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Stratigraphic Note: Orbital calibration of the Arabian Jurassic second-order sequence stratigraphy

Moujahed Al-Husseini and Robley K. Matthews

Jurassic biostratigraphic and strontium isotope data provide evidence that several regional stratigraphic discontinuities correspond to major hiatuses that each lasted one or more million years in the Arabian Peninsula (as characterized in Oman, Saudi Arabia and Kuwait). In contrast to other Jurassic hiatuses, these hiatuses more clearly mark extended periods of regional erosion and/or non-deposition (Figure 1 and Table 1). Four of these Jurassic hiatuses correlate closely to the model ages of four consecutive orbital second-order sequence boundaries (Table 1 and Figure 1, denoted SB^2) that are numbered as SB^2 10, 11, 12 and 13 (Al-Husseini and Matthews, 2005). This data-model correlation implies that the Jurassic second-order depositional sequences (denoted DS^2) may have been modulated by orbital-forcing, glacio-eustatic cycles and have depositional periods of approximately 14.58 million years (Al-Husseini and Matthews, 2005).

In this note, we briefly review the biostratigraphic and Sr-isotope literature (and written communications) that document the Jurassic hiatuses in Arabia, and estimate their age spans in million years (my) from the Geological Time Scale GTS 2004 (Gradstein et al., 2004). In particular, we estimate the ages of the oldest strata that lie above the discontinuities and set this equal to the age of the maximum regression surface and the base of the second-order depositional sequence. This approximation is adopted because the youngest strata below the disconformity or/and unconformity may have been eroded during the maximum regression. Moreover, the fossil content of the underlying unit may have been obliterated by diagenetic processes during the period of subaerial exposure.

The four model SB^2s and candidate hiatuses that are reviewed here form part of the AROS (Arabian Orbital Stratigraphy) framework, which is being tested and calibrated for the entire Phanerozoic Eon. The model ages in million years before the present (Ma) of the AROS SB^2s can be estimated by the linear formula (R.K. Matthews *in* Al-Husseini and Matthews, 2005):

$$SB^2\ N{+}1 = SB^2\ N + 14.58\ \text{Ma}$$

In the model calibration of Al-Husseini and Matthews (2005), the age of SB^2 1 was estimated at 13.9 Ma. In ongoing modeling studies to incorporate important new orbital calculations of Laskar et al. (2004), R.K. Matthews notes that changing boundary conditions effect the age of the nominal SB^2 1 (see Discussion below). For simplicity, we use here the 13.9 Ma estimate for SB^2 1 as a good average.

SB^2 13: 188.8 Ma, early Pliensbachian Stage, Early Jurassic Period

Second-order sequence boundary SB^2 13 has an orbital model age of c. 188.8 Ma and correlates to the early Pliensbachian Stage according to GTS 2004 (Gradstein et al., 2004). In the Arabian Peninsula, the Early Jurassic Hettangian and Sinemurian stages are not known to be represented. Following this hiatus, a regional transgression flooded the Arabian Platform, and its basal surface is correlated to the base Mafraq Formation in Oman, base Marrat Formation in Saudi Arabia and Kuwait, and to model SB^2 13.

Table 1

SB^2 N	Model	Discontinuity	Stage	Age (Ma)*	Deviation (Ma)*
10	145.1	base Sulaiy	base Berriasian	145.5	± 4.0
11	159.7	base Hanifa	base mid Oxfordian	159.4	± 4.0
12	174.3	base Dhruma	base Bajocian	171.6	± 3.0
13	188.8	base Marrat	base Pliensbachian	189.6	± 1.5

* *Age and standard deviation are after the Geological Time Scale GTS 2004 (Gradstein et al., 2004)*

Base Mafraq Boundary, Oman

In eastern Interior Oman, according to Rousseau et al. (2005, 2006), the Hettangian and Sinemurian stages are not represented, and the Mafraq Formation contains no Triassic deposits. The base Mafraq laps onto eroded Triassic and older strata and represents a time-transgressive regional flooding event (Rousseau et al., 2005, 2006; G. Grabowski, 2006 written communication). The Lower Mafraq Member constitutes a single Pliensbachian-Toarcian depositional sequence (Rousseau et al., 2005, 2006). In Al Jabal al Akhdar, the "Lithiotis Limestones" in the Lower Mafraq Member contains the benthic foraminifer *Orbitopsella praecursor* (Rabu, 1987; *in* Rousseau et al., 2005, 2006; Y.-M. Le Nindre and D. Vaslet, 2006 written communications), which is diagnostic of an early Pliensbachian age (Bassoullet, 1997). P. Osterloff (2005 written communication, *in* Al-Husseini and Matthews, 2005) confirmed that in some basin depocenters in northern Oman (Musandam Peninsula of north Oman according to D. Vaslet, 2006 written communication), the Pliensbachian Stage is represented in the Mafraq Formation.

