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Regional depositional history, stratigraphy and palaeogeography of the Shu'aiba

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Sedimentology, sequence stratigraphy and seismic stratigraphy of the Lower Cretaceous Shu'aiba Formation of northwest Abu Dhabi, United Arab Emirates

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A 3-D seismic analysis over an oil field in northwest Abu Dhabi was used to map the platform-to-basin geometries of the Lower Cretaceous Shu'aiba Formation. The areal extent of the interior platform, the platform margin, the clinoform belt (prograding wedges), and the Bab Basin were outlined by seismic cross-sections and seismic amplitude maps. Sedimentologic and petrographic core descriptions were used to identify 12 lithofacies types, ranging from shallow-marine, rudist-rudstone to deep-marine, planktonic-foraminifera wackestone and shale.

The Shu'aiba deposits of northwest Abu Dhabi conform to a sequence stratigraphic framework established for a giant oil field of central Abu Dhabi. The Shu'aiba transgressive and early highstand sequence sets were built by the Ap2 and Ap3 sequences. The Shu'aiba late highstand sequence set is comprised of the Ap4 and Ap5 sequences, and the Bab lowstand sequence set is represented by the Ap6 sequence. However, the platform margin appears to be steeper in northwest Abu Dhabi, as the area of the interpreted Upper Aptian (Ap4 and Ap5 sequences) distal clinoform belt is narrower than the one encountered in central Abu Dhabi.

A combined approach of biostratigraphy, carbon-isotope stratigraphy and strontium-isotope stratigraphy was used to constrain the sequence stratigraphic correlation. Rudist bivalves helped identify the Lower versus Upper Aptian sequences. Distinct taxa such as *Offneria* characterized the Lower Aptian high-energy environments, but were absent in the Upper Aptian due to a pronounced extinction event that affected rudists at the Lower/Upper Aptian transition. Carbon-isotope curves from individual wells were used to correlate prograding units, but the chronostratigraphic calibration to carbon isotopes proved difficult. Numerical ages were obtained for selected levels using strontium-isotope stratigraphy. This helped develop a more precise chronostratigraphy of the Shu'aiba Formation in the studied region.

Sediment control on fracture network of Cretaceous reservoirs, northern Oman

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The geometrical aspects of the fracture networks in the Cretaceous reservoirs of northern Oman were mainly controlled by the tectonic regime ("deformation"), and to a lesser extent, by the type of lithofacies ("sediment") deposited in the various fields. A review of outcrop analogues and the detailed descriptions of borehole-image logs indicated that the fractures in northern Oman can be divided into three types: (1) dispersed ("background") fractures in which the geometry ("vertical extent") is highly dependent on sediment types; (2) fracture corridors ("clusters") and fault-related fractures that appear to cut through the whole Cretaceous reservoir succession; and (3) fold-related fractures, which are related to local tectonic effects.

The mechanical layering is typified in northern Oman and can also be seen in the southeastern fields of northern Oman, where only the lower part of the Cretaceous reservoir occurs. The dynamic property of those fractures ("conductivity") is governed by: (1) the diagenetic history of the reservoir, and (2) the present-day magnitude and orientation of the stress field. The presentation will also shed light on the characteristics and modeling of micro-fractures that were observed in core samples from a few Cretaceous reservoirs.

Facies and high-resolution sequence stratigraphy of the Shu'aiba Formation, Shaybah field, Saudi Arabia

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The Early Cretaceous (Aptian) Shu'aiba Formation in Shaybah field, Saudi Arabia, contains a giant carbonate reservoir that formed on a regional carbonate ramp bordering an intra-shelf basin. The succession consists of a composite sequence of seven high-frequency sequences. Sequences 1 and 2 formed a deeper open platform of Palorbitolina-Lithocodium wackestone, with maximum flooding marked by planktic foram mudstone. Sequence 2 built relief over the northern and southern blocks, which are separated by an intra-platform depression. Sequence 1 and part of sequence 2 form the composite sequence transgressive systems tract (TST). The remaining sequences (3 to 7) developed a platform that was rimmed by rudist rudstone, backed by a rudist floatstone back-bank and a lagoonal fine skeletal peloidal packstone. The slope facies were fine skeletal fragmented packstone. Aggradational sequences 3 to 5 made-up the composite sequence early highstand systems tract (HST). Progradational sequences 6 and 7 formed the composite sequence late highstand systems tract. These sequences marked the deterioration of the Offneria rudist barrier and deposition of widespread lagoonal deposits. Accommodation space in the lagoon may have been created by syn-depositional normal faulting that moved the northern block down. The deposition of the Shu'aiba Formation on the platform was terminated by a long-term sea-level fall and karsting. The succession is dominated by fourth-order sequences (duration of approximately 400 thousand years, Ky) and parasequences (100 Ky), which were driven by long-term and short-term eccentricity, respectively, similar to the Pacific guyots of this age. This suggests that climate during the Early Cretaceous may have been cooler with small ice sheets, and was not an ice-free greenhouse period.

Integrated 3-D reservoir modeling of a complex heavy oil fractured carbonate in the Qarn Alam field, northern Oman

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The Shu'aiba reservoir in the Qarn Alam field is currently being developed using *thermally assisted gas oil gravity drainage* (TAGOGD). In this process steam is injected into the intensely fractured reservoir, at the crest of the field, so as to heat the oil in the low-permeability matrix. This procedure drains the oil into the oil rim where it collects in fractures.

During the process, the viscosity of the oil is significantly reduced thus accelerating the GOGD process. To address the key reservoir uncertainties, an integrated modeling approach was adopted. It integrated reprocessed 3-D seismic, borehole-imagelog and drilling losses data, and provided a better definition of the structural surface and fault locations.

Faults were accurately mapped and positioned at the fault cut-outs at the wells. Outcrop data were used to map the different reservoir sequences of the Shu'aiba reservoir, resulting in a better definition of the fault cut-outs. Shell's 3-D fracture-modeling software was used to characterize the fractures. Because the static and dynamic data were limited, fracture modeling was a challenge. A multiple realization approach addressed the uncertainty in the fracture distribution. Simulation models suggested a large increase in oil recovery ranging from 3–5 % under cold GOGD development to 20–35% under steam injection (TAGOGD).

Shu'aiba Formation, Block 9, northern Oman

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Wells Saqr-1 and 2, Diba-1 and Reham-1 are located on three small fault-block structures and produce oil from the Cretaceous Lower Shu'aiba reservoir in northern Oman. The reserves in each structure are not significant. Cores cut from the Saqr West-1 well, which was drilled on a small structure between Saqr and Diba fields, suggested that the lithology controls the distribution of hydrocarbons. Well Saqr-3 confirmed pay-on-logs 80 ft below the mapped oil-water contact in the Saqr structure.

The Diba-2 horizontal well confirmed movable hydrocarbon 65 ft deeper in the Diba-Saqr West structure. Logs, Special Core Analysis (SCAL) and production tests confirmed that lithology controls the hydrocarbon distribution in the Lower Shu'aiba reservoir in the central Block 9 resulting in added reserves and new well locations.

Alternative sequence stratigraphic framework in the upper part of the Shu'aiba Formation in field H, onshore Abu Dhabi, United Arab Emirates

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Field "H" is a low-relief structure located 15 km south of the largest Shu'aiba field in Abu Dhabi. In 2001, a thorough integration of 3-D seismic, log and core data from four wells was performed. It resulted in a comprehensive depositional model of the Shu'aiba Formation in this field. The study was supplemented by a comprehensive regional review of the development of the Shu'aiba Formation that integrated the available biostratigraphic and isotope data, and a high-resolution sequence stratigraphic framework was proposed.

In 2004, a joint ADCO-ExxonMobil detailed seismic-stratigraphic study covering both field "H" and the largest Shu'aiba field was completed and a new high-resolution sequence-stratigraphic framework was proposed. The topic of this paper is to compare the two frameworks and to highlight differences between them that occur in the upper part of the Shu'aiba sequence, at or near the Early to Late Aptian time line.

