## Use of surface analogue for 3-D geological modelling of the Arab D reservoirs - example from Jabaloyas outcrops (Eastern Spain)

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The Arab D Reservoir is one of the most important hydrocarbon reservoirs in the Middle East. Heterogeneity of this reservoir is mainly related to facies distribution and stratigraphic surfaces.

Outcrop analogue is now considered as an efficient tool for better understanding the sedimentary heterogeneity at reservoir scale. This poster illustrates how an Upper Kimmeridgian analogue exposed in northeast Spain has been used to characterise the internal heterogeneities of a low-angle carbonate ramp that includes the development of reef build-ups formed by colonial forms (corals, stromatoporoids), and microbial crusts with associated encrusting organisms. Results from this outcrop analogue have been applied for improving oil recovery from the Arab D Reservoir of a mature field in UAE.

The well-exposed outcrops around the Jabaloyas village (Eastern Spain) have been used for detailed facies and sequence-stratigraphic reconstructions within a 16–22 m thick series. These outcrops show strike and non-strike sections across a 12 sq km area (i.e. 4 x 3 km). Seventeen stratigraphic profiles were carried out to control vertical and lateral facies distribution. The facies follows an overall retrogradational-progradational trend with the development of low-energy, peloidal-skeletal wackestone-packstone in the middle part of the sequence. Different types of grain-supported facies (ooidal, peloidal, intraclastic, skeletal) are found both in high-energy mid-ramp domains and inner ramp areas. The studied series is bounded by discontinuities that are traceable across a total of 17.5 km linear distance and encompasses coral-microbial build-ups, 5 to 15 m high, developed in mid-ramp setting during the stages of maximum accommodation gain. A total of 274 reefs have been mapped across the different reconstructed 2-D transects. Most of them have pinnacle or conical geometry. Well-cemented discontinuity surfaces were used to identify four stages of sedimentary evolution, two of them including individual episode of reef growth. Some trends on the spatial density and on the fabric within each stage have been recorded.

The overall distribution of the main facies was included in a full-field model (20 x 20 m grid increment) while the geometry, size and distribution of the reefs were better adjusted in sector models (1 x 1 m). These models assess the distribution of reservoir bodies and their connectivity. They are now used as a template for diagenesis modelling and constitute the geological input for simulation models.

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## Burial dolomitization, late leaching and thermochemical sulphate-reduction diagenesis in Arab C and D reservoirs (Kingdom of Saudi Arabia): Impact on reservoir properties

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Diverse diagenetic processes have been proposed to explain the reservoir properties of the Arab C and D reservoirs in the Middle East: from early diagenesis (e.g. early cementation, dissolution and/or dolomitization) to burial and late burial diagenesis (e.g. compaction, cementation, burial dolomitization, leaching, hydrothermal/fault-related dolomitization). This contribution examines

the Arab C and D reservoirs from an onshore field in Saudi Arabia with specific focus on: (1) late diagenetic evolution; (2) timing of burial diagenesis with respect to charge; and (3) their impact on reservoir rock and fluid properties.

The Arab D Reservoir in the studied field is mainly formed by ooid grainstones corresponding to a carbonate shoal environment. The reservoir properties of the Arab D are mostly controlled by the interplay of: (1) porosity-destructing diagenetic processes (early and burial cementation, compaction and late burial cementation associated to themochemical sulphate reduction); (2) porosity preservation (interparticle porosity and intraparticle microporosity); and/or (3) the effect of porosity-enhancing diagenetic processes (dissolution of calcitic components and cements and/or dissolution of late anhydrite cements during late burial).

The Arab C Reservoir corresponds to the open-marine facies of salinity increase parasequences. The most prominent diagenetic process controlling Arab C Reservoir properties was burial dolomitization of: (1) skeletal-intraclast grainstones and rudstones; and (2) pervasively bioturbated peloidal grainstones. Lateral continuity of the Arab C Reservoir units mimics the original depositional architecture; however, leaching associated to dolomitization and/or leaching post-dating dolomitization, mostly improved rock properties in a pattern that appears to be strongly controlled by the early depositional and diagenetic products.

The products of thermochemical sulphate reduction have been observed in the Arab C and in Arab D reservoirs. Although volumetrically not very relevant, the impact in rock properties was locally significant, as newly formed cements have been observed to affect rock properties negatively (e.g. precipitation of dolomite, calcite and late anhydrite cements), or positively (e.g. dissolution of calcite and dolomite with localized increase of porosity and more general increase of permeability due to pore throat enlargement).

