The Mjølnir Impact Event and its Consequences

Geology and Geophysics of a Late Jurassic/Early Cretaceous Marine Impact Event

With 166 figures, 74 in colour
Preface

The study of the Mjølnir impact crater was initiated by Steinar Thor Gudlaugsson (Gudlaugsson 1993) who first had the idea that this peculiar inverted sombrero structure in the central Barents Sea had been created by an asteroid/comet impact. This “exotic” idea led to the acquisition of new geological and geophysical data at the structure and the further investigations and involvement of several scientists, as described in Sect. 1.4.

Impacts into marine environments and wet sediments have been common and important throughout the geological history of the Earth, which is covered by close to 75% of water. Only 27 of the 176 impact craters currently discovered on Earth have a marine origin, and just a couple of these have been studied in great detail. One of the important scientific features of the Mjølnir impact crater is the clear correlation between the crater and its very well preserved ejecta (Sindre Bed) found in boreholes in the Barents Sea and on land on Svalbard, and possibly in western Siberia. Furthermore, the Mjølnir impact is unique in targeting into thick successions of prolific marine source rocks for oil and gas, and thus the impact possibly resulted in an enormous post-impact fire on the paleo-Barents Sea seafloor. What are the morphological, structural and sedimentological characteristics of the Mjølnir impact crater, and what were the immediate environmental consequences of the impact event for life and later the petroleum generation? The present book outlines key features of the Mjølnir impact and sums up the results of nearly 20 years of studies of the impact crater. However, the study of the Mjølnir impact and its consequences will continue in the near future (see Sect. 1.6).

In this book the major scientific contributions of the Mjølnir impact studies are summarized, updated and presented in 10 chapters, together with a rich reference list and useful subject index. The introductory chapter gives the general setting of the different scientific involvements and sketches the hydrocarbon exploration of the region (Chap. 1). In Chap. 2, an overview of the Arctic geological setting is given, forming the foundation for the major structural, geomorphological and geophysical characteristics of the Mjølnir crater as presented in Chaps. 3 and 4. The sedimentation of the impact crater, both syn- and post-impact, is presented in Chap. 5, succeeded by the ejecta geology in Chap. 6. The mechanisms of cratering are treated in Chap. 7, but modeling and cratering mechanisms are also discussed in Chaps. 4 and 8. The generally poorly understood post-impact deformation in
impact craters, is elaborated in Chap. 9, where the Mjølnir results are compared to other, well-known impact sites. The dramatic Mjølnir impact tsunami is the theme of Chap. 10, clearly accounting for the post-impact sedimentological consequences of the shallow-water target area.

In a newly submitted proposal (December 2009), we suggest to drill 6 boreholes, up to 300 m long, to further gather new, unique information on the Mjølnir impact. Financial support was requested in a combined drilling proposal submitted to the Integrated Ocean Drilling Program (IODP) and International Continental Scientific Drilling Program (ICDP), oil companies active in the Barents Sea (20 companies), and the Research Council of Norway (NRC). The drill sites have been carefully selected to cover the full variety of lithologies and stratigraphies associated with the Mjølnir impact. The project is aiming at studying the mechanisms of crater formation, ejecta generation and distribution, and the shock and seismic disturbances in the area. We are aiming at drilling the structure in 2011. The proposed drilling operations are planned to be televised, which we hope will give great public relations for the natural sciences, beneficial for both academia and industry. An international science team has been established in relation with the proposed drilling operations.

We hope and expect the current book and the planned near-future activities will take the Mjølnir research one step further and inspire to more projects within the field of marine impact cratering.

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The Mjølnir project has involved a large number of project affiliated scientists and students and other persons and organisations outside the research group. Here we will just mention a few, which have been particularly important for us to finalize this book.

We wish to thank Research Council of Norway (grant No. 154831 and Mjølnirprosjektet), SINTEF Petroleum Research (Trondheim), the Norwegian Petroleum Directorate (NPD) and the International Centre for Geohazards (ICG) for their support.

In relation with the shallow drilling of the Mjølnir structure in 1998, The Norwegian Petroleum Directorate and the crew and shipowner of Bucentauer should be thanked as should the petroleum companies Phillips Petroleum, Saga Petroleum, Norsk Hydro, and Statoil for their financial support.

The ESF Impact program should be mentioned in particular for arranging inspiring meetings and discussions keeping the impact studies and research inspiration alive in the first years.

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Chapter 1
Introduction

Henning Dypvik, Morten Smelror, Atle Mørk, and Filippo Tsikalas

1.1 Background

Impact cratering is one of the fundamental processes in our planetary system and an important factor in forming the lithosphere of the Earth and the planets. The active surface processes on Earth, e.g. weathering, erosion, plate tectonics, and volcanism change the Earth’s surface continuously. Therefore only a modest number of crater structures have been preserved and discovered on the surface of the Earth, compared to what can be seen on the less disturbed surfaces on the Moon and Mars (Melosh 1989; French 1998; Montanari and Koeberl 2000; Koeberl 2007) (Fig. 1.1). So far only 176 impact structures have been recognized in the Earth Database, an apparent crater density of about 1/3,000,000 (176/509,600,000) km², in contrast the crater density at Moon, which is at least 3,000 times higher (Beals and Halliday 1967). If we look at the global distribution of land and sea (1:3) in combination with the 27 marine impact structures detected so far on Earth, it appears that less than 6% of the total number of possible marine impacts have been discovered (compared to the roughly more than 400 expected). This rough calculation is based on the present number of impacts on land (here called subaerial) (149, i.e. 149 · 3 = 447) (Dypvik et al. 2004a). The discrepancy, with a too low number of marine impacts discovered, is mainly the result of our limited knowledge of present submarine crater locations, the ocean water breakdown of impactors, along with the burial of marine craters by post-impact sediments, plate tectonics and the young ages of the ocean floors, and the limited geophysical information from the oceans and shelf seas. Many more marine impact structures should be expected and will probably be found in the future (Dypvik and Jansa 2003; Dypvik et al. 2004a).

