

New information on the Ediacaran–Cambrian transition in the Vestertana Group, Finnmark, northern Norway, from trace fossils and organic-walled microfossils

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The Vestertana Group on the Digermul Peninsula, Finnmark, northern Norway, presents one of the few, potentially continuous Ediacaran–Cambrian sections in Scandinavia. Trace fossils provide the main age constraint, with the boundary traditionally placed at the base of the Breidvika Formation. Here, we provide trace-fossil evidence to show that this boundary is at least as low as the third cycle of the Manndrapereelva Member, Ståhpogieddi Formation, where *Treptichnus pedum* is associated with trilobed trace fossils. Organic-walled microfossils from the same stratigraphic interval include *Granomarginata prima* and the first report from Scandinavia of *Cochleatina*. The second cycle of the Manndrapereelva Member contains trace fossils, including treptichnids and ?*Cochlichnus* isp. tentatively interpreted as latest Ediacaran. Reports of palaeopascichnids suggest a late Ediacaran age for the first cycle. The age of lower parts of the Ståhpogieddi Formation is poorly constrained but discoidal Ediacara-type fossils, vendotaenids, and possible simple trace fossils, suggest that the middle part of the Innerelva Member is younger than c. 560 Ma.

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Introduction

The increase in size and complexity of trace fossils from about 555 Ma to 535 Ma is an important manifestation of the radiation of bilaterian metazoans that took place at this time (e.g., McIlroy & Logan, 1999; Budd & Jensen, 2000; Droser et al., 2002; Erwin et al., 2011). This evolution of trace fossil morphotypes has been documented globally and is long known to have stratigraphical potential with the recognition of trace-fossil-based zones (e.g., Crimes, 1987; Mángano et al., 2012), culminating in the decision to define the basal Cambrian global stratotype section and point (GSSP) on trace fossils (Narbonne et al., 1987; Brasier et al., 1994). Although the broad patterns in trace-fossil evolution at this time are well established, sections where it can be observed without major breaks in sedimentation or facies changes are not common. The Ediacaran–Cambrian boundary type section on Fortune Head, Newfoundland, largely meets these criteria, with the GSSP defined at the then lowest known occurrence in the Chapel Island Formation of the three-dimensional burrow system *Treptichnus pedum* (as *Phycodes pedum*), and more generally at the base of the *Treptichnus pedum* Ichnozone, with the appearance of plug-shaped burrows

(*Bergaueria*) and vertical spiral burrows (*Gyrolithes*) (Narbonne et al., 1987). This contrasts with underlying beds where only morphologically simple trace fossils are found, and with the upper range of the problematic fossils *Harlaniella* and *Palaeopascichnus* a few decimetres below the GSSP. The ranges of Cambrian-type traces in the type section have subsequently been extended down-section, so that *Treptichnus* and *Gyrolithes* now overlap with *Palaeopascichnus* (Gehling et al., 2001). In addition, trace fossils similar (but not clearly identical) to *Treptichnus pedum* occur in strata traditionally considered Ediacaran in Namibia, and possibly elsewhere, where they overlap the stratigraphical range of some Ediacara-type fossils (Jensen et al., 2000). While this raises questions about stratigraphical resolution, it does not challenge the general validity of Ediacaran–Cambrian ichnostratigraphy, and may instead suggest a latest Ediacaran ichnozone with treptichnids (Jensen, 2003). Furthermore, recent revisions of radiometric ages from Namibia (Schmitz, 2012) suggest that some of these ‘Ediacaran’ occurrences of complex burrow systems (*Streptichnus narbonnei*; Jensen & Runnegar, 2005) are within the error of the currently accepted age of the base of the Cambrian (c. 541 Ma), and others (treptichnids; Jensen et al., 2000) may be only a few million years

older. Trace fossils therefore remain a powerful tool in Ediacaran–Cambrian transition biostratigraphy in successions dominated by siliciclastic rocks (Buatois et al., 2013).

The Digermul Peninsula, northern Norway (Fig. 1), is probably the only fossiliferous site in Scandinavia with sedimentation across the Ediacaran–Cambrian transition without a significant hiatus. The transition occurs in the Vestertana Group (Reading, 1965; Banks et al., 1971), which is a thick, largely siliciclastic unit. It contains in its upper part glacial diamictites possibly related to the Gaskiers glaciation, followed by mudstone and sandstone with Ediacara-type fossils and, higher still, Cambrian-type trace fossils and skeletal fossils (e.g., Farmer et al., 1992; Crimes & McIlroy, 1999). In an early study on trace-fossil evolution, Banks (1970) documented the initial appearance of small, simple trace fossils and, successively up-section, larger, simple trace fossils followed by branching trace fossils including

Treptichnus pedum, and higher still the appearance of trace fossils attributed to arthropods (*Rusophycus*). Later studies on trace fossils in the Vestertana Group (Farmer et al., 1992; McIlroy, 1995; McIlroy & Logan, 1999) have resulted in greater ichnotaxonomic diversity, but the general trend observed by Banks (1970) has been maintained, and to this date trace fossils provide the main age control on the upper part of the Vestertana Group. The base of the Cambrian has generally been positioned near the base of the Breidvika Formation, at the appearance of trace fossils like *Treptichnus pedum* and *Gyrolithes* (Banks, 1970; Farmer et al., 1992), an assemblage that corresponds closely to that of the *Treptichnus pedum* Ichnozone on Newfoundland. The appearance of *Rusophycus* further up-section in the Breidvika Formation indicates the succeeding *Rusophycus avalonensis* Ichnozone. Many workers have maintained the possibility of a slightly lower position of the Ediacaran–Cambrian boundary in the upper part of the Ståhpogieddi Formation (e.g., Farmer et al., 1992;

