An Arctic Lagerstätte – the Slottsmøya Member of the Agardhfjellet Formation (Upper Jurassic – Lower Cretaceous) of Spitsbergen

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Paleontological fieldwork on Spitsbergen, 2004-2011, has revealed the presence of abundant plesiosaur and ichthyosaur remains, a series of 15 seep carbonate bodies, as well as a rich invertebrate fauna from the Upper Jurassic – Lower Cretaceous Slottsmøya Member of the Agardhfjellet Formation, a 70-100 metre-thick unit of dark grey to black shale and paper shale. Deposition of the Slottsmøya Member occurred at high paleolatitudes, at or near the Arctic Circle, and molluscan and foraminiferal biostratigraphy indicates an Early Volgian – Ryazanian age for the unit. In this volume we present the organic carbon isotope chemostratigraphy, cyclostratigraphy, lithostratigraphy and sedimentology for the Member. A well preserved assemblage of fossil echinoderms, the first ultrastructural information on the lingulid brachiopod *Lingularia* and microfacies of nine seep carbonates are described. Comparative analyses of the marine reptile material found in the Slottsmøya Member indicate a diverse assemblage of new plesiosaurians (two new genera and three new species of plesiosauroids and one new species of pliosaurid) and ichthyosaurians (two new genera and species). Placed within a high-resolution stratigraphic framework, the diverse invertebrate and vertebrate assemblage of the Slottsmøya Lagerstätte provides an unparallelled opportunity to study the evolution and paleoecology of a high-latitude, Mesozoic, marine ecosystem.

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Introduction

The sedimentology and depositional environments of the Upper Jurassic of Svalbard were studied by Dypvik (1980, 1985) and Dypvik et al. (1991a+b) (Fig. 1). The fauna of the Late Jurassic Boreal Realm is suggested to be at least partly endemic from studies of e.g., ammonites, belemnoids and mega-onychites (cephalopod arm hooks) (Page 2008; Sachs et al. 1973; Stevens 1963; Doyle 1987; Hammer et al. in press). This is further strengthened by several of the studies presented in this volume.

Marine reptiles have been known from Svalbard for more than a century, the first discoveries being those of Early to Middle Triassic ichthyosaurians (Hulke, 1873; Yakowlew, 1903; Wiman, 1910, 1916). However, it was not until 1914 that the first Jurassic remains were described, consisting of a single pliosaurid cervical or caudal vertebral centrum interpreted to be comparable to the Callovian taxon *Peloneustes* (Wiman, 1914). The earliest significant find of plesiosaurians from Svalbard was an articulated, partial postcranial skeleton excavated by a team of American medical doctors in 1931; this specimen was donated to the Paleontological Museum in Oslo, later becoming part of the collections at the Natural History Museum of Oslo (PMO). The specimen was not described until much later when Persson (1962) erected a new species of a Callovian taxon from the UK, naming it *Tricleidus svalbardensis*. The specimen was subsequently redescribed as part of a Masters project (Andreassen, 2004). Scattered discoveries of marine reptiles were made during the 1970s to 1980s, but most were never properly excavated (Heintz 1964). With the exception of a partial, isolated, plesiosaur limb (Ginsburg & Janvier, 1974) and a fragmented, non-diagnostic, ichthyosaur rostrum (Angst et al. 2010), Jurassic-aged vertebrates have remained largely undocumented and no formal effort to systematically survey, excavate and study the assemblage has been made.

A new era in the research on Jurassic fossil vertebrates from Svalbard began in 2001 when a field party of researchers and students from the University Centre in Svalbard (UNIS) discovered the partial remains of

