The irregular base Cretaceous reflector offshore Mid Norway: a possible result of the Mjølnir impact in the Barents Sea?

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Since the time of the early seismic investigations offshore Mid Norway around 1970, a very characteristic bedrock reflector with a densely small-faulted appearance has been noted, mapped and eventually assigned a base Cretaceous age. The irregular shape of the reflector has been ascribed to tectonic activity, but without really providing a full explanation as to why and how it happened. The Mjølnir impact event in the Barents Sea about 142 million years ago may provide this explanation. Within the present accuracy of seismic interpretation and dating, the impact and faulting apparently occurred simultaneously. If the inferred mega-waves from the impact were strong enough, they would have caused intense disturbance over large areas. Geotechnical evaluations show that the formation of the irregular base Cretaceous reflector could be compatible with the expected results from the modelled impact mega-waves on the soft clay deposits forming the sea bed offshore Mid Norway at that time. If the base Cretaceous faulting was caused by the Mjølnir event, it will represent an important geohazard marker demonstrating the distant effects of extraterrestrial impacts.

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Introduction

The last few decades of oil exploration have dramatically increased the geological database of the North European continental margin, and resulted in a number of oil and gas discoveries on the Norwegian continental shelf. This exploration has answered many questions, but also revealed a number of new geological problems. The development of new investigation methods and interpretation techniques, combined with rapid and intense data collection, have resulted in the accumulation of enormous data sets. Recently, several important review papers have appeared (e.g.,, Fleet & Boldy 1999, Martinsen & Dreyer 2001, Eide 2002). Even so, it is clear that numerous geological correlations and causal connections are still to be discovered. In that context, catastrophic geological events with widespread imprints will be of special interest and importance.

The main purpose of this paper is to draw attention to a possible link between the characteristic irregular, base Cretaceous reflector offshore Mid Norway and the Mjølnir impact in the Barents Sea (Fig. 1). The deformed surface will also be compared to the results expected from geotechnical explanation models. If the faulting really has been caused by the impact, the base Cretaceous reflector will represent a very important geohazard marker and could make it possible to further evaluate distant geological effects of extraterrestrial impacts. A deeper evaluation of the regional geological implications, however, falls outside the scope of the present paper.

The Mjølnir impact

The large circular structure in the Barents Sea at 73°48'N, 29°40´E (Fig. 1) was first interpreted as an impact structure by Gudlaugsson (1993) and its impact nature was verified by Dypvik et al. (1996). The 40 km-wide structure has been named Mjølnir after the hammer of the old Norse god Tor, and has later been described in a number of papers (e.g., Dypvik & Ferrell 1998, Dypvik & Attrep 1999, Tsikalas et al.1998a-c, Smelror et al. 2001a, Dypvik et al. 2003, 2004 a, b). The crater was probably created by a 1.5 km to 2 km diameter asteroid, which crushed and melted the target rock and completely vaporized at impact. The results of the impact can be traced both inside and outside the crater as shock metamorphosed grains of quartz in the sediments, possible occurrences of glass fragments and its alteration products, and iridium anomalies.

Biostratigraphical evidence from a core drilled in the central part of the Mjølnir crater has provided a stratigraphic age for the impact approximating to the Volgian - Ryazanian boundary (Fig. 2). A calibration of the present biostratigraphical datums (zonations) from the Mjølnir impact ejecta to recent chronostratigraphic time-scales suggests a rough age of 142 ± 2.6 million years for the impact (Smelror et al. 2001a).

The environment at the impact site was marine with an estimated water depth of about 400 m. The Mjølnir impact caused both major shock waves and huge sea waves (tsunami), resulting in a mixing of water masses and sudden

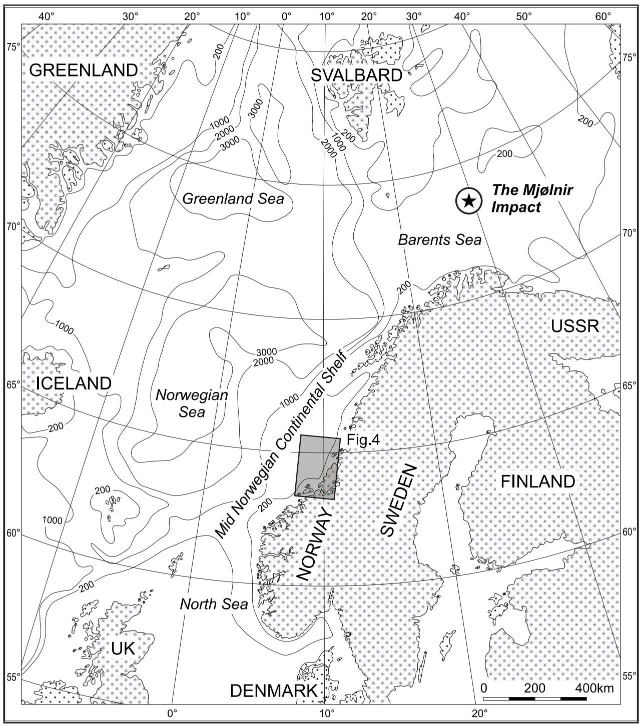

Fig. 1. Location map with present bathymetry showing the Mjølnir impact crater in the Barents Sea and the study area offshore Mid Norway (hatched).

introduction of nutrients into the water column. Phytoplankton blooms have been observed in the Jurassic - Cretaceous boundary beds of the Hekkingen Formation (Fig. 2) in the Barents Sea (Smelror et al. 2002). After tsunami withdrawal from the surrounding land areas, freshwater may have flushed the shelf. This could explain the conspicuous concentration of juvenile freshwater algae (*Botryococcus*) in the post-impact beds of the Hekkingen Formation (Smelror et al. 2002). An alternative freshwater source could be heavy rainfall following the massive evaporation that occurred during the impact.

