Sequence stratigraphic model for a Barremian-Aptian deltaic sandstone to carbonate platform transition (upper Biyadh and Sallah Formations, Central Saudi Arabia)

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ABSTRACT: This study elucidates the stratigraphic relationship between Barremian and Aptian proximal, siliciclastic dominated sediments of the Biyadh and Sallah formations, and their time equivalent shallow water carbonate and intrashelf basinal sediments (Kharaib and Shuaiba formations). It fills in a gap of the established regional stratigraphic models published for this time interval. A regional subsurface stratigraphic framework (Barremian to Aptian) is constructed based on 10 wells along a 750 km long transect from central Arabia to Rub' al-Khali and Abu Dhabi (UAE). The sequence stratigraphic correlation is based on total gamma-ray logs, spectral gamma-ray (SGR) logs (uranium U and thorium Th), lithology and calcareous nannofossil analyses from well cuttings. The subsurface study is complemented with an outcrop sedimentological measured section of the time-equivalent of the Shuaiba formation, the lower Aptian Sallah formation. Three composite sequences are distinguished (Biyadh sequence, lower Shuaiba sequence and upper Shuaiba sequence) that show an overall backstepping followed by a seaward stepping of the marginal marine sandstones. The main maximum flooding surface is MFS K80, which is placed in the upper part of the lower Shuaiba sequence and is dated as early Aptian based on the presence of the nannofossil *Lithraphidtes houghtonii* and the ammonite *Cheloniceras* sp. The succession evolved from (a) a very low angle shallow-marine mixed carbonate-siliciclastic sequence (Biyadh sequence; Kharaib formations; Barremian) with limited accommodation space, to (b) an aggrading and backstepping platform with time-equivalent source rock accumulation in the adjacent (Bab) intrashelf basin, reaching maximum coastal encroachment (MFS K80) in the upper part of the carbonate platform succession, followed by regression, (lower Shuaiba sequence; lower Aptian), and (c) a lowstand wedge and basin infill with detrital argillaceous limestone (upper Shuaiba sequence).

Keywords: Arabian Platform, Sequence Stratigraphy, Barremian, Aptian, Carbonate Platform, Mixed Carbonate-siliciclastic.

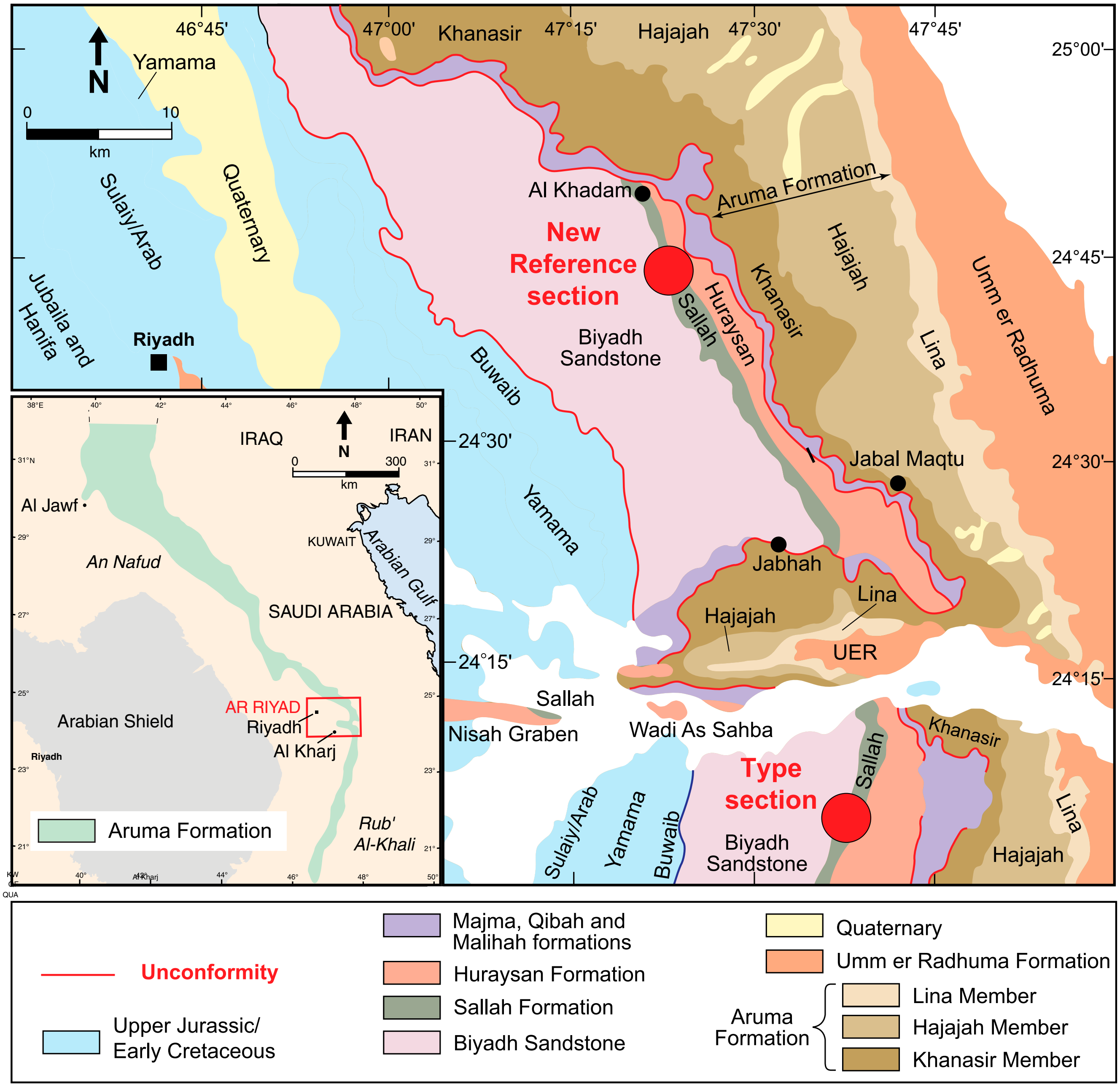
INTRODUCTION

Central Arabia represents the most western proximal depositional environment and coastal-onlap stratigraphic record of the subsurface Shuaiba Formation and its associated carbonate reservoir; an important hydrocarbon resource in the Arabian Peninsula. The aim of this study is to understand the depositional sequences, platform evolution and document the genetic relationships of major maximum flooding surfaces (MFS K50-80) of the Barremian and Aptian stratigraphic intervals in the proximal environment located in central Saudi Arabia, west of the Bab basin (Sharland et al.et 2001; Davies et al. 2002; van Buchem et al. 2010a, b; Le Nindre et al. 2010). Although a well-established sequence stratigraphic model for the Barremian and Aptian exists in the literature, there is little documentation of the facies changes and stratigraphic architecture of this time interval west of the Bab Basin in Saudi Arabia. This study aims to fill this information gap and provides a missing element of the regional sequence stratigraphic model of the Aptian, which is the stratigraphic relationship between the carbonate dominated units (Shuaiba and Bab basin) and the lateral facies transition towards the siliciclastic dominated proximal settings.

An integrated regional sequence stratigraphic framework (750 km long and 300 m thick) is constructed based on total gamma-ray logs, spectral gamma-ray (SGR) logs (uranium U and thorium Th), and lithology from well cuttings. The age is controlled by nannofossil analyses from the subsurface well cuttings and ammonite fauna from the outcrop type locality (Villalard 1985). The original type section of the Shuaiba Formation (Sallah Formation in outcrop) is not accessible to the public; thus, a new outcrop reference section is proposed herein (text-fig. 1), which represents a reference point for the most proximal facies and depositional environment of the Shuaiba Formation. The integrated sequence stratigraphic architecture of the Shuaiba Formation and Biyadh Sandstone Formation (Kharaib Formation) shows a logical lateral facies relationship, cyclic stacking patterns and geometries, organization and hierarchy of the depositional sequences, and insight on the development of the source rock rich intrashelf basin in a mixed carbonate-siliciclastic system.

GEOLOGICAL SETTING

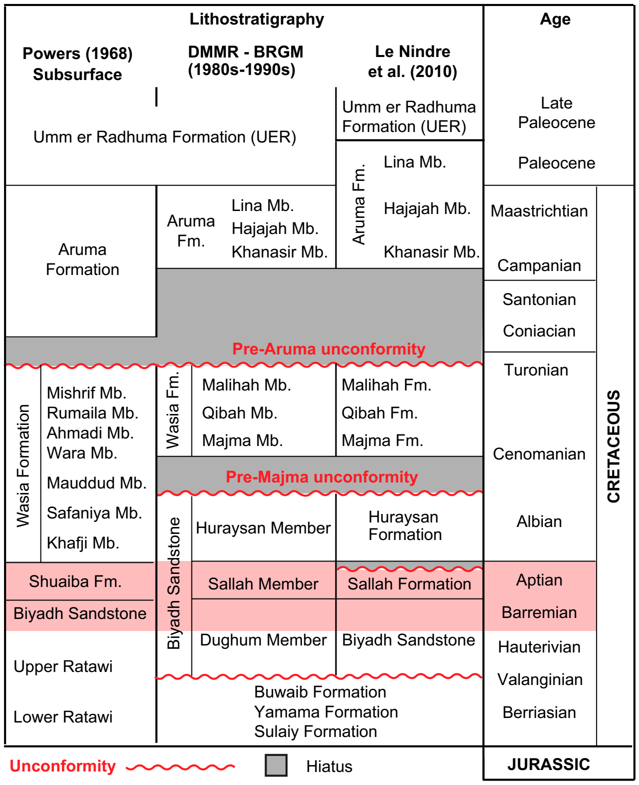
The type section of the early Aptian Shuaiba Formation (Sallah Formation in outcrop; 30 m thick) is located in Wadi As Sallah (24°05'58"N, 47°35'20"E and 24°06'02"N, 47°39'22"E), as recognized by Powers (1968) and then was explored by pits and drill holes by the French geological survey (Bureau de Recherches Géologique et Minières; BRGM) in the 1980s by Vaslet et al. (1991) and Le Nindre et al. (2008, 2010). The type section was logged by Le Nindre et al. (1988) and later was redrawn in Le Nindre et al. (2010; their Figure 3). A single ammonite fauna was



TEXT-FIGURE 1
Geological map of Ar Riyadh Quadrangle showing the Lower Cretaceous Biyadh Sandstone Formation, Shuaiba/Sallah Formation and Huraysan Formation (modified from Le Nindre et al. 2008). The new reference section of the Shuaiba/Sallah Formation is 60 km north of the type locality.

found in the middle of the formation in the type location (Villalard 1985) and the specimen was identified as *Cheloniceras* sp., which indicates an early Aptian age (Vaslet et al. 1991; Le Nindre et al. 2010).

