

Cambrian-Ordovician trace fossils of the Basissletta region, northeast Spitsbergen, Svalbard

ALFRED UCHMAN¹ and NILS-MARTIN HANKEN²

¹ Institute of Geological Sciences, Jagiellonian University, Gronostajowa 3a, 30-387 Kraków, Poland;
e-mail: alfred.uchman@uj.edu.pl

² Department of Geology, UiT The Arctic University of Norway, 9037 Tromsø, Norway. Present address:
Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, 0316 Oslo, Norway;
e-mail: n.m.hanken@geo.uio.no

ABSTRACT:

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Trace fossils of the Cambrian–Ordovician sedimentary succession of the Basissletta region, northeast Spitsbergen, Svalbard, belong to three ichnoassemblages. The first one, composed of *Monocraterion* and *Diplocraterion*, belongs to the Skolithos ichnofacies and characterises sandstones of the Tokammane Formation (lower Cambrian: Terreneuvian) deposited in a shallow subtidal setting. The overlying carbonates with pseudomorphs after evaporites (uppermost part of Terreneuvian and the Cambrian Series 2) display abundant *Balanoglossites*. These beds were deposited in an oxygenated but hypersaline environment. The younger Ordovician carbonates of the Kirtonryggen Formation and the mixed carbonate-clastic deposits of the Valhallfonna Formation display a more diverse but poorly preserved trace fossil suite (*Phycodes*, *Curvolithus*, *Planolites*, *Palaeophycus*) typical of the archetypal Cruziana ichnofacies. Some parts of the succession are not bioturbated, and these are characterised by dark coloured fine-grained sediments with primary lamination. They were mostly deposited between the normal and storm wave base or below the storm wave base in oxic to anoxic environments.

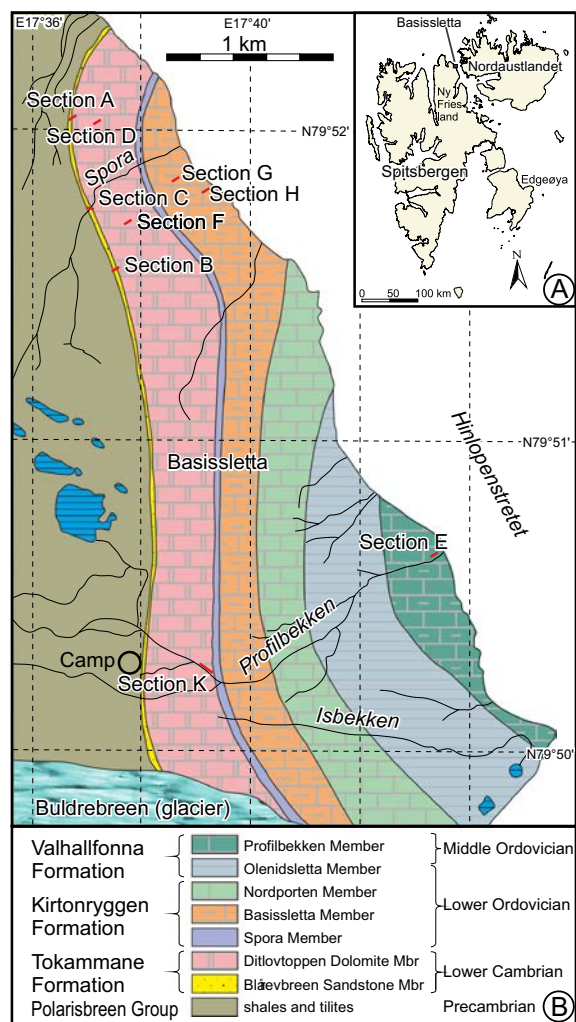
Key words: Ichnology; Ichnotaxonomy; Ichnofacies; Svalbard; Lower Palaeozoic.

INTRODUCTION

A sedimentary succession of the Cambrian–Ordovician shelf on the eastern margin of Laurentia is exposed in the north-west of the Svalbard Archipelago, in the so-called Northern Svalbard Tectono-Sedimentary Element (Smelror *et al.* 2024). It shows a transition from the nearshore basal Cambrian clastic deposits to a lower Cambrian–Ordovician carbonate platform (McKerrow *et al.* 1991; Stouge *et al.* 2012). Their stratigraphy and variable biota have been studied (e.g., Hansen and Holmer 2010, 2011; Lehnert *et al.* 2013) but trace fossils have only been mentioned. In this paper, systematic ichnological research is presented on the basis of field work in

the remote north-eastern part of Spitsbergen, in the Basissletta region. Its location is shown in Text-fig. 1 whereas the geology and stratigraphy of the investigated area is shown in Text-fig. 2. The investigation shows the response of the burrowing fauna through a changing environment and important evolutionary changes, such as the Great Ordovician Biodiversification Event (GOBE). Trace fossils in the Basissletta region have been recognised by Vallance and Fortey (1968, p. 92) who reported “worm trails on exposed surfaces” of the Nordporten Member of the Kirtonryggen Formation (Lower Ordovician). Fortey and Bruton (1973) and Stouge *et al.* (2012) mentioned trace fossils similar to *Monocraterion tentaculatum* Torell, 1870 and *Diplocraterion* Torell, 1870 in the





Text-fig. 1. Location maps. A – Map of Svalbard showing the location of the investigated area at Basissletta, Ny Friesland. B – Geological map of the Basissletta region based on Vallance and Fortey (1968) and Fortey and Bruton (1973), with indication of sections presented in the paper. The Topiggane Shaly Member is not labelled; it lies just above the Blårevbreen Sandstone Member.

sandstones of the Blårevbreen Sandstone Member (lowermost Cambrian) and pointed out the presence of trace fossils in the younger part of the sequence. In the description of the Cambrian–Ordovician strata at Basissletta, Swett (1981) noted the presence of trace fossils in parts of the sequence. ‘Furoid’ markings and *Monocraterion* Torell, 1870 were also noted by Gobbett and Wilson (1960). However, although the presence of unidentified trace fossils in the Cambrian–Ordovician sequence at Basissletta also has been mentioned by Fortey and Bruton (1973), Lehnert *et al.* (2013) and Krüger *et al.* (2017), no systematic ichnological investigations have been carried

out. Ichnological studies of the Cambrian–Ordovician succession in the Basissletta region presented in this paper are thus a step forward in improving this situation. The ichnoassemblages have also been used to achieve a better understanding of the facies interpretation during deposition of the Cambrian–Ordovician sequence in the Basissletta region.

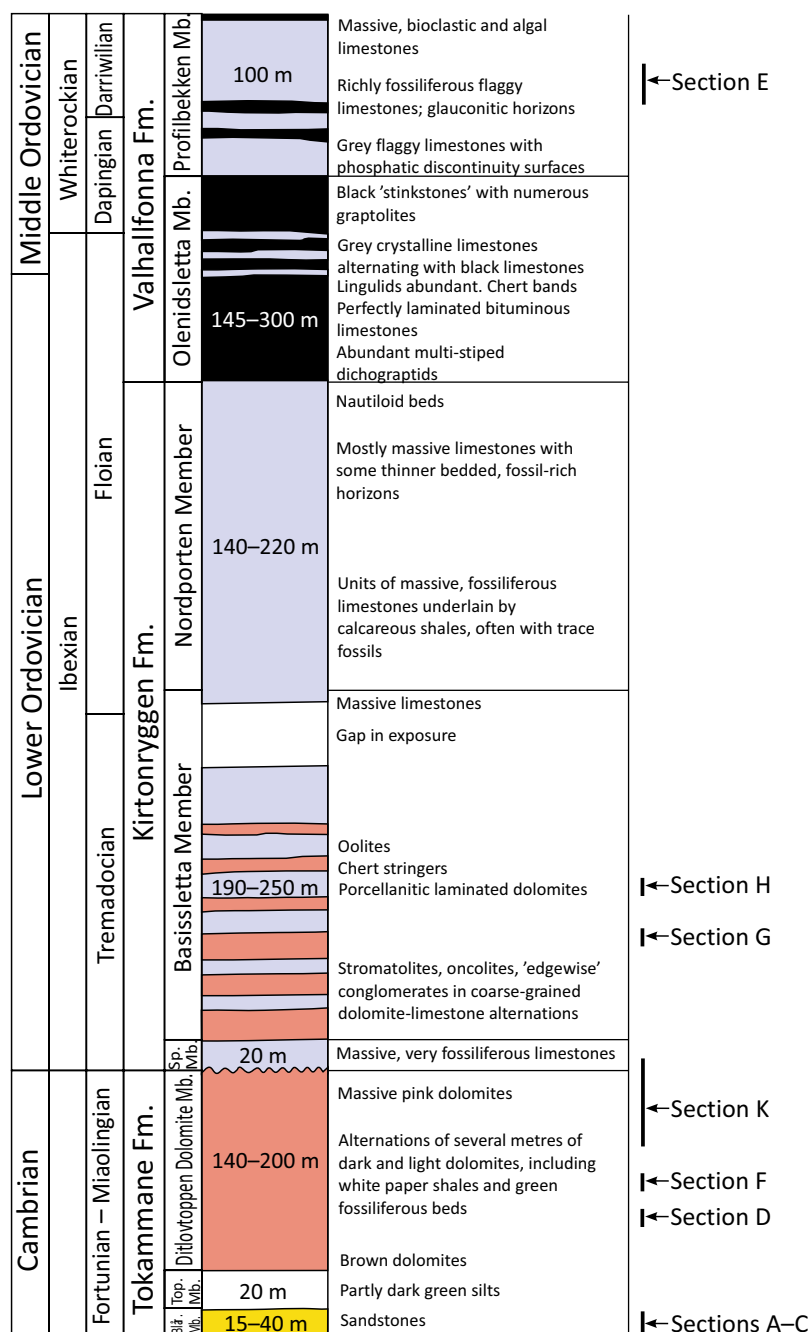
The trace fossils were investigated in the field during the summer of 2008. Representative specimens were collected and they are housed in the Nature Education Centre of the Jagiellonian University (CEP) – Museum of Geology in Kraków, Poland (institutional abbreviation INGJ208P).

