

Arabian Orbital Stratigraphy: Periodic Second-Order Sequence Boundaries?

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ABSTRACT

A simplified model of orbital-forcing suggests that the Phanerozoic Eon may be represented by 38 periodic second-order depositional sequences (DS²) each lasting about 14.58 million years (my). The DS²s are separated by second-order sequence boundaries (SB², maximum regression surface) that should be manifested as regional stratigraphic discontinuities (unconformity, disconformity, time hiatus). To test this simple model, the Arabian succession was reviewed to identify candidate regional stratigraphic discontinuities that might be periodic at 14.58 my. Of the 38 predicted SB²s, 34 regional stratigraphic discontinuities were identified within the uncertainty of biostratigraphic-radiometric age dating, or by stratigraphic position. One SB² could not be positioned in the succession because of ambiguous biostratigraphic dating. One was predicted within a long-lasting hiatus, and another two were predicted within an undifferentiated formation. The four unidentified SB²s reflect on the limitations of the data sample, rather than on the viability of the model.

Because the stratigraphic discontinuities represent age spans with bounding ages that are at best believed to have accuracies of about ± 3.0 my, the model-data correlation was considered inconclusive. The resulting analysis, however, demonstrates that the ages in million years before present (Ma) of interpreted Arabian (and possibly global) sequence stratigraphic surfaces and depositional sequences, as estimated by biostratigraphic-radiometric dating techniques, are highly inaccurate (± 5 – 10 my). This conclusion suggests that presently used chronostratigraphic correlations across the Arabian Platform should be treated with great caution. The correlation of model SB²s to regional stratigraphic discontinuities, affords an alternative time scale that may eventually assist in the calibration of the biostratigraphic-radiometric time scale. An orbital-forcing time scale has a decided advantage in that it comes with precise third- and fourth-order stratigraphic predictions imbedded as sea-level fluctuations. The next level of testing is whether these orbital-forcing predictions hold up to precise correlation to stratigraphy.

INTRODUCTION

Modeling sequence stratigraphy in terms of the variations of the Earth's orbit (Milankovitch Theory or orbital forcing; e.g. Laskar et al., 2004) has been proposed for the Arabian succession (Matthews and Frohlich, 1998; 2002; Mattner and Al-Husseini, 2002). A detailed orbital forcing study of the Albian succession in Oman was presented by Immenhauser and Matthews (2004) who concluded that glacio-eustasy is the most likely driving mechanism for the interpreted sea-level cycles in Oman. The interested reader is referred to their paper for a review of other mechanisms that drive sea-level changes. In this paper we present a simplified model of sea level that suggests that maximum regressions (lowstands) may have a constant period of approximately 14.58 million years (my). The resulting stratigraphic discontinuities are here referred to as a second-order sequence boundary (denoted SB²), and predicted to stand out as regional unconformities, disconformities, and time hiatuses (Figure 1). A second-order depositional sequence (denoted DS²) should therefore be bounded by two consecutive SB²s. Furthermore, a complete DS² that represents continuous deposition over time, is predicted to consist of six third-order depositional sequences (DS³) each deposited in a period of $2.430 \pm .405$ my (Matthews and Frohlich, 2002), or correspondingly 36 fourth-order depositional sequences (DS⁴) each deposited in a period of 0.405 my. However, in general, the six third- and 36 fourth-order sequences may not all be expressed in many localities due to erosion or/and non-deposition.

This paper presents the ages of the 38 predicted Phanerozoic SB²s and attempts to represent them in terms of regional stratigraphic discontinuities in successions from the Egyptian Gulf of Suez, Iraq, Kuwait, Oman, Saudi Arabia and the United Arab Emirates. Rock successions from these countries are

used because no single country provides a complete and ‘accurately’ dated succession for the entire Phanerozoic Eon. To identify a candidate discontinuity, we first correlate the age of the predicted SB²s via the recent publication “A Geological Time Scale 2004” (abbreviated GTS 2004; Gradstein et al., 2004), to the corresponding biostratigraphic stage. Next the stage correlation is used to identify the stratigraphic discontinuity that most closely matches the predicted age of the SB². The 38 predicted SB²s are listed by age (Ma) and stage position as implied by GTS 2004, together with the correlative stratigraphic discontinuities (Table 1). The latter are briefly described in terms of their stratigraphic aspects and regional extent.

CONVENTIONS AND CRITERIA

Notation: Rock unit boundaries are written as ‘upper unit/lower unit’ (e.g. Sulaiy/Hith); similarly for stage boundaries: ‘younger stage/older stage’ (e.g. Viséan/Tournaisian). To highlight a time hiatus of many millions of years, the corresponding contact is split into Base upper unit and Supra-lower unit (e.g. Berwath/Jubah is also Base Berwath that followed a hiatus, and Supra-Jubah that preceded a hiatus).

Stage, Age and Time Accuracy: If a stage position is qualified by “early, mid or late”, the age (Ma) is approximated by dividing the stage into three equal time periods (i.e. early = older third, mid = middle third, and late = youngest third: “1/3 approximation”). Brackets [Ma] are used whenever numerical ages are quoted from GTS 2004, and c. (circa) means approximate. In Table 1, the ages of the stratigraphic discontinuities are estimated from the ages of the ‘sandwiching’ rock units by GTS 2004 and the 1/3 approximation.

Regional Extent and Tectonic Criteria: In Arabia (as elsewhere) most formations are defined on the basis of their bounding stratigraphic discontinuities. Many of these surfaces are recognized regionally across 100s km (e.g. Oman-wide) to 1,000 km (e.g. Arabia-, Saudi Arabia-, Red Sea-

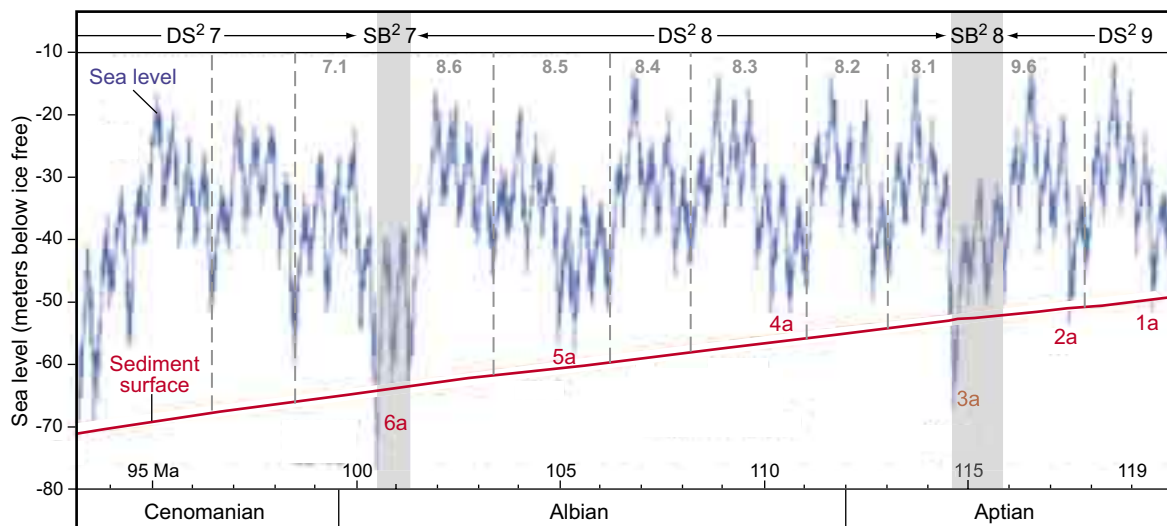


Figure 1: Orbital-forcing model of sea level (meters below ice-free level) and sediment surface for the Wadi Bani Kharus section, Oman (Immenhauser and Matthews, 2004). The stratigraphic discontinuity surfaces 1a to 6a are interpreted in several outcrops, and some are identified across a region of about 100–500 km. The crossovers of model sea level below the sediment surface at Discontinuity Surfaces 3a (c. 114.5 Ma) and 6a (c. 100.5 Ma) are interpreted as periods of subaerial exposure. In this paper, second-order sequence boundaries SB² 8 (116.0–114.5 Ma) and SB² 7 (101.5–100.4 Ma) are interpreted to bound second-order depositional sequence DS² 8. The DS² 8 is predicted to consist of six third-order depositional sequences (DS³ 8.1 to 8.6), some of which have distinctive third-order sequence boundaries: SB³ 8.2 = 4a and SB³ 8.4 = 5a. Some SB³s may not be prominent (e.g. 8.3 and 8.5) and fail to separate two third-order sequences clearly. A complete DS² is predicted to last 14.58 million years and to consist of 36 fourth-order transgressive-regressive cycles, some represented as depositional sequences (DS⁴), which ring like a “geological tuning fork” with a period 405 thousand years (0.405 my). Many DS⁴s, however, may be missing due to erosion or/and non-deposition, particularly during times of sea-level lowstands and subaerial exposures.

wide), and interpreted as major non-tectonic events (?unconformity, disconformity, surface of major transgression following a major regression, time hiatus, etc.). Very few surfaces are known to represent clear angular unconformities related to tectonic events (e.g. mid Carboniferous, Late Cretaceous, Oligocene). Because Saudi Arabia and Oman have 36 and 37 Phanerozoic formations, respectively (most are chronostratigraphic units), the formation boundaries provide a “limited” data set for finding the 38 SB²s. As such, many of the predicted SB²s are here positioned between members (or in a few cases informal units or assemblages) that could well be interpreted as second-order sequence boundaries.

