Distribution of *Sabellidites* (Annelida?) in the Basal Cambrian of the Digermulen Peninsula, Arctic Norway

Utbredningen av det kambriska fossiliet *Sabellidites* på Digermulenhalvön, Norge

Frida Hybertsen
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Abstract

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The Digermulen Peninsula, Arctic Norway, offers a unique section of late Ediacaran to Cambrian sediments in an almost complete succession within the Vestertana Group. The proposed annelidan fossil Sabellidites cambriensis is found here, within the Lower Breidvika Member and is believed to exist also in the underlying Manndrapselva Member of the Ståhpogieddi Formation. Three cycles are recognized from the Manndrapselva Member, the uppermost being the third cycle, and the sediment interval of interest for this study ranges from the third cycle of the Manndrapselva Member to the Lower Breidvika Member where the Ediacaran–Cambrian boundary is situated. The distribution of Sabellidites has been investigated in three different localities on the Digermulen Peninsula, and from two of these stratigraphical logs were made and the sections were documented with photographs. The logs were created over sediments from Locality 1: Bárdeluovttjohka and Locality 3: Manndrapselva in the interval of the top of the Manndrapselva Member and Lower Breidvika Member. Previous studies have shown that the stratigraphical distribution of Sabellidites is within the Lower Breidvika Member. New results presented in this study extended the temporal distribution downwards in the third cycle of the Manndrapselva Member and closer to the Ediacaran–Cambrian boundary. The boundary is indicated by the trace fossil Treptichnus pedum. A few samples, collected from the logged sections, were found below the T. pedum level, indicating late Ediacaran origin. Three samples were collected even further down, close to the base of the Manndrapselva log, but these could only loosely be identified as Sabellidites and further analysis is required on these specimens. The Sabellidites distribution range from the Digermulen Peninsula was briefly compared to other locations and a global correlation is possible. The results here indicate that Sabellidites is an excellent reference taxon for the terminal Ediacaran and early Cambrian and that the succession on the Digermulen Peninsula may be one of the most important for global correlation across the Ediacaran-Cambrian boundary.

Keywords: Ediacaran, Cambrian, Sabellidites, biostratigraphy, Digermulen Peninsula, Arctic Norway

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Frida Hybertsen


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Table of Contents

1. Introduction......................................................................................................................1
  1.1 Aim ..........................................................................................................................3
  1.2 Biostratigraphy .........................................................................................................4

2. *Sabellidites* ..................................................................................................................6

3. Background.....................................................................................................................7
  3.1 Previous work ...........................................................................................................7
  3.2 Geological Setting .....................................................................................................7

4. Methods .........................................................................................................................11

5. Results ..........................................................................................................................13
  5.1 Distribution of *Sabellidites* on the Digermulen Peninsula .....................................13
    5.1.1 Locality 1: Bárdeluovtjohka .............................................................................13
    5.1.2 Locality 2: Avžejohka ....................................................................................17
    5.1.3 Locality 3: Manndrapselva ............................................................................17
  5.2 Comparison with other areas ....................................................................................18

6. Discussion ......................................................................................................................24
  6.1 The distribution of *Sabellidites* .............................................................................24
  6.2 Global distribution of *Sabellidites* ........................................................................27
    6.2.1 *Sabellidites* sp. .............................................................................................27
    6.2.2 Bornholm, Denmark .......................................................................................27
    6.2.3 Eastern European Platform, Poland and Latvia ..............................................27
    6.2.4 Newfoundland, Canada ..................................................................................28
    6.2.5 Global correlation ...........................................................................................28
    6.2.6 Palaeobiogeography .......................................................................................29
  6.3 Further work .............................................................................................................29

7. Conclusion ......................................................................................................................30

8. Acknowledgements ........................................................................................................31

9. References .....................................................................................................................32

Appendix 1: Sample log ...................................................................................................36
1. Introduction

During the Proterozoic, Earth experienced extensive glaciations where most of the landmasses and seas were covered by ice. Eukaryotic cells and cyanobacteria, single-celled life forms, are early indications of life from this time; however, constant glaciations made establishment difficult for these early organisms (Fedonkin et al., 2007). Huge deposits of organic carbon had been trapped by the ice covers, creating anoxic oceans and making photosynthesis difficult, but increased volcanic activity following break-up of the supercontinent Rodinia led to a significant rise of atmospheric CO₂ levels. By the end of the Neoproterozoic, around 740–580 Ma, signs of warmer climate can be seen in the geological record (Fedonkin et al., 2007). The Ediacaran period starts where these signs and early life forms appear, in the shape of single-celled organic-walled microorganisms, and were evolving into advanced life forms around 600 Ma. This is when the earliest interpreted stem group metazoans (animals) appeared (Chen et al., 2014; Yin et al., 2016). Macrofossils are first known from rocks spanning the last 575–541 million years, during the Ediacaran period, preceding the event known as the ‘Cambrian explosion’ in the earliest Cambrian. Introducing new features such as mobility, skeletonization, sexual reproduction and the creation of complex ecosystems, these organisms gave rise to early diverse, multicellular metazoans (Droser and Gehling, 2013). This early fauna occurs in marine settings and is known globally from 40 localities and four of these are particularly interesting with their diverse and well-preserved Ediacaran fossils: southeastern Newfoundland, (Canada), Flinders Ranges, (South Australia), the White Sea region of Russia and southern Namibia. The first two hold each a GSSP defining the upper and lower boundary of the Ediacaran. Three successive Ediacaran assemblages have been described from these localities based on evolutionary controls: The Avalon, the White Sea and the Nama assemblages (Narbonne, 2005). The Ediacaran biota emerged after the glacial deposits of the late Proterozoic and the before appearance of diverse small shelly fossils. It was first described in Namibia by Gürich (1930), including fossils of around a hundred species of soft-bodied animals, and it is quite complex (Farmer et al., 1992). Developed under special environmental conditions and with an absence of predators, limited bioturbation and low atmospheric oxygen levels (Farmer et al., 1992), the Ediacaran biota could thrive. By the end of the Marinoan glaciation, the supercontinent Rodinia was breaking apart (Fig. 1) and the transition into the Cambrian began with a series of climate changes, ongoing orogenies and anoxic sea water (Schiffbauer et al., 2016). This is marked in the sediments by unconformities and sparser bioactivity. The beginning of the Cambrian diversity increase shows a heavily reduced Ediacaran biota due to many species going extinct from these environmental changes and the introduction of new life forms. Following this series of abiotic and biotic events, the Cambrian explosion, which has been described from, among others, the Burgess Shale fauna in Canada and the slightly older Chengjiang biota from China (Schiffbauer et al., 2016), has been known as the beginning of the development and diversification of all major metazoan phyla. Recent studies suggest that multicellular life and early metazoans already existed before the Cambrian explosion, pointing towards a gradual transition instead
of a rapid event (e.g. Schiffbauer et al., 2016). This important evolutionary transition is something that can be observed in particular detail in the sedimentary succession of the Digermulen Peninsula, Finnmark, Arctic Norway (Fig. 2), which is studied by the Digermulen Early Life Research Group.

