Canadian Science Publishing | Canadian Journal of Earth Sciences

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Journal:	*Canadian Journal of Earth Sciences*
Manuscript ID	cjes-2018-0035.R1
Manuscript Type:	Article
Date Submitted by the Author:	15-Apr-2018
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Keyword:	<i>Palaeopascichnus</i>, Norway, Ediacaran, glaciation
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)
Note: The following files were submitted by the author for peer review, but cannot be converted to PDF. You must view these files (e.g. movies) online.	
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New occurrences of *Palaeopascichnus* from the Stáhpogieddi Formation, Arctic Norway, and their bearing on the age of the Varanger Ice Age

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Abstract: We report on new occurrences of the late Ediacaran problematicum *Palaeopascichnus* (Protista?) from the Stáhpogieddi Formation, Arctic Norway. The stratigraphically lowest occurrences are in beds transitional between the Lillevannet and Indreelva members: the highest in the second cycle of the Manndrapselva Member, stratigraphically close to the lowest occurrences of Cambrian-type trace fossils. This establishes a long stratigraphical range of *Palaeopascichnus* on the Digermulen Peninsula, as has been previously documented from Newfoundland, South Australia and elsewhere in Baltica. The age range of *Palaeopascichnus* in Avalonia and Baltica is ~565 to 541 Ma. Since the transition from the Mortensnes Formation to the Stáhpogieddi Formation is without a major break in sedimentation, this supports the inference that the underlying glacigenic Mortensnes Formation is ca. 580 Ma, and therefore Gaskiers-equivalent, or younger.

Key Words: *Palaeopascichnus*, Norway, Ediacaran, glaciation

Introduction

Palaeopascichnids are Ediacaran bedding plane-parallel modular fossils consisting of simple or more complex series of closely spaced millimetric circular, sausage- or kidney-shaped units (e.g., Fedonkin 1981; Palij et al. 1983; Jensen 2003; Seilacher et al. 2003). Each unit has walls forming sub-spherical or cylindrical chambers (Wan et al. 2014; Golubkova et al. 2017). Earlier interpretations of palaeopascichnids as trace fossils, as evidenced by names such as *Palaeopascichnus* and *Yelovichnus*, are now considered unlikely (e.g., Haines 2000; Gehling et al. 2000; Jensen 2003), most obviously because of branching in which wider units divide into two narrower ones. Palaeopascichnids have been interpreted as xenophyophoran protists (Seilacher et al. 2003; Seilacher and Gishlik 2015) or protists of uncertain affinity (Antcliffe et al. 2011), and Grazhdankin (2014) included Palaeopascichnida within Vendobionta, which he considered to be an extinct group of protists. Gehling et al. (2000) noted possible connections between palaeopascichnids and the discoidal Ediacara-type fossil *Aspidella* in Newfoundland, but this has not been observed elsewhere. Palaeopascichnids are among the Ediacaran fossils with the longest stratigraphical ranges, spanning from ~565–541 Ma (e.g., Gehling and Droser 2013; Xiao et al. 2016), with rare possible early Ediacaran examples (Lan and Chen 2012; Wan et al. 2014).

The Cryogenian to lower Cambrian sedimentary succession of the Vestertana Group in eastern Finnmark, northern Norway (Fig. 1C), is comprised in stratigraphical order of the Smalfjorden, Nyborg, Mortensnes, Stáhpogieddi and Breidvika formations (e.g., Banks et al. 1971). Trace fossils, palaeopascichnids and organic-walled microfossils place the Ediacaran–Cambrian transition in the upper part of the Stáhpogieddi Formation, with Ediacara-type fossils occurring deeper in the same formation (Banks 1970; Farmer et al. 1992; McIlroy and Logan 1999; Högström et al. 2013; McIlroy and Brasier 2017; Jensen et al. in press). Glacial deposits of the Smalfjorden and Mortensnes formations, separated by the interglacial Nyborg Formation, are collectively known as the Varanger Ice Age (e.g., Nystuen 1985). Studies over the last several decades (e.g., Halverson et al. 2005; Rice et al. 2011) have placed the Smalfjorden Formation within the globally developed Marinoan glaciation of Cryogenian age (~645–635 Ma, Rooney et al. 2015; Shields-Zhou et al. 2016) and the Mortensnes Formation within the Ediacaran Gaskiers glaciation, which is probably regional and of short duration (~580 Ma, Pu et al. 2016). The cap dolostones at the base of the Nyborg Formation are considered to reliably associate the Smalfjorden Formation with the Marinoan glaciation (Halverson et al. 2005; Rice et al. 2011). Furthermore, low $\delta^{13}C$ values in the Nyborg and Mortensnes formations have been compared to those of the Shuram-Wonoka anomaly (Rice et al. 2011), in most models with a nadir at about 580 Ma (see Xiao et al. 2016). Other scenarios for the age of the Varangerian glacial deposits have been proposed (e.g., Nystuen et al. 2016; Grazhdankin and Maslov 2015; see below) and resolution to this problem is hampered by the lack of reliable radiometric dates and biostratigraphical data from the lower part of the Vestertana Group.

Here, we report new occurrences of palaeopascichnids from the Stáhpogieddi Formation, discovered during field trips of the Digermulen Early Life Research group in 2015, 2016 and 2017. Of particular interest is the discovery of *Palaeopascichnus* close to the base of the Stáhpogieddi Formation, which provides biostratigraphical age constraints for rocks in close stratigraphical proximity to the glacial diamictites of the Mortensnes Formation.

