

**Dinocyst stratigraphy of the Valanginian–Aptian Rurikfjellet  
and Helvetiafjellet formations on Spitsbergen, Arctic  
Norway**

Journal:	<i>Geological Magazine</i>
Manuscript ID	GEO-19-2278.R1
Manuscript Type:	Original Article
Date Submitted by the Author:	04-Sep-2019
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Keywords:	dinocysts, biostratigraphy, Lower Cretaceous, Spitsbergen, Arctic

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3 1 **Dinocyst stratigraphy of the Valanginian–Aptian Rurikfjellet and Helvetiafjellet**  
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5 2 **formations on Spitsbergen, Arctic Norway**  
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## 22 Abstract

23 In order to improve the understanding of how the high northern latitudes responded to  
24 the escalating warming which led to the middle Cretaceous super greenhouse climate,  
25 more temperature proxy records from the High Arctic are needed. One of the current  
26 obstacles in obtaining such records is poor age control **on** the Lower Cretaceous strata  
27 in the **Boreal and Pan-Boreal** regions.

28 Here, we provide a biostratigraphic framework for the Rurikfjellet and  
29 Helvetiafjellet formations representing the lower part of the Lower Cretaceous  
30 succession on Spitsbergen. We also attempt to date the boundary between the  
31 Agardhfjellet and the Rurikfjellet formations. This study is based on **dinoflagellate cysts**  
32 **(dinocysts)** from three onshore cores (DH1, DH2, and DH5R), and three outcrop  
33 sections (Bohemanflya, Myklegardfjellet, and Ullaberget). Relatively abundant and well-  
34 preserved dinocyst assemblages from the Rurikfjellet Formation date this unit **as** early  
35 Valanginian – early Barremian. The dinocyst assemblages from the Helvetiafjellet  
36 Formation are significantly impoverished and **are** characterised by reworking, **but**  
37 **collectively indicate** a Barremian–Aptian age for **this** formation.

38  
39 **Keywords:** dinocysts, biostratigraphy, Lower Cretaceous, Spitsbergen, Arctic

## 41 1. Introduction

42 The Early Cretaceous (~145–100.5 Ma; Ogg, Ogg & Gradstein, 2016) was  
43 characterised by major tectonic activity, climatic changes, and global perturbations in

1  
2  
3 44 the carbon cycle (e.g. Huber *et al.*, 2018). The breakup of the supercontinent Pangaea  
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5 45 which terminated around 175 Ma (e.g. Holden, 1970; Rogers & Santosh, 2004), led to  
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7 46 the formation of two minor supercontinents: Laurasia to the north, and Gondwana to the  
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10 47 south separated by the newly formed Tethys Ocean. The Barents Sea Shelf including  
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12 48 Svalbard (paleolatitude 60°N at 140 Ma; calculated after Van Hinsbergen *et al.*, 2015),  
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14 49 Arctic Canada, Greenland and northern Russia were located at the northern flank of  
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16  
17 50 Laurasia as part of the large circum-Arctic, relatively cold Boreal Basin (Scotese, 2014).  
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19 51 In the Tethys Ocean to the south, warm to tropical water conditions prevailed, leading to  
20  
21 52 a bloom of calcareous nannoplankton and foraminifera. The Tethys and Boreal seas  
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23 53 were connected by a shallow, narrow seaway between Greenland and Baltica. The  
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26 54 seaway formed in response to rifting during the initial stage of the formation of the North  
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28 55 Atlantic Ocean at that time (e.g. Gradstein, Kaminski & Agterberg, 1999). The  
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31 56 palaeogeographical configuration in the Early Cretaceous favoured a diversification of  
32  
33 57 marine organisms and diachrony of ammonite bio-events, which traditionally  
34  
35 58 constitute the primary tool for Cretaceous biostratigraphy (e.g. Lehmann, 2015). This  
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37  
38 59 has led to the creation of two separate biozonation schemes; one for the Boreal and  
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40 60 one for the Tethyan Realm. Both are still applicable across the Jurassic–Cretaceous  
41  
42 61 transition (Ogg, Hinnov & Huang, 2012).

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45 62 Temperature proxy data from Early Cretaceous high latitudes are limited  
46  
47 63 (Ditchfield, 1997; Littler *et al.*, 2011; Jenkyns *et al.*, 2012; Price and Passey, 2013), but  
48  
49 64 it is assumed that the global climate was generally warm and humid with low latitudinal  
50  
51 65 temperature gradients (e.g. O'Brien *et al.*, 2017). In contrast, some studies suggest that  
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54 66 the polar regions during the Early Cretaceous were rather cold (e.g. De Lurio and

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3 67 Frakes, 1999; Basov *et al.*, 2009). Increased volcanic activity (including oceanic crust  
4  
5 68 formation, formation of large igneous provinces, and subduction-related arc volcanism)  
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7 69 (e.g. Johnston, Turchyn & Edmonds, 2011; Koopmann *et al.*, 2014; Polteau *et al.*, 2016)  
8  
9 70 forced an increased concentration of atmospheric greenhouse gases (methane and  
10  
11 71 CO<sub>2</sub>), and led to a gradual global warming (e.g. Huber *et al.*, 2018). A climatic maximum  
12  
13 72 of this extreme global warmth, the so-called Cretaceous Hot Greenhouse climate, was  
14  
15 73 reached between 95 and 80 Ma (Huber *et al.*, 2018). During the Cretaceous Period a  
16  
17 74 number of oceanic anoxic events (OAEs) led to the deposition of organic carbon-rich  
18  
19 75 sediments (Leckie, Bralower & Cashman, 2002; Trabucho Alexandre *et al.*, 2010). At  
20  
21 76 least four of these events took place during the Early Cretaceous: The OAE1a, OAE1b,  
22  
23 77 OAE1c, and OAE1d (Erbacher, Thurow and Littke, 1996). The most widely recognised  
24  
25 78 is the OAE1a which occurred during the earliest Aptian (Leckie, Bralower and  
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27 79 Cashman, 2002; Jenkyns, 2010; Herrle *et al.*, 2015; Midtkandal *et al.*, 2016). The  
28  
29 80 characteristic stable carbon isotope ( $\delta^{13}\text{C}$ ) excursions related to OAEs can be used for  
30  
31 81 the correlation of carbon isotope records (Herrle *et al.*, 2015; Midtkandal *et al.*, 2016;  
32  
33 82 Vickers *et al.*, 2016). However, while the climatic history of the Tethys (e.g. Hochuli *et*  
34  
35 83 *al.*, 1999; Bottini *et al.*, 2015; Bottini and Erba, 2018) and the European Boreal Realm  
36  
37 84 (e.g. Mutterlose, Pauly & Steuber, 2009) are relatively well-studied, the climate of the  
38  
39 85 Early Cretaceous Arctic is relatively less understood. Many of the published  
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41 86 paleotemperature records contradict evidence for both warm and cool periods (e.g.  
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43 87 Galloway *et al.*, 2015; Hurum, Druckenmiller, *et al.*, 2016; discussion in Vickers *et al.*,  
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45 88 2016). Some of the contradictions may be due to limited temperature data from the high  
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3 89 Arctic and the lack of a concise biostratigraphic framework for the Cretaceous strata in  
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5 90 this region.

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8 91 On Spitsbergen (Svalbard, Arctic Norway) the Lower Cretaceous succession is  
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10 92 divided into three formations: the Rurikfjellet, Helvetiafjellet and Carolinefjellet  
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12 93 formations. The first biostratigraphic study of the Rurikfjellet Formation was based on  
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14 94 macrofossils (bivalves and ammonites), and dated the formation as Berriasian – upper  
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16 95 Hauterivian (for references see Grøsfjeld 1991). The first dinocyst-based study of the  
17  
18 96 Lower Cretaceous succession on Spitsbergen was provided by Bjærke and Thusu  
19  
20 97 (1976). The first comprehensive study of Lower Cretaceous dinocysts on Spitsbergen  
21  
22 98 was carried out by Bjærke (1978), who observed that the dinocyst assemblages of the  
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24 99 Berriasian, Valanginian and Hauterivian are similar to assemblages from NW Europe  
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29 100 and Arctic Canada.

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32 101 The aim of this paper is to provide a concise age model for the Lower  
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34 102 Cretaceous Rurikfjellet and Helvetiafjellet formations on Spitsbergen. The study is  
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36 103 primarily based on dinocysts from six onshore outcrop and sediment core sections. The  
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39 104 new data are discussed in the context of existing literature dealing with the palynology  
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41 105 of the Arctic and the European Boreal Province.

## 42 43 44 106 45 46 107 **2. Regional setting**

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49 108 Spitsbergen is the largest island in the Svalbard archipelago, and is located today at ca.  
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51 109 76–80°N. The Svalbard archipelago represents the uplifted and exposed northwestern  
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54 110 corner of the Barents Sea Shelf. The Barents Sea Shelf is bounded to the west by the  
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3 111 Western Barents Sea Margin, and to the south and east by the Baltic Shield and  
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5 112 Novaya Zemlya archipelago (e.g. Henriksen *et al.*, 2011). During the Early Cretaceous,  
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7 113 the Svalbard platform was part of a shallow, epicontinental sag basin (e.g. Henriksen *et*  
8  
9 114 *al.*, 2011) on the northern margin of Pangea (Torsvik *et al.*, 2002). The Lower  
10  
11 115 Cretaceous succession in Svalbard is over 1000 m thick and exhibits a large-scale  
12  
13 116 regressive–transgressive stacking pattern. This depositional cycle was controlled by  
14  
15 117 regional thermo-tectonic uplift in the north, followed by subsequent quiescence and  
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17 118 subsidence (Gjelberg & Steel, 1995; Midtkandal, Nystuen & Nagy, 2007; Midtkandal &  
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19 119 Nystuen, 2009). The magmatic activity in Svalbard and the surrounding areas related to  
20  
21 120 the emplacement of the High Arctic Large Igneous Province (HALIP) peaked in the  
22  
23 121 Barremian to early Aptian (Corfu *et al.*, 2013; Senger *et al.*, 2014; Polteau *et al.*, 2016).  
24  
25 122 An early Barremian uplift and associated southward tilting of the shelf caused the  
26  
27 123 formation of a regionally extensive subaerial unconformity, which now forms the  
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29 124 boundary between the Rurikfjellet and Helvetiafjellet formations (e.g. Gjelberg & Steel,  
30  
31 125 1995; Midtkandal & Nystuen, 2009; Grundvåg *et al.*, 2017). This event was followed by  
32  
33 126 a transgression related to a long-term relative global sea-level rise (Gjelberg and Steel,  
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35 127 1995; Midtkandal and Nystuen, 2009). In the Late Cretaceous, subaerial exposure of  
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37 128 Svalbard resulted in a major hiatus spanning the entire Upper Cretaceous (Harland,  
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39 129 1997; Dörr *et al.*, 2012).  
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49 131 <<Fig. 1>>  
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### 51 132 3. Lower Cretaceous lithostratigraphy of Spitsbergen 52 53 54 55 56 57 58 59 60

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3 133 The Lower Cretaceous succession on Spitsbergen is subdivided into the Rurikfjellet,  
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5 134 Helvetiafjellet and Carolinefjellet formations. The succession forms the upper part of the  
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8 135 Adventdalen Group (which also includes the Upper Jurassic Agardhfjellet Formation;  
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10 136 Parker, 1967), and is primarily exposed along the margins of the Central Tertiary Basin.  
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12 137 The Rurikfjellet Formation consists of a lower offshore shale-dominated succession (the  
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14 138 Wimanfjellet Member) which is overlain by a storm-dominated shallow marine  
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16 139 succession (the Kikutodden Member) of interbedded shale, siltstone, and sandstone  
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18 140 (Fig.1). The Rurikfjellet Formation unconformably overlies the Upper Jurassic –  
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20 141 lowermost Cretaceous Agardhfjellet Formation (Dypvik *et al.*, 1991), and its base is  
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22 142 marked either by i) a condensed glauconitic clay unit (the Myklegardfjellet Bed; Dypvik  
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24 143 *et al.*, 1991; Dypvik, Nagy & Krinsley, 1992); ii) a highly tectonised decollement zone; or  
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26 144 iii) by an abrupt change in the macrofossil fauna. In the central part of Spitsbergen, the  
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28 145 Wimanfjellet Member is intersected by a thick succession of gravity flow deposits  
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30 146 informally defined as the Adventpynten member (Grundvåg *et al.*, 2017). The  
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32 147 Kikutodden Member represents prodeltaic to shallow marine deposits which were  
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34 148 sourced from the NW and exhibit progradation towards the SE (Fig. 1; Dypvik *et al.*,  
35  
36 149 1991). The overall changes in the lithologies of the Rurikfjellet Formation reflect the  
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38 150 shallowing development of the basin as a response to uplift in the north.

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45 151 The boundary between the Rurikfjellet and Helvetiafjellet formations is marked by  
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47 152 a regionally extensive subaerial unconformity (e.g. Midtkandal & Nystuen, 2009;  
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49 153 Grundvåg *et al.*, 2017). The Helvetiafjellet Formation represents a fluvio-deltaic to  
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51 154 paralic depositional system reflecting long-term relative sea-level rise (Gjelberg and  
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53 155 Steel, 1995; Midtkandal and Nystuen, 2009). The Helvetiafjellet Formation represents  
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3 156 the most proximally deposited strata within the Lower Cretaceous succession on  
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5 157 Spitsbergen. The Helvetiafjellet Formation is overlain by storm-dominated open marine  
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7 158 shelf deposits of the Carolinefjellet Formation (Gjelberg and Steel, 1995; Grundvåg *et*  
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9 159 *al.*, 2017); Fig. 1.

#### 161 4. Previous studies of Lower Cretaceous Boreal dinocyst assemblages

162 Dinocyst studies of Arctic Lower Cretaceous successions are relatively rare and  
163 scattered across the Canadian Arctic (Pocock, 1976; Brideaux, 1977; McIntyre &  
164 Brideaux, 1980; Davies, 1983; Nøhr-Hansen & McIntyre, 1998), Greenland  
165 (Nøhr-Hansen, 1993; Pedersen & Nøhr-Hansen, 2014; Piasecki, Nøhr-Hansen &  
166 Dalhoff, 2018; Nøhr-Hansen, Piasecki & Alsen, this issue), the Barents Sea (Århus *et*  
167 *al.*, 1990; Smelror *et al.*, 1998; Smelror and Dypvik, 2005b, 2005a; Kairanov *et al.*,  
168 2018), Arctic Norway (Løfaldi and Thusu, 1976; Thusu, 1978; Bjærke, 1978; Århus,  
169 Verdenius and Birkelund, 1986; Århus *et al.*, 1990; Århus, 1991; Grøsfjeld, 1991;  
170 Smelror and Larssen, 2016; Hurum, Roberts, *et al.*, 2016; Smelror *et al.*, 2018; Hammer  
171 *et al.*, 2018; Rakociński *et al.*, 2018; Grundvåg *et al.*, 2019), and Arctic Russia (Smelror,  
172 1986; Lebedeva and Nikitenko, 1999; Riding, 1999; Pestchevitskaya, 2007; Nikitenko *et*  
173 *al.*, 2008; Pestchevitskaya, Lebedeva and Ryabokon, 2011). Some early Canadian  
174 studies provided dinocyst zonations (e.g. Pocock, 1976; Davey, 1982; Davies, 1983),  
175 but the diversity of the studied material was limited, and ranges of specific taxa were  
176 poorly constrained compared to the more recent and robust dinocyst zonation  
177 established for North-East Greenland (Nøhr-Hansen, 1993; Nøhr-Hansen, Piasecki &  
178 Alsen, this issue). A number of dinocyst studies from the North Sea Basin and

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3 179 northwest Europe, often referred to as the European Boreal Province, provide well-  
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5 180 constrained zonation schemes (Davey, 1979a, 1982; Heilmann-Clausen, 1987; Costa &  
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8 181 Davey, 1992; Duxbury, 2001; Bailey, 2019).  
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10 182 The first chronostratigraphic framework for the Rurikfjellet Formation (at that time  
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12  
13 183 known as the Rurikfjellet Member) was based on ammonites and bivalves (for  
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15 184 references see Grøsfjeld, 1991). An informally defined Lower Cretaceous palynological  
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17 185 zonation of Spitsbergen was introduced in a confidential report by Århus (1988). Low  
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19 186 dinocyst abundances and low diversities have been reported from studies of the Lower  
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21 187 Cretaceous succession on Spitsbergen and in the Barents Sea (e.g. Århus *et al.*, 1990;  
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23 188 Århus, 1992). The dinocysts of the Rurikfjellet Formation have been investigated in less  
24  
25 189 than a dozen peer-reviewed publications. Notable works include Bjærke & Thusu  
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27 190 (1974), Bjærke (1978), Århus *et al.* (1990), Århus (1991; 1992), Grøsfjeld (1991), and  
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29 191 more recently Midtkandal *et al.* (2016) and Grundvåg *et al.* (2017). The palynology of  
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31 192 the Helvetiafjellet Formation has been studied to an even lesser extent (Grøsfjeld, 1991;  
32  
33 193 Midtkandal *et al.*, 2016). A number of recent studies on the seismic stratigraphy of the  
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35 194 Lower Cretaceous succession in the southwestern Barents Sea provide an updated  
36  
37 195 preliminary age model based on dinocysts (Marín *et al.*, 2017; Kairanov *et al.*, 2018;  
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39 196 Marín, Escalona, Grundvåg, Nøhr-Hansen, *et al.*, 2018; Marín, Escalona, Grundvåg,  
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41 197 Olausson, *et al.*, 2018).  
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## 50 199 **5. Studied sections**

### 51 200 **5.a. The Bohemanflya outcrop section**

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3 201 The Bohemanflya outcrop section (N78°24'32.6"/E14°41'18.9") is the northernmost  
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5 202 locality investigated in this study, exposing Lower Cretaceous strata in central  
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7 203 Spitsbergen (Fig. 2). At this locality, the Wimanfjellet Member constitutes a measurable  
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9 204 thickness of c. 45 m and consists of generally black shale with scattered siderite  
10  
11 205 concretions and nodules or stratabound siderite layers. In certain intervals, the  
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13 206 Wimanfjellet Member is tectonically disturbed. The overlying Kikutodden Member (Fig.  
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15 207 1) is c. 83 m thick, and is siltstone- and sandstone-dominated. The upper part of the  
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17 208 succession exhibits gravel-rich hummocky cross-stratified sandstone, which is  
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19 209 occasionally truncated by the subaerial unconformity constituting the base of the  
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21 210 overlying Festningen Member of the Helvetiafjellet Formation. In this study, we collected  
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23 211 samples from across the entire exposed length of the Rurikfjellet Formation (~130 m;  
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25 212 Fig. S1).

