Sedimentary facies and cyclostratigraphy of a potential CO_2 storage reservoir: The Early Triassic Bunter Sandstone Formation in the Rødby area, southern Denmark

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The Early Triassic (Olenekian) Bunter Sandstone Formation represents a major prospective reservoir for CO2 storage in southern Denmark especially in the four-way dip structure in the Rødby area (Lolland, southern Denmark), and is expected to play an important role for reaching climate targets. The Bunter Sandstone Formation in southern Denmark formed along the northern margin of the North German Basin and is composed of terrestrial sediments and subdivided into the Volpriehausen, Detfurth and Solling members. Each member has a basal sandstone unit overlain by a mudstone unit. The sandstone units form potential reservoirs in the formation. Their thickness and composition, however, vary somewhat along the basin margin from west to east in southern Denmark. In this paper focus is on the 256 m thick Bunter Sandstone Formation in the Rødby-1 well on Lolland. Visual analysis of the gamma ray records from wireline logging of the sedimentary succession in the Rødby-1 well indicates the presence of a composite cyclicity both in sandstone and mudstone units. Spectral analysis finds identical, significant cycles both in mudstone-rich and sandstone-rich units; in mudstone-rich units cycles have the following thicknesses: 62, 16, 7.5, 5.8, 4.4, 3.6, 3.0, 2.6, and 2.3 m. Assuming that these sedimentary cycles record astronomical climate control on sedimentation and the 62 m cycle records the 405,000 years eccentricity cycle, then the remaining cycles represent the following periods: 104,500; 49,000; 38,000; 28,500; 23,500; 19,500; 17,000; and 15,000 years. Thus both a 100,000 years eccentricity as well as precession cyclicity with periods between 15,000 and 23,500 years can be identified. More surprising also a likely obliquity signal seems to be present as given by cycles with periods of 28,500, 38,000 and 49,000 years. In Rødby-1, the sandstone units vary in thickness between 23 and 29 m. The new cyclostratigraphy indicates that deposition of the sandstone units took place during the arid parts of a 405,000 years eccentricity cycle, when the central playa lake had its minimum extension. Mudstones units formed during the humid parts of these climate cycles when the central playa lake expanded in size. Internal lithological variation and thereby reservoir properties (sandstone-mudstone ratio) in the sandstone units are related to 100,000 years eccentricity variation in climate as well as to obliquity and precession variation. There is very limited core evidence on facies characteristics in the Rødby-1 well, but comparison with core data from the Tønder area in southern Jutland suggests that the sandstone unit in the Volpriehausen Member is composed of alternating aeolian and ephemeral river deposits with facies change mainly related to climate variation. A similar sedimentary facies pattern is probably also characterizing the sandstone unit of the Detfurth Member. In the Solling Member only fluvial facies are present, and it is suggested that the lithological variation primarily reflects climatic induced variation in fluvial style and transport capacity. Mudstones units that separate the sandstone units are interpreted to have formed on sabkhas and in large playa lakes.

Keywords: Bunter Sandstone Formation, Rødby area, reservoir sandstones, cyclostratigraphy, palaeolandscapes

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The Bunter Sandstone Formation, of Early Triassic (Olenekian) age, is widely distributed in the subsurface across a large part of southern Denmark as documented by core data and borehole logs from several deep wells in southern Denmark (e.g. Bertelsen 1980; Michelsen & Clausen 2002; Olivarius *et al.* 2015; Olivarius *et al.* 2017; Fig. 1). Wells cover a wide region from the Tønder area in the west to the Rødby area in the east (Fig. 1), but sediment cores of good quality and from thick stratigraphical intervals are only present in three wells in the Tønder area (Clemmensen 1985; Olsen 1987).

The Bunter Sandstone Formation in southern Denmark is typically between 200 and 300 m thick and composed of the Volpriehausen, Detfurth and Solling members (Michelsen & Clausen 2002; Olivarius *et al.* 2015). Each member has a basal sandstone unit overlain by a mudstone unit. The sandstone units are composed of alternating fluvial and aeolian facies or only fluvial facies, while the mudstone units are composed of fine-grained sabkha and playa-lake sediments (Clemmensen 1985); sediments were deposited at low palaeolatitudes at the northern margin of the North German Basin and south of the Ringkøbing-Fyn High (e.g. Clemmensen 1985, 1991; Olivarius *et al.* 2015, 2017).

In wells in southern Denmark the formation is found at depths between 1100 and 2100 meters and is estimated to have experienced a maximum burial depth of 1600-2300 meters prior to Neogene uplift (Japsen *et al.* 2007). Many levels in the sandstones units are characterized by high porosity and permeability (Olivarius *et al.* 2015). This, in combination with the appropriate burial depth has led to many investigations of the formation as potential geothermal reservoir (e.g. Hjuler *et al.* 2016, 2019; Hjuler & Kristensen 2017).

Most recently the formation has also been examined as a potential subsurface reservoir for CO_2 storage in the Rødby structure on Lolland (Hjelm *et al.* 2020). The stratigraphy of the Bunter Sandstone Formations is here known from two deep wells, Rødby-1 and Rødby-2 (Hjelm *et al.* 2020). However, sediment cores are only present from four short intervals in the Rødby-1 well (Fig. 2), and interpretations of lithology is therefore primarily based on petrophysical logs

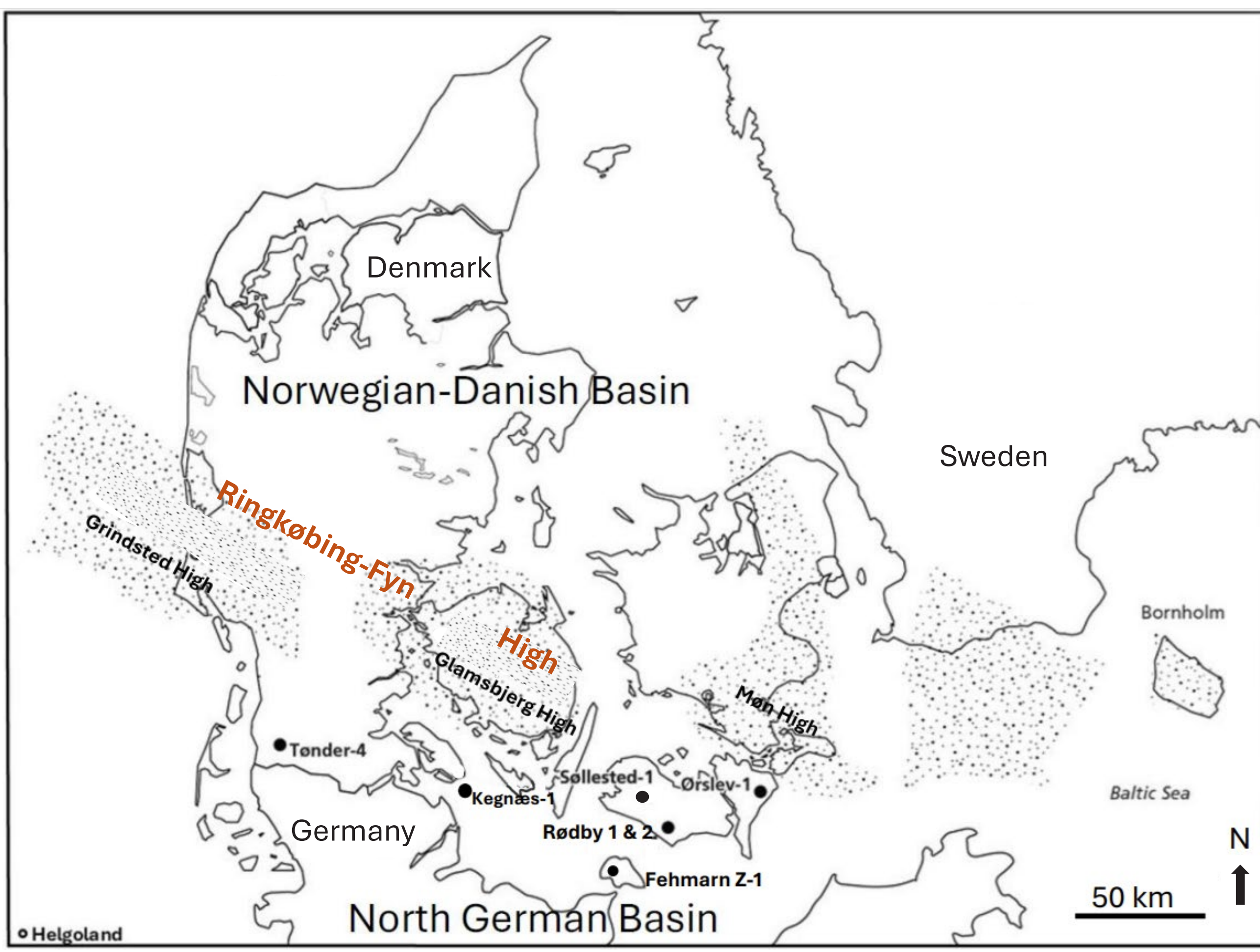

Fig. 1. Simplified geological map with location of wells described in the paper. The outline of the Ringkøbing-Fyn High modified from Olivarius & Nielsen (2016) and Olivarius *et al.* (2017).

and in particular gamma ray readings (Olivarius *et al.* 2015; this study).

In this study we examine the gamma ray logs from the Rødby-1 well on Lolland. An initial recognition of a composite cyclicity (lithological variation in mudstone-sandstone ratio) by visual inspection of gamma ray readings is tested by spectral analysis, and it will be discussed if these cycles can be related to orbital climatic control of precipitation. Orbital forcing of the Bunter Sandstone deposition was first suggested by Clemmensen (1991) and Clemmensen *et al.* (1994) from studies of outcrops on Helgoland. Geluk & Röhling (1997) also used orbital climatic control to explain a composite cyclicity in the Bunter Sandstone Formation (Middle Buntsandstein) in the Dutch North Sea and adjacent areas. Sedimentary cycles documented in core and petrophysical log data in the southern part of the North German Basin (Hessen, Germany) have in a similar way been ascribed to climatic control (Hugh-Diegel 2021).

The purpose of this paper is therefore to examine the cyclostratigraphy of the Bunter Sandstone Formation in the Rødby area by spectral analysis of gamma ray readings and relate the deduced sedimentary cycles to orbital climate change, and to describe the lithological composition of the sandstone units and interpret the variation in facies and related reservoir properties by climate theory and by comparison with core data from the Tønder area and outcrop data from Helgoland. Finally tentative maps will be constructed showing the distribution of Early Triassic landscape elements in the Rødby and nearby areas of Lolland and Falster during both arid and more humid climate intervals.

