Marine microplankton biostratigraphy of the Volgian-Ryazanian boundary strata, western Barents Shelf

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Dinoflagellate cyst assemblages from Volgian-Ryazanian boundary strata of the western Barents Shelf are generally of low species diversity and moderate to low abundance. The assemblages can be correlated with the *Paragonyaulacysta?borealis* assemblage Zone as defined in Arctic Canada and Northwest Siberia. The age of this zone is Late Volgian to Ryazanian, covering the *Chetaites chetae, Heteroceras kochi* and *Surites analogus* ammonite zones. Most of the dinoflagellate cyst biostratigraphic key species used for zonations in the sub-Boreal realm appear to be absent in the Barents Sea region, hampering the possibilities for long-distance correlations with successions in the North Sea and northern Tethys areas. There are no dinoflagellate cyst extinctions or first appearances which can be directly used to determine the Volgian-Ryazanian stage boundary in the region. However, a prolific bloom of *Leiosphaeridia* (prasinophytes), probably induced by the Mjølnir meteorite impact, is an excellent marker horizon for the Volgian-Ryazanian boundary (142.2 +/- 2.6 Ma) deposits of the shelf areas adjacent to the impact site.

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Introduction

During the past 25 years since the Norwegian part of the Barents Shelf was opened for hydrocarbon exploration, a large amount of geological data has been collected by the oil industry. Dinoflagellate cysts are recognised as a prime tool for biostratigraphic dating and for correlations of the Jurassic-Lower Cretaceous hydrocarbon source and reservoir rocks, but little information has been published (Bailey 1993, Smelror et al. 1998, Wierzbowski & Århus 1990, Wierzbowski et al. 2002, Århus 1991a, Århus et al. 1990). This is also the case on Svalbard, where the north-western part of the shelf succession has been uplifted and exposed (Bjærke 1977, 1978, 1980, Smelror 1988, 1991, Smelror & Aarhus 1989, Grøsfjeld 1991, Århus 1991b, 1992, Bailey 1993, Smelror & Below 1993,). This study documents the occurrence and stratigraphical distribution of dinoflagellate cysts in Volgian - Ryazanian boundary strata at two different sites on the western Barents Shelf; the Mjølnir impact crater (core 7329/03-U-01), which is located in the central part of the shelf, and the Troms III area (core 7018/05-U-01) off northern Norway (Fig. 1).

The Mjølnir Crater was formed at the time of the Volgian-Ryazanian boundary (142.2 +/- 2.6 Ma), when an asteroid in the range of 1.5-2 km in diameter hit the 300-400 m-deep northern part of the 'Kimmeridgian Clay Sea'(i.e. the paleo-Barents Sea) (Gudlaugsson 1993, Dypvik et al. 1996, Smelror et al. 2001a). The impact created the 40 km diameter Mjølnir Crater, displaced significant amounts of

