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15th International Ichnofabric Workshop



Prague, Czechia, April 27th – May 3rd, 2019

# Program Abstracts Field Guidebook by Radek Mikuláš

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# 15th International Ichnofabric Workshop Programme

#### FRIDAY 26th April

18:00 **Registration of the participants** 

#### SATURDAY 27th April

- 07:30 08:30 Breakfast & lunch packages taking
- Excursion: Marine Paleozoic of the Prague Basin
- 09:00 Departure from Vila Lanna

#### SUNDAY 28th April

- 07:30 08:30 Breakfast & lunch packages taking
- Excursion: Non-marine Late Palaeozoic and Early Mesozoic of the Intra-Sudetic Basin; transgression of the marine Cretaceous
- 09:00 Departure from Vila Lanna

#### **MONDAY 29th April**

- 07:45 08:45 Breakfast
- 09:00 09:30 **Opening ceremony**
- 09:30 10:00 D. Knaust: Ichnofabric
- 10:00 10:15 **coffee break**

#### Presentation session I

- 10:15 10:45 J. Dorador, F.J. Rodríguez-Tovar, A. Mena & G. Francés: Ichnofabric analysis of contouritic deposits from the NW Iberian margin
- 10:45 11:15 L.A. Buatois & C. Echevarría: Ichnofabrics from eolian systems: An example from the Cretaceous Mulichinco Formation, subsurface of western Argentina
- 11:15 11:45 M. Nara: Tectonically controlled ichnofabrics in the early to middle Miocene fore-arc basin fills of the Southwest Japan Arc
- 11:45 12:15 A. Uchman, G. Pieńkowski & K. Ninard: Ichnofabrics of upper Sinemurian lower Pliensbachian deposits in the Cardigan Bay Basin (western England) in the Mochras borehole core
- 12:15 13:30 lunch break

#### Presentation session II

- 13:30 14:00 A. Wetzel: Ichnofabrics in early diagenetic concretions
- 14:00 14:30 Zhifeng Xing, Jia Lin, Hu Zhou, Yong'an Qi & Wei Zheng: Trace Fossils in the terrestrial Lower Triassic of North China and their ecological implications
- 14:30 15:00 L.H. Vallon, J. Milàn, A.K. Rindsberg, H. Madsen & J.A. Rasmussen: Cutting-edge technology: Burrows lined with sponge bioclasts from the Upper Cretaceous of Denmark
- 15:00 15:30 A. Dronov & V. Kushlina: Ordovician trace fossils of Siberia: responses to climatic events and connection with Gondwana, Baltica and Laurentia
- 15:30 15:45 **coffee break**

#### Presentation session III

- 15:45 16:15 R.C. Gougeon, M.G. Mángano, L.A. Buatois, G.M. Narbonne & B.A. Laing: **The role of** *Psammichnites* in the origin of an Early Cambrian shelf sediment mixed layer
- 16:15 16:45 S. Celis, C.A. Giraldo-Villegas, F.J. Rodríguez-Tovar, F.J. Cardona-Sánchez, N.F. Gallego & A. Pardo-Trujillo: *Ophiomorpha* ichnofabric revealing delta front conditions in Cenozoic deposits of the Colombian Caribbean – NW South America
- 16:45 19:00 Discussion afternoon
- 19:00 **Dinner**

#### **TUESDAY 30th April**

07:45 - 08:45 Breakfast

#### Presentation session IV

- 09:00 09:30 D.H. Goldstein: The Ichnofabric of Urban Life: Using Architectural stone as a teaching resource. Examples from the New York Metropolitan area
- 09:30 10:00 A. Uchman: Ichnofabrics in Holocene inland dunes of SE Poland
- 10:00 10:30 M. Stachacz & M. Matysik: Ichnofabric changes in Polish Muschelkalk (Middle Triassic)
- 10:30 10:45 **coffee break**

#### Presentation session V

- 10:45 11:15 C.Z. Wang, B. Hu, L. Chang & C.H. Chen: Trace fossils and Sedimentological Significance in the Member III of the Shahejie Formation in southern Dongpu Sag
- 11:15 11:45 O. Miguez-Salas, L. Löwemark, Y.-Y. Pan & F.J. Rodríguez-Tovar: Ichnofabric evolution after storm events in a delta environment: A case from the Miocene of Taiwan
- 11:45 12:15 Da Li, Yongan Qi, Mingyue Dai & Min Wang: **Firmground Trace Fossils in the Mantou Formation, Cambrian, Western Henan**
- 12:15 13:30 **lunch break**

#### Presentation session VI

- 13:30 14:00 L. Piñuela & J.C. García-Ramos: Vertebrate ichnofabrics resulting from a multi-episodic reptile-track level
- 14:00 14:30 Y.B. Niu, J.D. Marshall, H.B. Song, B. Hu, Y.Z. Hu & S.L. Cui: Ichnofabrics and their role in the modification of petrophysical properties: the Ordovician Majiagou Formation, Northwest Henan Province, China
- 14:30 15:00 Hui-Bo Song, Feng-li Zheng & Bin Hu: Characteristics of ichnoassemblages and relationships with paleo-oxygenation facies of the Taiyuan Formation, western North China

#### 15:00 – 15:15 **coffee break**

#### Presentation session VII

- 15:15 15:45 R. Fodor & Á. Dávid: A Walk in the Gyrolithes Heaven (Ichnology of an Early Miocene Age Sand-pit, Tardona Hills, North-Hungary)
- 15:45 16:15 A. Ichaso, M.G. Mángano & L.A. Buatois: Ichnofabrics from the Cambrian-Ordovician Deadwood and Earlie formations: exploring evolutionary and environmental controls
- 16:15 16:45 R. Mikuláš: Ichnofabric of the Buchava Formation (Cambrian, Biskoupky site, Skryje-Týřovice Basin, Czechia)
- 16:45 19:00 **Discussion afternoon**
- 19:00 **Dinner**

#### WEDNESDAY 1st May

07:30 - 09:00 Breakfast

- Excursion: Non-guided trip to Prague
- 10:00 Departure from Vila Lanna

#### **THURSDAY 2nd May**

- 07:30 08:30 Breakfast & lunch packages taking
- Excursion: Day 3: Marine Upper Cretaceous and Oligocene to Miocene "brown coal basins"
- 09:00 Departure from Vila Lanna

#### **FRIDAY 3rd May**

07:45 - 08:45 Breakfast

#### Presentation session VIII

- 09:00 09:30 M.G. Mángano, A. El Albani, L.A. Buatois, S. Bengtson, A. Riboulleau, A. Bekker, K. Konhauser, T. Lyons, C. Rollion-Bard, O. Bankole, A. Meunier, A. Trentesaux, A. Mazurier, J. Aubineau, C. Laforest, S.G.L. Baghekema, C. Fontaine, P. Recourt, E.C. Fru, R. Macchiarelli, J.Y. Reynaud, F. Gauthier-Lafaye & D.E. Canfield: Paleoproterozoic ichnofabrics from 2.1 Ga shallow-marine strata (Francevillian Basin, Gabon)
- 09:30 10:00 F.J. Rodríguez-Tovar: The macrobenthic response after the K/Pg mass extinction event: An ichnofabric approach
- 10:00 10:30 F.J. Rodríguez-Tovar, O. Miguez-Salas & J. Dorador: Improving characterization of composite ichnofabrics by image processing techniques

#### 10:30 - 10:45 coffee break

- 10:45 12:00 Discussion block "Ichnofabrics seen in computer tomograph: our experiences and expectations."
- 12:00 13:00 Summary, discussion about post-conference field trip and future IIWs

13:00 – 14:00 **lunch break** 

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# Ichnofabrics from eolian systems: An example from the Cretaceous Mulichinco Formation, subsurface of western Argentina

Buatois, L.A.<sup>1</sup> & Echevarría, C.<sup>2</sup>

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The Lower Cretaceous (Valanginian) Mulichinco Formation of the Neuquén Basin in western Argentina encompasses a wide variety of sedimentary facies. In basin margin positions, this unit includes thick eolian deposits in its lower interval. Ten ichnofabrics are characterized for these deposits based on the analysis of cores from the El Mangrullo oil field. In turn, these ichnofabrics have been grouped in four ichnofabric associations, representing eolian dunes, eolian sand sheets, interdunes and fluvial sheet floods. The eolian dune ichnofabric association comprises the *Digitichnus* isp., *Arenicolites* isp., and dwelling burrow ichnofabrics, as well as some occurrences of the *Skolithos linearis* ichnofabrics 1 and 2. It is present in the lower and middle intervals of the Mulichinco Formation. The eolian sand sheet ichnofabric association comprises the *Planolites* isp.-*Palaeophycus* isp. ichnofabric 1 and the laminated filled vertical burrow ichnofabric, as well as some occurrences of the studied unit. The interdune ichnofabric association comprises the *Planolites* isp.-*Palaeophycus* isp. ichnofabric 2 and the *Taenidium* isp. ichnofabric 1. It occurs in the middle interval of the Mulichinco Formation. The fluvial sheet flood ichnofabric association is represented by the *Taenidium* isp. ichnofabric 2, which is present in the upper interval of the studied unit.

Integration of ichnologic information with sedimentologic and sequence-stratigraphic datasets allows characterizing the studied succession as a 3<sup>rd</sup>-order depositional sequence. This 3<sup>rd</sup>-order sequence is subdivided into three 4<sup>th</sup>-order sequences stacked in a backstepping pattern as a result of a rise in the water table. The base of the 3<sup>rd</sup>-order sequence is represented by the intra-Valanginian unconformity that in the El Mangrullo oil field separates marine deposits below from continental deposits above. No substrate-controlled trace-fossil suites have been identified in this surface. The 3<sup>rd</sup>-order sequence of eolian dune deposits to eolian sand sheet and fluvial sheet flood deposits, the latter intercalating with marginal-marine intervals. The eolian Mulichinco ichnofauna indicates a temporal evolution from hyper-arid to arid and semi-arid conditions.

The results of the present analysis argue against the common assumption of deserts as barren in life. Both the *Scoyenia* and *Entradichnus-Octopodichnus* ichnofacies are identified. The former is present in damp interdune and ephemeral fluvial deposits, whereas the latter occurs in eolian dune and sand sheet deposits. In addition, this study provides further support to the notion of an archetypal eolian ichnofacies. This study expands the application of ichnology in subsurface to eolian environments by providing a characterization of the ichnofauna from a desert setting based on core analysis.

# *Ophiomorpha* ichnofabric revealing delta front conditions in Cenozoic deposits of the Colombian Caribbean – NW South America

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The NW margin of South America has evolved since the Late Cretaceous as consequence of variable geological processes (e.g., subduction, accretion, extension, and tectonic inversion), being still a subject of debate, which gave rise to the Northern Andes and their associated sedimentary basins.

In the last 10 years, the National Hydrocarbons Agency (ANH) of Colombia has increased the study of potentially hydrocarbon-bearing sedimentary basins to improve its knowledge and capacity to respond to the energy requirements of the country. The Sinú-San Jacinto Basin, located in the Colombian Caribbean has been one of the most studied basins, given its geological potential related to the origin, migration and accumulation of hydrocarbons. So far, numerous studies have been carried out, to know the geological evolution of the basin, and then to understand, on a large scale, the stratigraphy and structures associated with the processes and elements of the petroleum system. However, due to its structural complexity, and the lateral changes of facies, multidisciplinary studies should be implemented to allow reliable paleoenvironmental reconstructions and to establish spatiotemporal relationships between the units.

As has been demonstrated in the last years, the ichnofabric of rocks is a key tool for sedimentary basin research, allowing to draw direct inferences of the depositional and ecological factors from the record of the primary sedimentary conditions, the structure of the original endobenthic tracemaker community, and the subsequent taphonomic history.

Some Oligocene-Miocene outcrop sections have been studied in the Sinú-San Jacinto Basin. Detailed sedimentological and ichnological analyses of the rocks have allowed interpreting shallow marine environments dominated by a deltaic system. The upper delta plain is characterized by argillaceous sedimentation, rhizoliths, coal seams, scarce bioturbation, and abundant plant debris. The lower delta plain is characterized by coals seams, mudrocks with abundant bivalves and gastropods associated with interdistributary bays, where, in addition, it is possible to locally recognize foreshore deposits characterized by well-selected quartzose sandstones with parallel-subparallel lamination, and the *Macaronichnus* assemblage. The delta front is characterized by often highly bioturbated sandstones with planar cross-bedding, trough cross-bedding, and monospecific robust *Ophiomorpha*. Finally, the prodelta deposits are characterized by mudrocks with plane parallel lamination, and, in some cases, sandstones with hummocky cross-stratification.

From the general trace fossil assemblage registered through the studied sections, analyses focused on the localized presence of a well-developed *Ophiomorpha* ichnofabric, in order to improve the interpretation of the depositional setting. This ichnofabric is preserved in planar cross-bedded and trough cross-bedded, slightly conglomeratic and massive, quartzose sandstones. Bioturbation indexes vary between 3 and 4, being *Ophiomorpha* the main ichnotaxa registered in the trace fossils assemblage. The *Ophiomorpha* burrows have diameters between 2 and 5 cm, and between 3 and 20 cm in length. Cutting relationships mainly occur between different specimens of *Ophiomorpha*. Very rarely *Ophiomorpha* has been observed in association with *Skolithos*, *Teichichnus*, and *Thalassinoides*.

According to previous studies in Mesozoic and Cenozoic sections, and to the detailed analysis here conducted in the study sections, the monospecific presence of abundant and robust *Ophiomorpha*, determining a well-developed *Ophiomorpha* ichnofabric, can be related to particular paleoenvironmental conditions mainly associated to delta front settings within the deltaic system. Available criteria for differentiation between sub-environments into deltaic systems are essential, reducing uncertainty during the characterization of reservoir intervals. Therefore, the study of *Ophiomorpha* ichnofabrics can become the first step to improve sub-environmental characterization of deltaic systems in the studied sections and subsurface of the Colombian Caribbean.

In conclusion, this study contributes to the understanding of specific sedimentary environments in the Sinú-San Jacinto Basin developed during the Cenozoic.

# Shallow marine trace fossils from the Early Ordovician Amanos mountains (north of Nurdağ-Kahramanmaraş, SE Anatolia)

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A well defined Early to Middle Paleozoic successions are cropped out in the Amanos mountains located in southeastern Turkey.

Trace fossils are found in the Kaman region northeast of Kahramanmaraş in the Lower Ordovician Kardere Formation. The succession is represented by quartz-arenite and shale alternations typical for shallow shelf-shore conditions where storms and waves are predominant.

The sequence contains abundant, diverse, and well-preserved arthropod and vermiform trace fossils assemblages which are represented by *Cruziana* isp., *Cruziana furcifera, Cruziana rugosa, Cruziana goldfussi, Daedalus* isp., *Didymaulichnus* isp., *Diplocraterion* isp., *Monocraterion* isp., *Monocraterion* isp., *Monomorphichnus* isp., *Teichichnus* isp., *Skolithos* isp., *Palaeophycus* isp., *Planolites* isp. *Rusophycus* isp. *Protovirgularia* isp., and *Trichophycus* isp. In the studied section the presence of *Cruziana furcifera, C. goldfussi* and *C. rugosa* indicates an Early Ordovician biostratigraphic age and a shallow marine subtidal low-energy depositional environment with typic *Cruziana* ichnofacies.

The authors thank Muğla Sıtkı Koçman University for the financial support on BAP project 18/054.

# Ichnofabric analysis of contouritic deposits from the NW Iberian margin

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Contourites are sediments deposited, or reworked by constant bottom currents (e.g., Rebesco *et al.*, 2014). These deposits are being a hot topic during the recent decades in several disciplines as palaeoenvironment, palaeoceanography, slope stability and oil exploration, but they are still poorly understood by the scientific community. Contourites deposits can be easily recognized from seismic lines, but their identification in small scale is still in debate and new criteria are being considered to refine the proposed facies model (e.g., Rebesco *et al.*, 2014). In this sense, ichnology has been considered by some authors as a potential criterion to characterise contourites (see Rodríguez-Tovar & Hernández-Molina, 2018 for a recent review).

Nowadays, new advances are being developed in the analysis of the ichnological content of contourites (e.g., Rodríguez-Tovar *et al.* in press). One of the most useful tools to clarify contourite identification at small scale would be the ichnofabric approach (Ekdale & Bromley, 1983), as a proxy to approach palaeoenvironmental conditions related to depositional processes. However, it has been rarely used in contourite research (e.g., Wetzel *et al.*, 2008; Alonso *et al.*, 2016). Here we present the ichnofabric analysis of some muddy contourite deposits from two gravity cores retrieved in the NW Iberian margin.

The study cores were taken from the Galicia Interior Basin. The lithofacies analysis was previously conducted by Mena *et al.* (2018) using a multi-proxy approach considering lithology, sedimentological structures, composition and bioturbation, among others. The ichnofabric study has been applied on identified contouritic intervals, supported by digital image treatment (Dorador & Rodríguez-Tovar, 2018 for a recent review) and Computed Tomography data.