Base Marrat Boundary, Saudi Arabia

In Saudi Arabia, according to Y.-M. Le Nindre (2005 written communication, *in* Al-Husseini and Matthews, 2005), the Hettangian, Sinemurian and probably the Pliensbachain stages are not represented. The Marrat Formation constitutes a single depositional sequence and the transgressive part of the Lower Marrat unit is dated as Toarcian (Enay et al., 1987; Le Nindre et al., 1990).

Base Marrat Boundary, Kuwait

In Kuwait, the Hettangian Stage and most (but possibly not the late Sinemurian) of the Sinemurian Stage is represented by a hiatus. According to Al-Sahlan (2005), the base of the Marrat Formation is dated as ?late Sinemurian and early Pliensbachian based on the foraminifera *Amijiella amiji* and the top of the Lower Marrat unit is early Toarcian based on *Nannoceratopsis triceras*. The Marrat Formation in Kuwait constitutes a single ?late Sinemurian-Pliensbachian-Toarcian depositional sequence (Al-Sahlan, 2005).

Age Estimate and Correlation

Following the Early Jurassic hiatus, the base of the first Arabian Jurassic transgression is dated as early Pliensbachian in Oman, Toarcian in Saudi Arabia, and ?late Sinemurian and early Pliensbachian in Kuwait. Thus an early Pliensbachian age appears to be consistent with the estimated ages for the start of the transgression in Oman and probably Kuwait, while the main flooding appears to have reached central Saudi Arabia by the Toarcian time. The age of the base Pliensbachian Stage is c. 189.6 ± 1.5 Ma (Gradstein et al., 2004) and correlates closely with the model age for SB^2 13 at 188.8 Ma. The regional correlation and age estimate for SB^2 13 is in general agreement with the estimate by G. Grabowski (2006 written communication). He noted that the Base Marrat also shows major onlap onto the Qatar Arch from the north and west (Kuwait and Saudi Arabia), and to a lesser extent, from the east and south (Abu Dhabi and Oman).

SB^2 12: 174.3 Ma, early Aalenian Stage, Middle Jurassic Period

Second-order sequence boundary SB^2 12 has an orbital model age of c. 174.3 Ma and correlates to the early Aalenian Stage according to GTS 2004 (Gradstein et al., 2004). SB^2 12 is correlated to the base Upper Mafraq Member boundary in Oman, and base Dhruma Formation boundary in Saudi Arabia and Kuwait.

Base Upper Mafraq Boundary, Oman

In Oman, the Aalenian Stage is not represented and the base Upper Mafraq Member is interpreted as the base of a regional Bajocian transgression (Rousseau et al., 2005, 2006). In the Al-Haushi-Huqf area, molds of the ammonite *Thambites* cf. *planus* were found in the basal part of the Upper Mafraq Member (Roger et al., 1992) that are characteristic of the late Bajocian-earliest Bathonian D3 unit of the Middle Dhruma Member in Saudi Arabia (Enay et al., 1987).

The Upper Mafraq passes conformably to the overlying Dhruma Formation. The Dhruma Formation yielded dinocyst assemblages in the Lekhwair-319 well that indicate a late Bajocian and Bathonian age (Rousseau et al., 2005, 2006). Rousseau et al. (2005, 2006) noted that in the Al-Haushi outcrops, a

