RESEARCH/REVIEW ARTICLE

Benthic foraminifera from the Lower Jurassic transgressive mudstones of the south-western Barents Sea—a possible high-latitude expression of the global Pliensbachian–Toarcian turnover?

Silvia Hess,[1] Jenő Nagy[1] & Gitte Vestergaard Laursen[2]

[1] Department of Geosciences, University of Oslo, PO Box 1047, Blindern, NO-0316 Oslo, Norway
[2] Statoil ASA, NO-4035 Stavanger, Norway

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Correspondence
Silvia Hess, Department of Geosciences, University of Oslo, PO Box 1047, Blindern, NO-0316 Oslo, Norway.
E-mail: silvia.hess@geo.uio.no

Abstract

The Lower Jurassic section of two commercial wells (7119/12-1 and 7119/12-2), drilled in the Hammerfest Basin, was analysed for foraminiferal assemblages in order to reconstruct palaeoenvironmental changes. Foraminifera occurred singularly in transgressive mudstone intervals of the Stø Formation in well 7119/12-1. High-energy marginal marine and offshore sandstones and freshwater sand- and mudstones were barren of foraminifera. Three distinct foraminiferal assemblages could be distinguished. They contain exclusively agglutinated taxa and have extremely low species diversities, indicating restricted environmental conditions. The main restricting factor was low salinity in strongly delta-influenced waters. Foraminiferal assemblage 1 is developed at the base of the Stø Formation and suggests transgressive, extremely hyposaline lagoonal conditions. Assemblages 2 and 3 occur in hyposaline prodelta shelf mudstones of the Stø Formation and reveal increased diversities in major local transgressive phases. The foraminiferal assemblages indicate Pliensbachian–Toarcian ages. The mudstones of the Stø Formation are regarded as a local expression of the global Pliensbachian–Toarcian turnover recording regional transgressive developments in the Toarcian.

Foraminifera have been used in numerous studies as palaeoenvironmental indicators in ancient marine environments. In siliciclastic marginal marine and coastal (paralic) systems, the palaeoenvironmental application of this biota is much more infrequent even though these environments, which contain coal and petroleum reservoirs, have high industrial potential. In the boreal realm, biofacies studies of paralic foraminiferal assemblages have recently intensified, resulting in several papers (e.g., Nagy & Johansen 1991; Nagy & Seidenkrantz 2003; Nagy & Berge 2008; Nagy et al. 2011).

The Early Jurassic was a period of considerable environmental changes resulting in marine biotic turnover events which are also documented at high latitudes (e.g., Nikitenko & Mickey 2004; Zakharov et al. 2006). Successions of organic-rich mudstones and shales associated with a negative carbon isotope excursion developed during transgressive phases in the Lower Toarcian (Suan 2011) and coincide with biotic turnover events.

This paper presents the results of an investigation of Early Jurassic foraminiferal assemblages from two commercial wells drilled in the Hammerfest Basin in the south-western Barents Sea (Fig. 1). Our study concentrates on Lower Jurassic deposits of the Stø and Nordmela formations, which compose the uppermost part of the Kapp Toscana Group (Fig. 2). This sand-dominated succession is widely developed on the Barents Sea shelf (including the Svalbard Archipelago) where it has a high petroleum reservoir potential, but is rather poor in age-significant fossils.

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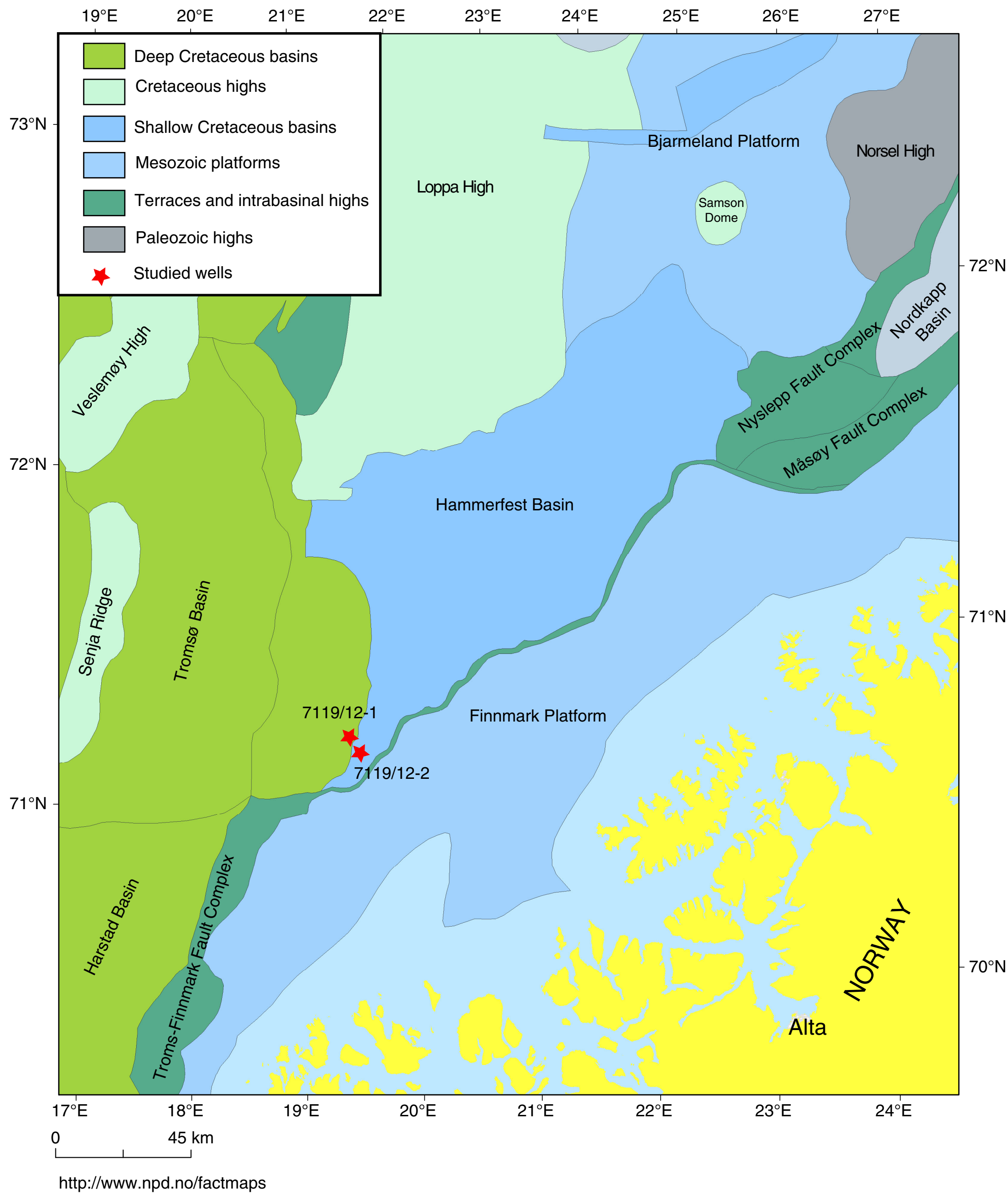