A multi-tiered trace fossils assemblage of the contouritic facies is identified, composed of five ichnotaxa (*Palaeophycus, Planolites, Thalassinoides, Thalassinoides*-like and *Zoophycos*) and six ichnofabrics were defined (Fig.1): A) Mottled ichnofabric: characterised by a mottling (i.e., bioturbate texture) and the absence of discrete trace fossils; B) *Palaeophycus* ichnofabric: dominated by *Palaeophycus* and abundant *Planolites* over a mottled background with a moderate to high degree of bioturbation and without crosscutting situations; C) *Planolites* ichnofabric: characterised by the presence of scarce *Planolites* over a mottled background in a low degree of bioturbation; D) *Thalassinoides* ichnofabric: composed of abundant *Thalassinoides* and *Planolites* overprinting a mottled background. The degree of bioturbation is medium and there are not cross-cutting relationships; E) *Thalassinoides*-like ichnofabric: dominated by *Thalassinoides*-like, abundant *Thalassinoides* and rare *Palaeophycus* and *Planolites* over a mottled background. Degree of bioturbation is low to medium and cross-cutting relations were not observed; and F) *Zoophycos* ichnofabric: dominated by *Zoophycos* and abundant *Planolites* and *Thalassinoides* over a mottling. Degree of bioturbation ranges from medium to moderate and sometimes *Zoophycos* is found overlapping *Planolites*.

The mottled background along the whole record points the complete reworking of the mixed layer under generalized relatively good palaeoenvironmental conditions. However, the local presence of *Zoophycos* ichnofabric or the frequent presence of *Palaeophycus* in *Palaeophycus* ichnofabric reveals punctual environmental changes during contourite deposition. These changes could be produced by modifications of ecological or depositional parameters during bottom-current activity, as hydrodynamic energy, oxygenation, organic matter content or sedimentation rate, among others.

The present study is a preliminary ichnofabric approach in muddy contourite deposits. This reveals that palaeoenvironmental conditions are changing during the deposition of bottom-current sediments. Ichnological features, with special attention to ichnofabric approach, reveals the trace fossil analysis as a potential tool to for contourite research.



Thalassinoides ichf.

Thalassinoides-like ichf.

Zoophycos ichf.

Fig. 1. Ichnofabrics defined in the contouritic intervals. ichf, ichnofabric. *Pa*, *Palaeophycus*; *Pl*, *Planolites*; *Th*, *Thalassinoides*; *Th*-1, *Thalassinoides*-like; *Zo*, *Zoophycos*.

#### Acknowledgements

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# Ordovician trace fossils of Siberia: responses to climatic events and connection with Gondwana, Baltica and Laurentia

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In recent years new data on distribution of trace fossils in the Ordovician succession of the Siberian palaeocontinent have been obtained. Giant Rusophycus traces (32x20 cm) were reported from the Baykit Sandstone (Vikhorevian and Mukteian regional stages, Darriwilian) for the first time from the outside of the Gondwana palaeocontinent. Rich and diverse Cruziana/Rusophycus ichnocoenosis was found in quartz sandstones of the upper part of the Moyero formation (Kirensko-Kudrinian regional stage, uppermost Darriwilian) on the northeastern margin of the Tungus basin. Appearance of these typical Gondwana trace fossils come together with typical Gondwana lithologies and accompany the wide distribution of the "Nubian facies" in the Tungus basin. Invasion of these facies marks destruction of previously existed warm-water carbonate platform and sea-level lowering probably coinciding with the beginning of cooling event. Lithology and position of the Baykit Sandstone and its counterparts (between the warm-water and cool-water carbonate series) strongly remind one of the lithology and position of the Upper Ordovician (Katian) Eureka Quartzite of Laurentia. Morphology of the Siberian Cruziana and Rusophycus traces, their size and claw formula suggests that they belong to a new ichnospecies probably endemic for the Siberian palaeocontinent. Trace fossils assemblages from the Darriwilian of the Irkutsk basin on the south of the Siberian platform also demonstrate closer affinity to Gondwana than to Baltica. The assemblages include Polycladichnus and Teichichnus for shallow-water settings and Palaeophycus, Arthrophycus, Megagrapton, Phycodes and Cochlichnis for relatively deepwater settings. Massive thick-bedded Thalassinoides ichnofabric identified in limestones of the Volginian regional stage (Upper Darriwilian) in the northern part of the Tungus basin is very similar to that described in Laurentia. That could be regarded as independent evidence for near equatorial position of this part of the basin in the Darriwilian time. From the Upper Ordovician of the Tungus basin traces of boring activity like Trypanites and Balanoglossites reported for the first time. In the Ordovician of Baltica, such traces appears much earlier in Floian and Dapingian but disappears when the palaeocontinent migrated into tropics. In Siberia, boring traces probably reflects onset of the coolwater conditions.

# A Walk in the Gyrolithes Heaven (Ichnology of an Early Miocene Age Sand-pit, Tardona Hills, North-Hungary)

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Vertical to inclined corkscrew-shaped burrows in the fossil record are generally assigned to the ichnogenus *Gyrolithes*. It is inferred to be produced by decapod crustaceans due to its common interconnection with *Ophiomorpha* and *Thalassinoides* or by the presence of scratch marks inside the burrow wall. *Gyrolithes* represents a permanent dwelling burrow produced mainly in marginal-marine settings. The helical morphology of *Gyrolithes* has been interpreted to be an adaptation to seek refuge from extreme salinity fluctuations, but corkscrew burrows also may represent feeding strategies in addition to a refuge against salinity fluctuations, or even be a multipurpose burrow" (Netto et al. 2007 and references therein).

The aims of our examination are (1) to interpret the ichnological characteristics of the studied outcrop; (2) to provide new data about the *Gyrolithes* ichnospecies of the Early Miocene age formations of Northern-Hungary.

The examined exposure is an abandoned sand-pit. It is situated at the north-eastern part of Tardona Hills, two kilometers from the village Nagybarca to the north. Two formations appear here. The one is the Salgotarjan Lignite Formation of the Early Miocene (Karpatian) age and the other one is the Sajóvalley Formation of the Middle Miocene (Late-Badenian) age. Bioturbation structures occur only in the Early Miocene sediments of the sand-pit. The profile of the exposure begins with 3 m thick medium grained sand. Its lower part contains a 25 cm thick lignite-bearing fine grained pebble layer. The grain size of the sediment is getting finer upwards and the gradual transition into fine grained sand can be detected. The original stratification is not visible. In the upper part of the sand, there are clavey marl clast strings showing the former cross-stratification. It is followed by 2 m thick clayey marl which settled disconformly onto the sandbody. It is a colonization surface. The majority of the bioturbation structures can be found here. It is followed by the alternation of cross-stratified coarse grained sand and fine grained pebble layers. Presence of any trace fossils is subordinate in this formation. Bioturbation structures occur abundantly in the sand-pit, but their diversity is low. The Gyrolithes ichnogenus is dominant in each formations (Table 1.). Characteristic trace fossil of the medium grained sand is the Gyrolithes nodosus MAYORAL. It often occurs with Ophiomorpha nodosa here. The frequency of the bioturbation structures is the highest at the top of the sandbody. There are some Gyrolithes and Ophiomorpha occur subordinately at the bedding surfaces marked by clayey marl clast strings, too. Thalassinoides isp. and Teredolites isp. can also be found sporadically in the sand. The density of the bioturbation structures is 32 trace fossils per square metre. The bioturbation index (BI) is 4. The clayey marl is also heavily bioturbated (BI 4). But the preservation of the trace fossils is extremely poor. Only Gyrolithes is could be determined in some cases. On the other hand, however, only one or two specimens of badly preserved Gyrolithes nodosus and Ophiomorpha nodosa can be seen in the exposure of the fine grained pebble formation (BI 1).

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No.	Direction of spiral	r	R	h	a	K (r/R)	δ (h/2*r)	β (h/2*π*R)	L	n	Ichnospecies	Host sediment
1	R	9,64	10,84	24,76	-27,9	0,889299	1,284232	0,363715	90,88	3	Gyrolithes nodosus	limonitic sand
2	L	7,84	12,47	32,88	7,79	0,628709	2,096939	0,419861	112,69	3	Gyrolithes nodosus	limonitic sand
3	L	8,81	17,8	20,92	0 - 5,24	0,494944	1,187287	0,187147	130,36	4	Gyrolithes nodosus	limonitic sand
4	L	5,53	9,8	33,06	32,01	0,564286	2,98915	0,537177	118,48	4	Gyrolithes nodosus	limonitic sand
5	R	5,43	5,43	16,12	-33,9	1	1,484346	0,472722	109,62	5	Gyrolithes nodosus	limonitic sand
6	R	5,64	8,29	27,59	-30,58	0,680338	2,445922	0,529953	120,56	5	Gyrolithes nodosus	limonitic sand
7	L	8,51	11,15	24,23	29,17	0,763229	1,423619	0,346034	162,47	7	Gyrolithes nodosus	limonitic sand
8	R	5,79	7	21,76	-26,99	0,827143	1,879102	0,494995	91,6	4	Gyrolithes nodosus	limonitic sand
9	L	5,37	8,48	25,98	31,02	0,633255	2,418994	0,487847	90,28	4	Gyrolithes nodosus	limonitic sand
10	L	4,48	9,32	21,27	25,35	0,480687	2,373884	0,363406	75,13	4	Gyrolithes nodosus	limonitic sand
11	L	9,17	16,21	24,56	12,99	0,5657	1,339149	0,24126	40,88	1	Gyrolithes nodosus	limonitic sand
12	R	4,9	6,04	17,24	-20,56	0,811258	1,759184	0,454507	61,58	4	Gyrolithes nodosus	limonitic sand
13	L	4,22	no data.	10,86	no data	#ÉRTÉK!	1,28673	no data	60,7	5	Gyrolithes nodosus	limonitic sand
14	alternating	12,95	22,95	45,75	19,94 -23,13	0,56427	1,766409	0,317431	108,93	2	Gyrolithes nodosus	limonitic sand
15	L	15,09	25,23	56,47	21,27	0,598098	1,871107	0,356403	233,86	5	Gyrolithes nodosus	limonitic sand
16	L	19,53	51,62	49,87	2,5	0,378342	1,276754	0,153837	110,02	2	Gyrolithes nodosus	limonitic sand
17	R	11,9	23,33	45,31	-27,53	0,510073	1,903782	0,309257	120,19	3	Gyrolithes nodosus	limonitic sand
18	L	13,46	16,35	62,59	25,1	0,823242	2,325037	0,609576	234,79	4	Gyrolithes nodosus	limonitic sand
19	L	19,51	29,76	77,02	29,91	0,655578	1,97386	0,412108	263,5	4	Gyrolithes nodosus	limonitic sand
20	L	8,92	9,44	22,38	24,86	0,944915	1,254484	0,37751	138,67	4	Gyrolithes nodosus	limonitic sand
21	L	14	16,04	36,41	35,58	0,872818	1,300357	0,361457	159,26	4	Gyrolithes nodosus	limonitic sand
22	L	8,46	13,67	21,22	27,65	0,618873	1,254137	0,247182	103,57	5	Gyrolithes isp.	clayey marl
23	R	7,86	9,29	no data.	-17,02	0,846071	no data	no data	15,43	1	Gyrolithes isp.	clayey marl
24	L	5,11	7,13	14,38	34,95	0,71669	1,407045	0,321151	41,86	3	Gyrolithes isp.	clayey marl
25	R	9,97	14,36	39,94	-1,08	0,69429	2,003009	0,442888	75,05	2	Gyrolithes nodosus	sand with finegrained pebbles
26	L	13,29	15,27	29,9	31,09	0,870334	1,124906	0,311797	80,15	3	Gyrolithes nodosus	sand with finegrained pebbles
27	L	5,2	11,3	14,11	10,62	0,460177	1,356731	0,198833	87,8	5	Gyrolithes nodosus	medium grained sand
28	L	6,86	8,68	16,26	14,04	0,790323	1,185131	0,298292	99,7	4	Gyrolithes nodosus	medium grained sand
29	L	12,38	19,15	no data.	7,62	0,646475	no data	no data	24,55	1	Gyrolithes isp.	soilbearing clayey marl

**Table 1.** Morphometric data of the *Gyrolithes* specimens observed at Nagybarca sand-pit (based on Laing *et al.*, 2018).

# The Ichnofabric of Urban Life: Using Architectural stone as a teaching resource. Examples from the New York Metropolitan area

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# Introduction

From ancient times building stone, chosen for its durability and its beauty, has been used in building the world's cities. The various stones have been noted as a resource for teaching about geology in both formal and informal settings (Passow, 2015; Livingston *et al.*, 2015), and have been discussed in detail in monographs (Olson, 2011), articles, and chapters of works dedicated to specific regions and periods (Merle, 2008). Although often dealing with the simple identification of the classification of the stone in question, some of these works and articles have gone further, into the origins, chemistry, and fossil content of the various stones (Merle, 2008; Kaylor *et al.*, 2002). In using the stone as a resource for teaching, the depth to which any of these aspects of stone will be investigated is determined by the level of the target audience, students, or general public. The following examples from the New York Metropolitan area illustrate the possibilities of using exotic building stones as a resource for observing, then discussing ichnology in the classroom.

#### The Examples

Zoophycos: a polished carbonate mudstone (Fig. 1).

The Westchester Mall, in White Plains New York, underwent renovation in 2015, including the installation of 25,000 square feet of new flooring, most of which consisted of a highly polished limestone containing extensive examples of *Zoophycos* and related traces. These closely resemble traces described by Gerard & Bromley (2008) from the Miocene of Italy. The management of the Mall claims an Italian source for the flooring, but this has not yet been confirmed. Traces included in the flooring are, *Zoophycos*, primarily vertical slices seen from the sides (Fig. 3), possible helical *Daedalus* (Seilacher, 2007) and various lined and unlined burrows, rarely branching.

Flooring made of cuts from an extensive Stromatolite colony (Fig. 2).

2600 Netherland Avenue, in the borough of the Bronx, New York, built in 1975, utilizes a brown to cream colored moderately porous stone made of various cuts both horizontal across the surface of a colony of stromatolites, and vertically cutting through some of the cone shaped colonies. The provenance and age of the stone has not yet been determined. In the vertical sections there is evidence of breakage of the cones, and the passive refilling of sand. The horizontal sections show growth rings, and intergrowth of colonies.

External wall cladding of Lutetian Limestone (Fig. 3).

Constructed in 1925, the apartment building with commercial spaces at the street level at 30 E. 68<sup>th</sup> Street, is clad with limestone exhibiting extensive reworking and fossils characteristic of Lutetian limestone from the Paris basin. *Serraticerithium denticulatum* and *S. serratum* are common as weathered molds in the stone (Fig. 3). Embedded shells of *Saxolucina sp.* The limestone shows weak layering and lag concentrations and is highly bioturbated as would be expected from an estuarine to shallow marine environment.

#### Conclusion

The very aspect of sedimentary stone which makes it visually interesting as an architectural material, its textural complexity, is the aspect which conveys information about the depositional and post depositional history to a geologist. In urban areas where cut and polished stone from local and distant sources is available, it can be used as a teaching resource to illustrate concepts such as tiering, burrowing styles, and relationships between the organisms and the original substrate.



Fig. 1. A Zoophycos dominated ichnofabric. Floor tiles, White Plains, N.Y.



Fig. 2. Vertical cut through Stromatolite.



Fig. 3. Serraticerithium Molds in 30 E 68<sup>th</sup> St. Façade.

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# The role of *Psammichnites* in the origin of an Early Cambrian shelf sediment mixed layer

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The mixed layer of modern oceans is a zone of fully homogenized sediment resulting from bioturbation (Berger et al., 1979; Teal et al., 2008). The mixed layer is host to complex biogeochemical cycles that directly impact ecosystem functioning, affecting ocean productivity and marine biodiversity. However, the timing of appearance of a mixed zone at the sediment-water interface remains uncertain within a 100 million year interval stretching from the early Cambrian to the late Silurian (Mángano & Buatois, 2014; Tarhan et al., 2015), hindering palaeontological and geochemical studies of this key milestone in Earth evolution. In our study (Gougeon et al., 2018) we provide detailed evidence from the Global Stratotype Section and Point (GSSP) of the basal Cambrian in the Burin Peninsula of Newfoundland, Canada, demonstrating that a mixed layer of similar structure to that of modern ocean was well established in shallow marine settings by the early Cambrian (approximately 529 my ago). In contrast with modern seafloors, Ediacaran marine sediment surfaces were pervasively coated with resistant microbial mats that acted as geochemical filter between the underlying sediment and overlying seawater (Seilacher, 1999). Significant reductions in the prevalence of microbial mats coupled with widespread bioturbation and associated bioirrigation would have permitted increasingly free-interchange between surface sediments and the water column, dramatically changing fluid chemistry of both of these regimes (Canfield & Farquhar, 2009; Seilacher, 1999).

Our analysis of bioturbation in this section shows that substrate exploitation in the Ediacaran was restricted to non-penetrative horizontal grazing of microbial mats, whereas a mixture of superficial mat grazing trails, undermat-mining burrows and small penetrative burrows characterize the Fortunian and the establishment of the marine sediment mixed layer is the main innovation of Cambrian Age 2. During the Fortunian, a drastic change in the ecosystem is typified by the appearance of *Psammichnites*, a large, backfilled horizontal burrow of the shallow-tier produced by sediment bulldozers. At first fairly scarce, the predominance of *Psammichnites* higher up in the section is coincidental with the general increase in sediment churning, reaching a critical point close to the Cambrian Age 2 where a sediment mixed layer has been identified. These findings imply that an accurate description of early Cambrian ichnocoenoses is a robust method to properly decipher major changes in the sediment sea-floor at this critical time.

