Following in the footsteps of Richard Granville Bromley

Abstracts

and

Field Guide

Edited by David C. Kopaska-Merkel, Jesper Milàn,
Kurt S. S. Nielsen, Andrew K. Rindsberg & Lothar H. Vallon

With contributions by Ulla Asgaard [†], Richard G. Bromley [†], Morten
Bjerager, Peter Frykman, Jan Kresten Nielsen & Arne Thorshøj Nielsen

This field guide is based upon previous guides written by various authors who kindly gave us permission to reproduce their texts. We are very grateful for this.

The 17th International Ichnofabric Workshop was kindly sponsored by these institutions:
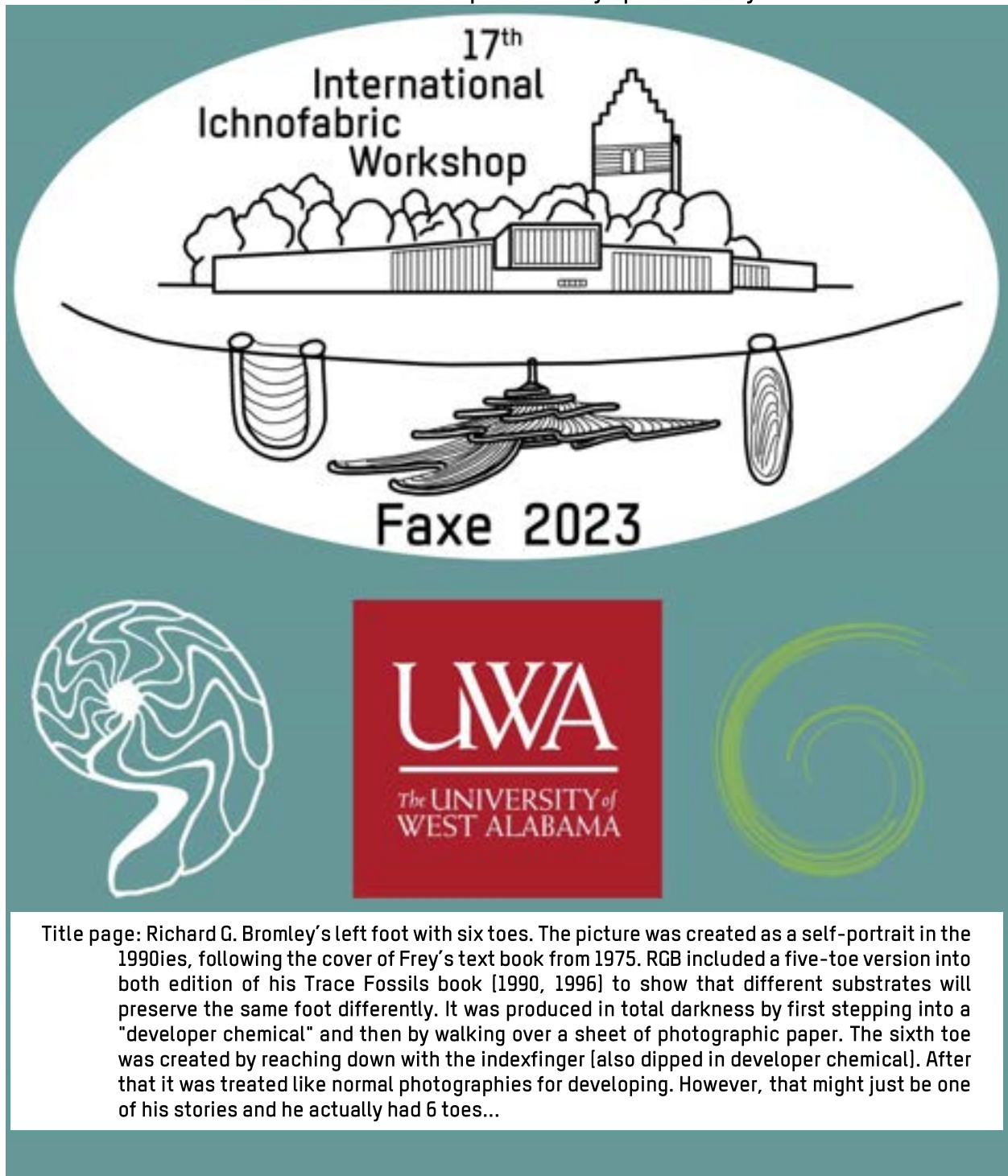
Title page: Richard G. Bromley's left foot with six toes. The picture was created as a self-portrait in the 1990ies, following the cover of Frey's text book from 1975. RGB included a five-toe version into both edition of his Trace Fossils book (1990, 1996) to show that different substrates will preserve the same foot differently. It was produced in total darkness by first stepping into a "developer chemical" and then by walking over a sheet of photographic paper. The sixth toe was created by reaching down with the indexfinger (also dipped in developer chemical). After that it was treated like normal photographies for developing. However, that might just be one of his stories and he actually had 6 toes...

Content

Conference Program

Fig. 1: Map of the town of Faxe with localities of the venue. Created with Google Maps.

In Faxe are two supermarkets, several restaurants and take-away shops. Everything is in walking distance from both the Kulturmuseum Øst and the DanHostel. Credit cards are widely accepted in Denmark, but cash payment almost does not exist. However, shops must accept cash payment by customers.

Monday, 23. October 2023

Pre-meeting field trip: Stevns Klint
Departure from the Dan Hostel in Faxe at 9:00 am, return to Faxe around 05:00 pm [= 17:00].
For details about the field trip, see pages: 43-56.

Icebreaker party and registration
...at the Geomuseum Faxe [only a few metres from the Dan Hostel]:

05:30 pm to 06:00 pm [18:00]:   Registration

06:00 pm to ca. 10:00 pm [22:00]: Icebreaker party

06:30 pm [18:30]:   Jakob Walløe Hansen [Chairman of
                                  the Geological Society of Denmark]
                                  will honour Ulla Asgaard and
                                  Richard Bromley in a brief talk.

The event is kindly sponsored by Royal Unibrew.
THANK YOU VERY MUCH!!!

Tuesday, 24. October 2023

Talks in the auditorium of the Kulturmuseum Øst, Rådhusvej 2, Faxe.

Time	Presenter	Title of presentation
10:00-10:30	Kasper Østervig [Director, Østsjællands Museum] Jesper Milàn [Østsjællands Museum] Andrew K. Rindsberg [University of West Alabama] Lothar H. Vallon [Østsjællands Museum]	Opening Ceremony
10:30-11:00	Coffee Break and poster session*	
11:00-11:45	GALE, A.S.	Rullard – Richard Bromley and Ulla Asgaard; a short account of their lives, their work and their food
11:45-12:10	VALLON, L.H. & KJELDAHL-VALLON, T.A.	The trace fossil collection of Richard G. Bromley
12:10-13:30	Lunch Break	
Session 1: PALAEOECOLOGY – Predators and prey; ecosystems through time		
13:30-13:55	FENG, X., CHEN, Z.-Q., BENTON, M.J., SU, C., BOTTJER, D.J., CRIBB, A.T. LI, Z., ZHAO, L., ZHU, G., HUANG, Y. & GUO, Z.	Resilience of infaunal ecosystems during the Early Triassic greenhouse Earth
13:55-14:20	CHEN, Z.-Q., FENG, X., BENTON, M.J., BOTTJER, D.J., CRIBB, A.T., SU, L. ZHAO, L., JIANG, Y., YAN, P., HUANG, Y. & GUO, Z.	Predator-prey interactions in the Early Triassic warming ocean
14:20-14:45	GOLDSTEIN, D.H. & MERLE, D.	Gastropod prey of the middle Lutetian muricid, *Crassimurex calcitrapa* [Lamarck, 1803]
14:45-15:15	Coffee Break and poster session*	
15:15-15:40	WANG, Z. & RAHMAN, I.A.	Numerical simulations reproduce the earliest excursions on land by animals
15:40-16:05	NIELSEN, K.S.S.	Are borings boring? – Bioerosional traces in a foraminiferal test
16:05-16:30	JAQUES, V.A.J., KERKHOFF, M., HOLCOVÁ, K., ŠALPLACHTA, J., ZIKMUND, T. & KAISER, J.	Microborings in foraminifera analysed with submicron X-ray Computed Tomography

* Posters will be set up at the area where we will have the coffee breaks.

<u>Wednesday, 25. October 2023</u>

Time	Presenter	Title of presentation
Session 2: ICHNOSTRATIGRAPHY – Focus on sediments		
09:00-09:25	LIMAM, H., OUALI MEHADJI, A., MAHBOUBI, C.Y. & OUDIA, L.	Trace fossils from the Grès de Sidi Saâdoun Formation (Callovo-Oxfordian transition) at its type locality (Nador Range, Preatlasic Trough, North-western Algeria): inventory and implications
09:25-09:50	KOPASKA-MERKEL, D.C., RINDSBERG, A.K. (speaker) & EBERSOLE, S.	Ichnostratigraphy of a storm in the Pennsylvanian of Alabama (USA)
09:50-10:20	**Coffee Break and poster session**	
Session 3: ICHNOTAXONOMY – Procedure in Classification		
10:20-10:45	RETALLACK, G.J.	Ediacaran "Epibaion", "Kimberichnus", *Aulozoon*, and Mistaken Point "locomotion traces" are not trace fossils
10:45-11:10	RETALLACK, G.J.	Latin names for microbial traces
11:10-11:35	WANG, Z. & RAHMAN, I.A.	A new quantitative framework to determine the trace makers of locomotory trace fossils: Palaeozoic *Gordia* as a case study
11:35-12:00	RINDSBERG, A.K. & HENSEN, C.J.	Making *Thalassinoides* and similar burrows useful in stratigraphy
12:00-13:00	**Lunch Break**	
13.00-17:00?	Mid-meeting field trip: Faxe Quarry	

Mid-meeting field trip: Faxe Quarry
Departure from the Geomuseum in Faxe at 01:00 am (13:00), return around 05:00 pm (= 17:00). For details about the field trip, see pages: 43-56.

Conference dinner at the Dan Hostel, Faxe, beginning at 06:00 pm (18:00).

Thursday, 26. October 2023

Time	Presenter	Title of presentation
Session 4: FORM AND FUNCTION – Case studies on trace fossils		
09:00-09:25	NARA, M.	Glow with the worm: a probable function of translucent burrow linings of *Schaubcylindrichnus*
09:25-09:50	CINCINNATUS, K.B., LYNGSIE, G. & ELSTRUP, M.	Determining ichnogenus and species of a trace fossil from the Gram Clay Pit (late Miocene, Denmark)
09:50-10:15	POKORNÝ, R., NOHRA, R., ABI SAAD, P. & VALLON, L.H. (speaker)	Death in "live broadcast": fish mortichnia from the Late Cretaceous plattenkalke of Lebanon
10:15-10:35	VALLON, L.H., RASMUSSEN, J.A. & MADSEN, H.	Underground pagodas: a new sequestrichnion from the Maastrichtian of Denmark
10:35-11:05	Coffee Break and poster session	
Session 5: ICHNOFABRICS – Making sense of mottling		
11:05-11:30	KNAUST, D. & SHARP, I.	Reconstruction of deltaic environments in the Jurassic Brent Group (Norwegian North Sea) by means of ichnofabrics
11:30-11:55	GOUGEON, R., MÁNGANO, M.G., BUATOIS, L.A., NARBONNE, G.M., LAING, B.A. & PAZ, M.	Ichnofabrics and paleoecologic turnovers from the Ediacaran-Cambrian Chapel Island Formation (Canada)
11:55-12:20	DORADOR, J., MÍGUEZ-SALAS, O. & RODRÍGUEZ-TOVAR, F.J.	The use of Computed Laminography for the study of deep-sea ichnofabrics in recent sediments
12:20-13:20	Lunch Break	
13:20-13:45	MIGUEZ-SALAS, O., RODRÍGUEZ-TOVAR, F.J., DORADOR, J., BETT, B.J., CHARIDEMOU, M.S.J. & DURDEN, J.M.	Ichnofabric comparison between hill and abyssal plain: going from palaeo- to neoichnological data
13:45-14:10	TOOM, U., KRÖGER, B. & KNAUST, D.	A *Balanoglossites-Trypanites* ichnofabric from the Upper Ordovician warm-water carbonates of Estonia
14:10-14:35	BELAÚSTEGUI, Z. & MUÑIZ, F.	*Parahaentzschelinia* in an *Ophiomorpha* ichnofabric from the lower Pliocene of Lepe (Huelva, SW Spain)
14:35-15:05	Coffee Break and poster session	
Session 6: LOOKING AHEAD – The future of ichnology		
15:05-15:30	Andrew K. Rindsberg & Lothar H. Vallon	Invertebrate ichnology, moving forward
15:30-15:45	Jesper Milàn (Østsjællands Museum) Andrew K. Rindsberg (University of West Alabama) Lothar H. Vallon (Østsjællands Museum)	Closure of the meeting

Friday, 27. to Sunday, 29. October 2023
Post-meeting field trip: Bornholm

For more details, see pages: 63-87.

Departure from the Youth Hostel in Faxe at 08:00 am. Ride on minibusses to Bornholm, via Sweden. Ferry from Ystad at 12:30. The ferry offers many possibilities to buy lunch.

Ferry from Rønne to Ystad [Sweden] at 02:30 pm [14:30]. Return to Copenhagen,

Airport: around 05:30 pm [17:30];

Main train station: around 06:00 pm [18:00].

Abstracts

Posters

Funnel-shaped trace fossils from the marine-nonmarine transition of the Upper Devonian in Tioga County, Pennsylvania, USA

by Donald H. GOLDSTEIN[1]*, Andrew M. BUSH[2], Lothar H. VALLON[3], Michael C. RYGEL[4], David R. BROUSSARD[5] & Pierre A. ZIPPI[6]

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5] Department of Biology, Lycoming College, 700 College Place, Williamsport, Pennsylvania 17701, USA; broussar@lycoming.edu
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* Corresponding author

Funnel-shaped trace fossils from marginal marine facies of the lower Catskill Formation in Tioga County, Pennsylvania, display variable preservation and unusual spatial arrangements on bedding planes. Brachiopod assemblages from underlying marine strata have been dated as early Famennian, and overlying strata have been dated to the early part of the late Famennian using palynology.

Burrows are typically about 0.5–1.0 centimeters in diameter and about 2–3 centimeters deep. The lower portions of the burrows taper gently and are preserved in full relief within sandstone bedding planes. The upper portions of the burrows widen more broadly, giving the burrows their funnel shape. Upper portions of the burrows are preserved in full relief or as casts on the bases of beds. Burrows were passively filled when buried by sandy sediment and have mud linings [Fig. 1]. We interpret the burrows as having a flared opening that was either open to the water column or occupied by the upper portion of the animal's body.

When buried by thin layers of sand [e.g., a couple of millimeters], the animals accommodated by migrating upwards so that the flared, upper portions of the burrows formed cone-in-cone traces. When buried by several centimeters of sand, the animals were still able to migrate upwards, as indicated by alignment of burrows on the bottoms and tops of sandstone slabs.

On some bedding planes, burrows are clustered in roughly linear groups that reflect the spatial organization of the living tracemaker population. Comparisons of bottoms and tops of slabs indicate that these groupings were maintained as the animals migrated upwards following burial by up to several centimeters of sediment. We discuss several possible explanations, which are not mutually exclusive, for the formation of these groups. In modern habitats subject to tidal currents, some animals form linear groupings or otherwise align themselves to the currents [e.g., Barwis, 1985]. More speculatively, the groupings might have improved the efficiency of upward migration following burial in a setting with frequent sedimentation events.

References:

Barwis, J.H. 1985: Tubes of the modern polychaete *Diopatra cuprea* as current velocity indicators and as analogs for *Skolithos-Monocraterion*. – SEPM Special Publication 35, 225–235.
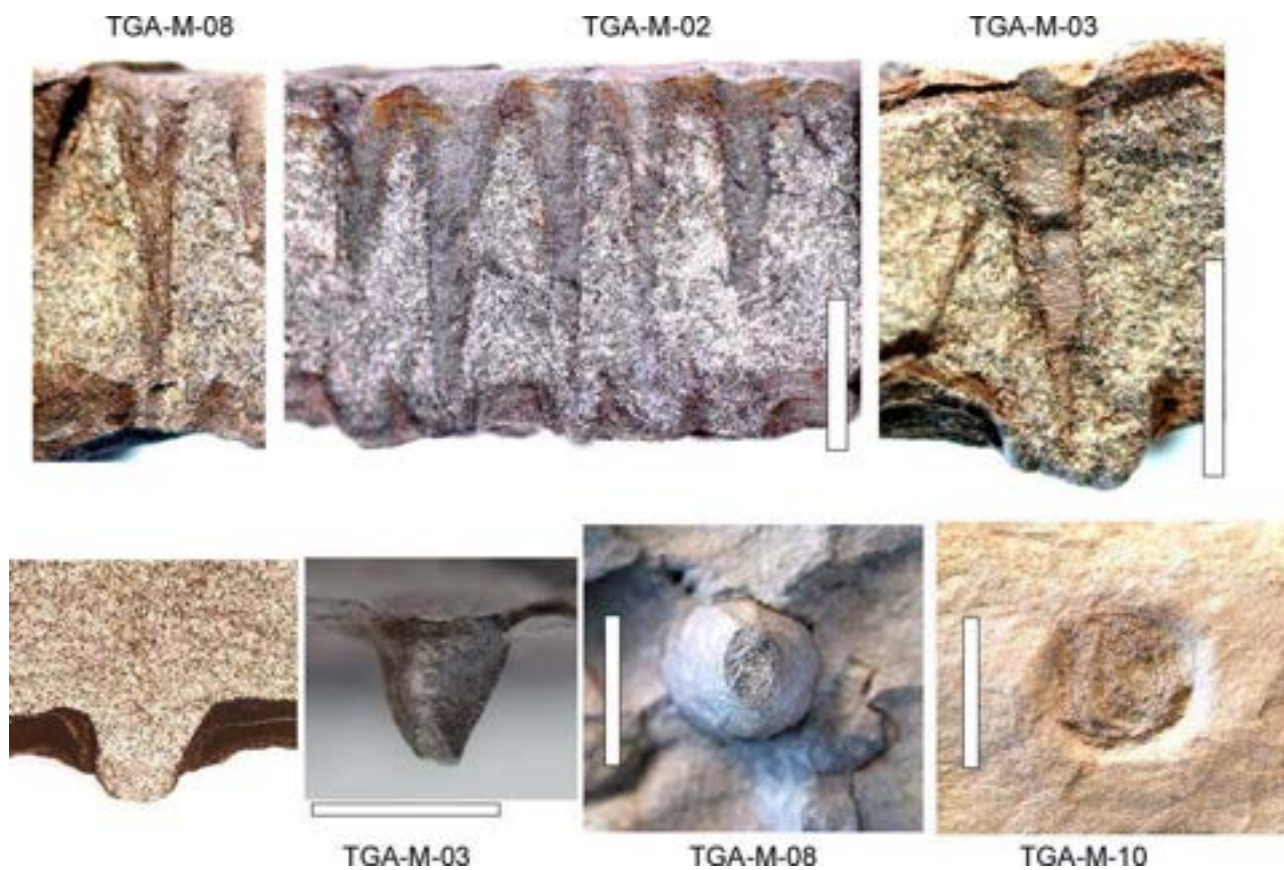
Figure: Top row: Cutaway lateral views of specimens TGA-M-02, 03 and 08.
Bottom row: Side view cutaway and close-up of one specimen on the lower surface of TGA-M-03.
Plan view, lower surface of one specimen of TGA-M-08.
Plan view, upper surface of one specimen on TGA-M-10.

Pairing traces and tracemakers – a case of isopod trace and body fossils from the middle Danian Faxe Formation of Denmark

by Jesper MILÀN[1]*, Matúš HYŽNÝ[2], Bo Wilhelm RASMUSSEN[1], Lothar H. VALLON[1], Sten Lennart JAKOBSEN[1] & Jan Audun RASMUSSEN[3,4]

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A new invertebrate trackway assigned to *Pterichnus* isp. was recovered on a slab of coral limestone from the middle Danian Faxe Formation at the Faxe limestone quarry. The specimen consists of small, scraped imprints that are arranged in an alternating chevron pattern, crossing over the midline of the trackway. The specimens are preserved as negative epichnia on hardened limestone surfaces. Experimental work with extant arthropods walking on carbonate mud has shown that under certain sediment consistencies, tracks from isopods show the closest match for the new trackway, suggesting the tracemaker to be a crustacean of the order Isopoda. The isopod tracemaker hypothesis was at first deemed unlikely, as isopods, except for the large *Palaega danica*, had never been reported from the middle Danian of Denmark. Recent finds of three specimens of small cirolanid isopods from the Faxe Formation, however, support the hypothesis. However, hermit crabs (Paguroidea) can in some circumstances produce similar trackways.

Penetrating the defences: a case of opercular drilling from the Miocene of the Central Paratethys (Czech Republic)

by Jaroslav ŠAMÁNEK[1]

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An operculum is a mineralized structure closing the aperture of many marine, freshwater and terrestrial gastropod shells (Checa & Jiménez-Jiménez 1998). An operculum represents a passive defensive strategy which increases the survival of the individual against predation or unfavourable environmental conditions (Vermeij 2015). The operculum also can be used as an anchor or as a weapon (Checa & Jiménez-Jiménez 1998; Vermeij 2015). In the fossil record, hard, calcareous opercula (rigiclaudent *sensu* Checa & Jiménez-Jiménez 1998) are the only kind present, as others have a low preservation potential (Checa & Jiménez-Jiménez 1998). The calcareous opercula are associated with gastropods without escape responses (e.g., Turbinidae; Vermeij & Williams 2007); a rigiclaudent operculum limits damage and therefore prevents predation by shell-crushing predators (Vermeij 2015).

The most common opercula found at early Badenian sites in the Moravian part of the Carpathian Foredeep are those of the genus *Astraea* (Turbinidae). Among the studied material, one operculum stands out. It was collected at the well-known lower Badenian fossiliferous locality Kralice nad Oslavou (Czech Republic) (Zágoršek et al. 2009 and references therein) and shows an unsuccessful predatory boring of the ichnogenus *Oichnus* on its outer surface. A similar boring strategy occasionally is used by extant muricids of the subfamily Rapaninae (e.g., *Dicathais orbita*, *Stramonita biserialis*) when encountering thick-shelled turbinids (Taylor & Glover 1999; Herbert 2004; Hayakawa et al. 2012). This bored operculum may be interpreted as indirect evidence of the possible boring behaviour of a member of the Rapaninae in the Central Paratethys. To my knowledge, it is the first fossil example of this behaviour.

References:

Checa, A.G. & Jiménez-Jiménez, A.P. 1998: Constructional morphology, origin, and evolution of the gastropod operculum. – Paleobiology 24(1), 109–132.

Hayakawa, J., Kawamura, T., Ohashi, S., Ohtsuchi, N., Kurogi, H. & Watanabe, Y. 2012: Predation by neogastropods on *Turbo cornutus* juveniles and other small gastropods inhabiting coralline algal turfs. – Fisheries Science 78, 309–325.

Herbert, G.S. 2004: Observations on diet and mode of predation in *Stramonita biserialis* (Gastropoda: Muricidae) from the northern Gulf of California. – Festivus 36, 41–45.

Taylor, J.D. & Glover E. 1999: Penetrating the defences: opercular drilling by *Dicathais orbita* (Mollusca: Gastropoda: Muricidae) on the turbinid gastropod *Ninella torquata*. – In: Walker, D.I. & Wells, F.E. (eds.): The Seagrass Flora and Fauna of Rottnest Island, Western Australia, 177–198, Perth: Western Australian Museum.

Vermeij, G.J. 2015: Gastropod skeletal defences: land, freshwater, and sea compared. – Vita Malacologica 13, 1–25.

Vermeij, G.J. & Williams, S.T. 2007: Predation and the geography of opercular thickness in turbinid gastropods. – Journal of Molluscan Studies 73, 67–73.

Zágoršek, K., Holcová, K., Nehyba, S., Kroh, A. & Hladilová, Š. 2009: The invertebrate fauna of the Middle Miocene (Lower Badenian) sediments of Kralice nad Oslavou (Central Paratethys, Moravian part of the Carpathian Foredeep). – Bulletin of Geosciences 84(3), 465–496.

Psammichnites ichnofabric associated with trilobite remains in the lower Cambrian of the Holy Cross Mountains, Poland

by Michał STACHACZ[1]

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The sandstone of the upper part of the Ociesęki Formation that represents the Cambrian series 2, *Protolenus-Stenuaeva* Zone, contains numerous specimens of *Diplocraterion parallelum,* which make up a distinctive ichnofabric. A second common ichnotaxon and ichnofabric in this part of the formation is *Psammichnites gigas,* which was formerly ascribed to *Arcuatichnus wimani* and *Plagiogmus arcuatus* by Kowalski [1978]. Orłowski [1992], who described this trace fossil as *Cruziana* isp., interpreted it as a burrow produced by the trilobite *Kingaspidoides santacrucensis*.

Some sandstone slabs on the Zamczysko hill and at Widełki village contain *Psammichnites gigas* and numerous remains of the large trilobite *Kingaspidoides santacrucensis*. The cooccurrence of this trace fossil with trilobites suggests that Orłowski's [1992] interpretation of the tracemaker was justified, despite ichnotaxonomic misdiagnosis. *Psammichnites gigas* are preserved here in a few taphonomic variants, which include horizontal sections displaying meniscate backfill, composed of series of arcs ["*Arcuatichnus wimani*" of Kowalski, 1978], positive hypichnial reliefs visible as bilobate ridges with a median furrow and V-shaped pattern ["*Cruziana* isp." of Orłowski, 1992] and concave furrows with a U-shaped cross section, resembling *Climactichnites* isp. [cf. Seilacher, 2007]. The burrows are ca. 25–30 mm wide, which equals the width of associated trilobite remains. Moreover, the morphology of the burrow corresponds to that of the trilobite; it displays a discrete trilobate shape in cross section. Some burrows even show distinct nodules, similar to imprints of coxae, that are characteristic of the trilobite resting trace *Rusophycus carleyi.*

A few trilobite thoracic segments and cranidia are preserved within the burrows, but no complete trilobite skeletons have been found at the terminations of burrows. Collection of further samples and their morphometric analysis is needed for full evaluation of the hypothesis that some *Psammichnites* were made by trilobites.

References:

Kowalski, W.R. 1978: Critical analysis of Cambrian ichnogenus *Plagiogmus* Roedel, 1929. – Rocznik Polskiego Towarzystwa Geologicznego 48, 333–344.

Orłowski, S. 1992: Trilobite trace fossils and their stratigraphical significance in the Cambrian sequence of the Holy Cross Mountains, Poland. – Geological Journal 27, 15–34.

Seilacher, A. 2007: Trace Fossil Analysis. – 226 pp., Berlin: Springer.