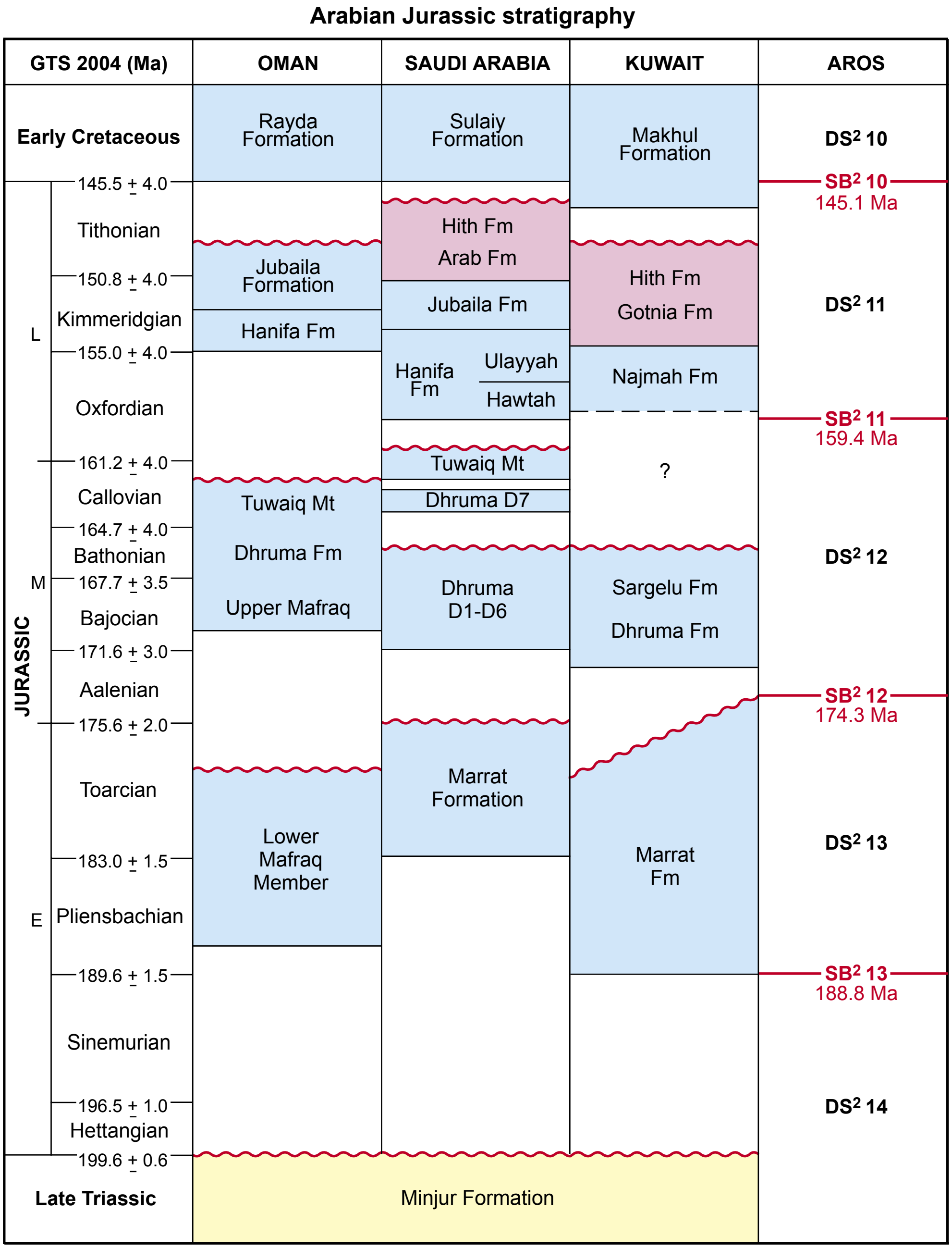

Figure 1: Correlation of Jurassic formations and hiatuses in Kuwait, Saudi Arabia and Oman. The ages of the Jurassic hiatuses are estimated by using biostratigraphic and Strontium-isotope data and the Geological Time Scale GTS 2004 (Gradstein et al., 2004). The Oman column is after Rousseau et al. (2006) except for the Tithonian and Berriasian, which is after Hughes Clark (1988). The Saudi Arabian column is after Enay et al. (1987), Le Nindre et al. (1990), Vaslet et al. (1991), Fischer et al. (2001) and D. Vaslet and Y.-M. Le Nindre (2006 written communications). The Kuwait column is after Al-Sahlan (2005) and A. Lomando (2006 written communication). The question mark in the Kuwait column indicates conflicting age interpretations for the Najmah Formation, which may extend to the Bathonian (G. Grabowski, 2006 written communication). The AROS (Arabian Orbital Stratigraphy) column indicates the orbital-forcing model second-order sequence boundaries (SB²) and depositional sequences (DS²).

Bathonian-Callovian age has been inferred from foraminiferal occurrences for the Dhruma Formation (Dubreuilh et al., 1992). However, they add that the presence of *Haurania* cf. *amiji* and *H. deserta* (*in* Dubreuilh et al., 1992) better suggests a Bajocian-Bathonian age (Bassoullet, 1997). Thus the Upper Mafraq Member, based on its stratigraphic position below the Dhruma Formation, would appear to be early and middle (rather than late) Bajocian in age.