An almost complete succession of mostly siliciclastic deposits ranging from the Cryogenian to the Lower Ordovician is found on the Digermulen Peninsula, including a well-defined Ediacaran-Cambrian boundary marked by the appearance of the trace fossil *Treptichnus pedum* (Banks, 1970; Högström et al., 2013). The transition lies within the Vestertana Group, which is made up of fluvial and marine sediments with two tillite horizons, indicating glaciations (Siedlecka and Roberts, 1992). The Vestertana Group ranges from the Cryogenian Smallfjord and Nyborg and Cryogenian/Ediacaran Mortensnes formations, through the Ediacaran/Cambrian Stáhpogieddi Formation and the Cambrian Breidvika
Formation. The sediments of the succession hold trace fossils, Ediacaran soft-bodied metazoans such as discoidal fossils (e.g. *Aspidellida* sp.), sphaeromorphic acritarchs, vendotaenids as well as the potential annelidan *Sabellidites cambriensis* (Banks, 1970; Vidal, 1981; Högström et al., 2013; Moczydłowska et al., 2014). *S. cambriensis* is particularly interesting owing to its distribution near the Ediacaran–Cambrian boundary as well as occurring in several palaeogeographic regions. The presence of *S. cambriensis* in the Vestertana Group was reported by Farmer et al. (1992) and Högström et al. (2013) within the Cambrian Breidvika Formation. However, new findings show a wider temporal distribution, presented in this study. *S. cambriensis* can also be found globally, e.g., in Denmark, on the East European Platform and in Newfoundland, and this distribution is briefly compared to the results of this study.

![Figure 2](image_url). Map of the Nordic countries with the Digermulen Peninsula marked by the red rectangle. VP indicates the Varanger Peninsula.

**1.1. Aim**

This study aims to investigate the stratigraphic distribution of the organic-walled tube-shaped fossil *Sabellidites cambriensis* within the deposits belonging to the Vestertana Group on the Digermulen Peninsula, Arctic Norway. The phylogenetic affinities of *S. cambriensis* remain unclear for now, although it was considered an annelidan by Moczydłowska et al. (2014). It is a fossil found near the Ediacaran-Cambrian boundary and it may be useful in defining the boundary and for global correlation.
Reported occurrences of *S. cambriensis* in the lower Cambrian Breidvika Formation have led to a closer investigation of the Lower Breidvika Member and the third cycle of the Manndrapselva Member of the Stáhpogieddi Formation, which lie in the upper part of the Vestertana Group and is the focus of this study. Mapping the occurrence of *S. cambriensis* in these well-documented and well age-constrained sediments gives a better understanding of the spatial and temporal distribution of *Sabellidites* which can be compared with other areas to improve international correlation. This work also highlights the uniqueness of the succession on the Digermulen Peninsula. The results of this thesis will add significantly to the studies in progress by the Digermulen Early Life Research Group, funded by the Research Council of Norway (NFR) for the 4-year project "The Digermulen Peninsula – a window into the early diversification of animal life".

1.2 Biostratigraphy

Geological nomenclature for stratified rock units is controlled by stratigraphic guides, which include nomenclature for lithostratigraphy, chronostratigraphy and biostratigraphy. Specific guides exist for different countries, i.e. the North American Stratigraphic Code by the North American Commission on Stratigraphic Nomenclature (NACSN), the rules and recommendations for geological units in Norway by Nystuen (1989), and in Sweden there is currently a sub-committee to the Swedish National Committee for Geology monitoring the application of a new guide by Kumpulainen (2017). These guides contain a system for naming units of rock or sediment defined by their composition, appearance, formation, content and other properties. There are several categories of stratigraphic units, the main ones being lithostratigraphic, chronostratigraphic and biostratigraphic units.

Lithostratigraphy describes and classifies layered rocks based on rock properties and boundary conditions of the units. Kumpulainen (2017, p. 11) describes a lithostratigraphic unit as “a body of sediments, sedimentary or volcanic rocks or metamorphosed sedimentary or volcanic rocks, which can be delimited on the basis of its stratigraphic position and specific lithological characteristics, observable in the field”. The units are described in terms of rank, which are, in descending order: supergroup, group, formation, member and bed. Chronostratigraphy is used internationally to distinguish rocks by age and time relations. Chronostratigraphical units that are commonly used are stage, series and system. Two or more stages forms a series and two or more series forms a system. Boundaries of these units are determined by a Global boundary Stratotype Section and Point (GSSP), which can be used for correlation in other sections. A major function of chronostratigraphy is to put the rocks and sediments of a section in chronological order based on the time of formation and dating of the units within. To define separate strata, “lower” and “upper” are used, and “early” and “late” define intervals of time.

