ORIGINAL RESEARCH ARTICLE

Chemostratigraphy of the Upper Albian to mid-Turonian Natih Formation (Oman) – how authigenic carbonate changes a global pattern

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ABSTRACT

The Oman Mountains preserve a Cretaceous continental margin transect with the proximal Arabian carbonate shelf and the adjacent deep Hawasina Basin. Today, the sediments from the Arabian Platform outcrop in the Oman Mountains (Jabal Akdhar and Saih Hatat) and in the Adam Foothills. The western part of the Adam Foothills provides insight into the evolution of a Late Cretaceous intra-platform basin with organic-rich sediments in the central part of this basin. The aims of this study are (a) to establish a biostratigraphy and chemostratigraphy of the Natih Formation and (b) to reconstruct depositional conditions of organic-rich sediments in an intra-platform basin during Cenomanian–Turonian times. The hypothesis that local black shale formation is an expression of global perturbations of the global carbon cycle will be tested. Reconstruction of the depositional history of the Arabian Platform and its intra-platform basin within a global palaeoclimatic framework requires an accurate time frame. The Upper Albian to mid-Turonian biostratigraphy of the Natih Formation has resulted in controversial age models that will be integrated into a solid chemostratigraphic framework with additional biostratigraphic data. A major positive $\delta^{13}C$ excursion (+4.6‰) has been identified as of Middle Cenomanian age, which is confirmed by an ammonite datum. A second positive $\delta^{13}C$ excursion (+4.5‰) following a major negative excursion (−1.0‰) confirms the existence of the Cenomanian/Turonian Boundary Event. The accurate chemostratigraphy and biostratigraphy confirms that major source rocks in the Mishrif-Natih Basin precede OAE2. Low $\delta^{13}C$ values measured in the sediments of the Natih B member are considered a consequence of diageneric alteration. Elevated organic carbon contents and argillaceous sediments alternating with limestones resulted in diageneric conditions favouring formation of authigenic calcite depleted in C-13.

INTRODUCTION

Oceanic Anoxic Events (OAE’s) were originally defined by Schlanger & Jenkyns (1976) as episodes in Earth history marked by widespread dysoxic to anoxic conditions in the world oceans, with global deposition of sediments enriched in organic carbon. During these events, organic-rich sediments were deposited in deeper basins under fully anoxic conditions and in shallower marginal settings within an expanded oxygen minimum zone (Schlanger & Jenkyns, 1976; Arthur & Schlanger, 1979; Jenkyns, 1980, 2010; Trabucho Alexandre et al., 2010). Oceanic Anoxic Events, and especially OAE2 at the Cenomanian/Turonian boundary, can easily be defined and correlated using C-isotope geochemistry as a stratigraphic tool (Scholle & Arthur, 1980; Jenkyns, 1980; Jarvis et al., 1988, 2006; Weissert, 1989). The Mid-Cenomanian Event I (MCE I) and the onset of OAE2 are characterized by important positive excursions in the $\delta^{13}C$ carbonate bulk-rock record (Schlanger et al., 1987; Erbacher et al., 1996; Jarvis et al., 2006; Voigt et al., 2008). Neritic carbonates, formed on a carbonate platform and within an intra-platform basin of Albian to Turonian
age are exposed in the Adam Foothills of the Oman Mountains. This succession provides the opportunity to investigate the evolution of an equatorial carbonate platform during a time of multiple perturbations of the global carbon cycle. The sediments accumulated on the platform and in the intra-platform Mishrif-Natih Basin, also called Rub’Al Khali Basin by Ziegler (2001), define the Natih Formation. Age control is given by biostratigraphy. However, numerous biostratigraphic investigations have resulted in controversial age models (Simmons & Hart, 1987; Simmons, 1994; Witt & Goekdag, 1994; Van Buchem et al., 1996, 2002, 2011; Sharland et al., 2001; Grélaud et al., 2006; Schroeder et al., 2010). Homewood et al. (2008) have summarized the available disputed biostratigraphic and sequence stratigraphic information.

This study aims at using the Natih Formation as an archive of the global C-isotope record. A high-resolution C-isotope record will provide data for an improved stratigraphic resolution of an Arabian platform succession during the time interval of interest. A robust stratigraphy offers the opportunity to test whether or not organic carbon-rich sediments accumulated within the intra-platform area of the Rub’Al Khali Basin are an expression of global carbon cycle perturbations. Of major importance is the accurate chemostratigraphic correlation of the uppermost Albian to lower Turonian Adam Foothills sections with the more distal Fahud Field successions because these are the closest outcrop analogues to the source rocks in the oil-producing subsurface of Oman.

REGIONAL GEOLOGICAL SETTING

Arabian Platform

The eastern part of the Arabian Plate was covered by an extensive shallow-water carbonate platform during Early to Late Cretaceous time (Fig. 1). The subsurface information from these shallow-water carbonate successions in Interior Oman (Hughes-Clarke, 1988; Vahrenkamp, 2010) and from the outcrop equivalents in the Adam Foothills and the Oman Mountains (Simmons & Hart, 1987; Van Buchem et al., 2002; Homewood et al., 2008) show that the carbonate platform can be divided into two larger sedimentary groups (Fig. 2). The Kahmah Group (Glennie et al., 1974) overlies Jurassic and older strata (Rabu, 1987; Pratt & Smeing, 1990, 1993), its top is karstified and it contains evidence of erosion (Immenhauser & Rameil, 2011) related to a major relative sea-level fall (Maurer et al., 2013) in the latest Aptian. The Kahmah Group is covered by shales and fine-grained clastics of the Nahr Umr Formation corresponding to the base of the Wasia Group (Immenhauser et al., 1999). Neritic limestones of the Natih Formation were deposited on top of Nahr Umr clastics. These carbonates record a 50 to 60 km northward progradation of the Arabian carbonate platform (Droste & van Steenwinkel, 2004). The Natih Formation and equivalent stratigraphic units such as the Mishrif Formation in the United Arab Emirates (Burket, 1993) contain several organic-rich intervals. The end of the Natih Formation and, hence, of the Wasia Group is again marked by a large regional unconformity, the Base Aruma unconformity (Fig. 2). This change in the sedimentary system occurred during mid-Turonian times as a result of the profound erosion following flexure of the continental lithosphere associated with beginning obduction of the Oman ophiolites (Robertson, 1987). The overlying Muti Formation represents infill of the foreland basin starting in the Late Turonian to the Campanian (Robertson, 1987).