The Shu'aiba geological setting in field "H" is quite unique in Abu Dhabi as it represents a distinctive transition from a platform setting into a back-platform, intra-seaway to a deep lagoonal setting. The transition exhibits strong lateral facies variations in the middle Unit H of the Shu'aiba Formation and in the lower part of the overlying Unit I: from high-permeability rudistic facies to low-permeability non-rudistic facies. The vertical succession of facies in Unit I strongly suggests that the sedimentation over the southern part of the main Shu'aiba platform took place over the time interval near the Early to Late Aptian time line.

Advanced well design to address the locally complex geological setting of the Shu'aiba Formation, onshore Abu Dhabi, United Arab Emirates

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The Shu'aiba Formation is locally quite complex with strong lateral variations in its middle Unit H. In a distance of only a few hundred meters the high-permeability rudistic facies (permeability in the order of 100 to 1,000s mD) pass laterally to the low-permeability non-rudistic facies (permeability in the order of 1 to 10 mD). This transition controls the oil distribution in a low-relief structure located south of the largest Shu'aiba field in onshore Abu Dhabi. In the low-relief structure the low-permeability reservoirs are water-bearing due to a significant level of capillary entry pressure value.

At the time of this study (year 2001), four wells provided control for defining the shelf edge. The lateral facies boundary was well-expressed on newly acquired 3-D seismic data by a significant time thickness variation. However, even seismic inversion techniques could not differentiate between the two facies because the porosity is very similar, in the order of 25–30%.

A very thorough integration of seismic, log, biostratigraphic, isotope and core data, supplemented by a regional synthesis of the Shu'aiba's depositional setting led to a comprehensive depositional model in a well-defined sequence stratigraphic framework. Based on this effort, a proposal was made to drill two appraisal/development wells with three holes each. The two appraisal vertical/deviated pilot holes are separated by about 1,200 ft laterally and the horizontal production section is 3,000 ft long.

The results that will be presented were consistent with expectations. The generation of a 3-D geological model and the related simulation work led to a *Full Field Development Plan* that has been successfully implemented. The field is now producing as predicted by the dynamic model.

Sequence stratigraphic framework of the Aptian Shu'aiba Formation in Oman

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The Shu'aiba Formation is the most important carbonate reservoir for oil in Oman. The formation shows a complex internal stratigraphic architecture and significant lateral variations in reservoir character. A sequence stratigraphic framework is presented that explains these regional variations. Incorporation of seismic data allowed significant refinement and improvement of the previous models, which were based on well data only.

The Shu'aiba Formation, which is up to 130 m thick, occurs as a unit within a Cretaceous epeiric carbonate platform system. It conformably overlies the dense carbonates of the Hawar Member (top Kharaib Formation) and is unconformably overlain by the shales of the Nahr Umr Formation. The Shu'aiba Formation is built by three major genetic units (systems tracts) each with a different

distribution, both in time and space, in response to different trends in relative sea-level change. Each of these contains different facies associations and internal stacking patterns and, consequently, also different reservoir architecture.

The lowermost unit is Early Aptian in age and includes the Hawar Member and the basal Shu'aiba Formation. It forms a transgressive systems tract (TST) with laterally extensive shallow-marine to intertidal sediments followed by shallow-marine algal limestones that transgressed over exposed limestones of the Kharaib Formation. The development of algal-mound complexes led to a differentiation on the platform. Between these mounds fine-grained, in places organic-rich, deeper-water deposits represent the maximum flooding interval (MFI).

The second unit is Early to Late Aptian in age, and consists of a highstand systems tract (HST) with progradational geometries. The "carbonate factory" was then dominated by rudist-biostrome complexes, which colonized the mounds. Intermound depressions were progressively filled leading to the formation of a large platform that surrounded an intra-platform basin.

The third unit was formed by a lowstand systems tract (LST) deposited in the Late Aptian during and following a regional drop in sea level. The drop caused subaerial exposure of the HST platform and the influx of fine-grained clastics. The early LST contained off-lapping wedges of argillaceous carbonates and carbonate-rich claystones along the margins of the intra-platform basin. Ultimately the whole platform interior was exposed and a late LST wedge was deposited along the ocean margin of the platform. The basal clays of the Nahr Umr Formation formed the TST, which is capped by an MFI, the Marker Limestone Bed, located a few meters above the Shu'aiba Formation.

Unraveling the depositional history of the Shu'aiba Formation at a regional scale: Key success factors

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An 18-month review of the Shu'aiba system in an ADNOC/Shell joint project resulted in a major advance of the understanding of its depositional history. This improved knowledge can now be exploited in focused exploration plays. The analyses provided important insights for unveiling new knowledge from existing data sets and experts. The key factors were meticulous planning, the participation of experienced geoscientists from various disciplines and countries, and the integration of existing data sets that ranged in quality from excellent to mediocre.

The planning relied on the integration of existing data sets and involvement of experts from various disciplines. The integration and quality control of the data from various vintages and areas was a difficult but crucial task for achieving success. After completion of this preliminary work the geoscientists benefited from the following factors. (1) A complete coverage of seismic and well data over Abu Dhabi compiled in a single, normalized format. Data from more than 370 wells were quality-controlled and loaded in a new project on IP. (2) Seismic facies identification and extraction proved successful in a study of a 3-D survey over a giant Shu'aiba field in Abu Dhabi in 2002–2003. This method was successfully applied to the regional study, integrating both 3-D and 2-D data. (3) Core material was available for the analysis and mapping of rock facies for correlation with the seismic data and evaluation of the geological model. (4) Interpretations could be shared across borders without revealing confidential data. Relevant results of analyses and interpretations were shared with neighboring countries, allowing the development of regional paleo-geographic maps.

In a final analysis, the assembly of all the existing data sets presented (a) an unprecedented opportunity for mining by scientists from various disciplines and companies; and (b) the integration of existing regional knowledge and new ideas. Both aspects taken together resulted in a leap forward towards the understanding of an hitherto little-known geologic system.

Regional Shu'aiba reservoir prediction integrating seismic attributes and sequence stratigraphy, Blocks 9 and 27, Oman

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The top Shu'aiba seismic horizon attributes, seismic facies, and isochore maps tied to a sequence stratigraphic framework in Sa'fah field provided a robust regional model for the distribution of the Shu'aiba reservoir throughout Blocks 9 and 27, northern Oman. The Upper Shu'aiba Formation is subdivided into three dominantly progradational third-order composite sequences (USh1, USh2, and USh3), while the Lower Shu'aiba Formation is subdivided into three dominantly aggradational third-order composite sequences (LSh1, LSh2, LSh3).

In Blocks 9 and 27, the Shu'aiba fields are either structural-stratigraphic traps (Sa'fah) or small structural traps, with column heights of less than 150 ft. Though regionally porous, the Lower Shu'aiba produces only where Upper Shu'aiba basinal facies are well-developed and form a suitable seal. In these areas, the upper part of the Shu'aiba interval tends to be composed of high-impedance mudstones overlain by low-impedance Nahr Umr shale (e.g. Saqr, Saqr West, Diba, and Reham fields), with corresponding high-impedance contrast.

The USh1 and USh2 composite sequences contain thick (up to 150 ft), porous highstand systems tracts that extend to or near the top of the Shu'aiba and have low-impedance contrast with overlying Nahr Umr shale (e.g. Sa'fah, Rayyan, Rawdah, Hebah, Badr, Dhiya, Dhiya West, Wadi Rafash, and Khamilah fields). Prominent USh2 ramp margin-parallel amplitude bands reflect prograding shoreface and ramp margin deposits composed of rudist wackestone to grainstone, grading seaward to rudist-stromatoporoid-algal coalesced bioherm and foreslope facies and deeper ramp burrowed to laminated mudstones.