Fig. 1 Study area map of the south-western Barents Sea Shelf with the well locations (modified from the Norwegian Petroleum Directorate's fact map).

Quantitative foraminiferal assemblage analyses are integrated with sedimentological data to enhance the understanding of depositional conditions of the delta-influenced, marginal marine succession of the Lower Jurassic. In addition, information from the distribution of modern foraminiferal faunas is used. Such information reflecting environmental parameters (i.e., food supply, oxygen content, salinity, sediment type, water depth) is useful in order to enhance the understanding of past analogue environmental conditions (e.g., Scott et al. 1983).

The foraminiferal faunas of the analysed succession are characterized by low diversities and consist entirely of agglutinated taxa. They reveal close similarities to agglutinant-dominated assemblages occurring in Jurassic deposits of several northern European and Arctic areas, as recorded from Svalbard (Løfaldi & Nagy 1980; Nagy et al. 2011), Arctic Canada (Souaya 1976; Wall 1983), Alaska

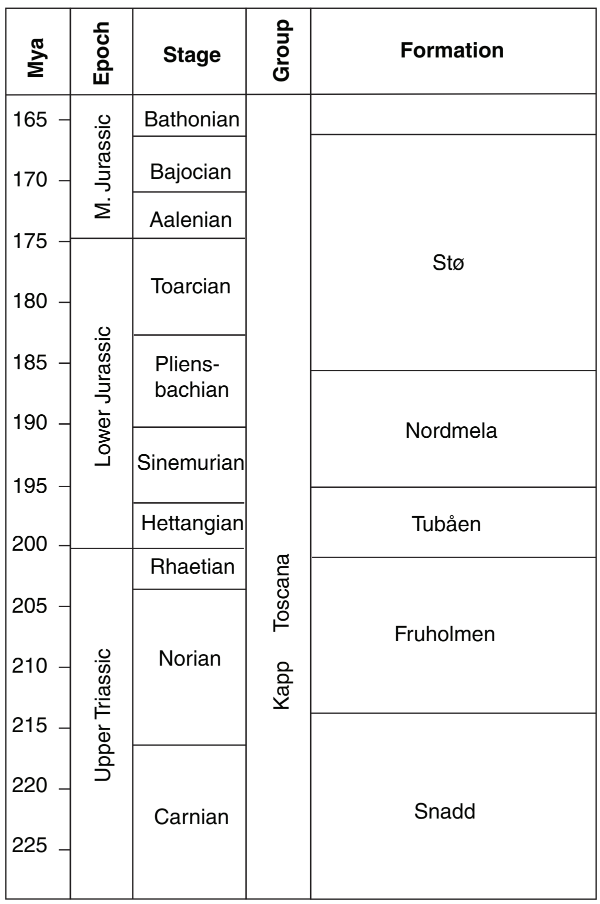

Fig. 2 Stratigraphic overview of the Kapp Toscana Group in the Hammerfest Basin.

(Tappan 1955), Siberia (Nikitenko & Mickey 2004) and the northern North Sea Basin (Nagy 1985a,b; Nagy & Johansen 1991; Nagy & Seidenkrantz 2003).