Biostratigraphy uses fossil content of geological units to interpret age and sequencing of beds making up the units. It is based on the notion that certain assemblages of animals are characteristic to specific time intervals and the sediments they were deposited in. The characteristics are features that control the fossil content and fossil distribution in an interval of strata, such as relative abundances or specific
morphological features. A biostratigraphic unit (biozone) can only exist where the defined conditions are met. Deposits with these types of fossil assemblages reflect the life of succeeding animal assemblages over periods of time and thus show evolutionary changes that cannot be illustrated by other stratigraphic units (Murphy and Salvador, 1999). On a broad scale, it is possible to recognize certain groups of fossils to be more abundant within a period of time, e.g. trilobites and brachiopods during the Early Palaeozoic (Clarkson, 1998). On a local scale once a fossil sequence has been thoroughly sampled and defined, it can be used for correlation with other areas. Certain fossil species that have been documented from several sections can be used as stratigraphical markers. In the geological succession, these fossils make up the biozones, which are named after one, or a combination of several characteristic species, comprising the rocks they are found in. A biozone is delimited by first and last occurrence of the selected species. Depending on the chosen attributes of the biozone, the same interval of strata may contain several biozones that overlap or have gaps between them. Murphy and Salvador (1999) defines five different types of biozones: range zones, interval zones, assemblage zones, abundance zones and lineage zones and these can be used together or separately to describe a stratigraphic interval. The range zones represent an interval where the stratigraphic and geographic range of occurrence for a taxon or taxa is known. Interval zones are defined and limited by specified biohorizons that are based on lowermost and highest known occurrence for described taxa. Lineage zones stricter divisions based on that the specimens found in a section have successive features belonging to an evolutionary lineage. The entire range of a taxon, or part of it, can be represented within the same lineage. Lineage zones are restricted by the biohorizons that hold the lowest occurrence of the featured elements of a considered evolutionary lineage. Assemblage zones (Fig. 3) contain assemblages of three or more fossil taxa that together distinguish the interval they were found in from adjacent stratigraphic intervals. Boundaries used for assemblage zones are biohorizons constraining the occurrence of the specified assemblage characteristic to the interval. Abundance zones describe intervals that contain taxa or groups of taxa in greater abundance than adjacent intervals, when traced laterally. Boundaries are defined by biohorizons where distinct changes in abundance of a specified taxon or taxa for that zone can be observed.

2. Sabellidites

Sabellidites was an organism that left tube-shaped fossils occurring in deposits from late Ediacaran and the Cambrian. Three species are named, Sabellidites cambriensis Yanishewsky 1926, Sabellidites yunnanensis Luo and Zhang 1986 and Sabellidites badaowanensis Luo and Zhang 1986. The last two have only been described from one locality in the Yunnan province in southern China (Luo and Zhang, 1986). S. cambriensis occurs in several European localities (e.g. Lendzion, 1972; Farmer et al., 1992; Moczydlowska et al., 2014) and is mostly recovered from Cambrian sections. Ongoing studies are being made in order to investigate the attributes of this species and Sabellidites is often referred only by the genus name in publications.
Sabellidites cambriensis, is recorded from the lower Cambrian as the earliest known animal which was organically preserved (Moczydłowska et al., 2014). Transitioning into the Cambrian, soft-bodied fossils were affected by bioturbation and covered by traces or destroyed by burrows, and they became sparser in the fossil records. In the early Cambrian, when atmospheric CO$_2$ levels increase (Fedonkin et al. 2007), biomineralization was used by several organisms. S. cambriensis appeared at the same time as biomineralizing forms, such as Cloudina Germs 1972, Namacalathus Grotzinger et al. 2000 and Namapoikia Wood et al. 2002 (Moczydłowska et al., 2014), and evolved robust chitinous tube walls that could resist late Ediacaran bioactivity and early diagenesis (Moczydłowska et al., 2014). This is believed to be the reason for the exquisite preservation.

The phylogenetic affinities of S. cambriensis are unclear. Its morphology and presumed chitinous tube material led Sokolov (1972) to propose a pogonophoran affinity. Today the phyla Pogonophora and Vestimentifera are placed in the polychaete family Siboglinidae (Rouse and Fauchald, 1997). This was tested by Urbanek and Mierzejewska (1977), but they failed to separate Sabellidites from siboglinids due to their inability to distinguish the fibrous structures of the fossilized tube walls. The presence of fibrous structures was described by Ivantsov (1990), but his results did not yield any suggestions on the affinity, which remained uncertain until Moczydłowska et al. (2014) revealed that the microstructure and biogeochemical features of the organic tubes in Sabellidites have a chitinous-proteinaceous fibrous composition matching that of extant siboglinid tubes. This recognition indicates that chitin synthesis has a role in early metazoan evolution and functioned as protection for plausible early annelids. Chitinous preservation in early annelids is with this, extended down towards the late Ediacaran (Moczydłowska et al., 2014), and the results of this study prolong it even further.

**Figure 3.** Assemblage zone. In this example, the assemblage zone includes nine taxa with different stratigraphic ranges. It may be necessary to provide information about the boundaries, such as: the lowermost boundary can be said to be placed at the lowermost occurrence of taxa a and the upper boundary at the highest occurrence of taxon e and d. Taxa defining the zone should be present. Redrawn from Murphy and Salvador (1999, fig 6).
Herein, the investigated fossils from the Vestertana Group will be referred to as *Sabellidites* sp. and further discussed in the Discussion chapter.

3. Background

3.1 Previous work

The Ediacaran-Cambrian boundary is a subject of great interest and the Digermulen Peninsula is unique for holding a seemingly complete succession of Ediacaran to Cambrian rocks (Högström et al., 2013). It is perfect for examining the conditions around the boundary. Early work on the succession has been done in terms of assessing the geology. For example, Reading (1965) adds to the work of Holtedahl (1918) and Føyn (1937) by describing the succession at the Digermulen Peninsula for the Geological Survey of Norway. Additional work was done by Banks (1970; 1973) and Banks et al., (1971) who also added to the descriptions of the fossil content. Farmer et al. (1992), Crimes and McIlroy (1999), Högström et al. (2013) and McIlroy and Brasier (2016) have all done and are doing continuous work on the sections on the Digermulen Peninsula to further assess the geology and fossil content.