In several cases the age of an SB² approximately correlates to the end of deposition before a major time hiatus (?regression), which might be inferred to be the termination or truncation of a second-order DS² as expressed by the upper SB² (shown as Supra-unit in Table 1 and Hiatus/County). In other cases, the age of an SB² approximately correlates to the start of deposition following a hiatus, which may indicate a regional transgression. These latter SB²s are shown in Table 1 as Base unit and Country/Hiatus.

“Rosetta Stone” Approach: If two consecutive SB²s are confidently identified, it should be possible to model and interpret the enclosed second-order sequence (DS²) in terms of third- and higher-order depositional sequences. This “Rosetta Stone” approach was illustrated by Immenhauser and Matthews (2004), and involves detailed correlation of the stratigraphy and model sea level (Figure 1). Two of their discontinuity surfaces stood out prominently; here interpreted as Discontinuity Surface 3a = SB² 8 (116.0 Ma in late Aptian) and Discontinuity Surface 6a = SB² 7 (101.4 in late Albian). A similar approach is presented in the Tectono-Stratigraphic Note for the late Carboniferous, Permian and Early Triassic times (Al-Husseini and Matthews, 2005; this issue of GeoArabia).

The following discussion will primarily focus on the accuracy of the age and regional extent of stratigraphic discontinuities that may correlate to the model SB²s. The internal stratigraphic architectures of the DS²s, and other higher-order boundaries within them, will not be addressed here. We believe that the fuller Rosetta Stone treatment of DS²s and their regional correlations is predicated on the clear identification of SB²s, as initiated here.

SECOND-ORDER SEQUENCE BOUNDARIES

SB² 1: 13.9 Ma, late Langhian Stage, Miocene Epoch, Neogene Period

Belayim/Kareem Boundary, Gulf of Suez, Egypt. Age correlation of SB² 1 to Belayim/Kareem in late Langhian is consistent with the biostratigraphic dating of both formations by Hughes and Johnson (2005). Other authors, however, show the position of Belayim/Kareem in early to mid Serravalian (e.g. Richardson and Arthur, 1988; Evans, 1988; Patton et al., 1994; Bosworth and McClay 2001). Some of these latter authors position the next-oldest Kareem/Rudeis in late Langhian. Therefore biostratigraphic-radiometric age range of Belayim/Kareem or/and Kareem/Rudeis is late Langhian to mid Serravalian [Table 1: 14.4–12.6 Ma]. The Belayim/Kareem and Kareem/Rudeis are both regional unconformities in the Gulf of Suez (e.g. Patton et al., 1994; Bosworth and McClay 2001), and their correlatives extend for more than 1,000 km across the entire Red Sea (e.g. Hughes and Johnson, 2005). Several authors interpret the Belayim/Kareem (rather than the Kareem/Rudeis) as the second-order sequence boundary (Webster and Ritson, 1984; Wescott et al., 1996), and we adopt this surface as the correlation to SB² 1.

SB² 2: 28.5 Ma, c. Chattian/Rupelian Stage Boundary, Oligocene Epoch, Paleogene Period

?Euphrates/Ibrahim or ?Ibrahim/Tarjil Boundaries, Iraq. The Oligocene Epoch in most of Arabia is represented by a time hiatus. In North Iraq, however, van Bellen et al. (1959) describe the Euphrates/Ibrahim and the Ibrahim/Tarjil as regional unconformable boundaries (c. 100s km) that are positioned at the “Miocene/Oligocene” and “upper/middle Oligocene” boundaries, respectively. However because they caution that these ages are not related to the European Oligocene and Miocene, the position of SB² 2 is not clear.

SB² 3: 43.1 Ma, late Lutetian Stage, Eocene Epoch, Paleogene Period

Supra-Dammam Boundary, Saudi Arabia. According to Powers (1968), the uppermost Alat Member of the Dammam Formation is “clearly” Lutetian in age. A hiatus occupies the time period from the

regional Supra-Dammam Boundary (c. 1,000 km) to the ?early Miocene Hadruk Formation (Powers, 1968). Following Powers, the estimated age of the Supra-Dammam is positioned at older than the Bartonian/Lutetian Boundary [40.4 Ma], and probably at younger than mid Lutetian [44.5 Ma].

SB² 4: 57.6 Ma, late Thanetian Stage, Paleocene Epoch, Paleogene Period

Upper/Lower Umm er Radhuma Boundary, Saudi Arabia. The Umm er Radhuma Formation is divided into the Eocene upper and Paleocene lower units (Powers, 1968). Powers highlights the Upper/Lower Umm er Radhuma Boundary as an erosional unconformity associated with the loss of section on crestal parts of local structures (c. 100s km). The predicted age of SB² 4 in the late Thanetian may be consistent with the age of the Upper/Lower Umm er Radhuma Unconformity if the hiatus started before the age of the Eocene/Paleocene Boundary [55.8 ± 0.2 Ma]. Between the Upper/Lower Umm er Radhuma (SB² 4) and the Supra-Dammam (SB² 3) boundaries, all intermediate rock units have conformable or/and diachronous contacts (Dammam/Rus and Rus/Umm er Radhuma; Powers, 1968) implying a single DS² 4 is bounded by these two unconformities.

SB² 5: 72.2 Ma, late Campanian Stage, Late Cretaceous Period

Base Aruma Boundary, Saudi Arabia. Placement of SB² 5 in late Campanian [74.9–70.6 Ma] is consistent with the age of the late Campanian Base Aruma transgression (Y.M. Le Nindre, personal communication, 2005). The Pre-Aruma Hiatus spans the late Turonian, Coniacian, Santonian and most of the Campanian, a period of approximately 30 my that is attributed to tectonism along the Tethyan margin and regional tilting of the Arabian Plate. The above correlations imply the Umm er Radhuma/Aruma and intra-Aruma boundaries (Lina Member/Hajajah Member = Paleogene/Cretaceous Boundary, Hajajah Member/Khanasir Member) are third-order sequence boundaries and unconformities (Philip et al., 2002).

Simsima/Fiqa Boundary, Oman. According to Hughes Clark (1988), the Simsima/Fiqa Boundary is generally sharp; the age, facies and seismic evidence indicate a disconformity between the Simsima and Fiqa formations. The Simsima/Fiqa Boundary is correlated to the Pre-Aruma Unconformity with an age close to the c. Maastrichtian/Campanian Boundary [70.6 ± 0.6 Ma].

Base Shiranish or Base Hartha Boundaries, Iraq. Age correlation of SB² 5 in late Campanian is consistent with the age of the basal part of the Shiranish Formation (van Bellen et al., 1959). Van Bellen et al. show the base of a regional second-order transgression (c. 1,000 km) along Base Shiranish = Base Hartha = Base Bekhme = Base Bahra (Kuwait) and Base Aruma (in Qatar and Saudi Arabia) in an isochronous position at the boundary between the “upper and lower” Campanian [?mid Campanian = 77.1 Ma].

SB² 6: 86.8 Ma, late Coniacian Stage, Late Cretaceous Period

?Base Fiqa Boundary, Oman. According to Hughes Clark (1988), microfossils and nannofossils evidence the start of deposition of the Fiqa Formation in Santonian [c. Santonian/Coniacian Boundary: 85.8 ± 0.7 Ma]. Hughes Clark notes that the Fiqa Formation comprises a new phase of sedimentation following the end of Natih Formation deposition. He describes the Pre-Fiqa Unconformity as always sharp, with age and facies changes that indicate a hiatus that represents a period of regional emergence and erosion associated with tectonism during the late Turonian, Coniacian and ?early Santonian over most of Oman (c. 100s km). The correlation of SB² 6 to Base Fiqa may only be appropriate in subsurface Oman, as van Buchem et al. (1996, figure 2, p. 67) show that the Fiqa Formation is not defined consistently in Abu Dhabi, Dubai, North Emirates and northwest Oman.

