

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

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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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3 **Abstract**
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6 In order to improve the understanding of how the high northern latitudes responded to
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8 the escalating warming which led to the middle Cretaceous super greenhouse climate,
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10 more temperature proxy records from the High Arctic are needed. One of the current
11 obstacles in obtaining such records is poor age control **on** the Lower Cretaceous strata
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13 in the **Boreal and Pan-Boreal** regions.
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18 Here, we provide a biostratigraphic framework for the Rurikfjellet and
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20 Helvetiafjellet formations representing the lower part of the Lower Cretaceous
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22 succession on Spitsbergen. We also attempt to date the boundary between the
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24 Agardhfjellet and the Rurikfjellet formations. This study is based on **dinoflagellate cysts**
25
26 (**dinocysts**) from three onshore cores (DH1, DH2, and DH5R), and three outcrop
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28 sections (Bohemanflya, Myklegardfjellet, and Ullaberget). Relatively abundant and well-
29
30 preserved dinocyst assemblages from the Rurikfjellet Formation date this unit **as** early
31
32 Valanginian – early Barremian. The dinocyst assemblages from the Helvetiafjellet
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34 Formation are significantly impoverished and **are** characterised by reworking, **but**
35
36 **collectively indicate** a Barremian–Aptian age for **this** formation.
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41 **Keywords:** dinocysts, biostratigraphy, Lower Cretaceous, Spitsbergen, Arctic
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45 **1. Introduction**
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50 The Early Cretaceous (~145–100.5 Ma; Ogg, Ogg & Gradstein, 2016) was
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52 characterised by major tectonic activity, climatic changes, and global perturbations in
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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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9 47 south separated by the newly formed Tethys Ocean. The Barents Sea Shelf including
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11 48 Svalbard (paleolatitude 60°N at 140 Ma; calculated after Van Hinsbergen *et al.*, 2015),
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13 49 Arctic Canada, Greenland and northern Russia were located at the northern flank of
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15 50 Laurasia as part of the large circum-Arctic, relatively cold Boreal Basin (Scotese, 2014).
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17 51 In the Tethys Ocean to the south, warm to tropical water conditions prevailed, leading to
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19 52 a bloom of calcareous nannoplankton and foraminifera. The Tethys and Boreal seas
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21 53 were connected by a shallow, narrow seaway between Greenland and Baltica. The
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23 54 seaway formed in response to rifting during the initial stage of the formation of the North
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25 55 Atlantic Ocean at that time (e.g. Gradstein, Kaminski & Agterberg, 1999). The
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27 56 palaeogeographical configuration in the Early Cretaceous favoured a diversification of
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29 57 marine organisms and diachronity of ammonite bio-events, which traditionally
30
31 58 constitute the primary tool for Cretaceous biostratigraphy (e.g. Lehmann, 2015). This
32
33 59 has led to the creation of two separate biozonation schemes; one for the Boreal and
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35 60 one for the Tethyan Realm. Both are still applicable across the Jurassic–Cretaceous
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37 61 transition (Ogg, Hinnov & Huang, 2012).

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45 62 Temperature proxy data from Early Cretaceous high latitudes are limited
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47 63 (Ditchfield, 1997; Littler *et al.*, 2011; Jenkyns *et al.*, 2012; Price and Passey, 2013), but
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49 64 it is assumed that the global climate was generally warm and humid with low latitudinal
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51 65 temperature gradients (e.g. O'Brien *et al.*, 2017). In contrast, some studies suggest that
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53 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 formation, formation of large igneous provinces, and subduction-related arc volcanism)
5 (e.g. Johnston, Turchyn & Edmonds, 2011; Koopmann *et al.*, 2014; Polteau *et al.*, 2016)
6
7 69 forced an increased concentration of atmospheric greenhouse gases (methane and
8 CO₂), and led to a gradual global warming (e.g. Huber *et al.*, 2018). A climatic maximum
9 of this extreme global warmth, the so-called Cretaceous Hot Greenhouse climate, was
10 reached between 95 and 80 Ma (Huber *et al.*, 2018). During the Cretaceous Period a
11 number of oceanic anoxic events (OAEs) led to the deposition of organic carbon-rich
12 sediments (Leckie, Bralower & Cashman, 2002; Trabucho Alexandre *et al.*, 2010). At
13 least four of these events took place during the Early Cretaceous: The OAE1a, OAE1b,
14 OAE1c, and OAE1d (Erbacher, Thurow and Littke, 1996). The most widely recognised
15 is the OAE1a which occurred during the earliest Aptian (Leckie, Bralower and
16 Cashman, 2002; Jenkyns, 2010; Herrle *et al.*, 2015; Midtkandal *et al.*, 2016). The
17 characteristic stable carbon isotope ($\delta^{13}\text{C}$) excursions related to OAEs can be used for
18 the correlation of carbon isotope records (Herrle *et al.*, 2015; Midtkandal *et al.*, 2016;
19 Vickers *et al.*, 2016). However, while the climatic history of the Tethys (e.g. Hochuli *et*
20 *al.*, 1999; Bottini *et al.*, 2015; Bottini and Erba, 2018) and the European Boreal Realm
21 (e.g. Mutterlose, Pauly & Steuber, 2009) are relatively well-studied, the climate of the
22 Early Cretaceous Arctic is relatively less understood. Many of the published
23 paleotemperature records contradict evidence for both warm and cool periods (e.g.
24 Galloway *et al.*, 2015; Hurum, Druckenmiller, *et al.*, 2016; discussion in Vickers *et al.*,
25 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
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18 96 Lower Cretaceous succession on Spitsbergen was provided by Bjørke and Thusu
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20 97 (1976). The first comprehensive study of Lower Cretaceous dinocysts on Spitsbergen
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22 98 was carried out by Bjørke (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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26 100 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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38 104 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.
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47 107 **2. Regional setting**
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50 108 Spitsbergen is the largest island in the Svalbard archipelago, and is located today at ca.
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52 109 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*
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9 114 *al.*, 2011) on the northern margin of Pangea (Torsvik *et al.*, 2002). The Lower
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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
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15 regional thermo-tectonic uplift in the north, followed by subsequent quiescence and
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17 117 subsidence (Gjelberg & Steel, 1995; Midtkandal, Nystuen & Nagy, 2007; Midtkandal &
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19 118 Nystuen, 2009). The magmatic activity in Svalbard and the surrounding areas related to
20
21 119 the emplacement of the High Arctic Large Igneous Province (HALIP) peaked in the
22
23 120 Barremian to early Aptian (Corfu *et al.*, 2013; Senger *et al.*, 2014; Polteau *et al.*, 2016).
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25 121 An early Barremian uplift and associated southward tilting of the shelf caused the
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27 122 formation of a regionally extensive subaerial unconformity, which now forms the
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29 123 boundary between the Rurikfjellet and Helvetiafjellet formations (e.g. Gjelberg & Steel,
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31 124 1995; Midtkandal & Nystuen, 2009; Grundvåg *et al.*, 2017). This event was followed by
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33 125 a transgression related to a long-term relative global sea-level rise (Gjelberg and Steel,
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35 126 1995; Midtkandal and Nystuen, 2009). In the Late Cretaceous, subaerial exposure of
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37 127 Svalbard resulted in a major hiatus spanning the entire Upper Cretaceous (Harland,
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39 128 1997; Dörr *et al.*, 2012).
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45 131 <>Fig. 1>>
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47 132 **3. Lower Cretaceous lithostratigraphy of Spitsbergen**

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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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7 135 Adventdalen Group (which also includes the Upper Jurassic Agardhfjellet Formation;
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9 136 Parker, 1967), and is primarily exposed along the margins of the Central Tertiary Basin.
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11 137 The Rurikfjellet Formation consists of a lower offshore shale-dominated succession (the
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13 Wimanfjellet Member) which is overlain by a storm-dominated shallow marine
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15 139 succession (the Kikutodden Member) of interbedded shale, siltstone, and sandstone
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17 140 (Fig. 1). The Rurikfjellet Formation unconformably overlies the Upper Jurassic –
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19 141 lowermost Cretaceous Agardhfjellet Formation (Dypvik et al., 1991), and its base is
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21 142 marked either by i) a condensed glauconitic clay unit (the Myklegardfjellet Bed; Dypvik
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23 143 et al., 1991; Dypvik, Nagy & Krinsley, 1992); ii) a highly tectonised decollement zone; or
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25 144 iii) by an abrupt change in the macrofossil fauna. In the central part of Spitsbergen, the
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27 145 Wimanfjellet Member is intersected by a thick succession of gravity flow deposits
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29 146 informally defined as the Adventpynten member (Grundvåg et al., 2017). The
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31 147 Kikutodden Member represents prodeltaic to shallow marine deposits which were
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33 148 sourced from the NW and exhibit progradation towards the SE (Fig. 1; Dypvik et al.,
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35 149 1991). The overall changes in the lithologies of the Rurikfjellet Formation reflect the
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37 150 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.
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16 161 **4. Previous studies of Lower Cretaceous Boreal dinocyst assemblages**

18 162 Dinocyst studies of Arctic Lower Cretaceous successions are relatively rare and
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20 163 scattered across the Canadian Arctic (Pocock, 1976; Brideaux, 1977; McIntyre &
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22 164 Brideaux, 1980; Davies, 1983; Nøhr-Hansen & McIntyre, 1998), Greenland
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24 165 (Nøhr-Hansen, 1993; Pedersen & Nøhr-Hansen, 2014; Piasecki, Nøhr-Hansen &
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26 166 Dalhoff, 2018; Nøhr-Hansen, Piasecki & Alsen, this issue), the Barents Sea (Århus et
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28 167 al., 1990; Smelror et al., 1998; Smelror and Dypvik, 2005b, 2005a; Kairanov et al.,
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30 168 2018), Arctic Norway (Løfaldal and Thusu, 1976; Thusu, 1978; Bjørke, 1978; Århus,
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32 169 Verdenius and Birkelund, 1986; Århus et al., 1990; Århus, 1991; Grøsfjeld, 1991;
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34 170 Smelror and Larssen, 2016; Hurum, Roberts, et al., 2016; Smelror et al., 2018; Hammer
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36 171 et al., 2018; Rakociński et al., 2018; Grundvåg et al., 2019), and Arctic Russia (Smelror,
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38 172 1986; Lebedeva and Nikitenko, 1999; Riding, 1999; Pestchevitskaya, 2007; Nikitenko et
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40 173 al., 2008; Pestchevitskaya, Lebedeva and Ryabokon, 2011). Some early Canadian
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42 174 studies provided dinocyst zonations (e.g. Pocock, 1976; Davey, 1982; Davies, 1983),
43
44 175 but the diversity of the studied material was limited, and ranges of specific taxa were
45
46 176 poorly constrained compared to the more recent and robust dinocyst zonation
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48 177 established for North-East Greenland (Nøhr-Hansen, 1993; Nøhr-Hansen, Piasecki &
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50 178 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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7 181 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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12 183 known as the Rurikfjellet Member) was based on ammonites and bivalves (for
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14 184 references see Grøsfjeld, 1991). An informally defined Lower Cretaceous palynological
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16 185 zonation of Spitsbergen was introduced in a confidential report by Århus (1988). Low
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18 186 dinocyst abundances and low diversities have been reported from studies of the Lower
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20 187 Cretaceous succession on Spitsbergen and in the Barents Sea (e.g. Århus *et al.*, 1990;
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22 188 Århus, 1992). The dinocysts of the Rurikfjellet Formation have been investigated in less
23
24 189 than a dozen peer-reviewed publications. Notable works include Bjørke & Thusu
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26 190 (1974), Bjørke (1978), Århus *et al.* (1990), Århus (1991; 1992), Grøsfjeld (1991), and
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28 191 more recently Midtkandal *et al.* (2016) and Grundvåg *et al.* (2017). The palynology of
29
30 192 the Helvetiafjellet Formation has been studied to an even lesser extent (Grøsfjeld, 1991;
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32 193 Midtkandal *et al.*, 2016). A number of recent studies on the seismic stratigraphy of the
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34 194 Lower Cretaceous succession in the southwestern Barents Sea provide an updated
35
36 195 preliminary age model based on dinocysts (Marin *et al.*, 2017; Kairanov *et al.*, 2018;
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38 196 Marín, Escalona, Grundvåg, Nøhr-Hansen, *et al.*, 2018; Marín, Escalona, Grundvåg,
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40 197 Olaussen, *et al.*, 2018).

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199 **5. Studied sections**

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

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3 201 The Bohemanflya outcrop section ($N78^{\circ}24'32.6''/E14^{\circ}41'18.9''$) 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
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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.
14
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
26 212 Fig. S1).