3.2 Geological setting

The Ediacaran is the period right after the break-up of the former supercontinent Rodinia where Laurentia and Baltica separated, forming the Iapetus Ocean in between them, initiating sedimentation along the continental rift margins (Nystuen et al., 2008). The position of Baltica at this time is believed to have been on the southern hemisphere, around 30–50°S (Torsvik and Rehnström, 2001). The position and shape of Baltica has shifted a lot due to collisions with other continents, accretions and rotation, that possibly caused the Timanide Orogeny and later played a part of the Caledonian Orogeny (Nikishin et al., 1996). The core of Baltica consists of the East European craton which has three segments: Fennoscandia, Volgo-Uralia and Sarmatia (Cocks and Torsvik, 2005). Part of the northwestern segment Fennoscandia is the Fennoscandian Shield where the Digermulen succession is situated.

The Digermulen Peninsula is located in the Finnmark county in the northeastern part of Norway, a county that borders Russia and Finland to the east and south and Barents Sea to the north. The area is made up of several fjords and lining the Digermulen Peninsula on both sides are the Tanafjorden and Langfjorden (Fig. 4). This area includes sedimentary rocks which belong to two groups: the Smalfjord, Nyborg, Mortensnes, Stáhpogieddi and Breidvika formations, oldest to youngest, making up the Vestertana Group and the Duolbagáisá, Kistedalen and Bearalgáisá formations, oldest to youngest, constituting the Digermulen Group (Reading, 1965). The sediments of these groups were accumulated in an autochthonous basin on the northern margin of the Fennoscandian Shield, where it is situated today, in association with the Timanide Orogeny (Nikishin et al., 1996; Gorokhov et al., 2001), and have undergone alteration in association with tectonic events and early-phase Caledonian Orogeny (Siedlecka and Roberts, 1992; Roberts and Siedlecka, 2002). Age constraints on the Vestertana Group are based
on glacial unconformities and the presence of bioactivity, such as trace fossils and body fossils (Banks, 1970; Högström et al., 2013; McIlroy and Brasier, 2016). The Ediacaran-Cambrian boundary is indicated by the trace fossil *Treptichnus pedum* and placed within the upper part of Vestertana Group in the Manndrapselva Member (Högström et al., 2013; McIlroy and Brasier, 2016). The Vestertana Group depicts a gradual transition between late Ediacaran and Cambrian rocks. The succession is also represented on the Varanger Peninsula; however, it holds the most complete section on the Digermulen

Figure 4. A: Map of the Nordic countries with the position of the Digermulen Peninsula marked by a red rectangle. B: Geological map of the Digermulen Peninsula with legend. The red rectangle marks the area where field studies were carried out. Map courtesy of J.O.R. Ebbestad.
Peninsula (Fig. 5). The most basal formation of the Vestertana Group is the Smallfjord Formation, formed during the Late Cryogenian and it consists of subglacial structured diamictites deposited during glacial shearing (Edwards, 2004). It is overlain by the Nyborg Formation consisting of fluviial/shallow-marine siliciclastic material and minor carbonates.

Figure 5. An overview of the complete succession at the Digermulen Peninsula. The studied level lies around 800 m and includes parts of the Lower Breidvika Member and the Manndrapselva Member. (G) indicates glacial sediments.
Above follows the Mortensnes Formation, which is marked by an unconformity at the base and it consists of glaciogenic diamictites. The unconformity is regional and the formation has been correlated with deposits in Newfoundland marking the c. 580 Ma Gaskiers glaciation (Rice et al., 2011). However, Nystuen et al. (2016) proposes a correlation to the Marinoan glaciation, which would make the formation much older. The lack of biostratigraphical age constraint in the Mortensnes Formation is because the fossils are mostly reworked organic-walled microfossils such as sphaeromorphic acritarchs and vase-shaped microfossils (Vidal, 1981; Vidal and Moczydłowska, 1995), which are non-diagnostic. The overlaying Stahpogieddi Formation has three members: the Lillevannet Member, the Indreelva Member and the Manndrapselva Member. The Lillevannet Member continues right above the Mortensnes Formation and consists of laminated siltstones and sandstones interpreted as fluvial to shallow-marine deposits. The Indreelva Member is dominated by laminated mudstones with interlaying coarser layers. It may have formed on a marine shelf with intervals of storm influence (Banks, 1973). Farmer et al., (1992) reported discoidal fossils from the middle part of this unit. The succeeding Manndrapselva Member is around 160 meters thick and consists of reddish sandstone at the base followed by cycles of coarsening sediments going from mudstones and fine sandstones to cross-bedded sandstones. Three cycles have been recognized, referred to as first, second and third cycle of the Manndrapselva Member. They are interpreted as distal and proximal turbidites having deposited fine-grained sediments whereas the coarser sediments were deposited in a shallow marine environment (Banks et al., 1971). The top of the third cycle of the Manndrapselva Member begins with two intervals with a transition from white to red quartzites (Reading, 1965). This was used as a reference to correlate the logs with each other and with photographs taken in the field. On top of the Manndrapselva Member is the Breidvika Formation is divided into Lower Breidvika Member and Upper Breidvika Member, the former consisting of interchanging mudstones, siltstones and sandstones deposited in a shallow marine environment and the latter dominated by mudstones interpreted as offshore shelf deposits.

4. Methods

Field work was carried out by the Digermulen Early Life Research Group between July 21– August 7 in 2016 on the Digermulen Peninsula. Three localities were chosen for examination based on previous field work and three sections spanning the third cycle of Manndrapselva Member and the lower Breidvika Member were investigated (Fig. 6). Sections were chosen based on their exposure of the Ediacaran-Cambrian boundary and the chosen interval of strata was either known to, based on observations from previous field work, or assumed to contain Sabellidites sp. Two of the sections were measured and sampled in detail for biostratigraphical purposes.

Two intervals of transition from white quartzite to red quartzite (see Reading, 1965), were used as reference layers for correlation of the logs with each other and with photographs taken in the field. These intervals were located within all three localities, although in Locality 1 and 2 the white quartzite was
not as distinct as in Locality 3 and therefore the red quartzite was used assuming that the white quartzite was there but not visible.