Natih Formation

The focus of this study is the Natih Formation, which was deposited on a very extensive, low-relief carbonate platform during the Late Albian to mid-Turonian. Assigned age is based on benthic foraminifera (Simmons & Hart, 1987; Smith et al., 1990; Piuz & Meister, 2013; Piuz et al., 2014), on rudists (Philip et al., 1995) and ammonites (Kennedy & Simmons, 1991; Van Buchem et al., 2005; Bulot, as summarized in Homewood et al., 2008; Meister & Piuz, 2013, 2015). Carbon-isotope chemostratigraphy published by Vahrenkamp (2013) and low-resolution C-isotope stratigraphy by Wagner (1990) supports the biostratigraphically constrained age models.

The carbonate platform covered the Arabian Platform between the Arabian shield to the south and the Tethys margin with the adjacent Hawasina Basin in the north (Philip et al., 2000; Droste & van Steenwinkel, 2004). The Natih Formation was subdivided, using subsurface information from Fahud (Type section: Well Fahud North-3), into seven informal members, labelled by the letters ‘a’ to ‘g’ from the top to the base (Hughes-Clarke, 1988). However, following precedents set by previous authors (Homewood et al., 2008), capital letters (‘A’ to ‘G’) will be used here. Subdivision is based on variations in the clay-carbonate ratio observed in cores and on gamma-ray data interpretation. Seismic data from Interior Oman (Droste & van Steenwinkel, 2004; Grélaud et al., 2006) and a high-frequency synthetic seismic model from the Adam Foothills Transect (Schwab et al., 2005) reveal that the platform system of the Natih and Mishrif formations was not completely flat. Instead, the platform consisted of several prograding carbonate platform units, separated by intra-platform basin deposits. These intra-shelf-basins show a typical pattern that starts with a regional flat platform top, which diversifies into a shallow-water rudist
barrier platform and a lagoonal part with locally organic-rich sediment infill. The deeper basins were filled with argillaceous carbonates sometimes with a high content of organic carbon, as it is documented in the Natih E and B members (Van Buchem et al., 2002). These argillaceous limestones and marlstones today are hydrocarbon source rocks, which produced the giant Natih and Fahud oilfields in Oman (Terken, 1999; Droste, 2014).

In the Adam Foothills and also the Oman Mountains several high-resolution sequence stratigraphic reconstructions, created from extensive outcrop studies, serve for better understanding of the depositional system (Van Buchem et al., 1996, 2002; Grélaud et al., 2006; Homewood et al., 2008). In these studies, four fully developed third-order sequences (sequence I to IV) were described. Sequence I includes the lower Natih Formation (Natih G,
F & E members), sequence II the middle Natih Formation (Natih D & C members), sequence III the upper Natih Formation (Natih B & lower A members) and sequence IV the upper Natih A member. In addition to these 4 third-order sequences, 34 higher frequency sequences have been documented (Grélaud et al., 2006; Homewood et al., 2008). Sequences I and III represent the evolution from a carbonate-clay ramp at the base upward into a carbonate ramp (Droste & van Steenwinkel, 2004). During the transgressive parts of these sequences, organic-rich sediments were accumulated in the intra-shelf basin (Van Buchem et al., 1996, 2002). The composition of the organic matter is confirmed as autochthonous Type II, marine algal material by hydrogen index (HI) values between 400 and 650 mgHC/g Total Organic Carbon (TOC), and palynofacies analysis (Van Buchem et al., 2002, 2005). The top of each third-order sequence (top Natih E, top Natih C, and top Natih A) corresponds to a phase of platform emersion due to a relative sea-level fall. In the upper part of the Natih E member, and even more pronounced in the upper part of the Natih A member, a network of channels has been observed on seismic maps and in outcrops in the Adam Foothill and the Oman Mountains (Van Buchem et al., 1996, 2002; Grélaud et al., 2006; Droste, 2010). These channels are more than 2 km wide and reach over 30 km in length. The channels drained into the intra-shelf basins and into seaways between the platforms (Grélaud et al., 2006, 2010).

LOCATIONS AND METHODS

Lithofacies, inorganic and organic C-isotope geochemistry, as well as data on inorganic and organic carbon content, were used to correlate the studied successions. Thin sections were prepared in order to get an overview of the different microfacies and possible depositional settings. The Natih B to A members were investigated by 12 thin sections for diagnostic planktonic and benthic microfossils. The thin sections were covered with acryl and analysed under transmitted light. All geochemical measurements were performed at the isotope laboratory of ETH Zurich (Geological Institute).

Two expanded sections at Jabal Madmar (Wadi H, 112 m and Wadi P, 99 m) and one at Jabal Quasaybah (110-5 m) were sampled at intervals of less than 1 m, sometimes with decimetre spacing (see Fig. 3 for locations). The Jabal Quasaybah section is a composite section starting with the lowermost part (0 to 68 m) at Location 11 (Homewood et al., 2008), followed by the middle part which exposes the most continuous section of the cherty mudstone (68 to 80 m) in the eastern wadi (22°32'49"N, 57°05'08"E). The uppermost part, consisting of the base of the bioclastic pack- to grainstone up to the top of the Natih Formation (80 to 110.5 m), is exposed in the western wadi (22°32'44"N, 57°04'39"E). Two additional shorter sections (Jabal Salakh, 43 m and Wadi Nakhr, 13 m) were sampled for regional correlation of important intervals.