The Mjølnir impact crater in the Barents Sea (Fig. 1.2) was recognized in 1993 and included in the Earth Impact Database of 1996; based on the discoveries of impact-related geological and geochemical features, such as shocked quartz, Ir-enrichments, possible glass remnants, fragments of nickel-rich iron oxides, in

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Fig. 1.1 Locations of the present known impact craters on the Earth. Ch = Chixculub, CB = Chesapeake Bay, Mo = Montagnais, Mj = Mjølnir (Modified from French 1998)

Fig. 1.2 Map with location of the Mjølnir crater, license areas in the western Barents Sea and locations of the Snøhvit and Goliat fields. Inset a circum-Arctic map, showing the positions of the Mjølnir crater (5), Nordvik in western Siberia (1), well 7120/12-1 off Troms (2), and studied onshore sections on Svalbard (3) and Greenland (4) (Modified from NPD website 2009)
addition to the convincing complex crater shape of the structure (Gudlaugsson 1993; Dypvik et al. 1996).

The marine impacts of Chixculub, Chesapeake Bay, Montagnais, and Mjølnir are found in submarine settings and consequently are difficult and expensive to study in detail. However, marine geophysical investigations along with several recent drilling campaigns have disclosed lots of information about these important events. On the marine shelves, seismic investigations can give us 3-dimensional impressions of the subsea structures, which may be a great advantage in crater research. Marine impacts, presently exposed on land in subaerial positions under shallow burial, such as, e.g., the Lockne and Kärdla craters are more easy accessible for direct study and have also contributed to our understanding of marine cratering and related processes (e.g., Jansa et al. 1989; Gudlaugsson 1993; Pilkington et al. 1995; Dypvik et al. 1996; Lindström et al. 1996; Morgan and Warner 1999; Ormö and Lindström 2000; Suuroja et al. 2002; Poag et al. 2004).

The impact of an asteroid or a comet results in instantaneous generation of shock waves that penetrate the target area and attenuate into the target environment. The shock waves affect the target lithologies by vaporizing, melting, and shattering both the projectile and target rocks. The passage of the impact-induced shock wave leads to development of extremely high pressure and temperature as reflected in the characteristics of, e.g., impact lithologies, shocked minerals, and shatter cones (Melosh 1989; French 1998; Montanari and Koeberl 2000).

The processes of impact cratering can be subdivided into several phases, Kieffer and Simonds (1980) suggest 5 phases, while Melosh (1989) suggested this simpler three phase subdivision:

(a) Contact/compression
(b) Excavation
(c) Modification

The contact/compression stage starts from contact when the projectile pushes target material, compressing and accelerating it, and ends when the projectile has unloaded from high pressure (Melosh 1989). During the excavation stage the almost hemispherical shock wave propagates into the target and in combination with the following rarefaction wave moves target material. Target material is displaced within the crater and excavated as ejecta. This stage ends when the crater has been fully excavated. The modification stage includes the filling of the excavated crater (transient crater) with loose debris; large slumps etc. down the sides and the possible highs in the crater (central peak, annular ring).

Marine impacts experience different and additional effects in all of the three cratering phases compared to the impacts on land (subaerial impacts). This is due to the presence of water and water-saturated sediment-covers of varying thicknesses, in addition to submarine post-impact modification by erosion and sedimentation (Ormö and Lindström 2000; Dypvik and Jansa 2003; Dypvik et al. 2004a).

The nature of the cratering processes also depends on whether the target is crystalline or sedimentary. However, the global cratering record is biased towards crystalline, water-poor targets. Using a multi-material hydrocode, numerical simulations for Mjølnir, Shuvalov et al. (2002) have pointed out the importance of
the target lithology for the cratering processes. In particular, the low-strength, water-saturated sedimentary target layer will lead to a modification and post-impact sedimentation crater stage that deviates considerably from the more typical scenarios of modification for large complex craters on land. Dypvik and Kalleson (2010) have recently recognized comparable crater filling process developments in the filling/sedimentation in marine impact craters.

The influence of water is in particular evident in the processes of vapor cloud formation, tsunami generation, and post impact sedimentation and modification. It is also reflected in the wide array of breccias and conglomerates occurring in and around the impact structures. In this compilation we will present the formation and modification of the marine Mjølnir impact structure in its Arctic geological framework, a typical marine impact crater. We will also place the Mjølnir structure in the global cratering picture, in order both to explain its formation and its regional and global significance.

1.2 Barents Sea Geology

The Svalbard and Barents Sea stratigraphy (Dallmann et al. 1999) and a review of the geological history is presented in Worsley (2008) and forms the base and main reference for the following presentation (stratigraphy in Chap. 2) (Figs. 1.3 and 1.4).

