the highest trilobite zones of the Kunda Series (Bohlin 1949). *Megistaspis centaurus*, *Megistaspis gigas* and *Megistaspis bombifrons* are present in the unit. The conodonts *Lenodus pseudoplanus* and *Microzarkodina ozarkodella* are characteristic species in the formation (Löfgren 2000; Stouge unpublished).

## MIDDLE ORDOVICIAN (VIRU SERIES) OF ÖLAND

Middle Ordovician (Viru) limestones are poorly exposed on Öland and only one locality will be visited in this excursion (Källa Limestone, Locality 7). This is due to the scarcity of Middle Ordovician exposures and the best of those are not easily accessible. Most of the exposures on the shore are found on the east coast, where the sections are poorly developed because of the eastward dip of the rocks. Inland exposures are confined to small quarries, now water-filled, or to ditches which today are mostly overgrown.

The Middle Ordovician units are named the Segerstad, Skärlöv, Seby, Folkeslunda, Furudal, Källa, Persnäs and Dalby Limestones (Jaanusson 1960).

The Segerstad Limestone (former term = *Platyurus* Limestone) overlies the Kunda succession without any distinct boundary. It comprises a bright red wackestone with mudcracks and stromatolitic algal mats. The limestone is up to 5 m thick. The fauna changes from below and pygidia of *Asaphus* (*Neoasaphus*) *platyurus* have been recorded from the formation.

The Skärlöv Limestone is red-brown, nodular and argillaceous with a thickness from 1.4 m (north) to 2.0 m (south).

The Seby Limestone is a variegated red and grey limestone. It is only some tens of centimetres thick. Fossils include cephalopods and hyolithids.

The Folkeslunda Limestone is a grey unit with many macrofossils with a thickness of about 2.8 m.

Using older terminology the Chiron (or '*Scroeteri*') Limestone corresponds to the Skärlöv, Seby and Folkeslunda Limestones. The Furudal, Källa and Persnäs Limestones (all three were part of the '*Crassicauda*' Limestone using older terminology) are of Uhakuan age and they represent different facies that developed on Öland during Uhakuan time. The Furudal Limestone is the offshore, finely nodular, grey lime mudstone recorded in southern Öland, whereas the Källa Limestone on northern Öland represents a nearshore equivalent. The Persnäs Limestone is a grainstone and becomes 5.5 m thick.

The Dalby Limestone (or '*Ludibundus*' Limestone) is developed as a grainstone and cannot easily be distinguished lithologically from the Persnäs Limestone as it is a topostratigraphic unit. Earlier the Dalby Limestone was exposed near Böda harbour, but it is completely covered today. The macrofauna of the Dalby Limestone includes cystoids and bryozoans.

## ITINERARY

## 5th SEPTEMBER

The first stop on the first day is a visit to the Fågelsång locality near Lund, Sweden. The rest of the day will largely be used to the travel from the Fågelsång locality to Öland, Sweden and the trip ends at Ekerum campsite on Öland (see Bergström & Ahlberg 2004, this volume).

In the Småland province, basal layers of Lower Cambrian sandstone are exposed along the coast and mostly cover the

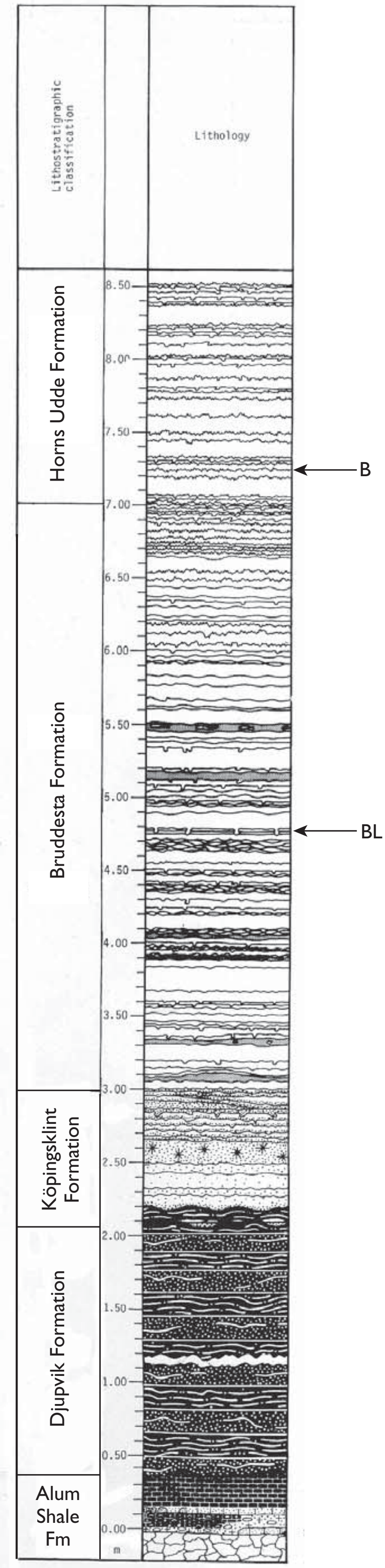


Figure 5: Section at Köpingsklint (from van Wamel 1974). Köpings Klint is the type-section for the Köpingsklint Formation of van Wamel (1974).

Precambrian rocks. This sandstone continues eastwards under the Baltic Sea, becoming covered by an increasingly thick succession of Cambrian, Ordovician, and ultimately Silurian sediments. The sandstone reappears at the surface on the south-east shores of the Baltic Sea. The Baltic Sea is thus a structural basin with the oldest deposits exposed at the western and eastern margins.
The Kalmar Sound, between Kalmar and Öland, is crossed by bridge. The sound is underlain by the continuation of the same Lower Cambrian sandstone that outcrops on the mainland coast. As the succession is built upwards by younger formations it rises above the seas as the Isle, which thus consists exclusively of Lower Palaeozoic sedimentary rocks in an undisturbed succession.

## 6th SEPTEMBER

The Lower and Middle Ordovician shelf-carbonate facies of the Ordovician epicontinental sea will be examined in outcrops on the northern half of Öland during the second day of the excursion. Collectively, these outcrops represent most of the rock-types of Öland and also of the Baltic Basin.

*Locality 1 ........................................................ Köpings Klint*
*Locality 2 ................................................................ Äleklinta*
*Locality 3 ............................................ North of Horns Udde*
*Locality 4 .................................................................... Byrum*
*Locality 5 ..................................................................... Haget*
*Stop in Byxelkrok*
*Locality 6 .............................................................. Hälludden*
*Locality 7 ....................................................................... Källa*
*Locality 8 ................................................................ Gillberga*

## 7th SEPTEMBER

The third day of excursion will take us to the southern part of Öland where Lower and Middle Ordovician sediments will be inspected.

*Locality 9 ............................................. Degerhamn harbour*
*Locality 10 ............................................. Degerhamn quarry*
*Locality 11 ..................................... Degerhamn quarry road*
*Lunch*
*Locality 12 .............................................. Grönhögen quarry*
*Locality 13 ............................................................... Ottenby*

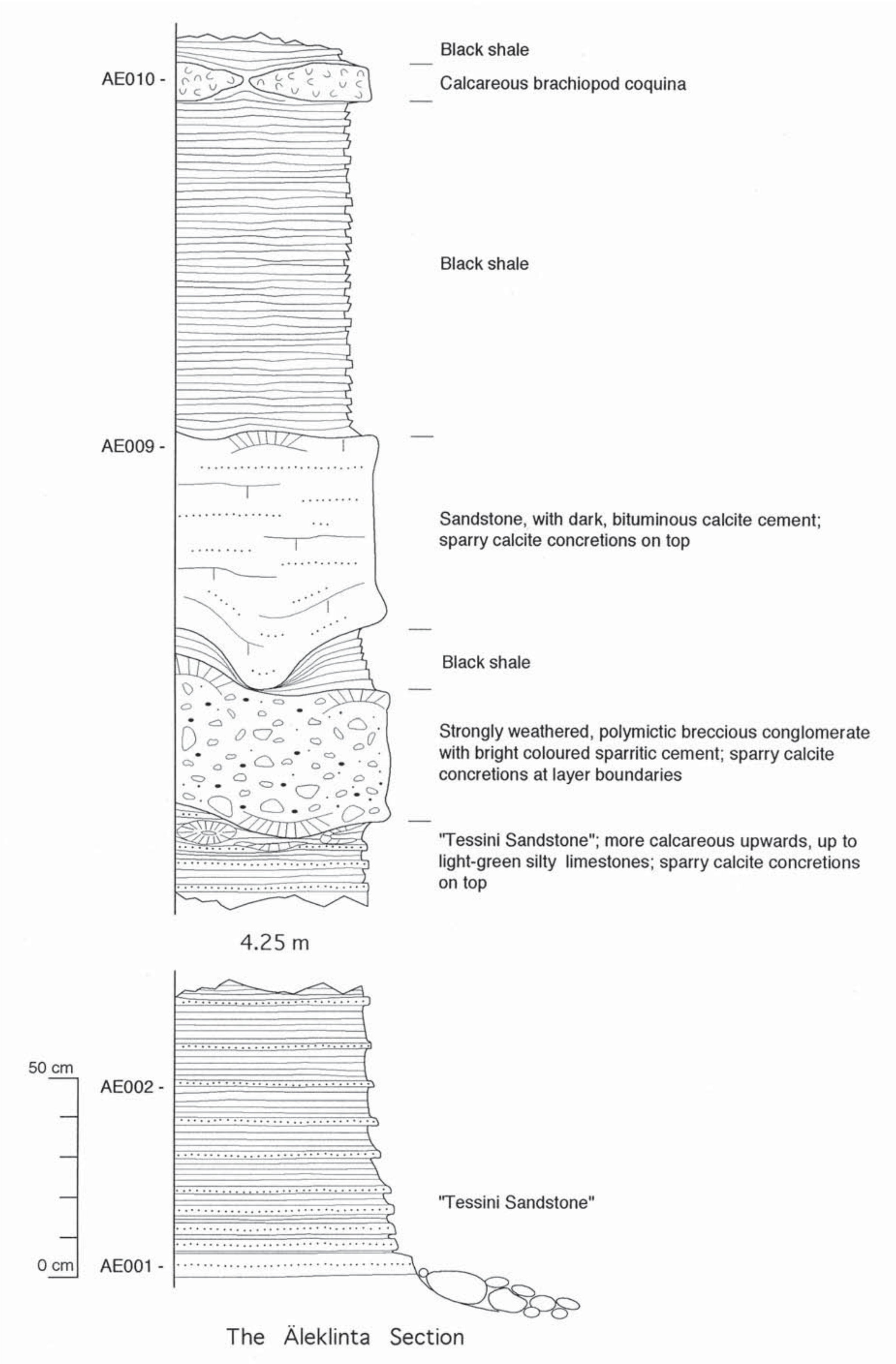


Figure 6: The Cambrian–Ordovician succession at Äleklinta. The top of Cambrian is the thick antraconite bed; the basal Ordovician sediments are composed by the '*Obolus*' conglomerate.

## 8th SEPTEMBER

On the fourth day we will depart from Öland and continue to Gotland.

## DESCRIPTION OF EXCURSION LOCALITIES

## NORTHERN ÖLAND: LOCALITIES 1–8

## LOCALITY 1: KÖPINGS KLINT SECTION – TYPE LOCALITY FOR THE KÖPINGSKLINT FORMATION

*Location*. – Raised sea-cliffs between Borgholm and Köpingsvik.
*Main topics*. - Köpingsklint and Bruddesta formations.
*Secondary topics*. - Djupvik Formation.
*Description*. – In this section 7 m of Latorpian and Volkhovian bedded limestone of the '*Orthoceras* Limestone' are well exposed in the cliff. Following formations are displayed in ascending order: The Alum Shale Formation, Djupvik Formation, Köpingsklint and Bruddesta Formations (van Wamel 1974) and the lower part of Formation A+B (Fig. 5).

Stratigraphic succession

>1 m - Formation A+B

Grey-green limestone with glauconite, mostly covered by vegetation and scree.

1.55 m - Horns Udde Formation

Red to grey and violet limestone, stylolitic. The 'Bloody layer' is seen near the base of the formation.

4.0 m - Bruddesta Formation

Red-brown limestone and marls with yellow discontinuity surfaces.

0.85 m - Köpingsklint Formation

Green, violet to red limestone, glauconite silt and sands.

1.70 m - Djupvik Formation

Green to dark grey siltstone and shale.

0.65 m - Alum Shale Formation

Black to dark grey limestone nodules, calcite prisms and dark shales. The outcrop is not well seen and may be covered on the day of our visit.

Few cm's - Borgholm Formation

Light Green sandstone and shale.

*Fossils and biostratigraphy*

Tjernvik (1956) recorded the *Shumardia*, *Ceratopyge forficula*, *Megistaspis (E.) armata, M. (V.) planilimbata*, *Megalaspides (M.) dalecarlicus* and *Megistaspis (V.) estonica* zones in the section. The *Megistaspis polyphemus* Zone is present in the Volkhov succession.
The black shale of the Alum Shale Formation contains *Rhabdinopora flabelliforme* (Westergård 1947).
Conodonts are present in the whole section and all conodont zones spanning the *Cordylodus angulatus*, *Paltodus deltifer* to the Volkhovian *Baltoniodus navis* Zones are represented (van Wamel 1974; Bagnoli *et al*. 1988).
Acritarchs are abundant in the Borgholm, Alum Shale and Djupvik Formations and are also very well preserved (Bagnoli *et al*. 1988).

## LOCALITY 2: ÄLEKLINTA

*Location*. – Sea-cliff at Äleklinta, about 11 km north north-east of Köpings Klint, and a small quarry above the sea-cliff about 400 m north of the village of Äleklinta.

*Main topics*. – The Middle Cambrian Borgholm Formation and the Lower Ordovician Alum Shale Formation.

*Secondary topics*. – The Djupvik, Köpingsklint and Bruddesta Formations.

*Description*. – The Cambrian–Ordovician transition can be observed at the Äleklinta locality (Fig. 6). The Middle Cambrian Borgholm Formation and the Lower Ordovician Alum Shale Formation will be examined.

*Borgholm Formation*
The formation consists of sandstone and siltstone with abundant trilobite fragments of trilobites. About 7 m are exposed in the sea-cliff.

*Alum Shale Formation*
The unit consists of polymict conglomerate, black shale and large coarse-grained antraconites with calcite cement capped by sparry calcite. A thin conglomerate or '*Obolus*' conglomerate (named after *Obolus apollinis*, which is present in the matrix) marks the start of Ordovician. The unit is approximately 2 m thick (Fig. 6).

*Köpingsklint Formation*
The unit is composed of glauconite sand and limestone with a recrystallised limestone at the base. It is 0.60 m thick at this locality.

*Bruddesta Formation*
This formation is exposed on top of the sea-cliff. The abandoned quarry has not been in use for many years and may be overgrown. The section exposes a green to grey and red limestone with marly interbeds.

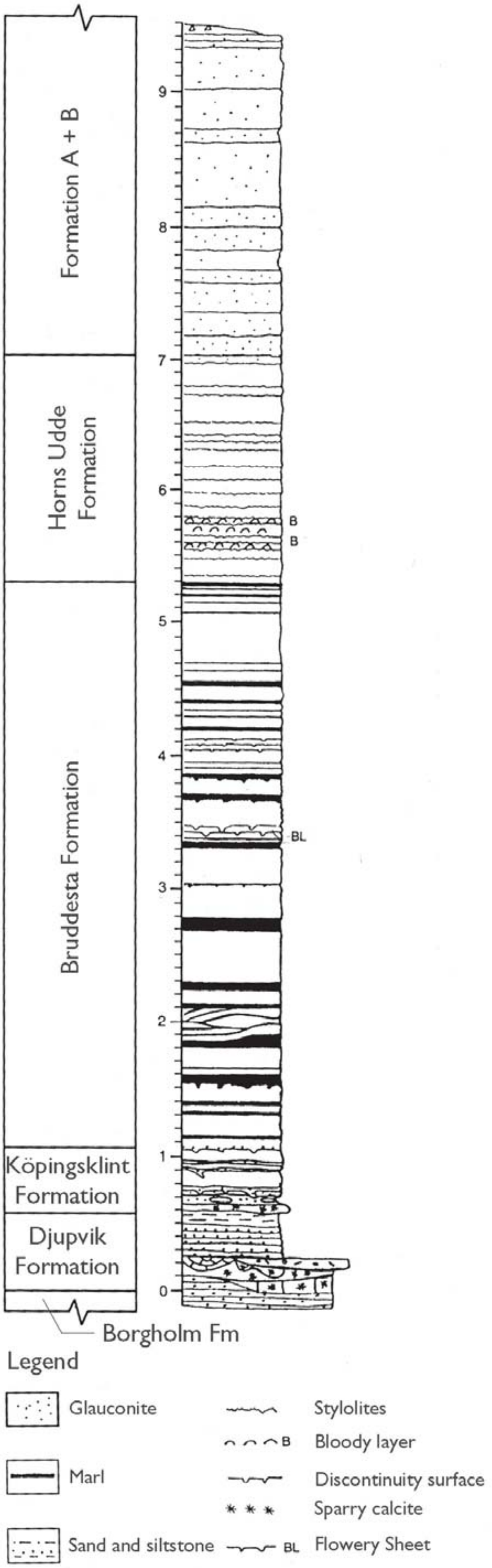


Figure 7: The succession at the north of Horns Udde section (from Bagnoli & Stouge 1997)

*Palaeontology and biostratigraphy*

The Cambrian System ends at the large antraconite, which is referred to *Agnostis pisiformis* Zone. The '*Obolus*' conglomerate marks the first appearance of the Ordovician beds. The overlying black shale yields *Rhabdinopora flabelliforme*.
Trilobites include the *Megistaspis* (*V.*) *planilimbata* Zone followed by the *Megalaspides dalecarlicus*, *M.* (*V.*) *estonica* and the *M.* (*M.*) *polyphemus* (previously *M.* (*M.*) *lata*, see Nielsen 1995) zones. The *M. armata* Zone (lower Hunnebergian Substage) is missing.
The conodonts from the '*Obolus*' conglomerate are referred to the *Cordylodus angulatus* Zone. The higher beds yield many well preserved conodonts with *Baltoniodus navis* and *Microzarkodina flabellum*.
Acritarch assemblages from the Middle Cambrian Borgholm Formation include *Adara alea* and *Cristallinium cambriense*. The acritarch assemblage from the Upper Cambrian antraconite horizon comprises *C. cambriense*, *Timofeevia pentagonalis* and *T. phorphoritica*. The '*Obolus*' conglomerate did not yield species of biostratigraphic significance as only sphaeromorphs have been observed (M. Tongiorgi pers. comm. 1999).

## LOCALITY 3: NORTH OF HORNS UDDE

*Main topics*. - Bruddesta Formation, 'Blommiga bladet', 'Bloody layer', Horns Udde Formation.

*Secondary topics*. - Middle Cambrian sandstones (Borgholm Formation), Lower Ordovician '*Obolus*' conglomerate (Alum Shale Formation), Djupvik Formation and Köpingsklint Formation.

*Location*. - Approximately 1 km north of Horns Udde.

*Description*. - Horns Udde, together with the coastal cliff immediately to the north of Horns Udde are excellent exposures showing the succession of northern Öland. The locality displays the succession from the Middle Cambrian Borgholm Formation (sandstone) to the Lower Ordovician (Volkhov) limestone of Formation A+B (Fig. 7).

The succession contains significant breaks in the upper Cambrian and early part of the Ordovician. Above this, the succession is complete or almost complete. The lower part of the section may be covered by beach gravel.

Locality 3 is one of the 'classical sections' on Öland and together with the Gillberga section ranks amongst the best sections that display the strata of the '*Orthoceras*' Limestone on northern Öland.

*Stratigraphic succession from top to bottom*

> 2 m - Formation A+B

Green-grey wackestone to grainstone, bedded to nodular with various amount of argillaceous material and abundant glauconite. Trilobites and orthocones are common allochems.

1.60 m - Horns Udde Formation

Grey, green to violet wackestone. The formation is characterised by numerous discontinuity surfaces and stylolites, which are yellow (goethite). The unit is very fossiliferous and cephalopods are most conspicuous.

A series of up to three bright red haematitic wart-like surfaces are present. These comprise the 'Bloody layer' (named by the local stonemasons and introduced into the literature as a local reference horizon by Bohlin 1949). Similar red surfaces are known on southern Öland, but at a different stratigraphic position.

3.40 m - Bruddesta Formation

A mainly red to red-brown argillaceous fossiliferous lime mudstone to wackestone interbedded with marl. The lower 40–50 cm are green to yellow rather than red-brown.

Disconformity surfaces are common and have goethitic coatings.

An interval with two spectacularly well-developed hardgrounds exists 2 m above the base of the formation; it is called the 'Flowery Sheet' (= Blommiga bladet in Swedish and named by Bohlin 1949). Sedimentary 'folds' are well displayed in the lower half of the formation. The 'folds' were described in great detail by Lindström (1963) from this locality.

0.5 – 0.8 m - Köpingsklint Formation

The limestones are composed of limemud, wackestone and grainstone. The limestone is associated with glauconite and interbedded with glauconite sand. The sediments are multicoloured and fossiliferous. The beds in the unit are laterally variable and recrystallised horizons are common to prominent. The horizons are developed as sparry calcite and are arranged in a rosette-like pattern.

Note: The base of the formation is situated at the foot of the cliff and it is not recommended to approach it.

0.25 – 0.45 m - Djupvik Formation

This unit is composed of siltstone with minor shaley intervals.

0.25 m - Alum Shale Formation

A thin layer of black shale may be found.

? m - Borgholm Formation:

Green silt to fine-grained sandstone. This unit is of Middle Cambrian age. The strata are exposed only at low tide and only the top beds may be accessible.

*Fossils and biostratigraphy*

Upper Cambrian taxa i.e. *Agnostus pisiformis* may be found in the clasts associated with the '*Obolus*' conglomerate.
The base of the Ordovician is exposed near the base of the cliff, but the beach shingle commonly covers the sediments. The base of Ordovician is found at the '*Obolus*' conglomerate.
The thin black shale of the Alum Shale Formation has yielded *Rhabdinopora flabelliforme*.
The Hunnebergian Substage is recorded from the Köpingsklint Formation, but only the *Megistaspis* (*E.*) *armata* Zone has been observed.
The Billingenian Substage i.e. the *Megalaspides* (*V.*) *dalecarlicus* and *M.* (*V.*) *estonica* zones are well displayed in the lower part of the Bruddesta Formation and below the 'Blommiga bladet'. Above the 'Blommiga bladet' and to the top of the section, the strata are referred to the Volkhov Stage. The Volkhovian *Megistapis* (*M.*) *polyphemus*, *M simon* and the lower part of *M. limbata* zones are presumably present in the section, but the precise ranges and the boundaries of the trilobite zones have not been established in this section.
Conodonts are omnipresent in the Ordovician strata and the *Cordylodus angulatus*, *Paltodus deltifer, Oepikodus evae*, *Baltoniodus*? *triangularis*, *Baltoniodus navis*, *Microzarkodina parva* and *Baltoniodus norrlandicus* zones have been recognised from this section (Lindström 1971; van Wamel 1974; Bagnoli & Stouge 1997).
Organic shelled fossils (chitinozoans and acritarchs) are fairly common in the upper grey to green limestones of the Volkhovian Formation A+B (Ribecai & Tongiorgi 1995), whereas the red-brown to red limestones of the Bruddesta and Horns Udde Formations are barren of these fossils. When present, the organic shelled fossils are well preserved.

## LOCALITY 4: BYRUM

*Main topics*. – Formation A+B, Fe-ooids.

*Secondary topics*. – Formation C.

*Location*. – South of Byrum and outside the protected area with 'Raukarna' ( = sea stacks: erosional remnants caused by the sea waves).

*Description*. – The section displays a short segment of Formation A+B. It is a low but laterally extensive outcrop and the beds can be traced northwards into the protected area with sea stacks ('Raukarna'). Here higher strata or Formation C are exposed. The area with 'Raukarna' is protected and sampling is not permitted.

The exposures at the coastal section include well-developed Fe-ooid horizons with varied composition in the glauconitic limestone of Formation A+B (Sturesson 1986, 1988). Phosphatic impregnations associated with burrows are present in Formation A+B at the foot of the low sea cliff. The ooid horizons are dark grey to nearly black. The ooids are white, red, yellow or brown.
The appearance of chamosite ooids in the Öland succession and elsewhere in the Baltic Basin (Jaanusson 1982) marks an important change in facies of authigenic silicate minerals (Sturesson 1986). Glauconite is the dominant authigenic silicate in the beds below the ooids whereas in the higher beds the dominating authigenic silicicate is chamosite. The significance of this change is not yet understood, but clearly relates to the upper Volkhov – lower Kunda regressive/transgressive transition.

*Stratigraphic succession*

>1.75m - Formation C

Yellow to light-grey wackestone.

> 2.75 m - Formation A+B

1.25 m Green grey nodular bedded limestones

0.25 m Horizon of Fe-ooids

0.25 m Green-grey limestone

0.10 m Zone with Fe-ooids

0.90 m Green-grey limestone with phosphatic burrows

(beach)

*Fossils and biostratigraphy*

The section has not been investigated systematically for fossils. Bohlin (1949) reported the presence of trilobites from the *Asaphus expansus* and *Asaphus* '*raniceps*' Zones. The former zone characterises the ooid horizons.
Conodonts (Stouge unpublished) occur frequently and the succession corresponds to the Haget, Hälludden and Gillberga successions (Stops 5, 6 and 8 in this guide). The Byrum section is the best exposure on Öland, where an interval with both a lower and an upper ooid horizon is displayed.
Acritarchs are present in high numbers (these results have not yet been published) (Ribecai *et al.* in prep.).

## LOCALITY 5: HAGET

*Main topics.* – The upper Volkhov to lower Kunda limestone of Formation A+B and Formation C.

*Secondary targets.* - Local D-surface and Fe-ooids in

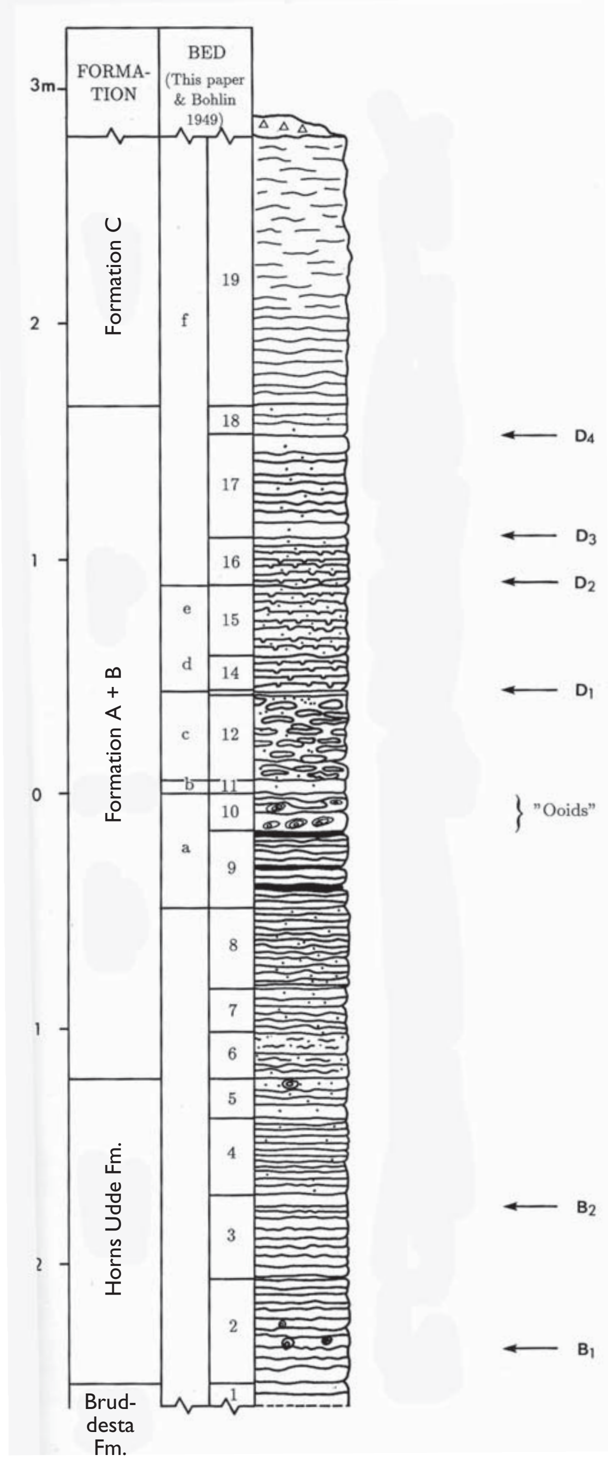


Figure 8: The succession at Haget (from Stouge & Bagnoli 1990). Formation A and B are now combined into one or Formation A+B.