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# Ichnofabrics from the Cambrian-Ordovician Deadwood and Earlie formations: exploring evolutionary and environmental controls

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The middle Cambrian to Lower Ordovician Earlie and Deadwood formations in western North America yield ichnofabrics reflecting the different ecological controls specific to each of the subenvironments represented in these strata. These units record the initial deposition within an epeiric sea formed during a widespread transgressive sequence that covered the western margin of Laurentia during the early Paleozoic (Slind *et al.*, 1994). They have a wide subsurface distribution inside the Western Canada Sedimentary Basin (Dixon, 2008) and the Williston Basin (Lefever, 1996), outcropping to the south in the Black Hills of South Dakota, United States. The above mentioned lower Paleozoic strata represent a complex pattern of sedimentary environments recording a transition from tide- to wave-dominated and deltaic-influenced regimes, encompassing bay margin, proximal bay, distal bay, offshore, offshore transition and lower to upper shoreface deposits.

The Earlie and the Deadwood formations display dominance of relatively simple ichnofabrics and tiering structures. Five ichnofabrics (IF) were defined along the depositional profile. IF1 (Skolithos-Palaeophycus) is characterized by the dominance of mid-tier Skolithos linearis and Palaeophycus isp. reflecting colonization at the top of small dunes and event beds in sandstone-dominated and mixedheterolithics from the Earlie Formation proximal bay deposits. Bioturbation intensity is generally low (BI=1-2). IF2 (Teichichnus-Planolites-Palaeophycus) consists of shallow- to mid-tier deposit feeding and dwelling structures, Planolites montanus and Palaeophycus isp., cross-cut by common mid-tier deposit feeding Teichichnus rectus. Bioturbation index is variable from low to moderately high (2-4). IF2 is commonly found in mudstone of mixed-heterolithic intervals from the Earlie Formation. IF3 (*Teichichnus*) is characterized by the dominance of mid-tier deposit feeding structures (*Teichichnus*) locally reworked by deep-tier *Cylindrichnus* isp. Degree of bioturbation is high to very high (4-5). This ichnofabric is found in mudstone-dominated distal bay deposits of the Earlie Formation. IF4 (Teichichnus-Planolites) contain horizontal, deposit feeding, shallow- to mid-tier structures, such as Teichichnus rectus, Planolites montanus and rare Asterosoma isp. Degree of bioturbation is highly variable (1-4) and ichnodiversity tends to be low in comparison to other ichnofabrics within the succession. In the Deadwood Formation, IF4 is commonly found in offshore, offshore transition, and lower shoreface facies, as well as in deltaic-influenced deposits. In the Earlie Formation, IF4 is found in heterolithics deposits with common soft-sediment deformation structures. IF5 (Skolithos) consists of generally monospecific suites of suspension-feeding, mid-tier Skolithos linearis colonizing the top of tempestites, hummocky beds, and dunes within the Deadwood Formation. Degree of bioturbation is commonly low (0-2), reflecting the activity of opportunistic fauna during shortly developed colonization windows. Dense assemblages of this ichnofabric (BI=3-4) are limited to trough crossbedded sandstone of the Deadwood Formation outcropping at the Black Hills in South Dakota. In this locality, Skolithos linearis is found forming pipe-rocks along with other vertical, mid-tier structures, such as Arenicolites isp., present at foresets and topsets of dunes, locally cross-cutting each other, reflecting multiple colonization events.

Tiering structures in the Earlie and Deadwood formations deposits reveal a relatively simple infaunal community. Simple tiering structure is interpreted as reflecting environmental constraints

during colonization rather than evolutionary controls. In comparison to older and younger Paleozoic units deposited in similar shallow-water environments within the same sedimentary basin, the lower Cambrian Lake Louise Formation (Desjardins *et al.*, 2010) or the overlying Middle Ordovician Winnipeg Formation (Dorador *et al.*, 2019), the Earlie and the Deadwood formations reflect an overall low ichnodiversity with variable degrees of bioturbation and uneven distribution of trace fossils, suggesting that colonization trends were controlled by factors specific to each subenvironment. Distal, low-energy deposits with prolonged colonization windows tend to present ichnofabrics dominated by detritus- and deposit-feeding structures, displaying higher degrees of bioturbation (IF2 and IF3). However, ichnodiversity levels remain low, suggesting the presence of stressing conditions such as salinity fluctuations or possible oxygen depletion. IF4 reflects even lower indexes of bioturbation indicating that the negative impact on the benthic fauna by these stressing factors was even greater. Proximal deposits contain ichnofabrics dominated by suspension feeders (IF1 and IF5) with low ichnodiversity and low degrees of bioturbation, reflecting periodic colonization windows, controlled mainly by sedimentation rate, substrate sand shifting and salinity changes.

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# Ichnofabric

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An ichnofabric originates from the interaction of burrowing and/or bioeroding organisms with their substrate and is subject to taphonomic and diagenetic alteration. In oxygenated, soft sediment, just below the surface, a mixed layer is established that is completely bioturbated and disturbed. Downward it grades into the transitional layer, characterized by discretely preserved traces, while below that, in the historical layer, no new traces are formed. The appearance of ichnofabrics can be manifold and depends on their developing history. Simple ichnofabrics are monospecific and originate from opportunistic short-term bioturbation or from successive phases of habitat utilization/sediment exploitation over time. Composite ichnofabrics contain several ichnotaxa and document continuous or interrupted sedimentation over a longer period of time (Fig. 1). They can be autocomposite (originating from a single benthic community shifting its position upward in pace with gradational sedimentation), heterocomposite (having one or more benthic communities acting in different sedimentary facies), or ultracomposite (being the product of benthic communities of contrasting age and depositional systems). Completely bioturbated sediment without any discernible stratification, tiers or discrete ichnotaxa is referred to as bioturbate texture (in its original meaning). Various physical, chemical and ecological conditions affect the development of an ichnofabric, including benthic community structure, sediment properties, oxygenation, salinity and nutrition. Ichnofabric analysis is performed stepwise and includes the recognition of bounding surfaces and sedimentological features, quantification of bioturbation structures, identification of ichnotaxa and tiering, mapping burrow size, ichnodiversity and ichnoabundance, and investigating the taphonomic and diagenetic overprint. Ichnofabrics store important information about environmental conditions and thus have a broad field of application, including facies reconstruction, sequence stratigraphy and reservoir characterization.

Over the past four decades, ichnofabric analysis has not only demonstrated its importance for various sedimentological, paleontological, geochemical and petrophysical interpretations, but in turn this intriguing concept was continuously refined and improved (e.g. Ekdale *et al.*, 2012; Knaust, 2017). Compared with the well-established ichnofacies paradigm, which was created to characterize broad facies zones across an ocean margin from the continent to the deep sea by means of recurrent trace-fossil communities, ichnofabric analysis was developed on vertical sections of sedimentary units, where subtle relationships of ichnological and sedimentary features reveal details about their origin and development (Fig. 2).

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Fig. 1. Elements of a composite ichnofabric as seen in a large-scale, vertical thin section through a Lower Jurassic calcite concretion from northern Germany. See Knaust (2012).



Fig. 2. Vertical core sections (ca. 9 cm wide) with ichnofabrics from brackish-water (A), fully marine (B) and anoxic environments (C) from offshore Norway. See Knaust (2018a, b, 2019).

# Firmground Trace Fossils in the Mantou Formation, Cambrian, Western Henan

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The blank ecological domains were gradually colonized by different categories of metazoan in the aftermath of Cambrian Explosion. The firmground is widespread in Cambrian because of the limited extent and depth of bioturbation in the virtual absence of a mixed layer. This kind of substrate can provide a good condition for the preservation of trace fossils. The integrated preservation and fine details of the firmground trace fossils are the ideal materials for us to analyze the relationship between Metazoa and sedimentary environments. This study takes firmground trace fossils from the Cambrian Mantou Formation of western Henan as the research objects to focus on the morphological characteristics and substrate controlling factors of firmground trace fossils including trails and trackways of trilobite, to recognize tracemaker's behavior and living paleoenvironments, and to uncover the characteristics of intertidal trophic web.

According to the characteristics of sedimentology and ichnology, 11 genera and 15 species of firmground trace fossils including burrows and repichnia have been identified in the Mantou Formation of Cambrian Series 2 and 3 of western Henan. The firmground repichnia were originally emplaced on or near the sediment-water interface (SWI) and usually formed on the surface of mudstone or silty mudstone, part of them were preserved on soles of overlying coarser sediments. The firmground burrows were characterized by sharp, often scratch-marked boundaries, unlined, passively filled with overlying coarser sediments or the sediments bypassing the bottom, that contrast markedly with surrounding sediments. Firmground substrates with trace fossils may have resulted from prolonged or intermittent subaerial exposure of sediments and low degree of sediment mixing.

# Paleoproterozoic ichnofabrics from 2.1 Ga shallow-marine strata (Francevillian Basin, Gabon)

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Pyritized, string-shaped structures are present in Paleoproterozoic (2.1-billion-year-old) shallowmarine strata from the Francevillian Basin. Approximately 80 specimens were recovered from black, silty shale deposited in offshore to offshore transition settings. The structures occur in close proximity to microbial mat horizons. They are mostly parallel to bedding, but locally crosscut horizontal laminae and display elliptic to subcircular cross sections. The string-shaped structures are 1-6 mm wide and up to 170 mm long. The simplest specimens are horizontal, unbranched, and straight, showing relatively constant diameters, although some local torsions and constrictions were observed. Rounded terminations are typical for the ends of the structures. Other specimens show short, low-wavelength sinuosity and angular bends. In some cases, there are two or more parallel strings that intertwine and display a contorted helicoid shape, in places involving several strings in a braided pattern. X-ray micro-CT and petrographic microscopy reveal that these string-shaped structures also intersect the stratification (penetrating up to 1.5 cm deep). Some strings traverse silty shale laminae and continue along other levels, with angles of penetration ranging from 12 to 85°. Integration of microscopic, microtomographic, geochemical, and sedimentologic analyses provides evidence for biogenicity and syndepositional formation, and suggests that the structures underwent fossilization during early diagenesis close to the sediment-water interface. These structures are superficially similar to simple grazing trails, which are commonly associated with microbial mats in Ediacaran strata. However, unlike Ediacaran trails, the Francevillian structures have rounded terminations and locally bulbous elements. Also, characteristic levees formed by sediment pushing on both sides, crucial in delineating the animal origin for Ediacaran trace fossils, are absent in the Francevillian structures. Morphological and 3D tomographic reconstructions suggest that the producer may have been an aggregate of cells able to move as a coherent mass. This could explain the ability to move laterally and vertically, most likely to reach food resources. At the same time, a multicellular aggregate is consistent with the torsions and width irregularities associated with some structures. As a potential modern analogue, we suggest the aggregation of amoeboid cells into a migratory slug phase in cellular slime molds at times of starvation. This unique ecologic window established in a well-oxygenated, shallow-marine environment represents an exceptional record of the biosphere following the dramatic changes in the atmosphere and oceans in the aftermath of the Great Oxidation Event (GOE) at roughly 2.3 billion years ago.



Fig. 1. Micro-CT-based reconstructions of string-shaped structures from the Francevillian Series, Gabon. (a) Volume rendering showing the external bedding plane surface displaying subcircular sections of vertical to oblique strings. (b, c, d, e) Volume transparencies of the same specimen showing string-like structures at two distinct horizontal levels. Box denotes portion (cross-section) figured in "a". (d, e) Note simple, relatively straight string directly associated to a microbial mat. Arrows point to string-shaped specimens (black) and microbial mats (white). All scales are 1 cm.

# Ichnofabric evolution after storm events in a delta environment: A case from the Miocene of Taiwan

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Delta environments are affected by a wide range of marine and fluvial hydrodynamic processes (e.g., rivers, waves, storms, tides) (Tonkin, 2012). Therefore, this complex emplacement results in an extensive assortment of ichnofabrics combinations (Taylor *et al.*, 2003; McIlroy, 2004). Exposure of Oligocene to Pliocene sedimentary sequences in Taiwan is mainly controlled by uplifted and tilted processes related with the collision of a volcanic arc on the Philippine Sea Plate and the Eurasian continental plate (Suppe, 1984). These shallow marine sedimentary deposits exposed in the northeast coast, record an exceptional preservation of sedimentary and biogenic structures due to acute weathering from waves and torrential rains. The area of study is located in one of the most emblematic places in Taiwan, Yehliu Peninsula Geopark (field trip stop point of the previous 14<sup>th</sup> International Ichnofabric Workshop in Taiwan).

Yehliu Peninsula records the Miocene Taliao Formation succession, composed primarily by sandstones deposited in an offshore to shoreface environment (Yu & Teng, 1999; Löwemark & Nara, 2013). The formation is composed of a lower mudstone unit, a middle sandstone unit (the Yehliu Sandstone Member), and an upper thin, interbedded sandstone and mudstone unit (Hong & Huang, 2000). Several paleoenvironmental interpretations have been proposed for the lower part of the Yehliu Sandstone Member based on different approaches, but ichnological studies are significantly scarce. The aim of this study is to refine paleoenvironmental interpretations based on a detailed ichnofabric analysis, focusing on storm beds, in order to interpret paleoenvironmental conditions before, during and after deposition. Two ichnofabrics, *Ophimorpha-Schaubcylindrichnus* ichnofabric and *Ophiomorpha* ichnofabric, have been differentiated, showing a variable record according to storm beds.

*Ophiomorpha-Schaubcylindrichnus* ichnofabric. Sandstones from the lower part of the Yehliu Member are medium to poorly sorted, and in most cases sedimentary structures were obliterated due to profuse bioturbation, constituting 60-80% of the sedimentary fabric. When preserved, sedimentary structures comprise regular planar cross-stratification and localized trough cross-stratification. This ichnofabric records high trace fossil diversity, with the presence of *Ophiomorpha, Phycosiphon, Piscichnus, Planolites, Rosselia, Schaubcylindrichnus, Scolicia, Thalassinoides* and vertical equilibrium adjustment structures.

*Ophiomorpha* ichnofabric. This ichnofabric is characterized by low trace fossil diversity with medium bioturbation abundance, comprising common *Ophiomorpha* and rare occurrences of middledeep tier *Macaronichnus*. Poorly sorted sandstones with no sedimentary structures are observed. *Ophiomorpha* ichnofabric is founded above storm bed deposits (mainly broken oysters) and coeval with broken pectinid shells, *Ditrupa* and patches of coralline algae.

Ophiomorpha-Schaubcylindrichnus ichnofabric documents a continuous high trace fossil diversity. This ichnofabric is related to stable paleoenvironmental conditions inside the prodelta (MacEachern *et al.*, 2005). Absence of trace fossils into the relatively thick storm-beds is interpreted as consequence of an extremely rapid deposition. After that, post-storm packages are rapidly dominated by the *Ophiomorpha* ichnofabric. Immediate record of *Ophiomorpha* after the storm event could indicate colonization by opportunistic tracemakers due to increase of suspended amount of organic matter after

the events. Predominance of deposit-feeders allows interpreting a mixed-influence delta; ichnological responses to river-induced stresses deltas, in general, appear to be marked by impoverishment of suspension-feeders (MacEachern *et al.*, 2005).

In conclusion, the integrative sedimentological and ichnological analysis conducted at the lower part of the Yehliu Sandstone Member allows interpreting conditions of mixed influence delta environment with fluvial control being less important.

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# Ichnofabric of the Buchava Formation (Cambrian, Biskoupky site, Skryje-Týřovice Basin, Czechia)

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The complex ichnologic research of the Buchava Formation (i.e., not only the list of ichnotaxa but also quantification of strongly bioturbated layers, tearing, etc.) has never be done. The locality Biskoupky (GPS: 49.879407N, 13.671244E) provides an extremely small tectonic scale with a minimum thickness of exposable strata. Nevertheless, in 2017, the layers, consisting of greywackes and siltstones and showing their rhythmical character of sedimentation, was exposed. Considering the finds of fossil traces in debris and the previous research (Mikuláš 2000), it can be concluded that the studied layers are very representative for the ichnology of the Buchava Fm., because they represent the frozen profile of ichnofabric.

The studied part of one layer of the sequence starts with a 7 cm thick layer, which is separated from the underlying siltstone by a smooth bedding plane. The greywacke shows in places oblique to herringbone lamination, which disappears upwards, partly to fully substituted by biogenic structures. The next 1 cm is intensively bioturbated (*Palaeophycus tubularis*, *Didymaulichnus* isp., *Diplocraterion* isp., *?Planolites* cf. P. *beverleyensis*); ichnofabric index after Droser and Bottjer = 3. Burrows of *Diplocraterion* and *Arenicolites* achieve the depth of 5 cm from the top of the layer. Also *Thalassinoides* isp. was found ca 5 cm above the base of the greywacke.

They overlying is lamina of greyish siltstone. Because of none lamination, it can be best interpreted as the completely bioturbated layer. Moreover, bioturbation is in some places discernible by reflection of mica scales, which may be either disordered or arranged during the penetration of an animal through the sediment. Following layer is characterised by well preserved, individually preserved *Teichichnus rectus* and *Palaeophycus tubularis*. The last lamina, rich in fragments of brachiopod *Bohemiella romingeri* and trilobite *Paradoxides* (*Eccaparadoxides*) pusillus, is sharply terminated by a layer of greywacke with flute marks and load casts.