Today Precambrian rocks crop out along the western and northern part of Svalbard, in North Greenland and in Northern Norway. So far Precambrian rocks have not been reached by any of the wells drilled during the petroleum exploration of the southern and western parts of Barents Sea. The Precambrian rocks surrounding the Barents Sea region are made up of granitic and amphibolitic gneisses, which may be covering or even cross cut metasedimentary successions of sandstone, shale and conglomerate along with Vendian tillites, stromatolites, and dolomitic formations (Gee and Tebenkov 2004). Overlying the Precambrian rocks there is a succession of Cambrian to Lower Silurian marine clastics and carbonates. The Precambrian and Caledonian formations of Svalbard are referred to as the Hecla Hoek Complex (or Pre-Old Red basement). During the Caledonian orogeny the Hecla Hoek rocks were faulted, folded, thrusted, and intercepted by igneous complexes. The Hecla Hoek Complex has been estimated to be 15–20 km in thickness, spanning ages from 1,275 to 340 million years (Harland 1969, 1971; Worsley 2008; Worsley and Aga 1986; Otha 1994; Gee and Tebenkov 2004).

In the Barents Sea region the main phase of the Caledonian orogeny was followed by extensive Devonian to Permian denudation and rifting. In this period Old Red Sandstones (Devonian) along with alluvial to sabkha and desert-like deposits (Devonian to Carboniferous), followed by Permian carbonate platform deposits were deposited. The Devonian, Carboniferous, and Permian successions may locally be more than 13 km in thickness (Dallmann et al. 1999; Johnsen et al. 2001; Worsley 2008; Smelror et al. 2009).

In Late Devonian times humid conditions prevailed and a change from the underlying red Early Devonian to grey fluvial sedimentary facies can be observed
Fig. 1.3 Lithostratigraphic correlation columns for the Bathonian-Albian successions of North Greenland, Svalbard, western Barents Shelf and East Siberia (Based on Dypvik et al. 2002; Dypvik and Zakharov 2010)
![Stratigraphy of the Barents Sea, with the Mjølnir impact crater included (R) (Dypvik et al. 2004b). The Mjølnir crater cuts into the Lower Triassic part of the sedimentary successions. During the subsequent crater filling processes the crater is filled by the reworked/redeposited beds, named the Ragnarok Formation (R).](image)

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<tr>
<th>Period</th>
<th>Age</th>
<th>Lithology units</th>
<th>Reflector</th>
<th>Group</th>
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<td>Quaternary</td>
<td>Late</td>
<td>Post Klippfisk Fm. bedrock eroded at drillite</td>
<td>SF</td>
<td>(Till)</td>
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<td>Early</td>
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<tr>
<td>Cretaceous</td>
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<td>Kapp Toscana</td>
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<td>Jurassic</td>
<td>Early</td>
<td>Sassendalen</td>
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<td>Middel</td>
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<td>Carboniferous</td>
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- SF: Sea Floor
- URU: Upper Regional Unconformity
- UB: Lower Barremian
- TD: Top Disturbance
- LB: Base Upper Jurassic
- TP: Top Permian

**Fig. 1.4** Stratigraphy of the Barents Sea, with the Mjølnir impact crater included (R) (Dypvik et al. 2004b). The Mjølnir crater cuts into the Lower Triassic part of the sedimentary successions. During the subsequent crater filling processes the crater is filled by the reworked/redeposited beds, named the Ragnarok Formation (R).
(Fig. 1.4). Renewed extension/ripping took place in the Carboniferous, and coarse grained siliciclastics and coal beds were deposited. The Carboniferous succession is dominated by alluvial sediments succeeded by the evaporites of the Gipsdalen Group (Middle Carboniferous age). During the Late Carboniferous, Permian, and Mesozoic stable platform conditions evolved in the region, comprising Svalbard and large parts of the present Barents Shelf. In Permian time, the region was dominated by limestone, dolomite, and evaporite sedimentation grading into cherty limestones and silicified shales and siltstones. The break between the siliceous Permian beds and the much less cemented siliciclastic Triassic formations forms one of the most pronounced stratigraphical boundaries on Svalbard (Fig. 1.4).

The succeeding Lower Triassic succession consists of shales and sandstones with only moderate degree of cementation, in great contrast to the firm, siliceous Permian formations below. Consequently, the Permian/Triassic boundary is fairly well exposed/expressed on Svalbard, and can also be traced as a pronounced reflector on seismic sections in the Barents Sea.

The Mesozoic succession of the Barents Sea region (Figs. 1.3 and 1.4) represents continental to open marine environments (Worlsey 2008; Smelror et al. 2009). The succession reaches close to 3 km in thickness on Svalbard and about 6 km in thickness on the Barents Shelf. Fluvial, deltaic and coastal deposits with shifting tidal influences are found along with more open marine, shelf deposits. Sand and gravel dominate in the coastal facies, while fine grained deposition of clays and silts with varying contents of organics matter typically can be found in the mid- to outer shelf regions of the epicontinental Mesozoic sea. At times, varying dysoxic/anoxic conditions existed on the shelf, alternating with periods dominated by oceanic ventilation and storm sand deposition.

In the Late Jurassic to Early Cretaceous black and dark grey clays of the Hekkingen Formation (Oxfordian – Ryazanian) (359 m in thickness in stratotype) formed the Barents Shelf seafloor and the target area for the Mjølnir impact. The uppermost Jurassic-lowermost Cretaceous parts of these thick shale and claystone units were interrupted by the Mjolnir impact, which created the impact strata named the Ragnarok Formation (Dypvik et al. 2004b, 2006). The Sindre Bed forms an impact-derived marker horizon outside the crater rim. The impact derived units are dominated by conglomeratic and brecciated formations with a rather high content of smectite, a possible alteration product of impact glass (Dypvik and Ferrell 1998; Dypvik et al. 2004a). The material excavated consists mainly of reworked Triassic formations (Dypvik et al. 2004b).