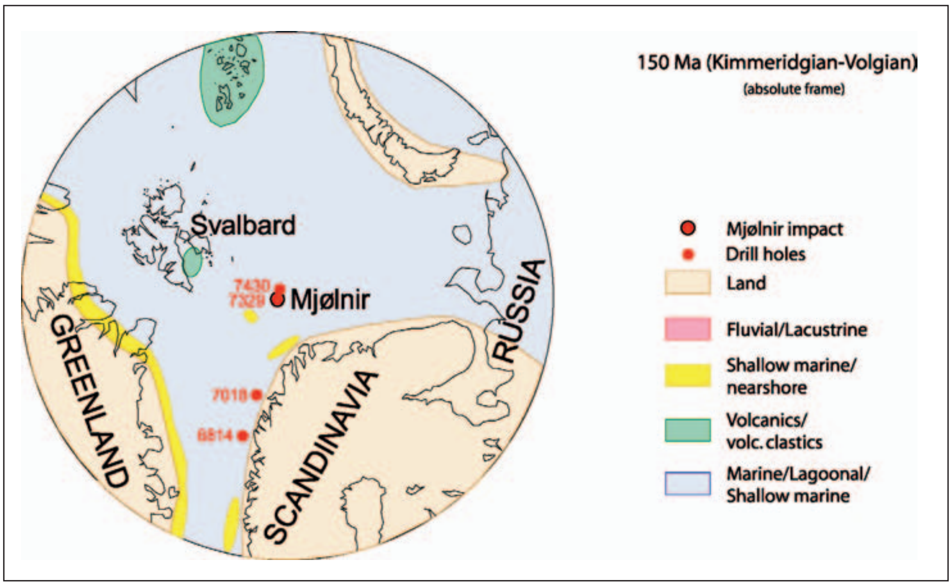
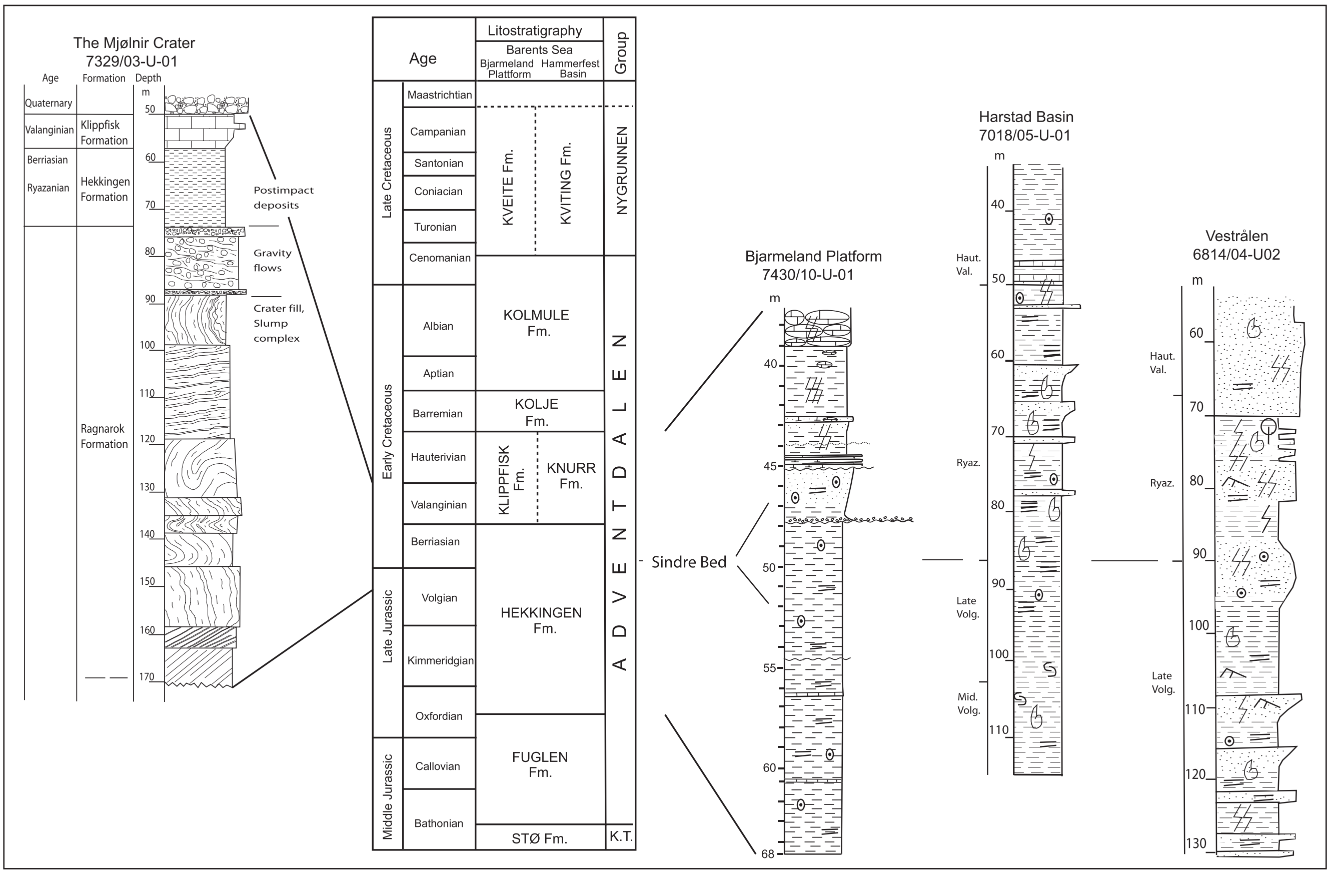


Fig. 1. Late Jurassic paleogeography and location map of the Mjølnir Crater on the central Barents Shelf, showing the positions of the boreholes discussed in the present study.



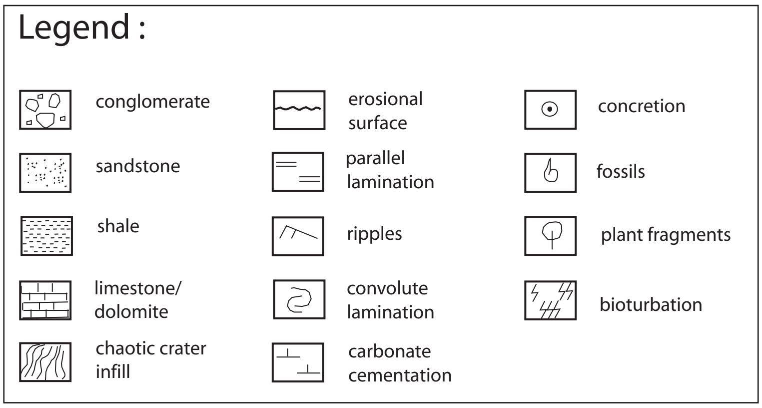


Fig. 2. Core logs and lithostratigaphical correlations of 7329/03-U-01, 7430/10-U-01, 7018/05-U-01 and 6814/04-U-02. For details on the phytoplankton in core 7430/10-U-01, see Smelror et al. (1998, 2001b).

The other location included in the study comprises borehole 7018/05-U-01 in the Troms III area (Fig. 1). This borehole location is 500 km south of the impact target area, and is located outside the main area of the ejecta fallout (Shuvalov et al. 2002). Consequently, no impact evidence such as shocked quartz, micro-tectites or anomalies of siderophilic elements (i.e. ir-peaks) has been found at this location. Good recovery of macrofossils (ammonites, bivalves) and the correlative phytoplankton bloom discussed in the following, provide, however, good means for detailed stratigraphical correlation with the contemporaneous strata in the Mjølnir Crater (i.e. borehole 7329/03-U-01).

sediments and sedimentary rocks from the crater site, and generated large-amplitude tsunamis. Ejecta from the impact were displaced over large areas of the paleo-Barents Sea shelf. There is no evidence of a major biotic extinction or changes in diversity related to the impact event, but a significant turnover in the overall compositions of the microfossil assemblages has been found within the impact-influenced strata. A discussion of the environmental changes and biotic responses following the impact is outside the scope of the present paper. Information can, however, be found in Bremer et al. (2001, 2004), Smelror (2000), Smelror et al. (2001b), and Smelror & Dypvik (2005).

