Late Albian, Cenomanian and Turonian Natih Supersequence of Oman: Type section for Orbiton 7 (103.6–89.0 Ma)

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ABSTRACT

The Upper Albian, Cenomanian and Turonian Natih Formation in Oman was interpreted by previous authors in terms of the regional Natih I to V depositional sequences comprising 34 higher-order subsequences (referred to as the Adopted Interpretation in this paper). It mainly consists of limestones, and is separated from the underlying Albian shales of the Nahr Umr Formation by the Natih Sequence Boundary. The interpreted position of the Cenomanian Stage within the formation differs substantially depending on carbon-isotope and/or biostratigraphic data (ammonite, microfaunal and nannofossil). The top of the Natih Formation is a regional subaerial exposure surface (incised by channels with depths reaching 150–200 m) that was transgressed by Lower Coniacian marine shales (Muti Formation at outcrop, and Shargi Member of the Fiqa Formation in subsurface; Fiqa Transgression above the Fiqa Sequence Boundary). Over paleohighs the lower part of the Fiqa, Natih and older formations are eroded by the Campanian angular Intra-Fiqa Unconformity that is attributed to far-field compressional tectonism along the margins of the Arabian Plate.

The paper tunes the 34 Natih subsequences (each named a Straton) at 405 Ky cycle: the period of the long-eccentricity signal of the Earth’s orbit. They are dated using a time scale that is based on an orbital-forcing model of glacio-eustasy, which consists of ca. 14.58 My (36 stratons) repeating, orbital cycles named orbitons. Orbitons are predicted to be separated by major glacio-eustatic lowstands (regional sequence boundary), with Orbiton 1 spanning ca. 16.1 to 1.5 Ma. The Natih Formation completely falls within Orbiton 7 (ca. 103.6–89.0 Ma) in the Late Albian – Turonian time interval of the Geological Time Scale of the International Commission on Stratigraphy (GTS). The Formation consists of only 34 subsequences (compared to the 36 predicted for a complete orbiton). This implies two stratons are represented by a hiatus (ca. 810 Ky) between ca. 89.8–89.0 Ma near the end of Orbiton 7 and the Turonian/Coniacian boundary (88.6 Ma in GTS). The hiatus corresponds to a Late Turonian – ?earliest Coniacian biostratigraphic break at the Sub-Fiqa Unconformity and is correlated to a model-predicted major polar glaciation and sea-level lowstand. The hiatus is unrelated to the structural deformation in Interior Oman (First Alpine Event), which started some 10 My later in Campanian time. Orbiton 7 (ca. 103.6–89.0 Ma) correlates by architecture (sequence boundaries and maximum flooding surfaces) and age to the global Late Albian – Turonian UZA 2 Supersequence inclusive of the short-lived 100+ m sea-level drop in latest Turonian (ca. 102.5–88.6 Ma in empirical time scale). The Formation is proposed as the Natih Supersequence and the type section of Orbiton 7.

INTRODUCTION

The Orbiton, with a duration of ca. 14.58 million years (My), is predicted by the tuned orbital-forcing model of glacio-eustasy to be the longest-period depositional sequence (Matthews and Al-Husseini, 2010; Al-Husseini and Matthews, 2010). Orbitons should manifest several stratigraphic aspects that can be tested.
(1) They are separated by major glacio-eustatic lowstands (regional sequence boundary or unconformity-hiatus).

(2) The age of Orbiton 1 is between ca. 16.1 and 1.5 million years before present (Ma), and older ones can be dated by adding ca. 14.58 My.

(3) When completely represented in the stratigraphic record (without hiatuses), they should consist of 36 transgressive-regressive sequences (Stratons) that tracked the long-eccentricity 405,000 years orbital signal (405 Ky; Laskar et al., 2004).

(4) Orbitons break into three groups, each consisting of 12 stratons (Dozon, ca. 4.86 My).

(5) In turn, dozons commonly break into two sequences that consist of five (short, ca. 2.0 My), six (nominal, ca. 2.4 My) or seven stratons (long, ca. 2.8 My) (Matthews and Frohlich, 2002).

This paper tests these aspects for Orbiton 7, predicted between ca. 103.6–89.0 Ma, using the Late Albian – Turonian Natih Formation of Oman. The Natih’s sequence stratigraphy is taken from studies by C. Grélaud, P. Razin and other authors (van Buchem et al., 1996, 2002; Droste and Van Steenwinkel, 2004; Grélaud, 2005; Grélaud et al., 2006) as presented in the Natih Field Guide of Homewood et al. (2008). The present paper adopts their framework, which is documented mainly from the Natih Eastern Platform and the Fahud Field area in the Natih Western Platform (Enclosure, Figures 1 to 3). Their framework is here referred to as the Adopted Interpretation so as to emphasize that its temporal completeness and regional correlation may be questionable (F.S.P. van Buchem, H. Droste and P. Homewood, written communications, 2010). In the Adopted Interpretation the Natih Formation is divided into the Natih I to Natih V sequences (in ascending order) comprising 34 subsequences. Two of their traverses are reproduced here to document the sequences for the reader’s convenience (see Enclosure, Figures 1 to 3):

(1) Traverse A: 110-km-long cross-section in outcrop and subsurface illustrating the oldest Natih Sequence I (Figures 1 and 2), and

(2) Traverse B: 64-km-long cross-section showing Natih sequences II to V at outcrop in Al Jabal al-Akhdar (Figures 1 and 3).

The paper also compares the orbital age estimates of the Natih sequences of the Adopted Interpretation and Arabian Plate (AP) maximum flooding surfaces (AP MFS K110 to MPS K150, Sharland et al., 2001; “K” for Cretaceous) to those of the global sequences of Haq et al. (1988), here recalibrated in the Geological Time Scale GTS 2004 (Gradstein et al., 2004) and GTS 2009 (www.stratigraphy.org) and by L. Hinnov (written communication, 2010, Tables 1 and 2, Figure 4).

Besides the five sequences, the Natih Formation is also divided into the seven “A, a” to “G, g” members in descending order (W.O. Gigon, 1967, unpublished report in Hughes Clarke, 1988). The Formation consists mainly of limestone (with local rudist development) alternating with calcareous shale (Figures 2 and 3). The Natih and its lateral equivalents contain several important petroleum reservoirs in the Arabian Plate. For example, in the giant Natih Field of Oman, Terken (1999) identified four reservoirs, as well as one source-rock interval (Figure 1). In the neighboring giant Fahud Field (Figure 1), Morettini et al. (2005) showed the relationship between the seven members (and their units) and sequences ranging from sixth to third order. Although the Natih’s five sequences and seven members are correlated across Interior Oman, at outcrop and subsurface, their stage assignments are conflictingly interpreted by carbon-isotope (V. Vahrenkamp, in preparation) and/or biostratigraphic data (Simmons and Hart, 1987; Smith et al., 1990; Scott, 1990; Kennedy and Simmons, 1991a,b; Philip et al., 1995; van Buchem et al., 1996, 2002; Sharland et al., 2001). Therefore the orbital model offers a new and independent approach for age-calibrating the Natih sequences without age-indicative empirical control.