GEOLOGICAL SETTING

General data

During the early Paleozoic the Basissletta region (Ny Friesland region) formed part of an extensive platform that bounded the eastern margin of Laurentia (see discussion by Stouge *et al.* 2012). The essential features of this extensive sedimentary basin are known both from north Greenland and Svalbard (e.g., Gee and Teben’kov 2004; Gee *et al.* 2008; Smith and Rasmussen 2008). The Cambrian–Ordovician sequence at Ny Friesland is a part of the North Atlantic/Arctic warm-water carbonate platform (McKerrow *et al.* 1991; Stouge *et al.* 2012). The lower part of the sequence includes a siliciclastic shoreline facies (Terreneuvian) while the upper part (Cambrian Series 2–Middle Ordovician) is dominated by shallow marine warm-water platform deposits. The plate reconstruction has also been supported by fossil evidence because the Lower and Middle Ordovician brachiopod fauna shows strong ties to the faunas in North America and Greenland at the generic level, although the fauna appears mostly endemic at the species level (Hansen and Holmer 2010, 2011). Lehnert *et al.* (2013) showed that the conodont fauna in the Lower and Middle Ordovician part of the succession at Basissletta is typical of the Laurentian shelf and slope deposits.

The Cambrian–Ordovician sequence at Basissletta was originally described by Harland (1959, 1977, 1997), Gobbett and Wilson (1960), Harland *et al.* (1966), and Vallance and Fortey (1968). However, the original stratigraphic nomenclature was later modified by Fortey and Bruton (1973) and Swett (1981). The sequence was again described by Kosteva and Teben’kov (2006), while Krüger *et al.* (2017) gave an updated description of the Ordovician part together with a revised bio- and lithostratigraphy, and an in-



Text-fig. 2. Stratigraphic scheme of the Cambrian and Ordovician succession at Basissletta. Blår. Mb. stands for the Blårevbreen Sandstone Member; Top. Mb. stands for the Topiggane Shaly Member; Sp. Mb. stands for the Spora Member. Stratigraphic position of the measured sections indicated.

terpretation of depositional cycles and relative sea level changes.

The biostratigraphy of the Ordovician part of the sequence was later worked out by Cooper and Fortey (1982) who refined the earlier graptolite stratigraphy, whereas Lehnert *et al.* (2013) used conodonts for the

same purpose. A well preserved Middle Ordovician (lower Darriwilian) radiolarian assemblage was described by Holdworth (1997), and Maletz and Bruton (2007, 2008). The scarcity of body fossils in the lower part of the sequence has hampered biostratigraphical correlation of this part of the sequence. Fortey

and Bruton (1973), and Hansen and Holmer (2011) indicated that the succession was far from complete, including a hiatus spanning the middle and upper Cambrian (Miaolingian–Furongian) and possibly the basal Ordovician. However, Smith and Rasmussen (2008) had not found evidence for such a hiatus. Palaeoenvironmental analysis based on skeletal fossil communities has been worked out by Fortey (1975a, b), Fortey and Barnes (1977), and Hansen and Holmer (2011), and indicates shallow marine settings in the lower part of the sequence followed by a middle Floian transgression and a Darriwilian regression. Stouge *et al.* (2011) described coeval strata from the western part of Nordaustlandet (about 30 km further to the northeast of the Basissletta region) and concluded that the deposits marked the transition from the inner to the outer shelf that evolved during the opening and spreading of the Iapetus Ocean. Kröger *et al.* (2017) have given a chronostratigraphic division of the Ordovician part of the sequence together with depositional cycles and relative sea level changes. In this paper we follow the lithostratigraphic nomenclature given by Stouge *et al.* (2012, fig. 14, pp. 612–616) and the biostratigraphy of Smith and Rasmussen (2008).

Especially the upper part of the sequence is bituminous, and carbonate rocks are often stained with bitumen. The presence of bitumen in the Ny Friesland area has been known for a long time, but the bitumen itself received limited attention until the organic geochemistry of the succession was investigated by Lee *et al.* (2019) and Abay *et al.* (2022).

The exposures of the bedrock are fairly variable in the Basissletta region. Some areas along the shore are covered with a series of raised beach terraces. To the west and south the rock surface is covered by moraines and outwash deposits which limit the area to be explored. In particular, the lower dolomitic part of the sequence is poorly exposed and commonly covered with loose blocks brought to the surface by frost heaving. These blocks often have a distinct lithology which cannot be matched with the lithology as exposed above or below in the section. This indicates that the loose blocks are allochthonous, and therefore parts of the following description have had to be based on these blocks where the *in situ* bedrock was not well exposed. The measuring of the profiles in 2008 was also hampered by patchy snow and ice cover because of unusually cold weather and much snow cover during the field season. Thus the investigations of the bedrock were largely confined to the banks of meltwater streams and along parts of the coast. A brief description of the sequence (Text-fig. 2) is given in the following section.

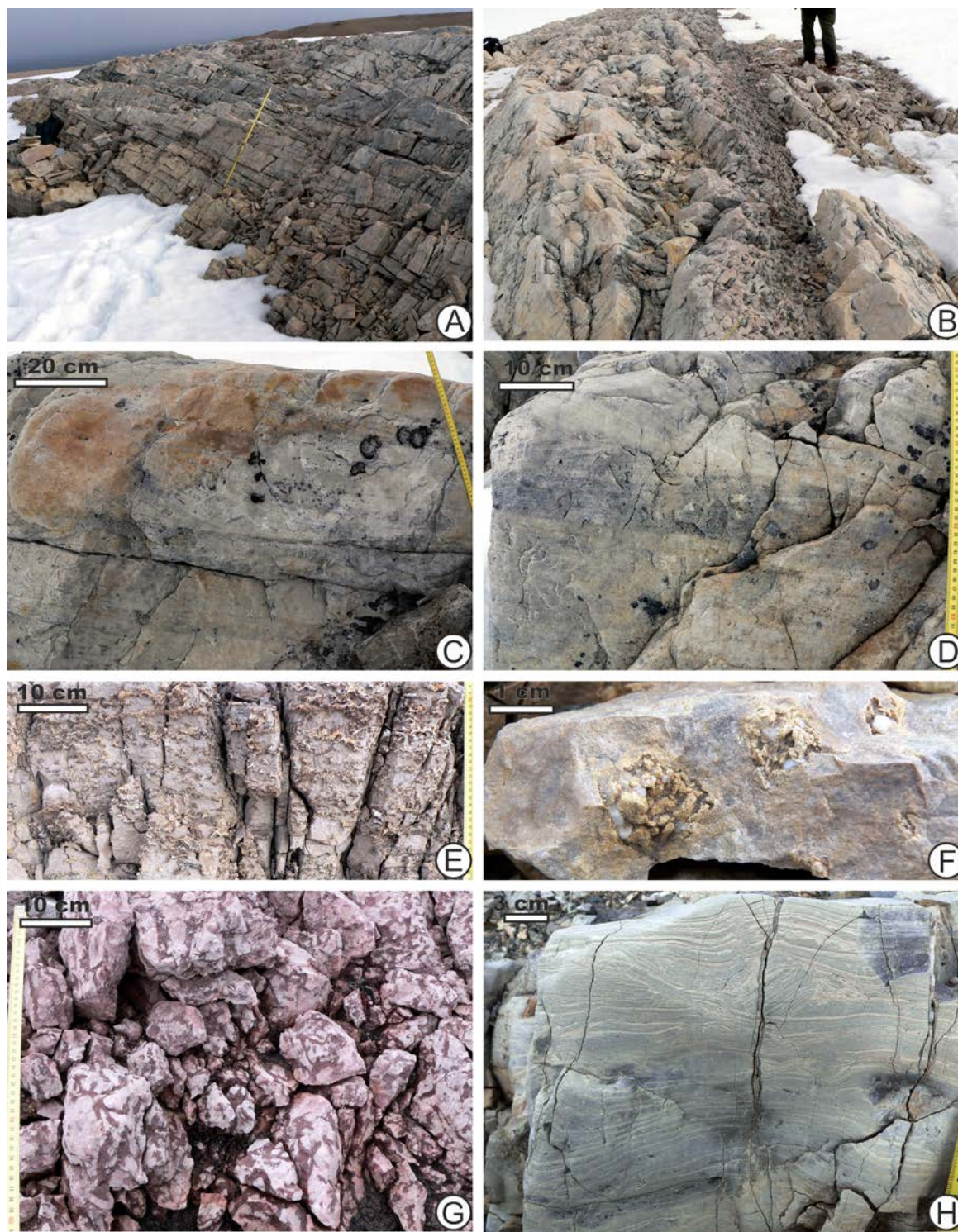
Tokammane Formation (Cambrian)

The Tokammane Formation (Harland *et al.* 1966) is composed of sandstone (Text-fig. 3A–D) overlain by dolomite (Text-fig. 3E). The fine to medium grained sandstone deposits (Blårevbreen Sandstone Member) are characterised by prominent cross-bedding interbedded with flaggy siltstones and shales (Text-fig. 3A–D). Swett (1981) noted the presence of herringbone cross-bedding which indicates deposition in reversing tidal flow cycles. The boundary to the underlying Upper Polarisbreen Shale (Ediacaran) is not exposed in the Basissletta region, but where exposed in other areas it has been described as sharp with an unconformity corresponding to the uppermost Ediacaran and perhaps lowermost Cambrian (Knoll and Swett 1987). The middle and upper parts of the Tokammane Formation consist of dolomite with a few body fossils. The meagre fossil content (some ollenelid trilobites marked on the log of Fortey and Bruton 1973) has hampered biostratigraphical correlation.