SB² 7: 101.4 Ma, late Albian Stage, Early Cretaceous Period

Discontinuity Surface DS 6a, Nahr Umr Formation, Oman. Based on modeling of the Nahr Umr Formation in Oman, Immenhauser and Matthews (2004, Figure 1) correlated SB² 7 (101.4 Ma) to Discontinuity Surface 6a. This surface is interpreted in outcrops over a distance of some 300 km, from the Oman Mountains to the southern Haushi-Huqf.

SB² 8: 116.0 Ma, late Aptian Stage, Early Cretaceous Period

Supra-Qishn Boundary, Oman. Immenhauser et al. (2004) identify the ‘top-Qishn Formation unconformity’ as a “regionally significant unconformity that represents a considerable hiatus (more than 5 my) spanning the early and the late Aptian” in the outcrops of central Oman (Haushi-Huqf region).

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Discontinuity Surface DS 3a, Oman. Based on modelling of sea level in the time period 120–85 Ma in Oman, Immenhauser and Matthews (2004, Figure 1) correlated a major regression at 114.5 Ma to Discontinuity Surface DS 3a. The model regression is predicted as three fourth-order (.405 my) sea-level lowstands spanning the interval c. 116.0–114.5 Ma. SB² 8 (116.0 Ma) appears to correlate to the oldest of their four lowstands. DS 3a is identified over a distance of about 100 km in the Oman Mountains.

Upper/Middle Shu'aiba Boundary, Oman. In North Oman, Boote and Mou (2003) position a prominent second-order sequence boundary between the upper and middle Shu'aiba Formation and assign an age of c. Aptian 4 (their red line at 117.07 Ma in figure 23, p. 408).

Base Unnamed Clastics Boundary, Kuwait. Al-Fares et al. (1998) identified a major time hiatus and disconformity that spans latest Aptian and early Albian. The unconformity separates the mid to early late Albian Burgan Formation from the underlying late Aptian "Unnamed Clastics Formation" (c. 100 km). The age of SB² 8 (116.0 Ma) compares closely to late/mid Aptian [c. 115.3 Ma] and the Base Unnamed Clastics Formation may represent a major second-order regressive event.

Base Bab Member Boundary, Shu'aiba Formation, United Arab Emirates. Van Buchem et al. (2002, their figure 15, p. 491) interpreted a major relative sea-level lowstand period in the late Aptian characterized by the Bab Member (their Upper Shu'aiba Sequences IV^a and IV^b). Their SB IV^a at the base of Sequence IV^a represents a regional regression (c. 100s km) and is positioned between upper/lower Aptian. They interpret the Bab Member as the lowstand of a second-order transgression that culminated in the Nahr Umr flood. Upper Shu'aiba Sequences IV^a and IV^b may correlate to lowstand interval 116.0–114.5 (Immenhauser and Matthews, 2004) and the Base Bab Member to SB² 8 (116.0 Ma).

Supra-Shu'aiba Boundary, Saudi Arabia. In the Shaybah field, Hughes (2000) interpreted a major unconformity between the early Aptian Shu'aiba Formation and late Aptian Khafji Member of the Wasia Formation. Hughes correlates the Khafji Member to the Nahr Umr Formation in Oman (see above) and the United Arab Emirates (his figure 5, p. 550), and notes that the Bab Member is absent over the Shaybah anticline.

SB² 9: 130.6 Ma, late Hauterivian Stage, Early Cretaceous Period

Base Zubair Boundary, Kuwait. Al-Fares et al. (1998) identified a major time hiatus and disconformity that started in late/mid Valanginian and ended in late/mid Hauterivian, and corresponds to the Zubair/Ratawi Boundary. The age of the Zubair Formation is late Hauterivian to early Aptian based on nannoplankton (Lacustrine Basin Research Report, 1996, in Al-Fares et al., 1998). The age of the Ratawi Formation is early Valanginian (Varol Research, 1996, in Al-Fares et al., 1998). The age of SB² 9 is late Hauterivian or older than Barremian/Hauterivian Boundary [130.0 ± 1.5 Ma] and offers a correlation to Base Zubair that marks a major second-order transgression identified in Kuwait (c. 100s km).

SB² 10: 145.1 Ma, c. Berrisian/Tithonian Boundary, Cretaceous/Jurassic Boundary

Sulaiy/Hith Boundary, Saudi Arabia. The Sulaiy/Hith Boundary separates the ?Tithonian-Berriasian-?Valanginian Sulaiy Formation from the ?Tithonian Hith Anhydrite; both formations are dated by stratigraphic position only (Powers, 1968). The Sulaiy marks a regional transgression above the massive anhydrites of the Hith (c. 1,000 km). According to Vaslet et al. (1991), the lower contact of the Sulaiy Formation with the Hith Anhydrite can only be seen at Dahl Hith (near Riyadh), where the Sulaiy truncates the top of the underlying Hith Anhydrite and is clearly disconformable. The contact is also affected by some bedding-parallel displacement between the ductile Hith and brittle Sulaiy formations (J. Mattner, personal communication, 2005). Vaslet et al. (1991) add that an oxygen and sulfur isotope study of a sample of anhydrite from Dahal Hith indicates "perfect agreement" with average values known elsewhere in the world in the late Late Jurassic. The age of Sulaiy/Hith in latest Jurassic (latest Tithonian) or c. Berriasian/Tithonian (also Cretaceous/Jurassic Boundary: 145.5 ± 4.0 Ma] provides a correlation to SB² 10.

SB² 11: 159.7 Ma, early Oxfordian Stage, Late Jurassic Epoch

Hanifa/Tuwaiq Mountain Boundary, Oman and Saudi Arabia. In Saudi Arabia, the Hanifa/Tuwaiq Mountain Boundary is interpreted as apparently conformable and placed at the sharp change from calcareous shale above to massive, coral-bearing limestone below (Powers, 1968). According

to Fischer et al. (2001), the Hanifa/Tuwaiq Mountain Boundary is early Oxfordian and marks an environmental change from reefal (uppermost T3 unit of Tuwaiq Mountain) to inner lagoon (basal Hanifa). The Hanifa/Tuwaiq Mountain is interpreted as a sequence boundary of regional extent (c. 1,000 km) (e.g. Mattner and Al-Husseini, 2002). In Oman, Droste (2001, unpublished chart; 2005, personal communication) interpreted Hanifa/Tuwaiq Mountain as a regional stratigraphic break (c. 100s km) of Oxfordian age. The correlation of Hanifa/Tuwaiq Mountain in early Oxfordian [i.e. younger than Oxfordian/Kimmeridgian Boundary: 161.2 ± 4.0 Ma] provides a correlation to SB² 11 (159.7 Ma).

SB² 12: 174.3 Ma, early Aalenian Stage, Middle Jurassic Period

Supra-Marrat Boundary, Saudi Arabia. A time hiatus in Saudi Arabia spans the ?late Toarcian and Aalenian stages [Aalenian: 175.6 ± 2.0 to 171.6 ± 3.0 Ma]. The corresponding unconformity (c. 1,000 km) separates the basal Bajocian part of the Dhurma Formation from the Toarcian Marrat Formation (Fischer et al., 2001). Age correlation of SB² 12 (174.3 Ma) to the Supra-Marrat Boundary [c. Aalenian/Toarcian: 175.6 ± 2.0 Ma] is consistent with a major regression in early Aalenian.

SB² 13: 188.8 Ma, early Pliensbachian, Early Jurassic Period

Base Marrat Boundary, Saudi Arabia. In Saudi Arabia, the Early Jurassic Hettangian, Sinemurian, and ?Pliensbachian stages are not represented. In Saudi Arabian outcrops, however, the basal part of the Marrat Formation is not dated while the transgression at the top of the lower Marrat unit is dated as Toarcian (Y.-M. Le Nindre, personal communication, 2005). Le Nindre notes: "the Pliensbachian (or older) is known in the more distal part of the shelf and commonly represented by the *Orbitopsella* facies". He suggests that "the Toarcian transgression seems to correspond more to a coastal onlap above the Minjur Formation, than to a 'true' unconformity". P. Osterloff (2005, written communication) notes that in some basin depocenters in northern Oman, the Pliensbachian is represented in the Mafraq Formation (*Nannoceratopsis gracilis*). It is therefore possible that the Base Marrat may represent a regional transgression (c. 1,000 km) that followed the SB² 13 maximum regression in early Pleinsbachian.

SB² 14: 203.4 Ma, c. Rhaetian/Norian Stage Boundary, Late Triassic Period

Minjur/Jilh Boundary, Saudi Arabia. The base Minjur Sandstone Formation is distinguished by a marker layer with silicified tree trunks up to 3 m long, and some basal sequences contain coarse clasts that have a diameter of 2 cm, marking the soles of channel infill (Robelin et al. 1994, Lebret et al. 1999). About 2 m above the Minjur/Jilh Boundary, a Norian age was obtained for a palynological association (Robelin et al. 1994), while Le Nindre et al. (1990) dated the uppermost Jilh as probably late middle Norian. The Minjur/Jilh Boundary represents a regional stratigraphic discontinuity (c. 1,000 km) that has an age of late Norian [i.e. older than Rhaetian/Norian Boundary: 203.6 ± 1.5 Ma] and could be correlated to SB² 14 (203.4 Ma) within the standard deviation of ± 1.5 my.