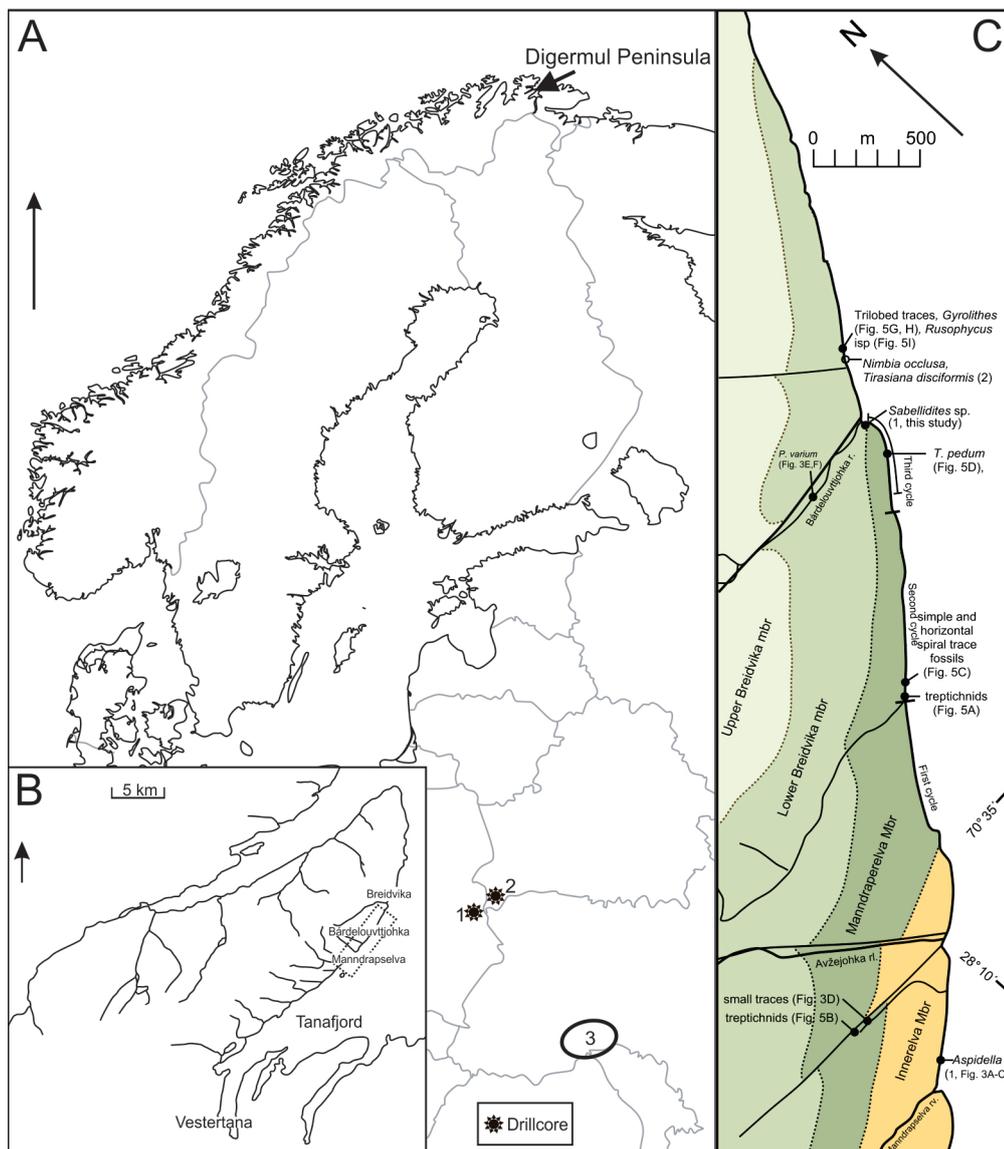


Figure 1. (A) Location of the Digermul Peninsula in northern Norway. Also indicated are selected locations in the East European Platform from which Lower Cambrian fossils comparable to those described from the Digermul Peninsula have been reported. 1: Kaplonosy drillcore in eastern Poland. 2: Stradech-17 drillcore in western Belarus. 3: Southern part of Podolia, Ukraine. (B) Map of the Digermul Peninsula, showing main geographical locations mentioned in the text. The stippled rectangle corresponds to an area detailed in Fig. 1C. (C) Map showing geology of the study area (based on Siedlecka et al., 2006) and fossil localities. Location of measured section (Fig. 2B) south of the mouth of the Bårdelouvtjøhoka rivulet is indicated by the curved line with terminal bars. Locations of Mandrapereiva Member cycle boundaries in coastal outcrop are indicated by vertical bars. Abbreviations: rv – river, rl – rivulet. References: 1 – Farmer et al. (1992), 2 – Crimes & McIlroy (1999).

Crimes & McIlroy, 1999), based on the relatively large size of some of the trace fossils in that unit. Nielsen & Schovsbo (2011) proposed that an even greater portion of the Ståhpogieddi Formation is Cambrian on the basis of an exhaustive sequence stratigraphy-based analysis of the Cambrian of Scandinavia. In their scheme, two regressive sedimentary cycles recorded at the top of the Ståhpogieddi Formation represent eustatic signals that may correspond to sequences in the Rovno Regional Stage of the Baltic area.

Here, we report on new finds of trace fossils from the upper part of the Ståhpogieddi Formation, including an extended stratigraphical range of *Treptichnus pedum*. We also present the first data on organic-walled microfossils from the Manndraperelva Member. Organic-walled microfossils have been widely used to characterise the Ediacaran–Cambrian transition in Baltica, and elsewhere (e.g., Moczyłowska, 1991). The new fossil data shed new light on the location of the Ediacaran–Cambrian boundary in the Vestertana Group, and more generally invites additional studies on the age of the lower part of the Ståhpogieddi Formation.

Geological setting

The Vestertana Group on the Digermul Peninsula is part of the basal Caledonian thrust sheet, the Gaiassa Nappe Complex, formed during an early phase of the Caledonian Orogeny. It is found elsewhere in Finnmark, notably on Varanger Peninsula, but the upper part of the Vestertana Group is nowhere so completely developed as on the Digermul Peninsula. The Vestertana Group was deposited in a shallow basin close to the northern (present coordinates) margin of Baltica, interpreted by Gorokhov et al. (2001), Roberts & Siedlecka (2002) and Nielsen & Schovsbo (2011) as a foreland basin developed ahead of the deformation front of the Timanian Orogeny. The lithostratigraphical terminology (Fig. 2) stems from Reading (1965) and Banks et al. (1971); the orthography used here follows Siedlecka et al. (2006), with common older spellings also indicated on the first mention below. The basal two formations of the Vestertana Group, the Late Cryogenian, glaciogenic Smalfjord Formation and the succeeding Nyborg Formation (siliciclastics and minor carbonates), are not developed in the study area and will not be further considered here. The Mortensnes Formation is a glaciogenic diamictite, the base of which is a regional unconformity; this formation has recently been tentatively correlated with the c. 580 Ma Gaskiers glaciation of Newfoundland on the basis of carbon isotope signals in the Nyborg Formation (see Rice et al., 2011). There exists no biostratigraphical age constraint on the Mortensnes Formation as the only fossils are non-age diagnostic and reworked organic-walled microfossils (sphaeromorphic acritarchs and vase-shaped microfossils) (Vidal, 1981; Vidal & Moczyłowska, 1995). The succeeding Ståhpogieddi (Stappogiedde) Formation is

divided into three members. The Lillevatn (Lillevatn) Member, in abrupt but apparently continuous succession with the Mortensnes Formation, consists of a lower unit of laminated siltstone and sandstone and an upper sandstone-dominated unit. It has been interpreted as a fluvial to shallow-marine deposit. The Innerelva (Innerelv) Member is dominated by laminated mudstone with several coarsening-upward sequences terminating in sandstone. Banks (1973) interpreted this member to have formed on a quiet marine shelf with occasional storm influence. Discoidal Ediacara-type fossils were recorded from the approximate middle of this unit (Farmer et al., 1992) (Fig. 2A). The basal part of the Manndraperelva (Manndrapselva) Member consists of a thick package of reddish sandstone, followed by two coarsening-upward cycles, each starting with mudstone and fine sandstone (greywackes), and terminating in cross-bedded sandstone. This development has been referred to as three cycles within the Manndraperelva Member (Fig. 2A), with the fine-grained sediments interpreted as distal and proximal turbidites, and the sandstone-dominated portions as deposited in a shallow-marine environment (Banks et al., 1971). The Breidvika (Breivik) Formation is divided into two informal members: the Lower Breidvika member consists of alternations of mudstone, siltstone and sandstone interpreted as a shallow-water marine deposit, and the Upper Breidvika member, dominated by mudstone, has been interpreted as an offshore shelf deposit. Compared to the Manndraperelva Member, the Lower Breidvika member shows a more rapid alternation of sediment types, and there is a greater proportion of green-coloured sediments.