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31 <<Fig.2>>  
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#### 34 214 **5.b. The Myklegardfjellet outcrop section**

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36 215 The Myklegardfjellet outcrop section (N78°03'18.8"/E18°42'15.4") is the easternmost  
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38 216 locality investigated in this study, exposing Upper Jurassic – Lower Cretaceous strata at  
39  
40 217 the northeastern side of Agardhbukta, east coast of Spitsbergen (Fig. 2). At this locality,  
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42 218 the Rurikfjellet Formation is entirely comprised of homogeneous shale of the  
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44 219 Wimanfjellet Member (Fig. 1), reaching a thickness of 166 m. The shale is characterised  
45  
46 220 by absent to low degrees of bioturbation as well as scattered siderite concretions,  
47  
48 221 nodules and fossiliferous stratabound siderite layers with abundant bivalves. The  
49  
50 222 Kikutodden Member is either not preserved in this locality, or it is covered by scree. This  
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52 223 outcrop section is the type locality of the Myklegardfjellet Bed (Birkenmajer,  
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3 224 Pugaczewska & Wierzbowski, 1979; Dypvik, Nagy & Krinsley, 1992), demarcating the  
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5 225 base of the Rurikfjellet Formation by a well-exposed c. 3 m thick unit of glauconitic,  
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7 226 plastic clays. The Rurikfjellet Formation is unconformably overlain by sandstones of the  
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9 227 Festningen Member of the overlying Helvetiafjellet Formation. In this study we  
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12 228 investigate ca. 130 m of deposits from the Wimanfjellet Member (Fig. S2).  
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### 18 230 **5.c. The Ullaberget outcrop section**

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21 231 The Ullaberget outcrop section (N77°37'04.2"/E15°11'17.9") is the southernmost locality  
22  
23 232 investigated in this study, exposing Lower Cretaceous strata at the northwestern side of  
24  
25 233 Van Keulenfjorden. At this locality, the Rurikfjellet Formation is ca. 200 m thick (the  
26  
27 234 base is not exposed) and dominated by homogeneous shale of the Wimanfjellet  
28  
29 235 Member. For the purpose of this study, only three samples from the uppermost 2 metres  
30  
31 236 of the Rurikfjellet Formation were collected (Fig. S3). The shale is characterised by a  
32  
33 237 lack of or low degrees of bioturbation. Siderite concretions, nodules, and fossiliferous  
34  
35 238 stratabound layers occur. Thin- and lenticular-bedded sandstone occurs sporadically in  
36  
37 239 the upper part of the unit, representing the distal part of the Kikutodden Member. The  
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39 240 Rurikfjellet Formation is unconformably overlain by sandstones of the Louiseberget Bed  
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41 241 of the Helvetiafjellet Formation (Midtkanal *et al.*, 2008). The remaining part of the  
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43 242 Helvetiafjellet Formation displays a transgressive development, comprising various  
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45 243 paralic deposits, including tidal channel fills, and coarsening-upwards bay fill sequences  
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47 244 (Gjelberg & Steel, 1995; Midtkandal & Nystuen, 2009) which lithostratigraphically belong  
48  
49 245 to the Glitrefjellet Member. At this locality, the Helvetiafjellet Formation is conformably  
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51 246 overlain by a 20–30 m thick shale unit of the Carolinefjellet Formation.  
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56 248 **5.d. The DH1 and DH2 cores**  
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9 249 The DH1 (N78°23'60.8/E15°54'57.6) and DH2 (N78°23'59.9/E15°54'68.4) cores were  
10  
11 250 drilled c. 3 km to the NW of Longyearbyen close to the airport, in relation to CO<sub>2</sub>  
12  
13 251 sequestration studies (Braathen *et al.*, 2012). The cores span the Rurikfjellet and  
14  
15 252 Helvetiafjellet formations, and the lower part of the Carolinefjellet Formation (Fig. 1). In  
16  
17 253 these wells, the Rurikfjellet Formation is ca. 225 m thick (~440–215 m) and conformably  
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19 254 overlies shale of the Agardhfjellet Formation (e.g. Grundvåg *et al.*, 2017). The boundary  
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21 255 between the two units is tectonically disturbed, representing a decollement zone that  
22  
23 256 formed during the Palaeogene shortening (Dietmar Müller & Spielhagen, 1990). The  
24  
25 257 lower part of the Rurikfjellet Formation consists of a ~140 m thick succession of gravity  
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27 258 flow deposits of the Adventpynten member. The upper part of the Rurikfjellet Formation  
28  
29 259 consists of a 30–40 m thick mudstone-dominated unit which grades upwards into the  
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31 260 sandstone-dominated Kikutodden Member. The Rurikfjellet Formation is unconformably  
32  
33 261 overlain by a 12 m thick sandstone unit representing the Festningen Member of the  
34  
35 262 Helvetiafjellet Formation (Grundvåg *et al.*, 2017). The upper c. 60 m of the Helvetiafjellet  
36  
37 263 Formation consists of interbedded sandstone, shale, and thin coal layers of the  
38  
39 264 Glitrefjellet Member, representing various alluvial to paralic depositional environments.  
40  
41 265 The thicknesses of all lithostratigraphic units across the investigated interval in the two  
42  
43 266 cores are shown on Fig. S4 (DH1) and Fig. S5 (DH2). The Helvetiafjellet Formation is  
44  
45 267 unconformably overlain by a ~10 m thick shale unit of the overlying Dalkjegla Member of  
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47 268 the Carolinefjellet Formation.  
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### 270 **5.e. The DH5R core**

271 The DH5R core (N78°12'13.1"/E15°49'08.6") was drilled c. 4 km to the SE of  
272 Longyearbyen in central Spitsbergen, also in relation to CO<sub>2</sub> sequestration studies  
273 (Braathen *et al.*, 2012). The studied part of the core spans from the uppermost  
274 Agardhfjellet Formation to the Carolinefjellet Formation. The Rurikfjellet Formation is c.  
275 230 m thick (410–180 m) and overlies shale of the Agardhfjellet Formation (Koevoets *et*  
276 *al.*, 2018). The lithology of the Rurikfjellet Formation differs from that observed in the  
277 DH1 and DH2 cores. In the DH5R core, the formation displays homogeneous to  
278 sparsely bioturbated shale with scattered siderite concretions and bivalves of the  
279 Wimanfjellet Member which coarsen into silty shale, heavily bioturbated siltstone and  
280 hummocky cross-stratified sandstone of the overlying Kikutodden Member. The  
281 Helvetiafjellet (180–120 m) and Carolinefjellet formations display the same stratigraphic  
282 development as in the DH1, and DH2 cores.

283

### 284 **6. Analytical methods**

285 Sediment samples for palynological analysis were collected during fieldwork and core  
286 logging campaigns in 2013–2016. 82 samples were collected, with 40 samples from  
287 Bohemanflya, Myklegardfjellet and Ullaberget, and 42 samples from the DH1, DH2, and  
288 DH5R cores. The majority of samples were collected from the Rurikfjellet Formation,  
289 including 8 samples from DH1, 14 samples from DH2, 15 samples from DH5R, 12  
290 samples from Bohemanflya, 13 samples from Myklegardfjellet and 3 samples from  
291 Ullaberget. The Helvetiafjellet Formation was sampled only in the DH2 core (3 samples)  
292 and Ullaberget outcrop section (12 samples). Furthermore, in order to improve the age

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3 293 of the base of the Lower Cretaceous succession in our study area, we have analysed  
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5 294 three samples from the upper part of the Agardhfjellet Formation from the DH5R core  
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7  
8 295 (at 458.0, 440.0, and 410.0 m).  
9

10 296 Preparation of palynological slides was performed at the Geological Survey of  
11  
12 297 Denmark and Greenland (GEUS). Between 20 and 45 g of sediment were dried in an  
13  
14  
15 298 oven for 24 hours at 30°C and manually ground. Hydrochloric (HCl; 3.5% and 18%) and  
16  
17 299 hydrofluoric (HF; 40%) acids were used for dissolving carbonates and silicates,  
18  
19  
20 300 respectively. After each step, samples were neutralized with 0.5% citric acid ( $C_6H_8O_7$ ) at  
21  
22 301 70°C. The organic residuum from each sample was filtered using an 11  $\mu\text{m}$  nylon mesh  
23  
24 302 and a first (kerogen) slide was prepared. Subsequently, the residua were oxidized with  
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26  
27 303  $HNO_3$  for 8 min in order to remove amorphous kerogen particles. Samples with high  
28  
29 304 concentrations of amorphous kerogen particles were oxidized for additional 1 to 5 min.  
30  
31 305 After each oxidation step, residua were washed with a weak solution (5%) of potassium  
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33  
34 306 hydroxide (KOH), and a fraction of the residue was taken for palynological slide  
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36 307 preparation. Some of the residua were additionally briefly submerged in a boiling  
37  
38 308 mixture of  $HNO_3$ :KOH (1:1), and filtered using a 21  $\mu\text{m}$  nylon mesh. The high  
39  
40  
41 309 concentration of coal and wood particles present in some of the samples was removed  
42  
43 310 by swirling, and minerals were removed by heavy liquid separation ( $ZnBr_2$ ; density 2.3  
44  
45 311 g/mL). After each of these steps, organic residua were filtered using a 21  $\mu\text{m}$  nylon  
46  
47 312 mesh. To concentrate palynomorphs, organic residua from some of the samples were  
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49  
50 313 filtered using a 30  $\mu\text{m}$  nylon mesh. All palynological slides and (if available) organic  
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52 314 residua are stored at GEUS.  
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3 315 The palynological slides were analysed using a transmitted light microscope.  
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5 316 When possible, a minimum of 300 dinocysts were counted in a single slide. In a few  
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7 317 cases, when a single slide contained less than 300 dinocysts, it was necessary to count  
8  
9 318 one or two additional slides. The dinocyst taxonomy follows Williams, Fensome &  
10  
11 319 MacRae (2017). All dinocysts recorded in this study are listed in Table 1. Selected  
12  
13 320 dinocysts are presented on Figs. 3-6. Coordinates of the photographed specimens are  
14  
15 321 given following the method described by Śliwińska (2019).  
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20 322 <<Fig.3>>

21  
22 323 <<Fig. 4>>

23  
24 324 <<Fig.5>>

25  
26 325 <<Fig. 6>>

## 30 31 326 7. Results and discussion

32  
33 327 Two out of three samples from the Agardhfjellet Formation were barren with respect to  
34  
35 328 dinocysts. Virtually all analysed samples from the Rurikfjellet Formation and the  
36  
37 329 Helvetiafjellet Formation yielded dinocysts. The diversity, abundance and preservation  
38  
39 330 are highly variable spatially and temporally. In samples where dinocysts were rare or  
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41 331 absent, the assemblages are dominated by black and dark brown wood particles, as  
42  
43 332 well as pollen grains.  
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48 333 In some levels, despite counting more than one palynological slide, there were  
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50 334 less than 300 dinocysts in total (e.g. in the uppermost samples of the DH5R core). The  
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52 335 dinocyst assemblages were particularly impoverished in the Ullaberget outcrop section,  
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3 336 and in the DH1 and DH2 cores. In comparison, the dinocyst assemblages of the  
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5 337 Myklegardfjellet outcrop section show the highest richness of species (Fig. S2).  
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8 338 Within the Rurikfjellet Formation we distinguish several age-diagnostic dinocysts:  
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10 339 *Endoscrinium hauterivianum* (Figs 3o,p; Section 8.a), *Gochteodinia villosa* subsp.  
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12 340 *villosa* (Fig. 4b; Section 8.b), *Muderongia australis* (Fig. 4e; Section 8.c), *Muderongia*  
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14 341 *tetracanta* (Fig. 4d; Section 8.d), *Nelchinopsis kostromiensis* (Figs 4m,n; Section 8.e),  
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16 342 *Oligosphaeridium complex* (Fig. 5h; Section 8.f), *Palaecysta palmula* (Fig. 5k; Section  
17  
18 343 8.i), *Subtilisphaera perlucida* (Fig. 6g; Section 8.l), and *Tubotuberella apatela* (Figs 6i-k;  
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20 344 Section 8.m). Other typical dinocysts observed within the formation include  
21  
22 345 *Cyclonephelium cuculliforme* sensu Århus 1990 (Fig. 5l), *Discorsia nannus* (Fig. 3m),  
23  
24 346 *Dissiliodinium acmeum* (Figs 3k), *Nyktericysta? pannosa* (Figs 4op), *Oligosphaeridium*  
25  
26 347 *abaculum* (Fig. 5f; Section 8.g), *Phoberocysta neocomica* (Fig. 5c), *Pseudoceratium*  
27  
28 348 *pelliferum* (Fig. 5j), *Rhynchodiniopsis aptiana* (Fig. 5d,g), *Stanfordella fastigiata* (Fig 6a),  
29  
30 349 *Stanfordella ordocava* (Figs 6b,c), and *Wrevittia perforobtus* (Figs 6n-p). Notably,  
31  
32 350 some of the well-known Lower Cretaceous markers, such as e.g. *Batioladinium*  
33  
34 351 *longicornutum*, were not observed in the studied material.  
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41 352 The age-diagnostic taxa within the Helvetiafjellet Formation include  
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43 353 *Odontochitina nuda* (Fig. 5e; Section 8.f), *Pseudoceratium anaphrissum* (Figs 5m-o;  
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45 354 Section 8.j), *Sirmiodinium grossii* (Figs 6e,f; Section 8.k), and *Subtilisphaera perlucida*  
46  
47 355 (Fig. 6g; Section 8.l). The Helvetiafjellet Formation is also characterised by low species  
48  
49 356 richness, low relative abundance of dinocysts and a moderate reworking of Valanginian  
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51 357 to Barremian dinocysts.  
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3 358 The age of the first (FOs) and last occurrences (LOs) as well as ranges of the  
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5 359 key dinocysts in the context of existing literature are discussed in Section 8.  
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8 360 <<Fig. 7>>  
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### 10 11 361 7.a. Palynological framework for the Agardhfjellet Formation 12

13  
14 362 The two lowermost samples from the DH5R core collected from the upper part of the  
15  
16 363 Agardhfjellet Formation (at 458.0 and 440.0 m) are barren of dinocysts (Figure S6). The  
17  
18 364 sample at 410 m yields only few, poorly preserved dinocysts (Figure S6). In this sample,  
19  
20 365 the co-occurrence of *Sirmiodinium grossii* and *Tubotuberella apatela* suggests a very  
21  
22 366 broad Bathonian – early Valanginian age (e.g. Costa and Davey, 1992). Our dinocyst-  
23  
24 367 derived age constrain is therefore not as good as the age based e.g. on macrofossils,  
25  
26 368 which dates this part of the Agardhfjellet Formation as Ryazanian (Wierzbowski *et al.*,  
27  
28 369 2011).  
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### 34 35 371 7.b. Palynological framework for the Rurikfjellet Formation 36

