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Traces of the marine Mjølnir impact event

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Abstract

The sediments of the Barents Sea region carry geological information reflecting the influence of the Mjølnir impact event at the Volgian–Ryazanian boundary, even in remote locations without any direct macroscopic geological and paleontological evidence. The ejecta distribution in the area was probably highly asymmetrical, but geological and related geochemical and paleontological signals in the sediments show the environmental consequences of the impact (e.g., impact generated waves, tsunami, currents, changing redox conditions) to be more symmetrically distributed. The influences of the asteroid impact are seen in the distributional anomalies (Ir, Th, U, Ni, Cr and prasinophycean algae of the genus *Leiosphaeridia*) of studied cores from 30 to 500 km away from the crater. A core from about 800 km southwest of the crater carries no obvious direct evidence of the impact.

This study shows that additional geological parameters other than, e.g., shocked quartz, spherules, Ir-anomalies, may carry information indicating possible environmental impact influence even more than 10 crater diameters away from the impact site.

Keywords: Mjølnir impact; Environmental effects; Trace elements; Microflora

1. Introduction

1.1. Geological background

The Mesozoic succession of the Barents Sea region is dominated by siliciclastic sedimentation. During the Jurassic and Cretaceous in particular clay and silt sedimentation took place (Fig. 1) (Dypvik et al., 1991a,b). In Late Jurassic and earliest Cretaceous, the fine-grained sedimentation in central parts of the epicontinental paleo-Barents Sea (Fig. 1) sporadically was disrupted by storm and storm generated currents, causing shifting from anoxic to hypoxic sea-floor conditions. These shale and siltstone dominated beds today form the Hekkingen Formation (Figs. 2 and 3). In the marginal areas of the paleo-Barents Sea basin, shallow marine to deltaic environments and wave and tidal dominated sedimentation took place (Worsley et al., 1988; Leith et al., 1993; Mørk et al., 1999). The well-known Jurassic/Cretaceous sections of Svalbard (the Janusfjellet Subgroup) can be correlated with those from the Barents Sea (Figs. 2 and 3) based both on detailed lithological and paleontological characteristics.

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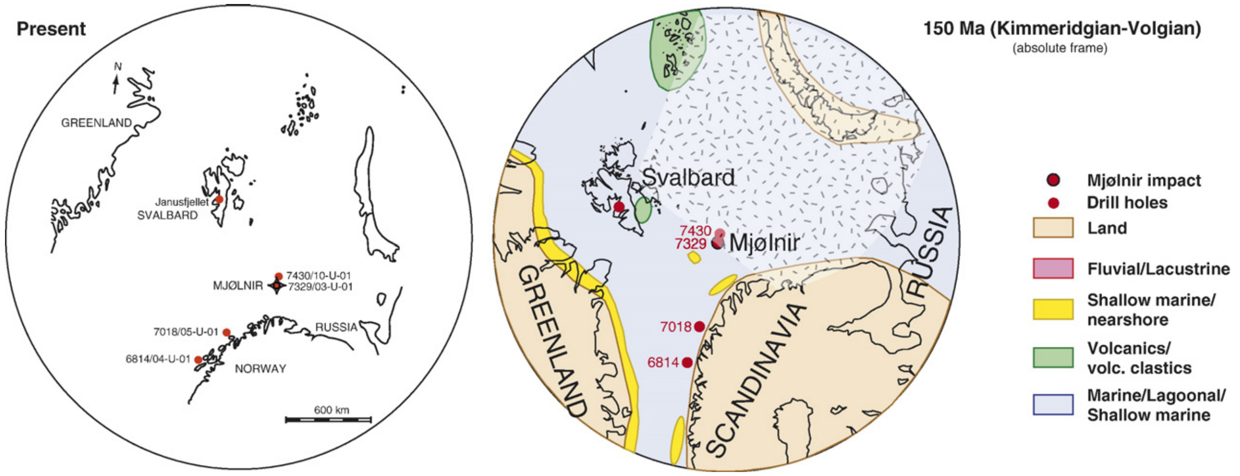

Fig. 1. The left map display the present location of the studied cores and outcrops. The right drawing shows the paleogeographical reconstruction of the Arctic in Late Jurassic time, based on the plate tectonic reconstructions of Larry Lawver (pers. comm. 2002). The ejecta distribution, according to the modelling of Shuvalov et al. (2002), is shown in the hatched area.

1.2. Impact effects related to sedimentation in areas surrounding the Mjølnir Crater

At 142±2.6 million years ago, an about 1.5–2.0 km in diameter asteroid hit the paleo-Barents Sea (Gudlaugsson, 1993; Dypvik et al., 1996; Tsikalas et al., 1998; Smelror et al., 2001a). The water was pushed and blown away for about 20 min. A 40 km in diameter crater was formed on the sea bed. The vaporized asteroid and target rocks along with crushed material were ejected (Smelror et al., 2001a). Based on geological and geophysical information, it has been demonstrated that ejecta were transported towards north–northeast, i.e., Siberia and northern Russian territories more than 2500 km away (Shuvalov et al., 2002; Shuvalov and Dypvik, 2004; Tsikalas, 2005). Ir-enrichments have earlier been described from time-equivalent Siberian successions (Zakharov et al., 1993), in the core from the central high (7329/03-U-01, called MC) (this paper) and in core 7430/10-U-01 (called BPC) (30 km outside the crater rim, Dypvik et al., 1996). In this paper, available sedimentological (Dypvik et al., 2004a,b) and paleontological information (Smelror and Dypvik, 2005, 2006) form a necessary foundation for discussing the new paleontological, mineralogical and geochemical information in a stratigraphical and sedimentological context.

After the explosion and crater formation, the crater was reshaped and modified by resurges, avalanches, slides, mass flows and turbidity currents created by returning water and collapse of the central high, peak ring and crater rim (Dypvik et al., 2004a). These collapse processes triggered waves, currents and tsunami, which then highly influenced the sedimentation in the paleo-Barents Sea region (Dypvik et al., 2004a). The stable sea level was re-established in the crater region about 20 min after impact, but it took probably hundreds of years before the region returned to a pre-impact situation (Shuvalov et al., 2002; Dypvik et al., 2004a). The central high and uplifted crater rim formed new and important geomorphological structures on the sea-floor but only with local environmental influence.

The post-impact waves and tsunami travelled the paleo-Barents Sea and severely reworked both sea bed and coastal areas (Shuvalov et al., 2002; Dypvik et al., 2004a,b; Glimsdal et al., in press). Some sediment reworking has been registered within the Mjølnir Crater (Dypvik et al., 2004a,b) and in the studied core from BPC (Dypvik et al., 1996; Dypvik and Ferrell, 1998; Dypvik and Attrep, 1999) (Figs. 1 and 4). In the present paper, we for the first time present variations in chemical and biological environmental parameters, which illustrate subtle, remote effects of this marine impact (Fig. 1).