Lithostratigraphy of the studied cores

The Mjølnir Crater

Lithological descriptions of the Mjølnir Crater core 7329/03-U-01 have been published by Smelror et al. (2001a), Sandbakken & Dypvik (2001) and Dypvik et al. (2004). The core is divided into three main lithostratigraphic units: the Ragnarok Formation representing the re-deposited crater infill, the Hekkingen Fomation representing the oldest post-impact deposits, and the overlying condensed carbonates assigned to the Klippfisk Formation (Fig. 2).

The Ragnarok Formation comprises the interval from the base of the core at 171.08 m up to 74.05 m (Dypvik et al.

2004.). This interval is divided into two units: unit I (171.08-88.35 m) consists of a mixture of Middle and Upper Triassic to Lower Jurassic target rocks impacted by the asteroid and re-deposited as fallout into the crater. The succeeding, and much thinner unit II (88.35-74.05 m), is interpreted as gravity-flow deposits with three main subunits recognised: IIA (88.35-87.43 m) is a conglomeratic debris flow of sand and small pebbles, IIB (87.43-75.73 m) represents a mudflow deposit, while IIC (75.73-74.05 m) consists of at least three separate gravity flows of a sand, silt and clay mixture. The sediments composing unit II most likely originated from the uplifted central high of the crater.

The Ragnarok Formation is overlain by Lower Ryazanian, dark brown to black, organic-rich shale of the Hekkingen Formation. Deposition of the Hekkingen Formation was initiated prior to the impact during the Late Oxfordian to Volgian, and dark shales assigned to this formation continued to accumulate during the Ryazanian after the impact event. In core 7329/03-U-01, the post-impact deposits of the Hekkingen Formation extend from 74.05 to 57.20 m in the core. The Hekkingen Formation has a wide distribution on the western Barents Shelf and is the most prolific hydrocarbon source rock in the area (Leith et al. 1993, Nøttvedt et al. 1993, Smelror 1994, Dallmann 1999, Smelror et al. 2001c, Bugge et al. 2002).

The Hekkingen Formation is capped by Valanginian condensed carbonates and marls of the Klippfisk Formation (Smelror et al. 1998) extending from 57.20 m to 50.00 m. The upper 50 m of the drilled succession comprises Quaternary overburden.

Core 7018/05-U-01

A brief lithostratigraphical description of core 7018/05-U-01 has previously been published in Smelror et al. (2001c). The Upper Volgian-Lower Ryazanian deposits of the Hekkingen Formation (Krill Member) consist of dark to very dark grey claystones, which are mostly finely laminated, with abundant carbonate beds (Fig. 2). Bioturbation is generally absent, except for some horizons close to the Volgian-Ryazanian boundary at around 88 m. Ammonites and bivalves are found at some levels, and a few coalified fragments are also present.

The laminated beds, the lack of bioturbation and the sparse benthic fauna, combined with the high organic content, indicate that sedimentation took place in a distal marine shelf environment, with fluctuating anoxic and hypoxic (0-0.2 ml O_2/l H_2O) conditions at the sea bottom.

Material and methods

The present study material includes 45 samples from core 7329/03-U-01 and 12 samples from core 7018/05-U-01. All samples were prepared for palynological analyses according to standard preparation techniques (HCL, HF treatment, sieving of residues using a 15 µm sieve, mounting in glycerin-jelly) at the Geological Survey of Norway (NGU Lab).

In addition to the preparations for ordinary qualitative and semi-quantitative palynological analyses, 32 post-impact samples from the Mjølnir Crater core 7329/03-U-01 were prepared for quantitative analyses. This involved the use of a method of adding a known number of *Lycopodium* spores to a known amount of dry sedimentary rock in order to determine the absolute amount of palynomorphs in the shale samples. The technique is described in details by Stockmarr (1971) and is commonly used in Quaternary palynology, but has rarely been attempted on pre-Quaternary material. The number of indigenous palynomorphs per gram of sample (P) is calculated by using the formula:

P = *Lycopodium* spores added to sample X indigenous palynomorphs counted / weight of sample (grams) X *Lycopodium* spores counted

The number of counted indigenous palynomorphs was more than 300 for each of the studied samples.

The reliability of the method has not been tested, but it has provided consistent results when applied to Paleogene material from the Norwegian Sea (Manum et al. 1989). In our present datasets we found overall agreement between quantitative data and the 'semi-quantitative' percentage distributions among the palynomorph groups in the datasets previously presented by Bremer et al. (2001, 2003) from the same core interval.

The slides containing the specimens illustrated in Fig. 8 are stored in the collection of the Palaeontological Museum (University of Oslo), Oslo, Norway.