The Hekkingen Formation is succeeded by Cretaceous limestones, marls, shales, and sandstones, of the upper Adventdalen and Nygrunnen groups (Figs. 1.3 and 1.4).

From the Late Jurassic/Early Cretaceous and until the Eocene – Oligocene transition (142–35 million years ago) sea floor spreading took place along the Nansen Ridge in the Arctic Ocean (Engen et al. 2008). The break-up of the north-east Atlantic rift system, however, started about 55 Ma (Skogseid et al. 2000) along the Mohns and Knipovich ridges, accompanied by strike-slip movements in the Fram Strait between Svalbard and North Greenland. These strike-slip movements
continued to the Eocene/Oligocene transition, connecting the spreading basins of Arctic Ocean and Norwegian Greenland Sea. At this point, however, the movements of the Fram Strait shifted towards oblique extension (33.3 Ma), and a deep-water gateway opened by seafloor spreading during Oligocene-Miocene (Lawver et al. 1990; Faleide et al. 1993; Eldholm et al. 1994; Torsvik et al. 2002). Since then spreading has taken place along this major lineament, with final establishment of the present seafloor spreading regime at 9.8 Ma.

On Svalbard the Paleogene successions (up to 1,900 m in thickness), comprise continental conglomerate and sand deposits and shallow marine sandstones along with marine shales and mudstones (Fig. 1.5). Related to the opening of the Fram Strait and Norway Greenland Sea, transpressive movements took place between Svalbard and Greenland and impressive folds and fractures structures developed along the western parts of Svalbard and the Barents Shelf (Harland 1971; Nøttvedt et al. 1993; Otha 1994; Bergh and Grogan 2003; Steel et al. 1985; Bruhn and Steel 2003).

Dimakis et al. (1998) discussed the Cenozoic erosion and preglacial uplift of the Svalbard – Barents Sea region. They demonstrate a subaerial preglacial Barents Sea with uplift events and intensive erosion. The most likely mechanism for the initial uplift is thermal, possibly related to the plate tectonic opening of the Arctic.

On the land areas around the Barents Sea, e.g., North Greenland and Svalbard, outcrops of Precambrian to Paleogene rocks are found, with distributions and structural setting heavily influenced by the many stages of rifting and seafloor spreading in the Norwegian Greenland region. In North Greenland a well-developed Oxfordian to Paleogene succession rests on Upper Paleozoic and Triassic strata. The Upper Jurassic to Lower Cretaceous successions of North Greenland, as those
on Svalbard, are made up of black to dark grey, partly silty shales and sandstones (Dypvik et al. 1991a; Håkansson et al. 1993, 1994; Dypvik et al. 2002) time-equivalent and comparable to the Hekkingen Formation of the Barents Sea.

The general structural mode of the western Barents Sea region is characterized by northeast-southwest-trending lineaments (Fig. 1.6). A thick wedge of Upper Pliocene to Quaternary deposits, with glacial deposits and postglacial marine beds and reworked sediments, present along the western Barents Sea margin (Eidvin et al. 1993; Sættem et al. 1994; Channell et al. 1999; Vorren and Laberg 2001). The present plate tectonic setting is also reflected in the Quaternary sedimentation of the region, e.g. along the steep Barents Sea margin and into the deep basins of the Norwegian Greenland Sea, colossal slides and slumps have taken place during the Holocene (Solheim et al. 1996).

Fig. 1.6 Structural map of the Svalbard, Greenland Barents Sea (Modified from Norwegian Petroleum Directorate (NPD) website 2009)
1.3 Mjølnir Impact at Volgian/Ryazanian Boundary

Due to about 30 years of petroleum exploration in the Barents Sea, an extensive geophysical database is available from the region. At the marginal parts of the southwestern Barents Sea basins several exploration wells have been drilled. In addition, many shallow stratigraphic drillholes aiming at sub-cropping reflectors have been drilled in the more central and remote areas of the Barents Sea. Based on this information the Mjølnir structure was found and its impact origin confirmed (Gudlaugsson 1993; Dypvik et al. 1996).

The Mjølnir crater is one of the 20 largest impact structures so far discovered on Earth, ranking eight among those presently not exposed at the surface (Earth Impact Data Base 2010). In order to access the possible consequences of the impact, estimate magnitude of the impact event, i.e. the energy release, impactor sizes, and mass, have been made (Tsikalas et al. 1998a). The energy release was estimated to be in the order of $16 \times 10^{20}$ J (range of $2.4-53 \times 10^{20}$ J; translating into $3.8 \times 10^5$ megatons TNT equivalent with range of $5.7 \times 10^4$ to $1.2 \times 10^6$), and the impactor’s size and mass were $1.8$ km in diameter (range, $0.9-3$ km) and $10 \times 10^{12}$ kg (range, $1.5-33 \times 10^{12}$ kg), respectively. These estimates are based on various scaling laws and on reasonably well-documented average impact velocities, impactor angles, and densities (Tsikalas et al. 1998a, b, c).