The Shuaiba/Sallah Formation conformably overlies the Biyadh Sandstone Formation and it is unconformably overlain by the Huraysan Formation (late Aptian unconformity; text-fig. 2; *sensu* Le Nindre et al. 2008). The Shuaiba/Sallah Formation is informally divided into three units, in ascending order; unit 1, unit 2 and unit 3 (text-fig. 3). The lithology of these units is described by Le Nindre et al. (2008) and is summarized as follows. Unit 1 is 10 m thick and consists of red, gray or white claystone mixed with medium to coarse grained ferruginous sandstone. Unit 2 is 11 m thick and made up of yellow to ocher calcareous claystone, pelleted limestone and red to gray claystone, capped by fossiliferous dolomitized limestone that yielded the early Aptian ammonite fauna (Villalard 1984). Unit 3 is 9 m thick and consists of gray to green calcareous claystone interbedded by several decimeter-thick black iron crusts.



TEXT-FIGURE 2
Lithostratigraphic column of the formations and the main unconformities of the Cretaceous. The studied interval is shaded in red (modified from Le Nindre et al. 2010).

Surface to subsurface lithologic correlation (without biostratigraphic control) between the Shuaiba/Sallah formation and the Shuaiba formation was conducted by Vaslet et al. (1991) and Le Nindre et al. (2008) by using a subsurface reference well located approximately 75 km northeast of the type section outcrops. The correlated section covers the Umm Er Radhuma Formation, Aruma Formation, Wasia Formation and Biyadh Sandstone Formation. The correlation datum used was the pre-Aruma unconformity (Le Nindre et al. 2008). The Shuaiba Formation in the reference well consists of dolomitic limestone and chalky limestone (29 m thick) with fossil fragments (*Orbitolina* sp.) and it was stratigraphically located between the Biyadh Sandstone Formation and the Wasia Formation (Le Nindre et al. 2008).

METHODS

The original outcrop type section of the Shuaiba/Sallah Formation is not accessible to the public and therefore we proposed a new outcrop reference section with detailed sedimentological description and depositional environments. The new reference section (text-fig. 3) is 31 m-thick and is located in Khadam area in the Ar Riyadh quadrangle (base: 24° 38' 26" N, 47° 26' 51"E; top: 24° 41' 13" N, 47° 27' 44" E; 60 km north of the type locality). The detailed sedimentological log of the section (text-fig. 3) is based on rock color, mineralogy, grain types, grain size, texture, sedimentary structures and fossil occurrence. The lithofacies are analyzed and used as proxies and indication for depositional environments. Vertical and lateral facies relationships (Walther's Law) and the paleogeographic locations were considered in the interpretation of depositional environments.

The subsurface reference well that was used by Vaslet et al. (1991) and Le Nindre et al. (2008) is represented by Well-1 in text-fig. 7. Well-to-well gamma-ray log correlation was constructed from 10 wells from central Arabia through Rub' al-Khali and up to onshore Abu Dhabi, UAE. The central Arabia wells (Well-1to Well-6) are around 50 km east of the reference sections and cover the Biyadh Sandstone formation and the Shuaiba stratigraphic intervals. Well cuttings from Well-6 were examined using a petrographic microscope (Leica DM 2500P) to define the relative percentage of the lithology of each sample interval. The sample interval of the lithology from cuttings is 10 feet and was plotted against the gamma-ray log with no depth shifts. Well cuttings from Well-8 provide nannofossil age control.

Biostratigraphic data were collected from prepared slides by light microscope examination. Nannofossil analyses were conducted on thickly concentrated smear slides involved counting all specimens within a standard traverse (60 fields of view) plus subsequent scanning of the remainder of the slide for rare species. Counts of calcareous nannofossil assemblages were made using an Olympus BX-51 microscope at x1000 magnification and species images were taken using an Olympus DP71 camera. The study used standard nannofossil zonation schemes (Perch-Nielsen 1985; Varol 1992; Bown et al. 1998) to assess the age assignment of the assemblage.

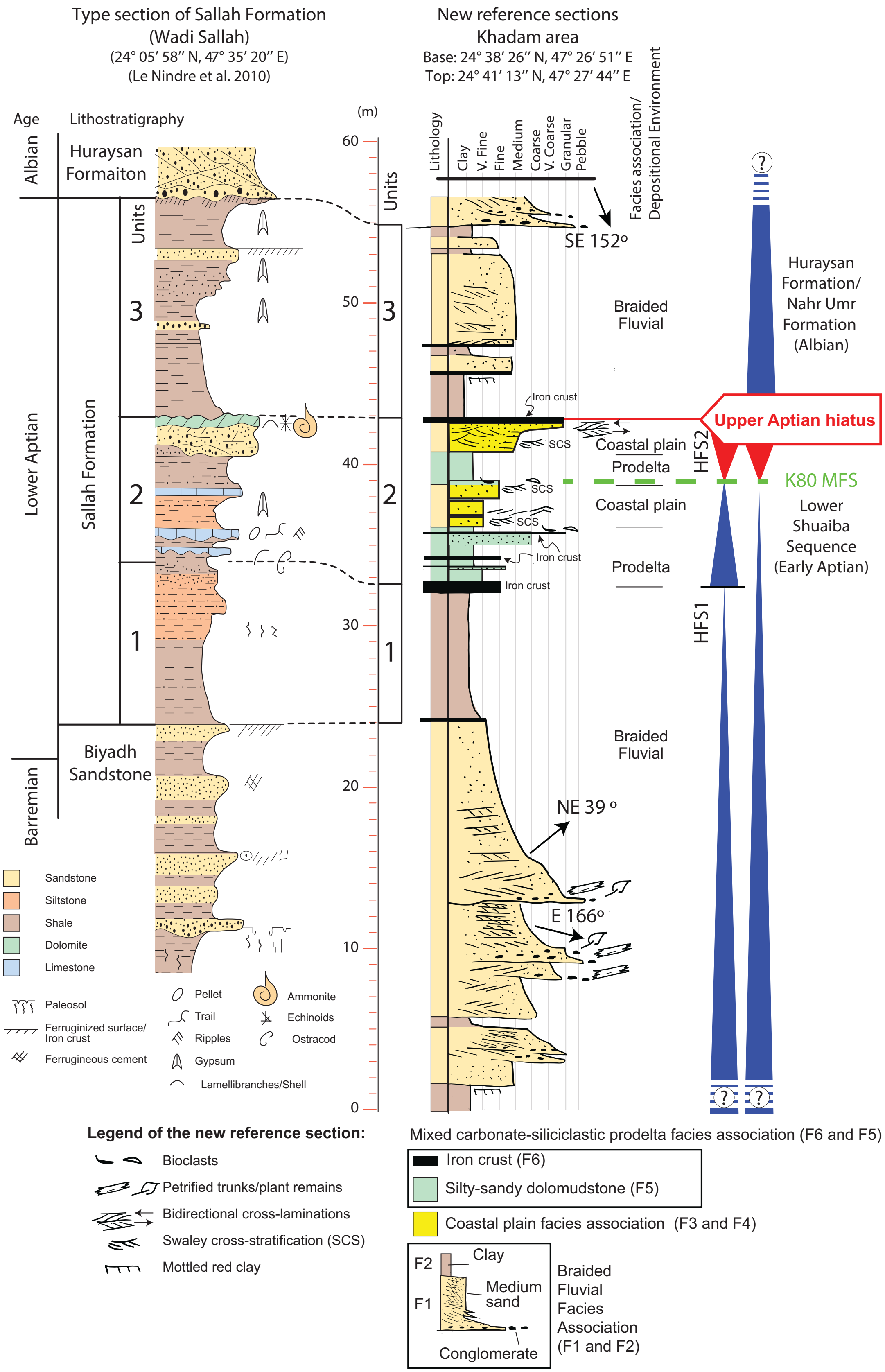
Spectral gamma-ray logs (SGR) are used in the study from Well-9 to characterize the basin-fill based on variants of uranium (U) and thorium (Th) that have a strong relationship to the lithology and paleo-depositional environment (Myers 1987; Davies 1993; Davies and Elliott 1996). The Th/U ratio from SGR can be used as a proxy for hinterland weathering conditions because Th is less soluble and can represent detrital transported sediment, especially kaolinite, which has a linear relationship with the Th (Ruffell and Worden 2000; Deconinck et al. 2003; Schnyder et al. 2006; Ruffell 2016). Uranium is more soluble under oxidizing conditions (Rosholt 1992) and can be concentrated, trapped and deposited with organic rich sediments under anoxic condition (Anderson et al. 1989; Lovley et al. 1991; Spirakis 1996). Thus, the Th/U ratio is a useful tool to correct the interpretation of the total gamma ray in which the peak of the total gamma ray is not always a response of a maximum marine transgression or maximum flooding surface (cf. Davies and Elliott 1996; Bhattacharya 1993).