The USh3 composite sequence filled the basin seawards of the USh2 terminal ramp margin and consists of at least four high-frequency sequences composed of alternating lime mudstones/shales and 20–30 ft thick peloidal skeletal packstone/grainstone with isolated rudist mounds. The best reservoir quality in the USh3 is developed on interpreted local highs (e.g. Sa'fah Far West, Lekhwair, Malaan, Daleel, Jalal and Al Barakah fields); southeasterly progradation was common and may reflect paleo-wind or paleo-storm orientation from the northwest. Top-USh3 amplitude patterns are complicated by the complex toplap relationships present in this composite sequence. Where thick lime mudstones occur at the top of the sequence, they have high-impedance contrast with the overlying Nahr Umr; where thick porous packstone/grainstone is present, it has low-impedance contrast with the overlying Nahr Umr shale. Seismic wedge models and synthetic seismograms were constructed to confirm the relationships described herein.

Safah field: Upper Shu'aiba reservoir development at the southern edge of an isolated Aptian Platform, Block 9, northern Oman

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Sa'fah field was developed within three interpreted composite sequences of the Upper Shu'aiba Formation (USh1, USh2, USh3), along the southern edge of a large (50 x 25 km), NE-elongated isolated platform (Sa'fah Platform). The platform was interpreted to have developed during the Late Barremian-Early Aptian along the trend of the Sa'fah-Lekhwair Arch, as documented by thickening of the Lower Shu'aiba sequences. Composite sequences and their component high-frequency sequences (HFS) were interpreted through the integration of core, wireline log and 3-D seismic data. The USh1 sequence forms an isolated, 6 x 3 km, 150-ft-thick rudist-shoal complex on the eastern edge of Sa'fah field. The entirely subtidal shoal complex consists of several upward-coarsening successions of whole rudist mud-dominated packstone to grain-dominated packstone with increasing rudist fragmentation and current lamination.

Uppermost USh1 rudist grainstones are overlain abruptly by an erosional contact with intra-clasts, followed by fenestral mudstones, suggesting an abrupt seaward shift in facies tracts. The overlying 30 ft succession consists of a cyclic succession of subtidal peloid-foram mud-dominated packstones overlain by intertidal fenestral mudstones and/or eroded hardground surfaces with truncated burrows/borings/root traces. This succession is interpreted to represent the inner ramp lagoonal island facies of the USh2 sequence. Downdip of the USh1 shoal complex, the USh2 sequence is composed of four high-frequency sequences (HFS) that prograded the ramp margin an additional 2.5–5 km basinward. The lower three HFS have proportionally thicker transgressive systems tracts composed of dysaerobic shale-rich Planolites-burrowed mudstone grading updip and vertically to porous outer ramp aerobic Thalassin-oides-burrowed peloid wackestone and fine peloid packstone. The upper two HFS exhibit upward-shallowing successions from foreslope stromatoporoid–rudist floatstone to ramp margin rudist-stromatoporoid-algal boundstone, representing moderate-energy environments near wave base. Boundstones pass landward to rudist-skeletal wackestone and floatstone.

Following the deposition of the USh2 sequence, the platform was subjected to moderate meteoric diagenesis and was only intermittently flooded while the USh3 ("Bab") sequence was deposited largely seaward of the USh2 margin. In the Sa'fah area, the USh3 is composed of at least three HFS. The oldest HFS developed a laterally discontinuous, 120-ft-thick fringing reef complex one km seaward of the USh2 margin, with a deep mud-dominated lagoon on the landward side. The two younger HFS offlap the older HFS fringing reef complex, and consist of more shale-dominated transgressive systems tracts overlain by a 20–30-ft-thick progradational rudist shoreface/shoal complexes deposited under relatively low accommodation conditions.

Al Barakah field: Upper Shu'aiba reservoir development within the Bab Basin, Block 9, northern Oman

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Al Barakah field, discovered in 1992, produces oil and associated gas from two reservoir zones in the Upper Shu'aiba USh3 ("Bab") sequence. The reservoir zones are compartmentalized by NW-trending normal faults into five fault blocks, and vertically separated by low-permeability shale to lime-mudstone facies. Shallow-water carbonate facies were initially localized to a NE-trending syndepositional high, the Al Barakah Arch, and subsequently prograded towards the southeast.

The oldest reservoir zone (Zone C) consists of an aggradational sequence of Orbitolina shale, peloid-foram packstone/wackestone, and rudist-algal boundstone/packstone, which is localized to the NE-trending axis of the field. This sequence is interpreted as a discontinuous fringing reef to low-energy shoreface succession. Zone C reaches a maximum thickness of 50 ft, but the width of the rudist-algal boundstone facies parallel to depositional dip (SE) is only 0.5–0.7 km. Cores exhibit abundant secondary porosity, suggesting early subaerial exposure and leaching. Degradation of permeability in the underlying and laterally equivalent peloid-foram wackestone facies is attributed to an increase in detrital clay drapes, pressure solution features and lime mud and a decrease in skeletal grains. Zone C is sealed updip (northwest) by pinch-out onto a base seal of older Orbitolina shales, and by the overlying Nahr Umr shale. This suggests a relative fall in sea-level due to possible syndepositional uplift and/or a fall in eustatic sea-level.

Zone B is either absent or very thin across the crest of Zone C and thickens to over 20 ft basinward; downdip, it is separated from Zone C by a shale unit. Zone B consists of an upward-shallowing succession of Orbitolina mudstone, stromatoporoid-rudist floatstone, small rudist floatstone, and fine skeletal grain-dominated packstone with rudist fragments. Secondary porosity development with local infiltration of overlying Nahr Umr Shale is attributed to subaerial exposure and meteoric leaching at the top-Shu'aiba unconformity. The combined effects of stratigraphic and structural compartmentalization, localized rudist-algal buildup development and subsequent secondary porosity development have complicated efforts to efficiently waterflood the reservoirs.

Reservoir compartmentalization and waterflood response in a Shu'aiba giant: Safah field, northern Oman

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Integration of core, log, 3-D seismic, surveillance, PVT (pressure-volume-temperature), oil geochemistry and production data into a full-field geologic model and history-matched reservoir simulation models has resulted in an improved understanding of reservoir compartmentalization, greater confidence in infill and injector well planning, and additional flank drilling opportunities in this maturing waterflood program. Stratigraphic compartmentalization is related to basinward progradation of three composite sequences (Upper Shu'aiba sequences USh1, USh2 and USh3) and their internal high-frequency sequences, setting up five major reservoir compartments (East, Main, West Lobe, Far West, and FF West). Further structural compartmentalization is caused by low-offset, WNW- and NNW-trending conjugate fault sets, which appear to be partially sealing in places, resulting in variations in fluid contacts and post-depletion reservoir pressures.

The Sa'fah East compartment is isolated from Sa'fah Main by a NW-trending normal fault with 10–30 ft of down-to-the-east throw, and by the west and southwest transition from permeable highstand ramp-margin facies of USh1 to low-permeability transgressive deeper ramp facies of USh2. The USh2 sequence in Sa'fah Main is internally composed of four high-frequency sequences that transition from aggradational and mudstone dominated at the base, to more progradational and rudist-rich at the top. The Sa'fah Main compartment is isolated from Sa'fah West Lobe by a southwestward transition from permeable, USh2 highstand ramp margin facies to impermeable mudstones of the basal USh3 transgressive systems tract.

The Sa'fah West Lobe is a NW-SE elongate trend of coalesced USh3 aggradational rudist-stromatoporoid mounds that parallel the USh2 ramp margin. These mounds represent the highstand systems tract of the basal USh3 high-frequency sequence. Inferred sub-compartments of Sa'fah West Lobe are attributed to along-strike variations in mound development. Two younger USh3 high-frequency

sequences offlap the basal USh3 mound sequence. The grain-rich (ooid-peloid) highstand units of these two sequences comprise the Sa'fah Far West and FF West compartments. The next phase of reservoir studies is focusing on mapping and prediction of fracture corridors prone to early water breakthrough.

Sequence stratigraphy of the Shu'aiba Formation and Hawar Member (Biyadh Formation) tectono-stratigraphic sequence

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Well-log and core data from Qatar and adjacent Bahrain, Abu Dhabi, Iran and Saudi Arabia have been used to identify and evaluate the Lower Cretaceous Shu'aiba Formation and Hawar Member (Biyadh Formation) tectono-stratigraphic sequence. Consistent with tectono-stratigraphic terminology, the Shu'aiba-Hawar sequence is bounded by prominent, regional unconformities. Between these unconformities, the sequence is a distinctive three-part succession of deposits that begins with siliciclastics and ends with carbonates.

