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Abstract

High porosity-high permeability stromatoporoid/coral facies are important components of the Late Jurassic carbonate reservoirs in the Middle East. This facies exhibits sub-seismic depositional heterogeneities that subsurface models often overlook due to the limited interwell resolution of subsurface data. Understanding the effect of this facies on the 3D distribution of static reservoir properties and uncertainty in volumetric calculations of hydrocarbons in-place will improve estimates of the ultimate recovery and hence reservoir development decisions. A 3D high-fidelity outcrop-based geocellular depositional model that honors the spatial and petrophysical heterogeneity of the stromatoporoid/coral facies was constructed based on the Hanifa reservoir outcrop analog in central Saudi Arabia. The model was constructed from a 1.2 km x 1 km drone photogrammetry survey, measured sections (total length 150m) and spectral gamma-ray data, >200 thin sections, a 50 m-long core, a 19 km-long network of 2D and 3D Ground Penetrating Radar, and 600 m-long 2D seismic profiles. The facies model was populated with porosity and permeability equivalent to subsurface reservoir facies and utilized as the baseline petrophysical model for the comparison study. A set of pseudo wells at ~1 km spacing were simulated from the model capturing the model's 1D facies stacking and properties around the wellbore. The pseudo wells were utilized to stochastically build facies and static reservoir models scenarios to replicate the baseline model from limited well data. The volumetric calculation of each realization is compared with the baseline to investigate the range of volumetric uncertainty that would be introduced by the lateral distribution of stromatoporoid/coral facies. Early results show that depending upon the modeling methodology, the volumetric discrepancy between stochastic simulations and the deterministic outcrop baseline model is ~10-15%. Using a high-fidelity outcrop-based reservoir model, we have demonstrated the strong influence of 3D depositional heterogeneity of the stromatoporoid/coral facies on the uncertainty associated with hydrocarbon in-place volumes. We conclude that a static reservoir model can be significantly improved by using data-driven geological models that reflect the 3D heterogeneity of depositional facies.

Introduction

Weber (1986) defines heterogeneity in the context of reservoir characterization as non-uniform variations of reservoir parameters in space. Relevant interwell depositional facies heterogeneity exists in typical carbonate reservoir sequences in 3D on a sub-seismic meter scale. This interwell heterogeneity is a critical geological factor behind properties (porosity, permeability, and hydrocarbon saturation) and fluid flow heterogeneities in subsurface reservoirs, potentially leading to sub-optimum ultimate recovery if left unaccounted. High porosity-high permeability stromatoporoid/coral facies are important components of many Late Jurassic supergiant carbonate reservoirs in the Middle East (Al-Khalifah and Makkawi 2002; Lindsay et al. 2006). This facies exhibits meter-scale sub-seismic depositional heterogeneities that subsurface models often overlook due to the limited interwell resolution of subsurface data. The integration of outcrop analog into reservoir models is commonly used to close this scale gap (Elzain et al. 2020; El-Sorogy et al. 2018). However, most Middle Eastern late Jurassic outcrop analog studies are typically done in a more traditional approach. The so-called “3D” outcrop-based depositional facies model in these studies mostly derived from interpolation of 1D measured sections of the outcrop face. This interpolation typically glossed over or overly simplified meter-scale lateral distributions of the stromatoporoid/coral facies. A proper 3D outcrop investigation is needed to decipher the lateral heterogeneity of this facies fully. Moreover, subsurface implications in volumetric calculations and static connectivity analysis of these heterogeneous depositional bodies are rarely discussed despite their importance.

The late Jurassic Hanifa formation is one of the most petroliferous conventional reservoirs in the Middle East and, in some respects, analogous to the Arab-D reservoir (Al-Khalifah and Makkawi 2002; Afifi 2004; Fallatah and Kerans 2018). The stromatoporoid/coral boundstone/floatstone facies partially characterizes the Hanifa reservoir in the subsurface, especially in Khurais, Berri, and Abqaiq fields in Saudi Arabia (Al-Khalifah and Makkawi 2002; Al-Mojel, Razin, and Dera 2020). The Hanifa formation outcropped in central Saudi Arabia is lithostratigraphically divided into two members; the lower Hawtah (H1) and the upper Ulayyah (H2) member (Vaslet et al. 1983; Al-Mojel, Razin, and Dera 2020). The upper part of the Ulayyah member outcropped in Wadi Birk (coordinate: 23.28124°; 46.64420°), Saudi Arabia, exposed rock analogous to the subsurface Hanifa reservoir and characterized by laterally heterogeneous stromatoporoid/coral boundstone/floatstone facies (Al-Mojel, Razin, and Dera 2020). Therefore, a 3D outcrop analogue studies in this area will provide significant insights into the architectural elements as well as vertical and lateral depositional heterogeneities in the subsurface reservoirs with similar facies association on an interwell scale.

This study aims to investigate the impact of stromatoporoid/coral facies heterogeneities on the 3D distribution of static reservoir properties, uncertainty in volumetric calculations of hydrocarbons in-place, and static reservoir connectivity. A 3D high-fidelity outcrop-based geocellular depositional model that honors the spatial and petrophysical heterogeneity of the stromatoporoid/coral facies was constructed based on the Hanifa reservoir outcrop analog in Wadi Birk, Saudi Arabia. The model was constructed from a 1.2 km x 1 km drone photogrammetry survey, measured sections and spectral gamma-ray data (total length of 150m), >200 thin sections, a 50 m-long core, a 19 km-long network of 2D and 3D Ground Penetrating Radar (GPR), as well as 600 m-long 2D seismic profiles. We utilized this comprehensive outcrop and “behind-the-outcrop” datasets to map the stromatoporoid/coral facies in three dimensions.