SB² 15: 218.0 Ma, late Carnian Stage, Late Triassic Period

upper/middle Jilh Boundary, Saudi Arabia. The Jilh Formation is divided into lower, middle and upper informal units that are regionally (c. 100s km) recognized in outcrop (e.g. Manivit et al., 1983, 1985; Vaslet et al., 1985, 1988; Robelin et al., 1994). The Jilh is overlain by the Minjur and underlain by the Sudair formations (Powers, 1968). Vaslet et al. (1985) indicated that the Jilh Formation is rich in conodonts, which enables accurate dating of the middle and upper units. The top of the middle Jilh unit is dated as middle and late Carnian, while the upper unit is dated as Carnian (south of 26°N) and Carnian to Norian (north of 26°N) (Vaslet et al., 1985, 1988), thus implying a diachronous lower boundary. Age correlation of SB² 15 (218.0 Ma) to upper/middle Jilh Boundary in late Carnian [i.e. older than Norian/Carnian Boundary: 216.5 ± 2.0 Ma] is consistent with a time transgressive upper Jilh unit.

SB² 16: 232.6 Ma, mid Ladinian Stage, Middle Triassic Period

middle/lower Jilh Boundary, Saudi Arabia. Based on conodonts, Le Nindre et al. (1990) interpreted a late Ladinian age for the upper part of the lower Jilh unit, and Vaslet et al. (1985) interpreted the age of the middle Jilh unit as Carnian. The lower Jilh unit is capped by a pedogenized layer (paleosol) above gypsiferous claystone, with beds of yellowish dolomitic sandstone (Manivit et al., 1986). The predicted age of SB² 15 at 232.6 Ma falls near mid Ladinian c. 231.5 ± 2.0 Ma [mid 237.0 ± 2.0 to $228.0 \pm$

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2.0 Ma]; however, the biostratigraphic age of middle/lower Jilh Boundary appears to be late Ladinian [231–228 ± 2.0 Ma]; a discrepancy of some 1.6 my (232.6 versus 231.0) falls within one standard deviation ± 2.0 my applied for Ladinian (GTS 2004).

The Jilh/Sudair Boundary is interpreted as conformable and accordingly is not a likely second-order sequence boundary (Powers, 1968). On the basis of palynological studies from well SHD-1 in central Saudi Arabia, Le Nindre et al. (1990) dated the base of the Jilh Formation as Anisian such that the Jilh/Sudair Boundary is intra-Anisian [245.0 ± 1.5 to 237.0 ± 2.0 Ma], and too old to correlate to SB² 16.

SB² 17: 247.2 Ma, mid Olenkian Stage, Early Triassic Period

Sudairic/Khuff Boundary, Oman and Saudi Arabia. The age of the Sudairic/Khuff Boundary is best estimated by the correlation proposed in Oman by H. Droste (in Blechschmidt et al., 2004): subsurface Base Sudair Formation = base of the late Olenkinian Sandstone and Shale Member of the Zulla Formation in outcrop. The maximum regression between the Sudair and Khuff formations is noted in the SHD-1 well in central Saudi Arabia (Manivit et al., 1983, 1985; Le Nindre et al., 1990), which encountered a basal Sudair Formation that consists of 18 m of interbedded gypsiferous claystone, sulfated dolomite, sulfurous gypsum, and massive halite in 1-m-thick beds. This evaporitic section is assigned by stratigraphic position to Early Triassic and reflects a major lowstand at Sudairic/Khuff that is mapped by Ziegler (2001) as a salina of limited areal extent (c. 100 km in diameter) in central Arabia.

SB² 18: 261.8 Ma, mid Capitanian Stage, Guadalupian Epoch, Permian Period

Middle/Lower Khuff Boundary, Oman. Age correlation of SB² 18 to the Middle/Lower Khuff Boundary in mid Capitanian cannot be accurately shown by biostratigraphic criteria as these two Khuff members are only dated as Permian and younger than Wordian (Osterloff et al. 2004b). The Middle/Lower Khuff is interpreted as a major sequence boundary across Oman (c. 100s km) by Osterloff et al. (2004b; see Al-Husseini and Matthews, 2005, this issue of GeoArabia).

SB² 19: 276.3 Ma, late Artinskian Stage, Cisuralian Epoch, Permian Period

Upper/Middle Gharif Boundary, Oman. Age correlation of SB² 19 to the Upper/Middle Gharif Boundary in late Artinskian cannot be accurately shown by biostratigraphic criteria as these two Gharif members are only dated by stratigraphic position as Artinskian-Wordian (Osterloff et al. 2004b). The Upper/Middle Gharif Boundary is highlighted as the maximum regression surface (c. 100s km) within the Gharif Formation (Guit et al., 1995; P. Osterloff, personal communication, 2003; see Al-Husseini and Matthews, 2005, this issue of GeoArabia).

SB² 20: 290.2 Ma, mid Sakmarian Stage, Cisuralian Epoch, Permian Period

Base Al Khlata AK P1 Blanketing Diamictite Boundary, Oman. Age correlation of SB² 20 to the base Blanketing Diamictite in mid Sakmarian is consistent with the stratigraphic position assignment by Osterloff et al. (2004a). The base Blanketing Diamictite represents a regional unit (c. 100s km) that marked a meltdown following a major glacial advance (Osterloff et al., 2004a; see Al-Husseini and Matthews, 2005, this issue of GeoArabia).

SB² 21 (305.5 Ma, mid Kasimovian Stage, Late Pennsylvanian Epoch, Carboniferous Period

Al Khlata AK P5/P9 Boundary, Oman. Age correlation of SB² 21 to Al Khlata P5/P9 Boundary in mid Kasimovian is consistent with palynological dating by Osterloff et al. (2004a). Al Khlata AK P5/P9 Boundary is recognized as a hiatus (glacial advance or maximum regression across 100s km) separating two depositional units (Osterloff et al., 2004a; see Al-Husseini and Matthews, 2005, this issue of GeoArabia).

SB² 22: 320.1 Ma, late Serpukhovian Stage, Late Mississippian Epoch, Carboniferous Period

Supra-Berwath Boundary, Saudi Arabia. The Supra-Berwath Boundary is Serpukhovian (Al-Hajri and Owens, 2000) or latest Visean (J. Filatoff, in Al-Husseini, 2004); i.e. ?within the Serpukhovian [326.4 ± 1.6 to 318.1 ± 1.3 Ma], and could correlate to SB² 22. The deposition of the Berwath Formation was followed by the Plate-wide (c. 1,000 km) Mid-Carboniferous Hiatus (?Serpukovian, Bashkirian to late/mid Moscovian) that is interpreted as a period of non-deposition and erosion associated with a tectonic event (so called 'Hercynian orogeny or unconformity') (Al-Husseini, 2004).

SB² 23: 334.7 Ma, mid Visean Stage, Middle Mississippian Epoch, Carboniferous Period

Base Berwath Boundary, Saudi Arabia. The Berwath/Jubah Boundary (c. 1,000 km) corresponds to a hiatus that extends from mid/early Tournaisian and late/mid Visean (Al-Hajri and Owens, 2000; J. Filatoff, personal communication, 2003, in Al-Husseini, 2004). A late Visean age for the Base Berwath would be about 332.7 Ma [2/3 into Visean: 345.3 ± 2.1 to 326.4 ± 1.6 Ma]. The Base Berwath (c. 332.7 Ma) could correspond to the start of the Berwath transgression after the maximum regression SB² 23 (334.7 Ma).

SB² 24: 349.2 Ma, late Tournaisian Stage, Early Mississippian Epoch, Carboniferous Period

?Supra-Jubah Boundary, Saudi Arabia. The continental Jubah Formation is dated as Middle Devonian (late Eifelian) to Early Carboniferous (early Tournaisian) (Al-Hajri et al., 1999; Al-Hajri and Owens, 2000; J. Filatoff, personal communication, 2003, in Al-Husseini, 2004). The mid/early Tournaisian age of the Supra-Jubah Boundary (c. 1,000 km) is estimated as c. 354.6 Ma [1/3 into Tournaisian: 359.2 ± 2.5 and 345.3 ± 2.1 Ma]. The Supra-Jubah is about 5 my older than the predicted age of SB² 24 indicating that the latter may be positioned within the Base Berwath-Supra-Jubah Hiatus.

?SB² 25: 363.8 Ma, late Fammenian, Late Devonian Period

?Upper/Middle Jubah Boundary, Saudi Arabia. On the basis of its predicted age, SB² 25 may occur within the Jubah Formation and separate it into upper and middle divisions.