A total of 658 specimens of limestones, argillaceous limestones and carbonate mudstones were sampled for stable carbon and oxygen-isotope analysis. Samples were drilled with a micro-drill in order to avoid diagenetic calcite from veins. Approximately 140 µg of powder was reacted with 100% phosphoric acid at 71°C in a Finnigan GasBench II carbonate device connected to a Thermo-Fisher Delta V PLUS mass spectrometer. The instrument is calibrated with international [National Bureaux Standards (NBS) 19] and internal standards (MS2 ‘Carrara marble’; δ13C = +2.16, δ18O = −1.85‰). The reproducibility of the measurements based on replicated standards was ±0.05‰ for δ13C and ±0.06‰ for δ18O. The isotope values are reported in the conventional delta notation with respect to Vienna Pee Dee Belemnite (VPDB).

The isotopic composition of organic carbon (δ13Corg) was measured on bulk-rock samples from 40 samples of carbonate mudstones and organic-rich black limestones. More than 5 g of the sample material was treated with HCl acid (3 M) over a 24 h period. The samples were treated a second time with HCl to completely remove any carbonate minerals. A few 100 µg of decarbonated powder were weighed in tin capsules and measured using a Thermo-Fisher Flash-EA coupled to a Delta V PLUS mass spectrometer. The reproducibility of the measurements based on replicated standards was <±0.1‰ for δ13Corg. The instrument is calibrated with the international standards NBS 22 and IAEA-CH-6 and the isotope values are reported in the conventional delta notation with respect to VPDB.

Total inorganic carbon (TIC) as well as total carbon (TC) in samples was determined using a UIC CM 5012 CO2 Coulomat. For each analysis, ca 10 mg of powdered sediment was used. The TIC contribution was determined by dissolution of the sample in 2N perchloric acid, whereas TC was obtained by sample combustion in a 950°C furnace. The difference between TC and TIC provided the TOC. For a reference sample 100% Na2CO3 was used.

RESULTS

Lower Natih Formation at Jabal Madmar (Wadi H)

The carbon-isotope data from the lower Natih Formation (Natih F-E members, Fig. 4) vary between −8.8‰ and −3.6‰ (Fig. 5). The δ13C profiles show significant
variation of up to 2\%_oo from one sample to the next in the Natih E member (Fig. 5). The systematic scatter around the average (5-point moving average) is usually very small with a few larger outliers of up to 1\%_oo. The oxygen-isotope data vary between $-6.1\%_oo$ and $-2.4\%_oo$ (Fig. 5) with most data confined to a narrow range between $-5.5\%_oo$ and $-3.5\%_oo$. The only outliers (93 to 95 m, Fig. 5) show a clear offset of around 2\%_oo to more positive values.

The TOC results reflect the organic-rich intervals in the Natih E member (Fig. 4B and Homewood et al., 2008). In the sequence I-3 (Natih E member, Fig. 5), the weight % of the TOC increases contemporaneously with the deepening trend towards maximum flooding of the fourth-order sequence from around 0.5% to a maximum 7.4%. In the following sequence I-4, the values increase to a maximum of 2.6% towards the maximum flooding surface, as defined by Homewood et al. (2008).

**Middle Natih Formation at Jabal Madmar (Wadi P)**

The carbon-isotope data from the middle Natih Formation (Natih D-B members, Fig. 6) vary between 0-6\%_oo and 4-6\%_oo (Fig. 7). The $\delta^{13}C$ profile (Fig. 7) shows two prominent positive peaks in the limestone layers at the top of the Natih D member. The highest values of the first peak are at the base of the limestone bed (D2 in Fig. 6B; 12 m in Fig. 7) and the values decrease upwards towards the marly interval separating the two limestone beds (D2-D1 in Fig. 6B; 12 to 23 m in Fig. 7). The second peak occurs within the marly interval itself. The $\delta^{13}C$-jump to 1-5\%_oo higher values at the boundary between the Natih D and C members indicates a sedimentary gap corresponding to sub-aerial exposure during a sea-level lowstand. Carbon-isotope values of the Natih C member record a smooth decreasing trend. In the lower Natih B member (Sequence III-1, Fig. 7) a distinct C-isotope excursion to low values near $+1\%_oo$ was identified in the Wadi P section. The top of the Natih B member is represented by regular bedding and bed thickness ranging from 15 to 20 cm.

The oxygen-isotope data vary between $-6.0\%_oo$ and $-3.4\%_oo$, and show a similar pattern to the $\delta^{13}C$-data with clear positive jumps following the individual fourth-order sequence boundaries (top of II-1, II-2 and III-1, Fig. 7). The $\delta^{18}O$ values show an overall trend to more positive values (increase by $+1\%_oo$) starting at 22 m and ending at the top of the section.

In the uppermost limestone bed of the Natih C member (42.5 m in Fig. 7), an ammonite was found loose within Natih C gravel. The ammonite belongs to the Acanthoceratidae and can be compared to several species of *Calycoceras*, which indicates a Middle Cenomanian age.