SEQUENCE STRATIGRAPHY

Natih Sequence Boundary

The boundary between the Natih Formation and underlying Nahr Umr Formation was interpreted as a hiatus (Hughes Clarke, 1988) and a regional sequence boundary (Droste and Van Steenwinkel, 2004;
Orbital Natih Supersequence, Oman

Grélaud et al., 2006; Homewood et al., 2008; Figures 2 and 4, Tables 1 and 2). It is here referred to as the Natih Sequence Boundary (Natih SB) although H. Droste (written communication, 2010) cautioned that its precise position is not necessarily at the Nahr Umr/Natih boundary. Based on an examination of cores from basinal settings, he found that the change from the Nahr Umr clastics to Natih carbonates appears to be related to changes in clastic influx but without evidence for significant shallowing or deepening events. He suggested this lithological change may represent the lateral migration of the Migratory Carbonate Suppressed Belt of Davies et al. (2004). Droste argued that it may therefore be linked to changes of siliciclastic influx, which could be climatic and/or linked to sea-level changes. He added that if it is related to sea level, the basal contact of the Natih Formation would be a flooding event but not a sequence boundary. The sequence boundary would then be more likely located within the Nahr Umr Formation.

Natih Sequence I

Natih Sequence I corresponds to the Natih G, F and E members in the Adopted Interpretation. The Natih Formation in the Madar 1 locality crops out in the Eastern Platform (Figures 1 and 2), where

<table>
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<tr>
<th>Stage</th>
<th>Haq et al. (1988) Surface</th>
<th>Age</th>
<th>GTS 04 Age</th>
<th>Revised Age</th>
<th>AP MFS</th>
<th>Oman Surface</th>
<th>Orbital Age</th>
<th>Diff 0.56</th>
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<td>K150</td>
<td>Fiqa MFS</td>
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<td>Sub-Fiqa Unc</td>
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<td>MFS V-2</td>
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<td>SB V-1</td>
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<td>93.5</td>
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<td>100.6</td>
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<td></td>
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<td>SB I-7a, IS1</td>
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<td>K110</td>
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</table>

MFS: maximum flooding surface; SB: sequence boundary; GTS 04: Gradstein et al. (2004)
Revised Age: Turonian/Coniacian at 88.6 Ma (GTS 2009, see www.stratigraphy.org).
Albian/Coniacian at 100.6 Ma (L. Hinnov, written communication, 2010) based on new Fish Canyon Tuff (FCT) monitor (28.293 My; Renne et al., 2009), the top of the Albian Stage becomes 100.57 Ma, i.e. 0.97 My older than the GTS 2004 argon-based age that used a previous 28.02 My FCT monitor of 99.6 Ma.
Orbital Age: see Table 2 and Figure 4
Difference: orbital age minus revised empirical age; average of absolute age differences 0.56 My (16 surfaces).
### Table 2

Orbital Calibration of Natih Formation (million years before present, Ma)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Dozon Surface</th>
<th>Straton Surface</th>
<th>Orbital Age</th>
<th>Oman and Arabian Plate Surface</th>
<th>Haq et al. (1988) Surface</th>
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<td>base 6A-2</td>
<td>base 219</td>
<td>88.6</td>
<td>Fiqa MFS, K150</td>
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<tr>
<td>Tur/Con</td>
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<td>?</td>
<td>unresolved</td>
<td>88.6</td>
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<tr>
<td>Turonian</td>
<td>SB 6</td>
<td>base 220</td>
<td>89.0</td>
<td>Fiqa SB, End Hiatus</td>
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</tr>
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<td>base 7C-12</td>
<td>base 221</td>
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<td>Hiatus</td>
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<tr>
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<td>base 252</td>
<td>102.0</td>
<td>SB I-5</td>
<td></td>
</tr>
<tr>
<td>Albian</td>
<td>mid-7A-4</td>
<td>mid-253</td>
<td>102.2</td>
<td>MFS I-4, K110</td>
<td>MFS UZA 2.1</td>
</tr>
<tr>
<td>Albian</td>
<td>base 7A-4</td>
<td>base 253</td>
<td>102.4</td>
<td>SB I-4</td>
<td></td>
</tr>
<tr>
<td>Albian</td>
<td>base 7A-3</td>
<td>base 254</td>
<td>102.8</td>
<td>SB I-3</td>
<td></td>
</tr>
<tr>
<td>Albian</td>
<td>base 7A-2</td>
<td>base 255</td>
<td>103.2</td>
<td>SB I-2</td>
<td></td>
</tr>
<tr>
<td>Albian</td>
<td>SB 7</td>
<td>base 256</td>
<td>103.6</td>
<td>SB I-1, Natih SB</td>
<td>SB UZA 2.1</td>
</tr>
<tr>
<td>Albian</td>
<td>8C-12</td>
<td>257</td>
<td>104.0</td>
<td>Nahr Umr</td>
<td></td>
</tr>
</tbody>
</table>

Note: Stage boundaries not determined by biostratigraphy and shown where their estimated age occurs (see Table 1).
Figure 4: Sea-level curve computed by R.K. Matthews compared to Natih sequences in Adopted Interpretation (Figures 1 to 3 in Enclosure) and global eustatic curve of Haq et al. (1988). Stage boundaries, maximum flooding surfaces (MFS) and sequence boundaries (SB) are age recalibrated as shown in Tables 1 and 2. Orbiton 7 is predicted between sequences boundaries SB 7 (103.4 Ma) and SB 6 (89.0 Ma), corresponding to the Natih SB and Fiqa SB. The Natih Supersequence correlates to global Supersequence UZA 2.
Natih Sequence I is divided into subsequences I-1 to I-7 in the Adopted Interpretation. At this locality the youngest Subsequence I-7 occurs between sequence boundaries that are incised by valleys that are up to one kilometer in width. The valleys that cut the older Incision Surface 1 (IS1) are about 20 m deep, and the ones that cut Incision Surface 2 (IS2) are about 30 m deep.

Based on 3-D seismic and borehole data Subsequence I-7 passes laterally to an intra-shelf basin located between the Eastern and Western Natih platforms (Figure 1, see also figures 6 and 7 in Homewood et al. 2008). The IS1 and IS2 incision surfaces are correlated to seismic reflections that are interpreted to bound major clinoforms that prograded from east to west (Figures 1 and 2). Accordingly Subsequence I-7 is here considered, in its own right, as a major sequence, hereafter referred to as Sequence I-7. It is interpreted to consist of six clinoforms (subsequences) I-7a to I-7f in Figures 2 and 4.

In the Fahud Field area, located in the Natih Western Platform, Natih Sequence I-7 is depicted in figure 43a of Homewood et al. (2008). It is shown as a mirror image of itself in the Eastern Platform and to also consist of six clinoforms prograding from west to east. The clinoforms of Natih Sequence I-7 are also shown in the Musallim 3-D seismic survey located on the southern part of the Eastern Platform (Figure 1, see figure 6 in Homewood et al., 2008). Here the clinoforms prograde from south to north but only five clinoforms are identified between IS1 and IS2 (labeled a to g). In the present paper it is assumed that six major clinoforms occur in Natih Sequence I-7 not only based on the presented data and interpretations, but also because of the predictions of the orbital model discussed below.