Energy release dissipation determines the distribution of ejecta and tsunami generation, which may have induced short-term perturbations/environmental stress in the Barents Sea and adjacent regions of the Arctic. In particular, palynological studies of the ~80-cm-thick ejecta-layer of borehole 7430/10-U-01 (Fig. 1.7) and other shallow stratigraphic drill holes from the Barents Sea have revealed a high abundance of marine prasinophycae algae and a minor abundance peak of freshwater algae attributed to the impact-induced water-column disturbance (Smelror et al. 2002; Bremer et al. 2004; Smelror and Dypvik 2006). The existing biostratigraphic age for the Mjølnir impact is based on detailed paleontological analyses, placing the impact event at the Volgian-Ryazanian boundary, corresponding to the informal “Jurassic-Cretaceous boundary”, as defined in the Boreal Realm (i.e., at 142 ± 2.6 Ma) (Smelror et al. 2001a, b). A correlation to the Tethys stratigraphic subdivision place the time of the impact in the earliest Berriasian (i.e., earliest Cretaceous) (Fig. 1.4). Because our study concerns the Boreal/Arctic region, we will for practical reasons refer to Volgian-Ryazanian boundary as the Jurassic-Cretaceous boundary.

The Jurassic-Cretaceous boundary represents one of the ten largest biological extinctions that occurred on the Earth. The Mjølnir impact alone was definitely not large enough to trigger such a global extinction spike. However, the occurrence of other roughly simultaneous impact events (e.g. Gosses Bluff in Australia, Morokweng in South Africa) and the weak possibilities for additional coeval impacts (Kgagodi, Liverpool, Obolon, Puchezh-Katunki, Tabun-Khara-Obo, Upheaval Dome, Vepriai, Zapadnaya) during a very short time-interval, may be of importance and capable of surpassing the threshold for a biological extinction at a global scale (data from Earth Impact Data Base 2009).
The ejected impact material of marine impacts is normally widely distributed. This will in particular be the case for ejecta from a marine impact due to the evaporation/cloud effect of the water which make it more violent compared to a similar size subaerial impact (Melosh 1989; Shuvalov and Dypvik 2004; Poag et al. 2004). In such cases both the sea-water and the water from the water-saturated sediments will take part in the formation of the vapor cloud. The water is in addition active in the later marine transportation of the ejecta.

The ejecta consist mainly of rock fragments from the target area and bolide, meteorite materials and spherules, shocked minerals, Ni-rich spinels and soot. It will have varying composition and distribution, controlled by several factors such as bolide and target area composition, sedimentary environment, mode of emplacement, timing and Earth rotation. The amount of ejecta will generally decrease away from the crater, and with increased crater size the ejecta may be dispersed over larger distances at a regional and even global scale (Shuvalov and Dypvik 2004). Consequently the ejecta forms a unique stratigraphic marker layer.

Ejecta deposits from the Mjølnir impact event (i.e., the Sindre Bed) have been recognized in the Barents Sea, on Svalbard, and possibly in Siberia (Nordvik Peninsula) (Zakharov et al. 1993; Smelror et al. 2001a; Dypvik and Zacharov 2010) at distances just 30 km from the crater (Barents Sea), via 600 km (Svalbard) and...
to more than 2,300 km away (Nordvik, Siberia) (Figs. 1.2 and 1.7). Furthermore, numerical simulations have shown that the presence of water at the Mjølnir impact did not have any major direct influence on the initial, first phase crater-forming process but became crucial during the subsequent crater infilling, by back-rushing water-resurge, as well as for the ejecta distribution and tsunami development and propagation (Shuvalov et al. 2002; Shuvalov and Dypvik 2004; Glimsdal et al. 2007). During the high pressure and high temperature conditions at the target area, the uppermost 100–200 m of the organic-rich claystones of the Hekkingen Formation were hit and may have caught fire. On average, the claystones of the Hekkingen Formation contain more than 8% total organic carbon (TOC), and serve as an important source rock for hydrocarbon in the Barents Sea. The effects of pressure, heat, tsunami, currents, and ejecta on such a target may consequently have provided a valuable marker horizon for the regional correlation of the Arctic region (Dypvik et al. 2008a).

Syn- and post-impact sediments reach considerable thicknesses in the Mjølnir area. Sediment loading above the primary impact structure may have resulted in substantial post-impact deformation and structural modification. Integrated geophysical modeling at Mjølnir demonstrates a close correspondence of geophysical anomalies to the radially-varying distribution of structural and morphological units, as well as the physical-property distributions (Tsikalas et al. 1998a, b, c; Tsikalas and Faleide 2004). The impact-induced substratum suffered differential compaction, triggered by a considerable overburden that altered the impact crater morphology and geometry. Indeed, at the Mjølnir site the deposits of brecciated periphery were compacted more than the denser central crater formations, resulting in a central high that maybe stood taller that the surrounding platform (Fig. 1.8). Details in the structural evolution and sedimentation around the central peak are discussed in Chap. 8. Post-impact modifications may have obscured or blurred many marine impact craters, which has caused their complex identification. The quantification of post-impact effects may be more difficult in the subaerial impact record compared to the submarine situation.

1.4 The Investigation History of Mjølnir

For more than 100 years, onshore geological exploration has been taking place in the onshore areas bordering the Barents Sea (i.e., Western Siberia, Novaya Zemlya, Franz Josef Land, Kola Peninsula, Bjørnøya, Hopen, Svalbard, and Greenland) (Fig. 1.2). During the last 30 years, extensive geophysical and geological investigations have been carried out in the Barents Sea (Fig. 1.7). This activity, including seismic analyses, gravimetric measurements, magnetic surveys, and drilling of stratigraphic and exploration wells, clearly picked up in late seventies when the petroleum industry threw their eyes on the region. Until today (2010) more than 70 exploration wells have been drilled in the Norwegian part of the Barents Sea, the first well being spudded on June 1. 1980. The exploration activity has shifted
through the years, but in the latest years the activity has increased, in particular triggered by high oil and gas prices, the Statoil-headed exploitation of the Snøhvit Field, and the recent oil discovery of the Goliat Field. In addition to the exploration wells, several shallow stratigraphic coreholes have been drilled with the aim to penetrate sub-cropping seismic reflectors and sample high-quality cores from the different Paleozoic to Paleogene formations (Figs. 1.7 and 1.9). These programs have been run by IKU (Continental Shelf Institute Norway)/SINTEF Petroleum Research in close cooperation with the Norwegian Petroleum Directorate. Shallow and deep well information is available from the Norwegian part of the Barents Sea. Along with the opened geophysical information, this formed the foundation for our first Mjølnir studies.