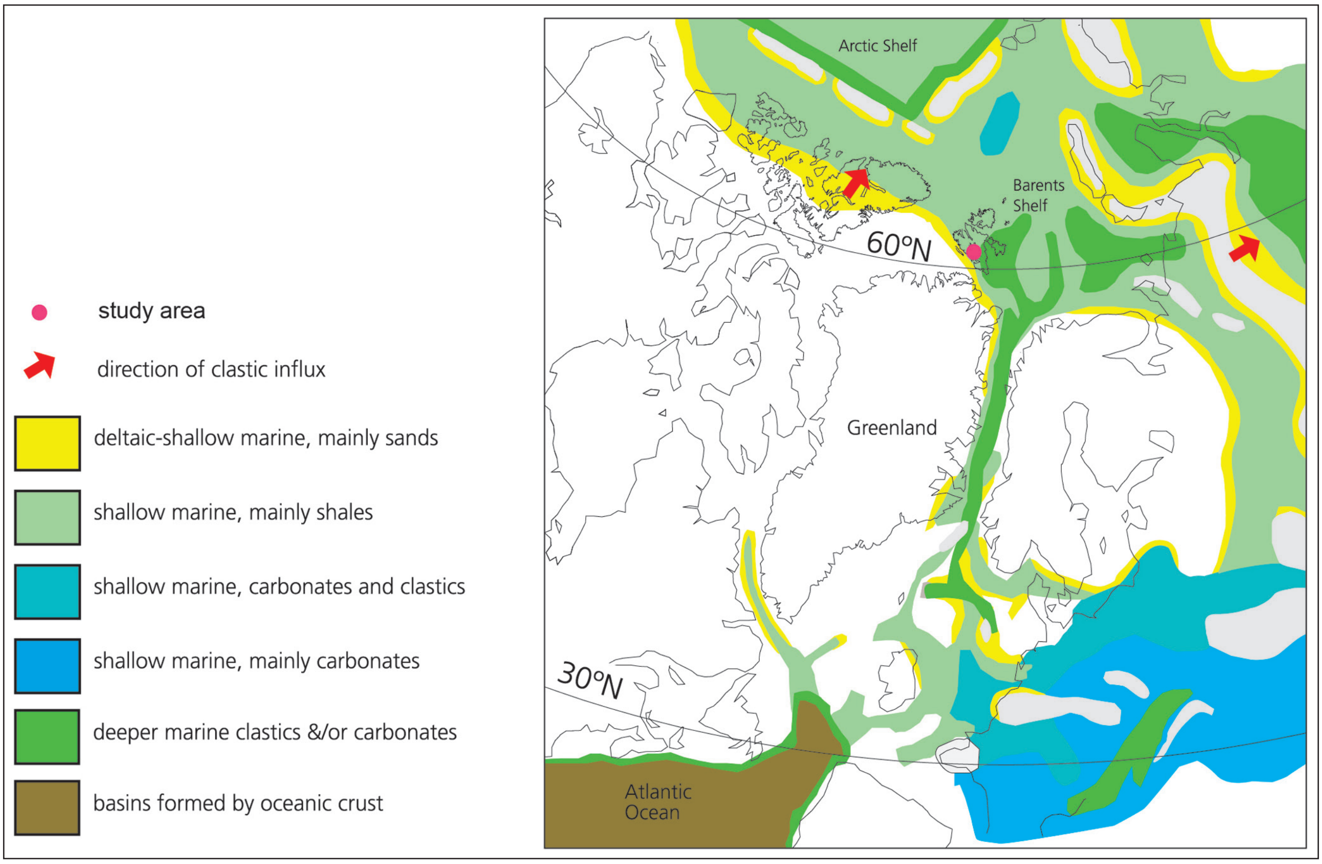

Figure 1. Paleogeographic map of the North Atlantic in the Late Jurassic (150 Ma) with the study area shown. Modified from Torsvik et al. (2002).

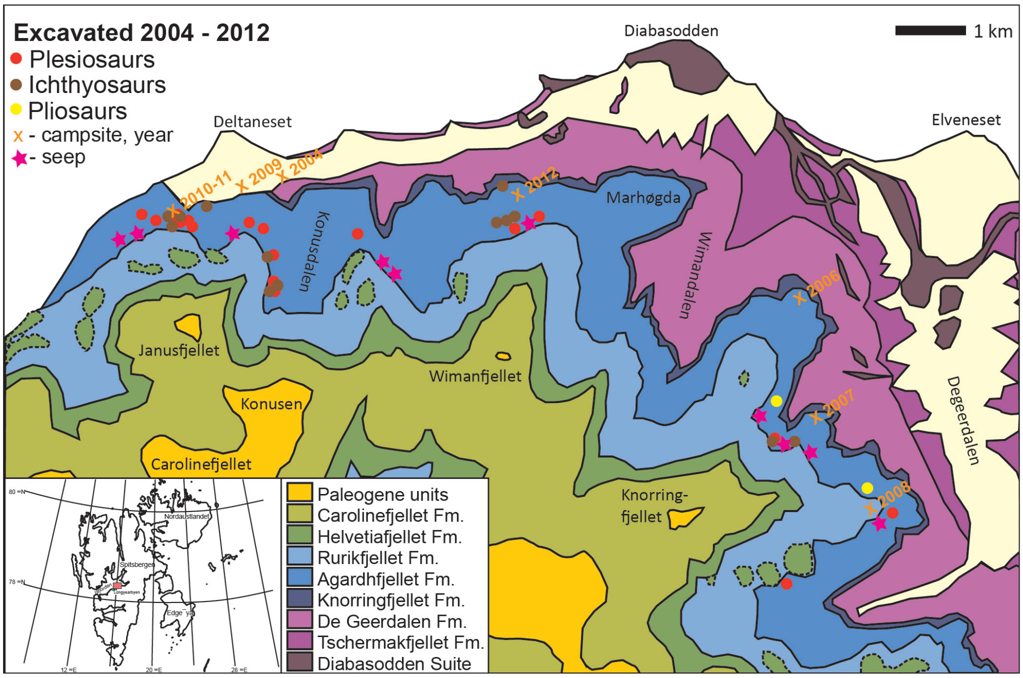

Figure 2. Map of the area with campsites, seeps and collected specimens, adapted from Dalmann et al. (2001).

a plesiosaurian in Upper Jurassic strata at Janusfjellet, approximately 15 km northeast of Longyearbyen. This find was then reported in 2003 to one of us (JHH) at the PMO by Sverre Ola Johnsen, a geologist at the Norwegian Technical University, Trondheim. In 2004, two of us (JHH and HAN) at PMO led an expedition to excavate the 2001 discovery in cooperation with the "Friends of the Paleontological Museum" (PalVenn), an organisation of amateur fossil enthusiasts (Fig. 2). Amazingly, in the span of a single week, the team located another eleven specimens of both plesiosaurians and ichthyosaurians at the site. Recognising the tremendous scientific potential