In Traverse A, clinoforms I-7a and I-7b are imaged above the seismic reflection corresponding to IS1 and dip at an angle of 2°–5° degrees (Figure 2). They attain a maximum thickness of ca. 30 m and form a lowstand wedge that is coeval to the sea-level drop associated with Incision Surface IS1 in Jabal Madar (Madar 1 locality). The four clinoforms I-7c to I-7f dip at lower angles (less than 1° degree). Clinoform I-7c contains the maximum flooding surface (MFS I-7c) and clinoforms 17d to I-7f form the regressive or highstand systems tract. The clinoforms decrease in thickness from ca. 50 m (Clinoform I-7c) to the order of a few meters (Clinoform I-7f).

**Maximum Flooding Surfaces:** Sharland et al. (2001) correlated Late Albian MFS K110 and Early Cenomanian MFS K120, respectively, to the similarly dated MFS UZA 2.1 and MFS UZA 2.2 of Haq et al. (1988; Table 1, Figure 4). They positioned MFS K110 in the lowermost Natih Member G corresponding to Subsequence I-1, and MFS K120 in the lowermost part of the Natih Member E corresponding to Subsequence I-3. This paper takes the MFS of the Adopted Interpretation and repositions: (1) MFS K110 in Subsequence I-4, which contains the MFS I-4 of Sequence I, and (2) MFS K120 in Clinoform I-7c, which contains the MFS I-7c of Sequence I-7 (Figures 2 and 4, Table 2).

**Natih Sequence II**

In Traverse A, Natih Sequence II is bounded below by the sequence boundary (SB II = SB II-1) that passes to Incision Surface IS2 (Figures 2 and 4). Natih Sequence II corresponds to the D and C members and is exposed at outcrop in Traverse B across Al Jabal al-Akhdaar (Adopted Interpretation, Figure 3). The traverse is constructed in the Permian – Cretaceous autochton that is preserved within a window surrounded by the Semail Ophiolite and related allochthonous units.

Sequence II is ca. 60 m thick and divided into subsequences II-1 to II-7 that are correlated as layer-cake units across the 64-km-long Traverse B (Figure 3). Homewood et al. (2008) noted that these subsequences have a very flat geometry and appear to have been deposited in water depths of several 10s of meters. The dominant pelagic micro- and nanofossil content of Sequence II suggests a deep-marine, intra-shelf basin environment. However in 2010, P. Homewood wrote to the present author that according to M. Simmons the so-called pelagic fauna is an error of determination. Simmons considered the planktic foraminifera to probably be discors. Modern *Discorbis* lives in very shallow-water depths. F.S.P. van Buchem (personal communication, 2010) also interpreted the depositional setting of Natih Sequence II as shallow-water with limited accommodation space. A shallow-water setting may explain why the Natih II subsequences are much thinner (ca. 5–10 m) in comparison to those of other Natih sequences.
Between the Eastern and Western Natih platforms (Figure 1) Natih Sequence II is characterized by several higher-order cycles that filled-up the residual accommodation space in the intra-shelf basin (see figure 6 in Homewood et al., 2008). They occur above sequence boundary SB II (Incision Surface IS2) and dip at a high-angle. They are difficult to correlate locally, and would correspond to the oldest subsequences of Natih Sequence II (H. Droste, written communication, 2010).

**Natih Sequence III**

In Traverse B, Natih Sequence III (Figures 1 and 3; Adopted Interpretation; B Member, and lower part of A Member) consists of subsequences III-1 to II-12. Subsequences III-1 to III-4 (together ca. 65 m thick) are layer-cake units. Subsequence III-5 is ca. 20 m thick in the middle of the traverse (Tanuk and Kamah localities, mislabeled as III-6 in Homewood et al.’s enclosure and corrected in Figure 3) and cannot be resolved from Subsequence III-4 in the western part of Traverse B.

Subsequences III-6 to III-12 consist of clinoforms that downlap onto the top of Subsequence III-5 between the Tanuf Palm and Al Munthar North localities (Figure 3). The present paper interprets the downlap surface at the top Subsequence III-5 as a sequence boundary (SB III-6). The maximum thickness of the clinoforms varies from 10–30 m and their lateral extent, where resolved, is typically several 10s of kilometers. They are overlain by Sequence IV in the west and eroded by an unconformity at the base of Sequence V to the east.

**Maximum Flooding Surfaces:** Sharland et al. (2001) correlated MFS K140 to MFS UZA 2.5 of Haq et al. (1988, Table 1), both of Early Turonian age, and placed it in the Natih B Member corresponding to Subsequence III-2. In the Adopted Interpretation a maximum flooding surface (MFS III-4) is positioned in Subsequence III-4 and another (MFS III-10) in Subsequence III-10 (Figures 3 and 4). The latter MFS III-10 is here considered MFS K140 (Tables 1 and 2).

**Natih Sequences IV and V**

Sequence IV is not divided into subsequences in the Adopted Interpretation. In the western part of Traverse B (Figure 3), it transgresses over a regional hardground at the top of the clinoforms of Sequence III, and is overlain by the Coniacian Muti (Fiqa) Formation. In the eastern part of Traverse B it is absent by non-deposition and/or erosion. The boundary between sequences III and IV is shown to cut the transgressive systems tract (TST) of Subsequence IV-12 at the School locality.

Sequence IV is apparently widespread in Oman. Both Filbrandt et al. (2006, their figure 26) and the Adopted Interpretation (see Homewood et al., 2008, their enclosure IIA-3, not repeated in the present paper) show that in the Fahud Field, Natih Sequence IV (units A1 and A2 of A Member) is the youngest Natih sequence below the Muti Formation or corresponding Shargi Member of the Fiqa Formation, not unlike the stratigraphic geometry in the western part of Traverse B (Figures 3 to 5).

The uppermost part of the Natih Formation is only represented in the eastern part of Traverse B by Sequence V in the Adopted Interpretation, where it is overlain by the shales of the Muti (Fiqa) Formation (Figure 3). Natih Sequence V consists of subsequences V-1 and V-2 and is absent in the Fahud Field area, and apparently in most of subsurface Interior Oman (Filbrandt et al., 2006).

**Maximum Flooding Surfaces:** This paper interprets Sequence IV as a maximum flooding interval containing MFS IV because of its regional extent above Sequence III (Figures 3 and 4). Subsequence Natih V-2 also contains a maximum flooding surface (MFS V-2) that is truncated below the Muti (Fiqa) Formation at the Tanuf Palm locality (Figure 3). In the eastern part of Traverse B, between the Sumayt and Wadi Mu’aydin localities, incised channels occur in subsequences V-1 and V-2.