Geological setting

In the Early Triassic southern Denmark, including the Rødby area, was situated at the northern margin of the North German Basin (e.g. Michelsen & Clausen 2002; Olivarius *et al.* 2015). The intracontinental North German Basin was a region under subsidence in the Early Triassic. Towards the north the basin was bounded by the Ringkøbing-Fyn High (e.g. Michelsen & Clausen 2002; Olivarius *et al.* 2015; Fig. 1). The High is penetrated by several grabens and can be divided into the Grindsted, Glamsbjerg, and Møn Highs (Fig. 1). The grabens connected the Bunter Sandstone Formation in the North German Basin with the Skagerrak Formation in the Norwegian-Danish Basin (e.g. Olivarius & Nielsen 2016).

The Bunter Sandstone Formation in southern Denmark is known from a number of deep wells including Rødby-1, Rødby-2, Søllested-1, Ørslev-1, Kegnæs-1, and from five closely situated wells in the Tønder area (Fig. 1). Sediment cores of good quality and thick stratigraphical intervals are only known from three of the Tønder wells; studies of these cores have given detailed information of sedimentary facies and depositional environments (Clemmensen 1985; Olsen 1987) and have been used to reconstruct the palaeogeography along the complete margin of the basin south of the Ringkøbing-Fyn High (e.g. Clemmensen 1985, 1991, Olivarius *et al.* 2015, 2017).

The Bunter Sandstone Formation in southern Denmark is composed of terrestrial sediments (red beds) with typical thicknesses between 200 and 300 meters. Nearest to the Ringkøbing-Fyn High fluvial and aeolian sand was deposited, while farther south more

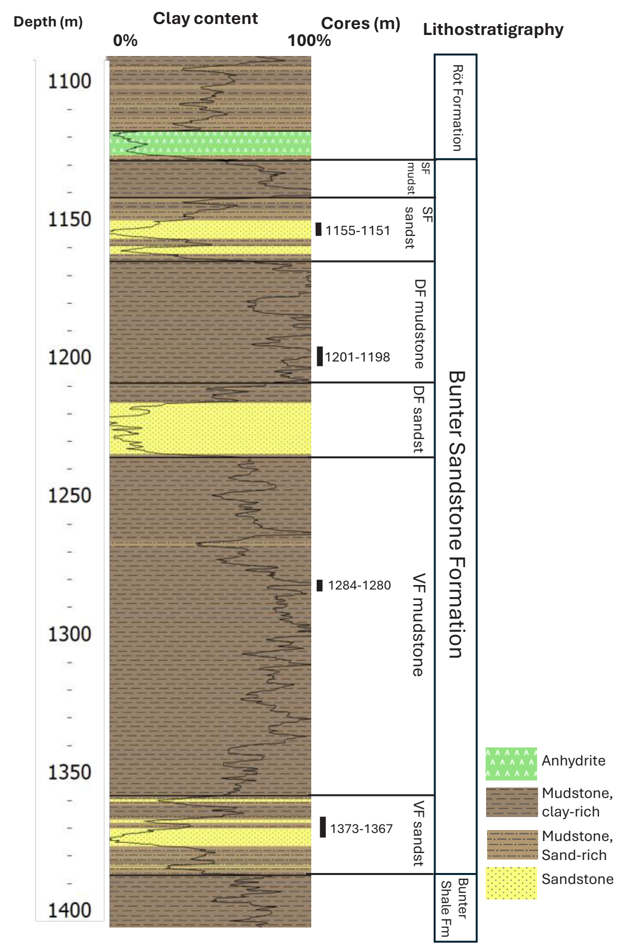

Fig. 2. General petrophysical log of the Lower Triassic (Olenekian) Bunter Sandstone Formation in the Rødby-1 well (Interpretation A). The formation is composed of the Volpriehausen Member (VF), the Detfurth Member (DF), and the Solling Member (SF). Each member is composed of basal sandstone unit overlain by a mudstone unit. Clay content is given by a 'normalised' gamma ray log where all gamma ray measurements are recalculated to have values between 0 (clean sandstones) and 100 (claystones). Sandstones are here defined as lithologies with less than 25% clay. The curve for clay content is given as an unbroken record, but in reality there is a significant time gap at the boundary between the Detfurth and Solling member.

fine-grained sediments were deposited (primarily mud rocks and heterolithic sediments) on sabkha plains and in shallow lakes (Clemmensen 1985, 1991; Olivarius *et al.* 2015). The source of the sediment for most of the fluvial deposits were exposed terrains at the Ringkøbing-Fyn High, while sediments transported from the south formed the main constituent of the aeolian sand deposits (Olivarius *et al.* 2017).

The boundary between the sand-rich fluvial and aeolian deposits towards the north and the fine-grained sabkha and lacustrine deposits towards the south changed much over time (Clemmensen 1991). During arid climatic periods, the fluvial and aeolian deposits formed a relative wide belt, while the mud-rich sabkha and lacustrine sediments covered the majority of the basin during humid climatic intervals. Clemmensen (1991) suggested that climate variations were related to orbitally controlled variation in precipitation and recognized cycles of 20,000, 100,000 and 400,000 years duration in the Bunter Sandstone (Middle Buntsandstein) Formation at Helgoland (Fig. 3). However, so far climate controlled cyclicity has not been documented from well data of the Bunter Sandstone Formation in Denmark.

Stratigraphy

The Bunter Sandstone Formation in the Rødby area is known from two deep wells; the Rødby-1 well (drilled in 1952) and the Rødby-2 well (drilled in 1953); both wells are situated near the top of the Rødby structure (Hjelm *et al.* 2020). The lithology in the wells is given by petrophysical logs including gamma ray records,

Fig. 3. Part of the Bunter Sandstone Formation (Middle Buntsandstein) exposed on the western side of Helgoland. The uppermost part of the mudstone unit of the Volpriehausen Member (VF) and the lowermost part of the sandstone unit in the Detfurth Member (DF) are seen. The exposed part of the mudstone unit in the Volpriehausen is composed of red, heterolithic lake sediments with a significant but variably sand content (cf. Clemmensen 1991; Binot & Röhling 1988). The boundary to the Detfurth Member is given by the first appearance of a white, and loosely cemented aeolian sand deposit. Five such, 10-50 cm thick, aeolian sand deposits are present and intercalated with thin red, lake and sabkha mudstones and heterolithic deposits; these sediments form a lower sand-rich interval in the member. There is a gradual contact upwards to red, clay-rich playa-lake mudstones of the so-called Zwischenmittel deposits (ZM) of the Detfurth Member that are overlain by a second sand-rich interval (cf. Binot & Röhling 1988). The thickness of the succession between the base of the first sand-rich interval to the base of the second sand-rich interval is approximately 12 m. This sedimentary cycle most likely representing a 100,000 years eccentricity period (cf. Clemmensen 1991; Clemmensen *et al*. 1994).

and by short intervals with sediment cores (Olivarius *et al.* 2024; this study). The gamma ray log was measured during drilling of the well and is considered to be of good quality. The Bunter Sandstone Formation is 256 m thick in Rødby-1 and 242 thick in Rødby-2; the formation overlies the Bunter Shale Formation and is overlain by the Röt Formation (Michelsen & Clausen 2002). The Bunter Shale Formation is 317 m thick and almost exclusively composed of red mudstones; the Röt Formation is 153 to 160 m thick and composed of mudstones with anhydrite horizons in the basal part (Michelsen & Clausen 2002; own unpublished observations).

The Bunter Sandstone Formation in southern Denmark can be subdivided into three members, the Volpriehausen Member, the Detfurth Member, and the Solling Member; each member has a sandstone unit at the base overlain by a mudstone unit (Michelsen & Clausen 2002). Similar stratigraphical units are named formations in North Germany and the Dutch offshore (Bachmann *et al.* 2009; Geluk & Röhling 1997). We have used two different approaches here to differentiate between units primarily composed of sandstones and those primarily composed of mudstones. In both approaches threshold values between sandstones and mudstones are based on gamma ray records; in interpretation A sandstones are defined as lithologies with a clay content below 25% (Fig. 2); while in interpretation B sandstones are defined as lithologies with gamma ray API values below 75 (Fig. 4). In Rødby-1, these sandstone units have according to interpretation A thicknesses from bottom to top of 29, 27 and 23 m, while associated mudstones units have thicknesses of 122, 44, and 13 m (Table 1). In interpretation B, the following thicknesses for sandstone units from bottom to top are: 28, 19, 22 m and for the mudstone units: 124, 52, and 11 m (Table 1). In Rødby-2 (interpretation A) sandstone units are 28, 21 and 12 m thick, while mudstone units are 120, 42 and 18 m thick (Table 2). Thus, there is good agreement between measured thicknesses in the two wells although sandstones units are slightly thicker in Rødby-1. In a nearby well on Lolland, Søllested-1, the three members in the formation are also present. Here sandstone units are 23, 36, 23 m thick, while mudstone units are 129, 76, and 7 m thick (Table 2). The stratigraphy of alternating sandstone and mudstone units can be traced southwards to Fehmarn Z-1 well on the island of Fehmarn in northern Germany. Here the sandstone unit of the Volpriehausen Member is 26 m thick, the sandstone unit of the Detfurth Member 24 m thick, and the sandstone unit of the Solling Member 9 m thick (Table 2). The Bunter Sandstone Formation is also known from other deep

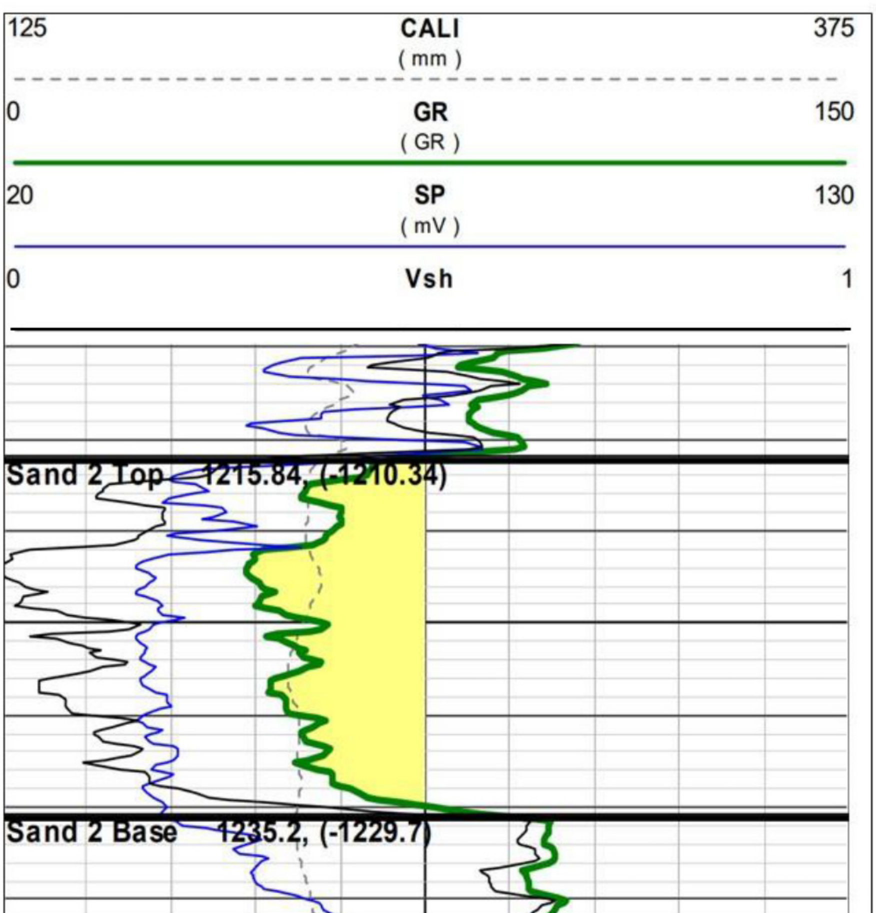

Fig. 4. Petrophysical log showing boundaries of the sandstone unit (Sand 2) in the Detfurth Member (interpretation B). Sandstones are defined by API (gamma ray, GR) values lower than API 75. The sandstone unit has a base in 1235.2 m and a top in 1215.84 m. Also shown are a caliper log (CALI), a spontaneous potential log (SP), and a log showing estimated clay content (Vsh). The sandstone unit is composed of relative clean sandstones with no intervening mudstone layers. Minor variations in clay content of the sandstones are probably related to precession and obliquity forcing of climate.