The Kapp Toscana Group in the Hammerfest Basin

The Kapp Toscana Group is a siliciclastic sediment succession attaining a thickness of 2000 m in the Hammerfest Basin, south-western Barents Sea. The succession was deposited in offshore shelf to dominantly coastal and deltaic environments with transport direction from south-east, east and north-east (Mørk et al. 1999). In this basin, the group is subdivided into the following five formations, in ascending order (ages and descriptions from Dalland et al. [1988]; Fig. 2). The Snadd Formation (Ladinian to Norian) consists mainly of shales with subordinate siltstones and sandstones, and was deposited under offshore shelf conditions. The Fruholmen Formation (Norian to Rhaetian) comprises mudstones and sandstones ascribed to open shelf, coastal to fluvial environments. The Tubåen Formation (Rhaetian to Sinemurian) contains thick sandstone bodies and thin mudstone intervals interpreted as estuarine deposits. The Nordmela Formation (Sinemurian to Late Pliensbachian) consists predominantly of alternating sand- and mudstones. Minor coal beds and numerous rootlet horizons are present (Fig. 3). The main facies associations recognized in this formation are distributary channels, interdistributary bays, back-barrier lagoons and tidal flats. Lacustrine mudstones also occur. It is assumed that the lagoonal, interdistributary bay and intertidal strata were deposited under hyposaline conditions. The Stø Formation (Late Pliensbachian to Bajocian) is dominated by fine- to coarse-grained sandstones alternating with subordinate mudstone intervals. The sandstones were deposited mainly in high-energy shoreface environments or as offshore bars. Some of the mudstones are probably formed in low energy marginal marine settings such as tidal flats, lagoons and interdistributary bays. Regionally extensive mudstone horizons represent transgression events depositing offshore marine facies between more proximal marine sandstones. Such transgressive mudstones are typical for the upper part of the formation (Fig. 3). Most sections show fining-upward parasequences and common bioturbation.

A sedimentological study of the Nordmela and Stø formations carried out by Olaussen et al. (1984) included the two wells analysed in this paper. The stratigraphy and regional development of the deltaic systems dominating the Kapp Toscana Group are further discussed by Van Veen et al. (1992) and Riis et al. (2008).

Material and methods

The two wells examined are located in the south-western part of the Hammerfest Basin: well 7119/12-1 (N 71°06′07.99′′, E 19°47′40.29′′) and well 7119/12-2 (N 71°00′51.81′′, E 19°58′20.81′′; Fig. 1). The wells were drilled to obtain information about the hydrocarbon reservoir properties of Jurassic sandstones. The sampled intervals of the Nordmela and Stø formations range from 2670 to 2850 m core depth in well 7119/12-1 and from 1470 to 1690 m in well 7119/12-2.

A total of 68 core samples were prepared for foraminiferal analyses: 57 from well 7119/12-1 and 11 from well 7119/12-2. In total, 36 samples contained foraminifera. All are from the Stø Formation of well 7119/12-1. Altogether 32 samples were barren of foraminifera. They are the following: all 11 samples taken from the Nordmela Formation of well 7119/12-2; 7 samples from the Nordmela Formation of well 7119/12-1; 14 samples of the Stø