Concerning the rather small number of ichnotaxa, we suppose the ichnoassemblage is poor mostly for taphonomic reasons. The whole spectrum lacks trace fossils preserved as convex hyporeliefs; if preserved, the strata would probably contain ichnofossils attributed to trilobites, i.e. ichnogenera Cruziana, Rusophycus, Monomorphichnus and few others. Regardless of the absence of the above-named ichnotaxa, the association can be best understood as impoverished Cruziana Ichnofacies, namely because of the relatively equal amount of horizontal and vertical trace fossils.



A, H, I – *Palaeophycus*; B – lamina with body fossils; C – *Teichichnus rectus*; D – overlying bed: flute cast; E – boundary of sparsely and intensively bioturbated layers; G, F, J – *Diplocraterion*; K, L – *Arenicolites*.


# Tectonically controlled ichnofabrics in the early to middle Miocene fore-arc basin fills of the Southwest Japan Arc

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During the early to middle Miocene, the Southwest Japan Arc, formerly attached to the eastern margin of the Eurasian Continent, rapidly rotated clockwise in accordance with spreading of its backarc, which now constitutes a marginal sea known as the Sea of Japan. The rate of the arc movement was significantly rapid; it was estimated to be at least 21 cm/year. To the south of the arc, another back-arc of the Izu-Bonin Arc, now called the Shikoku Basin, concomitantly spread. Then, the very young and hot oceanic plate of the Shikoku Basin started forced subduction underneath the SW Japan Arc. These tectonic events were also associated with, or followed by diverse volcanisms that formed various sorts of igneous rocks scattered in the "fore-arc" region. Although most of the sediments recording these "catastrophic events" have been removed due to uplifting of the entire arc since the late Miocene, early to middle Miocene sedimentary bodies are locally preserved. These sediments may allow estimating the influences of the extremely active tectonic events on ichnofabric developments.

The early to middle Miocene Misaki Group is a 3,000 meters thick, shallow-marine to non-marine succession, filling a fore-arc basin of the SW Japan Arc, and is characterized by low ichnodiversity and paucity of ichnofabrics across the entire basin. Such ichnological characteristics were ascribed to environmental stresses caused by over-sedimentation (highly frequent and rapid sedimentation), which was induced by sediment mass-production in the hinterland, as recorded in coeval, coarse-grained terrestrial deposits of the Kuma Group, located approximately 80 kilometers north (Nara & Aikou, 2016). Nara & Aikou (2016) considered that the main causal factor of the sediment mass-production was uplifting of the fore-arc land areas due to the forced subduction of the Shikoku Basin. If this interpretation is correct, other fore-arc basins should also show the similar characteristics of ichnofabrics.

Another time-equivalent fore-arc basin fill of the Tanabe Group located approximately 200 kilometers ENE of the Misaki Group is also characterized by less bioturbate sediments, comparing to "normal" ones deposited in more stable settings. However, in the Tanabe Group, intensely bioturbated beds are commonly seen, and unbioturbated or considerably less bioturbated sediments similar to those in the Misaki Group are not so common. Then, what made the differences between the Misaki and the Tanabe basins?

The Tanabe Group consists of up to 1,500 meters thick, shallow-marine to nonmarine sedimentary successions. Judging from the reconstructed palaeogeography of its hinterland, it is most likely that the hinterland of the Tanabe Basin was much smaller and less uplifted comparing to that of the Misaki Group.

In the case of the Misaki Basin, its sediment source (Kuma Group) was cut and/or overlain by igneous or pyroclastic rocks of the Ishizuchi Group, whose volcanism was chronologically overlapped with the deposition of the uppermost part of the Kuma Group. Moreover, the Kuma Group clearly shows several dome structures of which centers roughly correspond to large intrusive rock bodies or a sub-volcanic granitic pluton of the Ishizuchi Group. These suggest that sediment mass-production in the Misaki source areas was probably induced by considerable uplifting caused not only by the forced subduction but also by the Ishizuchi volcanisms.

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# Ichnofabrics and their role in the modification of petrophysical properties: the Ordovician Majiagou Formation, Northwest Henan Province, China

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The carbonate rocks of the Ordovician Majiagou Formation from the northwestern part of Henan Province and their diverse trace fossils provide an outcrop analogue for bioturbated, low permeability reservoirs. Three ichnofabrics can be defined according to their characteristic trace fossils and their individual abundances, diversities and overall bioturbation indices. The *Balanoglossites* ichnofabric indicates relatively high-energy sedimentary environments such as intertidal zone and subtidal shoals in the carbonate platform. The *Planolites* ichnofabric suggests relatively low-energy, protected sedimentary environments such as lagoons in a restricted carbonate platform but also occurs in sediments deposited in deeper-water depressions in the open carbonate platform. The *Chondrites* ichnofabric characterizes low-energy and reduced oxygen conditions, with burrows penetrating below a shallow redox interface in deeper-water settings that include the distal slope as well as local depressions in the open carbonate platform (Fig.1).

Our analysis suggests that the modifications of petrophysical parameters are controlled or influenced by the ichnofabric characteristics (burrow architecture, burrow incision relationship, bioturbation index and burrow connectivity), the permeability contrast between burrow-fills and matrix, and the dolomitization of burrow-fills. The micritic host sediments have negligible porosity and permeability. The bioturbated sediments have significant differences in fabric, texture, porosity and permeability. The burrow-fills are very commonly dolomitised. Each of the burrow-types can enhance reservoir properties, but the greatest differences are associated with the *Balanoglossites* ichnofabric, in which porosity and permeability can reach over 2% and 70 mD. Preliminary stratigraphic studies indicate that reservoir potential in the subsurface could be linked to an understanding of the distribution of shoal and intertidal facies as well as their associated *Balanoglossites* ichnofabrics.

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				1	r		1		
Degree of Bioturbation			1		1				
Ichnodiversity									
,			[	1					
		Restricted Platf	orm Facies			Open I	Platform Facies		
	Supratidal	Intertidal zone	Lagoon	Shoal	Inter-shoal	Shoal	Depression	Slope	
	20110	7/ - 7							_ MHWST - Sea Level
				107					MLWST
				(1)		Ais			Storm Wave Base
				4		TI		11111	REDOX Interface
Ichnofabric		А	В	А	В	А	B-C	С	
Depth	Near 1	he mean sealevel	<10m	<10m	>50m	10-50m	>50m	50-200m	A-Bal Ichnofabric
Energy	Low-High		Low-Medium	High	Low-Medium	Medium	Low	Low	B-Pla Johnofabrie
Salinity	High		Higher	High	Normal	Normal	Normal	Normal	B The tennorablic
Color	Light Grey, Grey		Grey Brown grey	Grey	Grey-Dark Grey	Grey	Dark Grey	Grey-Dark Grey	C-Cho Ichnofabric
Lithology	Dolomite, Muddy Dolomite Dolomitic limestone, Stromatolite Calcarcous dolomite		Dolomitic limestone Calcareous dolomite, Micrite	Bioclast limestone Calcarenite	Bioclast- limestone Micrite	Bioclast limestone Calcarenite	Bioclast-limestone Micrite	Micrite	
Texture	Mudstone& Wackstone		Wackstone	Grain- stone	Wackstone& Packstone	Pack- stone	Mudstone&Wackstone	Mudstone	
Sedimentary Structure	Stromatolite, Bird-eye structure Horizontal bedding, Gypsum pseudomorphs		Horizontal bedding Ripple marks	Massive bedding	Horizontal bedding	Massive bedding	Horizontalbedding	Massive bedding	
Body fossil		6 mm	-860	68	⊂®ª**	B	A080	$\stackrel{\wedge}{\to} \bigtriangledown \overset{\circ}{\multimap} \overset{\circ}{\multimap}$	
Ichnofossil		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~		No.	Se or	N.	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	Solution of the second	
Legend				1 1 1 1					
Trace fossil									
	В	alanoglossites Helminth	opsis Gordia	C	nondrites Rhizo	coralium	Planoittes Palaeoph	ycus	
Dodu for		my 🗸			Q	$\odot$	☆ &	)	
BODY TOS	511 (	Conodonts Ostraco	ds Armenoceras	Br	achiopods	Encrinite	Echinoderms Gastr	opods	

Fig. 1. Schematic diagram showing relationships between the ichnofabrics and sedimentary facies (Modified from Ye, 1983; Feng *et al.*, 1990). The *Balanoglossites* ichnofabric indicates high-energy sedimentary environments such as intertidal zones and subtidal shoals in the carbonate platform. The *Planolites* ichnofabric suggests relatively low energy, protected sedimentary environments such as lagoons in the restricted carbonate platform but also occurs in sediments deposited in deeper water depressions in the open carbonate platform. The *Chondrites* ichnofabric characterizes low energy and reduced oxygen conditions with burrows penetrating below a shallow REDOX interface (low oxygen levels) in deeper water settings that include the distal slope as well as local depressions in the open carbonate platform.

## Vertebrate ichnofabrics resulting from a multi-episodic reptile-track level

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Vertebrate tracks are very common along the "Dinosaur Coast" in the Upper Jurassic rocks of Asturias (N Spain). They belong to dinosaurs, pterosaurs, crocodiles, turtles and lizards and the most part of them are preserved as sandstone casts (García-Ramos *et al.*, 2006).

The studied slab (from Villaverde sea cliffs, Villaviciosa) is housed at the Jurassic Museum of Asturias (MUJA) and belong to the Lastres Formation, a fluvial-dominated deltaic system of Kimmeridgian age. Wave ripples, two isolated dinosaur footprints and two trackways belonging to pterosaur and crocodile are preserved as convex hyporeliefs on the sandstone bed (Piñuela *et al.*, 2013; Piñuela Suárez, 2016).

#### Pterosaur trackway MUJA-3990-a (Fig 1A, B)

The trackway consists of ten prints (five manus and five pes). Pes prints are triangular in shape, plantigrade, tetradactyl, symmetric and elongated. The mean length of the pes is 2,5cm. Manus prints are digitigrade, tridactyl, strongly asymmetric and elongated. The mean length of the manus is 2,4cm. The trackway belongs to a very small pterosaur with an estimated wingspan of 45-50cm and was assigned to *Pteraichnus*.

#### Crocodile trackway MUJA-3990-b (Fig 1A, B)

The trackway comprises four prints (two manus and two pes) belonging to a very small crocodile. Pes prints are digitigrade and tridactyl. The mean length of the pes is 2,6cm. Manus prints are digitigrades and pentactyls. The mean length of the manus is 1,6cm. The trackway is attributed to *Batrachopus* sp.

# Small dinosaur track MUJA-3990-c (Fig 1A, B)

The footprint is 19cm long, tridactyl and asymmetric. The claw impressions and the orientation of the claw in digit III indicate that print was produced by the left foot of a small theropod. The digit divarication angle is relatively high ( $57^{\circ}$ ). The anterior margin is deeper than the posterior one. Even though this print is preserved as the cast of a shallow undertrack reflects enough anatomical details to assign it to *Grallator*.

#### Diminutive dinosaur track MUJA-3990-d (Fig 1A, B)

The footprint is 6cm long, tridactyl and asymmetric. The claw impressions in the digit IV and the presence of a postero-medial indentation behind the digit II indicate that print was produced by the left foot of a very small theropod. The divarication angle is low (23°). The specimen was assigned to *Grallator*.

#### Understanding the formation of the tracked level (Fig 1C)

Symmetric wave ripples with slightly sinuous and sometimes discontinuous crests and troughs 3cm wide indicate very shallow water. There is no evidence to think the pterosaur tracks were produced under water and taking into account the very small size of the maker, probably the trackway was produced under subaerial conditions, after the ripple formation.

The slab preserves, therefore, a "multi-episodic track level" a variety of ichnofabric represented by a stratigraphic horizon where a set of diverse vertebrate tracks (in this case reptiles) is recorded. The prints were produced also in several stages and usually on substrates with different consistency. The succession of events which produced this "multi-episodic track level" are the following:

1. Very shallow-water sand deposition in an environment affected by small wave ripples.

2. Accumulation of calcareous muds above the sandy level with wave ripples.

3. The semi-consolidated lower part of the muddy substrate (firmground) was exhumed, just above of the ripple crests, as a result of partial erosion by water flows.

4. Formation of pterosaur and crocodile trackways as well as the very small theropod footprint on the muddy firmground.

5. A new sandy deposit (second) filled the pterosaur, crocodile and diminutive theropod tracks.

6. Impression of a small theropod footprint on the new sand level, going through all previous sediments.

7. A third sandy deposit filled the last print produced by the small theropod.

8. Diagenetic process (differential compaction) at the expense of the more compressible marly mudstone deposit.

9. A recent breakup of the sandstone slab took place along the most weakness plane, located in the softer thin and discontinuous marly mudstone remains filling the ripple troughs.



Fig. 1A, B. Sandstone block with the tracks. C. Succession of events which produced this "multi-episodic reptile-tracked level". Black and red arrows indicate the progression of pterosaur and crocodile specimens, respectively.

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# The macrobenthic response after the K/Pg mass extinction event: An ichnofabric approach

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The end-Cretaceous (K/Pg) mass extinction, 66.0 Ma ago, is one of the most phenomenal events in the history of Phanerozoic life, eradicating 76% of species on Earth, being essential for the subsequent evolutionary and ecological history of the continental and marine biota (Schulte *et al.*, 2010). This extinction was caused by the impact of an asteroid on the Yucatán carbonate platform in the southern Gulf of Mexico which formed the Chicxulub impact crater. Ichnological analysis have revealed the lower incidence of the impact event on the macrobenthic tracemaker community, at least in distal K/Pg boundary sections, showing minor disruption, colonization of highly contaminated substrates represented by the ejecta layer and the initial rapid recovery (Rodríguez-Tovar & Uchman, 2004, 2006, 2008; Rodríguez-Tovar, 2005; Labandeira *et al.*, 2016). In this context of the particular response of the macrobenthic tracemaker community, no studies have been conducted to investigate the evoluting diversity of this community after the the K/Pg boundary event, at the Early Palaeocene. Now we have the opportunity to study a continuous, extended record, of post-impact sediments of the recovered core from the drilled Site M0077 into the peak ring of the Chicxulub impact crater, conducted by the IODP/ICDP Expedition 364 (Morgan *et al.*, 2016, 2017).

Ichnological analyses on distal marine K/Pg boundary sections revealed a relatively diverse ichnoassemblage mainly composed of Chondrites, Zoophycos, Planolites, Thalassinoides, with frequent Alcyonidiopsis and Trichichnus, registered in post-impact sediments just above the K/Pg boundary ejecta layer, characterizing a well-developed multi-tiered trace fossil assemblage ascribed to the Zoophycos ichnofacies (Labandeira et al., 2016 and references therein). The minor incidence of the K/Pg boundary impact to the macrobenthic tracemaker community and the initial rapid recovery, have been also recently tested in the impact area "Ground Zero". Research revealed that appearance of life in the Chicxulub crater was very fast, within years of the impact, being the proximity to the impact of minor incidence on recovery in marine ecosystems (Lowery et al., 2018). Discrete trace fossils, including *Planolites* and *Chondrites*, characterize the upper 20 cm of the transitional unit, and then, at the base of the overlying limestone, trace fossil increase in diversity, including the first appearance of Palaeophycus, indicating an initial rapid recovery and the establishment of a macrobenthic tracemaker community at ~30 kyr after the impact. However, is very significant the absence of Zoophycos during the first 30 kyr of the initial recovery at the "Ground Zero", revealing that the full reestablishement of the community was not completed. On this base, we conduct a detailed ichnofabric analysis of postimpact Paleoecene sediments in order to approach the evolution of ichnodiversity from the initial recovery phase, to establish variation in the macrobenthic tracemaker community and the time for the reestablishment of the assemblage typical of the Zoophycos ichnofacies.

After the K/Pg impact event in the "Ground Zero", we recognize different phases in the evolutionary pattern of the macrobenthic tracemaker community, allowing characterization of the pace of recovery. As interpreted previously, a rapid initial recovery is observed at around the first 30 kyr from the K/Pg boundary impact event, starting with the only record of scarce, small, *Planolites*, but showing a first phase of increase in diversity (diversification I), abundance and size of burrows at around 30 kyrs, allowing development of a well-established tracemaker community consisting of *Planolites*,

*Chondrites* and *Palaeophycus* tracemakers, as well as a shallow undetermined infauna revealed by the mottled background. Tiering structure is dominated by shallow and middle tiers.

Following this phase, we found a long period of stabilization of this community, consisting of *Planolites*, *Chondrites* and *Palaeophycus*, accompanied by an increase in the bioturbation index from low (1-2) to moderate/high (4), as well as a generalized mottled background. This phase is maintained up to around 620 kyr, evidencing a time of favorable paleoenvironmental conditions. Minor fluctuations in environmental parameters, as oxygen and nutrient availability, can determine the changes in the relative abundance between tracemaker (*Planolites* vs *Chondrites* as the dominant trace). Increase along time in the abundance and size of traces, reveals the progressive rebuilding of a stable community structure.