?SB² 26: 378.4 Ma, late Frasnian, Late Devonian Period

?Middle/Lower Jubah Boundary, Saudi Arabia. On the basis of its predicted age, SB² 26 may occur within the Jubah Formation and separate it into lower and middle divisions.

SB² 27: 393.0 Ma, late Eifelian Stage, Middle Carboniferous Period

Jubah/Jauf Boundary, Saudi Arabia. Age correlation of SB² 27 to the Jubah/Jauf Boundary is consistent with the intra-Eifelian age of the boundary (Al-Hajri et al., 1999) [Eifelian: 397.5 ± 2.7 and 391.8 ± 2.7 Ma]. The Jubah/Jauf Boundary is described as a regional unconformity by Wallace et al. (1997) or regional disconformity (Al-Hajri and Owens, 2000), and is mapped in outcrop and subsurface (c. 1,000 km).

SB² 28: 407.5 Ma, late Pragian Stage, Early Devonian Period

Jauf/Tawil Boundary, Saudi Arabia. Age correlation of SB² 28 to Jauf/Tawil is consistent with late Pragian age [i.e. older than Emsian/Pragian = 407.0 ± 2.8 Ma] of the lowermost Sha'iba Member of the Jauf Formation (Al-Hajri et al., 1999; Al-Hajri and Owens, 2000). The basal Jauf Formation marked an abrupt transgression that reworked the paleosol capping the underlying Tawil Formation (Janjou et al., 1997a,b). According to Wallace et al. (1997), an angular discordance cannot be demonstrated between the Tawil and Jauf formations, so the contact is a disconformity inasmuch as the thickness of the uppermost Juraniyat Member of the Tawil Formation below the Jauf Formation is variable. The Jauf/Tawil Boundary is mapped in outcrop and subsurface (c. 1,000 km).

SB² 29: 422.14 Ma, intra-Gorstian Stage, Ludlow Epoch, Silurian Period

Tawil/Sharawra Boundary, Saudi Arabia. Age correlation of SB² 29 to Tawil/Sharawra is consistent with the intra-Gorstian age (Al-Hajri and Owens, 2000). The Tawil/Sharawra is recognized as the Pre-Tawil Unconformity (c. 1,000 km) and a possible time hiatus (e.g. Wender et al., 1998; Al-Hajri and Owens, 2000). According to Janjou et al. (1997a,b, 1998), the basal Samra Member of the Tawil Formation disconformably overlies the sandstone at the top of the Sharawra Formation, and the Tawil/Sharawra Boundary is marked by a regional erosion surface and slight channeling. The bedding on both sides of this surface is parallel, giving it the character of a disconformity that marks the limit between two major sedimentary cycles.

SB² 30: 436.7 Ma, late Aeronian Stage, Llandovery Epoch, Silurian Period

Base Mid-Qusaiba Sandstone Boundary, Saudi Arabia. Age correlation of SB² 30 is consistent with the age of the intra-Aeronian Base Mid-Qusaiba Sandstone (Miller and Melvin, 2005). The subsurface Mid-Qusaiba Sandstone is mapped regionally over Ghawar field and in parts of the Rub' Al-Khali (c. 500 km) (Wender et al., 1998; Miller and Melvin, 2005). An Aeronian age [439.0 ± 1.8 to 436.0 ± 1.9 Ma] for the sharp sea-level lowstand implied at the Base Mid-Qusaiba Sandstone (within an otherwise open-marine succession) would correlate with a regional regression predicted as SB² 30.

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SB² 31 (451.3 Ma, mid 'Ashgillian', Late Ordovician Period

Supra-Quwarah Boundary, Saudi Arabia. The Qasim Formation consists from base-up of the Hanadir, Kahfah, Ra'an and Quwarah members (Vaslet, 1990). The Supra-Quwarah Boundary is dated by stratigraphic position as 'late 'Caradocian'-?'Ashgillian' because the Quwarah Member lies above the 'Caradocian' Ra'an Member and below the Hirnantian Sarah Formation (Vaslet, 1990; Al-Hajri and Owens, 2000). The Supra-Quwarah Boundary represents the erosional surface in Saudi Arabia (c. 1,000 km) upon which the Gondwana ice sheet developed.

Intra-Hasirah Unconformity, Oman. In the upper part of the Hasirah Formation, the 'Intra-Hasirah Unconformity' reflects possible incision that Droste (1997) associates with Late Ordovician glaciation. Droste positions the Intra-Hasirah unconformable break at approximately the 'Ashgill/Caradoc boundary' [c. 455.8 ± 1.6 Ma]. The Intra-Hasirah Unconformity of Oman is correlated to the Supra-Quwarah Boundary of Saudi Arabia.

SB² 32 (465.9 Ma, mid Dariwillian, Late Ordovician Period

Hasirah/Saih Nihyada Boundary, Oman. Droste (1997) dated the Hasirah Formation as Late Ordovician ('Caradoc' and 'Ashgill'). The Hasirah/Saih Nihyada Boundary is interpreted as a regional unconformity (c. 100s km) and a hiatus, and positioned near the Late/Middle Ordovician Boundary (Droste, 1997) [460.9 ± 1.6 Ma].

Upper/Lower Kahfah Boundary, Saudi Arabia. The Kahfah Member of the Qasim Formation is divided into two informal assemblages, lower and upper, in outcrops in northwest and central Arabia (Vaslet et al., 1987, 1994). The top of the lower assemblage is a strongly ferruginized black surface of regional extent (c. 100s km). The age of the Upper/Lower Kahfah Boundary falls in the Dariwillian Stage [= 'Llandeillo'; 468.1 ± 1.6 to 460.9 ± 1.6 Ma]. The Upper/Lower Kahfah boundary marks the maximum regression surface between two second-order flooding events characterized by the 'Llanvirnian' Hanadir and 'Caradocian' Ra'an open-marine shales.

SB² 33 (480.5 Ma, late Tremadocian, Early Ordovician Period

Barakat/Mabrouk Boundary, Oman. By stratigraphic position, Droste (1997) suggested an age for Barakat/Mabrouk of Early Ordovician, ?Tremadoc ($?488.3 \pm 1.7$ to $?478.6 \pm 1.7$ Ma). The Base Barakat is interpreted by Droste as a 'low-angle truncation of underlying units and a time hiatus. He interprets the Base Barakat as a regional unconformity, and the marine deposits of the Barakat Member as an extensive transgression that extended over north and south Oman (c. 100s km).

SB² 34: 495.0 Ma, mid Furogonian Epoch, Cambrian Period

Base Al Bashair Boundary, Oman. The Base Al-Bashair (= Al Bashair/Miqrat-Mahwis) is Middle or Late Cambrian in age by stratigraphic position (Droste, 1997). The Base Al Bashair is interpreted by Droste as an onlap/truncation regional unconformity (c. 100s km) and time hiatus. Base Al Bashair would appear to most closely correlate to SB² 34 (495 Ma) in Late Cambrian [501.0 ± 2.0 to 488.3 ± 1.7 Ma].

SB² 35: 509.6 Ma, mid Middle Cambrian Period

Miqrat-Mahwis/Amin Boundary, Oman. Droste (1997) considers the Miqrat-Mahwis/Amin Boundary as a probable unconformity and an onlap surface, and Middle Cambrian in age by stratigraphic position. In the Ghaba Salt Basin, the Miqrat Formation overlies the Amin Formation, often abruptly, and the Miqrat/Amin Boundary may be an unconformity (Droste, 1997). Along the eastern edge of the Ghaba Salt Basin, however, the Miqrat/Amin contact is transitional. The Mahwis/Amin Boundary is abrupt and assumed to be disconformable; however in places transitions with interbedding of the two sediment types have been reported (Heward, 1989, in Droste, 1997). The correlation of Miqrat-Mahwis/Amin (c. 100s km) to SB² 35 is based on stratigraphic position.

SB² 36: 524.2 Ma, Early Cambrian Period

Base Amin Boundary, Oman. The age of the Base Amin Formation is Early Cambrian by stratigraphic position (Droste, 1997). The Base Amin is also the Angudan Unconformity (Loosveld et al., 1996), which appears as a clear angular truncation and is interpreted as a time hiatus (Droste, 1997). The Amin Formation is conglomeratic at the base and lithologically similar to the Early Cambrian Siq Formation in Saudi Arabia (c. 1,000 km); both formations are regionally widespread and were deposited on a peneplane. Correlation of Base Amin and Base Siq to the start of a major transgression as predicted by SB² 36 seems possible.