Formation A+B.

*Location.* – West coast, between Byrum and Byxelkrok.

*Description.* – The upper Volkhov to lower Kunda beds are exposed in the sea cliff at the Haget section (Fig. 8), which also displays the erosional morphology caused by the sea waves. The lower part of the section is an almost flat surface that is commonly covered by seawater. The foot of the low cliff lies approximately 30 cm below the Fe-ooid bed.

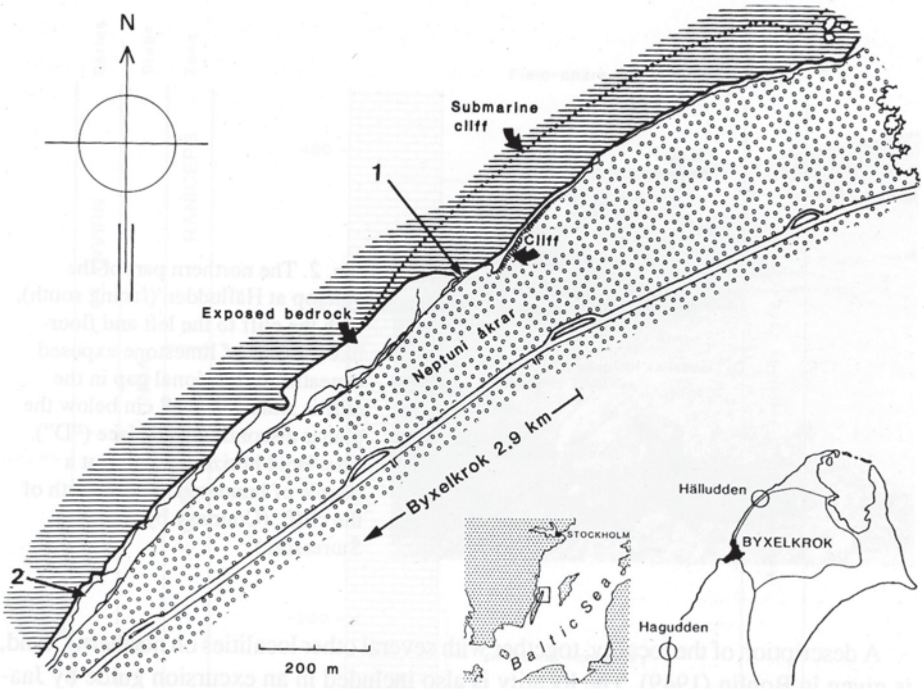


Figure 9: The Hälludden locality showing the location of the main section and the Neptuni åkrar (from Nordlund 1989a). The 'ooid' horizon (1) situated about 100 m to the south of the cliff-section. (2) is a cephalopod-rich level in Horns Udde Formation (from Nordlund 1989a).

*Stratigraphic succession*

>1.15 m – Formation C

Grey to beige wackestone with undular bedding. Trilobites are the most common allochems.

2.80 m - Formation A+B

Grey to dark grey wackestone with glauconite.

Grey to green wackestone with glauconite and glauconitic sand. Phosphatic burrows are common. Ooids in the formation are limonitic/goethitic.

1.30 m - Horns Udde Formation

Lime mudstone to wackestone with grey to violet and red stringers. The 'Bloody layer' is present at the base of the formation. Cephalopods are the most common allochems. This formation may be covered by seawater.

> 0.10 m - Bruddesta Formation

Red-brown, argillaceous lime mudstone with trilobites.

*Palaeontology and biostratigraphy*

Bohlin (1949) outlined a detailed stratigraphy of the Haget section. He reported the *Asaphus lepidurus*, *A. expansus* and *A.* '*raniceps*' zones from the section.
Graptolites (Arenig–Llanvirn) have been found in the green limestones (Skevington 1963, 1965a).
Conodonts are present in all beds. The conodont zones from the *B. navis* Zone to the *Lenodus pseudoplanus* Zone are recorded (Stouge & Bagnoli 1988).
Acritarchs are well represented in the green glauconitic limestone of Formation A+B and exceptionally high numbers of specimens have been recorded from this locality (C. Ribecai in prep.)
Stop: Byxelkrok for lunch, shopping etc.

## LOCALITY 6: HÄLLUDDEN

*Main topics.* – Formation A+B; D-surface.

*Secondary topics.* - Fe-ooids (if exposed).

*Location.* – North of Byxelkrok.

*Description.* – The Hälludden section is part of the long and extensive exposure that extends to the north of Byxelkrok as a narrow strip along the coast for several kilometres (Fig. 9). It starts just to the north of Byxelkrok and continues almost to the very tip of the island. The succession begins with the Billingenian limestone and the strata gradually become younger northwards and end with limestone of Kundan age (Bohlin 1949).
Inland from the cliff section, the beach ridges are composed of shingle. Linnaeus (1745) named the elevated beached 'Neptuni åkrar' (the fields of Neptune) and this name has gained general usage. Linnaeus also noted the fossiliferous exposures along the shore including cephalopods ('Ölandsspikar') and figured a pygidium of *Megistaspis* (*M.*) *limbata*.
The Hälludden section was the target in Project Hälludden (Jaanusson & Mutvei 1982). These workers used index horizons for determining the level of the succession. The index horizons are the top of the oolitic bed (0) at the base of the Hunderumian Substage, and a conspicuous, smooth

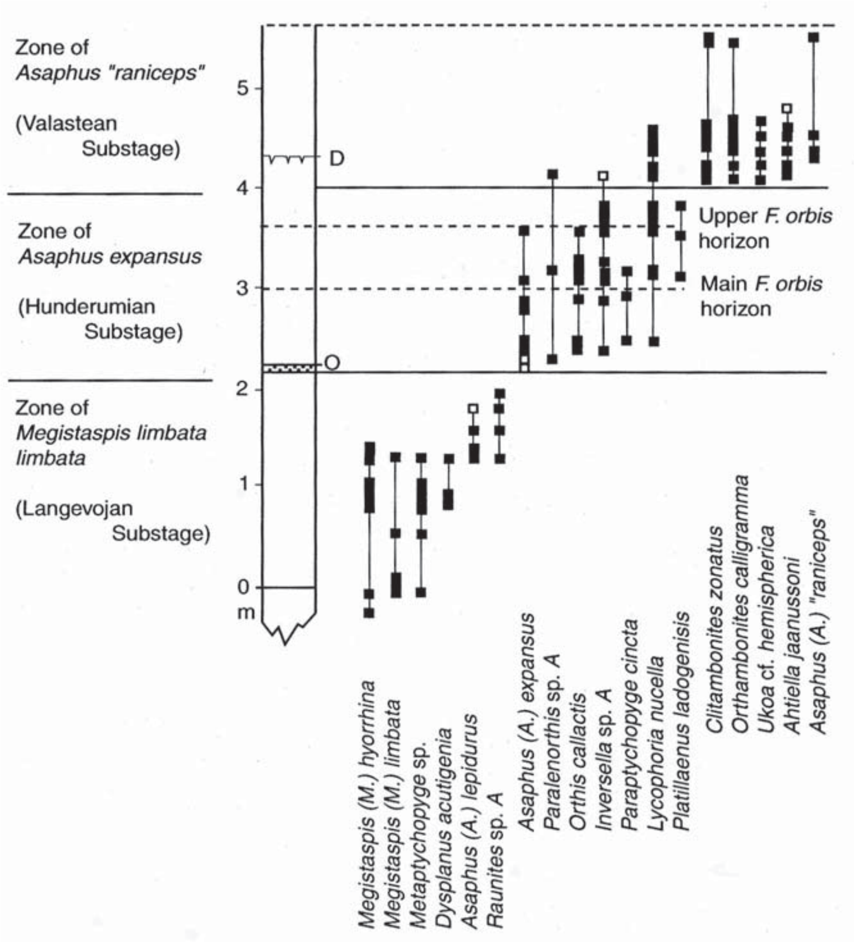


Figure 10: Biostratigraphy at Hälludden and the lower (main) and upper horizons with *Fisherites orbis*. D is the local discontinuity surface used as reference level. O marks beds with limonitic 'ooids' at the base of *Asaphus expansus* Zone (from Nitecki *et al.* 1999).

discontinuity surface (D) in the basal Valastean Substage. The levels above D were designated as + D, and those between D and the upper surface of 0 as – D.

The boundary between the upper Volkhov Stage and the Hunderumian Substage of the Kunda Stage is placed at the base of the oolitic bed, and that between the Hunderumian and Valastean substages, is at about - 30 D i.e. 30 cm below the index discontinuity surface (Jaanusson 1957).

*Stratigraphic succession*

< 1.5 m – Formation C (only seen to the north of the section)
Grey to yellow wackestone with some or no glauconite.
The smooth reference surface D with borings and ooids is seen - 0.40 m from the base.
2.9 m - Formation A+B
Grey to green wackestone with glauconite. The amount of glauconite decreases up through the section. The lower part of the section comprises green to grey glauconitic wackestone-grainstone and glauconite sand.
A 10 cm thick ooid horizon has been reported from the southern end of the section (Jaanusson 1957; Janusson & Mutvei 1982), but this interval may be covered by seawater.

*Palaeontology and biostratigraphy*

Gerhard Holm collected cephalopods and graptolites at Hälludden for many years (e.g. Holm 1882). Additional years of collecting under the Hälludden Project has yielded many additional fossils. So far, illaenid trilobites Jaanusson (1957), graptolites (Bulman 1936; Skevington 1963, 1965a), chitinous hydroids (Skevington 1965b), acritarchs (Eisennack 1976; Ribecai & Tongiorgi 1999), chitinozoans (Grahn 1980, 1982) and two horizons with receptaculitids (= *Fisherites orbis*) have been recorded and described from the section (Nitecki *et al.* 1999), but many more undescribed taxa including brachiopods are present, especially in Formation A+B (Jaanusson & Mutvei 1982; Fig. 10).
Additional trilobites to those described by Jaanusson (1957) have been listed (Jaanusson & Mutvei 1982; Nitecki *et al.* 1999) and the *M. limbata*, *A. expansus* and *A. 'raniceps'* zones are present (Fig. 10).

The graptolites are Darriwilian in age; those recorded between – 1.00 m and – 0.60 m in the middle of the *A. expansus* Zone are Arenig, whereas the fauna at + 0.20 i.e. *Asaphus* '*raniceps*' Zone is Llanvirn.
Conodonts are present in the whole section with a moderate yield and preservation in the lower part to good yield and preservation in the upper part. The fauna is currently being investigated (Stouge in prep.) and the fauna is referred to, from base to the top, the *Lenodus antivariabilis*, *Lenodus variabilis* to *Yangtzeplacognathus crassus* conodont zones.

*Depositional environment*. - The depositional environment has been debated for some time, especially for the sediments

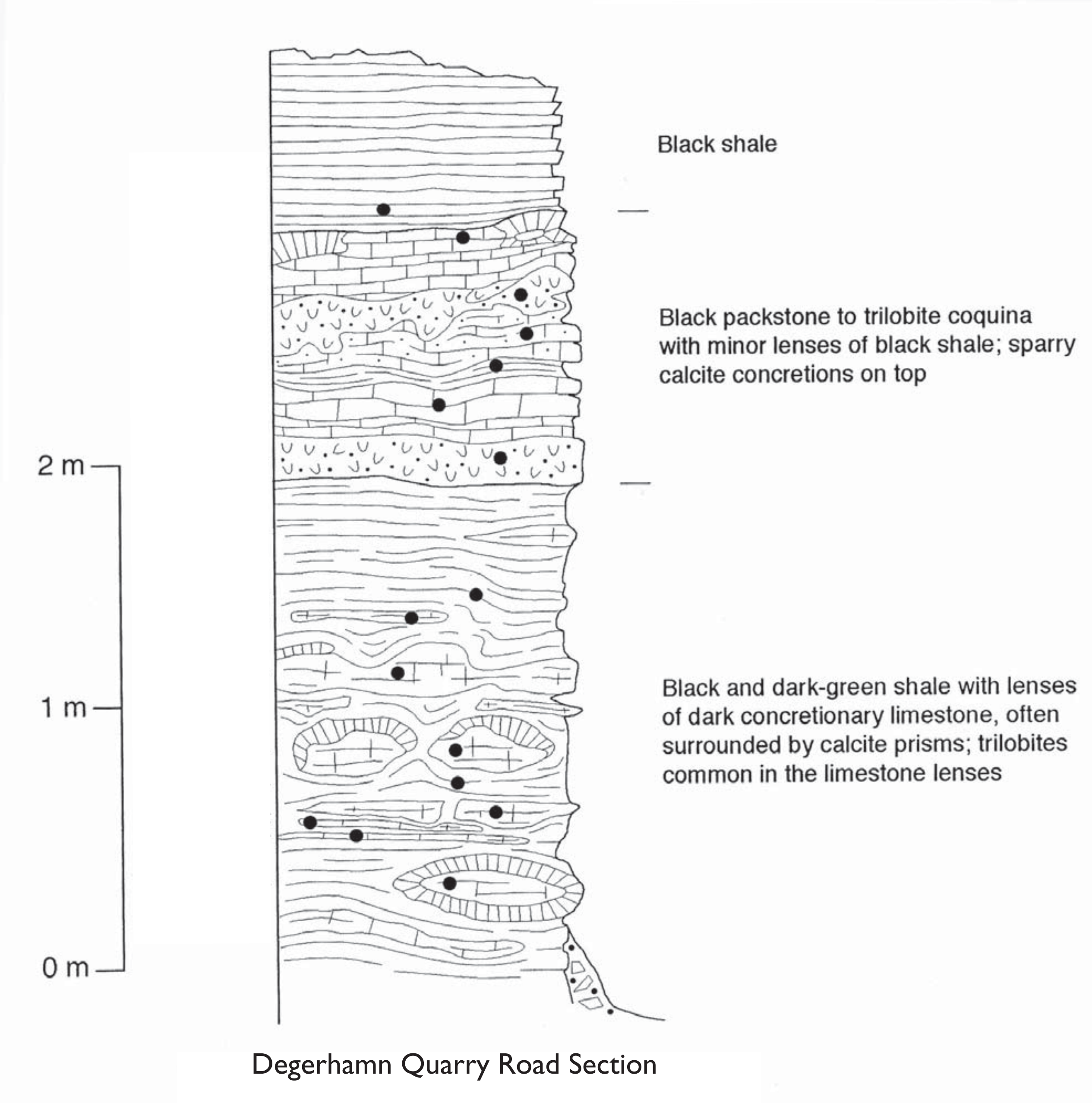


Figure 11: Degerhamn quarry road section – a road cut showing the Alum Shale Formation with the *Olenus* horizon (Upper Cambrian) characterized by antraconites in black shale overlain by shale with *Clonograptus tenellus* (Lower Ordovician). Trilobites are very

of Formation A+B at Hälludden. Chen & Lindström (1991) found that the deposition took place in a fairly deep sea, i.e. between 150–200 m. In contrast Bohlin (1949), Grahn (1982, 1986), Jaanusson (1982), Sturesson (1986, 1988 and Nordlund (1986, 1989a, 1989b) all argued that the strata of Formation A+B accumulated in a comparatively shallow sea and were storm generated deposits or tempestites. The arguments are equivocal and the debate is not yet settled.

## LOCALITY 7. - KÄLLA – TYPE LOCALITY FOR THE KÄLLA LIMESTONE

*Location*. – South-west of Källa Church.

*Main topic*. – Källa Limestone (Viru – Middle Ordovician).

*Description*. – The locality is mostly overgrown but approximately 1.5 m of strata can be seen. The sediment is a lime mudstone or wackestone with argillaceous interbeds and with some macrofossils.

*Palaeontology and biostratigraphy*

Macrofossils i.e. trilobites are not frequently found, but brachiopods are fairly common in the argillaceous layers. The conodonts are well preserved and the fauna represents the *Baltognathus robustus* Subzone of the *Pygodus serra*

Zone (= *Glyptograptus teretiusculus* graptolite Zone, Uhakuan Stage) (Stouge unpublished). Acritarchs are present and well preserved. These are currently under investigation (Ribecai in prep.).

## LOCALITY 8. – GILLBERGA QUARRY

*Location*. - Approximately 200 m to the south-west of the village of Gillberga.

*Main topics*. – Formation A+B and the formations above, C and D.

*Description*. – The locality is presently being quarried and thus the description given here may not quite correspond to its appearance on the day of our visit.
This locality is the northernmost of a series of large quarries located between Gillberga and Sandvik and up to the coast. Most of the quarries reveal the upper part of the Bruddesta Formation down to the 'Blommiga bladet', which often forms the bottom of the quarry and the Horns Udde Formation, but the top of the Gillberga Quarry succession displays the youngest exposed Kunda sediments on this part of the island.
Bohlin (1949) described the Hjorthamn Limestone from the Gillberga quarry. The Hjorthamn Limestone is a unit approximately 0.9 m thick and is part of Formation A+B. The base and the top of Formation A+B are well displayed in the quarry. The strata referred to as Formations C and D lie above Formation A+B and Formation D concludes the succession.

*Stratigraphic succession.*

>2.50 m – Formation D

Grey to red and green undular bedded wackestone with argillaceous partings. Cephalopods and trilobites are common.

2.90 m – Formation C

Light grey, mottled grey to dark grey or violet wackestone to grainstone with abundant stylolites. Cephalopods and trilobites are frequent. Pyrite is present.

8.20 m – Formation A+B

Wackestone with glauconite and glauconitic sand. This unit has a green appearance. Glauconite becomes more rare in the upper part of the unit. Several spectacular discontinuity surfaces, especially at the bottom of the formation can be traced to the section north of Horns Udde. Hjorthamn Limestone occurs within the upper one meter of this unit.

1.65 m – Horns Udde Formation

Wackestone with many disconformity surfaces. This unit is developed with the 'Bloody layer' at the base. The top is a prominent surface. Cephalopods are common.

2.5 m – Bruddesta Formation

Red micrite with silt or marl beds. The 'Blommiga bladet' is exposed at the base of the quarry and is often covered by water.

*Palaeontology and biostratigraphy*

The section has not been investigated for fossils.
The conodont biostratigraphy of this section was described by Löfgren (2000). The succession is almost complete and reaches up to the *Microzarkodina ozarkodella* Zone (Kunda Stage).

Table 1

| | |
|---|---|
| North Öland | |
| Upper Grey *Orthoceras* Limestone | *Centaurus* Limestone |
| Upper Red *Orthoceras* Limestone | *Platyurus* Limestone |
| | *Gigas* Limestone |
| Lower Grey *Orthoceras* Limestone | *Asaphus* Limestone (=*Vaginatum* Limestone sensu Holm 1882) |
| Lower Red *Orthoceras* Limestone | *Limbata* Limestone and *Planilimbata* Limestone (pars) |
| South Öland | |
| Upper Grey *Orthoceras* Limestone | *Centaurus* Limestone |
| Upper Red *Orthoceras* Limestone | *Platyurus* Limestone |
| | *Gigas* Limestone |
| | Transition beds |
| Middle Red *Orthoceras* Limestone | Upper *Asaphus* Limestone |
| Middle Grey *Orthoceras* Limestone | 'Sphaeronites bed' |
| Lower Red *Orthoceras* Limestone | Lower *Asaphus* Limestone |
| | *Limbata* Limestone |
| Lower Grey *Orthoceras* Limestone | *Limbata* Limestone and *Planilimbata* Limestone |

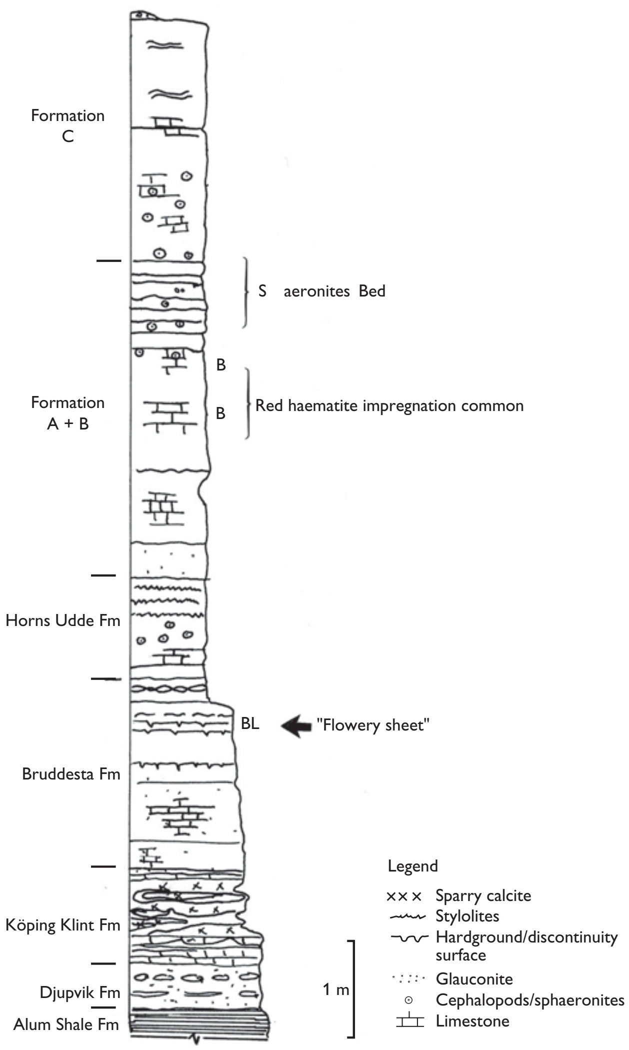


Figure 12: A log for the Degerhamn quarry section (it is also valid for Grönhögen see text). The '*Sphaeronites*' bed lies near the top of Formation A+B.

## SOUTHERN ÖLAND: LOCALITIES 9–13

## LOCALITY 9. – DEGERHAMN HARBOUR

*Location*. – In the harbour at Degerhamn.

*Main topic.* – Green Limestone with '*Sphaeronites.*'

*Description.* – The stop is in the small harbour where loose blocks with '*Sphaeronites*' are easy to investigate. The purpose of this stop is to show the parts of the facies of Formation A+B, which are not found on northern Öland. The unit is easy to recognise in the sections as it appears as a 'green unit' beneath a red limestone. The 'green unit' is intensively quarried in the Degerhamn Quarry (Stop 10) due to its low content of clay material. The 'green unit' is a marker horizon that can be traced from Kinnekulle, Väster Götland, central Sweden in the west to southern Öland and further on and across the Baltic Basin to Estonia in the east.

The unique fossils at the Degerhamn Harbour locality are the diploporite cystoids or '*Sphaeronites*'. The conodont fauna is typical of the Volkhov – Kunda transition (*Lenodus variabilis* Zone) in the Baltic Basin.

## LOCALITY 10. – DEGERHAMN QUARRY

*Location*. – East of the main road and approximately 2 km south-east of Degerhamn.

*Main targets*. – The unit with '*Sphaeronites*' of Formation A+B and the overlying Formation C.

*Additional targets*. – The Bruddesta and Horns Udde formations.

*Description.* – This is an extensive quarry and permission to enter the quarry from the owner is required. The entrance to the quarry is at the factory in Degerhamn village aproximately 2 km north-west of the quarry, but parts or even all of the quarry may not be accessible if production is taking place.
In this quarry the succession from the Alum Shale Formation to Formation C is well exposed (Fig. 11). The succession in southern Öland is largely the same as the succession on northern Öland, but differences are found in the thickness of the units and colour of the sediments. The most prominent colour change is that the Bruddesta Formation is brown-red on northern Öland but grey in southern Öland and the colour of Formation C is red in the Degerhamn quarry rather than being light grey to yellow as it is typically on northern Öland.
On Öland the *Orthoceras* Limestone was first divided into units according to colours as shown
in Table 1.
Comparison between northern Öland and southern Öland using the colour system however appeared to be difficult and is now abandoned.

*Stratigraphic succession*

> 1.90 m – Formation C

Red to brown grain- and wackstone with occasional green partings. Cephalopods are present.

1.25 m – Formation A+B

Green, grey and red wackestone with some glauconite. Cephalopods and trilobites are common in the formation and '*Sphaeronites*' mark the top of the formation on southern Öland. In the upper part, several bedding planes are encrusted by haematite.

1.50 m - Horns Udde Formation

Grey to violet wackestone with many disconformities developed as stylolites.

Cephalopods are common.

1.70 m – Bruddesta Formation

Grey to light grey lime mudstone and wackestone with green marly horizons. Beds usually 5-7 cm thick. Rusty weathering pyrite nodules are common at bedding planes.

1.05 m – Köpingsklint Formation

Glauconitic lime mudstone with green stringers and limestone nodules and glauconite sand. The middle part is strongly recrystallised at certain levels. Slump structures are present within the formation.

0.40 m – Djupvik Formation

Green silt with silty limestone nodules. Glauconite is common in the sediments.

> 1.30 m – Alum Shale Formation

Dark grey and black shale with occasional limestone lenses; rusty weathering is characteristic and pyrite nodules are present.

*Palaeontology and biostratigraphy*

The section has not been investigated for macrofossils. However the trilobite zones recorded from Ottenby (Tjernvik 1956; Stop 13) can be correlated with the section.
All conodont zones from the *Paltodus deltifer* Zone, which is found in the Djupvik Formation to the *Lenodus pseudoplanus* Zone, which is present in Formation C, have been recorded in the section (Stouge unpublished and in prep.).

## LOCALITY 11. – DEGERHAMN QUARRY ROAD SECTION

*Location*. – At the bridge on the main road approximately 1.5 km to the north of Degerhamn.

*Target*. – The Cambrian–Ordovician system boundary in the Alum Shale Formation.

*Description*. – The Degerhamn quarry road provides an excellent section of the Alum Shale Formation and the Cambrian – Ordovician boundary. The section is a road cut in the private road to the Degerhamn quarry on both sides of the road and of the bridge.

*Stratigraphic succession.*

See Figure 12 for a description of the section.

*Palaeontology and biostratigraphy*

The antraconite nodules are very fossiliferous and consist exclusively of trilobites. Olenids are the dominat trilobites and *Olenus gibbosus* and *O. truncatus* are present. *Peltura scarabaeoides* and *P. minor* are present in the uppermost beds. Acritarchs and conodonts also occur frequently and are well preserved. The graptolite *Clonograptus tenellus* (*Rhabdinopora flabelliforme* Zone) is recorded from the shale at the top of the section.

## LOCALITY 12. - GRÖNHÖGEN QUARRY

*Location*. – In Grönhögen village with the main entrance on the east side of the road and across the entrance to Grönhögen camping place (= old quarry in Alum Shale).

*Main target*. – The succession from the Bruddesta Formation to Formation C.

*Description*. - The quarry is large and the exposures are fairly good. The exposed succession is less complete than in the large Degerhamn quarry and the stratigraphically lower units i.e. the Alum Shale, Djupvik and Köpingsklint formations are not exposed in the quarry.

*Stratigraphic succession*

The exposed succession at this locality is identical to the succession in the Degerhamn quarry (Stop 10) and is not repeated here.