Marine microplankton assemblages

The Mjølnir Crater core (7329/03-U-01)

The marine microfloras of the oldest post-impact deposits of the Mjølnir Crater core (74.05-64.9 m) contain dominantly leiospheres comprising 60-90% of the total palynofloras (Fig. 3). The levels of dinoflagellate cysts are relatively moderate to low, and the diversity varies from 4 to 18 species in each sample (Figs. 4, 5). In addition, these samples also contain common freshwater algae identified as juvenile specimens of *Botryococcus*. This unique combination of abundant leiospheres and abundant freshwater algae in the Hekkingen Formation has previously been reported only from the ejecta-bearing strata recovered from borehole 7430/10-U-01 located about 30 km northeast of the Mjølnir Crater (Fig. 1) (Smelror et al. 2001b), and in the upper Agardhfjellet Formation at Janusfjellet on Svalbard (Dypvik et al. 2000).

The overlying uppermost deposits of the Hekkingen Formation (sampled at 64.9-58.5 m) contain significantly fewer leiospheres; and the marine microflora is dominated by dinoflagellate cysts. The abundance and diversity of dinoflagellate cysts in this interval are, however, not significantly different from those of the oldest post-impact deposits. The diversity varies from 9 to 11 species per sample (Fig. 5). These marine palynomorph assemblages are comparable to those found in the uppermost Hekkingen

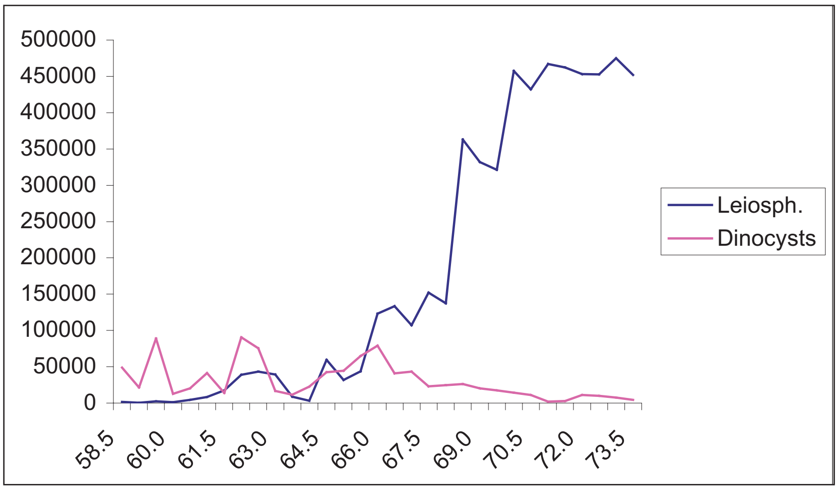


Fig. 3. The quantitative distribution (cysts/gram sediments) of dinoflagellate cysts and leiosphers in the Lower Ryazanian post-impact strata of the Mjølnir Crater.

Formation elsewhere on the Barents Shelf and Svalbard (Bjærke 1977, 1980, Wierzbowski & Århus 1990, Smelror et al. 1998).

Core 7018/05-U-01

The Upper Volgian-Lower Ryazanian strata of borehole 7018/05-U-01 contain well preserved and moderately rich assemblages of marine phytoplankton. The diversity of dinoflagellate cysts, however, is generally moderate, with 11 to17 species recorded in each sample (Figs. 6, 7). A reduced diversity with only seven species was found in the sample at level 87.1 m. Dinoflagellate cysts are common, comprising between 30-50 % of the total palynomorph assemblages up to 90.1 m, and in the investigated interval from 86.3 to 83.1 m.

In the interval from 89.3 to 87.1 m, a distinct bloom of leiospheres is found. Here dinoflagellate cysts are subordinate to the marine prasinophytes (Fig. 6), and comprise only 12-20% of the total palynomorph assemblages. The leiospheres comprise around 50-60% of the assemblage. Although pronounced, the leiosphere acme is somewhat reduced in size compared to the Mjølnir Crater (Fig. 3).

It should also be noted that, in contrast to the similar leiosphere bloom in the earliest Ryazanian beds of the Mjølnir Crater core, the leiosphere acme in 7018/05-U-01 is not associated with abundant *Botryococcus*.

Dinoflagellate cyst biostratigraphy

Dinoflagellate cyst zonations for the lowermost Cretaceous of Northwest and southern Europe have been published by several authors, amongst which those by Davey (1979), Woollam & Riding (1983), Riding & Thomas (1992), Monteil (1993) and Leereveld (1997) are the most cited. More recently, new zonations for the Jurassic and Lower Cretaceous of the Russian Platform and northern

7329/03-U-01	Early Ryazanian												
Sample depth (m):	58.5	59.0	59.5	60.0	60.5	61.5	62.0	63.0	64.9	67.1	70.5	72.8	73.9
Dinoflagellate cysts:													
Atopodinium haromense	•	•	•	•	•		•	•		•	•	•	•
Cassiculosphaeridia magna	•	•	•	•	•	•	•	•		•	•	•	•
Chlamydophorella sp. A	•	•						•	•	•	•	•	•
Cribroperidinium spp.	•	•	•	•	•	•	•	•			•	•	•
Escharisphaeridia pocockii	•	•		•	•	•			•			•	•
Paragonyaulacysta borealis	•	•	•	•	•	•	•	•			•	•	•
Sentusidinium sp. A	•	•	•	•	•								
Sentusidinium spp.	•	•		•	•	•		•			•	•	•
Sirmiodinium grossii	•	•	•	•	•	•	•	•	•		•	•	•
Chytroeisphaeridia hyalina		R											
Escharisphaeridia psilata		•	•				•	•		•		•	•
G. jurassica var. longicornis		R											
Pareodinia halosa		•		•	•						•		•
Rhynchodiniopsis martonense		•						•					
Scriniodinium crystallinum		R											
Senoniasphaera jurassica		•	•	•	•					•		•	•
Tubotuberella apatela		•	•	•	•	•		•	•	•	•	•	•
Valensiella ovula		•			•			•			•	•	•
Isthmocystis distincta			•					•					
Leptodinium sp. A			•		•						•		
Dingodinium tuberosum				•							•		•
Endoscrinium anceps				•									
Kalyptea stegasta				•		•							
Pareodinia ceratophora				•				•					
Ctenidodinium sp. A				•									
Cribroperidinium globatum					•			•			•		•
Escharisphaeridia rudis							•	•					•
Gochteodinia villosa							•						
Prolixisphaer. parvispinum							•				•	•	
Wallodinium krutzschii								•					
Scriniodinium inritibilum											•	•	•
Prasinophytes / Acritarchs:													
Leiosphaeridia spp.	•	•	•	•	•	•	•	•	•	●	●	●	●
Pterospermopsis spp.					•						•		
Veryhachium sp.					•								