Geological setting

The Cryogenian to lower Cambrian Vestertana Group comprises approximately 1.4 km of essentially siliciclastic sedimentary rocks preserved within the Gaissa Thrust Belt and para-autochthonous and autochthonous rocks in the Tanafjorden-Varangerfjorden region, eastern Finnmark (Fig. 1; Rice 2014). The base of the Vestertana Group is a major unconformity cutting into Cryogenian or Tonian age sedimentary rocks. The Smalfjorden Formation consists of several alternations of lodgement tillite and laminites representing successions of glacial retreat, which is overlain by the shale, siltstone and sandstone-dominated shallow marine to basinal interglacial Nyborg Formation. The basal Nyborg Formation locally consists of a buff-yellow dolostone (Edwards 1984) that has been interpreted as a cap carbonate. The Nyborg Formation is overlain, with a regional angular unconformity, by the glacigenic Mortensnes Formation (Edwards 1984; Rice et al. 2011). The succeeding Stáhpogieddi Formation starts with the Lillevannet Member consisting of sandstone and shale interpreted as a transgressive interval. The overlying mudstone and sandstone-dominated Indreelva Member yields Ediacara-type fossils dominated by discoidal taxa (Farmer et al. 1992; Högström et al. 2013, 2014). The highest member in the Stáhpogieddi Formation, the Manndrapselva Member, consists of a basal sandstone-dominated part and two upwards-coarsening cycles. The second cycle yields a moderate diversity of trace fossils among which can be noted horizontal spiral forms (Banks 1970; McIlroy and Brasier 2017). A late Ediacaran age is indicated by the presence of *Harlaniella* and *Palaeopascichnus* (McIlroy and Brasier 2017). Trace fossils, including *Treptichnus pedum* and *Gyrolithes*, and organic-walled microfossils place the Ediacaran–Cambrian boundary close to the base of the upper cycle of the Manndrapselva Member (Högström et al. 2013; McIlroy and Brasier 2017; Jensen et al. in press). The Vestertana Group terminates with the Terreneuvian Breidvika Formation, from which diverse trace fossils and a sparse record of skeletal fossils, including *Platysolenites*, have been reported (Banks 1970; Føyn and Glaessner 1979; McIlroy et al. 2001; Högström et al. 2013; McIlroy and

Brasier 2017). On the Digermulen Peninsula the Vestertana Group is conformably overlain by the siliciclastic Digermulen Group, which ranges from Cambrian Series 2 (McIlroy and Brasier 2017) to the Tremadocian (Henningsmoen and Nikolaisen 1985).

The Vestertana Group was deposited along the margin of the Fennoscandian Shield, with a thinner pericratonic succession and a thicker basinal succession (Rice 2014). The original position of Digermulen Peninsula rocks within the Gaissa Thrust Belt is believed to have been north of the Trollfjorden–Komagelva Fault Zone, with up to 200 km of dextral displacement along the fault (Rice 2014). Palaeocurrents and detrital zircon U–Pb ages both suggest southerly sediment sources for the lower part of the Vestertana Group, whereas the upper part of the Vestertana Group shows the addition of a northern, younger sediment source, related to the Timanide Orogeny (e.g., Banks et al. 1971; Zhang et al. 2015). The Stáhpogieddi Formation has been interpreted as a foreland basin succession (e.g., Nielsen and Schovsbo 2011; Zhang et al. 2015).

Material and sections

Palaeopascichnids were recovered from three horizons within the Stáhpogieddi Formation along the southeastern portion of the Digermulen Peninsula (Fig. 1C).

The stratigraphically lowest palaeopascichnids originate from coastal outcrops along the northern part of Árasulluokta Cove (locality A in Fig. 1D) at UTM (WGS 84) 35W 0541640E, 7829770N. This locality, in older literature (e.g., Reading and Walker 1966), known as the Areholmen (now Árasuolu) section from its location opposite the so-named island, exposes the transition from coarse- and fine-grained siliciclastic sediments of the upper part of the Lillevannet Member to the red and purple mudstone-dominated lower Indreelva Member (Fig. 2). The level with palaeopascichnids is within a channelized interval of siltstone and sandstone beds (Fig. 2C, D), ~10 m stratigraphically below the lowest occurrences of discoidal Ediacara-type fossils. It is underlain by 5 m of micaceous siltstone with thin sandstone beds, coarser-grained close to contact with a sandstone-dominated interval that forms the lowest accessible outcrop (Fig. 2A). This siltstone-dominated interval contains linear and curved structures (Fig. 2E, F) of uncertain interpretation. Reading (1965, p. 177) defined the base of the Indreelva Member at the base of the first more than 50 cm thick horizon of red-violet “slate”. It is at the present debatable if the palaeopascichnid-bearing level should be placed within the uppermost part of the Lillevannet Member or the basal part of the Indreelva Member. Of greater importance is that the transition between the two members is gradual (e.g., Reading 1965).

Palaeopascichnids were also collected 8.5 m above the base of the Manndrapselva Member in outcrops along the Manndrapselva River at UTM (WGS 84) 35W 0541858E, 7830555N (locality B in Fig. 1D) in alternations of red mudstone and sandstone. Banks (1970) reported "meander-trails" from the basal part of the Manndrapselva Member, which he compared with forms reported by Glaessner (1969) from South Australia that are now attributed to *Palaeopascichnus*.