Locality 1 is a coastal section south of the outlet of the Bárđeluovttjohka rivulet and referred to as the Bárđeluovttjohka locality. Here the section ranges from the lower part of the Lower Breidvika Member down to the third cycle of the Manndrapselva Member. The Bárđeluovttjohka log (Fig. 7) describes a section ranging from the top of the third cycle of the Manndrapselva Member and 20 meters downwards into the unit. In this section strata were logged from the lowermost layer of red quartzite at the top of the Manndrapselva Member, which was used as base reference layer (0 meters). The Treptichnus pedum level was identified (see Fig. 8D) with photographs of the locality and through previous field work (see Högström et al., 2013). A few of the samples collected from this locality are shown in Figure 9.

Locality 2 (Avžejohka) is situated by, and partly inside, a ravine above the Avžejohka rivulet. The lower part of the Lower Breidvika Member was well exposed and was easily sampled. The Manndrapselva Member was exposed on the walls of the ravine, but was inaccessible for sampling and logging. There is therefore no log from this locality, although the same units described above can be found here, and the boundary between the Lower Breidvika Member and the Manndrapselva Member was located. Figure 10 shows a large slab with a great number of specimens from this section.

Locality 3 (Manndrapselva) runs alongside the Manndrapselva river and 55 m of the section was stratigraphically logged (Fig. 11 (log) and Fig. 12). An interval consisting of siltstone layers with interbedded sandstone lenses, close to the base of the third cycle of Manndrapselva Member was used as reference layer (0 meters). An additional five meters were logged from the opposite side of the river (see Fig. 13A) from the reference layer and down towards the base of the third cycle of the Manndrapselva Member in order to make sure that the log would describe the whole third cycle. Some of the samples from this section can be seen in Figure 14. The section at the Manndrapselva locality was partly covered and the log was divided into four parts, A–D when logged in the field. These parts did not overlap and were later combined into the Manndrapselva log. In places where the section was not exposed, the thickness was estimated based on the dip of the strata and the horizontal distance between the last bit of exposure and the following exposure.

A total of 79 samples (Appendix 1) were collected for this study and the stratigraphical logs were created using the International Stratigraphic Guide (Murphy and Salvador, 1999) as a guide. Additional samples, e.g., for trace fossils, microfossils, biomarkers and provenance analysis were collected from the same sections by other members of the field group. These are still being analyzed and are not included in this study. All of the samples were transported from the field area to Tromsø University Museum, Norway and later the Sabellidites-samples were sent to the Museum of Evolution in Uppsala, Sweden to be further examined. Fourteen samples were selected for photography and photographed by using a LEICA MZ9.5 stereomicroscope with a Nikon DS-Fi1 camera head. Photoplates were created using Adobe Illustrator® for the two localities where the sections were logged and one photoplate with
Sabellidites-specimen were made for each. A thin coat of alcohol was applied to some specimens to enhance their features in the photographing process.

To map global distribution of Sabellidites comparative literature studies were made. Occurrences were plotted on a map of the early Cambrian, where Baltica is placed 30–50° south of the equator, resulting in a map showing the palaeogeographical distribution of fossil occurrences. These were also compared to distribution in time concerning first appearances. The Cambrian maps were created with BugPlates (Torsvik, 2009).

Figure 6. Detailed map over the studied area, enlarged from Figure 4. Localities are indicated with red squares with assigned numbers. Locality 3 stretches along the Manndrapselva river and is therefore indicated by a red line. For legend of the geological units, see Figure 4.

5. Results

5.1 Distribution of Sabellidites on the Digermulen Peninsula

5.1.1 Locality 1: Bárdeluovttjohka

Previous investigation of this locality by Farmer et al. (1992) recorded Sabellidites at 9 m and 16 m above the base of the Lower Breidvika Member at the Bárdeluovttjohka section. Högström et al. (2013) extended the distribution range into an 18 m interval up-section, still within the Lower Breidvika Member. In this study, the top of the log was placed close to the transition between the Lower Breidvika Member and the Manndrapselva Member to further investigate the Sabellidites distribution range down-section. At this locality, the section was logged (Fig. 7) from the second layer of red quartzite (see Högström et al., 2013), a little below the base of the Lower Breidvika Member, which was used as a
reference layer (0 meters) (Fig. 8A) and 20 meters down the section (see Fig. 7). Around -17 m there are units of massive sandstone with megaripples on the top surface (Fig. 8C). Distinct features within the units like this, were used as references levels while logging.

The Ediacaran-Cambrian boundary indicated by *Treptichnus pedum* was placed around -18 m in this section, based on the results by Högström et al. (2013) (Fig. 8D). The log shows *Sabellidites* distribution all the way down to -15.5 m, quite a bit into the Manndrapselva Member, although still above the *T. pedum* level. Samples D16-F01 to D16-F07 are from Bárdeluovttjohka. The samples from this locality are from the Manndrapselva Member and they are sparse, and some are quite small (length ~8-10 mm), however, they show some variety in shape and structure (see Fig. 9).
Figure 7. Logged section from Locality 1, the Bárdeluvttjohka log. 24 m of the section with reference (0) point at the second red quartzitic layer (see Högström et al., 2013). Sample numbers in red and Sabellidites distribution range is shown on the right.
Figure 8. Photoplate from Locality 1. A: Overview of the whole section. Red crosses indicate top and base of logged part of the section. Photo: M. Høyberget. B: Lower Breidvika Member above the arrow pointing at the top red quartzitic layer, the uppermost layer of the Mamndrapselva Member. Photo: J.O.R. Ebbestad. C: Massive sandstone beneath megaripples, indicated by red line. D: Massive sandstone units close to the base of the logged area, right below the T. pedum level which is where the person sits. Photo from Högström et al. (2013). E: Base of log. Photo: J.O.R. Ebbestad.
Figure 9. Photoplate of Sabellidites from Locality 1: Bárdeluvttjohka. A: Sample collected by the Digermulen Early Life Research Group in 2013. Detailed photo of the inner organic walls of the Sabellidites tubes. B: Sample D16-F03 collected from the Manndrapselva Member. Coated in alcohol. C–D: Sample D16-F06, counterparts, showing one, or possibly several, specimens of different shapes.