Table 1. Thickness of members and units, Bunter Sandstone, Rødby-1 well

Stratigraphy, Rødby-1	Interpretation A, m	Interpretation B, m
SF mudstone unit	13.3 (1128.7-1142)	11.4 (1131.1-1142.5)
SF sandstone unit	23 (1142-1165)	21.8 (1142.5-1164.3)
DF mudstone unit	44 (1165-1209)	51.5 (1164.3-1215.8)
DF sandstone unit	27 (1209-1236)	19.4 (1215.8-1235.2)
VF mudstone unit	122.3 (1236-1358.3)	123.6 (1235.2-1358.8)
VF sandstone unit	28.7 (1358.3-1387)	28.3 (1358.8-1387.1)

Interpretation A is based on calculated clay content based on gamma ray readings (sandstones defined as lithologies with a clay content less than 25 %); interpretation B is based on API gamma ray readings (sandstones defined as lithologies with API values less than 75).
VF=Volpriehausen Member, DF= Detfurth Member, SF=Solling Member.

wells in southern Denmark including the Ørslev-1, Søllested-1, Kegnæs-1 and Tønder-4 wells (Table 2). Also in these wells the Volpriehausen, Detfurth and Solling members are recognised. In the Ørslev-1 well on Falster, only two members are present, most likely in our opinion the Detfurth and Solling members (Table 2).

Climate theory

Based on a study of van Hinsbergen *et al.* (2019) it is concluded that the study area at Rødby was situated at about 17° N in an Early Triassic tropical, arid belt where precipitation was seasonal and controlled by summer monsoons (e.g. McKie 2014). Monsoonal intensity in such a climate belt can be demonstrated to be controlled by astronomical forcing of climate including the 20,000-years precession cycle, and the 100,000- and 405,000-years eccentricity cycles (e.g. Ruddiman 2008). Many Triassic sedimentary systems formed at low latitudes possess sedimentary cycles that can be related to precession and eccentricity climate forcing (e.g. Kemp & Coe 2007; Volmer *et al.* 2008; Kent *et al.* 2017; Mau *et al.* 2022). Modern precession cycles have periods of 24,000, 22,000, 19.000, 18.900, and 16.500 years and Early Triassic periods of 20,700, 19,700, 17,100, 17,000, and 15,000 years (Gradstein *et al.* 2012). Obliquity (the tilt of the Earth´s rotational axis) with modern cycles of 54,000, 41,000, 39,000, 29,000 and 28,000 years and Early Triassic periods of 42,700, 34,200, 33,300, 26,100, and 25,400 years (Gradstein *et al.* 2012), should on the other hand, have little influence on climate at these latitudes (e.g. Ruddiman 2008). Yet some records have indicated this signal in sedimentary systems formed at low latitudes (e.g. Li *et al.* 2016). Coupled ocean–atmosphere global climate model without dynamical ice sheets have shown that obliquity-induced changes in tropical climate can occur due to obliquity-induced changes in the cross-equatorial insolation gradient (Borsman *et al.* 2015).

The long eccentricity cycle of 405,000 years is especially important for establishing the exact periods of individual cycles in stratigraphic records (Laskar *et al.* 2004). Unlike other orbital cycles, the period of the long eccentricity cycle is almost unchanged for hundreds of millions of years. The long eccentricity cycle is created by the gravitational interaction with Jupiter and Venus. Due to the large mass and orbital stability of Jupiter, the period of the long eccentricity cycle is very stable. Theoretical calculations of the long eccentricity cycle show that the number of cycles from today to 250 Ma deviates by a maximum of one cycle from the expected number of cycles (Laskar *et al.* 2004), which has also been verified empirically (Kent *et al.* 2018). Therefore, the frequency interpreted as long eccentricity cycle in a stratigraphic record can be attributed to a period of 405,000 years with high confidence. The period of the remaining orbitally forced sedimentary cycles can be calculated based on the period of the long eccentricity cycle.

Methods

Age constraints and accumulation rate

The age of the Bunter Sandstone Formation (Middle Buntsandstein) is given by various sources including conchostracan biostratigraphy and magnetostratigraphy supplemented by cyclostratigrahy related to

Table 2. Thickness of members and units, Bunter Sandstone Formation, selected wells along the northern margin of the North German Basin

Stratigraphy	Rødby-1, m	Rødby-2, m	Søllested-1, m	Ørslev-1, m	Fehmarn Z-1, m	Kegnæs-1, m	Tønder-4, m
SF mudstone	13	18	7	8	56	25	43
SF sandstone	23	12	23	20	9	38	33
DF mudstone	44	42	76	73	59	37	25
DF sandstone	27	21	36	16	24	19	10
VF mudstone	122	120	129		183	84	66
VF sandstone	29	28	23		26	29	34

Values given are based on Interpretation A of petrophysical logs. VF=Volpriehausen Member, DF= Detfurth Member, SF=Solling Member.

astronomical forcing of climate (e.g. Geluk & Röhling 1997; Bachmann *et al.* 2009).

Sedimentary facies

Detection of lithology, primarily sandstones and mudstones, is based on gamma ray readings. Sandstones are defined as sediments with a calculated clay content less than 25%; while remaining lithologies are crudely classified as mudstones (Interpretation A; Fig. 2). Alternatively, sandstones are given by gamma ray readings lower than 75 API and mudstones by gamma ray reading higher than 75 API (Interpretation B; Fig. 4). These threshold values are commonly used in the industry to distinguish between reservoir sandstones and non-reservoir mudstones. These classifications of lithologies are used to define the boundaries of the three members in the formation as well as their sand-rich and mud-rich subunits. Supplementary information of sedimentary facies is given by investigation of sedimentary cores from four short intervals in the Rødby-1 well, and by comparison with well-described sedimentary facies from long core intervals in three Tønder wells (Clemmensen 1985; Olsen 1987, and by comparison with outcrops on Helgoland (Clemmensen 1991). Detection of reservoir properties in the Rødby-1 well is based on a limited number of thin sections and on porosity and permeability measurements from conventional core analysis (Olivarius *et al.* 2015).

Cyclostratigraphy and signal processing

The gamma ray record and derived clay content (Fig. 2) are given as unbroken curves and we decided in a first attempt to use the measured gamma ray curve to detect sedimentary cycles by spectral analysis in the complete formation.

The gamma ray record shows a clear composite cyclicity both developed in the sand-rich and mud-rich intervals. In the spectral analysis of sedimentary cycles, it has been decided to carry out the analysis separately on mud-rich and sand-rich intervals. This is because the abrupt and marked changes in gamma ray readings from sand-rich to mud-rich intervals significantly impact the detection of cyclicity by multitaper analysis. Thus, the gamma ray record is here clipped at 105 API and only show higher values to detect cyclicity in mud-rich intervals (Fig. 5) and clipped at 60 API and only show lower values to define cyclicity in sand-rich intervals (Fig. 6).

The Thomson multitaper method (MTM) is used as a robust estimator for detection of cyclicities in the gamma ray record. The power spectral density (PSD) is calculated using the signal processing toolbox in MathWorks MATLAB (the MathWorks Inc. 2024). This represents the proportion of the total power contributed by each frequency component of the climate signal. The time-bandwidth product is set to 2.5 for the mud-rich intervals and to 3.5 for the sand-rich intervals. The number of tapers used to calculate the PSD is 2×NW-1. The fast Fourier transform is set to the next power of 2 greater than the length of the dataset. To remove unwanted effects, the datasets are

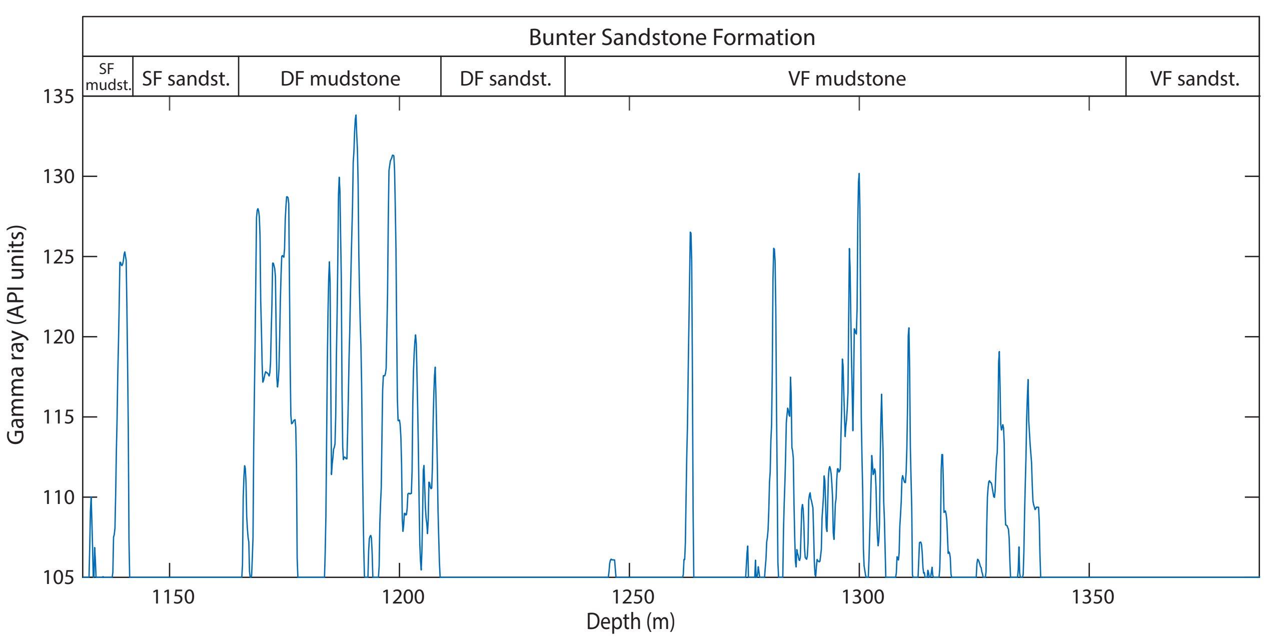

Fig. 5. Gamma ray data for clay-rich intervals (SF=Solling Member, DF= Detfurth Member, VF=Volpriehausen Member). The gamma ray data are clipped at 105 API showing only values equal to or higher than 105 API.