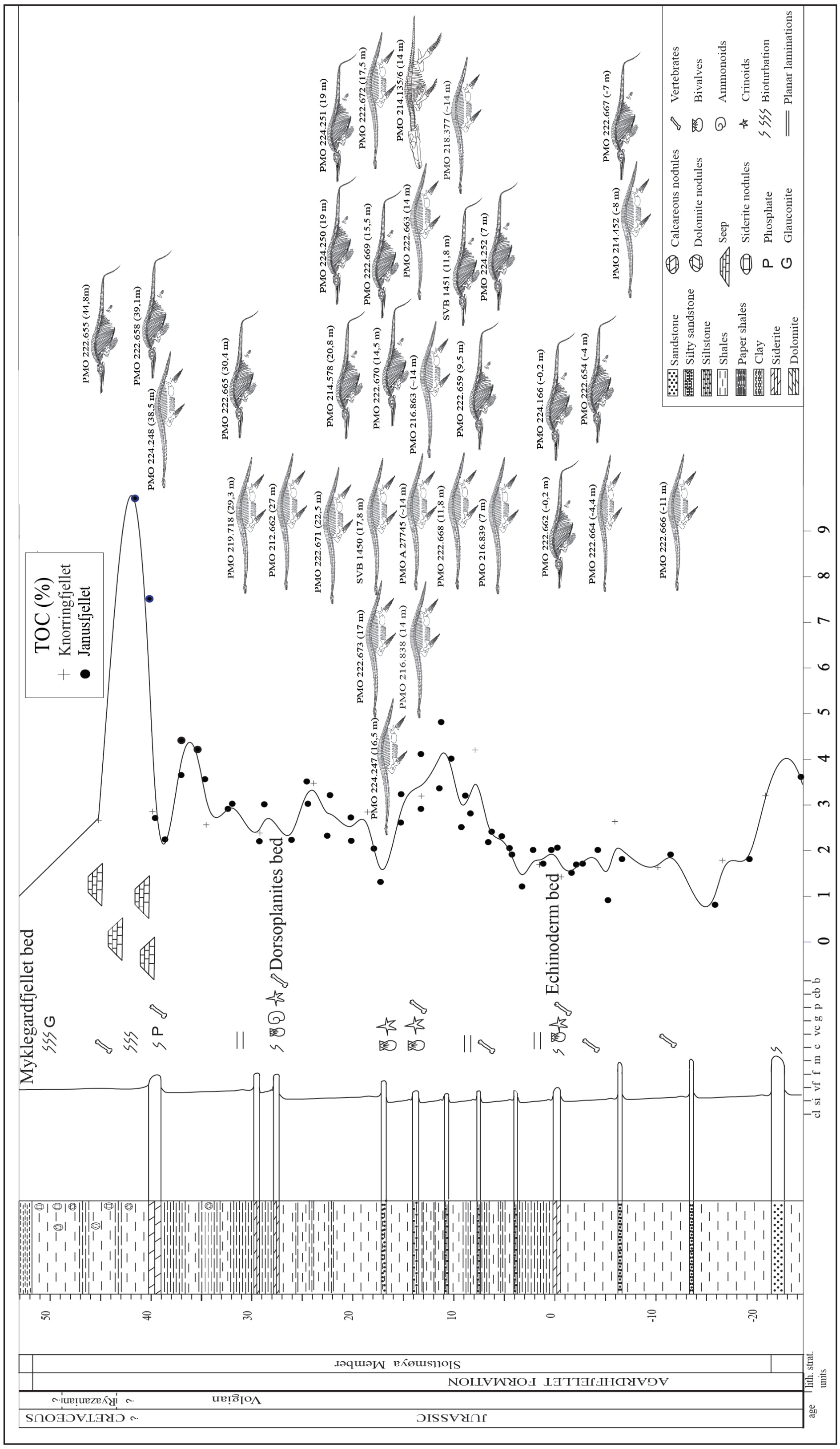

Figure 3. Stratigraphic scheme adapted from Novis (2012), Collignon & Hammer (this volume), Hammer et al. (this volume), Hammer et al. 2011 and Wierzbowski et al. (2011). Grain-size scales: b-boulders, c-coarse, cb-cobbles, cl-clay, f-fine, g-gravel, m-medium, p-pebbles, si-silt, vc-very coarse and vf-very fine.

of the area, a larger survey was launched in 2006 with PMO, PalVenn, and new team members EMK, PSD and LKN to map the skeletal occurrences in the Agardhfjellet Formation in the area of Knorringfjellet. The nine-day expedition yielded another twenty-nine discoveries, all of which were now recognised as occurring within a single highly productive, 70 to 100 metre-thick unit of shale known as the Slottsmøya Member (Fig. 3). Having located numerous skeletons of plesiosaurians and ichthyosaurs, it was now necessary to begin the arduous task of excavating specimens, many of which were preserved at least partially in permafrost.

Working in a remote, logistically challenging field site presented many challenges to the project. First and foremost, it was necessary to secure adequate funding for a larger-scale initiative that could support long-term research on the paleontology and geology of the Slottsmøya Member. In 2007, the Norwegian Minister of Education, Øystein Djupedal, provided critical support to the infrastructure of the project. Over the past six years, field and lab work has also been made possible through logistical support, donation of equipment and financial sponsorship by several businesses and organisations (see Acknowledgements), which have collectively made this project a scientific and educational success. A second obstacle involved the careful excavation of skeletons from permafrost under challenging environmental conditions (Fig. 4), which necessitated the development of innovative field methods.