Geochemical information obtained in late cements include $\delta^{13}C$ and $\delta^{18}O$ of carbonates, $\delta^{34}S$ and $\delta^{18}O$ of sulphates, $^{87}Sr/^{86}Sr$ of carbonates, sulphates and fluorite and fluid-inclusion microthermometry and gas-composition analyses. This information allows a refined interpretation of the late diagenesis processes and understanding of their impact on the reservoir properties (increase, decrease and/or redistribution of porosity). The fluid evolution of the Arab C and D reservoirs during late diagenesis until present-day can be inferred from fluid inclusion information.

The integration of diagenetic and geochemical signatures with charge evaluation and structural information suggest the inflow of deep-seated fluids, coeval to charge, in both the Arab C and Arab D reservoirs. The temperature increase, driven by the inflow of deep-seated fluids, could have triggered thermochemical sulphate reduction in the reservoirs. In this scenario, lateral reservoir heterogeneity is expected to be associated to the location of deep-seated faults.

**Acknowledgements**

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## Subsurface Jurassic–Cretaceous dolomitization front mapping and characterization, onshore-offshore northeastern Saudi Arabia

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Massive dolomite has long been documented in the Upper Jurassic and Lower Cretaceous carbonates in the northern regions (onshore and offshore) of Saudi Arabia. These dolomite bodies are characterized by their stratigraphically discordant geometries. Recently more geologic and seismic data have been acquired. Accordingly, a study with the following aims has been undertaken:

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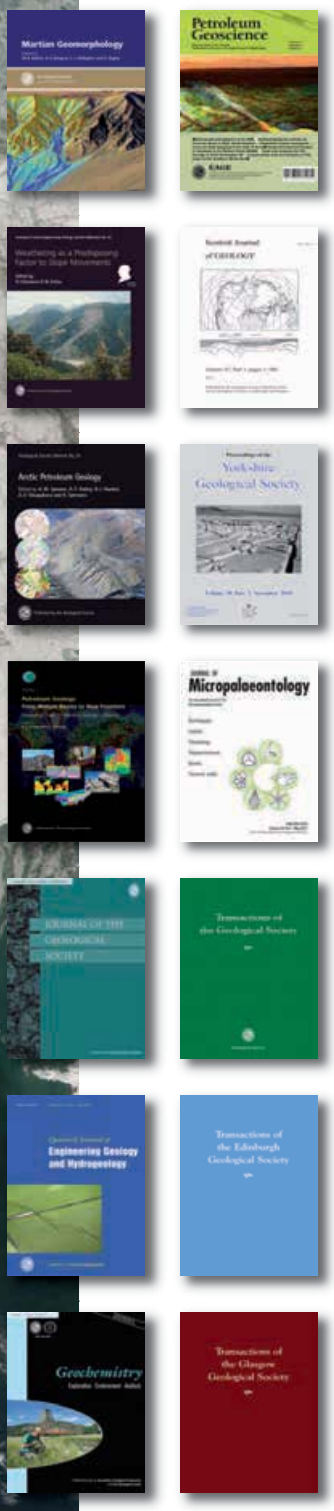


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(1) re-map the dolomite bodies and refine their spatial-temporal geometries;
(2) document diagenesis and reservoir qualities within dolomite bodies and across dolomitization front;
(3) define a dolomitization system that helps understand the mechanisms of dolomitization and associated diagenetic processes; and
(4) predict reservoir qualities within the dolomitization system. This study benefited from the integration of a variety of data such as core/cutting sedimentology, thin-section petrography, drilling attributes, well logs and seismic attributes. This integrated approach helped not only identify the geometries of dolomite bodies but also to depict their fractured nature.

Preliminary results revealed that the dolomitization system contains:

(1) massive dolomite bodies with a spectrum of dolomite textures, varying from very fine to macro-crystalline;
(2) a wide range of associated diagenetic processes, including precipitations of ferroan-nonferroan calcite, anhydrite, gypsum, fluorite, kaolinite, silicification (quartz/chert), dedolomitization, emplacement of pyrobitumen-hydrocarbon, and fracturing-leaching;
(3) dolomite bodies, which show chaotic seismic reflection characters, and exhibit *"tornado"* geometries when capped with anhydrite seals; and
(4) variations in reservoir qualities within dolomite bodies and across dolomitization fronts, which results in reservoir heterogeneities and the potential diagenetic-stratigraphic traps.

Two mechanisms have been proposed for onshore and offshore massive dolomitization in terms of their depositional and structural characteristics. This presentation offers our current understanding of the Upper Jurassic–Lower Cretaceous regional dolomitization system and diagenetic processes, and provides great insights for reservoir prediction and potential stratigraphic trap exploration opportunities.