**Upper Natih Formation at Jabal Qusaybah**

The Natih B member outcropping at Jabal Qusaybah most closely corresponds to the Natih B member described from the subsurface in the Natih and Fahud oil fields. Location 11, as it is described in Homewood et al. (2008), shows around 30 m of alternating organic-rich carbonate mudstones and limestones with a bedding thickness of 5 to 10 cm (Fig. 8B). For carbon and oxygen measurements, only the limestone layers were sampled in the Natih B member. C-isotope values range from $-1.3$ to 4.5$\%_oo$ while oxygen-isotope values fluctuate between $-7$ and $-3\%_oo$. The TOC of these dark to black limestone beds varies around 1 to 4 wt%. The argillaceous layers show much higher TOC values of up to 8 wt% (10 m in Fig. 9), which are similar to concentrations measured in the Natih oil field (up to 13.7 wt%; Al Balushi et al.,

Fig. 3. (A) Simplified geological map after Glennie et al. (1974) and Pillevuit et al. (1997). (B) Satellite image (Al Balushi et al., 2011).
2011). Oysters are the predominant macrofossils in this organic-rich interval of the Natih B member. The oxygen-isotope data show a clear outlier at 21 m above the base of the section with three values around $-3\%_\text{o}$ (Fig. 9), which is around $2\%_\text{o}$ more positive than the overall trend through the Natih B member. At 42 m above the base of the Jabal Qusaybah section (Fig. 9) organic-rich argillaceous sediments disappear and the TOC decreases to around 0-5 wt%. This significant lithological change reflects the boundary between the Natih B and A members (Fig. 8C). The lowermost 14 m of the Natih A member are represented by a 30 to 40 cm thick bedded, light grey to white limestone. Afterwards the bedding thickness decreases and even more obvious is a colour change to more grey and light brown limestones (Fig. 8D). The carbon-isotope data from the micritic limestones of the Natih A member show a continuous increase in the $\delta^{13}C$-values up to a peak near $+4.5\%_\text{o}$ (Fig. 8E and 58.2 m in Fig. 9).

From 68 m above the base of the section and upwards, chert nodules are common in the carbonate mudstone. At Location 11, the section has been truncated by the overlying pack- to grainstone (80 to 87 m). The bioclastic pack- to grainstone or calcarenite is described by Homewood et al. (2008) as a forced regressive prograding wedge at the surface boundary III-6/7 to III-8. It can be correlated

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**Table 1.** Locations of the different sampled Natih members and their coordinates

| Natih members | Locations                  | Coordinates (WGS 84) | Location |
|---------------|----------------------------|----------------------|----------|
| Natih F to D member | Wadi H, Jabal Madmar       | 22°26'40"N, 57°35'28"E | Location 1 |
| Natih F to E member | Jabal Salakh               | 22°21'01"N, 57°26'35"E | Location 4 |
| Natih D to B member | Wadi P, Jabal Madmar       | 22°26'35"N, 57°33'56"E | Location 11 |
| Natih B to A member | Jabal Qusaybah             | 22°32'36"N, 57°04'47"E | Location 11 |
| Natih B member   | Wadi Nakhr                 | 23°09'08"N, 57°12'20"E | Location 8 |

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Fig. 4. Detailed pictures of important sections in the lower Natih Fm. Subdivision into members of the Natih Fm after Homewood et al. (2008). For location see Fig. 3 and Table 1. (A) Panoramic pictures from the outcrops at Jabal Madmar, Wadi H. (B) Sequence I-3 with the organic-rich interval in the Wadi H at Jabal Madmar. (C) Sequence I-3 & I-4 from the lower Natih E mbr at Jabal Salakh.
with a calcarenite described from the Fahud area where this also marks the top of sequence III. Detailed section logging in multiple wadis along the northern flank of the Jabal Qusaybah indicates that erosion extended 10 m downward into the underlying cherty limestone. The $\delta^{18}O$ values of this calcarenite body show a clear offset of +1.5 to +2‰ (Fig. 9).

The overlying interval between 87 to 100 m [sequence III-8(7)] is absent in Fahud (Homewood et al., 2008) and therefore can only be described at Jabal Qusaybah. At 100 m above the base of the section, a small fault cuts the top and part of the overlying sequence IV. This is also reflected in an abrupt shift to more positive $\delta^{13}C$ and $\delta^{18}O$ values. Within the uppermost 12 m of the Natih A
member (sequence V), $\delta^{13}$C-values start to decrease. This trend terminates the $\delta^{13}$C plateau with numbers around $3\%_o$ measured between 60 to 102 m above section base.

In addition to the $\delta^{13}$C$_{\text{carb}}$ data, the $\delta^{13}$C$_{\text{org}}$ composition of 40 samples covering the Natih B member and the lower Natih A member (0 to 70 m), have been analysed (Fig. 9). The $\delta^{13}$C$_{\text{org}}$ data vary around $-27\%_o$ ($\pm 0.5\%_o$) until 56-1 m above the base of the section. Similar to the $\delta^{13}$C$_{\text{carb}}$ values the $\delta^{13}$C$_{\text{org}}$ also increase by around 2$\%_o$ reaching the most positive values ($-24.9\%_o$) with the sample at 58-2 m above section base. Afterwards, the values decrease again to $-27\%_o$ at the 66 m level.

**Micro- and macrofossils in the Natih A member**

The microfossil assemblage of the lower Natih A member at Jabal Qusaybah yields a Late Cenomanian to Early Turonian age (Fig. 10). The thin sections QA-4-0 at 46 m (Fig. 10) show the typically Cenomanian taxa *Chrysalidina* sp. and *Nezzazatinella* sp. The occurrence of *Pseudolitinella* sp. (perhaps *P. reicheli*) would indicate a mid-Upper Cenomanian age at 50-8 m above section base. The thin sections between 54-1 to 61-3 m (QA-12-1 – QA 19-3) show a typical Cenomanian/Turonian interval assemblage. In particular, the occurrence of *Marssonella oxycona* is often quite common around the C/T boundary where it is one of the few benthic taxa to survive the OAE2. In this interval, at 56-4 m above the base of the section, *Lingulogavelinella* sp. (also known as *Berthelina* sp.) is quite common. In the same thin sections, *Praeglobotruncana* sp., juvenile *P. stephani*, *Hedbergella amabilis* and *H. similis* can also be found and clearly confirm the C/T boundary interval. The final occurrence (FO) of *H. praehelvetica* at 61-3 m above the base of the section is an indicator of an earliest Turonian age.