Palaeopascichnids from the mid-portion of the second cycle of the Manndrapselva Member were recovered from thin partings of fine sandstone and mudstone from coastal outcrops at UTM (WGS 84) 35W 0544342E, 7832483N. This is close to the transition from heterolithic facies of the lower part of the cycle to the sandstone-dominated higher parts and approximates the level from which palaeopascichnids were reported by McIlroy and Brasier (2017).

Figured material from the Digermulen Peninsula is deposited in the Tromsø University Museum collections (TSGf).

Note on palaeopascichnid taxonomy

Palaeopascichnid taxonomy is in need of thorough investigation (cf. Grazhdankin 2014) but morphological end members can be accommodated in either *Palaeopascichnus*, with forms composed of elongate units, or *Orbisiana*, with circular units (Fig. 1E). In *Palaeopascichnus delicatus* Palij, units typically are elongate and often sausage-shaped (e.g., Palij et al. 1983; Fedonkin 1985). Forms with wider units have been assigned to *Yelovichnus gracilis* Fedonkin (Fedonkin 1985). Fedonkin (1985) also noted irregular development within the units but it is not clear if this justifies separation on the generic level. In particular, palaeopascichnids from the Wonoka Formation, South Australia, suggest that *P*. *delicatus* and *Y*. *gracilis* are transitional, although the latter could be retained as a species of *Palaeopascichnus*. *Curviacus* from the Dengying Formation, South China, has wide and curved units and notably differs in that some chambers have conical projections (Shen et al. 2017).

The majority of palaeopascichnids with circular units can be included in *Orbisiana simplex*. In its type area of the Moscow syneclise, as well as material from the Ladoga area, western Russia, this form is preserved in shale as pyritized husks (Sokolov 1976; Jensen 2003; Golubkova et al. 2017). Forms described as the trace fossil taxon *Neonereites biserialis* preserved in sandstone from the White Sea region, northern Russia, (Fedonkin 1981), appear to be identical to *Orbisiana* but in different preservation. The possibility that some of the palaeopascichnid taxa found in different styles of preservation may be synonymous is further supported by the recent illustration (Golubkova et al. 2017, part 4 of figure in their paper) of what is here interpreted as pyritized *Palaeopascichnus*.

*S*ome material of *Harlaniella* may be transitional with *Palaeopascichnus* (Palij 1976), but other material described as *Harlaniella* may be discrete non-palaeopascichnid taxa (Ivantsov 2013).

Palaeopascichnids in the Stáhpogieddi Formation

See Figure 1E for definition of dimension measurements in palaeopascichnid units.

Lillevannet Member–Indreelva Member transition

Among the palaeopascichnids from the northern part of Árasulluokta Cove, three are detailed below. Specimen TSGf 18401 (Fig. 3A) consists of 1.2 to 1.7 mm long and up to 14 mm wide units, in a somewhat fan-shaped arrangement, in places with units draping the terminal parts of earlier units. A different image of this material was figured in Høyberget et al. (2017). Fedonkin (1985, pl. 27:2) described forms of this morphology from the Verkhovka Formation of the White Sea region as *Yelovichnus gracilis*. As discussed above this form likely should be assigned to *Palaeopascichnus* as a species distinct from *P. delicatus*. Specimen TSGf 18402 (Fig. 3B) consists of ovoid units 1.1 to 1.2 mm long and 2.2 to 2.5 mm wide. Identical material has been described from the Verkhovka Formation as *Palaeopascichnus delicatus* (Fedonkin 1981, pl. 15:4). Specimen TSGf 18403 (Fig. 3C) has elongate to kidney-shaped units 1.5 to 1.6 mm long and 3.3 to 4 mm wide, although there is indication that portions of the specimen consists of more than one row. This makes it comparable to palaeopascichnids from the White Sea region (Fedonkin 1981, pl. 15:2, 5).

Manndrapselva Member, first cycle

Rare *Palaeopascichnus* from outcrops along Manndrapselva River consist of poorly preserved series of kidney-shaped units preserved on the base of a sandstone bed (Fig. 4A; TSGf 18404). This material can be assigned to *Palaeopascichnus delicatus*. Another specimen shows clear ovate to lunate units also attributable to *P. delicatus* (Fig. 4B; TSGf 18405) in similar preservation to material from the White Sea region (Fedonkin and

Vickers-Rich 2007, fig. 297).

Manndrapselva Member, second cycle

In addition to relatively poorly preserved material a slab with well-preserved small *Palaeopascichnus* with units 0.5 to 0.6 mm long and 0.6 to 2.5 mm wide was collected (Fig. 3D; TSGf 18406). Some specimens show progressive increases in segment width along a series before dividing into two narrower series of units. Some of this material falls below the reported size range of *Palaeopascichnus delicatus* but is morphologically identical. In places a slightly oblique arrangement of successive units is seen, suggestive of *Harlaniella podolica,* a fossil also found at this outcrop (McIlroy and Brasier 2017, fig. 4A, and unpublished observations). This would be further evidence that *Palaeopascichnus* includes some *Harlaniella*-like morphotypes.

McIlroy and Brasier (2017, fig. 4b, e) reported *Palaeopascichnus* and *Yelovichnus* from the second cycle of the Manndrapselva Member that are comparable to the White Sea morphotypes. This includes the presence of wide, sausage-shaped, units (Fig. 4C).