The sedimentary succession from the Innerelva Member to the Lower Breidvika member has been interpreted as recording several episodes of relative shallowing but to date without clear evidence for any substantial break in sedimentation (e.g., Banks et al., 1971).

Review of earlier reports of fossils from the Ståhpogieddi and Breidvika formations

In the absence of reliable radiometric dates, fossils provide critical age constraints on the upper part of the Vestertana Group. In order to place in context the new fossil data reported here from the Manndraperelva Member, the principal published reports of fossils from the Ståhpogieddi and Breidvika formations will be briefly reviewed.

Innerelva Member. Farmer et al. (1992) reported discoidal Ediacara-type fossils as *Nimbia* sp.? in float from the lower part of the Innerelva Member, and *Ediacara?* sp., *Beltanella* sp., *Hiemalora* sp. and *Nimbia?* sp. from outcrops in the middle part of the member. If a different approach to the naming of discoidal

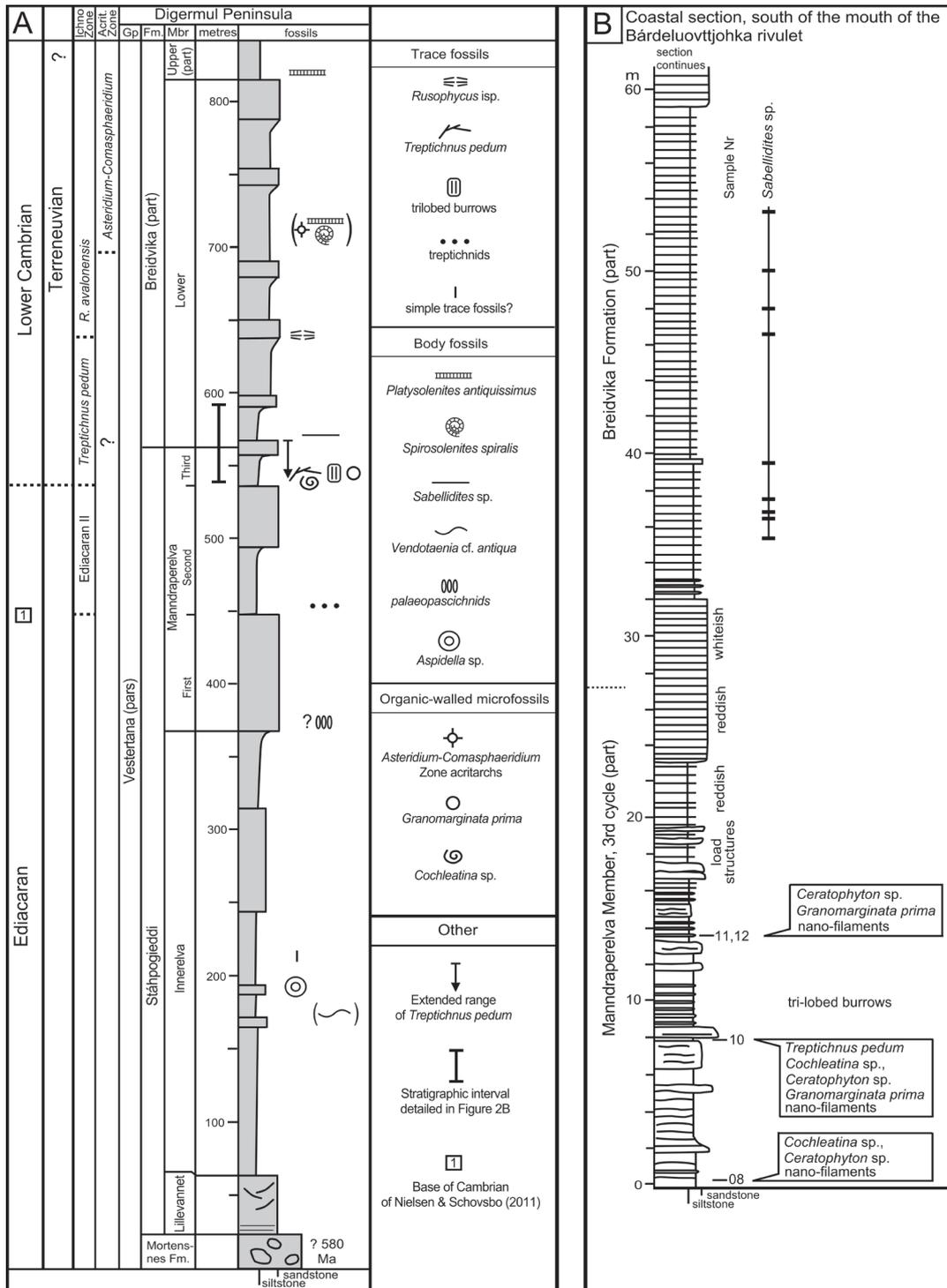


Figure 2. (A) Log showing a schematic representation of lithology and selected fossil occurrences in the Vestertana Group on the Digermul Peninsula. In general, only first occurrences of fossils are indicated. Fossil symbols in parenthesis refer to occurrences in the Vestertana Group outside of the Digermul Peninsula, placed in the approximate corresponding stratigraphical level. (B) Lithological log of upper part (part of third cycle) of the Manndrapereiva Member in the coastal section south of the mouth of Bårdelouvtjøhka rivulet.

Ediacara-type fossils is used, in which various discoidal taxa are considered preservational morphs (Gehling et al., 2000), the Finnmark material may, with the exception of *Hiemalora*, all belong to *Aspidella* (Narbonne in Vickers-Rich et al., 2007). Additional material illustrated here from the main fossil locality in the middle of the member includes a large disc-shaped *Aspidella* (Fig. 3A), and a twinned specimen (Fig. 3C) of a type that has been variously interpreted as asexual reproduction or as merged discs.