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31 213 <<Fig.2>>
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34 214 **5.b. The Myklegardfjellet outcrop section**
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37 215 The Myklegardfjellet outcrop section ($N78^{\circ}03'18.8''/E18^{\circ}42'15.4''$) is the easternmost
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39 216 locality investigated in this study, exposing Upper Jurassic – Lower Cretaceous strata at
40
41 217 the northeastern side of Agardhbukta, east coast of Spitsbergen (Fig. 2). At this locality,
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43 218 the Rurikfjellet Formation is entirely comprised of homogeneous shale of the
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45 219 Wimanfjellet Member (Fig. 1), reaching a thickness of 166 m. The shale is characterised
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47 220 by absent to low degrees of bioturbation as well as scattered siderite concretions,
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49 221 nodules and fossiliferous stratabound siderite layers with abundant bivalves. The
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51 222 Kikutodden Member is either not preserved in this locality, or it is covered by scree. This
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53 223 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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11 228 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 ($N77^{\circ}37'04.2''/E15^{\circ}11'17.9''$) is the southernmost locality
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23 232 investigated in this study, exposing Lower Cretaceous strata at the northwestern side of
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25 233 Van Keulenfjorden. At this locality, the Rurikfjellet Formation is ca. 200 m thick (the
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27 234 base is not exposed) and dominated by homogeneous shale of the Wimanfjellet
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29 235 Member. For the purpose of this study, only three samples from the uppermost 2 metres
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31 236 of the Rurikfjellet Formation were collected (Fig. S3). The shale is characterised by a
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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
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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
42
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
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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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6 248 **5.d. The DH1 and DH2 cores**
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8 249 The DH1 ($N78^{\circ}23'60.8/E15^{\circ}54'57.6$) and DH2 ($N78^{\circ}23'59.9/E15^{\circ}54'68.4$) cores were
9 250 drilled c. 3 km to the NW of Longyearbyen close to the airport, in relation to CO_2
10 251 sequestration studies (Braathen *et al.*, 2012). The cores span the Rurikfjellet and
11 252 Helvetiafjellet formations, and the lower part of the Carolinefjellet Formation (Fig. 1). In
12 253 these wells, the Rurikfjellet Formation is ca. 225 m thick (~440–215 m) and conformably
13 254 overlies shale of the Agardhfjellet Formation (e.g. Grundvåg *et al.*, 2017). The boundary
14 255 between the two units is tectonically disturbed, representing a decollement zone that
15 256 formed during the Palaeogene shortening (Dietmar Müller & Spielhagen, 1990). The
16 257 lower part of the Rurikfjellet Formation consists of a ~140 m thick succession of gravity
17 258 flow deposits of the Adventpynten member. The upper part of the Rurikfjellet Formation
18 259 consists of a 30–40 m thick mudstone-dominated unit which grades upwards into the
19 260 sandstone-dominated Kikutodden Member. The Rurikfjellet Formation is unconformably
20 261 overlain by a 12 m thick sandstone unit representing the Festningen Member of the
21 262 Helvetiafjellet Formation (Grundvåg *et al.*, 2017). The upper c. 60 m of the Helvetiafjellet
22 263 Formation consists of interbedded sandstone, shale, and thin coal layers of the
23 264 Glitrefjellet Member, representing various alluvial to paralic depositional environments.
24 265 The thicknesses of all lithostratigraphic units across the investigated interval in the two
25 266 cores are shown on Fig. S4 (DH1) and Fig. S5 (DH2). The Helvetiafjellet Formation is
26 267 unconformably overlain by a ~10 m thick shale unit of the overlying Dalkjegla Member of
27 268 the Carolinefjellet Formation.
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6 271 The DH5R core ($N78^{\circ}12'13.1''/E15^{\circ}49'08.6''$) was drilled c. 4 km to the SE of
7 Longyearbyen in central Spitsbergen, also in relation to CO₂ sequestration studies
8 (Braathen *et al.*, 2012). The studied part of the core spans from the uppermost
9 Agardhfjellet Formation to the Carolinefjellet Formation. The Rurikfjellet Formation is c.
10
11 274 230 m thick (410–180 m) and overlies shale of the Agardhfjellet Formation (Koevoets et
12
13 275 al., 2018). The lithology of the Rurikfjellet Formation differs from that observed in the
14
15 276 DH1 and DH2 cores. In the DH5R core, the formation displays homogeneous to
16
17 277 sparsely bioturbated shale with scattered siderite concretions and bivalves of the
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19 278 Wimanfjellet Member which coarsen into silty shale, heavily bioturbated siltstone and
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21 279 hummocky cross-stratified sandstone of the overlying Kikutodden Member. The
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23 280 Helvetiafjellet (180–120 m) and Carolinefjellet formations display the same stratigraphic
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26 281 development as in the DH1, and DH2 cores.
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37 284 **6. Analytical methods**
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40 285 Sediment samples for palynological analysis were collected during fieldwork and core
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42 286 logging campaigns in 2013–2016. 82 samples were collected, with 40 samples from
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44 287 Bohemanflya, Myklegardfjellet and Ullaberget, and 42 samples from the DH1, DH2, and
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46 288 DH5R cores. The majority of samples were collected from the Rurikfjellet Formation,
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48 289 including 8 samples from DH1, 14 samples from DH2, 15 samples from DH5R, 12
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50 290 samples from Bohemanflya, 13 samples from Myklegardfjellet and 3 samples from
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52 291 Ullaberget. The Helvetiafjellet Formation was sampled only in the DH2 core (3 samples)
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54 292 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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7 295 (at 458.0, 440.0, and 410.0 m).
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10 296 Preparation of palynological slides was performed at the Geological Survey of
11 Denmark and Greenland (GEUS). Between 20 and 45 g of sediment were dried in an
12 oven for 24 hours at 30°C and manually ground. Hydrochloric (HCl; 3.5% and 18%) and
13 hydrofluoric (HF; 40%) acids were used for dissolving carbonates and silicates,
14 respectively. After each step, samples were neutralized with 0.5% citric acid ($C_6H_8O_7$) at
15 70°C. The organic residuum from each sample was filtered using an 11 µm nylon mesh
16 and a first (kerogen) slide was prepared. Subsequently, the residua were oxidized with
17 HNO₃ for 8 min in order to remove amorphous kerogen particles. Samples with high
18 concentrations of amorphous kerogen particles were oxidized for additional 1 to 5 min.
19 After each oxidation step, residua were washed with a weak solution (5%) of potassium
20 hydroxide (KOH), and a fraction of the residue was taken for palynological slide
21 preparation. Some of the residua were additionally briefly submerged in a boiling
22 mixture of HNO₃:KOH (1:1), and filtered using a 21 µm nylon mesh. The high
23 concentration of coal and wood particles present in some of the samples was removed
24 by swirling, and minerals were removed by heavy liquid separation (ZnBr; density 2.3
25 g/mL). After each of these steps, organic residua were filtered using a 21 µm nylon
26 mesh. To concentrate palynomorphs, organic residua from some of the samples were
27 filtered using a 30 µm nylon mesh. All palynological slides and (if available) organic
28 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
6 cases, when a single slide contained less than 300 dinocysts, it was necessary to count
7
8 317 one or two additional slides. The dinocyst taxonomy follows Williams, Fensome &
9
10 318 MacRae (2017). All dinocysts recorded in this study are listed in Table 1. Selected
11
12 319 dinocysts are presented on Figs. 3-6. Coordinates of the photographed specimens are
13
14 320 given following the method described by Śliwińska (2019).
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17 321
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19 322 <>Fig.3>>
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22 323 <>Fig. 4>>
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25 324 <>Fig.5>>
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28 325 <>Fig. 6>>
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31 326 **7. Results and discussion**
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34 327 Two out of three samples from the Agardhfjellet Formation were barren with respect to
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36 328 dinocysts. Virtually all analysed samples from the Rurikfjellet Formation and the
37
38 329 Helvetiafjellet Formation yielded dinocysts. The diversity, abundance and preservation
39
40 330 are highly variable spatially and temporally. In samples where dinocysts were rare or
41
42 331 absent, the assemblages are dominated by black and dark brown wood particles, as
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44 332 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*
13
14 341 *tetricanta* (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),
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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 perforobtusa* (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.

352 The age-diagnostic taxa within the Helvetiafjellet Formation include
353 *Odontochitina nuda* (Fig. 5e; Section 8.f), *Pseudoceratium anaphrissum* (Figs 5m-o;
354 Section 8.j), *Sirmiodinium grossii* (Figs 6e,f; Section 8.k), and *Subtilisphaera perlucida*
355 (Fig. 6g; Section 8.l). The Helvetiafjellet Formation is also characterised by low species
356 richness, low relative abundance of dinocysts and a moderate reworking of Valanginian
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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11 361 **7.a. Palynological framework for the Agardhfjellet Formation**

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14 362 The two lowermost samples from the DH5R core collected from the upper part of the
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16 363 Agardhfjellet Formation (at 458.0 and 440.0 m) are barren of dinocysts (Figure S6). The
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18 364 sample at 410 m yields only few, poorly preserved dinocysts (Figure S6). In this sample,
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21 365 the co-occurrence of *Sirmiodinium grossii* and *Tubotuberella apatela* suggests a very
22
23 366 broad Bathonian – early Valanginian age (e.g. Costa and Davey, 1992). Our dinocyst-
24
25 367 derived age constrain is therefore not as good as the age based e.g. on macrofossils,
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28 368 which dates this part of the Agardhfjellet Formation as Ryazanian (Wierzbowski *et al.*,
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30 369 2011).

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36 371 **7.b. Palynological framework for the Rurikfjellet Formation**
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39 372 The distribution of dinocysts in the Rurikfjellet Formation (except the Myklegardfjellet
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41 373 Bed; Fig. 1) from the studied sites suggests that this formation is of early Valanginian to
42
43 374 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
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48 376 preservation, low diversity and low dinocyst abundance. Both cores penetrate the
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50
51 377 ca.150 m thick gravity flow deposits of the Adventpynten member (Grundvåg *et al.*,
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53 378 2017) that yield a number of reworked taxa. In the DH2 core, the lowermost samples
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55 379 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
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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 *tetricantha* (Fig. S4). Thus, this interval is of Valanginian – Hauterivian age. The
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15 386 presence of *Endocrinium hauterivianum* between 270.0 and 221.0 m implies that this
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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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24 390 We find the best-constrained age for the basal part of the Rurikfjellet Formation
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26 (early Valanginian) to be represented by the Myklegardfjellet outcrop section (the
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28 391 interval from the base of the section up to level 60.0 m; Fig. S2). This notion is based on
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30 392 the co-occurrence of *Palaecysta palmula* and *O. complex* in the lowermost sample at
31
32 393 0.05 m. The early Valanginian age for the base of the Rurikfjellet Formation confirms
33
34 394 previous observations (Bjærke, 1978; Århus, 1992).

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36 396 The LO of the stratigraphically persistent *T. apatela* at 60.0 m in the
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38 397 Myklegardfjellet outcrop section is used here as a marker for the top of the early
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40 398 Valanginian, since most records agree that this bio-event is close to the early–late
41
42 399 Valanginian boundary (see below; Fig. 7). This age assignment is in agreement with the
43
44 400 presence of a *Tollia* (*Neocraspedites*) aff. *subtilis* ammonite of middle early Valanginian
45
46 401 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
6
7 404 to 320.0 m. Based on these occurrences, we date this interval as earliest Valanginian.
8
9 405 Placing the early–late Valanginian boundary close to the top of the persistent
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11 406 occurrence of these two taxa is in agreement with the observations by Århus (cf. Fig. 2
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13 407 in Århus, 1992, and Enclosure 2 in Århus, 1988).
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17 408 We place the base of the Hauterivian at the FO of *E. hauterivianum* (Fig. 8). The
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19 409 FO of *E. hauterivianum* is followed by the FO of *Muderongia tetricantha*, 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
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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 Bjørke, 1978; Section 9.a.) is also present in several other outcrop sections of the
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33 416 Rurikfjellet Formation including Janusfjellet, Forkastningsfjellet and Helvetiafjellet.
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38 417 Many samples from the uppermost part of the Rurikfjellet Formation in the DH1,
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40 418 DH2 and DH5R cores are characterised by low dinocyst abundance and relatively low
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42 419 species richness. The best age constrain for the top of the formation is therefore based
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44 420 on outcrop sections. The upper part of the Rurikfjellet Formation is dated to the late
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46 421 Hauterivian – earliest Barremian. The youngest part of the formation dated to the early
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48 422 Barremian is observed at Ullaberget and Bohemanflya.
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53 423 In the Ullaberget outcrop section, two samples at 0.0 and 2.0 m, collected from
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55 424 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
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7 427 Hauterivian – Barremian boundary (Fig. S3). In the North Sea Basin, the LO of *N.*
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9 428 *kostromiensis* and the FO of *P. anaphrissum* are two important bio-events for
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11 429 recognition of the Hauterivian–Barremian boundary. Typically, the LO of *N.*
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13 430 *kostromiensis* marks the top of the Hauterivian, while the FO of *P. anaphrissum* marks
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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
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19 433 al., 1990; Smelror et al., 1998; Bailey, 2019) or the uppermost Hauterivian
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21
22 434 (Nøhr-Hansen, 1993; Nøhr-Hansen, Piasecki & Alsen, this issue). In the North Sea, the
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24 435 ranges of these two species either overlap (Costa & Davey, 1992) or don't (Bailey,
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26 436 2019). Overlapping ranges of the two taxa have been observed in North-East
27
28 437 Greenland (Nøhr-Hansen, 1993; Nøhr-Hansen, Piasecki & Alsen, this issue). An
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30 438 overlap of the stratigraphic ranges of the two species was previously reported from the
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32 439 Barents Sea (well 7245/9-U-1) (Fig. 5 in Århus et al. 1990). Based primarily on the
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34 440 foraminifera assemblage, the overlap interval was dated as early Barremian (Århus et
35
36 441 al., 1990). However, these authors recognised that the presence of *Buchia sublaevis*
37
38 442 bivalves within the same interval was problematic (p. 173 in Århus et al. 1990), because
39
40 443 *Buchia* extends only into the Hauterivian (Zakharov, 1987). In summary, these
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42 444 observations give three possibilities for assigning an age to the LO of *N. kostromiensis*
43
44 445 and the FO of *P. anaphrissum*: (i) In Spitsbergen, the Barents Sea and North-East
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46 446 Greenland, *P. anaphrissum* appears in latest Hauterivian; (ii) in Spitsbergen and the
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48 447 Barents Sea region, *N. kostromiensis* has a longer range reaching the earliest