*Palaeontology and biostratigraphy.*

Biostratigraphic studies have not been published on the exposed succession. Conodonts extracted from the section are currently being investigated. To date, the results are similar to those from the Degerhamn section.

## LOCALITY 13. – OTTENBY SECTION

*Location*. - Small sea-cliff west of Ottenby, the southernmost village of Öland.

*Main target*. – Köpingsklint Formation.

*Additional targets*. – Alum Shale and Djupvik formations.

*Description*. - Ottenby is a natural exposure along the shore of Kalmarsund. The cliff at Ottenby is the best exposure of the Köpingsklint Formation on Öland.

*Stratigraphic succession*

The section comprises the Alum Shale Formation, the Djupvik Formation, the Köpingsklint Formation and ends with the Bruddesta Formation. The section is shown in Figure 13 (from Tjernvik 1956).

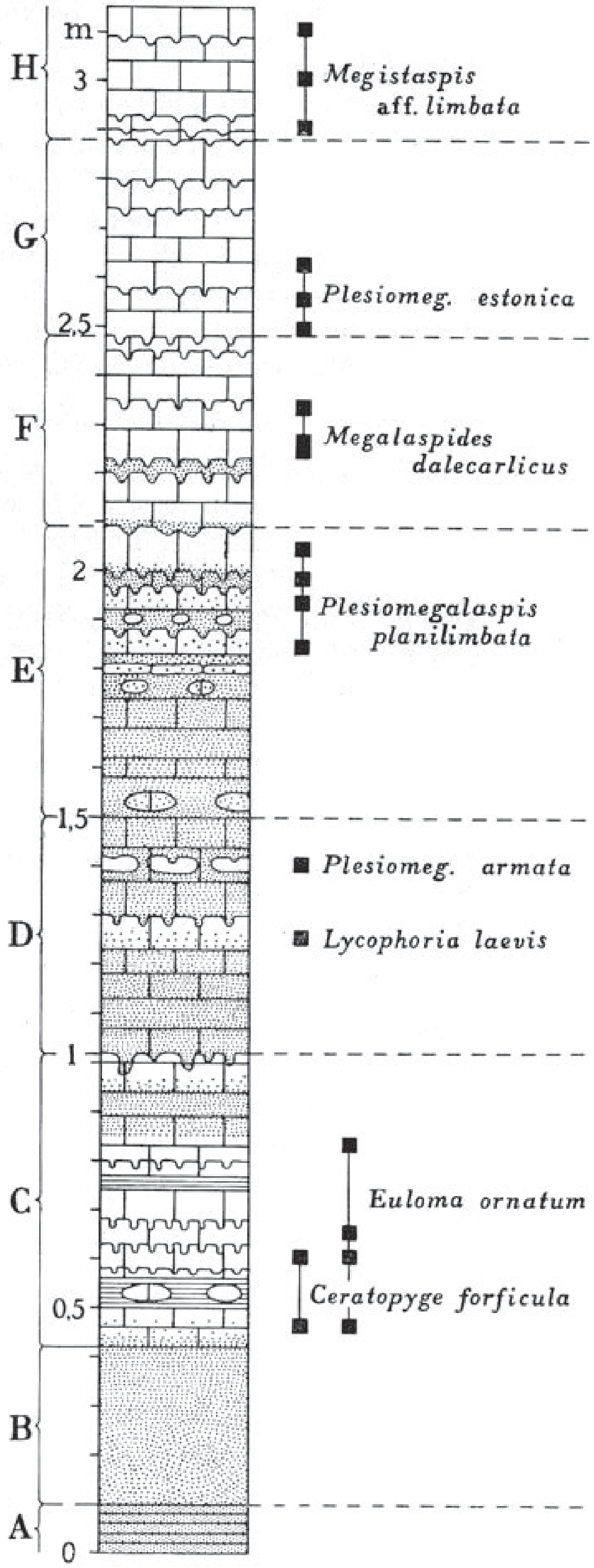


Figure 13: The section at Ottenby with trilobite data (from Tjernvik 1956). The *Ceratopyge* and *Dictyonema* shale are now referred to the Alum Shale Formation. The Djupvik Formation is 30–36 cm thick and the Köpingsklint Formation is about 2 m thick at this locality.

*Palaeontology and biostratigraphy.*

The Ottenby section has yielded around 20 trilobite species. The most common forms are *Ceratopyge forficula* (Sars), *Euloma ornatum* Angelin, *Orometopus elatifrons* (Angelin), *Niobe insignis* Linnarsson, *Niobella obsoleta* (Linnarsson), *Varvia longicauda* Tjernvik, *Ottenbyaspis oriens* (Moberg & Segerberg), *Symphysurus angustatus* (Sars & Boeck) and *Nileus limbatus* Brögger.

Conodonts are common and the basal limestone nodules and beds of the Köpingsklint Formation contain a *Paltodus deltifer* Zone fauna. The *Paroistodus proteus* Zone begins about 0.2 m above the base of the Köpingsklint Formation. It is complete except for a break at the base of the Billingen Substage 1.3 m above the base of the limestone. The *Oepikodus evae* fauna appears 1.55 m above the base of the limestone section. The uppermost layer of the section is basal Volkhov in age.

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# The Silurian of Gotland - Part I: Review of the stratigraphic framework, event stratigraphy, and stable carbon and oxygen isotope development

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## 1. INTRODUCTION

In the past 15 years our picture of the Silurian has changed dramatically. Based on palaeontological, geochemical, and sedimentological investigations, it is now known that the conditions during the Silurian were much more variable than previously assumed. The island of Gotland, Sweden, has played a very important role in these investigations. For the purpose of the IGCP 503 Field Meeting 2004, this paper reviews the current stratigraphic framework of Gotland, and how its strata and biotas reflect concurrent events (event stratigraphy), relative sea-level changes (sequence stratigraphy), and stable carbon and oxygen isotope evolution (chemostratigraphy). The combined database well illustrates the interaction of oceanographic, climatic, and biotic changes at low latitudes during the Silurian radiation.

MC is responsible for the sedimentological and sequence stratigraphic data, and conclusions based thereupon, LJ for biostratigraphic chapters and discussions of episodes and events ('the Jeppsson model'), and AM for isotopic data and discussions of the Bickert et al. model. However, we have all tried to use all the data available and read and helped to improve all of the text, making it as integrated as is possible.

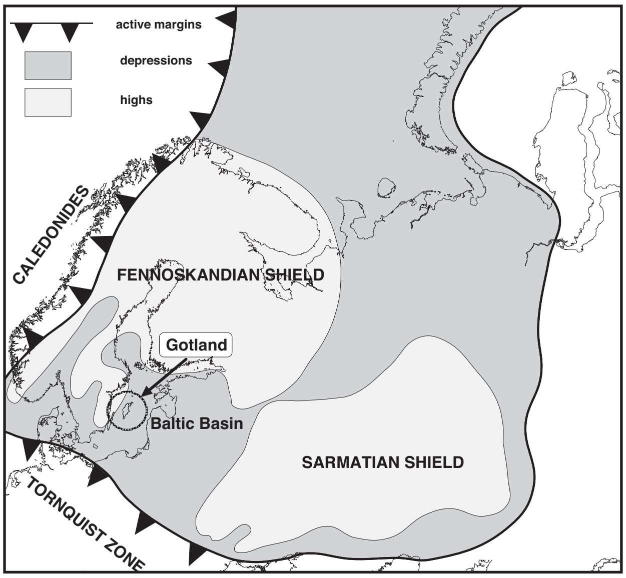


Fig. 1. Silurian Baltica showing principal shield areas and basins (redrawn after Baarli et al. 2003). Note the active margins in the NW and SW.

### *1.1 The Baltic Basin*

The low-latitude carbonate platform strata of Gotland formed in the Baltic Basin. This intra- to pericratonic basin developed on the southern margin of the Baltic Shield and the East European platform (Fig. 1). Following extension and later 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 collisional event resulted in a change in tectonic regime – from a passive margin to a foreland basin (Poprawa et al. 1999). This is reflected by the more than 3 000 m thick Silurian deposits in Poland. During the Silurian, the western margin of Baltica was strongly affected by the collision of the Scotland/Greenland complex and western Norway (at ca 425 Ma), resulting in the early Scandian Orogeny (Torsvik et al. 1996) and eastward migration of thrust sheets. The strata on Gotland thus formed on the comparably protected and slowly subsiding craton-attached shelves between a two-armed foreland basin system (Fig. 1). This is reflected by a comparably thin cover of Lower Palaeozoic strata below Gotland; the crystalline basement is situated 378.4 m below sea level at Visby (Hedström 1923). The northern erosional limit of Silurian sedimentary cover within the basin is situated just north of Gotland and the Estonian mainland (Martinsson 1958; Flodén 1980), showing a successive depositional offlap towards the south. The Silurian subsurface below the Baltic Sea is fairly well known from numerous seismic stratigraphic survey lines (e.g. Flodén 1980; Flodén et al. 2001; Bjerkéus & Eriksson 2001).

### *1.2 Gotland*

The Silurian bedrock of Gotland is an erosional remnant of an extensive carbonate platform complex that evolved along the margins of the Baltic Basin, from the western parts of the present-day Baltic Sea across the East Baltic and further southeast to Ukraine. The island is relatively small

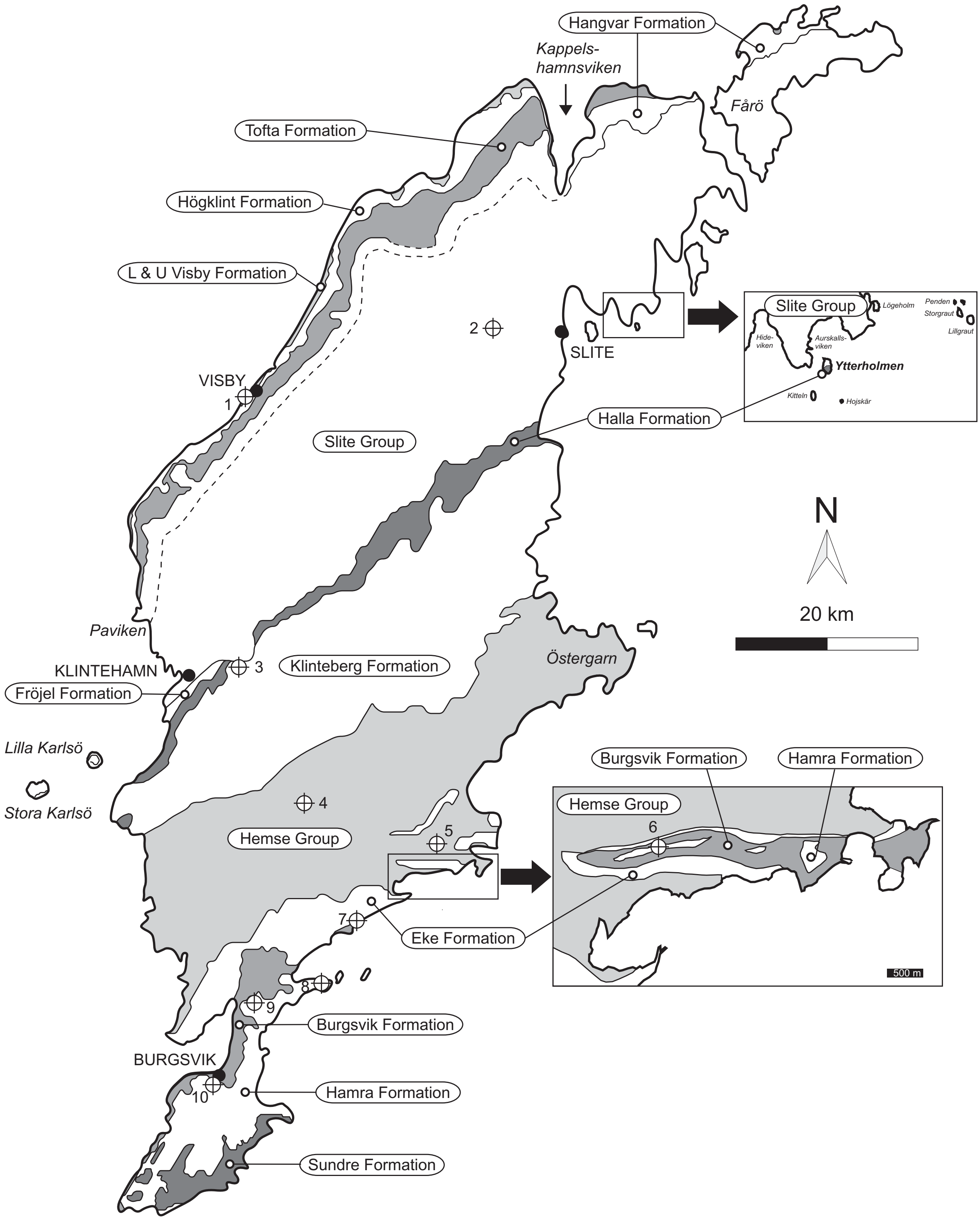


Fig. 2. A new geological map of Gotland (completed by LJ & MC), and position of borings; Visby boring (1), File Haidar boring (2), Hunninge-1 (3), Linde-1 (4), När-1 (5), Burgen-1 (6), Ronehamn-1 (7), Grötlingbo-1 (8), Uddvide-1 (9), Burgsvik boring (10). This preliminary map is chiefly based on Jeppsson & Calner (2003) and conodont data from Jeppsson (in manuscript; in prep.).

(ca 3 000 km$^2$), and outcrops are easily accessible along the coasts, in inland cliffs, ditches, and in still productive and abandoned quarries. The research history of the bedrock geology and fossils of Gotland goes back to the 18th century. Early studies focused primarily on the excellently preserved fossil biota and to resolve the large-scale stratigraphic relationships of the strata. The first comprehensive study of the geology and stratigraphy of Gotland was published in a series of detailed map descriptions published by the Swedish Geological Survey between the 1920's and the 1940's (summarised in Hede 1960 and refined by Laufeld 1974a, b).

The strata exposed on Gotland range in age from the latest Llandovery through Ludlow, i.e. encompassing ca 10 Ma of the Silurian System according to the ICS (2002) time scale. The entire succession is ca 500-700 m thick depending on were measurements are taken, the higher number is the sum of the maximum thickness for each interval.

The strata show no major late diagenetic alteration, and tectonic disturbances are rare and restricted to minor faults with limited vertical and/or lateral displacement. The excellent preservation is shown by, e.g., the conodont colour (very low CAI; Jeppsson 1983), and by the discovery of calcareous micro- and nannofossils that are previously unknown in rocks of this age (Munnecke et al. 1999, 2000). Studying the orientation of the present-day coastlines of Gotland, it is evident that the preservation of the island itself is partly inherited from larger-scale tectonic zones. The strata dip less than 1° towards the southeast, although this may vary substantially on a local scale, especially in the vicinity of major reef complexes. On a broad scale, the stratigraphy is easily comprehensible, with the oldest strata in the northwest of the island and successively younger strata towards the southeast (Fig. 2). The strata show a distinct facies transition southwestward along the erosional strike. Argillaceous limestones and marls of an open marine shelf facies dominate on western Gotland, whereas toward the NE contemporaneous sediments of shallower facies were deposited. This clearly shows that the palaeo-contour lines cannot have run SW-NE as proposed, e.g., by Bassett et al. (1989) but must have had a more E-W or ENE-WSW direction (cf. figure 6 in Baarli et al. 2003).

The Silurian subsurface stratigraphy of onshore Gotland is not known in detail. Apart from borings conducted by OPAB (Oil Prospecting AB) or quarry operators, often unavailable or inadequately described for the research community, these rocks have primarily been known from five borings (Fig. 2); the Burgsvik boring (Hede 1919), Visby (Hedström 1923), File Haidar (Thorslund and Westergård 1938), and the När-1 and Grötlingbo-1 borings (Snäll 1977). Additional shallow borings on southern Gotland were examined by Pusch (1969). At present, the cores still preserved are variably sampled and, due to their wide spatial distribution, of limited value for detailed stratigraphic analysis. For this reason, new cores have recently been recovered from parts of the Wenlock and Ludlow (co-ordinated by M. Calner), namely Hunninge-1 (42 m; GPS N: 6364427 O: 1647619), Linde-1 (102 m; GPS N: 6353227 O: 1654476), Burgen-1 (50 m; GPS N: 6348342 GPS O: 1667496), Ronehamn-1 (30 m; GPS N: 6342406 O: 1663083), and Uddvide-1 (70 m; GPS N: 6333020 O: 1653025)(Fig.2).

The present geomorphology of Gotland is the result of Quaternary glacial erosion and repeated post-glacial sea-level change. These processes have accentuated the topography into flat low-lying farmlands where argillaceous sedimentary rocks occur and somewhat higher, forested areas where more weathering resistant limestone occur.

### *1.2.1 Carbonate platforms of Gotland*

Carbonate platforms are marine ecosystems that are born, developed, and, for various reasons, eventually die (Bosellini 1989). The strata on Gotland reflect a series of stacked carbonate platform generations. Individual platform 'life cycles' do not correspond with the subdivision of formations and/or groups in use, although their boundaries may coincide. The minor dips indicate that individual platforms were of ramp type. However, intermittent development of extensive stromatoporoid-coral reef barriers (Hadding 1941; Manten 1971; Flodén et al. 2001; Bjerkéus & Eriksson 2001) indicates that these ramps developed steeper gradients with time, and transformed into distally steepening ramps, or even rimmed shelfs, in their mature stages. Individual platform generations are generally some tens of metres thick – from the incipient transgressive surface to the development of prograding reef complexes – and separated by variably pronounced stratigraphic discontinuities. Poorly to moderately developed palaeokarst or other evidence for subaerial exposure is associated with several of these discontinuities, e.g., within the middle Slite Group (Laufeld & Martinsson 1981), at the top of the Slite Group (Calner 2002), top Klinteberg Formation (Eriksson, in press), lower and middle Hemse Group (Keeling & Kershaw 1994), within the lower Eke Formation (Cherns 1982), and within the uppermost Sundre 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 short ranging or beyond biostratigraphic resolution on Gotland but increase substantially in magnitude in Estonian outcrops (cf. Jeppsson et al. 1994). However, despite the indications for Silurian subaerial exposure, especially in the shallower facies areas on the eastern part of the island, it must be assumed that at the end of the Silurian, a sedimentary cover (of unknown thickness) protected the whole succession. A Pridoli coastline south of Gotland (Bassett et al. 1989) is improbable because the "young" carbonates would have been affected by strong erosion and karstification.

### *1.2.2 Depositional environments*

A detailed description of the facies complexes occurring on southern Gotland is given in Samtleben et al. (2000), who distinguished 12 different facies. The variation in lithofacies may locally be considerable. On a broad scale, however, three major depositional environments may be resolved, each with different lithofacies associations. These are:

1) *Slope and basin areas*. Argillaceous skeletal limestones and marls with a mud-wackestone texture and thin shell coquinas dominate seaward of reef barriers and/or below the storm wave-base. These strata are often developed as limestone-marl alternations showing the typical "differential diagenesis", i.e. early-cemented limestones and compacted marls (Munnecke & Samtleben 1996). Fragments of brachiopods, trilobites, and ostracods dominate the skeletal composition. However, Cherns & Wright (2000) have shown that a massive early diagenetic dissolution of originally aragonitic-shelled organisms (e.g. molluscs) has taken place resulting in a strong bias in the preserved fauna, except where early silicification due to weathering of bentonites has silicified such shells (Laufeld & Jeppsson 1976). Bioturbation was generally abundant, e.g. as cm-wide burrows or as *Chondrites*-like mottling. 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.

2) *Biohermal, biostromal, and shoal areas*. These areas are characterised by stromatoporoid-coral reef complexes, related coarse-grained skeletal float- and rudstone reef flank deposits and well sorted crinoidal/peloidal grainstones. Basinward, patch-reefs normally less than 100 m in diameter dominate whereas toward shallower environments (generally toward the NE) these bioherms grade into biostromes. The patch-reefs were built mainly by stromatoporoids and tabulate corals. Crinoids, bryozoans, and rugose corals are common. The reefs on Gotland are mostly composed of pale boundstones, often with a micritic matrix. The colour varies from greenish to brownish-reddish. However, depending on the local environmental conditions, the composition, size, and structure of single reefs can vary considerably. Inter-reef strata may vary in composition from traction deposits such as cross-bedded skeletal and/or crinoidal grainstones, to very fine-grained mud- and wackestones. The biostromal areas, which are developed on eastern Gotland, can cover areas of more than 100 km$^2$ (Kershaw 1990; see Calner et al. 2004a, this volume). The biostromes were built mainly by stromatoporoids, which grew densely stacked and interlocking (Kershaw & Keeling 1994). Often, the stromatoporids are tilted, or transported and rounded. The sedimentary matrix between the colonial organisms normally is a grainstone. Truncation surfaces are common indicating high-energy, shallow-water environments, and repeated interruptions of reef growth.

3) *Back-reef and lagoonal areas*. The back-reef facies on Gotland comprises mostly light-brownish, strongly bioturbated mudstones and wackestones, with varying contents of benthic organisms from an impoverished marine fauna. In parts, oncolites are very common. Individual oncoids often show irregular cortices due to periods of stationary growth. The sediments were deposited in sheltered, calm areas behind the reef fringe. In places were the water energy was higher, thin-bedded, fine- to medium-grained grainstones and packstones were deposited, and occasional abraded hardgrounds are observed. In extremely shallow environments, the sediments are characterised by rapid alternations of different rock types, often from bed to bed. Ripple marks and desiccation cracks indicate very shallow water conditions. Correspondingly, the fossil content changes abruptly. Many beds are devoid of fossils whereas others show extremely high abundances of, e.g., rhynchonellid brachiopods, bivalves, or gastropods, but generally with a very low diversity.

A fourth environment, genetically unrelated to the platforms, is represented by the volumetrically less important mud-, silt-, and sandstones 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 units contain a marine fauna, although in certain intervals strongly impoverished (e.g. Stel & de Coo 1977). The siliciclastic material was derived from western source areas. Sedimentary structures like cross bedding, flute marks, tool marks, ripple marks and hummocky cross stratification indicate periods of rapid deposition.

Bentonites are a scientifically very important component of the strata. Several are found through the successions of the När-1 and Grötlingbo-1 cores but are in outcrops as yet only known in the Llandovery and the Wenlock. At least some of them caused beautifully silicified fossils (Laufeld & Jeppsson 1976; Stridsberg, 1985; Liljedahl 1991; Cherns & Wright 2000). The bentonites are also important for the Silurian radiometric time scale (Odin et al. 1986) and have been used in studies of the global bolide-impact frequency (Schmitz et al. 1994). They have been fingerprinted as an aid for long distance correlations (Batchelor & Jeppsson 1994, 1999), and have been used for intra-basinal high-resolution correlations Jeppsson & Männik 1993; Jeppsson & Calner 2003; Calner et al. 2004b).

### *1.2.3 Sequence stratigraphy*

Sequence stratigraphy is the study of stratal relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by unconformities. Sequence stratigraphical concepts have evolved tremendously over the years, and more recently they have been modified for ancient carbonate basins, which respond to relative sea-level change in a fundamentally different way from their siliciclastic counterparts. Since the early 1980's, sedimentologists and stratigraphers have conducted basin analysis by utilizing sequence stratigraphical concepts, considering relative sea-level changes to be the primary control on the facies architecture of basin fills and on the stacking pattern of depositional systems such as carbonate platforms. Unfortunately, global eustatic sea level changes are strongly invoked in sequence stratigraphy, despite the fact that true sea level change is not required to form depositional sequences (Burgess 2001). In stacked carbonate sequences, such as those on Gotland, the influence of a changing sea level can be unambiguously identified only if subtidal successions are capped by subaerial exposure surfaces (Burgess 2001), proven, e.g., by carbonate cements precipitated from freshwater. However, many features previously thought to be typical of freshwater diagenesis are now also known to originate during shallow marine burial diagenesis (Melim et al. 1995, 2002), and subaerial exposure surfaces often are difficult to distinguish from submarine hardgrounds.

A detailed sequence stratigraphic framework for the Silurian of Gotland remains to be established. However, a few comments on the relationships between the exposed strata and relative sea level change can be made. Pure limestone units, especially those including reefs, enclosed

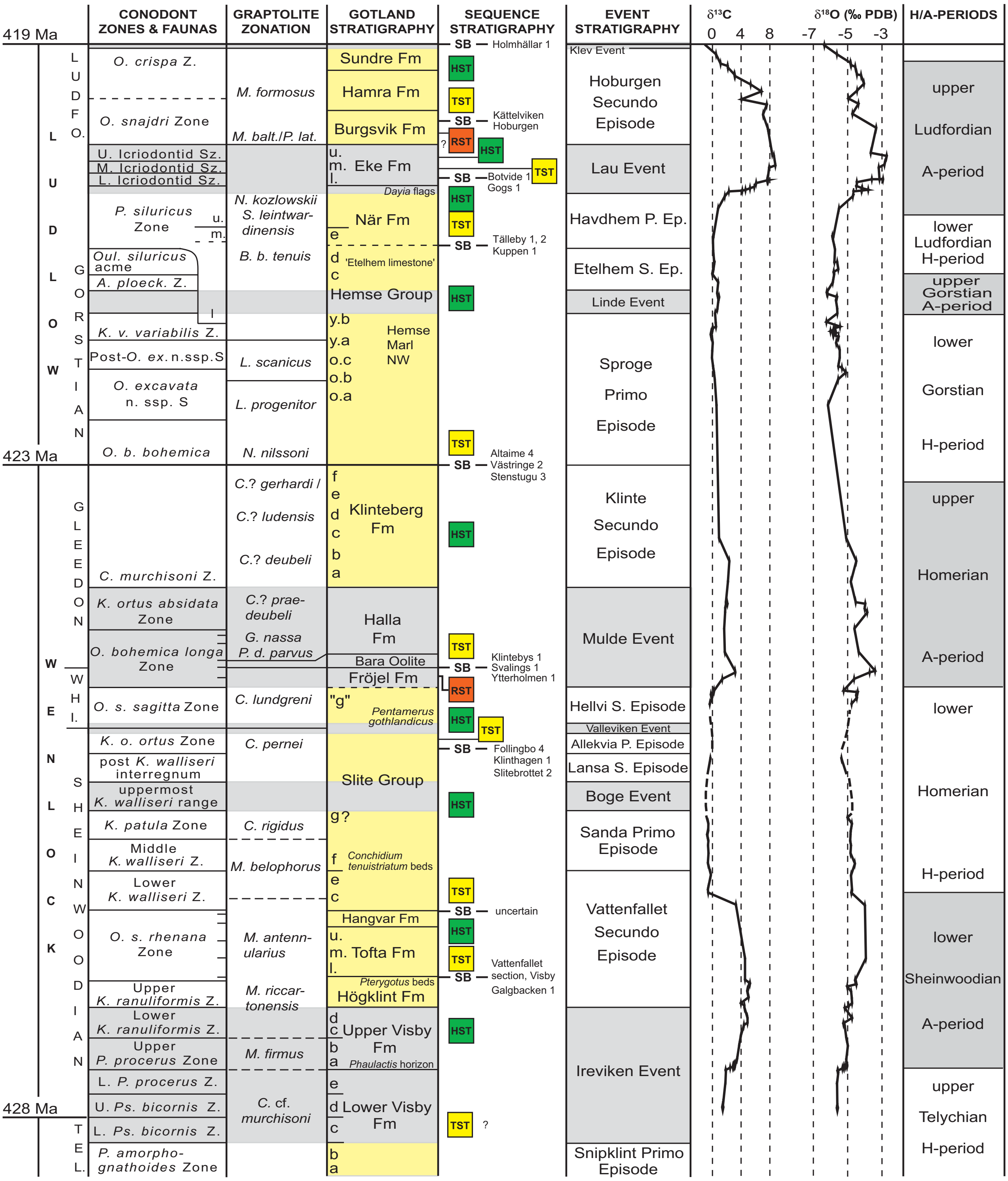


Fig. 3. Stratigraphic framework showing conodont zones and faunas and their relationship to graptolite biostratigraphy, stratigraphic units on Gotland, and a provisional sequence stratigraphic framework for the exposed strata. Also shown is the episodes and events of Jeppsson (1998) and Jeppsson & Aldridge (2000), and development of stable carbon isotopes and H/A-periods of Bickert et al. (1997), Samtleben et al. (2000), and Munnecke et al. (2003). The figure is partly based on stratigraphic data from Jeppsson (1997c) and Jeppsson (in manuscript), Calner (1999), and Calner & Jeppsson (2003).