Banks (1970, 1973) recorded small simple trace fossils from the Innerelva Member. Banks (1973) reported, but did not illustrate, simple burrows to be relatively abundant at Kvalneset in the southeastern part of the Varanger Peninsula. Farmer et al. (1992) studied material from this locality and considered these structures to be better explained as pseudofossils formed by fluid escape within the sediment. This interpretation seems convincing but may not apply to material that Banks (1970, pl. 1a) illustrated from the Digermul Peninsula

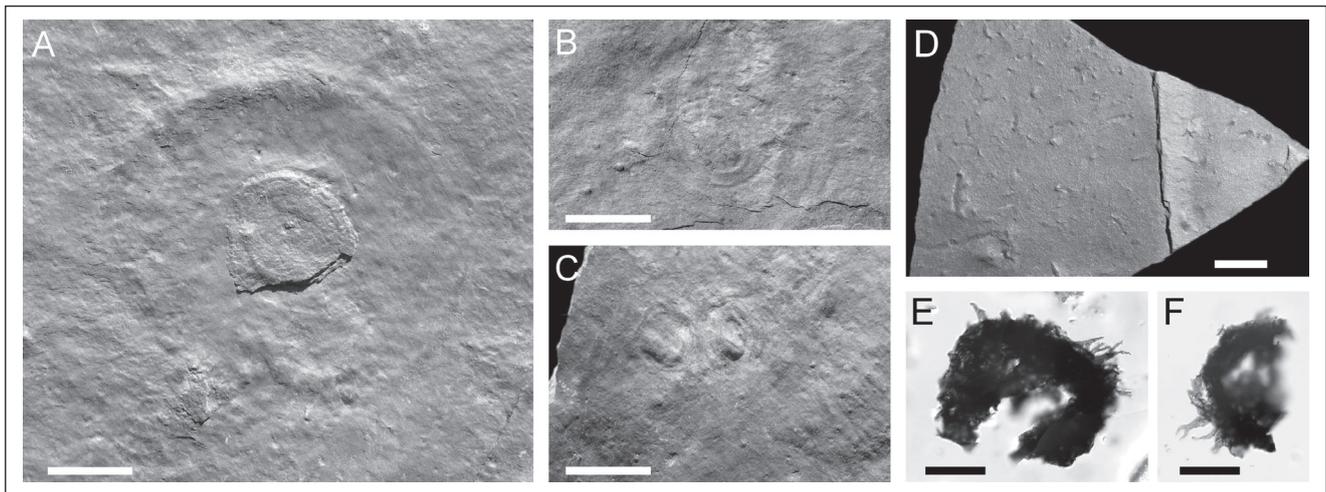


Figure 3. Fossils from the upper part of the Vestertana Group. (A–C) Discoidal Ediacara-type fossils from the middle part of the Innerelva Member in coastal outcrop north of the mouth of the Manndrapselva river. Scale bars are 20 mm. (A) Large *Aspidella* (TSGF 18239), about 8 cm wide, with two clearly developed discs and a faint central tubercle. (B) Discoidal form (TSGF 18240) with two well-developed concentric rings and several more faintly developed ones. (C) Two closely positioned (merged?) discoidal forms (TSGF 18241). (D) Small bow-shaped trace fossils (TSGF 18242) from the lower part of the second cycle, Manndrapereleva Member, from a section along a small rivulet north of the mouth of the Manndrapselva river. Scale bar is 10 mm. (E–F) Acritarchs (TSGF 18243 & 18244) from the approximate middle part of the Lower Breidvika member, along the Bårdelouvtjøhka rivulet. Scale bar is 20 μ m.

about 150 m above the base of the Innerelva Member. These are preserved on bed bases as short sand-filled knobs 1–2 mm in diameter, not on bed tops and bed bases as is the material from Kvalneset described by Farmer et al. (1992, fig 6). Banks (1970) interpreted these knobs as portions of passively filled vertical burrows, and they have been compared with both *Skolithos* and *Arenicolites* (Crimes, 1987, p. 104). Short, sand-filled knobs were observed during this study on surfaces containing discoidal fossils (Fig. 3). Some of these appear to have been spherical (Fig. 3A) and may represent mineral replacements. Others (Fig. 3B, C) have at least a superficial similarity to short knobs that represent partially preserved trace fossils from the Mandraperelva Member (Fig. 3D). Finally, one such structure is located within an *Aspidella* specimen, and may represent a central tubercle (Fig. 3A). Future studies are necessary to shed new light on the presence of trace fossils in the Innerelva Member.

Vidal (1981) reported sphaeromorphic acritarchs and vendotaenids (as *Vendotaenia* sp. and *Vendotaenia* cf. *antiqua*) from the Innerelva Member on the Varanger Peninsula. Awaiting description are ‘probably agglutinated tubular fossils’ reported to occur well below the discoidal fossils (Vidal & Moczyłowska, 1995, p. 206).

Manndraperelva Member. Banks (1970) mentioned poorly preserved trace fossils from the basal part of the Manndraperelva Member that he compared with structures from the Late Ediacaran of South Australia now assigned to *Palaeopascichnus*. Antcliffe et al. (2011) provided an affirmative identification of *Palaeopascichnus delicatus* in the Manndraperelva

Member without additional detail. *Palaeopascichnus* is a geographically widespread form, now generally interpreted as a body fossil of uncertain and debated affinity (Jensen, 2003; Antcliffe et al., 2011). From the second cycle of the Manndraperelva Member, Banks (1970) identified regularly sinuous horizontal burrows (i.e., *Cochlichnus*), horizontal spirals as cf., *Helicolithus*, and simple vertical U-tubes (i.e., *Arenicolites*), and also remarked on tool marks that he suggested were formed by the exoskeleton of an arthropod. Banks (1970) recorded larger-sized trace fossils from the third cycle of the Manndraperelva Member, including forms with lateral grooves (i.e., ‘*Curvolithus*’). Trace fossils from the second and third cycles of the Manndraperelva Member are discussed in more detail below.

Lower Breidvika member. The Lower Breidvika member has yielded a greater diversity of trace fossils. Banks (1970) reported *Treptichnus pedum* from the basal three metres, and *Rusophycus* to first appear about 70 m above the base of the formation. Farmer et al. (1992) recorded the tubular fossil *Sabellidites* sp. (reported as *Sabellidites cambriensis* in Vidal & Moczyłowska, 1995 and Moczyłowska, 2002) from the Lower Breidvika member and also mentioned the presence of the vertical spiral trace fossil *Gyrolithes*. McIlroy (1995) listed 27 ichnotaxa from this member. The discoidal fossils *Tirasiana disciformis* and *Nimbia occlusa*, taxa otherwise known exclusively from the Late Ediacaran, have also been reported from the lower part of the Lower Breidvika member (Crimes & McIlroy, 1999). Trace fossils from the Upper Breidvika member include *Teichichnus*.