Calibrating the diversification of early animals during the Ediacaran–Cambrian using a newly proposed measure of ichnodissimilarity

by Zekun Wang[1]*, Li-jun Zhang[1,3] & Imran A. Rahman[1,3]

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Trace fossils record the interactions between organisms and their surroundings, and can therefore provide unique insights into the coevolution of trace makers and the environment. However, identifying the producers of trace fossils is challenging because different animals can produce very similar traces. As a result, many traces can only be attributed to broad morphological grades; for example, simple locomotory trace fossils like *Gordia* are generally thought to have been created by vermiform worms. This uncertainty makes it difficult to decipher their palaeobiological significance through major evolutionary events and episodes of environmental change. To address this, we have developed a new mathematical approach for identifying previously unrecognized signatures left by the trace makers of simple marine locomotory traces. We calculated the deviation angle series of self-crossing trails made by extant polychaetes, isopods, marine gastropods and nematodes, computing the frequency spectrum and autocorrelation function in each case. The results reveal that each of these taxa left unique markers during the trace-making process, reflecting differences in their anatomy and stimulus-induced locomotory behaviours. Using these data, we were able to identify the trace makers of several early Palaeozoic *Gordia* ichnospecies, confirming that traces from the same ichnogenus can be created by distantly related animals with different morphologies and behaviours. This new mathematical framework has great potential for identifying the producers of traces through deep time, consolidating the link between ichnology and palaeobiology.

Rigging up a [bio-]stratigraphic framework for the "Barren Measures" in the Netherlands
by Onno WERVER[1]

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In contrast to recent developments in neighbouring countries [e.g. Germany], no biostratigraphic framework for Permian and Lower Triassic sediments has yet been established for the Netherlands. The exhibited poster shall present a conceptual plan to rig up such a framework in the coming years and describes how to do this by "achieving more by doing less and thinking more in advance". Many years ago, while gathering data for a proposed Ichnology Atlas for Permian and Lower Triassic Deposits, I made an unexpected discovery of a tropical palaeosol deposit intercalated between red-bed desert deposits. The colours of this palaeosol are identical to modern examples related to monsoonal climates and its trace fossils suggest humid soil conditions. Since my surprise discovery, an explanation for the sudden appearance and disappearance of water within an arid environment has bothered me.

The poster presents a 7-step plan for how to get from the trigger, a tropical palaeosol to a logical explanation. Going through sedimentological and ichnological evidence, I move to the expression of such deposits on geophysical logs and reconstruction of maximum flooding surfaces in a semi-confined basin, and finally tie together the aforementioned tropical palaeosol to a smoking-gun-yet-to-be-found marine equivalent. Shooting at the poster by good-natured opponents is allowed.

Of course, any good-natured criticism on the content of this abstract is welcome, too.

Oral Presentations

For talks with more than one author, the presenting author is **boldfaced and underlined**.

Parahaentzschelinia in an *Ophiomorpha* ichnofabric from the lower Pliocene of Lepe [Huelva, SW Spain]

by **Zain BELAÚSTEGUI**[1,2] & Fernando MUÑIZ[3]

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2] Institut de Recerca de la Biodiversitat [IRBio], Universitat de Barcelona, Barcelona, Spain
3] Departamento de Cristalografía, Mineralogía y Química Agrícola, Universidad de Sevilla, Avda. Reina Mercedes 6, 41012 Sevilla, Spain; fmuniz@us.es

Several units characterized by ichnofabrics dominated by the ichnospecies *Ophiomorpha nodosa* are described from a lower Pliocene outcrop of Lepe [Huelva, SW Spain]. Along the exposed stratigraphic section of this new outcrop [approximately 4 m thick], the ichnogenus *Parahaentzschelinia* is a component of one of these ichnofabrics. The studied section consists of alternating sandstones and microconglomerates, subdivided into six units. From bottom to top, they are: Unit 1] A monoichnospecific *O. nodosa* ichnofabric [ii1/2] characterizes this 90-cm unit of fine- to medium-grained sand with intercalations of centimetric microconglomerate strata and common cross-lamination. Unit 2] An *O. nodosa* ichnofabric [ii3] with at least two strata containing abundant specimens of *Parahaentzschelinia* isp. [preserved as full reliefs] in this 80-cm unit of fine- to medium-grained sand. Unit 3] An interval with abundant *Macaronichnus* isp. is observable in this 30-cm-thick biocalcarenitic unit [rich in *Mytilus* sp. remains] deposited over an erosive surface. Unit 4] This unit consists of a microconglomerate layer, 10 cm thick. Unit 5] An *O. nodosa* ichnofabric [ii2/3] characterizes this 80-cm-thick unit composed of cross-laminated and medium-grained sand rich in mollusks. Within this ichnofabric, *Ophiomorpha* burrows exhibit diameters up to 4 cm and have thick, pelleted linings [up to 8-9 mm]; frequently, these burrows are passively filled by microconglomerates from the overlying unit 6, and some penetrate the underlying units 4 and 3, terminating in unit 2. Unit 6] Rare *Thalassinoides*-like structures are present in this 70-cm-thick unit dominated by microconglomerates with ostreid remains. The paleoenvironmental and depositional conditions inferred for this section point to an estuarine setting with tidal and fluvial influence, which is consistent with previous interpretations for equivalent Pliocene outcrops from the Lepe area [Muñiz et al., 2010; Belaústegui & Muñiz, 2016].

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Predator-prey interactions in the Early Triassic warming ocean

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The Permian-Triassic mass extinction (PTME) punctuated the history of life by wiping out 81–96% of marine species, enabling the establishment of modern ecosystems (Chen and Benton 2012). Predation has been regarded as an important driving force of evolutionary change, but relevant evidence is scant in Early Triassic rocks. We report exceptionally preserved trackways of *Kouphichnium,* burrows and trails, as well as a surprising compound trace from the Daye Formation of the Early Triassic in the Dangwu section of Guiyang City, Southwest China, which also yields abundant and diverse ichnotaxa. The co-occurrence of the track traces is interpreted as an unusual case of preserved evidence of limulid predation on polychaete prey. A dataset of ecospace utilization of infaunal communities in shallow marine carbonate settings (Feng et al. 2022) indicates that infaunalization was enhanced during the Permian-Triassic, coinciding with diversification of marine predators. Enhanced infaunalization in the late Early Triassic either was driven by predation or was a product of amelioration of environmental conditions. Both the snapshot of predators caught in the act of hunting their prey and the diverse predator taxa suggests intense predation in the hot Early Triassic ocean, which may have played a substantial ecological role in the flourishing of the Modern Evolutionary Fauna (Sepkoski 1981).

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Determining ichnogenus and species of a trace fossil from the Gram Clay Pit (late Miocene, Denmark)

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Several fragments of large burrows from the late Miocene (Tortonian) Gram Formation have been found in the Gram Clay Pit located in southern Jutland. The burrows are preserved as fragmented concretions with a cylindrical shape. Cross sections of the burrows either show a noticeable fill and lining or a black fill with indistinguishable lining. The large and small diameters of the fill and of the exterior of the lining, together with the lining's thickness at its thinnest and thickest points, were measured on 49 untreated specimens. A clear cross section was cut and sanded (grain sizes 320, 400 and 600) on 17 randomly selected specimens. CT-scans were made of 51 specimens to examine the burrows' three-dimensional morphology.

The burrows likely belong to domichnia based on the lining and visible passive fill (very clear in one specimen). The burrows are straight and unbranched. A thickened part of the lining with accumulated fish debris throughout the burrows' lengths indicates that they were open tubes. The orientation of the tubes is assumed to have been primarily horizontal based on the orientation of specimens found in situ and the distribution of fish debris. This is supported by the slightly oval cross section of the tubes and their fill. The Gram Sea had a depth of 50-100 m (Rasmussen 2005), locating it between the Zoophycos and Cruziana ichnofacies (Bromley 1996), transitioning towards Cruziana because of a high rate of sedimentation. The lining with accumulated fish debris, horizontal orientation in the sediment, ethological category of domichnia and assignment of the Gram Sea floor to the transition zone between the Zoophycos and Cruziana ichnofacies indicate that the tubes found in the Gram Clay Pit belong to the ichnogenus *Lepidenteron*. The specimens resemble the ichnospecies *L. lewesiensis* (Bieńkowska-Wasiluk et al. 2015; Jurkowska & Uchman 2013; Suhr 1988).

The most likely maker of *L. lewesiensis* was a predatory organism in the family Eunicidae, because these burrows were created by a long organism with a diameter between 9 and 35 mm, and the fish debris shows no signs of being affected by gastric acid, which indicates that the meat was peeled off the bones (Bieńkowska-Wasiluk et al. 2015; Jurkowska & Uchman 2013). The fish debris in the tubes of the Gram Clay Pit is cause for further study to determine the ichnospecies, the tracemaker and its prey of choice.

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The use of Computed Laminography for the study of deep-sea ichnofabrics in recent sediments

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Trace fossils are proved as a powerful tool in the study of deep-sea settings due to their use as ecological indicators, especially for such environmental parameters as organic-matter content, oxygenation or sedimentation rate, among others. However, when working with modern deep-sea sediments, seeing trace fossils with the naked eye is difficult, hampering their identification. This has historically been resolved by X-ray radiography of core slabs, obtaining successful results. Later, Computed Tomography [CT] was also applied as a nondestructive technique, obtaining similar results but scanning the whole core. However, this requires a relatively complex processing and computer resources able to deal with a large amount of data. Here we present the use of Computed Laminography [CL], as an alternative nondestructive technique that generates a relatively small amount of data, obtaining results similar to X-ray radiography. Additionally, we compare the results obtained from linear and circumferential laminographs to analyse differences and to make recommendations for ichnological research. We analyse CL images from sediment cores extracted from two boxcores collected in the Porcupine Abyssal Plain [NE Atlantic]. Successful results were obtained in characterizing the ichnoassemblage and quantifying the amount of bioturbation. There were no notable differences between results from linear and circumferential CL. The use of circumferential laminography is recommended for quantification because it is less time-consuming. However, the use of both linear and circumferential images is recommended to clarify ambiguous situations. Computed Laminography is revealed as an alternative technique for the ichnological study of deep-sea sediment cores when CT is not available or cannot be processed.

Resilience of infaunal ecosystems during the Early Triassic greenhouse Earth

by <u>Xueqian FENG</u>[1], Zhong-Qiang CHEN[1]*, Michael J. BENTON[2], Chunmei SU[1], David J. BOTTJER[3], Alison T. CRIBB[3], Ziheng LI[4], Laishi ZHAO[4], Guangyou ZHU[5], Yuangeng HUANG[1] & Zhen GUO[1]

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The Permian-Triassic mass extinction severely depleted biodiversity, as observed primarily in the body fossils of well-skeletonized animals. Understanding how whole ecosystems were affected and rebuilt following the crisis requires evidence from both skeletonized and soft-bodied animals; the most comprehensive information on soft-bodied animals comes from ichnofossils. We analyzed abundant trace fossils from 26 sections across the Permian-Triassic boundary in China, and report key metrics of ichnodiversity, ichnodisparity, ecospace utilization, and ecosystem engineering. We find that infaunal ecologic structure was well established by the early Smithian. Decoupling in diversity between deposit feeders and suspension feeders of carbonate ramp-platform settings implies that trophic group amensalism could have delayed the recovery of sessile, suspension-feeding epifauna during the Early Triassic. This differential reaction of infaunal vs. epifaunal ecosystems to variable environmental controls thus played a significant, but heretofore little appreciated, evolutionary and ecologic role in the overall recovery of the marine biota in the hot Early Triassic ocean.

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Fig. 1: Reconstruction of marine ecosystems before and after the P-Tr mass extinction in China. [A] Pre-extinction marine ecosystem in the latest Permian. [B] early Griesbachian. [C] late Griesbachian. [D] Dienerian. [E] Smithian. [F] Spathian.

Rullard – Richard Bromley and Ulla Asgaard; a short account of their lives, their work and their food
KEYNOTE TALK

by Andy Gale[1]

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Richard Bromley (1939-2018) was an exceptional and very enthusiastic naturalist – an acute observer who progressed the science of ichnology. Ulla Asgaard (1936-2023) was a natural historian, working especially on brachiopods and echinoids. Together, they produced numerous excellent articles about traces and tracemakers. This talk provides a review of their lives, their scientific work and some of the original "recipies" which they cooked together.

Gastropod prey of the middle Lutetian muricid, *Crassimurex calcitrapa* [Lamarck, 1803]
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Drillholes provide a clear record of predation that can be used to define relationships between predators and their prey. In this study we survey the gastropod prey species of the muricid, *Crassimurex calcitrapa,* from the locality of la Ferme de l'Orme, Beynes, Yvelines, France, and examine specific aspects of the predatory record. This locality contains several strata of the uppermost middle Lutetian. Level 6, the source of our fossil material, contains only one drilling gastropod, *C. calcitrapa,* enabling us to catalogue its prey and use in-depth data from two of the common prey species, *Vicinocerithium calcitrapoides* [Lamarck, 1804] and *Serratocerithium denticulatum* [Lamarck, 1804], to make inferences about the development of prey selection with maturity. We find that juvenile *C. calcitrapa* preyed upon numerous small, thin-shelled gastropods, including other *C. calcitrapa*. There is some indication that, at all life stages, *C. calcitrapa* concentrated their drilling attacks at parts of the prey which were relatively thin: at the sutures, at intervarical spaces, and on thinner side walls [Fig. 1], typically avoiding the spines. When attacking *Vicinocerithium,* adults tended to drill nearer to the body whorl or in the sutures between the whorls closest to the aperture. *Serratocerithium* tended to be attacked along the thinner side walls of the shell between the rows of spines. The juveniles also attacked two larger species found in level 6, *S. denticulatum* and *V. calcitrapoides,* often in the presence of adults drilling the same specimen. The juveniles drilled farther toward the apex. Living members of the family Muricidae are sometimes attracted to prey by the trail of chemicals released into the water by conspecifics [Carriker, 1981, p. 407]. The authors propose that the multiple drillholes of *C. calcitrapa* at mixed levels of maturity is evidence of this process in the fossil record. The juveniles were, in effect, learning what prey to attack as adults. Multiple drillholes on prey have been observed in experimental situations which artificially reproduced a scarcity of prey [Carriker and Van Zandt, 1972, tables 1 and 2] and this may be the temporary case at times of hatching, when the new cohort puts pressure on the stock of prey species. As such, this may represent an early stage in the evolutionary development of this behavioral strategy, later adapted to any time of prey scarcity.

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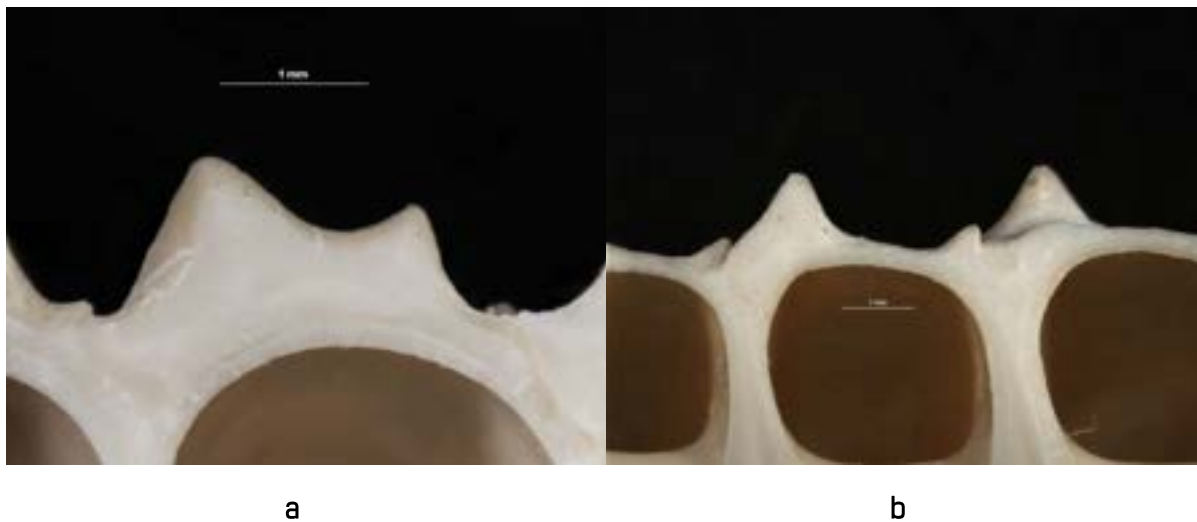a   b

Figure: Cutaway views of wall details of (a) *Vicinocerithium calcitrapoides* and (b) *Serratocerithium denticulatum.* Note the more robust side walls and spines between the sutures of *V. calcitrapoides*. Photos: Goldstein. Equipment courtesy of Cushman Foundation.

Ichnofabrics and paleoecologic turnovers from the Ediacaran-Cambrian Chapel Island Formation (Canada)

by **Romain GOUGEON**[1]*, M. Gabriela MÁNGANO[1], Luis A. BUATOIS[1], Guy M. NARBONNE[1,2], Brittany A. LAING[1] & Maximiliano PAZ[1]

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The Chapel Island Formation (CIF) in southeastern Newfoundland, Canada, is a 1000+ m-thick, mostly siliciclastic succession that contains a continuous record of trace fossils from late Ediacaran to Cambrian Age 2 [Narbonne et al. 1987; Gougeon et al. 2018]. Although the succession is renowned for hosting the Cambrian GSSP at Fortune Head since 1992, its sedimentology and ichnology have not been reviewed in detail during the last decades. Here, we provide new comprehensive datasets from six localities of the CIF that crop out in coastal cliffs of Burin Peninsula and cover altogether 1708.2 m of strata. The trace-fossil dataset focusses on bioturbation intensity, burrow width and depth, and ichnotaxonomic classification, whereas the sedimentologic dataset reports bed geometry, bed thickness, bed grain size, sandstone/mudstone ratio, and sedimentary structures. Notably, the characterization of fourteen sedimentary facies permits the identification of intertidal, shoreface, offshore, and shelf depositional environments. These allow the creation of time-environment matrices to decipher trace-fossil evolutionary trends in both time and space. At all localities, three paleoecologic stages established in shallow-marine seafloors: [1] an Ediacaran matground ecology, dominated by simple horizontal trails associated with microbially stabilized surfaces and limited vertical bioturbation; [2] a Fortunian matground/firmground ecology, with evidence of penetrative shallow-tier bioturbation and a burst in trace-fossil diversity; and [3] a late Fortunian/Cambrian Age 2 mixground ecology, with high bioturbation intensity and the development of modern-style seafloors. Notably, a turnover took place from Fortunian to Cambrian Age 2, with shallow-tier *Gyrolithes gyratus* and *G. scintillus* being impacted negatively by the increasing activity of shallow-tier sediment bulldozers [producers of *Curvolithus simplex, Didymaulichnus miettensis,* and *Psammichnites gigas circularis*] and mid-tier deposit-feeding activity of *Teichichnus rectus* tracemakers. Consequently, the substrate in lower shoreface, offshore, and shelf became partitioned into a shallow homogeneous mixed layer lacking discrete burrows, and a deeper transition layer with sharp-walled burrows cast in firmer sediment. In tidal settings, datasets are more limited but major changes in ichnofabrics are not demonstrated from Ediacaran to Fortunian, despite the appearance of very shallow infaunal *Treptichnus pedum*. Overall, the CIF represents an ideal succession to track the early steps of the Cambrian Explosion and the precise timing of the Agronomic Revolution.

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Microborings in foraminifera analysed with submicron X-ray Computed Tomography

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Microbioerosion traces in tests of foraminifera are made by fungi and cyanobacteria [Wisshak 2012]. The observation and quantification of bioerosion traces can provide valuable insights into the environmental conditions of early burial of foraminiferal tests [Heard 2007, Knaust 2012]. Microbioerosion [1–10 µm] is commonly observed by light or scanning electron microscopy to assess surface traces and tunnel apertures. To study subsurface tunnel morphology in more detail, a more thorough preparation is commonly used: resin-casting, following Golubić et al. [1970]. Surface observations are nondestructive, but rely on sample orientation, while resin-casting is totally destructive for the test. In order to improve the understanding of burrow orientations and patterns, three-dimensional observations can be particularly helpful because they can show how subsurface tunnels relate to test morphology.

Some studies have used X-ray Computed Tomography [CT] to study foraminifera [Görög et al. 2012] and bioerosion [Heřmanová et al. 2020], but could not effectively achieve a higher resolution than 1 µm/voxel.

We used submicron CT [< 1 µm/voxel] to improve visualization of microbioerosion structures [1–10 µm]. Three specimens of *Uvigerina* sp. were scanned by CT. The bioerosion traces found in their tests were highlighted and rendered as three-dimensional structures. Their shape, orientation, volume, distribution, and location in the test were analysed. Our preliminary work shows the possibilities of nondestructive submicron tomography for the visualisation and morphometry of microbioerosion.

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Reconstruction of deltaic environments in the Jurassic Brent Group (Norwegian North Sea) by means of ichnofabrics

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Deltaic successions of Jurassic age contain huge reserves of hydrocarbon and have potential for carbon capture and storage, thus providing several important targets in the Norwegian North Sea. The development and timing of these reservoirs are reasonably well understood from a tectonostratigraphic and sedimentological point of view. This framework provides a robust basis for the delineation of palaeoenvironmental changes of individual deltaic systems through time and space, in relation to their tectonic setting.

Several thousand metres of well core were examined with respect to the amount of bioturbation, trace-fossil content, burrow size and abundance, ichnodiversity and significant colonisation surfaces. This ichnofabric study was combined with routine sedimentological, biostratigraphical as well as special analyses. The results constrain the ichnological characteristics of fan deltas [e.g., Toarcian-Aalenian Oseberg and Broom formations] from the doming phase through to the development of extensive delta systems [e.g., Bathonian-Kimmeridgian Krossfjord, Fensfjord and Sognefjord formations] during the rifting phase.

For example, fan-delta deposits of the Oseberg Formation are sparsely bioturbated and mainly contain a low-diversity ichnofauna with *Siphonichnus, Ophiomorpha, Bornichnus, Palaeophycus* and *Planolites*, as a response to their proximity to and interaction with freshwater input from the hinterland. This helps to distinguish distal and proximal delta-front deposits. Adjacent shelf, restricted basin and prodelta deposits contrast to the delta-front deposits by increased heterogeneity, amount of bioturbation and ichnodiversity.

In contrast, the Sognefjord Formation consists of numerous metre-scale coarsening- [shallowing-] upward cycles [parasequences] that are stacked on top of each other, separated by flooding surfaces. An ideally developed parasequence is completely bioturbated in the lower and middle part, whereas the upper part has moderate to weak [or no] bioturbation. It comprises characteristic ichnofabrics of an overall low- to moderate-diversity ichnofauna [about 20 ichnotaxa]. From bottom to top, the following five recurrent ichnofabrics and their inferred depositional environments can be recognized: [1] *Phycosiphon* [offshore to prodelta], [2] *Teichichnus* [lower delta front], [3] *Planolites* [upper delta front], [4] *Ophiomorpha* [upper delta front, mouth bar and [partly] distributary channel], and [5] *Macaronichnus* [wave-dominated, sandy bay on lower delta plain]. The [6] *Lingulichnus-Skolithos* ichnofabric overprints ichnofabrics [2] to [5], but also demarcates flooding surfaces on top of some parasequences.

The methodology of ichnofabric analysis, which originally was developed on core material from these depositional systems in the 1980's, has become an integrated tool in the interpretation of sand distribution and reservoir characterisation.

Ichnostratigraphy of a storm in the Pennsylvanian of Alabama (USA)

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The Steven C. Minkin Paleozoic Footprint Site (Union Chapel Mine) is well known for its abundant vertebrate and invertebrate trackways (Buta et al. 2005a). Its invertebrate burrows are less celebrated, but are even more profuse (Buta et al. 2005b). The main source of these invertebrate burrows is from the tailings, the highwall being inaccessible. Detailed examination of trace fossils that occur only at the base of what seems to be a single, laminated sandstone bed (probably originally from a sequence of alternating sandstone and shale) reveals the response of burrowing organisms to a storm event. The bed is situated within the 30 m of strata overlying the trackway-bearing *Cincosaurus* beds. The bed is recognizable by its unusual reddish color, and by its fairly consistent thickness of 5-8 cm. The hypichnia are small (8.4–38.5 mm long), shallow, bilaterally symmetrical, and subquadrate, consisting generally of series of bracket-like pads of sediment ())]]. Several morphotypes can be distinguished. Axial shafts may be present. Judging from the traces' subquadrate outline, bracket-shaped pads, and embedded resting traces, the most likely makers are arthropods 6–12 mm long and 5–10 mm wide. They lack a strongly preferred orientation, but some morphotypes are significantly clustered. At first glance, they seem to be typical resting traces, but on further investigation they prove to be elongate locomotion-feeding traces, extending upward into the sandstone bed at both ends. It seems likely that the complete trace is topologically U-shaped, suggesting that their makers dug through the newly deposited sand to reach the underlying scoured clay. Evidently, the sand was deposited as a storm dissipated, immediately being draped by an unknown thickness of mud. By the time the sand was deposited, storm currents would already have been abating. At some point – possibly during the storm itself – the tracemakers dug into the bed, probably to feed on the organic-rich mud below. Later, the animals presumably returned upward through the bed. Probably these arthropods were not unusual members of the local fauna, but their work was recorded in this instance because their traces were made at a depth of sediment greater than most species tolerated in this setting.

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Trace fossils from the Grès de Sidi Saâdoun Formation (Callovo-Oxfordian transition) at its type locality (Nador Range, Preatlasic Trough, North-western Algeria): inventory and implications

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This report provides an ichnological overview of the trace fossils in the well-exposed sandstone strata of the Grès de Sidi Saâdoun Formation (Callovo-Oxfordian transition, Atrops & Benest 1981; Benest et al. 1981). This formation was mainly deposited in a deep-marine setting. The section consists of about 100m of clay and sandstone strata, organized into incomplete and repetitive turbiditic sequences. These consist of T_{ab}, T_{bcd} and T_{de} Bouma intervals (Bouma 1962), which are arranged into three intervals; (1) upward-thickening and fining in the lower part, changing to (2) fining and thinning beds deformed by slumps in the middle part, overlain by (3) thin-bedded sandstone and interbedded claystone cut by normal faults, and capped by lenticular bodies of reddish nodular limestone (about 20cm-thick) in the uppermost part of the section.

Sedimentary facies analysis indicates depositional environments passing from middle to outer deep-sea fan (channel complexes and inter-channel to inter-lobe deposits); ichnological data indicate the *Nereites* ichnofacies. The trace fossil assemblages contain *Helminthopsis* isp., *Neonereites biserialis*, *Neonerites uniserialis*, *Nereites* isp., *Nereites missouriensis*, *Planolites* isp., and *Palaeophycus* isp. The bioturbation intensity is very low in the basal part and low in the middle to upper parts, where most trace fossils are found on episodically deposited, thin to medium-bedded sandstone. The occurrence of these horizontal trace fossils, as well as the low ichnodiversity, implies variation in nutrient supply, substrate quality and oxygenation of pore and bottom water, probably due to varying detrital discharge caused by turbidity currents. These results within a regressive setting under tectono-eustatic control of the Nadorian Trough, document strong subsidence resulting from tectonic instability on the west-algerian tethyan margin during the Callovo-Oxfordian transition.