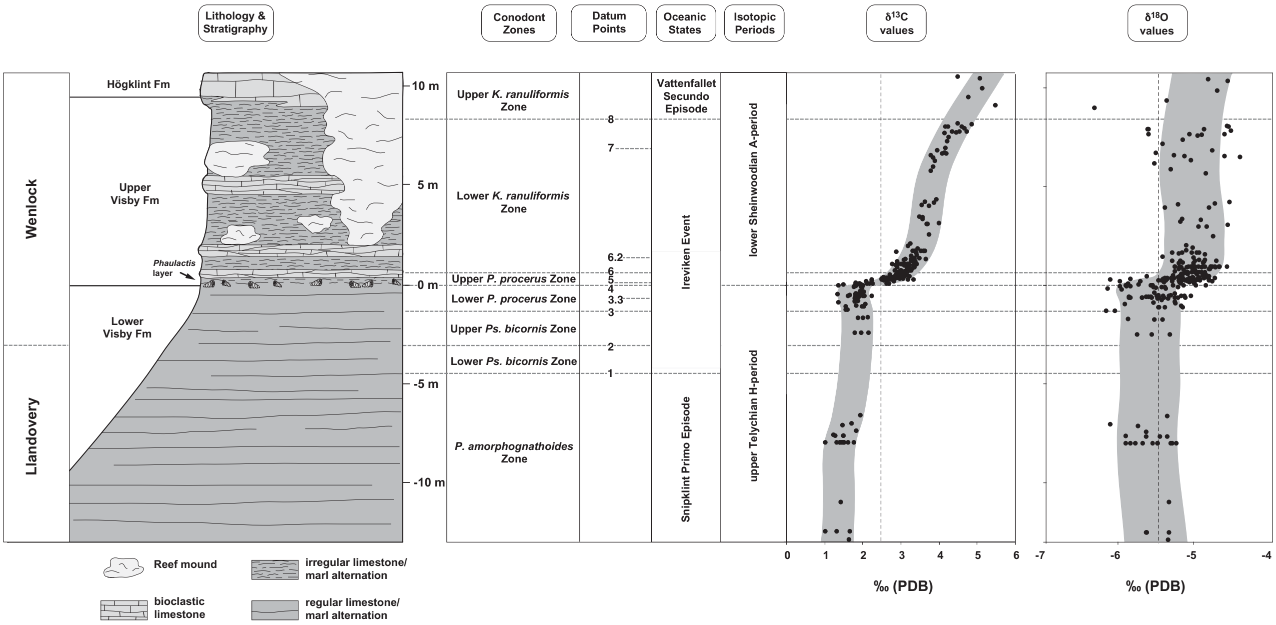


Fig. 4. Combined diagram of schematic weathering profile of the Lower and Upper Visby Formation (after Samtleben & Munnecke 1999), conodont zonation and extinction datum points (after Jeppsson et al. 1994; Aldridge et al. 1993; Jeppsson, 1997a, c), and δ18O and δ13C values (compiled from 9 localities, Munnecke et al. 2003).

in marls are surprisingly often taken as an indication of sea level lowering, because only the local (regressive) facies succession is considered. The discrimination of *depositional depth* and *true sea level change* is therefore of major importance in carbonate basins. Carbonate and siliciclastic basins respond fundamentally different to relative sea-level change. The different responses are inherited from the basic fact that siliciclastics are transported *to* the basin whereas carbonates form *in situ*, i.e., *within* the basin. In contrast to the siliciclastic depositional system, carbonate platforms produce and deposit most of their sediments during highstand situations (Schlager et al. 1994). This is primarily due to the increased areal extent of platform flooding and the associated increase in space available for skeletal carbonate production. This is well illustrated on Gotland. Here, the expansion and thickening of reef complexes across distal platform marls imply that reef barriers formed during relative highstand of sea-level (Calner & Jeppsson 2003). Such substantial progradation of reef complexes onto argillaceous limestone and marl deposited in deeper, distal settings can be seen e.g. in the Lower Wenlock north of Visby and in the Late Wenlock of the Klintehamn area. Further, substantial falling stage or lowstand deposits are rare in the majority of intracratonic carbonate platform successions, and also on Gotland. This is partly due to the comparably modest relief of carbonate basins. The siliciclastic-rich Gannarve Member (Fröjel Formation) on western Gotland (section 2.3.1) is an example of such deposits (Calner 1999).

At this stage, the cyclic development of barrier reef complexes, unconformities (including subaerial exposure surfaces), and general facies trends permit establishing only a provisional sequence stratigraphic framework (Fig. 3). Based on onshore mapping (Manten 1971) and offshore seismic reflection studies (Flodén et al. 2001; Bjerkéus & Eriksson 2001), ca 10 more or less well developed barrier reef complexes evolved during Wenlock–Ludlow time. If the ICS time scale is applied, individual cycles range over ca 1 Ma. If utilising barrier reefs as indicators of highstand systems tracts, this would indicate that the strata on Gotland correspond to about ten more or less developed depositional sequences. The successive dislocation of reef complexes towards the basin-centre implies a forestepping sequence stacking, i.e. that lateral infilling of the basin was important, and thus the creation of accommodation space (subsidence rate) was limited.

## 2. GENERAL LITHOLOGY AND A REVISED BIOSTRATIGRAPHIC FRAMEWORK

Traditionally, studies on Gotland geology rely heavily on the stratigraphic framework of Hede (1921, 1925, 1960) who, based on many seasons of careful mapping, subdivided the succession into thirteen formations and groups, from oldest to youngest: Lower Visby, Upper Visby, Högklint, Tofta, Slite, Halla, Mulde, Klinteberg, Hemse, Eke, Burgsvik, Hamra, and Sundre. This framework has successively been refined and revised. Based on large conodont collections, a detailed conodont zonation and stratigraphic subdivision is now possible, e.g. for the late Telychian – early Homerian (Jeppsson 1997c; in prep.), middle Homerian (Calner & Jeppsson 2003), Gorstian – early Ludfordian (Jeppsson & Aldridge 2000; Jeppsson, in prep.), and for the late Ludfordian – early Pridoli (Jeppsson, in manuscript; in prep.); data below are from these sources unless references are given. The stratigraphic resolution of conodont zones in carbonate strata is comparable to that of the most detailed graptolite zonation in shale successions. An updated and substantially constrained stratigraphic framework is soon to be published and the most important changes are reviewed below and illustrated in Figures 2 and 3.

## 2.1 Lower and Upper Visby formations

### *2.1.1 Lithology*

The Lower and Upper Visby formations form the oldest outcropping units on Gotland. These two formations are developed as a prograding limestone-marl alternation. The exposed part of the Lower Visby Formation consists of up to 12 m (at Lusklint 1) of fossil-poor, regular alternations of 2-5 cm thick, wavy-bedded to nodular argillaceous limestones (predominantly mudstones) and roughly 10 cm thick marls. The base is not exposed. The carbonate contents of the marls scatter around 20%, those of the limestones around 70% (Munnecke 1997). In some areas, up to 1 m thick *Halysites*-biostromes are observed. Thin layers of brachiopod and bryozoan debris are intercalated irregularly. The sequence was deposited below storm wave base and below the photic zone in a distal shelf environment. There are three distinct bentonites in the Lower Visby Formation: the Lusklint, the Storbrut (very thin), and the Ireviken bentonites (Batchelor & Jeppsson 1994).

The Upper Visby Formation is up to 12 m thick. Bedding is not as regular as in the Lower Visby Formation. The limestone-marl ratio increases, and detritic limestones (wacke- to grainstones) become more abundant, especially in the upper part of the formation. Erosional surfaces, ripple marks, and calcareous algae point to increased water energy and a depositional environment within the photic zone. Carbonate content is considerably higher than in the Lower Visby Formation, averaging 80% for limestones and 40% for marls (Munnecke 1997). The abundance of brachiopods, bryozoans, crinoids, tabulate corals, and stromatoporoids increases. The Upper Visby Formation contains numerous reef-mounds, ranging in size from a few decimetres to many metres. The main reef builders are tabulate corals, but also stromatoporoids and rugose corals.

### *2.1.2 Biostratigraphy*

Conodonts show that Hede's (1921) definition of the boundary between the Lower and Upper Visby Formations coincides with a faunally important boundary, Datum 4 of the Ireviken Event (now identified globally). This datum coincides with a pronounced increase of $\delta^{13}C$ values and a distinct lithological boundary that is identifiable in the field (Fig. 4). There are four important criteria for a correct identification of the boundary: 1) In places where active erosion is moderate, the Lower Visby Formation weathers to a clay-covered slope. In 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 angusta* (Lonsdale), det. Keith Mitchell 1990, a very large solitary rugose coral, had a mass occurrence in the basal bed of the Upper Visby Formation and this marker-horizon can be traced along a distance of over 50 km (Mitchell 1990; Samtleben et al. 1996; Jeppsson 1997a, c; see Plate 1 in Munnecke et al. 2003). 4) A thin layer of pyrite marks the exact boundary; where it is within a limestone bed, the pyrite may be seen as a sparse line of specular pyrite crystals, whereas it has weathered to a rust layer in marls. Previous confusion and reports of fossils on the 'wrong side of the boundary' are due to inconsistent use of Hede's definition, even in the geological map descriptions. The only exception hitherto is a single report of *P. porpita* in the Upper Visby Formation (Sheehan 1977).

Conodont correlations with the type locality show that the Llandovery-Wenlock boundary coincides with Datum 2 of the Ireviken Event (Jeppsson 1997c). Therefore, at Lusklint 1 for instance, up to ca 10.1 m of the Llandovery is exposed on Gotland.

## 2.2 Högklint, Tofta, and Hangvar formations

### *2.2.1 Lithology*

The up to ca 35 m (Hede 1960) thick Högklint Formation is well exposed along the NE coast of Gotland, and the spectacular patch-reefs along that coast belong to this formation. The unit is a reef-complex, composed of large patch-reefs and inter-reef limestone (Hede 1940; 1960; Manten 1971; Riding & Watts 1991; Watts & Riding 2000). The most abundant reef-builders are stromatoporoids, along with tabulate corals, calcareous algae, and cyanobacteria. The formation can be subdivided into four subunits (a-d). The two lower units include large bioherms, while the upper parts (upper b and c) are dominated by biostromes. The top of subunit c is an unconformity, only locally overlain by subunit d.

The Tofta Formation is at least ca 15 m thick and bounded by unconformities throughout much of the outcrop area. It consists of thin to thick bedded limestone rich in oncoids (calcifying cyanobacteria and problematica), and reflects deposition in a restricted, marginal marine environment (Hede 1940, Riding & Watts 1991).

A new formation, the Hangvar Formation, is to be introduced between the Tofta Formation and Slite Group (Figs. 2, 3). It similarly includes marls as far SW as near Paviken (previously Slite Marl), limestones S to NE of Visby (previously Slite Beds, units a and b) and north-eastwards across Fårö (previously Högklint Beds). A distinct reef generation occurs within this interval, low in the Hangvar Formation, or possibly in the upper Tofta (the spectacular sea stacks on northern Fårö probably represents this formation). The combined thickness of the Tofta and Hangvar Formations exceeds 20 m.

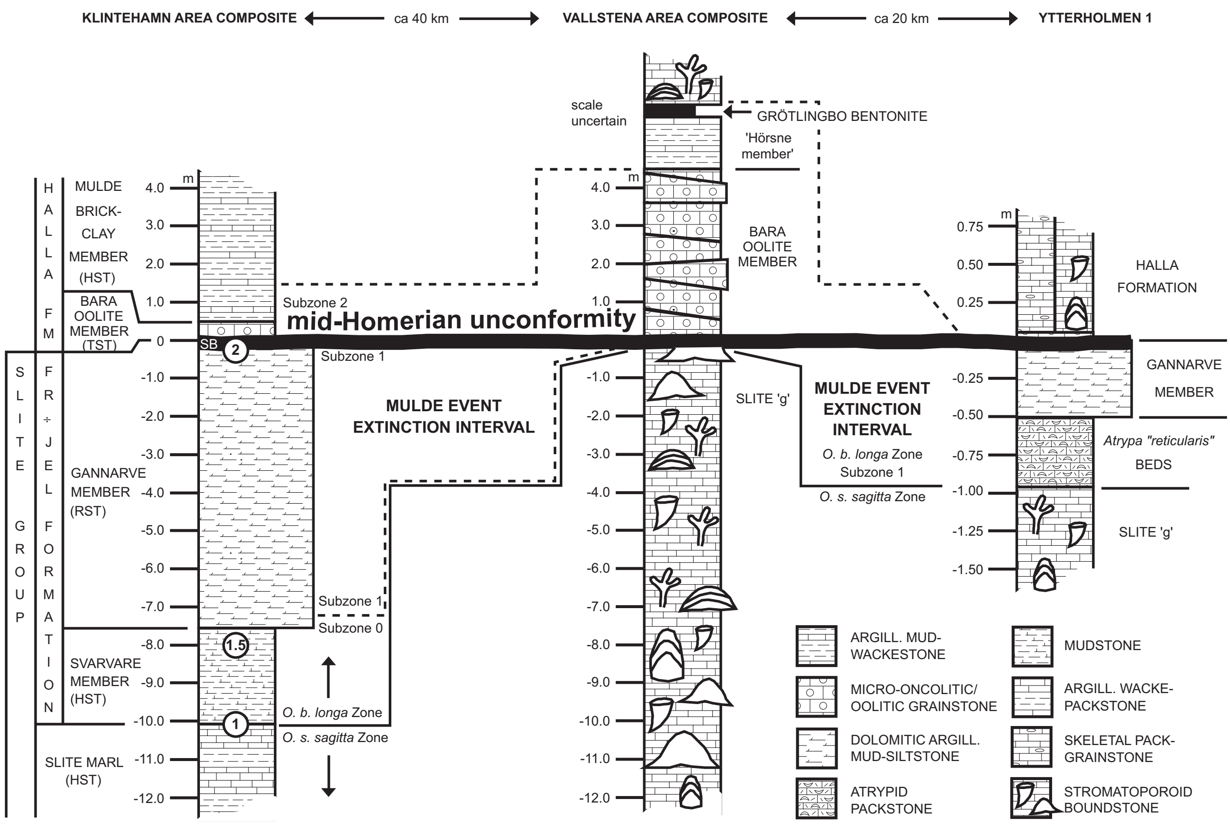


Fig. 5. General facies associations and stratigraphic correlation of the Slite Group–Halla Formation across Gotland. Thickness data and sequence stratigraphic subdivision in the Klintehamn area composite are from Calner (1999). The numbers 1, 1.5 and 2 in the Klintehamn composite profile indicate the three datum planes (points of extinction) of the Mulde Event identified by Jeppsson & Calner (2003). SB = sequence boundary, HST = highstand systems tract, RST = regressive systems tract, TST = transgressive systems tract. From Calner et al. (2004).

### *2.2.2 Biostratigraphy*

Establishing and applying a sequence of subzones of the *O. s. rhenana* Zone solves the old problem regarding the relation between the Högklint and the Tofta Formations. The previously assumed large gap between Högklint c and Slite c on Fårö and parts of main Gotland does not exist. The true Högklint Formation is found in a narrow strip along the coast, north-eastwards as far as Kappelshamnsviken (Fig. 2), only. The Tofta Formation ranges from marls in the SW (previously mapped as Slite Marl) and limestone northeast thereof (all the strata previously included in the Tofta), reaching across Kappelshamnsviken as far as to Fårö (previously included in the Högklint Beds). Lower, middle and upper parts of the Tofta Formation can be separated as far as they are exposed. Tofta is rich in algal limestone, and at least parts of the strata now identified seems to be so too, e.g. oncolites appeared between strata identified as upper Högklint and lower Tofta, respectively, at a recently identified section on the western shore of Kappelshamnsviken.

These conodont-based stratigraphic revisions also remove the discrepancy in the chitinozoan ranges on Gotland and in East Baltic cores (Nestor & Einasto 1997), and the chitinozoan zonation of Nestor (1994) can now be recognised on Gotland and correlated with the conodont zonation.

## 2.3 Slite Group and the Halla and Klinteberg formations

### *2.3.1 Lithology*

The Slite Group is exposed over a large area on northern mainland Gotland and on Fårö (Fig. 2). It is a complex and lithologically highly variable unit. The lower part, some 20 m thick (Hede 1960) is dominated by relatively pure limestone along most of the strike. This is followed by more limestones and above that, marls across Gotland. The uppermost formation of the Slite Group is the Fröjel Formation (Calner 1999). This formation is 9-11 m thick in the Klintehamn area and 0.5 m thick on NE Gotland (Ytterholmen). The formation is absent between these areas, but its former presence here is revealed by a residue micro-conglomerate in the basal centimetres of the overlying Halla Formation (see below). In the Klintehamn type area, the formation is subdivided into two members. The Svarvare Member is a 2-3 m thick, slightly calcareous mudstone that differs fundamentally from the underlying Slite Marl in its dark colour, comparably sparse bioturbation, and the lack of stromatoporoids, tabulate corals, and regularly alternating marls and limestone. This member includes an interval with an abundant but low-diversity graptolite fauna. The overlying Gannarve Member is characterised by shallowing associated with storm-dominated deposition of fine (silt-fine sand) siliciclastics across the platform. This member shows a rapid facies transition from laminated mudstone and siltstone, locally with graptolites, in its lower parts to hummocky cross-stratified strata, and eventually to intertidal epikarst at the upper boundary, where it is unconformable with overlying sediments (Calner 1999; 2002). The upper boundary of the Slite Group is a basin-regional unconformity that truncates different units along strike; the Fröjel Formation in the southwest (Klintehamn area and the Hunninge-1 core) and northeast (Ytterholmen), as well as between these areas; the Slite "g" or the *Atrypa "reticularis"* Beds depending on the extent of erosion (Fig. 5; Calner et al. 2004).

The Halla Formation rests on the mid-Homerian unconformity, and reflects the initiation of a new platform generation. The basal Bara Oolite Member is a transgressive peloidal oolite or micro-oncolitic grainstone formed in the shallow subtidal to intertidal environment. The unit is exposed in a narrow belt across most of the island, thinning from ca 4.5 m on east-central Gotland (Bara area) to ca 0.3-0.5 m in the Klintehamn area on west-central Gotland, where it pinches out. On eastern Gotland, the oolite is overlain by argillaceous limestone with small reefs and back-reef lagoonal, oncoidal packstone. Coeval strata on western Gotland were formed in deeper water and consist of argillaceous limestone and marl.

The Klinteberg Formation is a ca 70 m (Hede 1960) thick unit predominantly composed of crinoidal limestone and, especially in its upper parts, biohermal and biostromal limestone (Frykman 1989). Several metres thick, crossbedded units of crinoidal pack-, and grainstone are common throughout this unit. On eastern and central Gotland, the top of the formation is a conspicuously smooth unconformity with abundant clear-cut stromatoporoids, some of them more than one metre in diameter (Eriksson, in press). This unconformity is situated a few metres below the traditional stratigraphic level for the top of the Klinteberg Formation (Hede 1929).

*2.3.2 Biostratigraphy*

Conodont biostratigraphy permits splitting the Slite Group into at least 5 faunally and lithologically distinct formations. The Homerian succession of Gotland starts high in the Slite Group, that is, with the youngest Slite limestone and reef generation in the east (unit "g" of Jeppsson et al. 1994), and in the upper Slite Marl in the west. Revisions and refinements of the uppermost Slite – lowermost Klinteberg stratigraphy have been published by Calner & Jeppsson (2003), and Calner et al. (2004).

The overlying Halla Formation now includes also parts of the former Mulde Formation, a name introduced by van Hoepen (1910). Hede (1925) restricted it to strata on western Gotland, and extended it to include some immediately older and younger strata. Jeppsson & Calner (2003) divided his Mulde into three members: the Mulde Brick-clay Member, the Djupvik Member, and the informally named 'kronvald member', the latter forming a lateral facies equivalent to the more proximal parts of the Klinteberg Formation (cf. the map of Hede 1921). The former two members form distal equivalents to parts of the Halla Formation and therefore were included in that formation. For data on these and adjacent units, see Hede (1927a, b), Calner (1999), Calner & Säll (1999), Calner et al. (2000), and, in particular, Jeppsson & Calner (2003) and Calner & Jeppsson (2003).

The lowermost Klinteberg Formation includes a highly characteristic conodont fauna, the *C. murchisoni* Zone. The topmost Klinteberg includes another highly characteristic conodont fauna, with *Erika* cf. *divaricata*. Both faunas have hitherto been traced from eastern shore exposures to 5 km or less from the western coast. The faunas of the strata in between the *C. murchisoni* and *E.* cf. *divaricata* faunas, i.e. the major part of the Klinteberg Formation, are less well characterised, but each of the two distinct faunas refute the suggestion that the Wenlock-Ludlow boundary cut obliquely across the Klinteberg Formation (Bassett 1976, p. 216).

## 2.4 Hemse Group and the Eke, Burgsvik, Hamra and Sundre formations

*2.4.1 Lithology*

The Ludlow sequence of southern Gotland includes a wealth of rapidly changing lithofacies spanning from marlstone deposited below storm wave-base to oolites and stromatolites of intertidal origin, as well as local karst development and flat-pebble conglomerates.

The Hemse Group rests unconformably on the Klinteberg Formation, at least in central and eastern Gotland. On a broad scale, the western parts of the outcrop belt are dominated by marl and argillaceous limestone whereas shallow platform carbonates dominate the eastern parts. The eastern area is characterised by well exposed, stacked biostromes dominated by stromatoporoids (Kershaw & Keeling 1994; Samtleben et al. 2000; Sandström & Kershaw 2002). The När Formation (= the upper Hemse Group) consists of argillaceous, often laminated limestones and marls in the west and central parts of the outcrop belt and crinoidal limestone and reefs in the east (the Millklint Limestone of Hede, 1929). In the laminated deposits benthic fossils are nearly absent, except for coquinas with *Dayia navicula* (brachiopod), for which a pseudoplanktonic mode of life is discussed (Samtleben et al. 2000). The lamination and the very sparse occurrence of benthic fossils indicate unfavourable (probably anoxic or dysoxic?) bottom water conditions. The upper boundary of the Hemse Group is a discontinuity surface throughout the central and eastern parts of the outcrop belt.

he Eke Formation shows substantial changes in thickness and facies across its outcrop area. In the southwestern parts (Uddvide-1 and Ronehamn-1 cores), the formation is remarkably homogenous with regard to facies and thickness (ca 12.0-12.5 m thick) and composed of a shoaling succession of oncoid-rich wacke-, pack-, and grainstones, interbedded with marls. The oncoids generally have thick cortices, variable shapes, and co-occur with a diverse marine benthic fauna. In the Uddvide-1 drillcore, the lowermost part of the unit is composed of argillaceous crinoidal wackestone lacking oncoids. In the area of the Burgen outlier (Burgen-1 core), the formation thins substantially (Calner & Eriksson, in prep.). In the northeasternmost parts of the outcrop area, the Eke Formation consists of argillaceous biohermal accumulations and coarse-grained crinoidal grainstones and rudstones. Here, the lower parts of the formation exhibit karst features and stromatolites (Cherns 1982).

The Burgsvik Formation is the only coarse grained siliciclastic lithosome in the Ludlow of Gotland. Hede (1921) subdivided the Burgsvik Formation into the Burgsvik Sandstone and an overlying Burgsvik Oolite. Only the middle and upper parts of the formation are well exposed in coastal exposures and abandoned quarries on southernmost Gotland. The entire stratigraphy of the formation, including the lower parts, is today only represented in the Uddvide-1 core. In this core, the Burgsvik Sandstone is 31.12 m thick and consists of three primary lithofacies. The lower unit consists of dark shale and mudstone with rare fossils. The middle unit consists primarily of massive to laminated siltstone with abundant dewatering structures. The upper unit consists of 1-2 m thick bedsets of massive to laminated sandstone. Correlation to nearby exposures shows that the lamination in the upper member is related to large scale hummocky cross stratification. The conspicuous upper boundary of the Burgsvik Sandstone can be traced in outcrops and in the subsurface for ca 25 km, from Hoburgen to the area of Uddvide. The boundary is generally sharp and planar erosive but, in places, slightly irregular. This surface is overlain by the Burgsvik Oolite, which especially in the upper part is an oncolite rudstone with ooid-grainstone matrix. As with the Eke Formation, the Burgsvik Sandstone thins markedly towards the northeast. A west-east transect across southern Gotland shows the large-scale facies relationship, including two sandstone wedges separated by argillaceous platform carbonates.

The basal Hamra Formation consists of algal limestone with small bioherms. Bioherms and crinoidal limestones comprise the bulk of the formation.

The ca 10 m thick Sundre Formation is built by thick-bedded, coarse-grained crinoidal grainstones and massive stromatoporoid reef limestones.

*2.4.2 Biostratigraphy*

The Hemse Group can also be subdivided using conodonts (Jeppsson, in prep.). The Ludfordian uppermost Hemse – Burgsvik sequence on Gotland includes more substantial and more rapid facies changes than most older and younger intervals. A revised conodont zonation includes three zones, 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 (Jeppsson, in prep.). It permits the first high-resolution correlations across the island, and a more detailed stratigraphic subdivision of the strata. The Millklint Limestone, the main (unnamed), and the Botvide members of the När Formation (new formation, the upper part of the Hemse Group), the lower, middle, and upper Eke Formation, and the Burgsvik Formation are distinguished, resulting in a considerable increase in stratigraphic precision. Calculations based chiefly on biostratigraphic data from the När and Burgsvik cores, and the Vamlingbo drilling (Munthe 1921), indicate that the Ludlow strata on western Gotland are between 337 and 425 m thick instead of the 215 m given hitherto (Jeppsson, in prep.). New larger conodont collections from the Hamra and Sundre Formations indicate that a better stratigraphy of that interval is feasible and that the succession reaches at least to the top of the Ludlow.

## 3. EVENT STRATIGRAPHY AND STABLE ISOTOPES

*3.1 Event stratigraphy*

Event stratigraphy and its relation to changing oceanographic conditions is a topic that attracts much scientific attention today. This stratigraphical approach utilizes patterns of biotic extinction, innovation, and recovery among different lineages of taxa to delineate the architecture of biological extinctions. Although the majority of the major Phanerozoic extinction events are close in time to eustatic sea-level change (Hallam & Wignall 1999), extinctions do not correlate with the formation of sequence boundaries in individual basins, simply because different basins have different tectonic histories that may mask or enhance sea-level change. Nevertheless, it has been common to follow sequence stratigraphical concepts and identify sequence boundaries as important levels for past extinctions. The risk of pigeon-holing is obvious since stratigraphic resolution has often been far too low for identifying true ends of taxa, e.g. due to the Signor-Lipps effect, or as a result of sampling errors. The collection size and sampling density are of fundamental importance for a reliable stratigraphy.

*3.1.1 Oceanic and climatic cycles*

As recent as in 1991, Boucot concluded that no mass extinction had occurred during the Silurian. This (incorrect) conclusion was due to inadequate precision even in the best correlations of Silurian carbonate sequences – where most known taxa are found. The successively improved conodont zonation remedied this situation, and the first Silurian events were found.