The benthic and planktonic foraminifera between 101 to 110 m (QA-59 – QA-68) are clearly Turonian in age. The FO of *Marginotruncana* sp. cf. *sigali* indicates a mid-Turonian age in the thin-section QA-62. The uppermost
two thin sections indicate quite shallow-water and further, the dominance of Miloliidae at 110 m indicates a slightly hypersaline environment (Murray, 1991).

At 59.9 m above the base of the section, just above the most positive C-isotope values, two ammonite specimens have been found in situ. While identification has to be taken with caution because of the rather poor preservation, for the first specimen two interpretations are possible. Either it belongs to the subfamily of Euomphaloceratinae (Kameruoceras sp. or Para-

At the southern flank of Jabal Salakh (22°20'35"N, 57°15'58"E) 5 additional ammonites have been found ex situ in the middle Natih A member. Two specimens can be determined as Vascoceras sp. and one as a Hoplitoides sp. The two remaining specimens may be attributed to Hoplitoides sp. but the poor preservation does not allow a precise determination. The Vascoceras sp. and the Hoplitoides sp. confirm the Early Turonian age for the middle part of the Natih A member.

![Fig. 7. Natih D, C and B mbrs from Jabal Madmar, Wadi P (for location see Figs 3 and 6). Sequence stratigraphic data after Van Buchem et al. (2002); Grélaud et al. (2006) and Homewood et al. (2008). Legend in Fig. 5.](image-url)
Correlation of the two organic-rich intervals (Base Natih E and Natih B members)

In the Adam Foothills several workers proposed sequence stratigraphic correlations between the outcropping autochthonous Natih Formation and the subsurface records in the same area (Van Buchem et al., 1996, 2002; Grélaud et al., 2006; Homewood et al., 2008) based on cycles and stacking patterns. Notional, abstract surfaces at turnarounds and at minimum accommodation are used as 'timelines' on cross sections. Carbon-isotope chemostratigraphy is a powerful tool to test whether or not these surfaces are isochronous, because the variation in the δ13C-signal measured in the bulk-rock carbonates is considered to be a mirror of the isotopic composition of the marine (dissolved inorganic carbon) DIC and therefore, it is regarded as a global signal. Two stratigraphic intervals were measured at several locations: the lower Natih E member (Sequence I-3 and I-4; Fig. 11) and the Natih B member (Fig. 12).

The δ13C-values start at 3‰ at Jabal Madmar in the top of the Natih F member followed by two negative excursions of around 1-5‰ amplitude in the lower Natih E member (Fig. 11). The chemostratigraphic data from both studied Natih E sections show similar variations, whereas the absolute δ13C-values are shifted by around 1‰ towards lower values at Jabal Salakh. Both negative carbon-isotope intervals correlate with elevated organic carbon contents (up to 6 wt%, Fig. 11). The organic carbon content is coupled to the fourth-order cycles becoming enriched during maximal flooding (sequences 1-3 and 1-4). The C-isotope values fluctuating parallel with the fourth-order cycles may record changes in the global carbon cycle driven by orbital change (long eccentricity) as documented for the Albian in pelagic sediments by Giorgioni et al. (2012).

The Natih B member, as a hydrocarbon source rock in Interior Oman shows interesting chemostratigraphic features. Wagner (1990) and Vahrenkamp (2013) described a negative δ13Ccarb excursion over most of the Natih B member. The chemostratigraphic transect shown in Fig. 12, shows that sediments of the Natih B member outcropping west of Adam (Jabal Madmar) and the south-western part of the Oman Mountains belonged to an intra-shelf basin (Van Buchem et al., 2002 and Razin & Grélaud in Homewood et al., 2008) and that they are enriched in organic carbon. In the Fahud oil field, the source rock is of marine Type I/II origin with TOC contents of up to 15 wt% (Terken, 1999). In the Natih oil field, the TOC content of the source rock is up to 13-7 wt% (Al Balushi et al., 2011). The TOC content at Jabal Qusaybah reaches values up to 8 wt% (Fig. 9) in the carbonate mudstones alternating with limestones. This basin-ramp structure is also reflected in the carbon-isotope measurements along the west-east Adam Foothills section (Fig. 12). Most positive δ13C-values are measured at the ‘marginal’ intra-shelf basin at Jabal Madmar, while values in the ‘central’ part of the basin are lower by up to 2‰. The three measurements with less negative δ18O-values (around −3‰) around 21 m above the base of the Jabal Qusaybah section indicate a transgression level. This level is also identical to the subunit boundary between B1 and B2 from the Fahud Field ‘F’ section (Fig. 12, Vahrenkamp, 2013).

Negative C-isotope excursions: diagenesis or global C-isotope signal?

A plot of all available carbon-isotope data (Fig. 13) from the Natih Formation (Wagner, 1990; Zhao et al., 2012; Vahrenkamp, 2013; Arndt et al., 2014 and this study) points at differences in absolute values. Large variations in amplitude can also be observed. As already shown in Figs 11 and 12 there are intervals in the Natih Formation marked by distinctly lower C-isotope values. The trend to lower δ13C-values can be explained either by an early or late diagenetic overprint, by isotopic offset of the local water mass or by a global change in the δ13C-values. Of importance is the observation that the low C-isotope values of the Natih B member exist in a succession of alternating organic carbon-rich carbonate mudstones and limestones, formed in the intra-platform basin. Whether this ‘negative’ C-isotope excursion in the upper Cenomanian serves as a regional or global stratigraphic marker or if it is the result of diagenesis is discussed in the following paragraph.