McIlroy et al. (2001) reported the probable foraminiferans *Platysolenites antiquissimus* and *Platysolenites*

cooperi from near the base of the Upper Breidvika member on the Digermul Peninsula. The lowest occurrence of *Platysolenites antiquissimus* in the Vestertana Group may, however, be at a somewhat lower level. Føyn (1967, pp. 31, 32), Hamar (1967) and Føyn et al. (1983) recorded *Platysolenites antiquissimus* together with the spirally coiled *Spirosolenites spiralis* at Kunes in the Laksefjord area, Finnmark, from beds that they estimated to be some 100 to 150 m above the base of the Breidvika Formation. According to Føyn et al. (1983) only the Lower Breidvika member is present in this area. Correlation between the Laksefjord and Digermul successions is complicated by a significantly thinner development of the Ståhpogieddi Formation in the Laksefjord area, but a lower stratigraphical position of the Laksefjord *Platysolenites* is likely, and is indicated in Fig. 2A. The only other skeletal fossil reported from beds close to the transition between the lower and upper members are tubular fossils cited as *Circotheca* cf. *annae* (McIlroy, 1995) or *Ladatheca cylindrica* (McIlroy et al., 2001).

Vidal (1981) reported sphaeromorphic acritarchs and poorly preserved specimens of the acanthomorph *Asteridium* sp. (as *Micrhystridium* sp.) with vesicles 18–22 µm and processes 1.5–2 µm in length from the Lower Breidvika member in the Laksefjord area in samples containing *Platysolenites antiquissimus*. Moczydłowska (2002, p. 204) listed a greater diversity of acritarchs from an unspecified level within the Lower Breidvika member at Manndraperelva, with *Asteridium tornatum*, *Granomarginata squamacea*, *Lophosphaeridium tentativum*, and *Tasmanites tenellus*, indicating the *Asteridium–Comasphaeridium* Zone.

New fossil data from the Manndraperelva and Lower Breidvika members

Sections studied and material

This study is largely based on a coastal outcrop south of the mouth of the Bårdelouvtjohka rivulet (Fig. 1C), where the transition from the Manndraperelva Member to the Lower Breidvika member is well exposed (Fig. 2B). The lower part of the section consists of thick packages of fine-grained greywacke sandstone capped by mudstone (Fig. 4A) and thinner beds of coarser quartz arenite (Fig. 4B). There is an estimated additional 4–5 m of the third cycle below the measured section that could not be accessed. Reading (1965) defined the top of the Manndraperelva Member in the Manndrapselva river section in a 12–15 m-thick package of red quartzitic sandstone. A comparable thickness of red-coloured sandstone is present also in the Bårdelouvtjohka section, where it is followed by grey quartz arenite that Farmer et al. (1992) took to form the base of the Breidvika Formation. Locally, chaotic disruption of beds is observed in the upper part of the Manndraperelva Member in this section (Fig. 4C). Additional observations were made on the lower part of the Manndraperelva Member along coastal outcrops north of the mouth of the Manndrapselva river (Fig. 1).

Stratigraphic positions of trace fossils and samples collected for organic-walled microfossils are indicated in Fig. 2B. The designation Lower Cambrian is here used to encompass the Terreneuvian Series and the provisional Cambrian Series 2 of the recently proposed four-fold division of the Cambrian System. Illustrated material is stored with the palaeontological collection (TSGF) of Tromsø University Museum, Tromsø, Norway. Location details for sections and illustrated material is provided in Electronic Supplement 1.



Figure 4. Field images of the upper part (third cycle) of the Manndraperelva Member in coastal outcrop south of the mouth of the Bårdelouvtjohka rivulet. (A) View corresponding to c. 5–10 m in the log in Fig. 2B. The sample level 10 and in situ find of *Treptichnus pedum* are both located somewhat below shoulder height of the seated person. (B) Interval at 9 m in the log in Fig. 2B, with fine-grained sandstone grading into mudstone that is sharply overlain by medium-grained sandstone. Sample bag (c. 7 cm wide) is positioned within sample level 10. *Treptichnus pedum*, illustrated in Fig. 5D, originates from the thin sandstone ledge in the middle of the image. (C) View of interval with chaotic bedding at about 19 m in Fig. 2B.

Trace fossils

The lowest unquestionable trace fossils were observed in coastal outcrops (Fig. 1C) within the first two metres of the second cycle of the Manndraperelva Member in the form of a series of aligned sediment pods that are connected by a faintly visible horizontal ridge (Fig. 5A). A trace fossil from scree material west of Avzejohka rivulet, attributed to higher levels of the second cycle, consists of a series of circular knobs preserved on a bedding-plane (Fig. 5B) and represents a more distinctly developed form of the same type of trace fossil. This type of trace fossil is generally interpreted as sections through vertical shafts of a three-dimensional burrow system that consisted of a basal connecting tube, from which emerged vertical probes. For example, Geyer & Uchman (1995) identified trace fossils from the Lower Cambrian of Namibia with a morphology identical to that of the specimen in Fig. 5A as *Treptichnus pollardi*. This type of trace fossil has also been reported as *Hormosiroidea*, *Saerichnites* and *Ctenopholeus* (see Fürsich et al., 2006, for discussion). McIlroy's (1995) report of *Hormosiroidea* from the Ståhpogieddi Formation probably refers to a trace fossil of this type. Trace fossils of this type can also be included in a broadly defined *Treptichnus pedum* sensu Seilacher (2007). Here they are referred to as treptichnids.

A variety of small trace fossils were observed on a bed sole with prominent tool marks about 2.5 m into the second cycle. This bed can be traced laterally for many tens of metres and is probably the bed illustrated by Banks (1970, pl. 2b). On this surface, bow-shaped trace fossils are found (Fig. 5C), up to 4 mm wide and several centimetres long. These can be variously considered to be *Arenicolites* or short *Palaeophycus/Planolites*-type trace fossils. There are also a variety of smaller trace fossils, including horizontal spirally coiled burrows (cf., *Helicolithus* of Banks, 1970). Small forms of the same type of bow-shaped trace fossils were also observed in a section west of Avzejohka (Fig. 3D). Their interpretation is discussed below.

Unequivocal examples of *Treptichnus pedum* (Fig. 5D) were found in the third cycle, about 20 m below the top of the Manndraperelva Member in the coastal section south of the Bårdelouvtjohka rivulet. Probable additional examples of *Treptichnus pedum* were observed in vertical sections in the same succession but identification could not be confirmed because of lack of bed-sole exposure. The same interval contains trace fossils with a trilobed basal surface (Fig. 5E, F) and poorly preserved, plug-shaped trace fossils (cf., *Bergaueria*). The trilobed trace fossils present naming problems (Jensen & Grant 1998); Systra & Jensen (2006) proposed the term 'Bure ichnocomplex' for trace fossils that are united by a trilobed basal surface, but which may be straight and band-like, or form a succession of short segments that alternate in a regular manner. As such, they arguably span more than one ichnogenes and have been variously included in *Curvolithus* and *Treptichnus*. This informal

term was introduced to emphasise that these various forms likely had a common producer. Banks (1970, pl. 2d) illustrated examples of this type of trace fossil with a wide central lobe flanked by narrow marginal lobes from the third cycle, about 180 m above the base of the Manndraperelva Member. The material illustrated here all has proportionally wider lateral lobes, and compares more closely to better preserved material from the Lower Breidvika member (Fig. 5G, H).