An empirical model connected all of the then known changes during two Silurian cycles to a single cause;

transitions in oceanic state (Jeppsson 1990). The model describes two possible oceanic states with initially stable oceanic conditions, and how these gradually became destabilised. Among the many characteristics of the episodes it may be mentioned that 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. Some general characteristics of the oceanic model are summarised in Fig. 6.

The differences between primo and secundo episodes were so large that stable carbon isotope differences were also predicted (Jeppsson 1990). Since the publication of this model it has become clear that primo episodes are associated with low stable isotope ratios while secundo episodes are associated with high stable isotope ratios and isotopic excursions (Talent et al. 1993; Samtleben et al. 1996, 2000; Wenzel & Joachimski 1996; Wenzel 1997; Saltzman 2001; see chapter 3.2).

Events – brief intervals with unstable oceanic conditions – can develop after the end of an episode, causing both transient faunal changes and extinctions (even mass extinctions), as well as sedimentary and isotopic effects. Most importantly, this model can be tested: it predicted then unknown effects, e.g. where to search for Lazarus taxa. Some indications were found quickly (Jeppsson 1997) and confirmed with larger collections (see figure 3 in Jeppsson 1998). The model describes four potential kinds of events with different characters (Jeppsson 1998a). Two kinds of events were known then during the Wenlock and Ludlow, and a secundo-primo event has since been found (Jeppsson & Aldridge 2000) but the search for an example of primo-primo events continues. This part of the model has been very useful in the field, predicting where a more detailed collecting effort should reveal unknown events. Most of the minor events had only, or mainly, transient faunal effects, and can not be detected by comparing faunas from before and after the event. Their lithological effects were however, typical (and revealed their existence) although less widespread (Jeppsson 1993, 1998; Aldridge et al. 1993; Jeppsson et al. 1995; Jeppsson & Aldridge 2000).

Three major Silurian events were detected (Jeppsson 1993). In addition to faunal and sedimentological changes, these also resulted in higher $\delta^{13}C$ values (see chapter 3.2). These three events have already been detected in over 50 areas using conodonts, graptolites, and stable isotopes, from Alaska to Australia.

Finding the cause of an event must start with studying the sequence of changes during the event. This requires a much higher stratigraphic resolution for the event interval than needed to find the event. A five fold increase in the resolution and precision of the intervals containing the three major events has now been achieved (Jeppsson 1997c; in manuscripts; Calner & Jeppsson 2003). High-resolution stratigraphy has revealed that conodont extinctions during these events were stepwise (Jeppsson 1997a, c, in prep.; 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, chiefly the response of surviving taxa, permitting comparison of the severity (as felt by the conodonts) of different events and datum points (Jeppsson 1998). In contrast, extinction percentages are not fully comparable since the biota at the start of two events or at the onset of two datum points differ from each other. Faunal and sea level changes, as well as the sedimentary succession during the events fit well with predictions based on the oceanic model. Extinctions were caused by brief severe drops in primary planktic productivity, causing starvation among planktic larvae (Jeppsson 1990).

### *3.1.2 The Ireviken Primo-Secundo Event*

On Gotland, the start of this event is recorded in the upper part of the Lower Visby Formation, with its end near the top of the Upper Visby Formation. Like the Mulde and Lau events (reviewed below), this event reached a severity of 6.2, the highest point on the severity scale yet defined (Jeppsson 1998). It lasted ca 0.2 Ma but nearly all extinctions took place during the first 0.1 Ma (Jeppsson 1997a). Conodont extinctions during the Ireviken Event were stepwise and literature data have permitted most steps to be identified globally (Jeppsson 1997a, c). Datum points 2 and 4 had the strongest effects. The rare literature data with a similar precision and resolution of other major clades show the same pattern. The total effects on the fauna were large, e.g. 80 % of the globally known conodont species disappeared (the highest percentage perished at Datum 2; Jeppsson 1998), and over 50 % of the trilobites on Gotland (Ramsköld 1985) at or very close to Datum 2. If other major clades turn out to have been hit similarly, the extinction percentage would be comparable with the weaker ones of the so called 5 big mass extinctions. The fact that the Ireviken Event remained unknown until recently illustrates well the previous state of the correlation of Silurian carbonates. Extinctions have hitherto been identified among conodonts, graptolites, brachiopods, corals, ostracodes, and polychaetes. As expected from the model, conditions during this (and other) primo-secundo event deteriorated stepwise whereas the recovery at the end of the event was fast.

This part of the sequence on Gotland is deposited in deeper water than most other parts (Gray et al. 1974), and no spectacular sequence of sedimentary changes has been identified there. Like in many other areas, marls dominated before the event and reef boundstone and associated sediments after the event. $\delta^{13}C$ values begin to increase during the Ireviken Event, marking the onset of the early Sheinwoodian (basal Wenlock) positive carbon isotope excursion (Talent et al. 1993; Samtleben et al. 1996; Bickert et al. 1997; Munnecke et al. 2003; Cramer & Saltzman, submitted).

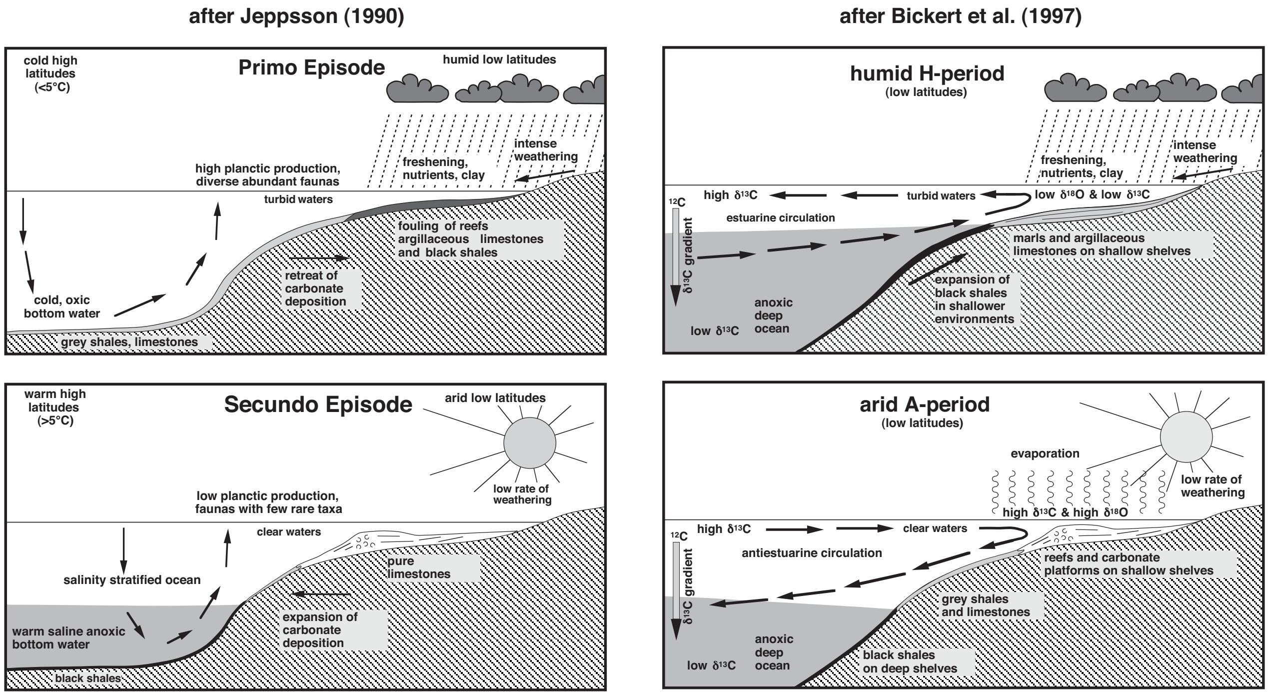


Fig. 6. Palaeoceanographic/climatic model of humid and arid periods in the Silurian, simplified after Jeppsson (1990) (left) and Bickert et al. (1997) (right). Bickert et al. (1997) have modified the Jeppsson model with respect to isotope geochemistry and oceanic circulation and restricted their model to low latitudes.

### *3.1.3 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 following brief review is partly based on Jeppsson & Calner (2003) unless indicated: Major graptolite extinctions during the middle Homerian (Late Wenlock) were observed and discussed before any other effect of a Silurian event had been described (Jaeger 1959). Historically, the Wenlock/Ludlow boundary had been placed at the point where the last of the doomed graptolites disappeared. The Wenlock /Ludlow boundary in graptolite facies was taken at this level until graptolite finds in the type area showed that the Wenlock Limestone Formation belonged in a younger zone. Laufeld et al. (1975, p. 220) found that the evidence available at that time indicated 'a world-wide event of great ecologic significance'... 'a regression caused by glaciation'. Application of the model of oceanic and atmospheric changes (Jeppsson 1990) showed that this interval is an oceanic event, the Mulde Secundo-Secundo Event (Jeppsson 1993; Jeppsson et al. 1995). 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 $C_1$ (figure 6 in Urbanek 1970, 1993) = the *lundgreni* Event (Koren´ 1991) etc.]. This correction, for the first time, tied extinctions among benthic taxa to this event. The event lasted ca 0.35 Ma but nearly all extinctions took place during the first 0.06 Ma (during datum points 1, 1.5, and 2). Graphic correlation using graptolites and conodonts has provided a high-resolution timescale for correlating from coastal to deep oceanic sections and, thereby, also a detailed record of the sequence of changes during the Mulde Event (Jeppsson & Calner 2003). The identified sequence of changes includes, in order of the onset: two extinctions (Datum points 1 and 1.5), a $\delta^{13}C$ increase of ca 3‰ (Samtleben et al. 2000), 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. Published detailed records indicate that most of the graptolite species perished well before Datum 2, probably at Datum 1, like most of the expiring conodonts did. Literature data indicate considerable extinctions among chitinozoans (Nestor 1994, fig. 20/4) and shelly faunas (e.g. Hede 1921, p. 51-52), but as yet these have not been fully studied. Datum 2 reached a severity of 6.2 on the severity scale. As predicted by the model (Jeppsson 1998), conditions during this secundo-secundo event reached the low point quickly and then improved slowly during the main part of the event. The first two extinction steps and the first lithological and isotopic changes predated the onset of sea level change, falsifying a popular explanation for many events, that sea level changes caused the mass extinctions. The major sea level drop was hence "only" another effect of the oceanic disturbance, not the cause of the extinctions. A minimum amplitude of the drop (16 m) was measured, and the maximum amplitude and approximate duration (in the order of 30 ka) calculated; these fit well and only with a glaciation (previously, Silurian sea level cycles had usually been drawn as smooth curves with a 'wave length' in the order of 0.5 to several Ma.). Temporal resolution is now high enough to permit some comparison with Quaternary glaciations.

In addition to the global identification of extinctions of the last of the expiring graptolites at Datum 2 in graptolite successions, biological and physical effects of the Mulde Event have now been identified in shallower successions on Gotland (Jeppsson et al. 1995; Calner 1999; 2002; Calner & Säll 1999; Calner et al. 2000; Calner & Jeppsson 2003; Jeppsson & Calner 2003; Calner et al. 2004), Britain (Jeppsson et al. 1995), Bohemia (Kríz 1992:16; Kríz et al. 1993; Jeppsson et al. 1995), Estonia (Nestor 1997), Nevada (Berry 1998), Arctic Canada (Lenz & Kozlowska-Dawidziuk 2001), and preliminarily in the central USA (Mikulic & Kluessendorf 1999; Calner et al. 2001). Previously described local effects can now thereby be placed into a broader context. 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).

*3.1.4 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. The Lau Event caused considerable extinctions and other faunal changes. Effects have hitherto been found in acritarchs, chitinozoans, corals, polychaetes, brachiopods, ostracodes, trilobites, tentaculites, graptolites, conodonts, and fishes. Imprecise knowledge of range-ends hampers calculation of extinction metrics but a loss, globally, of at least 30 to 50 % of the species seems probable. Among conodonts, no platform-equipped taxon survived. 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, similar to the Ireviken and Mulde events. As during other events studied in some detail, extinctions were stepped. The number of datum points and their exact position has not yet been identified with enough precision. The many changes during the event permit high-resolution correlations, based on conodonts, $\delta^{13}C$, and lithology changes. Across a wide range of different facies the locally typical sediment production was replaced by formation of other, often more unusual sediments. This continued into the immediate post-event time.

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). The zone fossil *Polygnathoides siluricus* became extinct during the early part of the event, identifying the event globally and facilitating the identification of the interval of interest for isotope sampling and other studies.

A positive $\delta^{13}C$ excursion started at the beginning of the event, increased through it, and culminated near its end; its amplitude is up to 9‰ on Gotland. This excursion has been identified – with varying amplitudes - on Gotland (Samtleben et al. 1996; 2000), 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), Oklahoma (Saltzman 2001), and probably in Nevada (Saltzman 2001) – the biostratigraphy quoted fits better with the Linde Event but that needs to be confirmed.

*3.1.5 Other Wenlock and Ludlow events*

Four more events during these epochs have hitherto been identified and named (Jeppsson 1993, 1998; Jeppsson et al. 1995; Jeppsson & Aldridge 2000). An unnamed probable secundo-secundo event spans the Högklint/Tofta boundary (Jeppsson in manuscript). A wellknown effect of the 'mid-Sheinwoodian' Boge Event was the extinction of the conodonts *Kockelella patula* and *K. walliseri*. The Valleviken Primo-Secundo Event spans the base of the Homerian (Jeppsson 1993; Jeppsson et. al. 1995). The *Pentamerus gothlandicus* Layer formed across the island close to, or during a part of this event. The Linde Primo-Secundo Event is found between the *K. v. variabilis* s. str. and *A. ploeckensis* zones (Jeppsson 1993; Jeppsson & Aldridge 2000). The Valleviken and Linde events caused the same kind of lithological changes (although less extensive) as the two known strong primo-secundo events, the Ireviken and Lau events. The Klev Secundo-Primo Event started during the latest Ludlow and ended at or possibly slightly after the beginning of the Pridoli (Jeppsson & Aldridge 2000). No high-resolution study has as yet been conducted on any of these events, hence they are still poorly known. These weaker events were probably also briefer than the three strong ones.

*3.2. Stable C and O isotopes*

Brachiopod shells are considered as the most reliable material for the determination of $\delta^{13}C$ and $\delta^{18}O$ values because they consist of diagenetically stable low-magnesium-calcite, and the shell is secreted in isotopic equilibrium with the ambient seawater (see discussion in Samtleben et al. 2001). Up to now, more than 2000 brachiopods from Gotland have been analysed for stable carbon and oxygen isotopes. Most of these results are published in Samtleben et al. (1996, 2000, 2001), Bickert et al. (1997), and Munnecke et al. (2003), to which the reader is referred. Here, a brief summary of these results and their interpretation is presented.

The Silurian succession on Gotland exhibits three major and one minor positive $\delta^{13}C$ and $\delta^{18}O$ excursions. At present, the three major excursions have been detected from other palaeo-continents indicating global steering mechanisms (Munnecke et al. 2003). The isotope excursions are closely correlated with lithological changes on Gotland (and also world-wide; summarised in Munnecke et al. 2003), and with the development of the conodont communities described above (Fig. 3). In general, times of high isotope values coincide with times of strongly enhanced reef and carbonate platform growth (Upper Visby to Hangvar Formation, Fröjel to Klinteberg Formation, parts of the Hemse Group, upper part of När to Sundre Formations), whereas times of low isotope values are characterised by argillaceous deposits, and strongly reduced reef growth (Lower Visby Formation, Slite Group, large parts of the Hemse Group). The isotope values, however, are not *directly* connected to the carbonate facies, because on Gotland contemporaneous deposits exhibit nearly identical $\delta^{13}C$ values regardless of the local depositional environment (Samtleben et al. 2000). Oxygen isotope values exhibit lower amplitudes but generally show a parallel trend to the $\delta^{13}C$ development, however, in extremely shallow environments on eastern Gotland they have been affected by local changes in temperature and salinity, and therefore show a higher variability than the $\delta^{13}C$ values.

The first excursion, with an increase from less than 2‰ to more than 5‰ in $\delta^{13}C$, occurs close to the Llandovery-Wenlock boundary. The onset of the isotope excursion coincides with the conodont extinction datum 4 (fig. 4), and the high values lasted from the Upper *P. procerus* Zone into the Lower *K. walliseri* Zone. The excursion is correlated with the lithological change from regular limestone-marl alternations of the Lower Visby Formation to the reefmound bearing Upper Visby Formation, and the reef- and/or algal-dominated Högklint and Hangvar Formations. The succeeding parts of the Slite Group are characterised by low isotope values ($\delta^{13}C \approx$ -0.5‰; Fig. 3). In the uppermost Slite Group, $\delta^{13}C$ values increase again from values below 0‰ to more than 3‰ in the Fröjel Formation (Gannarve Mb). High but more or less continuously decreasing values are observed in the succeeding Halla and Klinteberg Formations. Thus, the excursion ranges from the *O. bohemica longa* Zone to the *C. murchisoni* Zone. Again, strong facies changes are associated with the isotope excursion. On western Gotland, the increase corresponds to the lithological change from the marly, graptolite-bearing Svarvare Member to the siltstones of the Gannarve Member deposited under high-energy conditions. On eastern Gotland, limestone-marl alternations of a proximal shelf environment ($\delta^{13}C \approx$-0.5‰) grade into patchreef-bearing strata, in parts overlain by the *Atrypa "reticularis"* Beds ($\delta^{13}C \approx$ +2.3‰). Both reefs and *A. "reticularis"* Beds of the Slite Group are truncated by a prominent unconformity (Fig. 5; Calner 1999, 2002; Calner et al. 2004). Above the unconformity, oolites of the Halla Formation were deposited. In the east, these are overlain by marginal marine and backreef deposits ($\delta^{13}C \approx$ +2.3‰). Up to now, no isotope values from brachiopods exist from the Bara Oolite.

The third $\delta^{13}C$ excursion is the weakest one of the four observed on Gotland (≈ 1‰ $\delta^{13}C$ amplitude). It is, however, also accompanied by facies changes, at least in central and eastern Gotland. Here, reefs and extended biostromes were built during this time interval, e.g. the famous stromatoporoid biostrome on the Kuppen peninsula (Kershaw 1990; Kershaw & Keeling 1994; Calner et al. 2004, this volume). On western Gotland, no facies shift is observed in the open marine shelf deposits.

The final $\delta^{13}C$ excursion on Gotland lasted from the uppermost *P. siluricus* Zone to the *O. crispa* Zone (Fig. 3), and represents – to our knowledge - the strongest positive excursion of the entire Phanerozoic. On western Gotland, isotope values increase continuously from about 0.5‰ $\delta^{13}C$ in the upper När Formation to nearly 9‰ in the Eke Formation. On eastern Gotland, the När-Eke formational boundary is associated to a mineralised hardground and the base-level for a somewhat younger palaeokarstic surface (Cherns 1982).

Generally, there is a good correlation between stable isotope development and the primo and secundo episodes (see section 3.1.1 above; Fig. 3). However, up to now, no isotope data exist from the Boge, Valleviken, and Klev-events on Gotland.

The interpretation of the isotope values is still a matter of intense debate. The fact that the excursions have been found on different palaeocontinents clearly excludes a diagenetic origin. However, both the shifts in $\delta^{13}C$ and in $\delta^{18}O$ are too high to be explained by common mechanisms like productivity and temperature changes, respectively. Furthermore, interpretation is hampered by the fact that true pelagic sediments (i.e. deposited on oceanic crust) of Palaeozoic age are generally subducted and, thus, conclusions on the pelagic realm are mostly based on outer shelf deposits. Shifts in $\delta^{13}C$ exceeding 2-3‰ cannot be explained by fractionation due to changes in oceanic productivity (see discussion in Bickert et al. 1997), and no indication of enhanced deposition of organic-rich deposits during the excursions large enough to account for the extreme amplitudes observed were known by Bickert et al. (1997) and Wenzel (1997). According to the model of Jeppsson (1990) a reduced pelagic production occurred during secundo episodes (times of arid climate). However, despite of the reduced productivity, in order for a secundo episode to end as described by the model, an increased deposition of organic material on the deep shelves is necessary (see discussion in Cramer & Saltzman subm.). At least one such event of enhanced deposition of organic-rich sediments has been identified (Jeppsson & Calner 2003). According to Cramer & Saltzman (subm.) such increased $C_{org}$ deposition is responsible for the $\delta^{13}C$ excursion in the early Wenlock. However, Munnecke et al. (2003) noted that the fact that the Silurian $\delta^{13}C$ excursions are observed on various palaeo-continents, but with different absolute values and amplitudes (generally lower values, and lower amplitudes in deeper water environments) argues against deposition of organic matter as driving mechanism for the $\delta^{13}C$ development.

Also the interpretation of the $\delta^{18}O$ values is somewhat problematic. An interpretation in terms of temperature changes would result in temperature variations of up to 16°C which is unrealistic for tropical surface waters. Storage of $^{16}O$ in polar ice caps might have influenced the $\delta^{18}O$ composition of the acient sea-water however, up to now, no indications for major glaciations – al least in the late Silurian – have been found.

Based on isotopic results Bickert et al. (1997) have modified the oceanic model of Jeppsson (1990) with respect to stable isotope geochemistry and oceanic circulation (Fig. 6). Times of arid and humid climate are called A- and H-periods, respectively. This new nomenclature was used because (a) the onset of the climatic changes is seen slightly differently in Jeppsson (1990) and Bickert et al. (1997) (see Fig. 3), and (b) not every episode/event is documented by changing $\delta^{13}C$ values (Fig. 3). In their model, a shift between estuarine and anti-estuarine circulation in shallow seas, caused by precipitation changes, is the main driving mechanism (Fig. 6). Permanent euxinic conditions below the surface mixed layer of the ocean during the entire Silurian are predicted, resulting in a strong fractionation in $\delta^{13}C$ composition between surface and deep waters produced by the settlement and deposition of $^{12}C$-rich organic material in deep-sea sediments. Today, a similar fractionation is observed in the Black Sea (Fry et al. 1991). The shift from humid (H-period) to arid climates (A-period) led to changes in ocean circulation. During A-periods the formation and downwelling of saline surface water caused an anti-estuarine circulation pattern in shallow seas, and $O_2$-rich but $^{12}C$-depleted open ocean surface water reached the shelf areas, resulting in oxygenated deep shelf sediments observed during most A-periods. The low $\delta^{13}C$ values in the humid H-periods were produced by the upwelling of $^{12}C$-rich deep water (Fig. 6). The development of the oxygen isotopes is in accordance with both the Jeppsson (1990) and the Bickert et al. (1997) model. In arid periods intense evaporation resulted in an increase in salinity, and thereby a stronger $^{18}O$ fractionation, and, thus, enhanced $\delta^{18}O$ values. In humid times, fresh water influx resulted in a lower salinity, and in lower $\delta^{18}O$ values.

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# The Silurian of Gotland – Part II: Guide to the IGCP 503 field meeting 2004

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## INTRODUCTION

The major objective of the IGCP 503 project ”Ordovician Palaeogeography and Palaeoclimate” is to find the physical and/or chemical causes (e.g., related to changes in climate, sea level, volcanism, plate movements, etc.) of the Ordovician biodiversification, the end-Ordovician extinction, and the subsequent Silurian radiation. The island of Gotland (Fig. 1) represents one of the World's most famous outcrop areas for Silurian carbonate deposits. The strata are exceptionally well preserved, have neither underwent tectonic stress nor deep burial conditions, are very rich in fossils, and exhibit a considerable variety of carbonate depositional environments. Further, the outcropping sedimentary succession (latest Llandovery-Ludlow) has been at the centre for much of the recent discoveries in Silurian cyclic changes in faunas including extinction events, sedimentary changes, and stable isotope developments. All these changes have been tied to a new, high resolution conodont zonation permitting separating also changes that usually are accepted as coeval or even as causes and effects. Therefore, we decided to show this 'jewel' to the participants of the IGCP 503 field meeting in September 2004. For that purpose, we have written a review (Calner et al. 2004, this volume), and a field guide (this paper). In the review, we summarise the current knowledge of the stratigraphic framework, event stratigraphy, and $\delta^{18}O$ and $\delta^{13}C$ development on Gotland. The few localities there is time to study in less than three days field trip are described below in stratigraphical order (Fig. 2; some localities include coeval strata and hence their order is arbitrary). The lithological development of each outcrop is described briefly, and the meaning for sequence stratigraphy and isotopic development is shortly outlined. Subsequently, the "locality data" are given, including exact position of the outcrop, the biostratigraphic information, and a list of papers dealing with the outcrop (for space reasons the complete references cannot be listed here). These locality data are chiefly updated from Laufeld (1974b), and from the extensive catalogue for reference localities in the Silurian of Gotland (Jeppsson et al. in prep.; draft version available at the Allekvia Field Station, Lund University, in Follingbo).
Please, note that fossil collecting should be restricted to loose material. Note also that hammers and collecting is strictly forbidden at Holmhällar 1 (outcrop No 12).

## OUTCROPS

### Outcrop No 1: Ygne 4

**Target:** The Ireviken Event, the Llandovery-Wenlock boundary, and the Lower and Upper Visby, and Högklint formations.
**Description:** Walking from Ygne towards the patch reef complex of "Högklint" in the NE (Fig. 1), the Lower and Upper Visby formations are well exposed in cliff sections (Plate 1/1). The strata exposed in this section were formed during the Ireviken Event (see below). No biostratigraphic data are available from the visited localities, but are available from nearby Ygne 4 (see below). The Lower Visby Formation consists of regular alternations of 2-5 cm thick, wavy-bedded to nodular, bioturbated, argillaceous limestones (predominantly mudstones), and about 10 cm thick marls (Plate 1/2). Benthic fossils, e.g. brachiopods, bryozoans, and the index fossils for the Lower Visby Formation, *Palaeocyclus porpita* (small solitary rugose coral), are scattered, and algal remains are absent. The sediments were deposited under calm conditions below the wave base in well-oxygenated waters. The boundary between Lower and Upper Visby formations is a rather sudden change in facies, associated with a palaeontological change. Apart from the disappearance of the rugose coral *P. porpita*, at the formational boundary, the lowermost part (1-2 dm) of the Upper Visby Formation is characterised by an abundant occurrence of the large rugose coral *Phaulactis angusta*, sometimes with more than 10 specimens per square metre (Plate 1/3; Samtleben et al. 1996; Jeppsson 1997a, b). This layer is exposed several metres above present-day sea level, and can easily be located where the weathering angle in the cliff changes (Plate 1/2, and cf. fig. 4 in Calner et al. 2004, this volume). The Upper Visby Formation is more irregularly bedded than the Lower Visby Formation. The limestone-marl ratio increases, and detritic limestones (wacke- to grainstones) become more abundant, especially in the upper part of the formation. The abundance of benthic fossils (brachiopods, bryozoans, crinoids, tabulate corals, and stromatoporoids) increases, and the first reef mounds appear. The reef mounds consist of tabulate corals, stromatoporoids, and, subordinate, rugose corals. Some of the mounds show a narrow fringe of bioclastic limestones interfingering with the surrounding limestone-marl alternation (Plate 1/4).

**Isotope stratigraphy:** On Gotland, the first increase of stable carbon and oxygen isotopes (transition upper Telychian H-period / lower Sheinwoodian A-period; Fig. 2) starts at the boundary between the Lower and Upper Visby formations (base of *Phaulactis* layer; Datum 4 of the Ireviken Event; cf. fig. 4 in Calner et al. 2004, this volume; Munnecke et al. 2003). The increase of the isotope values correlates with a facies change from distal shelf deposits, deposited below wave base, to proximal shelf deposits with abundant reef mounds (Samtleben et al. 1996). This development continues, and culminates in the overlying Högklint Formation with the establishment of the first carbonate platform and abundant large reefs in the Upper *K. ranuliformis* Zone (Fig. 2). For further information of this stratigraphic interval, see also Outcrop No 2 (Ireviken 1-4).