After this prolonged phase of stabilization, a new phase of diversification (diversification II), is interpreted by the sudden appearance of *Zoophycos*. Macrobenthic tracemaker community, consisting of *Zoophycos, Chondrites Planolites*, and *Palaeophycus* tracemakers, shows the highest values in diversity, abundance and size of traces. This tracemaker community is maintained at least to the top of the studied interval, around 1,075 kyr, with dominance of *Zoophycos* producer. At this time, the full recovery is accomplished; a well-developed multi-tiered macrobenthic community was established from shallow, middle and upper tiers, revealing generalized favorable paleoenvironmental conditions from sea-floor to deeper into the sediment.

Thus, a progressive rebuilding of a stable, consolidated, macrobenthic community structure is interpreted from the K/Pg impact event to around 1,075 kyr, characterizing the *Zoophycos* ichnofacies.

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# Improving characterization of composite ichnofabrics by image processing techniques

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Composite ichnofabrics (Ekdale & Bromley, 1983; Bromley & Ekdale, 1986) refer to those ichnofabrics generated by the superimposition of different (successive) suites of biogenic structures (Ekdale *et al.*, 2012). The development of composite ichnofabrics (Ekdale & Bromley, 1983) may reveal the progressive upward migration of a single, tiered benthic community during continuous sediment accretion, or the successive occupation of the sediment by multiple communities of organisms in response to autogenic or allogenic changes in environmental conditions within a depositional system. Accordingly, Savrda (2016) defined two main types of composite ichnofabrics: autocomposite ichnofabrics in reference to the first mechanism, characterized by a single ichnocoenosis, and self-generated by a particular assemblage of tracemakers; and heterocomposite ichnofabrics produced by the second mechanism, comprising two or more different ichnocoenoses. The analysis of composite ichnofabrics, especially of autocomposite ichnofabrics, is no easy matter given the complexity of the multi-tiered macrobenthic tracemaker community, with continuous burrowing during sediment accretion (Ekdale & Bromley, 1991).

In the last years, digital image treatment revealed as a novel method for improving ichnofabric analysis allowing to differentiate between biodeformational structures and trace fossils, meaning better identification and discrimination of ichnotaxa, observation of cross-cutting relationships, quantitative estimation of the percentage of bioturbation, as well as enhanced evaluation of the depth of penetration of a particular tracemaker and an approach to the tiering structure (Dorador & Rodríguez-Tovar, 2014, 2016, 2018; Rodríguez-Tovar & Dorador, 2015). In spite of the probed usefulness of the high resolution images treatment in ichnofabric analysis, it can take too much time; thus in order to find a faster technique, we checked two image processing techniques, including the *Analyze Particles* tool offered by Fiji software and the *Intensity Profile* by ICY (IP-ICY).

*Analyze Particles* allows for the quantification of shape (roundness) and size of structures. Its application to the analysis of *Chondrites* assemblages in composite ichnofabrics from selected images of modern marine hemipelagic cores obtained at Site U1385 of IODP Expedition 339 reveals differences in size, relative abundance, density and distribution (Case 1). Large *Chondrites* (3-8 mm<sup>2</sup> in area) show a higher abundance and more or less homogeneous distribution in the studied core section, while small *Chondrites* (0.5-3 mm<sup>2</sup> in area) are less abundant and distributed in patches. Variations in size could be related to ontogenetic changes in the population or to different tracemakers. Larger *Chondrites* are dominant in number and occupation, possibly reflecting dominance of older (larger) tracemakers and thus a madurate population. The patchy distribution of smaller (younger, infant, juveniles) tracemakers could be related with more gregarious behavior. The concentration in patches might also reflect an opportunistic (r-selected strategy) character of the smaller forms linked to local concentration of organic matter.

Intensity Profile provides quantification of the intensity pixel values of the infilling material of traces, an aid to discriminate between specimens, evaluate the horizon of colonization, and appraise

penetration depth. The first outcrop application of this method is for the analysis of *Zoophycos* in composite ichnofabrics from deep-sea pelagic calcilutites of the Petra Tou Romiou section (Eocene Lefkara Formation; southern Cyprus). In the cases studied here (Cases 2a, b, 3), analysis of intensity pixel values could serve to identify different specimens of *Zoophycos* and several phases of colonization. Thus, in Case 2a, different pixel values are associated with more than one *Zoophycos* structure produced at different moments and in several colonization horizons during sediment accretion, as revealed by pixel values similar to those corresponding to the upper part of the greenish/whitish calcilutites and to the upper greenish calcilutite. In Case 2b, several structures of *Zoophycos* show similar intensity pixel values that can be associated with a single horizon of colonization within the upper greenish calcilutite, and could correspond to one specimen or to several ones. Especially interesting in Case 2b is the record of similar values in cross-cutting structures, suggesting different specimens produced from the same horizon of colonization (coetaneous?). In Case 3, the presence of several structures of *Zoophycos* with different intensity pixel values is illustrated, interpreted as several phases of colonization and diverse suites of *Zoophycos*.

Thus *Analyze Particles* offered by Fiji software and *Intensity Profile* by ICY (IP-ICY), are shown to be highly useful for enhanced characterization of autocomposite ichnofabrics in core and outcrops respectively. Both tools allow ichnological features to be quantified, supporting a more objective analysis than those based on semi-quantitative approaches.

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# Characteristics of ichnoassemblages and relationships with paleo-oxygenation facies of the Taiyuan Formation, western North China

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The relationships between the ichnofossil assemblages and paleo-oxygenation conditions of the Permian Taiyuan Formation in western North China have not been extensively studied. Thus, by researching the ichnofossils and ichnoassemblages, this work probed the paleo-oxygenation facies and the sedimentary environments of carbonates in the formation. This study involved a detailed investigation of the ichnofossils from four sections of the Taiyuan Formation in western North China (Jiaozuo and Yuzhou sections in Henan, and Fucheng and Taiyuan Xishan sections in Shanxi), and also tested and analyzed the iron components and trace elements of differently colored fillings in the Zoophycos burrows and their host rocks. Based on the composition, occurrence, and distribution of ichnofossils and the sedimentary characteristics of their host rocks, combined with analysis results of the iron components and redox-sensitive trace elements in the burrow fillings of Zoophycos, the following four types of ichnofossil assemblages with different paleo-oxygenation facies were identified (Fig.1): Type A, Zoophycos-Planolites ichnoassemblage, includes fodinichnia and pascichnia as Planolites, Gordia, Dichasialichnus and Zoophycos with red burrow filling, which is thought to have been produced in an oxygen-poor (dysaerobic) sedimentary environment at the bottom of a bay lagoon; Type B, Zoophycos-Skolithos ichnoassemblage, is dominated by domichnia and fodinichnia, such as Skolithos, Ophiomorpha, Thalassinoides, Taenidium, Rhizocorallium, Planolites and Zoophycos with grayish-white burrow filling, which was interpreted to have formed in a normoxic (aerobic) sedimentary environment in an upper shallow sea or bay lagoon; Type C, Zoophycos-Helminthopsis ichnoassemblage, consists mostly of fodinichnia in substrata with minimal pascichnia on the bedding plane, where spotted bioturbation is common. The most common ichnofossils in this assemblage include Rhizocorallium, Palaeophycus, Planolites, Teichichnus, Helminthopsis, Taenidium, and Zoophycos with gray burrow filling, suggested to have been generated in a suboxic (subaerobic) environment in the middle of a shallow sea; and Type D, the Nereites-Chondrites ichnoassemblage, consists mainly of fodinichnia in substrate, including ichnofossils such as Planolites, Nereites, Chondrites, and Zoophycos with black burrow filling, which was considered to have formed in an anoxic (anaerobic) environment in the lower part of a shallow sea.

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Ne- Nereites; Ch- Chondrites; Te- Teichichnus; Ta- Taenidum; Bi- Bioturbation structure; Rh- Rhizocorallium; Th- Thalassinoides; G- Gordia; Di-Dichasialichnus; Pl- Planolites; Pa- Palaeophycus; Sk- Skolithos; Z- Zoophycos

Fig. 1. Sedimentary environment and palaeo-oxygenation facies model of the ichnoassemblages in the Taiyuan Formation in western North China.

#### Ichnofabric changes in Polish Muschelkalk (Middle Triassic)

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The Polish Muschelkalk is characterized by a high bioturbation degree but an overall low ichnodiversity. Twenty ichnogenera have been recognized in the Polish Muschelkalk (Szulc, 2000; Kowal-Linka & Bodzioch, 2001; recent study) and about 26 ichnogenera have been described from the German Muschelkalk (Knaust, 2007). However, only several ichnotaxa are responsible for pervasive bioturbation and produced their own ichnofabrics; the other ichnotaxa occur as isolated specimens or in a few stratigraphic levels. It is noteworthy that the ichnological record of the Muschelkalk is one of the earliest records of activity of benthos after the P/T mass extinction. The relatively poor diversity of the trace fossils probably resulted from a slow recovery after the crisis.

Several different ichnofacies can be distinguished in the Polish Muschelkalk, each having specific sedimentary features, characteristic trace fossils, and ichnofabrics. This variability is mostly caused by third-order eustatic changes which are well recognized (Szulc, 2000). We focus mostly on micritic and marly limestones and the associated bioclastic coquinas and shoal sand facies, which collectively form so-called Wellenkalk (German synonym of wavy limestone).

Nearshore facies, typical of the earliest transgression phases (basal Lower and Upper Gogolin Beds), comprise large-scale cross-bedded calcarenites and the interbedded thin micritic limestones, which correspond to the Skolithos ichnofacies (sensu Seilacher, 1967). High-energy sand facies are generally devoid of trace fossils (local Arenicolites), while the micrite intercalations may contain Rhizocorallium. Progressing transgressions are recorded as marls, micritic limestones, and storm-deposited calcarenites, which are usually strongly bioturbated and contain numerous, but poorly diversified trace fossils of the Cruziana ichnofacies (Seilacher, 1967). These facies volumetrically dominate the Lower and Upper Gogolin Beds, Terebratula Beds, and Wilkowice Beds, representing four different transgressive pulses. Although the facies are basically the same in the four units, the bioturbation style and ichnofabrics are different. The Lower Gogolin Beds are dominated by Rhizocorallium ichnofabric which is locally replaced by Planolites, Oravaichnium, or mixed Oravaichnium-Rhizocorallium ichnofabrics. The dominant ichnofabric can be manifested in different ways because its index trace fossil occurs in many taphonomical variants reflecting different behaviours of polychaetes (cf. Knaust, 2013). In most cases, both the ichnofabric and burrows on bed surfaces are represented by R. commune var. irregulare (sensu Knaust, 2013). Most traces have an active fill of coprolites within the marginal channel and spreite. The coprolites, up to 2 mm long can be classified as Coprulus oblungus. Some Rhizocorallium have scratch traces, which indicates local induration of the sea bottom. A less abundant variant of *Rhizocorallium* ichnofabric is that formed by vertical, retrusive spreite of *R. commune problematica*. According to Kowal-Linka & Bodzioch (2010), the retrusive forms are fugichnia of rapidly buried organisms. Such structures co-occur together with typical protrusive forms and usually have an accumulation of calcite pseudomorphs after sulfates often accompanied by pyrite framboids. Bodzioch & Kowal-Linka (2001) have interpreted these aggregates to have resulted from the crystallization of primary sulfate minerals in aerobic conditions due to bacterial decomposition of buried animal tissues, followed by the replacement of sulfate by calcite in oxygen-depleted conditions due to activity of desulfurizing bacteria. Least frequently, Rhizocorallium ichnofabric is manifested as more or less regular spots with sharp or diffuse boundaries and a local centimeter-scale halo.

The Wellenkalk of the Upper Gogolin Beds, despite the same lithofacies composition as in their

lower part, exhibits a different bioturbation style and is dominated by *Oravaichnium* ichnofabric with various bivalve traces: *Ptychoplasma*, *Lockeia* and *Protovirgularia*. *Rhizocorallium* ichnofabric is still present, especially in the eastern part of the area. Both ichnofabrics include sporadic *Thalassinoides*, *Planolites*, and *Palaeophycus*. A characteristic feature of the Upper Gogolin Beds is several hardground levels recording ceased sedimentation. They are indicative of the *Trypanites* ichnofacies (Frey & Seilacher, 1980). The studied hardgrounds are marked by encrustations of bivalve *Placunopsis* and borings *Trypanites*. They are developed on an irregular top surface of micritic limestones or flat pebbles eroded from the early-lithified substrate.

In the eastern basin part, the Gogolin Beds are overlain by the **Olkusz Beds** which in the lower half comprise medium-bedded micritic limestones with firmground omission surfaces, belonging to the *Glossifungites* ichnofacies. The firmgrounds abound in *Balanoglossites* burrows, defining its ichnofabric. Like *Rhizocorallium*, the burrows are produced by polychaetes but in a firm substrate.

The Wellenkalk of the **Terebratula Beds** has a very similar facies composition as the Gogolin Beds, but much of the succession displays a different bioturbation style. The 2.5-m-thick basal package of thin-layered micrites is generally devoid of trace fossils, with only local mass occurrence of *Oravaichnium* and its ichnofabric. This *Oravaichnium* ichnofabric is difficult to identify in vertical cuts because individual traces occur as vague spots of semi-rectangular, amygdaloid or semi-circular shape. Some of them represent other bivalve trace fossils, mostly *Lockeia*. In contrast to this basal package, the remaining part of the Terebratula Beds is dominated by nodular limestones with *Thalassinoides* ichnofabric, while *Oravaichnium* and *Rhizocorallium* ichnofabrics have only a minor contribution.

To sum up, a general distribution of ichnofabrics in the Muschelkalk is controlled by lithology and environment, with Skolithos and Arenicolites ichnofabrics being associated with high-energy shoal calcarenites and other ichnofabrics occurring in deep-platform micrites and tempestites. This fits well to the zonation proposed for siliciclastic deposits by Seilacher (1967), corresponding to his Skolithos ichnofacies and Cruziana ichnofacies, respectively. Within the Cruziana ichnofacies, development of ichnofabrics was further controlled by substrate consistency, with borings and encrustations forming in the cemented sea floor, Balanoglossites ichnofabric developing in firm substrates, and Rhizocorallium, Oravaichnium, Thalassinoides, and other rare ichnofabrics being confined to unconsolidated sediments. The soft-sediment ichnofabrics additionally display a stratigraphic trend in the abundance. The Lower Gogolin Beds (earliest Muschelkalk transgression) are dominated by Rhizocorallium ichnofabric produced by polychaetes. The Upper Gogolin Beds (the second transgressive pulse) are occupied mainly by Oravaichnium ichnofabric produced by bivalves. The Terebratula Beds (the third transgressive pulse) are typified by *Thalassinoides* ichnofabric formed by crustaceans. This succession seems to reflect a gradual recovery of benthic communities after the P/Tr extinction. Polychaetes appeared first, which probably resulted from their good adaptation to different substrates, as their traces can be found in carbonate sands (Skolithos, Arenicolites ichnofabric), soft muds (Rhizocorallium ichnofabric), and firm muds (Balanoglossites ichnofabric) of the Muschelkalk. During the subsequent transgressions, the niches were largely taken over by bivalves and later on by deep-penetrating crustaceans. In most cases, the bioturbation is produced by monoichnotaxonomic assemblages and tiering is difficult to observe.

#### Acknowledgements

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## Ichnofabrics in Holocene inland dunes of SE Poland

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Post-glacial, stabilized, early Holocene inland sand dunes (a part of the European Sand Belt) in the Sandomierz Basin, SE Poland (50°–51° N) are bioturbated below the recent soil (usually forested or covered by pasture vegetation) or below buried soils. The bioturbated zone is 1.5–2.2 m thick. Its upper portion (about 0.3–0.9 m thick) shows total bioturbation, where the primary sedimentary structures are completely altered. It was reworked by different animals, mostly insects (e.g., hymenopteran solitary bees and wasps, ants, antlion larvae, beetles, e.g. tiger beetles of the subfamily Cicindelinae), oligochaetes (earth worms) and mammals (e.g. by the European mole *Talpa europaea* in more organic-reach places, and by fox on the slopes). The sediment is also disturbed by roots of trees and other vascular plants. The earth worm burrows (usually 2–4 mm wide) are associated burrows of the European mole (branched, 40–60 mm wide). Usually, they are well visible in the subsoil below thicker organic rich soils, mostly in the lower dune slopes and in the interdune areas.

The totally bioturbated zone passes downward through a partly bioturbated zone (0.8–1.3 m thick) and to a non-bioturbated zone with well visible lamination. In the partly bioturbated zone, primary lamination is cross cut by mostly vertical/subvertical meniscate burrows, which can be ascribed to *Taenidium, Entradaichnus* or *Naktodemasis* (irrespective of their ichnotaxonomic problems). They are 5–20 mm thick and can be traced at a distance of several tens of centimetres. Their menisci are usually concave down. The burrows can be concentrated in wedge zones which have been formed after decomposition of thick tree roots ("ghosts of roots), or they can follow thinner roots. Recent pine roots may extend a few metres down from the surface. The roots can follow disturbances after old frost wedges. The lower boundary of the totally bioturbated zone is uneven. Commonly, it deflects down around thicker, bioturbated wedges which are "ghosts" after tree roots

The meniscate burrows are produced by insects and their larvae. They fed on organic matter and died or living roots. In the totally bioturbated zone, the burrows are differently oriented. In the deeper zone, they follow thin roots, more or less vertically. They are interpreted as burrows of insects which overwinter below the level of frost (usually 1 m). The concavity of the menisci shows that they returned to surface or subsurface along the same path. Probably, the way up was easier along the already used burrow. Stabilized sand dunes seem to be a good place to overwinter, because they are well drained, with very low probability of flooding, well aerated, and with deep roots, which are the basis of the trophic chain.