37  
38 372 The distribution of dinocysts in the Rurikfjellet Formation (except the Myklegardfjellet  
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40 373 Bed; Fig. 1) from the studied sites suggests that this formation is of early Valanginian to  
41  
42 374 possibly earliest Barremian age (Fig. 8).  
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46 375 The dinocyst assemblages in the DH1 and DH2 cores are characterised by poor  
47  
48 376 preservation, low diversity and low dinocyst abundance. Both cores penetrate the  
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50 377 ca.150 m thick gravity flow deposits of the Adventpynten member (Grundvåg *et al.*,  
51  
52 378 2017) that yield a number of reworked taxa. In the DH2 core, the lowermost samples  
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54 379 from the Rurikfjellet Formation yield only a single highly corroded *Oligosphaeridium*  
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3 380 specimen (possibly *O. complex* or *O. asterigerum*). Thus, this interval is tentatively  
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5 381 dated as Valanginian or younger (Fig. S5). The two lowermost samples from the DH1  
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7 382 well (corresponding to the base of the Rurikfjellet Formation according to Grundvåg *et*  
8  
9 383 *al.*, 2017) also yield *O. complex* (Fig. S4). Furthermore, the sample at 414.0 m yields  
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11 384 *Gochteodinia villosa* subsp. *multifurcata* while the sample at 410.2 m yields *Muderongia*  
12  
13 385 *tetracantha* (Fig. S4). Thus, this interval is of Valanginian – Hauterivian age. The  
14  
15 386 presence of *Endoscrinium hauterivianum* between 270.0 and 221.0 m implies that this  
16  
17 387 interval is of early Hauterivian to earliest late Hauterivian age (see below). In summary,  
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19 388 in the DH1 core (i.e. 414.0 to 221.0 m depth) the Rurikfjellet Formation is dated as  
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21 389 Valanginian – earliest late Hauterivian (Fig. S4).  
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26  
27 390 We find the best-constrained age for the basal part of the Rurikfjellet Formation  
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29 391 (early Valanginian) to be represented by the Myklegardfjellet outcrop section (the  
30  
31 392 interval from the base of the section up to level 60.0 m; Fig. S2). This notion is based on  
32  
33 393 the co-occurrence of *Palaecysta palmula* and *O. complex* in the lowermost sample at  
34  
35 394 0.05 m. The early Valanginian age for the base of the Rurikfjellet Formation confirms  
36  
37 395 previous observations (Bjærke, 1978; Århus, 1992).  
38  
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41 396 The LO of the stratigraphically persistent *T. apatela* at 60.0 m in the  
42  
43 397 Myklegardfjellet outcrop section is used here as a marker for the top of the early  
44  
45 398 Valanginian, since most records agree that this bio-event is close to the early–late  
46  
47 399 Valanginian boundary (see below; Fig. 7). This age assignment is in agreement with the  
48  
49 400 presence of a *Tollia* (*Neocraspedites*) aff. *subtilis* ammonite of middle early Valanginian  
50  
51 401 age found at 47.30 m (unpublished data of P. Alsen and M. E. Jelby).  
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3 402 In the DH5R core, the top of the stratigraphically persistent *Gochteodinia villosa*  
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5 403 subsp. *villosa* is at 320.0 m, and it co-occurs with *O. complex* in the interval from 380.0  
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7 404 to 320.0 m. Based on these occurrences, we date this interval as earliest Valanginian.  
8  
9  
10 405 Placing the early–late Valanginian boundary close to the top of the persistent  
11  
12 406 occurrence of these two taxa is in agreement with the observations by Århus (cf. Fig. 2  
13  
14 407 in Århus, 1992, and Enclosure 2 in Århus, 1988).

15  
16  
17 408 We place the base of the Hauterivian at the FO of *E. hauterivianum* (Fig. 8). The  
18  
19 409 FO of *E. hauterivianum* is followed by the FO of *Muderongia tetracantha*, another  
20  
21 410 important marker for the Hauterivian (e.g. Costa and Davey, 1992), Fig. 7. The  
22  
23 411 stratigraphic range of *E. hauterivianum* observed in five sites (DH1, DH2, DH5R,  
24  
25 412 Bohemanflya and Myklegardfjellet) in the middle to upper part of the Rurikfjellet  
26  
27 413 Formation dates this part of the unit to the early Hauterivian – earliest late Hauterivian  
28  
29 414 (Figs S4, S5, and 4). Grøsfjeld (1991) noted that *E. hauterivianum* (as *Apteodinium* sp.  
30  
31 415 A of Bjærke, 1978; Section 9.a.) is also present in several other outcrop sections of the  
32  
33 416 Rurikfjellet Formation including Janusfjellet, Forkastningsfjellet and Helvetiafjellet.

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35  
36 417 Many samples from the uppermost part of the Rurikfjellet Formation in the DH1,  
37  
38 418 DH2 and DH5R cores are characterised by low dinocyst abundance and relatively low  
39  
40 419 species richness. The best age constrain for the top of the formation is therefore based  
41  
42 420 on outcrop sections. The upper part of the Rurikfjellet Formation is dated to the late  
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44 421 Hauterivian – earliest Barremian. The youngest part of the formation dated to the early  
45  
46 422 Barremian is observed at Ullaberget and Bohemanflya.

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48  
49 423 In the Ullaberget outcrop section, two samples at 0.0 and 2.0 m, collected from  
50  
51 424 the top of the Rurikfjellet Formation, yield *Pseudoceratium anaphrissum* and

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3 425 *Subtilisphaera perlucida*. The sample at 0.0 m additionally yields *Nelchinopsis*  
4  
5 426 *kostromiensis*, *P. anaphrissum*, and *S. perlucida*, which have their FOs close to the  
6  
7 427 Hauterivian – Barremian boundary (Fig. S3). In the North Sea Basin, the LO of *N.*  
8  
9 428 *kostromiensis* and the FO of *P. anaphrissum* are two important bio-events for  
10  
11 429 recognition of the Hauterivian–Barremian boundary. Typically, the LO of *N.*  
12  
13 430 *kostromiensis* marks the top of the Hauterivian, while the FO of *P. anaphrissum* marks  
14  
15 431 the base of the Barremian (e.g. Costa & Davey, 1992). However, in some studies both  
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17 432 bio-events are reported from the earliest Barremian (Heilmann-Clausen, 1987; Århus et  
18  
19 433 al., 1990; Smelror et al., 1998; Bailey, 2019) or the uppermost Hauterivian  
20  
21 434 (Nøhr-Hansen, 1993; Nøhr-Hansen, Piasecki & Alsen, this issue). In the North Sea, the  
22  
23 435 ranges of these two species either overlap (Costa & Davey, 1992) or don't (Bailey,  
24  
25 436 2019). Overlapping ranges of the two taxa have been observed in North-East  
26  
27 437 Greenland (Nøhr-Hansen, 1993; Nøhr-Hansen, Piasecki & Alsen, this issue). An  
28  
29 438 overlap of the stratigraphic ranges of the two species was previously reported from the  
30  
31 439 Barents Sea (well 7245/9-U-1) (Fig. 5 in Århus et al. 1990). Based primarily on the  
32  
33 440 foraminifera assemblage, the overlap interval was dated as early Barremian (Århus et  
34  
35 441 al., 1990). However, these authors recognised that the presence of *Buchia sublaevis*  
36  
37 442 bivalves within the same interval was problematic (p. 173 in Århus et al. 1990), because  
38  
39 443 *Buchia* extends only into the Hauterivian (Zakharov, 1987). In summary, these  
40  
41 444 observations give three possibilities for assigning an age to the LO of *N. kostromiensis*  
42  
43 445 and the FO of *P. anaphrissum*: (i) In Spitsbergen, the Barents Sea and North-East  
44  
45 446 Greenland, *P. anaphrissum* appears in latest Hauterivian; (ii) in Spitsbergen and the  
46  
47 447 Barents Sea region, *N. kostromiensis* has a longer range reaching the earliest  
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3 448 Barremian; or (iii) *N. kostromiensis* occurring in the lower Barremian strata is reworked.  
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5 449 We consider the first possibility to be the most plausible, since this is in agreement with  
6  
7  
8 450 other studies from the Arctic region (North-East Greenland, Barents Sea and Arctic  
9  
10 451 Canada; cf. Fig. 7).

11  
12  
13 452 In the three uppermost samples from the Bohemanflya outcrop section (99.29 m  
14  
15 453 to 132.63 m), we found a common to abundant dinocyst taxon previously recorded as  
16  
17 454 *Nyktericysta? pannosa* by Grøsfjeld (1991). However, we observe that *N.? pannosa*  
18  
19 455 from Bohemanflya (Figs 7o,p) with its generally less pronounced lateral horns differs  
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21  
22 456 from the holotype, which was described from “middle Barremian” strata from the  
23  
24 457 Speeton Clay in England (Duxbury, 1980). Nevertheless, Grøsfjeld (1991), and this  
25  
26 458 study show the only records of this taxon outside the type area. The restricted  
27  
28  
29 459 occurrence of *N.? pannosa* limited to the Bohemanflya section on Spitsbergen  
30  
31 460 (Grøsfjeld 1991; this study) and to the Speeton Clay in England (Duxbury, 1980), could  
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33  
34 461 suggest that the distribution of the taxon is controlled by some environmental factors.

35  
36 462 Based on the LO of *N. kostromiensis* at 127.58 m and the presence of *N.?*  
37  
38 463 *pannosa* between 99.29 m and 132.63 m, the interval is dated as latest Hauterivian –  
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40  
41 464 early Barremian.

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44 465 In the topmost sample of the Myklegardfjellet outcrop section at 150.0 m, we  
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46 466 observed an acme of *M. australis*. We consider this acme to be time-equivalent to the  
47  
48 467 *M. australis* acme observed in the Barents Sea by Århus *et al.* (1990). Thus, we date  
49  
50  
51 468 this level as late Hauterivian – early Barremian.

52  
53 469 Our new age framework for the Rurikfjellet Formation based on the dinocyst  
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56 470 stratigraphy is in agreement with previous studies from the study area (e.g. Bjærke,  
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3 471 1978; Thusu, 1978; Århus, 1992; Midtkandal *et al.*, 2016), which dated the majority of  
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5 472 the Rurikfjellet Formation as Valanginian – Hauterivian. Specifically, the Rurikfjellet  
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7 473 Formation at the Janusfjellet outcrop section was previously dated as early Valanginian  
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9  
10 474 – late Hauterivian (Århus, 1992). We observe that our dinocyst distribution of the  
11  
12 475 Myklegardfjellet outcrop section (Fig. S2) resembles the distribution of dinocysts from  
13  
14 476 Janusfjellet (Enclosure 2 in Århus, 1988). Furthermore, our results confirm the  
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16 477 observation by Grøsfjeld (1991) that the topmost part of the Rurikfjellet Formation is  
17  
18 478 most likely of early Barremian age. Some reworking is present which is minor compared  
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21 479 to the reworking in the Helvetiafjellet Formation (Figs. S1-S6).  
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27 481 <<Fig. 8>>

28  
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30 482 <<Fig.9>>

### 31 32 33 483 **7.c. Palynological framework for the Helvetiafjellet Formation**

34  
35 484 We observe that the dinocyst assemblages of the Helvetiafjellet Formation are highly  
36  
37 485 impoverished and yield a number of taxa reworked from the Rurikfjellet Formation. The  
38  
39 486 reworking of Pliensbachian to Early Oxfordian dinoflagellate cysts within the  
40  
41 487 Helvetiafjellet Formation was observed previously on Kong Karls Land (Smelror *et al.*,  
42  
43 488 2018). Redeposition is, however, not surprising, considering that the study area was  
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45 489 uplifted and subaerially exposed in the Barremian with large parts of the Svalbard  
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47 490 platform being subjected to erosion (Fig. 2).  
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51  
52 491 Based on the presence of *Odontochitina nuda*, *Pseudoceratium anaphrissum*,  
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54 492 *Sirmiodinium grossii* and *Subtilisphaera perlucida*, the Helvetiafjellet Formation is dated  
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3 493 here as Barremian to possibly early Aptian (Figs S3, S5 and 9). The boundary between  
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5 494 the Rurikfjellet and Helvetiafjellet formations is dated as early Barremian. Due to the low  
6  
7 495 diversity of the assemblages and rarity of dinocysts, it is not possible to precisely place  
8  
9 496 the Barremian–Aptian boundary.

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12  
13 497 Our age assignment of the Helvetiafjellet Formation is in agreement with a recent  
14  
15 498 stable carbon-isotope ( $\delta^{13}\text{C}$ ) stratigraphic study of the Festningen outcrop section  
16  
17 499 (Vickers *et al.*, 2016). These authors interpreted that the Helvetiafjellet Formation is of  
18  
19 500 Barremian to earliest Aptian age. Another study, based on the U–Pb dating of a  
20  
21 501 bentonite in the DH3 core (at 156.89 m in the middle part of the Helvetiafjellet  
22  
23 502 Formation) suggested an age of  $123.3 \pm 0.2$  Ma for this particular bed (Corfu *et al.*,  
24  
25 503 2013), corresponding to the late early Aptian (Ogg, Ogg & Gradstein, 2016) . However,  
26  
27 504 the biostratigraphic framework of this study & Midtkandal *et al.* (2016) suggests that this  
28  
29 505 part of the succession is of Barremian age. Nevertheless, the existing studies (e.g.  
30  
31 506 Corfu *et al.*, 2013; Midtkandal *et al.*, 2016; Vickers *et al.*, 2016) collectively agree that  
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33 507 the Helvetiafjellet Formation is of Barremian – early Aptian age.  
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## 40 41 509 **8. Conclusions**

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44 510 The Rurikfjellet and Helvetiafjellet formations on Spitsbergen, Svalbard, have been  
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46 511 studied in the DH1, DH2 and DH5R onshore cores as well as in the Bohemanflya,  
47  
48 512 Myklegardfjellet and Ullaberget outcrop sections. Our study suggests an early  
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50 513 Valanginian – early Barremian age for the Rurikfjellet Formation and a Barremian –  
51  
52 514 Aptian age for the overlying Helvetiafjellet Formation. We provide a number of age  
53  
54 515 diagnostic dinocyst bio-events for age determination of the Rurikfjellet and Helvetiafjellet  
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3 516 formations. The preservation of dinocysts is better and the diversity of assemblages is  
4  
5 517 significantly higher in the offshore to shallow-marine Rurikfjellet Formation than in the  
6  
7  
8 518 fluvio-deltaic to paralic Helvetiafjellet Formation.

9  
10 We observe some reworked dinocysts within the Helvetiafjellet Formation,  
11  
12 possibly from the Rurikfjellet Formation. The presence of reworked dinocysts implies  
13  
14  
15 521 that any proxy records performed on bulk sediments (e.g.  $\delta^{13}\text{C}$ , biomarkers) across the  
16  
17 522 Barremian – Aptian transition on Spitsbergen should be interpreted with care, since the  
18  
19  
20 523 signal may be biased.

21  
22 We further observe that the distribution of *N. ? pannosa* and *O. abaculum* is most  
23  
24  
25 525 likely controlled by local paleoenvironmental variations. For a better understanding of  
26  
27 526 these records, further paleoenvironmental proxy data from the area are required.

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29  
30 527 The dinocyst assemblages in the three samples collected from the Agardhfjellet  
31  
32 528 Formation are too impoverished to provide a reliable age constraint on the boundary  
33  
34  
35 529 between the Rurikfjellet and Argardhfjellet formations.

36  
37 530 Our age model is in agreement with the existing stratigraphic studies carried out  
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39  
40 531 in the study area. Notably, our study provides the first comprehensive, semi-quantitative  
41  
42 532 dataset of the distribution of dinocysts within the Lower Cretaceous (Valanginian–  
43  
44  
45 533 Aptian) succession on Spitsbergen.

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50 535 **9. Appendix A: Taxonomic notes on characteristic dinocyst taxa of the Rurikfjellet**  
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52 536 **and Helvetiafjellet formations**

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3 538 **9.a. Stratigraphic range of *Endoscrinium hauerivianum* (Duxbury, 2001) Riding &**  
4  
5 **Fensome, 2003**

6 539  
7  
8 540 **Figs 3o,p**

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10  
11 541 1978 *Apteodinium* sp. A (Bjærke, 1978)

12  
13  
14 542 1980? *Apteodinium* sp. A of Bjærke (1978) Bjærke plate X figs 1,2

15  
16  
17 543 1991 *Apteodinium* sp. A of Bjærke (1978) Grøsfjeld plate 4 figs D-F

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19  
20 544 2001 *Scriniodinium hauerivianum* Duxbury, 2001

21  
22 545 2003 *Endoscrinium hauerivianum* (Duxbury, 2001) Riding & Fensome, 2003

23  
24  
25 546 The holotype of *E. hauerivianum* was described from the UK sector of the North Sea  
26  
27 547 Basin (Duxbury, 2001). The taxon was described as restricted to the Hauterivian with  
28  
29 548 the LO within the lowermost upper Hauterivian (Duxbury, 2001). We here suggest that  
30  
31 549 *Apteodinium* sp. A of Bjærke (1978), which was recorded in the Valanginian to  
32  
33 550 Hauterivian succession of the Rurikfjellet Formation (Bjærke, 1980), is a synonym of *E.*  
34  
35 551 *hauerivianum*. Grøsfjeld (1991) noted that the species was present in numerous  
36  
37 552 locations on Spitsbergen and can be used as a Hauterivian marker in the region.  
38  
39 553 However, she also pointed out that at Janusfjellet the LO of *Apteodinium* sp. A of  
40  
41 554 Bjærke (1978) postdates the LO of *N. kostromiensis* (for the stratigraphic range of *N.*  
42  
43 555 *kostromiensis* see Section 9.e.) and thus it may range into the Barremian. Grøsfjeld  
44  
45 556 (1991) did not observe *N. kostromiensis* in the Bohemanflya outcrop section (see Fig 6  
46  
47 557 in Grøsfjeld 1991), only *N?. pannosa* (see below) and *Apteodinium* sp. A of Bjærke  
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49  
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51  
52  
53 558 (1978).