The Blårevbreen Sandstone Member is overlain by a succession of thin-bedded glauconitic siltstones and dolomitic shales with interbedded thin sandy beds (Topiggane Member). The succeeding dolomite unit, the Ditlovtoppen Dolomite Member, contains only a sparse skeletal fauna (*Salterella* sp., *Obolus* sp., and trilobite fragments; see Stouge *et al.* 2012) which hampers biostratigraphical correlation, but Fortey and Bruton (1973) consider it to be middle and upper Cambrian (Miaolingian and Furongian). In turn, Smelror *et al.* (2024) placed it in the uppermost part of the Terreneuvian and the Cambrian Series 2, but Stouge *et al.* (2012) positioned it roughly in the upper part of the Cambrian Series 2 and the lower Miaolingian, and this view is followed here. Some beds contain intraformational conglomerates and evaporites. The presence of evaporites indicates periods of subaerial exposure.

Kirtonryggen Formation (Lower Ordovician)

The dolomite of the Tokammane Formation is overlain by a unit consisting of dolomitic limestone and limestone (Text-fig. 3G) which has been referred to as the Spora Member of the lower Kirtonryggen Formation (Fortey and Bruton 1973; Harland 1977). The lower part of the Spora Member consists of dolomitic mudstone and wackestone, overlain by a shale-rich interval followed by a fossiliferous wackestone (Stouge *et al.* 2012). The conodont fauna indicates an Early Ordovician age (Ibexian–Skullrockian) for the Spora Member (Lehnert *et al.* 2009).



Text-fig. 3. Selected facies features. A–D – Inclined sandstone beds, Blårevbreen Sandstone Member of the Tokammane Formation (Fortunian), along the Spora stream. Cross-bedded pinching out beds (A) close to section C, and bioturbated horizons (B) in section C. Cross-bedding (C and D), south of the Spora stream. Yellow ruler in A is 1 m long. E – Dolomitic, laminated beds in the upper part of the Tokammane Formation, along the Spora stream. F – Caverns in dolomitic limestones, probably pseudomorphs after evaporites, Ditlovtoppen Dolomite Member of the Tokammane Formation, NW of section K. G – Bioturbated limestone of the Ditlovtoppen Dolomite Member of the Tokammane Formation, NW of section K. H – Hummocky cross-stratification in a limestone bed in the Basissletta Member of the Kirtonryggen Formation, coastal exposure close to section G.

The overlying Basissletta Member is characterised by dolomite with stromatolites and evaporites in the lower part succeeded by cherty limestone. Several beds contain dolomitic or silicified ooids. Intraformational conglomerates consisting of flat, more or less disc-shaped limestone flakes in a dolomitic matrix are common in parts of the sequence. Some beds show hummocky cross stratification (Text-fig. 3H). Except for stromatolites, body fossils are fairly rare, but the conodont fauna indicates the Stairsian Stage of the Ibexian series (Lehnert *et al.* 2013), i.e., middle Tremadocian.

The lowermost part of the Nordporten Member is composed of bedded homogeneous fossiliferous limestone succeeded by limestone interbedded with shale. Stromatolites, intraformational conglomerates and hummocky cross-stratification are common in the middle part of the sequence, which according to Fortey and Barnes (1977) is of late Ibexian ($\approx$ Floian) age.

Lipid biomarker and stable isotope analysis by Lee *et al.* (2019) has indicated that the formation was deposited in a semi-restricted and shallow oxygenated marine environment with high salinity dominated by bacterial primary producers.

Valhallfonna Formation (Lower–Middle Ordovician)

The base of the Valhallfonna Formation is placed where the limestone succession becomes dark coloured. The formation is subdivided into the Olenidsletta and Profilbekken members. The Olenidsletta Member is composed of partly nodular, black to dark grey finely laminated limestone interbedded with shale and marl. The sequence contains a rich trilobite and graptolite fauna which has been described by Fortey and Bruton (1973), Fortey (1974a, b, 1975a, b, 1976, 1979, 1980), and Cooper and Fortey (1982). The basal beds of the Olenidsletta Member have a profusion of current-oriented orthocone nautiloids. Reconstructions of the palaeofacies indicate that most of the Olenidsletta Member was deposited in calm deep water (Fortey and Barnes 1977; Fortey and Cocks 2003; Hansen and Holmer 2011; Lee *et al.* 2019) with low oxygen concentrations in the near-bottom water layers including episodes of photic zone euxinia.

The overlying Profilbekken Member is dominated by laminated limestone and discontinuity surfaces in the lower part. The basal part of the Profilbekken Member contains a conspicuous basal phosphatic horizon. Other phosphatic horizons also occur higher up in the section. Fortey (1980) presumed that these horizons are due to former upwelling. Well preserved radiolaria

(Maletz and Bruton 2007, 2008) are often associated with these horizons and their unusual abundance may also record plankton blooms. Low-relief discontinuity surfaces are common in the lower part of the member. The middle part contains several horizons with glauconitic sand followed by bedded limestones showing upward thickening. The skeletal faunal assemblage is rich and diverse. Bockelie and Fortey (1975) indicated that the sequence was deposited in a shallow shelf environment with a well oxygenated sea floor.

SYSTEMATIC DESCRIPTION OF THE TRACE FOSSILS

Ichnogenus *Alcyonidiopsis* Massalongo, 1856
Alcyonidiopsis isp.
 (Text-fig. 4A)

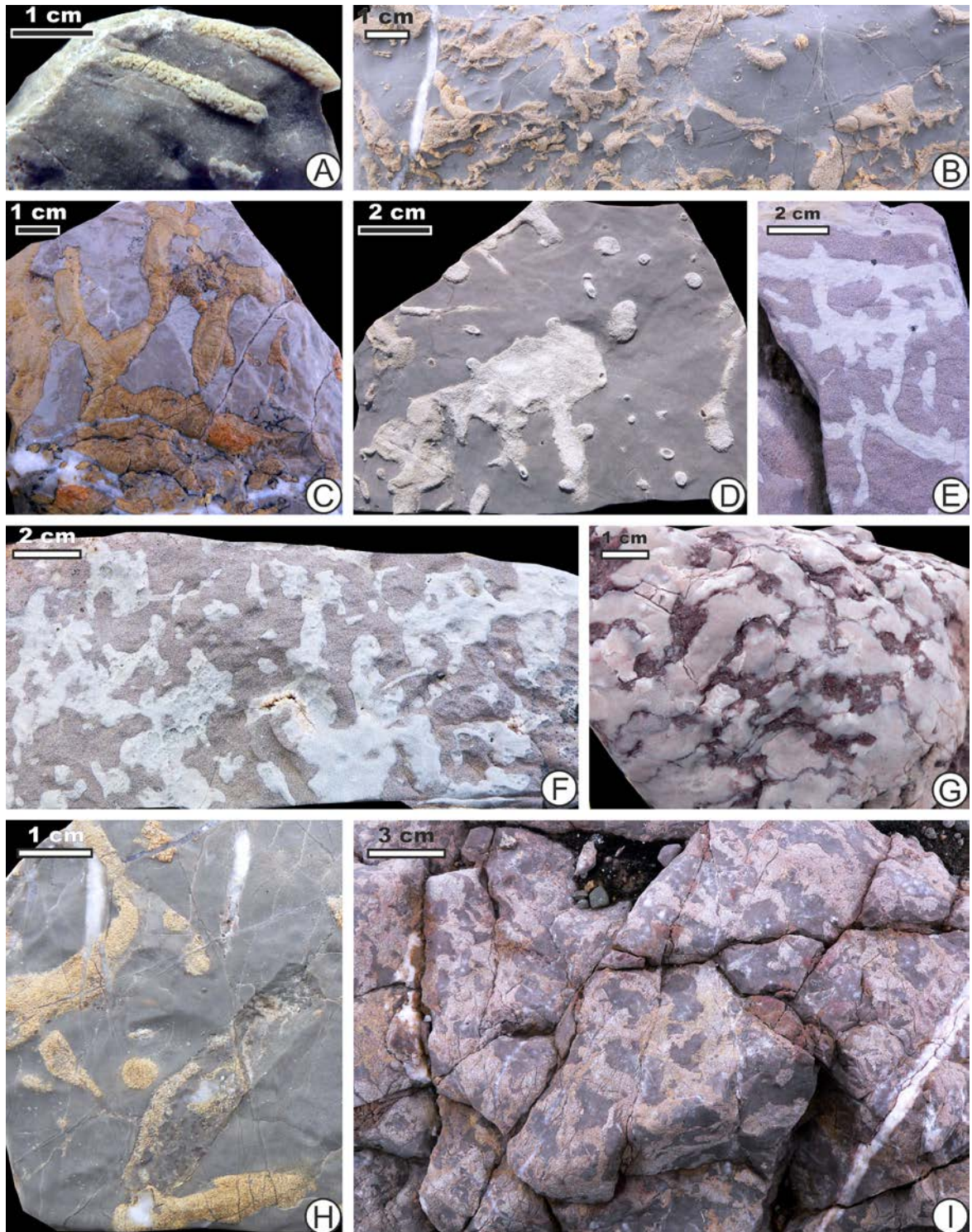
MATERIAL AND OCCURRENCE: Three specimens, INGUJ208P11, 21, and 22, rarely in the Ditlovtoppen Dolomite Member of the Tokammane Formation, to the east of section K.