Base Dhruma Boundary, Saudi Arabia

In Saudi Arabia, the Base Dhruma Formation represents the start of a major transgression of early Bajocian age as determined by ammonites (Y.-M. Le Nindre, 2006 written communication). The basal part of the underlying upper Marrat deposits is dated as middle Toarcian (e.g. Enay et al., 1987; Fischer et al., 2001). Thus an Aalenian biostratigraphic break is suggested between the Dhruma and Marrat formations. Y.-M. Le Nindre (2006 written communication) noted that the Dhruma/Marrat boundary represents a long period of time with condensed or absent sedimentation and no real biostratigraphic control. In central Arabia, some gypsum occurs close the top of the Marrat Formation. An approximate Toarcian to Aalenian age for the top of the Upper Marrat Formation was given by palynology in the borehole Zilfi Z1. G. Grabowski (2006 written communication) added that Base Dhruma shows onlap onto the truncated Marrat Formation.

Base Dhruma Boundary, Kuwait

In Kuwait, the Base Dhruma represents the start of a major transgression (Al-Sahlan, 2005; A. Lomando, personal communication, 2005). The age of the lower part of the Dhruma Formation, based on biostratigraphic data, is early Bajocian (Al-Sahlan, 2005; A. Lomando, personal communication, 2005), or early to middle Bajocian (G. Grabowski, 2006 written communication). G. Grabowski (2006, written communication) does not know of any age control for the Middle and Upper Marrat in Kuwait (about 1,000 ft thick), and that the youngest age of these units is not known. It is possible but unproven that the upper two-thirds of the Upper Marrat could extend up to the middle Aalenian. Thus in Kuwait a hiatus is interpreted to exist in the Aalenian, or possibly just the late Aalenian.

The Dhruma Formation in Kuwait passes conformably to the overlying Sargelu Formation, which is dated as late Bajocian to early Bathonian based on biostratigraphic and Sr-isotope data (Al-Sahlan, 2005; G. Grabowski, 2006 written communication).

Age Estimate and Correlation

If the Aalenian Stage is not represented in the Arabian Peninsula, then a time hiatus can be interpreted between c. 175.6 ± 2.0 to 171.6 ± 3.0 Ma (Gradstein et al., 2004). The base of the transgressive sequence that followed the Aalenian hiatus is close to the Bajocian/Aalenian boundary estimated at 171.6 ± 3.0 Ma (Gradstein et al., 2004) and correlates within one standard deviation with the model age for $SB^2 12$ at 174.3 Ma. G. Grabowski (2006 written communication) estimated the basal age of this hiatus to range between about 180 and 175.6 Ma (and perhaps as young as 173 Ma) in central Saudi Arabia.

SB^2 11: 159.7 Ma, early Oxfordian Stage, Late Jurassic Period

Second-order sequence boundary SB^2 11 has an orbital model age of c. 159.7 Ma and correlates to the early Oxfordian Stage according to GTS 2004 (Gradstein et al., 2004). SB^2 11, on the basis of its model age appears to best correlate to the base of the Oxfordian Hanifa Formation boundary in Saudi Arabia. However, this correlation was questioned because a more significant stratigraphic break is interpreted in Saudi Arabia between the Upper and Middle Dhruma members (between the Dhruma D6 and D7 units, Figure 1) in the late Bathonian and early Callovian (Y.-M. Le Nindre, D. Vaslet and G. Grabowski written communications, 2006). The correlation of SB^2 11 in Kuwait and Oman is confusing due to conflicting stratigraphic data and interpretations. In this section we review the various candidate surfaces that may correlate to model SB^2 11.

Upper/Middle Dhruma (D7/D6) Boundary, Saudi Arabia

The Dhruma Formation in central Saudi Arabia outcrops is divided into three parts (Powers, 1968) or seven units designated D1 to D7 (Le Nindre et al., 1990; Vaslet et al., 1991); from oldest to youngest (1) Dhruma Shale (D1 and lower part of D2 units) and overlying Dhibi Limestone member (upper part of D2); (2) Middle Dhruma (D3 to D6 units); and (3) 'Atash and Hisyan members (D7 unit). A significant biostratigraphic break was identified by Enay et al. (1987) between the Upper (D7 unit) and Middle Dhruma members (i.e. between the D6 and D7 units). The Lower and Middle Dhruma (D1–D6 units) constitute an apparently continuous Bajocian-Bathonian depositional sequence. The Upper/Middle Dhruma boundary represents a long period of hiatus in the marine domain during the (at least) late Bathonian and early Callovian time (based on nannoflora analyzed by H. Manivit as reported by Y.-M Le Nindre, 2006 written communication).