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3 559 *Spitsbergen - this study*. In the present study *E. hauterivianum* is recorded in all  
4  
5 560 studied sections. We apply the FO of *E. hauterivianum* as a marker for the base  
6  
7 561 Hauterivian and the LO as the marker for the earliest late Hauterivian. In the two  
8  
9  
10 562 sections with the highest dinocyst diversity and the greatest abundance assemblage  
11  
12 563 (Bohemanflya Fig. S1 and Myklegardfjellet, Fig. 5) the LO of *E. hauterivianum* predates  
13  
14 564 the LO of *N. kostromiensis*. This is in contrast to the observations by Grøjsfjeld (1991)  
15  
16 565 from the Bohemanflya outcrop section. We speculate that the longer range of *N.*  
17  
18 566 *kostromiensis* observed by us may be an effect of different sampling strategies carried in  
19  
20 567 both studies. In the studied material the taxon is rare to abundant (i.e. <1% or >50% of  
21  
22 568 the total dinocyst assemblage).

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27 569

### 29 570 **9.b. LO of *Gochteodinia villosa* (Vozzhennikova, 1967) Norris, 1978**

#### 32 571 **Figs 4a-c**

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38 573 *G. villosa* is divided into two subspecies, *G. villosa* subsp. *villosa* (Vozzhennikova,  
39  
40 574 1967) and *G. villosa* subsp. *multifurcata* (Davey, 1982). The stratigraphic ranges of  
41  
42 575 these subspecies are different (Fig. 7). The FO of *G. villosa multifurcata* postdates the  
43  
44 576 FO of *G. villosa villosa* and thus distinguishing the two subspecies is very useful for  
45  
46 577 increasing the resolution of the age framework. In the North Sea Basin *G. villosa*  
47  
48 578 *multifurcata* ranges from the lower Valanginian (Heilmann-Clausen, 1987) to the  
49  
50 579 lowermost Hauterivian (Heilmann-Clausen, 1987; Costa & Davey, 1992) or to the  
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52 580 Valanginian–Hauterivian boundary (Davey, 1982; Bailey, 2019). The youngest LOs of  
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3 581 *G. villosa villosa* are reported at the Ryazanian–Valanginian boundary  
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5 582 (Heilmann-Clausen, 1987) or in the earliest Valanginian (Costa and Davey, 1992;  
6  
7 583 Bailey, 2019). Davey (1982) and Nøhr-Hansen, Piasecki & Alsen (this issue) reported  
8  
9 584 the youngest occurrence of the taxon in the late Ryazanian–late Berriasian from  
10  
11 585 Denmark and North-East Greenland, respectively. In the Sverdrup Basin, Arctic  
12  
13 586 Canada, *G. villosa* (not differentiated into subspecies, and possibly *G. villosa*  
14  
15 587 *multifurcata*) was found in the Valanginian (Davies, 1983). In the Barents Sea (possibly  
16  
17 588 reworked) specimens of *G. villosa* were reported in the assemblages referred to the  
18  
19 589 Hauterivian – lower Barremian (Århus *et al.*, 1990). Århus (1991) shows that on Central  
20  
21 590 Spitsbergen *G. villosa* occurs in the Valanginian and Hauterivian strata, while *G. villosa*  
22  
23 591 *multifurcata* has a slightly shorter range: Valanginian to lowermost Hauterivian. In the  
24  
25 592 Valanginian part of the succession both taxa are present consistently. In post-  
26  
27 593 Valanginian strata both taxa occur only sporadically (Fig. 13 in Århus, 1988) and thus  
28  
29 594 their presence may be an effect of reworking.

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36 595 *Spitsbergen – this study.* Specimens referred to *G. villosa villosa* and *G. villosa*  
37  
38 596 *multifurcata* are slightly more elongate than the type material (cf. e.g. Davey, 1982). The  
39  
40 597 poor preservation of some of the specimens encountered in the present study  
41  
42 598 sometimes precludes an unambiguous separation of the two subspecies. We  
43  
44 599 distinguish subspecies only if the determination is possible. In few samples *G. villosa*  
45  
46 600 makes up 2–4 % of the total dinocysts assemblage. Otherwise, the species occurs  
47  
48 601 persistently in the lower part of the Rurikfjellet Formation (Myklegardfjellet, DH5R), but  
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50 602 is rather rare.

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3 604 **9.c. Stratigraphic range and abundance interval of *Muderongia australis* Helby,**  
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5 605 **1987**  
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7

8 606 **Fig. 4e**  
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11 607

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13  
14 608 The youngest record on North-East Greenland of the taxon is from **the** upper  
15  
16 609 Hauterivian (Nøhr-Hansen, 1993, Nøhr-Hansen, Piasecki & Alsen this issue). In the  
17  
18 610 other few existing studies *M. australis* is reported either **from** the Hauterivian (Århus *et*  
19  
20 611 *al.*, 1990; Prössl, 1990) or from the Barremian (Helby, 1987; Davey, 1988). In  
21  
22 612 Spitsbergen *M. australis* is restricted to the upper part of the Rurikfjellet Formation  
23  
24 613 (Århus *et al.*, 1990). Århus *et al.* (1990) also noted an acme of *M. australis* in the  
25  
26 614 interval referred to **the** Hauterivian – early Barremian and mentioned that the *M.*  
27  
28 615 *australis* acme may be related **to** the early Barremian flooding event.  
29  
30  
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32  
33 616 *Spitsbergen – this study.* We observe **the** persistent occurrence of *M. australis* in  
34  
35 617 the upper part of the Rurikfjellet Formation within all the studied sites. Thus, we confirm  
36  
37 618 the observations of Århus *et al.* (1990). In the topmost sample from the Rurikfjellet  
38  
39 619 Formation at the Myklegardfjellet outcrop *M. australis* **occurs as** a local acme, which we  
40  
41 620 interpret **to be** synchronous with the acme observed in the Barents Sea (Århus *et al.*  
42  
43 621 1990) and North-East Greenland (Nøhr-Hansen, 1993).  
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50 623 **8.d. *Muderongia extensiva* and *Muderongia tetracantha***

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52 624 **Figs 4d,g,h**  
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3 626 In the North Sea Basin the LO of *M. extensiva* is a well established earliest Hauterivian  
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5 627 marker (Heilmann-Clausen, 1987; Costa & Davey, 1992; Duxbury, 2001). *M. tetracantha*  
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7 628 has a slightly younger range from the Hauterivian to the earliest Barremian (Costa and  
8  
9 629 Davey, 1992; Duxbury, 2001) or even Aptian (Heilmann-Clausen, 1987; Nøhr-Hansen,  
10  
11 630 1993; Nøhr-Hansen and McIntyre, 1998). Notably, some authors merge *M. tetracantha*  
12  
13 631 with *Muderongia crucis* (Costa and Davey, 1992; Bailey, 2019) or consider *M. crucis* as  
14  
15 632 a junior synonym (e.g. Helby, 1987). Nevertheless, *M. tetracantha* is considered the  
16  
17 633 most typical taxon for Hauterivian – lower Barremian strata (see discussion in  
18  
19 634 Heilmann-Clausen, 1987). More details concerning the stratigraphic ranges of these two  
20  
21 635 taxa in the Boreal and the European Boreal realm is shown on Fig. 7.  
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26

27 636 The morphologies of the two taxa are distinctive. The lateral horns of *M. extensiva* are  
28  
29 637 long and extend almost at right angles from the tests (Duxbury, 1977), while in *M.*  
30  
31 638 *tetracantha* the horns bend downwards (Gocht, 1957). Furthermore, *M. extensiva* in  
32  
33 639 contrast to *M. tetracantha* show a distinct plate differentiation at the lateral edge (Helby,  
34  
35 640 1987).  
36  
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41  
42 642 *Spitsbergen-this study*. In the material encountered in the present study we  
43  
44 643 observe transitional forms between *M. extensiva* and *M. tetracantha*. Some of these  
45  
46 644 forms resemble *M. tetracantha* in their general outline, but on one or both lateral horns,  
47  
48 645 we observe a distinct plate differentiation, a feature typical for *M. extensiva* (Fig. 7g).  
49  
50 646 We observe the earliest record of *M. tetracantha* below the FO of *E. hauterivianum* (Fig.  
51  
52 647 S1) but in sections with high dinocyst diversity and high relative abundance, the FO of  
53  
54 648 *M. tetracantha* is observed within the range of *E. hauterivianum* (Figs S1, S2, S6, and 4)  
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3 6494  
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6 650 **9.e. Stratigraphic range of *Nelchinopsis kostromiensis* (Vozzhennikova, 1967)**7  
8 651 **Wiggins, 1972**9  
10  
11 652 **Figs 4m,n**12  
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16  
17 654 In the majority of existing studies of the North Sea Basin (Fig. 7) the range of this  
18  
19 655 species is limited to the upper lower Valanginian–upper Hauterivian (Costa & Davey,  
20  
21 656 1992; Duxbury, 2001) or to the Hauterivian (Davey, 1982; Heilmann-Clausen, 1987). In  
22  
23 657 North-East Greenland the taxon first occurring in the middle late Valanginian and is not  
24  
25  
26 658 observed above the early to late Hauterivian *N. kostromiensis* Subzone (Nøhr-Hansen,  
27  
28 659 1993; Nøhr-Hansen, Piasecki & Alsen this issue). Some studies, reports the FO of *N.*  
29  
30 660 *kostromiensis* as early as at the early–late Valanginian boundary (Bailey, 2019) and its  
31  
32 661 LO in the earliest Barremian (Bailey, 2019). However, the Hauterivian–Barremian  
33  
34 662 boundary in Bailey (2019) is dated as 130 Ma so it is slightly younger than in the  
35  
36 663 **Geological Time Scale 2016** where it is dated as 130.8 Ma (Ogg, Ogg & Gradstein,  
37  
38 664 2016). In the Svedrup Basin, Arctic Canada *N. kostromiensis* was observed together  
39  
40 665 with *Gochteodinia villosa* in the middle-late late Valanginian succession (Davies, 1983).  
41  
42 666 **In some older studies *N. kostromiensis* was reported from the earliest Barremian**  
43  
44 667 **(Heilmann-Clausen, 1987; Smelror et al., 1998), from the *Simbirskites variabilis***  
45  
46 668 **ammonite zone. Today the zone is considered to be Hauterivian (Ogg, Ogg &**  
47  
48  
49 669 **Gradstein, 2016).**  
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3 670 *Spitsbergen – this study*. The FO and LO of *N. kostromiensis* are important  
4  
5 671 stratigraphic events within the Rurikfjellet Formation. The range of *N. kostromiensis*  
6  
7 672 **virtually spans** the entire unit at the three outcrops and in the DH5R core. Applying the  
8  
9 673 age constraint based on the range of *E. hauerivianum*, the FO of *N. kostromiensis* in  
10  
11 674 Spitsbergen is an early Valanginian event, observed in the lower part of the Rurikfjellet  
12  
13 675 Formation. The LO of *N. kostromiensis* is observed in the upper part of the Rurikfjellet  
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15 676 Formation and is probably of latest Hauterivian – earliest Barremian age.  
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#### 21 22 678 **9.f. FO of *Odontochitina nuda* (Gocht, 1957) Dörhöfer & Davies, 1980**

#### 23 24 25 679 **Fig. 5e**

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30  
31 681 The holotype of *O. nuda* was described from **the** upper Hauterivian (Gocht, 1957). Other  
32  
33 682 studies from Europe and Canada also suggest **a** Hauterivian to Barremian stratigraphic  
34  
35 683 range for the taxon (see discussion in Nøhr-Hansen, 1993), Fig. 7. In North-East  
36  
37 684 Greenland *O. nuda* is restricted **to** the uppermost lower Barremian to lower Aptian  
38  
39 685 (Nøhr-Hansen, 1993). In the Barents Sea the taxon was reported from early Barremian  
40  
41 686 strata by Århus (in Århus *et al.* 1990), but notably this study was carried **out only on a**  
42  
43 687 **Berriasian** to lower Barremian succession. Therefore, the youngest occurrence of the  
44  
45 688 taxon in the Barents Sea is unknown.  
46  
47  
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49  
50 689 *Spitsbergen – this study*. *O. nuda* is restricted to the Helvetiafjellet Formation.

51  
52 690 The FO is observed within the middle (the DH2 core) or the upper (the Ullaberget  
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3 691 outcrop section) part of the formation. The most probable time span for the taxon in  
4  
5 692 Spitsbergen is Barremian to early Aptian.  
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11 694 **9.g. FO of *Oligosphaeridium abaculum* Davey, 1979**

12  
13  
14 695 **Fig. 5f**

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19 697 The holotype of *O. abaculum* was described by Davey (1979) from a Barremian  
20  
21 698 succession from the northern North Sea. In his study, Davey mentioned that abundant  
22  
23 699 *O. abaculum* was found in the same sample as *Odontochitina operculata*, which has its  
24  
25 700 first stratigraphic occurrence in the Barremian e.g. (Nøhr-Hansen, 1993; Bailey, 2019).  
26  
27 701 The common occurrence of *O. abaculum* in the upper Hauterivian was reported in the  
28  
29 702 UK and the Norwegian sectors of the North Sea Basin by Bailey (2019). Notably, Costa  
30  
31 703 & Davey (1992) reported that in the UK sector of the North Sea Basin *O. abaculum* has  
32  
33 704 a stratigraphic range from the upper Hauterivian to lower Barremian. However, the post-  
34  
35 705 Hauterivian–Barremian? age was suggested by these authors because they considered  
36  
37 706 the *Simbirskites variabilis* ammonite zone as Barremian. Recently the FO of *O.*  
38  
39 707 *abaculum* was recorded from the uppermost lower Barremian in North-East Greenland  
40  
41 708 by Nøhr-Hansen, Piasecki & Alsen (this issue).

42  
43 709 *Spitsbergen – this study.* Rare to common (<1% and 1-30% of the total dinocyst  
44  
45 710 assemblage) occurrences of *O.abaculum* are observed from all sites spanning the  
46  
47 711 Rurikfjellet Formation. However, in contrast to the North Sea and North-East Greenland,  
48  
49 712 in Spitsbergen the taxon appears in the Valanginian, i.e. much earlier than in the two  
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3 713 other regions (Fig. 7). We consider the FO of *O. abaculum* as an intra-late Valanginian  
4  
5 714 event. The diachroneity in the event (Fig. 7) would suggest that the appearance of *O.*  
6  
7  
8 715 *abaculum* is dependent on the local environmental changes.  
9

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11  
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13 717 **9.h. FO of *Oligosphaeridium* complex (White, 1842) Davey & Williams, 1966b**

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15  
16 718 **Fig. 5h**

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21  
22 720 The FO of *O. complex* is an important marker for the base Valanginian in the North Sea  
23  
24 721 Basin and the Svedrup Basin, Arctic Canada (Davies, 1983; Costa & Davey, 1992;  
25  
26 722 Duxbury, 2001; Bailey, 2019). From North-East Greenland, Nøhr-Hansen, Piasecki &  
27  
28 723 Alsen (this issue) recently recorded the FO of *O. complex* from the *Peregrinus albidum*  
29  
30 724 ammonite zone, which is uppermost Berriasian in age [or lower Valanginian according  
31  
32 725 to Ogg, Ogg & Gradstein (2016)]. On Andøya (Arctic Norway), the oldest record of *O.*  
33  
34 726 *complex* is observed within beds assigned to the *Buchia inflata*-*Buchia keyserlingi*  
35  
36 727 zones dated as Early Valanginian (Århus et. 1986). *Spitsbergen – this study*. In our  
37  
38 728 material the taxon is present in virtually all samples. In the oldest part of the record, the  
39  
40 729 taxon is often characterised by a small central body size and very tilted, long processes.  
41  
42 730 The processes terminations often have a “palm-like” appearance (Fig. 5j). We consider  
43  
44 731 the FO of *O. complex* as a marker for the base of the Valanginian. However,  
45  
46 732 considering the recent study from North-East Greenland it is possible that this event is  
47  
48 733 slightly older (Nøhr-Hansen, Piasecki & Alsen this issue).  
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3 735 **9.i. LO of *Palaecysta palmula* (Davey, 1982b) Williams & Fensome, 2016**

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6 736 **Fig. 5k**

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11 738 In the UK sector of the Central North Sea Basin the LO of *P. palmula* is observed in the  
12  
13 739 middle lower Valanginian (Duxbury, 2001; Bailey, 2019) while in the Danish sector the  
14  
15 740 LO is probably slightly younger, within the lower upper Valanginian (Davey, 1982;  
16  
17 741 Heilmann-Clausen, 1987), Fig. 7.