FACIES ANALYSIS AND INTERPRETATION OF OUTCROP SECTION

Six facies (F1 to F6) were recognized from the outcrop section of the Shuaiba/Sallah Formation and the underlying Biyadh Sandstone Formation and were grouped into three facies associations and depositional environments ranging from braided fluvial facies, coastal plain, and mixed carbonate-siliciclastic prodelta. The facies are illustrated in text-fig. 4 - 6 and their sedimentological description and depositional environment interpretation are discussed below.

F1: Trough and Planar Cross-Bedded Medium- to Very Coarse-Grained Sandstone

Facies F1 is poorly to moderately sorted as it is associated with gravel lag-deposits and petrified trunks (F1; text-fig. 5a, b and c).



TEXT-FIGURE 3
Detailed sedimentological description of the new reference section of the Shuaiba/Sallah Formation in the Khadam area that is correlated with the original type locality (redrawn from Le Nindre et al. 2010).

Facies F1 is characterized by erosional-base channel sets that are 3-5 m thick. The individual channel sets and the stacked co-sets show a fining upward trend to mottled red and pinkish clay and siltstone (F2). The cross-bedded sandstone deposits indicate unidirectional traction fluvial paleocurrent directed toward the NE (39-70°). The fluvial planar and trough cross-stratification formed as a result of migration of sinuous and straight crested subaqueous dunes (2D and 3D; Miall 1977, 1978; Allen 1982; Rubin 1987; Singh and Bhardwaj 1991; Collinson 1996). The gravel beds, petrified trunks, low-range paleocurrent direction and the lack of overbank inter-channels fine sediments indicate a low sinuosity braided system (Miall 1977; Allen 1983).

F2: Mottled Red and Pinkish Clay and Siltstone

Facies F2 is 0.5-8 m thick and lacks well-defined root traces, (text-fig. 5d). The mottled red and pinkish clay and siltstone (F2) is interpreted as a flood plain and final infill stage of the fluvial channel deposits (cf. Miall 2014; Labourdette 2011) and the mottled color was a result of oxidation and pedogenic process (Wright 1986; Vepraskas 1992).

COASTAL PLAIN FACIES ASSOCIATION (F3 AND F4)

F3: Tidal-Wave Influenced Sandstone Delta

Facies F3 is characterized by swaley cross-bedded sandstone (text-fig. 6) that results in a 6 m thick coarsening-upward succession (text-fig. 4c). The swaley and wavy laminations are intercalated with mud drapes (text-fig. 6a and 6b) and the coarsening-upward succession is capped by a 1 m thick herringbone cross-bedded sandstone (F4). The overall coarsening-upward facies successions indicate a proximal delta front or mouth bar (Bhattacharya 2006) with a weak sand supply and river input. The internal sedimentary structure that includes swaley cross bedding implies an oscillatory wave process with a weak physical reworking (cf. Leckie and Walker, 1982; Walker 1982; Tillman 1986).

F4: Herringbones Cross-Bedding Sandstone

Facies F4 is associated with bundled foresets along with mud drapes (text-fig. 4b and 6c) that suggest bidirectional current flow with a slack period of water (Tankard and Hobday 1977; de Mowbray and Visser 1984; Kreisa and Moila 1986; Banerjee 1991).

MIXED CARBONATE-SILICICLASTIC PRODELTA (F5 AND F6)

F5: Silty-Sandy Dolomudstone

Facies F5 is characterized by pebbly skeletal silty dolomitic mudstone/floatstone (text-fig. 5h). The fossil material consists mainly of lamellibranches, oysters and echinoids. The facies is slightly bioturbated and it is interpreted to be deposited in a distal prodelta or carbonate shelf with low-energy and minor siliciclastic input (Coleman 1981; Hoy and Ridgway 2003).

F6: Nodular Ironstone Crusts

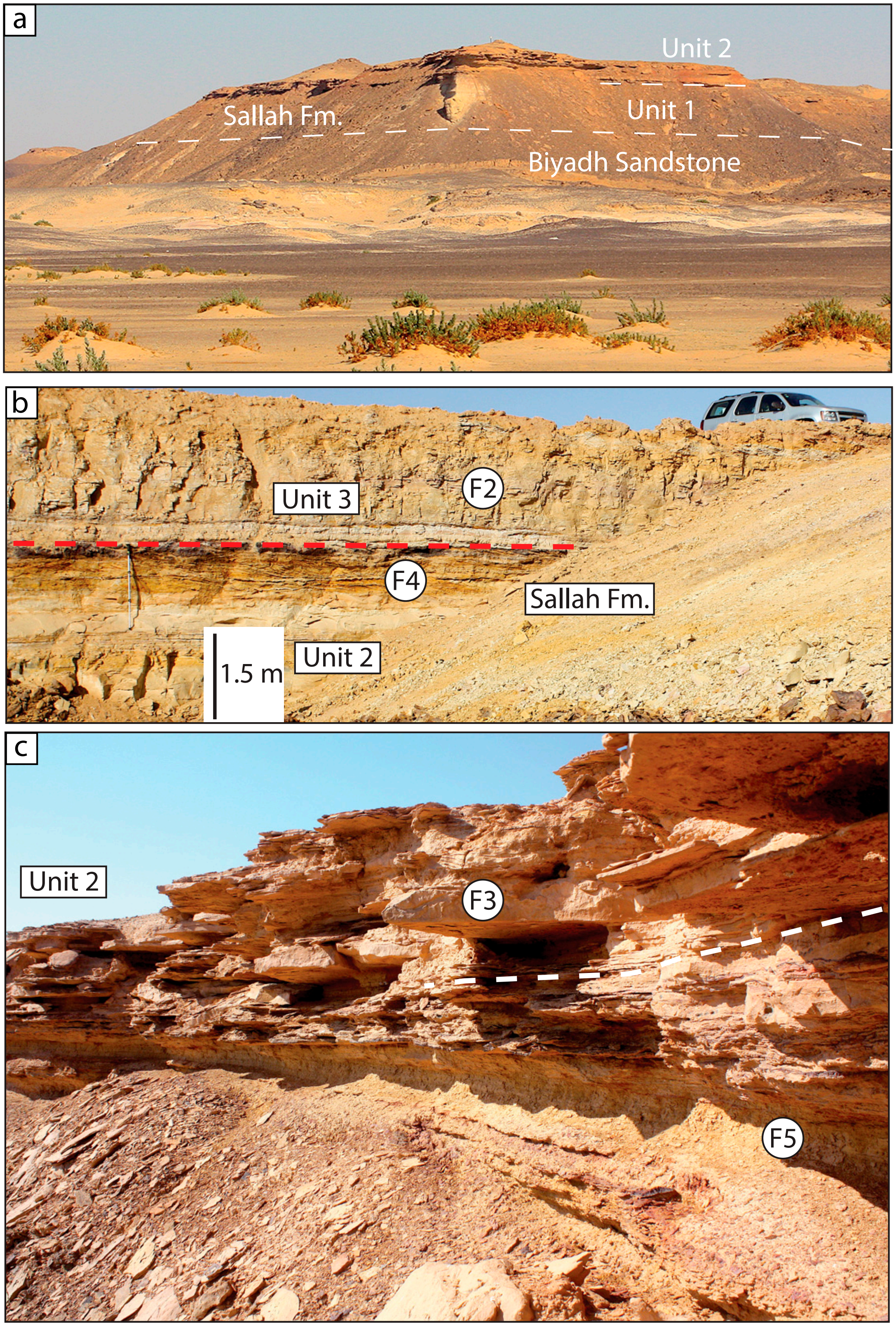
Facies F6 is 2-50 cm thick (text-fig. 4c) and it consists of shell lag deposits (text-fig. 5g). The ironstone crusts are a result of early diagenetic processes and are interpreted as a non-depositional product (Widdowson 2007; Tanner and Khalifa 2010).