2. Cores and samples

In this study, samples of 54 mm in diameter drill cores collected by IKU/SINTEF (drilled in the late 1980s and late 1990s) were studied. The cores from site 7329/03-U-01 (the Mjølnir core, MC) and site 7430/10-U-01 (drilled 30 km outside (NE) the crater rim, BPC) are both located on the Bjarmeland Platform (Fig. 1). Core 7018/05-U-01 (HBC) was drilled 500 km southwest of the crater, in the Harstad Basin. Core 6814/04-U-02 (VC) was drilled 800 km southwest of the crater rim, near the paleo-coastline of the mainland Norway at

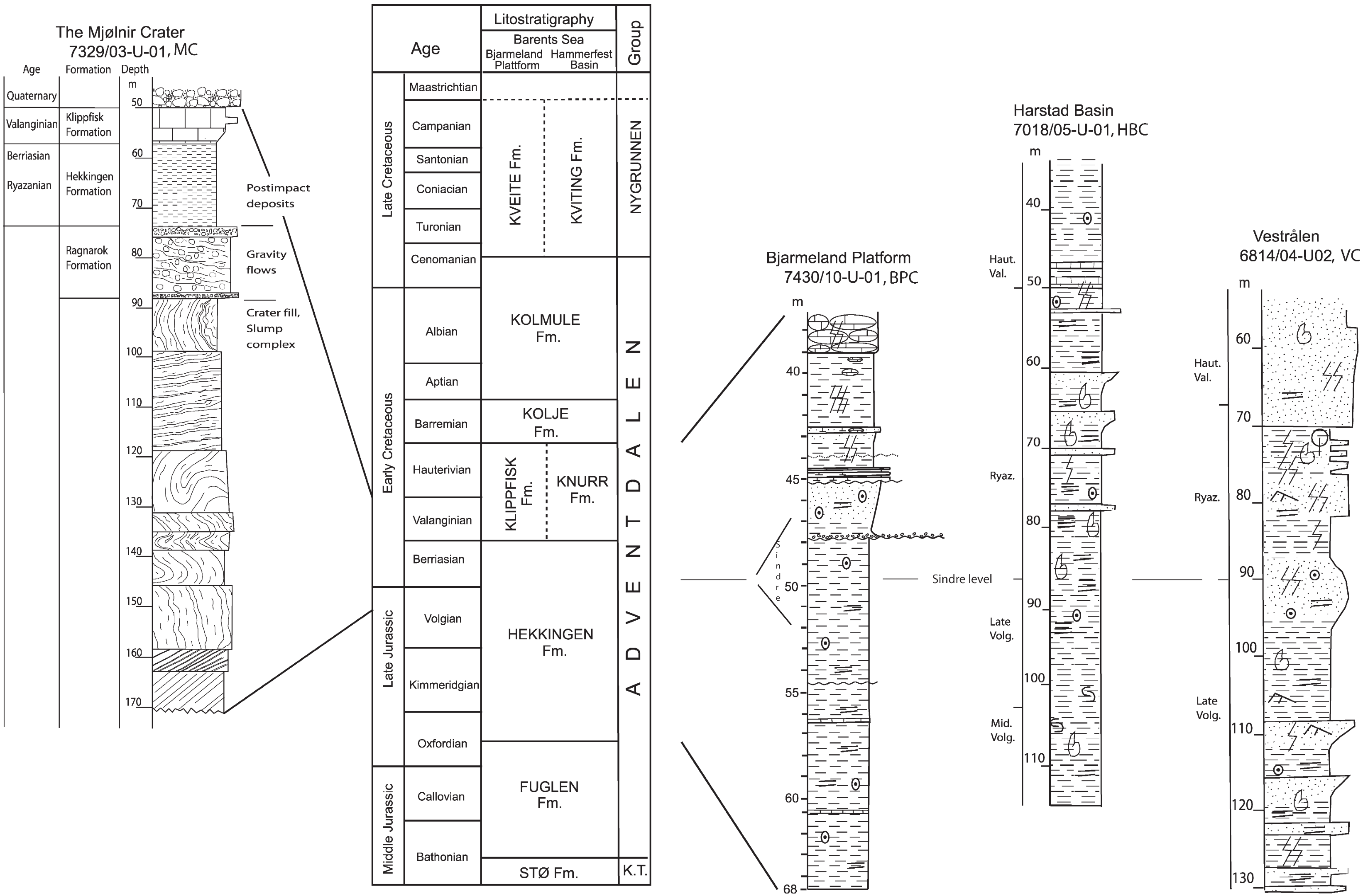

Fig. 2. The stratigraphy of the Barents Sea according to Mørk et al. (1999) in Dallmann et al. (1999) and the correlation of the various drillcores studied in this paper.

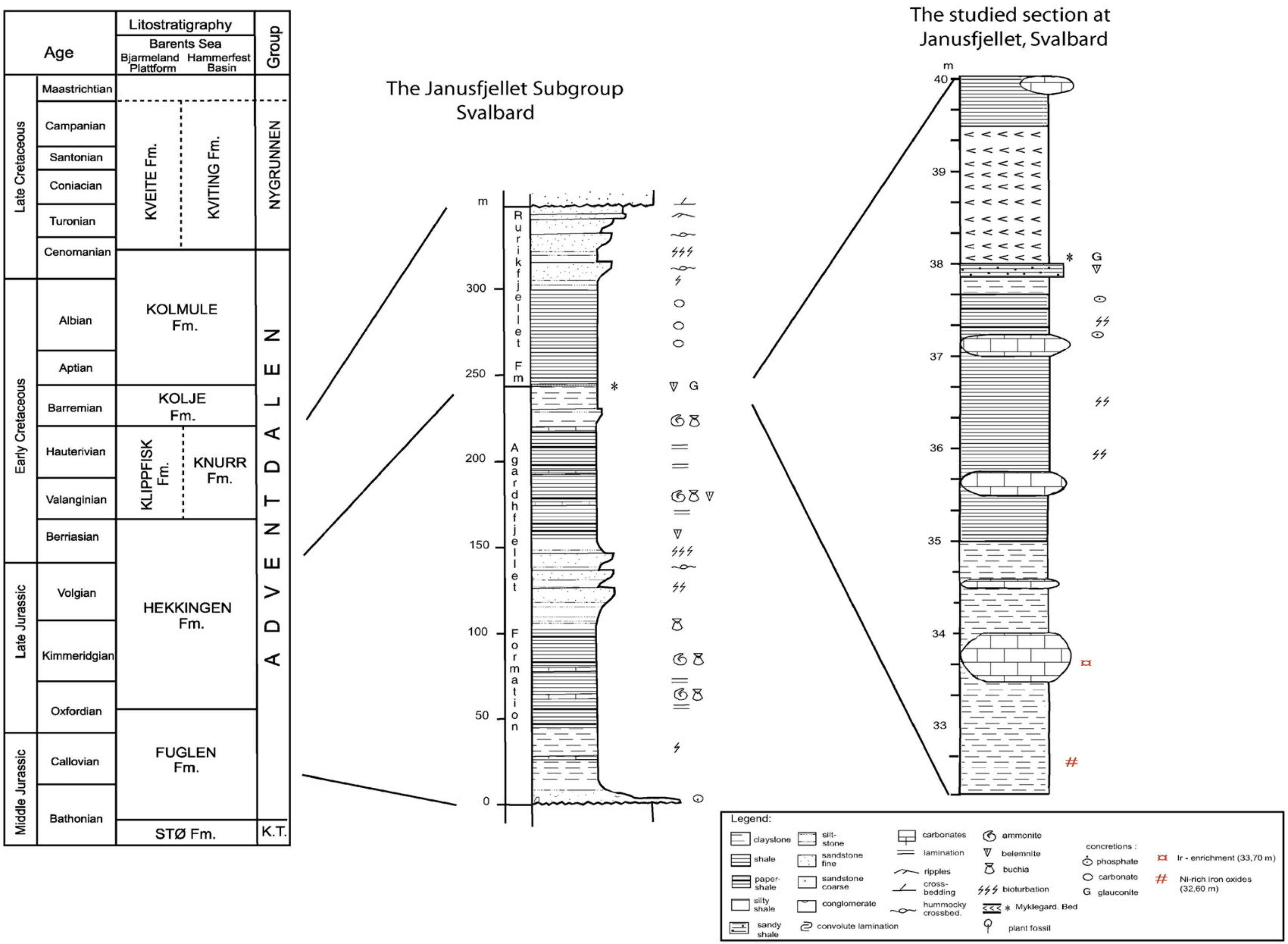

Fig. 3. The stratigraphy of the Janusfjellet Subgroup compared to the stratigraphy of the Barents Sea and the detailed Svalbard sections presented in this paper.

