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Mjølnir (Barents Sea) meteorite impact ejecta offers a Volgian-Ryazanian boundary marker

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with 5 figures

Abstract. New biostratigraphic evidences from a core drilled in the central part of the 40 km diameter submarine Mjølnir meteorite crater on the Barents Shelf are presented. The data suggest a stratigraphical age for the meteorite impact approximating the Volgian – Ryazanian boundary. This age corresponds to the later part of the Early Berriasian (*Berriasella jacobi* Zone) of the Tethyan Realm. A similar age for the impact is further documented from the macro- and microfaunas and microfloras found in the ejecta-bearing strata in an additional borehole located 30 km northeast of the crater. Iridium anomalies found in the Volgian-Ryazanian boundary strata on central Spitsbergen – Svalbard and Nordvik Peninsula in northern Siberia appear also to be related to the Mjølnir impact, providing additional support for a Volgian-Ryazanian boundary age of the impact.

Zusammenfassung. Es wird neues biostratigraphisches Beweismaterial von einem Bohrkern aus dem zentralen Teil des 40 km grossen, submarinen Meteoritenkraters Mjølnir auf dem Barents-Schelf vorgestellt. Die Daten deuten darauf hin, daß der Meteoriteneinschlag an der Volgium-Ryazanium-Grenze erfolgte. Dieses Alter entspricht im Tethysbereich dem späteren Teil des frühen Berriasiums (*Berrasiella jacobi* – Zone). Ein ähnliches Alter für den Einschlag wird zudem durch die Makrofaunen, Mikrofaunen und Mikrofloren dokumentiert, die in den ejektaführenden Schichten eines weiteren Bohrkerns 30 km nordöstlich des Kraters gefunden wurden. Iridiumanomalien in den Volgium-Ryazanium-Grenzschichten im zentralen Teil Spitzbergens (Svalbard) sowie auf der Nordvik-Halbinsel in Nordsibirien scheinen ebenfalls mit dem Mjølnir-Einschlag zusammenzuhängen und liefern zusätzliche Unterstützung für ein Einschlagsalter im Grenzbereich Volgium-Ryazanium.

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Introduction

The Mjølnir impact structure is located at 73° 48′ N, 29° 40′ E on the central Barents Sea Shelf (Fig. 1), at a water depth of around 350 m and beneath a 400 m thick cover of younger sedimentary strata. It is one of the 25 largest impact structures discovered on earth, and the Mjølnir structure and associated ejecta are among the best preserved crater and ejecta-layers in the presently known impact record (DYPVIK et al. 1996). From seismic reflection data (GUDLAUGSSON 1993, TSIKALAS et al. 1998a-c) it can be demonstrated that the well preserved structure exhibits a distinct radial zonation pattern, composed of a 12 km wide complex outer zone, including a marginal fault zone and a modestly elevated ring, a 4 km wide annular depression, and an 8 km diameter central high (Fig. 2). Seismic mapping shows that an 850–1400 km^3 disturbed sediment volume is connected to the crater formation (TSIKALAS et al. 1998b). The seismic data provide evidence of crater-influenced sedimentation and extensive secondary post-impact deformation expressed by structural reactivation and differential subsidence. TSIKALAS et al. (1998c) inferred that due to the shallow shelf location, the Mjølnir impact resulted in an atypically shallow crater depth, due to gravitational collapse at the crater periphery and considerable crater infill.