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## Regional stratigraphic framework, depositional environments, and exploration concepts of the Upper Jurassic carbonates and evaporites, Saudi Arabia

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The Jurassic carbonates host significant oil reserves and produce from giant and super-giant oil fields. The Upper Jurassic (Oxfordian) Hanifa Formation and Middle Jurassic (Late Callovian) Tuwaiq Mountain Formation contain world-class hydrocarbon source rocks and carbonate reservoirs. The grainy carbonates of the Arab A, B, C, and D members are among the best Jurassic carbonates reservoirs. The Hith Formation evaporites (Tithonian) provide excellent regional seal of the exceptionally prolific Jurassic petroleum systems. Understanding the regional stratigraphic framework by integrating core, well-logs, and 2-D/3-D seismic interpretations is essential for unlocking the hydrocarbon exploration potential and new exploration opportunities.

The Hanifa reservoirs (skeletal/oolitic limestones and packstones) were deposited as prograding clinoforms during the highstand of the Hanifa third-order composite sequence along the margins of the Hanifa intra-shelf basin, which was inherited from the Tuwaiq Mountain intra-shelf basin. The Hanifa grainstone shoaling complexes shifted further basinward as a result of continuous carbonate growth and progradation, progressively infilling most of the accommodation space that was created after Bathonian time. The organic-rich mudstones of both the Tuwaiq Mountain and Hanifa formations were deposited in the intra-shelf basins of the Jurassic Arabian carbonate platform interior.

An Early Kimmeridgian base-level fall, as revealed from core and 3-D seismic chronostratigraphic analysis, terminated the Hanifa carbonate platform and resulted in substantial subaerial exposure

of previous grainstone shoaling complexes and proximal areas. A renewed regional transgression occurred post-Hanifa time, leading to deposition of the Jubaila Formation and infilling the remaining accommodation space. Widespread deposition of packstones and grainstones of the Arab D Member represents the maximum flooding and the beginning of the Late Kimmeridgian sea-level fall, which resulted in the deposition of Arab A, B, C members, and pervasive Hith anhydrite deposits across the region, marking the turning point from a predominantly carbonate factory to an overall evaporite factory.

Gross depositional environment maps of the Upper Jurassic formations have been reconstructed by integrating core/drill cutting sedimentology, well-log electrofacies, and seismic attributes. These maps depict evolving depositional environments that span the Hanifa intra-shelf basin, Arab Formation carbonate platform, and finally the Hith evaporite system. A variety of new exploration concepts have emerged through the building of a robust stratigraphic framework and reconstruction of gross depositional environments.

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## Re-evaluation of the Late Jurassic to Early Cretaceous stratigraphy of Abu Dhabi

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The Late Jurassic to Early Cretaceous sequences of the Arabian Platform form a key petroleum province with super-giant carbonate reservoirs. Despite this economic importance and an excellent database the stratigraphy still contains ambiguities with possible alternative interpretations of far-reaching implications.

A re-evaluation of seismic, well and outcrop data reveals in Abu Dhabi a prominent Upper Jurassic angular unconformity with a westward tilt of strata. The Late Jurassic tectonism at the eastern margin of the Arabian Plate caused significant erosion in southeast Abu Dhabi of the Oxfordian to Tithonian Tuwaiq Mountain, Hadriya, Hanifa, Jubaila formations and Arab D Member. This interpretation is in line with progressively older Jurassic subcrops below the unconformity eastward towards the Tethys margin and reported block faulting in Oman. Tilting, exposure and erosion towards the east created an intra-cratonic basin towards the west in western and central Abu Dhabi. Westward progradation of Upper Jurassic third-order cycles may indicate a long duration of tectonism. Periodic restriction during the Tithonian led to carbonate/evaporite cycles of the Arab C to A members onlapping onto the tilted substrata. Evaporitic conditions peaked with the deposition of the Hith anhydrite, which onlaps against a north-south trending central Abu Dhabi high associated with the tectonic tilt. The Hith anhydrite not only forms a regional seal but also contains potentially prospective carbonate stringers. The overall depositional grain is eastward onlap during transgressions and westwards progradation of grainy carbonates during highstands and forced regression. Evaporites formed and eventually amalgamated during forced regression and subsequent early transgression.

The Late Tithonian transgression lapped onto the central Abu Dhabi high both from the west (Manifa shoals) and the east (Mender glauconite). Eventually, open-marine shoals established over the NS-trending high in central Abu Dhabi and subsequently prograded eastward during the deposition of the Early Cretaceous Thamama Group. The switch from westward to eastward progradation is associated with platform margin collapse documented in Oman, and points towards a change in large-scale tectonic stress from compression to extension.