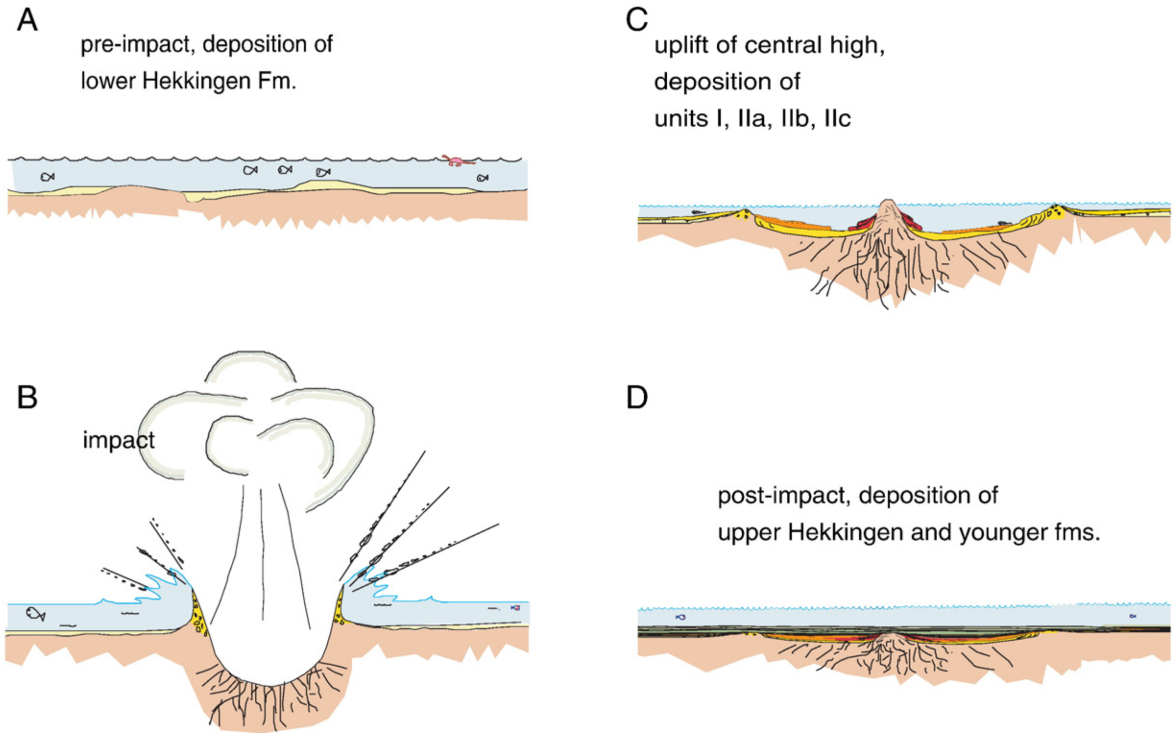

Fig. 4. A schematic, idealized development of the Mjølnir Crater formation.

Vestrålen (Fig. 1). These cores were studied/sampled in the SINTEF core-store in Trondheim. In addition, available data have been gathered of surface samples from the Janusfjellet (Svalbard) 450 km northwest of the crater (Kalleson, 1998; Salvigsen, 2004).

3. Analytical methods and geochemical parameters

The mineralogical and geochemical investigations were performed by thin section studies, X-ray diffraction (XRD), X-ray fluorescence (XRF) analyses and neutron activation analyses (NAA) (Ir) on selected core intervals. The sedimentological appearance and mineralogical composition of these Upper Jurassic and lowermost Cretaceous shales and claystones are rather similar and have partly been presented elsewhere (Table 1) (Dypvik et al., 1996; Dypvik and Ferrell, 1998; Dypvik and Attrep, 1999; Smelror et al., 2001a; Dypvik et al., 2004a). These results will therefore only briefly be mentioned here.

The new geochemical results presented in this paper include the Th, U, Ni and Cr data (Janusfjellet section and cores: MC, HBC, VC), in addition to the Ir-analyses of MC and Svalbard. These analyses (Ir-excepted) were performed by XRF (Philips Master of the Elements) on undiluted pressed pellets, mixed with paraloid-sol (2 ml for 10 g sample) and with counting time between 20 and 50 s. Precision for these trace element analyses are ±3%, with accuracies below 20% (Th/U) and 10% (Ni, Cr), respectively. The Ir-analyses were determined by radiochemical neutron activation analyses according to Kyte et al. (1991), with estimated average minimum error of 8% (% standard deviation). The XRD analyses were

Table 1
The average mineral composition (XRD %) of Lower Cretaceous and Upper Jurassic beds from the Barents Sea (wells 7430/10-U-01 (BPC) and 7329/03-U-01 (MC)) and the Janusfjellet Subgroup of Svalbard (Lardyfjellet section)

Core/section	No. samples	Chlorite	Mixed layer	Ill/musk	Kaol	Quartz	K-feld	Plag.	Cal.	Dol.	Sid.	Pyr.
7329/03-U-01, MC	14	1	15	8	9	28	4	6	16	1	2	10
7430/10-U-01, BPC	29	1	1	2	5	38	8	8	9	7	4	17
7018/05-U-01, HBC	29	1	5	12	8	32	9	7	1	7	7	11
6814/04-U-02, VC	18	3	4	8	8	28	6	15	4	3	10	11
Janusfjellet	137	3	4	11	7	51	5	11	3	1	3	1

