GeoArabia, Vol. 10, No. 2, 2005
Gulf PetroLink, Bahrain

Tectono-Stratigraphic Note:
Time calibration of late Carboniferous, Permian and Early Triassic Arabian stratigraphy to orbital-forcing predictions

Moujahed Al-Husseini and Robley K. Matthews

The recent publication of GTS 2004 (Gradstein et al., 2004) provides an opportunity to recalibrate in time the late Carboniferous, Permian and Early Traissic Arabian Stratigraphy (GeoArabia Special Publication 3, Edited by Al-Husseini, 2004) as represented by the rock units in subsurface Interior Oman (Osterloff et al., 2004a, b) and the Haushi-Huqf Uplift region (Angiolini et al., 2004) (Figure). Additionally, sequence stratigraphic models of orbital forcing (Matthews and Frohlich, 2002; Immenhauser and Matthews, 2004) provide new insights in regards to the time calibration of depositional sequences: the "Rosetta Stone" approach. The Rosetta Stone approach predicts that the period of a third-order depositional sequence is 2.430 $\pm$ 0.405 my (denoted DS^3 and here adjusted to increase the fourth-order 'geological tuning fork' from 0.404 to 0.405 my based on Laskar et al., 2004). The present calibration is also tied to the orbital-forcing model developed by R.K. Matthews (in Al-Husseini and Matthews, 2005; this issue of GeoArabia) that predicts that a second-order depositional sequence (denoted DS^2) consists of six DS^3s that were deposited in a period of about 14.58 my (6 x 2.430 my); the DS^2 being bounded by two regional second-order sequence boundaries (SB^2) corresponding to sea-level maximum regression surfaces.

Litho-Chronostratigraphic Units and Ages, and Tectonic Events

In order to convert the ages of rock units cited in terms of stages to numerical ages in million years before present (Ma), and vice-versa, the stage qualifiers "early, mid and late" are arbitrarily assumed to represent three equal time periods. Where age estimates are based on GTS 2004 they are shown in brackets [Ma]. For notational brevity, boundaries between rock units and stages are written upper/lower and younger/older. In the Figure for convenience of drafting, the rock units are shown as occupying all time as consistent with biostratigraphic age ranges and stratigraphic positions, however continuous deposition is not implied.

In subsurface Oman, the glaciogenic late Carboniferous-early Permian Al Khlata Formation (Haushi Group; abbreviated AK) is separated by the Base Al Khlata Unconformity from much older Palaezoic rocks (Figure). Prior to the deposition of the Al Khlata Formation, a regional compressional tectonic event (so called 'Hercynian orogeny') is interpreted to have occurred in the mid Carboniferous (Wender et al., 1998; Al-Husseini, 2004), such that the ?Serpukhovian, Bashkirian up to late Moscovian stages are not represented in Oman. The Al Khlata Formation is divided into three production units AK P9, AK P5 and AK P1, and 8 chronostratigraphic units; dated approximately from oldest to youngest (Osterloff et al., 2004a):

1. AK P9, late Moscovian to mid Kasimovian [c. 308.2–305.2 Ma].
2. AK P5, late Kasimovian, Gzhelian up to mid Asselian [c. 305.2–296.1 Ma].
3. AK P1A Unnamed Diamictite, late Asselian and Sakmarian [c. 296.1 and younger]
4. AK P1A Early Lake (early AK P1 Lake), late Asselian or/and Sakmarian.
5. AK P1A Blanketing Diamictite (AK P1A.BD), late Asselian or/and Sakmarian.
6. AK P1 Rahab Lake 1 (lower Rahab), Sakmarian.
7. AK P1 Intra-Rahab Glaciogenic and Delta, Sakmarian.
8. AK P1 Rahab Lake 2 (upper Rahab), Sakmarian.