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3 448 Barremian; or (iii) *N. kostromensis* 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 other studies from the Arctic region (North-East Greenland, Barents Sea and Arctic
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8 450 Canada; cf. Fig. 7).
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12 452 In the three uppermost samples from the Bohemanflya outcrop section (99.29 m
13 to 132.63 m), we found a common to abundant dinocyst taxon previously recorded as
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15 453 *Nyktericysta? pannosa* by Grøsfjeld (1991). However, we observe that *N.? pannosa*
16 from Bohemanflya (Figs 7o,p) with its generally less pronounced lateral horns differs
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18 454 from the holotype, which was described from “middle Barremian” strata from the
19 Speeton Clay in England (Duxbury, 1980). Nevertheless, Grøsfjeld (1991), and this
20
21 455 study show the only records of this taxon outside the type area. The restricted
22
23 456 occurrence of *N.? pannosa* limited to the Bohemanflya section on Spitsbergen
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25 457 (Grøsfjeld 1991; this study) and to the Speeton Clay in England (Duxbury, 1980), could
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27 458 suggest that the distribution of the taxon is controlled by some environmental factors.
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36 462 Based on the LO of *N. kostromensis* at 127.58 m and the presence of *N.? pannosa*
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38 463 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 observed an acme of *M. australis*. We consider this acme to be time-equivalent to the
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48 466 *M. australis* acme observed in the Barents Sea by Århus *et al.* (1990). Thus, we date
49
50 467 this level as late Hauterivian – early Barremian.
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55 469 Our new age framework for the Rurikfjellet Formation based on the dinocyst
56 stratigraphy is in agreement with previous studies from the study area (e.g. Bjørke,
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3 471 1978; Thusu, 1978; Århus, 1992; Midtkandal *et al.*, 2016), which dated the majority of
4
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
8
9 474 – late Hauterivian (Århus, 1992). We observe that our dinocyst distribution of the
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11 475 Myklegardfjellet outcrop section (Fig. S2) resembles the distribution of dinocysts from
12
13 476 Janusfjellet (Enclosure 2 in Århus, 1988). Furthermore, our results confirm the
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15 477 observation by Grøsfjeld (1991) that the topmost part of the Rurikfjellet Formation is
16
17 478 most likely of early Barremian age. Some reworking is present which is minor compared
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19 479 to the reworking in the Helvetiafjellet Formation (Figs. S1-S6).

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27 480
28 481 <<Fig. 8>>

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30 482 <<Fig.9>>

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

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34 484 We observe that the dinocyst assemblages of the Helvetiafjellet Formation are highly
35
36 485 impoverished and yield a number of taxa reworked from the Rurikfjellet Formation. The
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38 486 reworking of Pliensbachian to Early Oxfordian dinoflagellate cysts within the
39
40 487 Helvetiafjellet Formation was observed previously on Kong Karls Land (Smelror *et al.*,
41
42 488 2018). Redeposition is, however, not surprising, considering that the study area was
43
44 489 uplifted and subaerially exposed in the Barremian with large parts of the Svalbard
45
46 490 platform being subjected to erosion (Fig. 2).

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48 491 Based on the presence of *Odontochitina nuda*, *Pseudoceratium anaphrissum*,
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50 492 *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
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9 496 the Barremian–Aptian boundary.

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12 497 Our age assignment of the Helvetiafjellet Formation is in agreement with a recent
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14 498 stable carbon-isotope ($\delta^{13}\text{C}$) stratigraphic study of the Festningen outcrop section
15
16 499 (Vickers *et al.*, 2016). These authors interpreted that the Helvetiafjellet Formation is of
17
18 500 Barremian to earliest Aptian age. Another study, based on the U–Pb dating of a
19
20 501 bentonite in the DH3 core (at 156.89 m in the middle part of the Helvetiafjellet
21
22 502 Formation) suggested an age of 123.3 ± 0.2 Ma for this particular bed (Corfu *et al.*,
23
24 503 2013), corresponding to the late early Aptian (Ogg, Ogg & Gradstein, 2016). However,
25
26 504 the biostratigraphic framework of this study & Midtkandal *et al.* (2016) suggests that this
27
28 505 part of the succession is of Barremian age. Nevertheless, the existing studies (e.g.
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30 506 Corfu *et al.*, 2013; Midtkandal *et al.*, 2016; Vickers *et al.*, 2016) collectively agree that
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32 507 the Helvetiafjellet Formation is of Barremian – early Aptian age.

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36 509 **8. Conclusions**

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39 510 The Rurikfjellet and Helvetiafjellet formations on Spitsbergen, Svalbard, have been
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41 511 studied in the DH1, DH2 and DH5R onshore cores as well as in the Bohemanflya,
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43 512 Myklegardfjellet and Ullaberget outcrop sections. Our study suggests an early
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45 513 Valanginian – early Barremian age for the Rurikfjellet Formation and a Barremian –
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47 514 Aptian age for the overlying Helvetiafjellet Formation. We provide a number of age
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49 515 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
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5 517 significantly higher in the offshore to shallow-marine Rurikfjellet Formation than in the
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7 518 fluvio-deltaic to paralic Helvetiafjellet Formation.
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11 519 We observe some reworked dinocysts within the Helvetiafjellet Formation,
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13 520 possibly from the Rurikfjellet Formation. The presence of reworked dinocysts implies
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15 521 that any proxy records performed on bulk sediments (e.g. $\delta^{13}\text{C}$, biomarkers) across the
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17 522 Barremian – Aptian transition on Spitsbergen should be interpreted with care, since the
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19 523 signal may be biased.
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23 524 We further observe that the distribution of *N.? pannosa* and *O. abaculum* is most
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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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30 527 The dinocyst assemblages in the three samples collected from the Agardhfjellet
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32 528 Formation are too impoverished to provide a reliable age constraint on the boundary
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34 529 between the Rurikfjellet and Argardhfjellet formations.
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38 530 Our age model is in agreement with the existing stratigraphic studies carried out
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40 531 in the study area. Notably, our study provides the first comprehensive, semi-quantitative
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42 532 dataset of the distribution of dinocysts within the Lower Cretaceous (Valanginian–
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44 533 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 hauterivianum* (Duxbury, 2001) Riding &**

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5 539 **Fensome, 2003**

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

8
9 541 1978 *Apteodinium* sp. A (Bjærke, 1978)

10
11 542 1980? *Apteodinium* sp. A of Bjærke (1978) Bjærke plate X figs 1,2

12
13 543 1991 *Apteodinium* sp. A of Bjærke (1978) Grøsfjeld plate 4 figs D-F

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15 544 2001 *Scriniodinium hauterivianum* Duxbury, 2001

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17 545 2003 *Endoscrinium hauterivianum* (Duxbury, 2001) Riding & Fensome, 2003

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19 546 The holotype of *E. hauterivianum* was described from the UK sector of the North Sea

20
21 547 Basin (Duxbury, 2001). The taxon was described as restricted to the Hauterivian with

22
23 548 the LO within the lowermost upper Hauterivian (Duxbury, 2001). We here suggest that

24
25 549 *Apteodinium* sp. A of Bjærke (1978), which was recorded in the Valanginian to

26
27 550 Hauterivian succession of the Rurikfjellet Formation (Bjærke, 1980), is a synonym of *E.*

28
29 551 *hauterivianum*. Grøsfjeld (1991) noted that the species was present in numerous

30
31 552 locations on Spitsbergen and can be used as a Hauterivian marker in the region.

32
33 553 However, she also pointed out that at Janusfjellet the LO of *Apteodinium* sp. A of

34
35 554 Bjærke (1978) postdates the LO of *N. kostromiensis* (for the stratigraphic range of *N.*

36
37 555 *kostromiensis* see Section 9.e.) and thus it may range into the Barremian. Grøsfjeld

38
39 556 (1991) did not observe *N. kostromiensis* in the Bohemanflya outcrop section (see Fig 6

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41 557 in Grøsfjeld 1991), only *N?. pannosa* (see below) and *Apteodinium* sp. A of Bjærke

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43 558 (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
9 562 sections with the highest dinocyst diversity and the greatest abundance assemblage
10
11 563 (Bohemanflya Fig. S1 and Myklegardfjellet, Fig. 5) the LO of *E. hauterivianum* predates
12
13 564 the LO of *N. kostromiensis*. This is in contrast to the observations by Grøjsfjeld (1991)
14
15 565 from the Bohemanflya outcrop section. We speculate that the longer range of *N.*
16
17 566 *kostromensis* observed by us may be an effect of different sampling strategies carried in
18
19 567 both studies. In the studied material the taxon is rare to abundant (i.e. <1% or >50% of
20
21 568 the total dinocyst assemblage).
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30 570 **9.b. LO of *Gochteodinia villosa* (Vozzhennikova, 1967) Norris, 1978**
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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
4
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.
30
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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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PROOF FOR REVIEW

595 *Spitsbergen – this study.* Specimens referred to *G. villosa villosa* and *G. villosa*
596 *multifurcata* are slightly more elongate than the type material (cf. e.g. Davey, 1982). The
597 poor preservation of some of the specimens encountered in the present study
598 sometimes precludes an unambiguous separation of the two subspecies. We
599 distinguish subspecies only if the determination is possible. In few samples *G. villosa*
600 makes up 2–4 % of the total dinocysts assemblage. Otherwise, the species occurs
601 persistently in the lower part of the Rurikfjellet Formation (Myklegardfjellet, DH5R), but
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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8 606 **Fig. 4e**
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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
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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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53 624 **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
4
5 627 marker (Heilmann-Clausen, 1987; Costa & Davey, 1992; Duxbury, 2001). *M.tetraclantha*
6
7 628 has a slightly younger range from the Hauterivian to the earliest Barremian (Costa and
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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. tetraclantha*
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. tetraclantha* 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.

22
23
24 636 The morphologies of the two taxa are distinctive. The lateral horns of *M. extensiva* are
25
26 637 long and extend almost at right angles from the tests (Duxbury, 1977), while in *M.*
27
28 638 *tetraclantha* the horns bend downwards (Gocht, 1957). Furthermore, *M. extensiva* in
29
30 639 contrast to *M. tetraclantha* show a distinct plate differentiation at the lateral edge (Helby,
31
32 640 1987).