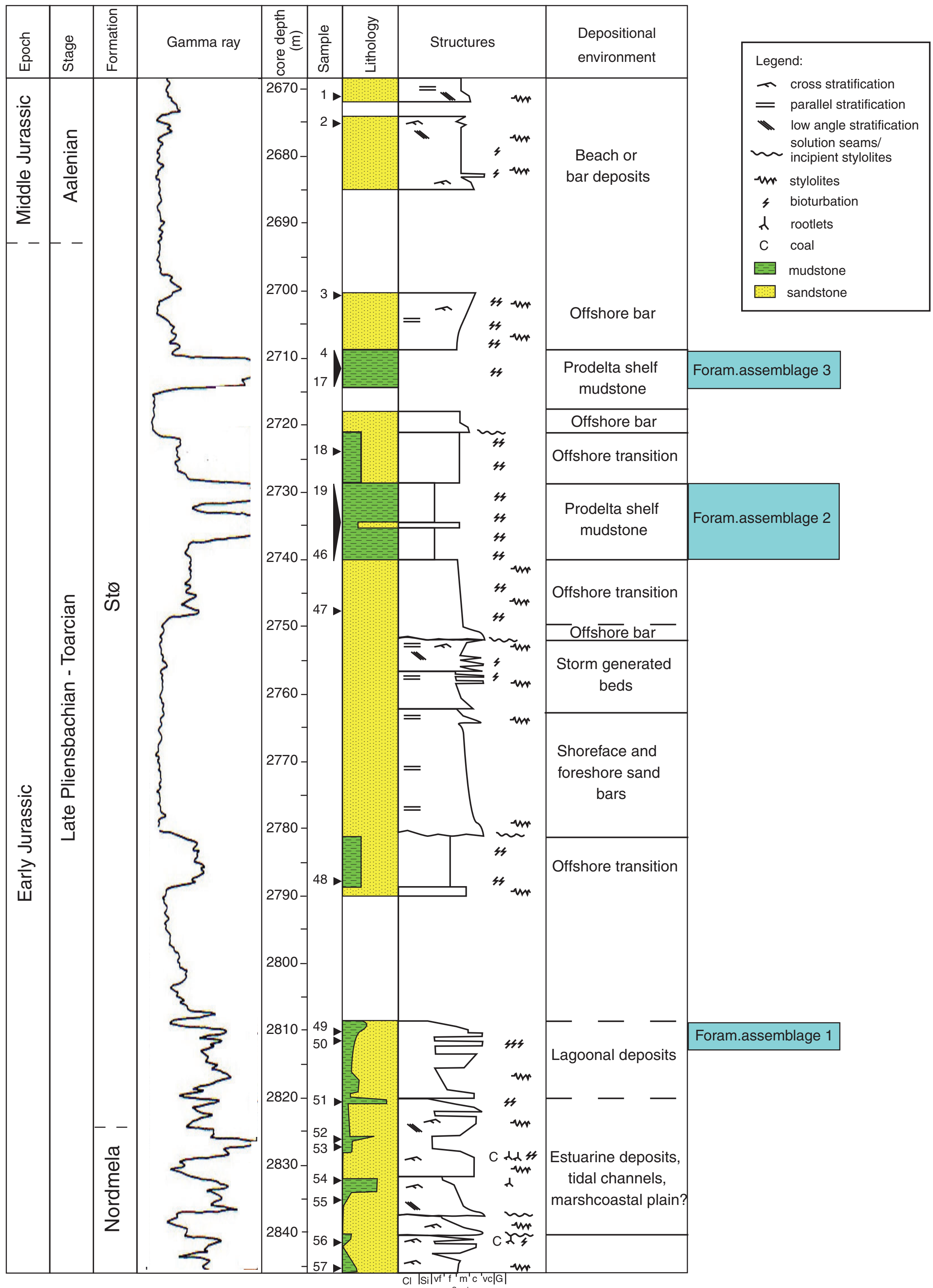

Fig. 3 Age relationships, lithological log and facies interpretation of the analysed interval of well 7119/12-1. The illustration is based on Olaussen et al. (1984) and the present study.

Formation of well 7119/12-1. The majority of samples were taken from mudstone layers, usually dark in colour.

The laboratory processing of samples required an unexpectedly intensive treatment owing to the high degree of diagenetic cementation (also reflected by common styloliths in the sandstones). To achieve disaggregation of the mudstones, the samples were first soaked in kerosene for approximately 30 min. After decanting the kerosene, the sediments were boiled in a solution of sodium hydroxide (NaOH). Thus, the disintegrated material was washed through sieves with >63 µm mesh size and dried at 40°C. If necessary, the procedure was repeated to achieve sufficient disaggregation. The dried residue >90 µm was analysed for its foraminiferal content. From the residue, at least 300 foraminiferal tests (if available) were picked and mounted on micropalaeontological slides, which are stored at the Department of Geosciences in Oslo. The foraminiferal abundance was calculated as the number of individuals per 10 g of dry sediment. Faunal diversity is expressed both by the Shannon-Wiener H(S) and Fisher α diversity indices (Fisher et al. 1943; Shannon 1948).

Most foraminiferal tests were compressed by diagenetic compaction of the sediments. Therefore, some species are kept in open nomenclature. The taxonomical identifications are mainly based on earlier descriptions and on subsequent papers by Nagy & Johansen (1991) and Nagy & Basov (1998).

Additionally, the organic carbon (TOC) and carbonate content of the well sections were measured with a CR-412 Carbon Analyzer (Leco Corporation, St. Joseph, MI, USA).

Benthic foraminiferal assemblage features of the Stø Formation

General characteristics of assemblages

In total, 3581 benthic specimens were picked and used in the analyses. Only agglutinated foraminifera are present in the sample set. Fourteen taxa are identified and listed in Table 1. The most common species are *Trochammina squamataformis*, *Ammodiscus pseudoinfimus* forma *granulata* and *Kutsevella memorabilis*. They are often accompanied by *Bulbobaculites vermiculus*, *B. strigosus*, *Thuramminoides* sp., *Lagenammina inanis*, *Psammosphaera* sp. and *Reophax metensis*.

In the examined part of well 7119/12-1, three biotic events are distinguished which reflect transgressive encroachments of marine shelf conditions in the Stø Formation (Fig. 3). The dark mudstone intervals deposited during these inundations show a range of foraminiferal abundance between 41 and 2 individuals per 10 g dry sediment (Fig. 4). The species diversities are generally low with Fisher α values below 5, indicating restricted environmental conditions (Fig. 5).

Table 1 All foraminiferal taxa identified in this study are listed alphabetically. Generic classification follows Loeblich and Tappan (1988). Open nomenclature is used for taxa that could not be identified to species level.