The integrated geophysical analysis, including modelling of possible different geological origins for the structure, substantiated the interpretation of the Mjølnir structure as an impact crater (GUDLAUGSSON 1993, TSIKALAS et al. 1998a-c). This interpretation is further supported by recovery of shock metamorphic quartz grains and an iridium anomaly reaching about 15 times the background value in the Volgian-Ryazanian boundary beds of corehole 7430/10-U-01, drilled about 30 km northeast of the Mjølnir crater (Fig. 1) (DYPVIK et al. 1996, DYPVIK & FERRELL 1998, DYPVIK & ATTREP 1999). Here the shocked quartz and the iridium anomaly are recovered from a 0.8 m thick interval (47.65–46.85 m). A 19 cm thick mudflake conglomerate is present at the base, while a distinct unit of smectite-enriched ejecta is found between level 50–46.5 m. At this location the ejecta were probably derived and transported by crater rim collapse and erosion, by suspension currents, and by the fallout of fireball material (DYPVIK & FERRELL 1998, DYPVIK & ATTREP 1999). The ejecta-bearing strata in this core further contain a conspicuous abundance peak of prasinophycean algae (SMELROR et al. 2001). This algal bloom probably evolved as a response to the large amounts of new, free nutrients in the water-column released by the impact and the associated crater-collapse and tsunamies.

Based on seismic correlation from the Mjølnir structure to corehole 7430/10-U-01 and biostratigraphic data from this corehole, DYPVIK et al. (1996) suggested a general Volgian-Ryazanian age for the Mjølnir meteorite impact. The aim of the present study has been to provide a more accurate age-determination of the impact based on new biostratigraphic evidences from the ejecta-bearing strata of corehole 7430/10-U-01 and from the oldest post-impact strata of a new core drilled inside the Mjølnir Crater (7329/03-U-01).

The Mjølnir crater core

The latest evidences of the Mjølnir structure as an impact crater come from a 171 m deep core drilled inside the crater (MØRK et al. 2000) in 1998 (7329/03-U-01, Fig. 1). The well