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41 642 *Spitsbergen-this study.* In the material encountered in the present study we
42
43 observe transitional forms between *M. extensiva* and *M. tetraclantha*. Some of these
44
45 forms resemble *M. tetraclantha* in their general outline, but on one or both lateral horns,
46
47 we observe a distinct plate differentiation, a feature typical for *M. extensiva* (Fig. 7g).
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49
50 646 We observe the earliest record of *M. tetraclantha* 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
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54 648 *M. tetraclantha* is observed within the range of *E. hauterivianum* (Figs S1, S2, S6, and 4)

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6 650 **9.e. Stratigraphic range of *Nelchinopsis kostromiensis* (Vozzhennikova, 1967)**
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8 651 **Wiggins, 1972**
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10 652 **Figs 4m,n**
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16 654 In the majority of existing studies of the North Sea Basin (Fig. 7) the range of **this**
17 species is limited to the upper lower Valanginian–upper Hauterivian (Costa & Davey,
18
19 655 1992; Duxbury, 2001) or to **the** Hauterivian (Davey, 1982; Heilmann-Clausen, 1987). In
20
21 656 North-East Greenland the taxon **first occurring** in the middle late Valanginian and is not
22
23 657 observed above the early to late Hauterivian *N. kostromiensis* Subzone (Nøhr-Hansen,
24
25 658 1993; Nøhr-Hansen, Piasecki & Alsen *this issue*). Some studies, reports the FO of *N.*
26
27 659 *kostromiensis* as early as at the early–late Valanginian boundary (Bailey, 2019) and **its**
28
29 660 LO in the earliest Barremian (Bailey, 2019). However, the Hauterivian–Barremian
30
31 661 boundary in Bailey (2019) is dated **as** 130 Ma so it is slightly younger than in the
32
33 662 **Geological Time Scale** 2016 where it is dated **as** 130.8 Ma (Ogg, Ogg & Gradstein,
34
35 663 2016). In the Svedrup Basin, Arctic Canada *N. kostromiensis* was observed together
36
37 664 with *Gochteodinia villosa* in the middle-late late Valanginian succession (Davies, 1983).
38
39 665 **In some older studies *N. kostromiensis* was reported from the earliest Barremian**
40
41 666 **(Heilmann-Clausen, 1987; Smelror *et al.*, 1998), from the *Simbirskites variabilis***
42
43 667 **ammonite zone. Today the zone is considered to be Hauterivian (Ogg, Ogg &**
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45 668 **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
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13 675 Formation. The LO of *N. kostromensis* is observed in the upper part of the Rurikfjellet
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15 676 Formation and is probably of latest Hauerivian – earliest Barremian age.
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22 678 **9.f. FO of *Odontochitina nuda* (Gocht, 1957) Dörhöfer & Davies, 1980**
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25 679 **Fig. 5e**
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31 681 The holotype of *O. nuda* was described from **the upper Hauerivian** (Gocht, 1957). Other
32
33 682 studies from Europe and Canada also suggest **a** Hauerivian 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
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48 689 *Spitsbergen – this study.* *O. nuda* is restricted to the Helvetiafjellet Formation.
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51 690 The FO is observed within the middle (the DH2 core) or the upper (the Ullabergset
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3 691 outcrop section) part of the formation. The most probable time span for the taxon in
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5 692 Spitsbergen is Barremian to early Aptian.
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11 694 **9.g. FO of *Oligosphaeridium abaculum* Davey, 1979**
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14 695 **Fig. 5f**
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19 697 The holotype of *O. abaculum* was described by Davey (1979) from a Barremian
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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).
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28 701 The common occurrence of *O. abaculum* in the upper Hauterivian was reported in the
29
30 702 UK and the Norwegian sectors of the North Sea Basin by Bailey (2019). Notably, Costa
31
32 703 & Davey (1992) reported that in the UK sector of the North Sea Basin *O. abaculum* has
33
34 704 a stratigraphic range **from the** upper Hauterivian to lower Barremian. However, the post-
35
36 705 Hauterivian–Barremian? age was suggested by these authors because they considered
37
38 706 the *Simbirskites variabilis* ammonite zone as Barremian. Recently the FO of *O.*
39
40 707 *abaculum* was recorded from the uppermost lower Barremian in North-East Greenland
41
42 708 by Nøhr-Hansen, Piasecki & Alsen (this issue).
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46 709 *Spitsbergen – this study*. Rare to common (<1% and 1-30% of the total dinocyst
47
48 710 **assemblage**) occurrences of *O. abaculum* **are** observed **from** all sites spanning the
49
50 711 Rurikfjellet Formation. However, in contrast to the North Sea and North-East Greenland,
51
52 712 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
7 715 *abaculum* is dependent on the local environmental changes.
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13 717 **9.h. FO of *Oligosphaeridium* complex (White, 1842) Davey & Williams, 1966b**
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16 718 **Fig. 5h**
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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
43 730 The processes terminations often have a “palm-like” appearance (Fig. 5j). We consider
44
45 731 the FO of *O. complex* as a marker for the base of the Valanginian. However,
46
47 732 considering the recent study from North-East Greenland it is possible that this event is
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49 733 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 middle lower Valanginian (Duxbury, 2001; Bailey, 2019) while in the Danish sector the
13
14 740 LO is probably slightly younger, within the lower upper Valanginian (Davey, 1982;
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16 741 Heilmann-Clausen, 1987), Fig. 7.
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21 742 *Spitsbergen – this study.* In the present study *P. palmula* is observed in the basal
22 part of the Rurikfjellet Formation in the Myklegardfjellet outcrop section.
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29 745 **9.j. Stratigraphic range of *Pseudoceratium anaphrissum* (Sarjeant, 1966c) Bint,**
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31 746 **1986**
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34 747 **Figs 5m–o**
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40 749 The taxon has a remarkably short range, limited to the Barremian, primarily to the lower
41
42 750 Barremian (Fig. 7). In the high Arctic the taxon has also been observed in the
43
44 751 Hauterivian (Fig. 7). The Barremian record of *P. anaphrissum* is very well known from
45
46 752 the Barents Sea (Århus *et al.*, 1990), Arctic Norway (Thusu, 1978), offshore south
47
48 753 Norway (Costa, 1981), North-East Greenland (Nøhr-Hansen, 1993), England (e.g.
49
50 754 Sarjeant 1966, Duxbury 1980), Germany (Prössl, 1990) and the North Sea Basin
51
52 755 (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 (Århush, 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
9 759 Basin, the species is abundant in a narrow interval in the middle part of its range (Nøhr-
10
11 760 Hansen, 1993; Bailey, 2018), see also summary Fig. 7.
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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 bulges, 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.
32
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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
9 781 and the European Boreal Realm is shown on Fig. 7.
10
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13 782 *Spitsbergen – this study.* We observe *S. grossii* in both the Rurikfjellet and
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15 783 Helvetiafjellet formations. The taxon is present in virtually all samples analysed in this
16
17 784 study.
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26 786 **9.I. FO of *Subtilisphaera perlucida* (Alberti, 1959b) Jain & Millepied, 1973**
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28
29 787 **Fig. 6g**
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31
32 788
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34 789 The majority of existing records from the Boreal and European Boreal Realm suggest
35
36 790 that *S. perlucida* appeared in the early Barremian (Heilmann-Clausen, 1987; Nøhr-
37
38 791 Hansen, 1993). In the DH1 core the FO of *S. perlucida* was observed within the
39
40 792 Helvetiafjellet Formation and dated as Barremian – Aptian (Midtkandal *et al.*, 2016).
41
42 793 Some records suggest however that the taxon appeared in the late Hauterivian (Fig. 7).
43
44
45 794 *Spitsbergen – this study.* The taxon is observed in the uppermost part of the
46
47 795 Rurikfjellet Formation (Ullaberget) and occurs consistently in the Helvetiafjellet
48
49 796 Formation (Ullaberget and the DH2 core).
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56 798 **9.m. LO of *Tubotuberella apatela* (Cookson & Eisenack, 1960b) Ioannides *et al.*,**
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58 799 **1977**

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3 **800 Figs 6 i-j**

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9 802 In the majority of studies on the North Sea the LO of *T. apatela* occurs approximately
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11 803 within the middle lower Valanginian (Fig. 7) and is considered synchronous with (Bailey,
12
13 804 2019) or slightly younger than (Duxbury, 2001) the LO of *P. palmula*. In the Barents Sea
14
15 805 *T. apatela* was not observed in the post-Ryazanian strata, but this may be biased by the
16
17 806 fact that the Valanginian succession is devoid of palynomorphs (Århus *et al.*, 1990).
18
19
20 807 Numerous studies report *T. apatela* from the upper Valanginian (Davies, 1983; Århus,
21
22 808 1988) or even Hauterivian (Piasecki, 1979; Davey, 1982; Heilmann-Clausen, 1987)
23
24
25 809 deposits. These studies report that the last persistent occurrence of *T. apatela* occurs
26
27 810 within the early Valanginian. In Spitsbergen and North-East Greenland the post-
28
29
30 811 Valanginian occurrence of the taxon is considered as reworked (Århus, 1988; Nøhr-
31
32 812 Hansen, 1993).

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35 813 *Spitsbergen – this study.* In the present study *T. apatela* is present within the
36
37 814 lower to middle part of the Rurikfjellet Formation. We observe that the LO on
38
39 815 Spitsbergen is diachronous. In the Myklegardfjellet outcrop section we apply the LO of
40
41 816 persistent *T. apatela* as the marker for the top of early Valanginian (Fig. 8). *T. apatela*,
42
43
44 817 in contrast to *Tubotuberella rhombiformis*, has a distinctive apical horn (on both
45
46 818 epitheca, and hypotheca), and lacks tabulation. These two features are clearly visible in
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48
49 819 virtually all specimens observed in this study.

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60 821 **Acknowledgements**

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8
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10
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19 manuscript.
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29 832 **Declaration of Interest**
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31 833 The authors declare no conflicts of interest.
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36 835 **Figure captions**
37
38 836 **Figure 1.** Stratigraphic cross-section showing the regional development of the Upper
39
40 Jurassic to Lower Cretaceous Adventdalen Group on Spitsbergen. Modified after Alsen
41
42 et al. (this issue). White bars show the time span for each of the studied sites: three
43
44 onshore cores DH1, DH2, DH5R, and three outcrop sections: Bohemanflya (BOH),
45
46 Ullaberget (UL), and Myklegardfjellet (MYK).
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50 841 **Figure 2. (A).** Black dots mark the positions of the studied sites: Bo – Bohemanflya, UI
51
52 – Ullaberget, My – Myklegardfjellet outcrop sections. Paleogeography of Spitsbergen
53
54 from the Valanginian to early Aptian (after Grundvåg & Olaussen, 2017; Grundvåg et
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2
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.
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11 847 **Figure 3.** Photographs of the most characteristic dinoflagellate cysts observed in the
12
13 Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all
14
15 849 photographs represent 20 µm. MC – microscope coordinates with the A-point of
16
17 850 0.4×90.3 (XM1 × YM1). For details, see Śliwińska (2019).
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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
24 853 (b) *Apteodinium spongiosum*, high focus, (c) low focus, Bohemanflya outcrop section,
25
26 854 level 25.00 m, sample 28450-9, MC 25 x 108.7
27
28 855 (d) *Apteodinium spongiosum* very dark, Myklegardfjellet outcrop section, level 30.00 m,
29
30 856 sample 27007-6, MC 32 x 109.1
31
32

33 857 (e) *Apteodinium spongiosum*, Myklegardfjellet outcrop section, level 120.00 m, sample
34
35 858 27013-9; MC 51.4 x 105.5
36
37

38 859 (f) *Atopodinium haromense*; Myklegardfjellet outcrop section, level 120.00 m, sample
39
40 860 27013-9; MC 42.7 x 102.3
41
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43 861 (g) *Circulodinium distinctum*, Myklegardfjellet outcrop section, level 105.00 m, sample
44
45 862 27012-6; MC 29.3 x 91.6
46
47

48 863 (h) *Circulodinium distinctum*, Myklegardfjellet outcrop section, level 120.00 m, sample
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50 864 27013-9; MC 21 x 104.5
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3 865 (i) *Circulodinium distinctum*, Myklegardfjellet outcrop section, level 120.00 m, sample
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5 866 27013-9; MC 17.5 x 105.5
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7 867 (j) *Circulodinium distinctum*, Bohemanflya outcrop section, level 28.00 m, sample
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9 868 28449-8; MC 44.7 x 96.7
10

11 869 (k) *Dissiliodinium acmeum*, Myklegardfjellet outcrop section, level 7.00 m, sample
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13 870 27005-4; MC 37.2 x 99.4
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15 871 (l) *Endoscrinium* sp.1 Bohemanflya outcrop section, level 25.00 m, sample 28450-9
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17 872 ; MC 25.5 x 110
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19 873 (m) *Discorsia nannus*, Myklegardfjellet outcrop section, level 120.00 m, sample 27013-
20

21 874 9; MC 49 x 103.3
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23 875 (n) *Dingodinium cerviculum*, Myklegardfjellet outcrop section, level 75.00 m, sample
24

25 876 27010-4; MC 47 x 108.5
26

27 877 (o) *Endoscrinium haoterivianum*, Bohemanflya outcrop section, level 36.00 m, sample
28

29 878 28448-7, MC 33.8 x 102.2
30

31 879 (p) *Endoscrinium haoterivianum*, Myklegardfjellet outcrop section, level 120.00 m,
32

33 880 sample 27013-9; MC 42 x 102.4
34

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37 882 **Figure 4.** Photographs of the most characteristic dinoflagellate cysts observed in the
38