Full scale excavation in the Slottsmøya Member commenced in the summer of 2007, and included the recovery of a very large pliosaurid, one plesiosauroid and one ichthyosaur. Over the duration of the project, a remarkable 37 partially to fully articulated skeletons of marine reptiles have been excavated and their associated geological data precisely recorded (see Figures 2, 3 and Table 1). Putting this into a broader perspective, the sheer volume and quality of material has elevated this unit to one of the most productive sites for marine vertebrates to have been discovered in the past century.

Work in the Slottsmøya Member took on an added scientific dimension in 2006 and 2007 with the discovery of peculiar, grey, calcareous limestone bodies in the unit. Based on paleontological, sedimentological and isotopic evidence, these bodies were identified by one of us (ØH) as being highly fossiliferous seep carbonates. To obtain more knowledge of seep carbonates in the informal group, Crispin T.S. Little (Leeds University) was asked to cooperate with us on the description of the material. Recognising the need to place the seeps, marine reptiles, as well as the invertebrate fossils into a precise geological context, a complementary effort to produce new detailed stratigraphic and sedimentological logs within the Slottsmøya Member was also initiated. Thus was born in 2008 the Spitsbergen Jurassic Research Group (SJRG), consisting of researchers, students and volunteers who collectively contribute to a broader understanding of the Slottsmøya Member ecosystem as a whole.

Outreach has been an important aspect of the financial and educational strategy of the project. Long-term projects of this nature (eight field seasons, years of preparation in the laboratory) are difficult to fund through normal channels. To this end, the Spitsbergen project has partnered with various media outlets to raise awareness of the scientific excitement of the project and to attract sponsors for each field season. In 2004, 2006 and 2007 the Norwegian Broadcasting Corporation (NRK) joined the expeditions. Short radio interviews and documentaries for a children's science programme (Newton) were made in 2004 and broadcasted in 2005. In 2006, several short clips were made for the popular television science programmes Schrödinger's katt and Newton. A 30 minute-long special was made in 2007 for another program series, called Ut i naturen. In 2008/09, the first international documentary, "Predator X", was produced by Atlantic Productions, and licensed to the History Channel. Finally, in 2009/10 the documentary "Death of a Sea Monster" was produced by National Geographic Channel, and premiered in 2011. The website www.nhm.uio.no/pliosaurus has been the project's main outreach channel since 2006 and is in regular use by primary and secondary schools all over Norway.

The Spitsbergen project has played an important role in graduate student training. Since 2008, eight masters students have joined the team, six of whom have completed thesis projects that have contributed to the geology and vertebrate and invertebrate paleontology of the SJRG (see papers in this volume by Collignon, Rousseau, Liebe and Hjálmarsdóttir). Two doctoral students studying the plesiosaurs (Knutsen) and seep carbonates (Hryniewicz) joined SJRG in 2008 and 2010, respectively, and have contributed to several papers in this volume. Other researchers who are not formal members of the SJRG have also contributed to the current work (Dypvik, Holmer, Kiessling, Kihle, Nagy and Zakharov).

Given the remarkable characteristics of the member, we argue that the Slottsmøya assemblage warrants classification as a special class of fossil assemblage known as a Fossil-Lagerstätte. Fossil-Lagerstätten contain exceptionally preserved and/or abundant fossils that deserve special scientific examination, and offer opportunities to yield unique information about extinct organisms (Seilacher, 1990; Seilacher, et al. 1985). Examples of these unusual deposits include Monte San Georgio (Triassic; Switzerland and Italy) and the Posidonienshiefer in the area of Holzmaden (Lower Jurassic; southern Germany) (Bottjer et al. 2002). Thus, long-term studies of this newly discovered locality promise to yield paleobiological data that are significant at a global level.

The research of the Spitsbergen Jurassic Research Group and this volume

This volume is a collection of papers on the geology, vertebrate and invertebrate paleontology of the Slottsmøya Member. The primary goal of this work is to provide a "first take", and to establish baseline data on the stratigraphy, sedimentology and faunal composition of the member following eight years of intensive field studies. Research on the Slottsmøya Member is a work in progress, and many questions regarding the faunal composition, paleobiogeography and paleoecology of the Slottsmøya Member remain to be addressed. It is our

Table 1: Collected skeletons, partially and complete, 2004-2012. Stratigraphic position measured as above or below (-) the yellow layer (see sedimentary log in Fig. 2). I-ichthyosaur, P-plesiosauroids, PL-pliosaur, Pr-prepared, and U-unprepared.