The negative δ13Ccarb-values measured in the Natih B member show remarkable agreement with the sediments enriched in TOC in the central intra-shelf basin. However, elevated TOC contents are also measured in the basal part of the Natih A member (around 1wt%, Fig. 9), whereas the δ13C-curve returns to more positive values in this part of Natih A. This indicates that the low C-isotope values of Natih B cannot be exclusively explained as result of diagenetic overprint due to elevated organic carbon content. Rather the negative δ13C – shift is linked to the distinct lithology of Natih B, characterized by alternating limestones and organic carbon-enriched carbonate mudstones. Diagenesis of this succession is controlled by both argillaceous sediments and by interbedded neritic carbonates. Elevated clay content in the intra-basin mudstones acted as a decelerator or inhibitor of early marine/meteoric diagenesis (Westphal, 2006). Argillaceous sediments enriched in organic carbon experienced sulphate reduction and anaerobic oxidation of methane during early
diagenesis. Both processes resulted in alkaline pore fluids (Meister et al., 2007; Schrag et al., 2013). Authigenic carbonate depleted in C-13 was precipitated from supersaturated pore fluids.

The Natih B succession with argillaceous sediments enriched in organic carbon and with interbedded neritic carbonates can, therefore, be considered an example of diagenetic alteration due to the formation of authigenic
calcite cement. Similar explanations of low C-isotope values have been proposed by Wagner (1990) and also Vahrenkamp (2013). The coupling of low C-isotope values with mudstones also explains why the δ^{13}C-values measured in Natih B are more negative (up to −1.5‰) in the deepest part of the intra-shelf basin, where argillaceous sediments rich in organic carbon reach maximum abundance, compared to sediments of the basin margins. At Jabal Qusaybah, the δ^{13}C-values jump by 1.5‰ to higher values at the Natih B to A member transition (Fig. 8C). This lithological boundary marks the end of the organic-rich argillaceous sediments of the Natih B member (Fig. 9). The change in lithology is synchronous in all measured sections (Fig. 12) and could be linked to the global sea-level rise in the latest Cenomanian (Voigt et al., 2006; Haq, 2014). This global sea-level rise probably reconnected the restricted intra-shelf basins with the open ocean. Better oxygenation and reduced input of clay minerals at a time of high sea-level resulted in a change of sedimentary facies and coupled change in diagenetic environment.

**Fig. 9.** Natih B and A members from Jabal Qusaybah (for location see Figs 3 and 8). Fourth-order sequence stratigraphic data: left Van Buchem et al. (2002) and right Homewood et al. (2008). Red points represent δ^{13}C_{org} and black ones the δ^{13}C_{carb} data. Legend in Fig. 5.
Low δ¹³C-values in upper Cenomanian carbonates have not only been identified in the interior of Oman and in certain areas of the Adam Foothills but similar trends can also be found in the High Zagros, SW Iran (Razin et al., 2010), in Central Jordan (Morsi & Wendler, 2010), NE Egypt (El-Saabagh et al., 2011) and also in parts of the Southern Apennines, Italy (Parente et al., 2007). The sediments from the High Zagros and probably also from Central Jordan may be linked to large intra-shelf basins on the Arabian Platform (Fig. 1). All of these successions may contain unusual amounts of isotopically depleted authigenic calcite. The hypothesis, that not only enrichment of sediments with organic carbon but also composition of the sediments controlled this peculiar diagenesis, will need further testing.

In contrast, the δ¹³Corg-data do not show any significant variation during the negative δ¹³Ccarb interval in the Natih B member (Figs 9 and 13). The δ¹³Corg-values vary around −27‰ (±0–5‰) throughout the negative δ¹³Ccarb excursion. Similar to the δ¹³Ccarb values, the δ¹³Corg also increase by around 2‰ reaching the most positive values (−24–9‰) 58–2 m above the base of the section. Afterwards the values decrease again to −27‰ around 66 m above section base. Therefore, the δ¹³Ccarb and δ¹³Corg data do not show the same trend. Based on the fact the δ¹³Corg-values correlate well with the global carbon-isotope trend, the negative δ¹³Ccarb excursion in the Natih B member is interpreted as being diagenetic in origin.

An additional factor which may have contributed to the difference between basinal and more coastal sediments is the original mineralogy of the sediments. The δ¹³Ccarb-values from shallow-water carbonates are one to several permil higher relative to samples from the open marine pelagic carbonates. This variation in absolute δ¹³C-values can be explained by a varying amount of aragonite in the bulk rock. Aragonite is enriched in ¹³C by about 0–9‰ relative to calcite (Lécuyer et al., 2012). Sediments with a larger amount of aragonite therefore show heavier δ¹³C-values (Swart & Eberli, 2005).

Composite chemostratigraphic section of the Natih Formation

In combining results from different locations in the Adam Foothills (Wadi H and P at Jabal Madmar and Jabal Qusaybah) a composite section for the Late Albian to mid-Turonian (see Fig. 14) has been constructed. The composite reference section shows clearly the negative δ¹³C-excursion in the Natih B member at Jabal Qusaybah (blue points in Fig. 14). The overlapping part of the Natih B member at Jabal Madmar (green points in Fig. 14) is characterized by δ¹³C-values up to 2‰ heavier, with the negative excursion representing a central part of the intra-platform basin. The more positive values with lower TOC values were measured along the margin of the basin in carbonate-dominated sediments.