Fig. 4. Distribution chart of dinoflagellate cysts in the Lower Ryazanian post-impact strata (i.e. the Hekking Formation) of core 7329/03-U-01. R = reworked dinocysts.

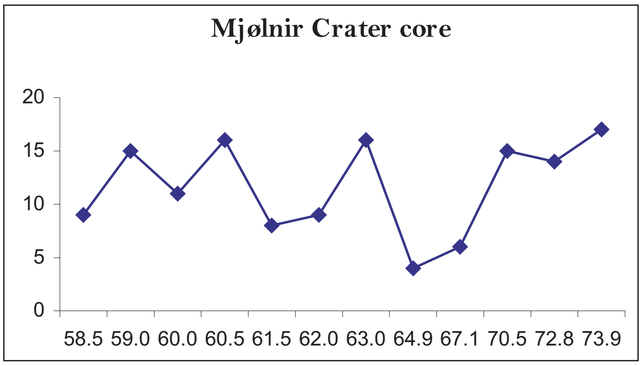


Fig. 5. Dinoflagellate cyst diversity (number of species/sample) in the Lower Ryazanian post-impact strata of core 7329/03-U-01 (Mjølnir Crater core).

Siberia have been published by Riding et al. (1999) and for Northwest Siberia by Lebedeva & Nikitenko (1999).

Most of the proposed zonations are of limited value for biostratigraphical correlations and age determinations in the Barents Sea Region. This is due to the fact that in most of the European zonations, key species are absent or very rare in this high Boreal region. For instance, none of the species used in the Tithonian and Berriasian of the southern European zonations of Monteil (1993) and Leereveld (1997) have been found in the time-equivalent interval of the Barents Shelf. Several key species used in the zonations by Davey (1979), Woollam & Riding (1983) and Riding & Thomas (1992) also seem to be missing or are rare on the western Barents Shelf.

Mjølnir Crater core

In the material from core 7329/03-U-01, one specimen of the marker species *Gochteodinia villosa* was recorded (Fig. 4). The presence of this species at 62.0 m allows a correlation to the *Gochteodinia villosa* (Gvi) Interval Biozone of Riding & Thomas (1992). The zone spans the Portlandian to Ryazanian of the British Jurassic. Riding & Thomas (1992) subdivided the Gvi Interval Biozone into two Sub-biozones a and b. The older Sub-biozone was defined as the interval between the first appearance datum (FAD) of *Gochteodinia villosa* and the last appearance datum (LAD) of *Dinogodinium tuberosum* and *Egmontodinium polyplacophorum*. The age of this sub-zone corresponds to the Oppressus to Primitivus ammonite zones. *Dingodinium tuberosum* occurs at 73.9 m, 70.5 m and 60.0 m in this core. According to Riding & Thomas (1993), the last occurrence of this species can be used to delineate the top of their Gvi Sub-biozone a, which they correlated with the boundary between the Late Portlandian Primitivus and Prelicomphalus ammonite zones. The oldest post-impact strata in core 7329/03-U-01 have previously been dated as Early Ryazanian based on macrofossils (Smelror et al. 2001a), and based on this age determination, it appears that *D. tuberosum* has a younger last appearance datum on the Western Barents Shelf compared to Britain. This seems also to be the case with I, which according to Riding & Thomas (1992), has its LAD at the base of the Oppressus ammonite zone in the British Jurassic, but is found up to 59.0 m in the Lower Ryazanian strata in core 7329/03-U-01. The consistent occurrence of *S. jurassica* suggests that reworking is unlikely; but since reworked, younger, late Middle Jurassic