**Fiqa Sequence Boundary**

The Natih Formation is overlain by the Muti Formation at outcrop or the correlative Shargi Member of the Fiqa Formation in subsurface (Hughes Clarke, 1988; Béchennec et al., 1995; Forbes et al., 2010;
Figures 3 to 5). According to Droste and Van Steenwinkel (2004) well data in Oman show that the lowermost part of the Shargi shale package is lignitic and contains thin streaks of sandstone and siltstone, as well as traces of glauconite and marine fauna. They suggested that this package was deposited in a marginal marine (lagoonal) to estuarine setting. This lowermost package passes further south at outcrop in Oman to the Qitqwat Formation (Béchennec et al., 1995; Forbes et al., 2010).

Béchennec et al. (1995) mapped the outline of the basin (Muti Basin) in which the correlative Muti Formation and Shargi Member were deposited. The basin extended over Al Jabal al-Akhdar where Traverse B is situated, and most of North and Central Oman including the locality of Traverse A. The Muti Formation and Shargi Member are here assigned to the Fiqa Transgression above the Fiqa Sequence Boundary (Fiqa SB, Figures 4 and 5).

**Sub-Fiqa Unconformity**

Béchennec et al. (1995) noted that the top Natih Formation is capped by a major ferruginous hardground (break in sedimentation) that was related to emergence over most the Arabian Platform. In their figure 3.30, Sharland et al. (2001) showed a photograph taken in Wadi Mu’aydin (location in Figures 1 and 3), where the top of the Natih carbonate grainstone is channelized. It is overlain by the Muti (Fiqa) Formation consisting of a bed of oolitic ironstone, one meter thick in its basalmost part, which passes abruptly to the deep-marine shales of the Muti (Fiqa) Formation.

Droste and Van Steenwinkel (2004, their figure 14) showed 3-D seismic data from North Oman that image several generations of highly sinuous channels that cut the top of the Natih Formation and are overlain by deep-marine shales of the Fiqa Formation. Some channels have widths of 100s of meters and depths of as much as 150 m. Filbrandt et al. (2006, their figure 26) also documented top-Natih incised channels up to 200 m deep below the Fiqa Formation in the Yibal, Natih, Fahud and Fahud West fields.

The term **Sub-Fiqa Unconformity** is adopted here for the valley-incised, exposure surface at the top of the Natih Formation (Figures 3 to 5). The unconformity separates the Aruma Group (Muti and Fiqa formations) from the underlying Wasia Group (Natih Formation) and is also known as the pre-Aruma unconformity or Wasia-Aruma break. Sharland et al. (2001) marked the lower boundary of Arabian Plate tectono-stratigraphic megasequence AP9 by their **middle Turonian unconformity**, which corresponds to the Sub-Fiqa Unconformity.

**AGE DATING OF NATIH SEQUENCES**

The stage assignments for the Natih sequences vary significantly according to the biostratigraphic criteria used by various authors (ammonite, microfaunal and nannofossil data) and carbon-isotope data. The below discussion is based on the summaries of previous works given in Homewood et al. (2008, see their figure 5) and Forbes et al. (2010).

**Fiqa Transgression**: Forbes et al. (2010) assigned the lowermost lignitic/clastic unit of the Shargi Member of the Fiqa Formation (Qitqwat Formation at outcrop) to the Coniacian (Sub-biozone F63b of Petroleum Development Oman). They dated the Shargi Member as Coniacian – Early Campanian, and estimated its basal age (Fiqa SB) at ca. 88.6 Ma at the Turonian/Coniacian boundary in GTS 2009. In contrast, the basal part of Muti (Fiqa) Formation was assigned an Early Turonian age (Rabu, 1987; Béchennec et al., 1992a,b).

Sharland et al. (2001) placed maximum flooding surfaces Lower Coniacian MFS K150 and Santonian MFS K160 in the shales near the base of the Fiqa and Muti formations. They considered the start of transgression that culminated in the MFS K150 flooding (here Fiqa Transgression) to be no younger than Mid-Turonian thus dating the Sub-Fiqa Unconformity as Mid-Turonian or older. They correlated MFS K150 to global MFS UZA 3.1 of Haq et al. (1988; Figure 4, Tables 1 and 2), which the latter authors correlated to the Turonian/Coniacian boundary.
**Sub-Fiqa Unconformity and Hiatus:** Forbes et al. (2010) reported that dating for the down-cutting event (incision of top Natih, Sub-Fiqa Unconformity) indicate a Mid- to Late Turonian age, possibly extending into earliest Coniacian. They suggested an approximate age for the event at ca. 91.0–88.6 Ma thus highlighting a hiatus of ca. 1.4 My between the Natih and Fiqa (Muti) formations. Searle (2007, his figure 4) approximated the age of the hiatus between ca. 93.0–88.0 Ma spanning most of the Turonian – earliest Coniacian. In contrast, other authors favored an Early and/or Mid-Turonian age for the hiatus (Rabu, 1987; Béchennec et al., 1992a,b; Sharland et al., 2001).

**Natih Sequences IV and V:** Whereas Hughes Clarke (1988) cited the age of the Natih Formation as Late Albian and Cenomanian, Forbes et al. (2010) extended its age into Mid-Turonian. They based this conclusion on: (1) discovery of Lower Turonian ammonites in the Natih A Member (Kennedy and Simmons, 1991a,b; van Buchem et al., 1996, 2002; Bulot et al., in preparation; in Homewood et al., 2008, their figure 5), and (2) Lower and Middle Turonian nannofossil and microfaunal data recovered from two wells in the uppermost Natih Formation in North Oman (Packer and Zucchi, 2002, unpublished Millenia report for PDO; in Homewood et al., 2008, their figure 5). Forbes et al. (2010) considered these Turonian units as probably time-equivalent to Sequence IV in Fahud Field and to sequences IV and V in Al Jabal al-Akhdar of the Adopted Interpretation (Figures 3 and 4).

**Cenomanian/Turanian Boundary:** The position of this boundary as summarized in Homewood et al. (2008, their figure 5) varies considerably: (1) from as high as within Natih Sequence III and/or Sequence IV (Sikkema, 1991, unpublished PDO report; Jacovides and Varol, 2002, unpublished Millenia Report for PDO; van Buchem et al., 1996, 2002; Bulot et al., in preparation), to (2) as low as Sequence II based on carbon-isotope data (V. Vahrenkamp, in preparation).

**Albian/Cenomanian Boundary:** The position of this boundary in the Natih Formation as summarized in Homewood et al. (2008, their figure 5) and discussed in Forbes et al. (2010) is also unresolved. Bulot et al. (in preparation) based on ammonites place it towards the base of the Natih Formation, as did V. Vahrenkamp (in preparation) based on carbon-isotope data. Jacovides and Varol (2000, unpublished Millenia Report for PDO), however, extend the top of the Albian Stage as high as the Natih C Member (upper part of Sequence II) based on their update of the microfaunal zonation of Sikkema (1991, unpublished PDO report).

**Summary:** The above interpretations taken together provide the following general age constraints:

1. The Natih Formation is Late Albian to intra-Turonian (ca. 104.0–91.0 Ma).
2. The boundaries of the Cenomanian Stage are not resolved in the Natih Formation.
3. A brief hiatus occurred in intra-Turonian to earliest Coniacian time (ca. 91.0–88.6 Ma).
4. The Fiqa Transgression started in ?intra-Turonian – Early Coniacian time (ca. 88.6 Ma).