The initial siliciclastic lowstand phase of deposition is characterized by a thick wedge of fluvial sandstones typical of the Biyadh Formation. These deposits thin from west to east and transition upward into marginal marine deposits as they onlap the basal unconformity. Ultimately, these deposits grade into thin marine shale that characterizes the Hawar Member before lapping out entirely to the east.

An abrupt shift from siliciclastic to carbonate deposition was recorded by transgressive carbonates that formed a relatively thin but laterally extensive ramp referred to as the Lower Shu'aiba Platform. The subsequent highstand phase of carbonate deposition was strongly influenced by the development of intra-shelf basins. Within these basins, the highstand was marked by a thin basinal carbonate, while relatively thick platform carbonates, referred to as the Upper Shu'aiba Platform, were developed along their margins.

Carbonate deposition was terminated by tectonic tilting that uplifted the northeastern part of the platform while generating subsidence in the southwestern part. Subsequently, much of the uplifted platform in the northeast was removed by erosion. The southwestern region was buried by an overlying siliciclastic wedge that onlaps and thins onto the uplifted portion of the platform. This unconformity surface marks the upper extent of the Shu'aiba-Hawar (Biyadh) tectono-stratigraphic sequence.

The Barremian-Lower Aptian Qishn Formation (Al-Huqf Area, Oman): An outcrop analogue for the Kharaib and Shu'aiba reservoirs

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Limestones of the middle Cretaceous Qishn Formation are exposed in the Al-Huqf Area of Oman. These carbonates preserved reservoir properties due to shallow burial and an arid post-exhumation climate. This characteristic makes the Qishn Formation an excellent outcrop analogue for the Upper Kharaib and Lower Shu'aiba oil reservoirs in the Interior Oman basins. The Qishn Formation is middle Barremian to mid-Early Aptian, the Hawar Member (equivalent) is earliest Aptian in age. The paleo-environments range from the tidal mudflat to the argillaceous platform setting (outer ramp). In terms of sequence stratigraphy, four large-scale transgressive-regressive cycles of Cretaceous age (Jurf and Qishn formations) were distinguished.

Sequence I, termed Jurf Formation, is the equivalent of the Lekhwair, the Lower Kharaib and possibly older Cretaceous units. Sequence II, forming the base of the overlying Qishn Formation represents the equivalent of the Upper Kharaib. Portions of Sequence III form the Hawar Member, and Sequence IV is the equivalent of the Lower Shu'aiba Formation. At least two lower orders of cycles are superimposed on these four sequences. Total porosity with a mean of 19.3% (standard deviation = 8.74%) and permeability with a mean of 6.36 mD (standard deviation = 6.57 mD) characterize the Qishn Formation limestones. The lateral variability (greater than 100 m) of porosity and permeability values within specific intervals is substantial and matches or even exceeds stratigraphic variability. Spectral gamma-ray logs from the Qishn limestones recorded in the outcrops are dominated by the Uranium (U) spectrum and to a lesser degree by the Thorium (Th) spectrum.

The Qishn carbonates in the Al-Huqf outcrops are extensively fractured. The studied outcrops display very widespread systematic jointing with dominant NW-SE to WNW-ESE trends. A second, subordinate system resulted in a potentially highly interconnected network. Joints are strictly confined to specific beds or groups of beds and have regular spacing of between 6 and 18 cm. Joints are related to the regional stress fields and did not show significant changes (in density or direction) in the vicinity of folds or faults. Faults are typically organized in corridors consisting of up to several-meter-wide zones with swarms of discrete fault planes. A characteristic feature of both the Qishn and the Lower Shu'aiba formations is the organization in rudist-dominated facies: Lithocodium-Bacinella dominated and Orbitolina dominated facies. A platform-wide correlation of key surfaces based on Sr-isotope stratigraphy is presently under way.

Facies architecture of Shu'aiba Carbonate Reservoirs: Global signal and composite sequence framework

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The Barremian-Aptian (Cretaceous) Shu'aiba Formation is an important producing interval in Oman, the United Arab Emirates (UAE), Saudi Arabia, and Qatar, hosting both vuggy and microporous reservoirs with a common Albian Nahr Umr Shale seal. Integration of detailed core-based facies descriptions, wireline logs, and to a lesser extent seismic data, from 12 reservoirs throughout the region has allowed the recognition of a range of heterogeneity styles distributed in a predictable sequence framework.

A global transgression coincident with OAE 1a and marking the start of a latest Barremian-Aptian third-order composite sequence initiated a three-part history of transgressive, aggradational, and forced-regressive high-frequency sequences. Phase 1 was deposition of a transgressive-dominated shelf with moderate to high-energy *Lithocodium*-rich cycles and local microbial buildups forming two widely recognizable sequences of the transgressive sequence set (TSS). Limited production from these sequences occurs in Lekhwair field in Oman, Idd El Shargi South Dome in Qatar, and lower intervals in Bu Hasa, UAE. This TSS is characterized by layer-cake, pay-zone architecture, locally made complicated by fracture-controlled heterogeneities.

Phase 2, the maximum flooding surface (MFS) or the aggradational phase (early highstand sequence set or HSS) included the hallmark phase of rudist-shoal development for the Shu'aiba Formation. Discontinuous nucleation of rudist-algal buildups with a colonization stage of glossomyophorids and culmination stage of caprinids formed significant relief and lateral heterogeneity, including prominent inter-mound channel systems and inter-mound mud-rich dense zones. Localization of these aggradational rudist buildups was controlled by thickening of phase 1 sequences, which typically double in thickness in a km-wide belt that defines the precursor rim of the Bab Basin.

Phase 3, a progressively more clastic-rich forced-regressive set of sequences (FRSS) with mixed rudist-microbial buildups and biostromes intercalated with calcareous shales, formed the final phase of infill of the intra-shelf basin. Strong impedance contrasts between shales and *Orbitolina*-algal carbonates allows clear imaging of this final phase of infill, setting up opportunities for smaller stratigraphic trap plays. Exposure of subaerially exposed HSS during FRSS deposition over the crest of buildups and on emergent salt structures led to the dissolution and reservoir quality enhancement locally.

Comparative architecture of the Early-Late Aptian carbonate shelf of the Gulf of Mexico illustrates many parallels to the Shu'aiba composite sequence architecture and supports the timing associated with the demise of older Barremian (Kharaib-Thamama) platforms during OAE 1a.

Reservoir architecture of a prograding intra-shelf basin margin: Case study from the Shu'aiba Formation, United Arab Emirates

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The facies architecture and depositional history of the Shu'aiba Formation (Lower Cretaceous) basin margin progradation has been interpreted from over 770 well penetrations, 3-D seismic and historical production data in a field with large structural closure (700 sq km). The initial Shu'aiba transgression established an algal-dominated shallow-water platform, with later differentiation of the margin deposits from a deeper-water basin to the north (Bab Basin). This continued into the early highstand

phase with the development of a rudist buildup margin flanked by the platform interior deposits to the south. The late highstand witnessed rapid progradation of detached clinoform sequences into the Bab Basin.

Detailed mapping of late highstand third-order sequences has been carried out using seismic attributes, core and wireline log data. Two third-order late highstand sequences (Ap4, Ap5) will be described in detail, showing: (1) basal sequence boundary with marked downward shift of onlap; (2) thick transgressive systems tract (TST) deposits comprising carbonate mudstones developed on a low-relief slope (less than one degree); (2) early highstand systems tract (HST) progradation of laterally continuous 'shingled' clinoforms with moderate dips and mixed facies assemblages (grainstones, packstones and some mudstone alternations); and (3) late HST clinoforms with steeper dips (up to 3 degrees), and well-segregated, alternating grainstones and wackestone/mudstones.

