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

by Morten Smelror, Simon R. A. Kelly, Henning Dyvik, Atle Mørk, Jenő Nagy and Filippos Tsikalas

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 (Berrissella 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.


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Introduction

The Mjælnir 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 Mjælnir 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 km² 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 Mjælnir 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 Mjælnir 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 Mjælnir 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 Mjælnir 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 Mjælnir 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 Mjælnir Crater (7329/03-U-01).

The Mjælnir crater core

The latest evidences of the Mjælnir 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...
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. 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).

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 (PAVLLOW) 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. 3), 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 Chetasites sikiricus ammonite zone 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 Vrgatophinctes tenacostatus to Hectoroceras kochi zones (SURLYK & ZAKHAROV 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 okensis Zone (YERSHOVA 1983). In borehole 7430/10-U-01, both pre-impact, post-impact as well as ejecta-bearing strata are preserved (DYPUK et 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 angulatus 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 Hectoroceras kochi Zone, is found at 44.1 m. At 42.65 m a typical Late Ryazanian marine microflora, with the dinoflagellates Systematothora palmula and Gochtiodina villosa as age-diagnostic species, is found (SMELR OR et al. 1998, ÅRHUS 1991).

In borehole 7430/09-U-01, the age of the Mjølnir core and the age of the Mjølnir impact ejecta offers a Volgian-Ryazanian boundary marker 135 nodiget Zone (YERSHOVA 1983). Buchia cf. unschensis was described from borehole 7425/09-U-01 on the Bjarmeland Platform (ÅRHUS et al. 1990).

Further upwards in the Mjølnir crater core Buchia okensis (PAVLLOW) occurs from level 66.80-60.13 m. This species ranges from the upper part of the Chetasites sikiricus ammonite Zone to the Bojarkia meszsekiwzi Zone in the central part of the Russian Platform (ZAKHAROV 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 Suurite spasskensis ammonite zone of Spitsbergen.

In borehole 7430/10-U-01, both pre-impact, post-impact as well as ejecta-bearing strata are preserved (DYPUK et 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 angulatus 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 Hectoroceras kochi Zone, is found at 44.1 m. At 42.65 m a typical Late Ryazanian marine microflora, with the dinoflagellates Systematothora palmula and Gochtiodina villosa as age-diagnostic species, is found (SMELR OR et al. 1998, ÅRHUS 1991).

The Barents Sea core 7430-10-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 sediments around the mudflake bed are 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 Rovnoeides obiskiensis (ROMANOVA). This species indicates a Late Volgian to Ryazanian age, but not older than the Chetasites chetae Zone, according to correlation with the Spitsbergen foraminiferal zonal scheme (NAJ & BASOV 1998). The closest age-diagnostic foraminiferal assemblage above the mudflake beds occurs at level 45.5 m, and contains R. obiskien-
Mjelnir (Barents Sea) meteorite impact ejecta offers a Volgian-Ryazanian boundary marker. 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 chronostatigraphic 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 (Gradsen 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 Runaonia runctoni Zone in the sub-boreal North Sea area, or at the base of the correlative Chetaites sibiricus Zone in northern Siberia. This is stratigraphically somewhat younger than the Tethyan Jurassic-Cretaceous boundary (i.e. the 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 Mjelnir impact ejecta to the recent chronostratigraphic time-scales suggests a rough age of 142 Ma +/- 2.6 Ma for the Mjelnir 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, Ganapathy 1982, Kye 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 (Zakhrov 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 Mjelnir impact have recently been found in Jurassic-Cretaceous boundary beds on central Spitsbergen and Nordvik Peninsula in northern Siberia, at some 2500 km from the Mjelnir crater (Zakhrov et al. 1993). The Mjelnir impact crater is located 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 Chetaxes sibericus 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 Mjellnir crater core itself.

The regional relationships and possible stratigraphical correlation of ejecta, consequently gives the Mjellnir 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 Mjellnir impact crater contain bivalves which can be correlated to the uppermost Volgian-lowest Ryazanian Buchia unschensis Zone. Its age range corresponds to the Suberaspides primitivi to Ramantonia ranctori ammone zones of the Standard boreal succession (Rawson et al. 1999), which are equivalent to the Suberaspides nodiger-Chetaxes sibericus ammone 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 (Berrasseula jacobi Zone) of the Tethyan Realm. Following the latest time-scale of Gradstein et al. (1999) a stratigraphic age of 142 ± 2 Ma is inferred for the Mjellnir impact event.

References


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

by Patrick R. Rachebeuf, Catherine Girard, Francis Lethiers, Claire Derycke, Zarela A. Herrera and Roland Trompette

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 Givetien 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 exceptionnellement du Ludlow, par les graptolites), les premières faunes dévoniiennes identifiables appartiennent à la zone à Polygnathus varcus du Givetien. Les échantillons...