The above-cited ages are from Forbes et al. (2010) based on estimates taken from the nearest stage/sub-stage boundary from GTS 2009.

**CAMPANIAN INTRA-FIQA UNCONFORMITY**

Over paleohighs in subsurface Interior Oman and the United Arab Emirates (UAE) an angular unconformity, the Intra-Fiqa Unconformity, cuts the Sub-Fiqa Unconformity (Figure 5). In the literature these two unconformities are not explicitly named nor clearly separated leading to some confusion as to the nature and origin of the Sub-Fiqa Unconformity and the Natih’s sequence stratigraphy. Therefore a digression is necessary to show that the Intra-Fiqa Unconformity is much younger and unrelated to the stratigraphic break between the Natih and Fiqa formations.

During the Late Cretaceous, the oceanic lithosphere and associated allochthonous units of the Neo-Tethys Plate were obducted over the northern, eastern and southern margins of the Arabian Plate (see figure 3.35 in Sharland et al., 2001, and references therein). In Oman and the UAE the Semail Ophiolite represents the remnants of the oceanic lithosphere (Figure 1; see recent review in Searle, 2007). The Semail Ophiolite is believed to have originated ca. 600 km to the east of Oman’s coast in the Neo-Tethys Ocean above a NE-downdropping subduction slab at ca. 95.0 Ma in Late Cenomanian (Breton et al.,...
The initiation of subduction is approximately coincident with the deposition of Natih Sequence III, leading to an interpretation that tectonism may have structurally affected the Natih's depositional setting or caused uplift associated with the Sub-Fiqa Unconformity.

The emplacement of the Semail Ophiolite and related allochthonous units ended at ca. 70.0–68.0 Ma in latest Cretaceous (Maastrichtian, Searle, 2007, see references therein; Figure 5). A second obduction emplaced the Masirah Ophiolite over southernmost Oman in latest Cretaceous (Maastrichtian) and Tertiary times (Schreurs and Immenhauser, 1999; Filbrandt et al., 2006). The associated structural manifestation of these events in Interior Oman and the UAE is commonly referred as the First Alpine Event (Loosveld et al., 1996; Terken, 1999; Figure 5).

The First Alpine Event is characterized by broad uplifted regions and faulting in Interior Oman (see figure 25 of Filbrandt et al., 2006), and the development of a foredeep basin (Suneinah Foredeep, Muti Basin) in front of the southwestward-advancing allochton (O’Connor and Patton, 1986; Patton and O’Connor, 1988; Robertson 1987a,b, 1988; Boote et al., 1990; Warburton et al., 1990; Scott, 1990; Burchette, 1993; Béchennec et al., 1995; see discussion and references in Droste and Van Steenwinkel, 2004; Searle, 2007; Homewood et al., 2008; Forbes et al., 2010). As noted above, the exposure and channel-incising event in Interior Oman (Sub-Fiqa Unconformity) is associated by some of the above-cited authors to the First Alpine Event. In addition to the uplift attributed to the First Alpine Event, Filbrandt et al. (2006) related the incision of channels to further uplift caused by Infracambrian Ara Salt and fault movements.

However, a review of the data and interpretations from Interior Oman
and the UAE indicates the structural deformation associated with the First Alpine Event started in the Campanian during rather than before the deposition of the Fiqa Formation (Figure 5). It is marked by the Campanian angular Intra-Fiqa Unconformity that splits the Fiqa Formation into the Lower and Upper Fiqa (Shargi) units. More specifically, G. Forbes (2010, written communication) reported that in North Oman a sandstone-prone interval occurs in the Shargi Member and its base correlates to the Intra-Fiqa Unconformity. Below the unconformity, the lower Shargi Member is Coniacian and Santonian and above it the upper Shargi Member is of Campanian age. The sandstone-prone interval is thought to be equivalent to the Fayah Formation along the Al Batain Coast (Forbes et al., 2010).

The position of the Intra-Fiqa Unconformity can be seen in seismic images that show deep-seated faults of Campanian age cutting the Natih Formation and Sub-Fiqa Unconformity that continue upwards through the Coniacian – Santonian Lower Fiqa unit (i.e. lower Shargi Member, Figure 5; Filbrandt et al., 2006, see their figures 10, 12 and 14). The giant Fahud Field provides a good example of Campanian faulting in Oman. Over the northeast flank of the Field the upper part of the Natih Formation (Natih A Member) is conformably overlain by the Fiqa Formation (see figure 4a in Morettini et al., 2005). The crest of the Field is partially eroded and bounded to the southeast by the main Fahud Fault. Based on biostratigraphic data the main Fahud Fault was vertically dislocated by ca. 1.0 km in Campanian time (Filbrandt et al., 2006). This implies that over the crest of the Fahud Field (and other paleohighs) the Coniacian – Santonian lower Shargi Member was conformably deposited over the Natih Formation. At the upper Natih was then eroded over the uplifted crest during the Early Campanian. In the later Campanian and Maastrichtian times the Upper Shargi and younger units were deposited over the Field. This stratigraphic geometry is similarly depicted in several papers (Terken, 1999, his figures 3 and 12; Forbes et al., 2010, their enclosure I; Figure 5) and for the Lekhwair Bulge (i.e. peripheral bulge) by Sharland et al. (2001, their figure 3.37, modified after Boote et al., 1990; see also Boote and Mou, 2003, their figure 17).

J. Filbrandt (written communication, 2010) confirmed that an unconformity occurs within the Fiqa Formation (Intra-Fiqa Unconformity of the present paper). Based on an internal review in Petroleum Development Oman of seismic data in North Oman it is identified as a sequence boundary (SSB3) at the base of the upper Shargi Member (base of the sandy unit, top of PDO Biozone F64). The top of the Natih Formation is named SSB1 in their study (Sub-Fiqa Unconformity of the present paper). Between the two sequence boundaries they identify sequence boundary SSB2, which forms significant channels best expressed east of the Maradi Fault Zone south of Jabal Salakh (base of PDO Sub-biozone F64c, top of PDO Biozone F63). J. Filbrandt interpreted these channels on 2-D seismic data and found that they are very clear and distinct from the channels at the top of the Natih A Member (Sub-Fiqa unconformity), and oriented broadly in a NW-SE direction off the Al Huqf High.

In the Saih Hatat region (located southeast of Al Jabal al-Akhdar, Figures 1 and 5) Searle (2007) interpreted the As Sifah Eclogite as recording the peak of high-pressure metamorphism. He cited a U-Pb zircon age for the eclogite at ca. 79.0 Ma (Warren et al., 2003) in Campanian time. He concluded: “the leading edge of the Arabian continental shelf was subducted to ca. 80 km depth beneath the oceanic crust and mantle during the Campanian, some 15 million years after the formation of the [Semail] ophiolite.” This compressional event approximately coincides by age with that of the Intra-Fiqa Unconformity and the deformation associated with the First Alpine Event (Figure 5).