Global stratigraphical range of palaeopascichnids

Although no tuffs have been reported from the Digermulen succession the occurrence of *Palaeopascichnus* through some 350 m of stratigraphy is comparable to the long stratigraphical range previously reported from Newfoundland and South Australia. The occurrence of *Palaeopascichnus* in the second cycle of the Manndrapselva Member is stratigraphically close to the lowest occurrences of *Treptichnus pedum* and *Gyrolithes*, suggesting a very latest Ediacaran age (McIlroy and Brasier 2017; Jensen et al. in press). There is greater uncertainty in the age of the *Palaeopascichnus* from the Lillevannet–Indreelva transition, but it is certainly Ediacaran in age—by comparison with other localities with chonostratigraphical data .

Palaeopascichnids have been widely reported from the late Ediacaran strata of Baltica (Fig. 1B). In the White Sea region, palaeopascichnids extend both below and above ashes dated at 555 and 558 Ma (Martin et al. 2000; Grazhdankin 2003). The type region and stratum for *Palaeopascichnus delicatus* is the Kanilov Formation of the Dniestr River area, Ukraine (Palij 1976). Fedonkin (1983) lists *Palaeopascichnus delicatus* found in the Komarovo Member of the Kanilov Formation, the Bernashev Member of the Yaryshev Formation (U–Pb zircon age of 553 Ma, Grazhdankin 2014), and the Yampol and Lomozovo members of the Mogilev Formation. Palaeopascichnids have also been reported from the Urals—under a variety of names—from the Basa and Zigan formations of the Asha Group (see Kolesnikov et al. 2015). An ash from the lower part of the Basa Formation gave a zircon U–Pb age of 547.6±3.8 Ma (Levashova et al. 2013). Grazhdankin et al. (2009) also documented palaeopascichnids from the Perevalok Formation and the lower and middle part of the overlying Chernyi Kamen Formation, of the central Urals. Grazhdankin et al. (2011) obtained a zircon U–Pb age of 567.2±3.9 Ma from a volcanic tuff low in the Perevalok Formation, which provides a maximum age for palaeopascichnids in the Urals and the East European Craton in general (cf. Grazhdankin et al. 2011, fig. 2). The stratigraphical range of palaeopascichnids from the East European Platform is therefore from between ~541 and 565 Ma (Grazhdankin and Maslov 2009, 2015).

Avalonian palaeopascichnids are best known from Newfoundland, where the youngest occurrences approach the Ediacaran–Cambrian boundary in the Chapel Island Formation (Narbonne et al. 1987). Older occurrences are known from the Fermeuse Formation (Gehling et al. 2000; Liu and McIlroy 2015; Liu et al. 2015), which has been considered to be ~560 Ma based on the stratigraphic thickness between the well-dated Mistaken Point Formation and the Fermeuse Formation (e.g., Liu and McIlroy 2015; Pu et al. 2016).

In southern Australia *Palaeopascichnus* is known from the upper part (Unit 8) of the Wonoka Formation (Haines 2000). By global carbon isotope correlation, the upper part of the Wonoka Formation is younger than ~560 Ma (Bowring et al. 2007). Younger palaeopascichnids are present in the Ediacara Member of the Rawnsley Quartzite, but without radiometric age constraint. The potentially oldest Australian *Palaeopascichnus* were reported by Lan and Chen (2012) from the Johnny Cake Shale of the Ranford Formation, east Kimberley, Northern Territory. These overlie glacial deposits of supposed Marinoan age. Higher in the stratigraphy, the Boonall Dolomite has been correlated with the glacigenic Egan Formation (Corkeron 2007), which has been considered a local event or a possible time equivalent to the Gaskiers glaciation (Grey et al. 2011). The Ranford Formation specimens have units up to 5 cm wide and 9 mm long making them the largest described. Additional material with better preservation is needed to confirm that these are comparable to late Ediacaran palaeopascichnids. Another record of a possibly early Ediacaran palaeopascichnid is the report of *Orbisiana* from Member II of the Lantian Formation of South China (Wan et al. 2014). The main age constraint on this occurrence is a pronounced negative $\delta^{13}C$ excursion in Member III of the Lantian Formation, corresponding to the EN 3 excursion in the Doushantuo Formation and considered equivalent to the Shuram-Wonoka anomaly. Wan et al. (2014) considered Member II to be between 635 Ma and 576 Ma and Cunningham et al. (2017) reported the Lantian biota as ~600 Ma. As alternative models position the nadir of Shuram-Wonoka anomaly at ~ 580 Ma or ~ 555 Ma (see Narbonne et al. 2012; Xiao et al. 2016; Fig. 5) a younger age remains possible.

Implications from palaeopascichnids for the age of the Mortensnes Formation glacigenic sediments

Age constraints on the Varanger Ice Age

Neoproterozoic glacigenic units are scattered along the Caledonian margin of Scandinavia from the Moelv Formation in southern Norway to the Smalfjorden and Mortensnes formations in Arctic Norway with a number of intermediate units in Sweden and Norway (e.g., Kumpulainen 2011; Kumpulainen and Greiling 2011; Nystuen and Lamminen 2011; Rice et al. 2011). Collectively, these are known as the Varanger Ice Age (e.g., Nystuen 1985). Age constraints on the Varangerian glacial deposits are poor and the relationship to Neoproterozoic glacial events is equivocal.