39 883 Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all
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41 884 photographs represent 20 µm. 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
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5 886 details, see Śliwińska (2019).
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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
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15
16 890 (c) *Gochteodinia villosa* subsp. *multifurcata*, Myklegardfjellet outcrop section, level
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18 891 15.00 m, sample 27006-5; MC 36 x 107
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20
21 892 (d) *Muderongia tetricanta*, Bohemanflya outcrop section, level 127.50 m, sample
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23 893 26290-8, MC 44 x 110.6
24
25
26 894 (e) *Muderongia australis*, Myklegardfjellet outcrop section, level 120.00 m, sample
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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
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36 898 (g) a transitional form between *Muderongia tetricanta* and *Muderongia extensiva*,
37
38 899 Bohemanflya outcrop section, level 46.00 m, sample 26293-5, MC 24.5 x 111
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42 900 (h) *Muderongia extensiva*, Bohemanflya outcrop section, level 46.00 m, sample 26293-
43
44 901 7; MC 18.5 x 108.4
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47 902 (i) *Isthmocystis distincta*, Myklegardfjellet outcrop section, level 7.00 m, sample 27005-
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49 903 4; MC 28 x 102.3
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52 904 (j) *Kleithriasphaeridium eoinodes*, Myklegardfjellet outcrop section, level 90.00 m,
53
54 905 sample 27011-8; MC 25.2 x 103
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3 906 (k) *Kiokansium unituberculatum*, Bohemanflya outcrop section, level 127.50, sample
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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
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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
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24 914 (o) *Nyktericysta? pannosa*, Bohemanflya outcrop section, level 99.29 m, sample 26291-
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26 915 7; MC 43 x 102.7
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29 916 (p) *Nyktericysta? pannosa*, Bohemanflya outcrop section, level 127.50 m, sample
30
31 917 26290-8; MC 50.2 x 100
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37 919 **Figure 5.** Photographs of the most characteristic dinoflagellate cysts observed in the
38
39 Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all
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41 photographs represent 20 µm. The figure in colour is available on the web version of
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43 this paper. MC – microscope coordinates with the A-point of 0.4×90.3 (XM1 × YM1). For
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45 details, see Śliwińska (2019).
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48 924 (a) *Oligosphaeridium poculum*, DH5R core, depth 320.00 m, sample 26196-7; MC 58.2
49
50 925 x 97.1
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54 926 (b) questionable *Escharisphaeridia rudis*, DH5R core, depth 288.00 m, sample 26195-7;
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56 927 MC 36.7 x 112.5
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3 928 (c) *Phoberocysta neocomica*, Myklegardfjellet outcrop section, level 90.00 m, sample
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5 929 27009-6; MC 24.3 x 113.8
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8 930 (d) *Rhynchodiniopsis aptiana*, Bohemanflya outcrop section, level 5.00 m, sample
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10 931 28453-7, MC 31.7 x 101
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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
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30
31 939 (i) *Oligosphaeridium asterigerum*, Bohemanflya outcrop section, level 99.29 m, sample
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33 940 26291-7, MC 44.7 x 94.3
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36 941 (j) *Pseudoceratium pelliferum*, Bohemanflya outcrop section, level 36.00 m, sample
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38 942 28448-7, MC 37 x 106.5
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41 943 (k) *Palaecysta palmula*, Myklegardfjellet outcrop section, level 0.05 m, sample 27004-8,
42
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44 944 MC 53 x 107.5
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46
47 945 (l) *Cyclonephelium cuculliforme* sensu Århus 1990, Myklegardfjellet outcrop section,
48
49 946 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
7 949 al., (2019).

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

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14
15 952 (o) questionable, poorly preserved *Pseudoceratium anaphrissum*, DH2 core, depth
16
17 953 149.50 m, sample 26511-11; MC 34.5 x 110.5. Shown also in Figure 15.H in Grundvåg
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20 954 et al., (2019).

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

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

40
41
42 963 (b) *Stanfordella ordocava*, Myklegardfjellet outcrop section, level 15.00 m, sample
43
44 964 27006-5; MC 31.6 x 111

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46
47 965 (c) *Stanfordella ordocava*, DH5R core, depth 380.00 m, sample 26198-6; MC 55.5 x
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49 966 102.4

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52 967 (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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7 970 (f) *Sirmiodinium grossii*, DH1, depth 258.90 m, sample 26285-7; MC 29.4 x 109

8
9 971 (g) *Subtilisphaera perlucida*, DH2 core, depth 186.55 m, sample 26513-9; MC 36.7 x

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11 972 92.6. Shown also in Figure 15.G in Grundvåg et al., (2019).

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13 973 (h) *Spiniferites*? DH5R core, depth 194.00 m, sample 26192-7; MC 50.8 x 101.2

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15 974 (i) *Tubotuberella apatela*, Myklegardfjellet outcrop section, level 30.00 m, sample

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17 975 27007-6; MC 30.6 x 105

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19 976 (j) *Tubotuberella apatela*, Myklegardfjellet outcrop section, level 0.05 m, sample 27004-

20
21 977 8; MC 34.5 x 109.4

22
23 978 (k) *Tubotuberella apatela*, DH2 core, depth 232.00 m, sample 26516-9; MC 19.4 x 93.3

24
25 979 (l) *Tubotuberella* sp. DH5R core, depth 380.0 m, sample 26198-6; MC 48 x 98.7

26
27 980 (m) *Wallodinium luna*, DH5R core, depth 350.0 m, sample 26197-6; MC 36.5 x 102.4

28
29 981 (n) *Wrevittia perforobtusa*, DH5R core, depth 194.00 m, sample 26192-7; MC 29.9 x

30
31 982 102.6

32
33 983 (o) *Wrevittia perforobtusa*, Bohemanflya outcrop section, level 55.25 m, sample 26292-

34
35 984 8, MC 50.3 x 101.7

36
37 985 (p) *Wrevittia perforobtusa*, Bohemanflya outcrop section, level 36 m, sample 28448-7,

38
39 986 MC 40.5 x 98.6

40
41 987 **Figure 7.** The stratigraphic ranges and/or first and last occurrences of the age

42
43 988 diagnostic dinoflagellate cysts (dinocysts) from the Boreal and European Boreal Realm,

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2
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).
6
7 991 The figure shows a compilation of the most characteristic dinocysts from the Rurikfjellet
8
9 992 and Helvetiafjellet formations discussed in the present study. Heilmann-Clausen (1987),
10
11 993 Costa & Davey (1992), and Duxbury (2001) plotted the dinocysts ranges against the
12
13 994 ammonite zonation (marked with asterix). All these authors considered the *Simbirskites*
14
15 995 *variabilis* ammonite zone as earliest Barremian, whilst today it is considered to be
16
17 996 Hauterivian (Ogg, Ogg & Gradstein, 2016). Nøhr-Hansen, Piasecki & Alsen (this issue)
18
19 997 updated the zonation proposed previously by Nøhr-Hansen (1993), and provided ages
20
21 998 in GTS2016. Note that the study by Davey (1982) does not cover sediments younger
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23 999 than early-?late Hauterivian, while the study by Davies (1983) does not cover sediments
24
25 1000 younger than late Valanginian.
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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.
39
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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2
3 1010 This file contains range charts with the quantitative data of the palynomorphs
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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
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13

14 1014 **Figure S2.** Distribution of dinocysts in the Myklegardfjellet outcrop section
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16

17 1015 **Figure S3.** Distribution of dinocysts in the Ullaberget outcrop section
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20 1016 **Figure S4.** Distribution of dinocysts in the DH1 well
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23 1017 **Figure S5.** Distribution of dinocysts in the DH2 well
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26 1018 **Figure S6.** Distribution of dinocysts in the DH5R well
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 3 1360 **Table 1. List of palynomorphs recorded in this study including a reference for**
 4
 5 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 granulatum</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 aff. 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>Criboperidinium</i> sp. 1			6	31			
<i>Criboperidinium</i> spp.		9	12		6	14	4
<i>Cyclonephelium cuculliforme</i> sensu Århus 1990	8l		10				
<i>Dinocyst</i> 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? aciculare</i>		45	64		23	27	54
<i>Endoscrinium hauerianum</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 rufa</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				

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3	<i>Kiokansium unituberculatum</i>	7k	19	38		35	42
4	<i>Kleithriaspaenidium eoinodes</i>	7j		55			
5	<i>Lagenorhytis delicatula</i>						22
6	<i>Leptodinium</i> spp.		21				
7	<i>Meiourogonyaulax stoveri</i>	7l	33	43			35
8	<i>Muderongia asymmetrica</i>						55
9	<i>Muderongia australis</i>	7e	40	62	40	30	15
10	<i>Muderongia extensiva</i>	7h	39				
11	<i>Muderongia parvata</i>					36	52
12	<i>Muderongia simplex</i>	7f		46			44
13	<i>Muderongia simplex</i> subsp.						
14	<i>Microperforata</i> sensu Nøhr-Hansen 1993						56
15	<i>Muderongia</i> spp.		10	50	24	9	17
16	<i>Muderongia tetricantha</i>		36	61	10	22	40
17	<i>Muderongia tetricantha/extensiva</i>	7g	31	59		28	41
18	<i>Nelchinopsis kostromiensis</i>	7m,n	6	39	4,41	27	10
19	<i>Nyktericysta?</i> aff. <i>pannosa</i>	7o,p	41			20	
20	<i>Nyktericysta vitrea</i>						34
21	<i>Nyktericysta</i> spp.						57
22	<i>Odontochitina nuda</i>	8e			36		30
23	<i>Odontochitina</i> spp.				26		
24	<i>Oligosphaeridium albertaine</i>				22		
25	<i>Oligosphaeridium abaculum</i>	8f	11	53		7	22
26	<i>Oligosphaeridium asterigerum</i>	8i	12	24	13	12	1
27	<i>Oligosphaeridium complex</i>	8h	13	17	18	15	4
28	<i>Oligosphaeridium complex</i> var. 1					3	2
29	<i>Oligosphaeridium poculum</i>	8a	2	13	14	16	18
30	<i>Oligosphaeridium</i> aff. <i>pulcherrimum</i>				9		
31	<i>Oligosphaeridium</i> spp.		14	18	17	4	23
32	<i>Oligosphaeridium</i> with broken processes		7	19	19	13	7
33	Other dinocysts		15	20	15	21	20
34	<i>Palaecysta palmula</i>	8k		3			
35	<i>Palaeoperidinium cretaceum</i>						37
36	Palynomorph A			57			8
37	Palynomorph B				11		
38	<i>Paragonyaulacysta capillosa</i>			4			
39	<i>Paragonyaulacysta</i> spp.			42	33	24	6
40	<i>Pareodinia</i> spp.		23	14	25	34	21
41	<i>Phoberocysta neocomica</i>	8c	17	47		31	
42	<i>Proligosphaeridiopsis spissa</i> (acritarch)			26			
43	<i>Pseudoceratium anaphrissum</i>	8m-o	46		16		31
44	<i>Pseudoceratium pelliferum</i>	8j	29	60	5	10	32
45	<i>Pseudoceratium</i> cf. <i>retusum</i> sensu Nøhr-Hansen 1993						35
46	<i>Pseudoceratium</i> spp.						51
47	<i>Rhynchodiniopsis aptiana</i>	8d,g	16	48		36	48

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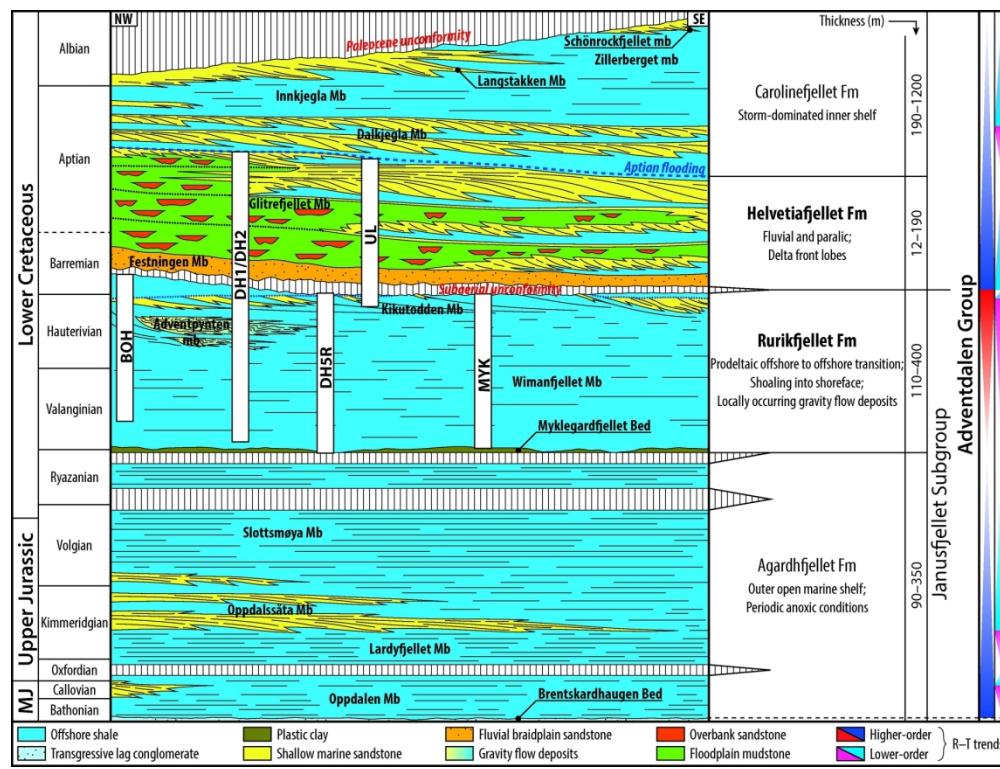