DESCRIPTION: Horizontal or oblique, straight or slightly winding unbranched cylinders, 1.0–1.2 mm in diameter, traced for maximum 11 mm, filled with subrounded, white pellets which are 0.2–0.3 mm in diameter.

REMARKS: The pellets are recrystallised. *Alcyonidiopsis* was probably produced by polychaetes who filled their burrows with faecal pellets. Its stratigraphic range was considered from the Ordovician (Chamberlain 1977) to the Miocene (Uchman 1995), but the occurrence in the Ditlovtoppen Dolomite Member of the Tokammane Formation pushes its back to at least the Cambrian Series 2. This corresponds to the occurrence of pelleted burrows having affinity for *Alcyonidiopsis*, which occur in the upper part of the Cambrian Series 2 in southern China (Hu *et al.* 2021).

Ichnogenus *Balanoglossites* Mägdefrau, 1932
Balanoglossites isp.
 (Text-figs 3G, 4B–I)

MATERIAL AND OCCURRENCE: Six specimens, INGUJ208P5, 6, 7, 9, 12, 15. Abundant in several horizons of the Ditlovtoppen Dolomite Member of the Tokammane Formation (section K, NW of section K, and along the Spora stream) and the Profilbekken Member of the Valhallfonna Formation, section E.



Text-fig. 4. Trace fossils from the Cambrian and Ordovician at Basissletta. A – *Alcyonidiopsis* isp., INGJ208P22, Ditlovtoppen Dolomite Member of the Tokammane Formation, E of section K. B–I – *Balanoglossites* isp. in field photographs; B, H – dolomitised, pelleted filling; C – dolomitised and silicified (?) filling; G – red, marly limestone between burrows; D–F – network of burrows with swellings, constrictions and blind tunnels; I – boxwork pattern; B is from the Ditlovtoppen Dolomite Member of the Tokammane Formation, NW of sections K; C, D, H are from the Ditlovtoppen Dolomite Member of the Tokammane Formation, lower part of section K; E, F are from the Ditlovtoppen Dolomite Member of the Tokammane Formation, along the Spora stream; G is from the Ditlovtoppen Dolomite Member of the Tokammane Formation, NW of section K; I is from the Profilbekken Member of the Valhallfonna Formation, along the Profilbekken stream.

DESCRIPTION: A system of branched galleries forming a boxwork structure comprising uneven, unlined tunnels showing swellings, constrictions, and blind ends. Within the same burrow system, the swollen parts can be up to 25 mm wide whereas the narrow passages can be 4–6 mm in diameter. In horizontal planes, the galleries form irregular polygons, the majority 20–25 mm wide. The filling differs in colour and/or grain size from the surrounding rock. The trace fossil occurs in limestones and dolomites. The filling can be dolomitic and the surrounding rock a limestone, or *vice versa*. Some galleries are filled with sub-millimetre pellets.

REMARKS: Some burrows have been strongly transformed by diagenetic processes. Dissolution seams are common along some galleries. This trace fossil can be mistaken for *Thalassinoides* Ehrenberg, 1944 (for example in Ordovician carbonates, see Ekdale and Bromley 2003), but the swelling, constrictions and blind ends are typical of *Balanoglossites* (Knaust 2008). The described trace fossil can be compared to *B. triadicus* Mägdelfrau, 1932 or *B. ramosus* Knaust, 2008, but it is not clear whether those two ichnospecies show a boxwork pattern.

Balanoglossites is commonly found in shallow-marine, soft, firm and hardground carbonate substrates in the lower Paleozoic, being first found in the Cambrian (Knaust and Dronov 2013) and it also occurs in the Triassic (Każmierczak and Pszczółkowski 1969; Knaust 2008), including hypersaline and/or oxygen-restricted facies (Jaglarz and Uchman 2010; Rychliński and Uchman 2010; Knaust and Costamagna 2012). It is interpreted as a burrow of sipunculans and polychaetes (Knaust 2008) or polychaetes only (Knaust and Costamagna 2012).

Ichnogenus *Curvolithus* Fritsch, 1908

Curvolithus simplex Buatois, Mángano, Mikuláš and Maples, 1998
(Text-fig. 5A–C)

MATERIAL AND OCCURRENCE: Three specimens, INGJ208P2, 4, and 10, rare in the Profilbekken Member of the Valhallfonna Formation, section E.

DESCRIPTION: Endichnial or hypichnial trilobate band-like, straight or slightly curved structure, which is 13–20 mm wide. Its central part is slightly convex and elevated or slightly concave and depressed. It is bordered by two lateral semicircular bevels which are up to 3 mm wide.

REMARKS: *Curvolithus* is interpreted as a locomotion trace (repichnion), produced most probably by carnivorous gastropods (Heinberg 1973) similar to those made by recent representatives of the Cephalaspidae family (Heinberg and Birkelund 1984) or by tubellarian flat worms (Seilacher 1990). Additionally, Buatois *et al.* (1998) included scavenging gastropods and nemertean worms as possible trace makers.

Curvolithus occurs from the Precambrian (Webby 1970) to the Miocene (Keij 1965) in various shallow marine or even brackish clastic sediments, including distal fan deltas, tidal flats and offshore settings (see Buatois *et al.* 1998, for review). It is rarely noted in calcareous sediments (Krobicki and Uchman 2003; this paper).

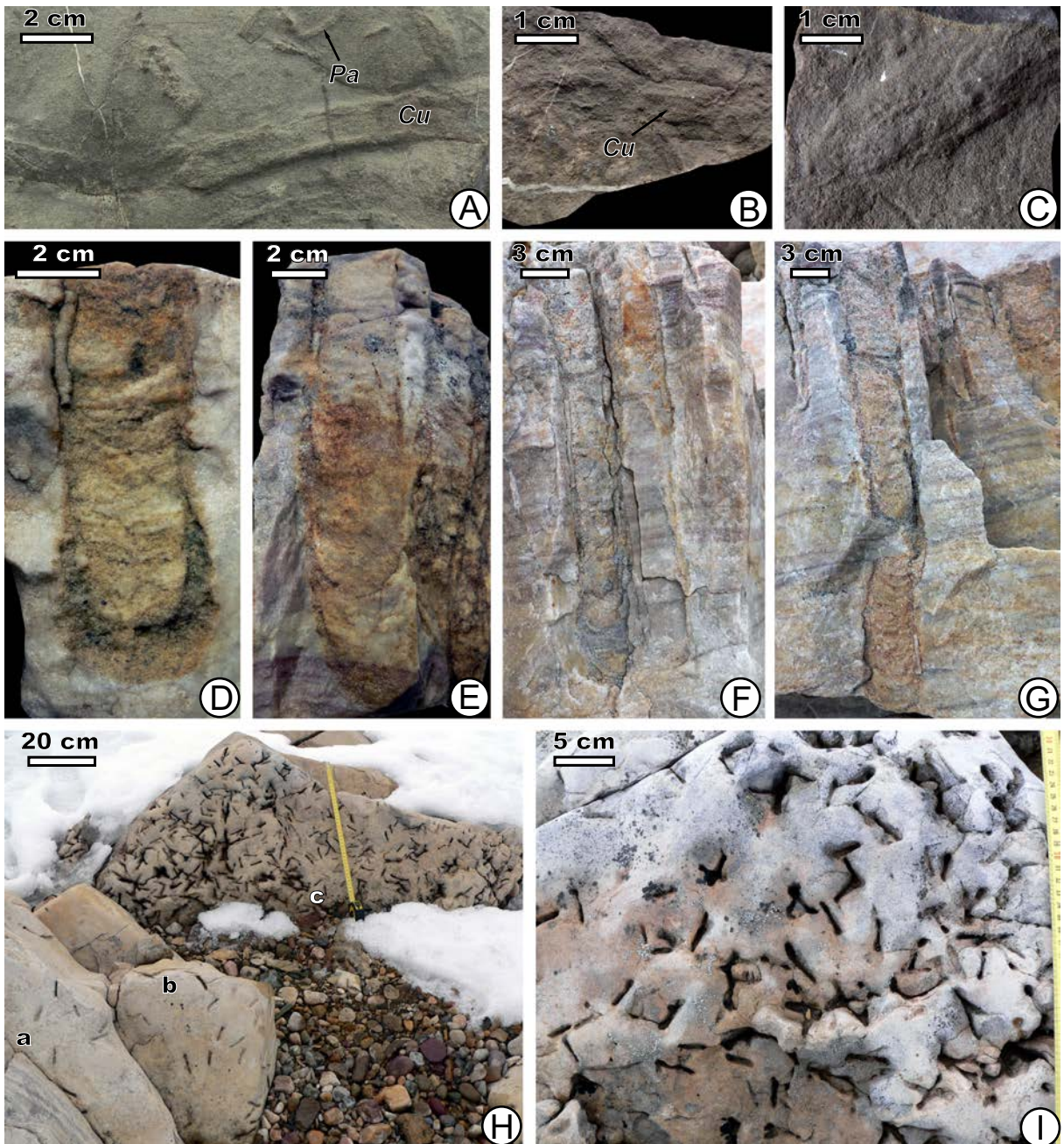
Ichnogenus *Diplocraterion* Torell, 1870

Diplocraterion parallelum Torell, 1870
(Text-fig. 5D–I)

MATERIAL AND OCCURRENCE: Four specimens, INGJ208P16, 17, 18, 19, common in the Blårevbreen Sandstone Member of the Tokammane Formation, along the Spora stream, and S of the Spora stream.