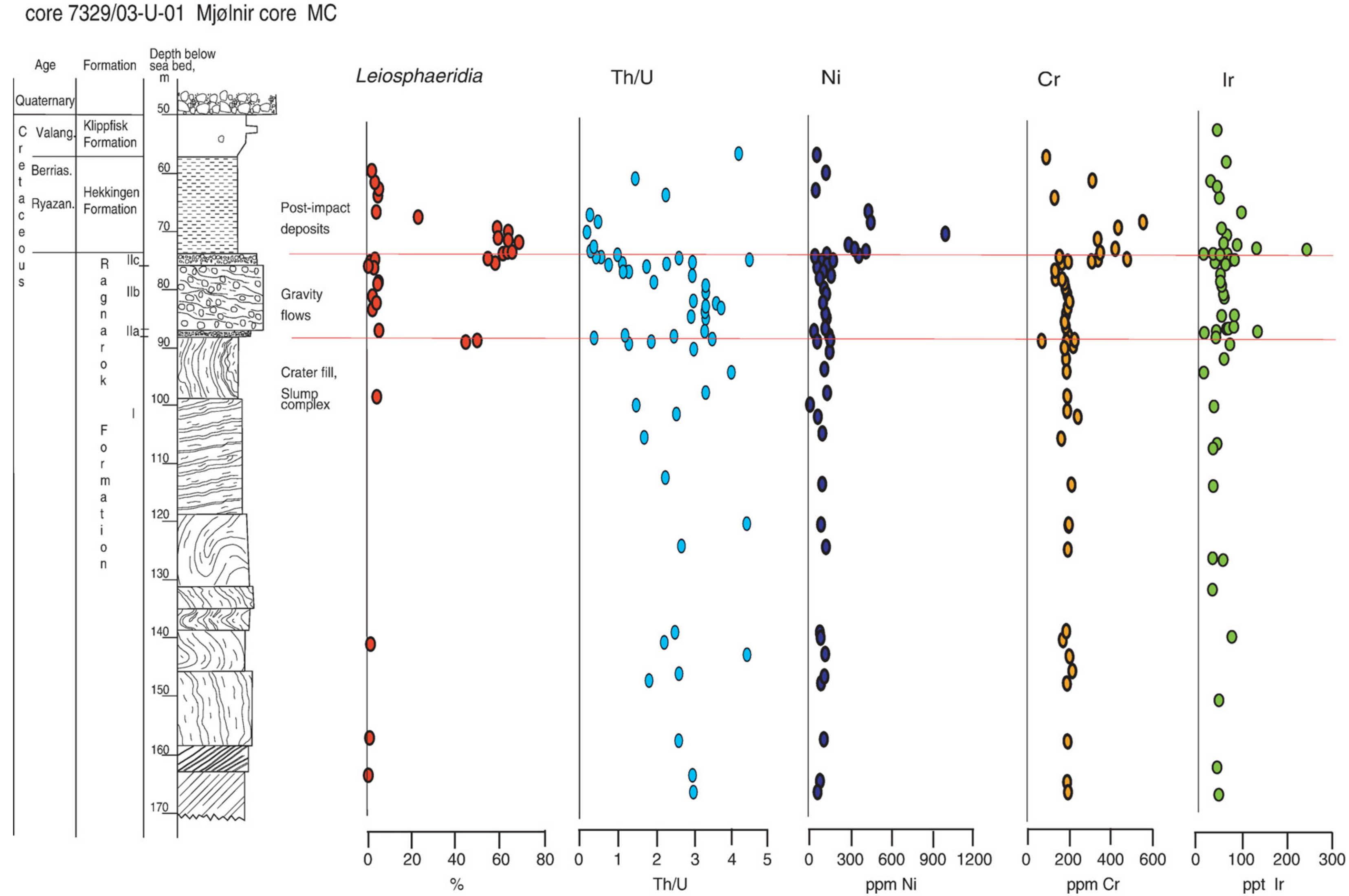

Fig. 5. The distributions of *Leiosphaeridia*, Th/U ratios, Ni, Cr and Ir concentrations in the samples from core 7329/03-U-01, the Mjølnir core (MC) from the central peak. The thin red lines run along the lower and upper boundaries of unit II. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

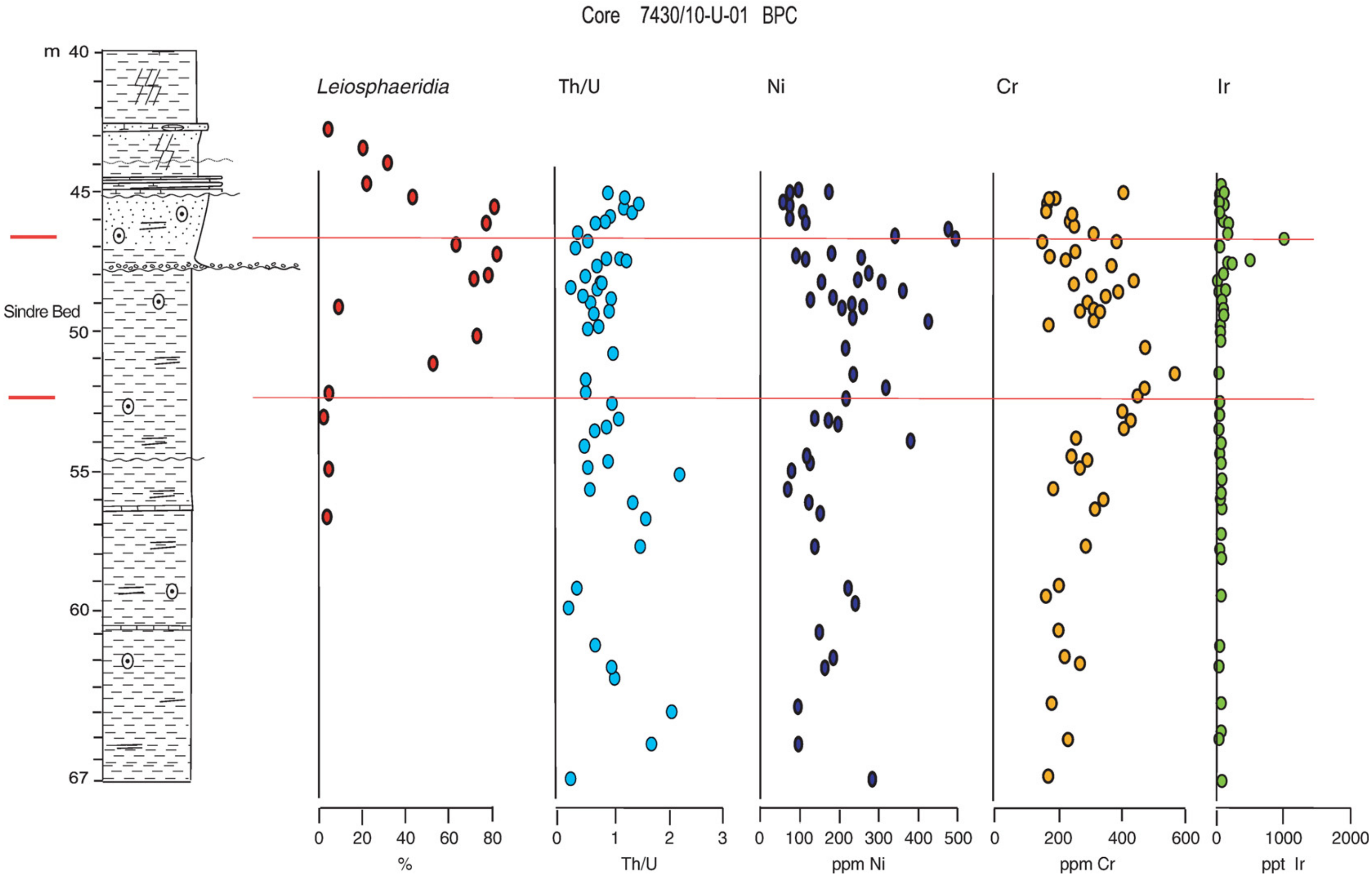

Fig. 6. The distributions of *Leiosphaeridia*, Th/U ratios, Ni and Cr concentrations in the samples from core 7430/10-U-01 (BPC), the core drilled 30 km outside the rim of the Mjølnir Crater. The thin red lines run along the lower and upper boundaries of the ejecta bed (Sindre Bed). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