The first *Rusophycus* (Fig. 5I) was observed in the Lower Breidvika member at a distance above the base of the Breidvika Formation closely comparable with that cited by Banks (1970). These are large forms with coarse scratch marks, and, as such, typical of *Rusophycus* from the Terreneuvian.

Organic-walled microfossils

Samples from the third cycle of the Manndraperelva Member in the section south of the mouth of the Bårdelouvtjohka rivulet yielded leiosphaerids, *Granomarginata prima* (Fig. 6C), horn-shaped *Cerato-phyton* and various filaments, including forms identical to *Eoschizotrix composita* as recorded by Moczyłowska (2008) from the Włodawa Formation of the Lublin Slope, Poland. Spirally coiled filaments with serrated margins (Fig. 6A, B) are here interpreted as the first reports from northern Scandinavia of *Cochleatina*. Well-preserved material of *Cochleatina* from the East European Platform have been described as chitinous flat ribbons of unknown affinity, typically arranged in a logarithmic spiral in which the width of the ribbon increases outwards (Burzin, 1996). Vidal (1981, p. 39) described a spirally coiled, organic-walled microfossil from the more than c. 650 Ma Dakkovarre Formation at Skallneset on the southeastern coast of the Varanger Peninsula, where it was found with various sphaeromorphic microfossils. The illustrated specimen is an opaque band about 2 µm wide forming a spiral that expands from about 20 µm to 40 µm. The Dakkovarre Formation specimen lacks the pronounced teeth seen in the Manndraperelva material and appears to be different. Species of *Cochleatina* are differentiated on the nature of vertical zonation within the ribbon (Burzin, 1996), not readily observed in the Manndraperelva Member material. However, Burzin (1996) observed that ribbon width decreased through time, so that basal Cambrian *C. rudaminica*, from the upper part of the Rovno Regional Stage and the lower part of the Lontova Regional Stage in Latvia, Lithuania and Belarus (Paškevičėnė, 1980), is 3.5 times narrower than *C. canilovica*, a species reported throughout the Late Ediacaran Kanilovka Group of Podolia, and the basal part of the Rovno Regional Stage in Volyn (Burzin, 1996). In the best preserved specimen from the Manndraperelva Member (Fig. 6A), the narrowest part of the ribbon is about 3 µm wide, expanding to slightly less than 10 µm at the fourth whorl, where the spiral has a diameter of about 40 µm. Paškevičėnė (1980) reported ribbon widths

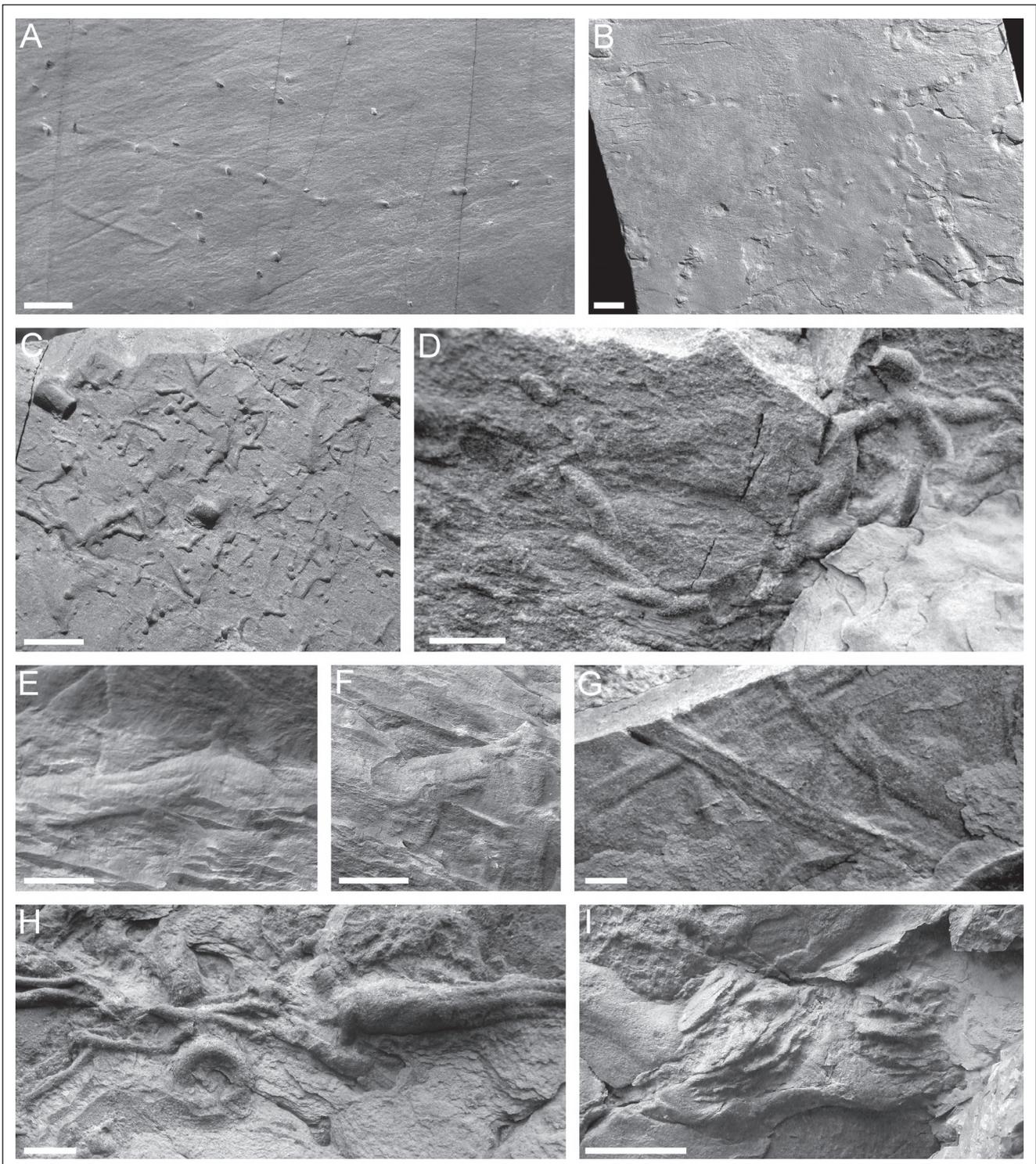


Figure 5. Trace fossils from the second (A–C), and third (D–F) cycles of the Manndraperelva member, and the Lower Breidvika member (G–I). (A) Trace fossil consisting of aligned sediment pods on bed sole photographed in the field in a coastal outcrop. Scale bar is 10 mm. (B) *Treptichnid* (TSGF 18245) in scree material from the second cycle of the Manndraperelva Member, north of the mouth of the Manndraperelva river. Scale bar is 10 mm. (C) Base of bed c. 2.5 m above base of second cycle in coastal outcrop with several shallow, U-shaped trace fossils (TSGF 18246) and, near the lower part of image, a clear example of a spirally coiled trace fossil (?*Cochlichnus* isp). Scale bar is 10 mm. (D) Field photo of *Treptichnus pedum* (TSGF 18247). See Figs 2B and 4 for details. Scale bar is 10 mm. (E, F) Trilobed trace fossils in coastal section south of the mouth of the Bårdelouvtjøhka rivulet. Scale bars are 10 mm. (G) Trilobed trace fossils in coastal section north of the mouth of the Bårdelouvtjøhka rivulet. Scale bar is 10 mm. (H) Trilobed trace fossil (TSGF 18248) and *Gyrolithes* in coastal section north of the mouth of the Bårdelouvtjøhka rivulet. Scale bar is 10 mm. (I) *Rusophycus* isp. in coastal section north of the mouth of the Bårdelouvtjøhka rivulet. Scale bar is 30 mm.