The Moelv Formation in southern Norway has been tentatively correlated with the Gaskiers glaciation on the basis of detrital zircon ages and acritarch biostratigraphy. Bingen et al. (2005) record detrital zircons with an U–Pb age of 620 ±14 Ma from sandstones of the Rendalen Formation, well below the Moelv Formation. Reports of acanthomorphic organic-walled microfossils, including *Papillomembrana* and *Ericiasphaera* from clasts in the Biskopåsen Formation, which underlies the Moelv Formation, suggest a post-Marinoan age on the basis of their stratigraphical range in China and Australia (see Zhang et al. 1998; Knoll 2000). Adamson and Butterfield (2014) report a greater diversity of acanthomorphic acritarchs from the Biskopåsen Formation and they note considerable overlap with the Ediacaran *Tanarium conoideum–Hocosphaeridium scaberfacium–Hocosphaeridium anozos* biozone of South China. Furthermore, Hannah et al. (2014) report Re–Os ages of 559 ±6 Ma from the Biri Formation, which underlies the Moelv Formation, suggesting a regional glaciation event that is younger than the Gaskiers.

Arguments for a post-Marinoan age for the Mortensnes Formation, Finnmark, are based on cap carbonate features at the base of the Nyborg Formation and $\delta^{13}C$ values from the upper part of the Nyborg Formation (~ -8‰ to -10‰) and the matrix of the Mortensnes Formation (~ -10‰) (Halverson et al. 2005; Rice et al. 2011). Within the Neoproterozoic such low $\delta^{13}C$ values are found only in the Ediacaran Shuram-Wonoka anomaly, and those of the Nyborg and Mortensnes formations have been suggested to post-date the nadir of this excursion (Halverson et al. 2005; Rice et al. 2011). However, the duration, timing and relative spatial extent of the Shuram-Wonoka anomaly remain uncertain. In some models the Shuram-Wonoka anomaly approximates the Gaskiers, in others it post-dates the Gaskiers (see Narbonne et al. 2012; Xiao et al. 2016; Fig. 5). On the other hand, Kumpulainen et al. (2016) and Nystuen et al. (2016) concluded that the Varangerian glacial units of Scandinavia correlate with the Marinoan glaciation (Fig. 5, Alternative 1). This was based on a 596 Ma U–Pb baddeleyite age from a dyke cross-cutting two Varangerian glacial levels of the Lillfjället Formation in Härjedalen, Sweden. In a further scenario presented by Grazhdankin and Maslov (2015) both the Smalfjorden and Mortensnes formations were deposited between ~600 and 580 Ma (Fig. 5, Alternative 2). This, however, was based on Rb–Sr dating of burial diagenesis of illite (Gorokhov et al. 2001) and so entails some uncertainties, and it would additionally implicate a cap carbonate younger than that associated with Marinoan glaciations.

Palaeopascichnus *and the transition from the Mortensnes Formation to the Stáhpogieddi Formation*

Taking into consideration palaeogeographical context, and the morphological similarity of the Digermulen and White Sea palaeopascichnids an age not in excess of ~565 Ma is suggested for the Lillevannet Member to Indreelva Member transition. This provides new age constraints on the postglacial succession and so may help in evaluating the different scenarios for the age of the Mortensnes Formation (Fig. 5).

The sedimentological nature of the Mortensnes to Stáhpogieddi transition must be considered as the various scenarios predict significant differences in the duration of lithostratigraphical units, in particular the Lillevannet Member and Nyborg Formation and likely breaks in sedimentation. Edwards (1984) interpreted the upper part of the Mortensnes Formation to show transition from lodgement tillite to subaqueous glacially influenced sedimentation. A thin lag conglomerate at the top of the formation in northern outcrops is formed from reworking during isostatic uplift (Edwards 1984). The lower submember of the Lillevannet Member is a 3 to 55 m thick coarsening-up succession interpreted as the progradation of a delta into marine waters. In the depocentre, dropstone laminites of the Mortensnes Formation grade into laminated mudstone of the upwards-coarsening lower submember of Lillevannet Member (Edwards 1984, p. 65). Edwards (1984) interpreted the ~40 m thick upper submember of the Lillevannet Member to have been formed under delta plain conditions containing fluvial and shallow marine facies. The base of the upper submember of the Lillevannet Member is erosive, and Edwards (1984, p. 68) suggested that the pebbly sandstones and conglomerates were deposited either as coarse-grained point bars or in braided streams at a point of maximum regression, which was suggested by Banks et al. (1971, p. 220) to be the result of isostatic rebound. Any major unconformity within the lower part of the Vestertana Group is likely between the Nyborg and Mortensnes formations. Between the Mortensnes Formation and Stáhpogieddi Formation there is evidence for relative sea level fall at the transition from the Mortensnes–Lillevannet transition (McIlroy and Brasier 2017) and between the lower and upper submembers of the Lillevannet Member. However, in neither of these scenarios is there any obvious reason to invoke substantial (many millions of years) times of non-deposition and erosion. In the scenario of a Marinoan age for the Mortensnes Formation

(Fig. 5, Alternative 1) the duration of the Lillevannet Member is larger than 60 Ma. This seems incongruous with the known sedimentological record and would require substantially larger breaks in sedimentation than that of our favoured interpretation, in such case perhaps most likely at the Mortensnes–Lillevannet contact (sequence boundary of McIlroy & Brasier 2017). We therefore consider the occurrence of *Palaeopascichnus* from the Mortensnes–Lillevannet transition provides support for a Gaskiers, or younger, age for the Mortensnes Formation. If the low $\delta^{13}C$ values from the upper Nyborg and Mortensnes formations are related to the Shuram-Wonoka anomaly, this would—based on current models—support a post-Gaskiers age.