Occurrences of ejecta material from the Mjølnir event could provide an important circum-Arctic correlation for the Volgian - Ryazanian boundary. Research is in progress both on Svalbard and in North Greenland in the search for geochemical and mineralogical anomalies of possible Mjølnir related material (Dypvik et al. 2004 a, b). In addition, both the shock wave and the inferred ocean mega-waves would have caused extensive and almost instantaneous erosion and sliding both along coastlines and in surrounding basins. Most of the coastal effects would have been removed by later erosion whereas the basinal clay deposits would have had a much higher preservation potential.

It seems obvious that both the direct shock wave from the Mjølnir impact and the huge ocean waves inferred from modelling would cause massive coastal erosion and could also have triggered both ground collapse and intense sliding activity in distant clay basins such as those occurring offshore Mid Norway at that time. The result could have been an uneven surface with a lot of depressions that were gradually infilled by the clay sedimentation which continued after the disaster. In this paper we will draw attention to this possible distant disturbance, with emphasis on the effects of the ocean mega-waves. The study area is as much as 1000 km away from the impact, and consisted of soft clay forming the sea bed on the Mid-Norwegian continental shelf at that time.

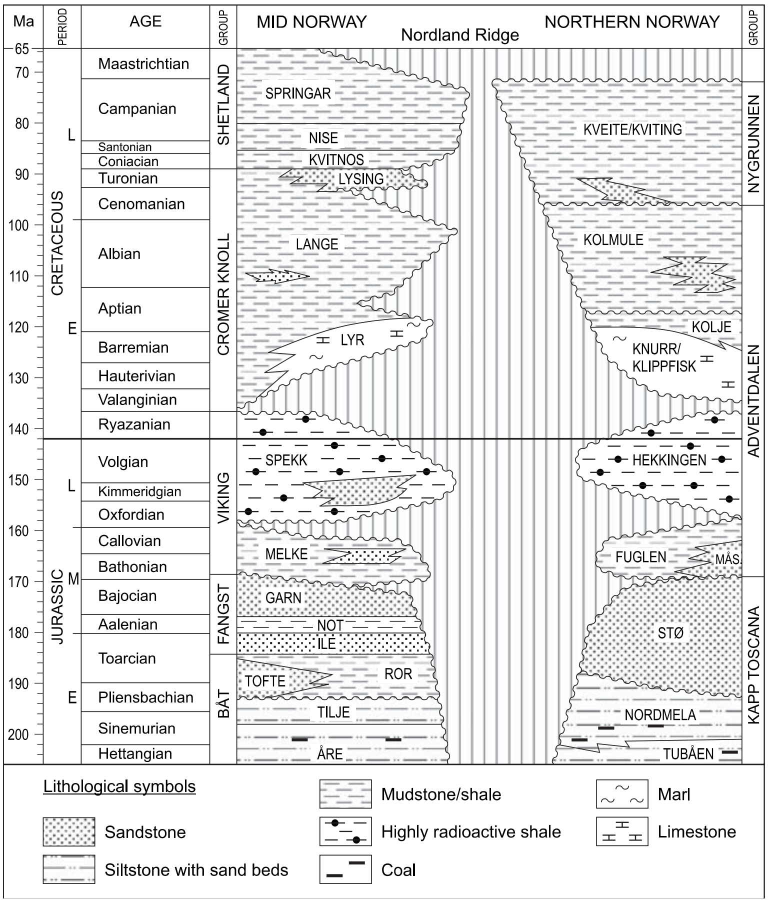

Fig. 2. Time correlation of stratigraphic formations offshore Mid-Norway (Dalland et al. 1988) and Northern Norway (Worsley et al. 1988, Smelror et al. 2001b). Based on Mørk et al. (2003).

The shallow bedrock geology offshore Mid Norway

As part of a regional mapping programme conducted by IKU (now SINTEF Petroleum Research), shallow seismic profiles were run and samples collected between 1973 and 1982 (Rise 1988, Rokoengen & Rise 1989). Based on the seismic mapping, shallow drillings were conducted for bedrock sampling (Bugge et al.