18  
19 742 *Spitsbergen – this study.* In the present study *P. palmula* is observed in the basal  
20  
21 743 part of the Rurikfjellet Formation in the Myklegardfjellet outcrop section.

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27 745 **9.j. Stratigraphic range of *Pseudoceratium anaphrissum* (Sarjeant, 1966c) Bint,**

28  
29 746 **1986**

30  
31 747 **Figs 5m–o**

32  
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36  
37 749 The taxon has a remarkably short range, limited to the Barremian, primarily to the lower  
38  
39 750 Barremian (Fig. 7). In the high Arctic the taxon has also been observed in the  
40  
41 751 Hauterivian (Fig. 7). The Barremian record of *P. anaphrissum* is very well known from  
42  
43 752 the Barents Sea (Århus *et al.*, 1990), Arctic Norway (Thusu, 1978), offshore south  
44  
45 753 Norway (Costa, 1981), North-East Greenland (Nøhr-Hansen, 1993), England (e.g.  
46  
47 754 Sarjeant 1966, Duxbury 1980), Germany (Prössl, 1990) and the North Sea Basin  
48  
49 755 (Heilmann-Clausen, 1987; Costa & Davey, 1992; Bailey, 2019). Notably, in Arctic  
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3 756 Norway a common occurrence of *P. anaphrissum* was found in a sample referred to  
4  
5 757 upper Hauterivian – lower Barremian (Århus, Verdenius and Birkelund, 1986). In North-  
6  
7 758 East Greenland, and possibly also in the UK and the Norwegian sector of the North Sea  
8  
9  
10 759 Basin, the species is abundant in a narrow interval in the middle part of its range (Nøhr-  
11  
12 760 Hansen, 1993; Bailey, 2018), see also summary Fig. 7.

13  
14  
15 761 *Spitsbergen – this study.* In the present study *P. anaphrissum* is present in the  
16  
17 762 uppermost part of the Rurikfjellet Formation (Ullaberget) and the Helvetiafjellet  
18  
19 763 Formation (DH2 and Ullaberget). The taxon is rare (< 1%), badly preserved and  
20  
21 764 incomplete (Figs 5m-o). All observed specimens have clearly visible antapical lobes and  
22  
23 765 lateral buldges, and with no operculum. Specimens observed in DH2 and Ullaberget are  
24  
25 766 covered by short spines and processes (Figs 5n-o). Due to a poor preservational state,  
26  
27 767 the ornamentation of the specimen observed in the topmost sample from the  
28  
29 768 Bohemanflya outcrop section (Fig. 8m) is difficult to establish and therefore the  
30  
31 769 specimen is referred to *P. anaphrissum* questionably.

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36 770 In the middle and upper part of the Rurikfjellet Formation we found the common  
37  
38 771 occurrence of dinocysts which we referred to *Cleistosphaeridium diversispinosum* (Figs  
39  
40 772 6g, 6i). The ornamentation may resemble *P. anaphrissum*, but the outline is more  
41  
42 773 typical for the genus *Circulodinium*.

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49 775 **9.k. LO of *Sirmiodinium grossii* Alberti, 1961**

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52 776 **Figs 6e,f**

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3 778 The LO of *S. grossii* marks the top of the Barremian (e.g. Bailey, 2019). In North-East  
4  
5 779 Greenland the youngest record of the taxon is observed within the lowermost Aptian  
6  
7 780 (Nøhr-Hansen, 1993). More details concerning the distribution of the taxon in the Boreal  
8  
9 and the European Boreal Realm is shown on Fig. 7.  
10  
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12  
13 782 *Spitsbergen – this study.* We observe *S. grossii* in both the Rurikfjellet and  
14  
15 783 Helvetiafjellet formations. The taxon is present in virtually all samples analysed in this  
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17 784 study.  
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23 786 **9.i. FO of *Subtilisphaera perlucida* (Alberti, 1959b) Jain & Millepied, 1973**

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25  
26 787 **Fig. 6g**

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29 788

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31 789 The majority of existing records from the Boreal and European Boreal Realm suggest  
32  
33 790 that *S. perlucida* appeared in the early Barremian (Heilmann-Clausen, 1987; Nøhr-  
34  
35 791 Hansen, 1993). In the DH1 core the FO of *S. perlucida* was observed within the  
36  
37 792 Helvetiafjellet Formation and dated as Barremian – Aptian (Midtkandal *et al.*, 2016).  
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39 793 Some records suggest however that the taxon appeared in the late Hauterivian (Fig. 7).  
40  
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42

43 794 *Spitsbergen – this study.* The taxon is observed in the uppermost part of the  
44  
45 795 Rurikfjellet Formation (Ullaberget) and occurs consistently in the Helvetiafjellet  
46  
47 796 Formation (Ullaberget and the DH2 core).  
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54 798 **9.m. LO of *Tubotuberella apatela* (Cookson & Eisenack, 1960b) Ioannides *et al.*,**  
55  
56 799 **1977**

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60

800 **Figs 6 i-j**

801

802 In the majority of studies on the North Sea the LO of *T. apatela* occurs approximately  
803 within the middle lower Valanginian (Fig. 7) and is considered synchronous with (Bailey,  
804 2019) or slightly younger than (Duxbury, 2001) the LO of *P. palmula*. In the Barents Sea  
805 *T. apatela* was not observed in the post-Ryazanian strata, but this may be biased by the  
806 fact that the Valanginian succession is devoid of palynomorphs (Århus *et al.*, 1990).  
807 Numerous studies report *T. apatela* from the upper Valanginian (Davies, 1983; Århus,  
808 1988) or even Hauterivian (Piasecki, 1979; Davey, 1982; Heilmann-Clausen, 1987)  
809 deposits. These studies report that the last persistent occurrence of *T. apatela* occurs  
810 within the early Valanginian. In Spitsbergen and North-East Greenland the post-  
811 Valanginian occurrence of the taxon is considered as reworked (Århus, 1988; Nøhr-  
812 Hansen, 1993).

813 *Spitsbergen – this study.* In the present study *T. apatela* is present within the  
814 lower to middle part of the Rurikfjellet Formation. We observe that the LO on  
815 Spitsbergen is diachronous. In the Myklegardfjellet outcrop section we apply the LO of  
816 persistent *T. apatela* as the marker for the top of early Valanginian (Fig. 8). *T. apatela*,  
817 in contrast to *Tubotuberella rhombiformis*, has a distinctive apical horn (on both  
818 epitheca, and hypotheca), and lacks tabulation. These two features are clearly visible in  
819 virtually all specimens observed in this study.

820

821 **Acknowledgements**

1  
2  
3 822 This research was carried out within the LoCrA consortium (<https://wp.ux.uis.no/locra>),  
4  
5 823 generously sponsored by 22 industry partners. Thanks are extended to Annette Ryge,  
6  
7 824 Charlotte Olsen, and Dorthe Samuelsen (GEUS) for preparation of palynological slides.  
8  
9  
10 825 S.-A. Grundvåg acknowledges funding from the ARCEX project (Research Centre for  
11  
12 826 Arctic Petroleum Exploration) which is funded by the Research Council of Norway (grant  
13  
14 827 number 228107). Figures 8, 9, and S1-S6 were prepared using the StrataBugs v2.0  
15  
16 828 charts. We thank reviewers Wiesława Viola Radmacher and Kari Grøsfjeld as well as  
17  
18 829 editor Jennifer Galloway for valuable comments and suggestions, which improved this  
19  
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21 830 manuscript.  
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## 832 Declaration of Interest

833 The authors declare no conflicts of interest.  
834

835

## 835 Figure captions

836 **Figure 1.** Stratigraphic cross-section showing the regional development of the Upper  
837 Jurassic to Lower Cretaceous Adventdalen Group on Spitsbergen. Modified after Alsen  
838 *et al.* (this issue). White bars show the time span for each of the studied sites: three  
839 onshore cores DH1, DH2, DH5R, and three outcrop sections: Bohemanflya (BOH),  
840 Ullaberget (UL), and Myklegardfjellet (MYK).

841 **Figure 2. (A).** Black dots mark the positions of the studied sites: Bo – Bohemanflya, UI  
842 – Ullaberget, My – Myklegardfjellet outcrop sections. Paleogeography of Spitsbergen  
843 from the Valanginian to early Aptian (after Grundvåg & Olausson, 2017; Grundvåg *et*

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3 844 *al.*, 2017) (**B**) Palaeogeography during the deposition of the Wimanfjellet Member; (**C**)  
4  
5 845 Palaeogeography during the deposition of the Kikutodden Member; (**D**) Paleogeography  
6  
7 846 during the earliest Barremian - deposition of the Festningen Member.  
8  
9

10 847 **Figure 3.** Photographs of the most characteristic dinoflagellate cysts observed in the  
11  
12 848 Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all  
13  
14 849 photographs represent 20  $\mu\text{m}$ . MC – microscope coordinates with the A-point of  
15  
16 850 0.4×90.3 (XM1 × YM1). For details, see Śliwińska (2019).  
17  
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19  
20 851 (a) a dinocyst, Bohemanflya outcrop section, level 99.29 m, sample 26291-7, MC 102 x  
21  
22 852 42.2  
23  
24

25 853 (b) *Apteodinium spongiosum*, high focus, (c) low focus, Bohemanflya outcrop section,  
26  
27 854 level 25.00 m, sample 28450-9, MC 25 x 108.7  
28  
29

30 855 (d) *Apteodinium spongiosum* very dark, Myklegardfjellet outcrop section, level 30.00 m,  
31  
32 856 sample 27007-6, MC 32 x 109.1  
33  
34

35 857 (e) *Apteodinium spongiosum*, Myklegardfjellet outcrop section, level 120.00 m, sample  
36  
37 858 27013-9; MC 51.4 x 105.5  
38  
39

40 859 (f) *Atopodinium haromense*; Myklegardfjellet outcrop section, level 120.00 m, sample  
41  
42 860 27013-9; MC 42.7 x 102.3  
43  
44

45 861 (g) *Circulodinium distinctum*, Myklegardfjellet outcrop section, level 105.00 m, sample  
46  
47 862 27012-6; MC 29.3 x 91.6  
48  
49

50 863 (h) *Circulodinium distinctum*, Myklegardfjellet outcrop section, level 120.00 m, sample  
51  
52 864 27013-9; MC 21 x 104.5  
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3 865 (i) *Circulodinium distinctum*, Myklegardfjellet outcrop section, level 120.00 m, sample  
4  
5 866 27013-9; MC 17.5 x 105.5  
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7

8 867 (j) *Circulodinium distinctum*, Bohemanflya outcrop section, level 28.00 m, sample  
9  
10 868 28449-8; MC 44.7 x 96.7  
11  
12

13 869 (k) *Dissiliodinium acmeum*, Myklegardfjellet outcrop section, level 7.00 m, sample  
14  
15 870 27005-4; MC 37.2 x 99.4  
16  
17

18 871 (l) *Endoscrinium* sp.1 Bohemanflya outcrop section, level 25.00 m, sample 28450-9  
19  
20  
21 872 ; MC 25.5 x 110  
22  
23

24 873 (m) *Discorsia nannus*, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-  
25  
26 874 9; MC 49 x 103.3  
27  
28

29 875 (n) *Dingodinium cerviculum*, Myklegardfjellet outcrop section, level 75.00 m, sample  
30  
31 876 27010-4; MC 47 x 108.5  
32  
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34 877 (o) *Endoscrinium hauterivianum*, Bohemanflya outcrop section, level 36.00 m, sample  
35  
36 878 28448-7; MC 33.8 x 102.2  
37  
38

39 879 (p) *Endoscrinium hauterivianum*, Myklegardfjellet outcrop section, level 120.00 m,  
40  
41 880 sample 27013-9; MC 42 x 102.4  
42  
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47 882 **Figure 4.** Photographs of the most characteristic dinoflagellate cysts observed in the  
48  
49 883 Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all  
50  
51 884 photographs represent 20  $\mu\text{m}$ . The figure in colour is available on the web version of  
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3 885 this paper. MC – microscope coordinates with the A-point of 0.4×90.3 (XM1 × YM1). For  
4  
5 886 details, see Śliwińska (2019).

7  
8 887 (a) *Gochteodinia villosa* subsp. *multifurcata*, Myklegardfjellet outcrop section, level  
9  
10 888 15.00 m, sample 27006-5, MC 36.3 x 114

11  
12  
13 889 (b) *Gochteodinia villosa*, DH5R core, depth 350.00 m, sample 26197-6; MC 22.5 x 96.2

14  
15  
16 890 (c) *Gochteodinia villosa* subsp. *multifurcata*, Myklegardfjellet outcrop section, level  
17  
18 891 15.00 m, sample 27006-5; MC 36 x 107

19  
20  
21 892 (d) *Muderongia tetracanta*, Bohemanflya outcrop section, level 127.50 m, sample  
22  
23 893 26290-8; MC 44 x 110.6

24  
25  
26 894 (e) *Muderongia australis*, Myklegardfjellet outcrop section, level 120.00 m, sample  
27  
28 895 27013-9; MC 31.4 x 108.5

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31 896 (f) *Muderongia simplex*, Myklegardfjellet outcrop section, level 105.00 m, sample 27012-  
32  
33 897 6; MC 33 x 105.8

34  
35  
36 898 (g) a transitional form between *Muderongia tetracanta* and *Muderongia extensiva*,  
37  
38 899 Bohemanflya outcrop section, level 46.00 m, sample 26293-5; MC 24.5 x 111

39  
40  
41 900 (h) *Muderongia extensiva*, Bohemanflya outcrop section, level 46.00 m, sample 26293-  
42  
43 901 7; MC 18.5 x 108.4

44  
45  
46 902 (i) *Isthmocystis distincta*, Myklegardfjellet outcrop section, level 7.00 m, sample 27005-  
47  
48 903 4; MC 28 x 102.3

49  
50  
51 904 (j) *Kleithriasphaeridium eoinodes*, Myklegardfjellet outcrop section, level 90.00 m,  
52  
53 905 sample 27011-8; MC 25.2 x 103

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3 906 (k) *Kiokansium unituberculatum*, Bohemanflya outcrop section, level 127.50, sample

4  
5 907 26290-6; MC 31x107.3

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8 908 (l) *Meiourogonyaulax stoveri*, DH5R core, depth 258.00 m, sample 26194-5; MC 24 x

9  
10 909 107.8

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12  
13 910 (m) poorly preserved *Nelchinopsis kostromiensis*, Bohemanflya outcrop section, level

14  
15 911 99.29 m, sample 26291-7; MC 52.4 x 109

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17  
18 912 (n) *Nelchinopsis kostromiensis*, Bohemanflya outcrop section, level 55.25 m, sample

19  
20 913 26292-7; MC 51.5 x 95.5

21  
22  
23 914 (o) *Nyktericysta? pannosa*, Bohemanflya outcrop section, level 99.29 m, sample 26291-

24  
25 915 7; MC 43 x 102.7

26  
27  
28 916 (p) *Nyktericysta? pannosa*, Bohemanflya outcrop section, level 127.50 m, sample

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30 917 26290-8; MC 50.2 x 100

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36 919 **Figure 5.** Photographs of the most characteristic dinoflagellate cysts observed in the

37  
38 920 Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all

39  
40 921 photographs represent 20  $\mu$ m. The figure in colour is available on the web version of

41  
42 922 this paper. MC – microscope coordinates with the A-point of 0.4x90.3 (XM1 x YM1). For

43  
44 923 details, see Śliwińska (2019).

45  
46  
47  
48 924 (a) *Oligosphaeridium poculum*, DH5R core, depth 320.00 m, sample 26196-7; MC 58.2

49  
50 925 x 97.1

51  
52  
53 926 (b) questionable *Escharisphaeridia rudis*, DH5R core, depth 288.00 m, sample 26195-7;

54  
55 927 MC 36.7 x 112.5

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3 928 (c) *Phoberocysta neocomica*, Myklegardfjellet outcrop section, level 90.00 m, sample  
4  
5 929 27009-6; MC 24.3 x 113.8  
6  
7  
8 930 (d) *Rhynchodiniopsis aptiana*, Bohemanflya outcrop section, level 5.00 m, sample  
9  
10 931 28453-7, MC 31.7 x 101  
11  
12  
13 932 (e) *Odontochitina nuda*, DH2 core, depth 141.80 m, sample 26510-9; MC 42 x 105.2  
14  
15  
16 933 (f) *Oligosphaeridium abaculum*, Myklegardfjellet outcrop section, level 75.00 m, sample  
17  
18 934 27010-5; MC 48.5 x 105.5  
19  
20  
21 935 (g) *Rhynchodiniopsis aptiana*, Myklegardfjellet outcrop section, level 105.00 m, sample  
22  
23 936 27012-6; MC 20.3 x 107.5  
24  
25  
26 937 (h) *Oligosphaeridium complex* with “palm-like” terminations of processes, DH1, depth  
27  
28 938 258.90 m, sample 26285-7; MC 32.8 x 97.1  
29  
30  
31 939 (i) *Oligosphaeridium asterigerum*, Bohemanflya outcrop section, level 99.29 m, sample  
32  
33 940 26291-7, MC 44.7 x 94.3  
34  
35  
36 941 (j) *Pseudoceratium pelliferum*, Bohemanflya outcrop section, level 36.00 m, sample  
37  
38 942 28448-7, MC 37 x 106.5  
39  
40  
41 943 (k) *Palaecysta palmula*, Myklegardfjellet outcrop section, level 0.05 m, sample 27004-8,  
42  
43 MC 53 x 107.5  
44  
45  
46 945 (l) *Cyclonephelium cuculliforme* sensu Århus 1990, Myklegardfjellet outcrop section,  
47  
48 level 15.00, sample 27006-3; MC 30.2 x 101  
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3 947 (m) questionable *Pseudoceratium anaphrissum* Bohemanflya outcrop section, level  
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5 948 132.63 m, sample 26289-8; MC 37.8 x 95.5. Shown also in Figure 15.P in Grundvåg *et*  
6  
7  
8 949 *al.*, (2019).