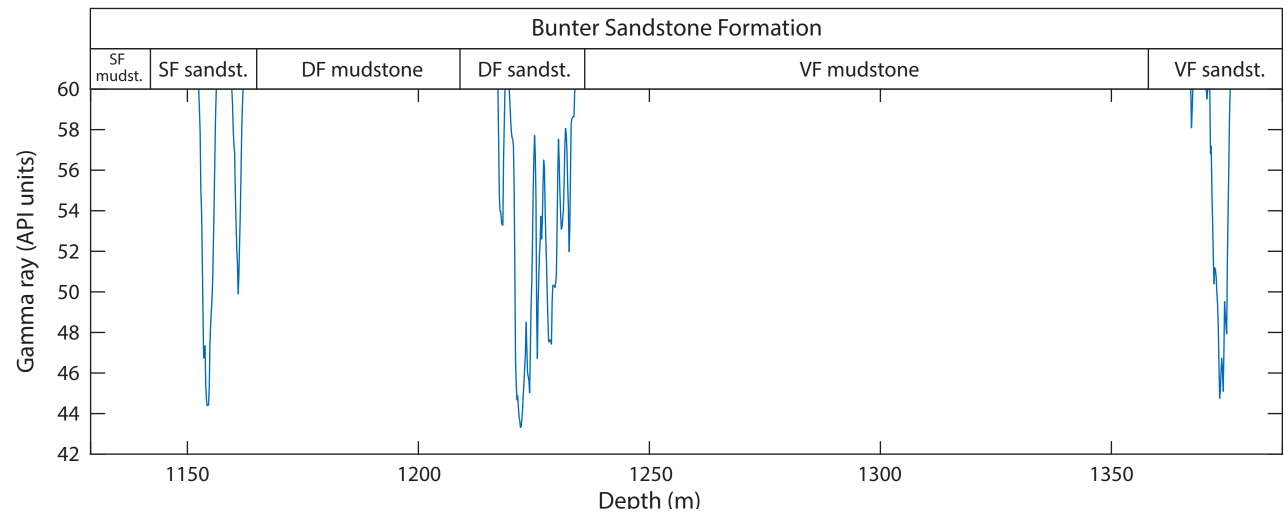

Fig. 6. Gamma ray data for sand-rich intervals (SF=Solling Member, DF= Detfurth Member, VF=Volpriehausen Member). The gamma ray data are clipped at 60 API showing only values equal to or lower than 60 API.

detrended before the MTM analysis by removing the best linear fit to the datasets. MTM confidence levels are estimated with the robust autoregressive noise model AR1 (Li *et al.* 2019). The PSD plots show several significant peaks above a 99.9 % confidence level. Peaks are best defined in the mud-rich intervals but also present in the sand-rich intervals (Figs 7, 8).

Sedimentary cycle variation throughout the complete formation is extracted with bandpass filters showing the stratigraphic position of specific significant cycles (Fig. 9). Bandpass filters were constructed with the bandpass function from the signal processing toolbox in MathWorks MATLAB. By defining specified bands of frequencies, the filers reveal the position,

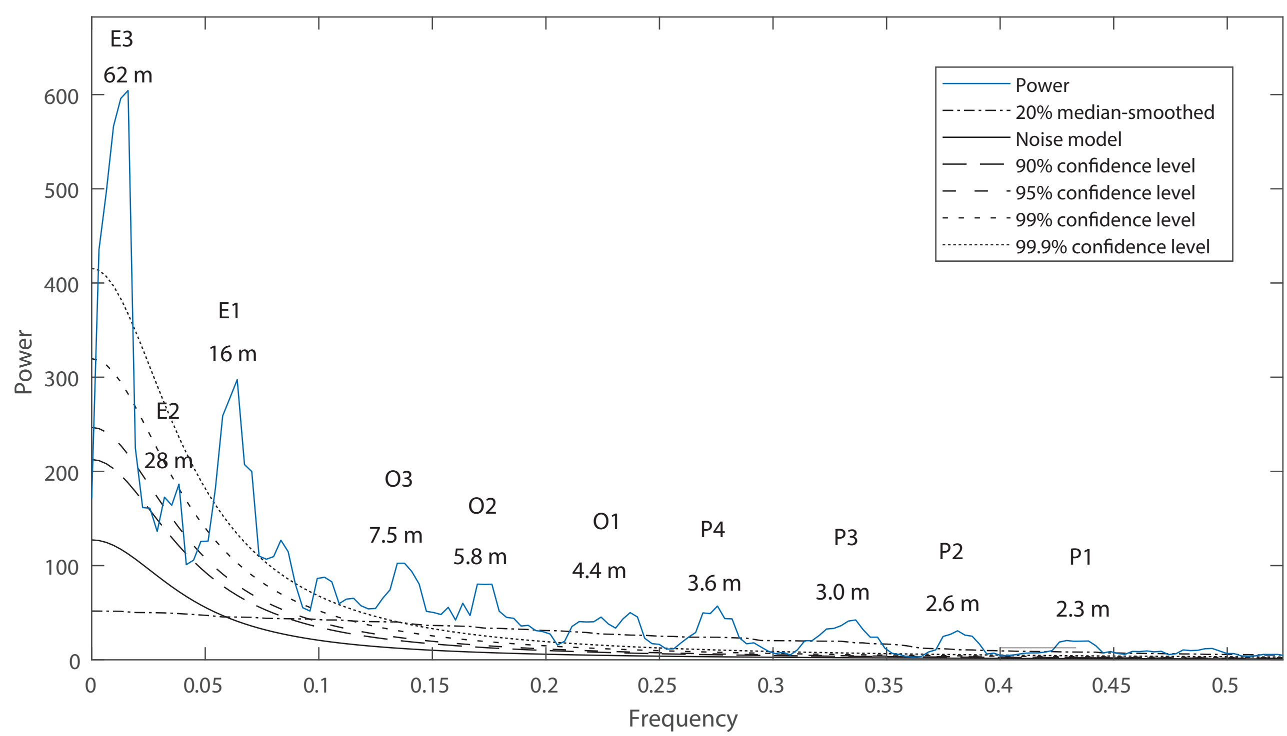

Fig. 7. Power spectral density of gamma ray data for the clay-rich intervals (Fig. 5) using Thomson's multitaper method. Density plot shows multiple significant (>CL 99.9%) and well-defined peaks. The most powerful peaks average around periods 2.3 m (P1), 2.6 m (P2), 3.0 m (P3), 3.6 m (P4), 4.4 m (O1), 5.8 m (O2), 7.5 m (O3), 16 m (E1), 28 m (E2), and 62 m (E3); where peaks marked with P are interpreted as precession cycles, peaks marked with O are interpreted as obliquity cycles and peaks marked with E are interpreted as eccentricity cycles. Interpreting the E3 peak as the 405,000-years eccentricity cycle, the remaining periods correspond to temporal periods of 183,000, 104,500; 49,000; 38,000; 28,500; 23,500; 19,500; 17,000; and 15,000 years (Table 3a).

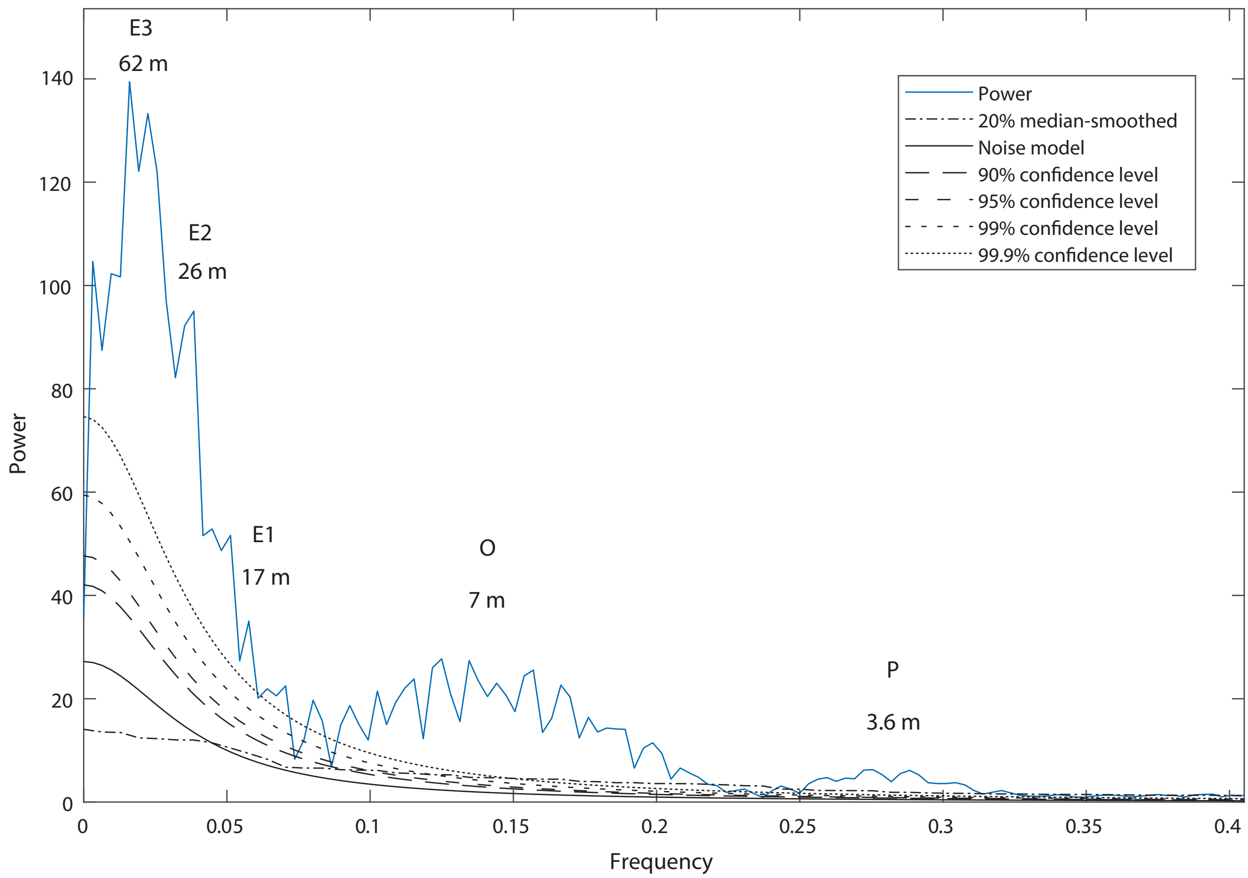

Fig. 8. Power spectral density of gamma ray data for the sand-rich intervals (Fig. 6) using Thomson's multitaper method. Density plot shows multiple significant (>CL 99.9%) but not well-defined peaks. The most powerful peaks average around periods 3.6 m (P), 7.0 m (O), 26 m (E2) and 62 m (E3). The peaks marked with P is interpreted as the precession band. The peak marked with O is interpreted as the Obliquity band. The peaks marked with E1, E2 and E3 are interpreted as the 100,000-, 200,000-, and 405,000-years eccentricity cycles respectively.

amplitude, and phase of the 405,000-years eccentricity cycle, the 100,000-years eccentricity cycle, and the 20,000-years precession cycle. The 405,000-years filter is created with frequency limits 0.014 and 0.018. The 100,000-years filter is created with frequency limits 0.054 and 0.071. The 20,000-years filter is created with frequency limits 0.262 and 0.349.