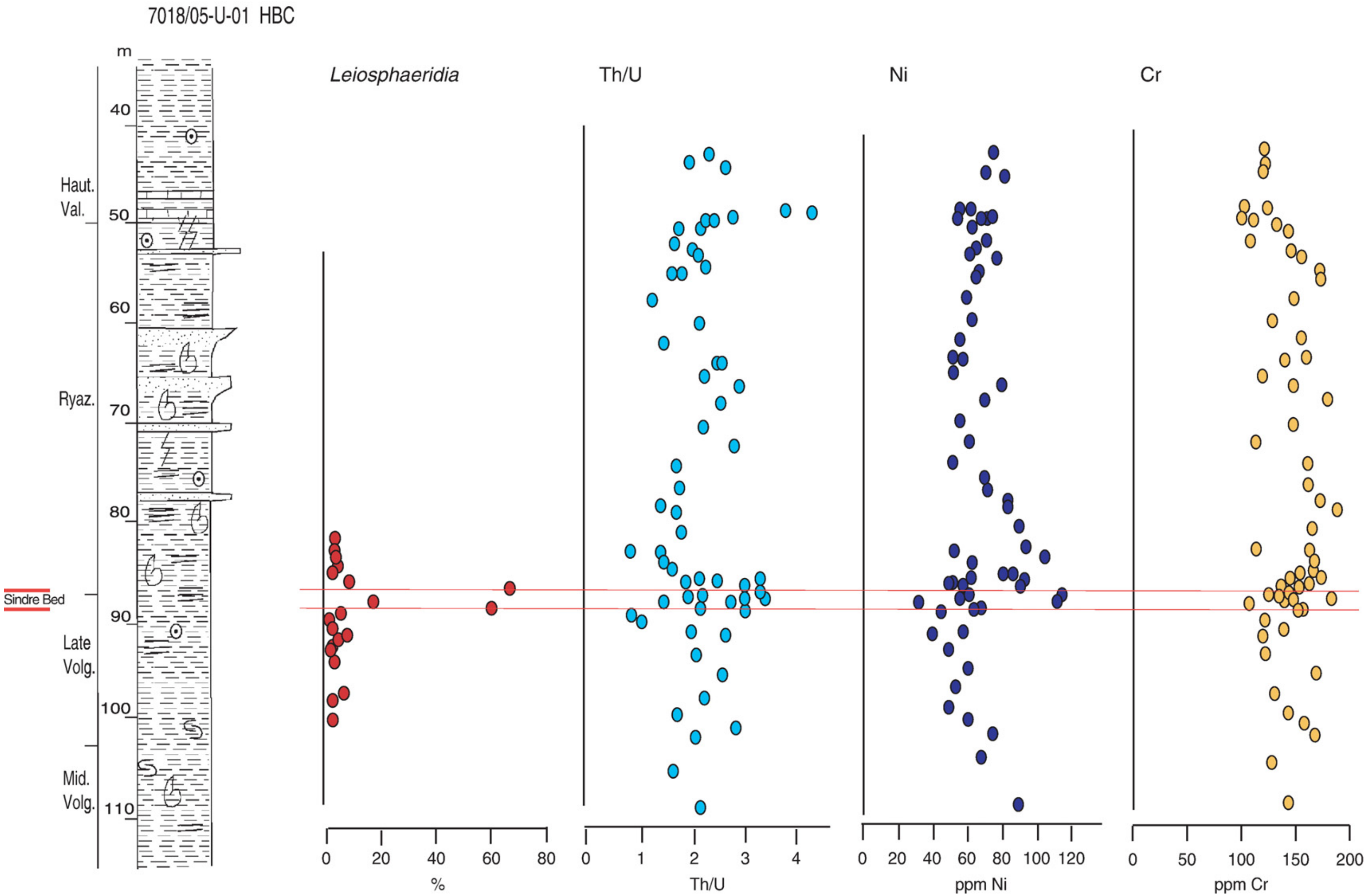

Fig. 7. The distributions of *Leiosphaeridia*, Th/U ratios, Ni, Cr and Ir concentrations in the samples from core 7018/05-U-01 (HBC). The core drilled 500 km from the Mjølnir Crater. The thin redlines follow the lower and upper borders of possible ejecta bed (Sindre Bed). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

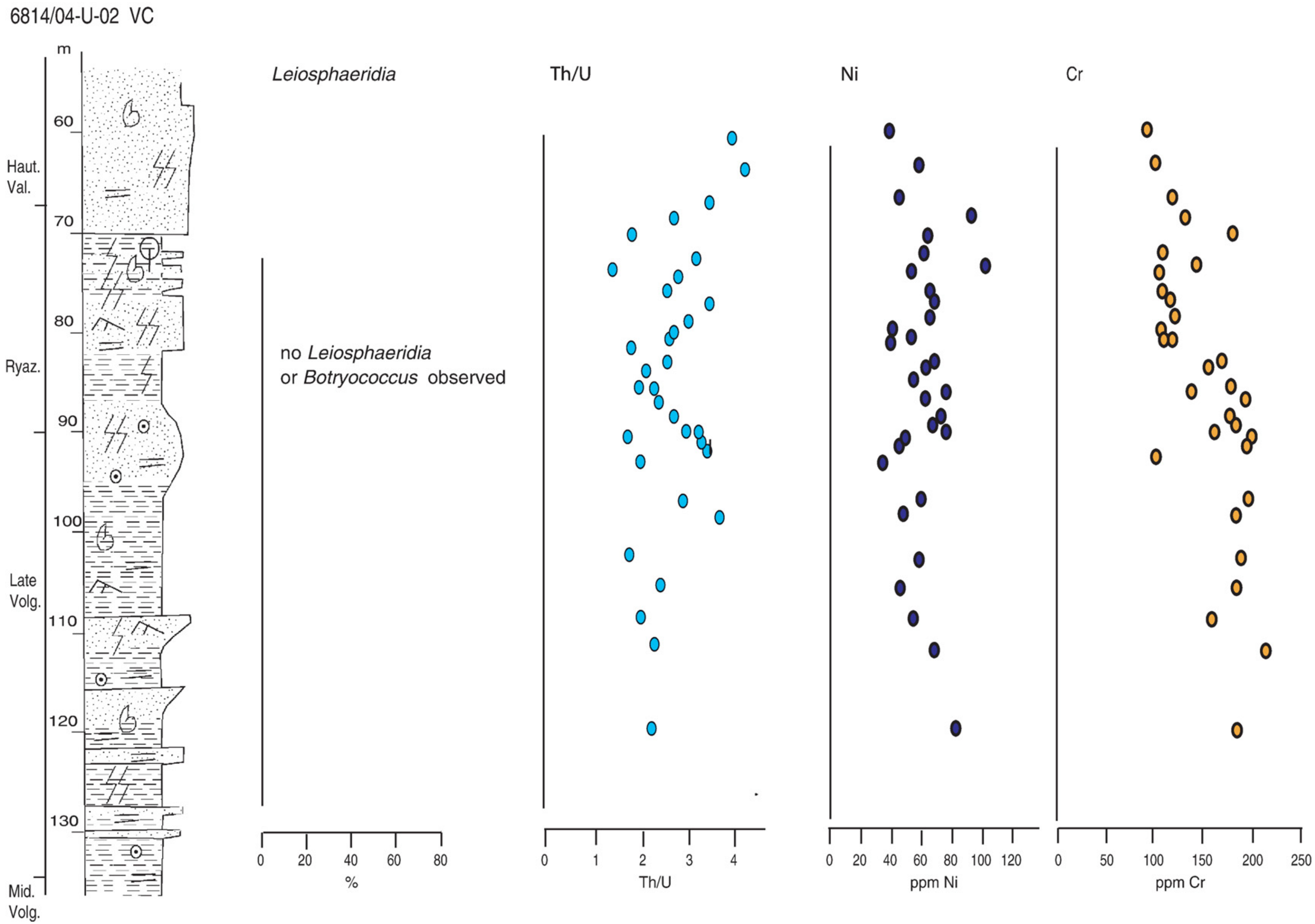

Fig. 8. The distributions of *Leiosphaeridia*, Th/U ratios, Ni and Cr concentrations in the samples from core 6814/04-U-02 (VC), the core drilled 800 km from the Mjølnir Crater, close to the shores of mainland Norway.