9  
10  
11 950 (n) *Pseudoceratium anaphrissum*, Ullaberget outcrop section, level 104.00m, sample  
12  
13 951 28482-7; MC 40.6 x 111.8

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15  
16 952 (o) questionable, poorly preserved *Pseudoceratium anaphrissum*, DH2 core, depth  
17  
18 953 149.50 m, sample 26511-11; MC 34.5 x 110.5. Shown also in Figure 15.H in Grundvåg  
19  
20 954 *et al.*, (2019).

21  
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23 955

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25  
26 956 **Figure 6.** Photographs of the most characteristic dinoflagellate cysts observed in the  
27  
28 957 Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all  
29  
30 958 photographs represent 20  $\mu\text{m}$ . The figure in colour is available on the web version of  
31  
32 959 this paper. MC – microscope coordinates with the A-point of 0.4×90.3 (XM1 × YM1). For  
33  
34 960 details, see Śliwińska (2019).

35  
36  
37  
38 961 (a) *Stanfordella fastigiata*, Myklegardfjellet outcrop section, level 30.00 m, sample  
39  
40 962 27007-6; MC 50.4 x 103.5

41  
42  
43 963 (b) *Stanfordella ordocava*, Myklegardfjellet outcrop section, level 15.00 m, sample  
44  
45 964 27006-5; MC 31.6 x 111

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47  
48 965 (c) *Stanfordella ordocava*, DH5R core, depth 380.00 m, sample 26198-6; MC 55.5 x  
49  
50 966 102.4

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53 967 (d) *Spiniferites* sp. 1, DH5R core, depth 194.00 m, sample 26192-7; MC 36.9 x 102  
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3 968 (e) *Sirmiodinium grossii*, Myklegardfjellet outcrop section, level 30.00 m, sample 27007-  
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5 969 6; MC 30.3 x 104.2  
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7  
8 970 (f) *Sirmiodinium grossii*, DH1, depth 258.90 m, sample 26285-7; MC 29.4 x 109  
9  
10  
11 971 (g) *Subtilisphaera perlucida*, DH2 core, depth 186.55 m, sample 26513-9; MC 36.7 x  
12  
13 972 92.6. Shown also in Figure 15.G in Grundvåg *et al.*, (2019).  
14  
15  
16 973 (h) *Spiniferites?* DH5R core, depth 194.00 m, sample 26192-7; MC 50.8 x 101.2  
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18  
19 974 (i) *Tubotuberella apatela*, Myklegardfjellet outcrop section, level 30.00 m, sample  
20  
21 975 27007-6; MC 30.6 x 105  
22  
23  
24 976 (j) *Tubotuberella apatela*, Myklegardfjellet outcrop section, level 0.05 m, sample 27004-  
25  
26 977 8; MC 34.5 x 109.4  
27  
28  
29 978 (k) *Tubotuberella apatela*, DH2 core, depth 232.00 m, sample 26516-9; MC 19.4 x 93.3  
30  
31  
32 979 (l) *Tubotuberella* sp. DH5R core, depth 380.0 m, sample 26198-6; MC 48 x 98.7  
33  
34  
35 980 (m) *Wallodinium luna*, DH5R core, depth 350.0 m, sample 26197-6; MC 36.5 x 102.4  
36  
37  
38 981 (n) *Wrevittia perforobtus*a, DH5R core, depth 194.00 m, sample 26192-7; MC 29.9 x  
39  
40 982 102.6  
41  
42  
43 983 (o) *Wrevittia perforobtus*a, Bohemanflya outcrop section, level 55.25 m, sample 26292-  
44  
45 984 8, MC 50.3 x 101.7  
46  
47  
48 985 (p) *Wrevittia perforobtus*a, Bohemanflya outcrop section, level 36 m, sample 28448-7,  
49  
50 986 MC 40.5 x 98.6  
51  
52  
53 987 **Figure 7.** The stratigraphic ranges and/or first and last occurrences of the age  
54  
55 988 diagnostic dinoflagellate cysts (dinocysts) from the Boreal and European Boreal Realm,  
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3 989 and the key events recognised in this study (to the right). Key dinocyst events in  
4  
5 990 Spitsbergen: primary markers (black), secondary markers (grey).  
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7

8 991 The figure shows a compilation of the most characteristic dinocysts from the Rurikfjellet  
9  
10 992 and Helvetiafjellet **formations** discussed in the present study. Heilmann-Clausen (1987),  
11  
12 993 Costa & Davey (1992), and Duxbury (2001) plotted the dinocysts ranges against the  
13  
14 994 ammonite zonation (marked with asterix). All these authors considered the *Simbirskites*  
15  
16 995 *variabilis* ammonite zone as earliest Barremian, **whilst** today it is considered **to be**  
17  
18 996 Hauterivian (Ogg, Ogg & Gradstein, 2016). Nøhr-Hansen, Piasecki & Alsen (this issue)  
19  
20 997 updated the zonation proposed previously by Nøhr-Hansen (1993), and provided ages  
21  
22 998 in GTS2016. Note that the study by Davey (1982) does not cover sediments younger  
23  
24 999 than early-?late Hauterivian, while the study by Davies (1983) does not cover sediments  
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26  
27  
28  
29 1000 younger than late Valanginian.  
30

31  
32 1001 **Figure 8.** The spatial distribution of the age diagnostic (colour code) and secondary  
33  
34 1002 dinocyst events (black) within the Rurikfjellet Formation. The correlation between the  
35  
36 1003 Bohemanflya, the DH5R core, and the Myklegardfjellet outcrop section, i.e. from NW to  
37  
38 1004 SE.  
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40

41 1005 **Figure 9.** The spatial distribution of the age diagnostic dinocyst events within the  
42  
43 1006 Helvetiafjellet Formation. The correlation between the Ullaberget outcrop section and  
44  
45 1007 the DH2 core.  
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52 1009 **online Supplementary Material at <http://journals.cambridge.org/geo>**  
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3 1010 This file contains range charts with the quantitative data of the palynomorphs  
4  
5 1011 recognised in this study. The palynomorphs are arranged after the first occurrence (FO),  
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7  
8 1012 R – reworked, DC – dinocyst, AC – acritarch, MP – palynomorph  
9

10  
11 1013 **Figure S1.** Distribution of dinocysts in the Bohemanflya outcrop section  
12

13  
14 1014 **Figure S2.** Distribution of dinocysts in the Myklegardfjellet outcrop section  
15

16  
17 1015 **Figure S3.** Distribution of dinocysts in the Ullaberget outcrop section  
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19  
20 1016 **Figure S4.** Distribution of dinocysts in the DH1 well  
21

22  
23 1017 **Figure S5.** Distribution of dinocysts in the DH2 well  
24

25  
26 1018 **Figure S6.** Distribution of dinocysts in the DH5R well  
27

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29  
30  
31 1020 **References**  
32

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36  
37

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39  
40 1024 Arctic with emphasis on the Janusfjellet Formation type section, Spitsbergen.  
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1360 **Table 1. List of palynomorphs recorded in this study including a reference for**  
 1361 **photographs (Figs. 6-9) and range charts (Figs S1-S6)**

Palynomorph name in alphabetical order according to genus then species	Photo	Fig. S1	Fig. S2	Fig. S3	Fig. S4	Fig. S5	Fig S6
<i>Apteodinium spongiosum</i>	9b-e		35		5		21
<i>Apteodinium</i> spp.				1			28
<i>Athigmatocysta glabra</i>							33
<i>Atopodinium haromense</i>	9f	37	58	34			
<i>Bourkidinium granulatatum</i>			33				
<i>Bourkidinium</i> spp.				32			
<i>Canningia reticulata</i>				23			
<i>Cassiculosphaeridia magna</i>							10
<i>Chlamydophorella nyei</i>				27	18		
<i>Chlamydophorella</i> spp.				2			
<i>Circulodinium</i> aff. <i>attadalicum</i> sensu Nøhr-Hansen 1993				28		33	
<i>Circulodinium distinctum</i>	6g-j	42	15	35	8	19	25
<i>Circulodinium</i> sp. 1			32				
<i>Circulodinium</i> spp.		8	36	12	19	26	31
<i>Cleistosphaeridium</i> spp.			44				37
<i>Cribroperidinium</i> sp. 1			6	31			
<i>Cribroperidinium</i> spp.		9	12		6	14	4
<i>Cyclonephelium cuculliforme</i> sensu Århus 1990	8l		10				
Dinocyst sp. A	9d						
<i>Dingodinium cerviculum</i>	6n	5	37	7	14	9	16
<i>Discorsia nannus</i>	6m	27	34				47
<i>Dissiliodinium acmeum</i>	6k		8				
<i>Downiesphaeridium?</i> <i>aciculare</i>		45	64		23	27	54
<i>Endoscrinium hauterivianum</i>	6o,p	22	56	39	33	13,38	36
<i>Endoscrinium</i> sp. 1	6l	1	51		1	3	29
<i>Endoscrinium</i> spp.				38			
? <i>Escharisphaeridia rudis</i>	8b		27				32
<i>Florentinia</i> spp.				3			
<i>Gardodinium trabeculosum</i>		43	65				
<i>Gochteodinia judilentiniae</i>			25				
<i>Gochteodinia villosa</i> subsp. <i>multifurcata</i>	7a,c		28		2		12
<i>Gochteodinia villosa</i>	7b		29			39	11
<i>Gonyaulacysta</i> sp. 1			41				
<i>Gonyaulacysta</i> spp.		25	16	30			14
<i>Heslertonia heslertonensis</i>		30	31				
<i>Hystrichodinium voigtii</i>		35	22				46
<i>Hystrichosphaeridium arborispinum</i>							49
<i>Isthmocystis distincta</i>	7i		23				





1	<i>Rhynchodiniopsis</i> spp.				25		
2	<i>Sepispinula? huguoniotii</i>		52				
3	<i>Scriniodinium campanula</i>			37		24	
4	<i>Sirmiodinium grossii</i>	9e,f	24	2	20	17	8
5	<i>Spiniferites</i> sp. 1	9d		54		29	30
6	<i>Spiniferites</i> spp.	9h		49	6		
7	<i>Stanfordella fastigiata</i>	9a	20	9	26	32	5
8	<i>Stanfordella ordocava</i>	9b,c		30		38	11
9	<i>Stiphrosphaeridium anthophorum</i>			63			
10	<i>Subtilisphaera perlucida</i>	9g			8		28
11	<i>Tanyosphaeridium boletus</i>		34	45			29
12	<i>Tanyosphaeridium salpinx</i>		28	40		37	25
13	<i>Tanyosphaeridium</i> spp.					26	17
14	<i>Tubotuberella apatela</i>	9i-k	47	1,66	42	39	40
15	<i>Tubotuberella uncinata</i>		32				
16	<i>Tubotuberella</i> spp.	9l	38	11	43	11	2,58
17	<i>Wallodinium luna</i>	9m					9
18	<i>Wrevittia helicoidea</i>		44	5			7
19	cf. <i>Wrevittia perforobtusa</i>	9n-p	26	7			12
20	unidentifiable dinocysts		4	21	21		16

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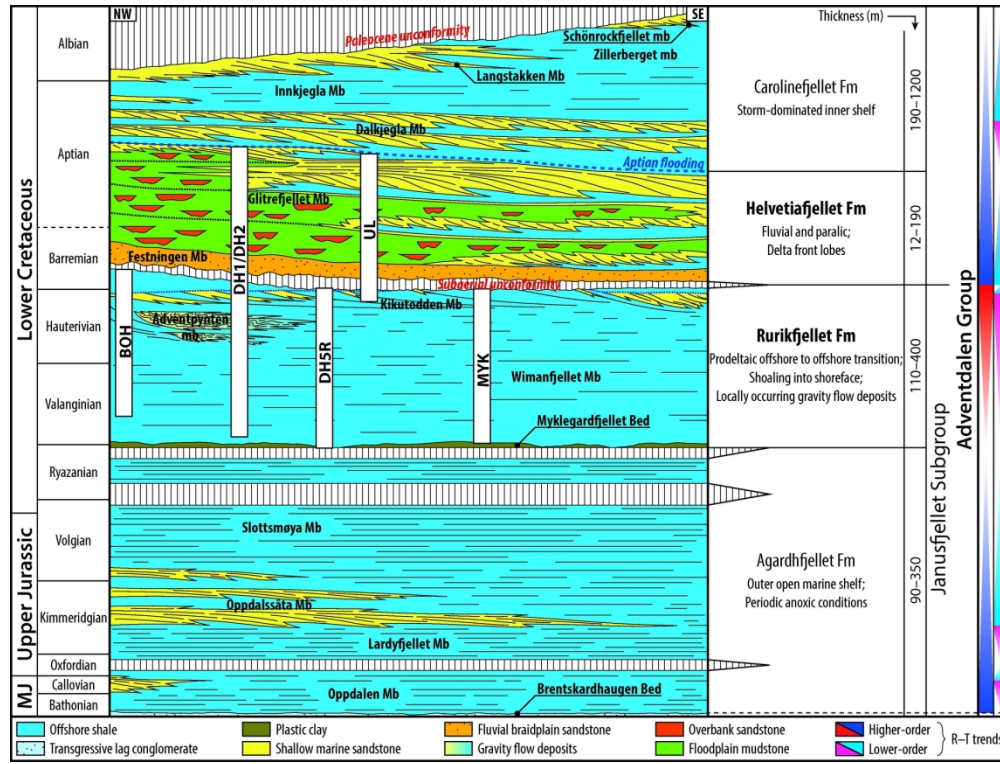


Figure 1. Stratigraphic cross-section showing the regional development of the Upper Jurassic to Lower Cretaceous Adventdalen Group on Spitsbergen. Modified after Alsen et al. (this issue). White bars show the time span for each of the studied sites: three onshore cores DH1, DH2, DH5R, and three outcrop sections: Bohemanflya (BOH), Ullaberget (UL), and Myklegardfjellet (MYK). The figure is available in colour on the web version of this paper.

169x128mm (300 x 300 DPI)

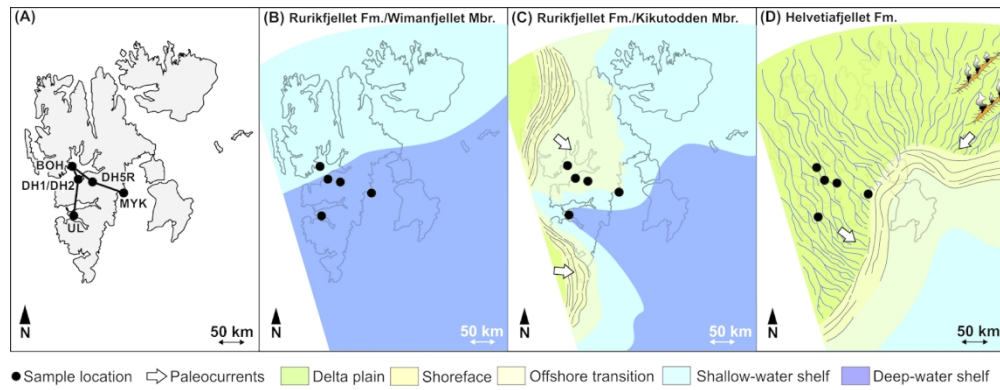


Figure 2. (A). Black dots mark the positions of the studied sites: Bo – Bohemanflya, Ul – Ullaberget, My – Myklegardfjellet outcrop sections. Paleogeography of Spitsbergen from the Valanginian to early Aptian (after Grundvåg & Olausson, 2017; Grundvåg et al., 2017) (B) Palaeogeography during the deposition of the Wimanfjellet Member; (C) Palaeogeography during the deposition of the Kikutodden Member; (D) Paleogeography during the earliest Barremian - deposition of the Festningen Member.