The Upper Dhruma (D7) and overlying Tuwaiq Mountain Limestone is middle Callovian in age (Le Nindre et al., 1990; Y.-M. Le Nindre, 2006 written communication). According to Y.-M. Le Nindre: "it is possible that the uppermost T3 reefal unit of the Tuwaiq Mountain Limestone is progradational (with the reefs corresponding to the highstand) and the late Callovian is likely to exist in northern Arabia. G. Grabowski (2006 written communication) considers the Upper Dhruma Member as early to middle Callovian and the Tuwaiq Mountain as mainly late Callovian and extending into earliest Oxfordian.

G. Grabowski and Y.-M. Le Nindre (2006 written communications) both emphasize that the Upper/ Middle (D7/D6 boundary) Dhruma break represents a significant sequence boundary with erosion and onlap at the top of the Middle Dhruma. G. Grabowski estimates that this break in central Arabia may have lasted about 2 million years. He notes that in the subsurface of Abu Dhabi the unit that is equivalent to the Upper Dhruma is thicker and may be a somewhat older at the base, thus reducing the time gap.

Base Tuwaiq Mountain Boundary, Saudi Arabia

According to G. Grabowski (2006 written communication) a sequence boundary occurs between the Dhruma Formation and overlying Tuwaiq Mountain Limestone. He indicated that it shows less erosion, less onlap, and is interpreted to be of shorter duration than the Upper/Middle Dhruma boundary.

Base Hanifa Boundary, Saudi Arabia

In Saudi Arabia, the Hanifa Formation is dated as middle Oxfordian and early Kimmeridgian (Enay et al., 1987; Vaslet et al., 1991). The base Hanifa is an erosional unconformity in subsurface Saudi Arabia (C.D. Redmond *in* Powers, 1968), and the hiatus between the Tuwaiq Mountain Limestone and overlying Hanifa Formation is dated as late Callovian and early Oxfordian (Enay et al., 1987; Hirsch et al., 1998; Fischer et al., 2003).

G. Grabowski (2006 written communication) noted that the Tuwaiq Mountain and Hanifa formations in central Saudi Arabia outcrop correlate with the subsurface quite well. He interpreted a sequence boundary at the top of the uppermost T3 reefal unit of the Tuwaiq Mountain Limestone with erosion and onlap onto it. He agrees that a stratigraphic gap between Hanifa and Tuwaiq Mountain formations occurs within the early Oxfordian at about 160–159 Ma. He adds, however, that the Hanifa/Tuwaiq gap is relatively shorter than the one between the D7 and D6 units of the Dhruma Formation.

Base Jubaila Boundary, Saudi Arabia

G. Grabowski (2006 written communication) interpreted a sequence boundary (with erosion and onlap) between the Oxfordian Hanifa Formation and Jubaila Formation. He assigns a late Oxfordian-Kimmeridgian age to the Jubaila Formation, whereas other authors date this formation as early Kimmeridgian (Enay et al., 1987; Vaslet et al., 1991). G. Grabowski estimated this time gap to be about 1.5 million years in duration.

Base Hanifa Boundary, Oman

In Oman, the Upper Mafraq Member, Dhruma Formation and Tuwaiq Mountain Limestone are interpreted as a single depositional sequence (Rousseau et al., 2005, 2006). Rousseau et al. (2006) interpret the Upper Mafraq as late Bajocian marine flooding deposits and the Bathonian-Callovian (Dhruma and Tuwaiq Mountain Limestone) time interval as one of permanent shallow-marine flooding over interior Oman. This interpretation suggests that the Upper/Middle Dhruma (D7/D6) sequence boundary (Callovian/Bathonian boundary) that is interpreted in Saudi Arabia (noted above) is not prominant in Oman

In Oman the post-Tuwaiq unconformity is a low-angle erosional surface that truncates, from west to east Interior Oman, the Tuwaiq Mountain Limestone and the Dhruma Formation (Rousseau et al., 2005, 2006). G. Grabowski (2006 written communication) notes that the Hanifa Formation in Oman is clearly time transgressive, lapping onto eroded Dhruma and Mafraq formations. He cautions that the Hanifa and Tuwaiq Mountain Limestone in Oman, Saudi Arabia and the United Arab Emirates may not be equivalent rock units. Above the post-Tuwaiq unconformity, the Hanifa and Jubaila formations are interpreted as a single second-order depositional sequence (Rousseau et al., 2005, 2006). The

Hanifa Formation is early Kimmeridgian in age (Hughes Clark, 1988; Rousseau et al., 2005, 2006). The age interpretations of the Tuwaiq Mountain and overlying Hanifa formations imply that the late Callovian and Oxfordian stages are not represented in Oman.