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Ichnofabric comparison between hill and abyssal plain: going from palaeo- to neoichnological data

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Ichnological research has generally assumed that abyssal plains are dominated by quiescent, homogenous environmental conditions. Thus, changes in deep-sea trace-fossil assemblages have usually been linked to significant spatial and temporal environmental variations. Here, we conduct a comparative ichnological analysis between a small abyssal hill [50 m elevation] and the surrounding abyssal plain. This topographic variation is known to generate substantial environmental heterogeneity for the benthic faunal community of the Porcupine Abyssal Plain [c. 4850 m depth], northeast Atlantic [Durden et al., 2020]. Based on X-ray data from two boxcores, we compare hill and plain biogenic sedimentary structures, including trace fossils [ichnotaxonomy], ichnofabrics and biodeformational structures [e.g., mixed-layer depth, transitional layer]. Our observations indicate that topographically enhanced near-bottom currents over the hill likely produce significant changes in depositional dynamics and sediment properties [e.g., grain size], and control biogenic sedimentary structures [i.e., ichnofabrics and biodeformational structures]. Neoichnological analyses allow characterization of mixed sediment layers with different attributes. Our results indicate that variation in [a] organic matter content and degradation, and [b] sediment grain size distribution are the main factors driving the observed mixed layer properties [e.g., thickness, mottled background, discrete traces]. Palaeoichnological data suggest that the abyssal plain has experienced consistent conditions for thousands of years. By contrast, the abyssal hill is dominated by stacked sequences of upward-increasing bioturbation intensity that may be related to improving environmental conditions for the tracemaker community. We note the presence of graphoglyptids, which may reflect gravity flow deposits, on the abyssal hill. Also, dense *Nereites* ichnofabrics on the hill reveal a more dynamic environment where hill-flow interactions may only have been temporarily active. On the plain, "mycelia" or *Scolicia* ichnofabrics may be related to temporal and/or local conditions within the sediment [e.g., occurrence of organic matter patches]. Our results highlight the complexity of deep-sea environments, demonstrating that substantive changes in bioturbational sedimentary assemblages [i.e., trace and biodeformational structures] can be related to local [km-scale] environmental heterogeneity [e.g., subtle topographic variations] rather than regional-scale spatial-temporal environmental variations [e.g., sea level changes, oxygenation events]. Considering the vast global extent of abyssal hill terrain, we suggest that their influence on the bioturbational sedimentary record may be significantly underappreciated and require more attention in palaeoenvironmental reconstructions.

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Glow with the worm: a probable function of translucent burrow linings of *Schaubcylindrichnus*

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In a looseground, or soft sandy substrate, burrows are commonly lined for reinforcement and effective irrigation. For this purpose, the burrowers utilise mucus or a mixture of mucus and other material such as mud, sand, and skeletal fragments. Among these, mud is the most used by marine burrowers because it is pervasive in the marine realm, and its cohesive fine grains provide sturdy and less permeable burrow walls.

Schaubcylindrichnus, a complex burrow system consisting of a sheaf of arcuate tubes with a feeding funnel and a faecal mound at each end, is a common marine trace fossil whose tubes are thickly lined [Nara 2006]. The linings consist of less cohesive, clean sands with higher interparticle porosity than the host sediment, when occurring in poorly compacted sandstones [Nara 2006]. Although the probably friable and permeable nature of such lining material may seem inadequate, Nara [2006] explained that the pores were then filled with mucus by the tracemaker.

The burrow lining of *Schaubcylindrichnus* is also characterised by its conspicuous white colour, due to the concentration of light minerals such as quartz and feldspar [Nara 2006], especially in its inner part [Nara 2006]. The function of the concentration of light minerals in the lining, however, has received no attention.

A modern funnel-feeding animal inhabiting a mucus-lined, large arcuate burrow comparable to *Schaubcylindrichnus* that repeatedly reburrows to form a sheaf of abandoned burrows, is the ptychoderid enteropneust *Balanoglossus* [Nara 2006]. Although little is known about the ecology of the worm, it is known to be bioluminescent [Cormier & Dure 1963].

Bioluminescence has been found in many major groups of organisms and probably serves such functions as defence, aposematism [warning colouration] and communication [Haddock et al. 2010]. Considering the tubicolous nature of the enteropneust, defense, including aposematism, is the most likely function of its bioluminescence. If the luminescent worm lived in a tube with an opaque lining, the light would not travel far. In contrast, glowing in a translucent tube made of colourless minerals and mucus like that of *Schaubcylindrichnus* would not interfere with light transmission. The colourless mineral-rich and mucous-impregnated lining of *Schaubcylindrichnus* is thus interpreted to have functioned like an optical fibre that could effectively emit the burrower's luminescence along the tube or to the surroundings for defence. Another well-known tubicolous bioluminescent worm, *Chaetopterus* [Rawart & Deheyn 2016], also has a translucent parchment-like lining, which supports this idea.

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Are borings boring? – Bioerosional traces in a foraminiferal test

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Even though foraminifera are a major element in all modern marine communities, sometimes comprising 50% or more of the eukaryotic biomass [Gooday et al. 1992], their trophic level is poorly investigated and in general not fully understood. Their full life cycles are only known for a handful of modern species. Modern foraminifera seem to inhabit all marine environments and display a large variety of feeding modes, which include both parasitic and predatory behavior. The latter appears to be common in the benthic as well as planktonic realms. Previous studies have shown that bioerosional traces on foraminiferal tests are quite common in many modern and fossil environments [Walker et al. 2017]. A few of the tracemakers are known, but most are not. Likewise, it is also unknown why such organisms make these traces. Some species of foraminifera are known to excavate pits or borings in different substrates such as the tests of dead as well as living organisms or limestone rock [Vénec-Peyré, 1996]. A few species of benthic foraminifera demonstrate what seems to be a parasitic or predatory mode of life. However, many more species are believed to have a similar behavior due to their ability to bore into different substrates and tests of calcareous organisms, including other foraminifera. In this study I will show the morphological variety of the bioerosional traces found in foraminiferal tests caused by unknown organisms.

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NOTE: The main title is a tribute to Markus Bertling [1959-2022], and has been "stolen" from a talk he presented in Florida.

Death in "live broadcast": fish mortichnia from the Late Cretaceous plattenkalke of Lebanon

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The trace fossils described here belong to the category of animal behaviour that Seilacher (2007) defined as mortichnia. However, Vallon et al. (2016) recommended against the usage of this ethological category because their recognition depends not only on trace-fossil morphology, but also on tracemaker physiology and environmental interpretation. The latter two assumptions cannot always be deduced correctly, rendering the interpretation dubious, especially when no modern analogues of such environments or closely related organisms exist. Nevertheless, the category remains in use, and with the recently recovered specimens, a redefinition is attempted.

The specimens from Lebanon can all be shown to be traces left by dying fish. At their initiation, the traces show the greatest physical strength of their makers. In particular, the tail fin created an *Undichna*-like trail. Over the course of the mortichnion, the undulating movements of the tail fin decrease and the resulting trail becomes more and more asymmetrical, reflecting exhaustion. Its depth becomes shallower. At the end, next to the fish, evidence of movement is hardly discernible, indicating that these imprints were made during the last moments of the tracemakers' lives. The trails end with the preserved corpses of the fish.

In our redefinition of mortichnia, we argue that trace fossils included in this ethological group must have the tracemakers body preserved in close connection. The tracemaker body fossil, however, is neither part of the trace fossil nor is it to be regarded as the actual trace fossil! Other trails or trackways, especially from non-fish tracemakers such as *Solemya* in the Solnhofen Lagerstätte (Kimmeridgian-Tithonian, Germany), may show signs of loss of orientation, or the tracemakers might have tried to avoid certain areas that imposed hostile living conditions, e.g., ripple crests if the environment were drying out and the tracemakers breathed with gills.

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Latin names for microbial traces

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Microbially induced sedimentary structures (MISS) can be classified by interpretation of their relative roles, such as growth, biostabilization, baffling-trapping, binding, and interference of these processes (Noffke et al. 2022). This classification assumes that thin microbial mats are to blame, but very different processes produce microbial traces on thick, microbial earth soils, and in three-dimensional skeins of periphyton algae hanging from mangroves and in salt marshes. A widely used classification of surface texture of microbial earth soils is smooth, rolling, rugose, and pinnacled (Belnap 2003) but this also has limited applicability. Microbial traces can be used to distinguish marine and terrestrial habitats, and are especially useful in Precambrian rocks. My preference is for Latin names, as in other trace fossil nomenclature. If not accommodated in the International Code of Zoological Nomenclature, such names for distinctive textures of microbial consortia could be regarded as form genera and species under the International Code of Botanical Nomenclature, which already supports the parataxonomy of stromatolites and microfossils. Microbial texture taxa such as *Rugalichnus matthewi* (also known as "Kinneyia") and *Neantia rhedonensis* show undulation and subtle fibrous textures of microbial mats from aquatic habitats, as in the Ediacaran Ediacara Member of South Australia, and Central Mount Stuart and Arumbera Sandstone of central Australia (Retallack & Broz 2021). Ribbons of dried cyanobacteria in mangroves, salt marsh and ephemeral streams also could be referred to *Neantia rhedonensis,* for example in the mid-Cretaceous Dakota Formation near Denver, Colorado (USA) (Retallack & Dilcher 2012). In contrast, *Rivularites repertus* (also known as "old elephant skin") and *Pustulichnus gregarius* show mounds due to radial expansion and healed cracks more like the surface of soils, also in the Ediacara Member of South Australia and Central Mount Stuart and Arumbera Sandstone of central Australia (Retallack & Broz 2021). Trail-like traces of *Myxomitodes stirlingensis* and *Lamonte trevallis* from the Paleoproterozoic Stirling Quartzite of Western Australia, and Ediacaran Denying Formation of China, respectively (Retallack & Mao 2019), blur the boundary between animal and microbial trace fossils. Both show levees defining a strongly tapering width and short distance between origin and bulbous end, and are interpreted as aggregation trails to sporulation of a slug (grex or pseudoplasmodium) of a cellular slime mold comparable with living *Dictyostelium discoideum* (Amoebozoa, Mycetozoa). The array of microbial textures and associated other traces in Precambrian rocks is diverse, and their formal classification, like that of stromatolites and microfossils, requires a system of agreed names and type specimens.

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Ediacaran "Epibaion", "Kimberichnus", *Aulozoon,* and Mistaken Point "locomotion traces" are not trace fossils

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Many genuine Ediacaran trace fossils are known, but the following ichnogenera are no longer accepted: [1] grooves radiating from Ediacaran fossils interpreted as radular feeding traces ["Kimberichnus"] of supposed molluscs [*Kimberella*], and [2] chains of fossil impressions interpreted as feeding traces ["Epibaion"] of supposed worms or placozoans [*Yorgia, Dickinsonia*] from the Ediacara Member of South Australia and the Mezen and Zimnie Gory Formations of the Russian White Sea region. The grooves are not ploughed nor curved with rounded ends like radular scratches, but have sharp or crudely bifid tips like frost flowers and frost needles extruded from plant debris. Fossil impressions in chains are not sequential feeding stations, but polygonal arrays, like vagrant lichens and mosses ["snow mice"] displaced by wind gusts and periglacial frost boils. Thus, neither the taphomorph "Epibaion" nor ice crystal pseudomorphs "Kimberichnus" can be regarded as valid ichnogenera. These newly recognized frost boils, snow mice, and needle ice are additions to geochemical and glendonite evidence that the Ediacaran was another period in Earth history when even low palaeolatitudes were cool.

Aulozoon scoliorum is best known from a large slab from the Nilpena Member of the Rawnsley Quartzite of South Australia, representing an Ediacaran palaeocommunity, including *Phyllozoon hanseni, Dickinsonia costata, Aspidella terranovica, Pseudorhizostomites howchini,* and *Somatohelix sinuosus. Aulozoon* has a high width to thickness ratio [14 ± 0.7] even after accounting for burial compaction. Burrows this much wider than high would be mechanically difficult for a burrower. Stronger objections to a burrow interpretation come from the taper of *Aulozoon* to half its width, and local lateral crimping. *Aulozoon* in thin section has an outer finished wall grading inwards to sandstone fill with loose filaments most like a fungal rhizomorph with loose internal hyphae, and was thus a body fossil, not a trace fossil. Furthermore, *Aulozoon* has been found attached to the base of many *Dickinsonia*. The source of this slab is the surface of a thick red sandstone with pseudomorphs of gypsum desert roses, which is a Gypsid palaeosol of the Muru pedotype, and a former hyperarid land surface.

Supposed "locomotion traces" from the Ediacaran Mistaken Point Formation at Mistaken Point, Newfoundland, do not have true backfills. Crescentic ridges marking successive positions are very marked where they climb up over ripple marks, but obscured by gliding where they slid down the other side. These marks also curve into irregular spirals, like "tilting traces", a form of tool mark from a flat object such as a leaf or vendobiont frond in shallow-water eddies. Although the Mistaken Point Formation has been interpreted as abyssal marine turbidites, evidence for shallow-water deposition includes ungraded airfall ash, maroon-red oxidized color, oscillation ripples, paucity of pyrite, tau analysis of beds, low B content, freshwater C/S ratios, and deposition on granitic rather than oceanic pillow-basalt basement.

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Making *Thalassinoides* and similar burrows useful in stratigraphy

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Large, multibranched network burrows, usually ascribed to crustaceans, are among the commonest trace fossils described from Mesozoic and Cenozoic strata. For the past fifty years, these have been identified as *Spongeliomorpha, Ophiomorpha,* and *Thalassinoides* [SOT group] – particularly the last two of these in the North American literature. Starting in the 1970s, ichnologists made an effort to simplify the ichnotaxonomy of SOT burrows in order to facilitate their use in stratigraphy, and this had the desired effect of making the names broadly understood among geologists. However, oversimplification rendered direct comparison with modern crustacean burrows in specific environments moot. In this talk, we demonstrate how different trace fossils of these ecological engineers can be identified in order to distinguish substrates of differing coherence, indicate methods of observation and description, and suggest additional uses to which they can be put. Examples are drawn largely from the Northeast Gulf Coastal Plain in rocks of Cretaceous to Eocene age.

Invertebrate ichnology, moving forward

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Ichnology – the study of traces, modern and ancient – is alive and well. Since Adolf Seilacher placed the science on a firm foundation in the 1950s, the number of papers on ichnology has greatly expanded in every decade; the publication rate is currently more than 900 papers per year. Although interest in ichnology has been slowing in its historical centers of Europe and North America, it is increasing rapidly in Asia, Africa, Australia, and especially South America. Today's "hot topics" are diverse: microborings; stowing traces [sequestrichnia]; predation traces; coprolites; root traces; reconstruction of ancient food webs; the effects of bioturbation on permeability and porosity; the changing patterns of bioturbation from Ediacaran through Phanerozoic time; the study of trace fossils at stratigraphic boundaries; the evolution of tracemakers and their behavior; new modern analogs to ancient trace fossils; changes in morphology associated with growth of the tracemaker [ichnogeny]; standardization of ichnotaxonomy and of terminology; reëvaluation of the ichnofacies concept; ichnology of remote modern environments such as contourites; and potential traces on the planet Mars, [xenichnology]. The list only begins here; there are still many unrealized opportunities for research.

A *Balanoglossites-Trypanites* ichnofabric from the Upper Ordovician warm-water carbonates of Estonia

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A succession of shallow-marine carbonates characterizes the Middle and Upper Ordovician of Estonia [Baltica]. *Balanoglossites–Trypanites* ichnofabrics are common in highly condensed Darriwilian temperate water sediments but are less abundant in Upper Ordovician warm-water carbonates of the region. An exception comes from middle Katian sediments. The boundary between the Nabala and Vormsi Regional stages [Saunja and Kõrgessaare formations] in northern Estonia is formed by a prominent discontinuity surface, which has been interpreted as a paleo-karst horizon. In the Sutlema Quarry, tropical carbonates of the Saunja and Kõrgesaare formations [middle Katian] are exposed. A flat, slightly wavy, hardground marks the boundary between these formations. The Kõrgessare Formation consists of interbedded wavy-bedded to nodular argillaceous skeletal wackestone and marl. The upper part of the exposed formation contains a flat double hardground and, at the top, an irregular hardground. All flat hardgrounds in the Sutlema Quarry are bored and show signs of karstification. The bioerosional ichnofauna of the hardgrounds is abundant, consisting of shallow *Trypanites sozialis,* elongate *Trypanites weisei,* winding and undulating *Trypanites* isp., algal bioerosional traces, and fine shallow grooves. In addition, large, subsurface U-shaped tubes of variable diameter occur, similar to *Balanoglossites triadicus* and *Planolites* isp. Epizoans on the hardgrounds comprise a typical marine fauna: cornulitids, crinoids, bryozoans, brachiopods, and tabulate corals. The flat hardgrounds in the Sutlema Quarry formed in a shallow-marine environment and parts of them were likely subaerially exposed briefly.
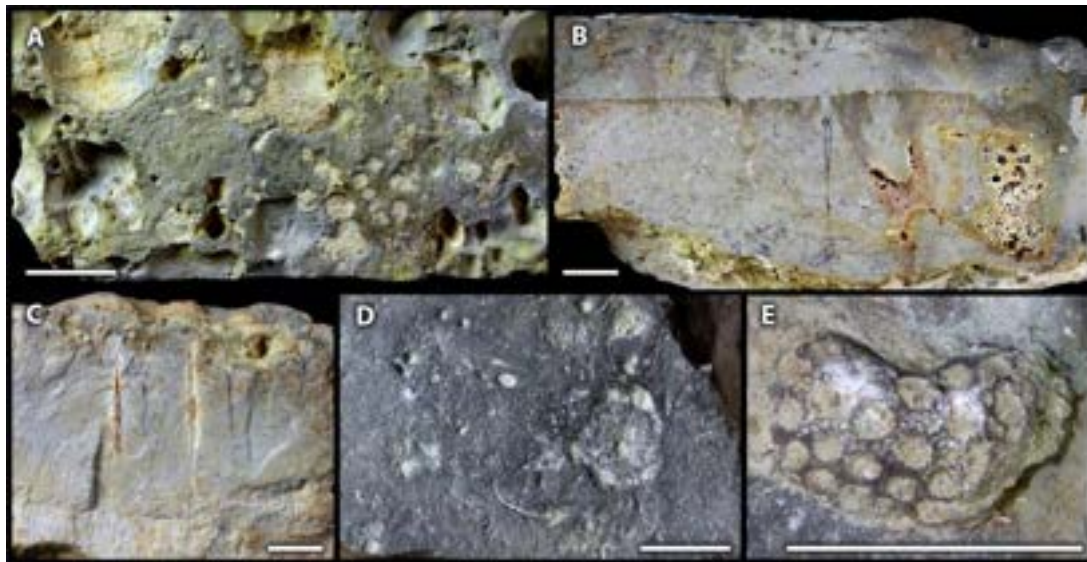

Figure: Middle Katian hardgrounds from the Sutlema quarry, Estonia. All scale bars are 1 cm. A: bored, bioeroded, and karstified hardground, top of the Saunja Formation, GIT 881-9; B: bored double hardground, Kõrgessare Formation, GIT 362-865; C: *Trypanites weisei*, top of the Saunja Formation, GIT 881-28; D: delicate algal bioerosional traces overprinting *Trypanites* borings, top of the Saunja Formation, GIT 881-35; E: tabulate coral *Propora* encrusting the hardground, top of the Saunja Formation, GIT 881-27-1. GIT – Department of Geology, TalTech.

The trace fossil collection of Richard Granville Bromley

by Lothar H. VALLON[1] & Tina A. KJELDAHL-VALLON[1]

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To any ichnologist, Richard G. Bromley [1939–2018] needs no introduction. Many living ichnologists have met him and his wife, Ulla Asgaard [1936–2023], or are familiar with their publications. Many have even had the pleasure of seeing the trace-fossil collection that was housed on the Danish island of Bornholm. Over the years, Richard established numerous new ichnotaxa and revised old ones. All the type material and most of the specimens figured in his papers were deposited in public collections, especially at the Natural History Museum [Statens Naturhistoriske Museum] in Copenhagen, where they remain to date.

However, the unpublished specimens suffered a different fate. This was his "trace fossil teaching collection" that was stored at the field station of the University of Copenhagen, Gravgærde on Bornholm. Before the old farm building was sold by the University, Richard himself reduced and packed it before it was shipped to be stored in the cellar of the Copenhagen Geological Institute. A few years later, during a reduction of space and staff at the institute, the collection was threatened with being discarded.

Through the courtesy of Richard and Ulla's son Peter and the Geological Institute, almost 500 remaining specimens are now stored privately. The collection contains several topotypes of ichnospecies that Richard described or coauthored. In addition, a few specimens were donated to him by friends and colleagues. The collection therefore is of great scientific importance. Unfortunately, during the several moves many labels disappeared, and reconstructing the data is an ongoing but time-consuming process. Parts of the collection are now again in use for teaching geology students.

Though the collection will remain in private hands for now, there are plans to make it generally accessible via the Internet. The goal is to expand the collection with additional specimens from type localities or other relevant sites. We aim to have at least one specimen of each described ichnotaxon for reference [knowing this goal will never be achieved!]. Donations of well-documented, but unpublished [i.e., unfigured or otherwise unmentioned] specimens are therefore welcome.

Underground pagodas:a new sequestrichnion from the Maastrichtian of Denmark

by Lothar H. VALLON[1]*, Jan Audun RASMUSSEN[2] & Henrik MADSEN[2]

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Samples described here were recovered from erratic blocks within clayey tills from the Saale or Weichsel ice age [Andersen & Sjørring 1997] at Lodbjerg Beach [northern Jutland, Denmark]. The first blocks containing the trace fossil were collected by one of us [HM] in 2011. Subsequent finds by two amateur collectors [Eva Yde and especially Christian B. Hansen] have brought new specimens to our attention and increased their number substantially. Nannofossil dating of a nicely preserved specimen from Lodbjerg [MM-13708] indicates a Maastrichtian age.

In the light-coloured, slightly silicified chalk blocks, long, darker grey vertical structures are preserved. From these shafts conical protrusions arise at equal distances, giving the trace fossil a pagoda-like appearance. The burrows are similar to *Patagonichnus calyciformis* described from Miocene siliciclastic deposits of Argentina, but probably represent a new ichnotaxon [email, Eduardo Olivero 2022]. The new trace fossil seems to belong to the newly erected ethological category of sequestrichnia or stowing traces [Uchman & Wetzel 2016]. In this group, the tracemakers collect nutritious sediment and stow it, often as pellets, below the Redox Potential Discontinuity. The new trace fossil has a darker, greyish colour than the surrounding, slightly silicified chalk, suggesting a different chemical composition. In some specimens, pellets can be recognized in the fill. The burrows are often reworked and again re-bioturbated by *Chondrites* isp., similar to the interactions reported by Šamánek et al. [2022].

In one specimen of this pagoda-like trace fossil, a *Chondrites* maker seems to have been attracted to the much larger stowing trace. At the top of the block, both burrow systems are about 3 cm apart. Within 7 cm depth, the *Chondrites* maker reached the pagoda-like burrow by shifting its own burrow system closer and closer towards the vertical shaft. From that depth downwards, *Chondrites* remains within the outline of the larger vertical burrow to the edge of the block, 5 cm below the joining point. This suggests exploitation of a food source readily available within the pagoda-like trace fossil.

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Numerical simulations reproduce the earliest excursions on land by animals

by Zekun Wang[1]* & Imran A. Rahman[1,2]

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The colonization of land by animals was one of the most important events in the history of life, dating back over 400 million years. However, long before this major terrestrialization event, animals had begun to make periodic excursions onto land, leaving behind trace fossils that provide a record of their activities. Here, we pinpoint three main cohesive structures induced by the locomotion of animals on wet sediments exposed to air: [1] shaky levees, [2] bilobate thick levees with sharp profiles along furrows, and [3] spatters around arthropod trackways. Using a coupled Computational Fluid Dynamics–Discrete Element Method [CFD-DEM; Fig. 1] model, we identified the physical origin of these cohesive structures: Liquid bridges between wet sediment particles made them cohesive enough to resist external forces like gravity and form sharp boundaries, but instability can randomly break the continuity of these structures. Based on numerical data and dimensional analyses, we quantified these features using the Capillary Number [Ca] and Bond Number [Bo]. Finally, we used the obtained scaling law to predict movement speeds of the tracemakers. Using this framework, we were able to identify evidence for excursions on land by animals as far back as the early Cambrian. These early animals were capable of speeds of approximately 3.5 mm/s, indicating that they would have had to spend considerable amounts of time on land to produce the relatively long trails preserved in the trace-fossil record. This suggests that some of the earliest animals were capable of air-breathing.

A new quantitative framework to determine the trace makers of locomotory trace fossils: Palaeozoic *Gordia* as a case study

by Zekun Wang[1]* & Imran A. Rahman[1,2]

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Trace fossils record the interactions between organisms and their surroundings, and can therefore provide unique insights into the coevolution of tracemakers and the environment. However, identifying the producers of trace fossils is challenging because different animals can produce very similar traces. As a result, many traces can only be attributed to broad morphological grades; for example, simple locomotory trace fossils like *Gordia* are generally thought to have been created by vermiform worms. This uncertainty makes it difficult to decipher their palaeobiological significance through major evolutionary events and episodes of environmental change. To address this, we have developed a new mathematical approach for identifying previously unrecognized signatures left by the trace makers of simple marine locomotory traces. We calculated the deviation angle series of self-crossing trails made by extant polychaetes, isopods, marine gastropods and nematodes, computing the frequency spectrum and autocorrelation function in each case. The results reveal that each of these taxa left unique markers during the trace-making process, reflecting differences in their anatomy and stimuli-induced locomotory behaviours. Using these data, we were able to identify the tracemakers of several early Palaeozoic *Gordia* ichnospecies, demonstrating that traces from the same ichnogenus can be created by distantly related animals with different morphologies and behaviours. This new mathematical framework has great potential for identifying the producers of traces through deep time, consolidating the link between ichnology and palaeobiology.

Pre-meeting Field Trip: The Cretaceous-Paleogene Boundary at the Stevns Klint UNESCO-Heritage Site

by Lothar H. Vallon & Jesper Milàn

Based in part on texts by courtesy of Richard G. Bromley, Ulla Asgaard & Jan Kresten Nielsen (1995), Lothar H. Vallon, Jesper Milàn & Tove Damholt (2016), and Peter Frykman & Morten Bjerager (2019).

Stevns Klint is a cliff wrapping around the Stevns peninsula on the island of Sjælland (Zealand; Fig. 1). An almost continuous section of the topmost Maastrichtian chalk and lowermost Danian bryozoan limestone is exposed for about 15 km. The strata and their fossils offer exceptional evidence of the Chicxulub meteorite impact at the end of the Cretaceous. The site harbours a record of these ash- and dust-cloud deposits. In particular, the fossilised fauna and microfauna document not only the life before and during this mass extinction event, but also its recovery afterwards. Stevns Klint, therefore, was inscribed on the UNESCO World Heritage List in 2014.

Most of this exposure is accessible, but there are only a limited number of places where the cliff may be descended. We shall examine the cliff at Højerup and Rødvig, at the southern end of the cliff.

Locality 1: Højerup
Location of Højerup: 55° 16′ 40.8″ N, 12° 26′ 45.4″ E

Stevn is an old Danish word for an anvil or stern-like topographic profile, and *klint* means cliff. The object of this field visit is to examine the Upper Cretaceous – Danian chalk and bryozoan limestone exposed in the coastal cliff at Stevns Klint. The outcrop stretches approximately 15 km along the coastline of the Stevns peninsula and reaches a height of about 30–40 m. The exposed carbonates correspond in age approximately to the upper Tor to lower Ekofisk Formations in the North Sea oil and gas reservoirs, and can in some aspects be used as a field analogue to these chalk formations.