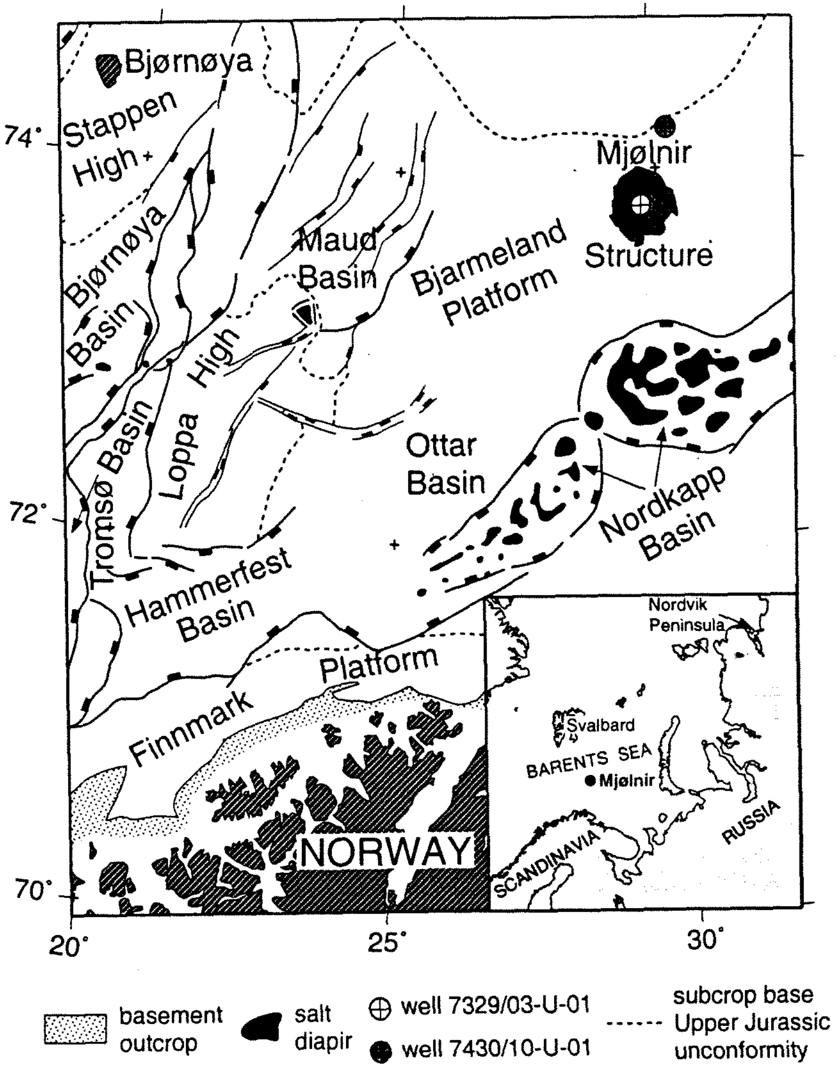

Fig. 1. Late Jurassic-Early Cretaceous structural framework of the southwestern Barents Sea and the locations of the Mjølnir impact crater and borehole 7430/10-U-01. (From TSIKALAS et al. 1998c).

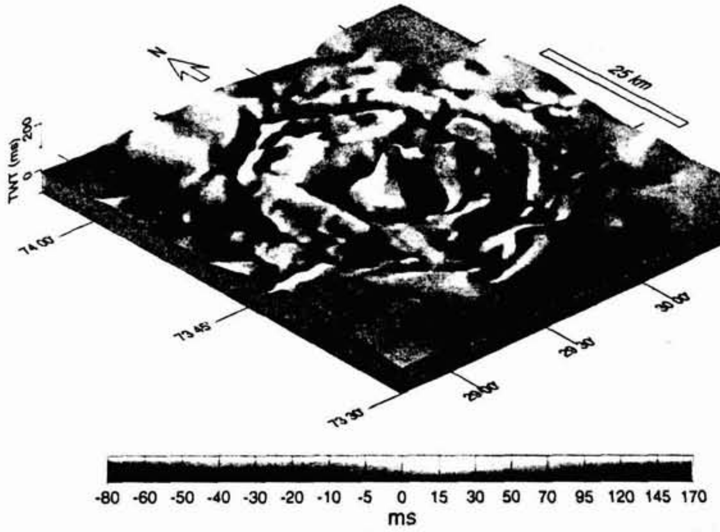

Fig. 2. Illuminated perspective image of the Mjølnir crater structure (i. e. perspective diagram of residual two-way traveltime to the Lower Barremian seismic reflector/top Klippfisk Formation). (From DYPVIK et al. 1996).

was drilled at the edge of the crater central high (Fig. 2) and a 121 m long core was recovered (Fig. 3). The lowermost 83 m of the core consist of possible slump complexes and chaotic deposits. These chaotic deposits may represent a mixture of impact ejecta and sediments derived from the crater walls during the subsequent crater collapse (DYPVIK & ATTREP 1999). The chaotic unit is succeeded by 14 m of shales and possibly current-transported coarse grained sandstones representing the final current action immediately after the impact. This impact-related succession is overlain by 16 m of Berriasian dark shales assigned to the Hekkingen Formation (WORSLEY et al. 1988) and 8 m of Valanginian-Hauterivian condensed carbonates of the Klippfisk Formation (SMELROR et al. 1998). The shales of the Hekkingen Formation contain relatively common bivalves and a few ammonites. The impact deposits in this core are unique in the sedimentological record and provide unambiguous evidence of an impact origin for the Mjølnir structure.