Ammodiscus pseudoinfimus forma *granulata* Gerke & Sossipatrova 1961
Ammodiscus glumaceus Gerke & Sossipatrova 1961
Bulbobaculites vermiculus Nagy & Seidenkrantz 2003
Bulbobaculites strigosus (Gerke & Sossipatrova 1961) = *Ammobaculites strigosus* Gerke 1961
Kutsevella memorabilis (Scharovskaja 1958)
Lagenammina inanis (Gerke & Sossipatrova 1961) = *Saccammina inanis* Gerke & Sossipatrova 1961
Psammosphaera sp.
Recurvoides sp.
Reophax metensis Franke 1936
Reophax sp.
Spiroplectammina sp.
Thuramminoides sp.
Trochammina squamataformis Kaptarenko-Chernousova 1959
Verneuilinoides subvitreus Nagy & Johansen 1991

Foraminiferal assemblage 1

The transitional beds between the Nordmela and Stø formations were checked for foraminifera by processing nine samples from the interval 2810 and 2845 m core depth. Only a single sample from the lower Stø Formation contains foraminifera (sample 50, 2811.6 m core depth). Just 15 individuals were found in 10 g of dry sediment (Fig. 4). The assemblage is composed entirely of agglutinated taxa and has an extremely low diversity; only three taxa are present (Fisher α index = 0.6). The assemblage is nearly monospecific with *Ammodiscus pseudoinfimus* forma *granulata* as the most abundant species (Fig. 6). The sample was taken from a fine-grained silty mudstone interval that appears to represent a minor flooding event.

Foraminiferal assemblage 2

The middle mudstone interval containing foraminiferal assemblages 2 in the Stø Formation is recognized in samples 19–46, which are located between 2729.3 and 2738 m core depth (Fig. 4). This interval is split by a silty–sandy bed into two foraminifera-bearing subunits (samples 19–29 from 2729.3 to 2732.3 m core depth, and samples 34–37 from 2734.1 to 2737.3 m core depth).

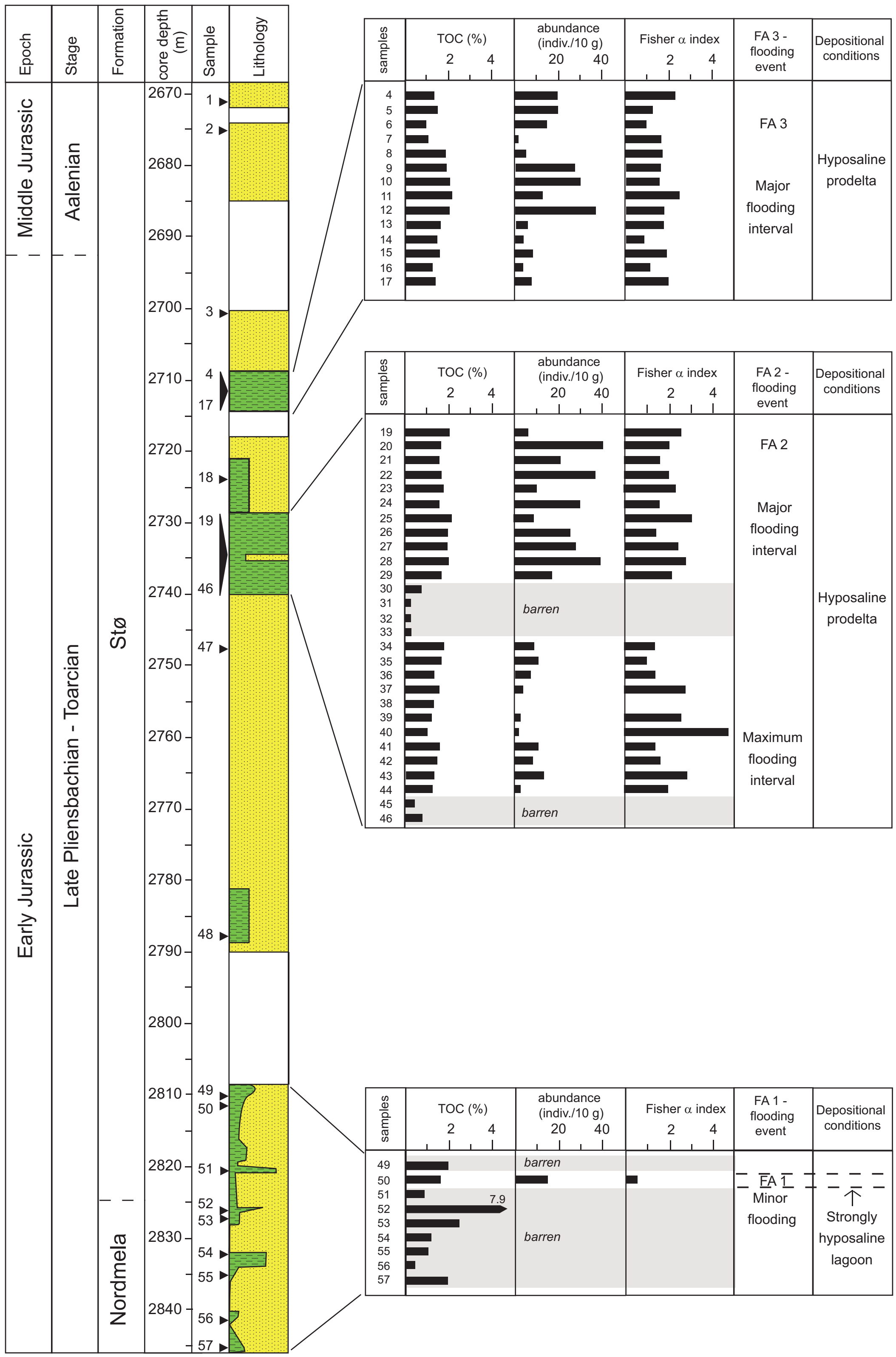

Fig. 4 Lithological features, main foraminiferal distribution proxies and foraminifera-based facies interpretation of the analysed interval of well 7119/12-1. FA stands for foraminiferal assemblage and TOC stands for organic carbon.