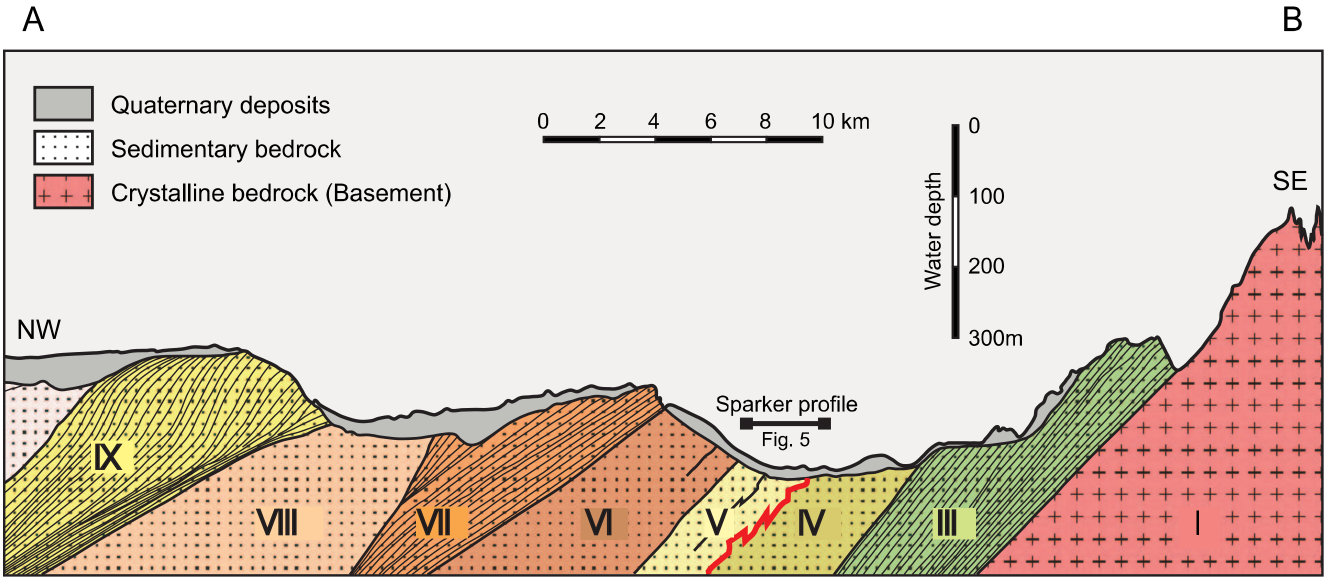

Fig. 3. Geoseismic section (line IKU B73-153) showing the shallow bedrock geology offshore Mid Norway. Approximately 30x vertical exaggeration. Location shown in Fig. 4. Modified from Bugge et al. (1976, 1984). The units I to XI are described in the text and the assumed Jurassic–Cretaceous boundary (contact between Units IV and V) is marked in red.

1984, Rokoengen et al. 1988). The main bedrock units characterised by different seismic layering and varying resistance to glacial erosion are quite striking on the shallow seismic profiles, as shown on the schematic, interpreted, shallow seismic (sparker) profile in Figure 3.

The tilted and later glacially eroded Mesozoic and Tertiary sediments offshore Mid Norway are overlain by only a thin Quaternary overburden and therefore offer a unique opportunity for collecting samples from the subcropping bedrock units (Figs. 3 & 4). Crystalline basement (Unit I) like that of mainland Norway is found in a zone along the coast. Farther offshore, the continental shelf is built up of sedimentary rocks overlying and onlapping this crystalline basement. The outcropping sedimentary bedrock units strike approximately parallel to the coast and generally dip slightly in an oceanward direction.

Offshore Mid Norway, eleven different seismic bedrock units were mapped (Figs. 3 & 4), based on shallow seismic records (mainly sparker) with penetration from approximately 100 to 500 m below the sea bed (Bugge et al. 1984, Rokoengen et al. 1988). Based on palynological and micropaleontological analyses, ages were assigned to the different seismic formations.

Sediments of unit II (of Triassic age) are mapped in several small areas, mostly north of 65°30´N. Unit III (Lower to Middle Jurassic) includes a broad range of lithologies, but is dominated by fine-grained marine sandstone. Unit IV (Upper Jurassic to Lower Cretaceous?) contains dark organic-rich claystones. Unit V (Cretaceous) contains a variety of lithologies including claystone, siltstone and limestone. Units VI to XI are Tertiary deposits comprising diverse lithologies. These units have been presented on a number of published bedrock geology maps although different designations have been used (Wøien et al. 1984, Askvik & Rokoengen 1985, Sigmond 1992, 2002, Gustavson & Bugge 1995).

One of the most marked reflectors in the area is the boundary between Units IV and V, with a characteristic irregular or densely small-faulted appearance (Figs. 3 - 5). Since the start of seismic investigations offshore Mid Norway, this very special reflector has been noted and mapped (e.g., Bugge et al. 1976). Subsequently, the 'block-faulted' reflector has been assigned a base Cretaceous age and linked to the formal lithostratigraphic scheme for offshore Mid Norway as the top of the Spekk Formation (e.g., Brekke & Riis 1987, Dalland et al. 1988).

As illustrated in Figure 3, this is one of the most characteristic reflectors found in the entire sedimentary sequence offshore Mid Norway. Its subcrop can be traced throughout most of the mid-Norwegian continental shelf (Fig. 4). On shallow seismic records, it has a very characteristic block-faulted or 'crenulated' appearance with an approximately vertical separation of up to 25 m (Fig. 5). The faulting cannot be traced down into Unit III on the seismic records and gradually fades out upwards as would be expected from a gradual infilling by sediments over an uneven surface.