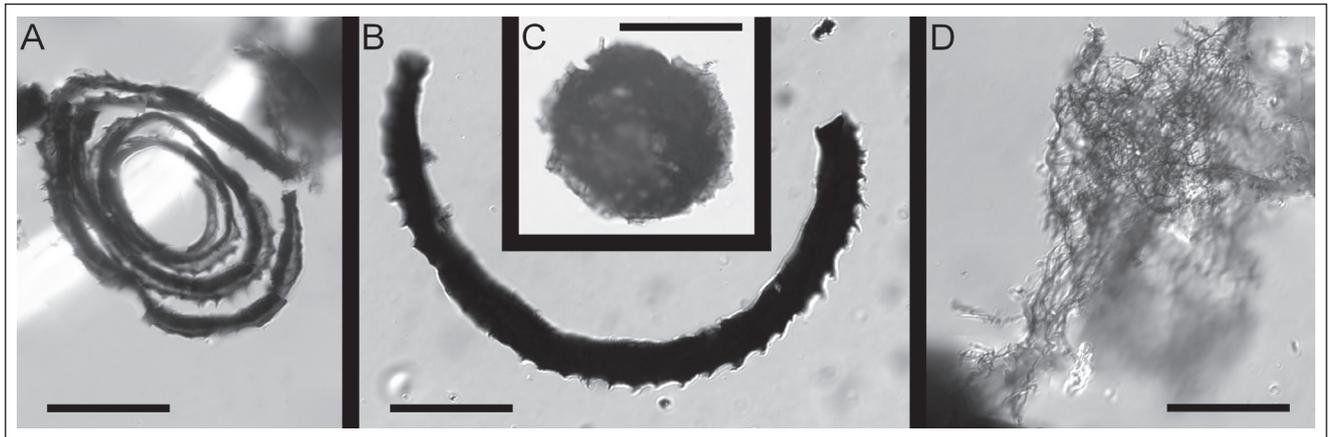


Figure 6. Organic-walled microfossils from the third cycle of the Manndraperelva Member in coastal section south of the mouth of the Bårdelouvtjohka rivulet. Scale bars represent 20 μm . For each slide, number and England finder coordinates are given. (A) Cochleatina sp. Sample 10, 10–2, E–45–3 (TSGF 18249). (B) Large fragment of Cochleatina sp. Sample 8, 8–1n, B–24–4 (TSGF 18250). (C) Granomarginata prima. Sample 10, 10–2, O–41–2 (TSGF 18251). (D) Nano-scale filaments, probably representing a degraded sabelliditid. Sample 10, 10–1, P–25–3 (TSGF 18252).

in *C. rudaminica* and *C. ignalinica* to be 9–13 μm and 10–15 μm , respectively, whereas ribbons of *C. canilovica* are 15–20 μm wide at the inner end, expanding to 70 μm at the fourth coil (Burzin, 1996). Fragments of larger specimens were also found, with ribbons about 10 μm (Fig. 6B). In terms of size, the Manndraperelva Member specimens compare to the younger occurrences of *Cochleatina* from the East European Platform.

Samples from the basal part of the Lower Breidvika member, to the level of the first *Rusophycus*, in coastal outcrops north of the mouth of the Bårdelouvtjohka rivulet yielded poorly preserved *Granomarginata prima*, *Ceratophyton* sp., leiosphaerids and filaments. A sample from the middle portion of the Lower Breidvika member, from an outcrop along the Bårdelouvtjohka rivulet, yielded poorly preserved process-bearing acritarchs comparable to *Polygonium* (or *Goniosphaeridium*) *varium* (Fig. 3E, F), although with unusually short processes.

Sabelliditids

Farmer et al. (1992) recorded the tubular fossil *Sabellidites* sp. from 9 and 16 m above the base of the Breidvika Formation in the Bårdelouvtjohka section. In the present study, specimens of *Sabellidites* sp. were observed on additional bed surfaces within the same part of the section over an interval of 18 m (Fig. 2B). Samples prepared for organic-walled microfossils from the lower part of the sampled interval contain masses of very fine filaments (Fig. 6D). Similar masses were recovered from the Lower Cambrian Ratcliffe Brook Formation of New Brunswick, eastern Canada, where they were interpreted as possible degraded sabelliditids (Palacios et al., 2011).

Discussion

Coastal exposures stretching from the mouth of the Manndrapselva river to just south of the Breidvika bay provide essentially uninterrupted exposure from the Ediacara fossil-bearing Innerelv Member to Cambrian fossils in the Breidvika Formation. Although there is sedimentological evidence for several episodes of relative shallowing, no indication of any substantial break in sedimentation has been identified. The present study extends the lowest occurrence of *Treptichnus pedum* in the Vestertana Group from the Lower Breidvik member to the upper part of the Manndraperelva Member, where it is found with trilobed traces and poorly preserved *Bergaueria*. This association of trace fossils is best attributed to the *Treptichnus pedum* Ichnozone, indicating that all or most of the third cycle of the Manndraperelva Member is Cambrian. The trace-fossil assemblage from the basal part of the Breidvika Formation compares closely to those described from the basal Cambrian Khmel'nitsky Formation of Ukraine, which includes *Treptichnus pedum*, *Gyrolithes polonicus*, and trace fossils of the Bure ichnocomplex (*Treptichnus triplex*, *Curvolithus*) (e.g., Palij et al., 1983). The only trace fossils reported from the underlying Okunets Formation are *Planolites* and 'Curvolithus' (e.g., Gureev, 1988), although Kiryanov (2006) extended the *Treptichnus pedum* Ichnozone to the base of the Okunets Formation. On the basis of trace fossils, the third cycle of the Manndraperelva Member may correspond in time with either the Khmel'nitsky or the Okunets formations. The only body fossil recorded from the Khmel'nitsky Formation is *Sabellidites cambriensis*, although it also contains problematic discoidal fossils as well as the scratch circle *Kullingia*, also found in the Lower Cambrian Dividalen Group of northern Sweden (Jensen & Grant, 1998; Jensen et al., 2002). The organic-walled microfossils from the third cycle of the Manndraperelva