The rate of progradation varied along the 25-km-segment of the margin, with more rapid rates and lower angle clinoforms in the southeast, possibly linked to the underlying structural controls. The late highstand margin of the third-order sequences showed irregularities, possibly linked to larger amplitude high-frequency sea-level falls. The models developed from this analysis provided critical insights into the distribution of the main reservoir facies and flow barriers at several orders of magnitude, from individual flow units to field-wide barriers/baffles.

4C seismic anisotropy integration for fracture characterization of carbonate reservoirs: Application in Idd El Shargi field, offshore Qatar

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Considering and mapping fractures are essential in developing oil fields with highly fractured carbonate reservoirs, especially when they have high porosity but very low matrix permeability. It is important to establish and locate the local intensity and orientation of the open-fracture corridors and fracture zones, because these provide the main conduits of fluid flow. The traditional 3-D seismic attributes, either horizon or volume based, provide some information about faults and fractures but this is far from adequate. A predominant near-vertical, open-fracture system causes anisotropy in the reservoir rock and is reflected in the seismic data as a measurable anomaly in azimuthal variation of amplitude/AVO, velocity/traveltime, and shear-wave splitting. All this information, usually called azimuthal anisotropy, can be extracted only from wide-azimuth, multi-component seismic data. Recently, Occidental Petroleum of Qatar, who operates under a Development Production Sharing Agreement (DPSA) from Qatar Petroleum, acquired over Idd El Shargi field one of the largest wide-azimuth 3D-4C surveys in the Gulf region. In this paper, we discuss the integration of seismic-anisotropy attributes with borehole image-log information to map the fracture intensity and orientation in carbonate reservoirs. The results have been instrumental in day-to-day drilling operations and were crucial data in reservoir fracture characterization and Discrete Fracture Network (DFN) reservoir model building.

Stratigraphy and depositional history of the Shu'aiba Formation in the southern Gulf region: A new regional view

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The regional integration of well data, seismic observations and published information from the southern part of the Arabian Peninsula has led to a breakthrough in understanding of the stratigraphy and depositional history of the Shu'aiba Formation and in extracting implications regarding hydrocarbon prospectivity. A subdivision of the Shu'aiba Formation into three major systems tracts is proposed: (1) a transgressive systems tract (TST), distributed more or less equally over the entire Shu'aiba province; (2) a highstand systems tract (HST), characterized by the development of the Bab Basin and a well-marked differentiation between basin and margins; and (3) a falling systems tract (FST) during which new carbonate facies prograded into the Bab Basin. On the basis of this subdivision, we propose a new, unified stratigraphic nomenclature for the Shu'aiba Formation.

Depositional facies types and spatial organization of the three major systems tracts are markedly different. Monotonous, widespread carbonate facies dominated the TST. During the early HST, organic-rich fine carbonates accumulated in the Bab Basin while rudist-rich facies lined and vertically enhanced the southern and western basin margin or developed as relatively large isolated platforms

on the eastern slope of the Bab Basin. During the late HST and following FST, new platforms prograded into the Bab Basin in a series of sub-linear, regular clinoforms that grew either parallel to the pre-existing southern and western margins of the Bab Basin or in a series of concentric rings, away from pre-existing isolated platforms. Progradation of this latter Upper Shu'aiba platform may have been controlled more by the large proportion of clay transported into the Bab Basin and by current patterns in the Bab Basin rather than by an active "carbonate factory".

Extracting the detailed sequence stratigraphy of the clinoforms and understanding reservoir quality, the presence of intra-formational seals and trap configuration has allowed us to identify and predict areas of higher hydrocarbon prospectivity in the southern part of the Arabian Peninsula.

Upper Shu'aiba Formation paleoecology and mechanisms of clinoform progradation

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Two major elements dominated and influenced the depositional environments and facies of Upper Shu'aiba deposits. The first was the Bab Basin, which was a relatively isolated sea, with a narrow connection to the Neo-Tethys Ocean to the east. The second element involved rivers, probably flowing from the Al-Huqf High and the Arabian Shield, which discharged large volumes of fine sediments, mainly clay particles, into the Bab Basin. Water circulation in the Bab Basin was controlled by dominant winds, probably from the northeast. The abundant clay particles pouring into the Bab Basin from estuaries were distributed along the entire coastline by longshore currents and tides. The waters of the "Bab Sea" were most likely turbid and the coastline muddy and swampy. In spite of those harsh environmental conditions, carbonate-producing organisms managed to colonize the shallow waters along the shoreline of the Bab Basin.

The most striking – and surprising – observation is the extremely regular and seaward progression of Upper Shu'aiba clinoforms, sub-linear along the southern margin and concentric around the eastern isolated platforms, resulting in a series of almost perfectly parallel clinoforms that persistently prograded into the Bab Basin over several tens of kilometers. There are two alternative mechanisms that would have sustained the platform and driven the progradation so uniformly.

The first was a continuous "carbonate factory" dominated by foraminifera, algae and mollusks, including rudists, which could have sustained a regular and continuous progradation. At any given time, the active carbonate system at the margin of the clinoforms provided a consistent and laterally continuous line source for the sediments, which would have prograded at the same rate along the entire margin. The second alternative mechanism could have been the transport and deposition of clay particles that may have been responsible for the Upper Shu'aiba clinoforms, rather than an active "carbonate factory". The regular input, distribution and deposition of abundant terrigenous clay particles in the "Bab Sea" could have produced a succession of parallel coastal barriers, capped by carbonate-rich layers formed *in-situ*.

In both models, the relentless and consistent production and deposition of sediments, by and large equal along the entire length of the platform, created a shallow-marine environment where a sub-continuous sheet of Upper Shu'aiba carbonates could be deposited as topsets over the clinoform series. This sheet of carbonates now forms the main reservoir of the Upper Shu'aiba clinoforms.

Significance of microbial-foraminiferal episodes in the Lower Shu'aiba Formation of Oman

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The Aptian Shu'aiba Formation is amongst the most important reservoir units in the Middle East. In order to better understand and predict the distribution of the main Shu'aiba reservoir property variations and flow-unit geometries in time and space, several sequence-stratigraphic interpretations have been proposed over the years. In the Lower Shu'aiba ramp environments of northern Central Oman that extend to the northwest of the Al-Huqf-Haushi area, intervals dominated by microbial-foraminiferal consortia (*Lithocodium/Bacinella*) play an important role. Carbon-isotope stratigraphy has established a first-order regional correlation framework (Vahrenkamp, 1996 and unpublished reports). Yet, independent high-resolution biostratigraphic data and/or Sr-isotope stratigraphy documenting the isochronous or diachronous nature of observed facies boundaries and/or possible sequence stratigraphic surfaces are lacking.

From the Qishn Formation (Kharaib/Lower Shu'aiba equivalent) outcrops in the Al-Huqf-