**Sequence stratigraphy:** The regressive facies succession from the *Phaulactis* layer upwards through the Upper Visby and Höklint formations is typical for prograding platforms during the highstand systems tract. By definition, the highstand systems tract starts at the change from retrograding or aggrading facies to regressive facies and is bounded below by the maximum flooding surface (mfs). In this case, the mfs is inferably very close to the *Phaulactis* layer, and their mass-occurrence may therefore partly have been promoted by sediment starvation

### Locality data

YGNE 1, 6387842 1642600, ca. 3750 m WNW of Västerhejde church. Map 66A Visby.

Cliff section NW of the end of the road towards Rövare Liljas håla (where the northwesternmost road turns to a path on the top. map), ca. 1060 m SW of the triangulation point at Högklint.

*Reference level*: The boundary between Upper Visby and Högklint Beds.

*Upper Visby Fm* and *Högklint Fm*.

*References*: Martinsson 1962, p. 47; Laufeld 1974a, b*; Eriksson & Laufeld 1978; Fredholm 1990; Johannessen 1993; Riding & Watts 1991.

YGNE 3, 638794 164270 (CJ 3223 8720), ca. 3675 m WNW of Västerhejde church. Top. map 66A Visby (6I Visby NO). Geol. map Aa 183 Visby & Lummelunda.

Cliff section at Rövar Liljas håla, ca. 150 m NE of the end of the road (on the top. map, where the northwesternmost road becomes only a path).

*Reference level*: The boundary between Upper Visby and Högklint Beds.

*Upper Visby Beds*, uppermost part, *Högklint Fm*, unit a.

*Note*: Rövare Liljas håla 1 is only a short distance to the NE.

*References*: Holm 1890, p. 14; Munthe 1921, Figs. 74, 75, p. 37, lines 14-35; Hede 1940, p. 17, line 7 from the bottom (reference to the area in general); Hede 1942, p. 4, locality 5; Ericsson & Laufeld 1977; Bengtson in Jaanusson et al. 1979; Larsson 1979*; Bengtson 1981a.

YGNE 4, 638719 164185, ca. 4325 m WNW (W) Västerhejde church. Top. map 66A Visby.

High section at Lillklint, immediately N the boundary to Tofta Skjutfält, which is very well marked on the shore.

*Reference level*: The top of the very large Precambrian boulder ca. 10 m N the boundary to the military area is 0. The best developed bentonite is at +1.79 m, and that level is easier to use in field work.

*Lower Visby Fm*, unit c and Lower *Ps. bicornis* Zone: at 3.9 m b.s.l.; Upper *Ps. bicornis* Zone from 3.3 m b.s.l. to 0.40 m below reference level (b.r.l.); unit e and Lower *P. procerus* Zone from 0.08 m to +3.18 m (the two highest *P. porpita* were found at 2.87 m and 3.18 m above reference level; a.r.l.). There is a lithologic change at +3.54 m and the base of the *Phaulactis* Layer is at 4.2l m (first noted at Buske 1 in 1984 by LJ; his second find, here, revealed its importance). The Lower/Upper Visby boundary is probably at or near below +4.2 m *Upper Visby Beds*, unit a was sampled at 4.21-4.36 m a.r.l. units b and c at 6.16-6.36 m a.r.l.

*References*: Spjeldnaes unpublished; Jerre 1993, 1994a; Schmitz et al. 1994; Jeppsson herein*.

RÖVAR LILJAS HÅLA 1, (CJ 3221 8700), ca. 8250 m SW of Visby Cathedral. Top. map 66A Visby.

Cliff section at the shore ca. 900 m SW of the triangulation point at Högklint. The locality comprises the cliff area at and outside the “pseudorauk”, a landslide.

*Reference point*: The southwesternmost part of the “pseudorauk” where the path meets the beach.

*Reference level*: The Upper Visby-Högklint boundary.

*Lower Visby Fm*, *Upper Visby Fm*, and *Högklint Fm*, unit a.

*Note*: The Lower-Upper Visby boundary is located 3-3.5 m above sea level.

*References*: Munthe 1921, p. 37, figs. 74-75 (photographs of the locality); Wienberg Rasmussen 1952; Laufeld & Martinsson 1981*, Riding & Watts 1991.

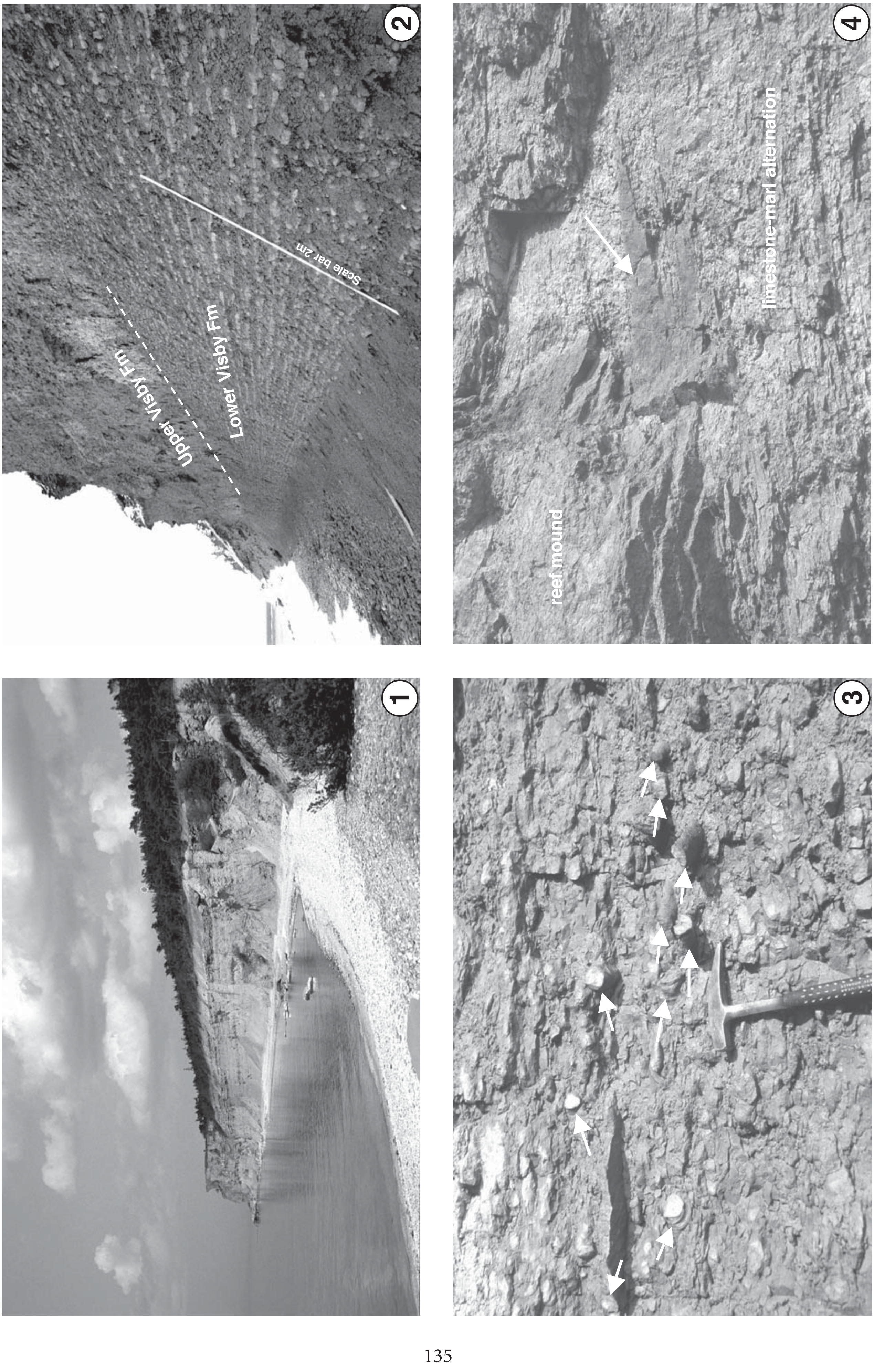
## Outcrop No 2: Ireviken 1-4

Target: The Ireviken Event, the Llandovery-Wenlock boundary, and the Lower and Upper Visby and Högklint formations.

**Description:** There are four protruding cliffs consisting of huge bioherms SW of the bay. We will walk along the beach towards the NW from the village of Irevik. The localities are in the following order from the parking lot: Ireviken 4 = the section before and including the first reef – Tretrivsklint; Ireviken 2 = the section beyond that reef to the second reef – Millingsklint – and that cliff; Ireviken 1 = the section beyond that reef to the third reef – Gaituklint – and that

Plate 1

1) The Ygne outcrop, showing the Lower and Upper Visby formations in the foreground, and an isolated patch reef (“Högklint”) of the Högklint Formation in the background.
2) Boundary between the Lower and Upper Visby formations at Ygne. Note the regular alternation of limestones and marls in the Lower Visby Formation, and the change in weathering profile across the boundary.
3) The *Phaulactis* layer in the lowermost part of the Upper Visby Formation at Nygårdsbäcksprofilen 1 (ca 1 km N of Ygne). Arrows point to specimens of the large (up to several decimetres) rugose coral.
4) Reef mound with fringe (arrow) of bioclastic limestones, interfingering with limestones and marls of the Upper Visby Formation (Ygne)



1
2
Upper Visby Fm
Lower Visby Fm
Scale bar 2m
3
4
reef mound
limestone-marl alternation

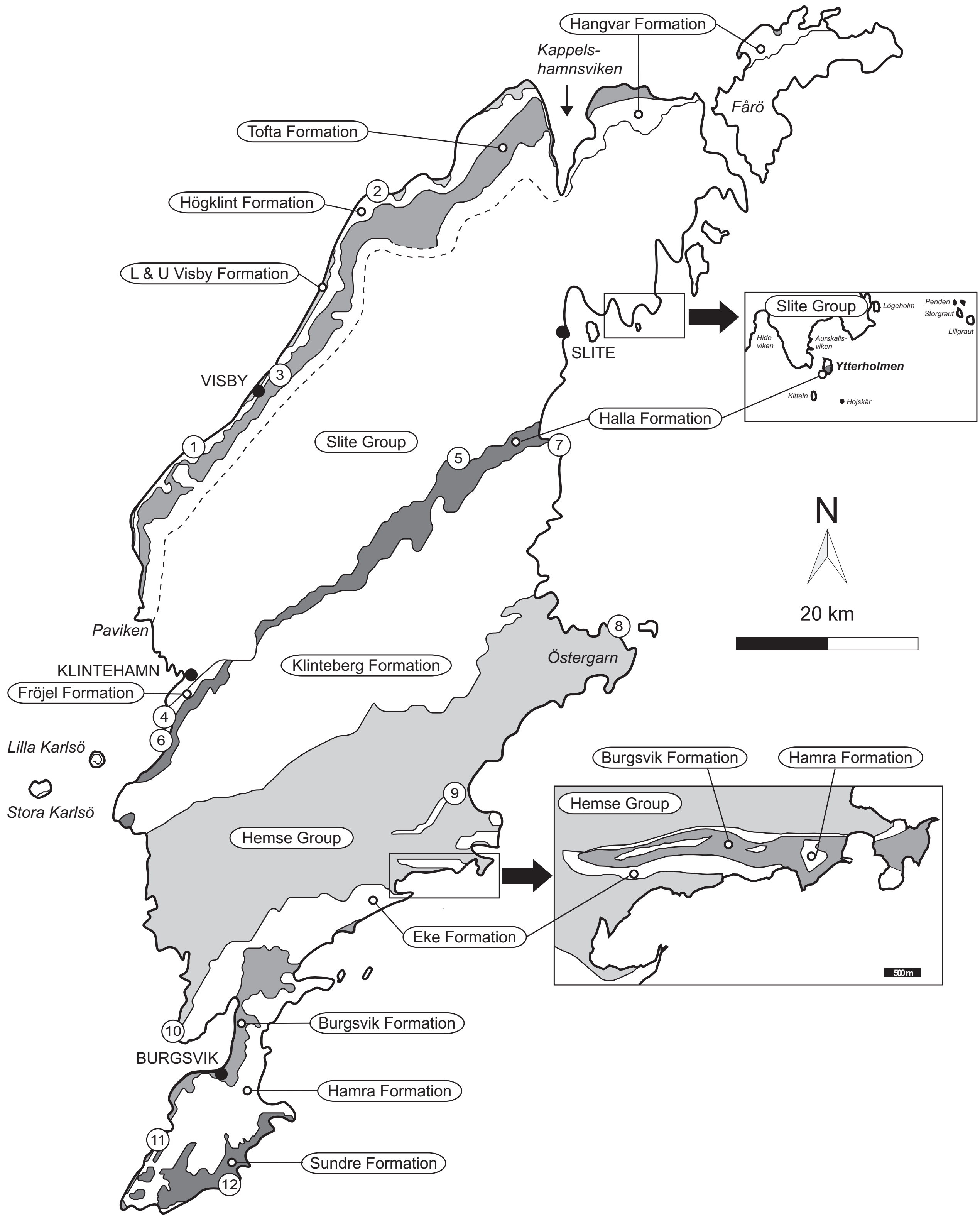



Figure 1. A new geological map of Gotland (completed by LJ & MC), and position of outcrops visited. This preliminary map is chiefly based on Jeppsson & Calner (2003) and conodont data from Jeppsson (in manuscripts; in prep.).

reef; and Ireviken 3 = the section beyond Gaituklint to the 4th reef – Snipklint – and 150 m beyond Snipklint.

The lithological and isotopic development of the Lower and Upper Visby formations are similar to that in the Ygne area (see above). The overlying Högklint Formation is characterised by isolated large bioherms (patch reefs) at intervals of several 100m. The reefs consist mainly of stromatoporoids and tabulate corals, but also of bryozoans, crinoids, and calcareous algae. Due to the steep cliff, the reefs are difficult to access, but many large boulders on the

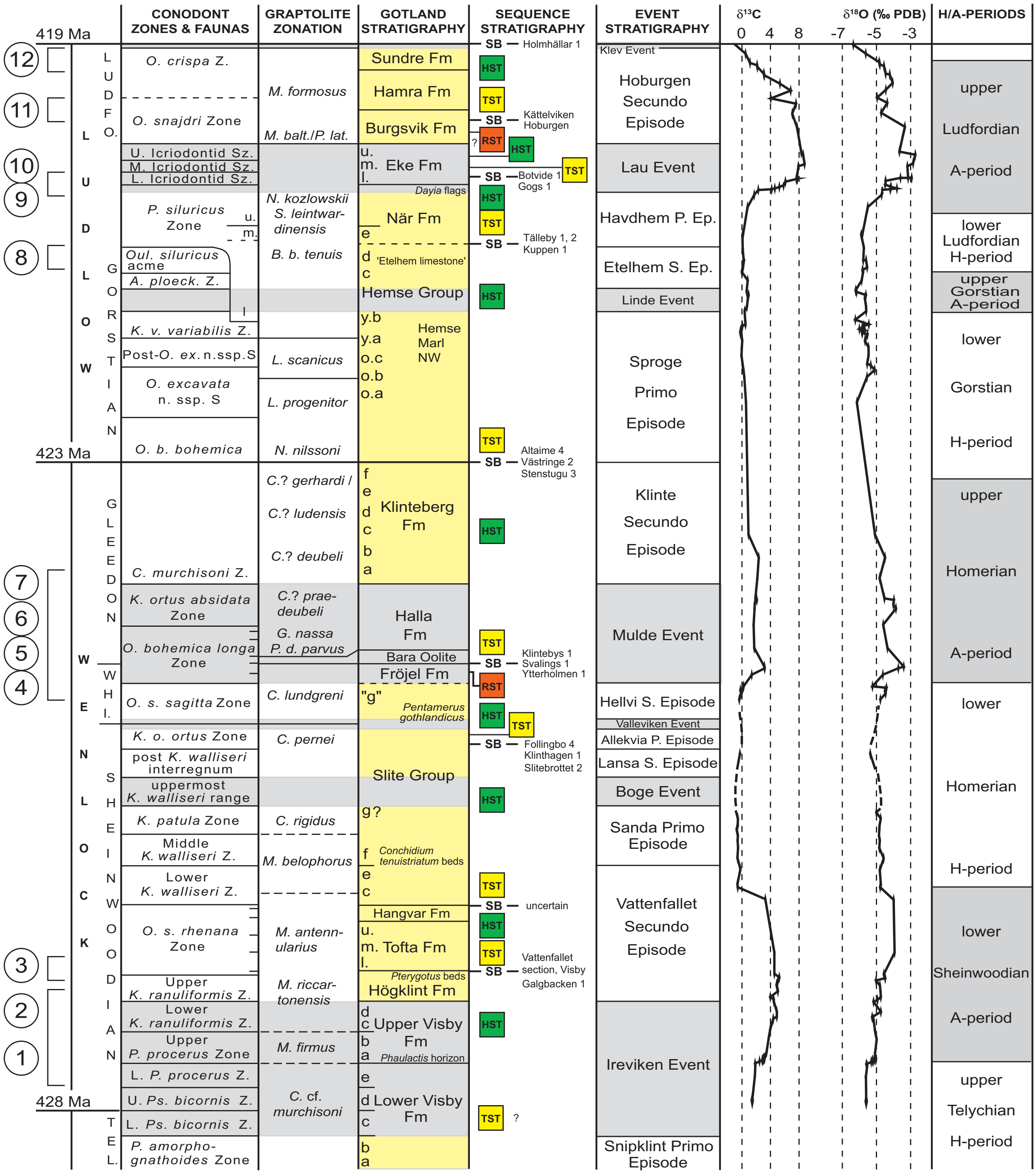



Figure 2 Stratigraphic position of the outcrops (no. 1 to 12; left). Stratigraphic framework showing conodont zones and faunas and their relationship to graptolite biostratigraphy, stratigraphic units on Gotland, and a provisional sequence stratigraphic framework for the exposed strata. The sequence of episodes and events are from Jeppsson (1993, 1998), Aldridge et al. (1993), Jeppsson et al. (1995), and Jeppsson & Aldridge (2000). The development of stable carbon isotopes and the sequence of H/A-periods are from Bickert et al. (1997), Samtleben et al. (2000), and Munnecke et al. (2003). The figure is partly based on stratigraphic data from Jeppsson (1997b) and Jeppsson (in manuscripts), Calner (1999), and Calner & Jeppsson (2003).

beach can be studied. The reefs are surrounded by a well-bedded to wavy-bedded limestone-marl alternation (plate 2/1). This alternation differs strongly from the underlying Upper Visby Formation. The about 10 cm thick bioturbated limestone beds have a slightly silty appearance, show a brownish colour, and sometimes a bituminous smell. The interbedded marls are dark-brownish and are strongly compacted. Whereas the thickness of the limestone beds remains more or less constant around 10 cm throughout the section, the thickness of the marl layers decreases from 20-30 cm in the lower part to less than 5 cm in the upper part of the section.

The four localities along the shore and the Ireviken Event were named after the Ireviken bay where the Ireviken Event was first discovered. Since then, a better locality, Lusklint 1, has been foundand studied in better detail, and now functions as reference locality for the main part of the event. The stratigraphic units are much thinner at the Ireviken localities than at Ygne south of Visby. Hence although the top of the Lower Visby Formation is at about the same altitude, three older members are also exposed here.

Several datum points have been identified, starting with Datum 1, at Ireviken 3 ca 4.5 m below the formational boundary. Datum points 2 had the most severe effects, e.g. >50% of the trilobite species disappeared on Gotland (Ramsköld 1985) and at least ca 20% (probably >30%) of the conodont species (global data). Datum 4 is at the formational boundary. Hence, old faunal lists from Gotland can also be used to identify extinctions in most major clades, e.g. brachiopods (Hede 1925, 1940), chitinozoans (Laufeld 1974a), corals, ostracodes (Martinsson 1962, 1967; Säll, unpublished), polychaetes (Eriksson 1997). Regarding conodonts, Datum 4 had globally the second worst effects.

**Isotope stratigraphy:** The Ireviken sections comprise the transition from the upper Telychian H-period (Lower Visby Formation; $\delta^{13}C \approx 1.9‰$) to the lower Sheinwoodian A-period (Upper Visby and Högklint formations; $\delta^{13}C > 5‰$; Fig. 2).

### Locality data

IREVIKEN 1, 6416594 1664242, ca. 6970 m W of Hangvar church. Map: 66C Tingstäde. Cliff section, ca. 710 m NW of the northwesternmost house at Irevik. The third cliff – Gaituklint - and the section towards the southeast as far as to the second bioherm (Millingsklint).

*Reference level*: The bentonite bed about 1.5 m above base of the section at the southeasternmost part of the bioherm (Gaituklint). The reference level is concealed under a thin layer of scree. It is located at the upper edge of the moist zone and is easily uncovered.

*Lower Visby Fm*, *Upper Visby Fm* and *Högklint Fm*, unit a.

*Note*: The boundary between the Upper Visby Fm and the Högklint Fm is located 13.5 m a.s.l. (Laufeld 1974b). If the reference level is the Ireviken Bentonite, then the *Phaulactis* Layer should be searched for at ca. 3 m above the reference level, and the Upper Visby may be about 9 m.

*References*: Hede 1933, Figs. 5-6 (photographs of the locality), p. 12, lines 4-28 (contains a list of fossils from the Lower Visby Fm at 1-2 m a.s.l.), p. 15, lines 2-30 from below (contains a list of fossils from the Upper Visby Fm at 11.5-13.5 m a.s.l.), p. 25, lines 1-14 from below (contains a list of fossils from the brownish argillaceous, "lagoonal" limestone of Högklint age, unit a, in the uppermost part of the section WNW of Millingsklint); Hede 1942, Loc. l, 1960, Loc. 13, pp. 61-62; Martinsson 1962, p. 47 (Martinsson's locality Irevik); Mori 1968, p. 22, Loc. 3 a, p. 25, Loc. 19; Laufeld 1974a, b*; Laufeld & Martinsson 1981; Nield 1982; Ramsköld 1983, 1984, l985a, 1986; Le Hérissé 1988, 1989; Bassett et al. 1989; Bergman 1989, 1995; Fredholm 1990; Neuman & Kershaw 1991; Riding & Watts 1991; Samtleben et al. 1996; Munnecke et al. 2000, 2001, 2003; Watts & Riding 2000.

IREVIKEN 2, 6416480 1664451, ca. 6770 m W of Hangvar church. Map: 66C Tingstäde. Cliff section, ca. 500 m NW of the northwesternmost house at Irevik. The second of these cliffs – Millingsklint – and the section towards southeast as far as to the first bioherm (Tretrivsklint).

*Reference level*: The thick bentonite bed about 12 m a.s.l. in the section about 35 m SE of Millingsklint. The reference level is located slightly below the uppermost parts of the talus material.

*Lower Visby Fm*, *Upper Visby Fm* and *Högklint Fm*, unit a. Near the centre of this locality, two bentonites are found at 1.81 and 4.75 m a.s.l. Their separation, 2.44 m fits well if the lower one is the Lusklint Bentonite and the upper one the Ireviken Bentonite.

*References*: Hede 1933, p. 12, lines 13-18 from below, p. 17, lines 14-31 (contains list of fossils from the crinoid limestone of Högklint age, unit a, immediately SE of Millingsklint); Martinsson 1962, p. 48 (Martinsson's Irevik II); Laufeld 1974b*; Eriksson & Laufeld 1978; Larsson 1979; Bergman 1989; Neuman & Kershaw 1991; Riding & Watts 1991; Johannessen 1999; Watts & Riding 2000.

IREVIKEN 3, 6416719 1663901, ca. 7320 m W of Hangvar church. Map: 66C Tingstäde. Cliff section, ca. 1060 m NW of the northwesternmost house at Irevik. The fourth protruding cliff – Snipklint or Snipan – and the section towards the southeast as far as to the next bioherm (Gaituklint) and from Snipklint 150 m towards the W.

*Reference point*: The agglomeration of huge boulders on the beach just W of Snipklint. Laufeld 1974b, Fig. 11 B.

*Reference level*: The Lusklint Bentonite, that is, the lowermost of the two major bentonite beds in the section just W of Snipklint. The reference level is located about 5 m a.s.l. but dips due to the bending down of strata below the bioherm, where it is only 3.5 m a.s.l.

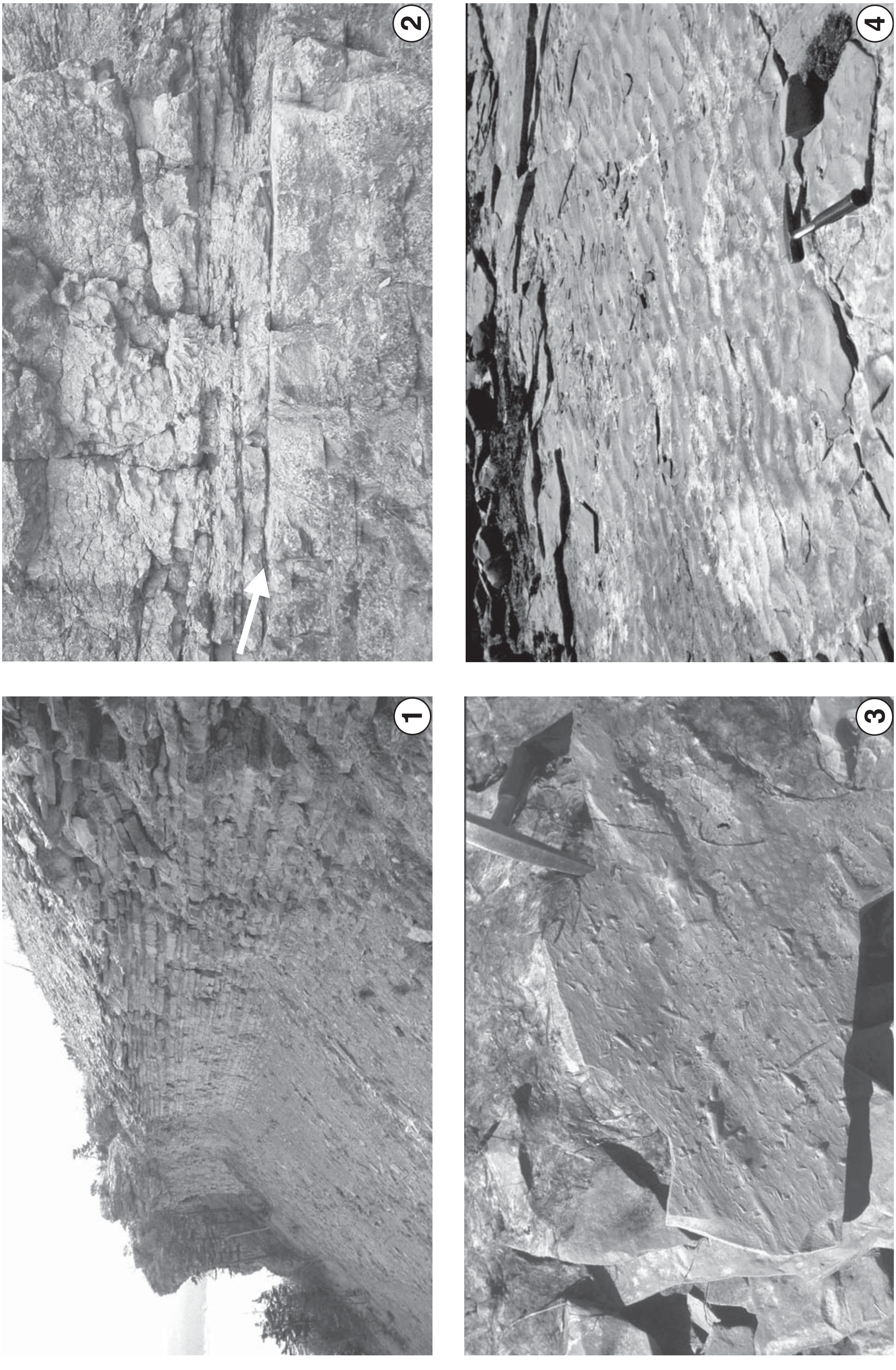
*Lower Visby Fm*, *Upper Visby Fm* and *Högklint Fm*, unit a.