7018/05-U-01	Early Ryazanian- Late Volgian											
Sample depth (m):	83.1	85.5	86.3	87.1	88.5	89.3	90.1	90.9	91.1	92.3	93.6	94.6
Dinoflagellate cysts:												
Aldorfia dictyota	•	•										
Apteodinium daveyi	•	•	•	•	•	•						
Atopodinium haromense	•	•			•	•	•	•	•	•		
Cassiculosphaeridia magna	•					•		•	•	•		
Chlamydophorella sp.	•	•	•		•				•			
Circulodinium spp.	•	•	•	•	•	•	•	•	•	•	•	•
Cribroperidinium globatum	•	•				•	•		•			•
Cribroperidinium spp.	•	•	•		•				•		•	•
Dichadogonyaulax pannea	•	•										
Escharisphaeridia pocockii	•		•				•					
Paragonyaulacysta borealis	•	•	•	•	•	•	•	•	•	•	•	
Sentusidinium spp.	•	•						•		•		•
Sirmiodinium grossii	•	•	•	•	•	•	•	•	•		•	•
Escharisphaeridia psilata	•	•		•		•		•	•			•
Pareodinia halosa	•	•	•		•		•	•	•	•	•	•
Tubotuberella apatela	•		•	•	•	•	•			•	•	•
Tubotuberella dangeardii	•	•	•		•							
Scriniodinium spp.		•	•	•	•	•	•	•	•		•	•
Apteodinium sp. indet			•		•	•						
Gonyaulacysta cf. helicoidea					•		•		•	•	•	•
Valensiella ovula						•	•	•	•	•	•	•
Heslertonia? pellucida							•					
Cometodinium habibii								•				
Pareodinia ceratophora									•			
Cribroperidinium gigas									•			
Prolixosphaeridium anasillum									•			
Lanterna saturnalis										•	•	
Scriniodinium cf. attadalense										•	•	
Pareodinia asperata												•
Wallodinium krutzschii												•
Prasinophytes / Acritarchs:												
Leiosphaeridia spp.	•	•	•	●	●	●	•	•	•	•	•	•

Fig. 6. Distribution chart of dinoflagellate cysts in the Upper Volgian - Lower Ryazanian strata (i.e. the Hekking Formation) of core 7018/05-U-01.

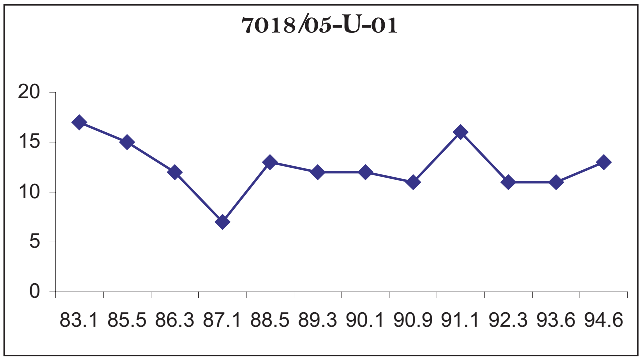


Fig. 7. Dinoflagellate cyst diversity (number of species/sample) in the Upper Volgian - Lower Ryazanian strata of core 7018/05-U-01.

dinoflagellate cysts (i.e. *Chytro-eisphaeridia hyalina, Gonyulacysta jurassica var. longicornis, Scrini-odinium crystallinum)* are found at 59.0 m (Fig. 4), this possibility cannot be excluded.

Core 7018/05-U-01

The studied samples from this core contain mostly *Circulodinium* spp., *Paragonyaulacysta borealis, Sirmiodinium grossii, Tubotuberella apatela* and *Valensiella ovula*, in association with a moderate number of other species (Fig. 6). Stratigraphically significant spec-ies are rare, and in general the dinoflagellate cyst recovery is of limited use for a precise age determination.

Apteodinium daveyi is restricted to the strata from 89.3 m to the uppermost sample at 83.1 m. This species has previously been reported from the latest Jurassic-earliest Cretaceous of the North Sea region (Poulsen 1996), and appears to be a reliable biostratigraphical marker for this interval. *Dichadogonyaulax pannea* is found at 83.1 m and 85.5 m. According to Riding & Thomas (1992), this species does not range above the Oppressus ammonite zone in Britain. The present data, however, suggest a somewhat extended range into the earliest Ryazanian on the western Barents Shelf.

A single occurrence of *Cribroperidinium gigas* at 91.1 m may be of biostratigraphical value, as this species is well known from mid Volgian to the Ryazanian of the North Sea region (Bailey 1993). *Heslertonia? pellucida*, which is recovered at 90,1 m, has its last appearance datum in the Early Ryazanian of the North Sea region (Poulsen 1996). The persistent occurrence of *Cribroperidinium globatum* may further be of some biostratigaphical significance, as this species is not known to range above the Early Ryazanian (i.e. above the *H. kochi* ammonite zone).

The persistent occurrence of *Paragonyaulacysta borealis* through the interval studied allows a correlation with the *Paragonyaulacysta? borealis* assemblage Zone as defined by Lebedeva & Nikitenko (1999). *Gochteodinia villosa* was not found within the present examined samples, but recovery of this key species higher up in the core at 44.9 m and 48.5 m, allows a correlation with the *Gochteodinia villosa* Interval Biozone of Riding & Thomas (1992) for the uppermost interval of the Hekkingen Formation in core 7018/05-U-01.

Regional correlations of dinoflagellate cyst assemblages

Based on the common occurrence of *Paragonyaulacysta borealis,* the present dinoflagellate cyst assemblages from the Lower Ryazanian post-impact deposits in core 7329/03-U-01, and from Upper Volgian-Lower Ryazanian strata in core 7018/05-U-01, can be correlated with the *Paragonyaulacysta?borealis* assemblage Zone as defined by Lebedeva & Nikitenko (1999). The age of this assemblage zone is Late Volgian to Ryazanian, covering the *Chetaites chetae, Heteroceras kochi* and *Surites analogus* ammonite zones. Similar low-diversity *Paragonyulacysta borealis* assemblages have previously been reported from time-equivalent strata in Arctic Canada (Brideaux & Fisher 1976), in North Greenland (Håkansson et al. 1981), on the Barents Shelf (Wierzbowski & Århus 1990, Smelror et al. 1998) and in Arctic Russia (Ilyina 1988).