SEQUENCE STRATIGRAPHY

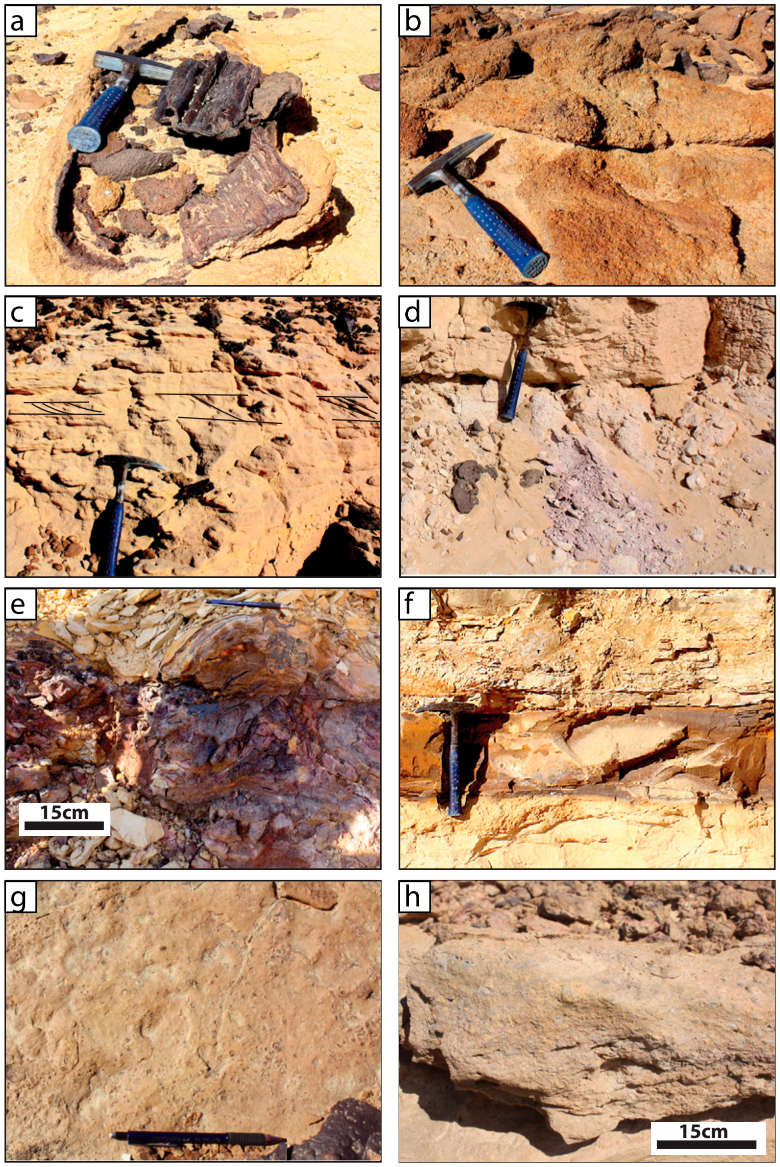
Correlation between ten wells from the subsurface resulted in a regional transect from central Arabia with proximal marginal-marine sandstone to carbonate shelf and intrashelf basin in Rub al-Khali and Abu Dhabi, UAE (text-fig. 7). The subsurface wells cover the Shuaiba Formation from its top to its basal contact with the underlying Biyadh Sandstone Formation with a 300-m thick interval. The cross-section can be divided into three stratigraphic composite sequences: Biyadh sequence, lower Shuaiba sequence and upper Shuaiba sequence. The calcareous nannofossils of the lower and upper Shuaiba sequences (from cuttings of Well-8) indicate an Aptian restricted age (Zone CC7) based on the presence of *Lithraphidtes houghtonii* (Bown et al. 1998). However, the presence of *Radiolithus orbiculatus* (Varol 1992), *Nannoconus calpidomorphus* (Perch-Nielsen 1985) and *Nannoconus quadriangulus quadriangulus* (Bown et al. 1998) along with *Lithraphidtes houghtonii* may indicate an upper Aptian placement for the upper Shuaiba sequence, as these markers indicate an age range of no older than lower upper Aptian, and may be used to approximate the lower/upper Aptian boundary. The Biyadh Formation has limited and non-conclusive biostratigraphic evidence; however, the log correlation and its stratigraphic position suggest that it is age equivalent to the Kharaib Member (Barremian age) of Abu Dhabi, UAE (Well-10 in Fig. 7; Well-20 in van Buchem et al. 2002). The wells in text-fig 7 were hung on two datums to reflect the depositional profile: 1) top lower Shuaiba sequence (Well-1-7); 2) top Biyadh sequence/upper Kharaib Member (Well-8-10). Datum (1) reflects the depositional profile of the delta system (flat delta plain, delta-front clinoforms and starved prodelta shelf platform). Datum (2) reflects the carbonate clinoform profile of the intrashelf basin (Bab basin).

Biyadh Sequence

A mix of carbonate, shale and sandstone lithology (in cuttings from Well-6), along with a stacked coarsening-upward trend in the gamma ray log (15-30 m thick; e.g., Well-4 and Well-5), indicate a prograding deltaic facies succession (cf. Prior and Coleman 1982; Bhattacharya 2006). Two distinct prograding delta cycles (HFS1 and HFS2) are picked in the central Arabian wells (Well- 1 to Well-6). The bases of these prograding deltas are shales and show some percentage of carbonate lithology, which is interpreted as an indication of a maximum marine flooding surface (K50 MFS and K60 MFS of Sharland et al. 2001, 2004; text-fig. 7). These MFSs are correlated with clean extensive carbonate shelf units in eastern Saudi Arabia, Rub' al-Khali and Abu Dhabi (Lower Kharaib and Upper Kharaib Members; Sharland et al. 2001, 2004; Davies et al. 2002; Pittet et al. 2002; van Buchem et al. 2002). The clean carbonate units are bounded by dense shaly units (Dense C, B and A), which are attributed to prodelta depositional environments deposited during maximum regression and/or initial transgression. HFS 2 is equivalent to the Upper Kharaib Member (Ap Bar 2 sequence), which is a well-dated unit (late Barremian age based on *Montseciella arabica* and *Eopalobitolina transiens*; Simmons 1994; Sharland et al. 2001; Schroeder et al. 2010; van Buchem et al. 2010) and has a robust regional biostratigraphic correlation (van Buchem et al. 2010). The age of the early Aptian cannot be excluded, thus far, for the HFS 2 and Ap Bar 2 sequence (cf. van Buchem et al. 2010) because of the occurrence of the calcareous nannofossil species *Lithraphidtes houghtonii* in Well-8 (Bown et al. 1998). The top Biyadh sequence boundary is a major surface as it shows



TEXT-FIGURE 4
a) An overview photo of the reference section shows the boundary between Biyadh Sandstone formation and the Shuaiba/Sallah formation. b) Photo shows the top sequence boundary and unconformity (red dash line) of the lower Shuaiba sequence which is placed within the Shuaiba/ Sallah formation. c) An overview succession shows a 6 m thick coarsening-upward from mixed carbonate-siliciclastic prodelta (F5) to tidal-wave influenced sandstone delta (F3) (note: oblique view).



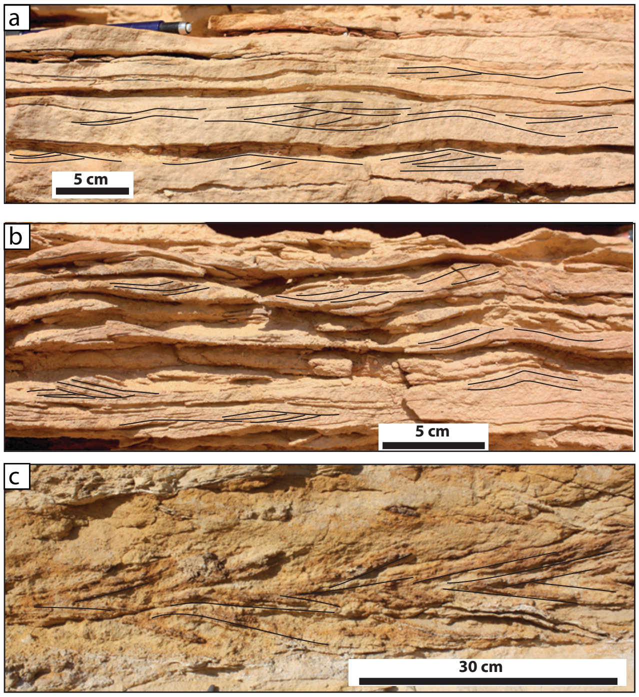
TEXT-FIGURE 5
Outcrop facies photography of the Biyadh Sandstone Formation and Shuaiba/Sallah Formation. a) Petrified trunk from the Biyadh Sandstone Formation (F1), b) Pebbly sandstone and conglomerates from the Biyadh Sandstone Formation (F1), c) Medium to coarse grain cross- bedded sandstone from the Biyadh Sandstone Formation (F1), d) Mottled red and pinkish clay and siltstone (F2; Shuaiba/Sallah formation, unit 1), e) and f) Iron crusts F6 (Shuaiba/Sallah formation, top unit 2), g) Silty-sandy dolomitic mudstone (F5; Shuaiba/Sallah formation, base unit 2), h) Pebbly skeletal silty dolomitic mudstone/floatstone (F5; Shuaiba/Sallah Formation, top unit 2).

evidence of erosion and karstification in Oman (van Buchem et al. 2002) and marks a major shift and depletion in the carbon isotope values in Rub' al-Khali (Al-Ghamdi and Pope 2014).

Lower Shuaiba Sequence

The lower Shuaiba sequence (lower Aptian) is made up of four depositional systems: marginal- marine siliciclastic delta (outcrops), mixed carbonate-siliciclastic prodelta (outcrops), shallow- marine carbonate platform, and intrashelf basin with source rock. The lower Shuaiba sequence consists of two high-frequency sequences (HFS1 and HFS2) that show maximum landward retreat and backstepping of the deltaic sandstone, which coincides with an extensive shallow carbonate platform and intrashelf basin development. The overall marine transgression of the lower Shuaiba sequence coincides with the early Aptian eustatic sea-level rise (Föllmi et al. 1994).