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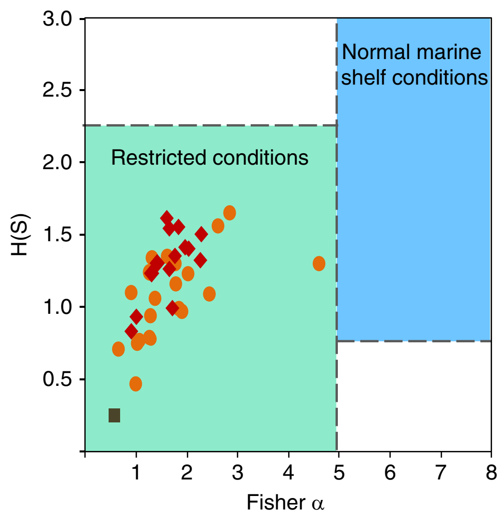

Fig. 5 Foraminiferal sample plot of Fisher α and H(S) diversity indices from the analysed interval of well 7119/12-1. Foraminiferal assemblages 1, 2 and 3 are represented by a square, dots and diamonds, respectively.

The foraminiferal abundance in this mudstone interval ranges between 2 and 41 individuals per 10 g of dry sediment (Fig. 4), reaching maximum values in the upper subunit (sample 20). The Fisher α diversities are low, with an average of 1.7. Simple species numbers range between 4 and 9. The assemblages contain only agglutinated taxa. The dominant species in both subunits is *Trochammina squamataformis,* which is accompanied by *Ammodiscus pseudoinfimus* forma *granulata* and *Kutsevella memorabilis* (Fig. 6).

Foraminiferal assemblage 3

The foraminiferal assemblage 3 is characteristic for the samples 4–17 from 2709.7 to 2714.3 m core depth in the upper mudstone interval of the Stø Formation. Foraminiferal abundances range between 2 and 35 individuals per 10 g dry sediment. The diversities are low; showing species numbers ranging between 3 and 10 and an average Fisher α index of 1.6 (Fig. 4). Dominant species include *Trochammina squamataformis, Ammodiscus pseudoinfimus* forma *granulata, Bulbobaculites vermiculus* and *Kutsevella memorabilis* (Fig. 6).

Foraminiferal facies reflecting depositional conditions

General aspects and modern analogues

A sedimentological framework of the Lower to Middle Jurassic deposits of well 7119/12-1 was provided by Olaussen et al. (1984) with assessments of the depositional conditions. This sand-dominated succession was deposited in several environmental settings ranging from delta-influenced shelf mudstones through shoreface sands (Stø Formation) to tidal flat/coastal plain fine-grained sandstones with thin coal layers and rooted horizons (Nordmela Formation).

As mentioned above, 32 samples treated for foraminiferal analysis were barren. Mudstone samples containing no foraminifera may represent freshwater deposits. Marginal marine and offshore sandstones are assumed to have been deposited in hyposaline waters.

The foraminiferal assemblages of the three mudstone intervals are typified by entirely agglutinated species composition, extremely low diversities, and the dominance of *Ammodiscus* and *Trochammina* taxa. The low Fisher α indices (all <5) suggest restricted environmental conditions in which low salinity or oxygen depletion were the potentially main controlling factors (Nagy et al. 2011), as indicated by modern analogues (Fig. 5). A compilation of foraminiferal distribution patterns in modern environments (Murray 1973) demonstrates that hyposaline conditions are typified by Fisher α indices lower than 5. Low diversity assemblages dominated by agglutinated taxa such as *Ammodiscus* and *Trochammina* are known from some modern brackish environments, although these genera also occur in normal marine habitats (Murray 1991). Of particular interest is the dominance of *Ammodiscus* and *Trochammina* taxa in some modern marginal marine environments with bottom water hypoxia developed in a salinity-stratified water column. Foraminiferal taxa adapted to such conditions often show reduced test dimensions (see Nagy et al. 2010 and references therein). This feature was used for the recognition of hypoxic conditions in Upper Triassic to Lower Jurassic deposits of the North Atlantic margin by Nagy et al. (2010).

Environments of the Nordmela Formation

The investigated well sections of the Nordmela Formation consist of fine-grained sandstones and siltstones with interbedded mudstone intervals. Several parasequences show fining upwards trends and might represent tidal channel fills. In some intervals in well 7119/12-1 (2845 to 2820 m core depth) some rootlet horizons and thin coal seams are present. No foraminifera were found in any sample from the Nordmela Formation. These barren samples and the presence of rootlets suggest extremely brackish tidal flat to coastal plain conditions.