SB² 37: 538.8 Ma, Early Cambrian Period

Karim/Ara Boundary, Oman. The Nimr Group consists of two Early Cambrian continental formations: Karim below the Haradh. Seismic data suggests that the Nimr Group was deposited in the central parts of the Ara Salt basins and onlaps the bordering basement highs and Ara Salt diapirs. The Haradh/Karim is interpreted as diachronous (Droste, unpublished chart), and the Karim/Ara as an isochronous event at c. 540 Ma (Droste, 1997; Cozzi and Al-Siyabi, 2004). The Karim/Ara represents the change from carbonates and evaporites below to continental clastics above (c. 100s km), and could be correlated to SB² 37 by stratigraphic position.

SB² 38: 553.4 Ma, late Ediacaran Period, Neoproterozoic Era

Shuram/Khufai Boundary, Oman. The Shuram/Khufai Boundary is late Ediacaran by stratigraphic position and older than 550 Ma as it occurs below the Base Ara Group (c. 550 Ma, Cozzi and Al-Siyabi, 2004). Cozzi and Al-Siyabi interpreted the Shuram/Khufai Boundary as a regional second-order sequence boundary (c. 100s km). Other significant boundaries such as Ara/Buah and the Cambrian/Ediacaran Boundary are 'accurately' dated at c. 550 and 542 Ma, respectively, and do not correlate to the age of SB² 38.

SUMMARY

Table 1 summarizes the model-data correlations in terms of age correlation and extent. Of the 38 predicted SB²s, 34 regional stratigraphic discontinuities/hiatuses can be correlated either numerically (Ma) within the uncertainty of biostratigraphic-radiometric age dating, or approximately by stratigraphic position. One SB² cannot be positioned in the succession because of a major Oligocene hiatus and ambiguous age dating in North Iraq (SB² 2). One is predicted within a long-lasting hiatus (SB² 24), and two more are predicted within the undifferentiated continental Jubah Formation (SB²s 25 and 26). These four unidentified SB²s reflect on the limitations of the data sample in the model-data correlation, rather than on the viability of the predictions.

Some of the model SB²s can be correlated with some numerical confidence by age (± 3 my) and regional extent (c. 1,000 km). An example of 'high-confidence' in age correlation and regional extent criteria is SB² 29 = Tawil/Sharawra Boundary in Saudi Arabia. The age of SB² 29 is predicted at 422.2 Ma within the Silurian Gorstein Stage [422.9 ± 2.5 to 421.3 ± 2.6 Ma] as consistent with an intra-Gorstein age dating for Tawil/Sharawra (Al-Hajri and Owens, 2000). The Gorstein Stage is estimated to have only lasted about 1.6 my and carries standard deviations of 2.5–2.6 my; thus implying an accuracy of about ± 3.0 my. The Tawil/Sharawra Boundary is indeed the widely recognized Pre-Tawil Unconformity (e.g. Wender et al., 1998; Al-Hajri and Owens, 2000) mapped across a scale of 1,000 km in outcrop and subsurface in Saudi Arabia, and extending into Oman where it corresponds to a hiatus separating the Llandovery Sahmah Formation from the Devonian Misfar Group (Droste, 1997). The Pre-Tawil Unconformity separates the continental sandstones of the Tawil Formation from the marginal marine clastics of the Sharawra Formation, and has been considered by some authors to be related to tectonism (see Al-Husseini, 2004); but it may in fact just represent a second-order sequence boundary.

Taken alone, the correlation Tawil/Sharawra = SB² 29 could be viewed as a coincidence. However when considered in the context of four consecutive correlations: SB² 30 = Base Mid Qusaiba Sandstone, SB² 29 = Tawil/Sharawra, SB² 28 = Jauf/Tawil and SB² 27 = Jubah/Jauf, the four-to-four correlation seems more robust. Three of these discontinuities occur as boundaries (disconformity or unconformity) between consecutive formations (Sharawra, Tawil, Jauf and Jubah). These three discontinuities are all interpreted as surfaces that separate regional regressions followed by regional transgressions, and could be tuned to about 14.58 my. The lithology of these formations ranges from continental sandstones (Tawil and Jubah), to marine clastics and carbonates (Jauf), to marginal-marine clastics (Sharawra and Qusaiba), and probably reflects phenomenon that are not related to orbital forcing (e.g. paleolatitude of Arabia, regional subsidence, sediment supply, global tectonics and climate, etc.). The fourth discontinuity, the Base Mid Qusaiba Sandstone, occurs within the subsurface Qusaiba Member, and according to Miller and Melvin (2005) represents a "major episodic drop in relative sea level", within an otherwise open-marine succession of shales and siltstones.

Many of the SB²s can be unambiguously correlated to just one regional stratigraphic discontinuity, but only by stratigraphic position (as there is no other known candidates within the predicted age

TABLE 1

| SB ² | Age | Strat Discontinuity | Stage | Age Range Ma | Regional Extent |
|-----------------|-------|-----------------------|----------------------|-------------------|-----------------|
| 1 | 13.9 | Belayim/Kareem | late Lan–mid Ser | 14.4–12.6 | Red Sea |
| 2 | 28.5 | ?Euprates/Ibrahim | “Mio/Oligocene” | | N. Iraq |
| | | ?Ibrahim/Tarjil | “late/mid Oligocene” | | N. Iraq |
| 3 | 43.1 | Supra-Dammam | mid Lut–Bar/Lut | 44.5–40.4 | hiatus/Saudi |
| 4 | 57.6 | Upper/Lower UER | c. Eoc/Paleocene | c. 55.8 ± 0.2 | Saudi Arabia |
| 5 | 72.2 | Base Aruma | late Campanian | 74.9–70.6 | Saudi/hiatus |
| 6 | 86.8 | ?Base Fiqa | c. San/Con | 85.8 ± 0.7 | ?Oman/hiatus |
| 7 | 101.4 | Discontin Surface 6a | late Albian | 103.7–99.6 | Oman |
| 8 | 116.0 | Discontin Surface 3a | late Aptian | 116.3–112.0 | Oman |
| 9 | 130.5 | Base Zubair | late Haut | 132.1–130.0 ± 1.5 | Kuwait |
| 10 | 145.1 | Sulaiy/Hith | c. Ber/Tith | 145.5 ± 4.0 | Saudi Arabia |
| 11 | 159.7 | Hanifa/Tuwaiq Mt | early Oxf | < 161.2 ± 4.0 | Oman, Saudi |
| 12 | 174.3 | Supra-Marrat | c. Aal/Toa | 175.6 ± 2.0 | hiatus/Saudi |
| 13 | 188.9 | Base Marrat | ?Pliensbachian | 189.6–183.0 | Saudi/hiatus |
| 14 | 203.4 | Minjur/Jilh | late Norian | 207.9–203.6 ± 1.5 | Saudi Arabia |
| 15 | 218.2 | Upper/Middle Jilh | late Carnian | 220.3–216.5 ± 1.5 | Saudi Arabia |
| 16 | 232.6 | Middle/Lower Jilh | late Ladinian | 231.0–228.0 ± 2.0 | Saudi Arabia |
| 17 | 247.2 | Sudairic/Khuff | late Olenkian | 246.6–245.0 ± 1.5 | Oman, Saudi |
| 18 | 261.8 | Middle/Lower Khuff | Capit-Chang | 265.8–251.0 | Oman |
| 19 | 276.3 | Upper/Middle Gharif | Art-Roadian | 284.4–268.0 | Oman |
| 20 | 290.9 | B. Blanket Diamictite | Sakmarian | 294.6–284.4 | Oman |
| 21 | 305.5 | Al Khilata AK P5/P9 | mid Kasimovian | 305.2 ± 1.0 | Oman |
| 22 | 320.1 | Supra-Berwath | ?Serpukovian | 326.4–318.1 | hiatus/Saudi |
| 23 | 334.7 | Base Berwath | late Visean | 332.7–326.4 ± 1.6 | Saudi/hiatus |
| 24 | 349.2 | ?Supra-Jubah | early Tournaisian | 359.2–354.6 ± 2.5 | intra-hiatus |
| 25 | 363.8 | ?Upper/Middle Jubah | unknown | | intra-formation |
| 26 | 378.4 | ?Mid/Lower Jubah | unknown | | intra-formation |
| 27 | 393.0 | Jubah/Jauf | c. mid Eifelian | 394.7 ± 2.7 | Saudi Arabia |
| 28 | 407.6 | Jauf/Tawil | c. mid Pragian | 409.1 ± 2.8 | Saudi Arabia |
| 29 | 422.1 | Tawil/Sharawra | mid Gorstein | 422.1 ± 2.5 | Saudi Arabia |
| 30 | 436.7 | B. Mid Qusaiba Sand | late Aeronian | 437.0–436.0 ± 1.8 | Saudi Arabia |
| 31 | 451.3 | Supra-Quwarah | ‘Ashgill’ | 455.8–445.6 | hiatus/Saudi |
| 32 | 465.9 | Upper/Lower Kahfah | Dariwillian | 468.1–460.9 | Saudi Arabia |
| 33 | 480.5 | Barakat/Mabrouk | ?Tremadoc | 488.3–478.6 | Oman |
| 34 | 495.0 | Al Bashair/Miqrat | ?Mid&Late Cambrian | 513.0–488.0 | Oman |
| 35 | 509.6 | Miqrat/Amin | ?Mid Cambrian | 513.0–501.0 | Oman |
| 36 | 524.2 | Amin/Haradh | Early Cambrian | 542.0–513.0 | Oman |
| 37 | 538.8 | Karim /Ara | Early Cambrian | 542.0–513.0 | Oman |
| 38 | 553.4 | Shuram/Khufai | late Ediacaran | ≥ 550 | Oman |