The initial transgression of HFS1 is marked by shallow-marine argillaceous limestone with *Palorbitolina* and *Orbitulina* foraminifera and algae which is represented by the Hawar Shale in Abu Dhabi and Rub' al-Khali (Sequence III in van Buchem et al. 2002; Al-Ghamdi and Read 2010). The Hawar Shale is equivalent to marginal marine sandstone in the updip section



TEXT-FIGURE 6
Outcrop facies of the tidal-wave influenced sandstone delta (F3), which is intercalated with mud drapes (a and b). Herringbone cross-bedded sandstone with tidal bundles and mud drapes (F4) (c).

(Well-1; text-fig. 7) that is probably laterally equivalent to the fluvial sandstone deposits with the petrified trunks occurring just below the base of the Shuaiba/Sallah formation in outcrop (text- fig. 3). The transgression of HFS1 shows a progressive decreasing gamma-ray trend or "cleaning-upward" carbonate unit in up section (Well-3-7) and its MFS (K70) is placed down section (Well-8-10) in the intrashelf basin (Bab basin) in Rub' al-Khali and Abu Dhabi. In outcrop and in the fluvial domain, this transgression and the rise of base level can be expressed by the overall fining upward of the fluvial channels with conglomerated trough cross-bedded deposits to medium-grained tabular cross-bedding sandstone (F1) that in turn grades upward to flood plain and final infill clay and siltstone (F2; text-fig. 3). This fining upward motif from channel fill to a flood plain is a genetic depositional succession and is considered to be a transgressive fill before the onlap surface of the silty-sandy dolomite/mudstone prodelta (F5; text-fig. 7) (cf. Allen 1991; Allen and Posamentier 1991, 1993; Shanley and McCabe 1994). The lithostratigraphic boundary between the Biyadh Sandstone formation and Shuaiba/Sallah formation is a conformable surface.

The main MFS of the lower Shuaiba sequence corresponds to the MFS HFS2 (K80) that shows a marine component in outcrop as represented by presence of silty-sandy dolomite/mudstone prodelta (F4; text-fig. 3) grading to a clean shallow carbonate platform (Well-1 to 7; text-fig. 7). Down section, MFS K80 is placed in a source-rock organic-rich intrashelf basin in Rub' al-Khali and Abu Dhabi (MFS of sequence III in van Buchem et al. 2002). The depositional profile of the lower Shuaiba sequence evolved from a very flat low-energy shallow-marine argillaceous limestone (Hawar Shale) to dipping clinoforms with high-energy bioclastic basin margin and basin geometry with source rock sediments (70-80 m water depth; estimated from the thickness of basin infill, the upper Shuaiba sequence). The flat platform with low carbonate production during the early transgression (lower HFS1, Hawar Shale and overlying shallow carbonate unit) is attributed to the limited accommodation space and high nutrient level (cf. Razin et al. 2010) and high-siliciclastic influx (cf. Al-Mojel et al. 2020; Al-Mojel and Razin 2022). The dipping platform and the creation of the intrashelf basin (HFS2) was formed during the high rate of accommodation space in the late transgression and early regression, which coincided with low nutrient levels that promoted a differential carbonate production and differential aggradation (cf. Ayres et al. 1982; van Buchem et al. 2002; Razin et al. 2010; 2017; Al-Mojel et al. 2020; Al-Mojel and Razin 2022).

The regression of HFS2 is marked by the prograding and coarsening tidal-wave delta sandstone (F3) in outcrops (text-fig. 3) and aggraded shallow carbonate platform (Well-1 to 7) and prograded rudist bank and margin in Rub' al-Khali (Well-7; cf. Al-Ghamdi and Read 2010) and in Abu Dhabi (van Buchem et al. 2002). The top sequence boundary in outcrop is marked by an iron crust (30-50 cm thick; text-fig. 5f) and an iron-encrusted hardground and exposure surface overlain by the Nahr Umr Shale in Rub' al-Khali and Abu Dhabi (van Buchem et al. 2002; Al-Ghamdi and Read 2010). The overlaying clay and fluvial sandstone in outcrops (unit 3 of the Shuaiba/Sallah Formation; text-fig. 3, text-fig. 4b) is laterally equivalent to the Nahr Umr Formation and is not genetically related to the underlying Sallah/Shuaiba sequence.

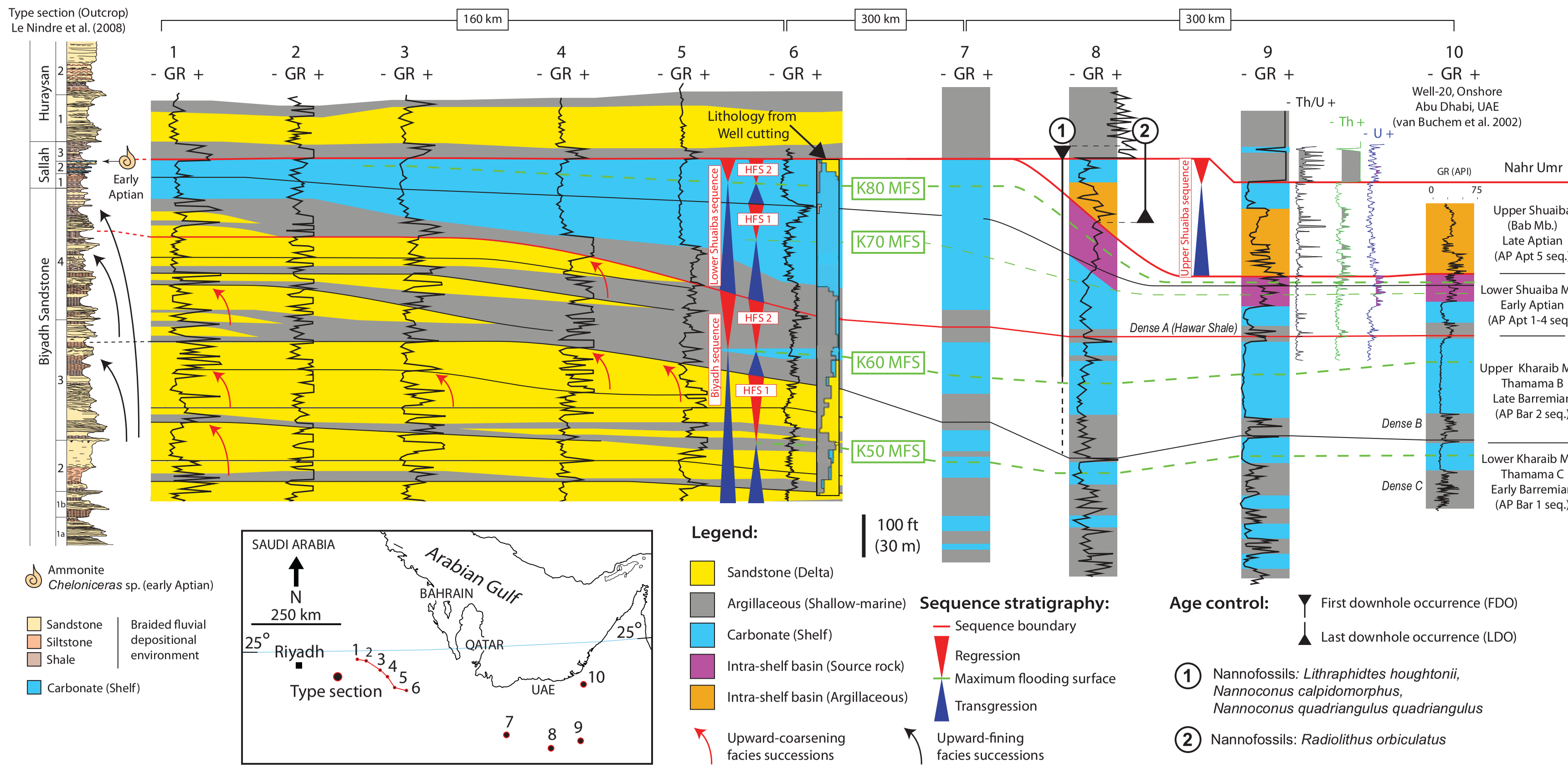
Upper Shuaiba Sequence

The upper Shuaiba sequence is equivalent to Sequence IV in the Bab Basin of van Buchem et al. (2002) and to the lowstand wedge AP Apt 5 sequence in van Buchem et al. (2010). The sequence is dominated by non-organic and high detrital argillaceous limestone sediments compared to the underlying lower Shuaiba sequence indicated by the sharp decrease of the U values and an increase of the Th signal at the basal boundary of the upper Shuaiba sequence (Well-9; text-fig. 7), which is consistent with the lithofacies observations of Well-10 in Abu Dhabi (Well-20 in van Buchem et al. 2002). The high Th value or the increase of the Th/U ratio in the lower two-thirds of the sequence signifies a high weathering rate and high detrital sedimentation (Ruffell and Worden 2000; Deconinck et al. 2003; Schnyder et al. 2006; Ruffell 2016) as the Bab Basin was surrounded by exposed platform at the top of the Shuaiba in Oman, Abu Dhabi and Rub' al-Khali (van Buchem et al. 2002; Al-Ghamdi and Read 2010). The sequence was controlled mainly by a major eustatic sea-level fall ($\sim$40 m during the early late Aptian; van Buchem et al. 2010).