In non-ploughed areas, the transition between topsoil and the burrowed subsoil is gradual. In the ploughed fields, even if the field was abandoned by tens of years, contact between the topsoil and the subsoil is sharp. In both cases, burrows filled with the topsoil dark particles are well contrasted with the lighter subsoil sediments. In some burrows, sediment from the subsoil is introduced into the topsoil. Visibility of burrows in the totally bioturbated zone can be low in so that the sand seems to be massive. Their visibility depends on moisture and light. Usually, the ichnofabric is less visible in dry sand. In some places, the visibility of burrows is enhanced by mineralization, mainly ferruginization. Locally, ferricretes are present. Shallowly buried soils can be burrowed from recent soils.

Investigations in old sand pits vegetated and abandoned since a few tens of years show much thinner and less developed ichnofabric below the exploitation surface. This shows that the thick ichnofabrics observed below natural surfaces/soils developed rather during hundreds of years.

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# Ichnofabrics of upper Sinemurian – lower Pliensbachian deposits in the Cardigan Bay Basin (western England) in the Mochras borehole core

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A 163 m-thick portion of the Mochras borehole core is occupied by the upper Sinemurian – lower Pliensbachian fossiliferous (ammonites, bivalves), calcareous and marly mudstones/siltstones. They are totally bioturbated except for single, thin horizons where remnants of primary lamination are preserved. The dominant trace fossil is *Phycosiphon incertum* (four morphotypes). Less common but frequent are *Thalassinoides, Schaubcylindrichnus* (mostly single tubes, former "*Terebellina*", *Teichichnus*, and *Zoophycos.* Other trace fossils (*Planolites, Arenicolites, Trichichnus, ?Polykladichnus, Skolithos, Siphonichnus, ?Phymatoderma, ?Rhizocorallium, ?Asterosoma*, undetermined branched tubes) are rare.

The trace fossil assemblage fits to the *Zoophycos* ichnofacies, with some elements of the *Cruziana/Skolithos* ichnofacies. The upper bathyal depths are inferred for these deposits and the ichnofacies confirms this approach. The nearly continuous bioturbation, with the dominance of *Phycosiphon*, which trace maker used oxygen from pore waters suggests generally good oxygenation of the sea floor. Most of the horizons showing remnants of the primary lamination are referred rather to increased deposition by weak bottom currents than to anoxia. The *Phycosiphon* trace makers record quick opportunistic colonization after deposition of turbiditic muds (Wetzel & Uchman, 2001). The same effect can be in other muddy deposits which are quickly deposited in well oxygenated environment, as in the interval studied, where the rate of accumulation was very high (mean 4.8 cm/ky). Similarly, abundant and morphologically diverse *Phycosiphon* is present in Eocene prodelta mudstones in Spitsbergen (Rodríguez-Tovar *et al.*, 2014). The absence of *Chondrites* is striking. It seems that its trace maker requires more stable depositional conditions, with the lower rate of accumulation. The presence of ammonites excludes abnormal salinity.

Occurrences of trace fossils fluctuate rhythmically. *Phycosiphon, Thalassinoides* and "*Terebellina*" have been subjected to analysis of periodicity in discrete time series. The spectral analysis based on the Walsh transform (module of Past 3.2 software; Hammer *et al.*, 2001) is considered as the most suitable method of finding periodicities within the discrete time series (Weedon, 1989; Negi *et al.*, 1993; Weedon, 2003). Ranges of trace fossils within the jamesoni Zone have been manually digitized with an even step of 10 cm, starting from the base of the Pliensbachian. Resultant time series have been analyzed as a whole and in halves, in order to find an optimal balance between the signal-to-noise ratio and the spectral resolution. In order to convert the depth ranges to time ranges, an average sedimentation rate of 4.8 cm/ky has been used.

The spectral analysis has revealed the presence of periodicities within the time series, well matching the periods of the Milankovitch cycles (de Boer & Smith, 2009). An effect of the orbital forcing is most notable within the upper halves of the logs, distinguished by more dense distribution of ichnofossils. Each of generated power spectra has revealed exceptionally significant peaks near the sequency value of 0.5 cycles/m, clearly corresponding to the 41 ka obliquity cycles. Peaks representing sequency values between 0.85–1.15 cycles/m, also present in all spectra, apparently correspond to the 18–23 ka precession cycles. Additionally, there is a periodicity of 0.7 cycles/m (circa 29 ka), which probably lies

in the obliquity bands (Tiwari, 1987). Time series based on the *Phycosiphon* morphotype 3 and "*Terebellina*" show significant peaks near the sequency values of 0.32–0.36 cycles/m. These may be interpreted as the combined effect of obliquity and precession, resulting in 59–63 ka cycles (Tiwari, 1987). The lowest frequency cyclic components appear as the most prominent peaks within whole spectra, apparently corresponding to 112 ka and 415 ka eccentricity cycles (Berger, 1977; Negi, 1993). All listed peaks are present in the power spectrum of time series based on the *Phycosiphon* morphotype 3, serving as a representative example (Fig. 1).

The cyclicity correlates with cyclicity based on  $CaCO_3$  and detrital minerals content elaborated by Ruhl *et al.* (2016). The results present in this abstract shows that analysis based on the distribution of trace fossils also allows recognition of the Milankovitch cyclicity even with larger accuracy.



Fig. 1. The Walsh power spectrum of time series based on the *Phycosiphon* morphotype 3. appearances within the upper half of the jamesoni Zone.

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# Cutting-edge technology: Burrows lined with sponge bioclasts from the Upper Cretaceous of Denmark

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Adding material to a burrow's wall to create a lining is common in many domichnia and some fodinichnia. This material may consist of mucus, silk, sediment particles, plant debris, bioclasts, or components shaped by the tracemaker itself, such as nodules. Linings are usually applied to a burrow's wall to prevent collapse of soft sediment, to optimise burrow irrigation by sealing off permeability to the surrounding sediment, or even for insulation (e.g., grass and moss linings in lemming burrows). Many of these linings allow microbial growth that may be exploited as a food source, marking transitions from domichnia or fodinichnia to agrichnia. Especially in long-lasting structures, tracemakers expend much time, not only collecting suitable materials, but also shaping and assembling them.

From three different locations spread across Denmark we report a new kind of burrow lined with bioclasts. All specimens are completely lined with cuboids, probably from hexactinellids or other sponges with siliceous sclerites. These cuboids have a uniform shape and size, suggesting active shaping of the material by the tracemaker. A relatively long-bodied, lobster-like tracemaker is therefore inferred.

The use of bioclasts in linings is uncommon compared to mucus-bound sediment (e.g. nodules in *Ophiomorpha*). In our case, the observed linings are composed of densely packed bioclasts and therefore must have been constructed in the softgrounds of the Danish Chalk to prevent the burrows from collapsing. Body fossils of organisms adapted to softgrounds dominate the Danish Chalk, but most preserved trace fossils were constructed in firmgrounds. This preservational contradiction is explained by the erasure of shallow tiers by deep-tier bioturbators. Such replacement of ichnofabrics is common where sediment accumulation is slow and continuous. Our reported sponge-lined burrows were clearly made in softgrounds based on their thick linings; they must have been excavated in less cohesive chalk than that of the more commonly preserved deep-tier burrows like *Zoophycos* and *Thalassinoides*. All investigated specimens derive from localities rich in Porifera, though only one locality allowed for observation of specimens in their sedimentological context. Here, they mainly occurred in a possible patch reef that probably shielded against deep-tier colonisation. Hence, the usual reworking of shallow-tier burrows by deep-tier bioturbation (e.g. *Zoophycos*) was prevented.

Owing to the softness of the Danish Chalk only short segments of the burrows could be recovered. However, branching in some of the collected material suggests a burrow system similar to that of *Ophiomorpha*. Most investigated specimens are horizontal; a few exhibit short (sub)vertical sections penetrating only a few centimetres deep into the sediment. All recovered specimens are predominantly straight; sharp horizontal bends (~90°) usually occur near the subvertical segments. Most burrows collapsed during early diagenesis; a few show passive fill and are only slightly compacted.

Although we know of no directly analogous modern behaviour, a partial analogy exists in the dromiids (sponge crabs), which cut sponges into living cases to cover their carapaces. Using specialized fourth and fifth appendages, the crabs hold the sponges as camouflage and deterrence from predation, as many sponges are toxic. The crabs trim the sponges to fit their carapaces. Some species select other materials, e.g., actinians, ascidians, seaweeds, and even paper, but often particular Porifera are chosen. We consider the trimming behaviour to be of higher ichnotaxonomic significance than the particular material that was chosen for the lining.

# Trace fossils and Sedimentological Significance in the Member III of the Shahejie Formation in southern Dongpu Sag

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The Dongpu Sag (Fig. 1A and B) lies in the Linqing Depression of Bohai Bay Basin, which is a composite basin polymerized by Mesozoic and Cenozoic rift basin and a Carboniferous remnant coalbearing basin. The Dongpu Sag is a NNE-trending, trapezoid shaped fault-bounded terrace, north about 16 km wide and south 62 km wide, the area of approximately 5300 km<sup>2</sup> (Fig. 1C).

The strata in Dongpu Sag consists of Quaternary Pingyuan Formation (Qh), Neogene Minghuazhen Formation (Nm) and Guantao Formation (Ng), and Paleogene Dongying Formation (Ed) and Shahejie Formation (Es) from top to bottom, in which  $Es_3$  Member in Es, both the main source rock and reservoir in this area, is composed of three sub-members from top to bottom: upper ( $Es_{3u}$ ), middle ( $Es_{3m}$ ) and lower ( $Es_{3l}$ ). There developed extensive salt lacustrine deposits in the middle to lower parts of  $Es_3$ .

Based on the observation of drill cores and trace fossil identification in the southern Dongpu Sag, 8 ichnogenus and 13 ichnospecies are discovered in the middle part of  $Es_{3m}$ , including *Beaconites* antarcticus, Helminthopsis abeli, Helminthopsis hieroglyphica, Palaeophycus tubularis, Palaeophycus hebertis, Planolites beverleyensis, Planolites montanus, Semirotundichnus dongyingensis, Taenidium serpentinum, Thalassinoides cf. calianassae, Tuberculichnus cf. Vagans, Mermoides brevilinearis, Mermoides chezhenensis and new ichnospecies Puyangichnus lacustris.

According to the lithology, sediment structure, composition and distribution characteristics of trace fossils, delta front, and predelta subfacies were developed. The delta front deposits consist of flaser and lenticular bedding, horizontal bedding, wavy cross-stratified sandstone with mud drapes. The tracefossil assemblage was dominated by Planolites montanus, Planolites beverleyensis, Palaeophycus tubularis, Palaeophycus hebertis, Palaeophycus tubularis, Beaconites antarcticus, Thalassinoides cf. calianassae, Taenidium serpentinum in the sandier beds, whereas the mud drapes blanketing the sandstone foresets commonly contain Helminthopsis abeli, Mermoides chezhenensis, Mermoides lineatus, Puyangichnus lacustris. The prodelta deposits were mainly characterized by lenticular, horizontal and wavy bedding, with low to medium bioturbation intensity and sporadic distribution of trace fossils. The trace-fossil assemblage was dominated by deposit-feeder structures (e.g., Planolites montanus, Mermoides lineatus, Mermoides chezhenensis, Parapaleodictyon irregularis, Puyangichnus lacustris). In addition, gravity flow deposits from semi-deep lacustrine have been investigated in the southern Dongpu Sag. The trace-fossil assemblage was parallel to the bedding plane (e.g., Semirotundichnus dongyingensis, Planolites montanus, Helminthopsis hieroglyphica, Mermoides brevilinearis, and Tuberculichnus cf. Vagans). The burrows were developed in dark grey, dark thinbedded mudstone or silty mudstone with pronounced horizontal lamination.

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Fig.1. Locations of the sampled drill cores at the third member of Shahejie Formation in Dongpu Sag.

#### Ichnofabrics in early diagenetic concretions

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Early diagenetic concretions are well known to preserve a nearly uncompacted sediment fabric. Carbonate and silica concretions can be etched and the sedimentary structures are seen in much more detail. In addition to these aspects, concretions may form in relation to bioturbation structures. For instance, *Thalassinoides* burrows among others are well known to act as nucleation sites of concretions.

Many concretions form while organic matter is oxidized under anaerobic conditions, while specific ions act as electron acceptors such as manganese, iron or nitrate and sulfate (Froehlich *et al.*, 1979; Irwin *et al.*, 1977). In particular important is the anaerobic oxidation of organic matter and methane within the sulfate reduction zone; just to recall, modern seawater contains about 8-times more oxygen bound within sulfate than dissolved oxygen. Anaerobic oxidation of organic matter provides alkalinity, mainly HCO<sub>3</sub><sup>-</sup>, that in turn leads to cementation when the solubility product of carbonate is exceeded (e.g., Raiswell, 1988). The anaerobic oxidation of organic matter and methane leaves a distinct isotope signature within the precipitated carbonates while the biogenic methane was microbially generated and hence, provides a lighter  $\delta^{13}$ C signal < -25‰ than oxidation of "normal organic matter" ( $\delta^{13}$ C > -25‰) (see Irwin *et al.*, 1977).

Concretions grow mainly due to diffusion (e.g., Raiswell, 1988). While these processes are slow, concretions need time to grow and, therefore, have to reside for a prolonged span of time within the same geochemical zone. Consequently, concretions are considered to indicate episodes of retarded sedimentation (e.g., Wetzel & Allia, 2000).

Very intriguing with respect to both concretion formation and bioturbation are cold methane seep sites while methane emanating out of the seafloor fuels light-independent chemobiotic primary production that provides benthic food (e.g., Kiel, 2011 and papers therein). Methane diffuses through the sediment column and emanates through conduits. If seawater is pumped downward within burrow systems at methane seep sites, sulfate is provided that can react with methane-charged fluids. Furthermore, burrows may act as conduits for methane-charged fluids and methane may diffuse from open tubes into the adjacent sediment.

For the latter two cases, anaerobic oxidation of methane occurs adjacent to the tubes and these domains become increasingly cemented. The only record of increasing cementation while a burrow is inhabited are ichnofabrics. Such cases have been observed in deep-water sediments in the upwelling area off southern Vietnam. There a succession of burrows *Thalasssinoides – Spongeliomorpha – Trypanites* documents increasing cementation (Wetzel, 2013). *Trypanites* was emplaced last in the walls of the *Spongeliomorpha* burrows and indicates water circulation within the crustacean burrows. Within the rock record increasing induration of burrow-related methane conduits has not yet been documented, but burrow geometry and stuffed fill are seen as evidence that burrows acted as methane conduits that became cemented during or briefly after inhabitation by the producing organisms.

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# Trace Fossils in the terrestrial Lower Triassic of North China and their ecological implications

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The end-Permian mass extinction resulted in the most severe life crisis on the earth, the marine and terrestrial ecosystems suffered a heavy loss at the same time, and both of them endured a tough biotic recovery process. After that, the reappearance of the metazoans signifying the beginning of the biotic recovery. Thus, understanding the post-Permian extinction recovery is crucial to understanding the history of life on Earth. There are so many researches on the time and pattern about the mass extinction. However, the consistency of the recovery between the marine and terrestrial facies remains controversial and the evolution of the trace fossils in terrestrial is poorly known. The Permian-Triassic continental succession of the western Henan Province North China sheds light on this obscure subject, because it plays an important role in the transformation from the flourishing of the microorganism to the reappearance of metazoans, and the Heshanggou Formation (in the Henan Province of North China) could be as a key strata that witness the biological recovery of the Early Triassic. So, the evolution research of metazoans generally based on their trace fossils may be revealed as an evidence to explore the recovery of terrestrial ecosystems in the Early Triassic.

In light of the abundance of trace fossils, the Heshanggou Formation in Yiyang area (North China) was selected for biological recovery analysis. Our study focused on several ecological indicators such as diameter, depth, abundance and diversity of the trace fossils. The characteristics and the indices of the trace fossils in this formation were described in detail including the quantitative methods. According to the studied data, the lower part of the Heshanggou Formation is confined to rich simple, small, vertical burrows, suggesting the ecological environment was suitable for the survival species, which is flourishing quickly. Till the middle part, the vertical burrows become deeper, which may suggest the periodic climate change, and gradual adaptation of trace makers may be an important impact factor. The disturbance is more intense and the diversity is obviously increasing in the upper part. With the increasing bioturbation and diversity of the trace fossils, the gradual biotic recovery pattern was discussed for the terrestrial ecosystem in the Early Triassic, and the recovery mode is similar with marine ichnofossils in South China.

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# Field trip guidebook

# Radek Mikuláš

# General remarks on the Bohemian Massif

In the geology of central Europe, the Bohemian Massif is a regional geological unit stretching over central Czech Republic, eastern Germany, southern Poland and northern Austria. More than onehalf of the massif consists of crystalline rocks, which are older than the Carboniferous and therefore deformed during the Variscan Orogeny.