Conclusions

Palaeopascichnids, mainly *Palaeopascichnus delicatus*, are found at three horizons within the Stáhpogieddi Formation. The youngest occurrences from the middle portion of the Manndrapselva Member are considered to be latest Ediacaran both on associated trace fossils and the fact that they underlie Cambrian-type trace fossils of the *Treptichnus pedum* Ichnozone. Palaeopascichnids from a horizon transitional between the Lillevannet and Indreelva members suggest that this part of the succession is no older than ~565 Ma. The absence of evidence for major breaks in sedimentation between the glacial Mortensnes Formation and the Stáhpogieddi Formation is consistent with a Gaskiers (~580 Ma), or younger, age for the upper Varangerian glaciation in this area. A Marinoan age for the Mortensnes Formation requires the presence of hitherto unrecognized major breaks in sedimentation.

Acknowledgements. We thank Jonathan Antcliffe and an anonymous reviewer for constructive reviews, and Marc Laflamme for editorial assistance. In the framework of the Digermulen Early Life Research Group financial support for fieldwork in Arctic Norway was provided by the Research Council of Norway (Grant No. 231103). Correspondence with Marc Edwards and Nigel Banks is gratefully acknowledged.

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FIGURE CAPTIONS

Fig. 1. Geographical and stratigraphical setting of *Palaeopascichnus* in the Stáhpogieddi Formation, Arctic Norway, and basic palaeopascichnid morphology. (A) Vestertana Group rocks, in grey shade, preserved within the Gaissa Thrust Belt (g) and para-autochthonous and autochthonous in eastern Finnmark. Circle marks study area. TKF, Trollfjorden–Komagelva Fault Zone. (B) Cratonic portion of Baltica, with late Ediacaran epicontinental basins (grey shading). Modified from Sliaupa et al. (2006). Principal occurrences of palaeopascichnids are: 1, Digermulen Peninsula, Arctic Norway; 2, White Sea region, northern Russia; 3, Ladoga region, western Russia; 4, central part of Moscow syneclise; 5, the Urals; 6, Podolia, Ukraine. (C) Simplified stratigraphy of the Vestertana Group, showing occurrences of palaeopascichnids and selected key fossils. CRYO, Cryogenian. (D) Geology of the southeastern portion of the Digermulen Peninsula, based on Siedlecka et al. (2006), showing localities yielding palaeopascichnids (see text for details). On Árasuolu island rocks of the Nyborg and Smalfjorden formations are exposed. (E) Schematic tracings of *Palaeopascichnus*-type (E1) and *Orbisiana*-type (E2) palaeopascichnids, branching *Palaeopascichnus* (E3) and definition of dimension measures (E4). E1 and E2 based on Jensen (2003, fig. 5B, C); E3 based on Haines (2000, fig. 7G).

Fig. 2. Transition from the Lillevannet to Indreelva members in coastal outcrops in northern portion of Árasulluokta cove. (A) General view with sandstone of the Lillevannet Member in the lower left hand part and red and purple mudstone of the Indreelva Member in the upper right hand. *Palaeopascichnus* were found in the upper part of ochre-weathering interval of sandstone and shale. (B) Transition from cross-bedded sandstone to micaceous

laminate siltstone. The latter contains thin stringers of sandstone, in places coarse-grained, in the lower part. (C) Transition from micaceous siltstone and fine-grained sandstone to ochre-weathering interval of sandstone and siltstone. Note erosive contact. (D) Guido Meinhold indicating level yielding *Palaeopascichnus*. (E) Top surface of thin micaceous fine-grained sandstone bed with various finger-shaped structures of uncertain origin. Scale bar represents 10 mm. (F) Base of thin fine-grained sandstone bed with tubular structures of uncertain origin. Scale bar represents 10 mm.

Fig. 3. Palaeopascichnids from the transition between the Lillevannet and Indreelva members (A–C) and the Manndrapselva Member (D). (A) *Yelovichnus*-type forms. TSGf 18401. (B) *Palaeopascichnus delicatus*. TSGf 18402 (C) *Palaeopascichnus delicatus.* In upper right hand part of the image with possible orbisianid development. TSGf 18403 (D) Small *Palaeopascichnus delicatus*, in places showing widening units that divide into narrower units. TSGf 18406. Scale bar in A represents 10 mm; scale bars in B, C and D represent 5 mm.

Fig. 4. Palaeopascichnus from the first (A, B) and second (C) cycle of the Manndrapselva Member. (A, B) *Palaeopascichnus delicatus* from the basal part of the Manndrapselva Member, Manndrapselva River. (A) TSGf 18404. (B) TSGf 18405. Scale bars represent 2 mm. (C) Slab showing typical *Palaeopascichnus delicatus* and wider units of *Yelovichnus* type. Scale bar represents 5 mm. Oxford University Museum OUM AZ 119.

