Orbital calibration of the Late Jurassic Hanifa, Jubaila and Arab Formations, Saudi Arabia

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ABSTRACT

In Saudi Arabia, the *Pre-Hanifa Unconformity* separates the Middle Jurassic Tuwaiq Mountain Limestone and the Upper Jurassic Hanifa Formation; it corresponds to a major hiatus (> 2.0 myr at outcrop) and a glacio-eustatic lowstand (Dromart et al., 2003). The Middle/Upper Jurassic (Callovian/Oxfordian Stage) Boundary is estimated at 161.5±1.0 Ma in GTS 2020, and correlates to the post-glacial sea-level rise predicted at 161.966 Ma by the deterministic Orbital Scale of glacio-eustasy (Matthews and Al-Husseini, 2010). In this study the stage boundary is anchored at 161.966 Ma and the high-frequency sequences (HFS) in the Upper Jurassic Hanifa and Jubaila Formations, and Arab D Reservoir (Al-Mojel, 2017) are interpreted and dated as c. 0.405-myr stratons in the Orbital Scale. The age calibrations also include the Arab D Anhydrite, and Arab C, B and A Members. The correlations of HFS to stratons are consistent with the limited biostratigraphic control. Numerical ages are estimated for key glacio-eustatic events that are observed in the sequence architecture of these formations (unconformities, sequence boundaries and maximum flooding surfaces).

1. INTRODUCTION

In Saudi Arabia the regional Pre-Hanifa Unconformity marks the boundary between the Middle Jurassic Tuwaiq Mountain Limestone and the Upper Jurassic Hanifa Formation (Powers, 1968). The unconformity is important on a global scale because it is related to a glacio-eustatic lowstand (Dromart et al., 2003). Its numerical age is also important because the deterministic Orbital Scale of glacio-eustasy predicts the post-glacial sea level rise started at 161.966 Ma (Matthews and Al-Husseini, 2010). The predicted age was initially within the ±4.0 myr uncertainty (95% 2-standard deviations) for base Oxfordian at 161.2±4.0 Ma in the Geological Time Scale GTS 2004 (Gradstein et al., 2004). However, when the boundary's age was revised to 163.5±1.1 Ma in GTS 2012 (Gradstein et al., 2012) and kept unchanged until early 2020, the scale's prediction far exceeded the ±1.1 myr uncertainty limit; but then in GTS 2020 the estimate was shifted back to 161.5±1.0 Ma (Hesselbo et al., 2020), and so perhaps the orbital prediction was right all along.

Pinning the age of base Oxfordian at c. 161.966 Ma is just a small first step towards dating the Upper Jurassic Hanifa, Jubaila, Arab and Hith Formations in Saudi Arabia. These formations have yielded very few age-diagnostic fossils that can be related to standard ammonite zones, and therefore they cannot be dated with any degree of numerical age accuracy to GTS 2020 (see review of Arabia's biostratigraphy in Chapter 3 of Wilson, 2020). To bypass this problem this study uses the Orbital Scale to predict the glacio-eustatic signal in the 14.58-myr interval between 161.966 and 147.386 Ma. This interval is referred to as *Orbiton 11* and spans the Oxfordian, Kimmeridgian and early Tithonian stages. It contains 36 c. 0.405-myr time-rock units named *stratons*, some of which are predicted as highstands and others as lowstands (Figs. 1 and 2, Matthews and Al-Husseini, 2010). The stratons are correlated to high-frequency sequences (HFS) in the Hanifa, Jubaila and Arab D Reservoir as interpreted by Al-Mojel (2017), resulting in a remarkable locking between model and data, particularly in the 2.4-myr interval spanning the Arab D Anhydrite to basal Hith Anhydrite.

2. TERMINOLOGY, DATA AND CONCEPTS

In sequence-stratigraphy the terms *high frequency sequence (HFS), high-frequency cycle, cycle set, parasequence set,* and *fourth-order sequence* are typically (but not necessarily) synonymous and generally (but not always) represent one c. 0.405-myr straton in the Orbital Scale. Stratons are identified by consecutive integers starting with base/start of Straton 1 at 0.371 Ma, as well as by their positions from 1 to 12 from base-up in 4.86-myr *Dozons A, B* and *C* (Figs. 1 and 2). The orbital ages of stratons are cited to the nearest thousand years in order to remain synchronized with the 0.405-myr long-eccentricity E-cycle in the Astronomical Time Scale (Fig. 2, Hinnov, 2018), while it is understood their ages are probably accurate to about ±100 thousand years (±0.1 myr). Composite and third-order sequences are interpreted as a group of stratons forming transgressive-regressive (T-R) sequences.

In the present study the 24 HFS described in the PhD thesis of Al-Mojel (2017) are considered likely candidates for c. 405-myr stratons. The names of the composite sequences (CS) of Al-Mojel (2017) are adopted and the identifying numbers of HFSs in each CS are more specifically indicated. For example, High-frequency Sequence 5 (HFS5) of Hanifa Composite Sequence 4 (HCS 4) is written as HFS-4.5 of HCS 4. In Al-Mojel et al. (2020) some of the HFS in HCS-1 to HCS-3 have been combined but this report will follow the higher-resolution scheme presented in Al-Mojel (2017).

The equivalence between HFS and stratons is mainly based on stratigraphic position and where possible by biostratigraphic constraints calibrated with GTS 2020 age estimates of biozones and stage boundaries. The main objective of the present study is to determine how well the observed and predicted sequence architectures compare and to establish a chronostratigraphic framework (Fig. 1).

The PhD thesis of Al-Mojel (2017) is comprehensively documented, with numerous illustrations and photographs, and available online in the open-access website *HAL Archives Ouverte*. The depositional environments and sequences are interpreted from facies and their associations in a c. 1,000 km transect and provide most of the data set upon which the present study is based. Al-Mojel (2017) reviews in detail previous works and provides a comprehensive reference list and so in many cases it will be referred to as "Al-Mojel (2017, and references therein)". Key references include Powers et al. (1966), Powers (1968), Vaslet (1987), Vaslet et al. (1991), Le Nindre (1987), Le Nindre et al. (1987, 1990), and the reports by late Jacques Manivit.

3. ANCHORING THE HANIFA FORMATION TO THE ORBITAL SCALE

3.1 Late Callovian–Early Oxfordian Glaciation

Dromart et al. (2003) were the first authors to interpret a glaciation spanned the Callovian/Oxfordian Boundary. They described the associated glacio-eustatic event as a rapid sea-level fall (c. 0.2 myr) followed by a lowstand (c. 0.6 myr) in the latest Callovian *Q. lamberti* Zone and a gradual post-glacial sea-level rise starting at the Callovian/Oxfordian Boundary and lasting c. 1.6 myr during the earliest Oxfordian *Q. maraie* Zone. They traced the glacio-eustatic lowstand using ammonite zones and documented lowstand-related sedimentary features in numerous localities, including Saudi Arabia (Fig. 3). They also presented climate-proxy data indicating global cooling occurred at that time.