Base Jubaila Boundary, Oman

In Oman, Rousseau et al. (2006) identified a subaerial exposure surface corresponding to a short hiatus following the deposition of the early Kimmeridgian Hanifa Formation and preceeding that of the late Kimmeridgian Jubaila Formation.

Base Najmah Boundary, Kuwait

In Kuwait, the Najmah, Gotnia and Hith formations are interpreted as a single Late Jurassic depositional sequence (Al-Sahlan, 2005; A. Lomando, personal communication, 2005). According to Al-Sahlan (2005), the top of the Sargelu Formation is Callovian or ?older based on the abundant presence of *Dichadogonyaulax sellwoodii*. The lower part of the Najmah Formation in North Kuwait is no older than Oxfordian based on the presence of the dinoflagellate *Systematophora* spp. and the nannofossil *Stephanolithion bigoti maximum* (latest Callovian-earliest Oxfordian). Thus the age of the base Najmah Formation appears to be early Oxfordian to near the Oxfordian/Callovian boundary.

According to G. Grabowski (2006 written communication) biostratigraphic and Sr-isotope data suggest that the Najmah spans the interval from middle Bathonian to early Kimmeridgian. He added that the Lower Najmah is wholly Bathonian, while the rest of the Najmah is Callovian and younger. The age interpretation for the Sargelu Formation as middle Bathonian to Callovian or younger implies that the long-lasting middle Bathonian to middle Oxfordian hiatus, noted by Al-Sahlan (2005), is not identified by G. Grabowski (2006 written communication).

Age Estimate and Correlation

A significant sequence boundary and biostratigraphic hiatus is identified between the Upper and Middle Dhruma (D7/D6 boundary) near the Callovian/Bathonian boundary in central Saudi Arabia (Enay et al., 1987) and possibly Kuwait (Al-Sahlan, 2005; G. Grabowski, 2006 written communication). This hiatus is not identified in Oman by Rousseau et al. (2004, 2005). A second, apparently less-significant sequence boundary is identified between the Tuwaiq Mountain Limestone and Dhruma formations in Saudi Arabia (G. Grabowski, 2006 written communication).

A regional sequence boundary and hiatus occurs near the age of the Oxfordian/Callovian boundary in Saudi Arabia (Powers, 1968). The hiatus spans the late Callovian and Oxfordian in Oman (Rousseau et al., 2005, 2006). In Kuwait it may span the late Bathonian, Oxfordian and early Kimmeridgian according to Al-Sahlan (2005) or it may not occur altogether according to G. Grabowski (2006 written communication). If the basal age of the transgressive sequence is picked at the base of the middle Oxfordian as dated in Saudi Arabia (approximately 1/3 the time interval [161.2 ± 4.0 to 155.7 ± 4.0 Ma], Gradstein et al., 2004), i.e. c. 159.4 Ma it would be close to the age of SB^{2}11 at 159.7 Ma.

Above the base Hanifa sequence boundary, in Saudi Arabia outcrops, a middle Oxfordian sequence boundary is interpreted between the Hawtah and Ulayyah members of the Hanifa Formation, and a middle Kimmeridgian sequence boundary is interpreted between the Jubaila and Hanifa formations (Al-Husseini et al., 2006; G. Grabowski, 2006 written communication). These two sequence boundaries are interpreted as third-order and may correlate to two distinct breaks represented by the intra-Oxfordian break of G. Grabowski (2006 written communication) and intra-Kimmeridgian break noted by Rousseau et al. (2004, 2005). The two members (Hawtah and overlying Ulayyah) are interpreted as two orbital third-order depositional sequences (DS^3 11.1 and DS^3 11.2; Al-Husseini et al., 2006).

SB^2 10: 145.1 Ma, c. Berriasian/Tithonian Boundary, Cretaceous/Jurassic Boundary

Second-order sequence boundary SB^2 10 has an orbital model age of c. 145.1 Ma and correlates closely to the Berriasian/Tithonian and Cretaceous/Jurassic boundaries (145.5 ± 4.0 Ma) according to GTS 2004 (Gradstein et al., 2004). SB^2 11 is correlated to the base Rayda Formation boundary in Oman, base Sulaiy Formation boundary in Saudi Arabia, and the base Makhul Formation boundary in Kuwait.