Jabal Qusaybah (Natih Fm)

Fig. 10. Stratigraphic occurrences of planktic and benthic foraminifera and other microfossil and macrofossil fragments in the Natih A mbr at Jabal Qusaybah.
The C-isotope stratigraphy of the Natih Formation confirms that organic carbon-enriched sediments deposited in the Cenomanian Mishrif-Natih-Basin do not coincide with OAE2. The formation of organic-rich sediments in this intra-platform basin was controlled by regional factors, including intra-platform basin palaeoceanography. Most important was that the sea-level controlled the degree of restriction of the Mishrif-Natih Basin. Correlation of sea-level history with C-isotope stratigraphy indicates that late Cenomanian sea-level rise ended a period of restriction.

Fig. 11. Correlation from the fourth-order sequences (I-2, I-3 & I-4) from Jabal Madmar and Jabal Salakh. Correlation of the organic-rich mudstone from the intra-shelf basin (Jabal Salakh) and the more proximal section at Jabal Madmar (Homewood et al., 2008). Sequence Stratigraphy after Grélaud et al. (2006) and Homewood et al. (2008).

Fig. 12. Several chemostratigraphic results from the Natih B mbr. Fahud Field and Jabal Salakh by Vahrenkamp (2013); Natih Field by Al Balushi et al. (2011). Lithostratigraphic subunits (C1, B4-B1 & A7) are correlated with the Fahud Field subdivision (Vahrenkamp, 2013). Datum based at the base of the Natih A mbr.
with elevated Corg burial rates in the basin. The end of Corg-rich argillaceous sediments coincides with the end of the regionally limited carbonate C-isotope excursion.

**Correlation of Interior Oman and Adam Foothills with global reference curves**

A comparison of all carbon-isotope data from Interior Oman and Adam Foothills compared to two reference curves (English Chalk, Jarvis et al., 2006 and Gubbio, Stoll & Schrag, 2000) is shown in Fig. 15. The Oman sections comprise several chemostratigraphic anchor points for a precise timing:

The *Albian/Cenomanian boundary*, defined by Kennedy et al. (2004), can be placed between peak b and c of the Albian/Cenomanian Boundary Event (Jarvis et al., 2006). The $\delta^{13}$C-values decrease afterwards in the lower Cenomanian (Mitchell et al., 1996). The same C-isotope positive excursion can be seen in the Natih G and F members in the Fahud section (Vahrenkamp, 2013) and also at the Jabal Madmar (Fig. 13). Therefore, the Albian/Cenomanian boundary was adapted from Vahrenkamp (2013) and it coincides with the top of the sequence I-2 (Homewood et al., 2008).

The cycles identified in the lower Natih E member may be correlated with the Lower Cenomanian Events (LCE I-III; Mitchell et al., 1996). Mitchell et al. (1996) already concluded that the LCE’s (I-III) are clear evidence of a link between short-term fluctuations in sea-level and significant $\delta^{13}$C excursions. The chemostratigraphic data show the same link on the Arabian Platform and therefore the signal could be a global signal. The amplitude of the LCE’s are much larger in the shallow-water sections compared to the more open marine sections (Mitchell et al., 1996).

The *lower/middle Cenomanian boundary* can be placed at the base of the onset of the MCE I (Mitchell et al., 1996; Jarvis et al., 2006). Within the uppermost part of the sequence I-7 the $\delta^{13}$C-values already show a trend to lighter values. Afterwards, within the lower Natih D member, the $\delta^{13}$C-values show a clear trend to more positive values, which culminate in the MCE I (see discussion...
| Stage | Substage | Litho-stratigraphy | 3rd-order | 4th-order | Thickness [m] | Outcrop composite reference section |
|------|----------|--------------------|-----------|-----------|---------------|----------------------------------|
| Cenomanian | Early | Natih E | IS1 | IS2 | 100 | |
| | Middle | Natih D | IS1 | IS2 | 150 | |
| | Late | Natih C | IS1 | IS2 | 200 | |
| | | Muti Formation | IS1 | IS2 | 250 | |
| Turonian | Early | Natih A | IS1 | IS2 | 300 | |
| | Late | Natih B | IS1 | IS2 | 350 | |
| | | | IS1 | IS2 | 400 | |
| Albian | Late | | IS1 | IS2 | 450 | |

**Chemostratigraphy of the Natih Formation**

Composite section (Jabal Qusaybah & Jabal Madmar)

**Fig. 14.** Composite chemostratigraphic section from the Adam Foothills. Outcrop composite reference section modified after Grélaud et al. (2010); red: Wadi H, Jabal Madmar; green: Wadi P, Jabal Madmar and blue: Jabal Qusaybah.
below). Therefore, the lower/middle Cenomanian boundary coincides with the boundary at the Natih E/D boundary, which is a major emersion surface with a hiatus at Jabal Madmar. A stratigraphic lower position in the uppermost part of the Natih E member, as it is discussed by Piuz et al. (2014), cannot be excluded.

The first positive carbon-isotope excursion (+4.6‰) coincides with the two massive limestone beds (D2 and D1 in Fig. 6B) at the top of the Natih D member in the sequence II-1 (Homewood et al., 2008). The positive peak is also observed at the Jabal Salakh section (Razin, 2011 in Vahrenkamp (2013); Fig. 13). The correlation with the Fahud area (Vahrenkamp, 2013) contains some uncertainties. The δ¹³C-trend still increases in the subunit D1 of the Natih D member compared to the Jabal Salakh and Madmar section (Fig. 13). Therefore, the subunit D1 and D2 do not have exactly the same age in the Fahud area compared to the Adam Foothills. Nevertheless, the positive peak can be correlated with the Middle Cenomanian Event I (MCE I) (Paul et al., 1994; Mitchell et al., 1996) (Fig. 15). The MCE I can be divided into two smaller peaks MCE Ia & Ib (Mitchell et al., 1996). Whether these two peaks are resolved in the two peaks in the Jabal Madmar at the base of the D2 subunit and just above in the marly interval or as proposed by Vahrenkamp (2013) in the peaks at the top of Natih D and C members remains debatable. It seems that the negative excursion between the two peaks at Fahud (subunit C2-C4; Vahrenkamp, 2013) is absent at Jabal Salakh and Madmar due to emersion at the top of Natih D member.