An algal bloom marking the Volgian-Ryazanian boundary beds

One important aspect in the study of the Mjølnir impact crater has been to determine how the phytoplankton groups responded to the environmental changes caused by the impact. In a study of ejecta-bearing, Volgian-Ryazanian boundary strata at core-site 7430/10-U-01, 30 km northeast of the Mjølnir Crater (Fig. 1), Smelror et al. (2001b) found remarkably high abundances of prasinophycean algae assigned to the genus *Leiosphaeridia*. A contemporaneous and similar acme of prasinophytes was also found in the Volgian-Ryazanian boundary strata at Janusfjellet on Svalbard (Dypvik et al. 2000). These algal blooms are associated with layers of high iridium anomalies at both locations. In addition, grains of shocked quartz have been found in the beds with the prasinophyte acme in borehole 7430/10-U-01 (Dypvik et al. 1996). Both biostratigraphy (Smelror et al. 2001a) and seismic control provide direct evidence for the ejecta-crater correlation.

In the post-impact strata of the present Mjølnir Crater core 7329/03-U-01, we found a more prolific abundance peak of *Leiosphaeridia*. This acme of *Leiosphaeridia* reaches 513,000 specimens per gram of sediment (post-compacted) in the lowermost sample at 74 m (below the top of the core). Abundances remain at around 450,000 specimens/gram sediment up to about 71 m (Fig. 3). From 69.5-68.5 m the abundance varies between 320,000 and 360,000 specimens/gram sediment, and from 68-66 m the abundance drops to between 107,000 and152,000 specimens/gram sediment. From 65.5 m and to the uppermost sample at 58.5 m the abundance drops further and is reduced to between 50,000 specimens/gram (at 64.5 m) and around 500 specimens/gram sediment (at 59 m). The prolific abundance peaks documented here from the oldest post-impact deposits are comparable to those reported from 'algal blooms' in modern and Holocene sediments.