Stevns Klint is situated over a structural high between the eastern end of the Ringkøbing-Fyn High and the Sorgenfrei-Tornquist Zone. The Upper Cretaceous-Danian succession on the northwest European shelf was deposited over about 25 Ma and thus represents one of the largest and longest-lived cool-water carbonate accumulations in the stratigraphic record. The locality yields a staggering amount of ca. 450 different species of invertebrates (Damholt & Surlyk 2012) and trace fossils (Bromley & Ekdale 1984; Ekdale & Bromley 1984).

The water depths in the Danish Basin probably never exceeded a few hundred metres, with varying facies types from coastal to pelagic. The climate was temperate, although relatively warm and arid. Most of continental Europe, including the Danish Basin and its margins, experienced an extensive transgression during the Late Cretaceous. During the early Maastrichtian sea-level highstand, chalk was deposited in a broad shallow sea extending

across northern Europe, with its northern margin at the Viking Graben (Surlyk 1997). To the east the Danish Basin connected to an even more extensive sea covering most of Russia, Ukraine and Central Asia (Figs 2 and 3).
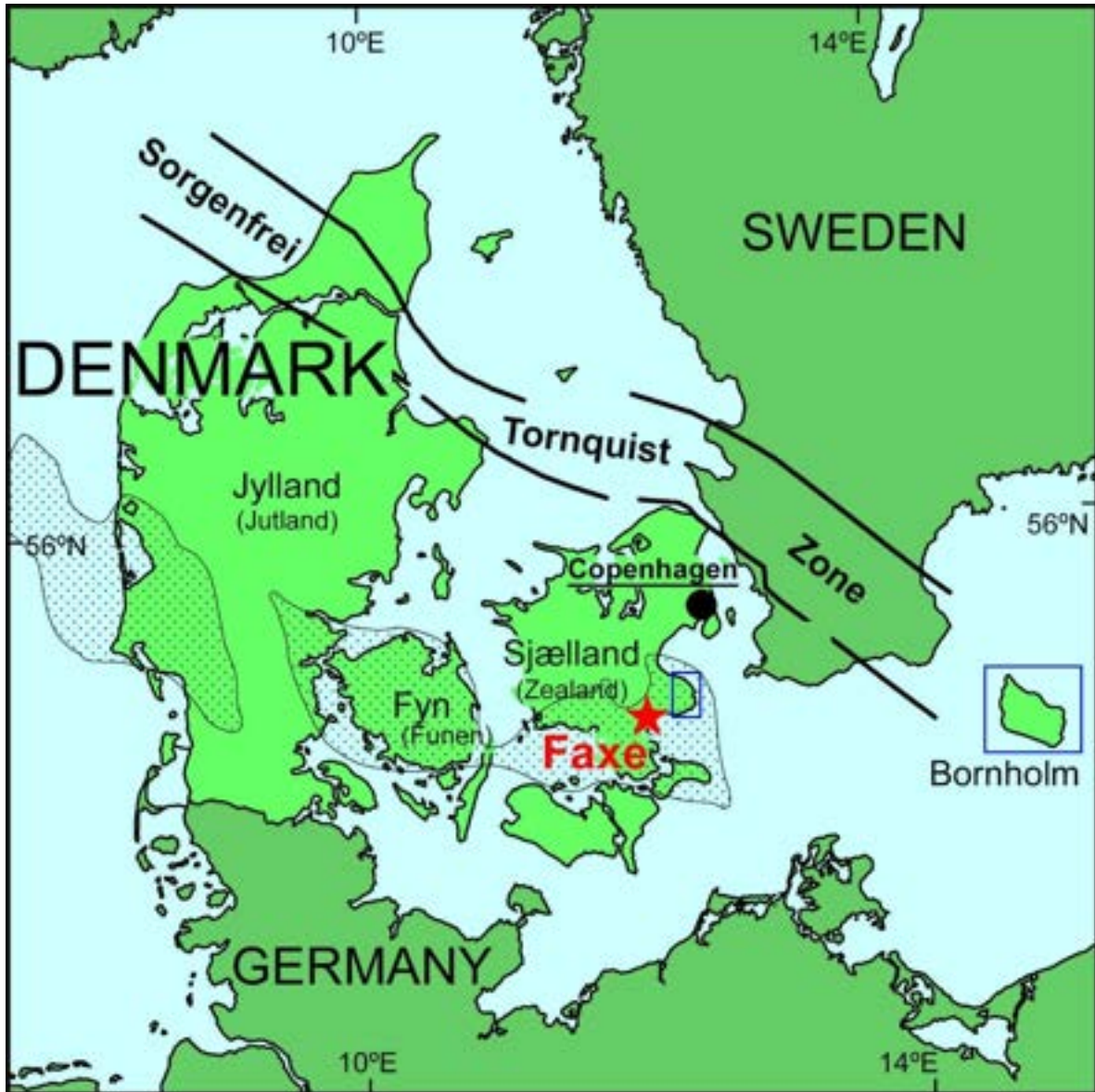

Fig. 1: Overview-Map of Denmark with the Sorgenfrei-Tornquist Zone and the Ringkøbing-Fyn High (dotted). Faxe marked with a red star. Blue frames show the more detailed location maps of Stevns Klint and Bornholm (on the last pages of this guide).

When we look out over the cliff from the vantage point at the Old Church in Højerup, we immediately recognise a division in two parts. In the lower half of the profile, the relatively soft Cretaceous chalk is eroded by the gentle waves of today's Baltic Sea, and at the top overhangs the slightly more resistant bryozoan limestone. To examine the stratigraphy in detail and in the correct chronological order we will need to descend a steep staircase with 112 steps. While doing so, we will observe that the cliff is built up of more than just two units (Figs 4, 5 and 8).
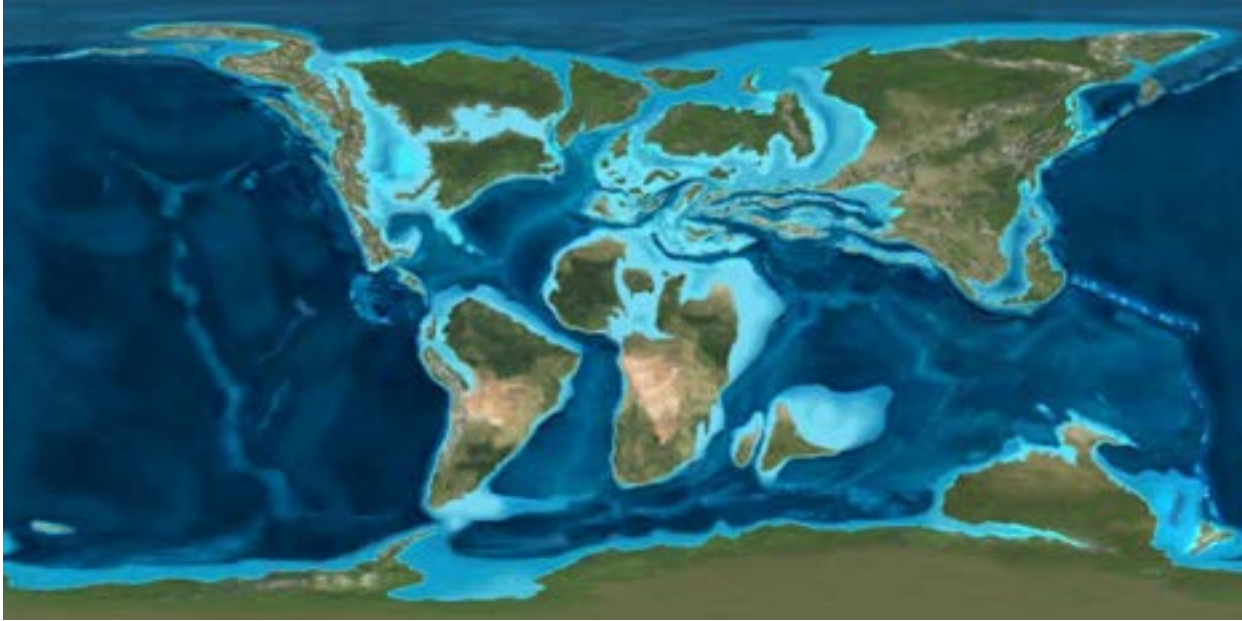
Fig. 2:   Paleogeographic map for the Late Cretaceous showing the relatively high sea level and large shallow-water areas (light blue). (Ron Blakey, NAU Geology.)

The Maastrichtian Chalk

From the beach level upwards emerges the white chalk of the Sigerslev Member (Møns Klint Formation, Fig. 4) which was deposited during the Maastrichtian. This chalk is extremely fine-grained and mainly consists of coccoliths with subordinate bryozoan and sponge fragments. The mainly pelagic, coccolith ooze was shaped into mounds below the photic zone by gentle bottom currents (Surlyk et al. 2006), which provided nutrients for bryozoans and other invertebrate filter feeders (e.g., siliceous sponges). The top of the Sigerslev Member is an evenly bedded, benthos-poor but *Zoophycos*-rich chalk. Two closely spaced incipient hardgrounds cap the Sigerslev Member.

In the uppermost Maastrichtian Højerup Member (Fig. 4), mounded bryozoan-rich chalk reappears, but reaches only a thickness of a few meters (Surlyk et al. 2006). Trace fossils, mainly *Zoophycos* and *Thalassinoides*, are common throughout the formation (Bromley & Ekdale 1984; Ekdale & Bromley 1984) and extensive paramoudras (*Bathichnus*) may be observed in the cliff face.

During the time of deposition, the seafloor had an almost soupground to softground consistency requiring special adaptations of the fauna to prevent drowning in the sediment. The oyster *Pycnodonte vesicularis* (Figs. 6A, B) had an enlarged, bowl-shaped valve that allowed it to float on the sediment; hexactinellid sponges grew deep root-like protrusions for anchorage; echinoids like *Tylocidaris baltica* (Fig. 6H) evolved, club-shaped spines to keep themselves afloat on the sediment surface.
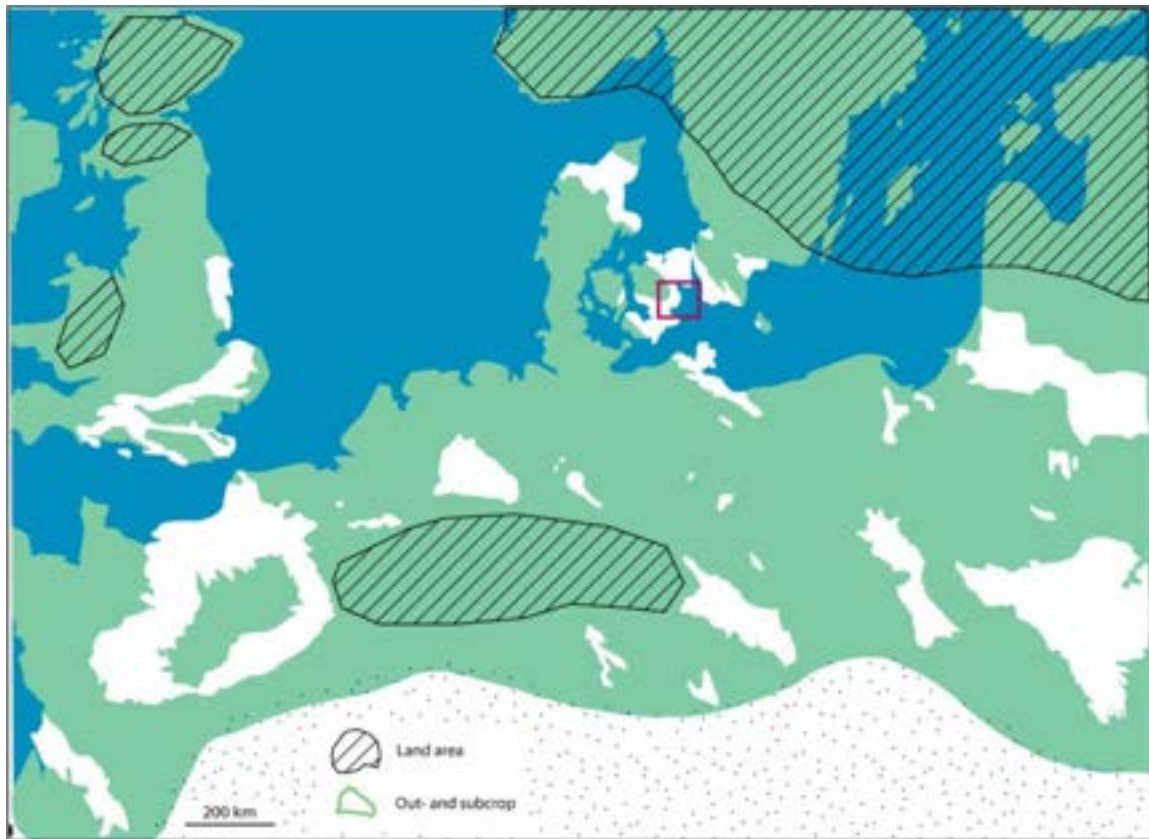
Fig. 3:   Onshore outcrop and subcrop of chalk [white] and Cretaceous land areas [shaded]; the Alpine region is dotted. The Stevns Klint area is framed. [Modified from Frykman & Bjerager 2019].

Fig. 4:   Stratigraphy of the typical Stevns Klint profile with the K/Pg boundary marked. The Upper Maastrichtian chalk extends into the age-equivalent Tor Formation in the North Sea. [Foto by Tove Damholt; taken from Frykman & Bjerager 2019.]

Within the water column swam ammonites, belemnites and other cephalopods. Fish and larger predators, such as mosasaurs and sea-crocodiles left uncommon predation traces on one another, and rare digestichnia in the form of coprolites and geogastroliths.

Life within the seafloor, however, is recorded more comprehensively through its trace fossils. In contrast to the epifauna, the tracemakers here show adaptations to stiff- and firmgrounds [Vallon et al. 2020]. Concretionary, nodular flint of early diagenetic origin commonly occurs in horizons parallel to bedding at relatively regular intervals of about one to three metres. These typically represent silicified burrow systems of *Thalassinoides suevicus,* generally preserved as replacements of the burrow fills. The large *Bathichnus paramoudrae* typically is preserved unsilicified but is encased in ring-like paramoudra flints [Bromley & Ekdale 1984]. The recently described *Koptichnus rasmussenae* [Fig. 7] is an armoured burrow system similar to *Ophiomorpha*. Its silicified lining, however, consists of cuboids, probably cut and shaped by the tracemaker from hexactinellid sponges [Vallon et al. 2020]. *Chondrites*, *Muensteria* and *Zoophycos* [amongst others] occasionally occur in or on the surface of flint nodules as well [often as cross-sections]. The nodules, therefore, can be utilised for observing the otherwise nearly invisible ichnofabric of the chalk [Bromley & Ekdale 1984]. In flint, trace fossils may be preserved:

1] in three dimensions as the external form of the flint, or as incompletely silicified cavities within it;
2] two-dimensionally, as sculptural ornamentation of the flint, representing the surface expression of the burrow; or
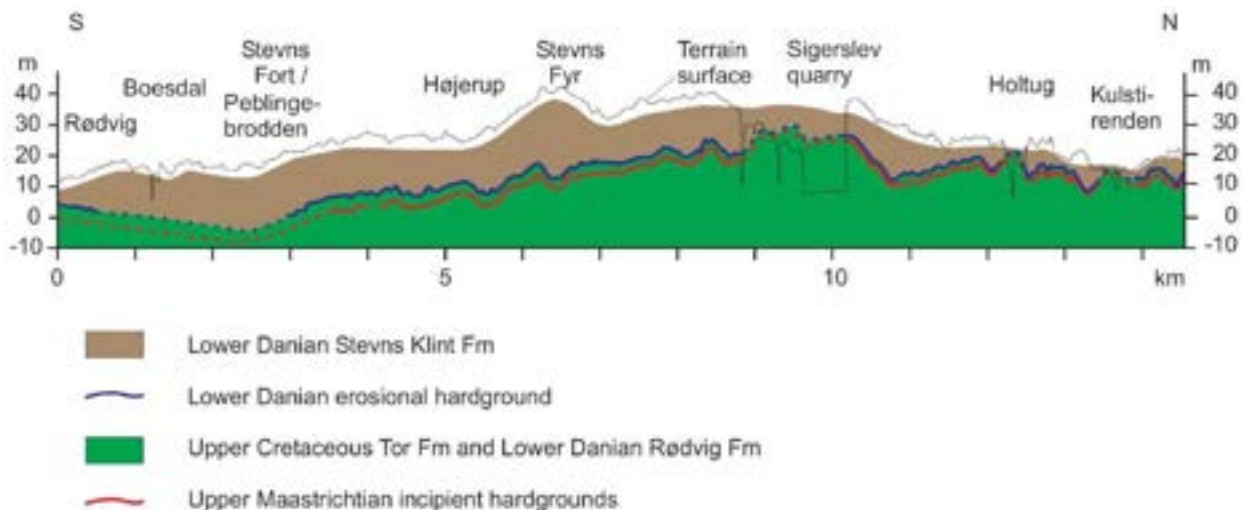3] as ghost structures silicified within the flint.

Fig. 5: Cut through Stevns Klint as exposed by the cliff showing the topography of the Upper Cretaceous – Danian succession, vertically exaggerated ×40. [From Surlyk et al. 2006].
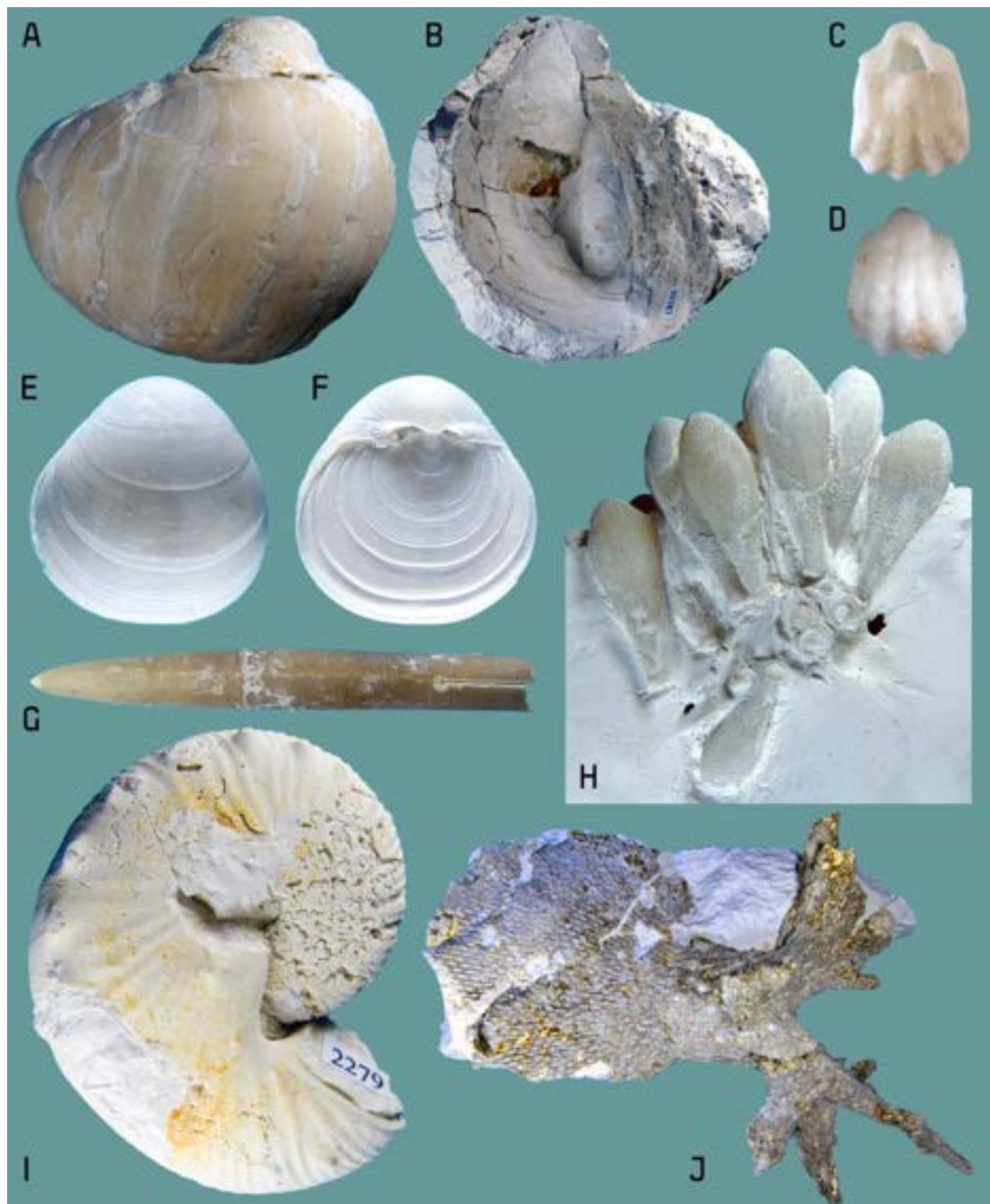
Fig. 6: Some common [and not so common] body fossils of the Maastrichtian from Stevns Klint. A, B: *Pycnodonte [Phygraea] vesicularis*, ca. 105 mm. C, D: *Argyrotheca stevensis*, ca. 2 mm. E, F: *Magas chitiniformis*, ca. 9 mm. G: *Belemnella casimirovensis*, ca. 70 mm. H: *Tylocidaris baltica*, ca. 50 mm. I: *Hoploscaphites constrictus*, ca. 40 mm, with *Arachnostega* isp. In living chamber. J: *Ventriculites radiatus*, ca. 290 mm. [Pictures taken by L. Rasmussen].

In the uppermost few metres of the Cretaceous chalk, the carbon content increases, giving the rocks a slightly greyish tinge. The carbon probably has a volcanic origin related to the Deccan Traps eruptions in India. It was so abundant in the atmosphere that even bivalves at Stevns Klint incorporated it into their shells as black stripes. Simultaneously released volcanic gases and ashes affected the atmosphere and with it, flora and fauna on land and in the seas. The mass extinction had begun.

The Fish Clay

When the Chicxulub Impactor hit the Earth, ash and dust were ejected into the atmosphere. The sunlight was dimmed substantially and chalk production came to a stand-still. The end of the Cretaceous is therefore marked by a dark layer of clay, in Danish named *fiskeler* [fish clay]. The iridium content of the Fish Clay is about 60 times higher than its average occurrence in Earth's surface rocks [Alvarez et al. 1980].

Fig. 7:   *Koptichnus rasmussenae* Vallon et al. 2020. A: Overview of the armoured burrow with cuboids cut from hexactinellid sponges as lining. B: View of cross-cut from left side of A. Scale 10 mm. [Pictures taken by L.H. Vallon].

The Cerithium Limestone

After sedimentation of the Fish Clay, carbonate production was restored gradually. The hard yellowish Cerithium Limestone is named after the gastropod *Metacerithium balticum* [Fig. 13] and has a maximal thickness of one metre. Body fossils are poorly preserved, mainly as cavities or steinkerns. The top of the stratum is eroded and cemented as a hardground.

The Bryozoan Limestone

The Bryozoan Limestone creates a prominent overhang because it is significantly harder than the underlying chalk. This limestone has even been exploited as building stone and was formerly used regularly on the Stevns Peninsula. The rock was created by bryozoan reefs. Between the thickets, the epibenthos was rather similar to the preexisting Cretaceous inhabitants. Echinoids, brachiopods, sponges, oysters and other bivalves employed the same strategies to stay afloat on a relatively soft seafloor [Fig. 13].

Within the sediment, not much had changed, and the characteristic *Thalassinoides* burrow-systems cast in flint are easily observed redrawing the bryozoan mounds.

The main innovations of the Palaeogene environment with regard to the Cretaceous one are recorded in the nektonic fauna: Ammonites and belemnites had died out and were partially replaced by their not so commonly encountered cousins, the nautiloids. The large marine reptiles also had died out, whilst marine crocodiles had not only survived but were now thriving.
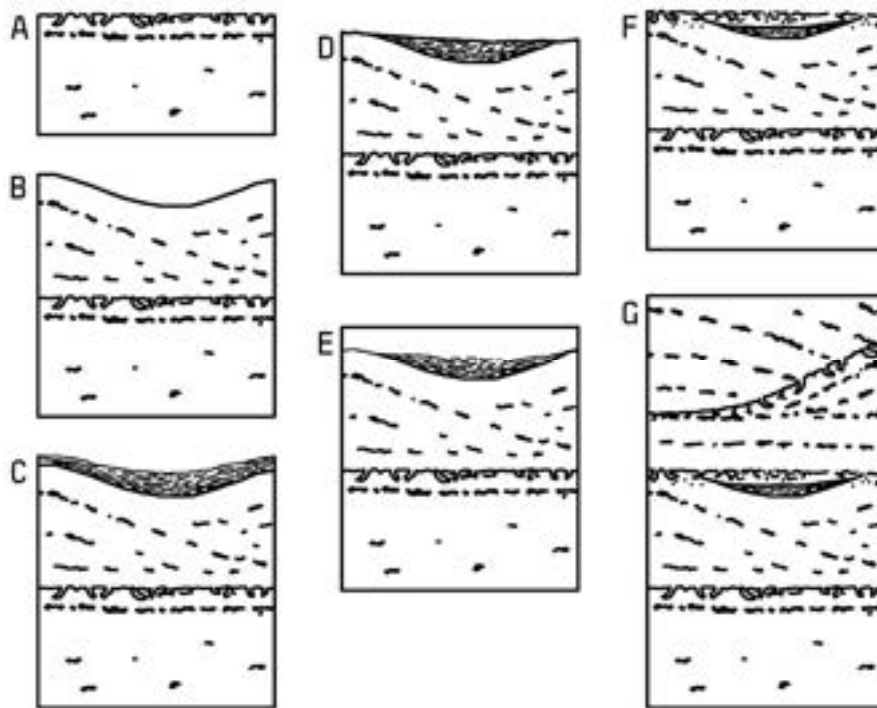

Fig. 8: Stage-by-stage development of the Stevns Klint K/Pg boundary succession. A: Deposition of the white chalk ends with a firmground omission surface. A thick nodular flint developed 0.5 m below this surface. B: Deposition of the grey chalk as bryozoan bioherms. C: Deposition of the Fish Clay, a noncarbonate, organic-rich clay. The K/Pg boundary lies at the base of, or within this bed (according to which authority you consult...) D: Slight reworking of the Fish Clay, which becomes restricted to the intermound troughs. E: Deposition of the Cerithium Limestone. F: Removal of most of the Cerithium Limestone, restricting it to the troughs. The topmost Maastrichtian Chalk of the bioherms was simultaneously removed. The erosion surface was cemented as a hardground. G: Deposition of Lower Danian bryozoan bioherms. Hardground (and flint bed) terminating the first bryozoan bioherm. (Modified from Surlyk in Hâkansson 1971.)

Cultural highlights
Just outside the village of Højerup, at the very edge of the cliff, stands the old church. Tradition says that a seafarer in distress at sea promised to erect a chapel on the cliff, if he was saved. Obviously, he did survive, because in 1250 the chapel (Fig. 9) was erected, built of bryozoan limestone from the cliff itself. In the centuries that followed, the cliff was gradually undermined by the sea.

Fig. 9: The Old Church in Højerup before [left] and after [right] the cliff collapse of 1928.