range – typically more than ± 5 million years). For example, the age of SB² 10 (145.1 Ma) falls near the age of the Berriasian/Tithonian Boundary [c. 145.5 ± 4.0 Ma], and can only be correlated to the regional Sulaiy/Hith Boundary (?Tithonian according to Powers, 1968; late Late Jurassic according to Vaslet et al., 1991). So although SB² 10 = Sulaiy/Hith = c. Berriasian/Tithonian represents a good correlation, it does not resolve the stage assignment (?Tithonian) of Sulaiy/Hith, nor the age (Ma) of the Cretaceous/Jurassic Boundary.

Oligocene SB² 2 predicted at 28.5 Ma [Chattian/Rupelian: 28.4 ± 0.1 Ma] could not be uniquely correlated in the Arabian succession because the ages of the only known Oligocene rocks in North Iraq are not dated. Three SB²s (24, 25 and 26) in the Devonian and Carboniferous could not be positioned because of limited stratigraphic data.

CONCLUSIONS

Within the resolution of biostratigraphic and radiometric age-dating techniques (e.g. GTS 2004), the age and time span of most Arabian Phanerozoic stratigraphic discontinuities/hiatuses cannot be

estimated to an accuracy of better than several million years; even in the best of cases the implied accuracies are about ± 3.0 my. This inherent inaccuracy is comparable or greater than the duration of a third-order cycle ($2.43 \pm .405$ my), and suggests that third-order chronostratigraphic correlations across the Arabian Platform should be treated with great caution. Because the stratigraphic discontinuities listed here have estimated ages that are inaccurate, the model-data test is considered inconclusive; i.e. the second-order sea-level signal could be periodic (14.58 my), or simply appear to be periodic on average. However, the limited number of regional stratigraphic discontinuities identified during this study (and some others that are here considered to be third-order), suggests that a second-order sequence stratigraphic framework may be manifested in the data (possibly with a period that is comparable to 14.58 my).

Orbital-forcing prediction of SB²s and their correlation to stratigraphic discontinuities, could ultimately afford a new time scale that may compliment the traditional biostratigraphic-radiometric time scale. An orbital-forcing time scale has the decided advantage in that it comes with precise third- and fourth-order stratigraphic predictions imbedded as sea-level fluctuations. To conclusively establish whether the Phanerozoic sea level is indeed second-order periodic ($DS^2 = 14.58$ my) requires the identification of the 36 fourth-order depositional sequences ($DS^4 = 0.405$ my) within each second-order depositional sequence (DS^2). This approach may also prove difficult, particularly in marginal-marine sections where several fourth-order sequences may be missing by erosion or not deposited. These possibly missing DS^4 s may be represented by hiatuses corresponding to the lower and upper SB²s, or/and near the intermediate five SB³s. As such, 36 cycles should be regarded as the maximum number of DS^4 s per DS^2 . Therefore the initial challenge of testing the model may be in finding no more than six third-order depositional sequences (DS^3 s) with distinctive ' DS^4 signatures' that are bounded by two consecutive SB²s (see Al-Husseini and Matthews, 2005).

ACKNOWLEDGEMENTS

The authors thank Lucia Angiolini, John Bova, Henk Droste, Adrian Immenhauser, Yves-Michel Le Nindre, Joerg Mattner, Peter Osterloff, Frans van Buchem, Denis Vaslet, and Larry Wender for reviewing the manuscript.

REFERENCES

- Al-Fares, A.A., M. Bouman and P. Jeans 1998. A new look at the Middle to Lower Cretaceous stratigraphy, offshore Kuwait. *GeoArabia*, v. 3, no. 4, p. 543-560.
- Al-Hajri, S.A., J. Filatoff, L.E. Wender and A.K. Norton 1999. Stratigraphy and operational palynology of the Devonian system in Saudi Arabia. *GeoArabia*, v. 4, no. 1, p. 53-68.
- Al-Hajri, S.A. and B. Owens 2000. Sub-surface palynostratigraphy of the Palaeozoic of Saudi Arabia. In, S. Al-Hajri and B. Owens (Eds.), *Stratigraphic Palynology of the Palaeozoic of Saudi Arabia*. *GeoArabia Special Publication 1*, Gulf PetroLink, Bahrain. p. 10-17.
- Al-Husseini, M.I. 2004. Preface; Pre Unayzah Unconformity, Saudi Arabia. *GeoArabia Special Publication 3*, Gulf PetroLink, Bahrain, p. 7-59.
- Al-Husseini, M.I. and R.K. Matthews, 2005. Tectono-Stratigraphic Note: Time calibration of late Carboniferous, Permian and Early Triassic Arabian stratigraphy to orbital-forcing predictions. *GeoArabia*, v. 10, no. 2, p. 189-192.
- 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.
- Blechschildt, 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.
- Boote, D.R.D. and D. Mou 2003. Safah field, Oman: retrospective of a new-concept exploration play, 1980 to 2000. *GeoArabia*, v. 8, no. 3, p. 367-430.
- Bosworth, W. and K. McClay 2001. Structural and stratigraphic evolution of the Gulf of Suez rift, Egypt: a synthesis. In, P.A. Zeigler, W. Cavazza, A.H.F. Robertson and C. Crasquin-Soleau (Eds.), *Per-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins*. *Mémoire Musée Histoire Naturelle*, v. 186, p. 567-606.
- Cozzi, A. and H.A. Al-Siyabi 2004. Sedimentology and play potential of the late Neoproterozoic Buah Carbonates of Oman. *GeoArabia*, v. 9, no. 4, p. 11-36.
- Droste, H.H.J. 1997. Stratigraphy of the lower Paleozoic Haima Supergroup of Oman. *GeoArabia*, v. 2, no. 4, p. 419-472.
- Evans, A.L. 1988. Neogene Tectonic and Stratigraphic Events in the Gulf of Suez Rift Area, Egypt. *Tectonophysics*, v. 153, p. 235-247.
- Fischer, J.-C., Y.-M. Le Nindre, J. Manivit and D. Vaslet 2001. Jurassic gastropod faunas of central Saudi Arabia. *GeoArabia*, v. 6, no. 1, p. 63-100.
- 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.