In the UAE, the Intra-Fiqa Unconformity also separates the Lower and Upper Fiqa units (Ali et al., 2008, Floor Thrust fault in their figures 7 and 13; Searle and Ali, 2009, Jabal Hafit, see their figures 11 and 12). Ali and Watts (2009) modeled the flexure of the lithosphere in the UAE using different parameters to characterize loading by the Semail Ophiolite. The model was constrained by geophysical data (seismic line and gravity profile) and four wells with biostratigraphic control. In their preferred model the transition from an extensional rifted margin (Peronian to Cretaceous Lower Fiqa unit) to a compressional foreland basin (Upper Fiqa unit) occurred at ca. 80 Ma, in Campanian time (Figure 5). Their preferred age for the start of compression coincides with that of the As Sifah Eclogite and their conclusion is similar to that of Filbrandt et al. (2006) who stated: “the major faults (Fahud, Burhaan, Saih Rawl and Maradi) can be shown to have accommodated significant growth only in the Campanian. Thus the Mesozoic carbonate platform in North Oman remained largely stable, undisturbed by faulting and subsided gradually until that time” [Campanian].
The structural and age data and their interpretations indicate that whereas the obduction of the Semail Ophiolite and related allochthonous units started in Late Cenomanian (ca. 95.0 Ma) and was approximately syn-depositional with Natih Sequence III, the earliest structural deformation (Intra-Fiqa Unconformity) in Interior Oman and the UAE started in the Campanian (ca. 80 Ma, Figure 5). Therefore attributing the Sub-Fiqa Unconformity, which occurred ca. 10 My earlier in Late Turonian - earliest Coniacian, to tectonism is unsupported.

Most reviewers of this study, however, caution against this conclusion and consider the contribution of tectonic uplift to remain a likely factor during the deposition of the upper part of the Natih Formation. For example, J. Filbrandt (2010, written communication) suggests that the interval between the Sub-Fiqa and Intra-Fiqa unconformities:

“may have been in part influenced by tectonic loading far-field (100 to 200 km distant) associated with the stacking of the nappes farther north with a (fortuitously-timed) sea-level drop between 90 and 80 Ma. Whilst erosion at the top of the Natih [Sub-Fiqa Unconformity] may not be directly related to proximal tectonics associated with obduction or telescoping of the Tethyan margin, perhaps the loading of the margin and the formation of the foredeep created a low-relief forebulge that migrated southwards through time. The diachronous nature of the Muti Formation may reflect this loading response. Indeed, in our figure 25 we note that the Natih is incomplete in the northern and eastern domains. Both these areas may have experienced some (diachronous) uplift caused by far-field loading by ophiolites, especially in the north. It may turn out, of course, that the Semail Ophiolite was simply too far away. In this latter case, major eustatic sea-level drop would be the most likely explanation for SSB1 [Sub-Fiqa unconformity].”

H. Droste (2010, written communication) similarly concludes:

“the Wasia/Aruma unconformity along the northeastern flank of the Arabian Plate has a major tectonic component with several hundreds of meters of erosion. In Interior Oman major incisions suggest a regional relative sea-level drop of some 150 m. On a regional scale the amount of truncation at top Natih [Sub-Fiqa Unconformity] progressively decreases from the Oman Mountains towards the Rub' Al Khali Basin (see correlation panel in figure 1 in Homewood et al., 2008). This suggests there was a broad regional uplift, which was strongest along the margin of the Arabian Plate. If the top Natih erosion was caused by a eustatic sea-level drop one would expect more erosion towards the interior of the platform. This does not exclude the presence for a Turonian eustatic sea-level drop. However, given the much stronger tectonic overprint evidence for such a drop cannot be conclusively extracted from the sedimentary record in the Oman area.”

Sharland et al. (2001) also attributed the short-lived (less than one million years in their estimation) relative sea-level drop associated with the Sub-Fiqa Unconformity to tectonic uplift. Importantly, however, they added that it may also be related to the Late Turonian global ca. 100+ m sea-level drop (long minus short term) interpreted by Haq et al. (1988; SB UZA 3.1 in Figure 4, Tables 1 and 2). Harris and Frost (1984) also suggested the Sub-Fiqa Unconformity was primarily linked to a eustatic sea-level fall. As discussed below a eustatic origin for the Sub-Fiqa Unconformity is consistent with the orbital-forcing model of glacio-eustasy.

**ORBITAL STRATIGRAPHY**

_Natih Sequence Boundary:_ In the orbital time scale of Matthews and Al-Husseini (2010) the age for the basal sequence boundary of any orbiton (SB n) is calculated by the formula SB n = n x 14.58 + 1.5 Ma. For SB 7 the age is predicted at ca. 103.6 Ma within the Late Albian (Figure 4, Tables 1 and 2). The age of SB 7 falls between the estimated ages of the Nahr Umr/Natih boundary at ca. 102.0 Ma (Sharland et al., 2001) and ca. 104.0 Ma (Forbes et al., 2010). In Figure 4 the Natih SB is correlated to SB 7 between the sea-level lowstands of stratons 257 and 258. This lowstand interval represents the transition between the Nahr Umr and Natih formations, which is not fully documented in terms of sequence-stratigraphic architecture. As noted by H. Droste (written communication, 2002) in subsurface basinal
areas the base Natih Formation may be a flooding event. It may therefore correspond to the maximum flooding surface in Straton 256, or the major sea-level rise predicted in the lowermost part of Straton 255 (Figure 4).

SB 7 is correlated to the interpreted drop of ca. 50 m between the long-and short-term sea-level curves at the base of global Supersequence UZA 2 (SB UZA 2.1 of Haq et al., 1988, previously 98.0 Ma, Table 1, Figure 4). Adopting the revised estimate for the Alban/Cenomanian boundary at ca. 100.6 Ma (L. Hinnov, 2009, written communication, see footnote of Table 1) implies SB UZA 2.1 has an empirical age estimate of ca. 102.5 Ma, compared to 103.6 Ma in the orbital calibration (Figure 4).

Stratons: The orbital time calibration of the Natih Formation assumes that its 34 subsequences tracked without hiatuses the sea-level fluctuation caused by the long-eccentricity ca. 405 Ky orbital signal predicted by Laskar et al. (2004). Each subsequence is named a Straton to avoid confusion with terms involving order in sequence stratigraphy. An integer number is given to each straton and corresponds to a counting system that starts with the Earth today in Straton 1. The integer can also be used to closely estimate the age of the basal sequence boundary (SB) of the straton: age of straton’s SB = ca. integer x 0.405 My. Orbiton 7 consists of the 36 strats 256 to 221 (Figure 4 and Table 2).

Model Sea Level: In Figure 4 the model sea-level curve was computed by R.K. Matthews using the Parametric Forward Model software (PFM, see Matthews and Frohlich, 2002; Matthews and Al-Husseini, 2010). The model is generic because the parameters used to determine ice making and melting in Antarctica (i.e. sea-level fluctuations) were not specifically optimized to simulate the Late Albian to Early Coniacian time interval. The curve oscillates between ca. –15 and –55 meters relative to an ice-free Antarctica. It shows many patterns that resemble aspects of the Natih sequence stratigraphy (MFSs and SBs), and those of the global curve (Haq et al., 1988).