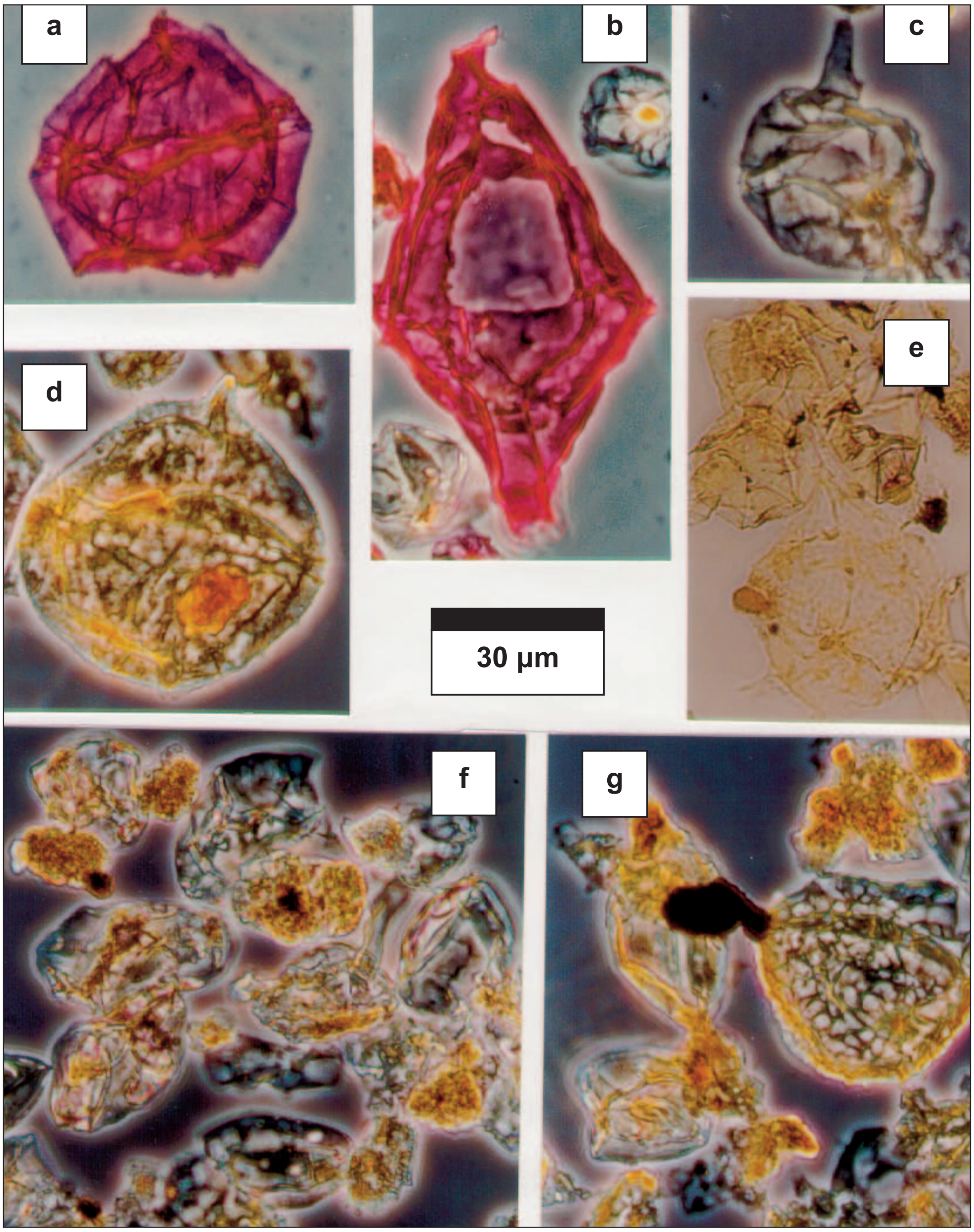


Fig. 8. Palynomorphs from the oldest post-impact deposits in core 7329/03-U-01 (Mjølnir Crater) and core 7430/10-U-01. The 30µm scale indicates the enlargement of the palynomorphs. (a) *Sirmiodinium grossii* Alberti 1961, 7329/03-U-01, sample 88.20 m; (b) *Tubotuberella apatela* (Cookson & Eisenack) Ioannides et al. 1977, 7329/03-U-01, sample 88.20 m; (c) *Pareodinia ceratophora* Deflandre 1947, 7329/03-U-01, sample 88.20 m; (d) *Cribroperidinium globatum* (Gitmez & Sarjeant) Helenes 1984, 7329/03-U-01, sample 88.20 m; e) Palynofacies from pre-impact deposits in core 7430/10-U-01, 53,0 m; f) Bloom of *Leiosphaeridia sp*. and *Botryococcus* sp. in the ejecta deposits (Sindre Bed) in core 7430/10-U-01, 51,0 m; g) as Fig. 8g, with the dinoflagellate cysts *Cassiculosphaera reticulata* Davey 1969 to the right.

The bloom of leiospheres is also found in the Volgian-Ryazanian boundary strata in borehole 7018/05-01 offshore Troms (i.e. 500 km SW of the Mjølnir Crater). In this core, the algal peak is recorded from level 89.28-87.11 m, where the leiospheres comprise between 50 and 65% of the total palynomorph assemblage. In contrast, no traces of the algal bloom have been found in borehole 6814/04-U-01 located off northern Nordland about 800 km south of the site of the impact (Figs. 1 & 2).

The prolific bloom of *Leiosphaeridia* and the low content of dinoflagellate cysts in the sediments deposited first after the impact, apparently shows that these two groups of marine microplankton responded differently to the abrupt environmental change caused by the impact. It appears that the leiospheres were able to adapt rapidly to the new situation and were able to take advantage of the large amounts of suspended nutrients in the water column. In contrast the dinoflagellates were stressed by the sudden change, and the number of cysts produced became significantly reduced. There could be several reasons for this difference in response, including different tolerance of salinities and seawater pH, and different length of time used for reproduction and growth (i.e. difference in duration of their life cycles).

The regional distribution of this bloom event, reaching from the Mjølnir Crater and up to Svalbard some 450 km to the north, and the Troms III offshore areas some 500 km to the south, points towards an extensive ocean eutrophication (Smelror et al. 2000, Smelror & Dypvik 2005). Smelror et al. (2001a) suggested that the algal bloom was possibly induced by the large amounts of nutrients released into the water column by the impact. Presumably, the period of eutrophic conditions was relatively short (Bremer et al. 2004). The short duration and the regional extent of this bloom make it a reliable stratigraphical marker. The event is previously dated by bivalves and foraminifera recovered in association with the 'bloom strata' in cores 7329/0-U-01 and 7430/10-U-01 (Smelror et al. 2001a). In borehole 7018/05-U-02, an ammonite of the genus *Borealites* sp. was found at 87.95 m, i.e. within the beds with the algal bloom which serves as a marker unit between 89.28 and 87.11 m. This finding supports the previous assignment (Smelror et al. 2001a) of an age close to the Volgian-Ryazanian boundary for the impact event.

Summary and conclusions

Dinoflagellate cyst assemblages in the oldest post-impact deposits of core 7329/03-U-01 from inside the Mjølnir Crater, and from the Upper Volgian-Lower Ryazanian strata in borehole 7018/05-U-01, can be correlated with the *Paragonyaulacysta?borealis* assemblage Zone as defined by Lebedeva & Nikitenko (1999). The age of this assemblage zone is Late Volgian to Berriasian, covering the *Chetaites chetae, Heteroceras kochi* and *Surites analogus* ammonite zones. The dinoflagellate cyst biostratigraphy supports the previous Volgian-Ryazanian boundary age for the Mjølnir impact, as suggested by the macrofossils and foraminifera (Smelror et al. 2001a).

Most of the biostratigraphical markers used for zonations in the sub-Boreal realm appear to be missing, hampering the possibilities for long-distance correlations to the North Sea and northern Tethys areas. There are no species which can be directly used to determine the Volgian-Ryazanian stage boundary in the region.

A prolific bloom of prasinophytes (*Leiosphaeridia*), probably induced by the Mjølnir meteorite impact, was recognised in the oldest post-impact strata in the Mjølnir Crater core (7329/03-U-01), in the ejecta-bearing strata in core 7430/10-U-01 from 30 km north of the crater, and from time-equivalent beds on Svalbard and offshore Troms, northern Norway. These bloom deposits make an excellent marker horizon for the Volgian-Ryazanian boundary (142.2 +/- 2.6 Ma) strata on the shelf areas adjacent to the impact site, and at distances of more than 450 m north and 500 km south of the crater.

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