5.1.2 Locality 2: Avžejohka

Samples from Locality 2 were taken above the top red quartzite layer from the Lower Breidvika Member. The samples showed a great abundance of specimens, some which were quite large (length end-to-end up to 5 cm), which further indicates that Sabellidites was more abundant within the Lower Breidvika Member compared to the third cycle of the Manndrapselva Member. Samples D16-F58 to D16-F79 are from Avžejohka. Specimens are very abundant and can be found on big slabs. Figure 10 shows an example of a collected slab with a great number of specimens. Their size varies, but they do show an increase in size compared to the samples from Bárdeluvttjohka. A slight N-S orientation of the specimens on the slab could be seen, but this has not measured for this study.

5.1.3 Locality 3: Manndrapselva

The results from Locality 3 comprises a 55 m log (Fig. 11) from reference sediments of siltstone with sandstone lenses, close to the base of the third cycle of the Manndrapselva Member, and upwards and into the Lower Breidvika Member along Manndrapselva (Fig. 12). The log presented here has been compiled from four parts, because some areas alongside the river were covered. Figure 13 F shows a
patch that is covered and parts of the section where it was possible to log again. These areas are marked as ‘covered’ in the log and no samples were recovered from these parts. The log therefore shows a gap in the *Sabellidites* distribution from 19–35.5 m. Samples D16-F08 to D16-F19, D16-F23 to D16-F29, D16-F31 to D16-F57 and D16-F80 to D16-F82 are from Locality 3. In the Manndrapselva Member they start out to be sparse and small, but getting into the Lower Breidvika Member there are a greater abundance as well as an increase in size, from ~6 mm in the Manndrapselva Member and up to ~16 mm in length in the Lower Breidvika Member (see Fig. 14). Samples D16-F80 to D16-F82 are from layers close to the base reference level (0) of the log. These oldest specimens had a reddish colour and showed signs of alteration. They are loosely assigned to *Sabellidites*; however, a closer analysis is required in order to confirm this notion. Sample D16-F54 was collected from the Lower Breidvika Member and showed similar signs of alteration. The *T. pedum* level was identified a 20.1 m. the recorded temporal distribution of *Sabellidites* in Locality 3 extends below the *T. pedum* level.

### 5.2 Comparison with other areas

The literature studies yielded information regarding the global distribution of *Sabellidites*, with occurrences found at several localities. Most of these only have single occurrences or a few, such as in Russia (Sokolov, 1972), China (Jinbiao et al., 1981) and Spain (Fernández-Remolar, 2001). Other sections where multiple occurrences are reported and there is an attempt on measuring the stratigraphical distribution will be briefly discussed further. These sections are situated in Denmark (Nielsen and
Figure 11. Logged section from Locality 3, the Manndrapselva log. Around 55 m of the section containing variations of siltstone and sandstone with some non-exposed parts. Sample numbers in red and *Sabellidites* distribution range is shown on the right. Samples D16-F80 to D16-F82 need further analysis and have yet to be determined if *Sabellidites* or not. The *T. pedum* level was identified at 20.1 m.
Figure 12. The logged section at Locality 3, Manndrapselva, with starting point to the right in the picture. The section runs alongside the Manndrapselva river. Illustration from Kartverket, NIBIO og Statens vegvesen (2016).
Figure 13. Photoplate from Locality 3. A: Logging of the 5 m beneath the reference point on the opposite side of the river. Reference point (0) in the layer indicated by the red line. Photo: J.O.R. Ebbestad. B: Base of log and reference point (0) layer indicated by red line, in siltstone layers with sandstone lenses. Location right beside a small waterfall. Photo: B. Harrison. C: Further up in the section and a second waterfall. Around 14 m in the log. Photo: J.O.R. Ebbestad. D: Right above the 20 m mark and the T. pedum level. The top surface of these units contains red quartzite and the top of the third cycle of the Mannrapselva Member. Photo: J.O.R. Ebbestad. E: The transition into the Lower Breidvika Member seen as white quartzite is introduced. Photo: B. Harrison. The white units are on the north side of the river. F: After the covered parts. The Lower Breidvika Member. Photo: J.O.R. Ebbestad. G: Panoramic view of the top of the section. Photo: J.O.R. Ebbestad.

Figure 14. Caption on the following page.
Figure 14. Photoplate of Sabellidites from Locality 3. A: Sample D16-F81, one of the stratigraphically oldest samples at 2.5 m in the log, in a reddish colour and signs of alteration. Coated with alcohol. B: Sample D16-F56 from the third cycle of Manndrapselva Member, at 19 m in the log. C: Sample D16-F54 from 42 m in the log, in reddish colour. D: Sample D16-F12 from 42.5 m in the log. Coated with alcohol. E: Sample D16-F51 from 41 m in the log. An example of a larger specimen.

6. Discussion

6.1 Distribution of Sabellidites

From previous studies Sabellidites is known to occur within the Lower Breidvika Member on the Digermulen Peninsula. Studies by Högström et al. (2013) from Locality 1 (Bårdeluovttjohka), showed the range to be longer than previously recognized and ranges further down the Lower Breidvika Member than previously recorded by Farmer et al. (1992). Högström et al. (2013) logged a little over 60 m of the section at the Bårdeluovttjohka locality (Locality 1 in this study), from the Lower Breidvika Member down to the Manndrapselva Member, including most of the third cycle. Their log shows Sabellidites sp. occurring between 35–53 m from the base of the log and only within the Lower Breidvika Member. In comparison with the new results Sabellidites also occurs in the uppermost part of the third cycle of the Manndrapselva Member (Fig. 15). In this comparison, there is a gap of ~17 m between the old log and the new concerning the distribution of Sabellidites; however, there are notations of ‘nano-filaments’ in the old log, and these may be Sabellidites, thus vaguely indicating Sabellidites occurrences further down in the Manndrapselva Member. The new log shows distinct occurrences down to ~15.5 m from the reference layer (0), (around 10 m in the log of Högström et al., 2013) and the result of this comparison is that the distribution of Sabellidites needs to be extended ~24 m down.