Fig. 5. Global context and alternative temporal scenarios for the Vestertana Group. The carbon isotope stratigraphy with two alternative placements of negative excursion EN3, which is believed to correspond to the Shuram-Wonoka anomaly, is based on Narbonne et

al. (2012). The Lillevannet to Indreelva transition is fixed as being no older than about 565 Ma on the basis of *Palaeopascichnus*. Our preferred interpretation is similar to that of Halvorsen et al. (2005) and Rice et al. (2011). However, if the Shuram-Wonoka anomaly is recorded in the upper Nyborg and Mortensnes formations these units are younger than depicted. A Marinoan age for the Mortensnes Formation (Alternative 1; cf. Nystuen et al. 2016), results in a time span of ~65 Ma between the Mortensnes Formation and the lower part of the Stáhpogieddi Formation (Lillevannet and Indreelva members). Alternative 2 follows Grazhdankin and Maslov (2015). See text for additional details.

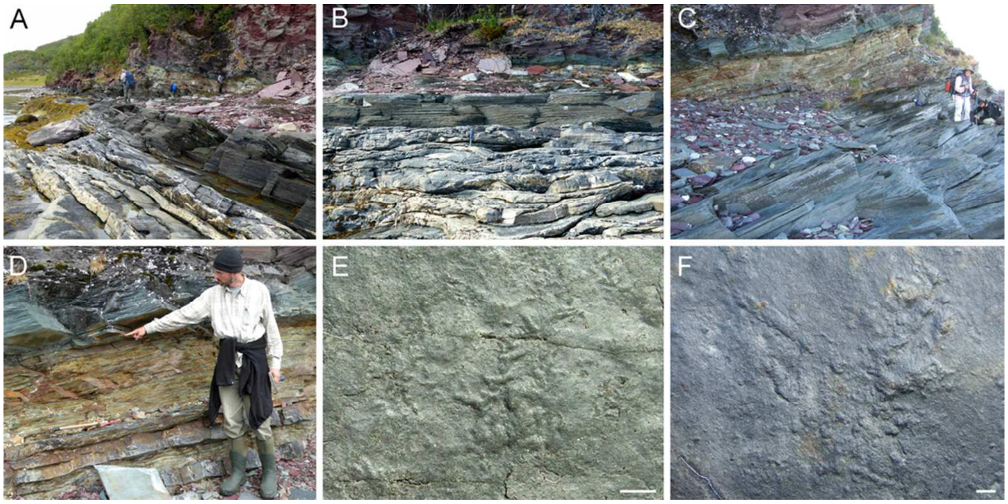

Figure 2

90x44mm (300 x 300 DPI)

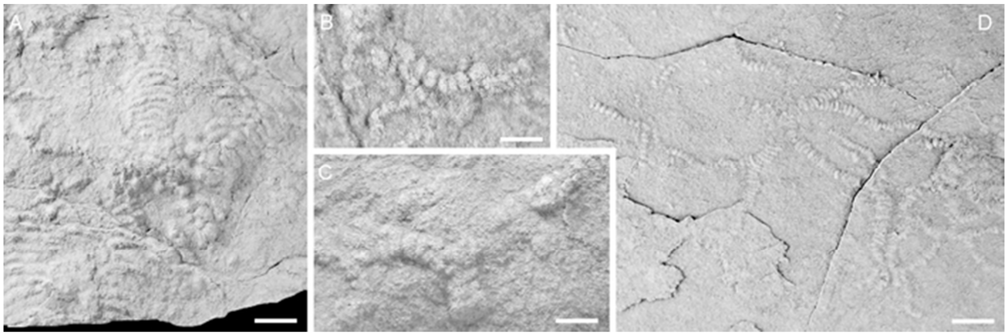

Figure 3

59x19mm (300 x 300 DPI)