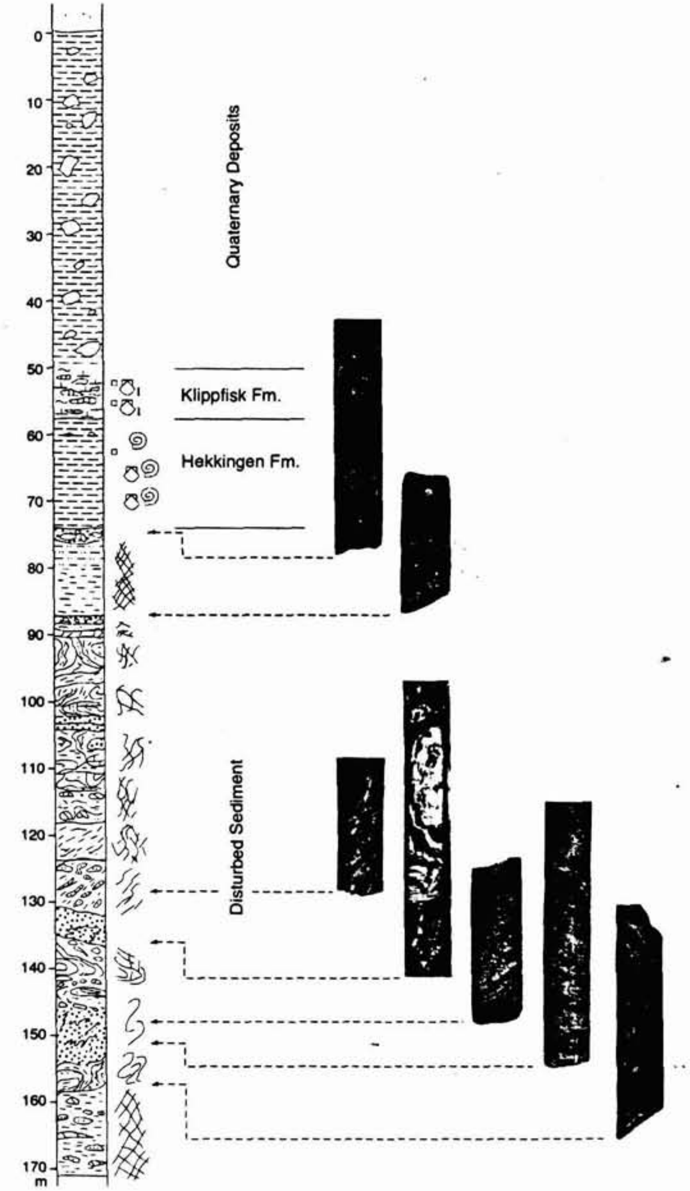

Fig. 3. Lithostratigraphic log and selected core-photos of the Mjølnir crater core (7329/03-U-01).

Biostratigraphy of the Mjølnir core and the age of the Mjølnir impact

The post-impact macrofauna recovered in the Hekkingen Formation in the Mjølnir core (7329/03-U-01) is dominated by bivalves of the genus *Buchia.* Only two ammonites were recovered. *Buchia* is generally confined to the uppermost Jurassic-lowermost Cretaceous of the Boreal realm. In the black shales of the Hekkingen Formation, *Buchia* species occur commonly, and are often complete with valves in occlusion. At the base of the post-impact succession *Buchia unschensis* (PAVLOW) appears at 73.97 m. It is the first identifiable species to occur above the disturbed strata and therefore is most important for identifying the date of return to normal sedimentary conditions after the Mjølnir impact. Specimens of *Buchia unschensis* are found at several levels upwards in the core (Fig. 5), with the youngest occurrence at 67.14 m. The *B. unschensis* Zone was correlated by ZAKHAROV (1981) to the upper part of the *Craspedites okensis* to lower part of the *Chetaites sibiricus* ammonite zones in Siberia. In Northern Greenland, *B. unschensis* occurs in strata of the *Craspedites okensis* to *Hectoroceras kochi* ammonite zones and in East Greenland from the *Virgatosphinctes tenuicostatus* to *Hectoroceras kochi* zones (SURLYK & ZAKAHROV 1983). The East Greenland record is the southernmost occurrence in the North Atlantic region for the species. The species was also recovered from Spitsbergen in the *Craspedites nodiger* Zone (YERSHOVA 1983). *Buchia* cf. *unchensis* was described from borehole 7425/09-U-01 on the Bjarmeland Platform (ÅRHUS et al. 1990).