As early as 1675, contemporary drawings show the removal of the eastern churchyard wall due to erosion of the cliff. For centuries people found consolation in the tale, which said that the Old Højerup Church would survive by moving a cock's stride further inland every Christmas night. But even all the cock's strides were not enough, and on March 16th, 1928 the choir and altarpiece tumbled into the sea. The church was then anchored, the cliff reinforced with concrete, and the beach protected. The church retains several frescoes with the oldest from the late 1300s, and a pulpit from 1605 [extract from Poulsen 1985, translated].

The latest, although dark chapter of Stevns Klint was written over the past 60 years deep inside the cliff. The Stevns Fort museum retells the history of the Cold War.

Locality 2: Stevns Klint Experience [Visitor centre]
Location of Stevns Klint Experience: 55° 15' 29" N, 12° 24' 04" E

The newly opened exhibition centre "Stevns Klint Experience" showcases the uniqueness of Stevns Klint. The story of the End-Cretaceous mass extinction is told by means of fossils and a 5×2 metre polished section of the K-Pg boundary. The latter offers an excellent opportunity to examine the evolution of bioturbation across the boundary interval.

Locality 3: Boesdal – Korsnæb Odde
Location of a point at the beach near Boesdal: 55° 15' 26" N, 12° 24' 08" E

Bryozoan limestone mound complex [Danian, Stevns Klint Formation, Korsnæb Member]

Walk along the beach to the K-Pg boundary at Korsnæb Odde [halfway between Boesdal and Rødvig], which is the best place to see the Fish Clay. The boundary section here is approximately at eye height. The Danian limestones with their unique bryozoan mounds are most easily observed here.
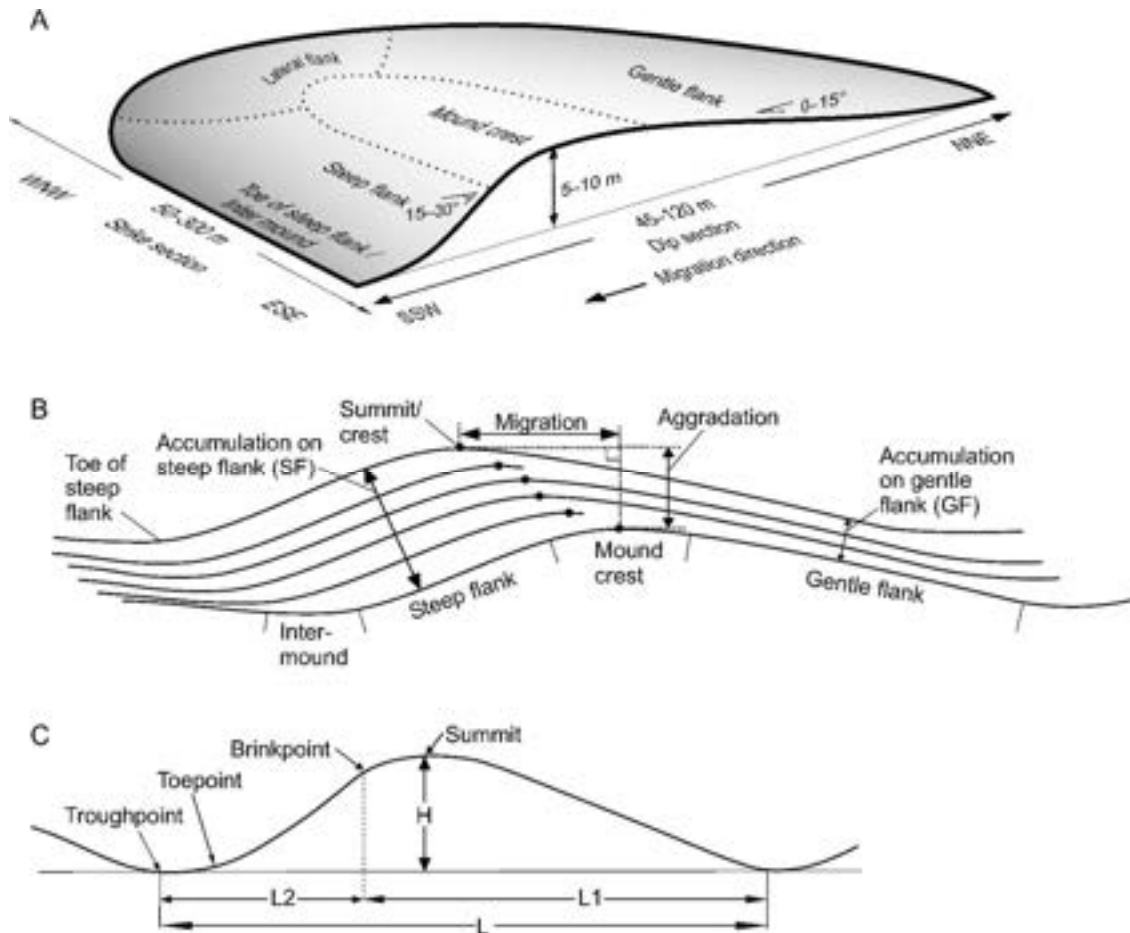
Fig. 10: A: Schematic three-dimensional reconstruction of a bryozoan mound with a cross-section parallel to the main migration direction [dip section]. The boundaries between the mound areas are gradational. B: Idealized ''dip'' section showing six successive mound stages represented by flint bands [black lines]. C] Mound parameters [by analogy with ripple shape parameters]. From Bjerager & Surlyk [2007a].

Bryozoan Mounds

The Danian bryozoan mounds of the Danish Basin are skeletal deepwater mounds dominated by delicate bryozoan fragments and carbonate mud. They are interpreted to have formed in an outer-ramp setting, probably around the inflection of a distally steepened ramp [Fig. 12; Surlyk, 1997]. The bryozoans did not form a rigid skeletal framework; instead, mound formation depended more or less on matrix stabilization by the bryozoan carpet on the sea floor.

Individual mounds are oval in plan view, but in dip-parallel cross-section are internally asymmetrical with a height of 5 to 11 m and a length of 45 to 110 m. At Stevns Klint, the mounds are oriented with their longitudinal axes in a WNW–ESE direction with their dip sections parallel to the direction of mound migration, their strike sections being between 50 to 300 m long. The southern flanks are steep and dip 15–30° mainly towards the SSW, whereas northern flanks have gentle dips of 0–15° towards the NNE [Fig. 10].
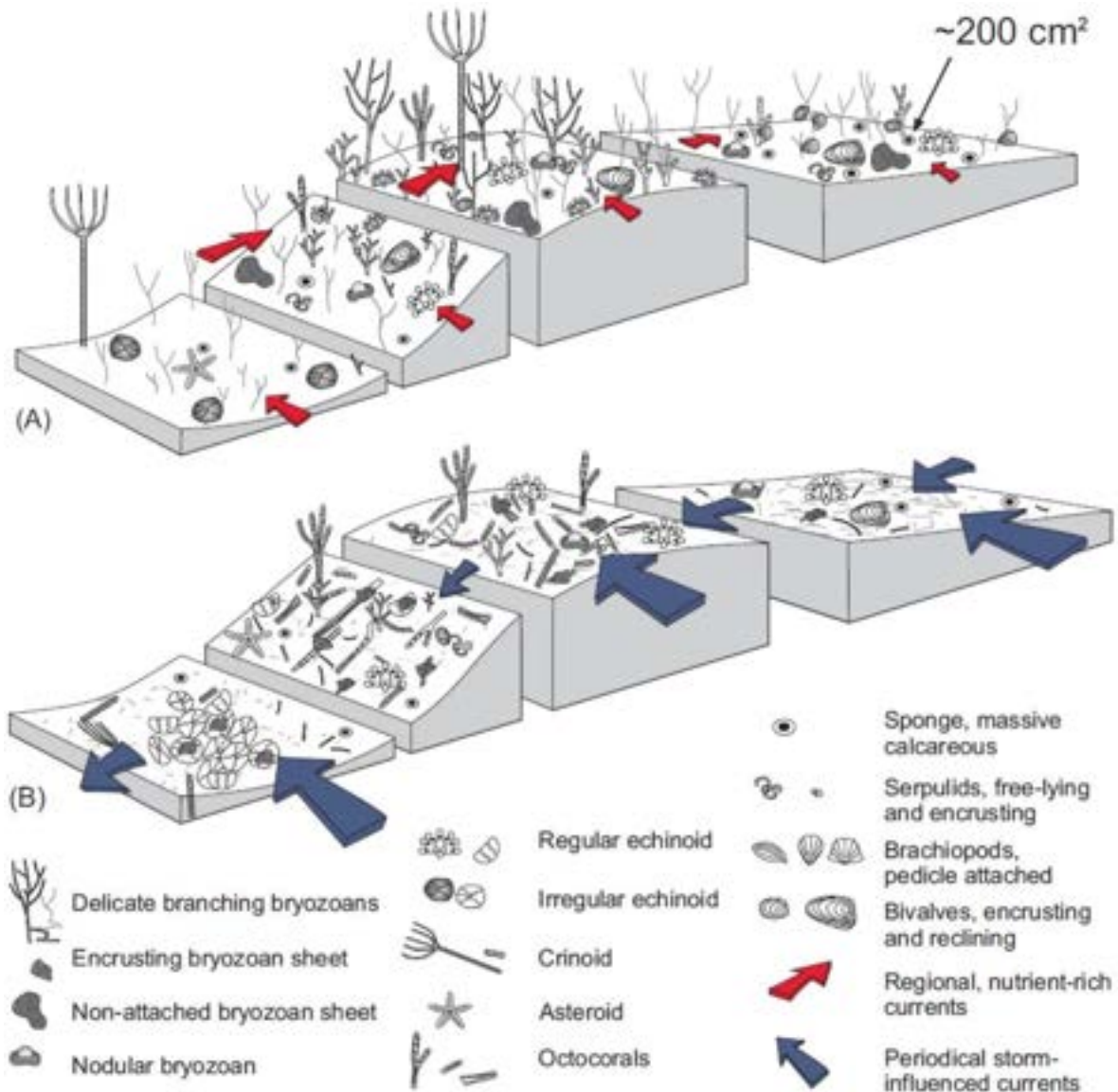
Fig. 11: A: Rich benthic growth, especially on the steep flank and crest. Regional nutrient rich bottom currents are indicated. Depending on environmental conditions, the crest positions were dominated by a rich growth of octocorals, or blooms of bryozoan. B: Storm setting with enhanced current velocity resulting in reworking, skeletal fragmentation and predominantly down-flank and along-flank orientations of elongate skeletons (modified from Bjerager & Surlyk 2007b).

Four facies associations are distinguished (Figure 11):

1) the initial mound association, consisting mainly of bryozoan packstone–rudstone;
2) the steep flank–mound crest association, consisting of bryozoan rudstone with subsidiary octocoral and encrusting bryozoan rudstone and bryozoan grainstone;
3) the gentle-flank association, characterized by bryozoan packstone, and incipient to fully developed hardgrounds;
4) the intermound association, consisting of echinoid rudstone, packstone, and minor occurrences of bioclastic grainstone and argillaceous wackestone–packstone beds and laminae.
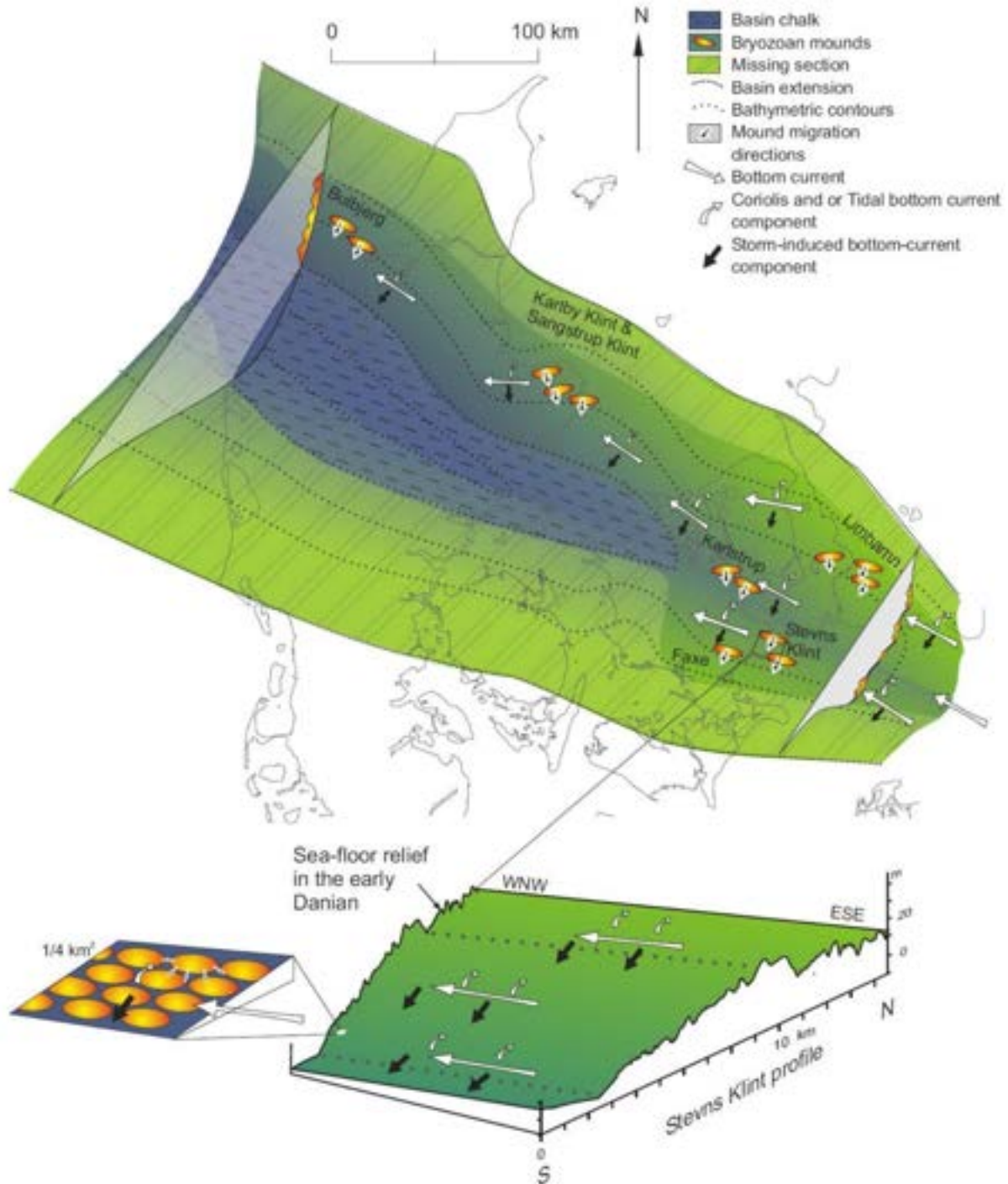
Fig. 12: Palaeogeography and main facies of the Danish Basin in the early Danian, with two highly simplified basinal cross-sections. Bryozoan mounds formed along the northeastern ramp and in the southeastern gateway. They migrated in overall down-ramp or oblique down-ramp directions. The hydrodynamic regimes during mound growth and during storm events are indicated. Slope-parallel bottom currents flowed towards the WNW, combined with a Coriolis effect and/or tidally induced upslope current component, which favoured enhanced growth on the southern flanks of the bryozoan mounds. A down-slope current component was induced during storms, which resulted in erosion on north-dipping flanks (modified from Bjerager & Surlyk 2007a).

Fig. 13: Some common (and not so common) body fossils of the Danian from Stevns Klint. A-C: Body fossils from the Fish Clay. A: *Odontaspis* sp., ca. 5 mm. B: Fish vertebrae, ca. 1-2 mm. C: Coprolites, ca. 0.5-1 mm. D-E: Cerithium Limestone. D: *Metacerithium balticum*, ca. 20 mm. E: *Dentalium* sp., ca. 22 mm. F-J: Bryozoan Limestone. F: *Tylocidaris abildgaardi*, ca. 10 mm. G: Cyclostomata indet., ca. 25 mm (Picture by Jesper Milàn). H-J: *Cyclaster danicus*, ca. 22 mm. (Pictures if not stated otherwise taken by L. Rasmussen).

Facies analysis and mesoscale mapping indicate that the bryozoan mound complexes were formed in relatively deep, cool water below the photic zone and swell wave base. Deposition was influenced by along-slope currents, with prominent seasonal and long-term variations.

Mound growth was governed primarily by in-place benthic carbonate production of mainly delicate branching bryozoans that baffled and trapped pelagic and detrital benthic carbonate mud. Gentle currents rich in particulate nutrients flow towards the WNW, deflected by the Coriolis effect, possibly with a tidally or wind-induced upslope component towards the NNE, resulting in mound growth mainly towards the SSW. High production in the surface waters combined with effective tidal mixing of the water column was important for transporting particulate nutrients to the bottom waters.

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Mid-meeting Field Trip: Faxe Quarry

by Jesper Milàn & Lothar H. Vallon

based on texts by courtesy of Jesper Milàn, Sten Lennart Jakobsen & Carsten Niss (2022), Richard G. Bromley, Ulla Asgaard & Jan Kresten Nielsen (1995).

Locality 1: Faxe Quarry

Centre of Faxe Quarry: 55° 15' 33" N, 12° 07' 43" E

The middle Danian limestones on Faxe Hill (old spelling Fakse) have been quarried for at least 900 years. With approximately 2 square kilometres, the working quarry is the largest man-made hole in Denmark (apart from the one in the Danish Treasury). Faxe Quarry is currently operated by the Belgian Lhoist Group, which owns limestone quarries in 25 countries around the world.

Before quarrying started, the locality of Faxe probably was a windswept hill with wind-bent trees on its top. This gave the hill the appearance of a horse's mane which in Old Norse is called *faxe*.

Two distinct facies are present: Bryozoan Limestone (Stevns Klint Formation) and Coral Limestone (Faxe Formation), which are both biohermal. The quarry walls offer a few good exposures of the transition between the two formations or facies respectively. However, abundant material lying on the quarry floor gives a good idea of the many sub-facies present. Just three million years after the erathem boundary, this is the earliest known example of a scleractinian coral buildup (Lauridsen et al. 2012, Lauridsen & Bjergager 2021) and it was already teeming with life.

The Coral Limestone

The coral mounds in Faxe are typically 20 – 40 metres wide and 100 – 200 metres in length. They were oriented parallel to each other on the sea-floor in an ENE-WSW direction (Lauridsen et al. 2012; Lauridsen & Bjerager 2021). In the quarry walls, cross sections through several mounds of different sizes may be observed, that have overgrown the bryozoans on the surrounding seafloor. The coral limestone consists of tightly packed fragments of coral branches (such as *Dendrophyllia candelabrum* and *Faksephyllia faxoensis*) that may be more or less cemented together with carbonate mud. In addition to the coral fragments, the limestone also contains fossils of reef inhabitants (such as gastropods, bivalves, brachiopods, echinoids, crabs etc.). The coral limestone is geographically restricted to the area around Faxe, with small patches recovered in Limhamn quarry in southern Sweden and in drill cores around the town of Slagelse (Denmark). However, these occurrences are nowhere near as large as the ones at Faxe (Lauridsen et al. 2012; Lauridsen & Bjerager 2021).

The quarry wall below the Geomuseum Faxe is the type locality for the Faxe Formation exhibiting a very sharp transition between the bryozoan limestone and the coral limestone.

Fig. 1: Palaeogeographic map of northern Europe showing the distribution of land and sea during the Danian, about 63 million years ago. Faxe marked with red star. (From Milàn et al. 2022.)

Although developed in waters underlying a subtropical climate, the coral reef at Faxe is the only known fossil cold-water coral reef (Bernecker & Weidlich 1990). Cold-water corals live below the photic zone and therefore are different from corals in tropical warm, surface and sun-lit waters.

Primarily aragonitic organisms are usually preserved as steinkerns or as cavities. Calcitic recrystallisation is restricted to the so-called Næsekalken or Baunekule Facies, which is rarely encountered. Trace fossils are rare. Apart from the occasional casts of bioerosional traces in fossil shell imprints (e.g., *Entobia*), praedichnia in bivalve or brachiopod shells (e.g. *Oichnus*) or *Arachnostega* in steinkerns, other trace fossils are restricted to the rarely encountered hardgrounds. These usually show a diverse bioerosional assemblage of *Entobia*, *Trypanites* and *Gastrochaenolites* on their surfaces.

On the floor of a small cave between the corals, an isopod left the only trackway known from Faxe so far (see Fig. 2K; Milàn et al., this guide, p. 11).
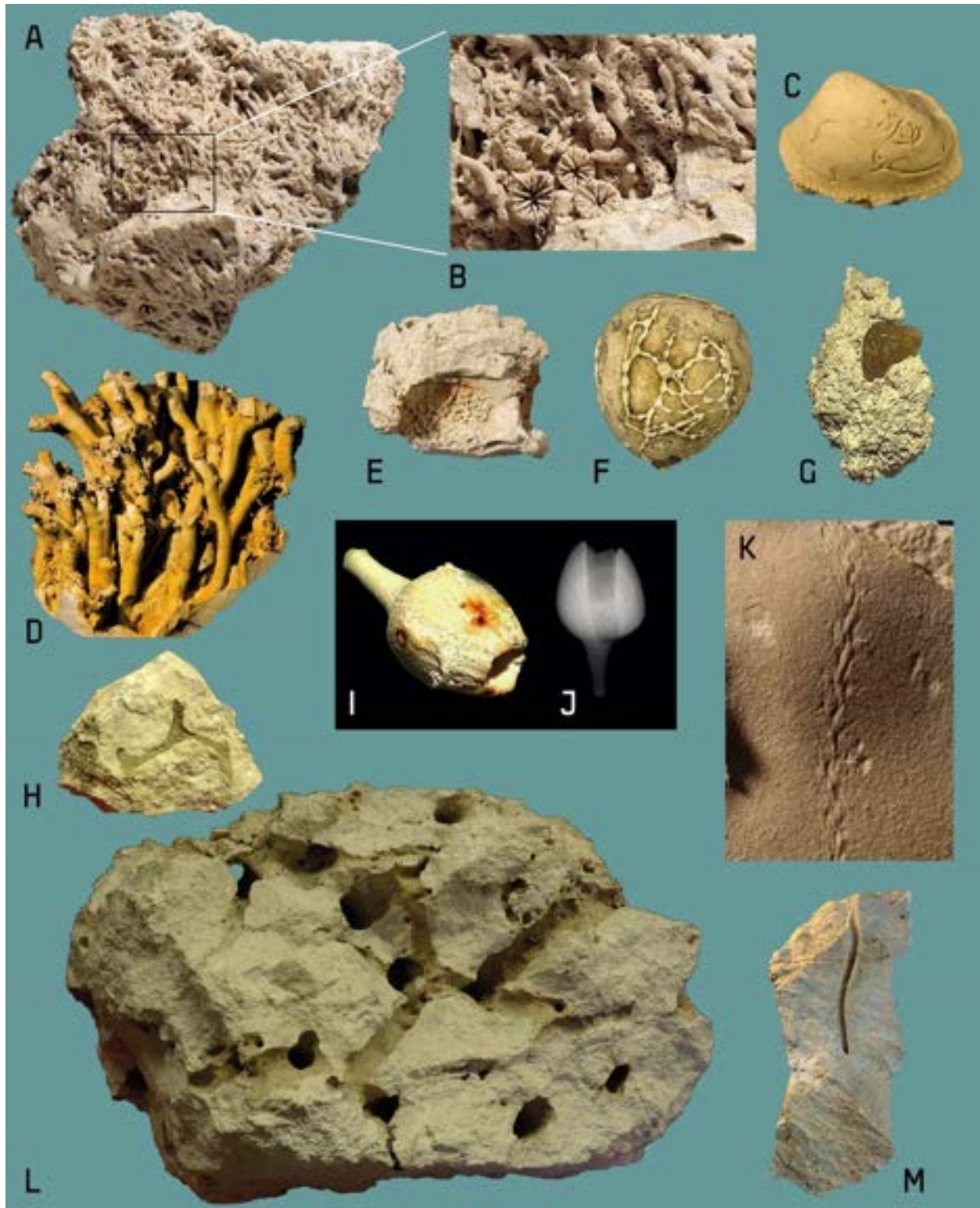
Fig. 2: Common fossils and trace fossils from the Faxe Quarry. A, B: *Dendrophyllia candelabrum* and *Faksephyllia faxoensis*, ca. 350 mm wide. C: Stenkern of *Cucullaea crenulata* with *Arachnostega* isp., 28 mm. D: *Faksephyllia faxoensis* [cast in silicone rubber], ca. 100 mm wide. E: *Entobia cretacea?* in an undetermined bivalve shell, 35 mm. F: *Entobia cateniformis?* in the shell of the gastropod *Cypraea*. G: Polished quartz gastrolith, ca. 5 mm, in matrix. H: *Thalassinoides* isp. burrow diameter ca. 20 mm. I, J: Echinoid spine of *Tylocidaris* with boring *Trypanites mobilis*. J: X-ray photography of same. K: Isopod trackway, L-M: *Thalassinoides* isp., diameter of burrows 10-30 mm. [Pictures by S.L. Jakobsen.]

The Bryozoan Limestone

On the seafloor of the ocean that covered the whole of Denmark during the Danian, large bryozoan mounds were slowly shifting [Rygaard 2006; see also above: Pre-meeting field trip, especially Figs. 10-12]. When bryozoan colonies died, their skeletons fragmented rapidly and new colonies grew atop the old ones, slowly forming large mounds on the seafloor. The spaces among bryozoan fragments were then filled by carbonate mud, cementing the bioclasts together. Bryozoan Limestone is encountered everywhere in Denmark, but is, apart from Faxe Quarry, prominently exposed only at the top of Stevns Klint, in the Limhamn quarry in southern Sweden and at several smaller locations in mid- and northern Jylland.

Thalassinoides is predominant in the Bryozoan Limestone facies, but several other trace fossils occur. The burrows are either passively filled or preserved as open cavities in the limestone. Some of the club-shaped spines of the regular sea urchin *Tylocidaris* may be bored, containing the domichnion *Trypanites mobilis*. The tracemaker, a worm, used the spine as a mobile home and dragged it along the seafloor [Øhlenschlæger et al. 2022]. Other ichnospecies of *Trypanites* may also be observed in starfish ossicles or crinoid columnals.

Digestichnia — coprolites of sharks and other fishes, sea crocodiles and perhaps turtles — are relatively rare. Marine crocodiles brought exoclasts as geogastroliths with them to Faxe [Milàn 2010; Milàn et al. 2012, 2022; Fig. 2G].

Cultural Note: A short history of quarrying in Faxe

From the early Middle Ages onward, people began to use lime for many different purposes. For the first couple of hundred years, limestone blocks were collected from the surface around Faxe Hill. The blocks were only roughly hewn and were fused together like boulders to build walls. Numerous examples of this building style survive to date in the many churches built on southern Sjælland during and after the 13th century. The right to mine limestone in Faxe was initially divided between numerous larger and smaller mining interests, including the large estates of the area. Other authorities such as the priest, dean and innkeepers could also take limestone as needed.