- Hughes-Clarke, M.W. 1988. Stratigraphy and rock unit nomenclature in the oil-producing area of interior Oman. *Journal of Petroleum Geology*, v. 11, no. 1, p. 5-60.
- Hughes, G.W. 2000. Biostratigraphy of the Shu'aiba Formation, Shaybah field, Saudi Arabia. *GeoArabia*, v. 5, no. 4, p. 545-578.
- Hughes, G.W. and R. Johnson 2005 (in press). Lithostratigraphy of the Saudi Arabian Red Sea. *GeoArabia*, v. 10, no. 3.
- Immenhauser, A., H. Hillgärtner, U. Sattler, G. Bertotti, P. Schoepfer, P. Homewood, V. Vahrenkamp, T. Steuber, J.-P. Masse, H. Droste, J. Taal-van Koppen, B. van der Kooij, E. van Bentum, K. Verwer, E.H. Strating, W. Swinkels, J. Peters, I. Immenhauser-Potthast and S. Al Maskery 2004. Barremian-lower Aptian Qishn Formation, Haushi-Huqf area, Oman: a new outcrop analogue for the Kharai/Shu'aiba reservoirs. *GeoArabia*, v. 9, no. 1, p. 153-194.
- 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.
- Janjou, D., M.A. Halawani, M.S. Al-Muallem, C. Robelin, J.-M. Brosse, S. Courbouleix J. Dagain, A. Genna, P. Razin, J.M. Roobol, H. Shorbaji and R. Wyns 1997a. Explanatory notes to the geologic map of the Al Qalibah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-135, scale 1:250,000, sheet 28C. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 44 p.
- Janjou, D., M.A. Halawani, J.-M. Brosse, M.S. Al-Muallem, J.F. Becq-Giraudon, J. Dagain, A. Genna, P. Razin, M.J. Roobol, H. Shorbaji and R. Wyns 1997b. Explanatory notes to the geologic map of the Tabuk Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-137, scale 1:250,000, sheet 28B. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 49 p.
- Janjou, D., M.A. Halawani, M.J. Roobol, A. Memesh, P. Razin, H. Shorbaji and J. Roger 1998. Explanatory notes to the geologic map of the Jibal Al Misma Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-138, scale 1:250,000, sheet 27D. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 36 p.
- Laskar, J., P. Robutel, F. Joutel, M. Gastineau, A. Correia and B. Levrard 2004. A long term numerical solution for the insolation quantities 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.
- Le Nindre, Y.-M., D. Vaslet and J. Manivit 1990. Le Permo-Trias d'Arabie centrale. *Documents de la Bureau de Recherches Géologiques et Minières*, v. 193, p. 1-559.
- Lebret, P., M.A. Halawani, A. Memesh, C. Bourdillon, D. Janjou, Y.-M. Le Nindre, J. Roger, H. Shorbaji and H. Kurdi 1999. Explanatory notes to the geologic map of the Turubah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-139, scale 1:250,000, sheet 28F. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 46 p.
- Loosveld, R.J.H., A. Bell and J.J.M. Terken 1996. The tectonic evolution of interior Oman. *GeoArabia*, v. 1, no. 1, p. 28-51.
- Manivit, J., D. Vaslet, Y.-M. Le Nindre and F.X. Vaillant 1983. Stratigraphic drill hole SHD-1 through the lower part of the Jilh Formation, Sudair Shale and Khuff Formation in the Durma quadrangle (sheet 24H). Saudi Arabian Directorate General of Mineral Resources, open file report 0F-03-50, p. 1-34.
- Manivit, J., C. Pellaton, D. Vaslet, Y.-M. Le Nindre, J.-M. Brosse, J.-P. Breton, J. Fourniguet and J.-C. Prevot 1985. Explanatory notes to the geologic map of the Darma' Quadrangle, Kingdom of Saudi Arabia. Geoscience map GM-101C, scale 1:250,000, sheet 24H. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 33 p.
- Manivit, J., D. Vaslet, A. Berthiaux, P. Le Strat and J. Fourniguet 1986. Explanatory notes to the geologic map of the Buraydah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-114 C, scale 1:250,000, sheet 26G. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 32 p.
- Matthews, R.K. and C. Frohlich 1998. Forward modelling of sequence stratigraphy and diagenesis: application to rapid, cost-effective carbonate reservoir characterization. *GeoArabia*, v. 3, no. 3, p. 359-384.
- 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.
- Mattner, Joerg and Moujahed Al-Husseini 2002. Essay: applied cyclo-stratigraphy for the Middle East E&P industry. *GeoArabia*, v. 7, no. 4, p. 734-744.
- Miller, M.A. and J. Melvin 2005. Significant new biostratigraphic horizons in the Qusaiba Member of the Silurian Qalibah Formation of central Saudi Arabia, and their sedimentologic expression in a sequence stratigraphic context. *GeoArabia*, v. 10, no. 1, p. 49-92.
- Osterloff, P., R. Penney, J. Aitken, N. Clark and M. Al-Husseini 2004a. The Al Khilata Formation in Interior Oman. *GeoArabia Special Publication 3*, Gulf PetroLink, Bahrain, p. 61-81.
- Osterloff, P., R. Penney, J. Aitken, N. Clark and M. Al-Husseini 2004a. The Al Khilata 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.
- Patton, T.L., A.R. Moustafa, R.A. Nelson and S.A. Abdine 1994. Tectonic evolution and structural setting of the Gulf of Suez rift. In: S.M. Landon (Ed.), *Interior rift basins*. American Association of Petroleum Geologists Memoir no. 59, p. 9-56.
- Philip, Jean M., Jack Roger, Denis Vaslet, Fabrizio Cecca, Silvia Gardin and Abdullah M.S. Memesh 2002. Sequence stratigraphy, biostratigraphy and paleontology of the (Maastrichtian-Paleocene) Aruma Formation in outcrop in Saudi Arabia. *GeoArabia*, v. 7, no. 4, p. 699-718.
- Powers, R.W. 1968. *Lexique stratigraphique international*. Volume III, Asie, Fas. 10 b1, Arabia Saoudite. Centre Nationale de la Recherche Scientifique, Paris, 177 p.
- Richardson, M. and M.A. Arthur 1988. The Gulf of Suez-northern Red Sea Neogene rift, a quantitative basin analysis. *Marine and Petroleum Geology*, v. 5, no. 3, p. 247-270.
- Robelin, C., M.S. Al-Muallem, J.-M. Brosse, J. Fourniguet, M. Garcin, J.-F. Gouyet, M.A. Halawani, D. Janjou and Y.-M. Le Nindre 1994. Explanatory notes to the geologic map of the Qibah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-136, scale 1:250,000, sheet 27G. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 33 p.
- 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.

- van Bellen, R.C., H.V. Dunnington, R. Wetzel and D.M. Morton 1959. Iraq. Lexique Stratigraphique International Centre National de la Recherche Scientifique, III, Asie, Fasc. 10a, Paris, 333 p.
- van Buchem, F.S.P., P. Razin, P.W. Homewood, J.M. Philip, G.P. Eberli, J.-P. Platel, J. Roger, R. Eschaed, G.M.J. Desaubliaux, T. Boisseau, J.-P. Leduc, R. Labourdette and S. Cantaloube 1996. High resolution sequence stratigraphy of the Natih Formation (Cenomanian/Turonian) in northern Oman: distribution of source rocks and reservoir facies. *GeoArabia*, v. 1, no. 1, p. 65-91.
- van Buchem, Frans S.P., Bernard Pittet, Heiko Hillgärten, Jürgen Grötsch, A. Al-Mansouri, Ian M. Billing, Henk H.J. Droste, Heiko Oterdoom and Mia van Steenwinkel 2002. High-resolution sequence stratigraphic architecture of the Barremian-Aptian carbonate systems in northern Oman and the United Arab Emirates Kharaiib and Shu'aiba Formations. *GeoArabia*, v. 7, no. 3, p. 461-500.
- Vaslet, D. 1990. Upper Ordovician glacial deposits in Saudi Arabia. *Episodes*, v. 13, no. 3, p. 147-161.
- Vaslet, D., M. Beurrier, M. Villey, J. Manivit, P. Le Strat, Y.-M. Le Nindre, A. Berthiaux, J.-M. Brosse and J. Fourniguet 1985. Explanatory notes to the geologic map of the Al Faydah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-102C, scale 1:250,000, sheet 25G. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 28 p.
- Vaslet, D., J.-M. Brosse, J.-P. Breton, J. Manivit, P. Le Strat, J. Fourniguet and H. Shorbaji 1988. Explanatory notes to the geologic map of the Shaqra Quadrangle, Kingdom of Saudi Arabia. Geoscience map GM-120C, scale 1:250,000, sheet 25H. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 29 p.
- Vaslet, D., K.S. Kellogg, A. Berthiaux, P. Le Strat, and P.-L. Vincent 1987. Explanatory notes to the geologic map of the Baq'a Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-116 C, scale 1:250,000, sheet 27F. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 45 p.
- Vaslet, D., M.S. Al-Muallem, S.S. Maddah, J.-M. Brosse, J. Fourniguet, J.-P. Breton and Y.-M. Le Nindre 1991. Explanatory notes to the geologic map of the Ar Riyadh Quadrangle, Kingdom of Saudi Arabia. Geoscience map GM-121, scale 1:250,000, sheet 24I. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 54 p.
- Vaslet, D., R. Christian, M.S. Al-Muallem, M.A. Halawani, J. Brosse, J.P. Breton, S. Courbouleix, M.J. Roobol and J. Dagain 1994. Explanatory notes to the geologic map of the Tayma Quadrangle, Kingdom of Saudi Arabia. Geoscience map GM-134, scale 1:250,000, sheet 27C. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 51 p.
- Wallace, C.A., S.M. Dini and A.A. Al-Farasani 1997. Explanatory notes to the geological map of the Al Jawf Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-128C, scale 1:250,000, sheet 29D. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. 31 p.
- Webster, D.J. and N. Ritson 1984. Post-Eocene stratigraphy of the Suez rift in SW Sinai, Egypt. Proceedings of the 6th Exploration Seminar, Cairo, 1982, Egyptian General Petroleum Corporation, Cairo, Egypt, v. 1, p. 276-288.
- 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.
- Wescott, William A., William N. Krebs, John C. Dolson, Salah A. Karamat and Dag Nummedal 1996. Rift basin sequence stratigraphy: some examples from the Gulf of Suez. *GeoArabia* v. 1, no. 2, p. 343-358.
- Ziegler, M.A. 2001. Late Permian to Holocene paleofacies evolution of the Arabian Plate and its hydrocarbon occurrences. *GeoArabia*, v. 6, no. 3, p. 445-504.

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