It is evident that a correct interpretation of such an uneven reflector is not simple (Figs. 5 & 6). With no perceptible change in the composition of material deposited before and after the faulting event, the disturbance could also be deeper in the stratigraphy than interpreted. The very strong reflector (Fig. 5) could represent a change in lithology that occurred some time after the faulting when the sea bed was still irregular. The regional extent and spatial shape of the irregular base Cretaceous reflector should be studied further, especially in areas where 3-D seismic grids are or will become available.

The irregular shape of the reflector has been ascribed to tectonic activity, but without really providing a full explanation as to why and how it happened. In the following, we will discuss if it is possible that the Mjølnir impact event in the Barents Sea about 142 million years ago could provide this explanation.

Possible connection between the Mjølnir impact and the base Cretaceous faulting offshore Mid Norway

During the last ten years the Mjølnir impact has been well documented, and both its age and unique geological effects have been determined (Figs. 1 & 2). The faulted Unit IV/Unit V reflector offshore Mid Norway also represents a unique event in the Triassic to Quaternary seismic record from this part of the continental shelf (Figs. 3 & 4). To evaluate if the two events can be correlated, the ages of the faulted reflector and the Mjølnir impact must be compared, the depositional environment and impact waves evaluated, and the probable geotechnical effects of the Mjølnir impact as far distant as the mid-Norwegian continental shelf (1000 km away) should be estimated.

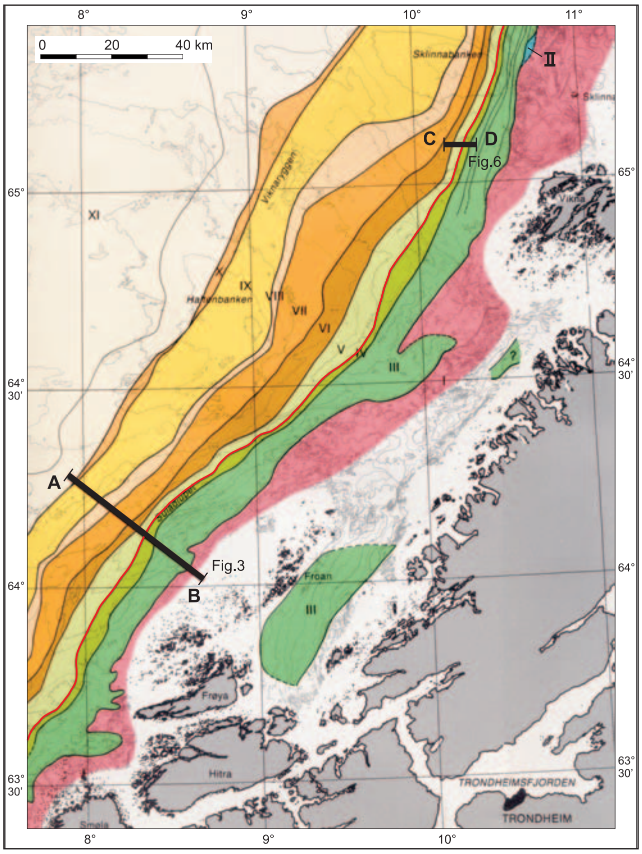

Fig. 4. Bedrock geology on the Mid-Norwegian continental shelf based on the mapping of IKU (Continental Shelf Institute); after Rokoengen et al. (1988). See text for more details about the different bedrock units. The locations of Figs. 3 and 6 are shown and the assumed Jurassic–Cretaceous boundary (contact between Units IV and V) is marked in red.

Age

During the IKU shallow drilling programme in 1982, the faulted reflector was one of the targets (Fig. 6) and was assumed to have been penetrated by the 28.55 m-deep drillhole 7B (Mørk et al. 1983). The problem of defining the exact position of a reflector or geological contact as uneven as the Unit IV/Unit V boundary is evident, even on high-resolution seismic (Figs. 5 & 6). Due to faulting and infilling, the reflector is difficult to trace in detail and it might therefore deviate slightly from that shown in Figure 6 at the site of drillhole 7B. Århus et al. (1986) assigned a Ryazanian age to the interval from 11 m to 28.55 m, which is somewhat too young to correspond to the Volgian - Ryazanian age of the Mjølnir impact (Smelror et al. 2001a). At the present time, however, the published biostratigraphic age assignments from the core 7B are not considered to be conclusive, and a new evaluation is given below.

In borehole 7430/10-U-01, drilled 30 km northeast of the Mjølnir Crater, *Buchia* cf. *volgensis* has been recovered just a few centimetres above the youngest impact ejecta material (Smelror et al. 2001a, Dypvik et al. 2004 a, b). The presence of crushed bivalves assigned to *Buchia* cf. *volgensis* in the interval from 11.95-12.0 m in core 7B suggests a late Early Ryazanian age (i.e., not younger than the *Hectoroceras* kochi ammonite zone) at this level. The recovery of the ammonite *Surites* sp. cf/aff. *tzikwinianus* at 13.2 m provides further support for a similar age down to this level. The last appearance of the dinoflagellate cysts *Egmontodinium expiratum* at