After the Dano-Swedish war [1658–1660], limestone was in high demand to reconstruct the many destroyed houses. In the mid-1880s, the shipping harbour at Faxe Ladeplads and the narrow-gauge railway between the quarry and the harbour were built. Now export of large quantities of limestone was possible. At the same time, several stone-carving businesses arose producing stepping stones, tiles, ornaments, tombstones, doorjambs, lintels and cornices for larger townhouses. Around the same time, the businessman C.F. Tietgen founded the company Faxe Kalk A/S, and the new company invested heavily in the market for custom-made limestone products. The business, however, was short-lived. The vogue for carved limestone decorations had shifted towards cast concrete instead. The last large project to use limestone from Faxe as building material was the construction of "The Marble Church" in Copenhagen. Nowadays this church is one of the main attractions of Copenhagen, lying not far from the Royal Residence Amalienborg Palace. The church was opened in 1894. Faxe Kalk A/S largely closed down their production of custom-cut limestone in 1887.

Up to the 1920s all quarrying work was done by hand. The limestone was blasted loose with explosives, then cut into suitable pieces and loaded onto wagons. For a considerable period of time approximately 500 people executed this backbreaking work. Today only 12 people are directly concerned with quarrying. Lime has been burned for mortar and cement production for several thousand years, but it was not until the beginning of the 18th century that lime burning was included in operations at Faxe Quarry. To burn lime, and create quicklime, it needs to be heated up to 1100–1200 °C. Burnt lime mixed with sand is called mortar. Burnt lime can also be mixed with water and then is used to whitewash houses. Initially, the kilns were built in the quarry, and later also at the beach at Faxe Ladeplads. Until 1932, high-shaft kilns were used, where the lime was burned with heat from below. After firing, the kiln was emptied and prepared for the next firing. With the construction of a large inclined rotary kiln south of the quarry, this process was speeded up immensely. The system is supposed to work non-stop. Unburned lime is added to the upper end of the kiln and conversion to quicklime takes place while the kiln tube rotates and leads the burnt lime towards the lowest point of the kiln where it is removed. The rotary kiln in Faxe is the largest in northern Europe.

Fig. 3:   Frederikskirken, "The Marble Church" in Copenhagen, picture taken from Amalienborg [Wikipedia.org].
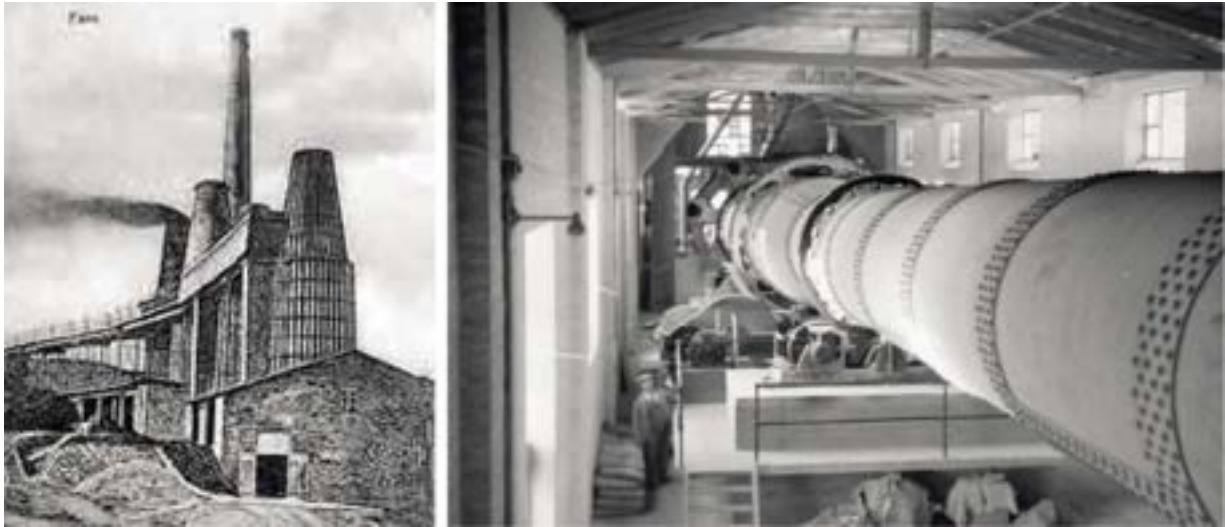
Fig. 4:   Old limestone kilns, south of Faxe [left] and the rotating kiln, installed in 1932 [right].

Lime from Faxe was and is used in many industrial products as neutral filler owing to its clean white colour. From the mid-1850s, lime from Faxe has been sold for tanning hides and making paper, fabric, glass, porcelain, steel, sugar and paint. The lime was also used for soil improvement in agriculture and nutritional supplements for domesticated animals. Waste products from limestone production were used as fill in road construction. In recent times, lime has been used for emission purification in fossil-fuel-fired powerplants by removing sulphur, and to treat man-made acidification of lakes and streams.

Faxe Church
The church lies on top of the Faxe Hill and may be seen from far away. The large 40 m long building is a late medieval longhouse that was built shortly before 1492 when the church was donated by King Hans [1481–1513] to the University of Copenhagen. This ownership was not terminated until 1934.

Annexes are on the north side, one being a registry built more or less at the same time as the church, the other a pretty spacious chapel that was further enlarged in 1638-39. Between these annexes stands a small burial chapel from the beginning of the 17th century. The tower with its decorative stripes of limestone masonry and red brickwork was built about 1500. The pulpit is from the 17th century, and the altarpiece from 1717. Frescoes can be seen in the entrance hall, the so-called *våbenhus* [armoury house, where churchgoers would have to deposit their weapons and armour before being allowed to take part in the church service].

The church underwent major restoration in 2014.

[translated   from: https://www.sydsjaellandmoen.dk/sydsjaelland-moen/soeg-efter-oplevelser/faxe-kirke-gdk1059152]

Fig. 5: Faxe [Fakse] Church from the north side with its large annexes [picture by Jesper Milàn].

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Post-meeting Field Trip: Bornholm

Arne Thorshøj Nielsen & Lothar H. Vallon

based in parts on texts by courtesy of Richard G. Bromley, Ulla Asgaard & Jan Kresten Nielsen (1995) and Bromley & Uchman (1999).

This field guide gives a very brief outline of the geological setting and sediments of Bornholm, and is inspired by an excellent series of guide-books produced by Varv. There is not much about trace fossils in the Varv Guides and the ichnological content has been added by Bromley et al. (1995) and Bromley & Uchman (1999), mainly from unpublished material. Rather than pepper the text with references, the literature has been collected as an appendix for Further Reading. A map with the visited localities is on the last pages of this guide.
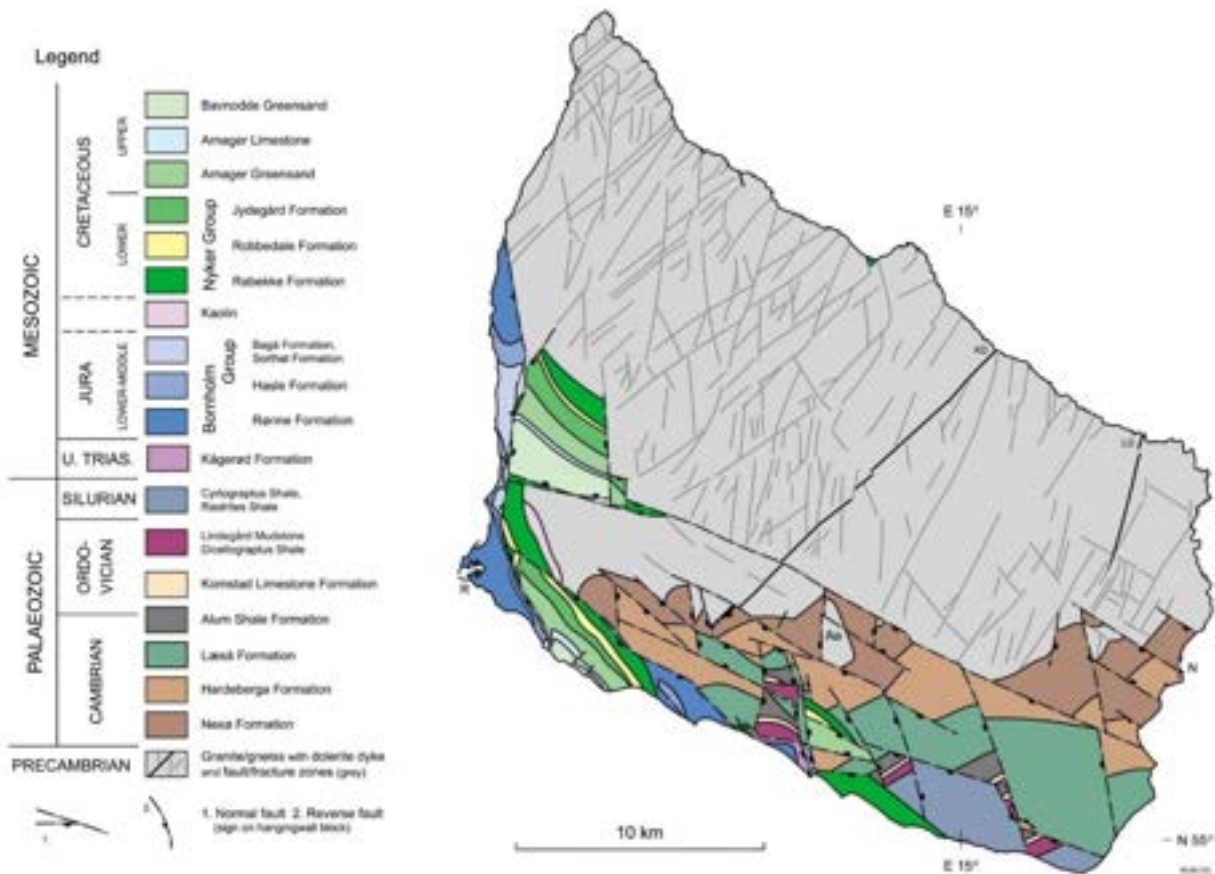
Fig. 1:   Bedrock geology of Bornholm. From Graversen (2009).

Bornholm's 588 km^2 represents but 1.4% of the area of Denmark. However, in this tiny space is crowded an extraordinary amount of geology. The island lies directly on the boundary between "New Europe" to the south (i.e. the Roman, Celtic and Anglo-Saxon region) and "Old Europe" (Scandinavia) to the north. Bornholm represents the southernmost extension of the Precambrian basement of the Fennoscandian Shield, and the northern half of the island consists of gneiss and granite, cut by dikes of dolerite. This shield comprises most of southern Norway, Sweden, Finland and Karelia (Berthelsen 1989). On Bornholm, the granites

and gneiss are some 1.5 billion years old, whereas different generations of the cross-cutting dolerites date at 1400–900 million years.

Fig. 2:   A: Structural map of the Sorgenfrei-Tornquist Zone. KSS: Kattegat-Skagerrak segment; BSS: Bornholm-Skåne segment; TTZ: Teisseyre-Tornquist Zone. B: Major structural elements of central, eastern and northern Europe. From Graversen (2009).
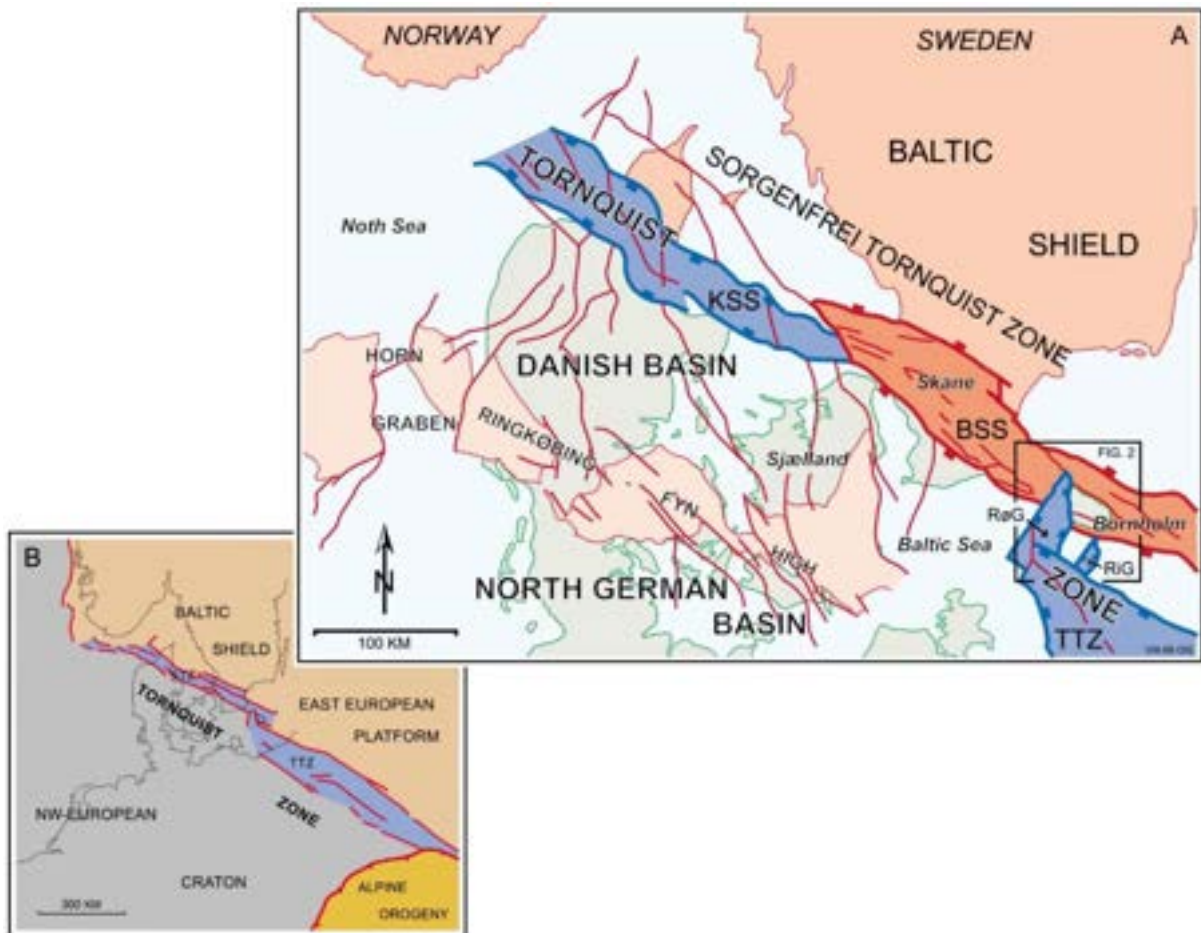
The southern half of Bornholm witnesses a great tectonic drama, for the Tornquist Zone runs immediately adjacent to the south and west coasts of the island (Fig. 1-4). Hence, southern Bornholm consists of sediments broken into tectonic blocks, and having Mesozoic sedimentary facies reflecting the active marginal setting. This deep-crustal fault zone can be followed from the Black Sea in the southeast to the North Sea in the northwest. It passes right through Skåne (Scania, southernmost Sweden), the square chunk of southernmost Sweden, where a similar sedimentary history to that of Bornholm is developed in a series of elongate graben basins running NW-SE.

The first faulting was developed towards the close of the Precambrian, and since then, both vertical and lateral movements have occurred during periodic bouts of activity right up to the Quaternary. Bornholm lies so close to the zone of movement that the great orogenic events of Europe are recorded by lengthy hiatuses in the sedimentary record of the island (Berthelsen 1989).
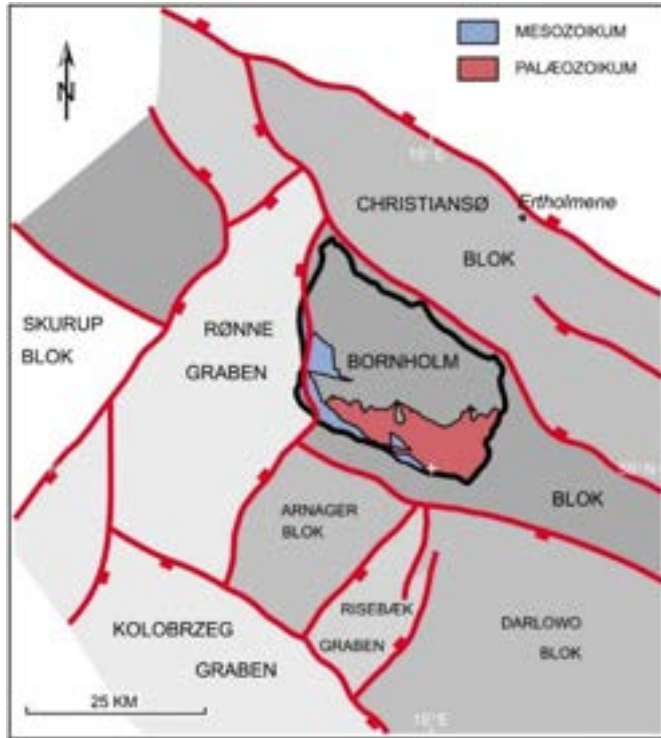
The oldest great hiatus of south Bornholm occurs between the eroded basement and the oldest Cambrian beds. This break spans more than 300 million years [ca. 900–540 million years] and corresponds to the breakup of "Old Europe" south of the Trans-European Faultline, and the subsequent Late Precambrian [Cadomic] plate-tectonic development, which formed the foundation of "New Europe's" crust.

Fig. 3: Tectonic map of area around Bornholm [after Graversen 2009].
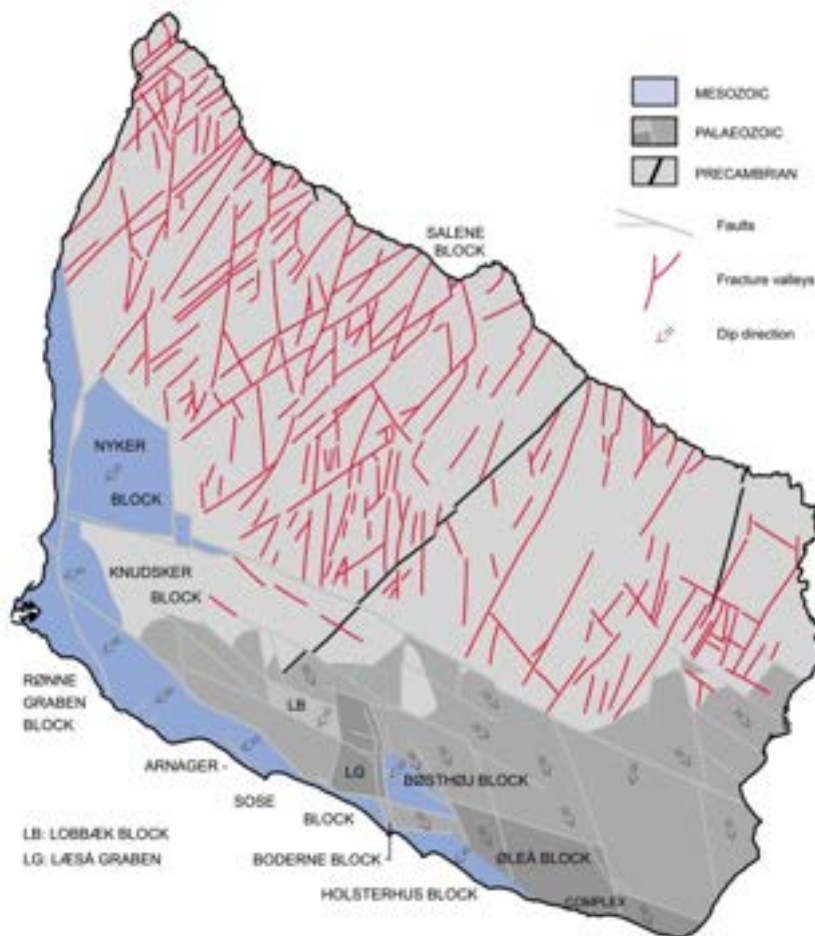

Fig. 4: Fault block map of Bornholm. From Graversen [2009].

The second great hiatus in Bornholm's sedimentary stratigraphy lies between the latest Silurian shales and the oldest Triassic redbeds. The first part of this lacuna corresponds to the closing phase of the Caledonian Orogeny, when the mountain chains of Scandinavia and the north German and Polish caledonides were built. The latter tectonic front is hidden under southern Jylland and the Baltic Sea, where it runs between Bornholm and Rügen.

The second hiatus also includes the period of the Hercynian plate-tectonic evolution, producing the middle-European Hercynian mountains and the initial breakup of Gondwana. It was the Hercynian development that led to the creation of the northwest part of the Tornquist Zone [this segment is referred to as Sorgenfrei-Tornquist Zone], where the great fracture system extends from Bornholm's southwest coast northward across Skåne to Kattegat and north Jylland. Any sediments that accumulated onshore Bornholm in this period were eroded away before the Triassic.

The latest great hiatus spans from the Late Cretaceous to the Quaternary. This time corresponds to the Alpine plate-collision, during which the Alps, Caucasus, Tatras and the Mediterranean Sea were produced, with the subsequent compression of Europe against Africa. Ask any Greek or Italian – the earthquakes in southern Europe are not over yet - and Bornholm is still dry!

The result of this long story is that the sediments of Bornholm are broken up into several blocks, each having slightly to considerably different depositional histories [Fig. 4].

The Palaeozoic
Lower Cambrian

The oldest sedimentary unit on Bornholm is the **Nexø Formation** [Nielsen & Schovsbo 2007]. This formation is slightly more than 90 m thick and comprises two members. The lower **Gadeby Member** consists of a reddish arkosic sandstone and is 40 m and maybe locally up to 50 m thick. At many horizons the sands are cross-bedded and muddy intercalations are adorned with dramatic desiccation cracks. The sediment structures and mudcracks were taken as evidence of deposition in a braided river environment [Clemmensen & Dam 1993]. At Gadeby Quarry, these features are well demonstrated. However, in view of the environmental interpretation, it is exciting to note trace fossils within some of the thin, muddy partings! These are very miserable *Planolites*, but if the interpretation is correct, they are absolutely the earliest nonmarine trace fossils documented! Or are they merely evidence of an unsuspected marine environment? The Gadeby Member contains at least one bed with glauconite [Nielsen & Schovsbo 2011].

The Gadeby Member is overlain by the **Langeskanse Member**, ca. 40 m thick, becoming increasingly quartzitic upwards and representing a gradual transition to the Hardeberga Formation. The Nexø Formation contains no fossils, but is probably of earliest Cambrian age [Nielsen & Schovsbo 2011].

The Nexø Formation is overlain by the **Hardeberga Formation**, the greater part of which is a clean orthoquartzite. This unit is a little more than 100 m thick. Lower and middle parts

contain mudstone and were deposited in a mid-shelf setting. The quartz cement is a deep-burial cement [Møller & Friis 1999]. Poorly preserved palynomorphs and rare body fossils give an early Cambrian age [Nielsen & Schovsbo 2011]. The uppermost part of the Hardeberga Formation contains horizons rich in *Skolithos linearis* [pipe-rock] and, even more spectacular, beds rich in *Diplocraterion parallelum*. Hamberg [1991] interpreted the Hardeberga Formation of Skåne as representing stacked deposits of barrier islands and backbarrier tidal systems, but most of the unit on Bornholm seems to represent stacked storm beds deposited in a slightly deeper environment.

Above this in turn comes the **Læså Formation**, comprising two members. The **Norretorp Member**, just over 100 m thick, is largely siltstone containing muddy intercalations and numerous beds of fine sand [tempestites]. Glauconite and chlorite impart a greenish shade, and phosphorite concretions are locally common. These concretions contain fossils [e.g. acritarchs and hyoliths] and an early Cambrian age is indicated [Moczydlowska & Vidal 1986].

Considering its age, the Norretorp Member shows surprisingly high levels of bioturbation and a large ichnodiversity. Bioturbation is mainly horizontal in the siltstone, and suggests a dominantly deposit-feeding community in shallow water below fair-weather wave-base. Ichnospecies of *Teichichnus, Phycodes, Planolites, Palaeophycus* and *Rhizocorallium* are characteristic. Some of the fine sand beds, however, have been colonized from the top by an animal that produced remarkable oblique *Diplocraterion* isp. [Clausen & Vilhjálmsson 1986].

The Norretorp Member represents a sea-level rise that outpaced the sedimentary supply, but upwards the unit contains an increasing amount of sand. The overlying **Rispebjerg Sandstone Member**, 3-4 m thick, represents a high energy coastal deposit. Trace fossils are not spectacular, but rare *Cruziana* has been reported [Poulsen 1967]. Above is a major hiatus, and the overlying **Alum Shale** [representing the middle Cambrian to lower Ordovician, up to 35 m thick] hold little joy for the ichnologist. This unit was predominantly deposited under dysoxic to anoxic conditions and trace fossils are exceedingly rare [none reported from Bornholm]. However, thin intercalations of limestone in the middle Cambrian record transient periods of improved oxygenation at the seafloor and these units are intensively bioturbated.

Lower Ordovician

Sandwiched by the shales [Fig. 5], ichnology returns with the Middle Ordovician **Komstad Limestone Formation**, which is ≤ 5 m thick and totally bioturbated. On Bornholm, the hiatuses below and above this limestone are much longer than in Skåne, owing no doubt to local tectonic activity [uplift of the southern margin of Baltica]. The Komstad Limestone has never received ichnological study, but Ekdale & Bromley [2001, 2003] and Ekdale et al. [2002] published on the Swedish correlatives of this unit.

The Komstad Limestone is a condensed deposit, containing repetitive omission surfaces. Some of these surfaces are phosphatized and clearly were cemented hardgrounds. One of the problems involved is fabric visibility, as is so often the case with limestones. There is little to be seen in the field on fracture surfaces. The dominant ichnotaxon seems to be narrow *Thalassinoides* mazes.