DESCRIPTION: Vertical or subvertical, straight, slightly curved or slightly twisted, U-shaped structure showing cylindrical, lined marginal tunnel and arcuate, convex-down spreiten between the tunnel limbs. The trace fossil is 15–30 mm wide, 60–240 mm deep. The spreiten are 1.5–5 mm thick, and the marginal tunnel is 2–5 mm in diameter. Limbs of the marginal tunnel are parallel and the vertices are semi-circular in outline. In some specimens, the lower part of the trace fossil is slightly wider than the higher part (Text-fig. 5D). In horizontal section, this trace fossil is visible as ‘dumbbell’ structures (Text-fig. 5H, I). They do not show any distinct orientation. Some of them intersect when they are crowded (up to 1100 burrows/m²).

REMARKS: Most burrows are protrusive, rarely retrusive, *sensu* Goldring (1962). Intersections between crowded *D. parallelum* are a usual feature (Bromley and Hanken 1991; Goldring *et al.* 1998). The enlarged lower part can be an expression of ontogenic growth of the tracemaker (see Bromley and Hanken 1991). *Diplocraterion parallelum* is common in lower Cambrian shallow-marine sandstones (e.g., Bromley and Hanken 1991; Paczeńska 1996; Jensen 1997; Stachacz 2016). In Jurassic shallow-marine si-



Text-fig. 5. Trace fossils from the Cambrian and Ordovician at Basissletta. A–C – *Curvolithus* isp. (*Cu*) and *Palaeophycus tubularis* (*Pa*), Profilbekken Member of the Valhallfonna Formation, section E; A – field photograph; B – INGJ208P2; C – INGJ208P4. D–I – *Diplocraterion parallelum*, Blårevbreen Sandstone Member of the Tokamane Formation, along the Spora stream; note slightly widened lower part of the burrow in D (INGJ208P18, protrusive form, section C), but not in E (INGJ208P19, retrusive form, section C); slightly curved burrow in F (field photograph, section C) and winding in G (field specimen, section C); three colonisation surfaces (a, b, c) in H (field photograph, S of the Spora stream) and bedding plane view in I.

liciclastics, *D. parallelum* occurs commonly in very shallow subtidal to intertidal facies (e.g., Fürsich 1974b, 1981; Bromley and Uchman 2003), characteristically in transgressive surfaces (e.g., Mason and

Christie 1986; Dam 1990; Taylor and Gawthorpe 1993; Goldring *et al.* 1998), but also in sequence boundaries in physically unstable environments showing a transition from the Cruziana ichnofacies

to the mixed *Cruziana*-*Skolithos* ichnofacies (Olóriz and Rodríguez-Tovar 2000). The absence of correlation with grain size suggests a suspension-feeding trace maker (Fürsich 1974a, 1981). *Diplocraterion parallelum* occurs mostly in fully marine deposits, less commonly in brackish deposits, as exemplified by the Bathonian of Kutchch, India, on the basis of the associated macrofauna (Fürsich *et al.* 1994).

Ichnogenus *Monocraterion* Torell, 1870

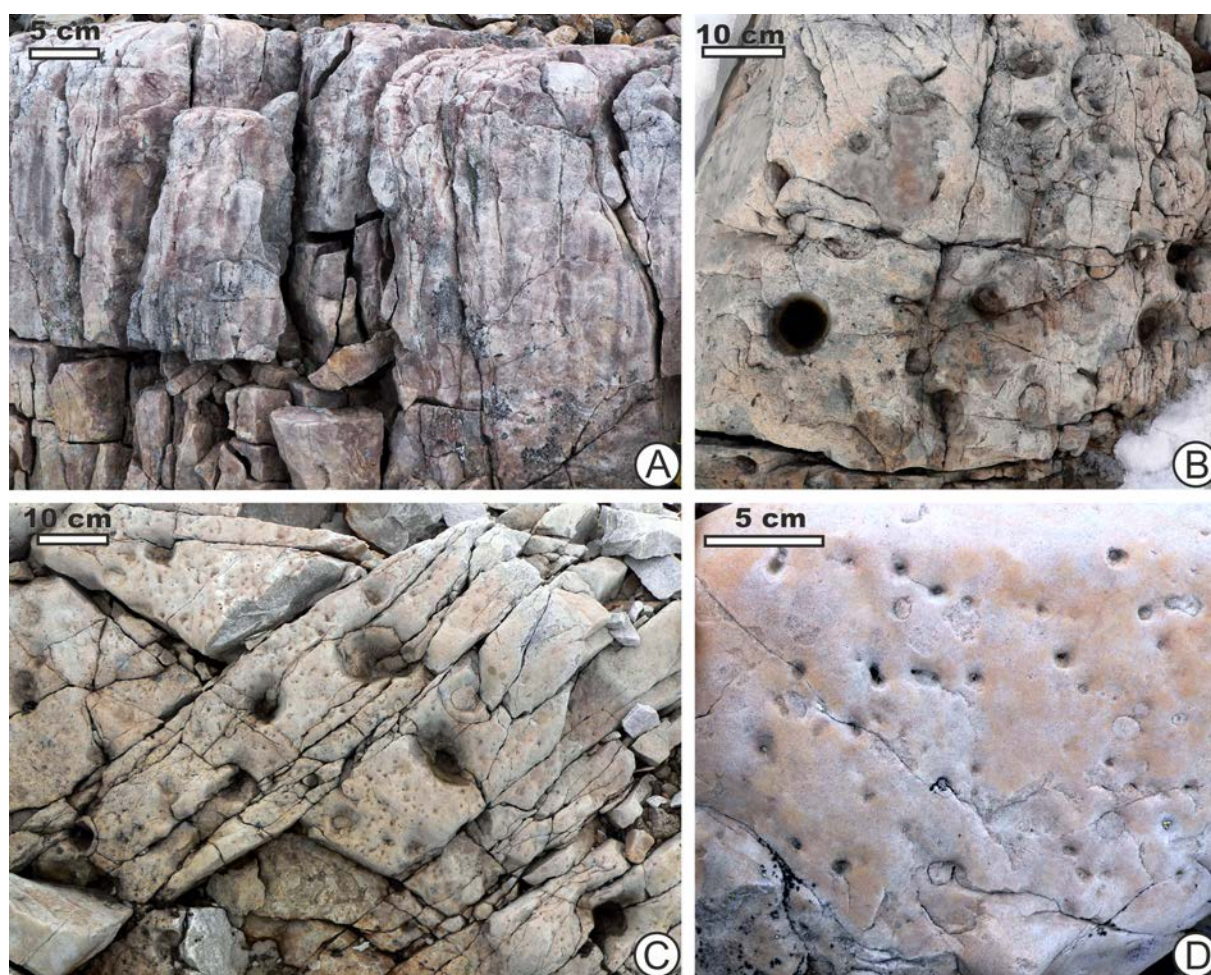
Monocraterion isp.

(Text-fig. 6A–D)

MATERIAL AND OCCURRENCE: Field observations, Blårevbreen Sandstone Member of the Tokammane Formation, along the Spora stream, and S of the Spora stream.

DESCRIPTION: Vertical or subvertical, cylindrical tubes, 3–6 mm in diameter, up to at least 400 mm long, with a deep funnel at the top. The funnel is circular, elliptical or oval in outline, up to 30–100 mm wide and up to 120 mm (mostly 30–45 mm) deep. It is empty or filled, with or without a rimming levee (Text-fig. 6B, C). The filling is either massive or shows concentric partitioning (usually only two rings in horizontal section). In some bedding planes the funnel is much narrower, with maximum width up to 10–15 mm (Text-fig. 6D).

REMARKS: *Monocraterion tentaculatum* Torell, 1870, the type ichnospecies of this ichnogenus, is characterised by tubular elements radiating from the funnel (Jensen 1997), but this feature is absent in the trace fossil studied. The burrows showing the smaller funnel could have been truncated at the top by ero-



Text-fig. 6. *Monocraterion* isp., field photographs, Blårevbreen Sandstone Member of the Tokammane Formation (Fortunian). A – Pipe rock appearance, vertical cross-section, section C; B–D – Bedding plane views with filled and unfilled funnels; B is from locality close to section C; C is from section B; D shows small, probably truncated funnels from section C.

sion, rendering them similar to *Skolithos* Haldeman, 1840 (see Hallam and Swett 1966; Fillion and Pickerill 1990).

Monocraterion is a domichnial structure produced by suspension feeders, common in lower Cambrian sandstones (e.g., Westergård 1931; Hallam and Swett 1966; Jensen 1997; Paczeńska 2006; Stachacz 2016). For discussion of this ichnogenus see Jensen (1997) and Schlirf and Uchman (2005).

Ichnogenus *Palaeophycus* Hall, 1847

Palaeophycus tubularis Hall, 1847

(Text-fig. 7D)

MATERIAL AND OCCURRENCE: One specimen, INGJ208P4, rare in the Profilbekken Member of the Valhallfonna Formation, section E.

DESCRIPTION: Horizontal, straight or curved, unbranched, thinly lined cylinders, 2–3 mm in diameter.

REMARKS: *Palaeophycus* is produced by deposit-feeding or carnivorous ‘worm-like’ invertebrates in many environments (e.g., Pemberton and Frey 1982; Fillion and Pickerill 1990; Keighley and Pickerill 1995).