Base Rayda Boundary, Oman

In Oman, Hughes Clark (1988) described the Rayda/Jubaila boundary as "always a hiatus or disconformity". The Base Rayda boundary cuts down into the Jubaila Formation in the western subsurface of Oman, and into the Dhruma Formation in the Al Jabal al Akhdar outcrops in the Oman Mountains (Hughes Clarke, 1988). G. Grabowski (2006 written communication) added that this surface represents substantial erosion and must have involved tectonic deformation of eastern Arabia; following this erosion, a large portion of northern Oman subsided greatly. According to Hughes Clarke (1988), the age of the Rayda Formation as indicated by fossil content is Early Cretaceous (Berriasian-Valanginian), and that of the underlying Jubaila Formation is late Jurassic early Tithonian based on palynofossil assemblages. Rousseau et al. (2005, 2006), based on a calpionellid assemblage, assigned the Rayda Formation an age that spans the Berriasian/Tithonian (Cretaceous/Jurassic) boundary.

Base Sulaiy Boundary, Saudi Arabia

In Saudi Arabia, the Sulaiy/Hith boundary is disconformable (Vaslet et al., 1991), and it separates the lowstand associated with the Hith Anhydrite from the transgressive Sulaiy Formation carbonates. The two formations cannot be dated biostratigraphically; however, on the basis of a study of oxygen and sulfur isotopes from the Hith Formation, Vaslet et al. (1991) noted "perfect agreement" with average values known from elsewhere in the world in the latest Late Jurassic Epoch. According to G. Grabowski (2006 written communication) Sr-isotope age control for units that are coeval to the Hith and Sulaiy formations suggest that the Hith may be early to middle Tithonian and the Sulaiy middle to late Tithonian in age.

Base Makhul Boundary Kuwait

In West Kuwait, the age of the top of the Hith Formation is c. 150.0 Ma based on Sr-isotope analysis (Al-Sahlan, 2005; G. Grabowski, 2006 written communication). This age is close to the estimated age of the Tithonian/Kimmeridgian boundary (150.8 ± 4.0 Ma; Gradstein et al., 2004). The age of the overlying Makhul Formation may be middle and late Tithonian based on dinocyst *Muderongia* sp. cf. A Davy (1979); however the occurrence of *Phoberocysta neocomica* indicates an age no older than Berriasian (Al-Sahlan, 2005). Thus the age of the base Makhul appears to be middle to late Tithonian or early Berriasian.

Age Estimate and Correlation

The estimated gap for the youngest Jurassic hiatus is the middle to late Tithonian. The age of the following transgression is middle to late Tithonian or early Berriasian. Considering that the standard deviations for the stage boundaries of the Late Jurassic are ± 4.0 million years, an age ranging from middle to late Tithonian to the Berriasian/Tithonian boundary [145.5 ± 4.0 Ma], could well correlate with the model age of SB^2 10 at 145.1 Ma.

DISCUSSION

The sequence stratigraphic interpretations and biostratigraphic ages of most of the Phanerozoic stratigraphic discontinuities in Arabia are not well constrained (Al-Husseini and Matthews, 2005). In this note, we have reviewed published and written communications regarding biostratigraphic and Sr-isotope data, and sequence stratigraphic interpretations from the Arabian Peninsula. The review suggests that it is somewhat possible to calibrate the ages of several significant regional and semi-regional hiatuses across a distance of more than 1,000 km in the Arabian Peninsula.

The oldest Jurassic hiatus was previously interpreted by Al-Husseini (1997) as Hettangian, Sinemurian and Pliensbachian and informally named the "Early Jurassic Hiatus". Its cause was attributed to the pronounced long-term global sea-level lowstand during the Hettangian to Pliensbachian times (Haq et al., 1988). Recent publications and written communications, however, indicate that the Pliensbachian Stage is indeed represented in Oman and Kuwait, and that the Pliensbachian-Toarcian (and possibly early Aalenian) succession forms a single second-order depositional sequence. The base of the Pliensbachian Stage has an age (189.6 ± 1.5 Ma) that correlates with the age of SB^2 13 (188.8 Ma). Second-order depositional sequence DS^2 13 may correlate to the Pliensbachian cycles UAB 3.3 and UAB 3.4 and late Pliensbachian, Toarcian and early Aalenian supercycle UAB-4 of Haq et al. (1988; see Al-Husseini, 1997).

The Aalenian Stage is not proven to be represented in the Arabian Gulf region, and this gap was informally referred to as the "Aalenian Hiatus" by Al-Husseini (1997; see references cited therein). The age of model SB^2 12 (174.3 Ma) may correlate to a global early Aalenian second-order sequence boundary that separates sequences UAB-4 and LZA-1 (Haq et al., 1988). With the benefit of the more recent GTS 2004 (Gradstein et al., 2004), the age of this hiatus in Saudi Arabia was moved from 177.0 Ma (Haq et al., 1988) to between 178.0–174.0 Ma in the late Toarcian and early Aalenian (Haq and Al-Qahtani, 2005). Thus the model age for SB^2 12 of 174.3 Ma seems consistent with an early Aalenian age (c. 174.0 Ma).