The recognition of the tectonic tilt, the angular unconformity, multiple source rock intervals in shallow and deeper platform settings and westward shoal progradation during the Late Jurassic opens the way for a better understanding of stratigraphy at the eastern Arabian Plate margin. This in turn may lead to new play concepts and renewed exploration activity.

## Callovian to Valanginian chemostratigraphy of the eastern Arabian Plate margin

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and Abdulla al Mansoori (ADCO)

Following the breakup of Gondwana the northeastern passive margin of the Arabian Plate entered during the Permian a period of long-term thermal subsidence that lasted until renewed tectonic activity in the Early Turonian. This resulted in the more-or-less continuous deposition of mainly carbonate shelf sediments with the section reaching a thickness of up to 4,000 m. A composite carbon-isotope profile for the Callovian to Cenomanian time period has been generated for the eastern Arabian Plate using more than 2,000 carbon-isotope data. The profile has some 1,800 m thickness, is anchored by biostratigraphy, Sr-isotope data and tightly sampled carbon-isotope profiles from various cross-correlated cored wells in the United Arab Emirates and Oman. Further time control is provided by correlation with published curves of carbon-isotope ratio variations through time mainly from the northern Tethys carbonate sequences. A large data set of strontium-isotope data provides absolute time control via correlation with well-dated curves of strontium-isotope ratio variations in seawater over time.

The Callovian to Valanginian interval covers some 900 m of section. The carbon-isotope signal contains two intervals with obvious overprinting by diagenesis based on $\delta^{13}C$ ratios < 0.0‰. The first is the major Late Tithonian unconformity separating the Sila Group from the Thamama Group. The second are the Mid- to Late Berriasian dolomitic sequences of the Habshan Formation. This overprinting occurs in several wells at the same intervals and is hence considered to reflect overprints caused by regional diagenetic events. However, the rest of the data fall in the range expected for carbonates derived from seawater and show no obvious signs of alteration of their carbon-isotopic composition by subsequent diagenesis. A comparison with published profiles of $\delta^{13}C$ ratios of seawater over time shows very good correspondence of trends. In particular, recognized are: (1) a significant positive carbon-isotope excursion associated with the Oxfordian Hanifa Formation; (2) a positive carbon-isotope excursion in the Lower Berriasian associated with the transgressive deposits of the lower part of the Habshan Formation; and (3) a positive carbon-isotope excursion during the Valanginian (Thamama units F, G and H), which likely correlates with the oceanic anoxic event OAE1.

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## Northern Rub' Al-Khali Upper Jurassic–Lower Cretaceous petroleum system

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The Jurassic–Lower Cretaceous petroleum system in the northern Rub' Al-Khali Basin contains some of the largest oil and gas accumulations of the Middle East. Carbon isotopes and biomarkers indicate that the main source of hydrocarbons originated from the Jurassic-aged Tuwaiq Mountain and Hanifa basinal source rocks. Other source rocks, despite being less significant and being often overlooked, have also contributed in considerable amounts to the charge and include the Jurassic Jubaila and the Lower Cretaceous Habshan, Thamama and lower Bab intervals. All these source rocks are marine carbonates and the kerogen type is mainly, but not exclusively, represented by the oil-prone, low-activation energy and sulphur-rich type IIS. We are presently reviewing the stratigraphic setting of the source rocks to better map-out their thickness distribution and initial source-rock properties.

The main reservoirs are the Lower Cretaceous Thamama and Shu'aiba formations and the Upper Jurassic Arab Formation. The main seals are the Hith anhydrite, the dense unit above the Thamama F reservoir and the Nahr Umr Formation.

Heat-flow analysis and thermal history derived from burial history and large-scale tectonic constraints indicate that most of the petroleum from the previously mentioned source rocks was generated/expelled during the Cenozoic whereas the main phase of structural development started earlier in the Turonian.

Migration to the reservoirs occurred both by vertical and lateral migration. Sets of reservoirs bounded by one of the main seals may show close to common free-water level (FWL). Besides top-seal capillary entry pressures, faults/fractures do also control vertical migration. The fault behavior is dependent on their respective orientation and the maximum horizontal stress rotation through geologic time. The lateral migration has also a major impact on the hydrocarbon distribution. It is linked to the development of the Oman foreland, which resulted in the eastward tilting of the structures, which in turn, induced substantial dismigration towards the west.

The major in-reservoir alteration is represented by Thermochemical Sulphate Reduction (TSR) in the Arab reservoirs, which controls the cracking of hydrocarbons and the generation of vast amounts of $H_2S$.