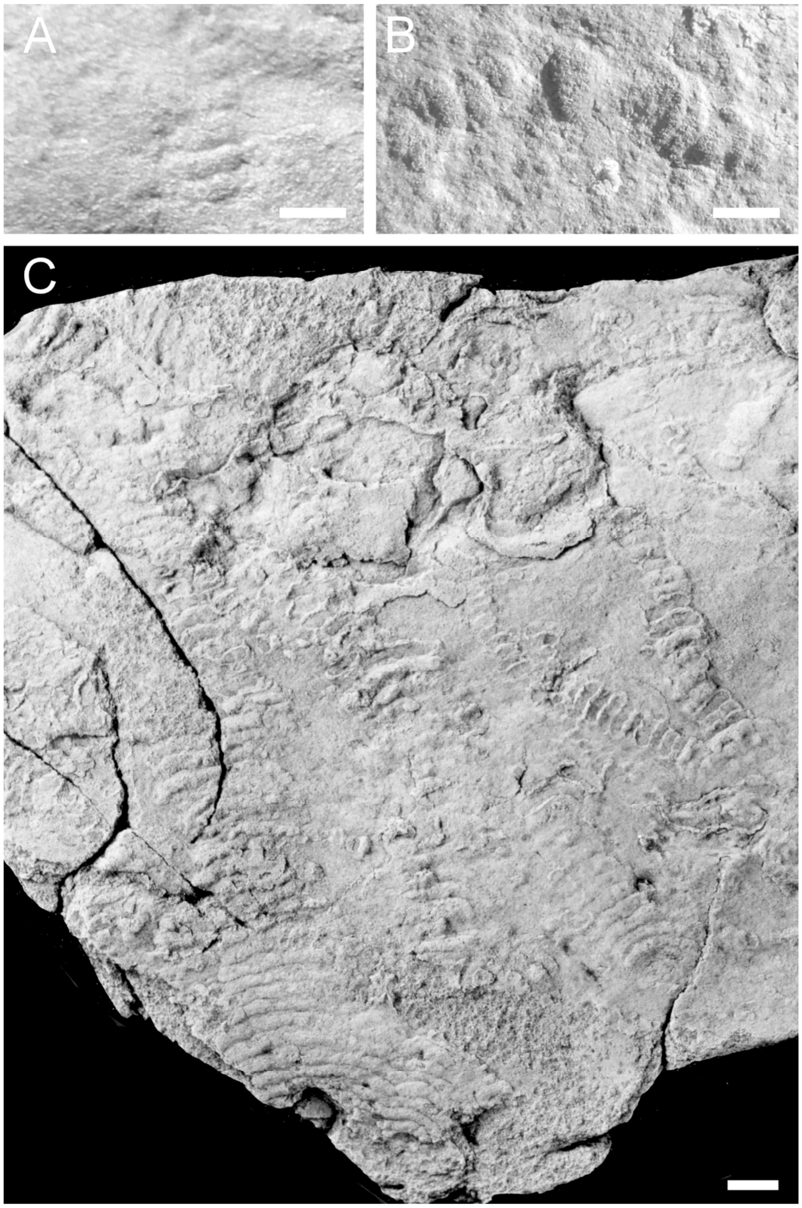

Figure 4

118x179mm (300 x 300 DPI)

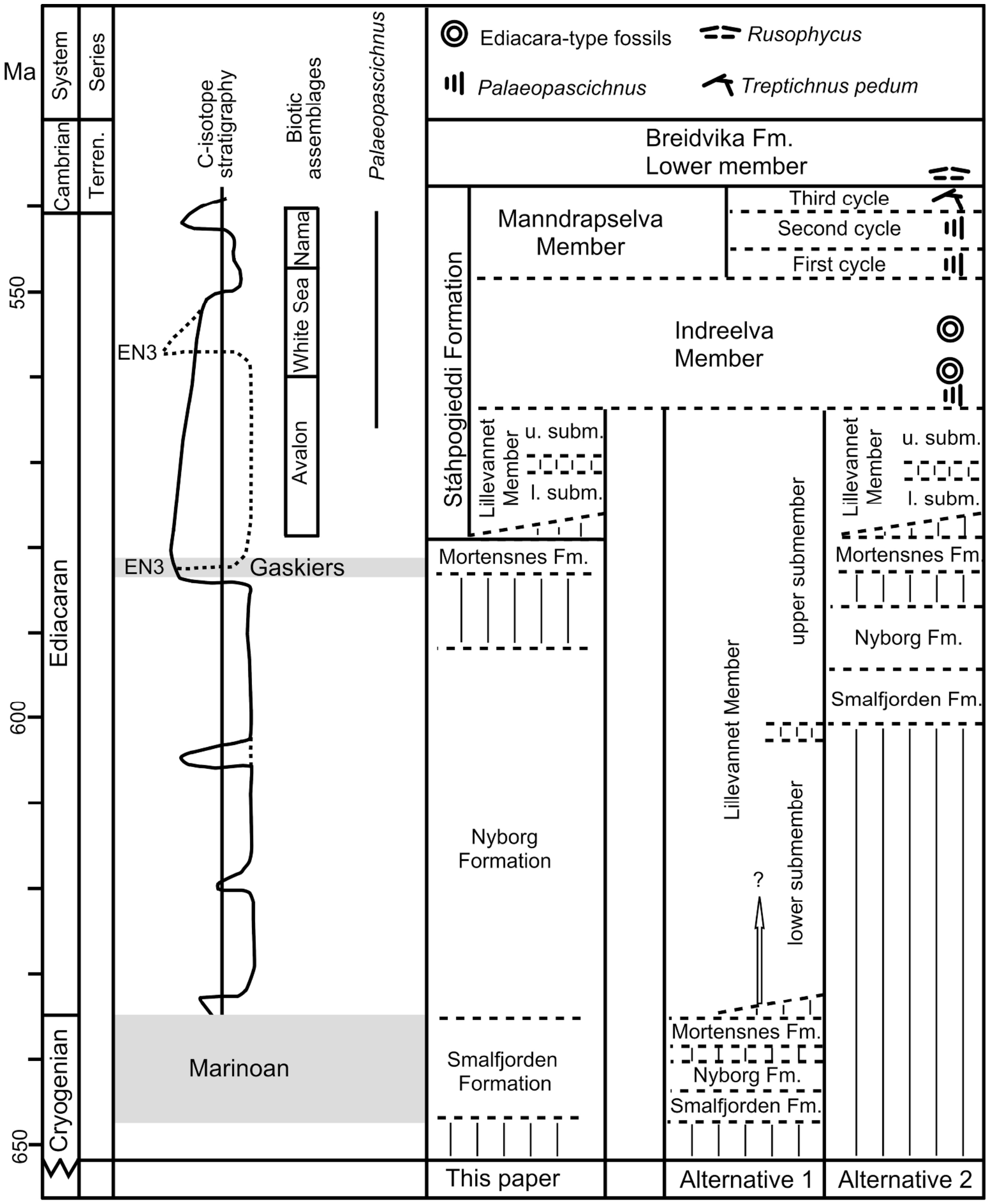

Figure 5

121x148mm (600 x 600 DPI)