Figure 1. Stratigraphic cross-section showing the regional development of the Upper Jurassic to Lower Cretaceous Adventdalen Group on Spitsbergen. Modified after Alsen et al. (this issue). White bars show the time span for each of the studied sites: three onshore cores DH1, DH2, DH5R, and three outcrop 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)

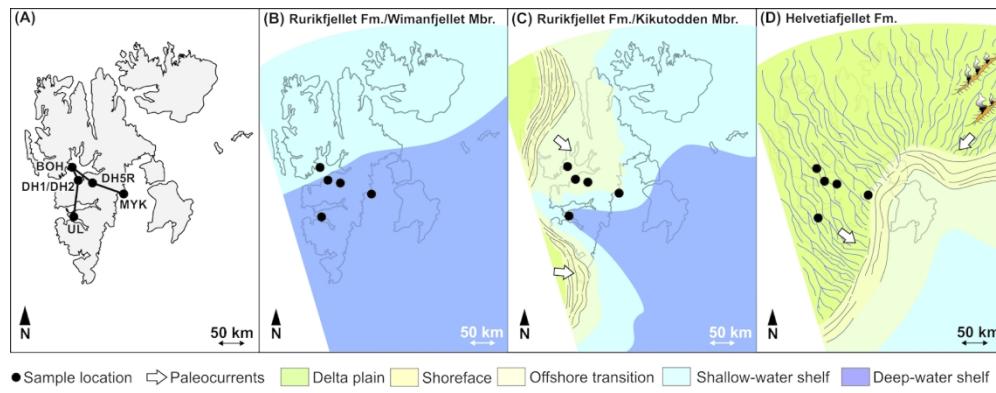


Figure 2. (A). Black dots mark the positions of the studied sites: Bo – Bohemanflya, Ul – Ullaberget, My – Myklegardfjellet outcrop sections. Palaeogeography of Spitsbergen from the Valanginian to early Aptian (after Grundvåg & Olaussen, 2017; Grundvåg et al., 2017) (B) Palaeogeography during the deposition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

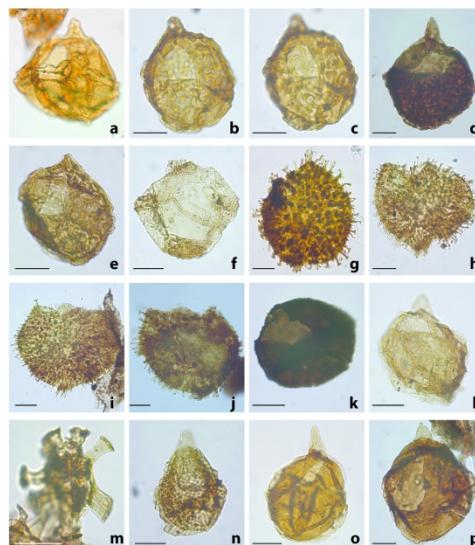


Figure 3. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20 µm. The figure is available in colour on the web version of this paper. MC – microscope coordinates with the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

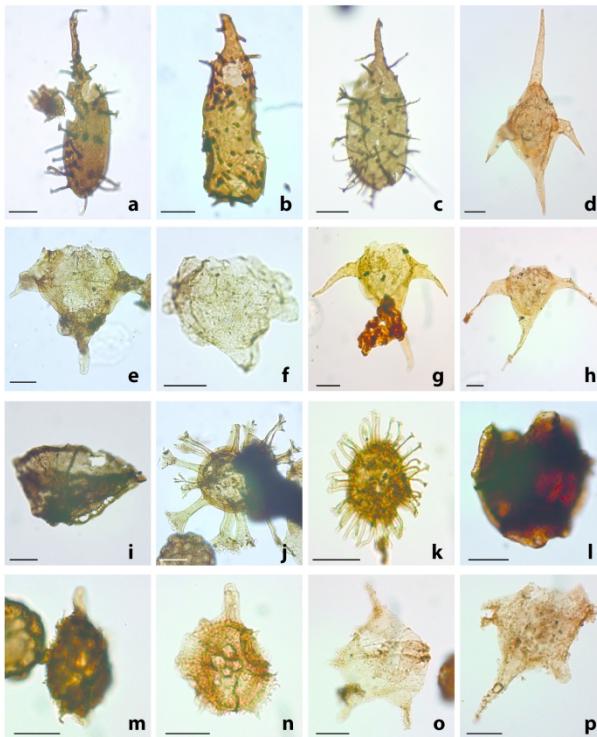


Figure 4. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20 µm. The figure in colour is available on the web version of this paper. MC – microscope coordinates with the A-point of 0.4×90.3 (XM1 × 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) *Kleithriasphaeridium 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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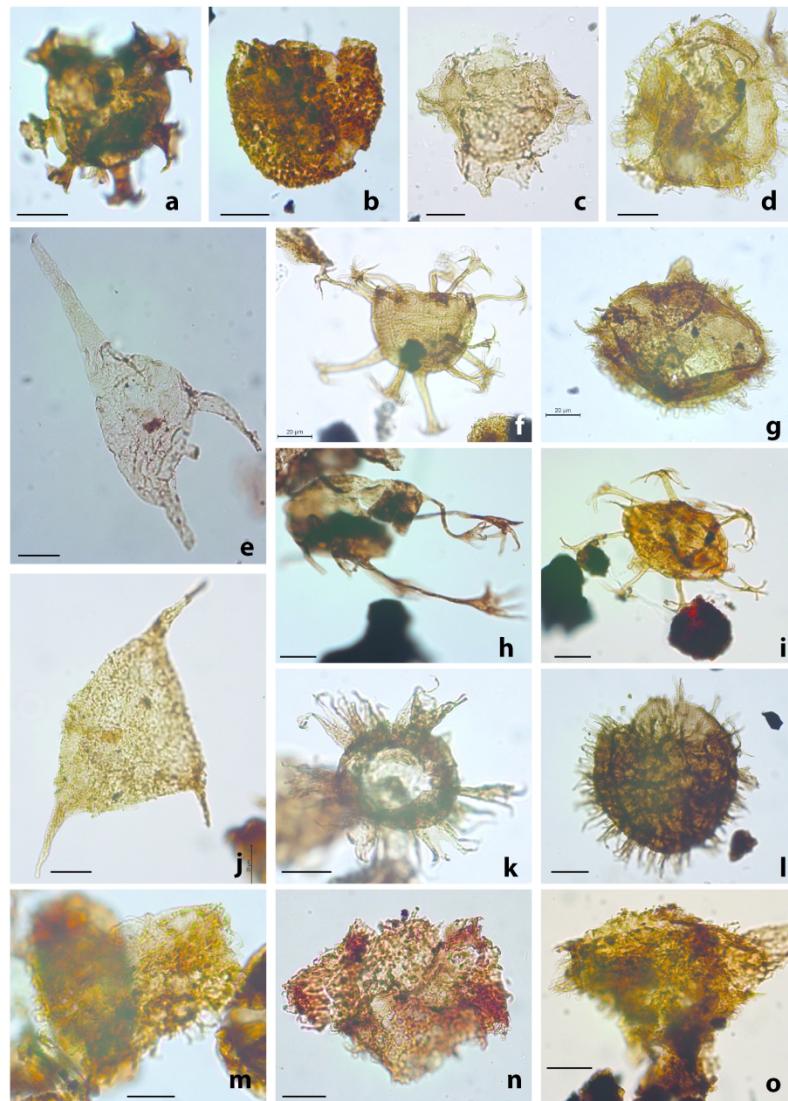


Figure 5. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20 µm. The figure in colour is available on the web version of this paper. MC – microscope coordinates with the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

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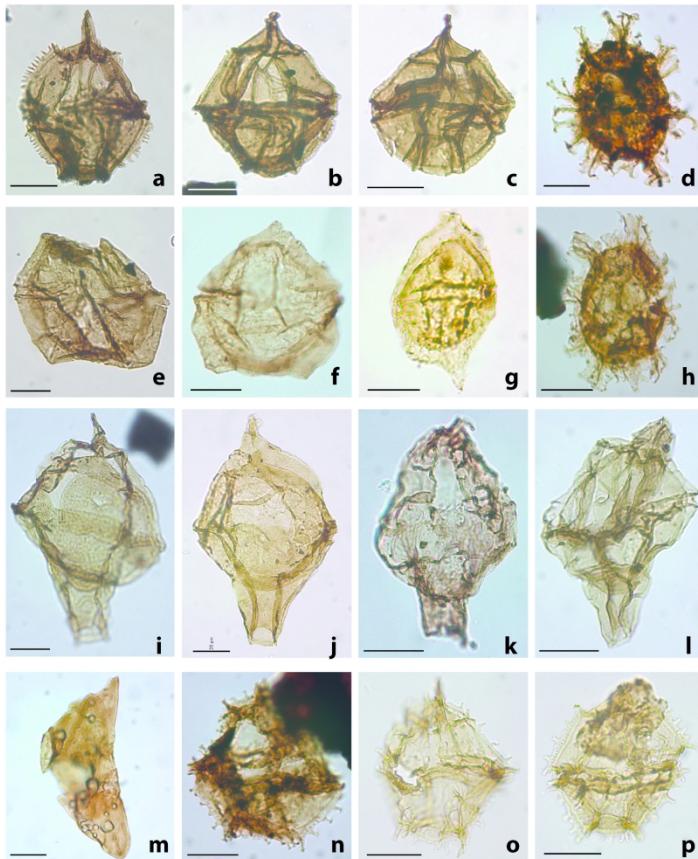


Figure 6. Photographs of the most characteristic dinoflagellate cysts observed in the Rurikfjellet and Helvetiafjellet formations in the present study. Scale bars on all photographs represent 20 µm. The figure in colour is available on the web version of this paper. MC – microscope coordinates with the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

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

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3 (m) *Walldinium 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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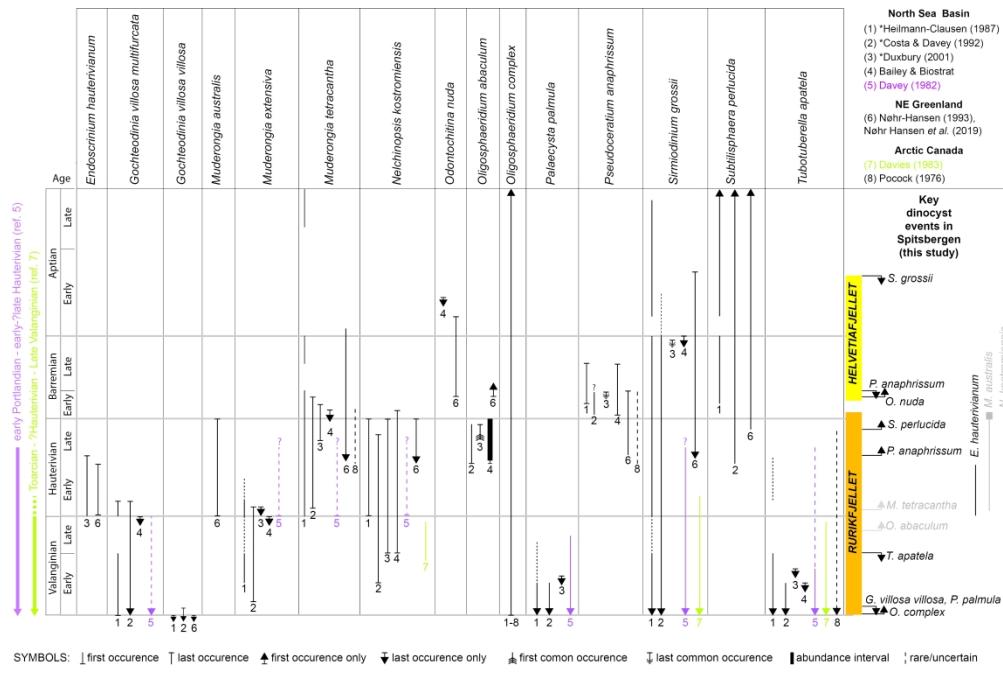


Figure 7. The stratigraphic ranges and/or first and last occurrences of the age diagnostic dinoflagellate cysts (dinocysts) from the Boreal and European Boreal Realm, and the key events recognised in this study (to the right). Key dinocyst events in Spitsbergen: primary markers (black), secondary markers (grey).