However, this does not mean that all rocks older than the Carboniferous are metamorphosed and crystalline. The internal tectonic structure of the Bohemian Massif was formed during the Variscan Orogeny, which left many Upper Proterozoic and Paleozoic rocks either anchi-metamorphosed or not metamorphosed at all. These occurrences, lying especially in the so-called Barrandian area, are famous by the rich diversity of fossils. During the 19<sup>th</sup> century, they helped the French paleontologist Joachim Barrande to write the as yet largest scientific volume written by a single person.

The Variscan Orogeny was a phase of mountain building and accretion of terranes that resulted from the closure of the Rheic Ocean when the two paleocontinents Gondwana (in the south) and Laurussia (in the north) collided. The regional literature (Havlíček *et al.*, 1980) considers a microcontinent called Perunica the core of the Bohemian Massif; however, this view is not generally accepted. The result of the Variscan Orogeny was that almost all the continental mass became united in a supercontinent called Pangaea. From the Permian period onward the Variscan mountain belt became eroded and partly covered with younger sediments.

The platform or "semi-platform" sediments of the Bohemian Massif are of several ages:

1. Carboniferous to Permian. These are exclusively fluvial and lacustrine, with coal seams mined till the end of the  $20^{\text{th}}$  century. Sedimentation continued to the Triassic in a small area in NE Czechia.

2. Jurassic. On the eastern margin of the Bohemian Massif, shallow-marine Jurassic sediments are preserved as denudation remnants. In NNE Bohemia, marine Jurassic rocks were dragged out from underneath the vast bodies of the Upper Cretaceous sediments in the latest Cretaceous to Paleocene. This occurred along the major structure of the Lusatian Fault.

3. Upper Cretaceous. A worldwide transgression occurred, being accompanied by subtropical to tropical conditions. Marine Upper Cretaceous sediments usually transgressed on fluvial Upper Cretaceous, Carboniferous to Triassic platform sediments, on Uppermost Proterozoic and Paleozoic marine, faulted and folded sedimentary and volcanic rocks. The most prominent lithofacies of the Upper Cretaceous are quartzose sandstones, forming the so-called *rock cities* (Migoń, 2018).

4. Oligocene to Miocene "brown coal basins" in the northwestern and northern part of the Czech Republic. The basins have been the energy base of the industry of the Czech Republic since 1930s. Coal was especially demanded between 1950–2000.

# Day 1: Marine Paleozoic of the Prague Basin

# Radek Mikuláš

The Prague Basin represents a unique complex of chiefly sedimentary, much less pyroclastic and volcanic rocks (Havlíček, 1992). The sequences start with transgressive Tremadocian sediments and end in the Middle Devonian (Givetian), apparently without important hiatuses and without fully developed nappes. Moreover, the basin fill represents ultimately only a denudation remnant, as the upper boundary is not preserved. In any event, the recorded time interval between the beginning and the end of the preserved basin fill (i.e., 100 million years) is considerably long. The long lifetime of the basin is still most convincingly explained by Havlíček (1998) by synsedimentary tectonics providing still new accommodation space. The Prague Basin was tectonically divided both longitudinally (especially in the Ordovician) and transversally (in the Silurian and Devonian). It is noteworthy that the Prague Basin was honored by the designation of the first International Global Stratotype of the world (Silurian/Devonian boundary at Klonk Hill near the Suchomasty village).

For the Ordovician, ICS Stages are partly used in the Prague Basin (Tremadocian; Hirnantian); British epochs are still traditionally taken, as well as stages proposed for the Mediterranean region (Havlíček & Marek, 1973).

# Stop 1: Rokycany – Slope

# GPS: 49.748632N, 13.595063E

Chronostratigraphy: Early/Middle Ordovician (Arenigian).

Lithostratigraphy: Klabava Formation.

#### Lithology: Shales.

The name of Rokycanská Stráň (Rokycany-Slope) is a relatively large (3 km long) hillslope that exposes dozens of natural and artificial outcrops that together represent most of the Klabava Formation. Rocks of this unit are highly fossiliferous in places (especially graptolites). We will visit only the eastern part of the hillside in a municipal forest park.

The Klabava Formation is the oldest unit of the Bohemian Massif that can be considered strongly bioturbated; ii = 5 in many beds. Besides the background bioturbation, some younger trace fossils are frequent at many places, including *?Asterichnus* isp. and *Phycodes noha* Mikuláš, 1992. The history of the last ichnotaxon is interesting: being overlooked for over 25 years, it is presently reported from several localities in the Mediterranean realm.

The Klabava Formation is not suitable for the preservation of surface and very-shallow-tier trace fossils.



Fig. 1. Visit of the Rokycany – Slope site (interrupted red line).



Fig. 2. Klabava Formation (shales) in the eastern part of the Rokycany – Slope site.



Fig. 3. ?Asterichnus isp. Eastern part of the Rokycany - Slope site.



Fig. 4. Phycodes noha Mikuláš, 1992. Eastern part of the Rokycany - Slope site.

## Stop 2: Hlásná Třebaň

#### GPS: 49.926369N, 14.202177E

Chronostratigraphy: Uppermost Ordovician (Hirnantian).

Lithostratigraphy: Kosov Formation.

Lithology: Sandstones to quartzites rhythmically alternating with green-greyish micaceous shales.

The name of the site (then Vorder Třebaň, meaning Front Třebaň) appeared in the "Problematica Silurica" by A. Fritsch in 1908. Since then, the site remains sporadically visited by mapping geologists (Bouček & Přibyl, 1958), students of sedimentary geology etc. Students of palaeontology from Charles University in Prague, to my knowledge, have never visited the site, as "it contains no fossils, only fossil traces".

The site appears in the southern slope of a prominent ridge. The southern slope is poorly vegetated; therefore, rock outcrops are numerous and relatively large. The whole area suitable for the study of the Kosov Formation is ca.  $30 \times 300$  m. The surface is partly terraced, probably because of the historical use the slope for cultivating grapevine (local name Vinice – "vineyard").

A complete section/set of sections at the site has not been documented yet. Mikuláš (1987, 1990) briefly described the site and its ichnofossils; however, in the 1980s, the slope was much more overgrown by shrubs than today, and extensive collection of trace fossils was not possible.

Presently, two basic lithologies can be observed at the site: 1, up to 3 m thick sets of sandstone/quartzite beds showing herringbone bedding; 2, a few tens of centimetres to a few metres thick rhythmically-bedded sand-shal sequences showing hummocky cross-stratification. While the rocks of the first-mentioned lithology are poor in trace fossils (in places, with exception of the uppermost bed), the hummocky cross-stratified beds contain rich trace fossil assemblages both in hyporelief and in epirelief (*Rusophycus* div. isp., Cruziana problematica, Asteriacites isp., *Helminthoidichnites* isp., *Bifungites* isp.). Frequent and still problematic is the trace fossil named *Curvolithus gregarius* by Fritsch (1908).



Fig. 1. Hlásná Třebaň – an overall view from the SW.



Fig. 2. Hlásná Třebaň – herringbone and hummocky cross-stratified rocks; weak bioturbation.



Fig. 3. Hlásná Třebaň – hummocky cross-stratified beds.



Fig. 4. "Curvolithus gregarius" Fritsch, 1908.


Fig. 5. "Curvolithus gregarius" Fritsch, 1908.



Fig. 6.? Rusophycus isp.



Fig. 7. Helminthoidichnites isp.

#### Stop 3: Kazín

#### GPS: 49.94782N, 14.33848E

Chronostratigraphy: Basal part of Late Ordovician (Sandbian); mid-Berounian Stage of the local scale (Havlíček & Marek, 1973).

Lithostratigraphy: Letná Formation.

Lithology: dark clay shales, micaceous silty shales, siltstones, greywackes, sandstones/quartzites.

The Letná Formation is the thickest of all the Ordovician formations in the Prague Basin. The thickness exceeds 600 m in the central part between Prague and Beroun. A large part of the Letná Formation is characterized by rhythmical flysch-like sedimentation, e.g., alternation of greywackes, subgreywackes and quartzites with siltstones and shales in beds of centimetre to rarely decimetre thickness (Havlíček, 1982). Because of the relatively high thickness and rock composition, the Letná Formation often forms landscape elevations with numerous natural exposures. Therefore, the Letná Formation can be considered the only Ordovician formation of the Prague Basin that permits a direct observation of sedimentary architectural features in the scale of dozens to first hundreds of metres in size.

Finds of fossils are relatively rare, being concentrated to several intervals only. Trace fossils are ubiquitous except for lenses and beds of black shales occurring along the basin axis in places (e.g., Prague area, building of Metro in the 20<sup>th</sup> century). Mikuláš (1990, 1998) studied trace fossils; he based the study nearly completely on newly collected material. However, looking back, it is obvious that the study was (as many previous studies) conducted selectively; most attention was given to localities bearing "typical" Palaeozoic shallow marine trace fossils, like *Rusophycus*. The large, sedimentologically illustrative site at Kazín was merely checked and abandoned because of its low diversity of trace fossils.

Strata of the Letná Formation at Kazín are (rather randomly) more or less horizontal. It is a rock body at a direct contact with water of the Berounka River; the possibility to study at least part of the section is made possible by a man-made notch running approximately in <sup>1</sup>/<sub>4</sub> of the height of the cliff. Near the centre of the cliff, a vertical cleft is widened enough to meet the requirements of a pseudokarst cave. Its walls provide good opportunity to study the relatively upper beds of greywackes and sandstones.

The most conspicuous lithological and ichnological boundary of the outcrop lies about 2 m above the pathway maintained in the notch: nearly completely to repeatedly bioturbated rock (ii = 3-5) passes to massive, non-bioturbated greywackes and subgreywackes, only rarely bearing individual trace fossils (e.g., *Palaeophycus tubularis*). The strongly pronounced ichnobabric consists nearly exclusively of *Teichichnus rectus*, rarely with *Phycodes palmatus*.

Under current knowledge, the *Teichichnus* interval can be considered a typical example of the *Teichichnus* ichnofacies (Pemberton...), i.e., the brackish settings. The whole outcrop, taking into consideration channel fills observable in the cave, gives all the requirements for deltaic settings, as presumed for other places in the Letná Formation by Kukal (1963), Mikuláš (1998), a.o.



Fig. 1 (left). A terrace modelled by the Berounka River on the poorly bedded clay shales to clay greywackes of the Letná Formation.

Fig. 2 (right). A view from the broadly opened pseudokarst cave to the Berounka River and town of Černošice on the opposite bank.



Fig. 3. An approximately plan view of clayey subgreywackes with Teichichnus ichnofabric.



Fig. 4. The top of the interval bearing Teichichnus Ichnofabric: Phycodes palmatus.



Fig. 5. Channel fill in the cave, several metres wide. Poorly bioturbated subgreywackes.



Fig. 6. A typical side view of the *Teichichnus* Ichnofabric.



Figs. 7–8. A sharp boundary between *Teichichnus* ichnofabric and the overlying greywackes, occasionally silicites.

## Stop 4: Quarry at Kozolupy

## GPS: 49.96035N, 14.19312E

Chronostratigraphy: Silurian, the Ludlow Series.

Lithostratigraphy: Kopanina Formation.

Lithology: tuffaceous limestones.

The quarry, though small and overgrown with vegetation, comprises nearly the whole thickness of the Kopanina Formation in the facies of tuffaceous limestones. Fauna is extremely rich, including particularly stromatoporoids, corals, brachiopods, cephalopods and trilobites. The tuffaceous admixture enables preservation of trace fossils in epireliefs, hyporeliefs and full reliefs.

Unfortunately, the bedding planes rich in trace fossil weather quickly; nevertheless, the site is still worth visiting. Limestone slabs in large numbers were collected in 1980s and 1990s.

The most common trace fossil can be classified as *Taenidium* isp., followed by *Planolites montanus*. Ichnofabric index may reach 2–3 in places.



Fig. 1. *Taenidium* isp. with discernible menisci of the former backfill (at top centre). Other trace fossils are weathered and partly washed-up *?Taenidium* isp.



Fig. 2. Present state of the Kozolupy Quarry, southern side.



Fig. 3. Platy limestone, concave epireliefs of *Taenidium* isp. and *?Taenidium* isp.



Fig. 4. A brachiopod shell (family Atrypidae) with a biting trace or a broken drilling trace.

## Stop 5: Mramorka Quarry at Chýnice

## GPS: 50.003858N, 14.270087E

Chronostratigraphy: Early Devonian (Pragian and Emsian).

Lithostratigraphy: Praha and Zlíchov formations.

Lithology: Mostly grey to reddish, well-bedded limestones with smooth or nodular bedding planes; rarely, black graptolite-bearing shales highlighting the so-called Basal Emsian (Zlichovian) event.

As mentioned earlier, the Devonian of the Prague Basin is not preserved completely; the youngest Devonian rocks (i.e., denudation remnant) are of Givetian age (non-calcareous flysch-like Srbsko Formation presently seen on a dump at the entranceway to the Mramorka Quarry). Otherwise, most of the Devonian consists of limestones. Notably, the Uppermost Silurian Požáry Formation passes to the lowermost Devonian Lochkov Formation, e.g., the slope of Klonk Hill at Beroun (GPS: 49.9005392N, 14.0627475E) hosts a Global Stratotype of the Silurian/Denonian boundary (since 1972). The Lower and Middle Devonian in the Prague Basin show about 15 clearly discernible lithotypes. Lateral variations in accommodation space as well as ambiguously interpreted tectonic structures striking either parallel or perpendicular to the basin axis (more in Čejchan & Hladil /ed./, 1997, a.o.).

Bioturbation of Devonian rocks of the Prague Basin is mostly weak. In some cases, cryptobioturbation can be observed in thin sections (*Planolites montanus*, *Palaeophycus tubularis* less than 1 mm in diameter; cf. Mikuláš and Hladil 2015). Relatively frequent, especially in calcareous shales and in limestones of darker hues, are *Chondrites* isp. and *Zoophycos* isp. (Chlupáč, 1990) locally occurring in the Lochkov and Praha formations. Surface or shallow subsurface trace fossils are very rare (Mikuláš & Hladil, 2015). Trace fossils of the Devonian of the Prague Basin are generally understudied. Especially vertical tubes attributable to *Trypanites* isp. (Mikuláš & Hladil, 2015) have probably been overlooked many times; this means that the hardgrounds themselves were missed.

In the Mramorka Quarry, Zoophycos isp. is well exposed on the uppermost bedding plane of the Pragian. It can be studied *in situ*; the place is not suitable for collecting. Some 2–3 m higher in the section, eight beds of dark shales can be observed (but not from the closest distance). These beds represent a remnant of the Basal Emsian Event (deepening of the world ocean). Some of the limestone intercalations of the "event beds" comprise *Chondrites* isp.





Figs. 1–3. Zoophycos isp., top of the Pragian succession. Field photograph, Mramorka Quarry.



Fig. 4. Quarry face from the "*Zoophycos* bed" to the middle of the Zlíchov Formation. The thin-bedded interval at about 2/3 of the section from the bottom to the top represents the Basal Zlíchovian Event.



Fig. 5. A large star-shaped fossil damaging the nodules. Dvorce-Prokop Limestone, Braník Rock (Mikuláš & Hladil, 2015).

## Day 2: Non-marine Late Palaeozoic and Early Mesozoic of the Intra-Sudetic Basin; transgression of the marine Cretaceous

The Intra-Sudetic Basin represents the easternmost part of a complex of Late Paleozoic continental basins of the Bohemian Massif located along the Czech–Polish border. Its basement consists of various crystalline complexes and Variscan granitoids. The deposition started around the Tournaisian/Viséan boundary in the NE Polish part of the basin and spread into the rest of the basin by the late Viséan. Sedimentation then continued until the Triassic with several hiatuses. The stratigraphic column of the Czech part of the basin is divided into seven lithostratigraphic units (formations) with most of them being further subdivided into members. The succession is characterized by alternating grey coal-bearing and red coal-barren strata, with a tendency for the red beds to become more prominent above the upper Westphalian. In contrast to all others post-Variscan continental basins of the western, central and north-eastern Bohemia, sedimentation in the Intra-Sudetic Basin crossed the Paleozoic/Mesozoic boundary and ended in the Triassic.

## Stop 1: Žacléř, Jan Šverma coal mine, now a mining museum

## GPS: 50.6699636N, 15.9247175E (original outcrop)

Chronostratigraphy: Carboniferous, Westphalian stage.

Lithostratigraphy: Lampertice Member of the Žacléř Formation.

Lithology: Coal seams, siltstones, sandstones/arkoses, conglomerates.

The interval of strata exposed by both deep mining and surface quarrying belongs to the Lampertice Member of the lower part of the Žacléř Formation; the member represents up to 680 m of continental, coal-bearing fluvial strata of late Namurian to Duckmantian age. They are dominated by conglomerates and coarse- to medium-grained sandstones with scattered pebbles, generally interpreted as channel-fill deposits. Overbank facies including coal are a less common but characteristic part of the succession. Coal seams were mined for more than two centuries during the 19th and 20th centuries, lastly in the "Jan Šverma" underground coal mine, lying between the town of Žacléř and the Lampertice settlement (NE Bohemia, Czech Republic). Remaining parts of the "Coal Seam 9", lying close to the surface, were occasionally exploited in an opencast quarry till 2008.