Above the Al Khlata Formation, the Gharif Formation is divided into three members and 8 cycles (Osterloff et al., 2004b):

1. Lower Gharif Member, Cycle 1; contains marine Maximum Flooding Shale (Guit et al., 1995).
2. Lower Gharif Member, Cycle 2; contains the Haushi Limestone considered time-correlative to the Saiwan Formation in the Haushi-Huqf outcrops. The age of the Lower Gharif Member is interpreted as early Artinskian (Osterloff et al., 2004b); the coeval Saiwan Formation as late Sakmarian (Angiolini et al., 2004); or c. Artinskian/Sakmarian Boundary (Stephenson et al., 2003) [c. 284.4 $\pm$ 0.7 Ma].

3. Middle Gharif Member, Cycle 3, Artinskian (Osterloff et al., 2004b).
4. Middle Gharif Member, Cycle 4, undated.
5. Upper Gharif Member, Cycle 5, undated.
6. Upper Gharif Member, Cycle 6, undated.
7. Upper Gharif Member, Cycle 7, undated.
8. Upper Gharif Member, Cycle 8, undated; believed to be coeval with the outcropping "Redefined Gharif Formation", Upper Unit, Subunit B immediately below the Khuff Formation (Angiolini et al., 2004).

The overlying Khuff Formation represents the main carbonate transgression that started in the Wordian and approximately coincided with the formation of the Neo-Tethyan proto-rift along the Gulf of Oman. The start of the rift event is manifested by widespread Wordian volcanic rocks in the basal part of the Saiq Formation in the Oman Mountains (= Khuff Formation of subsurface Oman and Haushi-Huqf region) (Le Métour et al., 1968). In subsurface Oman, the Khuff Formation consists of (Osterloff et al., 2004b):

1. Lower Khuff Member; Angiolini et al. (2004) dated the basalmost part of the Khuff Formation in the Haushi-Huqf outcrop as Wordian [within 268.0–265.8 Ma].
2. Middle Khuff Member below the Middle Anhydrite, unspecified stages, Permian.
3. Middle Khuff Member above the Middle Anhydrite, unspecified stages, Permian.
4. Upper/Middle Khuff Boundary, Triassic/Permian Boundary [251.0 $\pm$ 0.4 Ma].
5. Upper Khuff Member, unspecified stages, Early Triassic.

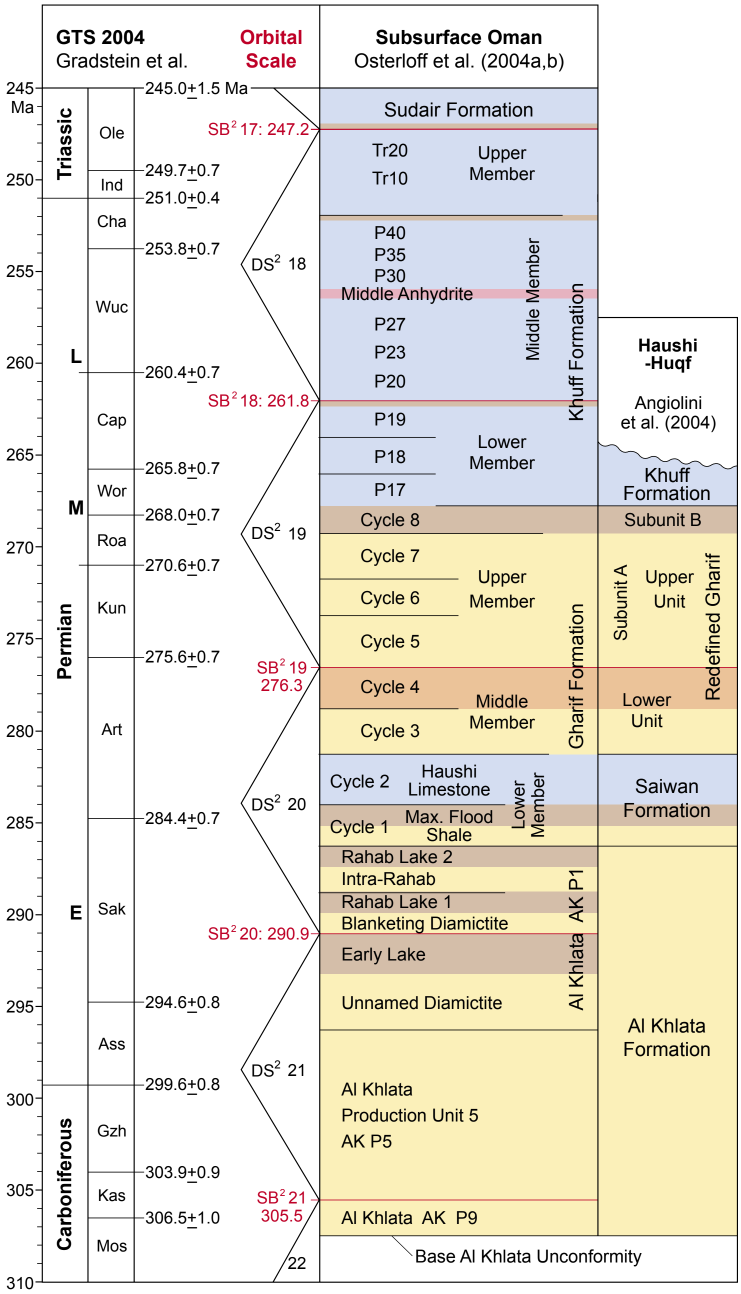
Above the Khuff Formation, the age of the overlying Sudair Shale is probably late Olenkian-early Anisinian by correlation to the Zulla Sandstone and Shale Member in the Oman Mountains (H. Droste, in Blechschmidt et al., 2004).