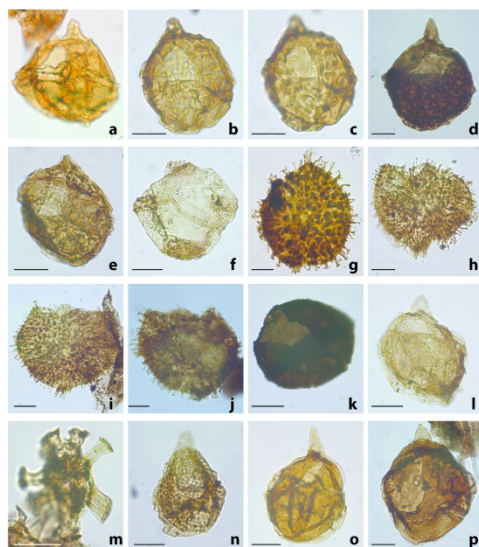


Figure 3. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20  $\mu\text{m}$ . The figure is available in colour on the web version of this paper. MC – microscope coordinates with the A-point of  $0.4 \times 90.3$  (XM1  $\times$  YM1). For details, see Śliwińska (2019). (a) a dinocyst, Bohemanflya outcrop section, level 99.29 m, sample 26291-7, MC 102  $\times$  42.2 (b) Apteodinium spongiosum, high focus, (c) low focus, Bohemanflya outcrop section, level 25.00 m, sample 28450-9, MC 25  $\times$  108.7 (d) Apteodinium spongiosum very dark, Myklegardfjellet outcrop section, level 30.00 m, sample 27007-6, MC 32  $\times$  109.1 (e) Apteodinium spongiosum, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-9; MC 51.4  $\times$  105.5 (f) Atopodinium haromense; Myklegardfjellet outcrop section, level 120.00 m, sample 27013-9; MC 42.7  $\times$  102.3 (g) Circulodinium distinctum, Myklegardfjellet outcrop section, level 105.00 m, sample 27012-6; MC 29.3  $\times$  91.6 (h) Circulodinium distinctum, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-9; MC 21  $\times$  104.5 (i) Circulodinium distinctum, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-9; MC 17.5  $\times$  105.5 (j) Circulodinium distinctum, Bohemanflya outcrop section, level 28.00 m, sample 28449-8; MC 44.7  $\times$  96.7 (k) Dissiliodinium acmeum, Myklegardfjellet outcrop section, level 7.00 m, sample 27005-4; MC 37.2  $\times$  99.4 (l) Endoscrinium sp.1 Bohemanflya outcrop section, level 25.00 m, sample 28450-9; MC 25.5  $\times$  110 (m) Discorsia nannus, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-9; MC 49  $\times$  103.3 (n) Dingodinium cerviculum, Myklegardfjellet outcrop section, level 75.00 m, sample 27010-4; MC 47  $\times$  108.5 (o) Endoscrinium hauterivianum, Bohemanflya outcrop section, level 36.00 m, sample 28448-7, MC 33.8  $\times$  102.2 (p) Endoscrinium hauterivianum, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-9; MC 42  $\times$  102.4

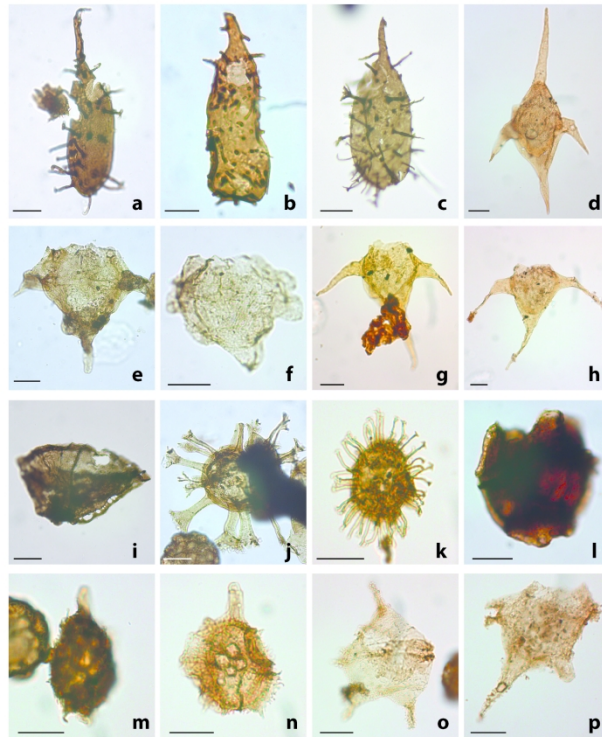


Figure 4. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20  $\mu\text{m}$ . The figure in colour is available on the web version of this paper. MC – microscope coordinates with the A-point of 0.4x90.3 (XM1 x YM1). For details, see Śliwińska (2019).

- (a) *Gochteodinia villosa* subsp. *multifurcata*, Myklegardfjellet outcrop section, level 15.00 m, sample 27006-5, MC 36.3 x 114
- (b) *Gochteodinia villosa*, DH5R core, depth 350.00 m, sample 26197-6; MC 22.5 x 96.2
- (c) *Gochteodinia villosa* subsp. *multifurcata*, Myklegardfjellet outcrop section, level 15.00 m, sample 27006-5; MC 36 x 107
- (d) *Muderongia tetracanta*, Bohemanflya outcrop section, level 127.50 m, sample 26290-8, MC 44 x 110.6
- (e) *Muderongia australis*, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-9; MC 31.4 x 108.5
- (f) *Muderongia simplex*, Myklegardfjellet outcrop section, level 105.00 m, sample 27012-6; MC 33 x 105.8
- (g) a transitional form between *Muderongia tetracanta* and *Muderongia extensiva*, Bohemanflya outcrop section, level 46.00 m, sample 26293-5, MC 24.5 x 111
- (h) *Muderongia extensiva*, Bohemanflya outcrop section, level 46.00 m, sample 26293-7; MC 18.5 x 108.4
- (i) *Isthmocystis distincta*, Myklegardfjellet outcrop section, level 7.00 m, sample 27005-4; MC 28 x 102.3
- (j) *Kleithrasphaeridium eoinodes*, Myklegardfjellet outcrop section, level 90.00 m, sample 27011-8; MC 25.2 x 103
- (k) *Kiokansium unituberculatum*, Bohemanflya outcrop section, level 127.50, sample 26290-6; MC 31x107.3
- (l) *Meiourogonyaulax stoveri*, DH5R core, depth 258.00 m, sample 26194-5; MC 24 x 107.8
- (m) poorly preserved *Nelchinopsis kostromiensis*, Bohemanflya outcrop section, level 99.29 m, sample

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3 26291-7; MC 52.4 x 109  
4 (n) *Nelchinopsis kostromiensis*, Bohemanflya outcrop section, level 55.25 m, sample 26292-7; MC 51.5 x  
5 95.5  
6 (o) *Nyktericysta? pannosa*, Bohemanflya outcrop section, level 99.29 m, sample 26291-7; MC 43 x 102.7  
7 (p) *Nyktericysta? pannosa*, Bohemanflya outcrop section, level 127.50 m, sample 26290-8; MC 50.2 x 100  
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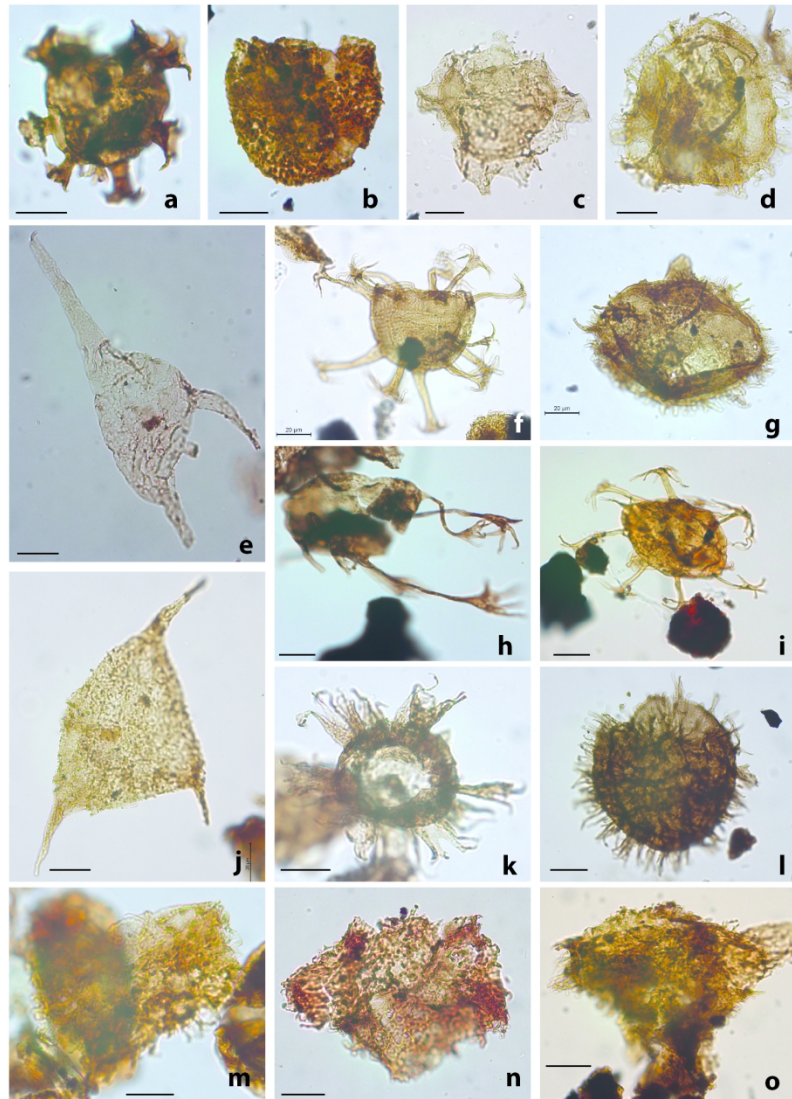


Figure 5. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20  $\mu\text{m}$ . The figure in colour is available on the web version of this paper. MC – microscope coordinates with the A-point of 0.4 $\times$ 90.3 (XM1  $\times$  YM1). For details, see Sliwińska (2019).

- (a) *Oligosphaeridium poculum*, DH5R core, depth 320.00 m, sample 26196-7; MC 58.2  $\times$  97.1  
 (b) questionable *Escharisphaeridia rudis*, DH5R core, depth 288.00 m, sample 26195-7; MC 36.7  $\times$  112.5  
 (c) *Phoberocysta neocomica*, Myklegardfjellet outcrop section, level 90.00 m, sample 27009-6; MC 24.3  $\times$  113.8  
 (d) *Rhynchodiniopsis aptiana*, Bohemanflya outcrop section, level 5.00 m, sample 28453-7, MC 31.7  $\times$  101  
 (e) *Odontochitina nuda*, DH2 core, depth 141.80 m, sample 26510-9; MC 42  $\times$  105.2  
 (f) *Oligosphaeridium abaculum*, Myklegardfjellet outcrop section, level 75.00 m, sample 27010-5; MC 48.5  $\times$  105.5  
 (g) *Rhynchodiniopsis aptiana*, Myklegardfjellet outcrop section, level 105.00 m, sample 27012-6; MC 20.3  $\times$  107.5



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3 (h) *Oligosphaeridium* complex with "palm-like" terminations of processes, DH1, depth 258.90 m, sample  
4 26285-7; MC 32.8 x 97.1  
5 (i) *Oligosphaeridium asterigerum*, Bohemanflya outcrop section, level 99.29 m, sample 26291-7, MC 44.7 x  
6 94.3  
7 (j) *Pseudoceratium pelliferum*, Bohemanflya outcrop section, level 36.00 m, sample 28448-7, MC 37 x 106.5  
8 (k) *Palaecysta palmula*, Myklegardfjellet outcrop section, level 0.05 m, sample 27004-8, MC 53 x 107.5  
9 (l) *Cyclonephelium cuculliforme* sensu Århus 1990, Myklegardfjellet outcrop section, level 15.00, sample  
10 27006-3; MC 30.2 x 101  
11 (m) questionable *Pseudoceratium anaphrissum* Bohemanflya outcrop section, level 132.63 m, sample  
12 26289-8; MC 37.8 x 95.5. Shown also in Figure 15.P in Grundvåg et al., (2019).  
13 (n) *Pseudoceratium anaphrissum*, Ullaberget outcrop section, level 104.00m, sample 28482-7; MC 40.6 x  
14 111.8  
15 (o) questionable, poorly preserved *Pseudoceratium anaphrissum*, DH2 core, depth 149.50 m, sample 26511-  
16 11; MC 34.5 x 110.5. Shown also in Figure 15.H in Grundvåg et al., (2019).  
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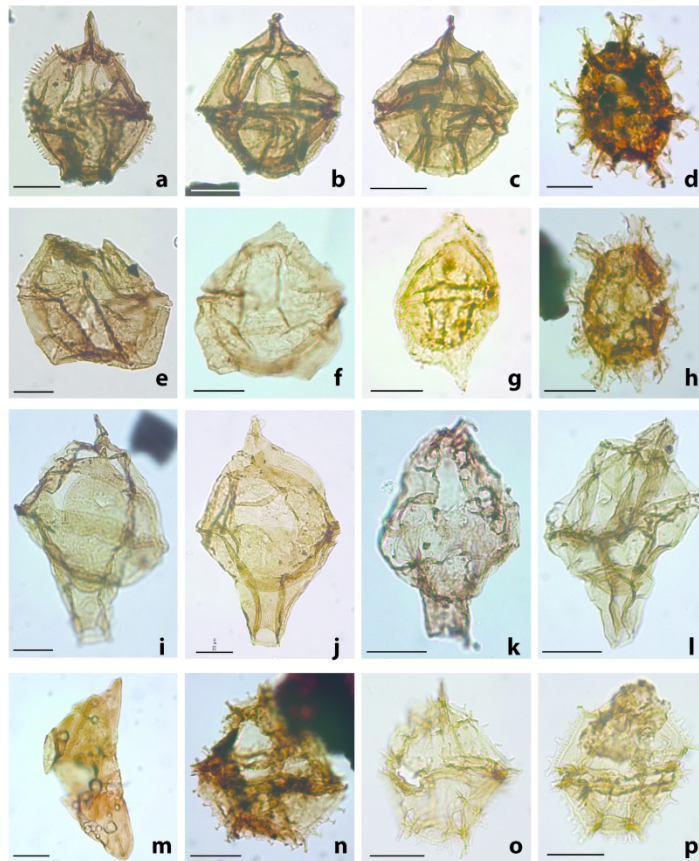


Figure 6. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20  $\mu\text{m}$ . The figure in colour is available on the web version of this paper. MC – microscope coordinates with the A-point of 0.4 $\times$ 90.3 (XM1  $\times$  YM1). For details, see Śliwińska (2019).

- (a) *Stanfordella fastigiata*, Myklegardfjellet outcrop section, level 30.00 m, sample 27007-6; MC 50.4  $\times$  103.5
- (b) *Stanfordella ordocava*, Myklegardfjellet outcrop section, level 15.00 m, sample 27006-5; MC 31.6  $\times$  111
- (c) *Stanfordella ordocava*, DH5R core, depth 380.00 m, sample 26198-6; MC 55.5  $\times$  102.4
- (d) *Spiniferites* sp. 1, DH5R core, depth 194.00 m, sample 26192-7; MC 36.9  $\times$  102
- (e) *Sirmiodinium grossii*, Myklegardfjellet outcrop section, level 30.00 m, sample 27007-6; MC 30.3  $\times$  104.2
- (f) *Sirmiodinium grossii*, DH1, depth 258.90 m, sample 26285-7; MC 29.4  $\times$  109
- (g) *Subtilisphaera per lucida*, DH2 core, depth 186.55 m, sample 26513-9; MC 36.7  $\times$  92.6. Shown also in Figure 15.G in Grundvåg et al., (2019).
- (h) *Spiniferites?* DH5R core, depth 194.00 m, sample 26192-7; MC 50.8  $\times$  101.2
- (i) *Tubotuberella apatela*, Myklegardfjellet outcrop section, level 30.00 m, sample 27007-6; MC 30.6  $\times$  105
- (j) *Tubotuberella apatela*, Myklegardfjellet outcrop section, level 0.05 m, sample 27004-8; MC 34.5  $\times$  109.4
- (k) *Tubotuberella apatela*, DH2 core, depth 232.00 m, sample 26516-9; MC 19.4  $\times$  93.3
- (l) *Tubotuberella* sp. DH5R core, depth 380.0 m, sample 26198-6; MC 48  $\times$  98.7