Collection number	Type	Stratigraphic position	GPS	Collection year	Status
PMO 222.655	I	44.8m	33X 0518847 8696044	2010	U
PMO 212.662/SVB1452	P	27.0m	N78 20.248 E15 51.339	2004/2009	Pr
PMO 214.578	I	20.8m	N78 20.195 E15 50.094	2009	Pr
PMO 222.663	P	14.0m		2010/2011	Pr
PMO 222.657	P	?		2008	Pr
PMO 222.658	I	39.1m	33X0518844 8696066	2010	Pr
PMO 222.659	I	9.5m	33X0519396 8696106	2009/2010	U
PMO 222.660	I	?		2008	U
PMO 222.661	?	ca 2-4m	33X0519136 8696262	2009	U
PMO 222.662	I	-0.2	N78 18.238 E16 15.496	2008	Pr
PMO 214.135	PL	14.0m	N78 18.927 E16 10.988	2007	Pr
PMO 214.136	PL	14.0m	N78 18.238 E16 15.577	2008	Pr
PMO 216.839	P	7.0m	33X0519395 8696110	2009	Pr
SVB 1451	P	17.8m	33X518788 8696104	2004	
SVB 1450	I	11.8m		2004	Pr
PMO 216.863	P	14m	33X0528291 8691950	2008	Pr
PMO 219.718	P	29.3m	33X0519395 8696112	2010	Pr
PMO 222.654	I	- 4 m	N78 20.264 E15 50.044	2010	Pr
PMO 214.452	P	- 8.0m	N 78 18629 E 01613290	2007	Pr
PMO 222.664	P	- 4.4m		2010	U
PMO 222.665	I	30.4m		2010	U
PMO 222.666	P	- 11m		2009	U
PMO 216.838	P	14.0m	33X0519278 8696300	2009	Pr
PMO 222.667	I	- 7m	33X0518982 8696356	2011	U
PMO 222.668	P	11.8m		2011	U
PMO 222.669	I	15.5m	33X0519622 8695649	2011	U
PMO 222.670	I	14.5m	33X0519609 8695600	2011	U
PMO 222.671	P	22.5m	33X0519594 8695629	2011	U
PMO 222.672	P	17.5m	N78 20.095 E15 47.087	2011	U
PMO 222.673	P	ca 17m		2011	U
PMO 224.166	I	- 0.2m	N78 20.262 E15 49.900	2004	U
PMO 218.377	P	?			
PMO 224.247	P	16.5m	33X0523404 8696369	2012	U
PMO 224.248	P	38.5m	33X0523620 8696396	2012	U
PMO 224.249	I	-51m	33X0523219 8696664	2012	U
PMO 224.250	I	19 m	33X0523549 8696407	2012	U
PMO 224.251	I	19 m tectonics?	33X0523232 8696394	2012	U
PMO 224.252	I	7m	33X0523426 8696386	2012	U

Figure 4. Photo of camp and typical outcrops in A. Janusfjellet. B. Wimanfjellet. *Photo: A. Jørn H. Hurum. B. Tommy Wensaas.*

intent that the works presented in this volume, published here in an open-access journal, will generate interest and lay the groundwork for future studies on this remarkable unit.

The sedimentology and stratigraphy

The sedimentology and stratigraphy of the Upper Jurassic in the Arctic are covered by three papers in this volume.

Dypvik & Zakharov first provide an overview of the Late Jurassic/Early Cretaceous fine-grained epicontinental Arctic sedimentation, with emphasis on the mineralogical and geochemical context. The study concludes that the interval is characterised by a shallow epicontinental sea with open geometry and well-developed circulation.

Collignon & Hammer detail the lithostratigraphy and sedimentology of the Slottsmøya Member at Janusfjellet, presenting lithostratigraphic, mineralogical, chemical and magnetic susceptibility logs. This provides a high-resolution stratigraphic framework for the other studies presented in this volume.

This scope of this geological framework is further strengthened by work on the organic carbon isotope chemostratigraphy and cyclostratigraphy of the unit by Hammer, Collignon & Nakrem. They present $\delta^{13}C_{org}$ curves from three sections at Janusfjellet and Knorringfjellet and indicate that this can be used as a tool for high-resolution, local chronostratigraphic correlation in central Spitsbergen, and can be compared with carbonate isotopic data from the Russian Platform and elsewhere. There are indications of a c. 400 kyr periodicity, which can be interpreted as a result of orbital forcing (long eccentricity).

Seep carbonates

Two papers have already been published from these studies. Hammer et al. (2011) described fifteen carbonate bodies, interpreted as having been formed at hydrocarbon seeps, found in the upper part of the Slottsmøya Member. The carbonate bodies show complex and heterogeneous structures typical of hydrocarbon seeps, including zoned (botryoidal) cement textures and fissure-infilling sparite. Stable isotope analyses show highly negative $\delta^{13}C$ values (down to ca. -43‰ VPDB) in the zoned carbonate cements, consistent with authigenic precipitation in a hydrocarbon-rich environment. The species-rich, well-preserved fauna includes 15 species of small- to medium-sized bivalves, some of which are abundant, as well as rarer rhynchonelliform and lingulid brachiopods, gastropods, echinoderms, sponges, and serpulid and probable vestimentiferan worm tubes. The seep fauna contains few, if any, seep obligate taxa, consistent with formation in a relatively shallow-water paleoenvironment.

Wierzbowski et al. (2011) described a collection of 55, well preserved, ammonite specimens from the hydrocarbon seep carbonates and used them as a basis for a chronostratigraphic interpretation of the seep deposits. The ammonites were used to give a detailed biostratigraphic framework for the carbonates, showing that they range through the Upper Volgian Substage to the Upper Ryazanian with an episode of erosion or non-deposition possibly caused by tsunami waves from the Mjølnir meteorite impact (Dypvik et al. 2006). The ammonites described by Wierzbowski et al. 2011 included several genera and species that have not previously been reported from Spitsbergen, and provided new constraints on the age of the Slottsmøya Member and on timing of hydrocarbon seepage through the latest Jurassic – earliest Cretaceous time interval in Spitsbergen.

Hryniewicz, Hammer, Nakrem & Little describe in this volume the microfacies of nine of the 15 hydrocarbon seep carbonates recorded from the area. They point out that the carbonates were formed mainly within the sediment column, with only thin blankets of diverse deposits covering the surfaces of seep carbonates. Most of the seeps were relatively small and short-lasting with carbonate hardgrounds developed on the surface, and only one long-lasting seep was covered with a blanket of worn grainy carbonate. The stratigraphic distribution of microfacies indicates a change of the original sediment from muds to more permeable silts and sands in the Late Ryazanian, which may be attributed to a shallowing episode.