Price and Rogov (2009) measured Oxygen-18 isotope ($\delta^{18}O$) values in several localities on the Russian Platform and used them to estimate Late Jurassic temperatures (Fig. 4). The temperature profile indicates near-freezing levels started in the late Callovian *P. athleta* Zone, spanned the *Q. lamberti* Zone and started rising at the Callovian/Oxfordian Boundary.

During the Oxfordian, Kimmeridgian and early Tithonian the interior part of the Arabian Plate was partially separated from the Neo-Tethys Ocean by a barrier situated along the outer rim of the plate (Wilson, 2020, and references therein). The *Tethyan Barrier* consisted mainly of shoals and in Oman of an uplifted region. In the intra-plate basin in Saudi Arabia the range of lithofacies and biofacies indicate relative sea level (accommodation space) fluctuated by as much as 30 m during the Oxfordian to early Tithonian times (Wilson, 2020, and references therein).

A glacio-eustatic fall of c. 30 m implies one or more ice sheets developed on land areas and held a total ice volume of about one-half that on present-day Antarctica. During the Late Jurassic cold continental regions, including Antarctica, were situated in the cold belts between 60 degrees and the poles and would have hosted one or more ice sheets.

3.2. Tying the Callovian/Oxfordian Boundary to SB 11

In the Orbital Scale the start of the post-glacial sea-level rise (transgression) is predicted at SB 11 and calculated by the simple arithmetical formula: SB N = 1.586 + N x 14.58, and for N = 11, SB 11 = 161.966 Ma. The Callovian/Oxfordian Boundary is estimated at 161.5±1.0 Ma in GTS 2020. It closely correlates to SB 11 at 161.966 Ma, which is used as an anchor for base Oxfordian in this study.

The duration of the sea-level fall and lowstand in latest Callovian *Q. lamberti* Zone was estimated as 0.8 myr (Dromart et al., 2003) but it may have been somewhat longer. According to the $\delta^{18}O$ curve it may also include the *P. athleta* Zone (Price and Rogov, 2009) and these two zones span c. 1.0 myr in GTS 2020. This interval would therefore correspond to at least Straton 12C-11 predicted as a glacio-eustatic fall, and major lowstand Straton 12C-12 (Dozon 12C of Orbiton 12) between 162.776 and 161.966 Ma, Fig. 1). The ice sheets apparently melted over a period of c. 1.6 myr in the *Q. maraie* Zone (Dromart et al., 2003), which has an estimated duration of c. 2.2 myr (Boulila et al., 2010).

In the present study the base of the Oxfordian (i.e., base *Q. maraie* Zone) is anchored at SB 11 at 161.966 Ma, but the age of the hiatus at outcrop between the top of the Tuwaiq Mountain Limestone and base of the Hanifa Formation is not known and may vary by locality. As a result a correlation between a specific straton and the base of the Hanifa Formation at outcrop cannot be established at the stage boundary and used as a correlative anchor in Saudi Arabia.

3.3. Anchor at the Early/Middle Oxfordian Boundary

A better-constrained anchor between the Hanifa and the Orbital Scale occurs at the Lower/Middle Oxfordian Boundary by correlating ammonite zones to Composite Sequences HCS 1 and HCS 2 (Fig. 1). Boulila et al. (2010) used cyclostratigraphy to determine the durations of the Early Oxfordian *Q. maraie* (2.2 myr) and *C. cordatum* (0.36–0.60 myr) Zones, and the Middle Oxfordian *P. plicatilis* (0.72–0.87 myr) and *G. transversarium* (0.65 myr) Zones. The Early/Middle Oxfordian Substage Boundary has an age of between 2.56 and 2.8 myr younger than the stage boundary (2.2 + 0.36, or 2.2 + 0.60). The stage boundary is taken at SB 11 (161.966 Ma) implying the Early/Middle Oxfordian Substage Boundary has an age between 159.406 and 159.166 Ma and occurs within Straton 13A-7 (159.536–159.131 Ma). The younger age of 159.166 Ma is considered a sufficiently accurate anchor between the substage boundary and base Straton 11A-8 at 159.131 Ma.

Hanifa Composite Sequence HCS 1 is dated as Early Oxfordian (*C. cordatum* Zone) based on brachiopod fauna (*Ornithella* gr. *hudlestoni* DAV.) and on nautiloids (*Paracenoceras* sp. aff. *Arduennense*; Manivit et al., 1990). HCS 2 is dated as Middle Oxfordian (*P. plicatilis* Zone) based on ammonite fauna (*Euaspidoceras catenaperarmatum* and *Perisphinctidae*?), nautiloids (*Paracenoceras* aff. *hexagonum*) and nannoflora (*Vekshinella stradneri*) present in the upper part of the Hawtah Member (Manivit et al., 1990; Al-Mojel et al, 2020). These ages imply the boundary between HCS 1 and HCS 2 occurs at the Early/Middle Oxfordian Boundary at 159.131 Ma. Therefore a robust anchor for calibrating the Hanifa to the Orbital Scale is base of HCS 2 to base Straton 11A-8 at 159.131 Ma.

3.4 Early Oxfordian Hiatus and Hanifa Composite Sequence HCS 1

The temperature curve in Fig. 4 indicates the *Q. mariae* Zone contains a minor increase and the *C. cordatum* Zone a major one (Price and Rogov, 2008). These temperature increases may correspond to flooding events in Composite Sequence HCS 1 (Fig. 4). However, at outcrop the Early Oxfordian Q.

Mariae Zone is interpreted as a hiatus (Y.-M. Le Nindre, pers. comm., 2015, 2021) and Al-Mojel (2017, and references therein) confined HCS 1 to the *C. cordatum* Zone.

The Pre-Hanifa Unconformity occurs in the outcrop belt along the eastern edge of the Arabian Shield. The NS-trending belt represents proximal settings where the unconformity corresponds to a major hiatus. G. Wilson (pers. comm., 2021) pointed out that in the subsurface in the intra=plate basin the unconformity passes to a sequence boundary or possibly a correlative conformity (see Figs. 5.1 and 5.2 in Wilson (2020). Therefore in the subsurface basinal regions the hiatus may have a much briefer duration if it exists at all.

The *C. cordatum* Zone has an estimated duration of only 0.36 to 0.6 myr (Boulila et al., 2010) implying it is just one or one-and-a-half stratons. Early Oxfordian HCS 1 is 20 m thick and bounded by unconformities corresponding to subaerial exposure surfaces and consists of four HFSs (Al-Mojel, 2017). If the four HFSs are indeed stratons then they would correspond to Stratons 11A-4 to 11A-7 between 160.751 and 159.131 Ma and occur in both the *C. cordatum* and upper part of the *Q. mariae* Zones. This correlation would imply the earliest Oxfordian hiatus only spans part of the *Q. maraie* Zone (probably Stratons 11A-1 to 11A-3) and not its entirety.