Finally, the evolution of sedimentary cycles throughout the formation was investigated by evolutionary wavelet analysis (Fig. 10). This is done to add knowledge of evolution of cycle frequencies by depth. Contrary to the evolutionary wavelet analysis, the Thomson multitaper method assumes a uniform geological record, which is rarely a valid assumption for most geological records because they often undergo significant changes in accumulation rate. The evolutionary wavelet spectrum was computed with a morlet wavelet using a MathWorks MATLAB script (Torrence & Compo 1998). The evolutionary wavelet analysis shows the power to a specific period and depth. Red dashed lines have been added to the density plot to show the interpreted development of the 405,000-year cycle (E3), the 200,000-year cycle (E2), the 100,000-year cycle (E1), the obliquity cycles (O), and the precession cycles (P).

Palaeogeography

Early Triassic palaeogeographical reconstruction of parts of southern Denmark has previously been constructed by Clemmensen (1985, 1991), Olsen (1987), and Olivarius *et al.* (2015). Only Clemmensen (1991) concluded that it was necessary to make maps for both arid and humid climatic periods as climate strongly controlled landscape evolution. This approach is followed here and new maps showing the palaeolandscapes during the deposition of the Detfurth Member are given for the Rødby and nearby areas on Lolland and Falster. The maps are primarily based on petrophysical log data in the Søllested-1, Ørslev-1, and Rødby-1 wells.

Table 3a. Sedimentary cycles identified by spectral analysis in mudstone units; Rødby-1 well

Orbital period	Sedimentary cycle thickness, m	Duration, years
E3	62	405,000
E2	28	183,000
E1	16	104,500
O3	7.5	49,000
O2	5.8	38,000
O1	4.4	28,500
P4	3.6	23,500
P3	3.0	19,500
P2	2.6	17,000
P1	2.1	15,000

E=eccentricity cycles, O=obliquity cycles, P=precession cycles.

Table 3b. Sedimentary cycles identified by spectral analysis in sandstone units; Rødby-1 well

Orbital period	Sedimentary cycle thickness, m	Duration, years
E3	62	405,000
E2	26	170,000
E1	17	111,000
O	7	46,000
P	3.6	23,500

E=eccentricity cycles, O=obliquity cycles, P=precession cycles.

Results

Age constraints and accumulation rate

The Bunter Sandstone Formation (Volpriehausen, Detfurth, Hardegsen and Solling members) belongs to the Middle Buntsandstein of the German Triassic stratigraphical subdivision and is of Olenekian age (Bachmann *et al.* 2009). This stage spans a time interval of 4 myr between 247.2 and 251.2 Ma (Bachmann *et al.* 2009). According to Bachmann *et al.* (2009), however, two hiati are present in the formation at many sites (at the base of the Detfurth and Solling members) causing the actual accumulation time to be less than 4 myr. Using magnetostratigraphy and cyclostratigraphy the following age constraints are given for accumulation time in northern Germany: Volpriehausen Member 0.9 myr, Detfurth Member, 0.4 myr, Hardegsen Member 1.2 myr, and Solling Member 0.3 myr (Table 4).

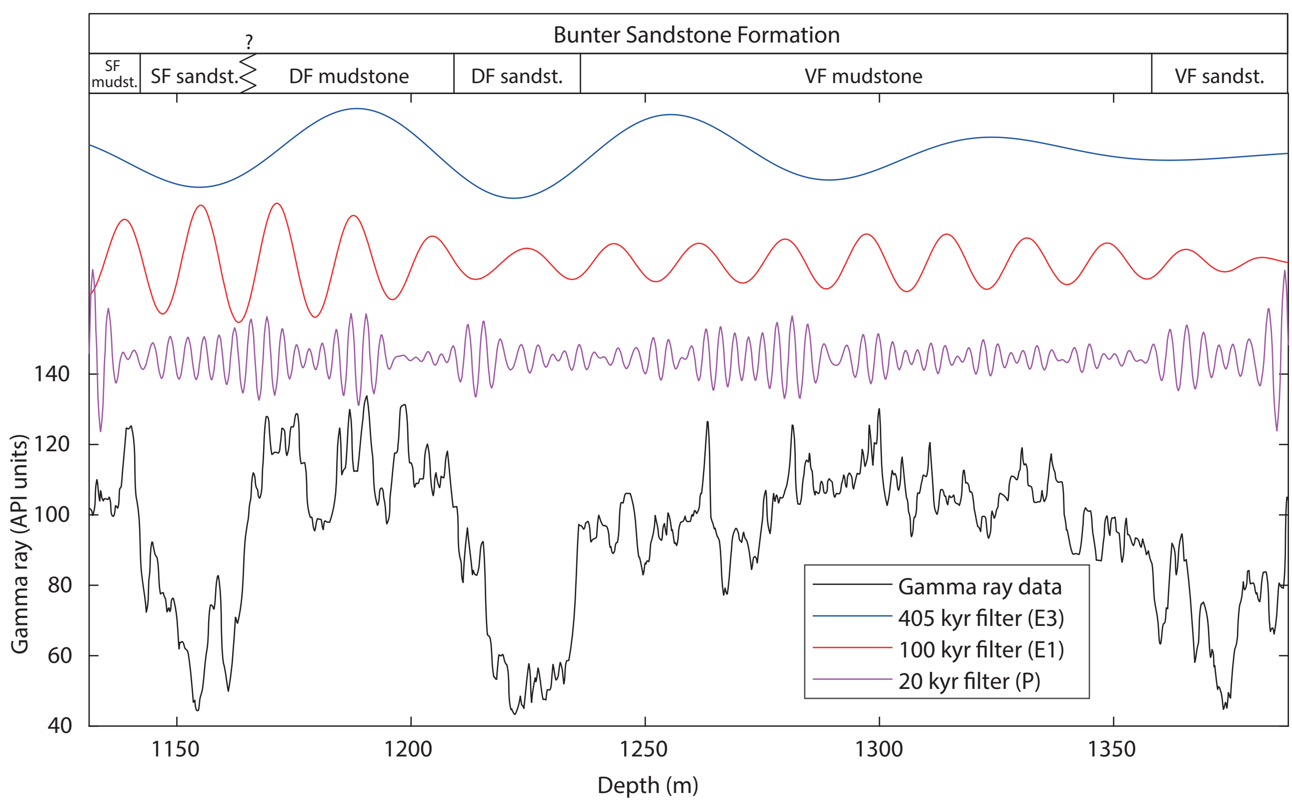

Fig. 9. Gamma ray data (black) with bandpass filters showing 20,000-year cycles (purple), 100,000-year cycles (red), and 405,000-year cycles (blue). The filters show around 80 precession cycles, 15 short eccentricity cycles, and 4 long eccentricity cycles. Peaks of the 405,000-years cycle filter mostly corresponds to clay-rich intervals (humid climate) in the Bunter Sandstone Formation while valleys of the filter correspond to sand-rich intervals (arid climate). There is a significant time gap at the boundary between the Detfurth and Solling members. Thus the continuation of orbital cycles across this boundary is a statistical artefact. Still we believe that the sand-rich interval in the Solling Member corresponds to an arid interval in the long eccentricity curve and the overlying mud-rich interval to a humid interval in this orbital period.

The spectral analyses and suggested interpretation of climate cycles (see later) show that Volpriehausen Member in Rødby is composed of about 9 short eccentricity (100,000 years) cycles recording accumulation over about 0.9 myr, and that the Detfurth Member is composed of about 4 short eccentricity cycle recording accumulation over about 0.4 myr (Fig. 9; Table 4). The Solling Member is composed of slightly more than 2 short eccentricity cycles and thereby recording accumulation over about 0.22 myr (Fig. 9; Table 4). These data give time spans of the members in very good agreement with the age estimates given for the members in North Germany (Table 4).

As only the Volpriehausen, Detfurth and Solling members are present in the Rødby area (and at most other sites in southern Denmark), it can be concluded that the Bunter Sandstone Formation here should records accumulation over 1.6 myr. However since the Hardegsen Member is not present at Rødby a significant time gap must exist at the boundary between the Detfurth and Solling members in the Rødby well (Fig. 9). The Volpriehausen and Detfurth members apparently form a continuous succession with a combined thickness of 218 m (interpretation A); the succession formed over 1.3 myr with an average accumulation rate of 0.17 m/1000 years. The overlying Solling Member with a thickness of 36 m (interpretation A) formed over 0.22 myr with an average accumulation rate of 0.16 m/1000 years.

It should be mentioned, however, that Geluk & Röhling (1997) reached somewhat different age estimates of the members in the Bunter Sandstone Formation using presumed 100,000 years cycles of this formation in the Dutch North Sea. They found 18 such cycles in the Volpriehausen Member, 4 in the Detfurth Member, and 4 in the Solling Member (Table 4). Thus while the number of identified short eccentric cycles in the Detfurth and Solling members is almost identical to those recognized in North Germany and in this study, the number of 18 cycles in the Volpriehausen Member is surprisingly high. At present we are not able to explain this discrepancy convincingly, but tentatively suggest that the identified sedimentary cycles could be obliquity cycles with an age of about 50.000 years and thereby comparably to obliquity cycles identified in this study with an age of about 49.000 years (see later).