The fossils

Two papers on the **microfossils** are included in this volume. Nakrem & Kiessling describe a radiolarian fauna characterised by an abundance of spongy spumellarians and a dominance of parvicingulids among the nassellarians. The fauna shows all characteristics of the Northern Boreal Province.

Hjálmarsdóttir, Nakrem & Nagy present a preliminary report on the foraminifera from the hydrocarbon seep carbonates. The agglutinated benthic foraminifera species composition is comparable to faunas previously described from the surrounding dark shales as well as from time-equivalent deposits of Arctic Russia and other areas of the Boreal Realm. Calcareous foraminifera are observed only in thin-sections. The foraminiferal datings are partly conflicting with ammonite datings previously recorded from these carbonates by Wierzbowski *et al.* (2011).

Macro **invertebrates** found by the project are already published in two papers; ammonite stratigraphy by Wierzbowski et al. (2011) and large cephalopod hooks by Hammer et al. (in press). Other invertebrates are described in this volume in two papers. Rousseau & Nakrem describe, for the first time, a well preserved assemblage of fossil echinoderms from the lower Middle Volgian in the Slottsmøya Member. Five species are recognised and a depositional environment model reconciling autecologic, taphonomic and sedimentary evidence is presented. The echinoderm layer was formed by a single, rapid burial event during a storm, entombing together autochthonous and allochthonous species on a dysoxic muddy sea-floor.

Holmer & Nakrem describe the lingulid brachiopod *Lingularia* from the hydrocarbon seep carbonates and provide the first critical ultrastructural information for this important extinct member of the extant Lingulidae.

The Slottsmøya Member assemblage is significant in being one of the most prolific new localities for Mesozoic **marine reptiles** discovered in recent years, and one of the few known from high paleolatitudes. To date, approximately 60 individual skeletal occurrences have been mapped, of which 37 have been excavated. Individual skeletons are fully to partially articulated, while bone preservation varies due to permafrost conditions and secondary growth of gypsum and iron oxides. The faunal composition, which includes ichthyosaurs and long- and short-necked plesiosaurians, is most readily comparable to other well-known Middle to Late Jurassic localities such as the Oxford Clay and Kimmeridge Clay Formations of the UK. However, the younger temporal occurrence of the Slottsmøya fauna, its taxonomic composition, and paleogeographic position help fill the gap between better known Late Jurassic and Cretaceous assemblages. Here we present eight papers on the marine reptiles from the Lagerstätte. In the **first** paper by Knutsen, Druckenmiller & Hurum (A), a redescription and taxonomic clarification of the 1931 plesiosaurian discovery is made and compared to the newly acquired material of this taxon by SJRG and by the Norwegian Polar Institute. The exact location of the excavation site from 1931 is established for the first time. The new study shows clearly that the specimens are not referable to the British *Tricleidus* material, rather they are more similar to that of the Kimmeridgian taxon *Colymbosaurus*. However, the Svalbard material exhibits characteristics of the hind limbs that separate it from other species of *Colymbosaurus*, warranting the new combination *Colymbosaurus svalbardensis* to encompass the Svalbard taxon.

In the **second** paper on plesiosaurians, Knutsen, Druckenmiller & Hurum (B) describe a new plesiosauroid genus comprising two new species. These new specimens are the first juvenile plesiosaurians to be described from the unit and possess a column of three or more well developed, preaxial accessory ossicles in the limbs, which may be supernumerary ossifications of an extra digit, something previously only associated with ichthyosaurs. The most complete specimen shows that this genus possesses 60 cervical vertebrae. This represents the highest cervical count of any plesiosaurian known in the Jurassic and is comparable in number only to Late Cretaceous elasmosaurids. The occurrence of these new taxa and others described below in Middle Volgian (Tithonian)-aged strata contribute greatly to filling the temporal and geographic gap between better known Middle to Late Jurassic forms from Europe and Cretaceous taxa from North America.

The **third** paper by Knutsen, Druckenmiller & Hurum (C) describes the disarticulated remains of one of the most complete plesiosaurian fossils found on Svalbard, preserving an incomplete cranium and lower jaw, 40 cervical vertebrae, a nearly complete shoulder girdle, both incomplete front limbs, much of the torso, a partial hind limb, and an incomplete pelvic girdle. This specimen represents another new genus and species of plesiosauroid. The presence of several distinct taxa of long-necked plesiosauroids from the Slottsmøya Member provides new insight into their ecological role in marine environments at high paleolatitudes.

The **fourth** paper on vertebrate fossils is on the pliosaurs found in 2006 and excavated in 2007 and 2008, again by Knutsen, Druckenmiller & Hurum (D). This paper describes the remains of both specimens, and concludes that they are the same taxon representing a new species. The species, based on the unique tooth morphology, is referable to the previously described, large-bodied macropredator *Pliosaurus*. Skeletal dimensions show this new taxon to represent one of the largest pliosaurids ever described. Results of morphometric comparisons with other, previously described, pliosaurid taxa, indicate a wide range of interspecific variability in the relative paddle lengths compared to body size.