Alternatively, if the four HFS are precisely confined to the *C. cordatum* Zone its short duration (0.36–0.6 myr) implies they are tuned by the 0.1-myr short-eccentricty cycle, probably in Straton 11B-7. Whether the four HFS of HCS 1 are stratons or tuned by 0.1-myr short-eccentricty cycles does not alter the correlation between Early/Middle Oxfordian and the boundary between HCS 1 and HCS 2.

4. HANIFA COMPOSITE SEQUENCES HCS 2 TO HCS 4

4.1 Hanifa Composite Sequence HCS 2

Hanifa Composite Sequence HCS 2 (30 to 70 m thick) consists of HFS-2.1 to HFS-2.4 bounded by minor firmgrounds and hardgrounds (Al-Mojel, 2017). If these four HFSs are stratons and deposition during HCS 2 was relatively continuous then by stratigraphic position they would correspond to Stratons 11A-8 and 11A-11. HCS 2 is assigned to the Middle Oxfordian *P. plicatilis* Zone, which has an estimated duration between 0.72 and 0.87 myr (Boulila et al., 2010) implying HFS-2.1 and HFS-2.2 correlate to Stratons 11A-8 and 11A-9.

The upper part of HCS 2 consists of iron-stained hardgrounds that can be locally eroded by an overlying transgressive ravinement surface at the base of HCS 3 (Al-Mojel, 2017). The orbital calibration indicates the upper part of HCS 2 (HFS-2.3 and HFS-2.4) is younger than the *P. plicatilis* Zone and occurs near the Middle/Late Oxfordian transition. As observed by Al Mojel (2017) the upper two HFSs may contain erosional unconformities, which would occur in unconformity-prone regressive Straton 11A-11.

4.2 Maximum Flooding Surface MFS J50

Sharland et al. (2001, their Table 4.64) interpreted Middle Oxfordian MFS J50 in the *P. plicatilis* ammonite Zone in lower Hanifa Formation in Saudi Arabia. Y.M. Le Nindre (pers. comm., 2015, 2021) also placed MFS J50 in the *P. plicatilis* Zone (*Euaspidoceras* gr. *Catena-perarmatum* Sowerby), and Al-Mojel (2017) reported the MFS of HCS 2 is not well defined but may occur in HFS-2.3, which would correspond to Straton 11A-10.

The $\delta^{18}O$ curve in Fig. 4 shows the lower part of the *P. plicatilis* Zone was a rapidly warming time suggesting the flooding event occurred in highstand Straton 11A-8. These interpretations point to placing Middle Oxfordian MFS J50 in either Straton 11A-8 or 11A-10; both are highstands in the *P. plicatilis* Zone. In this study the anchor for the *P. plicatilis* MFS J50 is placed in Straton 11A-8 at c. 159.13 Ma, while recognizing an additional MFS could be positioned in Straton 11A-10 at c. 158.32 Ma. Both MFS would have ages much older than the estimate of 156.0 Ma in Sharland et al. (2001).

4.3 Hanifa Composite Sequence HCS 3

HCS 3 (30 to 45 m thick, Fig. 1) consists of HFS-3.1 to HFS-3.4 (Al-Mojel, 2017). By stratigraphic position these four HFSs would correlate to Stratons 11A-12 to 11B-3 in Late Oxfordian. Straton 11A-11 and 11A-12 are predicted as unconformity-prone regressive and lowstand intervals and correlated to HFS-2.4 and HFS-3.1, respectively. These correlations seems likely because Al-Mojel (2017) recorded the first clear transgressive stage in the MFS of HFS-3.2 implying HFS-3.1 is a lowstand.

A regionally extensive grainstone bed in lower HFS-3.3 is a stratigraphic marker that separates the Hawtah (H1) and Ulayyah (H2) Members of the Hanifa Formation (Vaslet et al., 1991). Y.-M. Le Nindre (pers. comm. 2015, 2021) described this boundary as a reworked surface, and Al-Mojel (2017) reported it is a conformable transgressive surface and placed the main MFS of HCS 3 in HFS-3.3. Fallatah (2017) and Fallatah and Kerans (2018) also considered the Hawtah/Ulayyah Boundary as the main MFS of the Hanifa Formation.

Straton 11B-2 is predicted as a major highstand containing the main MFS of Dozon 11B and it is correlated to Late Oxfordian HFS-3.3 containing the *Main Hanifa MFS* (Fig. 1). Therefore this correlation is considered a robust anchor at c. 156.7 Ma. The Main Hanifa MFS in HFS-3.3 (Straton 11B-2) would occur by numerical age correlation to GTS 2020 in Late Oxfordian *A. hypselium* ammonite Zone and it has no "J" designation in the MFS framework of Sharland et al. (2001).

4.4. Hanifa Composite Sequence HCS 4 and the Oxfordian/Kimmeridgian Boundary

HCS 4 (35 to 55 m thick) is bounded by two erosional surfaces and consists of HFS-4.1 to HFS-4.7 (Al-Mojel, 2017). Its lower part is dated as Oxfordian by foraminifer (*Alveosepta Jaccardi*) and brachiopods (*Terebratula bisuffarcinata*) and its upper part dated Early Kimmeridgian based on echinoids (*Monodiadema kselensis* and *Pseudocidaris thurmanni*) and *Alveosepta Jaccardi* (Manivit et al., 1990). By stratigraphic position the seven HFS would correlate to Stratons 11B-4 to 11B-10.

The basal unconformity of HCS 4 is not predicted by the Orbital Scale; it may represent accommodation space reaching a limit near the end of the major transgression and highstand of the Main Hanifa flooding event. The position of the Oxfordian/Kimmeridgian Boundary in HCS 4 is not constrained by biostratigraphy, but by numerical age correlation to GTS 2020 it may occur near lowstand Straton 11B-6 (HFS-4.3).

A possible constraint for the age of top Hanifa is suggested by Hughes (2006) who stated that if the echinoid evidence is reliable the Hanifa Formation may extend into the *A. hypselocyclum* ammonite Zone. This zone occurs between 153.5 and 152.7 Ma (after adjusting its age relative to base Oxfordian at 161.966 Ma) implying correlating HFS-4.7 to Straton 11B-10 (153.461–153.056 Ma) would indeed result in top Hanifa intersecting the *A. hypselocyclum* Zone. Al-Mojel et al. (2020) show a similar calibration in their fig. 16.

4.5 Maximum Flooding Surfaces MFS J60 and MFS J70

Sharland et al. (2001) interpreted Early Kimmeridgian MFS J60 and Late Kimmeridgian MFS J70 in the Arabian Plate. They concluded MFS J60 was eroded in Saudi Arabia and MFS J70 occurs above the Pre-Jubaila Unconformity in the Jubaila Limestone. This interpretation has caused some uncertainty in regards to the position of MFS J60 (see discussion by Y.M. Le Nindre and R. Davies in Kadar et al., 2015).