The distribution is sparser further down in the older sediments, only two samples were collected and identified as Sabellidites from the Manndrapselva Member in Locality 3, D16-F56 (19 m) and D16-F57 (13.8 m). From Locality 1, the first six samples (D16-F01 to D16-F06) were collected from the Manndrapselva Member, and the distribution ranges a little further down here than in Locality 3. These eight samples indicate that Sabellidites distribution extends well into the Manndrapselva Member and the samples from Locality 3 indicates that Sabellidites has a temporal range that extends beneath the Treptichnus pedum level and the Ediacaran-Cambrian boundary. There was also a difference in size and arrangement between the specimens in older and younger units, the older, the smaller the specimens. The younger sediments have bedding planes with larger and more specimens that seem organised in a N-S direction (Fig. 10), but this was not examined further for this study. Locality 2 (Avžejohka) showed a great abundance of specimens on slabs from the Lower Breidvika Member, that were larger here compared to other occurrences. This could also be seen in Locality 3 (Manndrapselva), although here there was a gap in the temporal distribution of 16.5 m in the upper parts of the Manndrapselva Member and the Lower Breidvika Member. The gap coincides with areas where the section was not exposed, which explains why sampling was difficult. At this locality some specimens, collected from different levels showed signs of alteration and had a reddish colour. The stratigraphically oldest specimens
(samples D16-F80 to D16-F82) were most affected by this and poorly preserved making the identification as *Sabellidites* uncertain. It is possible that the organic-walled tube is mostly gone and replaced by inorganic material (see Fig. 14A).

Sampling of all three localities showed that there is a continuity between the different sections on Dgermulen Peninsula. Reference layers and could be found in all three localities making correlation easier when logging the sediments and more strongly certified the results.

The focus of this study lies on the stratigraphical distribution of *Sabellidites* and other fossils have not been considered when logging the sediments, in order to highlight the *Sabellidites*-distribution and the importance of this particular fossil. However, other fossils such as trace fossils, microfossils and body fossils have been sampled and are being studied by the Dgermulen Early Life Research Group.
Figure 15. A comparison between the Högström et al. (2013) log (to the left) and the log from Locality 1. Dashed lines show top and base levels of the Locality 1 log in comparison to the previous log. *Sabellidites* distribution is extended approximately 24 m down into the third cycle of the Mannrapselva Member.
6.2 Global distribution of *Sabellidites*

6.2.1 *Sabellidites* distribution range

The phylogenetic affinities of *S. cambriensis* are still uncertain and since it was first described it has been assigned to Problematica. There have been detailed descriptions of the fossil (see Moczydłowska et al., 2014) strengthening a siboglinid affinity and placing *S. cambriensis* within the phylum Annelida. Moczydłowska et al. (2014) further describes the robust chitinous tube-walls of *S. cambriensis* that were resistant to the late Ediacaran biodegradation, extending chitin preservation downwards close to the Ediacaran-Cambrian boundary. The results presented in this study support a stratigraphic distribution of *Sabellidites* down to the third cycle of the Manndrapselva Member and close to the Ediacaran-Cambrian boundary. There is therefore no doubt that this fossil can be effectively used for biostratigraphic analyses and is an excellent reference taxon for terminal Ediacaran and earliest Cambrian.

The stratigraphic range of *Sabellidites* on the Digermulen Peninsula has been compared to localities such as the Hardeberga Formation on Bornholm, Denmark, from boreholes in strata belonging to the Eastern European Platform from Poland and Latvia, and the Chapel Island Formation in Newfoundland, Canada (Nielsen and Schovsbo, 2011; Lendzion, 1972; Urbanek and Mierzejewska, 1977; Landing et al., 1989). *Sabellidites* occurs in similar sediments, mostly from a shelf environment occasionally affected by storms and transgression/regression. On the East European Platform, the species occurs mostly in the Rovnian stage, but also sparsely in the Lontovan stage of the lower Cambrian.

6.2.2 Bornholm, Denmark

The Hadeborg Member of the Hardeberga Formation, Bornholm, Denmark is reported to have common and abundant occurrences of *Sabellidites* (Nielsen and Schovsbo, 2011). This member belongs to the sub-trilobitic zone in the earliest Cambrian, but no age diagnostic fossils have been recovered to constrain the age of the member (Nielsen and Schovsbo, 2007). The sediments of the Hadeborg Member consist mainly of thin sandstone interbedding mudstone. The most basal layers are made up of glauconitic sandstone. These sediments formed in a deep marine setting following a sea-level rise recorded as the Hadeborg Drowning (Nielsen and Schovsbo, 2011). The upper part of the member contains coarser material indicating outer shelf conditions and *Sabellidites* occurs mostly in the middle part of the Hadeborg Member. The Hardeberga Formation correlates to the Lontovan stage based on *Sabellidites* occurrences (Nielsen and Schovsbo, 2011).

6.2.3 Eastern European Platform, Poland and Latvia

There are several occurrences of *Sabellidites* reported from borehole sections on the Eastern European Platform. Lendzion (1972) reports sparse occurrences in a borehole from a locality in north-eastern Poland. *Sabellidites* marks the lower horizon of the Sub-*Holmia* Zone, preceding the fossil rich *Holmia kjerulfia* Assemblage Zone, and dates to the lower Cambrian. These sediments contain sandstones interbedded with claystones and siltstones (Lendzion, 1972).
Occurrences in eastern Latvia are reported by Urbanek and Mierzejewska (1977) from boreholes taken in green/gray clays or finely laminated mudstones. These sediments were assigned to the lower Cambrian (Urbanek and Mierzejewska, 1977). There are several occurrences of *Sabellidites*, however they are all from two different boreholes and there is no distribution range indicated.