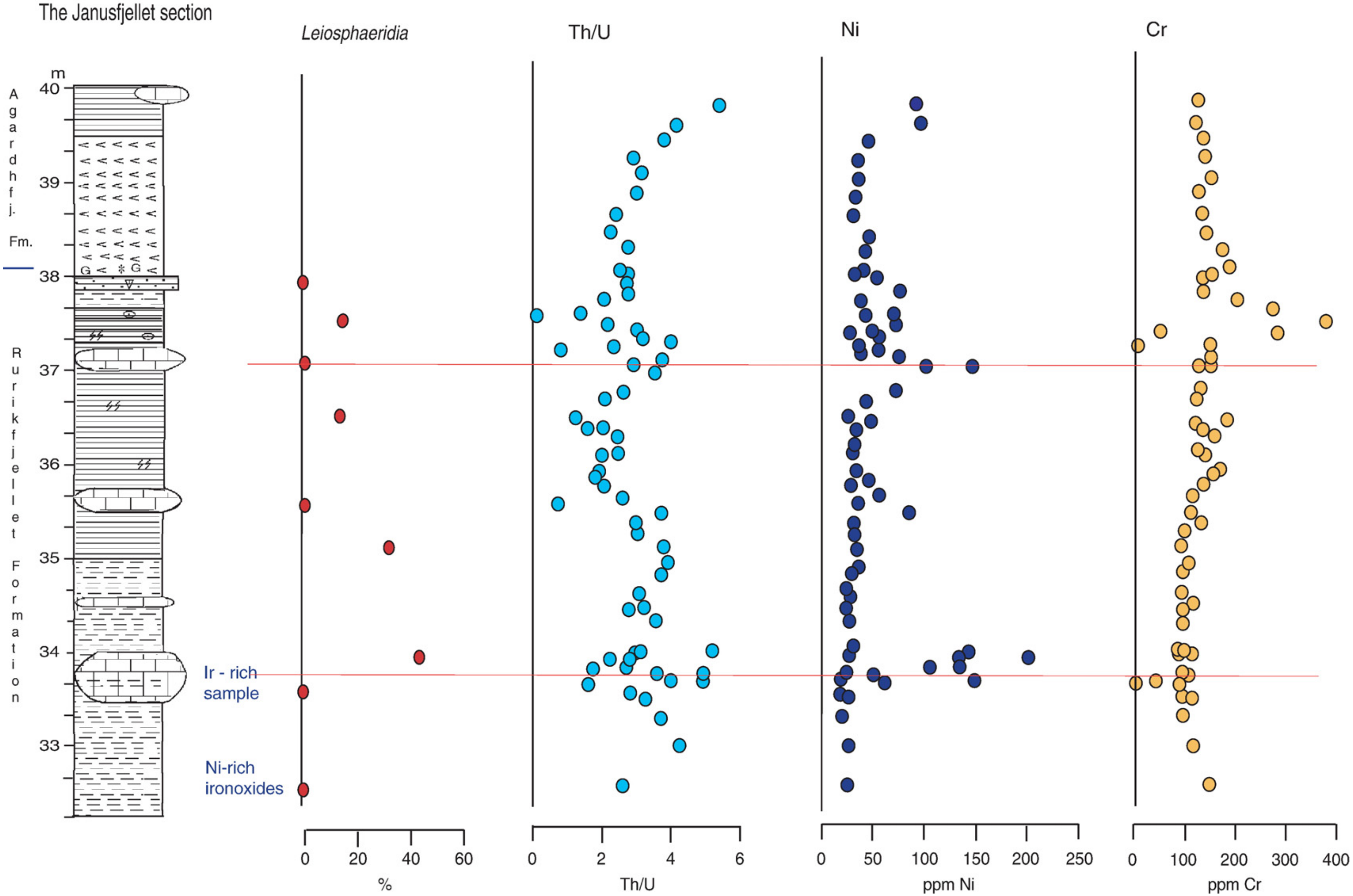

Fig. 9. The distributions of *Leiosphaeridia*, Th/U ratios, Ni and Cr concentrations in the samples from the Janusfjellet section of a part of the Janusfjellet Formation. The lower thin red line marks the location of Ir-enriched sample (F.T. Kyte, pers. comm.), while the upper, thin, red line indicates the level of Ni-enrichment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

done at the University of Oslo (Philips X'Pert MPD) on randomly oriented, pressed pellets of crushed rock powder. A numerical estimate of mineral abundance in these whole rock samples was derived from simple peak height percentage calculation without mineral reference intensity correction factors (Table 1). The geochemical results are presented in Figs. 5–9, while complete geochemical data tables are made available by contacting the first author.

The Th/U ratio was analysed to give an indication of oxygen availability (anoxisity) in the fine-grained clay dominated sediments (Adams and Weaver, 1958; Jones and Manning, 1994; Dypvik and Harris, 2001). The Ni concentrations may both reflect oxygen deficiency (anoxic conditions), organic content, sulphide enrichments, as well as possible asteroid contamination. Cr-enrichments could also be due to asteroid contamination, as well as heavy minerals and partly anoxic depositional conditions (Taylor, 1965; Dypvik and Harris, 2001). Consequently, high Th/U ratios and low Ni and Cr values could characterize oxidizing conditions. Low Th/U ratios and high Ni (and partly Cr) concentrations would be more typical for anoxic to hypoxic bottom conditions, as long as, e.g., the clastic source rocks and diagenetic conditions did not change within the section (Taylor, 1965; Dypvik and Harris, 2001). Ir-enrichments are typically found in beds contaminated by extraterrestrial material (Melosh, 1989), e.g., asteroids, accompanying Ni and Cr anomalies could be expected.

The microscopical palynology investigations were performed after acid treatments (HCl- and HNO_3-dissolution) of selected samples, following standard methods. The distribution of the marine prasinophycean algae *Leiosphaeridia* is the only new palynological information highlighted here, while the major part of the related and supporting palynological results are published in Smelror et al. (2001a), Bremer et al. (2004) and Smelror and Dypvik (2005, 2006).

4. Results

The results of the core analyses are presented separately (core-wise) below, while compiled development discussions are found in Section 5. The compilations are based on comparing results from similar lithologies (shales and claystones) and focusing on stratigraphical developments within each section. The mineralogical compositions of these fine-grained sediments are fairly similar, as demonstrated in their average mineralogy (Table 1). It should be noted, however, that the samples from the Janusfjellet are enriched in quartz and depleted in pyrite compared to the Barents Sea core samples, which in turn mutually are very similar in composition. The Mjølnir core (MC) samples have a high content of "mixed-layered clay minerals", a possible hydrothermal, diagenetic alteration product in the fractured crater beds (Dypvik et al., 2003).

4.1. 7329/03-U-01 (the Mjølnir core) (MC)

4.1.1. Background

MC consists of avalanche and slump deposits from the slopes of the central peak, covered by various mass-and suspension flow deposits. These crater fill deposits are named the Ragnarok Formation (Dypvik et al., 2004a,b). The core is rich in geochemical and mineralogical impact traces (Sandbakken, 2002; Smelror et al., 2002; Dypvik et al., 2003, 2004a; Bremer et al., 2004) (Figs. 1 and 2). In this paper, the *Leiosphaeridia*, Th/U ratios, Ni, Ir and Cr distributions are in focus (Fig. 5).

4.1.2. Results

The *Leiosphaeridia* distribution shows extreme enrichments in units IIa and IIc, breached by a low in unit IIb. The *Leiospheridia* enrichments continue upwards into the very lowermost part of the succeeding post-impact part of the Hekkingen Formation (Fig. 5), about 5 m above the Ragnarok Formation.

The Th/U ratios are relative high throughout the Ragnarok Formation, while they drop to minimum values in unit IIa and in the lower part of the Hekkingen Formation (Figs. 4 and 5). The low Th/U ratios in the Hekkingen Formation are accompanied by extreme enrichments in both the Ni and Cr concentrations. The Ni/Cr ratio is found to be 3.0 in one sample, while average value in that zone (67.10–73.50 m) is just above 1.

The Ir distributions generally show background values between 50 and 60 ppt, with minor enrichments in units IIa (250 ppt) and IIc (125 ppt). The Ir concentrations in the unit IIb display background values. The Ir-enrichments follow the peaks in the *Leiosphaeridia* distribution. In bed IIc, the Ir-rich sample carries somewhat higher Cr and Ni concentrations, while the Ir-rich samples from unit IIa are relatively low in both Cr and Ni.

4.2. 7430/10-U-01 (located 30 km outside the crater rim to the northeast) (BPC)

4.2.1. Background information

The geological composition of the claystones and conglomerates of BPC have been studied and presented before. A minimum of information is presented here to be used in the sedimentological, geochemical (Ir-enrichments) and mineralogical (smectite enrichments) comparisons (Dypvik et al., 1996; Dypvik and Ferrell, 1998;

Dypvik and Attrep, 1999). Grains of shocked quartz have been described from a thin conglomeratic horizon (Dypvik et al., 1996; Langenhorst and Dypvik, 1996). Only local paleontological changes are seen in the macro- and microfossil studied (Smelror et al., 2002; Bremer et al., 2004) (Figs. 1 and 2). In this paper, the *Leiosphaeridia*, Th/U ratios, and Ni, Cr and Ir distributions are presented below (Fig. 6), their general trends have only been mentioned briefly earlier (Dypvik and Attrep, 1999).

The *Leiosphaeridia* distribution of samples from well BPC is extreme and spanning the same stratigraphical levels as the smectite enrichments (originated from impact glass alteration), shocked quartz and Ir-enrichments combined (Dypvik et al., 1996; Dypvik and Ferrell, 1998; Dypvik and Attrep, 1999) (Fig. 6). The *Leiosphaeridia* enriched zone covers the Sindre Bed, which is comparable to the distributions of units IIa and IIc in the Mjølnir core (MC) (Fig. 5).