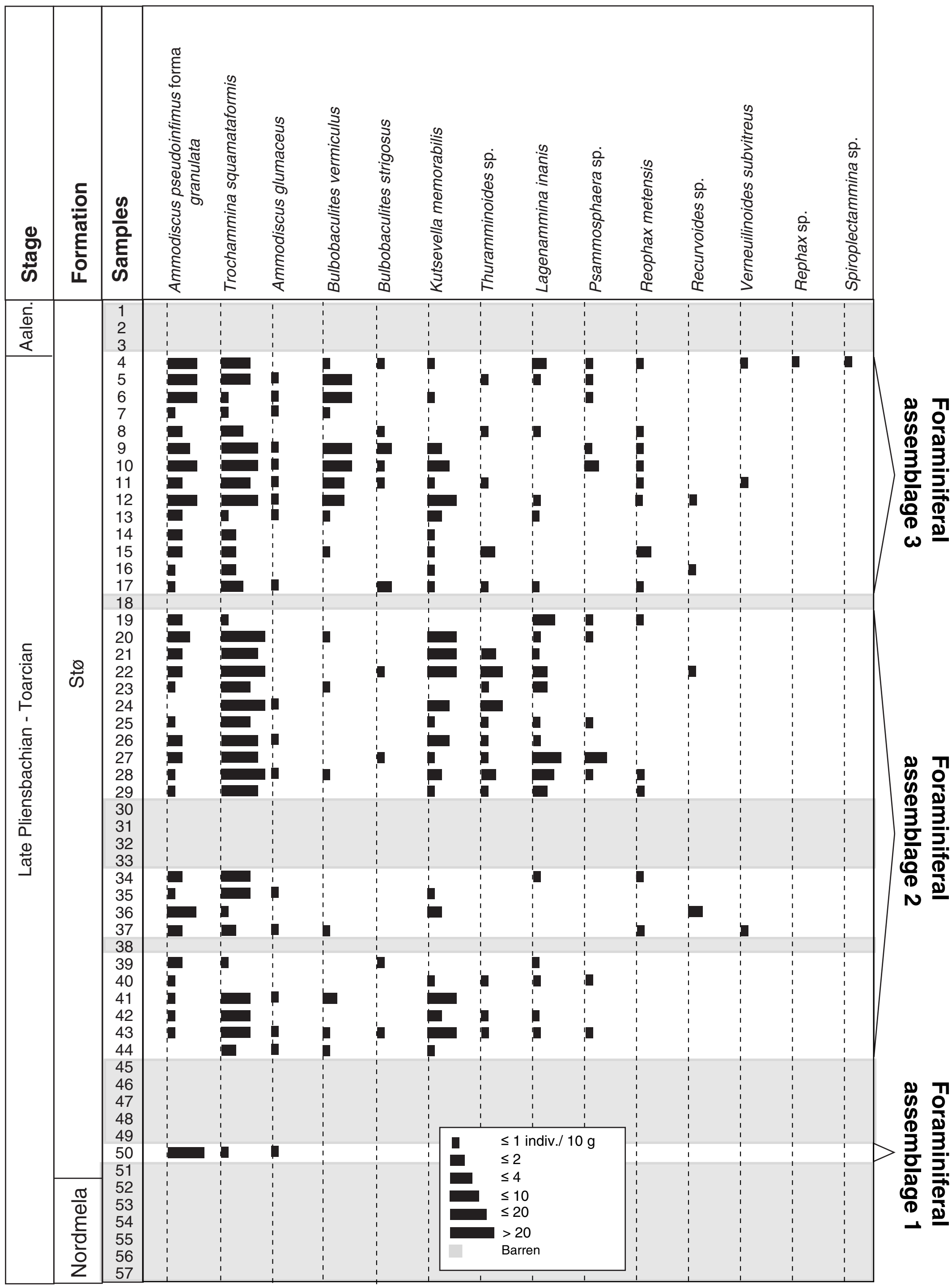

Fig. 6 Stratigraphic distribution of foraminiferal taxa through the analysed interval of well 7119/12-1.

Environments of the Stø Formation

The sedimentary succession composing the Stø Formation reveals shallow marine environments with transgressive trends. The thick and homogeneous sandstones with no or sparse bioturbation are interpreted as shoreface and foreshore sand bars (Fig. 3). Fine-grained sandstones, commonly silty, often bioturbated and locally with storm beds are ascribed to the offshore transition zone. The sandstones are barren of foraminifera.

The three main mudstone intervals containing the described foraminiferal assemblages 1–3 represent transgressive pulses superimposed on the overall transgressive development of the Formation (Fig. 3). The lowermost fine-grained and bioturbated siltstone–mudstone beds of the Stø Formation represent a transgressive event in a still coastal near environment. This is confirmed by the presence of a low diversity foraminiferal assemblage in sample 50 of well 7119/12-1 (foraminiferal assemblage 1). The nearly monospecific composition of this assemblage suggest slightly increased salinity in a possibly lagoonal environment. The upper two mudstone intervals are referred to prodelta shelf environments. The siltstone bed appearing in the middle of the lower mudstone interval is interpreted as a storm deposit, which explains why it is barren of foraminifera (Fig. 4). The water masses of the shelf area with prodelta mud deposition were hyposaline as indicated by the low diversity agglutinated foraminiferal assemblages 2 and 3. In accordance with this, the assemblages include *Ammodiscus, Trochammina, Bulbobaculites* and *Kutsevella* among the dominant genera. Development of hyposaline conditions in the prodelta shelf outside the Kapp Toscana deltas is in accordance with the large dimensions of this deltaic system, as it is apparent from the reconstructions presented by Van Veen et al. (1992) and Riis et al. (2008).