The figure shows a compilation of the most characteristic dinocysts from the Rurkjellet 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 asterix). 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)

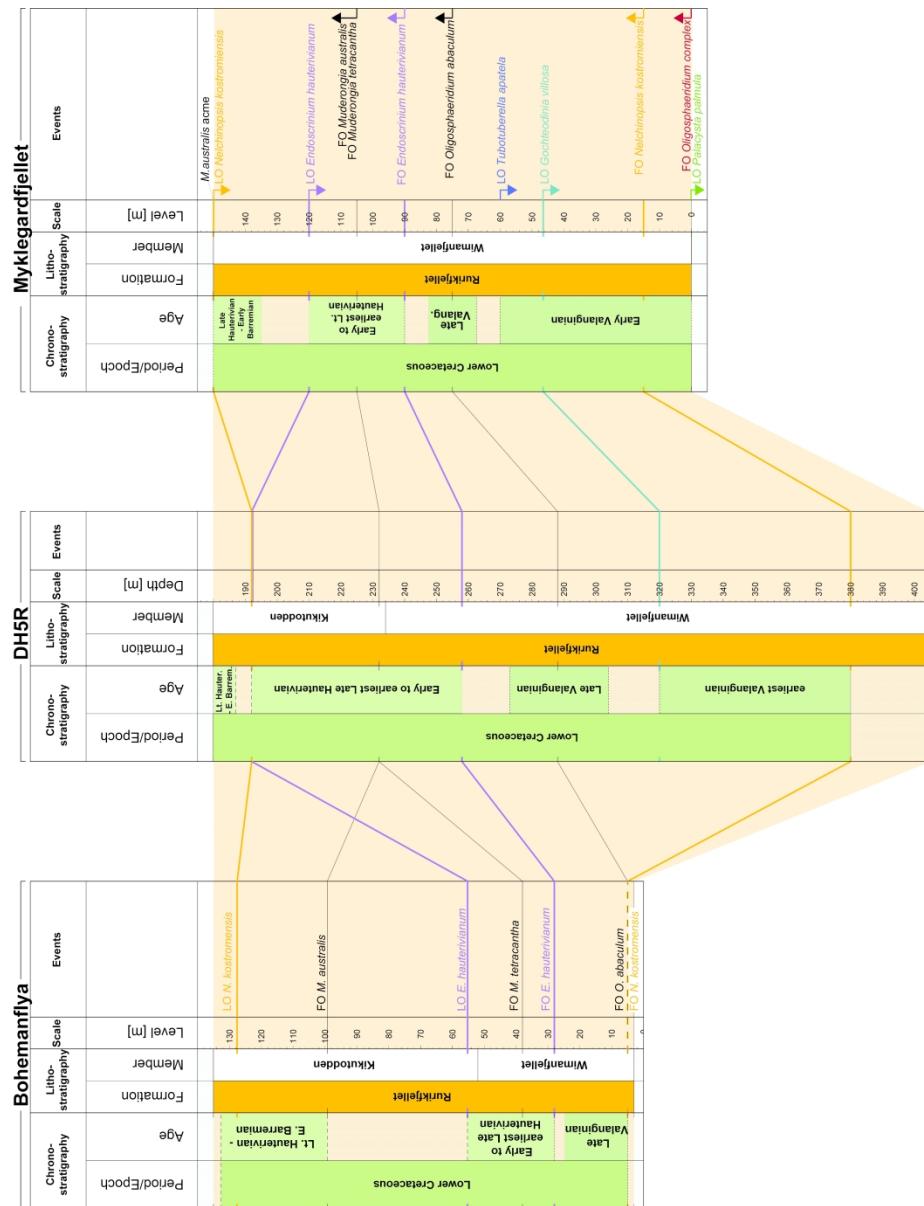


Figure 8. The spatial distribution of the age diagnostic (colour code) and secondary dinocyst events (black) within the Rurikfjellet Formation. The correlation between the Bohemanflya, the DH5R core, and the Myklegardfjellet outcrop section, i.e. from NW to SE.

288x376mm (300 x 300 DPI)

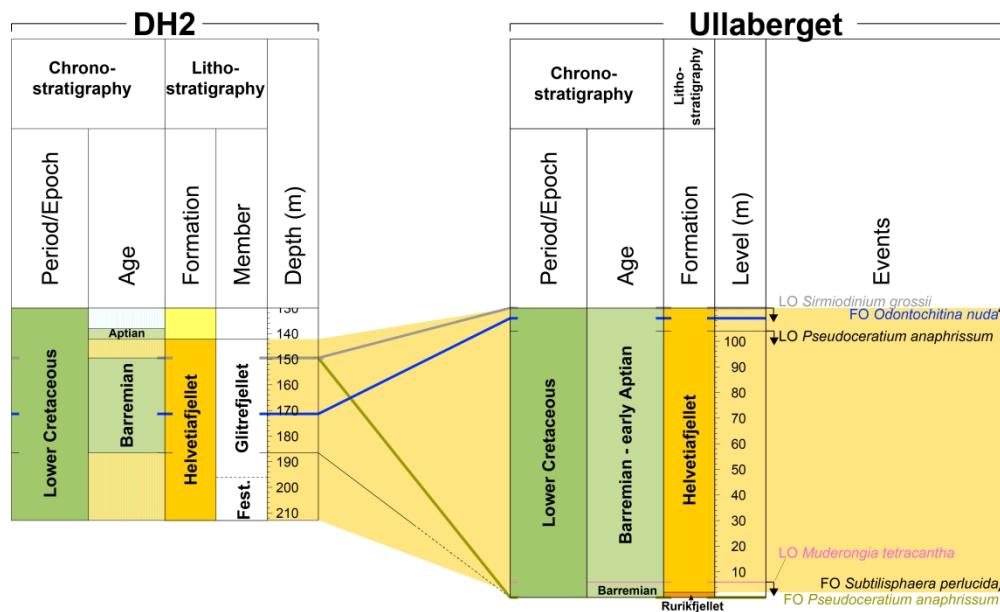


Figure 9. The spatial distribution of the age diagnostic dinocyst events within the Helvetiafjellet Formation.
The correlation between the Ullaberget outcrop section and the DH2 core.

390x236mm (300 x 300 DPI)

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

Figure S1: Bohemanflya

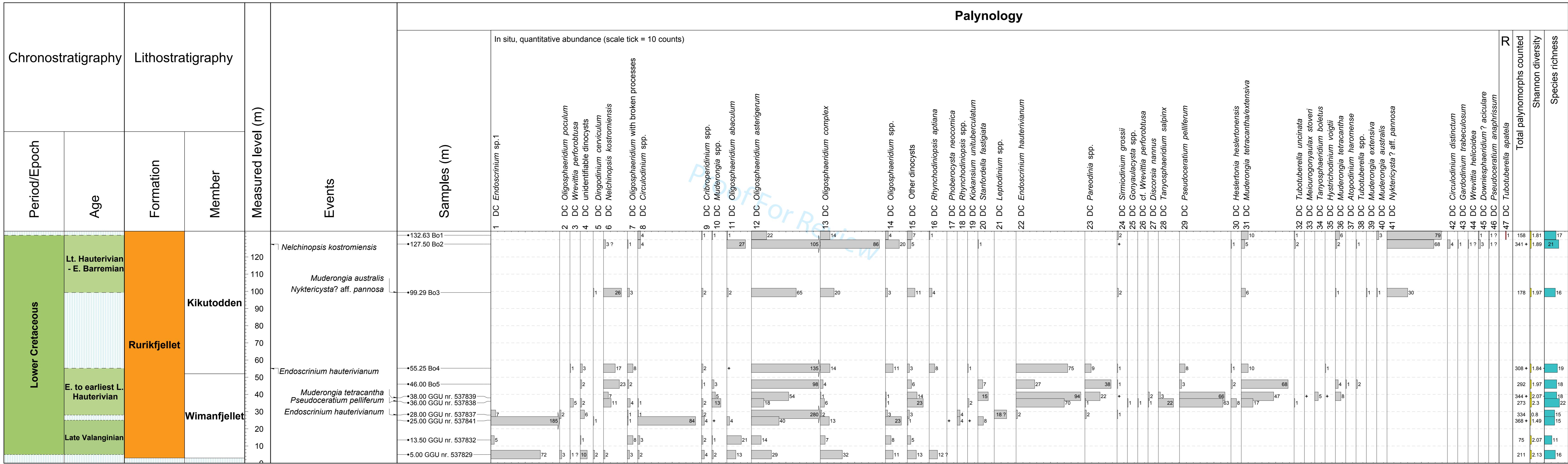


Figure S1. Distribution of dinocysts in the Bohemanflya outcrop section. This file contains range charts with the quantitative data of the palynomorphs recognised in this study.

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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Figure S2: Myklegardfjellet

Supplementary material



Figure S2. Distribution of dinocysts in the Myklegardfjellet 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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Figure S3: Ullaberget

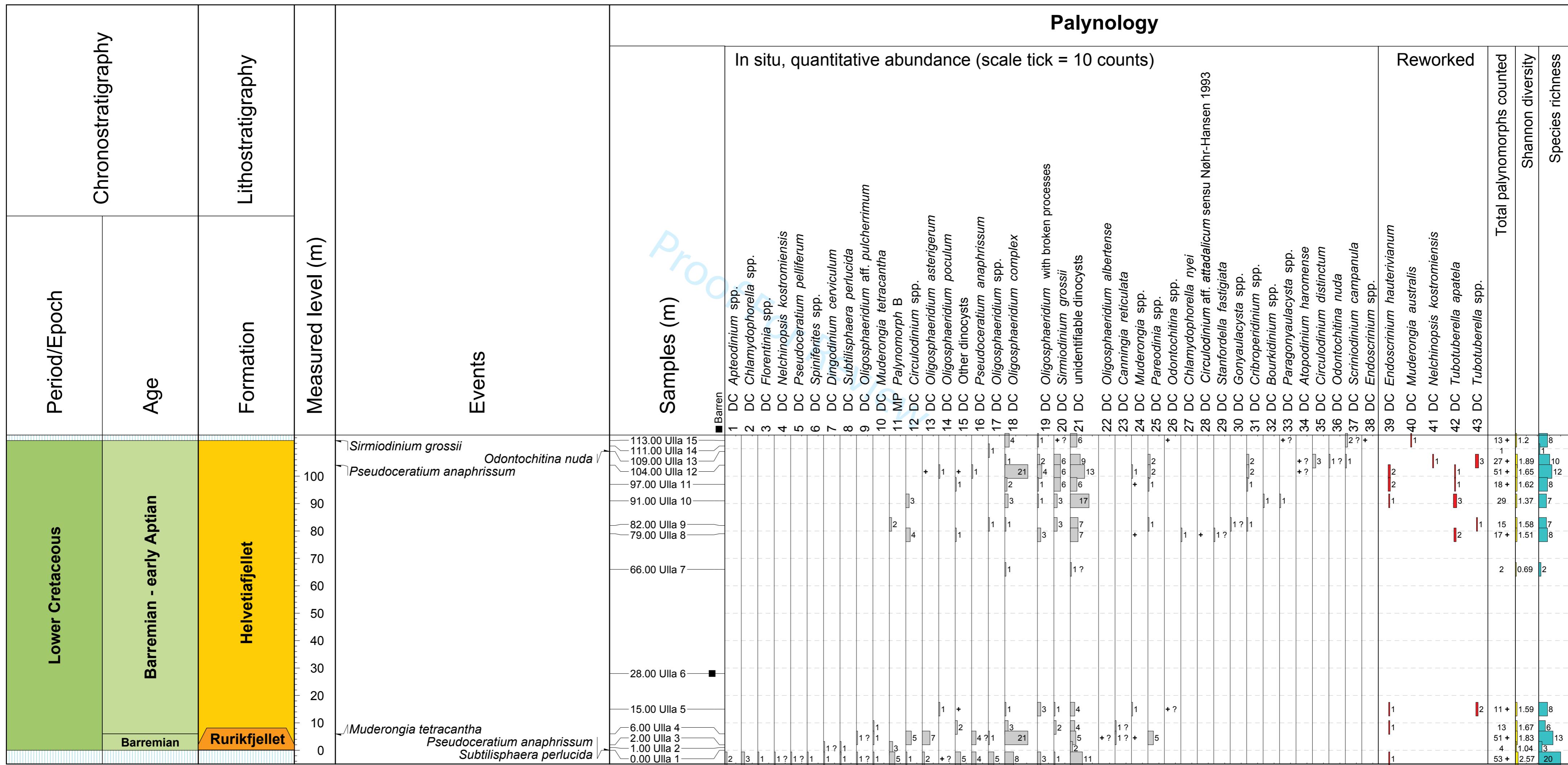


Figure S3. Distribution of dinocysts in the Ullaberget outcrop section. This file contains range charts with the quantitative data of the palynomorphs recognised in this study. The palynomorphs are arranged after the first occurrence (FO), R – reworked, DC – dinocyst, AC – acritarch, MP – palynomorph,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