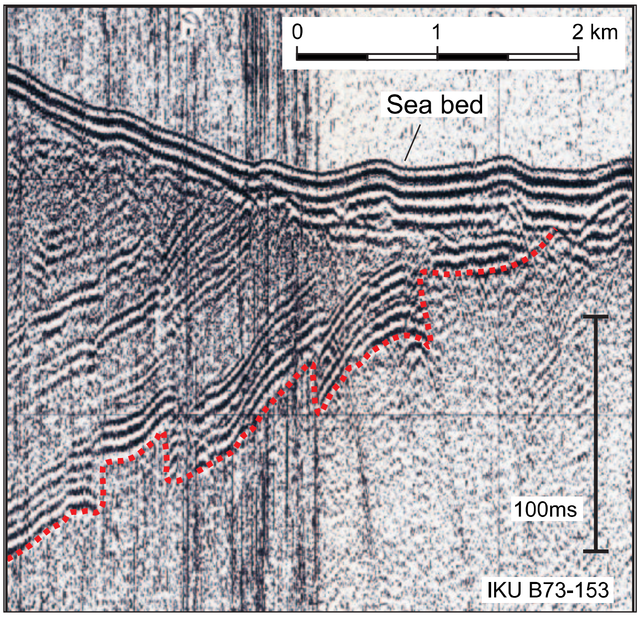

Fig. 5. Shallow seismic (sparker) section showing the block-faulted reflector forming the border between Units IV and V (red dots). For location, see Fig. 3.

16.65 m indicates an age not younger than earliest Ryazanian (*Runctoni* ammonite zone) at this stratigraphic level. In contrast, the recovery of *Stiphrosphaeridium arabustum* and *Systematophora palmula* from 23.32 m and upwards is indicative of an age not older than Late Ryazanian, provided that the ranges for these species reported in Costa & Davey (1992) for the British Cretaceous are valid in the Norwegian Sea area. Furthermore, the recovery of *Stiphrosphaeridium dictyophorum* and *Gochteodinia villosa* from 25.6 m and upwards provides evidence for an age no older than Late Volgian for the lower part of core 7B.

Based on the palynostratigraphic evidence, it therefore seems probable that sediments deposited in the Barents Sea at the time of the Mjølnir impact are correlative with the sediments located somewhere between 12 m and 25.6 m in core 7B.

Compared to the Barents Sea, we would expect to find traces of the impact-related deposits also in the samples from the Trøndelag Platform, but in much smaller amounts. The freshwater algae *Botryococcus*, found in post-impact beds in the Barents Sea (Smelror et al. 2002), is reported in one sample from Core 7B (Fig. 6) at 20 m depth (Mørk et al. 1983), i.e., within the interval assumed to represent the Mjølnir impact, based on the new age evaluation.

Another effect that has been considered to be a result of asteroid or comet impacts is global firestorms. Soot from combustion of vegetation is reported from the Cretaceous–Tertiary boundary (e.g., Wolbach et al. 1988). Soot from fires related to the Mjølnir impact has also been found in cores from the Barents Sea (Wolbach et al. 2001). Worldwide methane blow-outs from the sediments at the Cretaceous-Tertiary boundary are a suggested cause of global firestorms (Max et al. 1999). The Spekk Formation is characterised by a high organic content, and at the time of deposition it probably had a considerable biogenic gas content. Mega-waves from the Mjølnir impact could, therefore, both have provided methane for firestorms by gas blow-out and disrupted the sediments due to gas release. Whether or not soot particles of Jurassic – Cretaceous age are present in the successions offshore Mid Norway remains to be seen.

In addition to closer biostratigraphic examination of Core 7B to pinpoint the position of the Volgian – Ryazanian boundary, the cores from offshore Mid Norway should be examined for possible impact-related anomalies of *Botryococcus*, soot, iridium, etc. Within the present accuracy of seismic interpretation and dating, the Mjølnir impact and the described faulting offshore Mid Norway appear, however, to have occurred simultaneously.

Depositional environment and impact waves

In order to evaluate the effects of the Mjølnir impact offshore Mid Norway 1000 km away, we have to consider the depositional environments prevailing both before and after the impact, i.e., during the deposition of the black clays of the Spekk Formation (e.g., Dalland et al. 1988). Partly time-equivalent claystones and shales are found both in the North Sea (the Draupne Formation) and in the Barents Sea (the Hekkingen Formation, Fig. 2).

Several plate tectonic reconstructions have been published (Ziegler 1990, Dore et al. 1999, Brekke et al. 2001, Torsvik et al. 2002). The Late Jurassic model from Torsvik et al. (2002) is shown in Figure 7. Other reconstructions (e.g., Brekke et al. 2001) indicate that parts of mainland Mid Norway were below sea-level at that time. The main configuration offshore Trøndelag seems, however, to have been marine in the study area of the present paper (Figs. 1 & 4) with deeper marine conditions farther to the west (Fig. 7).

The Barents Shelf, where the Mjølnir impact occurred, was part of a wide, epicontinental sea with a narrow channel connection between Norway and Greenland (Fig. 7). The mega-waves (tsunami) from the impact would have created severe coastal erosion which in places, was probably enhanced due to the effects of focusing. Almost all coastal imprints would have been removed by later erosion.