### 6.2.4 Newfoundland, Canada

On Newfoundland, Canada, *Sabellidites* occurs in the uppermost part of member 1, in an interval 155–165 meters above the base of member 2A and up to member 4 of the Chapel Island Formation at Fortune Head (Landing et al., 1989; Narbonne et al., 1987). These members make up a section that is approximately 600 m thick. *Sabellidites* is found in “dark green-grey to grey-black siltstone and shale” according to Landing et al. (1989). It is found in association with the vendotaenid alga *Tryasotaenia Gnilovskaya 1971* and coincides with the *Phycodes pedum* and *Harlaniella podolica* zones of the Chapel Island Formation, who mark the uppermost zone in the Ediacaran (Landing et al., 1989). *Sabellidites* distribution is extended to the lowest parts of the Placentian Series of the lower Cambrian (Landing et al., 1989). This shows a *Sabellidites* distribution range into the lower Cambrian and close to the boundary, which is also the case in the Digermulen succession.

### 6.2.5 Global correlation

Mens et al. (1990) describes the Cambrian system from the East European Platform in detail and compares the *Sabellidites cambriensis* Zone Kirjanov 1969 (p. 49) to different localities. The Hardeberga Formation and boreholes from Poland and Latvia are represented here within intervals close to the same level of the lower Cambrian, showing that the assemblage zone exists in these localities and that they can be correlated to each other. The sections of the Chapel Island Formation on Newfoundland also include the assemblage zone in the lowermost part and is named the Placentian Series by Landing et al. (1989). The sections in Europe and Newfoundland all correlates to the lower Cambrian, although further biostratigraphic work is required to gain accuracy in the correlations.

The *Sabellidites cambriensis* assemblage zone is defined to the base of the Cambrian by Mens et al. (1990) and Landing et al. (1989) hints of an extension into the late Ediacaran without defining it further. However, this correlates quite well to the distribution on the Digermulen Peninsula succession. The *Sabellidites* distribution is well-defined down to the lower Cambrian, close to the Ediacaran-Cambrian boundary. A global correlation can now be made between different sections and supports the results from the Digermulen Peninsula; however, more comparative studies should be carried out to strengthen this notion.
6.2.6 Paleobiogeography

The position of the continents during late Neoproterozoic and early Cambrian times is uncertain. During the late Ediacaran and early Cambrian Baltica is believed to be situated 30–50° on the southern hemisphere (Torsvik and Rehnström, 2001). However, recent provenance studies on the succession on the Digermulen Peninsula show signs of increased weathering and carbonates (unpublished data, Perschl, 2016; Schröpfer, 2016; Steichert, 2016). This supports a predicted northwards drift of Baltica and an increasingly warm and humid climate in the Cambrian, as suggested by Cocks and Torsvik (2005). With Baltica placed further to the north, global distribution of *Sabellidites* can be plotted in a sub-tropical belt across the continents (see Fig. 16), where previously mentioned global occurrences (Sokolov, 1972; Lendzion, 1972; Urbanek and Mierzejewska, 1977; Jinbiao et al., 1981; Landing et al., 1989; Fernández-Remolar, 2001; Nielsen and Schovsbo, 2011) line up closer to the equator.

6.3 Further work

The collected *Sabellidites* samples await to be analysed in terms of taphonomy. This will add to the affinity issue around the fossil. To further assess the succession on the Digermulen Peninsula and strengthen the global correlation between different sections, microfossil and trace fossil samples from the succession have been collected and additional analyses will be carried out on these as well. Biostratigraphical and lithostratigraphical studies combined will yield extensive information about the succession on the Digermulen Peninsula. This study has only touched briefly on global sections due to a short time frame, however additional comparative studies should be carried out to be able to use the succession on the Digermulen Peninsula as a reference section.
Figure 16. Map of the Lower Cambrian with *Sabellidites* distribution (blue dots). Occurrences plotted around to the equator, between 0–30°, mostly on the southern hemisphere. Baltica is shown in the generally accepted high latitude position (grey) and in a lower latitude position (red). Map created with BugPlates (Torsvik, 2009).
7. Conclusions

Field work was carried out in the late summer of August 2016 on the Digermulen Peninsula, Arctic Norway together with the Digermulen Early Life Research Group. Based on previous field work, three localities were chosen for investigation and in Locality 1 and 3, the section was stratigraphically logged. All three sections were sampled for Sabellidites, from the third cycle of the Mannndrapselva Member and the Lower Breidvik Member. The Ediacaran–Cambrian boundary sits within these units and is indicated by the trace fossil Treptichnus pedum. The results from the field studies show a wider temporal distribution of Sabellidites compared to previous studies. The results were compared to other localities where Sabellidites occurrences have been reported. The comparison shows a global correlation of occurrences, but further comparative work is needed to strengthen this notion. The temporal distribution of Sabellidites is hereby extended down into the third cycle of the Mannndrapselva Member and can be correlated globally, which shows that Sabellidites works well as a reference taxon for terminal Ediacaran and earliest Cambrian. The localities investigated on the Digermulen Peninsula can also be correlated with each other which gives a significant and a close to complete overview of the Ediacaran–Cambrian boundary.

Investigating the Sabellidites distribution seems to be difficult in most areas, as seen by the results of the comparative literature studies. There are reported occurrences but many locations lack distribution ranges. The almost complete succession on the Digermulen Peninsula offers great opportunity to map a section that can be used as a reference section in terms of biostratigraphy, palaeoclimate, palaeogeography and Ediacaran–Cambrian boundary definitions in addition to early life research.

8. Acknowledgements

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9. References


Appendix 1: Sample log

Table 1. A log of the total number of samples from all three localities. Logs A–D mark intervals before a covered patch in the Manndrapselva log, Locality 3. A = 0–37 m, B = 0–1 m (above A), C = 0–7 m (above B) and D = 0–12 m (above C). Numbers in brackets indicate level in the compiled Manndrapselva log. Question marks indicates samples that are not yet defined as *Sabellidites*. Samples D16-F20 to D16-F22 were not defined as *Sabellidites* and removed from Table 1.

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Locality 1 = Bárðelouvtjohka
Locality 2 = Avžejohka
Locality 3= Manndrapselva,
*Manndrapselva Mbr 3rd cycle*
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