Sedimentary facies

Gamma ray records are used to identify main lithologies as sandstones and mudstones by using thresholds values of 75 API (Fig. 4) and a clay content of 25% (Fig. 2) as stated above. From the distribution of the main lithologies the Bunter Sandstone Formation is divided into the Volpriehausen, Detfurth and Solling members and further subdivided into sandstone and mudstone units (Fig. 2). Depth of boundaries in the Rødby-1 well indicated on the gamma

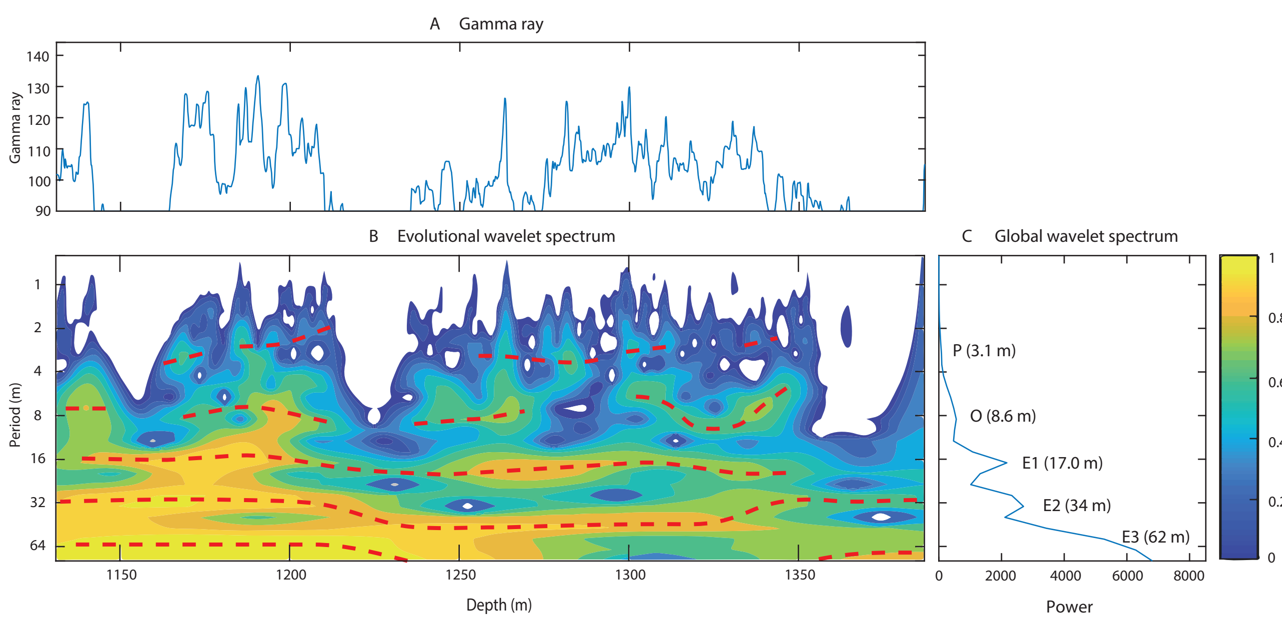

Fig. 10. Evolutionary wavelet analysis (see Torrence & Compo 1998 for analytic methods). (A) Gamma ray data clipped at 90 API. (B) Evolutionary wavelet spectrum of the gamma ray data. The spectrum shows high densities around 17.0 m, 34 m and 62 m interpreted as the 100,000-, 200,000-, and 405,000-years eccentricity cycles respectively. Less prominent densities show two cycles with thicknesses around 3.1 m and 8.6 m interpreted as the precession cycle band and the obliquity cycle band respectively. Red dashed lines show the interpreted frequency evolution of the five identified cycles. (C) Global wavelet spectrum shows the prominent peaks of power around 17 m (E1), 34 m (E2) and 62 m (E3).

ray log is given in Table 1. The lower boundary of sandstone units of all members is given by the first appearance of a sandstone deposit; the upper boundary is defined by the last appearance of a sandstone or muddy sandstone/sandy mudstone deposit.

Gamma ray records using API values indicate that relatively clean sandstone comprise the complete thickness of the 19 m thick sandstone unit in the Detfurth Member (Fig. 4). In the Volpriehausen Member relatively clean sandstones make up 14 m of the 28 m thick sandstone unit, and in the Solling Member sandstones comprise 12 m of the 22 m thick sandstone unit (Interpretation B). An alternative gamma ray log interpretation using clay content indicates that sandstones comprise 7 m of the 29 m thick sandstone unit in the Volpriehausen Member, 17 m of the 27 m thick sandstone unit in the Detfurth Member, and 8 m of the 23 thick sandstone unit in the Solling Member (Interpretation A). Mud-rich intervals are present in between sand-rich intervals in the Volpriehausen and Solling members defining a cyclic pattern. The thickest relative clean sandstone intervals are about 7 m thick both in the Volpriehausen and Solling members.

The gamma ray records do not reveal details on the characteristics of the sandstone facies in the three members. By comparison with core data from wells in the Tønder area (Clemmensen 1985), it is assumed, however, that the sandstones in the Volpriehausen Member comprise both aeolian and fluvial (ephemeral river) facies; the frequency of aeolian facies in the Tønder wells varies between 35 and 75 %. The only core data from this stratigraphic interval in Rødby (see below) comprises fluvial overbank and sabkha facies; typical fluvial channel and/or aeolian sand facies are not present in the sampled core section in Rødby-1. There are no core data from the sandstone unit in the Detfurth Member. Comparison with facies observations in outcrops on Helgoland (Fig. 3; Clemmensen 1991) and from well cores in Germany (Hug-Diegel 2021), however, suggest that also this unit has aeolian as well as fluvial facies. Core data from the sandstone unit in the Solling Member in Rødby indicate the presence of fluvial facies (see below), and core data from the Tønder wells indicate that all sandstones of this member are fluvial, in many cases as part of terminal fan systems (Clemmensen 1985; Olsen 1987).

Limited core data from Rødby (see below) indicates that the mudstones units are composed of variety of sabkha and playa-lake sediments including claystones, heterolithic sediments and mud-rich sandstones. Core data from mudstone units in the Tønder wells (Clemmensen 1985) as well as outcrop data from Helgoland (1991) also indicate the occurrence of heterolithic sabkha and playa-lake sediments and that these deposits are the primary facies in thick intervals in the mudstone unit of the Volpriehausen Member (Fig. 3). The clay content of the heterolithic sediments and associated facies on Helgoland varies on a decimeter-scale clearly reflected in fluctuating gamma ray signatures (Binot & Röhlig 1988 and own unpublished results). These facies variations impose a cyclic pattern to the sedimentary succession (Clemmensen *et al.* 1994; Geluk & Röhling 1997).

Available data from conventional core analysis of sand-rich intervals in Rødby-1 (n=6) show a porosity between 22 and 30 % and permeability between 100 and 500 mD (Olivarius *et al.* 2015). These values are relatively high and suggest that sandstone-rich intervals may form good reservoir units. Comparable data from sandstones elsewhere in the basin indicate that fluvial sandstones have a porosity between 1 and 34 % and a permeability between 0 and 6538 mD, and aeolian sandstones have a porosity between 1 and 27 % and a permeability between 1 and 2838 mD, though these values are underestimated since many aeolian sediments are unconsolidated and could not be analysed, so aeolian sandstones are considered to have the best reservoir properties (Olivarius *et al.* 2015). The data show, however, that the aeolian facies have only marginally better reservoir properties than the fluvial facies. One reason for this could be that many fluvial deposits formed by reworking of pre-existing aeolian sand.

Available data from conventional core analysis of mud-rich intervals in Rødby-1 (n=11) a show a porosity between 7 and 17% and a permeability between 1 and 8 mD. These values would indicate that the mud-rich deposits form relative tight intervals. The reported values are somewhat lower than those reported from fine-grained desert lake and sabkha sediments elsewhere in the basin; here porosity is between 1 and 26% and permeability between 0 and 369 mD (Olivarius *et al.* 2015).

Cyclostratigraphy

Gamma ray records

The sedimentary facies and their cyclic development are here examined in the Rødby-1 well based on gamma ray readings. Visual inspection of gamma ray records in the Rødby-1 well was carried out within each of the two main lithologies comprising the three sandstone units and the three mudstone units. Sedimentary cycles are present both in sandstone and mudstone units. The identified cycles have thickness between 3 and 16 m both in the sandstone units and mudstone units, and they are best developed in the mudstone unit of the Detfurth Member. There is no apparent shift in visual cyclicity in the Solling Member as compared to cyclicity seen in Volpriehausen and Detfurth Members.

Table 4. Number of short (100,000 years) eccentricity cycles and deduced duration in the members of the Bunter Sandstone Formation in the North German Basin

Stratigraphy	Rødby	North Germany	Dutch North Sea
Solling Member	2.2 (0.22 myr)	3 (0.3 myr)	4 (0.4 myr)
Hardegsen Member	0	12 (1.2 myr)	20 (2.0 myr)
Detfurth Member	4 (0.4 myr)	4 (0.4 myr)	4 (0.4 myr)
Volpriehausen Member	9 (0.9 myr)	9 (0.9 myr)	18 (1.8 myr)

The number of identified short eccentricity cycles in the Volpriehausen, Detfurth and Solling members are almost identical in Rødby and North Germany.

The analysis of the gamma ray record in Rødby-1 indicates that the formation contains significant cyclicities with a composite cyclicity that here initially is related to the long eccentricity (405,000 years), the short (100,000 years) eccentricity and the precession (20,000 years) periods (Fig. 9). To analyze the gamma ray record in more detail it was decided to carry out spectral analysis in sand-rich and mud-rich units separately. Thus, the gamma ray record is clipped at 105 API and only show higher values to detect cyclicity in mud-rich intervals (Fig. 5.) and clipped at 60 API and only show lower values to define cyclicity in sand-rich intervals (Fig. 6). Looking only at the mud-rich layers the following significant (>99.9 % CL) cycles can be seen: 62, 16, 7.5, 5.8, 4.4, 3.6, 3.0, 2.6 and 2.3 m; a less prominent but still significant (>95 % CL) cycle is seen at 28 m (Fig. 7; Table 3a). Looking only at the sand-rich layers the following significant (>99.9 % CL) but less well-defined cycles are seen: 62, 17, 7, and 3.6 m; a less prominent cycles is seen at 26 m (Fig. 8; Table 3b). The long eccentricity cycle of 405,000 years is considered to be of constant duration during Cenozoic ad Mesozoic time (Kent *et al.* 2018). Assuming that the 62 m cycle records the 405,000-years eccentricity cycle (E3), then the remaining cycles defined in the mud-rich intervals represent the following periods: 104,500; 49,000; 38,000; 28,500; 23,500; 19,500; 17,000 and 15,000 years; the less prominent cycle at 28 m has an assumed period of 183,000 years. In sand-rich intervals the significant cycles have the following periods: 405,000; 111,000; 46,000 and 23,500 years; the less prominent cycle at 26 m has a period of 170,000 years. The deduced orbital periods agree well with other Triassic cyclostratigraphical records from terrestrial successions (e.g. Kemp & Coe 2007; Volmer *et al.* 2008; Kent *et al.* 2017; Mau *et al.* 2022) as well as with theoretical values for Early Triassic orbital periods (Gradstein *et al.* 2012). Thus both a 100,000 (E1) years eccentricity as well as a 20,000 years precession cyclicity (P1-P4) can be identified (Figs 7, 8). More surprising also a likely obliquity signal seems to be present as given by cycles with periods of 28,500 (O1), 38,000 (O2) and 49,000 (O3) years (Figs 7, 8). The less prominent 183.000 (170,000) years cycle is here interpreted as a week eccentricity cycle (E2); alternatively, it can be viewed as a long obliquity cycle (Hilgen *et al.* 2020).