Based on available seismic lines along with gravimetric and magnetic information, Steinar Gudlaugsson in 1993 launched the innovative idea that the domal structure on the Bjarmeland Platform was an impact crater (Gudlaugsson 1993). Prior to that, both salt- or mud-dome and volcanic explanations had been presented for this shallow structure that is buried beneath 50–800 m of younger sediments and about 350 m of water (Figs. 1.7 and 1.10). Gudlaugsson claimed the structure to be about 40 km in diameter and with an appearance resembling a typical complex crater as defined by Melosh (1989). Gudlaugsson’s idea soon got great support and triggered new and more detailed geological analyses on available geophysical data and corematerial.

In 1993 Steinar Gudlaugsson contacted Henning Dypvik, who had 20 years of research experience from the Jurassic-Cretaceous strata on Svalbard and Barents Sea. A multidisciplinary group was put together and the detailed search for impact

Fig. 1.8 The classical, base Barremain reflector, seismic model of the Mjølnir structure (Dypvik et al. 1996)
Fig. 1.9 The drillship Bucentaur RS was used to drill boreholes 7430/10-U-01 adjacent to the Mjølnir crater and 7329/03-U-01 within the crater.

Fig. 1.10 A generalized seismic line across the Mjølnir crater (Modified from Tsikalas 1998a, b)
evidences started on available core and cuttings material from the region. Of particular interest were the well-dated shallow, stratigraphic drillcores of IKU/SINTEF and in particular from borehole 7430/10-U-01, which included a well preserved core across the Jurassic/Cretaceous boundary (location map in Fig. 1.7). After 3 years of tedious search and thousands of analyses, the first grains of shocked minerals and samples with enrichments of Ir were discovered in the 7430-core (Dypvik et al. 1996; Langenhorst and Dypvik 1996; Dypvik and Attrep 1999). This formed the geological evidence and confirmation of Gudlaugsson’s suggestion. During this time Filippos Tsikalas had started his PhD studies and detailed analyses of all available geophysical information from the area. This work was performed in close cooperation with the supervisors Jan Inge Faleide and Steinar T. Gudlaugsson. Tsikalas finalized his PhD in 1997, and has since continued the geophysical analyses of the structure. His and Jan Inge Faleide’s interest have in particular focused on the subsidence and uplift history of the structure along with its asymmetric structural developments, underlining the oblique impact configuration. Based on these analyses, detailed geometrical information of the Mjølnir structure has been achieved.

The geochemical and mineralogical studies, in combination with analysis of the sedimentological ejecta developments and crater filling sediments have continued since 1993, coordinated by Henning Dypvik. Detailed sedimentological and petrological studies showed the shocked quartz and Ir carrying beds of well 7430 to reflect deposition from suspension currents, most likely derived from the crater rim (Dypvik et al. 1996). The sedimentological, mineralogical, and geochemical studies have recognized possible altered impact glass and Mjølnir ejecta in Svalbard and several Barents Sea cores (Dypvik et al. 2004c; Dypvik and Ferrell 1998; Dypvik et al. 2003). Palaeontological studies have mainly been performed by Morten Smelror, Jenø Nagy, Jorunn Os Vigran, Merethe A. Bremer and Simon R. A. Kelly (Smelror et al. 2001a, 2002; Bremer et al. 2004; Smelror and Dypvik 2006). The first dating of the impact event, and the correlation of seismic lines and the impact structures formed natural key geological and geophysical information in understanding the impact evolution (Figs. 1.10 and 1.11). Macro- and micropalaeontological along with palynological analyses confirm an age at the Volgian-Ryazanian boundary, i.e., $142 \pm 2.6$ Ma, of the impact event (Smelror et al. 2001a). In addition the palynological discoveries of algal blooms of disaster species just after impact, in concert with geochemical enrichments made it possible to trace the effects of impact in even wider areas around the Mjølnir structure (Smelror and Dypvik 2005, 2006; Dypvik et al. 2006). During some short spring weeks in 1998 we were able to collect sufficient industrial support and sponsorship to hire the drillship Bucentaur for a week operation, allowing us to drill the so-called Mjølnir crater drillhole (7329/03-U-01) (Figs. 1.7, 1.9 and 1.10). The 7329/03-U-01 borehole is located on the central peak, below 350 m of water. The drill-site was selected for maximum stratigraphical depth of penetration at a place with only 54 m of overburden. The operation was generously supported by the Norwegian Petroleum Directorate, Statoil ASA, Norsk Hydro ASA, Saga Petroleum ASA and Phillips Petroleum, the ship-owner Seateam and the operator IKU/SINTEF Petroleum Research (Fig. 1.9). The 121 m long core
has since been studied in great detail and much new information has been added to our knowledge about the structure. It is the only core from inside the crater and consequently a firm evidence for the impact origin.