As a result of the study on the new pliosaur, Knutsen in the **fifth** paper taxonomically revises the genus *Pliosaurus*. Based on his observations and literature studies, this paper reviews the characters formerly used in species level diagnosis for the genus *Pliosaurus*, and assesses the validity of earlier recognised taxa and the previous assignation of more complete specimens to this taxon. This study is also the first to collectively illustrate an accurate stratigraphic provenance for the primary specimens (types and/or more complete skeletons) referred to *Pliosaurus*. It also allows for a more accurate assessment of the newly discovered pliosaurid remains from the Late Jurassic of Svalbard.

The series of plesiosaur papers mentioned above are all discussed and analysed in a cladistic analysis by Druckenmiller & Knutsen in the **sixth** paper. They expand on a data matrix previously constructed for use in the investigation of global plesiosaurian relationships, by adding the five new taxa (four plesiosauroid and one pliosaurid) from the Late Jurassic of central Spitsbergen and three specimens of the pliosaurid genus *Pliosaurus* to the matrix. The addition of all valid taxa of *Pliosaurus* species makes this the first species-level analysis of this genus. The results yielded a tree topology closely conforming to the traditional plesiosauroid and pliosauroid dichotomy. However, tree support for this topology is low, and the stability of a traditionally conceived Pliosauroidea remains uncertain. The three, new, long-necked taxa from Svalbard (the fourth was defined as a "wildcard" taxon and pruned from the matrix) form a monophyletic sister group to the Cretaceous Elasmosauridae. These results should, however, be considered preliminary pending the discovery of more complete cranial material and adult specimens.

The biology of the plesiosaurians is described in the **seventh** paper by Liebe & Hurum who use thin-sections to describe the gross internal structure and microstructure of four specimens. This study is the first to describe the microstructure of mesopodials and metapodials in plesiosaurians. The inner bone structure fits an active marine animal living in cold water. Many of the features in the present material are often found in animals with rapid growth and high metabolism, including secondary osteons, high vascularisation, pits on the outside of the epiphysis, and woven and possibly fibro-lamellar bone. The propodials have a defined and quite compact cortex in the sub-adult, a finding that rejects the view that all plesiosaur bones became more porous through ontogeny. There is a microstructural difference between bones from different ontogenetic stages: juvenile bones lack remodelling and completely ossified endochondral cones. Three of the bones have regular trabecular rings in a porous cortex, maybe resulting from cyclic growth caused by seasonality, migration or ontogeny.

The last and **eighth** paper on the marine reptiles is on the ichthyosaurs by Druckenmiller, Hurum, Knutsen & Nakrem describing two new ichthyosaurs that represent two new taxa of ophthalmosaurids. One taxon is based on a nearly complete and largely articulated skeleton and the second taxon includes a nearly complete skull and fragmented postcranial remains. The Slottsmøya Lagerstätte is established as one of the most productive horizons for Upper Jurassic ichthyosaurs, considerably expanding our knowledge of ophthalmosaurid diversity and distribution in the latest Jurassic.

Oil

The final paper of the volume is by Kihle, Hurum & Liebe and is the first published study on liquid petroleum from Spitsbergen. The liquid petroleum occurs in fluid inclusions trapped in intracellular mineral precipitates in the vertebrae in both pliosaur specimens. The source rock expelling petroleum was potentially the rock occurring just below the Pliosaurus-bearing strata. In addition to inclusions validating a petroleum origin, a few low-viscosity, reddish- brown coloured inclusions, not likely to represent a bituminous liquid, are observed, potentially of animal origin

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References

Andreassen, B. H. 2004: Plesiosaurs from Svalbard. *Master thesis/dissertation, Natural History Museum, University of Oslo*, 109 pp.

Angst, D., Buffetaut, E., Tabouelle, J. & Tong, H. 2010: An ichthyosaur skull from the Late Jurassic of Svalbard. *Bulletin de la Societe Géologique de France 181*, 453-458.

Bottjer, D. J., Etter, W., Hagadorn, J. W. & Tang, C. M. 2002: Fossil-Lagerstätten: jewels of the fossil record *In* Bottjer, D.J., Etter, W., Hagadorn, J.W. & Tang C.M. (eds.), *Exceptional fossil preservation; a unique view on the evolution of marine life*, 1-10. Columbia University Press.

Collignon, M. & Hammer, Ø. (this volume): Lithostratigraphy and sedimentology of the Slottsmøya Member at Janusfjellet, Spitsbergen: evidence for a condensed section. *Norwegian Journal of Geology 92*, 89-101.

Dallmann, W.K., Major, H., Haremo, P., Andresen, A., Kjærnet, T. & Nøttvedt, A. 2001: Geological map of Svalbard 1:100,000, sheet C9G Adventdalen. With explanatory text. *Norsk Polarinstitutt Temakart 31/32*, 4-55.

Doyle, P. 1987: Lower Jurassic – Lower Cretaceous belemnite biogeography and the development of the Mesozoic Boreal Realm. *Palaeogeography, Palaeoclimatology, Palaeoecology 61*, 237-254.

Dypvik, H. 1980: The sedimentology of the Janusfjellet Formation, central Spitsbergen (Sassenfjorden and Agardhfjellet areas). *Norsk Polarinstitutt Skrifter 172*, 97-134

Dypvik, H. 1985: Jurassic and Cretaceous black shales of the Janusfjellet Formation, Svalbard, Norway. *Sedimentary Geology 41*, 235-248.