Al-Mojel (2017) interpreted HCS 4 as a transgressive sequence without a regressive systems tract and positioned its MFS in HFS-4.6. Uppermost HFS-4.7 is truncated by the Pre-Jubaila Unconformity and the absence of a regressive tract in HCS 4 suggests the MFS may occur in HFS-4.7 in Straton 11B-10 as predicted by the Orbital Scale (instead of HFS-4.6). In this scenario Early

Kimmeridgian MFS J60 occurs in HFS-4.6 or HFS-4.7 of HCS 4 and Late Kimmeridgian MFS J70 occurs in Jubaila JCS 1 in HFS-1.2 (see below discussion).

5. JUBAILA-ARAB SEQUENCES

5.1 Pre Jubaila Unconformity

Al-Mojel (2017 and references therein) described the boundary between the Hanifa and the Jubaila at outcrop as a sharp regionally extensive erosional unconformity and a subaerial exposure surface. The surface is iron-stained and shows a sharp sedimentological contrast between the Hanifa coral/stromatoporoid-rich deposits and Jubaila high-energy storm-influenced, quartz-rich (c. 30% quartz sandstone) transgressive grainstones and floatstone/rudstone with rip-clasts. Y.-M. Le Nindre (pers. comm, 2015) described the interval between the Hanifa and Jubaila as consisting of sandstone and conglomerates (south of 22°30'N) and a complex transition elsewhere.

The duration of the hiatus corresponding to the Pre-Jubaila Unconformity at outcrop and subsurface is not constrained by biostratigraphy. In the orbital calibration it is correlated to a c. 0.8-myr hiatus at outcrop in regressive Straton 11B-11 and major lowstand Straton 11B-12. This correlation is considered reliable because it maintains the model and observed sequences aligned by stratigraphic position and MFS correlations below and above the Pre-Jubaila Unconformity. By numerical age correlation to GTS 2020 the unconformity would straddle the Early Kimmeridgian *A. hypselocyclum*/*C. divisum* ammonite zonal boundary.

5.2 Jubaila Arab-D Sequences JCS 1 and JCS 2

Above the Pre-Jubaila Unconformity, Al-Mojel (2017) interpreted the interval spanning the Jubaila Limestone and Arab D Reservoir (carbonate below the Arab D Anhydrite) as Composite Sequences JCS 1 and JCS 2 (Fig. 1). The combined thickness of JCS1 and JCS2 attains a maximum of 160 m in their main depocenter and decreases to the south and north to about 110 to 115 m (Al-Mojel, 2017).

Biostratigraphic control in the Jubaila-Arab-D Sequences indicates its lower 25 to 30 m is Early Kimmeridgian based on nautiloids (*Paracenoceras* gr. *hexagonum, Paracenoceras* aff. *wepferi*) and endemic ammonites (*Perisphinctes* aff. *Jubailensis*) (Manivit et al., 1990). Y.-M. Le Nindre (pers. comm., 2015, 2021) reported the upper Jubaila lacks ammonite and is dated as Kimmeridgian based on benthic foraminifera (Manivit et al., 1990; Hughes et al., 2009).

Al-Mojel (2017) cited thicknesses for the Jubaila Composite Sequences and their HFSs as follows: JCS 1 (55 to 98 m thick) consists of HFS-1.1 (30–65 m thick) and HFS-1.2 (30–35 m thick), and JCS 2 (48 to 62 m thick) consists of HFS-2.1 (15–25 m thick), HFS-2.2 (17–25 m thick) and HFS-2.3 (12 m thick).

The five Jubaila HFS are correlated to Straton 11C-1 to 11C-5, and by numerical age correlation to GTS 2020 would occur in Late Kimmeridgian. Jubaila JCS 1 and JCS 2 would therefore form the predicted lower c. 2.03-myr T-R sequence of Dozon 11C. MFS J70 is positioned in HFS-1.2 of JCS 1 at c. 151.84 Ma and may coincide with the Early/Late Kimmeridgian Boundary at base *C. divisum* Zone. Al-Mojel (2017) characterized the top boundary of JCS 2 (top Arab D carbonate) at outcrop as a significant erosional ravinement surface overlain by dolomitized grainstones and in turn by anhydrite solution and deformed stromatolitic dolomite beds.

6. ARAB FORMATION AND ARAB/HITH BOUNDARY

Above the Arab D Reservoir (i.e., top JCS 2) the Arab Formation consists of the Arab C, B and A Members and their carbonate intervals are formally defined as reservoirs (Powers, 1968). Al-Mojel (2017) did not interpret the sequence stratigraphy of the Arab Formation above the Arab D Reservoir (carbonate).

Dating of the Arab Formation and the overlying Hith Anhydrite only indicates their age occurs near the Kimmeridgian/Tithonian Boundary (Manivit et al., 1990; Hughes, 2000, 2006). Hughes (2000) reported the presence of *Pfenderilla salemitmw* in the uppermost part of the Arab-D Reservoir (upper JCS2) restricts its age to Kimmeridgian. Therefore the ages of the Arab D Anhydrite up to the Arab/Hith boundary are unconstrained (i.e., Kimmeridgian or Tithonian?).

The Orbital Scale uses a different paradigm to calibrate the numerical ages of the Arab Formation: it compares their distinct lithofacies (Fig. 5, Wilson, 2020) to the predicted sea level highstands and lowstands in Stratons 11C-6 to 11C-12. If the Jubaila-Arab-D Sequences JCS 1 and JCS 2 represent the lower c. 2.03-myr T-R sequence of Dozon 11C (Stratons 11C-1 to 11C-5) then by stratigraphic position the Arab D Anhydrite correlates to lowstand Straton 11C-6. This correlation resolves the sequence architecture of the upper T-R sequence of Dozon 11B as follows. The Arab C Member consists of three distinct units that highlight three stratons: two occur in the carbonates of the Arab C Reservoir (transgressive Straton 11C-7 and highstand Straton 11C-8) and one in the Arab C Anhydrite in lowstand Straton 11C-9. The Arab B Member (carbonate capped by a thin anhydrite bed) is correlated to highstand Straton 11C-10, and the Arab A Member (carbonate) and the thin basal Hith Anhydrite stringer to regressive Straton 11C-11.

The orbital age for the Arab C Member implies the Kimmeridgian/Tithonian Boundary apparently occurs in the Arab C Reservoir. Importantly, the robust comparison between Arab Formation lithofacies and predicted sea-level highstands and lowstands provides a strong series of numerical age anchors for the upper part of Orbiton 11 and MFS J80, J90 and J100 (Figs. 1 and 5).