Rumor has it that still in the summer of 1998, while drilling the Mjølnir core on the central peak, betting was going on among doubtful geologists not believing the impact hypothesis. Some hard-core geologists and geophysicists, still at that time, preferred other explanations (e.g., volcanism, salt diapirism, liquefaction). The first papers from these core studies were presented in the ESF (European Science Foundation) supported workshop of the successful IMPACT program, which was arranged in Longyearbyen the fall of 2001 (Dypvik et al. 2004a; Smelror et al. 2001c).

Based on the paleontological analyses of Mjølnir crater core samples the dating of the impact was further confined (Smelror et al. 2001a). Through the master thesis of Pål Sandbakken (Sandbakken 2002) on core material from borehole 7329/03-U-01, additional pressure relations of the impact were disclosed (Sandbakken et al. 2005). Detailed discussions of the Mjølnir core also resulted in sedimentological descriptions of the formations and mechanical interpretations of the processes active along the central peak. In addition stratigraphical descriptions and formal definitions of the syn-impact and post-impact formations were done (Dypvik et al. 2004c).

In the Mjølnir crater core, in surface samples from Svalbard and in the 7430-core soot particles have been found, expressing a story of intense, impact-induced sea-floor fires. Potential petroleum source rocks within the crater, an about 5–10 km² area of the Barents Sea, were locally put on fire by the Mjølnir bolide (Wolbach et al. 2001; Dypvik et al. 2008b).

A major advance in our understanding of the Mjølnir Crater was achieved when Valery Shuvalov joined the research group with advanced numerical modeling of both impact mechanics and ejecta distribution. In this way, timing of various impact phases along with the first insight of impressive tsunami generation events was evident (Shuvalov et al. 2002; Shuvalov and Dypvik 2004). The simulations also displayed asymmetrical ejecta distribution, along with an interesting downrange
movement of the central peak during crater evolution (Fig. 1.12). The recent direct involvement of structural geologist Roy H. Gabrielsen has demonstrated how the different mechanical phases in the crater development in combination with such numerical information can explain, in this case, some of the mechanisms in the crater-fill processes.

During and immediate after marine impacts, tsunamis will be generated. Tsunami-generated deposits (tsunamites) are well known from the Chicxulub impact in the Mexican Gulf area (Smit 1999; Claeys et al. 2002). The Eltanin impact event tsunami in the Pacific has been modeled by Asphaug and Ward (2002) and Korycansky et al. (2003). The palaeogeographical reconstructions of the Barents Sea area shows that an extensive epicontinental sea covered the area at the time of impact and tsunamis must have been formed. The initial tsunami was also evident in the first simulations of Shuvalov et al. (2002). These simulations formed the starting point for PhD-student Sylfest Glimsdal and his supervisors Geir Pedersen, Hans Petter Langtangen, Shuvalov, and Dypvik for modeling the Mjølnir tsunami (Glimsdal et al. 2005, 2007). Simulation of tsunami generation in relation to marine impacts is a new and important topic, which has not been carried out in great detail before. Large amounts of new, basic knowledge were gained in the study of Glimsdal et al. (2007) and formed the basis of Glimsdal’s PhD thesis defended in June 2007. This work was continued in the PhD studies of Rolv Bredesen, focusing on the tsunami runup problematic.

The colossal starting heights of the first tsunami (more than 200 m), along with its fast advancement across the paleo-Barents Sea are evident. Series of tsunamis were formed and had obvious influence on the Barents Sea sedimentation, and
the marine life of paleo-Barents Sea region. The Mjølnir ejecta distribution is asymmetrical around the structure, as evident from both the sedimentological investigations (Dypvik et al. 2006) and in the numerical modeling (Shuvalov and Dypvik 2004) (Fig. 1.12). This asymmetrical ejecta distribution and environmental disturbances are in great contrast to the modeled, symmetrical tsunami wave propagation (Glimsdal et al. 2007). Ejecta material traced as Ir-enrichments, along with some Ni-rich iron-oxides have been found in the Barents Sea, on Svalbard and along the bolide direction of movement, towards the North East (Dypvik et al. 2006; Robin et al. 2001).

Zakharov et al. (1993) found extremely high Ir-enrichments in time-equivalent sedimentary beds from north-central Siberia (Nordvik) (Figs. 1.2, 1.3 and 1.13). Recent Siberian investigations of new, comparable samples from Nordvik have been carried out by Zacharov, Kyte and Dypvik. Correlatable stratigraphical sections from Siberia have been analyzed mineralogically and geochemically and compared with the Barents Sea and Svalbard sections. The stratigraphical developments are comparable, but the Ir-anomaly of Zacharov et al. (1993) has not been confirmed (Dypvik and Zacharov 2010; Koeberl, personal communication).

### 1.5 The Search for Oil and Gas in the Barents Sea

According to the Norwegian Petroleum Directorate website (2006) totally about 0.2 billion Sm³ o.e. (Standard cubic meters oil equivalents) of extractable oil and gas (mainly gas) has been identified on the Norwegian side in the Barents Sea. Another estimated 1 billion Sm³ o.e. unidentified oil and gas are probably present. On the Russian side of the border the numbers are of another dimension, 2 billion Sm³ o.e. are discovered and up to 15 billion Sm³ o.e. may be undiscovered (USGS 2000).