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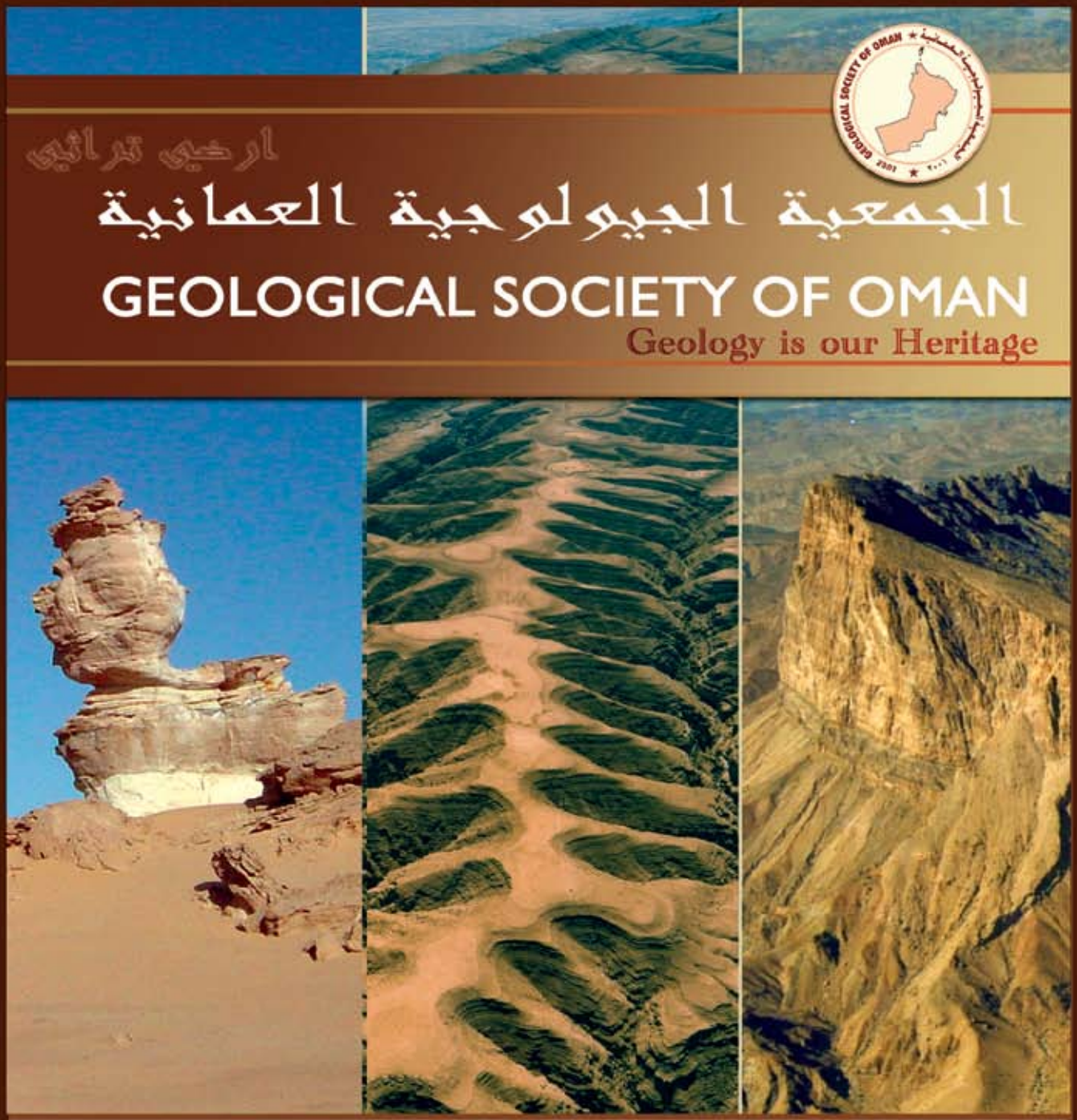

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Haushi area, Immenhauser et al. (2005) documented two stratigraphic intervals containing meter-scale *Lithocodium/Bacinella* buildups. *Lithocodium/Bacinella* facies alternates with stratigraphic intervals dominated by rudist bivalves. Judging from high-resolution chemostratigraphy and biostratigraphic evidence, these algal-foraminiferal-microbial episodes represent short-lived (approximately 150,000 years) occurrences of an out-of-balance facies that might represent the shoal-water equivalent of the oceanic anoxic event 1a (OAE 1a) black-shales.

Detailed logging of nine cored wells in Oman showed that the two *Lithocodium/Bacinella* intervals can possibly be traced downramp into the intra-shelf environment. Compared to the shoal-water, meter-scale buildups of the Al-Huqf-Haushi, *Lithocodium/Bacinella* intervals in more distal wells are less well-defined and their stratal architecture is more complex. The exact geometries of carbonate bodies, however, are difficult to pinpoint from subcrop data (1-D core analysis).

The stratigraphic significance of *Lithocodium/Bacinella* intervals is discussed on the basis of a multi-disciplinary approach including high-resolution sequence-stratigraphy, carbon- and oxygen-isotope data, and Sr-isotope stratigraphy. The preliminary results presented here lead to a more detailed understanding of the stratigraphic evolution of the Lower Shu'aiba ramp system. This is of direct significance for hydrocarbon exploration and production as vertically stacked facies units directly translate into regionally correlatable flow units.

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The development of an integrated reservoir model for an Upper Shu'aiba clinoform reservoir in northern Oman

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The Upper Shu'aiba carbonate reservoirs are associated with clinoforms deposited as an infill to the Bab Basin during the Cretaceous. The clinoform trends, each of which is around 800–1,000 m wide and over 10 km long, can be imaged on seismic amplitude extractions due to tuning effects at the up-dip pinch-out. The reservoirs lie in thin (generally less than 5 m thick) shoal facies located on the top of clinoforms. The shoal facies form producible reservoir geo-bodies with permeabilities of 10–100 mD within generally low-permeability (1–5 mD) non-reservoir facies. In a dip-direction the seal is formed by reservoir-quality changes on transitioning into deeper water facies, or lagoonal deposits across the clinoform; in a strike-direction by normal faulting and vertically by overlying Nahr Umr shales, or shales of the overlying clinoform.

The field has been appraised with off-structure vertical pilot holes and horizontal sidetracks that targeted the shoal facies. Each of the wells has resulted in a revision of the reservoir model and the realization that the reservoir was considerably more complex than initially modeled. The shape (thickness and width) of the clinoforms together with lateral variations in reservoir quality and rock types are not, as yet, fully understood.

The limited quantity of well data has resulted in a combination of data types being used to build truly integrated field-scale reservoir models. Seismic amplitude extractions were used as trend data to constrain the broad-scale shape of the geo-bodies. Directional density and resistivity data were used as a constraint on reservoir thickness, and well test and production data were used to constrain the lateral extent of the producible facies. The reservoir concepts from the more developed areas were also used to constrain the reservoir models for the less well-appraised areas.

This poster will chart the development of an integrated reservoir model for an upper Shu'aiba clinoform reservoir and its use in appraisal and development planning.

Sequence architecture of the Shu'aiba at Idd El Shargi, Offshore Qatar: Facies, unconformities, diagenesis, stacking patterns and paleogeographic elements observed in core

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The Idd El Shargi North Dome and South Dome fields are located in the Arabian Gulf approximately 90 km east of Doha, Qatar. Production is concentrated along the crest of two domal features

that were formed above deep infra-Cambrian salt structures. The producing reservoirs consist of faulted and fractured uppermost Jurassic through Lower Cretaceous sediments sourced from the underlying Jurassic Hanifa Formation. The data incorporated in this study included 16 slabbed cores (approximately 1,100 m), approximately 800 thin sections, routine and special core analysis, cuttings, scanning electron microscope studies, X-ray diffraction analysis, borehole image data, and seismic. Stratigraphic analysis also benefits from more than 350 Shu'aiba laterals as well as numerous throughgoing, Arab reservoir penetrations. Hard data (e.g. core and well logs) encompass an area of approximately100 sq km.

The Shu'aiba Formation (approximately 95-m-thick) consists of a succession of microporous muds and thin, hemipelagic shales that were deposited below fair-weather wave-base in an intra-shelf, basinal setting. Moderate shallowing during the latest depositional phase of the Shu'aiba Formation is indicated by localized shoals of dasycladacean-rich, grain-dominated rocks and stromatoporoid bioherms deposited along the western margin of Idd El Shargi North Dome. Depositional facies patterns were influenced by active salt movement, sea level, and prevailing, regional wind direction. Stacking patterns observed in core reflect recent joint regional studies undertaken by the authors that indicate the Hawar shale recorded a third-order, base-level turn-around from the progradationally-stacked Thamama-Kharaib system. The sequence is defined as follows: (1) retrogradationally-stacked, Hawar and Shu'aiba D; (2) aggradationally-stacked, Shu'aiba C (maximum flooding) and B; (3) progradationally-stacked, Shu'aiba A and Bab Member. The Shu'aiba A and Bab recorded highstand deposition across a structurally-active Idd El Shargi North Dome. During latest Aptian, the Shu'aiba Formation was exposed at Idd El Shargi North Dome concurrent with minimal accommodation and a major facies tract offset recorded by the Bab Member. Recent 4C, multi-azimuth, seismic mapping and attribute analysis verified internal architecture and facies differentiation across both domal structures.