The mega-waves would also have affected the deeper areas and the basinal clay deposits would have had a much higher preservation potential than the coastal deposits. Numerical simulations of the wave heights will naturally depend on the model used and the input data. In early modelling, estimated wave amplitudes were 30-60 m at 50 km radius, 5-10 m at 400 km radius and only 2-3 m at 1000 km radius (Tsikalas et al. 1998b). As the distance to the mid-Norwegian continental shelf is about 1000 km, these amplitudes would probably not have been high enough to affect

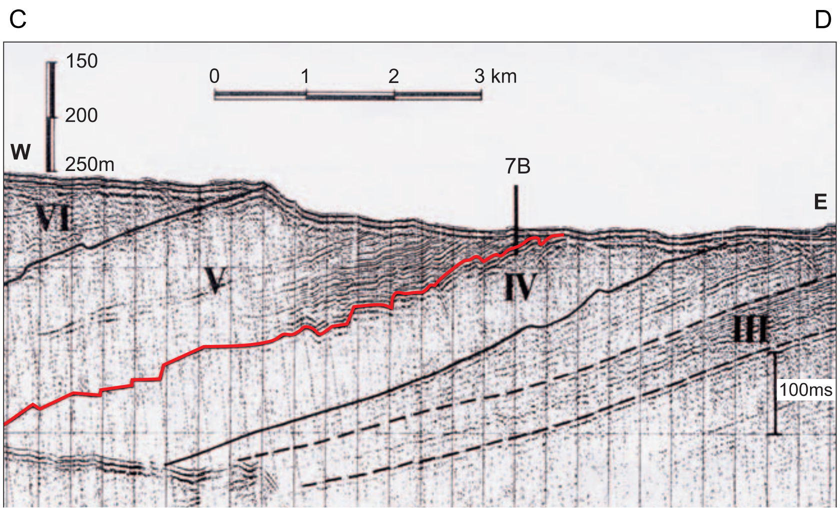

Fig. 6. Shallow seismic (sparker) line IKU B78-103 with location of borehole 7B. Location shown in Fig. 4. The border between Units IV and V is marked in red. After Mørk et al. (1983) and Århus et al. (1986).

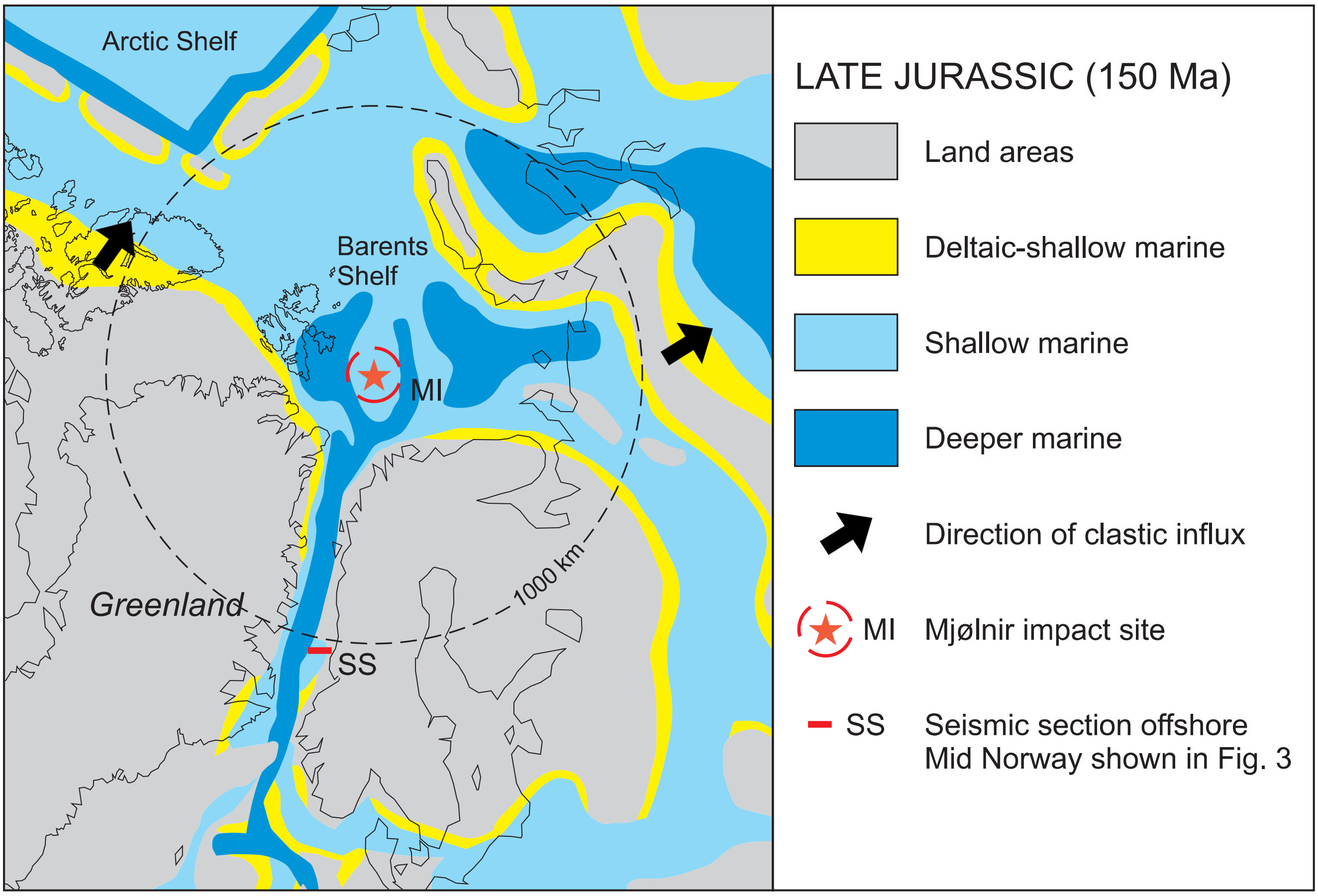

Fig. 7. North Atlantic paleogeography in Late Jurassic time. Modified after Torsvik et al. 2002.