Model SB^2 11 correlates with the base of the lower Oxfordian Hanifa Formation in Saudi Arabia. In Oman, the Oxfordian Stage is missing, and in Kuwait the existence and age control for this sequence boundary is reported in a conflicting manner. As noted in several written communications, another candidate for SB^2 11 may be the older early Callovian Upper/Middle Dhruma (D7/D6) boundary. We prefer the early Oxfordian base Hanifa correlation to SB^2 11 for two reasons. Firstly, the preferred hiatus is identified in Oman, Saudi Arabia and possibly Kuwait, whereas the alternative hiatus is not identified in Oman and unclear in Kuwait. Secondly, a major global hiatus straddles the age of the Late/Middle Jurassic (Oxfordian/Callovian) boundary. This hiatus is consistent with orbital-forcing as it has been interpreted as a sea-level lowstand due to the formation of high-latitude continental ice sheets (Dromart et al., 2003; *in* Rousseau et al., 2006).

Finally, the uppermost Jurassic model sequence boundary SB^2 10 marks the top of the evaporite deposits over most of the Arabian Peninsula and appears to be middle to late Tithonian or base Berriasian in age.

In the orbital model developed by R.K. Matthews (*in* Al-Husseini and Matthews, 2005), a second-order sequence boundary occurs every 14.58 my. Based on the orbital calculations of Laskar (1990), the age of the first second-order sequence boundary (SB^2 1) was estimated at 13.9 Ma. Ongoing modeling by R.K. Matthews, incorporating the greatly improved orbital calculations of Laskar et al. (2004), indicate the age of nominal SB^2 1 to vary with boundary conditions. While 13.9 Ma remains a reasonable generalization, the more likely nominal age for SB^2 1 ranges from younger by eight fourth-order cycles (about 3.2 my or SB^2 1 = 10.7 Ma) to older by four fourth-order cycles (about 1.6 my or SB^2 1 = 15.5 Ma). These model predictions appear testable against observed sequence stratigraphy and are under consideration.

In the meantime, it is interesting to consider the estimated ages of the four second-order transgressions in terms of a least-square linear fit (Table 1). A simple least-square fit yields the following result:

$$Y = 14.45\ N + 0.35\ \text{Ma, for } N = 10, 11, 12 \text{ and } 13$$

$$\text{or } SB^2\ N{+}1 = SB^2\ N + 14.45,\ SB^2\ 1 = 14.80\ \text{Ma}$$

This fit estimates the second-order period as 14.45 million years, which is about 100 thousand years less than the model period of 14.58 million years. The age of SB^2 1 is estimated as 14.80 Ma instead of the model's 13.90 Ma. We consider this to be an acceptable model/data comparison.

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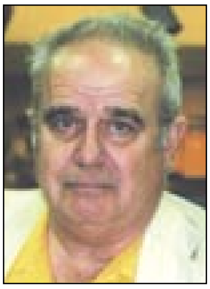
ABOUT THE AUTHORS

__Moujahed Al-Husseini__ founded Gulf PetroLink in 1993 in Manama, Bahrain. Gulf PetroLink is a consultancy aimed at transferring technology to the Middle East petroleum industry. Moujahed received his BSc in Engineering Science from King Fahd University of Petroleum and Minerals in Dhahran (1971), MSc in Operations Research from Stanford University, California (1972), PhD in Earth Sciences from Brown University, Rhode Island (1975) and Program for Management Development from Harvard University, Boston (1987). Moujahed joined Saudi Aramco in 1976 and was the Exploration Manager from 1989 to 1992. In 1996, Gulf PetroLink launched the journal of Middle East Petroleum Geosciences, GeoArabia, for which Moujahed is Editor-in-Chief. Moujahed also represented the GEO Conference Secretariat, Gulf PetroLink-GeoArabia in Bahrain from 1999-2004. He has published about 30 papers covering seismology, exploration and the regional geology of the Middle East, and is a member of the AAPG, AGU, SEG, EAGE and the Geological Society of London.

geoarabi@batelco.com.bh



__Robley K. Matthews__ is Professor of Geological Sciences at Brown University, Rhode Island,USA, and is general partner of RKM & Associates. Since the start of his career in the mid 1960s, he has had experience in carbonate sedimentation and diagenesis and their application to petroleum exploration and reservoir charcterization. Rob's current interests center around the use of computer-based dynamic models in stratigraphic simulation.

rkm@brown.edu