In BPC, the highest Th/U ratios are found in the lower part of the core (below the Sindre Bed) (Fig. 6), while low to modest values appear throughout the ejecta unit (Sindre Bed) and above. In this core, the typical black shales of the Hekkingen Formation are missing above the impactite. The bioturbated, greenish grey marls of the Klippfisk Formation continue after a break in sedimentation (Fig. 2). Rather high Ni concentrations are characterizing the beds below the Sindre Bed, while the highest concentrations are found in the Sindre Bed itself. The Ni-enrichments are well-developed in the low Th/U-ratio zone.

4.3. 7018/05-U-01 (located 500 km southwest of the crater) (HBC)

4.3.1. Background

HBC consists of a shale dominated succession representing Middle Volgian to Hauterivian strata (Figs. 1 and 2). A few dispersed sand beds, most likely representing storm and tide generated sandbars, are found dispersed in this package of mainly parallel laminated, dark grey shales. The sediments generally represent open marine depositional conditions. The sedimentology and stratigraphy of this core have been discussed in more detail by Smelror et al. (2002).

4.3.2. Results

The amounts of *Leiosphaeridia*, Th/U ratios, Ni and Cr distributions are presented in Fig. 7, while Ir-analyses have not been executed. The macrofossil contents of this core support the stratigraphical subdivision (Smelror et al., 2001a,b), while the *Leiosphaeridia* distribution shows a pronounced high at level 88 m. This part of the core is made up of parallel laminated shales, only very faint traces of possible bioturbation and no other clear-cut sedimentological structures have been observed. The amounts of *Leiosphaeridia* are modest below and above this 0.5 m thick enriched zone.

At the same stratigraphical level, the Th/U ratios show a high. Simultaneously, the Ni and Cr distributions display dramatic excursions and well-developed jumps from the decreasing trends below. In this case, however, the Ni and Cr concentrations are significantly lower than in comparable beds from both BPC and MC. Decreasing Ni and Cr concentrations are displayed from the peak level and stratigraphicaly upwards.

4.4. 6814/04-U-02 (located 800 km southwest of the crater) (VC)

4.4.1. Background

VC was drilled close to the margin of the paleo-Barents Sea, in the coastal region (Vestrålen) of mainland Norway (Figs. 1 and 2). The studied core samples represent Mid-Volgian to Hauterivian beds (Smelror et al., 2001a,b) (Fig. 8). The succession consists of sandier sediments than in the other wells studied, reflecting its original coastal paleo-position (Fig. 1). Several upwards-coarsening sand units are observed in the core. An about 10 m thick sand-body is present at the Volgian/Ryazanian boundary.

4.4.2. Results

No significant amounts of *Leiosphaeridia* or *Botryococcus* algae have been observed in this core.

The Th/U ratios as well as the Ni and Cr concentrations display normal values. They show faint excursions around level 90 m, in the middle part of the bioturbated sand-body (level 87 m–96 m). The core consequently represents an area outside the region where the *Leiosphaeridia* bloomed and possible related Th/U, Ni and Cr distributions could be traced.

4.5. The Janusfjellet section, Svalbard

4.5.1. Background

The outcrops of the Janusfjellet section (Figs. 3 and 9) are dominated by shales, silt-/claystones and carbonate concretions. The section has been sampled in great detail and described in the thesis studies of Kalleson (1998) and Salvigsen (2004). In this paper, only the 5 m section carrying impact related sediments will be mentioned; this is located in the upper most part of the Agardhfjellet Formation. The lower part of this section consists of dark grey claystones up to level 35 m, while the overlying part from 35 to 37.3 m consists of dark grey shales (Figs. 3 and 9). Between levels 37.3 and 38 m, black paper shales, grey claystones and sandy shales with belemnites are found. This selected 5 m succession is characterized by parallel lamination, only very modest degrees of bioturbation and dispersed carbonate lenses of a few centimeters up to 1 m length. The carbonate lenses in this part of the Janusfjellet section consist mainly of calcite and siderite, less than 5% of dolomite is present (Salvigsen, 2004). The soft, yellowish to greyish green claystones of the Mykelgardfjellet Bed are found between levels 38 and 39.5 m. The silty, prismatic fracturing, dark grey shales of Rurikfjellet Formation occur above the Mykelgardfjellet Bed (Kalleson, 1998; Salvigsen, 2004).

4.5.2. Results

Since only a few and widely spread samples have been analysed for palynomorphs, the *Leiosphaeridia* distribution in the Janusfjellet section is rather weakly defined. In the lower part of the studied section, the present data show positive relations between the peak abundances of *Leiosphaeridia* and elevated Th/U ratios and Ni concentrations. The Cr values are low in this interval. One sample (sample number 79, level 33.7 m) (Figs. 3 and 9) has been found to contain 2 ppb Ir (F. Kyte, pers. comm.).

The Janusfjellet distributions of the Th/U ratios and the Ni, Cr concentrations are similar to the ones found in HBC. In the Janusfjellet section, a general drop in the Th/U ratio is found accompanied by a Ni high at level 33.7 m. The geochemical developments above this level are varying, with some minor shifts along the general decreasing Th/U ratios and three well-defined Ni-enrichments. The Cr concentrations are normal and stable except for a peak at level 37 m.

At level 32.6 m, Robin et al. (2001) reported the findings of several micrometer sized grains of Ni-rich iron oxides, comparable to the ones found in samples from BPC. This sample does not carry high Ni or Cr concentrations (Fig. 9).

5. Discussion

It is well-demonstrated that the green algae *Leiosphaeridia*, together with the freshwater algae *Botryococcus*, bloomed in the paleo-Arctic just after the time of impact (Smelror et al., 2002; Bremer et al., 2004; Smelror and Dypvik, 2005, 2006). The sudden bloom of *Leiosphaeridia*, the first invader to take the advantage of catastrophic environmental changes, appears well before the return of other species. Studies of the life cycle and growth of modern prasinophytes have shown that the entire process from the time of cust formation to the release of new motile cells requires only up to 6 h (Guy-Ohlson, 1996). Such short life cycles may have been a major competitive advantage for rapid growth and maximum utilisation of the enormous amounts of nutrients that were released by the Mjølnir impact and the subsequent crater collapse. During such extreme conditions, only few species might quickly utilise the rich nutrients in the water column (Smelror et al., 2002). When the situation returns to normal conditions, the algal bloom decreases and the "normal" marine microflora is re-established. In the case of MC, the return to the pre-impact Hekkingen situation can be traced in the dark grey shales about 5 m above the Ragnarok Formation.

This distinct *Leiosphaeridia* bloom pattern is well-documented in the studied sections of Janusfjellet and cores MC, BPC, HBC. In the MC, the *Leiosphaeridia* peak was interrupted at by low values in unit IIb. This level, however, represents an influx of reworked, autobrecciated mud flows of pre-impact, non-contaminated crater sediments (Dypvik et al., 2004a). The *Leiosphaeridia* peak is also developed in the ejecta bed (Sindre Bed) of BPC. Both MC and the ejecta carrying BPC from 30 km outside the crater rim display sedimentary compositions directly influenced by the impact (Dypvik et al., 1996; Dypvik and Ferrell, 1998; Dypvik and Attrep, 1999; Sandbakken, 2002; Dypvik et al., 2003, 2004a,b Smelror and Dypvik, 2005, 2006). Both cores have well-developed *Leiosphaeridia* peaks, MC in the immediate post-impact levels and in BPC throughout the ejecta bed (the Sindre Bed).

The *Leiosphaeridia* blooms and the geochemical and mineralogical indicators of impact (Ir-anomalies, shocked quartz) are occurring in the correlative stratigraphical horizons in the studied sections of MC and BPC. The *Leiosphaeridia* enrichments consequently could be a result of the extreme environmental and depositional conditions characterizing the basin just after impact. The *Leiosphaeridia* bloom may therefore be used in the Barents Sea region as an *indirect* reflection of impact related sedimentation, occurrences of special importance especially in more remote localities, far from the regions characterized by direct impact influence. The *Leiosphaeridia* bloom has also been recognized in HBC and in the studied section of the Janusfjellet (Svalbard). In the VC, 800 km to the southwest of the Mjølnir Crater, no bloom has been observed.