Sequence Stratigraphic Architecture and Age Calibration

In the Figure, the proposed sequence stratigraphic interpretation illustrates the following second- and third-order architecture. Following (and possibly accompanying) the mid Carboniferous tectonic event a major glacial period spanned the time up to late Moscovian. This ice-making cold period ended with the first major meltdown, represented by the oldest Al Khlata AK P9 Unit that was deposited in braidplain, glacio-fluvial and glacio-lacustrine warmer environments (Osterloff et al., 2004a). The next stratigraphic break AK P5/P9 Boundary occurs in c. mid Kasimovian. P. Osterloff (2005, written communication) notes that a thick 'lacustrine package' near the top of AK P9 and base AK5 may reflect a major melt-out (diamictite facies) associated with a significant glaciation. The AK P5/P9 lacustrine package with diamictite facies is here interepreted as a melt-out that followed a second major glacial advance (i.e. SB^2). Based on GTS 2004, a mid Kasimovian age for AK P5/P9 is c. 305.2 Ma; the age of AK P5/P9 correlates closely to the age of SB^2 21 at 305.5 Ma (Al-Husseini and Matthews, 2005).

In the Figure and following discussion, we correlate AK P5/P9 to SB^2 21 at 305.5 Ma, and look for the second- and third-order orbital stratigraphic signal. Above SB^2 21, DS^2 21 is interpreted to consist of ice-melt and inter-glacial deposits reflecting a warm interglacial period: AK P5, AK P1 Unnamed Diamictite, and AK P1 Early Lake units, and to terminate with SB^2 20 positioned at the Base AK P1 Blanketing Diamictite. The implication is that the time period prior to the deposition of the AK P1 Blanketing Diamictite is represented by a third major glacial advance; SB^2 20 = Base Blanketing Diamictite is predicted at c. 290.9 Ma in mid Sakmarian. This interpretation suggests that whereas the main mid Carboniferous glaciation was triggered by global tectonics (i.e. closure of the equatorial Iapetus Sea between Laurassia and Gondwana, see Figure 27 in Al-Husseini, 2004), the subsequent two glacial advances (SB^2 21 and 20) were caused by orbital forcing.