DISCUSSION

Sequence stratigraphic model of mixed carbonate-siliciclastic

The coherent stratigraphic pattern of a backstepping siliciclastic system during second-order transgression and the regional scale of this study enables the development of a reference sequence model for mixed carbonate-siliciclastic systems (text-fig. 8). The model has been built on observations made at third-order scale which can be repeated and recognized at second-order



TEXT-FIGURE 7
Regional sequence stratigraphic framework from central Arabia with proximal marginal- marine sandstone to carbonate shelf and intrashelf basin in Rub al-Khali and Abu Dhabi, UAE. Well-10 in the cross-section is in Abu Dhabi (Well-20 in van Buchem et al. 2002).

scale. The key point in this model is the position of the true MFS in shallow carbonate platform deposits. The model is controlled by stratal termination, variation in sediment supply between carbonate and siliciclastic systems and changing in accommodation/sedimentation rates.

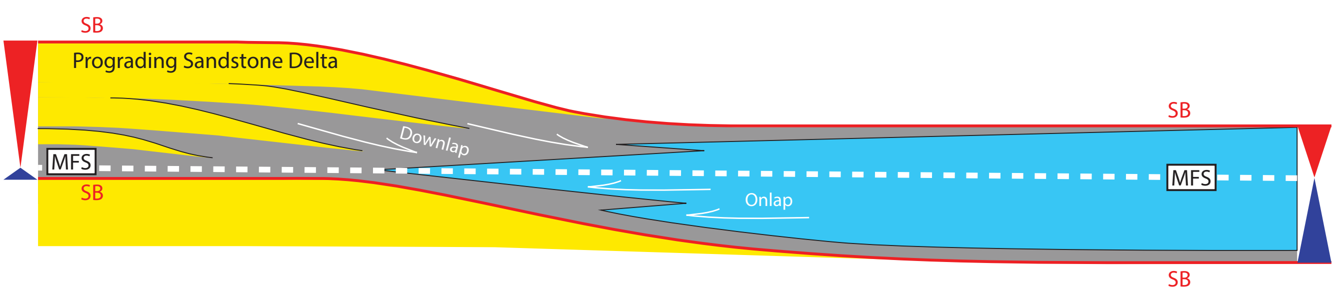
The prograding delta sandstone creates clinoform geometries due to the shelf equilibrium profiles (cf. Swift and Thorne 1991) as the sedimentation rate increases toward the shoreline and the grain size decreases seaward responding to the shelf dispersal system (cf. Pomar and Kendall 2008). The top of the preceding clinoform geometry is a subaerial exposure, as the initial transgression down section is characterized by very shallow water calcareous shale and argillaceous lime mudstones. For example, the Hawar Member is characterized by intertidal desiccation cracks alternating with orbitolinid-rich and miliolid-dominated shale in Oman that suggests 0-3 m water depths (van Buchem et al. 2002; Davies et al 2002). At this stage, the carbonate sedimentation rate is low due to high levels of nutrients. Thus, the sedimentation rate is less than the accommodation space (S < A) which creates a backstepping trend and onlap terminations of the carbonate units on the preceding delta sandstone unit. The maximum onlap position of the carbonate unit represents the MFS where the shoreline and siliciclastic input are most landward. In the outer platform, the MFS is placed high in a clean carbonate unit that represents maximum carbonate production, where accommodation space is equal to the production rate. From the gamma-ray perspective, the transgression shows a progressive decreasing gamma-ray or "cleaning-upward" carbonate trend and the MFS is placed in a lowest gamma-ray reading. The high carbonate production, during transgression, fills up the available accommodation space left by the prior marginal sandstone clinoforms. This could be also associated with differential subsidence, which explains the wedging geometry of the carbonate units toward the land. The MFS is the downlap surface onto which the prograding clinoforms of marginal marine sandstone downlap (cf. Van Wagoner et al. 1988). The highstand system tract in the outer part of the basin is aggrading as the carbonate production is higher than the accommodation which maybe have resulted in several subaerial exposure surfaces in the clean limestone unit. For example, the top cycle of the Kharaib sequences in Oman, Wadi Mu'aydin, is a clean limestone, capped by enlarged burrows, vugs and hardground surface interpreted to represent subaerial exposure (Davies et al. 2002).

The depositional model proposed here is not specific for the Shuaiba Formation. A very similar analog was observed in the Middle Jurassic Dhruma Formation of Saudi Arabia (cf. Fig. 15 of Al-Mojel and Razin 2022). The top unit of the Dhruma Formation (D1) is a prograding delta and the initial transgression of the overlying sequence (D2 unit) onlaps on the delta and the MFS can be placed higher in a maximum onlap surface in a clean limestone with a low gamma-ray reading (Dhibi Limestone Member). The main MFS of the Dhruma sequence is in an extensive clean limestone (D4 unit) which is overlain by prograding delta plain distributary channels that downlap on the MFS. Although the sequence model is a predictive tool, the prograding delta is not always recorded in the system as it is influenced by many factors like proximity to shoreline, availability of accommodation space and short-lived climate changes.

The existing classical carbonate sequence stratigraphic models were designed for open-marine depositional conditions such as a shelf margin (e.g. Sarg et al., 1988, 1999; Handford and Loucks 1993) and there was little consideration of restricted inner-platform systems. The first proposal for the Cretaceous mixed carbonate-siliciclastic sequence model of the Arabian Platform was made by Davies et al. (2002). It was an attempt to explain the true MFS in such mixed inner-platform system and the relationships between limestone, shale and marginal sandstone from a synthesis of previous regional studies. They placed the MFS at the basal part of a clean limestone, but it was based on a regional conceptual prospective without direct evidence. Horbury and Poppelreiter (2018) proposed a broad general sequence stratigraphic depositional model for mixed carbonate-siliciclastic system of the Triassic to Middle Jurassic of the Arabian platform. The model suggested here is rather in agreement with Davies et al. (2002) and Horbury and Poppelreiter (2018) in that the MFS is placed in the maximum onlap carbonate units not in a shelf shale deposit.

CONCLUSION

The depositional environment of the Shuaiba/Sallah Formation in outcrop (Khadam area) ranges from braided fluvial facies, coastal plain, to mixed carbonate-siliciclastic prodelta which represents the most western proximal depositional setting and coastal-onlap stratigraphic record of the subsurface Shuaiba formation and its associated carbonate reservoir.



TEXT-FIGURE 8
Sequence stratigraphic model for inner-platform mixed carbonate-siliciclastic system. The model is designed for a third-order scale cycle which can be repeated and recognized at second- order scale. The model highlights the position of the true maximum flooding surface (MFS) in shallow carbonate platform deposits, taking into consideration the stratal terminations, variation in sediment supply between carbonate and siliciclastic systems and changing in accommodation/sedimentation rates across the platform.

A regional subsurface stratigraphic framework of 10 wells (300 m thick and 750 km long) with gamma-ray logs and lithology shows an overall backstepping of marginal marine sandstone during the initial marine transgression. The carbonate platform evolved from flat shallow- marine mixed carbonate-siliciclastic (Biyadh sequence; Kharaib Member; Barremian) to a dipping clinoform platform with source rock intrashelf basin that represents the maximum marine transgression and early regression (MFS K80; Bab Basin; lower Aptian). The source rock intrashelf basin is overlain by lowstand wedge and basin infill with detrital argillaceous limestone (upper Shuaiba sequence) surrounded by an exposed Shuaiba carbonate platform.

The creation of the intrashelf basin was formed during a high rate of accommodation space, which coincides with a low siliciclastic supply and a low nutrient level that promotes a differential carbonate production and differential aggradation. Spectral gamma-ray, especially uranium (U) and thorium (Th), are a powerful tool for sequence stratigraphic analysis that can be used to differentiate between deep high-organic matter sediment and restricted lowstand argillaceous limestone in a basinal setting.

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REFERENCES

AL-GHAMDI, N. and READ, F. J., 2010. Facies-based sequence-stratigraphic framework of the Lower Cretaceous Rudist platform, Shu'aiba formation, Saudi Arabia. In: van Buchem, F. S. P., Al-Husseini, M. I., Maurer, F. and Droste, H. J., Eds., *Barremian—Aptian stratigraphy and hydrocarbon habitat of the eastern Arabian Plate*, 2: 367–410. GeoArabia Special Publication 4. Bahrain: Gulf PetroLink.

AL-GHAMDI, N. and POPE, M., 2014. Integrated high-resolution chemostratigraphy and facies-based stratigraphic architecture of the Lower Cretaceous (Aptian), Shu'aiba Formation, Saudi Arabia. *AAPG Bulletin*, 98 (8): 1521–1549.

AL-MOJEL, A. and RAZIN, P., 2022. Sequence stratigraphy and facies analysis of the NE Gondwana Middle Jurassic inner-platform mixed carbonate-siliciclastic succession, Saudi Arabia. *Arabian Journal of Geosciences*, 15 (9): 820.

AL-MOJEL, A., RAZIN, P. and DERA, G., 2020. High-Resolution sedimentology and sequence stratigraphy of the Oxfordian-Kimmeridgian, Hanifa, Jubaila and Arab outcrops along Jabal Tuwaiq, central Saudi Arabia. *Journal of African Earth Sciences*, 165: 103803.

ALLEN, J. R. L., 1982. *Sedimentary structures: Their character and physical basis.* Amsterdam: Elsevier, 1: 611 pp.

———, 1983. Studies in Fluviatile Sedimentation: Bars, Bar-complexes and Sandstone Sheets (Low-Sinuosity Braided Streams) in the Brownstones (L. Devonian), Welsh Borders. *Sedimentary Geology*, 33 (4): 237–293.