The *Leiosphaeridia* enrichment of HBC is narrow, well-defined and occurs at the appropriate stratigraphical impact level (Smelror et al., 2002). We therefore interpret this bloom, with the associated macrofauna distribution and the accompanying geochemical distributions of Th/U, Ni and Cr, to span an equivalent of the Sindre Bed. The lack of palynological enrichments, and related comparable geochemical anomalies in VC samples, illustrates the possible maximum distance for detecting such depositional effects south of the crater. VC is located south of the Mjølnir in the direction towards the incoming bolide, and shows impact effects to disappear between 500 and 800 km from the impact site. Recent simulations (Shuvalov and Dypvik, 2004) demonstrate the asymmetrical ejecta distribution of the Mjølnir impact. More than 90% of the ejecta were transported towards the northeast, along the direction of impact (Tsikalas, 2005). In contrast, less than 10% of the ejecta was transported in a southerly direction (Fig. 1).

The high in the Th/U ratios of MC (Fig. 5) (level 89 m to 74 m) is a likely result of mass flow deposition of unit IIb, consisting of reworked fine-grained, uncontaminated pre-impact deposits (Dypvik et al., 2004a,b). A similar break in unit IIb was seen in the *Leiosphaeridia* distribution. The high Th/U ratios of unit IIb reflect increased oxygen activity in that unit, a result of intense wave/current reworking. In BPC, no related increase in the Th/U ratio was detected. The rather low to moderate ratios found through the Sindre Bed (ejecta bed) indicate that the post-impact beds deposited just outside the crater rim may have been reworked masses of dark grey, Hekkingen Formation clays. A reduced renewal of oxygen supply to the sea bed in the BPC case (30 km from the crater rim) demonstrates the sediments to consist of mainly reworked, original anoxic Hekkingen Formation deposits. In HBC, however, the Th/U distribution shows a well-developed high, partly accompanying the *Leiosphaeridia* enrichment, an indication of increased aeration in those water masses (Fig. 7).

The increase in the Ni concentrations within a core generally reflects reducing oxygen levels, i.e., increasing reducing conditions along the sea-floor and Ni-precipitation in sulphides or associated the organic matter. A similar relation is partly mirrored in low Th/U ratios (see Section 3). Ni- and Cr-enrichments can, however, also be found associated with possible bolide contamination. Microscopic fragments of Ni-rich iron oxides have been found in the Svalbard section and BPC samples (Robin et al., 2001), while high Ni concentrations and the Ir-enrichments (BPC) are found about 1 m above that stratigraphic level. The increased Ni and Cr concentrations of MC and BPC and the microscopic Ni-rich iron oxides grains in BPC are partly accompanied by the *Leiosphaeridia* blooms. High Ni values throughout the Sindre Bed of BPC, accompanying the Th/U low, most likely inherited original reducing conditions of reworked Hekkingen sediments and high degree of sulphide precipitation. The distribution of Ni, Cr and Ir, their enrichments in the Sindre Bed, and relative enrichment of Ni compared to Cr around the Ir-peak may also indicate some Ni to be derived from the bolide (Fig. 5) (Dypvik and Attrep, 1999). In HBC, the Ni- and Cr-enrichments are well-defined, partly simultaneous, but mostly after a combined *Leiosphaeridia* bloom and Th/U high. The details of such mutual relations may be difficult and speculative to sort out. The late Ni-enrichments and Th/U low possibly mirror the establishment of more reducing conditions succeeding the ventilation episode demonstrated by the Th/U high. The Ni-enrichments occurring together with the Th/U high is difficult to explain, but we suggest that they are most likely due to additional Ni-enrichments in sulphide accumulations. If they were caused by enrichment of meteoritic material, simultaneous high Ni concentrations and grains of Ni-rich iron oxides should be found on Svalbard. This is not the case.

In the remote VC, only a very faint and dubious increase in the Th/U ratio is indicated (Fig. 8). No particular Ni or Cr distribution is observed, just common, expected background variations. This may, together with the normal Th/U ratios, be due to several processes, e.g., increasing distance to crater, increasing grain sizes and/or changes in the depositional environment.

The reduced Th/U ratios in the Hekkingen Formation in MC are accompanied by extreme enrichments in both the Ni and Cr concentrations. This may be a possible result of anoxic depositional conditions and high sulphide enrichments or possibly a mutual presence of asteroid-derived material. The Ni/Cr ratio in MC is found to be 3.0 in one sample, while average value in that zone (67.10–73.50 m) is just above 1. The normal values in the Hekkingen Formation are below 1. Could the raised Ni/Cr ratio indicate an asteroid contamination?

The Ir distributions in MC generally show background values between 50 and 60 ppt, with minor enrichments in units IIa (250 ppt) and IIc (125 ppt). The Ir concentrations of the unit IIb display low values of background level, indicating only minor (if any) bolide contamination in those layers. The Ir-enrichments follow the peaks in the *Leiosphaeridia* distribution. The Ir-rich sample from unit IIc carries somewhat higher Cr and Ni concentrations, while the Ir-samples from unit IIa are relatively low in both Cr and Ni.

During and just after impact, severe tsunami and waves were generated and travelled the paleo-Arctic seas (Shuvalov et al., 2002; Dypvik et al., 2004a,b; Glimsdal et al., in press) as direct results of the impact. In addition, crater collapse, avalanches, slides and mass flows along the unstable crater topography controlled the sedimentation and triggered waves and currents. Tsunami and currents traversed large distances and directly or indirectly disturbed the sea-floor sediments. They may have contributed to renewed oxygen supply to the deeper, originally anoxic–hypoxic sea-floor environments. Periods with high Th/U ratios and low Ni concentrations reflect such aeration activity along the sea bed; in some cases, it may be disturbed by reworking and deposition of originally sulphide and Ni-rich Hekkingen clays (VC and partly HBC).

These geochemical and palynological distributions found in the studied Svalbard section and different Barents Sea cores both stratigraphically and geologically support some impact influence. Consequently, we interpret these results to demonstrate the significance of ejecta distribution and possibly tsunami, wave and current activity related to the Mjølnir impact. Even in remote areas opposite the main ejecta distribution, at least 450–500 km away from the crater (in direction towards the bolide) (Svalbard and HBC), these faint traces of the drama have been traced. In the most distal core studied (VC), 800 km away, no clear-cut evidence has been found. Its coastal location and high sand content in correlative stratigraphical levels (Fig. 8) may represent possible run-back material from a tsunami or train of waves hitting the coastal and marginal parts of the paleo-Barents Sea.

6. Conclusion

The studied section from Svalbard and cores from the Barents Sea show that effects of the Mjølnir impact event can be traced palynologically and geochemically, up to at least 500 km away from the impact site in the direction towards the incoming bolide. In the direction of impact, towards the northeast, simulation models and Siberian investigations show ejecta to have been transported thousands of kilometers. In the Mjølnir case, in addition to crater appearance and related impactites, carefully selected parameters, e.g., the *Leiospheridia* amounts, the Th/U ratios and Ni and Cr concentrations have been shown to carry basic geological information. These or similar parameters can make promising searching tools for other, less accessible marine impacts structures.

Leiospheridia characterize extreme living conditions in the water masses and the variations in Th/U ratios and Ni concentrations characterize anoxic/hypoxic to oxic depositional conditions close to the sea-floor. The influence of impact generated tsunami, waves and current activity can be traced by these distributions. It is, however, important to study fine-grained sediments of related source rocks in well-correlated stratigraphical sections.

In contrast to the distribution of ejecta, which in the Mjølnir case has been modelled to be highly asymmetrical, these paleo-environmental parameters will generally display a symmetrical distribution. In this study, the environmentally impact disturbed sediments have been recognized in the direction towards the incoming bolide. More information is needed to refine this or related methods for a broad application in marine impact sedimentology. The combination of easy detectable, palynological and geochemical parameters can be valuable in future studies of marine impacts.

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