Ichnogenus *Phycodes* Richter, 1850

Phycodes cf. *palmatus* (Hall, 1852)

(Text-fig. 7A–C)

MATERIAL AND OCCURRENCE: One specimen, INGJ208P1, rare in the Profilbekken Member of the Valhallfonna Formation, section E.

DESCRIPTION: Hypichnial or endichnial bunch of 5–9 diverging tubular cylinders or petal structures, which are subhorizontal or inclined, straight or slightly curved, rarely branched, 3–10 mm wide and up to 50 mm long.

REMARKS: The petal structures (Text-fig. 7A) may result from overlaps of cylinders. *Phycodes* is regarded as a feeding structure produced by unknown organisms. In the Paleozoic, it is known mostly from shallow-marine sediments. For discussion of this ichnogenus see Osgood (1970), Fillion and Pickerill (1990), Han and Pickerill (1993), and Seilacher (2000).

Ichnogenus *Planolites* Nicholson, 1873

Planolites beverleyensis Billings, 1862

(Text-fig. 7E–H, L)

MATERIAL AND OCCURRENCE: Four specimens, INGJ208P2, 3, 13, and 14, a few specimens in the Profilbekken Member of the Valhallfonna Formation, section E. Moreover, Ditlovtoppen Dolomite Member of the Tokammane Formation, section D.

DESCRIPTION: Endichnial or hypichnial horizontal or subhorizontal, simple, tubular, straight, curved or slightly winding structures without a wall, which can be traced for several centimetres. Their filling is the same as the host rock or differs only slightly. Two size classes are observed: 5–10 mm and 14–15 mm wide.

REMARKS: It cannot be excluded that some of the poorly preserved forms may belong to other ichnospecies of *Planolites* or even other ichnogenera. *Planolites* is interpreted mostly as a deposit-feeding structure mainly produced by ‘worm-like’ invertebrates belonging to many systematic groups and in many environments (e.g., Pemberton and Frey 1982; Fillion and Pickerill 1990; Keighley and Pickerill 1995; and references therein).

Planolites montanus Richter, 1937

(Text-fig. 7F, L)

MATERIAL AND OCCURRENCE: Two specimens, INGJ208P3 and 23, and a few observations in the Profilbekken Member of the Valhallfonna Formation, section E.

DESCRIPTION: Horizontal, oblique, curved, rarely straight, unbranched cylinders without a wall, 1.5–2.5 mm, plunging into or emerging from interfaces. Usually, they occur in dense aggregations.

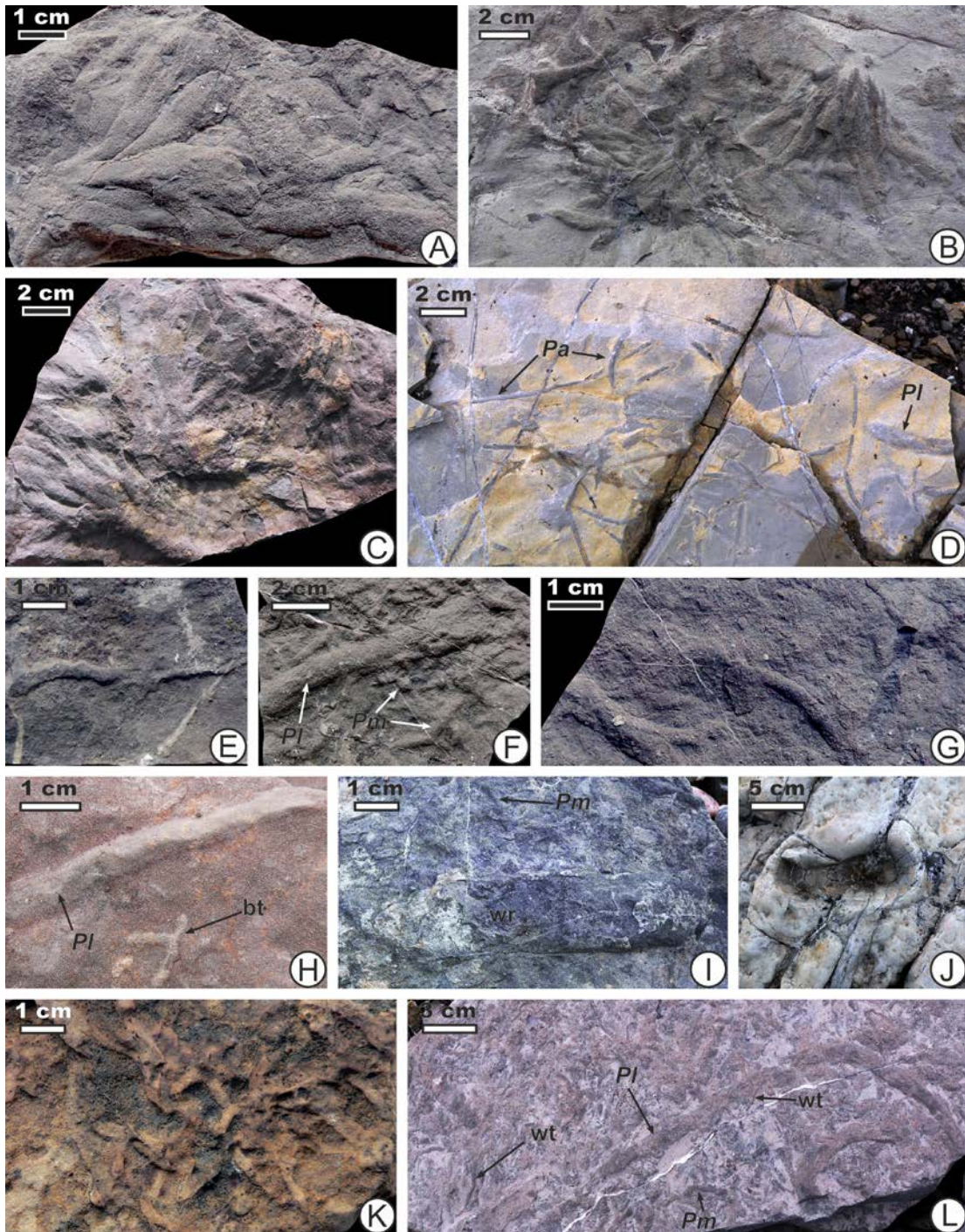
REMARKS: Dense covering of the interfaces suggests deposit feeding activity.

Branched tunnels

(Text-fig. 7H, K)

MATERIAL AND OCCURRENCE: Two specimens, INGJ208P5, 15, Basissetta Member of the Kirtonryggen Formation, section G. Also field observations in the Ditlovtoppen Dolomite Member of the Tokammane Formation, section D.

DESCRIPTION: Horizontal, rarely branched tunnels, 1.5–2 mm in diameter, traced for a distance of about 10 mm, and filled with different material than the surrounding rock. The only branch runs at an angle of <80°.



Text-fig. 7. Trace fossils from the Cambrian and Ordovician at Basissletta. A–C – *Phycodes* cf. *palmatus*, Profilbekken Member of the Valhallfonna Formation, section E; A – INGJ208P1, B, C – field photographs. D – *Palaeophycus tubularis* (Pa) and *Planolites beverleyensis* (Pl), field photograph, along the Profilbekken stream. E – *Planolites beverleyensis*, INGJ208P2, Profilbekken Member of the Valhallfonna Formation, section E. F – *Planolites beverleyensis* (Pl) and *Planolites montanus* (Pm), INGJ208P3, Profilbekken Member of the Valhallfonna Formation, section E. G – *Planolites beverleyensis*, INGJ208P13, Profilbekken Member of the Valhallfonna Formation, section E. H – *Planolites beverleyensis* (Pl) and a branched tunnel (bt), field photograph, Ditlovtoppen Dolomite Member of the Tokammane Formation, section D. I – Wide ridge (wr) and *Planolites montanus* (Pm), field photograph, Profilbekken Member of the Valhallfonna Formation, section E. J – Elongate depression, field photograph, Blårevbreen Sandstone Member of the Tokammane Formation (Fortunian), south of the Spora stream. K – Branched tunnels, INGJ208P5, Basissletta Member of the Kirtonryggen Formation, section G. L – *Planolites beverleyensis* (Pl), winding tunnels (wt), and *Planolites montanus* (Pm), field photograph, Profilbekken Member of the Valhallfonna Formation, along the Profilbekken stream.

REMARKS: Some similarities to *Chondrites* can be invoked but the limited preservation precludes a closer determination.

Winding tunnels
(Text-fig. 7L)

MATERIAL AND OCCURRENCE: Field observations in the Profilbekken Member of the Valhallfonna Formation, section E.

DESCRIPTION: Horizontal, winding or strongly curved tunnels, 1.0–1.3 mm wide, observed over a distance of up to 25 mm.

REMARKS: It is not excluded that this trace fossil belongs to *Helminthoidichnites* Fitch, 1850 but the limited preservation precludes a closer determination.

Wide ridge
(Text-fig. 7I)

MATERIAL AND OCCURRENCE: Field observations in the Profilbekken Member of the Valhallfonna Formation, section E.

DESCRIPTION: Horizontal, low, semicircular, straight, smooth ridge, 184 mm long, up to 19 mm wide, with semicircular terminations which seem to plunge gently into the bed.

REMARKS: This single specimen probably is part of a wide U-shaped burrow.

Elongate depression
(Text-fig. 7J)

MATERIAL AND OCCURRENCE: Field observations in the Blårevbreen Sandstone Member of the Tokammane Formation, south of the Spora stream.