ALLEN, G. P., 1991. Sedimentary processes and facies in the Gironde estuary: A model for Macrotidal Estuarine Systems. In: Smith, D. G., Reinson, G. E., Zaitlin, B. A. and Rahmani, R. A., Eds., *Clastic Tidal Sedimentology*, 219–226. Canadian Society of Petroleum Geologists Memoir, 16.

ALLEN, G. P. and POSAMENTIER, H. W., 1991. Facies and stratal patterns in incised valley complexes: Examples from the Recent Gironde estuary (France), and the Cretaceous Viking Formation (Canada) (abs.). *American Association of Petroleum Geologists Bulletin,* 75: 534.

———, 1993. Sequence stratigraphy and facies model of an incised valley fill: The Gironde estuary, France. *Journal of Sedimentary Petrology,* 63: 378–391.

ANDERSON, R. F., LEHURAY, A. P., FLEISHER, M. Q. and MURRAY, J. W., 1989. Uranium deposition in saanich inlet sediments, Vancouver island. *Geochimica et Cosmochimica Acta*, 53 (9): 2205–2213.

AYRES, M. G., BILAL, M., JONES, R. W., SLENTZ, L. W., TARTIR, M. and WILSON, A. O., 1982. Hydrocarbon habitat in main producing areas, Saudi Arabia. *AAPG Bulletin*, 66 (1): 1–9.

BANERJEE, I., 1991. Tidal sand sheets of the Late Albian Joli Fou-Kiowa-Skull Creek Marine transgression. Western Interior Seaway of North America. In: Smith, D. G., Ed., *Clastic Tidal Sedimentology*, 335–347. Canadian Society of Petroleum Geologists, Memoir 16.

BHATTACHARYA, J. P., 1993. The expression and interpretation of marine flooding surfaces and erosional surfaces in core; examples from the Upper Cretaceous Dunvegan Formation, Alberta foreland basin. In: Posamentier, W., Summerhayes, C., Haq, B. and Allen, G., Eds., *Sequence stratigraphy and facies associations,* 125-160. Oxford: Blackwell.

———, 2006. Deltas. In. Posamentier, H. W. and Walker, R. G., Eds., *Facies models revised*, 84: 237–292. Tulsa: Society for Sedimentary Geology SEPM.

BOWN, P. R., RUTLEDGE, D. C., CRUX, J. A. and GALLAGHER, L. T., 1998. Lower Cretaceous. In: Bown, P. R., Eds., *Calcareous nannofossil biostratigraphy*, 86-131. London: British Micropalaeontological Society Publication Series.

COLEMAN, J. M., 1981. *Deltas: Processes and model of deposition for exploration*, 2nd ed. Minneapolis: Burgess CEPCO Division, 124 pp.

COLLINSON, J. D., 1996. Alluvial sediments. In: Reading H. G. Eds., *Sedimentary environments: Processes, facies and stratigraphy*, 37–82. Malden: Blackwell Science.

DAVIES, S. J., 1993. "The radiochemical evolution of the Devonian Orcadian Basin, NE Scotland and comparison with coeval clastic systems from Wales, Norway and the Clair Field." Unpublished PhD thesis, University of Leicester, United Kingdom.

DAVIES, S. J. and ELLIOTT, T., 1996. Spectral gamma ray characterization of high-resolution sequence stratigraphy: Examples from Upper Carboniferous fluvio-deltaic systems, County Clare, Ireland. *Geological Society, London, Special Publications*, 104 (1): 25–35.

DAVIES, R. B., CASEY D, M., HORBURY A, D., SHARLAND P, R. and SIMMONS M, D., 2002. Early to mid-Cretaceous mixed carbonate-clastic shelfal systems: Examples, issues, and models from the Arabian Plate. *GeoArabia*, 7 (3): 541–598.

DE MOWBRAY, T. and VISSER, M., 1984. Reactivation surfaces in subtidal channel deposits, Oosterscheide, southwest Netherlands. *Journal of Sedimentary Petrology,* 54: 811–824.

DECONINCK, J. F., HESSELBO, S. P., DEBUISSER, N., AVERBUCH, O., BAUDIN, F. and BESSA, J., 2003. Environmental controls on clay mineralogy of an Early Jurassic Mudrock (Blue Lias Formation, southern England). *International Journal of Earth Sciences*, 92 (2): 255–266.

FÖLLMI, K. B., WEISSERT, H., BISPIN, M. and FUNK, H., 1994. Phosphogenesis, carbon isotope stratigraphy, and carbonate platform evolution along the Lower Cretaceous northern Tethyan margin. *Geological Society of America Bulletin*, 106 (6): 729–746.

HANDFORD, C. R. and LOUCKS, R. G., 1993. Carbonate depositional sequences and systems tracts–responses of carbonate platforms to relative sea-level changes: In: Loucks, R. G. and Sarg, J. F., Eds., *Carbonate sequence stratigraphy: Recent developments and applications*, 57:3–42. Tulsa: American Association of Petroleum Geologists.

HORBURY, A. and POPPELREITER, M. C., 2018. Petroleum geology and its relation to stratigraphic architecture of the triassic to middle Jurassic (Induan to Aalenian) interval on the Arabian Plate. In: Pöppelreiter, M. C., Ed., *Lower Triassic to Middle Jurassic Sequence of the Arabian Plate*, 49-100. DB Houten: SAGE Publications.

HOY, R. G. and RIDGWAY, K. D., 2003. Sedimentology and sequence stratigraphy of fan-delta and river-delta deposystems, Pennsylvanian Minturn Formation, Colorado. *AAPG Bulletin*, 87 (7): 1169–1191.

KREISA, R. D. and MOILA, R. J., 1986. Sigmoidal tidal bundles and other tide-generated sedimentary structures of the Curtis Formation, Utah. *Geological Society of America Bulletin*, 97 (4): 381–387.

LABOURDETTE, R., 2011. Stratigraphy and static connectivity of braided fluvial deposits of the lower Escanilla formation, south central Pyrenees, Spain. *AAPG Bulletin*, 95 (4): 585–617.

LE NINDRE, Y. M., VASLET, D., MADDAH, S. S. and AL-HUSSEINI, M. I., 2008. Stratigraphy of the Valanginian? To early Paleocene succession in central Saudi Arabia outcrops: Implications for regional Arabian sequence stratigraphy. *GeoArabia*, 13 (2): 51–86.

LE NINDRE, Y. -M. and BROSSE, J. M., 1988. Bauxites de Az Zabirah-Qibah (Royaume d'Arabie Saoudite). Etude sédimentologique des formations du toit et du mur, éléments de gîtologie prévisionnelle. Bureau de Recherches Géologiques et Minières Report 88-SAU-157-GEO, 21 p.

LE NINDRE, Y.-M., VASLET, D. and BUSNARDO, R., 2010. Aptian ammonite of the Sallah formation, Central Saudi Arabia. In: Van Buchem, F. S. P., Al-Husseini, M.I., Maurer, F. and Droste, H. J., Eds., *Barremian—Aptian stratigraphy and hydrocarbon habitat of the eastern Arabian Plate.* 97-106. GeoArabia Special Publication 4. Bahrain: Gulf PetroLink.

LECKIE, D. A. and WALKER, R. G., 1982. Storm- and tide-dominated shorelines in Cretaceous Moosebar-Lower Gates interval–outcrop equivalents of Deep Basin gas trap in western Canada. *American Association of Petroleum Geologists Bulletin*, 66 (2): 138–157.

LOVLEY, D. R., PHILLIPS, E. J., GORBY, Y. A. and LANDA, E. R., 1991. Microbial reduction of uranium. *Nature*, 350 (6317): 413–416.

MIALL, A. D., 1977. A review of the braided-river depositional environment. *Earth-Science Reviews*, 13 (1): 1–62.

———, 1978. *Fluvial sedimentology.* Canadian Society Petroleum Geologists, Memoir 5. Cambridge University Press, 105–127 pp.

———, 2014. *Fluvial depositional systems.* Switzerland: Springer, 316 pp.

MYERS, K. J., 1987. "Onshore outcrop gamma ray spectrometry as a tool in sedimentological studies." Unpublished PhD thesis, University of London, 180 pp.

PERCH-NIELSEN, K., 1985. Mesozoic calcareous nannofossils. In: Bolli, H. M. and Saunders, J.B. Eds., *Plankton stratigraphy*, 329-426. Cambridge: Cambridge University Press.

PITTET, B., VAN BUCHEM, F. S. P., HILLGÄRTNER, H., RAZIN, P., GRÖTSCH, J. and DROSTE, H. J., 2002. Ecological succession, palaeoenvironmental change, and depositional sequences of Barremian-Aptian shallow-water carbonates in northern Oman. *Sedimentology*, 49 (3): 555–581.

POMAR, L. and KENDALL, C. G. ST. C., 2008. Architecture of carbonate platforms: A response to hydrodynamics and evolving ecology. In: Simo, A. and Lukasik, J., Eds., *Controls on carbonate platform and reef development*, 89:187–216. Special Publication. Tulsa: Society of Economic Paleontologists and Mineralogists (SEPM).

POWERS, R. W., 1968. *Lexique Stratigraphique International, v.III, Asie, 10bl, Saudi Arabia.* Paris: Centre National de la Recherche Scientifique, 177 pp.