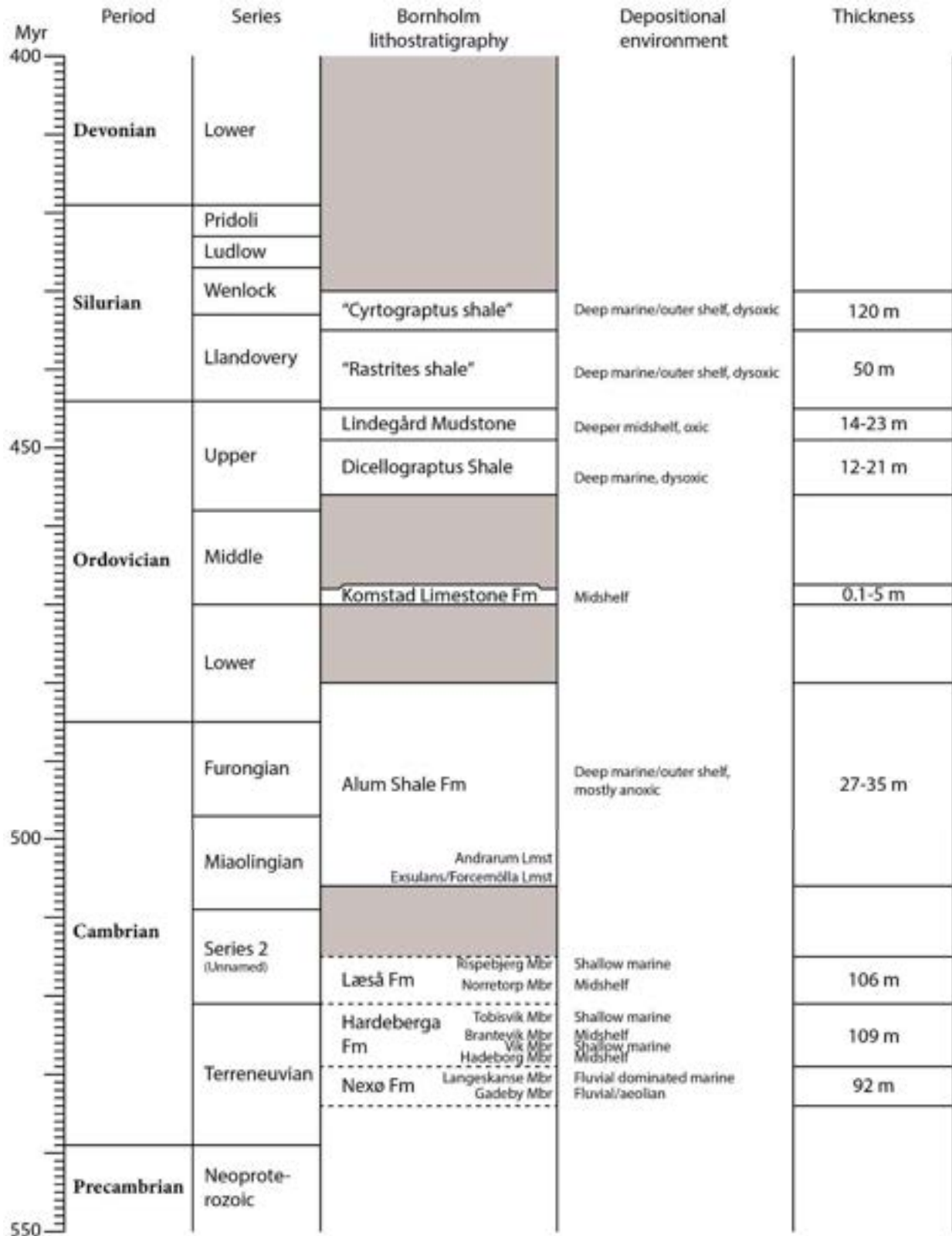| Myr	Period	Series	Bornholm lithostratigraphy	Depositional environment	Thickness
400	Devonian	Lower			
	Silurian	Pridoli			
		Ludlow			
		Wenlock	"Cyrtograptus shale"	Deep marine/outer shelf, dysoxic	120 m
		Llandovery	"Rastrites shale"	Deep marine/outer shelf, dysoxic	50 m
450	Ordovician	Upper	Lindegård Mudstone	Deeper midshelf, oxic	14-23 m
			Dicellograptus Shale	Deep marine, dysoxic	12-21 m
		Middle			
			Komstad Limestone Fm	Midshelf	0.1-5 m
		Lower			
	Cambrian	Furongian	Alum Shale Fm	Deep marine/outer shelf, mostly anoxic	27-35 m
500		Miaolingian	Andrarum Lmst / Exsulans/Forcemölla Lmst		
		Series 2 (Unnamed)	Læså Fm — Rispebjerg Mbr / Norretorp Mbr	Shallow marine / Midshelf	106 m
		Terreneuvian	Hardeberga Fm — Tobisvik Mbr / Brantevik Mbr / Vik Mbr / Hadeborg Mbr	Shallow marine / Midshelf / Shallow marine / Midshelf	109 m
			Nexø Fm — Langeskanse Mbr / Gadeby Mbr	Fluvial dominated marine / Fluvial/aeolian	92 m
550	Precambrian	Neoprote-rozoic			

Fig. 5: The Palaeozoic stratigraphy of Bornholm. Compiled by A.T. Nielsen.

Body fossils are abundant. Orthocone cephalopods, orthacean and rhynchonellacean brachiopods and nileid and asaphid trilobites, the latter especially, tell of much shallower water than during the shale deposition before and after the limestone interval (Nielsen 1995).

Upper Ordovician and Silurian

The overlying shales are Late Ordovician (30-40 m) and Early Silurian (170 m preserved onshore Bornholm). They are more bioturbated than the Cambrian ones, especially the Lindegård Mudstone at the very top of the Ordovician. To some extent this may be a result of the evolution of the dysaerobic benthic biofacies, rather than better oxygenation in the Ordovician-Silurian, but a globally recognisable sealevel lowstand characterises the latest Ordovician and is associated with glaciation in Gondwana.

Mesozoic

We jump to the second Great Hiatus. The Tornquist Zone became active in the late Palaeozoic and Mesozoic (Gravesen et al. 1982; Liboriussen et al. 1987; Hamann 1989; Graversen 2004a,b, 2009). The Atlantic Ocean was opening! Tectonics are extensional again!

Around Bornholm one can identify three structural regions: the rapidly subsiding Rønne Graben, the slowly subsiding Sose Platform, and the proud, erosive Bornholm Horst (Fig. 6; Hamann 1988; Jensen & Hamann 1989). Mesozoic sediments in the Rønne Graben are thick, reaching over 5 km, but little is visible in onshore exposures.

Depositional history is complicated: subsidence is different for the different fault blocks, and the tectonic history interplays with eustatic sea-level changes. However, there are four periods of deposition of Mesozoic sediments on Bornholm (Fig. 7), separated by intervals of nondeposition and erosion.

Triassic

In the Middle to Late Triassic, NW Europe lay within the northern subtropical high-pressure belt and had a warm and dry climate. The redbed desert covered Germany, England, Scotland and East Greenland. Trace fossils are abundant elsewhere in the aquatic areas of this red region, but the **Kågeröd Formation** of Bornholm has few (the thickness of this unit is estimated at 60 m). The red and green fluviatile sandstones, conglomerates and floodplain mudstones locally contain carbonate concretions of caliche origin. Within these caliche horizons, large, mud-filled shafts and tunnels (*Camborygma*) are attributed to burrowing crayfish. Some caliche nodules may contain rhizoliths. In the fine sandstones of the floodplain sediments vertical U-shaped burrows, passively filled with sand (*Arenicolites*) and winding unbranched burrows with an active fill (*Taenidium*) may be encountered (Knaust 2015).
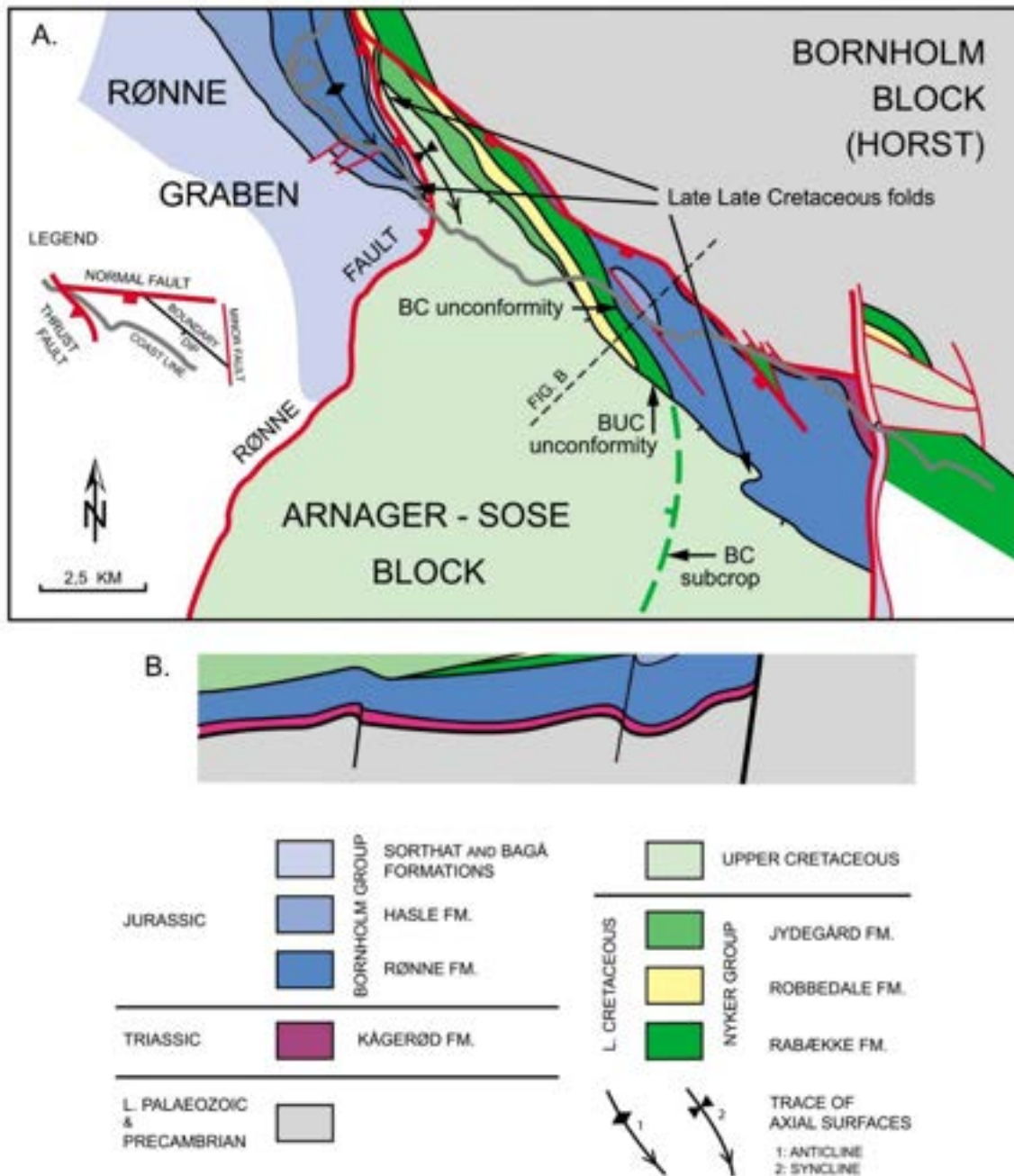
Fig. 6: Geological map of the Mesozoic formations on- and offshore southwest Bornholm. Modified from Graversen (2009). BC: Base Cretaceous; BUC: Base Upper Cretaceous.

Lower to Middle Jurassic.
The next transgression is nicely documented. The **Rønne Formation** begins with lacustrine or lagoonal, clayey, plant-rich deposits. There are root-beds and thin coal layers. Cross-bedded sands follow, representing delta plain environments, and these are succeeded by heterolithites deposited in a tidal environment cut by sand-filled channels (Sellwood 1972; Arndorff 1993; Surlyk et al. 1995). Trace fossils are remarkably rare, owing perhaps to salinity variation or exceedingly rapid deposition.
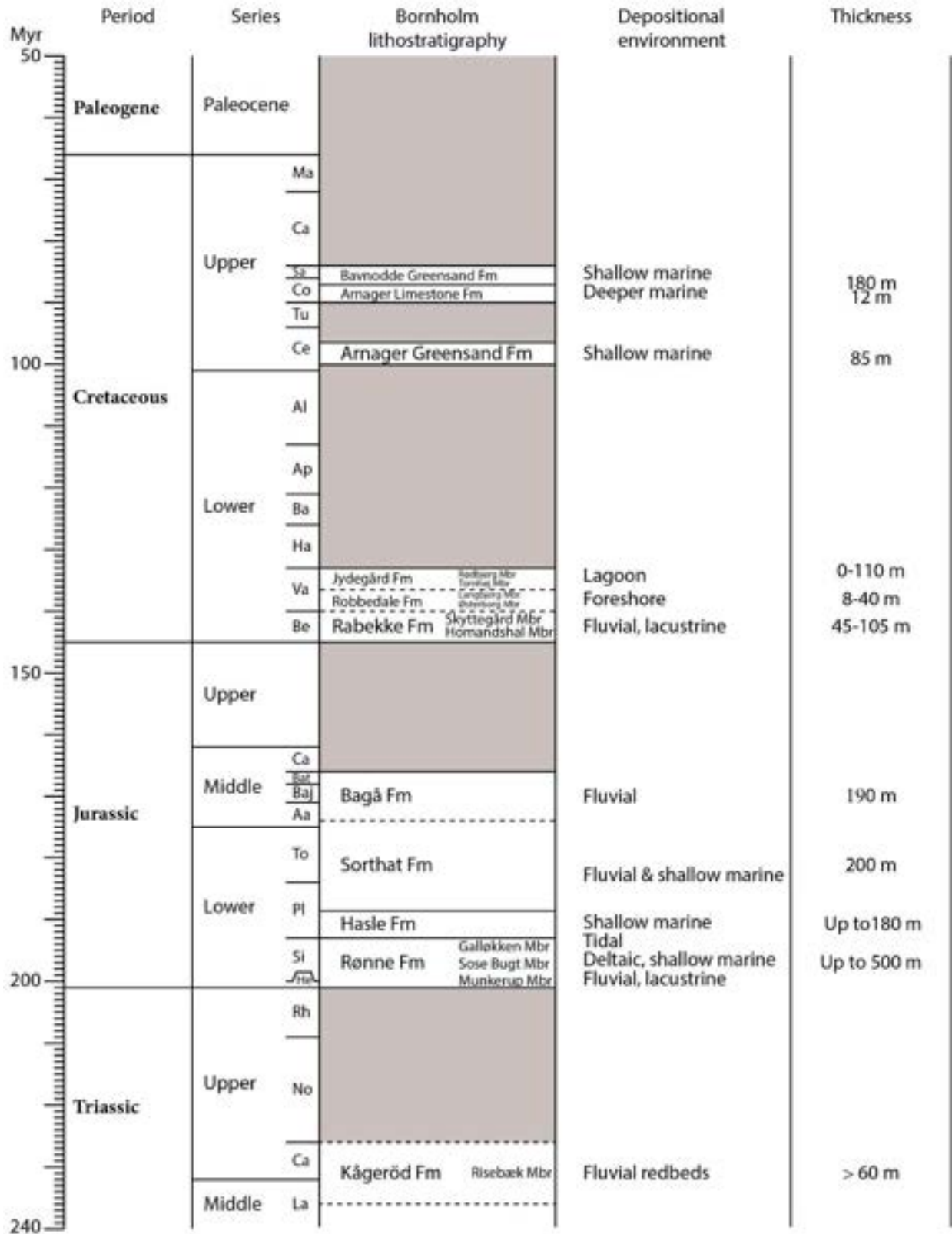
Fig. 7: Mesozoic stratigraphy of Bornholm. Compiled by A.T. Nielsen, based on Gravesen et al. [1982] and Michelsen et al. [2003].

In the Pliensbachian, water depth increased during deposition of the **Hasle Formation** [Surlyk & Noe-Nygaard 1986]. Despite leaching, a good marine fauna has been obtained from the micaceous sands and corresponding offshore clays, but the ichnology is disappointing, probably because the sands predominantly represent storm deposits.

During the following regression, a return is seen to plant-rich delta sands [**Sorthat and Bagå Formations**]. Again, ichnology is not a strong point, except for a marine incursion which we shall see at Korsodde south of Rønne from where *Bornichnus* is reported [Bromley & Uchman 2003]. Unfortunately, all clay and coal pits on Bornholm are now water-filled or obliterated.

Lowermost Cretaceous

Between the 2nd and 3rd depositional phases of the Mesozoic, crystalline basement and Palaeozoic rocks were exposed to weathering [Gravesen 1982; Gravesen & Bjerreskov 1984]. The **Rabekke Formation** consists of proximally deposited products of this weathering interval: coarse quartz grains and lumps of kaolin. Eventually a coastal plain was established. The **Robbedale Formation** starts with sand associated with plant debris, seat-earths and thin coal beds. Higher in the unit the grain size increases to coarse sand and gravel, but there are intervals of very pure, creamy white "glass sand".

Flooding of the coastal plain is indicated by the appearance in the well-sorted quartz sands of slender *Skolithos* isp. and narrow but long *Ophiomorpha nodosa*. These bioturbated sands may represent bars protecting marine lagoons, because they are interbedded with muddy units [Noe-Nygaard et al. 1987]. These muddy sands are totally bioturbated, dominated by *Teichichnus* isp. and small *Thalassinoides*. Continuity could locally be demonstrated between the *Ophiomorpha* of the clean sand and the *Thalassinoides* of the muddy sand; unfortunately, these instructive gravel pits have all since been levelled and this phenomenon can no longer be observed.

Higher in the formation, the lagoonal units contain brackish faunas, but these are now poorly exposed. A pity, because there were rather unusual *Diplocraterion*-like structures developed in these beds [Noe-Nygaard & Surlyk 1988]. Grain size and degree of sorting are reduced in the **Jydegård Formation**.

Owing to rapidity of sedimentation, basin accommodation was always nearly filled and water depths remained very shallow. However, subsidence was considerable, the Jydegård Formation comprising 100 m of sediment. After deposition of the Jydegård Formation, inversion tectonics commenced and the Bornholm area was uplifted and tilted so there is an angular unconformity between the Lower and Upper Cretaceous. As a result, the Jydegård Formation was removed by erosion in some parts of Bornholm.

Mid-Cretaceous.

The final marine flooding of Bornholm, as might be guessed for the Late Cretaceous, was the most substantial. Down-faulted blocks have preserved evidence that the Bornholm Horst itself was again flooded, and the sediments have that "very Cretaceous" facies of chalk [nearly] and greensand with phosphorites. But land was close at hand [the Scandinavian Shield and likely horsts forming islands within the Tornquist Zone], and water never became very deep.

At the close of the Early Cretaceous, deposition of the **Arnager Greensand** commenced [85 m thick]. Its base is abrupt on the eroded yellow sands of the Jydegård Formation [and locally the Robbedale Formation]. The coarse sediment is poorly sorted quartz sand, rich in glauconite grains and carbonate skeletal fragments. Clasts of phosphorite, Palaeozoic shale and silicified wood are common within the basal 0.5 m. The phosphorite clasts contain two distinct faunas, lower Albian and lower Cenomanian, whereas the matrix has yielded a sparse, autochthonous middle Cenomanian fauna [Tröger & Christensen 1991]. Trace fossils are hard to see but the sediment appears to be fully bioturbated. *Thalassinoides suevicus* is common at the basal phosphoritic horizon and probably throughout the greensand [Bromley 1979].

Thin, glauconite-free sand beds may be storm layers. Vertical escape shafts are locally found in these.

The upper boundary of the Arnager Greensand is very complicated. Phosphorite pebbles are incorporated within compound clasts by repeated processes of cementation and clast formation. These clasts have glauconitic and phosphoritic impregnation rinds, testifying to lengthy periods of nondeposition. The trace fossils tell the same story. The preomission ichnofabric of the greensand is transected by large omission-suite *Thalassinoides suevicus*. Later suites of *Thalassinoides* activity cut through these. The fills of the successive suites of trace fossils have microfossil ages from Cenomanian, Turonian[?] and Coniacian [Hart 1979]. The final hardground also was broken up. A considerable shallowing from the underlying greensand is indicated.

Upper Cretaceous.
Above the conglomeratic horizon, a dramatic change in lithology occurs. At its base, the **Arnager Limestone** [12 m thick] is a well-bedded, rather pure chalk-like rock on the south coast. Its Coniacian age is based on ammonites, inoceramid bivalves and foraminifera [Kennedy & Christensen 1991]. Basically composed of coccoliths, and poor in terrigenous components, it contains much silica. This occurs not as flint concretions [which are rare] but as lepispheres of tridymite and cristobalite. On abundant bedding planes, flattened siliceous sponges abound, their spicules are now clean, empty voids or filled with oxidised pyrite. Many of these sponges are lyssacine hexactinellids [Mehl 1992], a group very little known as fossils as their spicules are not fused together like those of other hexactinellid groups. Yet these sponges are preserved quite undisturbed, suggesting obruption events in an otherwise exceptionally quiet benthic environment. Tracemakers also exploited these sponges as a source for building material for their burrow linings [Vallon et al. 2020].

Bedding is not flat, but is mounded and irregular [Noe-Nygaard & Surlyk 1985]. It has been suggested that the sponges formed baffles and traps, thereby producing mounds. However, they are the wrong type of sponges, and are preserved prostrate and compressed, not upright in life position. There must be another explanation for the mud mounds.

Bedding planes follow the mound topography. There is also a larger-scale rhythmic bedding as so often in pelagic chalk, indicating a rhythmic input of terrigenous mud. Upward through

the limestone unit there is a gradual increase in clay, suggesting regression and exposure of source areas on the shield, probably resulting from inversion tectonics.

Regression continued and the limestone is abruptly overlain by another greensand, the **Bavnodde Greensand Formation** [180 m thick onshore Bornholm]. Ammonites, inoceramids and foraminifera indicate an upper Coniacian to lower Santonian age [Kennedy & Christensen 1991]. This unit is ichnologically much more interesting than the Arnager Greensand. Visibility can be poor, but in Spring, when surfaces are clean and damp, *Teichichnus* isp. and *Thalassinoides suevicus* are seen to be dominant in a thoroughly bioturbated sediment. Sandy event beds occur with increasing abundance upward and some of these have colonization surfaces on top. Some of these beds have an irregular base and contain lags of fist-sized lumps of granite, indicating that the horsts of the Tornquist Zone were rising into the erosion zone again. These beds are cemented with silica. Increase in numbers and thickness of the event beds upwards indicates regression. The presence of unimodally oriented belemnites in these lag deposits led Schmidt [1992] to consider the beds as **current**-deposited turbidites as opposed to wave-deposited storm beds. This is our last glimpse of marine deposition on Bornholm.

Quaternary.

The products of 60 million years of weathering were removed from the island during the Pleistocene glaciations. On Bornholm today, there are signs of only the last glacial advance, the Weichsel glaciation. The evidence is in part the rounded ice-smoothed and scratched topography of the crystalline basement and Palaeozoic rocks, and partly the very limited deposits, both till and melt-water and lake deposits. Along the south coast there are aeolian deposits. These dunes are still active at Dueodde; living spiders make *Skolithos* and ant-lion larvae make *Monocraterion* in them, while tourists bioturbate seasonally!

The Weichsel ice approached Bornholm from the NE, and swung round to an E-W direction over the sediments to the south. Thus, the crystalline horst acted as a barrier, protecting the soft Mesozoic sediments in its shadow. Of course, the feeble Robbedale sands were not soft at that time, but temporarily cemented with ice. Meltwater carved caves in the sands and the ice movements shifted them as megabreccias.

Bornholm became an island about 11,000 BP. Temperatures were warm enough during the brief summers to allow colonization by rodents and invertebrates. Amphibians could swim the Baltic Lake later. Foxes can still cross the sea-ice in exceptionally cold winters today. The badger never arrived.

And eustasy and tectonics continue. During post-glacial time [the last 10,000 years] there has been a transgression. In Palaeolithic time, 5-6,000 years ago, sea-level rose several metres and modelled raised beaches around the island. Fragments survive to record the event: they are 4 m over today's sea-level on the south coast, but rise to 12 m on the north coast, so they also record the continuing tilting of the horst.

Locality 1: Snogebæk

Snogebæk: 55° 1′ 34.98″ N, 15° 7′ 19.61″ E

The uppermost part of the early Cambrian Hardeberga Formation is exposed in the beach as southward sloping ledges. Now at last the *Skolithos*- and *Diplocraterion*-makers could establish themselves! The outcrop highlights the most bioturbated part of the unit, likely due to a shallowing of the depositional environment.

The sandstone is thickly bedded. As we walk south, we climb the stratigraphy bed by bed. Most beds are cross-stratified, suggesting bedforms 50 cm high. The environment is interpreted as intertidal. Clausen & Vilhjálmsson (1986) measured 292 *Diplocraterion parallelum* individuals and found no preferred orientation. Worms were rather stupid in the early Cambrian (Bromley & Hanken 1991). If we are lucky, we can find some bedforms preserved near the harbour, where *Skolithos linearis* on eroded sandwave tops grade into *Monocraterion tentaculatum* in the troughs, where their funnel aperture is preserved. Taphonomy determines ichnotaxonomy?

Above the quartzite unit (southwards) are the silty, glauconitic sandstones of the Norretorp Member, but usually this transition is below the water table. Many units show complete bioturbation, which is not so usual in such ancient rocks. They may be better exposed at the next locality.

Locality 2: Broens Odde

Broens Odde: 55° 0′ 55.08″ N, 15° 7′ 12.01″ E

This is a foreshore exposure. It is only accessible at low water, which depends on the wind. Besides, seaweed is occasionally a problem, covering all the interesting stuff. The Norretorp Member is rich in trace fossils here (Clausen & Vilhjálmsson 1986; Nielsen 1988).

There is a clear difference, especially in the middle part of the member, between fairweather and storm assemblages. The background lithology, poorly sorted sandy siltstones rich in glauconite, is dominated by horizontal trace fossils, including the ichnogenera *Planolites*, *Palaeophycus*, *"Buthotrephis"* (*Phycodes*?), *Rhizocorallium* and *Teichichnus*. In the clean-sand storm beds, *Skolithos* and a strange, oblique *Diplocraterion* attract attention.

Locality 3: Sose

Sose Bugt: 55° 2′ 33.71″ N, 14° 50′ 9.56″ E

Sose Bugt (bay) and Sose Odde (headland) expose the lower part of the Rønne Formation. The sands and clays are of Early Jurassic age and have been dated by pollen as Hettangian and Sinemurian (Surlyk et al. 1995). Exposure is rather poor at present; spectacular channels and other large structures are obscured by landslides and vegetation. However, we will probably be able to uncover one of the coal beds and its corresponding root bed. Some of these roots reach over 50 cm long. These coals and their underlying palaeosols have been studied by Arndorff (1993).

The environment is paralic, dominantly nonmarine but with evidence of marine incursions. Surlyk et al. [1995] tell a detailed sequence-stratigraphic story based on hard digging work in the days when exposure was better. Evidence for its marine character is largely ichnological and rests on the observation of intervals containing *Diplocraterion parallelum* and slender *Skolithos*.

Towards the spit, increasing clay produces heterolithic facies and cleaned vertical surfaces reveal nice physical structures [current ripples and clay drapes], and beg the question, "Why so little bioturbation?" [cf. Sellwood 1972]. Rapid deposition? Increased salinity?

Above the heterolithites is a bench of claystone cemented with siderite. It is this that caused the headland. The trace fossils in this bed are quite different and have a marine appearance. They include *Ophiomorpha nodosa*, *Planolites*, *Palaeophycus* and *Chondrites*. The degree of exposure varies and this bed is not always easy to see *in situ*.

Locality 4: Homandshal
Homandshal: 55° 3′ 4.93″ N, 14° 48′ 16.00″ E

Here the lower part of the Early Cretaceous Rabekke Formation is exposed in the coastal cliff. The bottom layers consist of poorly sorted coarse sand with angular quartz grains, cemented by iron compounds. These beds are probably fluvial in origin. Upwards follow kaolin-mixed sand with lumps and layers of kaolin, still fluvial in origin. The sand grains are little rounded, evidencing short transport: the source was the kaolinized basement of the Bornholm Horst. Further to the west is found a section with fine-grained sand overlying dark clay, interpreted as shallow lake deposits. Palynological data show that the lake was surrounded by gymnospermous vegetation of low diversity. The sand-clay contact is very irregular [we probably need to bring spades to clean the exposure], with decimetre-long vertical and oblique sand-filled 'shafts' extending into the clay. This surface has been interpreted as a 'dinosaur trampling ground' [Surlyk et al. 2008]. Possible aestivation burrows of lungfish have also been described. The authors of these lines look forward to hearing the opinion of expert ichnologists on this site. Small teeth of dinosaurs and various other vertebrate fossils have been reported from the Rabekke Formation [Lindgren et al. 2008].