DESCRIPTION: A single, elongate epichnial depression in a sandstone bed, 150 mm long, up to 40 mm wide, encircled by a semicircular levee, which is 10–50 mm wide.

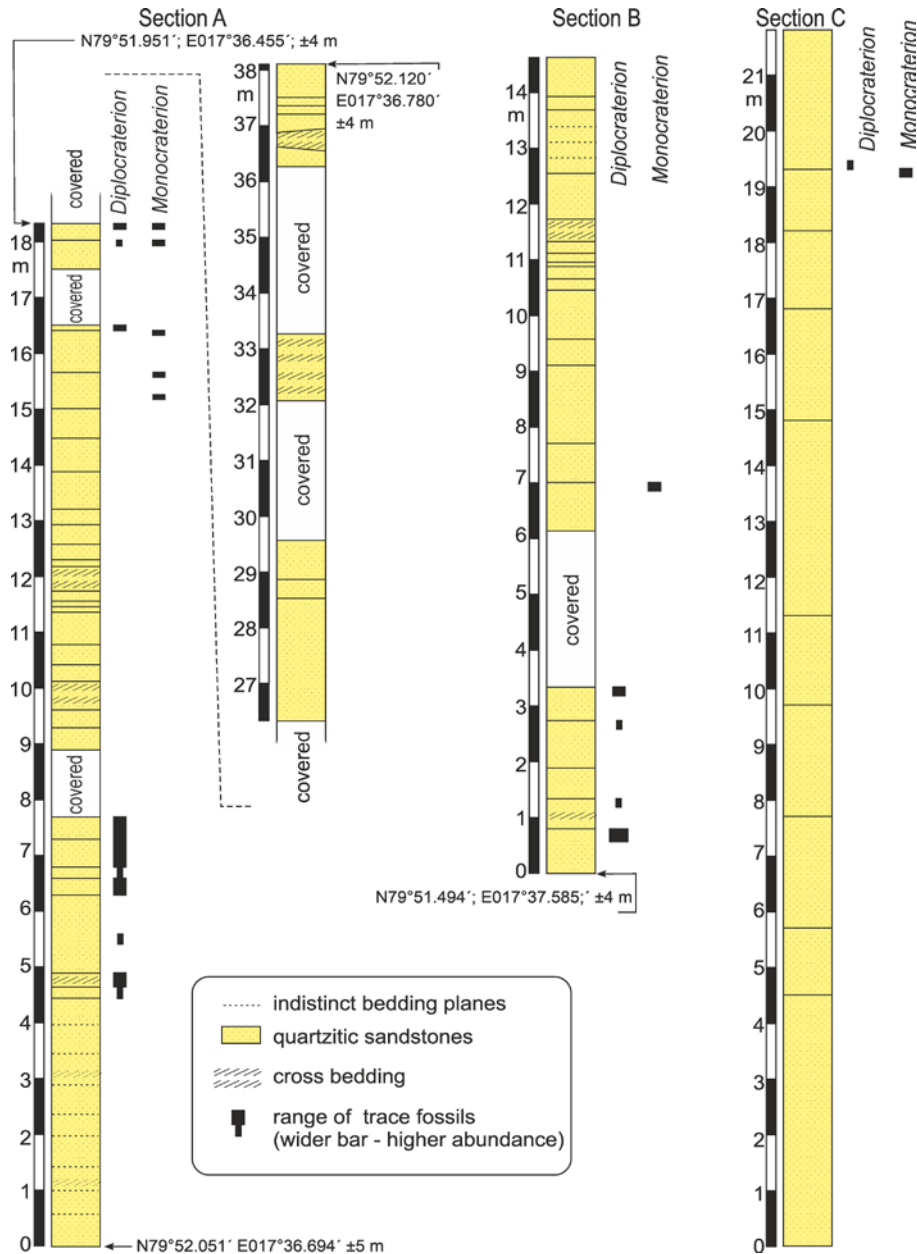
REMARKS: The shape of the depression does not fit any particular ichnotaxon, but it does suggest a cubichnion.

DISCUSSION

There have been several attempts to reconstruct the geological setting of the Ordovician sequence at Basissletta. The first palaeogeographic model by Fortey (1975a) was based on Early Ordovician trilobite communities whereas a sea-level curve was based on the diversity of the brachiopod fauna (Hansen and Holmer 2010). Kröger *et al.* (2017) subdivided the Ordovician part of the sequence into five 3rd-order depositional sequences which were interpreted as representing the Laurentian platform Sauk IIIB Supersequence. The analysis of trace fossils described in this paper allows us to supplement these interpretations.

The trace fossils can be grouped into ichnoassemblages attributed to major facies groups. The lower Cambrian sandstones (Tokammane Formation: Blårevbreen Sandstone Member) are characterised by the *Diplocraterion*–*Monocraterion* ichnoassemblage, which also includes the only find of an elongate depression. This ichnoassemblage is typical of the Skolithos ichnofacies, which indicates the high-energy zone above the normal wave base and with a shifting substrate, where animals construct mainly domichnia for filter feeding (Seilacher 1967; Pemberton *et al.* 2001). These trace fossils occur in some beds or bed packages (Text-figs 3B, 8), while other beds are unbioturbated (Text-figs 3A, 8). The density of the trace fossils can vary from bed to bed, from dense ('pipe rock' type) to sparse occurrences. The colonisation surfaces may reflect lowered energy periods during which the bedforms were stable (cf. Hallam and Swett 1966) and the colonisation window was open. The bedforms suggest a shelf sea floor with migrating and periodically stabilised subtidal sand dunes (Desjardin *et al.* 2010). It is worth mentioning that the Terreneuvian (Fortunian) age of the sandstones presented by Smelror *et al.* (2024, their fig. 2) is somewhat challenging because the similar Pipe Rock Member of the Eriboll Formation in Scotland (part of Laurentia) is placed in the lower part of the Cambrian Series 2 (Rushton and Molyneux 2011), similarly to the Swedish Mickwitzia Sandstone in Baltica (Nielsen and Schovsbo 2011), which is rich in *Diplocraterion* and *Monocraterion* (Westergård 1931; Jensen 1997). More realistically, Stouge *et al.* (2012) marked the Blårevbreen Sandstone Member in the upper part of Cambrian Series 2.

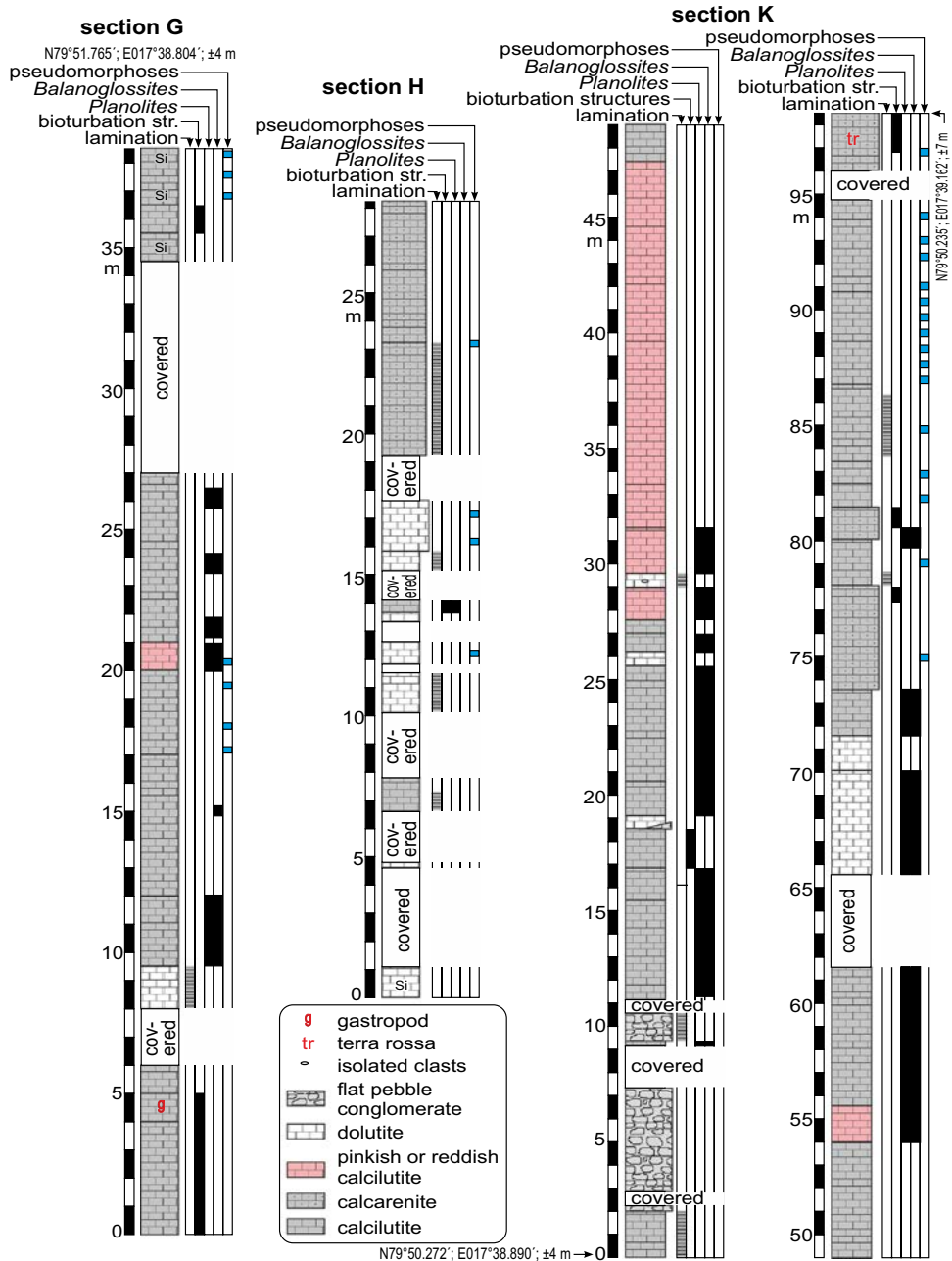
The overlying carbonate sediments of the Ditlovtoppen Member of the Tokammane Formation and the Kirtonryggen Formation display many horizons with *Balanoglossites*, which is locally accompanied