The middle/upper Cenomanian boundary can be placed at the small positive excursion of the Jukes-Browne Isotope Event which occurs in the upper beds of the Acanthoceras jukebsrowniei and lowest Calycoceras guerangeri zones (Jarvis et al., 2006). This isotope event is identified in the middle Natih B member (Fig. 15). The isotope

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**Fig. 15.** Correlation of Late Albian to mid-Turonian δ¹³C events between England, Italy and the Arabian Platform. The English Chalk reference curve in black (Jarvis et al., 2006) is an unsmoothed composite curve plotted against age; Italian profile from Gubbio in grey (Stoll & Schrag, 2000); Oman Field ‘F’ in green (Vahrenkamp, 2013); Oman Adam Foothills in blue and purple (blue with negative excursion in the Bab basin and purple on the platform) and Jordan (Morsi & Wendler, 2010). Sections are anchored by the onset of the CTBE (increase into the peak ‘a’). Correlation of major (grey bands) and minor (grey lines) positive and negative excursion (Jarvis et al., 2006). Ci = Cunningtoniceras inerme; Ar = Acanthoceras rhotomagense; Aj = A. jukebsrowniei, Cg = Calycoceras guerangeri; Mg = Metoicoceras geslinianum; Nj = Neocardioceras juddii; Wd = Watinoceras devonense; Fc = Fagesia catinus; Mn = Mammites nodosoides; LCE I-III = Lower Cenomanian Event I-III; MCE I = Middle Cenomanian Event I.
excursion is more pronounced in the Jabal Madmar section but the correlation by lithology and also chemostratigraphy works also at Jabal Qusaybah and at Fahud (Vahrenkamp, 2013). The position of this substage boundary is supported by ammonites at Jabal Salakh (Meister & Piuz, 2015).

The positive C-isotope excursion (+4.5‰) in the lower part of the Natih A member at Jabal Qusaybah can also be seen in the Jabal Salakh section [P. Razin in Vahrenkamp (2013)] but it is absent in the Fahud area, probably due to an emersion and erosion phase at the end of sequence III in the earliest Turonian (Homewood et al., 2008). The pronounced positive C-isotope excursion (+4.5‰) was interpreted as the expression of OAE2 (Fig. 15) and therefore, the Cenomanian/Turonian boundary is shifted downwards compared to Vahrenkamp (2013). The position of this boundary is again supported by ammonites at Jabal Qusaybah (Meister & Piuz, 2015). These authors place the Cenomanian/Turonian boundary in the lower part of the ‘grey limestone’ (see Fig. 8D). Compared to other expanded CTBE-sections (Paul et al., 1999; Jarvis et al., 2006) the section must have been truncated just above the first peak of the CTBE.

The negative δ13C-shift in the Natih A member (sequence V) at the platform top (Jabal Qusaybah) can be correlated with the decreasing trend in the middle mid-Turonian observed on a global scale (Fig. 15). The δ13C-plateau ends with a distinct peak which can be seen in the higher values of sequence IV. This peak can be correlated with the Tu10 (Low-woollgari) Event (Voigt et al., 2007). The end of the Natih Formation and, hence, of the Wasia Group, is again marked by a large regional unconformity, the Base Aruma unconformity (Fig. 2). This change in the sedimentary system occurred during the mid-Turonian as a result of the profound erosion due to the flexure of the continental lithosphere associated with beginning obduction of the Oman ophiolites (Robertson, 1987; Van Buchem et al., 2002).

CONCLUSION

This study provides a stratigraphic model for the uppermost Albian to mid-Turonian Natih Formation through integration of stable chemostratigraphy with biostratigraphy and sequence stratigraphy. Two major positive C-isotope excursions can be correlated with global C-isotope anomalies in the Cenomanian and lower Turonian. The lower one, in the top of the Natih D member, corresponds to the Middle Cenomanian Event 1 (MCE 1) and the upper one, in the lower Natih A member, with the Cenomanian/Turonian Boundary Event (CTBE) and Oceanic Anoxic Event 2 (OAE2). The CTBE seems to be truncated just above the first peak of the CTBE, a conclusion confirmed by ammonites and planktic foraminifera. The chemostratigraphic data at Jabal Qusaybah suggest a mid-Turonian age for the uppermost Natih Formation. Therefore, although tectonically controlled, the top of the Natih Formation coincided with a major global short-term sea-level drop in the mid-Turonian. This transition is indicated by a change in the benthic foraminifera to an assemblage dominated by Miliolidae, reflecting elevated salinity in shallow water.

The petroleum source rocks in the lower Natih E member and the Natih B member were not formed during one of the major Oceanic Anoxic Events (OAE1d, MCE and OAE2). The organic-rich interval in the lower Natih E member has an earliest Cenomanian age while the one forming part of the Natih B member clearly pre-dates the OAE2. Both source rock successions were formed in a restricted intra-shelf basin covering wide parts the Arabian Platform. The Natih B member of the intra-platform basin preserves a C-isotope excursion towards low values. This negative excursion is not seen in δ13Corg-values. Therefore, the negative isotopic excursion does not represent a change in the global marine carbon pool of the Late Cenomanian. Peculiar conditions during diageneis of argillaceous intra-platform basin sediments enriched in organic carbon and alternating with neritic limestones may explain this excursion to negative C-isotope values. Early diageneic sulphate reduction and anaerobic oxidation of methane both contributed to elevated pore-water alkalinity and to precipitation of authigenic carbonate depleted in C-13. Both, argillaceous sediments and neritic carbonates contain a C-isotope signature indicative of unusual diagenetic conditions and not changes in global DIC.

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