A recurring argument is sure to reflect the conspicuous lack of high-energy sedimentary structures below a subaerial unconformity in the uppermost Shu'aiba Formation. The following explanations will be examined: (1) nondeposition of current-stratified, nearshore sediments, (2) erosion of relatively thin, current-stratified, nearshore sediments, (3) rapid basinward shift of facies tracts (i.e. Bab Member as a lowstand systems tract, or a down-shifted, offlap wedge recording conditions associated with a late highstand systems tract, or (4) sampling bias related to coring program. Unraveling the timing and duration of this unconformity is important for understanding the distribution of Shu'aiba "sweet spots" related to crestally-focused, meteoric diagenesis. Locating Bab Member onlap is critical for unraveling the various diagenetic processes affecting reservoir quality. Parallel considerations are whether meteoric diagenesis is of late Shu'aiba/Bab, or of Nahr Umr age and whether it records a composite-scale sequence boundary.

Orbitolinid biostratigraphic zonation of Barremian-Aptian carbonate platforms of the southern Arabian Plate

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The biostratigraphic zonation of the Barremian/Aptian shallow-water carbonate systems has a low resolution due to the slow evolutionary rate of most species living in these environments. A notable exception is the orbitolinid foraminifers that show relatively rapid evolutionary trends mainly in the embryonic structures, and can thus be used for high-resolution dating of these environments. In this presentation an orbitolinid biostratigraphic zonation scheme is presented for the southern and eastern part of the Arabian Plate in the context of a sequence stratigraphic framework.

Detailed work on orbitolinid-rich successions has been carried out in Iran (Fars and Khuzestan provinces), offshore Abu Dhabi, Oman (northern Oman Mountains and Al-Huqf), Yemen and Somalia. A subdivision into several zones is proposed for the Barremian and Aptian stages. This subdivision was based on the evolutionary lineages *Montseciella* (= ex-*Dictyoconus*) *arabica – Rectodictyoconus giganteus, Eopalorbitolina – Palorbitolina* and *Praeorbitolina – Mesorbitolina*.

Examples show how these biostratigraphic timelines provide fundamental constraints for regional sequence stratigraphic correlations. For instance, the regional appearance of the short range, late Barremian species *Montseciella arabica* can be used to correlate a third-order sequence in low-angle, carbonate ramp systems across Somalia, Oman (Upper Kharaib), United Arab Emirates (Thamama B), Qatar (Upper Kharaib) and Iran (Khalij Member).

During the Aptian, when the stratigraphic architecture was much more complicated due to the presence of an intra-shelf basin, surrounded by aggrading and prograding carbonate platforms of the Shu'aiba Formation, Palorbitolina/Praeorbitolina biozonation is one of the very few tools available to constrain the depositional geometries, and thus the stratigraphic correlations.

Cretaceous carbonate platforms and rudist bivalves: Rates of evolution and timing of events correlated by strontium-isotope stratigraphy

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The biostratigraphy of Cretaceous carbonate platforms can be challenging, particularly in restricted inner platform environments. Consequently, correlation with data from the Boreal realm and the deep-sea, and thus the evaluation of the history of many carbonate platforms in relation to global environmental change, has been difficult. Rudist bivalves evolved rapidly into a large variety of shell structures and morphologies, but a precise zonation based on these abundant and characteristic fossils has not yet been developed. Examples will be presented which demonstrate the approach of screening of samples for the original seawater Sr-isotope composition. Applications of Sr-isotope stratigraphy for correlation both on the local, sequence-stratigraphic scale, and on a global scale with respect to climate change and eustatic sea-level change, will be discussed.

Pristine biological calcite of rudist shells was the preferred material analyzed. Numerical ages for more than 60 Tethyan localities of rudist bivalves from the Caribbean to the Middle East have been derived from Sr-isotope stratigraphy. The results have several implications for the evolution of both, rudist bivalves and carbonate platforms. The age and ranges of several taxa and lineages are significantly revised. Heterochronic evolution was demonstrated for several lineages and tied to chronostratigraphy. In the Upper Cretaceous, two important extinction events occurred: (1) at the Santonian-Campanian boundary, and (2) in the late Campanian. Correlation with Boreal events based on Sr-isotope stratigraphy indicates that these two extinction events correspond to sea-level lowstands, carbon-isotope excursions, and in the case of the late Campanian event, to a significant climatic cooling both in equatorial and higher latitudes.

Ongoing work aims at an improved calibration of the Sr-isotope curve for the Campanian based on belemnites, on the pattern of demise of the characteristic rudist-dominated ecosystems at the end of the Cretaceous, and on the chronostratigraphy of Barremian-Albian carbonate platforms of the United Arab Emirates.

Carbon-isotope signatures of the Aptian Shu'aiba Formation

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A well-established correlation exists between carbon isotope profiles from the Aptian Shu'aiba Formation in the Arabian Gulf region and isotope variations of contemporaneous seawater. Anchored by biostratigrahy, Strontium-isotope measurements, gamma ray-logs and a regional correlation framework, a reference curve has been established for the Aptian in the Gulf region, which offers excellent time resolution and definition. More than 3,500 data points from some 70 locations were available in Oman and the United Arab Emirates to use this reference curve for refining stratigraphic correlations.

Even though an increase in carbon values was observed in parts of the curve between the Shu'aiba Formation shallow-water carbonates and pelagic reference curves, the character of the signature in the measured sections seemed little changed from its original marine signature. Preservation was despite long-term subaerial exposure prior to burial and extensive early and/or late diagenesis. This lack of diagenetic alteration has important implications for primary mineralogy and climate during Shu'aiba Formation times.

Increased stratigraphic resolution helped to constrain the time intervals during which individual sections accumulated. Correlation of time-equivalent sections, both on a regional and field scale, established a stratigraphic architecture of the Shu'aiba Formation, which is often significantly more complex than suggested by traditional lithostratigraphic or even more recent sequence stratigraphic correlations. For example, complete infill of accommodation space during the Early Aptian by rudist buildups at Al Huwaisah field caused multidirectional progradation into adjacent incompletely filled areas (e.g. northwestwards towards Yibal field and the shallow-shelf Bab Basin; southeastwardly towards a broad interior platform lagoon between Al Huwaisah and Saih Rawl fields). The interior platform lagoon, which contains the areas of both Burhaan and Musallim fields, was finally filled during another depositional sequence in the

latest Early Aptian.

Without control from chemo-, bio- and/or seismic stratigraphy, it is difficult to define an order of depositional sequences or correlate over large distances using stacking patterns in cores or gamma-ray logs.

Aptian organic-rich intra-shelf basin creation in the Dezful Embayment (Kazhdumi and Dariyan formations, southwest Iran)

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In the Zagros Mountains of southwest Iran, a well-developed mid-Cretaceous succession is exposed in a number of giant anticlinal structures. These outcrops vividly document the evolution from a regional shallow-water carbonate platform (Hauterivian to Barremian) to the initiation and development of an intra-shelf basin (Aptian). A high-resolution time framework, based on the integration of biostratigraphic, chemostratigraphic and sequence stratigraphic data, was developed to characterize the step-by-step geometrical and ecological evolution of this system.

The Hauterivian/Barremian shallow-water carbonate platform was a very flat, layer-cake organized system, with meter- to decameter-scale cycles that can be traced over several hundreds of kilometers. Sedimentation was mixed, with the influx of clays shed from the Arabian Shield. In Early Aptian times (Deshayesi ammonite zone) a reorganization took place, initiating an intra-shelf basin in the Dezful Embayment, which led to very distinct lateral facies changes. The shallow-water deposits contain rudists in the lower part, locally overlain by thick packages of Orbitolina-dominated facies. In the organic-rich intra-shelf basin, a pelagic fauna was found of ammonites, pelagic foraminifera and Radiolaria. Around the margin, prograding packages of Orbitolina-dominated facies interfingered with the pelagic facies.

The creation of this Early Aptian intra-shelf basin was not only time-equivalent with the formation of other intra-shelf basins on the Arabian Plate (Bab Basin), but probably also with similar sedimentation patterns in Mexico and Texas.