Evolutionary wavelet analysis of the gamma ray record in Rødby-1 indicates multiple cycles of high power throughout the entire Bunter Sandstone Formation (Fig. 10). To avoid unwanted effects from the long-term shifts in lithology, the gamma ray data is cut at 90 API and only higher values are used for the analysis corresponding to the mud-rich intervals. This makes the power spectral density plot more well-defined but also limits the detection of high frequency cycles (obliquity and precession cycles) in the more sand-rich intervals. The three identified eccentricity cycles (E1, E2 and E3) are most significant in the evolutionary wavelet analysis. The analysis shows cycles with periods averaging around 17 m corresponding to the 100,000-years eccentricity cycle, 34 m corresponding to the 200,000-years eccentricity cycle, and 62 m corresponding to the 405,000-years eccentricity cycle. The analysis also shows less significant cycles with periods of around 8.6 m interpreted as obliquity cycles and 3.1 m interpreted as precession cycles. The evolutionary analysis shows some change in accumulation rate. Most significant seems to be an increase in accumulation rate from around 1225 m depth to around 1300 m depth corresponding to the upper part of the Volpriehausen mudstone unit.

The deduced short eccentricity (100,000 years) cycles in Rødby have an average thickness of about 16 m (Table 3a and 3b). Similar cycles have an average thickness of 11-12 m on Helgoland, (Clemmensen 1991; Clemmensen *et al.*1994), thicknesses between 5 and 25 m in the Dutch North Sea (Geluk & Röhling 1997), and thicknesses between 10 and 30 in northern Germany (Bachmann *et al.* 2007).

Sedimentary core data

The sedimentary facies in the Rødby area are examined in 4 short cores in the Rødby-1 well; these cores are here described and interpreted in light of the new cyclostratigraphical data.

Interval 1367-1373 m (4486-4506'), lower part of Volpriehausen Member, sandstone unit. Based on gamma ray readings the core interval seems to represent a nearly full 7 m thick sedimentary (obliquity) cycle with two sandstone intervals separated by a 2 m thick mud-rich interval. Recovery was only 35% and sampled cores (150 cm) of sabkha and fluvial overbank deposits seem to comprise the most mud-rich part of the cycle (Figs 2, 11).

Interval 1280-1284 m (4200-4212'), upper part of Volpriehausen Member, mudstone unit. Based on gamma ray readings the core interval seems to represent the initial part of a 6 m thick sedimentary (obliquity) cycle with varying content of mud (clay). Recovery was 60% and sampled cores (230 cm) of sakha and playa-lake deposits seem to comprise the most mud-rich part of the cycle (Figs 2, 12).

Interval 1198-1201 m (3930-3941'), upper part of Detfurth Member, mudstone unit. Based on gamma ray readings the core interval seems to represent the basal and middle part of a 7 m thick sedimentary (obliquity) cycle with varying content of mud (clay). Recovery was 80% and sampled cores (240 cm) of sandflat and sabkha deposits seem to comprise the most sand-rich part of the sedimentary cycle (Figs 2, 13).

Interval 1151-1155 m (3775-3790'), Lower part of Solling Member, sandstone unit. Based on gamma ray readings the core interval seems to represent the upper half of a sandy 7 m thick sedimentary (obliquity) cycle. Recovery was 40% and sampled cores (155 cm) of fluvial channel sandstones and a fluvial channel base conglomerate seem to comprise a sand-rich part of the sedimentary cycle (Figs 2, 14).

Palaeogeography

Hornung & Aigner (2002) proposed a palaeoclimate-driven sedimentary model to explain sedimentary cycles of fluvial and playa-lake deposits in the Late Triassic of Germany. The playa lake in the basin center was modulated by climate changes; the lake had its largest extent at the end of a humid phase and its smallest extent at the end of an arid phase. Climate variation in the Late Triassic was probably related to orbital control of the intensity of summer monsoons (e.g. Volmer *et al.* 2008). Here we use a similar approach to evaluate the origin of the sedimentary cycles and landscape evolution in the Early Triassic Bunter Sandstone Formation in Rødby by orbitally controlled climate variation. This study suggests that the major 62 m cycles was controlled by the 405,000

Fig. 11. *Interval 1367-1373 m (4486-4506'), Volpriehausen Member, sandstone unit.*
Cores from 150 cm with mud-rich sabkha and heterolithic fluvial overbank deposits; both facies contain anhydrite nodules Shown core interval is illustrating the heterolithic, fluvial overbank sediments at the topmost 40 cm of the core. Scale in cm.

years eccentricity cycle (Tables 3a, 3b). We interpret this cyclic lithological change as a record of long-term shifts in the character of the palaeolandscape. The general setting of the palaeolandscape was a central playa lake flanked northwards by sabkha flats, and marginal aeolian and fluvial sedimentary systems; closets to the uplands alluvial fans probably existed (e.g. Olivarius *et al.* 2015). Lake size reached its maximum during the humid phases of this cycle and its minimum during the arid phases; marginal aeolian and fluvial deposits accordingly had their maximum distribution during arid phases and their minimum distribution during humid climatic phases. It should also be mentioned that the suggested climatic fluctuations that drove these variations in palaeolandscapes took place over the complete spectrum of orbital climatic change from 20,000 to 405,000 years probably with the strongest and most predictable change in landscape evolution coupled to the eccentricity cycles (Fig. 9). While the fluvial deposits were sourced by material eroded on the Ringkøbing-Fyn High, most aeolian sand was transported to the study area from southerly directions (Olivarius *et al.* 2017).

The new data indicates that one arid phase in the long eccentricity variation of climate is not linked to the formation of prograding sand plains of ephemeral river and aeolian deposits and the middle part of the mudstone unit in the Volpriehausen Member only becomes slightly more sandy during this arid phase indicating that the lake environment was only little modified by this climatic change (Figs 2, 9). At present we are not able to explain this unusual landscape response to climate change.

Clemmensen (1991) concluded that it was necessary to construct two palaeogeographical maps for each member as the landscape changed drastically during climatic shifts from arid to humid and back again. In this paper we follow this approach and discuss the evolution of the palaeolandscape during maximum aridity and humidity respectively during a 405,000 years eccentricity cycle. Landscape evolution during the Volpriehausen and Detfurth members were probably almost identical apart from the fact that the lake phase (mudstone deposition) was of longer duration in the Volpriehausen Member. During the time the sandstone units of the Volpriehausen and Detfurth members were deposited, the aeolian

Fig. 12. *Interval 1280-1284 m (4200-4212′), Volpriehausen Member, mudstone unit.*
Cores from 230 cm with heterolithic sabkha and clay-rich playa-lake deposits; both facies contain anhydrite nodules. Shown core interval is illustrating the sabkha deposits (sa) overlain by playa-lake deposits (la) in the middle part of the core. Uppermost part of sabkha deposits is deformed and lake sediments are strongly fragmented. Scale in cm.

sand plains were frequently eroded by ephemeral rivers causing a succession of alternating aeolian and fluvial facies. Available data from the Tønder wells indicate that the proportion of aeolian and fluvial facies not only was controlled by short-term orbital climatic change but also by frequent shifts in the position of ephemeral rivers. While the sandstone unit of the Solling Member was deposited, the marginal sand-rich depositional environments were composed of fluvial facies only; these fluvial deposits frequently formed terminal fans at the margin to the central sabkha flats/lake environment (Clemmensen, 1985, Olsen 1987). Only maps for the Detfurth Member are shown here as it was during the long-term arid phase of the long eccentricity period that the best potential reservoir deposits in the Rødby area formed. The map focuses on the Rødby and nearby areas on Lolland and Falster.

Detfurth Member, sandstone unit

The palaeolandscape of the Lolland and Falster area in southern Denmark south of the Møn High during deposition of the sandstone unit of the Detfurth Member is shown in Fig. 15. In this part of the basin uplands were situated at the Møn High and on the Glamsbjerg High. The map shows the distribution of landscapes during maximum aridity of the long eccentricity cycle with low lake levels and a wide distribution of marginal sand flats with aeolian deposits cut by ephemeral rivers (cf. Clemmensen 1985, 1991; Olivarius *et al.* 2015). Sabkha flats and the central playa lake was were situated far to the south of the study area. It is tentatively suggested that aeolian sand, driven by resultant sand-transporting winds towards the west-northwest, covered a large part of the study area and even reached the margins of the river plain and alluvial fans flanking the northern uplands. The aeolian sand plain composed of small dunes and sand sheets were cut by river systems. These river systems were primarily active during the rainy summer seasons when monsoons brought precipitation to the area. It is likely that the river systems frequently shifted positions and thereby caused repeated reworking of the aeolian material when they cut through the aeolian sand belt (cf. Krapf *et al.* 2003).

Fig. 13. *Interval 1198-1201 m (3930-3941'); Detfurth Member, mudstone unit.*
Cores from 240 cm with sandflat and sabkha deposits composed of red (or occasionally greenish grey), very fine-grained, muddy sandstones with a few anhydrite nodules; the structureless, muddy sandstones alternate with thin heterolithic intervals with lamination (hl). Shown core interval is illustrating the sandflat and sabkha deposits at the topmost 50 cm of the core. Scale in cm.

The complete lack of core material in the sandstone unit of Detfurth Member in Rødby-1 (and elsewhere in wells in southern Denmark) makes the map tentative in particular with respect to the presence and distribution of aeolian facies. Outcrops on Helgoland (Fig. 3), however, supports the existence of aeolian facies in this time interval as do core data from Hessen in NW Germany (e.g. Hug-Diebel 2021).

Detfurth Member, mudstone unit

The palaeolandscape of the Lolland and Falster area in southern Denmark, south of the Møn High, during deposition of the mudstone unit of the Detfurth Member is shown in Fig. 16. The map shows the distribution of landscapes during maximum humidity during the long eccentricity cycle with high lake levels and minimum extent of the river plain flanking the Ringkøbing-Fyn High; the aeolian sand plain is no longer existing and marginal alluvial fans are now flanked by a narrow, mud-rich river plain (cf. Clemmensen 1991). The scarcity of core material of mudstone units in Rødby-1 reduces the precision of the map and in particular the knowledge of the size and distribution of the more sand-rich sabkha belt flanking the mud-rich playa lake.

Discussion

The new cyclostratigraphical analysis suggests that the long eccentricity period of 405,000 years was the main control on Bunter Sandstone landscape evolution and that sand was deposited in the study area in up to 200,000 years long periods with an overall dry climate. The strong influence of this long eccentricity period on landscape evolution and thereby the character of the resulting sedimentary facies was also shown by cyclostratigraphical analysis of the Late Triassic lake system (Newark Group) in Northeast USA (Kent *et al.* 2017). Change in climate related to the short eccentricity, obliquity and precession periods, also strongly affected landscape evolution and thereby the character of the Bunter Sandstone sedimentary facies including periods with increased and decreased aeolian sedimentation in the Volpriehusen and Detfurth members.