the sea bed stability in the study area (Figs. 1 & 7). In later modelling, however, the impact wave heights have been upgraded. The simulations of Shuvalov et al. (2002) assumed that the wave's amplitude is inversely proportional to the distance from the impact site and estimated that at 1000 km distance from the impact site the wave amplitude would have reached 10 m, assuming an open ocean.

Dypvik (2002) reported later comparisons with calculations of Van den Bergh (1989) and Jansa (1993) for extraterrestrial impacts into oceans with waves as high as 200 m some 300 km from the impact site. With the assumed inverse connection between wave height and distance, that would give waves about 60 m in height at a distance of 1000 km.

Considering the Late Jurassic paleogeography (Fig. 7), with a channel between Norway and Greenland giving less damping of the waves than in open sea and possible focusing effects, the Mjølnir impact would have resulted in megawaves even on the mid-Norwegian shelf, 1000 km away.

Geotechnical effects

The geotechnical response to the Mjølnir impact would depend on several factors such as water depth, natural frequency of the clay basin, shear strength and permeability of the clay. At the time of deposition the Spekk Formation apparently represented a normally consolidated clay with quite high clay and clay-mineral contents. The clays of the Spekk Formation (Fig. 2) from the Trøndelag Platform and Froan Basin contain more smectite and mixed layer minerals than the time-equivalent clays of the Hekkingen Formation offshore Nordland and Troms farther north (Mørk et al. 2003). Such differences in mineralogy affect the geotechnical properties, as a higher smectite content gives a more plastic clay. Regardless of the differences in clay mineralogy, the clay deposits would have very anisotropic properties. For instance, the permeability in the vertical direction will normally be much lower than in the horizontal.

A large number of stability investigations have been carried out in the field of geotechnical earthquake engineering (e.g., Kramer 1996) and complex technical problems have been solved. In the case of the Mjølnir impact, the uncertainty in data input does not, however, at this stage, justify sophisticated and complicated calculations, but only the use of classical geotechnical principles (e.g., Janbu et al. 1966, Terzaghi & Peck 1967).

To illustrate the development, a simplified two-dimensional explanation model considering just the static pressures has been sketched in Figure 8. Before the Mjølnir impact, a long period of clay deposition had resulted in the accumulation of a normally consolidated clay representing the present Spekk Formation. The effective vertical stress will be equal to the total stress minus the pore pressure (symbols explained in the text of Fig. 8):

$$P_z' = P_{total} - P_w = \gamma' \cdot z + \gamma_w(H + z) - \gamma_w(H + z) = \gamma' \cdot z \quad \text{(Fig. 8a)}$$

The water-level rise of the mega-wave can simplified be treated as a bearing capacity problem with undrained conditions. At the sea bed and with equilibrium (safety factor = 1), the bearing capacity q_a can be expressed as:

$$q_a = N_c \cdot s \quad \text{(Janbu et al. 1966)}$$

where N_c is a dimensionless factor depending on the geometry of the foundation and s is the undrained shear strength of the clay material. Considering a very broad wave front, N_c will be between 5 and 6 (Janbu et al. 1966). The water level rise will act as an additional external load which is added too quickly for the pore pressure in the soil to build up (Fig. 8b). The equation above implies a linear relationship between critical shear strength for instability and impact wave height. The shear strength of the clay at that time is, of course, not known, but considering a probable range of 20, 40 and 60 kN/m^2 as examples of shear strength, unstable conditions will occur with wave heights of about 10, 20 and 30 m, respectively.

The water-level fall of the mega-wave can be treated as an excess pore-pressure problem (Fig. 8c) partly analogous to gas blow-outs. The lowered water level will reduce the total pressure in the area, and the low permeability in the sediments will not allow an instant adjustment (fall) of pore pressure. It will consequently remain at the same high value below the sea bed.

Theoretically, instability, with zero effective pressure, will occur when the effective pressure of soil, $\gamma' \cdot z$, is equal to the excess pore pressure $\Delta H_2 \cdot \gamma_w$ created by the drop in total pressure, as shown in Figure 8c. With γ' about equal to γ_w, the theoretical depth of instability will simply be equal to the impact water-level fall.

In practice, the conditions during both water-level rise and fall will be far more complex and both the shear strength of the soil and the gas content in the sediments will be important. With crack development, horizontal drainage will be possible and weak or permeable layers may act as failure planes.