DS^2 20 can be interpreted in terms of six third-order depositional cycles (DS^3): (1) DS^3 Blanketing Diamicite and Rahab Lake 1; (2) DS^3 Intra-Rahab and Rahab Lake 2; (3) DS^3 Lower Gharif Cycle 1; (4) DS^3 Lower Gharif Cycle 2; (5) DS^3 Middle Gharif Cycle 3; and (6) DS^3 Middle Gharif Cycle 4. The pattern shows a second-order sea-level cycle that started with the Blanketing Diamictite glacial



meltdown and then rose to fill Rahab Lakes 1 and 2 cycles. The two Rahab Lake third-order cycles are regional at the scale of Oman (100s of km in diameter) although lithofacies variations, isostatic rebound and erosion/deposition due to much higher-order ice advances and retreats may mask them locally. The Lower Gharif (Maximum Flooding Shale and Haushi Limestone/ Saiwan Formation) represents the second-order marine flood that spanned late Sakmarian and early Artinskian. The final two regressive Gharif Cycles 3 and 4 successively evolved from shoreface, to alluvial, to lacustrine (Osterloff et al., 2004b).

The second-order orbital calibration positions the next regional sequence boundary at the Upper/ Middle Gharif Boundary (c. 276.3 Ma or c. Kungurian/Artinskian). This undated boundary is indeed interpreted as the maximum intra-Gharif regression surface by Guit et al. (1995) and Osterloff (personal communication, 2003), and is here interpreted as SB^2 19.

Above SB^2 19, the overlying DS^2 19 is also interpreted in terms of six third-order cycles. The first three are fluviatile: (1) DS^3 Upper Gharif Cycle 5; (2) DS^3 Upper Gharif Cycle 6; and (3) DS^3 Upper Gharif Cycle 7. The fourth is DS^3 Upper Gharif Cycle 8 together with Lower Khuff Cycle P17. Upper Gharif Cycle 8 represents a tidal/estuarine environment (TST) that passed conformably to the Lower Khuff Cycle P17 (MFI and HST) (Osterloff et al., 2004b). The onset of the Khuff marine transgression within the mixed clastic-to-carbonate third-order cycle suggests the Neo-Tethyan proto-rift caused rapid subsidence and new accommodation space. The final two cycles of DS^2 P19 are: Lower Khuff Cycles DS^3 P18 and DS^3 P19 (Osterloff et al., 2004b). DS^3 P19 is dominated by shale in south Oman and contains the Maximum Flooding Interval MFI^3 P19 that stands out as the Khuff Marker Limestone.

Third-order DS^3 P19 closed second-order DS^2 19 (recurrence of 19 is coincidental) with an undated continental shale marker in south Oman that represents SB^2 18 at the Middle/Lower Khuff Boundary; here estimated at c. 261.8 Ma or c. late Capitanian.

DS^2 18 straddles the Triassic/Permian Boundary and correlates in age to the Middle and Upper Khuff members. The Middle Khuff Member was interpreted by Osterloff et al. (2004b) in terms of six cycles (P20, P23, P27 below the Middle Anhydrite, and P30, P35 and P40 above it), and the Upper Khuff Member in terms of two cycles (Tr10 and Tr20). In this note, the Middle and Upper Khuff members are recast into three nearly equally-thick, carbonate-dominated sections: (1) Middle Khuff below the Middle Anhydrite; (2) Middle Khuff above the Middle Anhydrite; and (3) Upper Khuff. In this 3-fold division, each equally-thick section is interpreted as deposition in an equal period of time of 4.86 my (i.e. two third-order cycles: 2 x 2.43 my; or 12 fourth-order cycles: 12 x 0.405 my). This calibration implies that the Middle Khuff Anhydrite is a third-order lowstand (SB^3).