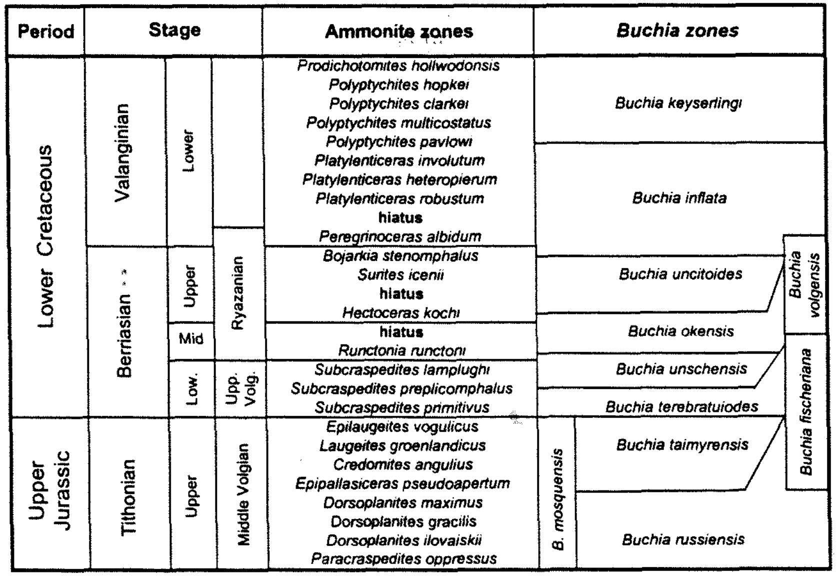

Fig. 4. Summary of the uppermost Jurassic to lowermost Cretaceous Boreal ammonite succession (after RAWSON et al. 1999), showing the Boreal and Tethyan stages. The *Buchia* zonation is modified after ZAKHAROV (1981).

Further upwards in the Mjølnir crater core *Buchia okensis* (PAVLOW) occurs from level 66.80–60.13 m. This species ranges from the upper part of the *Chetaites sibiricus* ammonite Zone to the *Bojarkia mesezhnikowi* Zone in the central part of the Russian Platform (ZAKAHROV 1981). The species is also recovered from the Ryazanian of Spitsbergen (YERSHOVA 1983). In the North Atlantic area, *B. okensis* does not reach further south than Jameson Land, East Greenland (SURLYK & ZAKHAROV 1983), where it is abundant in association with *Hectoroceras kochi* (SURLYK 1973, SURLYK & ZAKHAROV 1983, KELLY pers. obs.). At 60.37 m in the Mjølnir core an ammonite identified as *Borealites* sp. is recorded. This specimen is closely comparable to *Borealites* sp. aff. *fedorovi* KLIMOVA, as figured by HÅKANSSON et al. (1981) from the *Hectoroceras kochi* Zone of Peary Land, North Greenland. A less well preserved specimen of probably the same taxon occurs at 60.12 m. The two specimens from the Mjølnir core also compares to a specimen labelled *Subcraspedites* (*Borealites*) *subrasubditus* (BOGOSLOVSKY) figured by YERSHOVA (1983) from the *Surites spasskensis* ammonite zone of Spitsbergen.