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- 3 (m) *Walloedinium luna*, DH5R core, depth 350.0 m, sample 26197-6; MC 36.5 x 102.4
- 4 (n) *Wrevittia perforobtusa*, DH5R core, depth 194.00 m, sample 26192-7; MC 29.9 x 102.6
- 5 (o) *Wrevittia perforobtusa*, Bohemanflya outcrop section, level 55.25 m, sample 26292-8, MC 50.3 x 101.7
- 6 (p) *Wrevittia perforobtusa*, Bohemanflya outcrop section, level 36 m, sample 28448-7, MC 40.5 x 98.6
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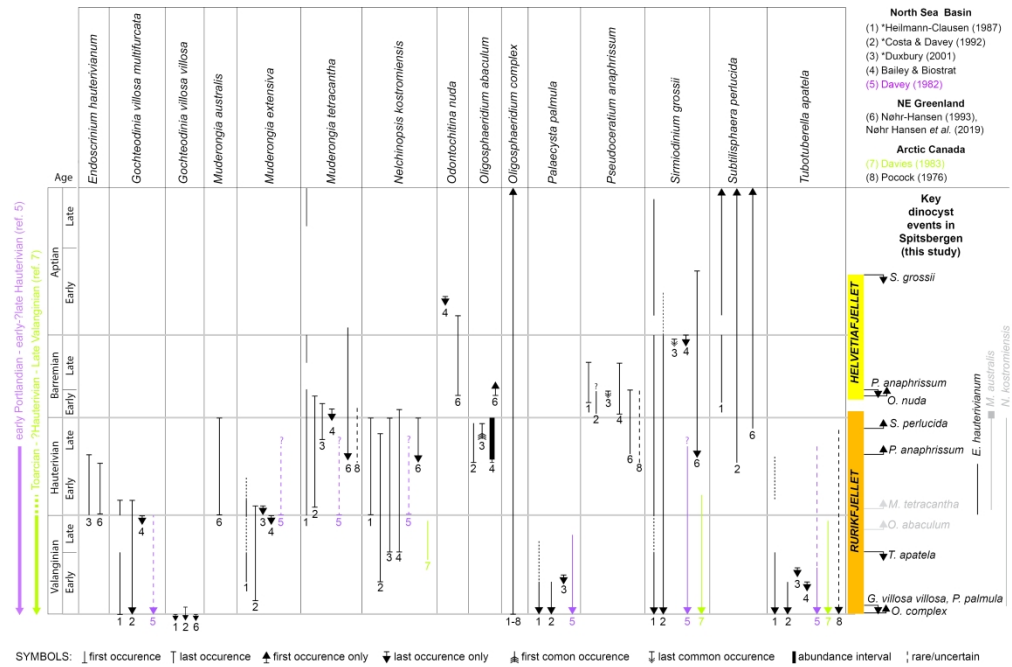


Figure 7. The stratigraphic ranges and/or first and last occurrences of the age diagnostic dinoflagellate cysts (dinocysts) from the Boreal and European Boreal Realm, and the key events recognised in this study (to the right). Key dinocyst events in Spitsbergen: primary markers (black), secondary markers (grey). The figure shows a compilation of the most characteristic dinocysts from the Rurikfjellet and Helvetiafjellet formations discussed in the present study. Heilmann-Clausen (1987), Costa & Davey (1992), and Duxbury (2001) plotted the dinocysts ranges against the ammonite zonation (marked with asterisk). All these authors considered the Simbirskites variabilis ammonite zone as earliest Barremian, whilst today it is considered to be Hauterivian (Ogg, Ogg & Gradstein, 2016). Nøhr-Hansen, Piasecki & Alsen (this issue) updated the zonation proposed previously by Nøhr-Hansen (1993), and provided ages in GTS2016. Note that the study by Davey (1982) does not cover sediments younger than early-?late Hauterivian, while the study by Davies (1983) does not cover sediments younger than late Valanginian.

415x273mm (300 x 300 DPI)

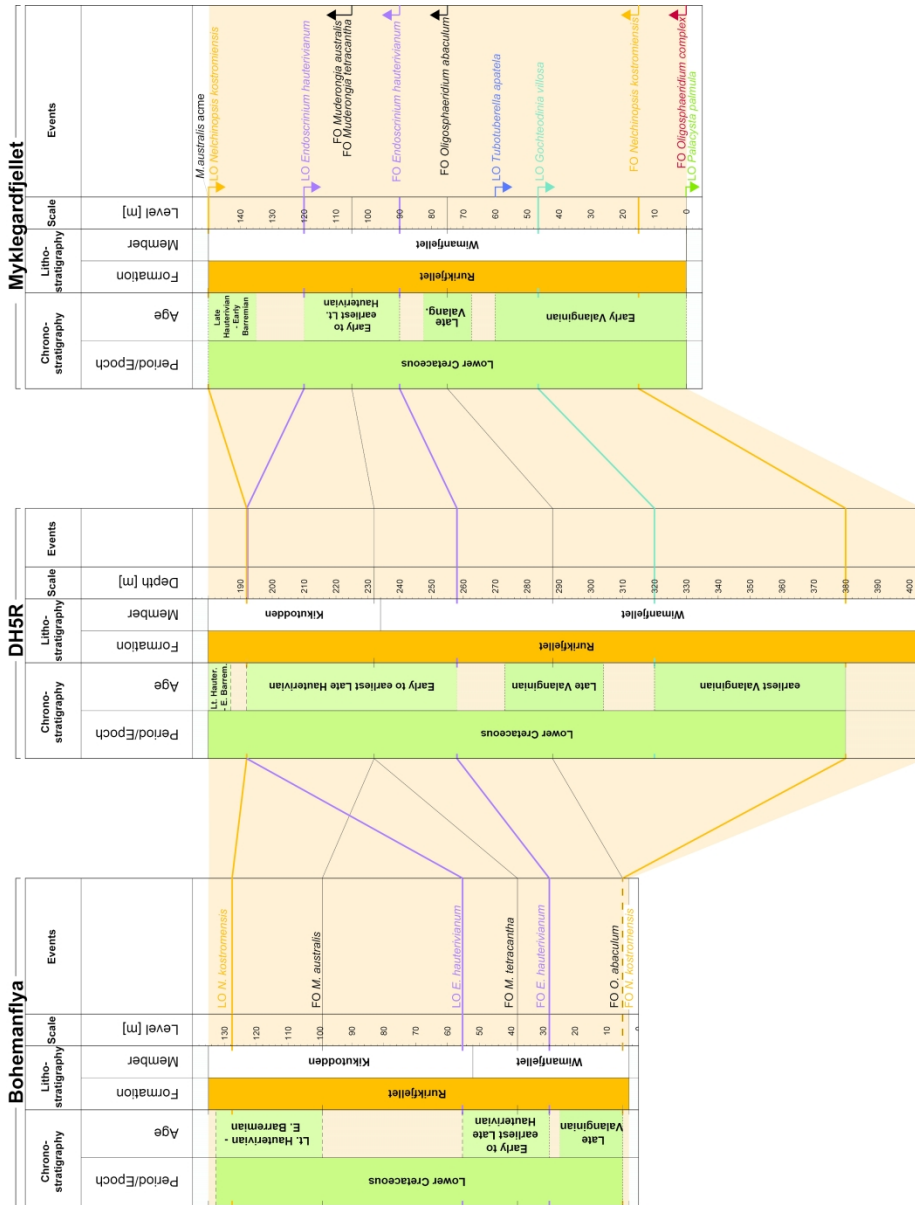


Figure 8. The spatial distribution of the age diagnostic (colour code) and secondary dinocyst events (black) within the Rurikfjellet Formation. The correlation between the Bohemanflya, the DH5R core, and the Myklegardfjellet outcrop section, i.e. from NW to SE.

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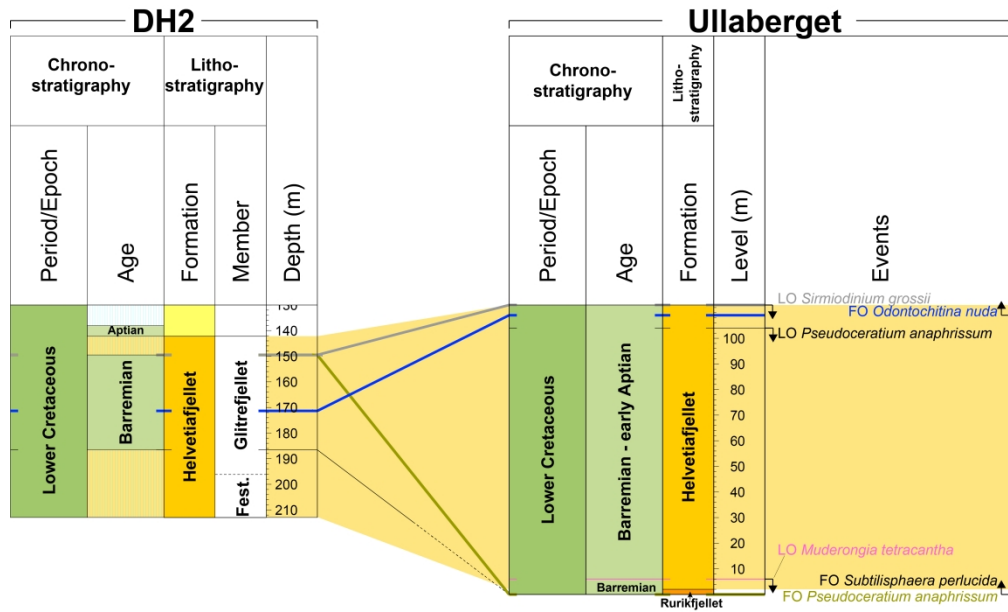


Figure 9. The spatial distribution of the age diagnostic dinocyst events within the Helvetiafjellet Formation. The correlation between the Ullaberget outcrop section and the DH2 core.

390x236mm (300 x 300 DPI)







Dinocyst stratigraphy of the Valanginian–Aptian Rurikfjellet and Helvetiafjellet formations on Spitsbergen, Arctic Norway

Kasia K. Śliwińska, Mads E. Jelby, Sten-Andreas Grundvåg, Henrik Nøhr-Hansen, Peter Alsen, and Snorre Olausen

Supplementary material

Figure S3: Ullaberget

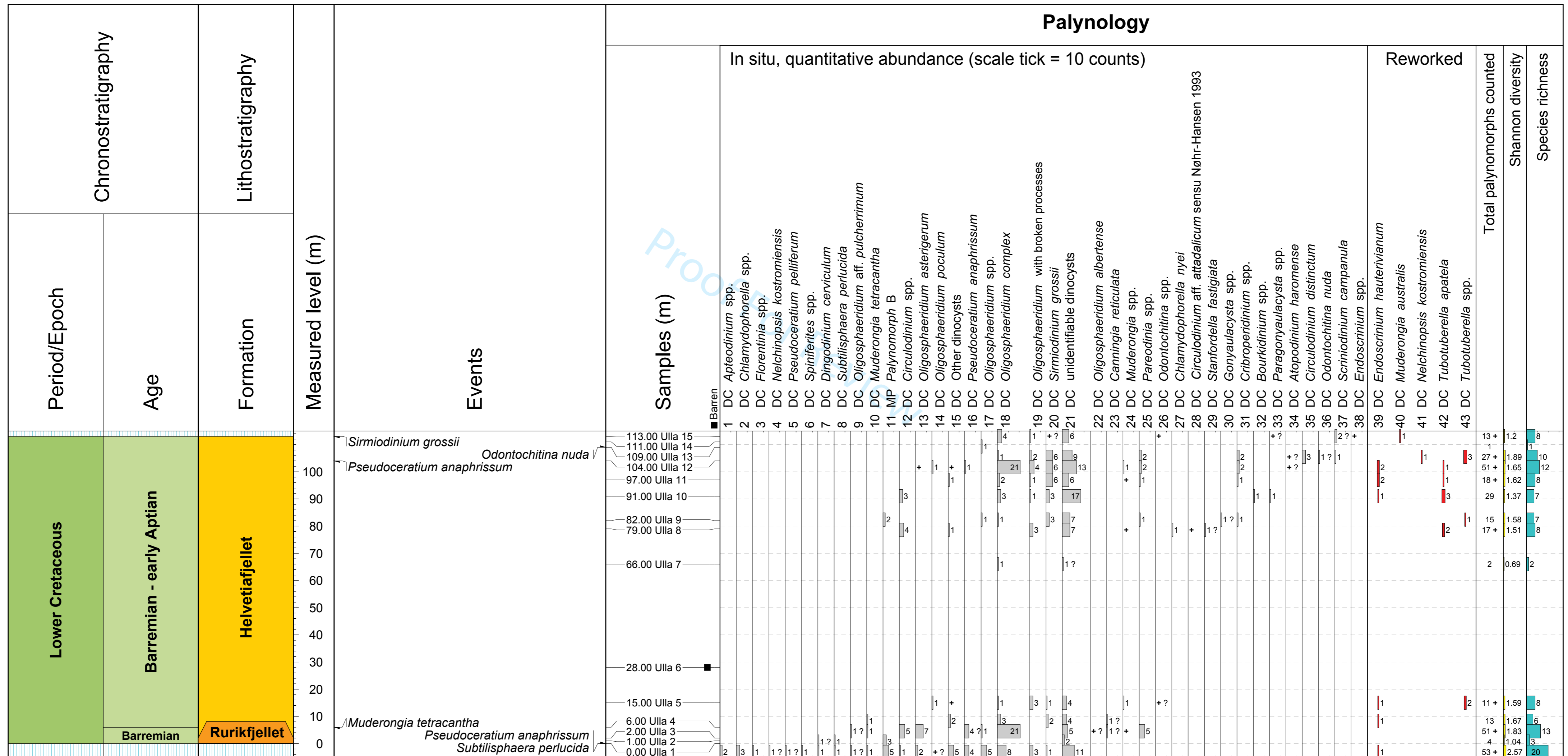


Figure S3. Distribution of dinocysts in the Ullaberget outcrop section. This file contains range charts with the quantitative data of the palynomorphs recognised in this study. The palynomorphs are arranged after the first occurrence (FO), R – reworked, DC – dinocyst, AC – acritarch, MP – palynomorph, “+” – present outside counting, “?” – questionable





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Dinocyst stratigraphy of the Valanginian–Aptian Rurikfjellet and Helvetiafjellet formations on Spitsbergen, Arctic Norway

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Supplementary material

Figure S6: DH5R

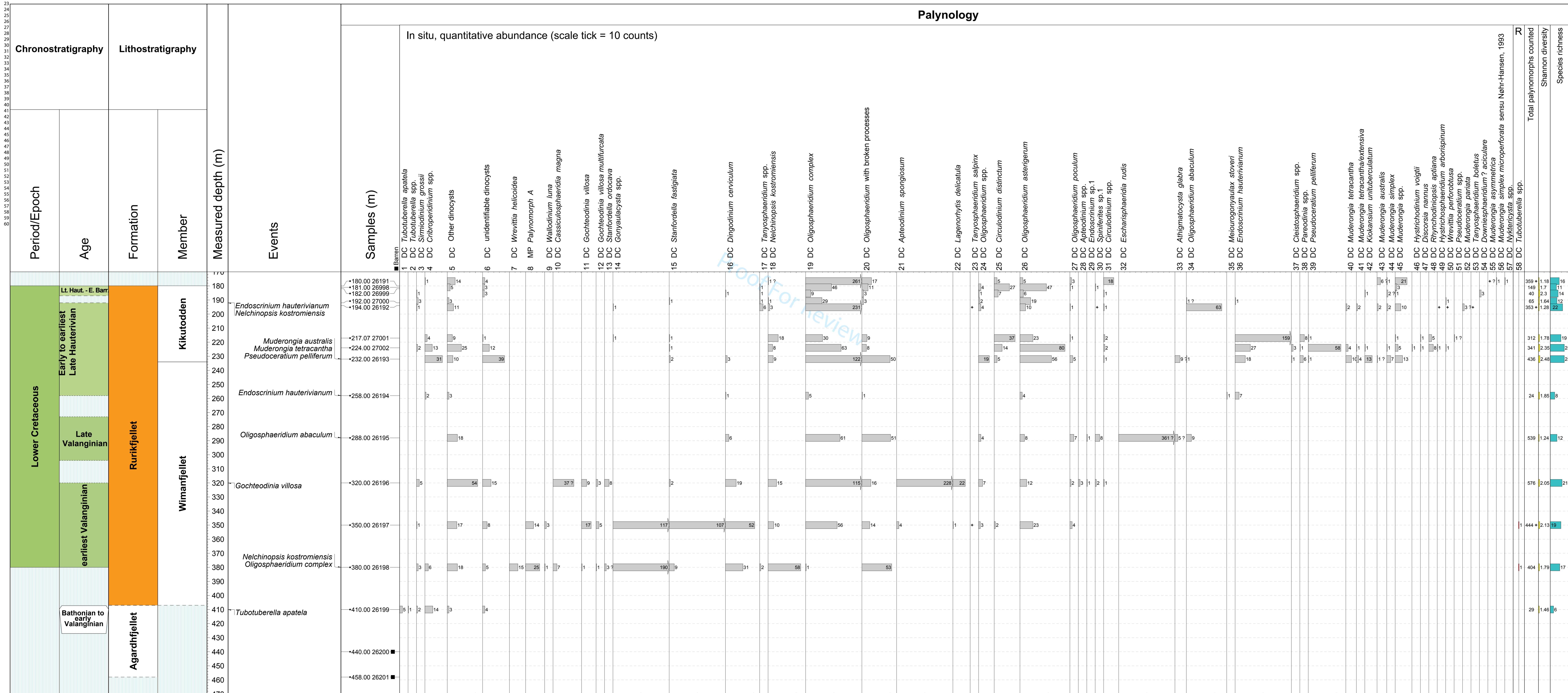


Figure S6. Distribution of dinocysts in the DH5R well. This file contains range charts with the quantitative data of the palynomorphs recognised in this study. The palynomorphs are arranged after the first occurrence (FO), R – reworked, DC – dinocyst, AC – acritarch, MP – palynomorph, “+” – present outside counting, “?” – questionable