After the mega-wave event, the situation will have returned to normal with new clay deposition (Fig. 8d). Based on the simple geotechnical evaluation, it seems possible that the mega-waves of the Mjølnir impact inferred from modelling could have caused extensive deformation and could also have triggered both ground collapse and intense sliding activity in clay basins such as those occurring offshore Mid Norway at that time. The result could have been an uneven surface with a lot of depressions that were gradually infilled by the clay sedimentation that continued after

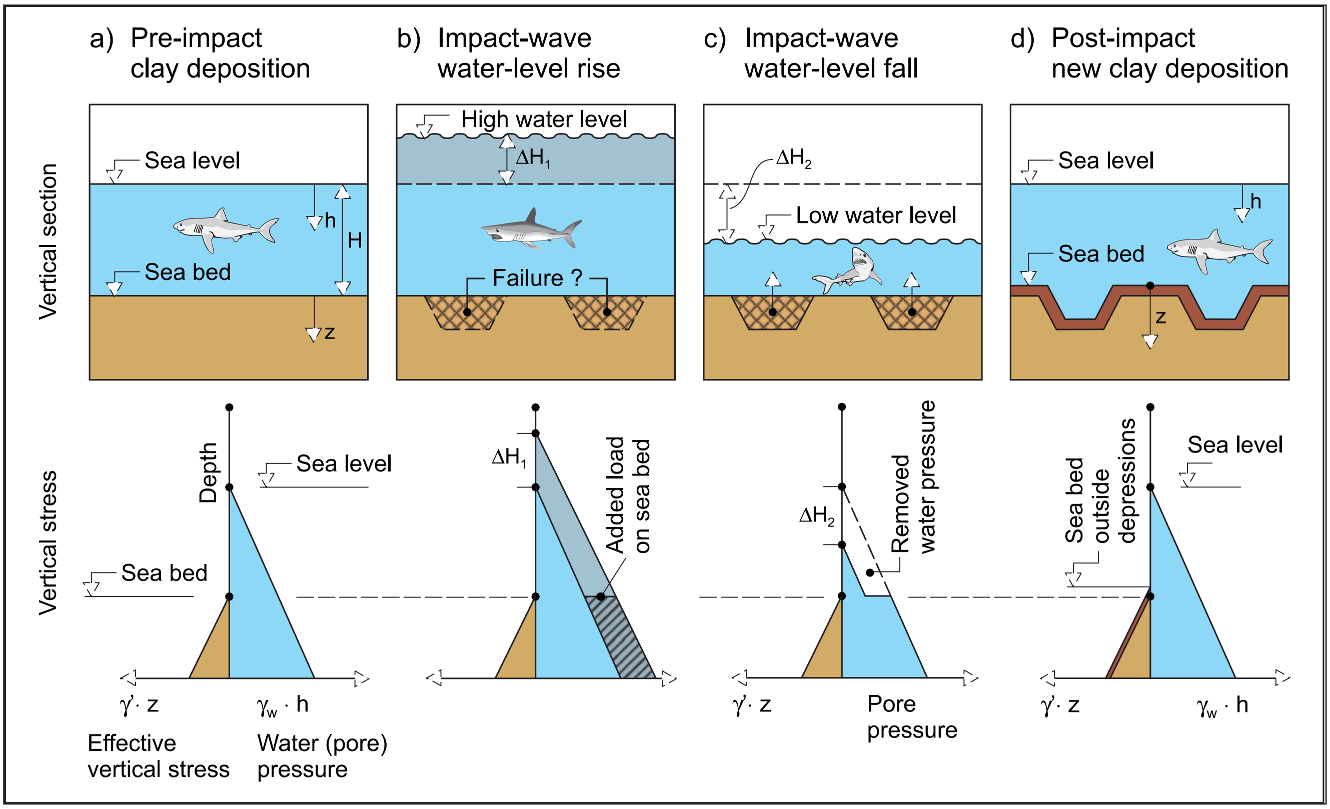

Fig. 8. Simplified two-dimensional, geotechnical explanation model for the formation of the irregular base Cretaceous reflector offshore Mid Norway. See text for more details about the different cases. γ' – dry unit weight of soil (kN/m^3); γ_w – unit weight of water (kN/m^3); z – depth below sea bed; H – original water depth; h – depth below sea level; ΔH_1 – impact water level rise; ΔH_2 – impact water level fall

the disaster. When taking the vertical exaggeration into consideration, the expected deformation could well be in accordance with what we can observe in the seismic profiles in the offshore Mid Norway area (Figs. 3, 5 & 6).

Conclusions

- Both the Mjølnir impact in the Barents Sea and the irregular base Cretaceous reflector offshore Mid Norway represent unique events (geohazards) in the geological record of this region, and the present paper evaluates if the two events may have a causal connection.

- Within the present limits of accuracy of seismic interpretation and dating, the impact and faulting apparently occurred simultaneously. In addition to closer biostratigraphic examination of Core 7B to pinpoint the position of the Volgian - Ryazanian boundary beds, the cores offshore Mid Norway should be examined for possible impact-related anomalies of *Botryococcus*, soot, iridium content, etc.

- Geotechnical evaluations show that the formation of the irregular base Cretaceous reflector could be compatible with the expected results of the huge modelled waves from the impact on the soft clay deposits forming the sea bed offshore Mid Norway at that time.

- If the base Cretaceous faulting was caused by the Mjølnir impact, it will represent an important geohazard marker demonstrating the distant effects of extraterrestrial impacts.

Acknowledgements

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