In borehole 7430/10-U-01, both pre-impact, post-impact as well as ejecta-bearing strata are preserved (DYPVIK el al. 1996). In this borehole, age-diagnostic Volgian microfossils are recovered from the pre-impact sediments above level 56.7 m, while middle or younger Volgian ammonites related to Craspeditidae are found at 53.7 m (Fig. 5). *Buchia* species occur throughout the Hekkingen Formation in the core. The record of *Buchia mosquensis* at 57.48 m indicates an age no younger than Middle Volgian at this level. Other species of *Buchia* are found in the ejecta-bearing interval between 50–46.5 m (ÅRHUS 1991) in corehole 7430/10-U-01. The presence of *Buchia unschensis* between 49.95 m and 46.45 m is of importance since this species also is found in the oldest post-impact deposits of the Mjølnir core. The recovery of *Buchia* cf. *volgensis* (found at 46.9 m and 46.45 m) is of special interest since this recovery is approximately at the level of the iridium anomaly in the core, and since *Buchia* cf. *volgensis* is previously reported as an indubitable Ryazanian species (ÅRHUS et al. 1990, ÅRHUS 1991). Other bivalves referable to *Buchia unschensis* and *Buchia terebratuloides* are also present in the interval from 51.88–46.45 m. *Buchia unschensis* is common at 47.75 m and 47.25 m. An ammonite, i. e. *Borealites* sp., which is attributed to the early Ryazanian *Hecteroceras kochi* Zone, is found at 44.1 m. At 42.65 m a typical Late Ryazanian marine microflora, with the dinoflagellates *Systematophora palmula* and *Gochteodinia villosa* as age-diagnostic species, is found (SMELROR et al. 1998, ÅRHUS 1991).

The Barents Sea core 7430-U-01 contains impact indicators (shocked quartz and Ir-anomaly) in the interval 47.65–46.85 m, with a mudflake conglomerate at the base. The sediment around the mudflake bed is barren of benthic foraminifera or contains strongly impoverished assemblages, probably as a response to the impact. The closest age-diagnostic assemblage below the bed is situated at 48.45 m and contains *Recurvoides obskiensis* (ROMANOVA). This species indicates a Late Volgian to Ryazanian age, but not older than the *Chetaites chetae* Zone, according to correlation with the Spitsbergen foraminiferal zonal scheme (NAGY & Basov 1998). The closest age-diagnostic foraminiferal assemblage above the mudflake beds occurs at level 45.5 m, and contains *R. obskien-*

Mjølnir Core 7329/03-U-01

Hekkingen Formation																				Klipp-fisk F.			Lithostratigraphical unit
(latest Volgian-) Ryazanian																		■		Early Valan n			Age
73.97	73.65	72.95	72.33	72.08	71.90	71.06	71.05	69.22	69.21	69.08	68.05	67.20	67.14	66.80	60.37	60.13	60.12	58.57	58.56	57.06	57.05	57.04	m / Macrofossils
X	X	X	X	X		X	X		X	X	X		X										*Buchia unschensis*
					X			X				X						X	X				*Buchia sp./spp.*
														X		X							*Buchia okensis*
															X		X						*Borealites sp.*
																				X	X	X	*Buchia keyserlingi*

Core 7430/10-U-01

62.00	61.90	61.05	57.48	53.65	51.88	50.40	50.23	50.06	49.95	47.82	47.75	47.25	47.20	47.16	46.90	46.45	44.35	44.10	42.40	40.95	40.70	40.20	m / Macrofossils
X																							*Streblites cf. taimyrensis*
	X																						*Buchia cf. mosquensis*
		X																					*Onychites sp.*
		X	X																				*Buchia mosquensis*
				X																			Craspeditidae
					X	X		X	X														*Buchia cf. terebratuloides*
							X																*Buchia terebratuloides*
								X															*Buchia cf. unschensis*
									X	X	X	X	X		X	X							*Buchia unschensis*
												X											*Buchia ex gr. terebratuloides*
														X			X						*Buchia ex gr. volgensis*
															X	X							*Buchia cf. volgensis*
																		X					*Subcraspedites (Borealites) sp.*
																			X				*Buchia cf. jasikovi*
																			X	X	X	X	*Buchia cf. okensis*
Kimmer.-M. Volg.					latest Volgian - Ryazanian														Ryaz.-Valang.				Age
Hekkingen Formation																			Klipp-fisk F.				Lithostratigraphical unit

Fig. 5. Range-chart of macrofossils in core 7329/03-U-01 from the Mjølnir crater and core 7430/10-U-01 from the Bjarmeland platform. (Core-log of 7329/03-U-01 is shown in Fig. 3, while core-log of 7430/10-U-1 is published in Dypvik et al. 1996).

sis, *Gaudryina gerkei* (Vasilenko) and *G. rostellata* (Nagy & Basov). The assemblage indicates a Boreal Berriasian age, but not older than uppermost *Chetaites sibiricus* Zone. Thus, the age of the interval containing the impact indicators is restricted to the time range defined by the uppermost Volgian *Chetaites chetae* Zone and Lower Boreal Berriasian *Chetaites sibiricus* Zone, according to the foraminiferal stratigraphy.