Whereas the main conventional hydrocarbon resources of the Upper Jurassic–Lower Cretaceous have been discovered in the large four-way closures, substantial additional resources are anticipated in more complex fault and stratigraphic trapping settings, as well as in production from unconventional hydrocarbon sources.

## A 3-D seismic chronostratigraphy and attribute assessment of Late Jurassic evaporite sequences at the Gotnia Basin margin, Saudi Arabia

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The Jurassic sequences on the Arabian Platform contain widespread carbonate reservoirs, source rocks and seals, which contribute to a world class petroleum system. Since the Triassic Period, the platform was subjected to alternating periods of transgression and regression and differentiation with intra-shelf basins. One key variation in sediment deposition was the formation of evaporite seal beds associated with these intra-shelf basins.

To elucidate the basin depositional history near the flank of the Gotnia Basin margin, a 3-D seismic chronostratigraphic technique and associated attribute assessment were adopted to assess the evaporite distribution during the Late Jurassic. Seismic chronostratigraphy cubes and Wheeler transform models of the chronostratigraphic horizons were generated and interactively assessed for both structural controls to deposition and assessment of transgression and regression, unconformity and hiatus events at the basin margin. The seismic chronostratigraphic model, which represents dense semi-automatically-generated horizons placed in chronostratigraphic order, was derived from mapping every sample in the seismic trace. This allowed the interactive assessment of the depositional history of the Late Jurassic basin margin in both time and space, and use of key horizon sets for further attribute assessment.

Use of the extracted 3-D seismic chronostratigraphic horizon sets tied to well log data (gamma-ray, density and sonic), increased the precision in the interpretation of the evaporites and specifically the lateral extent of at least two main salt beds. Using limited well data and key horizon picks in the Arab sequences, selected 3-D seismic volumetric attributes – based mainly on frequency decomposition – were generated and utilized for visualization of the salt. The techniques allowed for the definition of the salt beds and the extraction of attributes, from a red, green, blue color blend of three main frequencies. Geobody analysis was conducted on each salt-related voxel frequency attribute to further assess the bounding limits of each bed, and the discrimination from surrounding lithologies. Visualizing the individual frequencies showed an overlap of successive salt beds and their regression over time.

The results from the analyses revealed an active basin flank affected by localized structural growth and eustatic changes. Salt beds onlapped the flanks from the north and showed successive retreat during the later Jurassic in time, and towards the Gotnia Basin, spatially. The techniques applied in this study area proved beneficial in accurately defining the limits of the evaporite salt beds, and elucidating the basin history during the Late Jurassic. These findings proved the occurrence of distinct salt layers, each with varying vertical and lateral extents at the Gotnia Basin margin.

## Sequence-stratigraphic framework and depositional facies interpretations in Late Jurassic to Early Cretaceous section in Saudi Arabia/Kuwait Partitioned Zone (PZ)

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A preliminary sequence-stratigraphic framework for the Late Jurassic to Early Cretaceous section is interpreted using a regional 2-D seismic grid, four 3-D surveys and five deep wells. In local stratigraphy, the studied section covers the Middle Jurassic Dhruma, Sargelu and Najmah formations, the Upper Jurassic Gotnia and Hith formations, and the Lower Cretaceous Makhul, Ratawi Oolite and Ratawi Limestone formations. A total of eight sequences have been interpreted. After the detailed sequence interpretations, isopach maps of all the sequences are made.

Based on these isopach maps, the stratigraphic relationships observed on seismic and well data, the interpreted sequences could be grouped into Sargelu-Najmah transgressive/highstand composited sequences, Gotnia-Hith lowstand composite sequences, and Makhul-Ratawi transgressive-to-highstand composite sequences. The isopach map of the Sargelu-Najmah composite sequences showed that a local carbonate platform in the southwestern part of PZ area was built-up on a potentially low-relief high on a previous ramp setting. The platform kept up with the sea-level rises and eventually a high-relief platform was formed. The Gotnia-Hith composite sequences are mainly composed of salt and anhydrite, which filled the topographic lows and pinched out against the Sargelu-Najmah carbonate platform. A subsequent transgression and highstand during the Makhul-Ratawi depositional time further flattened the topography, and a ramp setting was formed again.

As a result of this study, depositional facies, the history, and reservoir distributions could be better interpreted with the calibration with wells. The results showed that most of the depositional facies distributions within this period were not affected by current local structures, consistent with the conclusions made by Kelsch et al. (2013) that the current structures hosting the major fields in the PZ area were actually generated by middle-late Cretaceous age tectonics.

### Reference

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