7. HITH ANHYDRITE FORMATION

Base Hith Anhydrite is marked by the sea level fall in late Straton 11C-11 leading to the lowstand in Straton 11C-12. The Hith Anhydrite represents a broad shallow-marine, evaporitic intra-plate sea separated from the Neo-Tethys Ocean by the Tethys Barrier (Wilson, 2020). The climate was fully arid and the lowstand persisted well into the Tithonian times.

The type section of the Hith Anhydrite is located at Dahal Hit southeast of Ar Riyadh. The formation is exposed in a large dissolution sinkhole and a narrow cavern at the foot of Jabal Hit. At this locality the Hith Anhydrite is c. 90 m thick between the Arab Formation and the Sulaiy Formation (Wolpert et al., 2015). Due to the difficult access in the cave only three cycles were interpreted in the Hith (P. Wolpert, pers. comm, 2021). The cycles have a thickness ranging from c. 7.0 to 9.5 m implying the Hith may consist of 8 to 12 stratons.

DISCUSSION

The Upper Jurassic Hanifa, Jubaila and Arab high-frequency sequences (HFS), composite sequences (CS), maximum flooding surfaces (MFS), major unconformities, and their biostratigraphic ages were not interpreted by previous authors with a view to test the predictions of the Orbital Scale of glacio-eustasy. Nor was the dating of the Middle/Upper Jurassic Boundary in various vintages of the Geologic Time Scale aimed at converging on the predicted age of the late Callovian–early Oxfordian glaciation. Indeed the prevailing view in the Earth Science literature is that the Jurassic was an ice-free greenhouse time. So it is therefore remarkable that all of these observations and unbiased interpretations seem to support the predictions of the Orbital Scale of glacio-eustasy.

The Tethyan Barrier provides a measure of how restricted the Arabian Basin was during global sea level lowstands. Unconformities in proximal settings and uplifted regions indicate the global sea level in the Neo-Tethys Ocean was at a minimum. During these lowstands deposition was mainly in the intra-shelf basin of the Arabian Plate (e.g., see figs 5.1 and 5.2 in Wilson, 2020). Conversely highstands in proximal areas represent maximum global sea levels.

In the intra-plate basin in Saudi Arabia the range of lithofacies and biofacies indicate relative sea level (accommodation space) fluctuated by as much as 30 m during the Late Jurassic (Wilson, 2020, and references therein), and this is likely the magnitude of the glacio-eustatic lowstand associated with the Pre-Jubaila Unconformity. The late Callovian glacio-eustatic lowstand was apparently greater than 30 m because it is evident at a global scale.

The Arab and Hith evaporites represent times when global sea level was in relative equilibrium with that in the Arabian Basin and the climate was fully arid. Any water spills into the basin were rapidly evaporated leaving halite, gypsum and anhydrite in shallow hypersaline seas or sabkhas. The fully arid conditions associated with the Hith Anhydrite are related to a lowstand that lasted several million years and cannot be explained by the aquifer-eustasy model. The absence of humid conditions over the entire Arabian Plate imply terrestrial aquifers did not collect rainwater, and lakes and rivers did not exist. The fully arid climate and lowstand were associated with a cool climate and polar glaciations.

7. CONCLUSIONS

It is concluded that the predictions of the Orbital Scale of glacio-eustasy are consistent with the general biostratigraphic constraints and sequence architecture of the Upper Jurassic Hanifa, Jubaila and Arab Formation in numerous and significant aspects.

1. The Pre-Hanifa Unconformity at outcrop represents a latest Callovian–earliest Oxfordian hiatus lasting at least 2.0 myr. The duration of the hiatus in Early Oxfordian *Q. mariae* Zone is unclear and may occupy its lower 1.2-myr part at outcrop. The unconformity was caused by a glacio-eustatic lowstand involving a sea-level fall of the order of 30 or more meters.
2. The Middle Oxfordian maximum flooding surface MFS J50, which is positioned in the only ammonite-dated zone (*P. plicatilis*), occurs in lower Hanifa HCS 2 in Straton 11A-8 at c. 159.13 Ma.
3. The Main Hanifa MFS occurs at the boundary between the Hawtah and Ulayyah Members in HFS-3.3 of HCS 3 in Late Oxfordian Straton 11B-2 at c. 156.70 Ma. This major MFS has no "J" designation in the original framework of Sharland et al. (2001).
4. The uppermost Hanifa HCS 4 contains Early Kimmeridgian MFS J60 in Straton 11B-10 at c. 153.46 Ma.
5. MFS J60 occurs below the Pre-Jubaila Unconformity, which is interpreted as a c. 0.8-myr hiatus between c. 153.06 to 152.25 Ma. MFS J60 may be truncated in some localities by the Pre-Jubaila Unconformity.
6. The Jubaila and Arab D carbonates (Sequences JCS 1 and JCS 2, below the Arab D Anhydrite) consist of five HFS (Stratons 11C-1 to 11C-5) forming a predicted c. 2.03-myr transgressive-regressive (T-R) sequence, between c. 152.25 and 150.22 Ma.
7. MFS J70 occurs in the Jubaila in HFS-1.2 of Sequence JCS 1 near the Early/Late Kimmeridgian Boundary in Straton 11B-2 at c. 151.84 Ma.
8. The Arab D Anhydrite corresponds to predicted lowstand Straton 11B-6 between c. 150.22 and 149.82 Ma.
9. The Arab C Member consists of three stratons forming a c. 1.2-myr T-R sequence. The carbonate reservoir consists of transgressive Straton 11B-7 and highstand Straton 11B-8, as predicted by the Orbital Scale. The capping Arab C Anhydrite occurs in a predicted lowstand Straton 11B-9.
10. The Arab C Reservoir is calibrated between c. 149.82 and 148.60 Ma and may contain the Kimmeridgian/Tithonian Boundary estimated at 149.2±0.7 Ma in GTS 2020.
11. The Arab B Member corresponds to highstand Straton 11B-10, predicted between c. 148.60 and 148.20 Ma.
12. The Arab A Member is correlated to the lower part of regressive Straton 11B-11 and represents the final significant flooding of the Arabian Basin in Orbiton 11. It was followed by a major lowstand in Straton 11C-12, which appears to have triggered a climate change to a fully arid and highly restricted setting associated with the evaporitic Hith Sea at c. 148.0 Ma.

Both boundaries of Orbiton 11 are marked by significant glacio-eustatic and climate events caused by the 14.58-myr tuning of the Earth's eccentric orbit.

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This study follows the advice of the late Professor Emeritus Robley K. Matthews (Brown University, Rhode Island) to stratigraphers: switch from the path of *observe and seek to explain* (inductive mode) towards *predict and seek to observe* (deductive mode). I am greatly indebted to him for his guidance, and privileged to have coauthored his final contribution to the Earth Sciences: "Orbital-forcing glacio-eustasy: A sequence- stratigraphic time scale". I thank Sadad Al-Husseini, Abdullah Al-Mojel, Yves-Michel Le Nindre, Philipp Wolpert and Gus Wilson for their important comments and discussions. Arnold Egdane is thanked for designing the manuscript.