As mentioned above, size reduction of foraminifera is regarded as an adaptation to low oxygen conditions. By using taxa of *Ammodiscus* and *Trochammina*, this feature is applied as a proxy for oxygen depletion by Nagy et al. (2010) in several Upper Triassic to Middle Jurassic sections including an interval of the Ragnarok Formation of the Mjølnir structure (central Barents Sea). In the foraminiferal assemblages 2 and 3, these genera show no size reduction although a small degree of hypoxia is expected owing to the somewhat increased TOC content of the mudstone samples (Fig. 4). It seems probably the oxygen depletion was too small to cause a test size reduction. The presence of bioturbation in the mudstones also suggests that oxygen depletion was not a significant restricting factor in this environment.

Stratigraphic significance of foraminiferal assemblages

Age relationships

The foraminiferal assemblages of the upper Kapp Toscana Group are of low diversity, and the study of these faunas is still in a pioneering stage. In spite of these factors, the faunal content of the foraminiferal assemblages 1–3 reveals a significant stratigraphic potential as shown by the age distribution pattern of the various species in other regions. *Ammodiscus pseudoinfimus* forma *granulata* is recorded from the Pliensbachian of Western Siberia (Azbel & Grigalis 1991) and *Ammodiscus glumaceus* ranges from Toarcian to Aalenian in western Siberia and occurs in the Toarcian of Middle Siberia (Bulynnikova et al. 1990). *Bulbobaculites vermiculus* is originally described from Pliensbachian to Toarcian strata from Anholt, Denmark (Nagy & Seidenkrantz 2003). *Lagenammina inanis* occurs in Pliensbachian to Toarcian beds in Western and Middle Siberia (Bulynnikova et al. 1990) and *Reophax metensis* ranges from upper Sinemurian to lower Bathonian with an acme in the Pliensbachian and Toarcian (Nagy & Johansen 1989). *Trochammina squamataformis* is reported from the Pliensbachian and Toarcian of the Caucasus and Ukraine (Azbel & Grigalis 1991). *Verneuilinoides subvitreus* was first described from the upper Toarcian of the northern North Sea Basin but the closely related *Verneuilinoides mauritii* (Terquem) occurs in the Pliensbachian (Nagy & Johansen 1991).

The stratigraphical ranges mentioned above reveal the significant Pliensbachian–Toarcian affinities of the foraminiferal assemblages in this study. Therefore, they are referred to these stages. Of particular interest in this connection are the taxa *A. pseudoinfimus* forma *granulata, B. vermiculus, L. inanis* and *T. squamataformis.* For the beds above and below the mudstone levels, we follow the ages proposed by Olaussen et al. (1984).

A new reference section for the Pliensbachian–Toarcian biotic turnover?

Striking features of the analysed Stø Formation mudstone intervals are their transgressive nature and increased TOC content, which are coupled with a Pliensbachian–Toarcian age (Fig. 4). These relationships warrant a closer consideration of their possible connection to the global Pliensbachian–Toarcian turnover comprising several biotic extinction events.

The main stages of the Pliensbachian–Toarcian turnover were a regression followed by a transgression leading to oceanic hypoxia (Zakharov et al. 2006; Wignall & Bond 2008). The turnover with its main phase in the Early Toarcian *falciferum* Zone affected primarily the marine realm expressed by a development and widespread extinction of invertebrates such as ammonites and bivalves. In northern Siberia, the turnover comprises two major intervals with reduction of species diversities, the first in the *antiquum* Zone and the second in the *falciferum* Zone (Zakharov et al. 2006).

The Stø Formation mudstones and corresponding stratigraphic levels in the Hammerfest Basin can be regarded as reference sections for the Pliensbachian–Toarcian turnover in the boreal seas. Their foraminiferal assemblages might potentially define key horizons that could be used for basin-wide layer correlations and dating. However, prior to this additional research needs to be conducted to confirm the connection to the global Pliensbachian–Toarcian biotic turnover.

Conclusions

Lower Jurassic foraminiferal assemblages from a marginal marine succession of the Nordmela and Stø formations cored in two commercial wells (7119/12-1 and 7119/12-2) in the Hammerfest Basin were analysed in order to contribute to the stratigraphy and to reconstruct palaeoenvironmental conditions. Foraminiferal assemblages only occurred in samples from well 7119/12-1, where they are located in three mudstone intervals of the Stø Formation. The foraminiferal assemblages 1–3 contain exclusively agglutinated taxa and are characterized by low diversities (Fisher $\alpha < 5$). These features and analogies to some modern faunas indicate restricted environmental conditions. The main restricting factor was low salinity in strongly delta-influenced waters.

The foraminiferal assemblage 1 is developed at the base of the Stø Formation and represents transgressional conditions bringing strongly hyposaline lagoonal waters over freshwater strata. Assemblages 2 and 3 occur in mudstone intervals higher in the Stø Formation and reveal increased diversities. They represent two major transgressions leading to extension of hyposaline waters with prodelta shelf mudstone deposition into more proximal hyposaline sandstone environments.

The three foraminiferal assemblage compositions indicate a Pliensbachian–Toarcian age. The mudstones of the Stø Formation are considered as local developments of the global Pliensbachian–Toarcian transgressions and associated faunal change. In addition to the age relationships, this consideration is based on the highly transgressive nature of these mudstone horizons and their slightly increased TOC content.

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