Because of the problems of correlation between the Tethyan and Boreal palaeo- and biogeographic realms, the chronostratigraphic age of the actual Jurassic-Cretaceous boundary is also somewhat uncertain, and published ages in the past twenty years range between 144 Ma and 132 Ma. Currently, the boundary is generally accepted to be placed at the base of the *Berriasella jacobi* Zone, corresponding to the Tithonian-Berriasian boundary in the Tethyan realm (Rawson et al. 1999). This boundary is correlated with the base of the *Subcraspedites primitivus* ammonite zone of the Boreal succession (Fig. 4). Recent Mesozoic time scales give an age of 144.2 ± 2.6 Ma (Gradstein et al. 1994, 1999) for the Tithonian-Berriasian boundary (Jurassic-Cretaceous boundary). In the Boreal realm the boundary between the top of the Volgian Stage and the base of the Ryazanian Stage is placed at the base of the *Runctonia runctoni* Zone in the sub-boreal North Sea area, or at the base of the correlative *Chetaites sibericus* Zone in northern Siberia. This is stratigraphically somewhat younger than the Tithonian-Berriasian boundary (i. e. the Tethyan Jurassic-Cretaceous boundary) and corresponds approximately to the base of the Middle Berriasian in the Tethyan realm (i. e. within the upper part of the *Berriasella jacobi* Zone). A simple calibration of the present biostratigraphic datums (zonations) from the Mjølnir impact ejecta to the recent chronostratigraphic time-scales suggests a rough age of 142 Ma +/– 2.6 Ma for the Mjølnir impact.

Regional correlation of iridium anomalies

Enrichments of iridium, together with other siderophile elements, are frequently cited as potential geochemical evidence of extraterrestrial material (Alvarez et al. 1980, Ganaphathy 1982, Kyte 1988, Hildebrand et al. 1991, Dypvik et al. 1996, Rampino & Haggerty 1996), although several workers have suggested other biological and non-biological mechanisms for iridium enrichments in sedimentary strata (Colodner et al. 1992, Orth et al. 1993). Elevated iridium levels have previously been reported to be associated, or closely linked, to a number of geological and biotal extinction boundaries (Rampino & Haggerty 1996), including the Jurassic-Cretaceous boundary (Zakahrov et al. 1993).

In addition to the previously described iridium anomaly in the ejecta-bearing strata in borehole 7430/10-U-01, iridium peaks which probably can be related to the Mjølnir impact have recently been found in Jurassic-Cretaceous boundary beds on central Spitsbergen – Svalbard (Dypvik et al. 2000), and on the Nordvik Peninsula in northern Siberia, at some 2300 km from the Mjølnir crater (Zakharov et al. 1993). In the Janusfjellet section on central Spitsbergen, the iridium anomaly is observed about 200 m above the base of the Agardhfjellet Formation, within the uppermost Volgian to Ryazanian *Recurvoides obskiensis* (R7) Zone (Nagy & Basov 1998). The recovery of *Buchia volgensis* ca. 0.5 m above the iridium peak provides good evidence for a Volgian-Ryazanian boundary age for the iridium-enriched bed.