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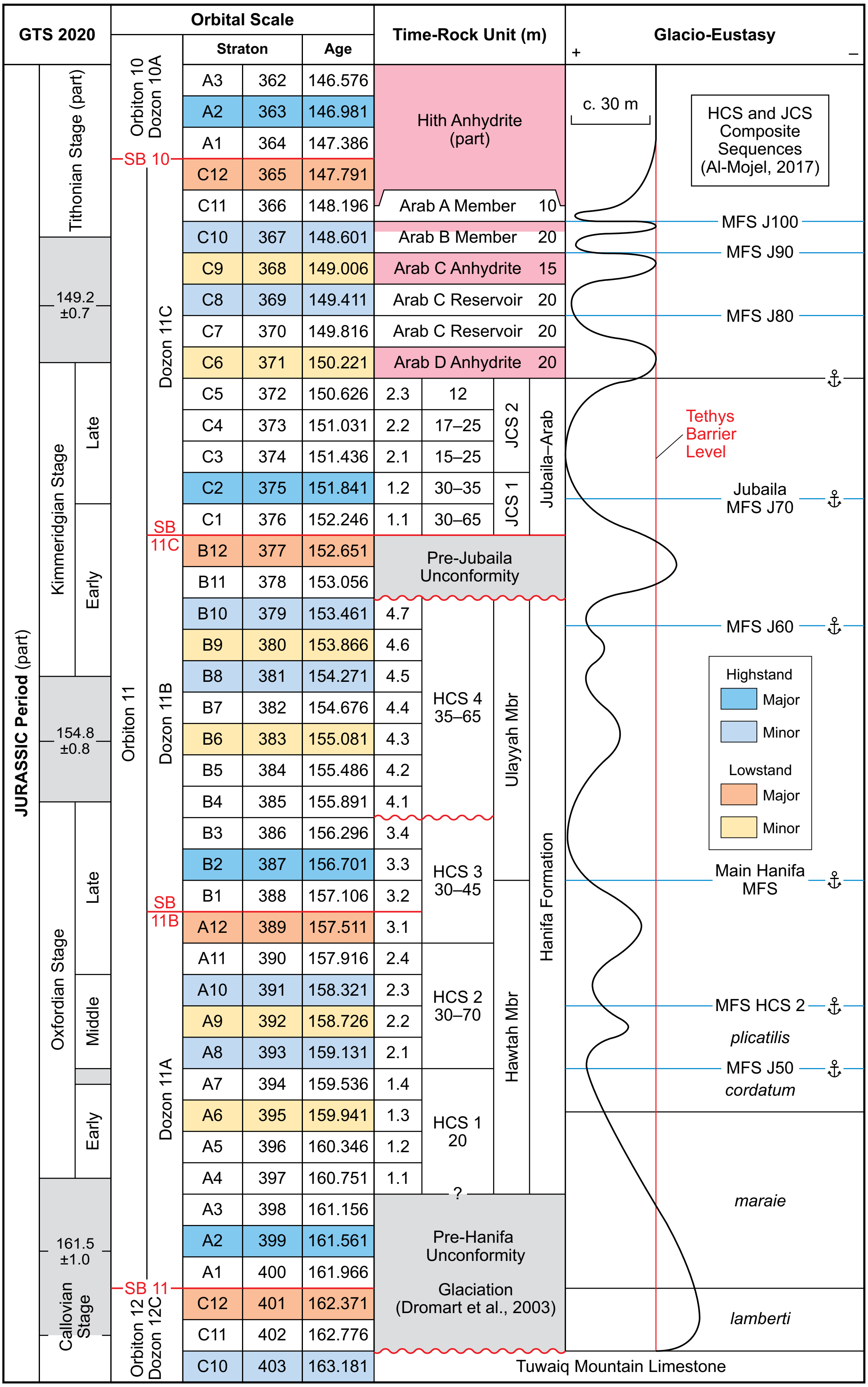

Figure 1: Calibration of the Hanifa, Jubaila and Arab Formations using the glacio-eustatic template for Orbiton 11. Height of Tethyan Barrier estimated at c. 30 m. For details of time-rock units see Al-Mojel (2017).