The Žacléř coal deposit has been the subject of many studies focused on lithostratigraphy, paleontology, biostratigraphy, and the quality and characteristics of coal seams, including their petrographic composition.

The ichnoassemblage further described in the text comes from the already infilled quarry (GPS coordinates 50°40'8.315"N, 15°55'29.894"E). The sequence is interpreted, considering its context in the basin, as a sedimentary fill of occasional floodplain channels (Libertín *et al.*, 2008)."Coal Seam 9" is overlain by an interval of rather monotonous clayey siltstone and siltstone, about 1.6 m thick. The sequence contains well-preserved *in situ* vertical trunks of *Lepidodendron* (Lycopodiopsida) and *Calamites* (Equisetophyta) preserved throughout the strata. Colonization horizons containing the trace fossil *Cochlichnus anguineus* occur both in the lower, fine part of the section (clayey siltstone) and the

upper sequence of siltstone. The total number of the colonization horizons exceeds 10. Most of the collected trace fossils, however, come from debris around the exposure; this concerns mainly the less frequent trace fossils, others than *Cochlichnus*.

Tree trunks preserved *in situ* in standing position are a rare but conspicuous feature of the fossil record; besides other things, they have a potential to be an attraction for geo-tourism (e.g., Melchor *et al.*, 2004; Czászár *et al.*, 2009). Rapid burial is a requirement for the preservation of upright plant assemblages. The burial mechanism can be volcanic (e.g., Melchor *et al.*, 2004; Bedatou *et al.*, 2009; Márton *et al.*, 2007; Mikuláš *et al.*, 2003), rapid sedimentation of detrital grains in fluvial or deltaic settings (cf. Czászár *et al.*, 2009), or transgressive events in estuaries (Buatois *et al.*, 1998).

The above described assemblage from the Žacléř site shows a comparable geologic age and similar ichnogeneric composition to the Carboniferous Buildex Quarry succession (Kansas, USA), which contains root traces, *in situ* trunks and trace fossils, especially the ichnogenera *Diplichnites*, *Kouphichnium*, *Gordia*, *Helminthopsis*, *Treptichnus* etc. (Buatois *et al.*, 1997).

At Žacléř, the rapid burial of the forest cannot be ascribed to a transgressive event as no influence of marine settings was ascertained in the Intrasudetic Basin (Pešek *et al.*, 2001). A complex analysis of the environment at Žacléř was presented by Libertín *et al.* (2009). According to these authors, the sedimentation took place in an intramontane valley drained with a braided to low-sinuosity meandering river with a well-developed floodplain. *Lepidodendron* growths occurred in planar peat swamp-arborescent settings.

At Žacléř, the distribution of colonization horizons in strata containing upright stems shows a multiple gradual sedimentation of this ca 2 m thick interval. Nonetheless, the burial must have been rapid and must have occurred within several years. Otherwise the stems would succumb to decay under the humid tropical climate.

The beginning of rapid sedimentation of silts on the previous afforested peat might be connected, e.g., with blocking of a river channel or opening a new channel to a swamp setting, or with the origin of an obstructed lake in an intramontane valley. It is probable that the accumulation of silt beds caused a compaction of the underlying peat, which further augmented the sedimentation.

Considering the approximate number of colonization horizons to ten, intervals between the sedimentary events must have lasted several months, or more often several weeks if we consider the irregularity in the sedimentation rate. Therefore, rhythmicity of the studied interval might reflect common meteorological situations as torrential rains that appeared in the above characterized time intervals.

To summarize, siltstones deposited in fluvial settings of the Late Carboniferous of the Czech Republic yielded recurring colonization horizons with *in situ*, upright preserved stems of *Lepidodendron* and *Calamites*. Time intervals between openings of the colonization windows were most probably weeks (maximum – months; minimum – days). These intervals probably correspond to the periodicity of torrential rains in the mountainous hinterland of the river.

The ichnoassemblages were dominated by *Cochlichnus anguineus*, accompanied by tetrapod traces and minute invertebrate traces, e.g., *Planolites*, *Gordia* and *Treptichnus*. *Cochlichnus* usually occurs in groups of interacting specimens. The interaction may be so tight that crossing/touching of specimens forms open networks, similar to (*Proto*) *Paleodictyon*.

The object of the former mine is partly re-built into a mining museum, with excellently preserved technology of the early 20<sup>th</sup> century. The museum also includes a gallery that crosses a coal seam with the vertical *Lepidodendron* stem surrounded by siltstones. It is not possible to collect in the subsurface gallery, but it is still possible to find samples with the *Cochlichnus* ichnofabrics on a presently levelled quarry. In addition, the palaeontologists of the National Museum in Prague saved large collections (hundreds of specimens).



Fig. 1. Schematic sketch of ca. 2.5 m thick section above "Coal Seam 9".

silts to he

Cochlicknus

Coal

noriaa



Fig. 2. Gradual opening and closure of fossilization windows.



Fig. 3 (above). Abandoned opencast mite with tree trunks (mostly Lepidodendron).

Figs. 4-5 (below). Stems of *Lepidodendron* and *Calamites* preserved vertically, immediately above the coal seam. The already abandoned quarry, photo by R. Mikuláš (2008).



Fig. 6. Slabs of siltstones with *Cochlichnus anguineus* (both convex hyporeliefs and concave epireliefs).



Fig. 7. Cochlichnus ichnofabric, a remain of debris in the opencast mine.



Figs. 8–9. Lookouts from the tower of the former Jan Šverma Coal Mine.



Fig. 10. Lepidodendron tree trunk in situ in the museum shaft "Jitřenka".



Fig. 11. An orthogneiss quarry at Královec, visible from the mine tower.

## Stop 2: Červený Kostelec, U Devíti Křížů (also Krákorka) Quarry

## GPS: 50.491006N, 16.056399E

Chronostratigraphy: Early to Middle/Upper Triassic; Upper Cretaceous (Cenomanian).

Lithostratigraphy: Devět Křížů sandstones; Bohdašín Formation, overlain by Turonian (Cretaceous) conglomerates.

Lithology: Triassic – thin-bedded, strongly cemented quartzose sandstones; Cretaceous – poorly sorted gravels/conglomerates.

The quarry lies 430 m WSW of the settlement of Devět Křížů. Presently, the quarry is a shallow (10 m of overburden) pit quarry with subhorizontal sandstone beds, partly used for the production of hand-made pavements slabs, internal and external panelling and so on. Plan view of the quarry is approx.  $100 \times 200$  m in size.

The white, medium- to coarse-grained quartzose sandstone represents the upper part of the Bohdašín Formation – so-called Devět Křížů Member (Holub, 1966). Quartz grains are held together by silica cement, with locally elevated sericite content. The pore fills (rather than cement) are also kaolinite, montmorillonite and illite. The sediment was deposited in shallow seasonal lakes and river channels; in dry periods, migrating sand dunes (i.e. eolian sedimentation) were formed. Sandstones are well sorted; at the bottom of the quarry, irregular beds of conglomerates (with silicites in individual clasts) can be found.

Sandstone of the Devět Křížů Member is topped by a slight unconformity, followed by Cretaceous (Cenomanian) basal sandstones with glauconite, which is chiefly known only from the fills of trace fossils. Conglomerates contain abundant fossils: oysters *Rhynchostreon*, shark teeth, non-oyster bivalves, echinoderms, gastropods and brachiopod fragments. Towards the Triassic sandstones, the Cretaceous trace fossils, chiefly *Thalassinoides*, penetrate to the depth of up to 2 m. Vertical shafts up to 10 cm in diameter and slightly narrowing downwards are also present, interpreted as repeatedly used root canals (?mangrove growths of Cenomanian age) by Mikuláš & Prouza (1999). It is noteworthy that Mader (1990) considered these vertical bodies in his magnificent volume on Buntsandstein and Keuper flora as lycopod body fossils.

*Vertebrate trace fossils*: As yet studied material constitutes a unique record of three to four tridactyl traces reminiscent of dinosaur tracks; few other specimens can be imagined to appear by random, though unlikely mechanical processes. The first clue was found in a quarry in mid-1990s (Fig. 1a; Zajíc 1998). The specimen evoked a debate on the stratigraphic value of the object. The pertinence of the tracemakers to the original group of Coelurosauria is often disputed. E.g., Madzia (2014) declared that the tridactyl foot may be a plesiomorphy typical of the larger group called Dinosauromorpha. This is the name of development branch, which contains dinosaurs and their immediate relatives. After all, none tridactyl Dinosauromorpha older than mid-Triassic have been found yet; the tridactyl tracks are still the strongest stratigraphic indicator for the Devět Křížů Member.

Other vertebrate trace fossils: Smaller vertebrate trace fossils with indiscernible or partly discernible imprints of digits are relatively common. Traces of swimming in the shallow water show finger imprints. The controversy is what creature could leave it, and whether it was one, or several. An

important indicator is found in any of the samples: non-existence of a tail groove. Prior opinions pointed to either therapsids (sometimes incorrectly referred to as mammal-like reptiles) or representatives of predecessors of amphibians (frogs).

*Invertebrate trace fossils*: Interesting is a thin bed (0.5-1 cm) in the western wall of the quarry, approximately 2 m from the bottom. Bedding planes were crowded by *Cruziana problematica*. Some unique finds are shown in figures below.

*MISS:* Fossil biofilms (abbreviated MISS – Microbially Induced Sedimentary Structures) are a poorly known phenomenon in the Krákorka Quarry. Several discernible morphotypes can be recognized (Fig. 3). MISS are not bound to a small number of the beds or bedding planes; we expect that the algal coatings originated in dozens of small pools and ponds.

#### References

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Fig. 1 (left). Dinosauromorph traces (photos by M. Souček).

Fig. 2 (right). Traces of other vertebrates than dinosauromorphs; a, tetrapod trace; b, swimming trace of a tetrapod; c, *Undichna* isp. – probably fish swimming traces. Photos by M. Souček.



Fig. 3 a, b, c – various types of microbially induced sedimentary structures. Photos by M. Souček.



Fig. 4. Traces of invertebrates: a, *Cruziana problematica*; b, *?Diplichnites* isp.; c, an undetermined starshaped trace fossil; d, *?Climactichnites* isp.; e, *Planolites beverleyensis*. Photos by M. Souček.

# Day 3: Marine Upper Cretaceous and Oligocene to Miocene "brown coal basins"

#### Stop 1: Bílina brown-coal opencast mine

#### Leader of the excursion: Karel Mach

Chronostratigraphy: Oligocene to Miocene.

#### Introduction

Before 1980s, the study of trace fossils was limited mostly to descriptions of clearly discernible, isolated traces of invertebrates from marine sediments, or vertebrate footprints from various settings. Later, a considerable attention was paid to ichnofossils in non-marine sequences. The growing effort in the ichnological study of continental settings recently enabled to assess ichnologic record of the continental invertebrate invasion, its evolutionary trends, ecospace utilization, and behavioural complexity (Buatois *et al.*, 1998).

At the same time, the methods of study of intensively bioturbated rocks, involving time and space relationships between individual components of bioturbation and widely using core material and vertical stratigraphic sections, developed into ichnofabric analysis (e.g., Ekdale & Bromley, 1983; Taylor & Goldring, 1993).

In the Miocene of the Most Basin, three distinct patterns of bioturbation have been found in a relatively thick sequence of mudstones and sandy mudstones overlying the Main Coal Seam. A different style of bioturbation is displayed in the tuffaceous substrate underlying the seam. *Geological setting* 

The Most Basin is one of the four major sedimentary basins preserved in the Ohře Graben and separated from one another by volcanic domains and by fault systems which cross-cut the Ohře Graben at high angles (Rajchl & Uličný, 2001). In the vicinity of Bílina, the fill of the basin overlies Upper Cretaceous marls and starts with the Oligocene tuffs, volcanic breccias and their weathering products, proluvial and colluvial deposits, allochthonous coal seams, coal clays, lacustrine clays, and autochthonous coal seams. Units overlying the main seam belong to the so-called Bílina delta (e.g., Rajchl & Uličný, 2001). The delta formed at the mouth of a river that drained into a fairly shallow lake (not more than several metres deep), which formed on a subsiding mire and was surrounded by peatbogs during most of the time of deltaic sedimentation. Wedge-shaped and lenticular bodies of the delta sediments, interfering with the surrounding sheet-like bodies of lacustrine clays, characterized the basic depositional pattern of the fluvio-deltaic system. The delta is interpreted as a fluvial-dominated, mouth-bar type (or "birdfoot" delta), with distributaries terminated by friction-dominated mouth-bars (Rajchl & Uličný, 2001).

This sequence bears four ichnoassemblages, each of them dominated by one ichnotaxon. Tuffitic substrates underlying the main coal seam ca. 300 m of the present western margin of the quarry yielded *Taenidium* isp. The body of lacustrine clays above the Main Coal Seam, developed in the thickness of 45 m in the mid-western part of the quarry, contains frequent *?Selenichnites* isp. The persistent horizon of dark lacustrine clay approx. 10–40 m above the seam provided finds of *Unisulcus*. A substantial part of the mudstone deposits of the Bílina delta shows a well-visible, intensive

bioturbation by *Planolites montanus* (Fig. 2). This type of bioturbation was preliminarily described and interpreted by Mikuláš (1998).

To summarize, most of the giant outcrop of the Bílina Mine contains only one ichnotaxon from the quartet of *Planolites* cf. *P. montanus*, ? *Selenichnites* isp., *Taenidium* isp. and *Helminthoidichnites* isp.

#### Ichnofabric analysis

A systematic description of individually recognizable morphological patterns of traces (i.e., of individual ichnotaxa) provides little information about their time and space relationships. To evaluate this important factor of bioturbation, the ichnofabric analysis has been introduced (Ekdale & Bromley, 1983, Pollard *et al.*, 1993, Taylor & Goldring, 1993). The ichnofabric time sequence diagrams are helpful especially when a number of ichnotaxa occur in one interval, involving their numerous cross sections, or even almost complete destruction of the previous "generation" of bioturbation by the subsequent one. This is not the case of the described bioturbation, where only one morphological type is present.

Nevertheless, for the described occurrence of *Planolites montanus*, the ichnofabric time sequence diagram (Mikuláš *et al.*, 2002) shows well the vertical stratification of the bioturbation, i.e. the cyclicity of its appearance. Less traditionally, several distinct beds are shown on the picture of the characterized ichnofabric to document its rhythmical occurrence also quantitatively.

The function of the light, mottled laminae is not very clear. They appear to be fully bioturbated, but the colour contrast of this bioturbation is vague; therefore, the morphological analysis of the bioturbation is nearly impossible. This, however, does not argue against the apparent cyclicity of the bioturbation pattern, showing the vertical distance of the individual "generations" of usually 5–15 mm.

#### Conclusions

For the palaeogeographical and sedimentological evaluation of the described bioturbation, two points are important: 1, empirical comparison of the described bioturbation with similar occurrences and their presumed environments, and 2, time characteristics of the rhythmicity of the bioturbation.

For *Taenidium* isp., its occurrences described in the Cenozoic of the South America come from periodically inundated paleosols (Genise *et al.*, 2001).

*Selenichnites* isp., interpreted as cubichnia of small fish or amphibian larvae, generally occurs in calm, very shallow-water lacustrine settings. The lack of traces of in-fauna points to the deficit of oxygen in the sediment. The same regime could be characteristic for the *Unisulcus*-dominated sediment, with perhaps even stronger ecological stress for most of the benthic fauna.



Fig. 1. Bílina Mine, an overall view from southwest to notheast. Krušné hory (Ore Mts.), tectonically active during the Cenozoic, in the background. Photos by Karel Mach.



Fig. 2. *Planolites montanus* Ichnofabric, rhythmically alternating in its density. Natural size. Bílina Mine, approx. in the middle of the outcrop. Photos by Karel Mach.



Figs. 3–4. ?*Selenichnites* Ichnofabric from the upper part of the claystones overlying the Main Coal Seam. Photos by Karel Mach.

# Stop 2: Děčínský Sněžník Hill

Chronostratigraphy: Upper Cretaceous (Turonian).

Lithostratigraphy: Uppermost part of the Jizera Formation.

Lithology: Medium- to coarse-grained, quartzose, mostly quartz-cemented sandstones.

The largest table mountain in the Czech Republic, formed by Upper Cretaceous (Turonian) sandstones, is almost entirely forested; however, the rocky margins represent a nearly complete rock outcrop 4 km wide. There is yet another cliff level represented by block debris along most of the hillside; in the SW part of the hill, the cliff level is built of compact rock. Otherwise, most of the slopes are covered with spruce and pine forests.

The upper cliff level shows, especially in the eastern part of the hill, rhythmical occurrence of colonization horizons of *Thalassinoides* isp., in intervals of ca. 2.0 to 2.5 mm.

The lower cliff level contains blocks several cubic metres in size, whose lower sides show (from a small block cave) at least 12 specimens of *Asterosoma* isp. As far as we know, this important and interesting ichnotaxon has its type locality nearby, in Saxony; but the exact place is unknown.



Fig. 1. The lower rock belt in the Děčínský Sněžník Hill.



Figs. 2-3. Asterosoma isp., Děčínský Sněžník Hill.



Figs. 4–5. Asterosoma isp., Děčínský Sněžník Hill.



Fig. 6. A slab with *Thalassinoides* isp.