Aeolian facies are considered to have the best reservoir properties, and according to Olivarius *et al.* (2017) most aeolian sand in the Bunter Sandstone

Fig. 14. *Interval 1151-1155 m (3775-3790'), Solling Member, sandstone unit.*
Cores from 155 cm with fluvial channel sandstones and a channel bottom conglomerate. Shown core interval is illustrating the channel bottom conglomerate at the topmost 30 cm of the core; conglomerate (cgl) is under- and overlain by channel sandstones (sst). Scale in cm.

Formation of southern Denmark had source areas south of the study area. Clemmensen (1979, 1991) suggested from data on Helgoland that dry winters with winds from northeasterly directions were replaced by wet summers where monsoonal winds from southeasterly directions brought precipitation to the area. Knowing now that the Germanic basin has been rotated 30 degrees clockwise since the Anisian (van Hinsbergen *et al.* 2019) these estimates must be corrected to alternating east-southeasterly and southerly (or less likely northerly) palaeowinds. The east-southeasterly winds are here interpreted as dry winter trade winds deflected by the topography of the Ringkøbing-Fyn High; while the southerly winds are interpreted as summer monsoon winds bringing precipitation to the area. Dominant southerly palaeowinds have been reported from Early Triassic aeolian sandstones in central Poland (Gradzinsky 1979) and may have been the primary sand-transporting palaeowind direction in much of the North German Basin (Mader 1982); precipitation here may have been less intense than farther north in the study area close to the Ringkøbing-Fyn High.

The new interpretation of Early Triassic palaeowinds gives an annual resultant sand drift direction towards the west-northwest in the southern Denmark obliquely towards the trend of the Ringkøbing-Fyn High; it is therefore suggested that aeolian sand initially was transported across the North German Basin by dominant southerly winds before it was transported towards the west-northwest along the lake margin forming the aeolian sand belt in southern Denmark during dry climatic intervals. It is possible that aeolian sand reached far northwards and even to the margins of the river plains and alluvial fans south of the Møn High during arid climatic intervals of the long eccentric period in Volpriehausen and Detfurth time (Fig. 15). It also possible that aeolian sand did not form an unbroken belt along the margin of the North German Basin south of the Rinkøbing-Fyn High but was concentrated in smaller areas separated by more permanent river systems. During humid climatic intervals in the long eccentricity period marginal depositional plains were of restricted size and probably composed of relatively mud-rich fluvial systems; sabkha flats and playa-lake sediments now covered the complete study area (Fig. 16).

The ancient aeolian sand facies form excellent reservoir deposits, and it is therefore important to determine the amount and stratigraphical distribution of such facies in the sandstone units of the Volpriehausen and Detfurth members in Rødby-1. The present data, however do not allow a recognition of aeolian facies in these members although it is speculated that aeolian facies primarily form in arid intervals during the precession, obliquity, and short eccentricity periods in the arid part of the long eccentricity period. Present data suggest that the mudstone units formed dung the humid part of the long eccentricity period constitute tight reservoir intervals. The new

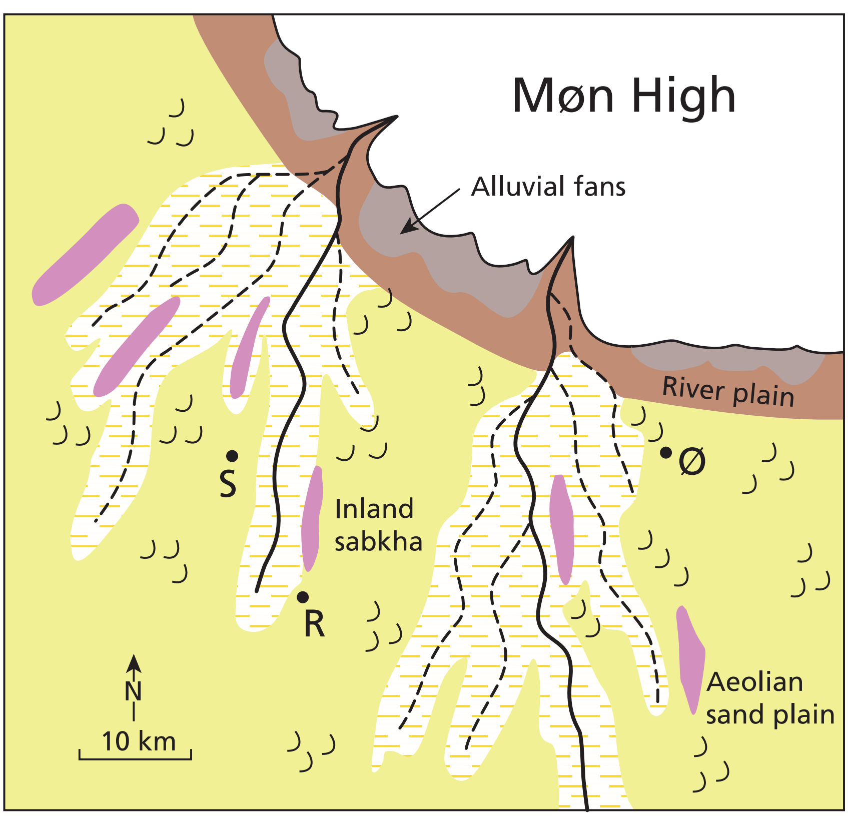

Fig. 15. The map shows a tentative distribution of palaeolandscapes in the study region of Lolland and Falster in southern Denmark south of the Møn High in the time interval forming the sandstone unit of the Detfurth Member. The time interval represents the most arid phase of the long eccentricity period. The approximate positions of the Søllested-1 (S), Ørslev-1 (Ø), and Rødby-1 (R) wells are given. Fluvial sand was derived from the Møn High, while aeolian sand was brought to the study area from southerly sources before it was transported towards the west-northwest and formed relative wide sand plains in the study area.

cyclostratigraphical interpretation, however, also suggests that the upper part of the mudstone unit in the Volpriehausen Member, which formed during decreasing humidity in the long eccentricity period is relatively sandy and might form a less tight sedimentary interval. A new petrophysical log including gamma ray readings is planned and may hopefully create new data useful for supplementary interpretations of sedimentary facies as well as for additional detection of porosity and permeability both in sandstone and mudstone units.

Conclusions

The cyclostratigraphical analysis of the Bunter Sandstone Formation in Rødby-1 indicates that deposition took place during strong influence of orbital climate control. Long-term climatic variation related to the long eccentricity period of 405,000 years not only controlled landscape evolution in the Rødby area, but also the alternating formation of sandstone and mudstone units.

In Rødby-1, the sandstone unit in the Volpriehausen Member is 29 m thick. The new cyclostratigraphy indicates that deposition of the complete sandstone unit took place during the arid part of a 405,000 years cycle. Internal lithological variation and thereby reservoir properties (sandstone-mudstone ratio) in the unit are related to 100,000 years eccentricity precession variation in climate as well as to obliquity variation of 28,500 to 49,000 years and precession variation of 15,000 to 23,000 years. There is very limited core evidence on lithology in Rødby-1, but by comparison with core data from the Tønder area in southern Jutland, it is suggested that the sand-rich intervals of this unit is composed of alternating aeolian and fluvial deposits with facies change primarily related to climate variation. Mud-rich intervals that separate the sand-rich interval probably comprise inland sabkha and fluvial overbank sediments and formed during the most humid intervals of the precession and obliquity cycles.

The sandstone unit of the Detfurth Member in Rødby-1 is of a rather uniform character with 19 m thick clean sandstones; deposition of the sandstone unit took place during an overall arid climate in the 405,000 years cycle. Minor variations in lithology and reservoir properties (mud content of sandstones) seems primarily related to the precession period probably changing the depositional environment from aeolian to fluvial. However, no core data exist to support this interpretation.

The sandstone unit of the Solling Member has a thickness of 23 m in Rødby-1 and probably represents deposition during an overall arid climate in a 405,000 years cycle. Sand-rich intervals are separated by mud-rich intervals and by comparison with core data from wells at Tønder, it is suggested that the lithological variation observed at Rødby primarily reflects climatic induced variation in fluvial style and transport capacity linked to the full spectrum of orbital cycles. Frequent shifts in river courses caused more unsystematic variation in facies and lithology.

All three sandstone units form reservoirs. But while sandstone intervals in the Volpriehausen and Solling

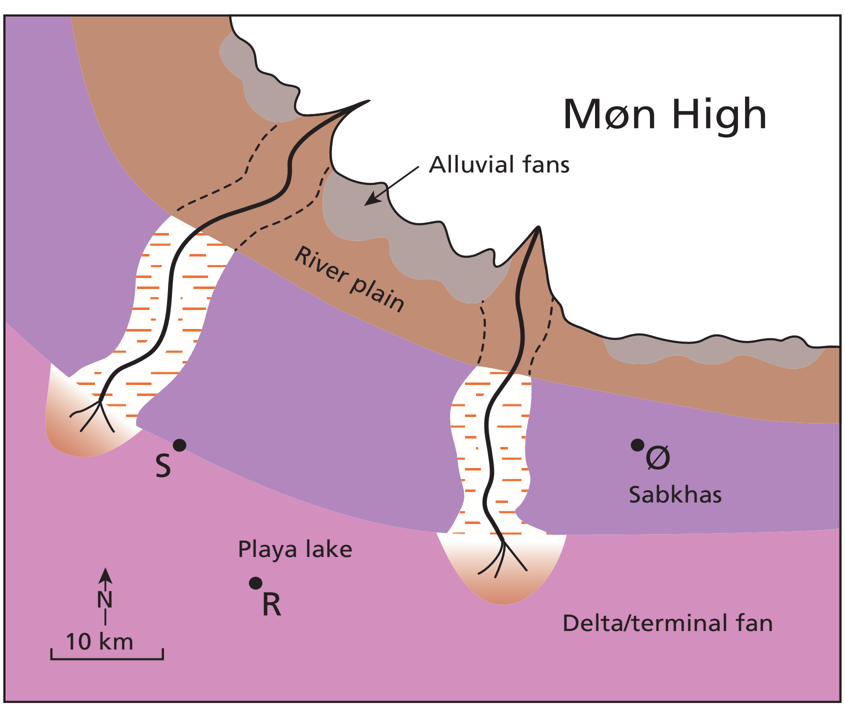

Fig. 16. The map shows a tentative distribution of palaeolandscapes in the study region of Lolland and Falster in southern Denmark south of the Møn High in the time interval forming the mudstone unit of the Detfurth Member. The time interval represents the most humid phase of the long eccentricity period. The approximate positions of the Søllested-1 (S), Ørslev-1 (Ø), and Rødby-1 (R) wells are given.

members are separated by mud-rich intervals reducing the overall quality of these reservoir units, the sandstone unit of the Detfurth Member is of rather uniform lithology and forms an excellent reservoir.

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