*Note*: In a major rock-fall in 1966 the most easily accessible part of the section was buried.

*References*: Wedekind 1927, p. 44, line 3; Hede 1933, p. 44, line 3; Laufeld 1974b*; Kershaw & Riding 1978; Stel 1978a; Larsson 1979; Kershaw 1980, 1984; Riding 1981; Nestor, V.-K. 1982; Nield 1982, 1985; Odin et al. 1984, 1986; Sandford & Mosher 1985 (note, the Lower-Upper Visby contact is mistakenly identified as the Upper Visby-Högklint contact; hence their data are not affected, only some conclusions), 1994, p. 12; Ramsköld 1985a; Cavell & Baadsgaard 1986 (sample 102); 1989; Baadsgaard & Cavell 1988 (sample 102); Le Hérissé 1988, Bergman 1989; Jeppsson 1987, 1989d, 1993, 1997a, c; Fredholm 1990; Sivhed 1990; Copper & Branton 1991 (p. 230, Lower Visby reefs); Neuman & Kershaw 1991; Riding & Watts 1991; Aldridge et al. 1993; Jeppsson & Männik 1993; Johannessen 1993 (Snipklint), 1999; Jerre 1993, 1994a; Jeppsson et al. 1994; Batchelor &

Plate 2

1) Inter-reef sediments between Millingsklint (background) and Gaituklint in the Ireviken area showing a classical shallowing upward (prograding) succession.
2) Boundary (arrow) between the Högklint and Tofta formations at Galgberget 1 (hammer for scale).
3) Slab showing bioturbation (hypichnial ridges) and tool marks on the lower bedding plane of calcareous siltstone, Gannarve Member, Fröjel Formation (Klinteenklaven 2; hammer for scale).
4) Almost symmetrical, slightly bifurcated ripple marks in a calcareous siltstone of the Gannarve Member, Fröjel Formation (Gannarveskär 1; hammer for scale).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Jeppsson 1994; Kleffner 1995 (Ireviken); Le Hérissé & Gourvennec 1995; Samtleben et al. 1996; Bates 1997; Eriksson 1998a; Mõtus & Klaaman 1999; Calner et al. 2000; Watts & Riding 2000.

IREVIKEN 4, 6416244 1664780, ca. 6435 m W of Hangvar church. Map: 66C Tingstäde. Cliff section, ca. 150 m N of the northwesternmost house at Irevik. The first bioherm – Tretrivsklint and the section towards the southeast.
*Reference level*: The lowermost of the three major bentonite beds in the section inside the bight SE of Tretrivsklint. The bentonite beds are easily traced, because their upper surfaces are aquifers and the percolating water is giving rise to a border of herbaceous plants. The reference level is located about 4 m a.s.l. (Laufeld 1974b).
*Lower Visby Fm*, *Upper Visby Fm* and *Högklint Fm*, unit a.
*References*: Laufeld 1974b*; Neuman & Kershaw 1991; Riding & Watts 1991; Watts & Riding 2000.

## Outcrop No 3: Galgberget 1

**Target:** The Högklint Formation-Tofta Formation boundary strata north of Visby.
**Description:** The uppermost Högklint Formation and the basal stromatoporoid-rich Tofta Formation are exposed in the SW wall of this abandoned quarry (Plate 2/2). The unconformable boundary between the two formations is potentially the upper sequence boundary of the oldest, incomplete depositional sequence on Gotland, although it should be noted that other erosional surfaces in the underlying parts of the Högklint Formation might be potential sequence boundaries.
Jeppsson et al. (1995) interpreted the Högklint – lower Slite as a very long stable episode, the Vattenfallet Secundo Episode, based on the absence of indications for a consistent pattern within this interval. However, increased precision and stratigraphic revisions has yielded evidence for the kind of pattern that has been useful for revealing the oceanic signal in other parts of the sequence (cf. Jeppsson 1998).
The contact between Högklint unit c and the very thin unit d of Laufeld (1974a, b) has not been accessible for a long time. The previously unpublished detailed fieldwork of Liljevall in 1908 was the basis for the Vattenfallet volume. In that, Jaanusson (1979, fig. 13) published Liljevall's original drawing of that contact and quoted and discussed his results. Högklint c was lihtified and eroded before the deposition of unit d, which rested against an at least 1.0 m high wall (the top was truncated by Quaternary erosion). The dark colour of unit d, its character of a Lagerstätten (scorpion, eurypterids, almost complete ophiurid, asteroid, and crinoid; Regnéll 1973; Franzén 1979) and the centimetre scale changes in lithologies and faunas indicate an environment with little or no bioturbation, most probably caused by more or less dysaerobic bottom conditions. The sequence of the changes is as follows (4, 5, 6, and 7 can not be seen at Galgberget 1):

1) After the Ireviken Event, an extensive reef generation formed and lithified; the Högklint Formation.
2) A rapid regression after deposition of Högklint c (truncated by Liljevall's unconformity).
3) Formation of a rocky shoreline.
4) A transgression.
5) Formation of Högklint d in depressions with more or less stagnant water in this eroded surface. A diverse conodont fauna.
6) Reduction in faunal diversity, both transient changes and extinctions.
7) The characters of the Högklint d/Tofta contact remains to be identified.
8) A low diversity conodont fauna strongly dominated by *Oz. s. rhenana* in the lower Tofta Formation (just above the unconformity).
9) A protracted recovery through the lower and the middle Tofta Formation (the latter, with a more balanced conodont fauna, is not identified here).
10) A new reef generation in the lower Hangvar Formation (or upper Tofta).

Thus, this early Sheinwoodian interval, instead of forming one of the longest Silurian secundo episodes, seems to have included two secundo episodes, separated by a secundo-secundo event. Pending that enough data for describing and formally naming this event and the succeeding secundo episode are assembled, these three intervals may be discussed as the Vattenfallet 1 and 2 secundo episodes, and the Vattenfallet 1/2 event, respectively.
No isotope data exist from this outcrop.

### Locality data

GALGBERGET 1, 6394547 1649711, ca. 1360 m NE of Visby cathedral. Map: 66A Visby. 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 E, into the quarry. This is the most widely quoted locality with this boundary.
*Reference point*: The protruding part of the SW quarry wall.
*Reference level*: The Högklint - Tofta boundary (marked in the wall), see

Plate 3

1) Bioturbation (*Diplocraterion/bifungites*) on the upper bedding plane of a calcareous siltstone of the Gannarve Member; Fröjel Formation (Gannarveskär 1; hammer for scale).
2) Crossbedded oolites of the Bara Oolite Member (Halla Formation) at Bara 1. The hills in the background are reefs of the "underlying" Slite Group. Here, the unconformity between Slite Group and Halla Formation exhibits a pronounced palaeorelief.
3) Flat-lying argillaceous limestones and marls of distal platform origin at Blåhäll 1 (Mulde Brick-clay Member, Halla Formation). A 0.3-0.5 m thick halysitid-heliolitid autobiostrome occurs high in the section throughout the length of the exposure.
4) Detail of the halysitid-heliolitid autobiostrome in Blåhäll 1 (cf. Plate 3/3). The dominant species are *Stelliporella* cf. *parvistella* and *Halysites laticatenatus*.


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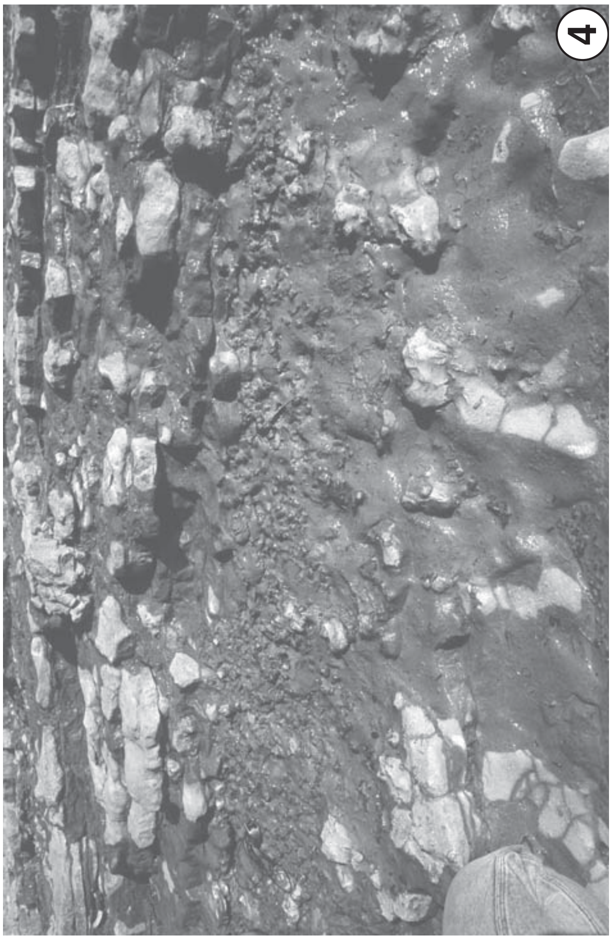
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Hede 1940, Fig. 10.

*Högklint Fm* and *Tofta Fm*.

*Lower part of the Tofta Fm*.- (Description based on LJ in ms). The leperditiocopid-rich basal Tofta Fm, the Stajnkrogen Mbr of Riding & Watts (1991) contains the *O. s. rhenana* Zone (Jeppsson 1997c), Subzone 1. The same distinct lithology and Subzone occur at Stajnkrogen 2. The subzone has also been found at Kopparsvik 2 in the Plågan Mbr and at least 0.26 m up into the succeeding Halsjärnet Mbr of Riding & Watts. The fauna is much less diverse than that of Subzone H, in the topmost Högklint Fm at Vattenfallsprofilen 1. Further, *Oz. paraconfluens*, characteristic of the Högklint Fm, had become extinct.

*References:* Hede 1940, Figs. 10, 14, 15, p. 32, lines 6-7 from below; 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; Jeppsson in manuscript

## Outcrop No 4: Klinteenklaven-Gannarveskär localities

Target: The Mulde Event and the Slite Group-Halla Formation boundary strata in distal platform areas on western Gotland.

**Description:** These low coastal exposures form the type sections for the Gannarve Member of the Fröjel Formation (Calner 1999). The lowermost parts of the overlying Halla Formation are exposed in the southernmost exposures at Gannarveskär 2 and 4. 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 orientated orthocones, rare shell lags, and abundant primary sedimentary structures, e.g. wave and current ripples (Plate 2/4), undulating lamination, and hummocky cross stratification. The lower bedding planes of these beds are sharp to erosive (locally with gutter casts), and display abundant trace fossils (hypichnial ridges) and tool marks (Plate 2/3, 3/1), the latter 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 in outcrops only a few kilometres further towards the northeast and in the Hunninge-1 core. The succession reflects deposition during alternating storm- and fair-weather conditions during progressive shallowing and siliciclastic input to distal platform environments.

Due to the event, the environmental conditions had deteriorated to the point that faunas are strongly unbalanced, e.g. a single conodont, *Ozarkodina excavata*, makes up over 90% of the fauna in the Fröjel Formation. Regarding the succeeding fauna, see Outcrop No 5: Bara 1.

**Isotope stratigraphy:** The early part of the upper Homerian A-period will be visited in this coastal section. The latest part of the preceding lower Homerian H-period is exposed in the Värsändeojk localities ca 1 km of Klinteenklaven 2, with $\delta^{13}C$ values around 0‰. Up to now, no isotope data exist from the succeeding Svarvare Member of the Fröjel Formation. In the overlying Gannarve Member $\delta^{13}C$ values increase rapidly from ca. 1.4‰ at Klinteenklaven 4 to >3‰ at Klinteenklaven 2 and Gannarveskär 1 (Samtleben et al. 2000).

### Locality data

KLINTEENKLAVEN 2, 636106 164253, ca. 2180 m NNW Fröjel church. Map: 56C Klintehamn. Shore-line exposure ca. 100 m N the southern side of the bay, just W a locked gate.

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

*References*: Calner 1999 (includes a measured section); Samtleben et al. 2000; Calner & Jeppsson 2003; Jeppsson & Calner 2003.

GANNARVESKÄR 1, 636100 164235. Map: 56C Klintehamn. Low cliff section along the western shore of Skäret. The locality includes the exposure from the NE tip of the peninsula to the end of the exposures, ca. 150 m to the SSW.

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

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

*Note*: The thin-bedded alternating strata above the reference level are usually poorly exposed.

*References*: Kiesow 1888, p. 15 ("Skäret" bei Gannarfve); Westerberg 1895, p. 419; Hede 1927, p. 16, lines 10-20; Bassett & Cocks 1974, p. 28 (Gannarfleskar); Ramsköld in Jaanusson 1986*; Calner 1999 (includes a measured section); Samtleben et al. 2000; Calner & Jeppsson 2003; Jeppsson & Calner 2003.

GANNARVESKÄR 2, 636080 164234. Map: 56C Klintehamn. Small exposure of argillaceous limestone at the strand-line of the small bight which faces southwest on the western side of Skäret, 100 m S of Gannarveskär 1.

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

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

GANNARVESKÄR 4, 636084 164231, 2.12 km NW Fröjel church. Map: 56C Klintehamn. Section in a small hole 10 m N the northern shore of the small bay, ca. 70 m S the concrete building.

Reference level: The ground level.

*Slite Group*, *Fröjel Fm*, Gannarve Mbr. and *O b. longa* Zone, Subzone 1 to -0.55 m; the topmost sample with a more diverse fauna than in other samples from that member. *Halla Fm* and Subzone 2. Mulde Event.

*References*: Calner & Jeppsson 2003; Jeppsson & Calner 2003

## Outcrop No 5: Bara 1

Target: The Mulde Event and the Slite Group-Halla Formation boundary strata in proximal platform areas on eastern Gotland.

**Description:** Abandoned quarry showing a large reef of the topmost Slite Group (Slite "g"; a small collection indicates the *O. s. sagitta* Zone), and light-coloured, cross-bedded oolites of the basal Halla Formation (Bara Oolite Member, *O. bohemica longa* Zone; Plate 3/2). The oolite is thin 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. The oolite crops out stratigraphically well below the top of the older Slite reefs indicating a pronounced palaeorelief. The contact between the Slite Group and Halla Formation is not exposed here, but is known at a nearby locality unconformable. No isotope data exist from this locality.

The sequence of changes is (2-5 are not seen at Bara 1):

1) The formation of an extensive reef complex (Slite "g").

2) Datum 1 of the Mulde Event.

3) Formation of the Svarvare Member mudstones in distal platform areas; Datum 1.5.

4) Formation of the Gannarve Member siltstones during a substantial regression (see above, outcrop No 4). This member were deposited across Gotland but was eroded in the Bara area during the subsequent lowstand.

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). The conodont fauna is strongly dominated by coniforms, mostly *Panderodus equicostatus*. This disaster fauna was formed during the worst part of the Mulde Event and is found as far offshore as the corresponding interval in the När-1 core on southern Gotland. Hence, the faunal composition was not an effect of the ooid-forming environment.

### Locality data

BARA 1, 6387900 1667569, ca. 3300 m SW of Vallstena church. Map: 66B Gothem. Abandoned quarry, ca. 575 m W of the Bara church ruin.

*Halla Fm*, Bara Oolite Mbr, type locality, and up in the hill, *Slite Group*. *O. b. longa* Zone, Subzone 2; the hill is older, the *O. s. sagitta* Zone, although the zonal indicator has not been found here.

*Note*: In old collections and literature the name is often Bara Backe.

*References*: Hede 1928, p. 45, line 18 - p. 46, line 12 (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. 2004.

## Outcrop No 6: Blåhäll 1

Target: Mulde Event, the Late Wenlock distal platform marls, and a thin halysitid-heliolitid autobiostrome.

**Description:** This is a ca 450 m long coastal exposure showing flat-lying, argillaceous limestone (mudstone and wackestone) and marls of distal platform origin (Plate 3/3; Calner et al. 2000). The benthic fauna is exceptionally rich and includes frequent brachiopods and trilobites. Two large cephalopods with a diameter of ca 10 cm have been found at the locality. A 0.3-0.5 m thick halysitid-heliolitid autobiostrome (bafflestone) is traceable throughout the outcrop. This biostrome (Plate 3/4) is exceptional because it 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 palecopid and metacopid ostracodes.

The strata at Blåhäll 1 were formed during the recovery stage of the Mulde Event. The faunal recovery had progressed so far that the conodont fauna was balanced. Further, two conodonts returned and has been found in the topmost stratum. Two species of graptolites, *Gothograptus nassa* and *Pristiograptus dubius*, were widespread in the oceans at this time. Both species have been found here.

**Isotope stratigraphy**: This outcrop belongs to the upper Homerian A-period (Fig. 2), and 31 brachiopods have been measured for carbon and oxygen isotopes so far. Whereas the $\delta^{13}C$ values remain more or less constant throughout the section ($\delta^{13}C \approx 1.5‰$) the $\delta^{18}O$ values increase slightly but continuously from ca. –3.7‰ (1.4m below the biostrome) to -4.2‰ (0.4m below the biostrome). No brachiopods have been found within the biostrome, and 0 – 40 cm below.

### Locality data

BLÅHÄLL 1, 6356759 1641910, ca. 2940 m SW of Fröjel church. Map: 56C Klintehamn. Cliff section, immediately SW of the parish boundary at Blåhäll. For a detailed description, see Hede 1927b.

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

*Halla Fm*, *Mulde Mbr*, 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 restricted sense of Jaeger (1991).

*Note*: As regarding many other place names on Gotland, there are several Blåhäll. For example, the locality "Blåhäll fiskeläger" of Johannessen 1993 is another locality (S of Stavsklint 1).

*References*: Hennig 1905, p. 16, line 15 from below; Hede 1927b, p. 19, lines 29-32; 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 Hérissé 1988, 1989; Frykman 1989; Bergman 1989; Scrutton 1989 (Blahall); Fredholm 1990; Young & Scrutton 1991; Neuman & Kershaw 1991; Samtleben et al. 1996, 2000; Mõtus & Klaaman 1999; Calner et al. 2000 (includes a measured section); Adrian et al. 2000; Munnecke et al. 2001; Jeppsson & Calner 2003; Calner & Jeppsson 2003.

## Outcrop No 7: Gothemshammar 3

Target: Late Wenlock marginal marine strata of the Halla and Klinteberg formations on eastern Gotland.

**Description:** The coastal exposures show marginal marine oncolitic wacke- and packstones of the upper Halla and the basal Klinteberg formations. The strata are thin-bedded, often intensely bioturbated and arranged as an aggradational to slightly progradational limestone-marl alternation. Oncoids are very abundant, several centimetres across, and often highly irregular due to periods of stationary growth. Brachiopods and bryozoans are sometimes exceedingly common (Plate 4/1), especially in Gothemshammar 6 (not visited). A polished and mineral-stained discontinuity surface (abraded hardground) with clear-cut oncoids 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, indicating slight diachrony along the base of the Klinteberg Formation. The strata immediately overlying the discontinuity surface at Gothemshammar is developed as a thin marl with well preserved brachiopods and trilobites (Plate 4/2).

The first post-Mulde Event conodont fauna has been found both below and above the discontinuity surface.

**Isotope stratigraphy**: This outcrop belongs to the upper Homerian A-period. The $\delta^{13}C$ values decrease from 2.3‰ in the middle part of the Halla Formation (Gothemshammar 6) to 1.5‰ in the lowermost part of the Klinteberg Formation (Gothemshammar 3; Samtleben et al. 2000).

**Locality data**

GOTHEMSHAMMAR 3, 6390750 1679250, ca. 5350 m NE of Gothem church. Map: 66B Gothem. Low section on the beach, where the road along the shore is split in two.

*Reference level*: The Halla-Klinteberg boundary.

*Halla Fm,* 'gothemshammar member', and *Klinteberg Fm*, unit a. The *Ctenognathodus murchisoni* Zone.

*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, Samtleben et al. 2000; Jeppsson & Calner 2003; Calner & Jeppsson 2003.

## Outcrop No 8: Kuppen 1-4

Target: Early Ludlow stromatoporoid biostromes, rocky shorelines, and fossil sea stack of the Hemse Group, unit d.

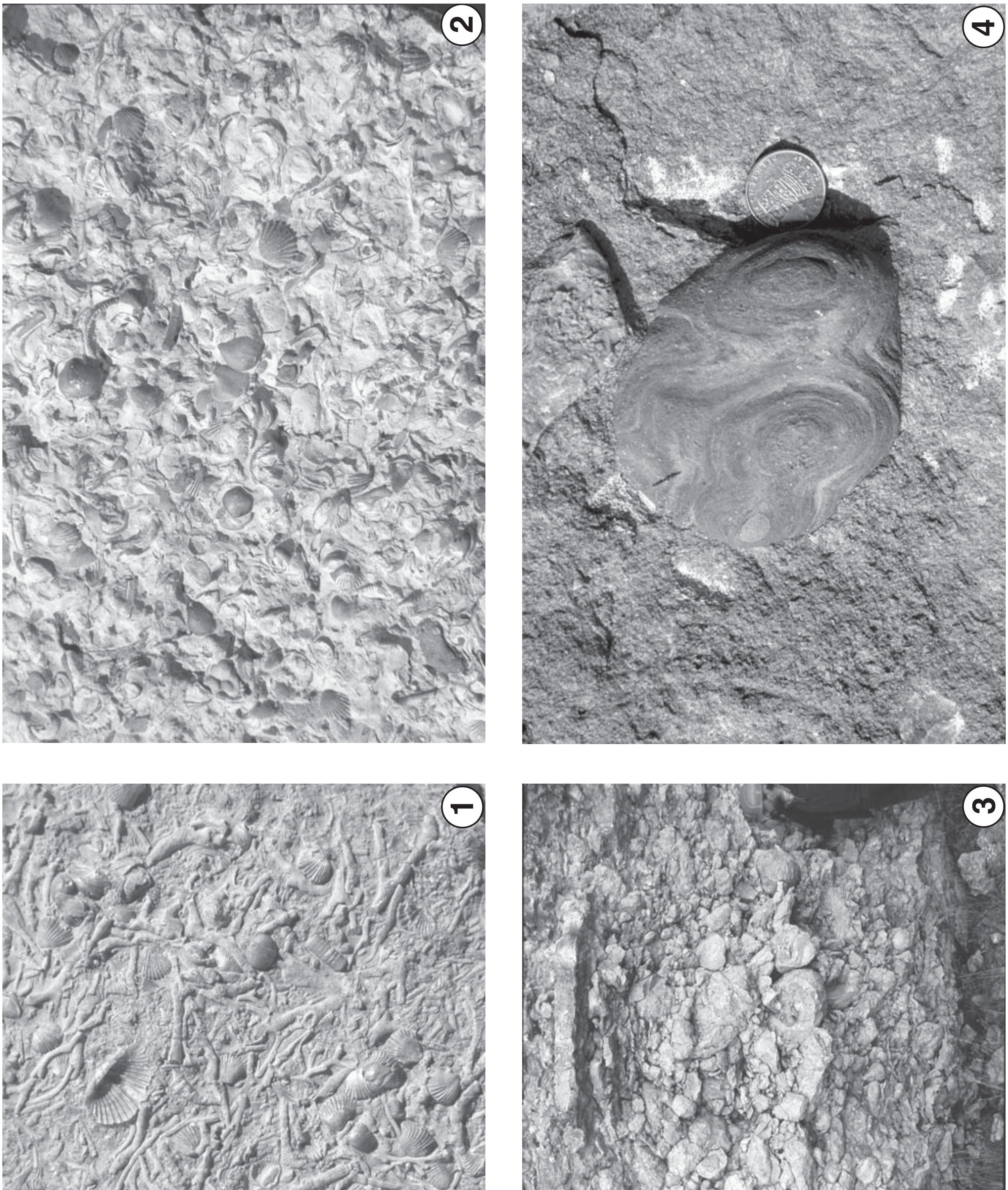
**Description:** In the Kuppen area some of the world's most famous Palaeozoic stromatoporoid deposits are exposed (for overview see Sandström & Kershaw 2002). The Kuppen localities include several hundred of metres of well-exposed coastal sections in the easternmost parts of the Östergarn peninsula on east-central Gotland. The peninsula is characterized by several hills composed of stacked stromatoporoid biostromes and interbedded skeletal grainstones. The outliers have conspicuously planar tops. These surfaces are likely inherited from prominent transgressive surfaces separating underlying reef tracts from overlying, now eroded, argillaceous limestone and marl. Spectacular stromatoporoid biostromes consisting of large (up to few dm), non-framebuilding stromatoporoids form the coastal cliffs also at Kuppen (Plate 4/3, 4/4). The biostromes grew on a broad, shallow-water carbonate platform. A high-energy environment (at least temporarily) is indicated by abundant bioclastic grainstones, truncation surfaces, abraded boulders (plate 4/4), and by a nicely preserved fossil sea stack (Fig. 3). According to Sandström & Kershaw (2002) hurricanes and storms often disrupted the internal structure of the biostromes.

Unconformable relationships at this locality were identified as a Silurian rocky shoreline by Keeling & Kershaw (1994). Conodonts show that the youngest strata here were formed early during the Havdhem Primo Episode. Hence, although only few conodonts have been found in the subjacent biostromes, these probably represents the preceding Ethelhem Secundo Episode. A change from a secundo to a primo state ocean had been predicted to result in a drop in sea level (Jeppsson 1990, p. 667). The unconformity here may be the first described example of such a drop.

**Isotope stratigraphy**: 5 brachiopods have been measured from the stromatoporoid biostrome at the Kuppen 3 locality. The $\delta^{13}C$ values of around 0.9‰ indicate an affiliation to the upper Gorstian A-period (Fig. 2). Similar $\delta^{13}C$ values from biostromes are observed in Grogarns 4 (1.1‰), and in Ljugarn 1 (1.3‰), the latter value is close to the maximum value of this isotope excursion. With an amplitude of slightly more than 1‰ in $\delta^{13}C$ values, this A-period represents the weakest of the four positive $\delta^{13}C$ excursions on Gotland (Fig. 2). It is remarkable, however, that it is also accompanied by a pronounced facies shift towards pure carbonates and reefal build-ups (Samtleben et al. 2000; the Etelhem Secundo Episode of Jeppsson 1998; Jeppsson & Aldridge 2000). In the Linde area on western Gotland, pre-excursion limestone-marl alternations of an open marine shelf facies ($\delta^{13}C$ values around 0‰) grade into isolated biohermal reefs (and surrounding sediments; $\delta^{13}C$ values up to 1‰). In the shallow facies areas on eastern Gotland (e.g. in the Kuppen area), pre-excursion marginal marine deposits are overlain by extended stromatoporoid biostromes. In contrast to the other, stronger, A-periods no oncolites have been reported from the upper Gorstian A-

Plate 4

1) Bedding plane association of an argillaceous limestone from the Halla Formation at Gothemhammar. The low-diversity assemblage of abundant rhynchonellid brachiopods and branching bryozoans indicates extreme ecological conditions in a marginal-marine environment. Width of the figure is ca 8 cm
2) Bedding plane association of an argillaceous limestone from the lowermost Klinteberg Formation at Gothemhammar showing abundant brachiopods and trilobite fragments. Width of the figure is ca 8 cm
3) Biostrome consisting predominantly of large stromatoporoids at Kuppen 3.
4) Abraded stromatopore boulder embedded in coarse bioclastic grainstone indicating deposition in a high-energy environment (Kuppen 3).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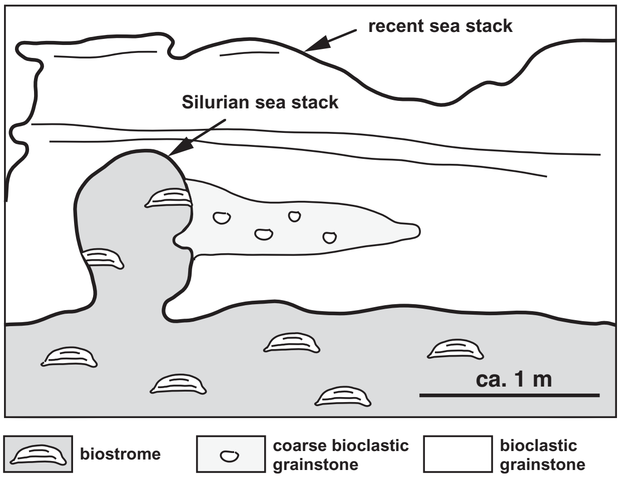



Figure 3 Sketch of a fossil sea stack (Kuppen 1). A very nice photograph of this sea stack taken by Björn Sundquist is published on the GFF cover, volume 116/2.

period so far.