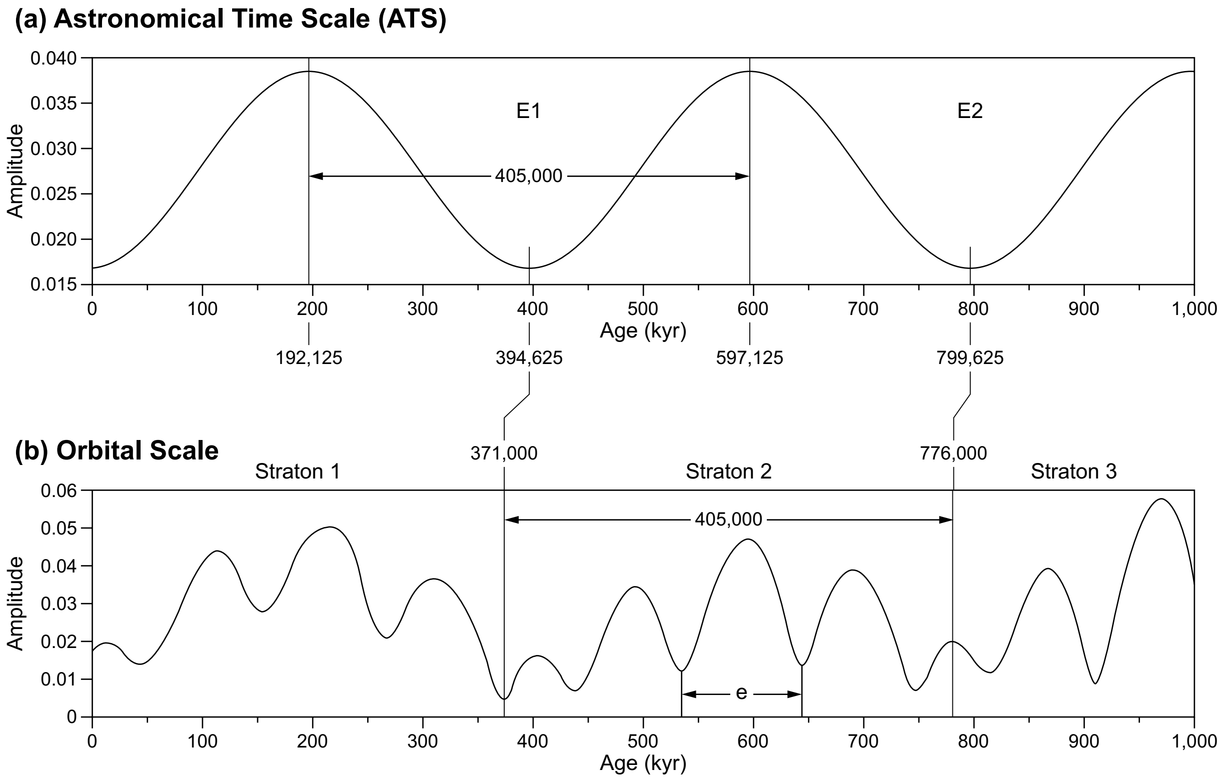

Figure 2: (a) The Astronomical Time Scale (ATS) subdivides time according to the 0.405-myr sinusoidal component of the Earth's eccentric orbit (E-Cycle) and numbers them between the maxima of the sine wave. **(b)** The Orbital Scale defines time-rock units named "Stratons" between the minima of the eccentricity curve and estimates their duration as 0.405-myr with Straton 1 starting at 371,000 years before present. Four c. 100-kyr short-eccentricity cycles (e) typically form a straton. The two scales differ by 23,625 years (Hinnov, 2018). Glacio-eustatic falls and stratigraphic breaks occur at eccentricity minima.

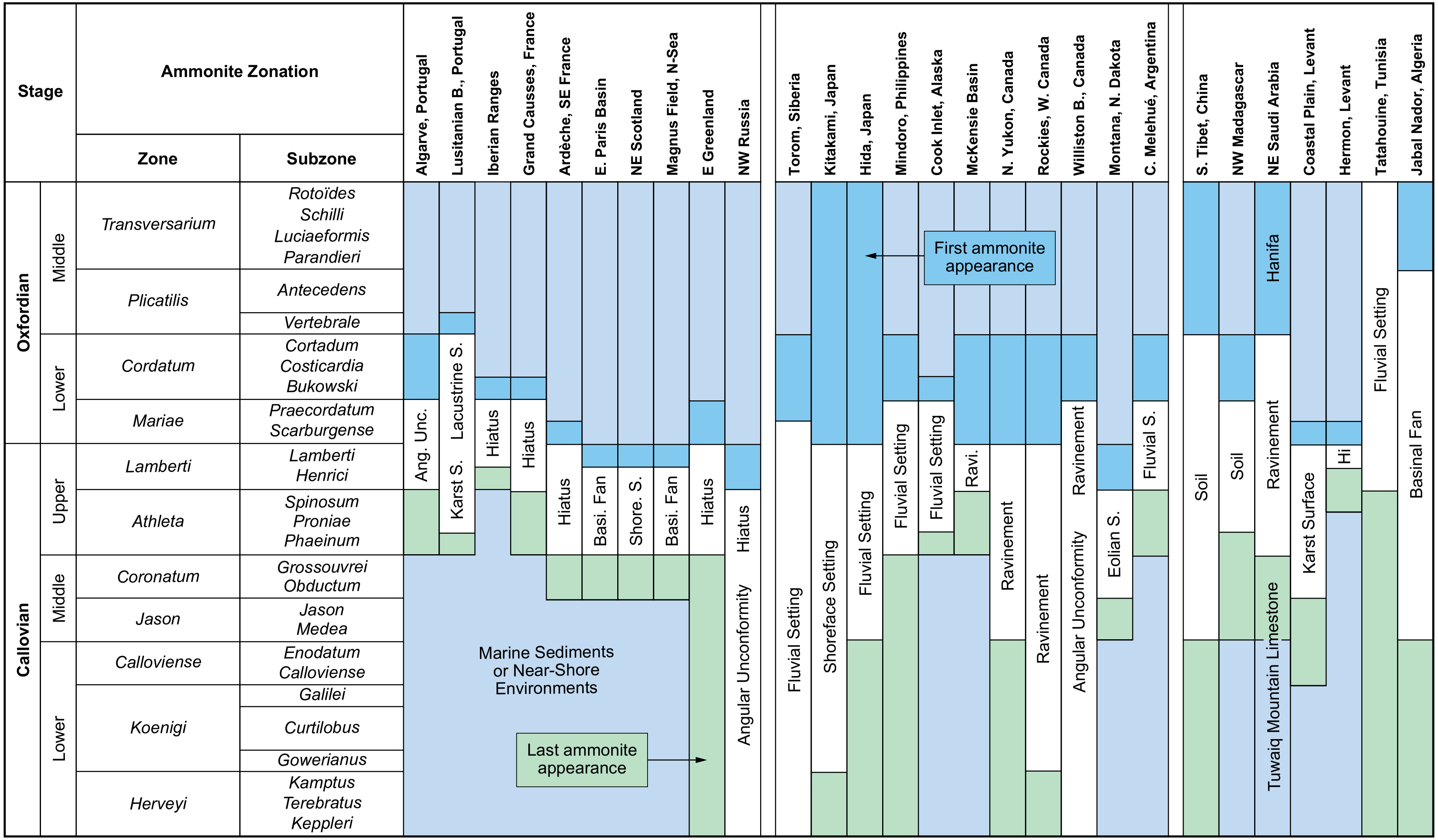

Figure 3: Sedimentary expression of glacio-eustatic fall in latest Callovian and post-glacial rise in earliest Oxfordian (Dromart et al., 2003).