Sequence stratigraphy and reservoir architecture of the Shu'aiba carbonate reservoir in the Al Shaheen field (Block 5, offshore Qatar)

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The Shu'aiba carbonate reservoir in the Al Shaheen field (Block 5, offshore Qatar; c. 2,000 sq km) is characterized by fast lateral and vertical changes in the depositional facies, which are a challenge for reservoir modeling and drilling. A high-resolution sequence stratigraphic study has been undertaken to construct a predictive geological model for this complex depositional system. The dataset consists of wells, core material, and seismic, and has been complimented with biostratigraphic (foraminifera, nannos, palynology), chemostratigraphic (C and O isotopes) and petrographic analyses (sedimentary facies and porosity). The studied interval covers both the Hawar Member and the Shu'aiba Formation, and varies in thickness from 280 to 320 ft. The overall setting of the Shu'aiba Formation in Block 5 was a platform-to-margin transition, with the platform top setting in the north, and a clear progradational trend towards the south. This placed the study area along the northwestern margin of the Aptian intra-shelf Bab Basin.

Different orders of sequences were distinguished. The large-scale sequence is bounded at the base by the Kharaib B/Hawar contact, and at the top by Shu'aiba/Nahr Umr contact. The upper boundary shows clear evidence for exposure (incision, increasing stratigraphic hiatus towards the north). Medium-scale sequences show a stacking pattern in a lower, transgressive, retrogradational to aggradational part, and a regressive, strongly progradational part. During the early transgression sedimentation was laterally very continuous, with the deposition of the clay-rich Hawar facies. During the late transgression the proximal northern part aggraded faster with widespread occurrence of microbial (Lithocodium/Bacinella) boundstones, while condensation occured in the basinal south-

ern part. This platform-to-basin topography was filled-in during the regression, when the platform prograded over a distance of about 40 km in a number of medium-scale sequences. These created considerable heterogeneity, both by their shape (low-angle clinoforms), and internal lithological variations. Dating of the system showed that aggradation took place during the Early Aptian, and most of the progradation during the early part of the Late Aptian (*Mesorbitolina parva*).

Comparison of this model with time-equivalent Shu'aiba deposits along the Bab Basin and outcrops in Oman showed a great similarity in the overall stratigraphic architecture.

Integrated bio- and chemostratigraphy of the Shu'aiba equivalent Aptian-Albian formations in southwest Iran: Implications at the scale of the southern Tethys margin

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During the Aptian-Albian times the eastern part of the Arabian Plate (southwest Iran) was characterized by large intra-shelf basins surrounded by shallow-water platforms. In order to unravel this complex architecture, a detailed biostratigraphic and chemostratigraphic analysis has been carried out. Excellent ammonite biostratigraphy was used to estimate variations in sedimentation rate, and demonstrate the effects this had on the expression of the C stable isotope curve. Along a NW-oriented transect seven sections were analyzed for standard biostratigraphy (ammonites, planktonic foraminifera, orbitolinids), carbon-isotope stratigraphy (13Ccarb), and sequence stratigraphy. The transect covers the Fars Platform in the southeast, the intra-shelf Kazhdumi Basin in the Khuzestan area, and the Lurestan Basin in the northwest, which was connected to the Neo-Tethys Ocean.

The combined biostratigraphic and chemostratigraphic analyses showed significant differences in sedimentation rates, and thus the shapes of the C isotope curves, between the different main areas. In the dominantly pelagic deposits of the Lurestan Basin ammonites and pelagic foraminifera provided a consistent dating. A comparison of the 13Ccarb curve to the recently published Aptian-Albian curves along the northern Tethys margin did indeed show a strong resemblance, with as a common characteristic a thin lower Albian interval.

In the shallow-water carbonate platform settings of the Fars Province, biostratigraphic resolution was relatively low, except for intervals where orbitolinids were abundant. The combined carbon-isotope stratigraphy and orbitolinid biostratigraphy revealed platform development during the Early Aptian and non-deposition during the Late Aptian and Early Albian. A pattern that compared well to other Tethyan Aptian platforms.

The intra-shelf basin, in Khuzestan, was very rich in ammonites, resulting in a time-resolution at the subzone level. Thus the initiation of this intra-shelf basin has been dated as earliest Aptian, an age comparable to the adjacent Bab intra-shelf basin. A particularity of the 13Ccarb curve was the very heavy values observed in a well-dated and expanded lower Albian interval that differs from the „reference" curves of the northern Tethys margin. It was however similar to other published curves that show such heavy early Albian values in similar depositional settings.

Our biostratigraphically well-constrained regional correlation demonstrated that reference curves needed to be established for different environments, since the shape of the carbon isotope curves strongly depends on the variations in sedimentation rate and geometry of the depositional system.

Correlation of rock properties and facies in the Lower Shu'aiba Formation of northern Oman to model data poor fields

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When building static models for fields with limited well data, the use of analogue data can help

to constrain property modeling and uncertainty ranges. Several Lower Shu'aiba Formation fields in northern Oman with good well coverage were used as analogues to model two nearby fields with poor well coverage. These analogue fields are located within a 50 km radius, roughly along strike of the paleo-Shu'aiba basin and in a similar stratigraphic and tectonic setting.

Correlations between the modelled fields and the analogue fields were set within a regional sequence-stratigraphic framework and were based on gamma ray and porosity logs, Carbon- and Strontium-isotope curves, as well as facies successions. This ensured a better understanding of the three-dimensional property distribution, as depositional facies and diagenetic overprint are genetically linked within this framework.

Systems-tract thicknesses and vertical facies successions followed the predicted trends, thus making it possible to confidently delineate 'rock types' with similar reservoir characteristics. Porosity histograms were established for each systems tract and porosity-permeability relationships were determined for each rock type from all the analogue fields in the area. The established relationships and data ranges help constrain the rock-property uncertainties in the two fields with poor well data considerably and ensure a common modeling approach for the genetically related fields.

Carbonate system response to long-term sea-level fall: Example from the Lower Cretaceous (Shu'aiba Formation) in Abu Dhabi, United Arab Emirates

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The Lower Aptian to Lower Albian section of onshore Abu Dhabi records a second-order accommodation cycle that is capped by a Supersequence Boundary. An integrated, three-dimensional dataset over a large field in Abu Dhabi provides a detailed record of sequence stratigraphic relationships across the Shu'aiba platform-to-basin transition (Yose et al., 2006). The present study documents the Supersequence Boundary expression from shelf-to-basin and the impact of long-term sea level fall on carbonate reservoir architecture and quality.

The exposure surface is time transgressive (c. 1 to 4 million years) and becomes younger basinward due to progressive downslope shifts of the carbonate system. Reservoir quality was enhanced in the facies underlying the unconformity due to selective grain dissolution (grainy facies) and microporosity development (muddy facies). Despite long-term subaerial exposure of the carbonate buildup, there is no evidence for karst development below the unconformity. Seismic data from the platform interior reveal a system of channels and sub-circular features that were originally interpreted as subaerial channels and karst (sink holes). However, calibration of these features with core and well data confirmed that the seismic features predate the unconformity and are syndepositional (tidal channels, ponds, and possibly some rudist patch reefs).

In this system, there is limited evidence for erosion of the shelf margin or for slope-margin collapse during sea-level fall. The low-angle (1–3 degrees) slopes flanking the buildup provided a large area for *in situ* carbonate production as sea level lowered. Accordingly, the slope and basin environments recorded progressive down-slope shifts of the "carbonate factory" that resulted in over 10 kilometers of progradation. The slope-restricted sequences are interpreted as the falling-stage systems tract (i.e. forced regression) of the second-order sequence and have a large influence on reservoir connectivity and quality. The lowstand of the next overlying second-order sequence is marked by an influx fine-grained siliciclastics that onlapped the slope-restricted carbonate sequences. In the subsequent transgression, fine-grained siliciclastics and carbonates (Nahr Umr Shale) were deposited above the Supersequence Boundary and formed a regional top seal for the Shu'aiba reservoir system.

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