In the Nordvik Peninsula section, an iridium anomaly (averaging close to 7.4 ± 4.7 ppb) occurs in a 5–6 cm thick, phosphatic limestone layer and is associated with siderophile elements with chondritic distributional ratios and abundant pyrite spherules. The limestone layer occurs at the base of the *Chetaites sibiricus* Zone and is regarded a Jurassic-Cretaceous boundary layer (Zakharov et al. 1993). Faunas of the *Hectoroceras kochi* Zone occur about 3 m above the iridium-rich layer (Zakharov et al. 1993). This gives the Nordvik Peninsula iridium anomaly the very same stratigraphic age as the ejecta layer from core 7430/10-U-01 and as the first post-impact crater infilling deposits from the Mjølnir crater core itself.

The regional relationships and possible stratigraphical correlation of ejecta, consequently gives the Mjølnir impact an additional value as a Volgian-Ryazanian boundary marker bed in the Arctic. It might be an important aid in circum-Arctic correlation, since both Arctic Jurassic/Cretaceous correlation and plate tectonic relations are quite complex.

Conclusions

The first post-impact sediments from the Mjølnir impact crater contain bivalves which can be correlated to the uppermost Volgian-lowermost Ryazanian *Buchia unschensis* Zone. Its age range corresponds to the *Subcraspedites primitivus* to *Runctonia runctoni* ammonite zones of the standard Boreal succession (Rawson et al. 1999), which are equivalent to the *Craspedites nodiger-Chetaites sibericus* ammonite zones of northern Siberia (Zakharov 1981). The ejecta-bearing strata in borehole 7430/10-U-01 also contain numerous *Buchia unschensis*, supporting the described age-determination. The recovery of *Buchia* cf. *volgensis* within the upper ejecta-bearing strata of 7430/10-U-01 may further restrict the stratigraphic age of the impact to correspond fairly accurately to the Volgian-Ryazanian boundary, which is within the upper part of the Lower Berriasian Stage (*Berriasella jacobi* Zone) of the Tethyan Realm. Following the latest time-scale of Gradstein et al. (1999) a stratigraphic age of 142 ± 2.6 Ma is inferred for the Mjølnir impact event.

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Evidence for Givetian stage in the Mauritanian Adrar (West Africa): biostratigraphical data and palaeogeographic implications

by Patrick R. Racheboeuf, Catherine Girard, Francis Lethiers,
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with 4 figures and 2 tables

Abstract. A palaeontological study of Devonian samples from the Mauritanian Adrar allows for the first time to establish the development of Givetian deposits in this part of western Africa, owing to abundant microfossils (ostracods, conodonts, vertebrate microremains). Above the Llandovery to Ludlow Silurian deposits, locally dated by graptolites, the first Devonian faunal elements recognized belong to the *Polygnathus varcus* zone of conodonts of the Givetian stage. Some of the highest samples may possibly belonging to the Frasnian stage. Biogeographic relationships with both the NE American Realm and the Old World Realm as well as the significance of palaeotethysian faunal elements are discussed. A new palaeogeographic scheme implying a rising of the western part of the W African shield (due to a collision) is used to explain the depositional gap between Upper Silurian and Middle Devonian deposits. Such a collision between North America and West Africa precedes the incoming of North American Givetian benthic faunal elements in the Mauritanian Adrar. The Givetian (lower *Polygnathus varcus* zone) part of the first Devonian faunas above the basal coarse sandy transgressive Devonian deposits strongly suggests a positive eustatic movement responsible for the North American Taghanic Onlap.

Résumé. L'étude paléontologique d'échantillons du Dévonien de l'Adrar de Mauritanie permet, trente années après leur récolte, de mettre en évidence le développement du Givétien dans cette région de l'ouest africain, en particulier grâce à la présence de nombreux microfossiles (ostracodes, conodontes, microrestes de vertébrés). Au-dessus du Silurien (localement daté du Llandovery, du Wenlock ou, plus exceptionellement du Ludlow, par les graptolites), les premières faunes dévoniennes identifiables appartiennent à la zone à *Polygnathus varcus* du Givétien. Les échantillons

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