Dozons and Third-order Orbital Sequences: Besides an integer, each straton is also numbered from 1 to 12 in ascending order within one of the three dozons 7A to 7C that form Orbiton 7 (Figure 4 and Table 2). Dozons, besides consisting of 12 stratons, can also be recognized because they too are bounded by significant sequence boundaries. As discussed below this parallel numbering scheme provides robust criteria for confirming that subsequences are indeed stratons (ca. 405 Ky cycles) and not higher-order cycles (e.g. ca. 100 Ky or 20–40 Ky orbital cycles, Matthews and Al-Husseini, 2010).

Dozon 7A, consisting of the twelve stratons 7A-1 to 7A-12 (256–245), is completely represented by the twelve subsequences of Natih Sequence I: six subsequences I-1 to I-6 and six clinoforms I-7a to I-7f (Figure 4 and Table 2). It is bounded by the Natih SB (SB 7 same as SB 7A) below (ca. 50 m sea-level drop in Haq et al., 1988), and above by Incision Surface IS2 (SB 7B, with 30 m sea-level drop implied by the depth of valleys). Dozon 7A also carries the signature of two nominal orbital sequences each with a duration of ca. 2.4 My consisting of six stratons (Matthews and Frohlich, 2002). The intervening sequence boundary (Incision Surface IS1) is due to a 20 m sea-level drop (glaciation) caused by orbital tuning (low eccentricity) at the end of Straton 7A-6 (251).

Dozon 7B, consisting of the twelve stratons 7B-1 to 7B-12 (244–233), is also completely represented by twelve subsequences: subsequences II-1 to II-7 and III-1 to III-5 (Figure 4 and Table 2). In the Adopted Interpretation it breaks out into a long orbital sequence lasting ca. 2.8 My (II-1 to II-7, respectively 7B-1 to 7B-7) and short orbital sequence lasting ca. 2.0 My (subsequences III-1 to III-5, respectively 7B-6 to 7B-12). The downlap surface at the top of Subsequence III-5 (SB III-6) is taken as its upper sequence boundary (SB 7C) and closes Dozon 7B.

Dozon 7C (stratons 7C-1 to 7C-12, 232–221) starts with a new transgression characterized by prograding clinoforms III-6 to III-12 that downlap onto surface SB III-6 from east to west (Figures 3 and 4). This Dozon is only represented by ten Natih subsequences (III-6 to III-12, IV, V-1 and V-2) instead of twelve (Figures 3 and 4, Table 2). The final two stratons 7C-11 and 7C-12 (222 and 221) are not represented in the Natih Formation and their absence is very significant as discussed below.

Sub-Fiqa Unconformity: The 34 Natih subsequences do not complete the 36 count that is predicted for an orbiton (Figure 4 and Table 2). The discrepancy is resolved by attributing stratons 7C-11 and
7C-12 (222 and 221) to a hiatus of ca. 810 Ky (between ca. 89.8–89.0 Ma) following the deposition of Natih Subsequence V-2 (Sub-Fiqa Unconformity). The hiatus falls by age in Late Turonian (older than the Turonian/Coniacian boundary at 88.6 Ma in GTS 2009) as consistent with the age of the biostratigraphic break between the Natih and Fiqa (Muti) formations (Forbes et al., 2010). The hiatus may also extend into the model lowstand predicted for Stratron A-1 (220) in lowermost Orbiton 6.

As noted in the Introduction one of the main tests for the orbital time scale is that orbitons should be separated by major glacio-eustatic, sea-level lowstands (Matthews and Al-Husseini, 2010). The model’s prediction for lowstands in stratons 7C-11 and 7C-12 (and possibly 6A-1) is consistent with the Late Turonian 100+ m global sea-level drop (long minus short term) of Haq et al. (1988, Figure 4). The amplitude and age of the global sea-level drop correlates closely to the Late Turonian – ?earliest Coniacian 150+ m-deep channel cutting event at the top of the Natih Formation in subsurface Interior Oman (Droste and Van Steenwinkel, 2004; Filbrandt et al., 2006; Forbes et al., 2010).

Maximum Flooding Surfaces: Tables 1, 2 and Figure 4 list the names and ages of the 16 Late Albian to earliest Coniacian maximum flooding surfaces (MFS) and sequence boundaries (SB) of Haq et al. (1988). The 16 surfaces are tentatively correlated to those of the Natih as mainly interpreted in the Adopted Interpretation. Also shown are the five Arabian Plate maximum flooding surfaces MFS K110 to K150 as correlated by Sharland et al. (2001) to the global MFSs. In the present paper SB II-6 (SB II-57), MFS III-4 and the downlap surface SB III-6 (Figures 3 and 4) were added and apparently the latter two have no correlatives in the other schemes.

The estimated orbital ages for the 16 surfaces differ by at most ±1.1 My (average of absolute differences = 0.56 My) relative to their empirically estimated ages (Figure 4 and Table 1). Given the great number of surfaces (16) and the cited standard deviations for this time interval (range from ±0.8 to ±1.0 My in GTS 2004) this result is not considered significant.

Fiqa Sequence Boundary and Fiqa Maximum Flooding Surface: In the proposed correlation the Fiqa (Muti) Transgression started in the sea-level lowstand of Stratron 6A-1 (220, Figure 4) above the Fiqa SB (89.0 Ma). This surface is ca. 405 Ky older than the rapid 25 meter increase in sea level predicted at the base of Stratron 6A-2 (219) with an age of ca. 88.6 Ma. The latter surface is correlated to the Fiqa MFS (Forbes et al., 2010), MFS K150 (Sharland et al., 2001), MFS 3.1 (Haq et al., 1988) and the Turonian/Coniacian boundary with the exact same age in GTS 2009 (www.stratigraphy.org).

Duration and Order of Sequences: The orbital calibration implies that the global sequences vary substantially in duration. For example, Sequence UZA 2.5 has an estimated duration of 4.8 My (95.8–91.0 Ma); it has the duration of one dozon but apparently straddles dozons 7B and 7C. Sequence UZA 2.1 and UZA 2.2 each consist of six stratons (Figure 4 and Table 2; ca. 2.4 My) and correspond to Natih subsequences I-1 to I-6, and Sequence I-7, respectively. Other sequences are much shorter: UZA 2.7 is two stratons (ca. 810 Ky; Sequence V), and UZA 2.6 just one straton (ca. 405 Ky; Sequence IV).

GLACIO-EUSTASY AND SEA-LEVEL FLUCTUATIONS

In their cyclo-stratigraphic study of the Albian Nahr Umr Formation in Oman, Immenhauser and Matthews (2004, see p. 22–27) reviewed the many possible causes of global sea-level fluctuations. They concluded that orbital-forcing of glacio-eustasy is the only known mechanism that can explain the observed high-frequency, cyclo-stratigraphy of the Nahr Umr Formation. The present paper continues where their paper left off by considering the same driving mechanism for the cyclo-stratigraphy of the overlying Upper Albian – Turonian Natih Formation. Unlike their targeted Albian outcrop sections in Oman that may mask unknown but significant hiatuses, the present paper’s search for subsequences extends from outcrop to subsurface (Figures 2 and 3, Adopted Interpretation). The Natih subsequences are believed to represent a continuous string of stratons because they group into dozons that break up into short, nominal and long sequences (Matthews and Al-Husseini, 2010).