### Locality data

KUPPEN 1, 6370598 1687580, ca. 4170 m E of Östergarn church. Map: 56D Ljugarn. Cliff section at the southernmost end of the cliff at the innermost part of the bight, ca. 30 m NW 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.
*Hemse Group*, unit d. *P. siluricus* Zone in the bedded limestone unit.
*References*: Munthe 1910, Fig. 28; Hede 1929, Fig. 12, p. 40, lines 11-31; Hede 1960, Loc. 39 *pars*, p. 78, line 15 from below - p. 79, line 8; 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, ca. 4140 m E of Östergarn church. Map 56D Ljugarn. Cliff section, ca. 110 m NW of the easternmost tip of Snabben, ca. 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 is marked in the section.
*Hemse Group*, unit d.
*References*: Hede 1929, Fig. 13, p. 40, lines 1-13 from below; Hede 1960, Loc. 39 *pars*, p. 79, lines 9-30; 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, ca. 4120 m E of Östergarn church. Map 56D Ljugarn. Cliff section ca. 170 m NW of easternmost tip of Snabben, ca. 70 m NW of Kuppen 2.
*Reference point*: Marked on the cliff in red paint.
*Reference level*: The erosion surface at the top of the lowest biostrome.
*Hemse Group*, unit d and *P. siluricus* Zone at least 1 m above the third biostrome.
*References*: Kershaw 1987a, b, 1990, herein*; Neuman & Kershaw 1991; Samtleben et al. 2000.

KUPPEN 4, (CJ 7548 6668), ca. 4050 m E of Östergarn church. Map 56D Ljugarn. Cliff section ca. 280 m NW of easternmost tip of Snabben, ca. 170 m NW of Kuppen 2.
*Reference point*: Marked on the cliff in red paint.
*Reference level*: The base of the lowest biostrome.
*Hemse Group*, unit d.
*References*: Kershaw 1987a, 1990, herein*; Neuman & Kershaw 1991.

## Outcrop No 9: Botvide 1

Target: The beginning of the Lau Event and the Late Ludlow Hemse Group-Eke Formation boundary strata.

**Description:** Road-section along the Lau outlier. The section exposes the uppermost Hemse Group (Botvide Member, När Formation) and the lower Eke Formation. The Hemse Group consists of thin-bedded, argillaceous dolomite-rich (8-17%) limestones and marls (Munthe 1902, 1910; Munnecke 1997), partly rich in *Dayia navicula* (brachiopod). The upper boundary is marked by a discontinuity surface, overlain by coarse, conglomeratic bioclastic grainstones of the Eke Formation. In the upper part of this outcrop, massive reefal limestones with abundant favositid corals, rugose corals, and bryozoans are cropping out.
The discontinuity surface at the top of the Hemse Group and the basal Eke Formation conglomerate occur across most of Gotland but the conodont faunas indicate that only a few decimetres of sediments are missing. At nearby localities, the top Hemse decimetre(s) has a distinct fauna with the brachiopod *Shaleria* aff. *ornatella* (described by Munthe 1902) covering most bedding planes. Further, in about the same interval, conodonts are rarer, small specimens dominant, and *Oz. excavata* more frequent than *Oz. c. confluens*. Neither of these faunal characters has been found at this locality, indicating that erosion has cut slightly deeper here, at the northernmost exposure of the Hemse/Eke boundary. About 20 conodont taxa existed on Gotland when the main part of the När Formation was formed (its topmost part was exposed locally in the road ditch when the section was new). 15 of these taxa, including all with platform elements, had become extinct or disappeared on Gotland before the Eke begun to form (two taxa have been found in the basal Eke but contamination from a reworked Hemse conglomerate pebble can not be excluded). The extinctions were probably stepwise like during the Ireviken and Mulde events, but most of the expiring taxa were so rare that it is difficult to identify the exact positions of the datum planes. The youngest collected halysitid specimens on Gotland were recently found here (by O. Sandström and by LJ; further finds would be scientifically important). As far as we know, these may well have been the last representatives of this order. Similarly, major extinctions affected most major clades during the Lau Event.

**Isotope stratigraphy**: Three isotope samples (each consisting of shell material from several *D. navicula*) located 5mm below the discontinuity surface have been measured for stable isotopes. The δ$^{13}$C values of 1.5‰ indicate a position during the early part of the upper Ludfordian A-period. No brachiopods were found in the Eke Formation from Botvide 1. In Nyan 2, which is located ca. 4 km to the SE, δ$^{13}$C values of 4.6‰ have been recorded in the lowermost Eke Formation (Samtleben et al. 2000).

#### Locality data

BOTVIDE 1, 6355803 1671542, ca. 2350 m NE of Lau church. Map: 56D Ljugarn. A ca. 3 m high road cutting W of the road, SSW of the S house at Botvide. Hede 1925, 1960 gave a detailed description. The section was improved in May 1993 but has then slowly deteriorated.

*Reference level:* The Hemse-Eke boundary, marked by a basal Eke conglomerate (see below). 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.

*Lithologies:* Exposed *Hemse* consists of interbedded limestone and marls. The contact between the main part of the När Fm and the Botvide Mbr is indistinct (it is close to the bottom of the ditch). The distinct upper ca 0.5 m of the member was once referred to as the *Dayia* Flags (Munthe 1902) because of coquinas of the brachiopods *Dayia navicula* in some beds and a higher weathering resistance (it is dolomitic) than subjacent strata. This "*Dayia* lithology" is found across Gotland and at most other localities is overlain by ca 0.1 m of *Shaleria* aff. *ornatella* coquinas (Munthe 1910).

*Eke Fm* starts with a thin basal conglomerate of Hemse Marl pebbles. This conglomerate is found at least as far SW as Malms 1. However, erosion was slight, at the most c. 0.1 m of Hemse is missing here (see above). It is overlain by more or less oncoidal crinoid limestone. 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. Due to the more weathering-resistant character of the boundary strata, the Hemse/Eke boundary is exposed in several sections.

*Age: Polygnathoides siluricus*, indicator of the *P. siluricus* Zone, occurs up to −1.40 m here, but to within 0.1 m below the base of the Eke at Malms 1 (its frequency is below 1/10 000 specimens in the Botvide Mbr). *Neobeyrichia lauensis and N. scissa* correlate the exposed strata with the 'middle' Ludfordian (or more precise, the Late Leintwardinian, Martinsson 1967, and/or the earliest Early Whitcliffian).

*Oceanic conditions:* Strata below c. -2.15 m probably represent the Havdhem Primo Episode; succeeding Botvide Mbr the early Lau Event; the Eke the middle Lau Event. The event started at c. -2.15 m with Datum 1. As during other primo-secundo events, initially the conodont faunas remained essentially the same as during the preceding Havdhem Primo Episode, although large collections reveal some differences. *P. siluricus* became exceedingly rare. About 50 % of the conodont taxa disappeared during the time represented by the strata exposed. Most of these taxa had a frequency of ca 1 % to <1‰, hence the position of the succeeding datum points is not yet precisely known. The fate of other major clades is less precisely known but literature data indicate substantial macrofaunal differences between the main part of the När Fm and the Eke Fm.

*References:* Munthe 1902:41, lines 20-22, line 26 - p. 42, line 11 (incl. lists of fossils); van Hoepen 1910:50; Hede 1925:45, lines 17-32 (incl. lists of fossils); Hede 1960:80-81, Loc. 42; Martinsson 1962:57, 1967:370, line 21; Fåhraeus 1969:12, 14; Laufeld 1974a, b*; Jeppsson 1975:10, 1982, 1983; Hurst 1975b; Larsson 1979; Laufeld & Martinsson 1981; Cherns 1982, 1983; Klaaman & Einasto 1982; Ramsköld 1986; Fredholm 1988a, b; Le Hérissé 1988, 1989; Bergman 1989, 1995; Sivhed 1990; Young & Scrutton 1991; Sanford & Mosher 1994; Jeppsson & Aldridge 2000; Samtleben et al. 2000.

### Outcrop No 10: Bodudd 1 and 2

Target: The Lau Event and the Late Ludlow Hemse Group-Eke Formation boundary strata in distal platform environments.

**Description:** The three members exposed here are lithologically and faunally easily recognised. The Botvide Member (När Formation, Hemse Group) consists of well-bedded more or less shaly, calcareous, dolomitic mudstones, and a few very argillaceous limestones. The member also includes a distinctly pale, 26 mm thick, hard (resounding when a handheld slab is struck by the hammer) dolomite layer. Further, the member includes at least one typical *Dayia navicula* coquina bed (5-15 mm). It crops out c. 15-20 m from the dolomite, in the direction of the dip. Another 8 m away there is a thin limestone bed. Near the top of the member, some beds are rich in small cephalopods, and one interval is enriched in hyolithids (O. Sandström, pers. comm.).

The lower Eke member consists of c. 2.55 m (O. Sandström pers. comm.) of ± unbedded dolomitic mudstones without oncoids. The dolomite content in the lower Eke Fprmation is among the highest observed on Gotland so far, and varies between 15 and 22% (Munnecke 1997). The Hemse/Eke contact is conformable in contrast to in more proximal localities (compare Outcrop No 9: Botvide 1). Most of the strata are markedly jointed, probably because they are at or close to a disturbance (fault?). As a result, they weather into angular pieces. Conodonts up to 0.15 m below the assumed top of this member identify these strata as lower Eke. Hede (1919) similarly identified a 1.57 m thick lowermost Eke interval without oncoids in the Burgsvik core. The middle Eke member consists of oncolitic mudstones. It is exposed below the vegetation in the southern part of the bay. Conodonts from 0.15 m above the first oncolites identify these strata as middle Eke.

At Bodudd 2, south of the road and somewhat eastwards, conodonts identify the strata as upper Eke member. The thin-bedded argillaceous limestones and marls are extremely rich in oncolites (see Plate 2/3 in Samtleben et al. 2000), and contain a diverse, fully marine brachiopod fauna (often preserved as nuclei of the oncoids). With respect to conodonts, this member represents the worst part of the Lau Event. The conodont fauna is closely similar to those during the worst parts of the Ireviken and Mulde events. All three faunas are strongly dominated by taxa with coniform elements, chiefly a single taxon of the *Panderodus equicostatus* group with very slender elements.

Isotope stratigraphy: Up to now, the strongest positive δ$^{13}$C excursion (upper Ludfordian A-period) of the Phanerozoic is reported on a global scale in the late Silurian (summarised in Munnecke et al. 2003). At Bodudd 1 δ$^{13}$C values increase continuously from 2.3‰ (Botvide Member; lower part of Bodudd 1) to 7.8‰ in Bodudd 2 (upper Eke Formation) (Samtleben et al. 1996, 2000).

**Locality data**

BODUDD 1, 6329554 1644709, ca. 6220 m SW of Näs church. Map: 56B Hemse. Shore exposure north of the point.

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

*Reference level*: The Hemse-Eke boundary (Laufeld 1974b). There has been some confusion regarding the identification of this level. Hence, a physical distinct layer is selected here as: *Auxiliary reference level for the lower part of the section*: The upper surface of the dolomite bed.

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

*Auxiliary reference level for the upper part of the section, the strata nearer to the contact between strata without and those rich in oncolites*: The upper surface of the most distinct, laterally continuous layer 0.52 m below the first scattered small oncolites. Below the water it has a slippery dark brown coating of recent alga with grassing traces. Two similar, but less distinct, beds are found at +0.20 and +0.35 m, respectively. The frequency of oncolites increases rapidly upwards.

Hemse Group, *När Fm*, Botvide Mbr. The upper part of the *P. siluricus* Zone. *Eke Fm*, the boundary between the lower part and the middle part is below the FAD of *Pa. equicostatus* at +0.67/0.70 m, that is, at or very close to where the first oncoids appeared; it is also the boundary between the lower and the middle subzones of the Icriodontod Zone.

*Oceanic conditions:* See the description of Botvide 1.

*References:* Munthe 1921, p. 25, lines 19-20, p. 26, lines 8-10 and 20-23; Laufeld 1974a, b*, c, 1993; Larsson 1979; Jeppsson 1982, 1983; Cherns 1983; Ramsköld 1986; Fredholm 1988a, b; Bergman 1989; Samtleben et al. 2000.

BODDUD 2, 6329417 1644750, ca. 6300 m SW of Näs church. Map 56B Hemse.

Shore exposure SW of the field road, ca. 750 m WNW of the triangulation point at Skåls. Bodudd 2 is located to the W of the tail of erratic boulders in the sea.

*Eke Fm*, upper member.

*References*: Munthe 1921, p. 26, lines 2-3 from below; Laufeld 1974a, b*; Larsson 1979; Cherns 1983; Bergman 1989; Sivhed 1990; Samtleben et al. 1996; 2000.

## Outcrop No 11: Husryggen 4

**Target:** The Burgsvik Sandstone and oolite.

**Description:** Abandoned quarry exposing thick bedded, massive to hummocky cross stratified sandstones overlain by cross bedded, bivalve-rich oolites and oncolites (Plate 5/1). The boundary between the sandstones and the overlying carbonates represents a major transgressive surface and sequence boundary. The Burgsvik Sandstone has been used at least since medieval time for sculptures e.g. in churches. It has been famous as a grinding stone, and large quantities have been quarried and exported. The fossil content is variable but generally scarce (especially for shelly fossils). Vertical burrows, various kinds of traces, grazing tracks, and imprints of resting animals (plate 5/2) are observed, and document the activities of a vagile benthic fauna in this environment. In the abandoned quarry Uddvide 3 beautiful load casting structures can be observed (plate 5/3). At nearby Kettelviken 1, the oolite contains conodonts from the *O. snajdri* Zone, including *O. excavata*, which had returned when these strata were formed. It had been absent since the worst part of the Lau Event and a period afterwards.

**Isotope stratigraphy**: No isotope data exist from this outcrop. In the Burgsvik Sandstone, measurements of stable C and O isotopes from brachiopods have been carried out on samples from Kulhaken 2, Uddvide 3, Ronehamn 4, and from Närs Hamn 3 and 4. The values vary from 7.0 to 8.7‰ for $\delta^{13}C$, and from −4.7 to −2.6‰ for $\delta^{18}O$, and are close to the maximum values observed in the upper Ludfordian A-period on Gotland. It might be interesting to note that despite the fact that these brachiopods are sampled from a sandstone with a high permeability (aquifer), no indications for a fresh-water alteration of the isotope signal are observed.

**Locality data**

Husryggen 4, 631571 164281, ca. 2110 m WNW of Sundre church. Map 56A Hoburgen.

Abandoned quarry about 10 m W of the road, SW and NE of a small road leading down towards the beach, ca. 850 m S of the house at Klasens.

*Reference level*: The highest massively bedded sandstone bed below the first accumulation of *Pteronitella retroflexa*.

*Burgsvik Fm*, uppermost part.

*Reference*: Stel & de Coo 1977*.

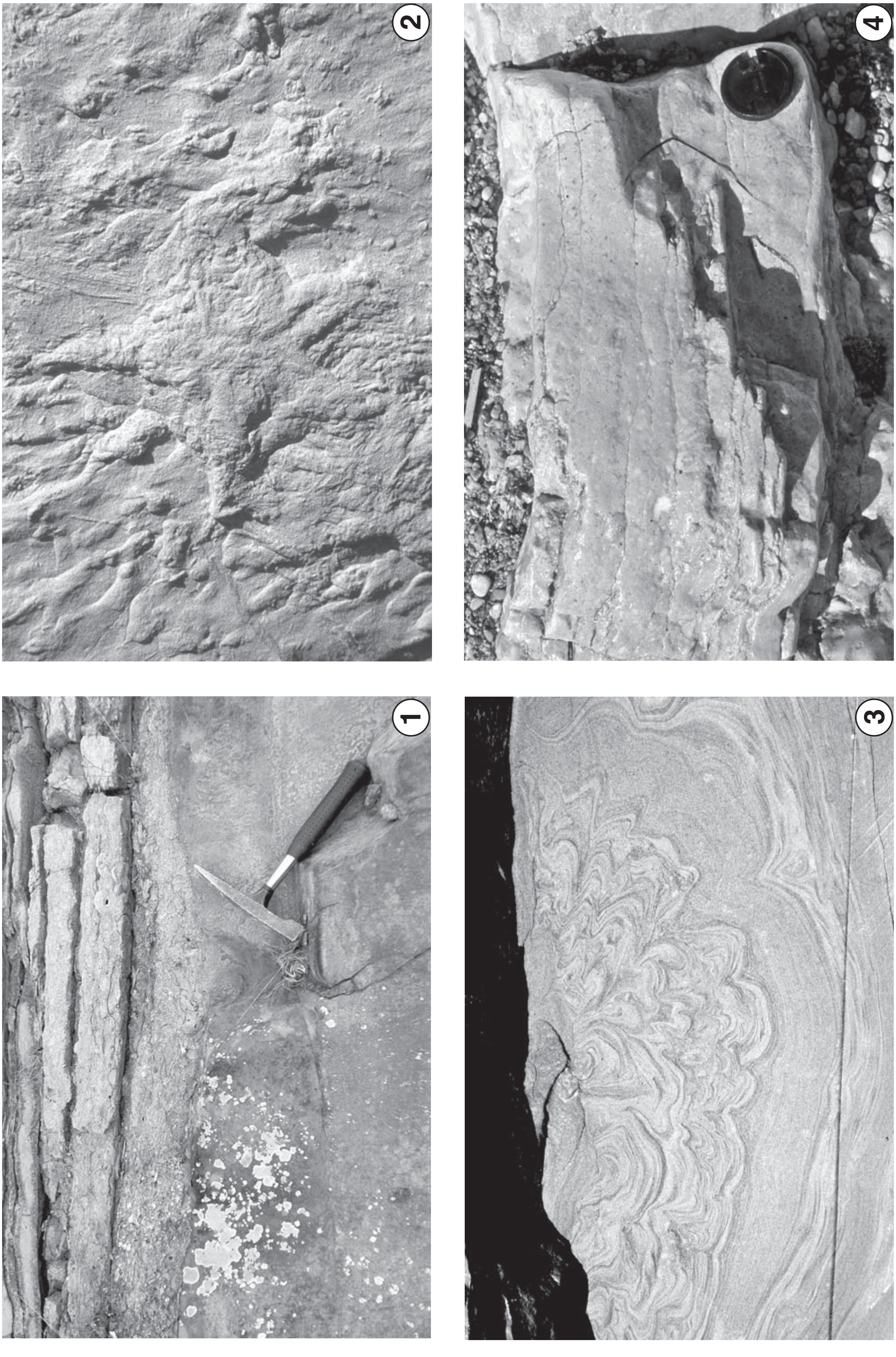
## Outcrop No 12: Holmhällar 1

**Target**: Faro reef in the latest Ludlow (Sundre Formation) just before the Klev Event.

**Description:** In the area around Holmhällar a very special reef type is exposed (cp. Fig. 2 in Samtleben et al. 2000). The characteristic form is that of an atoll-like semicircle (open to the NW) with a diameter of 0.5-1km, and with distally dipping biostromal surfaces. In analogy to similar structures observed in the Maldives this reef type is called "faro" (Samtleben et al. 2000). On Gotland, this reef type is only known from the uppermost Sundre Formation (Samtleben et al. 2000). The reefs are composed of dense stromatoporoid framestones and/or bindstones, and

Plate 5

1) The boundary (transgressive surface) between the Burgsvik Sandstone and the Burgsvik Oolite (both of Burgsvik Formation) at Kättelviken. Note rugged and slightly irregular top of the sandstones.
2) Lower bedding plane of Burgsvik Sandstone with imprint of starfish (*Palaeasterina*). (Kettelvik Stenmuseum)
3) Load casting in the Burgsvik Sandstone (cut perpendicular to bedding; from the abandoned quarry Uddvide 3).
4) Vertical fissure in reef limestone (view from above), repeatedly opened and filled with sedimentary material during reef growth. This is a typical phenomenon in the faro-like reefs of the Sundre Formation in southern Gotland (Holmhällar 1)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crinoidal bafflestones, normally with a fine-grained matrix. Occasionally, solenoporaceen algae are observed. The reef rocks alternate with micritic or sparitic crinoidal limestones, and coarse, partly conglomeratic grainstones. The interior areas of the faros formed lagoons which were presumably filled with soft sediments (not exposed). At least 5 of these faros are known on Gotland, including Hammarshagehällar (ca. 1.5km toward the NE), Salmundsudd (ca. 3km toward the NE), and the small island Heligholmen (the islet ca. 1km SW of here). Conspicuous vertical fissures, up to 0.5m wide, cut radially and concentrically through these reef rings. These neptunian dykes have been opened and refilled with sediment material repeatedly (plate 5/4). The faros were situated on the southeastern margin of an extended stromatoporoid biostrome. During rising sea level, they grew predominantly in SE direction, and due to their increasing size/weight fissures opened, and were repeatedly filled with sedimentary material (Samtleben et al. 2000).

At least some of the strata here were deposited only slightly before the Klev Event, the first secundo-primo event detected (Jeppsson & Aldridge 2000). A better knowledge about the faunal sequence during the Klev Seundo-Primo Event is needed before it is possible to tell if the discontinuity surface described by Kano (1989) and the youngest sediments here were formed during that event.

**Isotope stratigraphy**: No isotope data exist from this locality, or from one of the other faros. Isotope data from the underlying biostrome at Hammarshagehällar 3 ($\delta^{13}C$ = 2.13‰) indicate a position in the uppermost part of the upper Ludfordian A-period.

Please note that hammers are strictly forbidden.

### Locality data

HOLMHÄLLAR 1, 6314268 1651201, ca. 5670 m SE of Vamlingbo church. Map: 56A Hoburgen. The sea stack area mapped in detail by Manten 1971, his Enclosure 2.

*Reference point*: The coordinates given above refer to Manten's 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 and is figured in a coloured post-card to be obtained at the boarding-house at Holmhällar.

*Sundre Fm. O. crispa* Zone.

*References*: Lindström 1890, p. 30, last line, p. 33, line 8, p. 38; Hennig 1906, p. 44, line 11 from below; Munthe 1921, Figs. 73-75, p. 67, line 5 from below; 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; Jeppsson 1982; Ramsköld 1983; Le Hérissé 1988, 1989; Bergman 1989; Kano 1989 (detailed map), 1990, 1994; Fredholm 1989; Neuman & Kershaw 1991; Kershaw & Keeling 1994; Kershaw 1998; Jeppsson & Aldridge 2000; Samtleben et al. 2000.

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# Authors Index


ACHAB **17**
AHLBERG 81
AL-RUWAILI 72
ALBANESI **18,** 57
ALBANI 20
ÁLVARO **18,** 74
ANTOSHKINA **19**
ARMSTRONG **20**
ASSELIN 17
BABIN 34
BAGNOLI **20**
BARNES 69
BASSETT **21**
BERGSTRÖM 30, **81**
BICKERT **22**
BLANCHON **22**
BOGOLEPOVA **23,** 39
BOMBACH 63
BOUCOT 26
BREISIG 43
BRENCHLEY **24**
BROCKE 36
BRUCH 54
BUGGISCH 43
BUTTLER 27
CALNER **25,** 30, **113, 133**
CHELLAI 49
CHEN **26,** 35, 65
CHERNS **27,** 75
CHOI 47
CHOUGH 76
COCKS **27,** 37
COUTO **28**
CRAMER **29**
DAHLQVIST **30**
DASTANPOUR 21
DESTOMBES 18, 73
DEYNOUX 55
DÍAZ-MARTÍNEZ **31**
DOBEŠ 48
DRONOV **32**
DUBININA **32**
EBLE 34
ÈERNÝ 48
EGGINS 69
ERIKSSON 41
ERNST **33**
ESPRIT **34,** 50
FAN 26, **35**
FATKA **36,** 48
FORTEY **37**
FRANCOIS **38**
FRIGERIO 57
FRÝDA 48, 57
GEIGER 54
GELDERN, van 43
GHIENNE 49, 55
GHOBADIPOUR 21, **38**
GÓMEZ 74
GRAHN 31
GRITITE 42
GROOTEL, van 71
GUBANOV **39**
GUTIÉRREZ-MARCO 28
HAIRAPETIAN 38
HARPER 24, 30, **40,** 62, 80
HERRMANN **40**
HINTS **41**
HOSSEINI 38
HOUICHA 49
JANKAUSKAS **42**
JAVIER ÁLVARO 73
JENDRYKA-FUGLEWICZ **42**
JEPPSSON 113, 133
JOACHIMSKI **43**
KALJO **44**
KERSHAW **45,** 51
KHOUKHI 49
KIIPLI, E 45
KIIPLI, T **45**
KOENIGSHOF **46**
KOZŁOWSKA-DAWIDZIUK 25
KRAFT 48
LAZAUSKIENE 46
LEE **47**
LEFEBVRE 47, **50,** 55
LEHNERT 38, **48,** 57, 65
LE HÉRISSÉ 61, 72
LE HERON **49**
LI Jun **51**
LI Yue **50**
LUBNINA **52**
MAKHLOUF 20
MANDA **52**
MAØÍK 48
MARSHALL 24
MARTMA 44
MASIAK 25
MASSA 27
McCRACKEN 69
McCULLOCH 69
MELCHIN 26
MERGL **53**
MICHEELS **54**
MITCHELL 26
MONTENARI 54
MOREAU **55**
MOSBRUGGER 54
MUNNECKE 22, 66, 113, 133
NARDIN **55**
NICOLL 69
NIEUWENHOVE, van 70
NÕLVAK 17, **56**
NOTEN, van 71
NOWLAN 69
NÜTZEL **57**
ORTEGA **57**
OWEN **58**
PARIS 17, **59,** 65
PATZKOWSKY 40
PAWLIG 63
PODHALAŃSKA **60**
POPOV 21, 32, 38
PROSS 66
RAEVSKAYA 22, **61**
RIBECAI 20
ROGER 28
RONG 26, **62**
ROZHNOV **62**
RUBINO 55
RYAZANTSEV 32
SAADRE 44
SALTZMAN 29
SAMTLEBEN 22
SCHINDLER 46
SCHULBERT 57
SCHULZ **63**
SCOTESE **64, 65**
SEGHEDI 70
SERVAIS 22, **65,** 66
SHI 67
SIVETER 23
SODRÉ-BORGES 28
STEEMANS 61
STEPPUHN 54
STOUGE **91**
STRICANNE **66**
SU **67**
SUTTNER 33
TOLMACHEVA **68**
TORTELLO 65
TROTTER **69**
TURNER 20
TYCHSEN 40
UHL 54
UNDERWOOD 24
VAIDA **69, 70**
VANDENBROUCKE **70**
VANMEIRHAEGHE **71**
VECOLI 22, **72**
VELICIU 69
VENNIN 18, **73**
VERNIERS 69, 70, 71
VILLAS 18, 73, **74**
VIZCAÏNO 18
VOLDMAN 18
VYHLASOVÁ **75**
WEBBY 59
WHEELEY **75**
WILDE 46
WOO **76**
WRIGHT 75
WRONA **77**
XU **78**
YALÇIN 46
YAN 50
YOUNG 45
YU 78
ZHAN 26
ZHANG 35
ZIGAITE **79**
ZUYKOV **80**