Locality 5: Carl Nielsen's gravel pit [Optional]
Carl Nielsen's gravel pit: 55° 4′ 50.54″ N, 14° 45′ 9.19″ E

If time permits, we can visit this abandoned gravel pit to take a quick look at the Lower Cretaceous Robbedale and Jydegård Formations. When active, this locality was a highly instructive, site but nowadays the water-filled gravel pit is far from its past glory. It is still possible to see the upper part of the clean quartz sand of the Robbedale Formation here and there along the water pond, but there is not much for the ichnologist to look at nowadays. Previously, *Ophiomorpha nodosa* and *Skolithos* could be observed in the lower part of the unit. The Robbedale Formation represents a sand barrier environment [shoreface]. Farther west in the gravel pit, a low exposure in the overlying Jydegård Formation has been excavated by entrepreneurial fossil hunters, primarily searching for dinosaur teeth. The Jydegård Formation was deposited in a lagoonal environment, conceivably protected from

the open sea by the barriers represented by the Robbedale gravel. Many fossils have been found in the Jydegård Formation: bivalves [that died because of algal poisoning], gastropods [that died due to desiccation of the lagoon], sharks, turtles, bony fishes, dinosaur teeth etc. We will, however, only be able to find gastropods and maybe ostracods.

Locality 6: Arnager
Arnager coastal cliff: 55° 3' 11.37" N, 14° 46' 31.07" E

West of the village, a coastal cliff exposes the top of the Arnager Greensand and the lower half of the Arnager Limestone. The firmground suites at the boundary are well exposed where we first reach the shore [Fig. 8].

The ichnology of the overlying limestone is best visible in vertical section in the cliff immediately above the boundary, and in horizontal section in the foreshore. Trace fossils are clearly visible in the basal limestone, but visibility fades upward. This may be due to long-term deep weathering. At the base, rather compacted fabrics include [guess what!] *Zoophycos* [very simple, single-lobe forms], *Thalassinoides*, *Chondrites* and *Planolites:* a very chalk-like assemblage. Even glauconitised and fish-scale-lined burrows and the sponge-cube-lined *Koptichnus* occur. There is also what was thought to be a sponge-like burrow, lined tightly with transverse spicules. A specimen was sent to Keith Rigby, who commented that it was a burrow-like sponge! Body-fossil palaeontologists are incurable.

It would seem to have been a very sudden deepening of the sea, some say to 200 m or more! However, as we shall see at the next stop, the greensand facies was not far away, so a depth of 200 m must be regarded as a maximum. The rusty body fossils of sponges are abundant, especially the bunches of giant anchoring spicules of several species of lyssasine hexactinellids. Hexactine hexactinellids and lithistids are less two-dimensional and some of these contain poorly developed flint concretions [rare]. The tourists will have removed any ammonites and other exciting body fossils but they always leave the trace fossils.

Locality 7: Stampen
Stampe Å: 55° 4' 18.08" N, 14° 44' 21.43" E

A beautiful path in the forest along the small Stampe stream gives us several glimpses of the complex edge to the Rønne Graben. Watch out for dark squirrels with red tails, and the colourful northern thrushes called fieldfares. In the Spring there are several species of orchids.

A little weathered Arnager Limestone is visible along the banks of the stream. Interestingly, it is rather glauconitic, i.e. forms a transitional facies to the greensand [we are only three kilometres from the white impure chalk at Arnager]. Five kilometres further north, the Arnager Limestone is developed as a highly glauconitic marl.
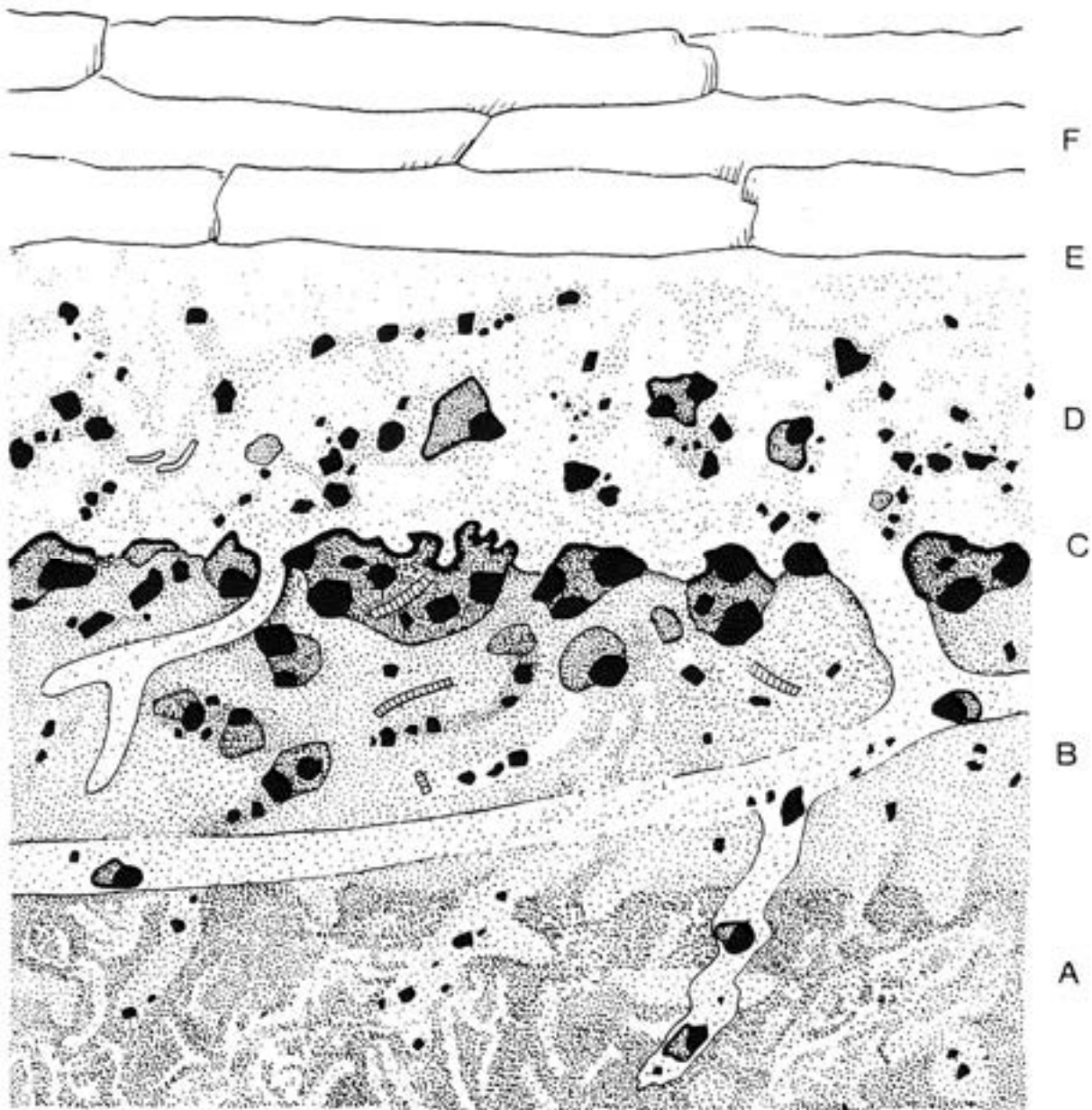
Fig. 8: Lithology of the bottom bed of the Arnager Limestone. Overlying the Arnager Greensand. A: Arnager Greensand: a highly bioturbated greensand, richly glauconitic, containing no phosphoritic clasts except those piped down from the overlying beds by burrowers. Top junction not very sharp. B: richly glauconitic limestone the basal bed of the Arnager Limestone. containing dark brown. phosphatized clasts of a limestone that is less rich in glauconite grains than the surrounding matrix [clasts indicated in black]. Chiefly towards the top of unit B, these clasts are incorporated within compound intraclasts of richly glauconitic limestone. Sediment [with clasts] of unit B is extensively piped down into the topmost levels of Unit A within. numerous burrows. C: sharp junction tinted dark green with impregnated glauconite: the impregnation most strongly affects the compound intraclasts where these are in contact with the junction. Although encrusting organisms and organic borings are not in evidence, this glauconitised surface is clearly a hardground. D: fairly hard limestone, pale grey. containing irregularly distributed glauconite grains together with phosphoritic and compound intraclasts, chiefly in burrow fills. From the base, large *Thalassinoides suevicus* up to 8 cm in diameter, and much smaller *T. paradoxicus* penetrate the underlying unit B. Some of the *T. suevicus* continue down into the uppermost metre of unit A. E: well defined parting plane. F: slabby, hard Arnager Limestone of normal lithofacies, almost free of glauconite grains. From Bromley 1979.

Shortly downstream follows a little frog statue, dribbling water, that marks the site of a boring made in 1819 by the world-famous chemist H.C. Ørsted [known for discovering magneto-electricity and aluminium]. He was investigating the geology on Bornholm at the king's command after Norway was lost in the Kieler Peace of 1814. Ørsted knew from the UK that there was coal beneath greensand. However, strong water inflow soon stopped the boring activities. Besides, what Ørsted did know: the strata at this site are nearly vertical owing to inversion of the Rønne Graben, so it would have been an impossible task to reach the Jurassic coal beds. This disturbance we will see a little farther downstream, where a cave-like overhang exposes the Arnager Greensand in a bend of the stream – one of the best exposures of this unit! On a smoothed surface the ichnofabric is seen to contain elite *Ophiomorpha* isp. Way-up is slightly overturned!

The next exposure further downstream is quite dramatic. The base of the Arnager Greensand contains a phosphorite conglomerate overlying the strongly bioturbated Jydegård Formation. The conglomerate is overturned; we are very close to the [unexposed] Rønne Graben boundary fault.

From here we continue to the beach and turn south, where a rather fractured exposure of the Lower Jurassic Hasle Formation is seen. We are now within the Rønne Graben. Due to the many fractures and liesegang structures, it is difficult to observe any primary structures – and there are no trace fossils to dwell on. The Hasle Formation tilt landwards some 20°: We are in the inversion zone. From here we continue southwards along the beach, and here and there exposures of the Sorthat Formation are seen, which was deposited in a fluviatile-lacustrine environment around the Lower to Middle Jurassic transition. As we walk southeastward, the dip steepens from about 20° to about 70° at Korsodde.

Locality 8: Korsodde
Korsodde: 55° 4′ 8.92″ N, 14° 44′ 9.94″ E

Steeply sloping [about 70°] sand, clay and coal beds of the Middle Jurassic Bagå Formation are exposed in the cliffs along the shore. This is the edge of the inverted Rønne Graben and the combined Sorthat-Bagå Formations are 450 m thick here [although not much is exposed]. The succession was predominantly deposited in a terrestrial environment, but the sea was never far away and sand-dominated incursions are recorded, even including intervals with beautiful hummocky cross-bedding [well, probably mostly swaly]. The bottoms of some sand beds are conglomeratic, containing sizable, locally derived boulders of granite, kaolin and othoquarzite.

The marine intervals contain a diverse trace fossil assemblage, typical for lower shoreface [*Diplocraterion* and *Skolithos*] to offshore environments [*Teichichnus* and *Asterosoma*]. Bioturbation degree and ichnodiversity are low. Combined with the sedimentological features, these indicate an environment influenced by salinity fluctuations, probably an estuary.

This is the type locality of *Bornichnus tortuosus* Bromley & Uchman, 2003, named after the island of Bornholm. The crowded and tortuous tangles of thickly lined tubes exhibit closely

spaced T-branches. They often are impregnated with ferruginous material, making these loosely tangled balls of unoriented bent and looped burrow systems slightly more resistant to weathering than the surrounding matrix (spades or larger knives might be needed to make clear sections). *Bornichnus* is interpreted as a farming trace and occurs in a section dominated by repetitive heteroliths, and interpreted as tidal flat deposits (Bromley & Uchman 2003).

From Korsodde we will proceed southeastwards and again enter the Bornholm block. But like all great faults in soft rocks: the main bounding fault of the Rønne Graben is not exposed!

Locality 9: Bavnodde

Bavnodde: 55° 4' 1.76" N, 14° 44' 23.31" E

A series of exposures beneath the airport show the Late Cretaceous Bavnodde Greensand. We shall try to smooth the cliff surface so that the ichnofabric can be seen. The greensand contains well-cemented (silica) quartz-sand storm beds, up to 50 cm thick. The irregular base contains a lag conglomerate in some cases. The presence of unimodally orientated belemnites in these lags led Schmidt (1992) to consider the beds as current-deposited (turbidites) as opposed to wave-deposited (storm beds). Increase in numbers and thickness of the event beds upwards indicates regression.

Body fossils are common. Rounded wood fragments containing *Teredolites clavatus* are occasionally observed. The belemnites have been bioeroded by algae, so the sea floor was photic.

Further eastwards, a large channel has cut into the greensand, its floor cemented with silica. In order to get there, we will have to climb numerous basement boulders, dumped on the beach as protection against erosion, so we will do this only if time permits. The channel fill contains less glauconite and more quartz than the greensand. The age of the channel is unknown, but the fill is apparently reworked Bavnodde Greensand, and so it must be the youngest pre-Quaternary sediment on the island. Seismic mapping indicates that the Bavnodde Greensand is some 800 m thick in the Baltic Sea south of Bornholm and the high clastic supply probably reflects renewed inversion of the Tornquist Zone during the Santonian.

Locality 10: Coastal cliff at Hasle [Optional]

Hasle coastal cliff: 55° 10' 45.70" N, 14° 42' 9.09" E

Provided time permits, we will visit the coastal cliff south of the harbour at Hasle. This is the most instructive exposure of the Lower Jurassic Hasle Formation (Pliensbachian). The rusty brown, cemented sandstones show extremely large-scale hummocky cross-stratification (Surlyk & Noe-Nygaard 1986) but are very little bioturbated.

Locality 11: Coastal cliff at Galgeløkken [Optional]

Galløkken: 55° 5' 8.21" N, 14° 42'14.92" E

If time permits, we can visit the coastal cliff south of the harbour at Rønne. Although far from previous standards, the exposure of Lower Jurassic tidal sediments, assigned to the Rønne Formation, are still worth seeing. Unfortunately, it must be foreseen that this previously spectacular outcrop will deteriorate in years to come due to the expansion of the harbour at Rønne. Not much for the ichnologist to see in the section, but you can ponder on why there is so little bioturbation. Best guess is rapid deposition, as indicated also by the occasional presence of water-escape structures (ahem, by some suggested to represent dinosaur foot prints). In channel fills, double mud drapes allow counting of the tidal cycles. Maybe the whole thing was deposited in something like 10 years!

A little history

From field stones to churches
The retreating ice left Bornholm strewn with stones. There is little evidence of this at first sight today; the stones have served many purposes and few are left in their original position. We shall make some diversions to see examples of used and reused stones.

Barrows and tombs

The first inhabitants were of the Mesolithic Maglemose Culture, and are known from tools and burial finds. From the Neolithic there are two dolmens and some ten passage tombs. Typical of Bornholm and Skåne are the *røser*, consisting of large mounds of stones covering graves or set as memorials. Dating is difficult, but they are considered to be Bronze Age (1500–400 BC). Some large earth mounds also occur, probably Iron Age (400 BC-800 AD).

Fig. 9:   Long barrow (langdysse) near Vasagård. Late Mesolithic to early Neolithic, about 3500–2800 BC. (Picture by "Fyrtaarn", https://commons.wikimedia.org/w/index.php?curid=92395196).

Petroglyphs *(helleristninger)* and goldmen *(guldgubber)*
The largest collection of rock carvings is on the glacially striated roche moutonnée Madsebakke, between Allinge and Sandvik. Represented here are 11 ships, one bearing a sun disc. Bronze Age carvings still turn up on the island, many of them on loose boulders. Below pictured is a particularly interesting example for the ichnologist. The Storløkkebakke locality

lies about 1 km to the south of the village Allinge and to the east of the road between Allinge and Olsker. Three associated urns containing human remains date the site to the younger bronze age, about 900-700 BC. On the larger of the two exposed surfaces [Fig. 10] are four ships, four ring ornaments, several circular pits and two rather flat-footed anthropomorphic tracks. The footprints are interpreted as being divine, likely belonging to the god Njord who was the "god with beautiful feet" and one of the most important gods of the Vanir, a family of gods associated with fertility, wisdom and the ability to see into the future. The other family of gods, the Æsir, might have derived from Asia during the time of the great migration. This group is associated with war and is known to us nowadays as the "typical" Norse Gods: Odin, Thor, Loki etc. [in parts translated from Mogens Flemming Jensen; http://bornholmsoldtid.dk/bronzealder/storloekkebakke-helleristningerne-allinge/].

Fig. 10: The large of the two fields with Bronze Age petroglyphs south of Allinge at Storløkkebakke containing four ship and two divine footprint carvings. Note, not only Richard G. Bromley had an abnormal number of toes… [Picture by Mogens Flemming Jensen; http://bornholmsoldtid.dk/bronzealder/storloekkebakke-helleristningerne-allinge/].

Guldgubber [Fig. 11] are postage-stamp-sized flakes of gold embossed with a human figure. They have been found at several sites in Denmark and Sweden, but by far the most were discovered at the locatity "Sorte Muld" [Black Soil], a dark field near Ibsker, Bornholm. Over 2500[!] were found by careful sieving of the earth. Roman and other coins date the place to have been inhabited from 200 to 1000 AD. The guldgubber are considered to be from the Great Migration Age, about 500 AD.

Fig. 11: *Guldgubber* from Sorte Muld on Boirnholm, 6. Century. Modified from https://de.wikipedia.org/wiki/Guldgubbe#/media/Datei:SorteMuld_guldgubber_600px.jpg

Bauta and rune stones

There are about 250 monoliths on Bornholm, but old documents say that they were much more common in times past. Bauta stones or Bretonic *menhirs* are elongate, inscriptionless stones, standing upright as part of cultural sites; when standing in circles they form a henge. They are dated as Bronze Age. At the Gryet [The Twilight] wood, the largest collection survives, 56 stones: a frightening place in October with ascending mist and setting sun.


Runestones [Fig. 12] are similar standing stones, but inscribed with telegraphic texts in runes. There are about 40, most of them now placed in or near churches. They are late Viking Age monuments, about 1100 AD. Most proclaim the loss of Danes who "went East". Three are at Østerlars church, five at the ruins of Østermarie church.

Fig. 12:   The largest runestone on Bornholm at Brogård ved Salhøj [Klemensker-runesten #3], raised sometime between 1050-1100. Its inscription on granite translates to: "Sveingeir let this stone raise for his father Toste and for his brother Alvlak and for his mother and for his sister". Picture by Robert Fortuna/Nationalmuseet.

Churches

The christianising of the Vikings led to a collapse of their warlike culture. [Or was it the other way around?] It was now the turn of the Vendic people from Pomerania and Poland to raid and plunder the ex-Vikings! Communities on Bomholm [and elsewhere in southern Scandinavia] built round fortress churches [Fig. 13] into which they could withdraw at times of invasion.
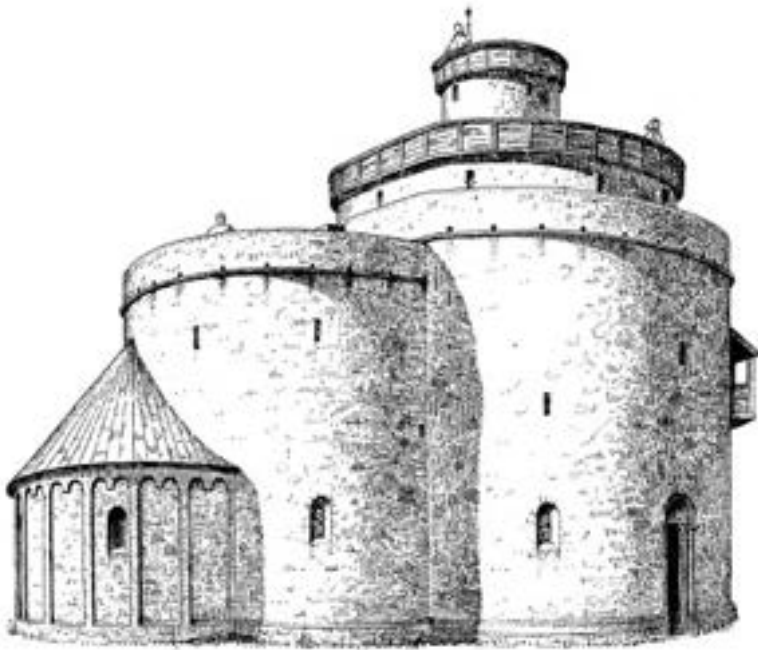
Four of these have survived on Bornholm [few elsewhere]. The church at Østerlars is the largest, built in the middle of the 12th century of field stones, except the apse at the east end. The apse and window frames are of Komstad Limestone, but all three parts of the church were built at the same time. The immense buttresses, porch and conical roof were added in the 16-17th centuries. A round church has no place for a bell, so a bell-tower had to be erected beside it.

Fig. 13: Reconstruction of Østerlars Roundchurch as a fortress without roof. Sketch taken from https://www.oesterlarskirke.dk/fileadmin/group/161/Dokumenter/plancher_om_kirken/02_-_Hvorfor_er_kirken_rund.pdf

Inside the church, numerous lime paintings decorate the walls. Created between 1300 and 1350, they were painted over with white paint after the Reformation and rediscovered in 1889. Since then, four major restorations have been conducted, the latest in 2005-2006 [in parts translated from https://www.oesterlarskirke.dk]. The two devils who take away the lost souls in the "Dooms day" painting carry hammers. Among geology students, the scene is therefore called "geological fieldtrip" [https://www.ullaasgaard.dk/excursion-til-bornholm-maj-1956/].

Å Church [Fig. 14] in Aakirkeby is the largest medieval one on the island. *Å* means river, but prior to 1948 the letter was written Aa. The tower has a double-A-shaped gable and the town has retained the old spelling. The chancel, apse, and lowest part of the nave were built first. A second period of construction completed the nave and tower. A third period extended the tower westward and added the porch: all this before 1225. Most exceptional is the Romanesque "Gotland" font. Gotland was a great centre for font construction in the 12th and 13th centuries. Made of Silurian Burgsvik Sandstone, this one is important in having been signed in runes by the sculptor-mason: Sigraf. However, the chuch is built of tempestites

deriving from the Lower Cambrian Norretorp Member and glacial erratic blocks, some of ichnologic interest. Next to the entrance portal in the tower, is a boulder from the Cambrian Hardeberga Formation containing *Rosselia* [Fig. 14].

Fig. 14: Aakirkeby-Kirke ["Water church town-church"] to the left. Next to its main entrance door in the tower are boulders immured from the Cambrian containing *Rosselia* isp. [right]. Pictures taken by L.H. Vallon.

The great fortress

At the northwestern tip of the island lie the ruins of the largest castle in Scandinavia, Hammershus [Fig. 15]. Building was initiated in 1250, when the archbishop of Lund was at war with the king. The upper stories of the tower were added in the time of domination by Hanseatic Lübeck [1525-1576]. The bridge up to it is the only intact Gothic bridge in Denmark. However, the castle was much decayed by the time of the Swedish invasion of 1645. At the Peace of Roskilde [1658] the island was ceded to Sweden, but in Bornholm's most glorious moment, led by Jens Kofoed and the priest Poul Anker, the Swedish commandant was shot, his troops imprisoned and the Bornholmers presented their island to the Danish king.

In 1684 the fortification of offshore Christians Ø was begun and the Hammershus castle became a quarry. Finally abandoned in 1743, the ruins were declared a quarry for local builders. But times change. In 1814, further removal of stones was prohibited, and now the remaining ruins are a leading tourist attraction!

Fig. 15: The ruin of the fortress Hammershus. Picture by Nationalmuseet.

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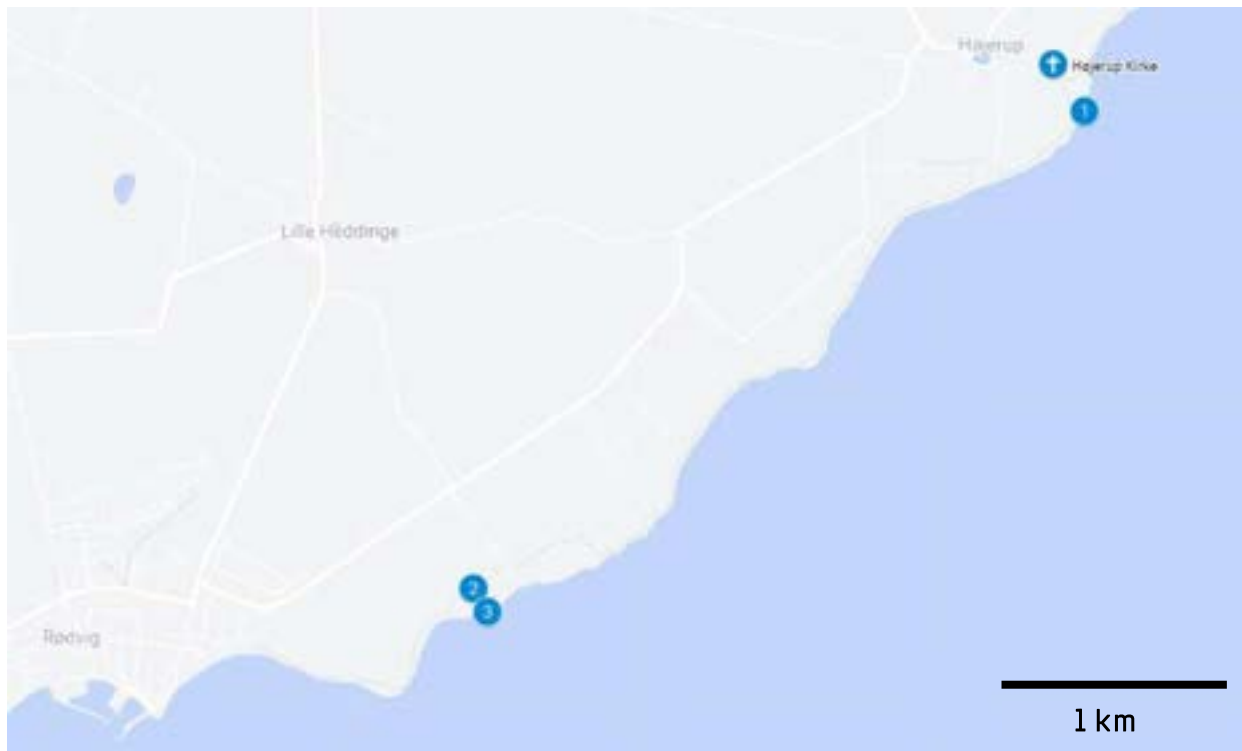
Detail map of Stevns Klint with the visited localities of the pre-meeting field trip. 1: Højerup, 2: Stevns Klint Experience, 3: Boesdahl.

Detail map of the island of Bornholm with the visited localities during the post-meeting field trip. 1: Snogebæk, 2: Broens Odde, 3: Sose Beach, 4: Homandshal, 5: Carl Nielsen's gravel pit, 6: Arnager coastal cliff, 7, 8, 9: see next page! 10: Hasle coastal cliff, 11: Galløkken.

Detail map for localities 7–9. 7: Stampe Å, 8: Korsodde, 9: Bavnodde. All maps created with Google Maps.