The depths of incised channels in Oman are an important proxy for the amplitudes of relative sea-level fluctuations (van Buchem et al., 1996, 2002; Droste and Van Steenwinkel, 2004; Grélaud, 2005; Grélaud et al., 2006; Homewood et al. 2008). The shallower 20–30-m-deep incised channels (IS1 and
IS2) are generally accepted by the above-cited authors as eustatic and representative of absolute sea-level drops. They are global, not only because they correlate to those of Haq et al. (1988; Figure 4, Tables 1 and 2), but also because they occur at orbitally predicted positions between stratons. For example, the Natih SB coincides with orbiton-level sequence boundary SB 7; Incision Surface IS1 to a sequence boundary that breaks Dozon 7A into two nominal orbital sequences; Incision Surface IS2 to the upper sequence boundary of Dozon 7A (SB 7B), and so forth (Figure 4 and Table 2).

Equally important is the regular beat of the 34 Natih subsequences that can only be attributed to a rhythmic driving mechanism for sea-level fluctuations, namely orbital forcing. The depth of valleys that cut incision surfaces IS1 and IS2 suggest sea-level fluctuations of the order of 10–30 m. Such amplitudes are consistent with polar ice making and melting in Antarctica driven by the 405-Ky long-eccentricity orbit of the Earth (Matthews and Frohlich, 2002; Figure 4).

As argued above the subaerial exposure and 150+ m valley-incision event at the Sub-Fiqa Unconformity is not here attributed to tectonic uplift of a forebulge. According to the orbital model the hiatus, at its briefest manifestation, only lasted ca. 800 Ky (1.2 My if Straton 6A-1 is included), while empirical estimates vary from a fraction of one million years to several million years: it is much too brief to be of tectonic origin. It is some 10 million years older than the Intra-Fiqa Unconformity that marked the start of block faulting and uplifting in Interior Oman (Figure 5). This structural deformation is more representative of far-field tectonism associated with the gradual build-up of compressional stress along the margins of the Arabian Plate. It started in Early Campanian and continued throughout the Campanian and Early Maastrichtian times. The associated unconformity is represented by a hiatus that can span the Aptian (or much older units in easternmost Oman) to Maastrichtian in many parts of the Arabian Plate. If the Sub-Fiqa unconformity is of a eustatic origin and correlated to the 100+ m global sea-level drop then it cannot be explained by ice making in Antarctica alone (Figure 4). Immenhauser and Matthews (2004, their figures 8 and 9, and discussion on p. 26–27) showed that besides Antarctica, Australia was also at high southern latitudes during the Late Cretaceous and could therefore have added a much greater landmass upon which to accumulate ice.

Finally, an interesting pattern emerges if the Natih/Fiqa transition is interpreted as a major polar glaciation that lasted about one million years. The glaciation not only implies a sharp and great sea-level drop but also reflects a profound change in lithology and depositional settings (Figure 5).

(1) Natih carbonate platform during Late Albian – intra-Turonian (Orbiton 7),
(2) abrupt exposure with incised channels in Late Turonian (SB 6 Glaciation),
(3) start of Fiqa Transgression in Coniacian with marginal marine (lagoonal-estuarine) facies (Orbiton 6 early transgression), and
(4) deep-marine shales in the Fiqa and Muti basin (Orbiton 6).

The basal Natih Sequence Boundary (SB 7) shows the opposite pattern with a switch from the Nahr Umr shales to the Natih carbonates (Figure 5). These switches from carbonates to shales and vice-versa coincide with orbiton-level glaciations and imply they are unrelated to paleo-latitudes or active tectonism. They are more probably related to significant changes in global climatic conditions, a matter that deserves further investigation.

CONCLUSIONS

The present paper, like Matthews and Frohlich (2002) and Immenhauser and Matthews (2004), concludes that orbital-forcing of glacio-eustasy is the mechanism that explains sequence stratigraphy. Unlike these previous papers the periodicity of depositional sequences is extended to 14.58 million years (Matthews and Al-Husseini, 2010) by documenting the proposed type section of Orbiton 7 in Oman. To test this hypothesis, an orbital time calibration of the Natih Supersequence was started by correlating its basal Natih Sequence Boundary (ca. 102.0 Ma, Sharland et al., 2001; ca. 104.0, Forbes et al., 2010) to a model-predicted, sea-level lowstand caused by a major polar glaciation that ended just before Orbiton 7 (SB 7 = ca. 103.6 Ma). Working upwards, the 34 Natih subsequences documented in the Adopted Interpretation (Figures 2 and 3; C. Grélaud and P. Razin in Homewood et al., 2008) are numbered as stratons that are believed to have tracked the long-eccentricity 405-Ky orbital signal.
The assumption is supported by how the subsequences adhere to the prediction that stratons group into twelve (Dozon) separated by sequence boundaries, which in turn break into subgroups of five (short orbital sequence), or six (nominal orbital sequence) or seven stratons (long orbital sequence; Figure 4 and Table 2).

The resulting correlation ended at the top of the Natih Formation (Sub-Fiqa Unconformity) with two of the predicted 36 stratons in Orbiton 7 unaccounted for in the Formation (Figure 4). Their absence was taken to imply a ca. 810 Ky hiatus (ca. 89.8–89.0 Ma) occurred in Late Turonian – ?earliest Coniacian, as consistent with biostratigraphic data (Forbes et al., 2010). The Sub-Fiqa Unconformity is characterized as an exposure surface that is cut by 150+ m incised channels in Oman. It is unrelated to tectonism and should not be confused with the Campanian angular Intra-Fiqa Unconformity (Figure 5). Instead, the Sub-Fiqa Unconformity (hiatus) is attributed to erosion/non-deposition due to a sea-level drop caused by glaciation in Antarctica and Australia. The age and depth of the channels imply a sea-level drop of ca. 150+ m, comparable to the 100+ m drop (long- minus short-term sea level) in the global eustatic curve of Haq et al. (1988).

Not surprisingly, Orbiton 7 (103.6–89.0 Ma) correlates to global Late Albian – Turonian Supersequence UZA 2 of Haq et al. (1988) inclusive of their latest Turonian sea-level lowstand (Figure 4 and Table 1). The 16 sequence boundaries and maximum flooding surfaces of Haq et al. (1988) that include MFS K110 to K150 of Sharland et al. (2001, as here repositioned following mainly the Adopted Interpretation) can be correlated to the orbital framework to within ± 1.1 million years (average of 0.56 My; Tables 1 and 2). The absolute age accuracy of the orbital calibration is believed to be less than 400,000 years.

The sequence stratigraphy of the Natih Formation of Oman has been extensively studied, mainly because of it importance for petroleum exploration and production. It was arbitrarily selected for this study because it is comprehensively documented at outcrop and subsurface. The results that are presented here are therefore not specific to the Natih Formation nor Orbiton 7, and should apply to other Phanerozoic orbitons (Al-Husseini and Matthews, 2010; Matthews and Al-Husseini, 2010).

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