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Supplementary material

Figure S4: DH1

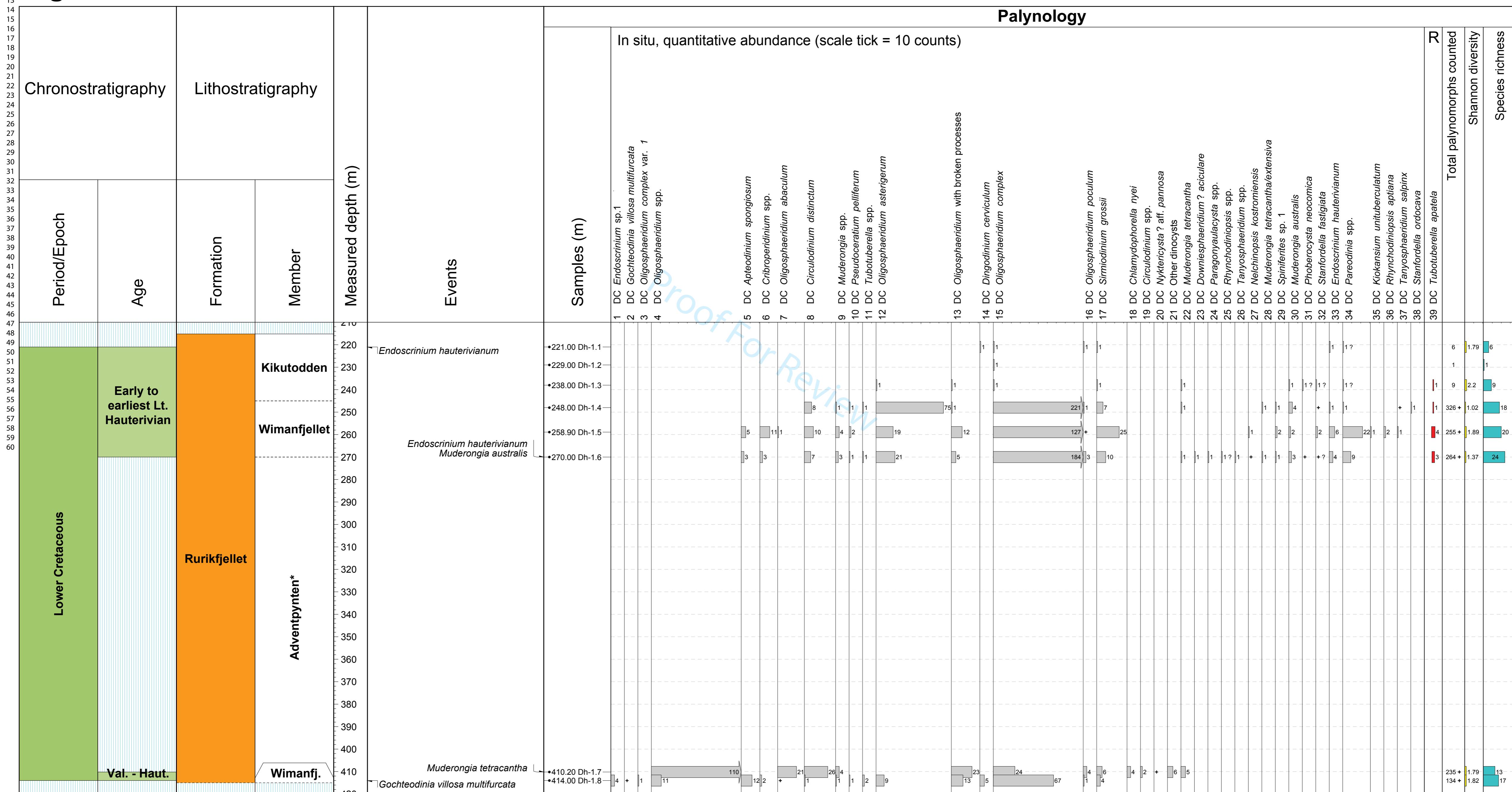


Figure S4. Distribution of dinocysts in the DH1 well. This file contains range charts with the quantitative data of the palynomorphs recognised in this study.

The palynomorphs are arranged after the first occurrence (FO), R – reworked, DC – dinocyst, AC – acritarch, MP – palynomorph, “+” – present outside counting, “?” – questionable

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12 **Figure S5: DH2**
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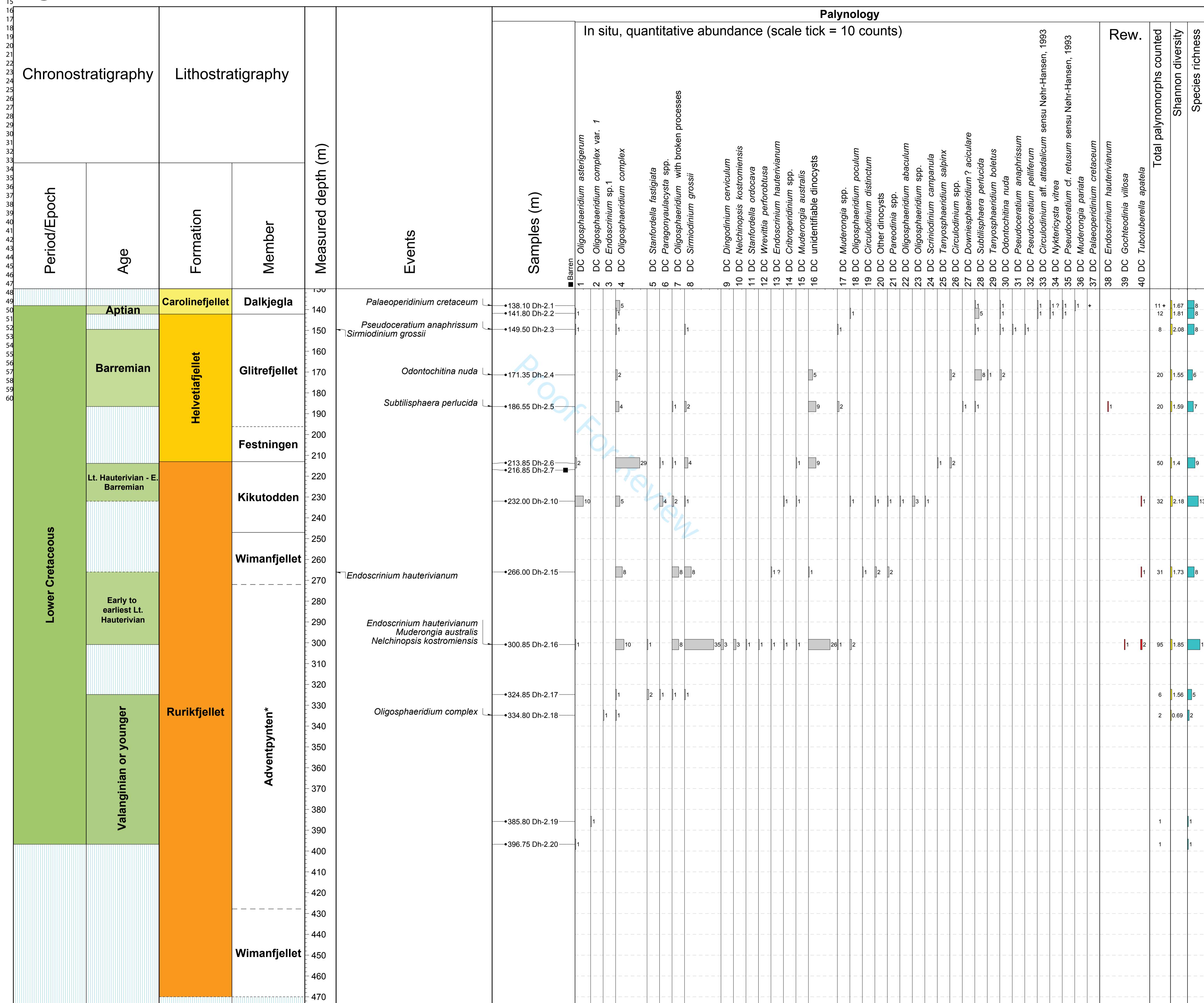


Figure S5. Distribution of dinocysts in the DH2 well. This file contains range charts with the quantitative data of the palynomorphs recognised in this study. The palynomorphs are arranged after the first occurrence (FO), R – reworked, DC – dinocyst, AC – acritarch, MP – palynomorph, “+” – present outside counting, “?” – questionable

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Supplementary material

Figure S6: DH5R

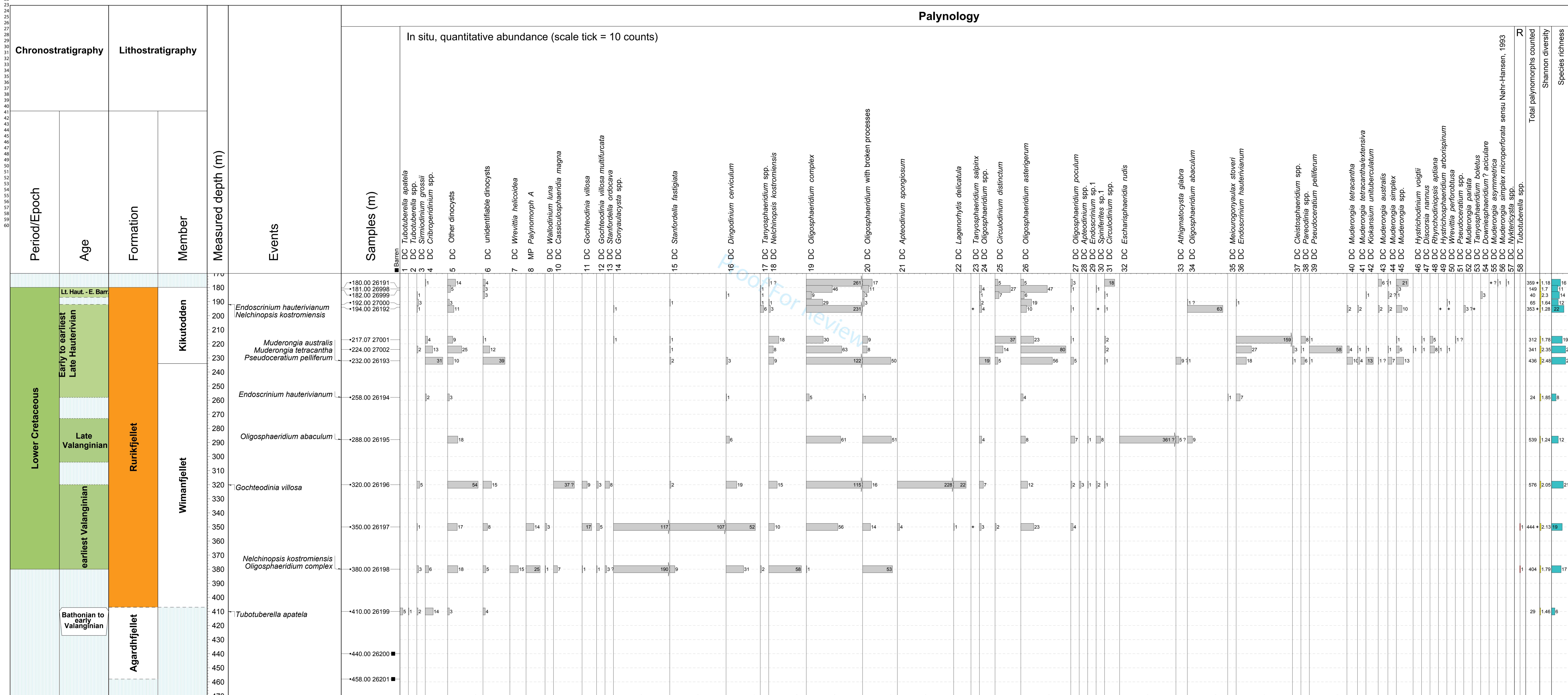


Figure S6. Distribution of dinocysts in the DH5R well. This file contains range charts with the quantitative data of the palynomorphs recognised in this study.

The palynomorphs are arranged after the first occurrence (FO), R – reworked, DC – dinocyst, AC – acritarch, MP – palynomorph, “+” – present outside counting, “?” – questionable