Text-fig. 8. Lithological logs of sections A–C of the Blårevbreen Sandstone Member of the Tokammane Formation (Fortunian), along the Spora stream, showing the distribution of trace fossils. For location of sections see Text-fig. 1.

by *Planolites* (Text-figs 9 and 10). This ichnoassemblage represents the impoverished Cruziana ichnofacies. For comparison, the Middle Ordovician carbonate deposits of the Trenton Group in eastern Canada show a diverse trace fossil assemblage (23 ichnogenera) of the Cruziana ichnofacies (Pickerill and Forbes 1979; Fillion and Pickerill 1984). The *Balanoglossites* ichnofabric is the main macroscopic feature of the rock. The visibility of the burrows is diverse. They

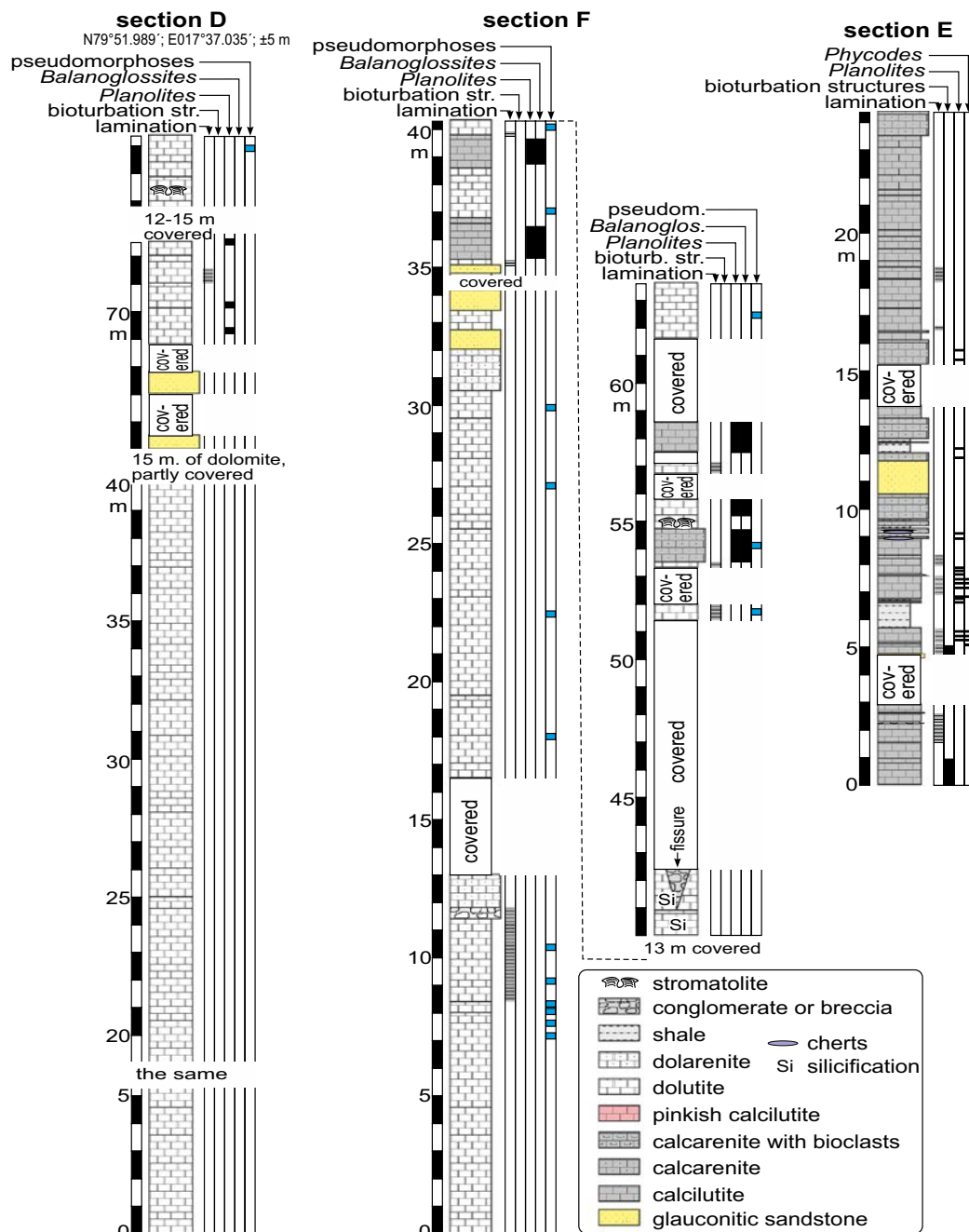
are commonly partly transformed by diagenetic processes. The presence of caverns with pseudomorphs after evaporites (Text-figs 3F, 9, 10), horizons of collapse breccia, flat-pebble conglomerates, absence or scarcity of macrofossils, and prevailing lutitic grain-size suggest a low-energy evaporitic environment, probably a lagoon, where the hypersaline stressed conditions limited the diversity of burrowing organisms (cf. Jaglarz and Uchman 2010).



Text-fig. 9. Lithological logs of measured sections of the Basissletta Member of the Kirtonryggen Formation (sections G, H), and the Ditlovtoppen Dolomite Member of the Tokammane Formation (section K) showing the distribution of trace fossils and selected sedimentary features. For location of sections see Text-fig. 1, for their stratigraphic position see Text-fig. 2.

The younger Ordovician carbonate and the mixed carbonate-clastic sediments with bioclasts of the Valhallfonna Formation display a more diverse but poorly preserved trace fossil assemblage typical of the archetypal and distal *Cruziana* ichnofacies (*Phycodes*, *Curvolithus*), characterised mostly by horizontal fodinichnia and pascichnia (see Seilacher

1967; Pemberton *et al.* 2001). This indicates an environment between the normal and storm wave base. The influence of storms is confirmed by the presence of beds showing hummocky cross-stratification (Text-fig. 3H) and beds showing graded bedding, though both are rare and the sediments are mostly bioturbated. However, packages of dark grey



Text-fig. 10. Lithological logs of measured sections of the Ditlovtoppen Dolomite Member of the Tokammane Formation (sections D, F) and the Profilbekken Member of the Valhallfonna Formation (section E) showing the distribution of trace fossils and selected sedimentary features.

For location of sections see Text-fig. 1, for their stratigraphic position see Text-fig. 2.

and black carbonate deposits showing thin bedding or fine lamination (observed also by Vallance and Fortey 1968) may indicate oxygen-depleted sediment intervals, possibly deposited below the storm wave base. Oxygenation fluctuated as indicated by the alternations of bioturbated and unbioturbated

(laminated) sediments (Profilbekken Member of the Valhallfonna Formation, section E).

The succession from the Skolithos ichnofacies, to the archetypal and then the distal Cruziana ichnofacies indicates the general decrease in energy of this relatively stable margin of Laurentia. The change took

place during c. 70 myr (including the possible gap for the Miaolingian and Furongian). The significant evolutionary changes, such as the Great Ordovician Biodiversification Event (e.g., Servais and Harper 2018) are masked by unfavourable environmental conditions (periodic hypersalinity, lower oxygenation). The increase in trace fossil diversity in the Vallhallfonna Formation took place after the event and was linked to local environmental changes (transition from hypersaline to normal saline conditions). Moreover, deposition of carbonates with a low sedimentation rate, as also reported from coeval Baltica sites (e.g., Dronov 2013), caused a concentration of edible organic matter close to the sediment/water interface and consequent shallow burrowing with low preservation potential of trace fossils (cf. Stachacz *et al.* 2018). Together these factors are responsible for the much lower ichnodiversity in the investigated Ordovician of Laurentia in comparison with, e.g., the peri-Gondwanan sections or other parts of Laurentia.

CONCLUSIONS

The sandstones of the Tokammane Formation (Terreneuvian) in the Basissletta region are characterised by the Skolithos ichnofacies, which points to deposition in a shallow subtidal setting.

The overlying carbonates of the Tokammane and Kirtonryggen formations show an impoverished Cruziana ichnofacies related to oxygenated and partly hypersaline environments. The hypersaline conditions mask the expected record of the Great Ordovician Biodiversification Event.

The carbonates and the mixed carbonate-clastic deposits of the Vallhallfonna Formation (Lower–Middle Ordovician) display a more diverse but poorly preserved assemblage of trace fossils of the archetypal Cruziana ichnofacies. They, along with sedimentary features, suggest deposition mostly between normal and storm wave base or below the storm wave base in oxic to anoxic environments.

The succession of the ichnofacies points to long-term slow decrease in energy (possible deepening) in this part of Laurentia

Postscript

This paper is addressed to the jubilee of Prof. Michał Szulczewski, who is known from his work in Palaeozoic deposits, including ichnology, during his expedition on Spitsbergen.

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