Member can be compared with associations reported from the East European Platform. In many areas of the East European Platform, the first appearance of *Granomarginata prima* is in beds attributed to the lower part of the Lontova Regional Stage, or the upper part of the Rovno Regional Stage. For example, in the Stradech-17 core of western Belarus, *Granomarginata prima* and *Ceratophyton* are found with *Cochleatina rudaminica* and *C. ignalinica* in the lower part of the Stradech Formation, in beds attributed to the lower part of Lontova Regional Stage, a short distance below the first *Platysolenites antiquissimus* (Paškevičėnė, 1980). Although the Manndraperelva Member *Cochleatina* compare in size to the younger occurrences of this genus from the East European Platform, a better understanding of its stratigraphical implications for the Vestertana Group must await a fuller sampling of the Stáhpogieddi Formation for organic-walled microfossils. In the Lublin slope, eastern Poland, Moczyłowska (1991) equated the *Asteridium-Comasphaeridium* Zone with the upper part of the Rovno Regional Stage and the Lontova Regional Stage, and proposed the Kaplonosy core as a regional reference section for the Ediacaran-Cambrian transition. Direct comparison of the Manndraperelva assemblage with the *Asteridium-Comasphaeridium* Zone is complicated by the absence of species of *Asteridium* and *Comasphaeridium*, and largely hinges on the first appearance of *Granomarginata prima* in the basal Cambrian *Asteridium-Comasphaeridium* Zone. *Cochleatina* has not been reported from the Polish part of the East European Platform, but a fragmentary fossil from the *Asteridium-Comasphaeridium* Zone in the Kaplonosy core (Moczyłowska, 1991, p. 12, fig. 15D) could represent this genus. To date, a more diverse assemblage of taxa indicative of the *Asteridium-Comasphaeridium* Zone appears only in higher levels of the Lower Breidvika member.

Trace fossils comparable to the treptichnids reported here from the basal part of the second cycle of the Manndraperelva Member have a long stratigraphical range but specimens from Namibia are older than $c. 543 \pm 2.5$ Ma and younger than $c. 547 \pm 0.65$ Ma (Jensen et al., 2000; ages from Schmitz, 2012). Trace fossils comparable to *Treptichnus* (but not *T. pedum*) also occur in the GSSP section, Newfoundland, in the upper part of Member 1 of the Chapel Island Formation (Gehling et al., 2001). Small, horizontally coiled trace fossils from about the same level as these treptichnids on the Digermul Peninsula, previously compared to *Helicolithus*, are of interest as this would be the earliest record of this ichnogenus. The Late Ediacaran *Harlaniella* had been interpreted as a horizontal, spirally coiled trace fossil, but Jensen (2003) found that the morphology of *Harlaniella* does not match the expected geometry for a spiral and that it may be closer to *Palaeopascichnus*. *Streptichnus narbonnei* from beds of either Ediacaran or Cambrian age in Namibia (Jensen & Runnegar, 2005) appears to be, at least in part, spirally coiled but correspond to a more

complex burrow system. A closer comparison of the Manndraperelva spirals can probably be made with the sinusoidal *Cochlichnus*, a form commonly reported from basal Cambrian and possibly also older beds. Seilacher (2007, p. 96) noted that “*In a three-dimensional substrate, the undulation of Cochlichnus can easily switch to a corkscrew motion.*” Palij et al. (1983, pl. 61:4) reported a “crawling trace close to *Cochlichnus*” from Late Ediacaran beds of the White Sea Region, Russia, that is larger but otherwise comparable to the Manndraperelva specimens. There is, thus, no positive evidence from trace fossils for a Cambrian age for the second cycle of the Manndraperelva Member. Here it is suggested that the association of trace fossils corresponds to a latest Ediacaran trace-fossil zone (Jensen, 2003). Of great importance to further constrain the location of the Ediacaran-Cambrian boundary within the Vestertana Group will be the publication of detailed information on the exact occurrence of *Palaeopascichnus* within the Manndraperelva Member. In both Newfoundland and Ukraine the upper stratigraphic range of *Palaeopascichnus* and *Harlaniella* is close to that of Cambrian-type trace fossils. In Ukraine, *Palaeopascichnus* has a long stratigraphic range with the youngest occurrences in the Studenitska Formation (Fedonkin, 1983). In Newfoundland, *Palaeopascichnus* ranges from the upper part of the Fermeuse Formation ($c. 560$ Ma) to within a few decimetres of the basal Cambrian GSSP in the Chapel Island Formation (Narbonne et al., 1987; Gehling et al., 2001). As discussed above, the available information on the location of the Manndraperelva *Palaeopascichnus* supports an Ediacaran age for the first cycle.

Discoidal Ediacara-type fossils of the type found in the middle (and lower) portion of the Innerelva Member have long stratigraphical ranges. In Ukraine and in the White Sea Region, Russia, similar forms are known from beds about 555 Myr old (e.g., Grazhdankin et al., 2011), but both *Aspidella*- and *Hiemalora*-type fossils extend from $c. 580$ Ma. Narbonne (2005) included the Innerelva Member fossils in his category of Fermeuse-style preservation, with associations formed in slope or outer shelf environments where only bases of hold-fasts are preserved, reflecting a taphonomic bias rather than a true picture of the benthic assemblage (see also Laflamme et al., 2011). The absence of core Ediacara-type taxa such as *Dickinsonia* and *Tribrachidium*, that would indicate the younger portion of the stratigraphical range of Ediacara-type fossils, may therefore be taphonomic. Simple trace fossils (*Planolites* isp.) would indicate an age younger than about 560 Ma, but their presence in the Innerelva Member requires confirmation. In Ukraine, *Vendotaenia antiqua* ranges from the Nagoryany Formation (<553 Ma) into the Okunets Formation. Although tentative, the fossils from the middle part of the Innerelva Member suggest that this portion of the Stáhpogieddi Formation is younger than $c. 560$ Ma. If the Mortensnes Formation is related to the Gaskiers glaciation ($c. 580$ Ma), the $c. 200$ m comprising the Lillvannet Member and lower

part of the Innerelva Member represent more than 20 million years, raising the possibility of some hitherto unrecognised break in sedimentation, as previously indicated by Nielsen & Schovsbo (2011, p. 288).

Conclusions

New records of trace fossils, including *Treptichnus pedum*, and organic-walled microfossils from the upper part (third cycle) of the Manndraperelva Member, Ståhpogieddi Formation, show that this portion of the Vestertana Group is Cambrian. The middle part (second cycle) of the Manndraperelva Member contains trace fossils consistent with a latest Ediacaran age, which may in the future be corroborated when more detailed information on the stratigraphical level of earlier reports of palaeopascichnids in this section becomes available. The improved precision in the location of the Ediacaran–Cambrian boundary reported here, in addition to Ediacara-type fossils further down-section in the Ståhpogieddi Formation, and diverse Cambrian-type trace fossils higher in the Breidvika Formation, demonstrate that coastal exposures of the Vestertana Group on the Digermul Peninsula provide a rare case in which metazoan evolution can be observed in a continuous outcrop.

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