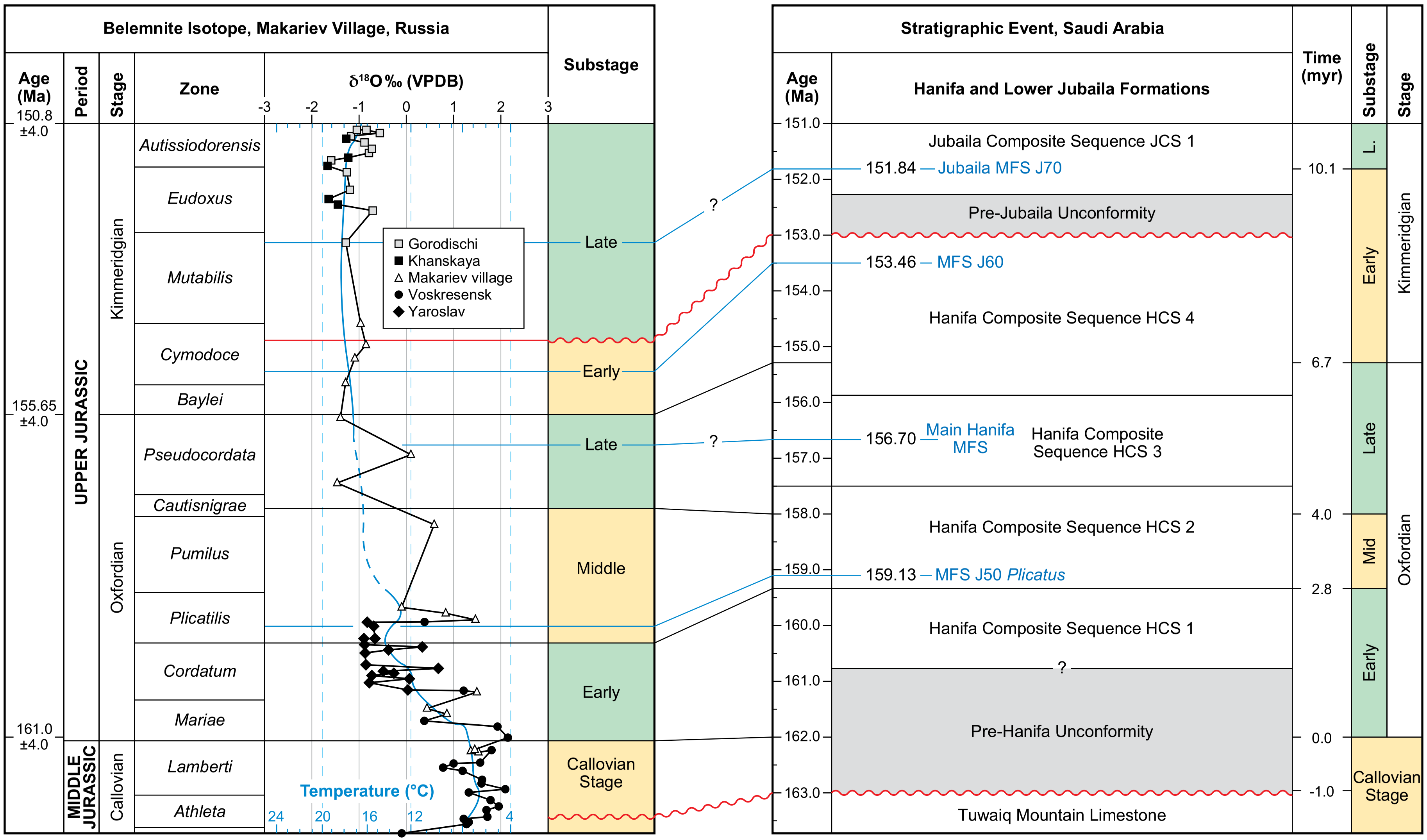

Figure 4: Belemnite δ18O isotope data and temperature estimate in the Russian Platform with 10-point moving average calibrated with GTS 2004 (Gradstein et al., 2004) by Price and Rogov (2009). Boreal ammonite zones recalibrated to Oxfordian and Kimmeridgian substages according to GTS 2020 (Figs. 26.9 and 26.10 in Hesselbo et al., 2020). Ages of composite sequences (CS), MFS and unconformities based on Callovian/Oxfordian Boundary at c. 162.0 Ma.

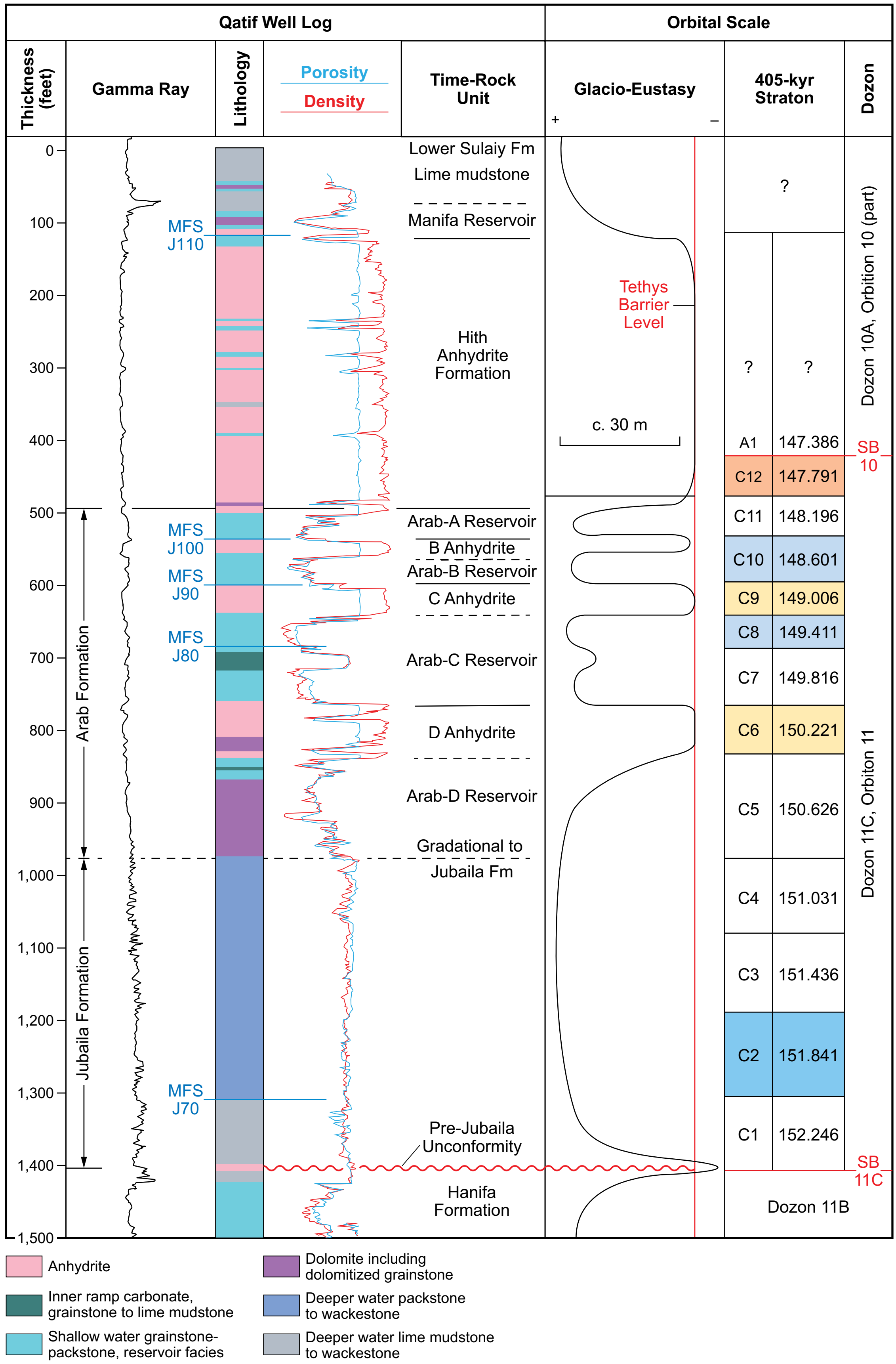

Figure 5: Qatif field well log in Saudi Arabia (Wilson, 2020) showing orbital calibration of Late Jurassic Pre-Jubaila Unconformity, Jubaila and Arab Formations.