PRIOR, D. B. and COLEMAN, J. M., 1982. Active slides and flows in underconsolidated marine sediments on the slopes of the Mississippi Delta. In: Saxov, S. and Nieuwenhuis, J. K., Eds., *Marine slides and other mass movements*, 6:21–49. Boston: Springer.

RAZIN, P., GRÉLAUD, C. and VAN BUCHEM, F. S. P., 2017. The mid-Cretaceous Natih Formation in Oman: A model for carbonate platforms and organic-rich intrashelf basins. *AAPG Bulletin*, 101 (04): 515–522.

RAZIN, P., TAATI, F. and VAN BUCHEM, F. S. P, 2010. Sequence stratigraphy of Cenomanian–Turonian carbonate platform margins (Sarvak Formation) in the High Zagros, SW Iran: An outcrop reference model for the Arabian Plate. In: van Buchem, F. S. P., Gerdes, K. D. and Esteban, M., Eds., *Mesozoic and Cenozoic carbonate systems of the Mediterranean and the Middle East: Stratigraphic and diagenetic reference models-an introduction*, 329: 187–218. London: Geological Society.

ROSHOLT, J. N., 1992. Mobilisation and weathering. In: Ivanovich, M. and Harmon, R.S., Eds., *Uranium-series disequlibrium: Applications to earth, marine and environmental sciences*, 167–178. Oxford: Clarendon Press.

RUBIN, D. M., 1987. *Cross-bedding, bedforms and palaeocurrents.* Tulsa: Society for Sedimentary Geology SEPM, 1:187 pp.

RUFFELL, A., 2016. Do spectral gamma ray data really reflect humid–arid palaeoclimates? A test from Palaeogene Interbasaltic weathered horizons at the Giant's Causeway, N. Ireland. *Proceedings of the Geologists' Association*, 127 (1): 18–28.

RUFFELL, A. and WORDEN, R., 2000. Palaeoclimate analysis using spectral gamma-ray data from the Aptian (Cretaceous) of southern England and southern France. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 155 (3-4): 265–283.

SARG, J. F., WILGUS, C. K., HASTINGS, B. S., KENDALL, C. G., ST, C., POSAMENTIER, H. W., ROSS, C. A. and VAN WAGONER, J. C., 1988. Carbonate sequence stratigraphy. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A., Van Wagoner, J. C., Eds., *Sea Level Changes—An Integrated Approach*, 42:155–181. Special Publication. Tulsa: Society of Economic Paleontologists and Mineralogists (SEPM).

SARG, J. F., MARKELLO, J. R. and WEBER, L. J., 1999. The second-order cycle, carbonate-platform growth, and reservoir, source, and trap prediction. In: Harris, P. M., Saller, A. H., Simo, J. A., Eds., *Advances in carbonate sequence stratigraphy: Application to reservoirs, outcrops and models*, 11-34. Society of Sedimentary Geology (SEPM) Special Publication 63. Tulsa: Society of Economic Paleontologists and Mineralogists (SEPM).

SCHNYDER, J., RUFFELL, A., DECONINCK, J. F. and BAUDIN, F., 2006. Conjunctive use of spectral gamma-ray logs and clay mineralogy in defining late Jurassic–early Cretaceous palaeoclimate change (Dorset, UK). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 229 (4): 303–320.

SCHROEDER, R., VAN BUCHEM, F. S. P, CHERCHI, A., BAGHBANI, D., VINCENT, B., IMMENHAUSER, A. and GRANIER, B., 2010. Revised orbitolinid biostratigraphic zonation for the Barremian—Aptian of the eastern Arabian Plate and implications for regional stratigraphic correlations. In: van Buchem, F. S. P., Al-Husseini, M. I., Maurer, F. and Droste, H. J., Eds., *Barremian—Aptian stratigraphy and hydrocarbon habitat of the eastern Arabian Plate*, 1:49–96. Bahrain: Gulf PetroLink.

SHANLEY, K. W. and MCCABE, P. J., 1994. Perspectives on the sequence stratigraphy of continental strata. *AAPG Bulletin,* 78: 544–568.

SHARLAND, P. R., ARCHER, R., CASEY, D. M., DAVIES, R. B., HALL, S. H., HEWARD, A. P., HORBURY, A. D. and SIMMONS, M. D., 2001. *Arabian plate sequence stratigraphy.* GeoArabia Special Publication 2. Bahrain: Gulf PetroLink, 371 pp.

SHARLAND, P. R., CASEY, D. M., DAVIES, R. B., SIMMONS, M. D. and SUTCLIFFE, O. E., 2004. Arabian plate sequence stratigraphy–revisions to SP2. *GeoArabia*, 9 (1): 199–214.

SIMMONS, M., 1994. Micropaleontological biozonation of the Kahmah Group (Early Cretaceous), Central Oman Mountains. In: Simmons M.D., Ed., *Micropaleontology of carbonate environments.* 176–207. Chister: Ellis Horwood.

SINGH, A. and BHARDWAJ, B. D., 1991. Fluvial facies model of the Ganga River sediments, India. *Sedimentary Geology*, 72 (1-2): 135–146.

SPIRAKIS, C. S., 1996. The roles of organic matter in the formation of uranium deposits in sedimentary rocks. *Ore Geology Reviews*, 11 (1-3): 53–69.

SWIFT, D. J. P. and THORNE, J. A., 1991. Sedimentation on continental margins, I: A general model for shelf sedimentation. In: Swift, D. J. P. and Oertel, G. F., Eds., *Shelf sand and sandstone bodies: Geometry, facies and sequence stratigraphy*, 14:189–255. Oxford: Blackwell Scientific Publications. International Association of Sedimentologists Special Publications.

TANKARD, A. J. and HOBDAY, D. K., 1977. Tide-dominated back-barrier sedimentation, early Ordovician Cape Basin, Cape Peninsula, South Africa. *Sedimentary Geology*, 18 (1-3): 135–159.

TANNER, L. H. and KHALIFA, M. A., 2010. Origin of ferricretes in fluvial-marine deposits of the lower Cenomanian Bahariya formation, Bahariya Oasis, Western Desert, Egypt. *Journal of African Earth Sciences*, 56 (4-5): 179–189.

TILLMAN, R. W., 1986. Swaley cross-stratification and associated features. Upper cretaceous western inter seaway United States. *Bulletin of the American Association of Petroleum Geologists*, 5: 656.

VAN BUCHEM, F. S. P., PITTET, B., HILLGÄRTNER, H., GRÖTSCH, C., MANSOURI, A. I. A., BILLING, I. M., DROSTE, H. H. J., OTERDOOM, W. H. and VAN STEENWINKEL, M., 2002. High-resolution sequence stratigraphic architecture of Barremian/Aptian carbonate systems in northern Oman and the United Arab Emirates (Kharaib and Shu'aiba formations). *GeoArabia*, 7 (3): 461–500.

VAN BUCHEM, F. S. P., AL-HUSSEINI, M. I., MAURER, F., DROSTE, H. J. and YOSE, L. A., 2010. Sequence-stratigraphic synthesis of the Barremian–Aptian of the eastern Arabian Plate and implications for the petroleum habitat. In: van Buchem, F. S. P., Al-Husseini, M. I., Maurer, F., Droste, H., Eds., *Barremian—Aptian stratigraphy and hydrocarbon habitat of the eastern Arabian Plate*, 1: 9–48. Bahrain: Gulf PetroLink.

VAN WAGONER, J. C., POSAMENTIER, H. W., MITCHUM, R. M., VAIL, P. R., SARG, J. F., LOUTIT, T. S. and HARDENBOL, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A., Van Wagoner, J. C., Eds., *Sea level changes an integrated approach*, 42:39–45. Special Publication. Tulsa: Society of Economic Paleontologists and Mineralogists (SEPM).

VAROL, O., 1992. Taxonomic revision of the Polycyclolithaceae and its contribution to Cretaceous biostratigraphy. *Newsletters on Stratigraphy*, 27 (3): 93–127.

VASLET, D., AL-MUALLEM, M. S., MADDEH, S. S., BROSSE, J. M., FOURNIQUET, J., BRETON, J. P. and LE NINDRE, Y. M., 1991. *Explanatory notes to the geologic map of the Ar Riyad Quadrangle, Sheet 24I, Kingdom of Saudi Arabia. Geosciences Map GM-121.* Jeddah: Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, 54 pp.

VEPRASKAS, M. J., 1992. Redoximorphic features for identifying aquic conditions. *Technical Bulletin North Carolina Agriculture Research Service*, 301: 1–33.

VILLALARD, P., 1984. Explanatory Notes to the Industrial Mineral Resources map of Khushaym Radi. BRGM/Rr-02709-Fr, 84, Jeddah, Saudi Arabia, 26 p.

———, 1985. Explanatory Notes to the Industrial Mineral Resources Map of Khushaym Radi. BRGM 84-82-JED-025-OR.

WALKER, R. G., 1982. Hummocky and swaley cross stratification. In: Walker R. G., Ed., *Clastic units of the area between field BC and Drumheller, Alberta/Guidebook to Excursion 21A*, 22–30. Hamilton, Canada: International Association of Sedimentologists, 11th International Congress on Sedimentology.

WIDDOWSON, M., 2007. Laterite and Ferricrete. In: Nash, D. J. and McLaren, S. J., Eds., *Geochemical sediments and landscapes*, 45–94. Hoboken: Blackwell.

WRIGHT, V. P., 1986. The role of fungal biomineralization in the formation of Early Carboniferous soil fabrics. *Sedimentology*, 33 (6): 831–838.