Dypvik, H., Nagy, J., Eikeland, T.A., Backer-Owe, K., Andresen, A., Haremo, P., Bjærke, T., Johansen, H., & Elverhøi, A. 1991a: The

Janusfjellet Subgroup (Bathonian to Hauterivian) on central Spitsbergen: a revised lithostratigraphy. *Polar Research 9*, 21-43.

Dypvik, H., Nagy, J., Eikeland, T.A., Backer-Owe, K. & Johansen, H. 1991b: Depositional conditions of the Bathonian to Hauterivian Janusfjellet Subgroup, Spitsbergen. *Sedimentary Geology 72*, 55-78

Dypvik, H., Smelror, M., Sandbakken, P.T., Salvigsen, O. & Kalleson, E. 2006: Traces of the marine Mjølnir impact event. *Palaeogeography, Palaeoclimatology, Palaeoecology 241*, 621-636

Ginsburg, L., & Janvier, P. 1974 : Un nouveau gisement à Plésiosaures dans le Jurassique du Spitsbergen (Archipel du Svalbard). *Årbok - Norsk Polarinstitutt 1974*, 262-265.

Hammer, Ø., Nakrem, H.A., Little, C.T.S., Hryniewicz, K., Sandy, M.R., Hurum, J.H., Druckenmiller, P., Knutsen, E.M. & Høyberget, M. 2011: Hydrocarbon seeps from close to the Jurassic-Cretaceous boundary, Svalbard. *Palaeogeography, Palaeoclimatology, Palaeoecology 306*, 15-26.

Hammer, Ø., Hryniewicz, K., Hurum, J.H., Høyberget, M., Knutsen, E.M., & Nakrem, H.A. (in press): Large onychites (cephalopod hooks) from the Upper Jurassic of the Boreal Realm. *Acta Palaeontologica Polonica.*

Hammer, Ø., Collignon, M. & Nakrem, H.A. (this volume): Organic carbon isotope chemostratigraphy and cyclostratigraphy in the Volgian of Svalbard. *Norwegian Journal of Geology 92*, 103-112.

Heintz, N. 1964: Mesozoic reptiles from Norway and Svalbard. *Norsk Polarinstitutt Meddelelser 19*, 1-39. (in Norwegian)

Hulke, I. W. 1873: Memorandum on some fossil vertebrate remains collected by the Swedish expeditions to Spitzbergen in 1864 and 1868. *Bihang till Kongliga Svenske Vetenskapsakademiens Handlingar 1*, 3-11.

Novis, L.K. 2012: A taphonomic study of marine reptiles from the Upper Jurassic of Svalbard. *Master thesis/dissertation, Natural History Museum, University of Oslo*, 54 pp.

Page, K.N. 2008: The evolution and geography of Jurassic ammonoids. *Proceedings of the Geologist's Association 119*, 35-57.

Persson, P. O. 1962: Plesiosaurians from Spitsbergen. *Årbok - Norsk Polarinstitutt 1961*, 62-68.

Sachs, V.N., Basov, V.A., Dagis, A.A., Dagis, A.S., Ivanova, E.F., Meledina, S.V., Mesezhnikov, M.S., Nalenyayeva, T.I., Zakharov, V.A. & Shulgina, N.I. 1973: Paleozoogeography of Boreal-Realm Seas in Jurassic and Neocomian. *In* Pitcher, M.G. (Ed.), *Arctic Geology. AAPG Memoir 1*, 219-229. Thulsa.

Seilacher, A., W.-E. Reif, & Westphal, F. 1985: Sedimentological, ecological and temporal patterns of fossil Lagerstätten. *Philosophical Transactions of the Royal Society of London B 311*, 5-23.

Seilacher, A. 1990: Taphonomy of Fossil-Lagerstätten. *In* Briggs, D.E.G. & Crowther, P.R. (eds.), *Palaeobiology: A synthesis*, 266-270. Blackwell Science.

Stevens, G.R. 1963: Faunal realms in Jurassic and Cretaceous Belemnites. *Geological Magazine 100*, 481-497.

Torsvik, T.H., Carlos, D., Mosar, J., Cocks, L.R.M. & Malme, T.N. 2002: Global reconstructions and North Atlantic palaeogeography 400 Ma to Recent. *In* Eide, E.A. (ed.): *BATLAS – Mid Norway plate reconstructions atlas with global and Atlantic perspectives*, 18-39. Geological Survey of Norway, Trondheim.

Wierzbowski, A., Hryniewicz, K., Hammer, Ø., Nakrem, H.A. & Little, C.T.S. 2011: Ammonites from hydrocarbon seep carbonate bodies from the uppermost Jurassic – lowermost Cretaceous of Spitsbergen, Svalbard, and their biostratigraphic importance. *Neues Jahrbuch für Geologie und Paläontologie 262*, 267–288.

Wiman, C. 1910: Ichthyosaurier aus der Trias Spitzbergens. *Bulletin - Uppsala Universitet, Mineralogisk-geologiska Institut 10*,124-148.

Wiman, C. 1914: Ein Plesiosaurierwirbel aus dem jüngeren Mesozoicum Spitzbergens. *Bulletin - Uppsala Universitet, Mineralogisk-geologiska Institut 12*, 201-204.

Wiman, C. 1916: Ein Plesiosaurierwirbel aus der Trias Spitzbergens. *Bulletin - Uppsala Universitet, Mineralogisk-geologiska Institut 13*, 223-226.

Yakowlew, v. N. 1903: Neue Funde von Trias-Saurier auf Spitzbergen. *Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft 40*, 179-202.