Petroleum exploration started in the Norwegian part of the Barents Sea in the seventies, and the first well, 7120/12-1 in the Troms I area, was spudded 1. June 1980 (Fig. 1.2). The semi-submersible installation Treasure Seeker drilled to TD at 3,573
m (1/6/80 to 12/10/80). Based on seismic interpretations and regional geological data, the well location was selected to test possible sandstone reservoirs of Middle Jurassic, Early Jurassic, and Late Triassic ages. Post-Jurassic sediments were not considered prospective, due to lack of closure and/or reservoir rocks. The results showed traces of hydrocarbons in thin sandstone reservoirs of both Early Cretaceous and Late Triassic formations.

Since then, more than 70 wells have been drilled in 39 production licenses, all in the southern part of the Norwegian section in the Barents Sea. A number of these wells yielded minor and medium sized gas discoveries. The Snøhvit Field is currently in production (July 2009), while the Goliat Field is under evaluation (Fig. 1.2). The Upper Jurassic-lowermost Cretaceous black to dark grey, organic rich shales of the Hekkingen Formation and possible the Middle Triassic Botneheia and Steinkobbe formations are the main source rocks in this part of the Barents Sea. The Stø and Tubåen formations of the Kapp Toscana Group form possible reservoirs (Figs. 1.3 and 1.4). In the Barents Sea, Paleozoic carbonates are also possible reservoir targets. The main reservoir proven so far are, however, Middle and Upper Jurassic sandstones found in the giant Stokhman Field.

The Goliat discovery (48 km from Norwegian shores) was made in 2000, an ENI discovery of 100 million bbl (barrels) oil (Fig. 1.2). It is a rather small field compared to others on the Norwegian shelf, but recent information has doubled the size of the discovery. The Goliat structure is a faulted structural closure in the crest part of a major northeast-southwest trending rollover anticline situated in the southeastern part of the Hammerfest Basin. The Kapp Toscana Group (Tubåen Formation) of Early Jurassic to Late Triassic age is the main reservoir. In addition to oil, the Goliat discovery also includes oil-bearing gas.

When the proto-Atlantic Ocean rifted open in Paleogene times, areas along the rift were uplifted and eroded with decreasing erosional effects, eastwards, away from the rift zone, along the western side of the Barents Shelf. The erosion resulted in released burial pressure, cracking of rocks and extensive leakage of oil and gas out of the originally deeply buried traps close to the rift. Gas expansion after pressure release forced the oil out of the traps. This explanation has been given as the major reason for the presences of almost only gas in the Snøhvit field and other areas in the Hammerfest Basin (Stewart et al. 1995; Nyland et al. 1992).

This uplift and pressure release effect was less effective in the eastern regions towards Russian territories, possibly explaining the much larger amount of hydrocarbons discovered in the Russian sector. The giant Russian Stokhman Field is an excellent example, 3.2 million Sm³ o.e. in one field, one of the largest gas fields in the world.

### 1.6 Future Mjølnir Studies

During 2002 and 2003, ICDP (International Continental Scientific Drilling Program) and IODP (Integrated Ocean Drilling Program) were approached with applications for scientific drilling of the Mjølnir Crater. The ICDP application received a positive recommendation, while the IODP application was not
recommended full proposal. Based on this mixed response, and founded on discussions and recommendations from several scientists, we submitted workshop proposals (ICDP, IODP, ESF (European Science Foundation Magellan Workshop), Statoil ASA, Hydro ASA) in spring 2006. The aim was to obtain financial support for a meeting to discuss marine cratering and its consequences, aiming at a future scientific drilling of the Mjølnir impact structure (Mjølnir Scientific Drilling Project). The workshop was approved and financially supported by ICDP, ESF (Magellan Workshop), Statoil ASA, and Norsk Hydro ASA, and arranged in Longyearbyen, Svalbard, during September 2007. The main objective of the workshop was to shed new light on one of the basic geological processes on the Earth; the mechanism and consequences of marine impact cratering. The following scientific sub-goals are of particular importance:

1. The Mjølnir crater is one of the very few cases where a source-crater and ejecta-layer (shock effects, geochemistry, paleontology) correlation has been established and correlated directly. A drilling project will deepen our understanding of this relation and make it applicable to other locations where the relations are not that obvious.

2. Through the proposed Mjølnir drilling a better stratigraphic control of the target and impact-induced lithologies will be reached. Combined with the entire spectrum of seismic reflection profiles better constraints on the amount of excavated (allochthonous) breccia volume, structural uplift, gravitational collapse, and infilling will be reached.

3. The passage of the impact-induced shock wave leads to development of extreme high pressure and temperature. The proposed drilling aims to resolve the pressure and temperature distribution occurring during the Mjølnir impact. This work should, initially, include detailed geochemical (inorganic/organic) and mineralogical analyses (optical, electron-microscopical) of shocked mineral grains along with authigenic formations. When comparing pressure/temperature distribution to theoretical models, a testable framework for increased understanding of impact cratering physics can be achieved.

4. The nature of the cratering processes depends on whether the target is crystalline or sedimentary. However, the existing global cratering record used to represent typical impact craters is biased toward crystalline, water-poor targets. Using a multi-material hydrocode, numerical simulations for Mjølnir (Shuvalov et al. 2002) have documented the importance of the target lithology for the cratering processes.

5. Magnetic modeling shows that dispersed melts are most probably located at the periphery of the structure (Tsikalas et al. 1998b). Therefore, the proposed Mjølnir drilling will contribute to the understanding of the actual impact processes by providing, for the first time in impact crater research, a direct calibration to both empirical relationships and numerical simulations.

6. Impact energy released dissipation determines the distribution of ejecta and tsunami, that may have induced short-term perturbations/environmental stress