The orbital calibration places SB^2 17 at the Sudair/Khuff Boundary at c. 247.2 Ma in mid Olenkian. This interpretation suggest that the Sudair Formation represents the start of a second-order cycle that extends into the Jilh Formation. Also of interest, a third-order lowstand is predicted at c. 252 Ma (247.2 + 4.86 Ma), and before the estimated age of the Triassic/Permian Boundary [251.0 $\pm$ 0.4 Ma].

ACKNOWLEDGEMENTS

The authors thank Lucia Angiolini, Joerg Mattner, Peter Osterloff, and Michael Stephenson for their useful comments.

REFERENCES

Al-Husseini, M.I. 2004. Preface and Pre Unayzah Unconformity, Saudi Arabia. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, p. 7–59.

Al-Husseini, M.I. and R.K Matthews, 2005. Arabian Orbital Stratigraphy: Periodic second-order sequence boundaries. GeoArabia, v. 10, no. 2, p 165-184.

Angiolini, L., S. Crasquin-Soleau, J.-P. Platel, J. Roger, D. Vachard, D. Vaslet and M.I. Al-Husseini 2004. Saiwan, Gharif and Khuff formations, Haushi-Huqf Uplift, Oman. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, p. 149-183.

Blechschmidt, I., P. Dumitrica, A. Matter, L. Krystyn and T. Peters 2004. Stratigraphic architecture of the northern Oman continental margin - Mesozoic Hamrat Duru Group Hawasina complex, Oman. GeoArabia, v. 9, no. 2, p. 81-132.

Gradstein, Ogg, Smith et al., 2004. A Geological Time Scale 2004, GeoArabia, v. 10, no. 1, p. 142.

Guit, F.A, M.H. Al-Lawati and P.J.R. Nederlof 1995. Seeking new potential in the early-Late Permian Gharif play, west central Oman. In, M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences Conference, GEO'94. Gulf PetroLink, Bahrain, v. 2, p, 447-462.

Immenhauser, A. and R.K. Matthews 2004. Albian sea-level cycles in Oman: the 'Rosetta Stone' approach. GeoArabia, v. 9, no. 3, p. 11-46.

Laskar, J, P. Robutal, F. Joutel, M. Gastineau, A. Correia and B. Levrard 2004. A long term numerical solution for the insolation quantaties of the Earth. Astronomy and Astrophysics. Preprint available from http://hal.ccsd.cnrs..fr/ccsd-00001603.

Le Métour, J., M. Villey and X. de Gramont 1986. Geologic Map of Masqat, sheet NF-40-4D, scale 1:100,000, with Explanatory Notes. Directorate General of Minerals, Ministry of Petroleum and Minerals, Oman.

Matthews, R.K. and C. Frohlich 2002. Maximum flooding surface and sequence boundaries: comparisons between observation and orbital forcing in the Cretaceous and Jurassic (65-190 Ma). GeoArabia, v. 7, no. 3, p. 503-538.

Osterloff, P., R. Penney, J. Aitken, N. Clark and M. Al-Husseini 2004a. The Al Khlata Formation in Interior Oman. GeoArabia Special Publication 3. Gulf PetroLink, Bahrain, p. 61-81.

Osterloff, P.L., A. Al-Harthy, R. Penney, P. Spaak, F. Al-Zadjali, N.S. Jones, R.W.O.B Knox, M.H. Stephenson, G. Oliver and M.I. Al-Husseini 2004b. Gharif and Khuff formations, subsurface Interior Oman. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, p. 83-147.

Stephenson, M.H., P.L. Osterloff and J. Filatoff 2003. Palynological biozonation of the Permian of Oman and Saudi Arabia: progress and challenges. GeoArabia, v. 8, no. 3, p. 467-496.

Wender, Lawrence E., Jeffrey W. Bryant, Martin F. Dickens, Allen S. Neville and Abdulrahman M. Al-Moqbel 1998. Paleozoic (pre-Khuff) hydrocarbon geology of the Ghawar area, eastern Saudi Arabia. GeoArabia, v. 3, no. 2, p. 273-302.

ABOUT THE AUTHORS, please see page 184.