Geologic Settings

The Hanifa, Jubaila, Arab, and Hith formations are part of the Late Jurassic strata outcropped along the ~800 km-long north-south Tuwaiq Mountain escarpment in Central Saudi Arabia (Figure 1A, 1B). During Late Jurassic, the Arabian plate was located 10°-15° south of the equator in the western margin of Neotethys Ocean (Figure 1C) with an arid to semi-arid paleoclimate (Scotese 2003; Markello et al. 2008;

Thierry et al. 2000). Due to the combination between favored climate, relatively stable passive margin, and vast shallow-water epeiric sea, colossal (~1000s of km) shallow-water marine carbonate deposits were developed during this time (Al-Mojel, Razin, and Dera 2020). The Hanifa Formation is assigned to the Oxfordian-Early Kimmeridgian (Manivit, Le Nindre, and Vaslet 1990; Al-Mojel, Razin, and Dera 2020). The depositional settings and sequence stratigraphic model of the Hanifa formation is a subject of ongoing discussion. This study follows the sequence stratigraphic model of Al-Mojel, Razin, and Dera (2020), where the Hanifa formation is deposited on a flat-topped shelf inner-platform setting and divided into two third-order sequences: Hanifa Composite Sequence-1 (HCS1) and Hanifa Composite Sequence-2 (HCS2). The interval of interest in this study is the HCS2 which is equivalent to the upper part of the Ulayyah member (Figure 1D). This composite sequence is characterized by intercalation between grainstone and wackestone/packstone at the bottom and stromatoporoid/coral facies capped by oncolithic grainstone at the top. An extensive erosional iron-stained surface and abrupt facies changes from coral/stromatoporoid dominated facies found at the top of the Hanifa Formation to dark-colored quartz-rich grainstones found at the base of the Jubaila Formation marks the end of HCS2 (Powers et al. 1968; Al-Mojel, Razin, and Dera 2020).

Figure 1. (A) Satellite image of the Arabian Peninsula where blue-colored polygon east of the Arabian shield is the Jurassic outcrops along the Tuwaiq Mountain escarpment. The red-colored rectangle is the location of the study area. (B) The late Jurassic stratigraphic column in Central Saudi Arabia. The gray rectangle highlights this study's interval of interest (Al-Mojel, Razin, and Dera 2020). (C) Paleogeographic map of the Arabian Peninsula during Early Kimmeridgian (Fallatah and Kerans 2018; Scotese 2003; Markello et al. 2008). The study area is located in the middle part of the platform with a dominant northwestern paleo trade wind direction. (D) Generalized lithofacies of the HCS2 in Wadi Birk using Al-Mojel, Razin, and Dera (2020) sequence stratigraphic model. The dark gray rectangle highlights the interval of interest in this study.

Data Acquisition and Processing

The study area is a 1.2 km by 1 km rectangle in Wadi Birk, which includes approximately 5.5 km-long 48 m-thick vertical outcrop exposures of HCS2 (Figure 2A). Aerial photography survey using fixed-wing drone covered the entire study area while hexacopter drone acquired high-resolution imageries of the vertical outcrop cliff (Figure 2B). Both drones were equipped with a 42-megapixel camera to collect up to 2 cm pixel resolution images of the outcrop. The images were spatially calibrated with ground control points using a differential Global Positioning System (GPS). The drone imageries were processed and converted into 3D point clouds, then mesh interpolation and texture building to construct the 3D digital outcrop model (DOM). We measured two sedimentological sections (~50 m long each) and measured spectral gamma-ray at 50 cm spacing for one of them. We calculated the total gamma-ray count in the API unit following Luthi (2001) empirical formula from field-measured % of K, ppm of U, and ppm of Th. We calibrated both sections using blue-dyed resin-impregnated and alizarin red-stained thin sections.

Figure 2. (A) Panoramic picture of the study area (Wadi Birk). The interval of interest (HCS2) is well-exposed, and the stromatoporoid/coral complex part of HCS2 is characterized by a vertical weathering-resistant cliff with maximum outcrop exposure. (B) Top-down image of the study area with data acquisition layout. Aerial photography surveys using fixed-wing and hexacopter drones cover the entire study area.

A 50 m-long cylindrical core (~3.2 inches in diameter) was drilled in the study area (Figure 2B) within the HCS2. We performed laboratory-scale spectral gamma-ray measurements to the intact core at 20 cm spacing and calculated the total gamma-ray count in the API unit using Luthi (2001) formula. Acoustic velocity measurements were also performed at 4 cm spacing using a 300 KHz ultrasonic probe integrated into the core scratch tester. We drilled A total of 193 cylindrical horizontal plugs at ~25 cm spacing from

the core for thin sections. The core was also slabbed (1/3 – 2/3 vertical slab) and utilized for depositional facies description.

A total of 19 km-long equivalent 2D and 3D 50 MHz and 100 MHz Ground Penetrating Radar (GPR) were acquired “behind-the-outcrop” in the study area (Figure 2B). All GPR surveys conducted were constant offset reflection surveys with 1 m antenna separation. We acquired 8 km-long networks of 2D 100 MHz and 50 MHz GPR lines and three grids of 3D 50 MHz GPR (60 m x 50 m; 50 m x 20 m; 50 m x 36 m. This study's maximum depth penetration of 50 MHz GPR is ~23 m with ~50 cm vertical resolution, while 100 MHz GPR has ~20 cm vertical resolution and ~12 m maximum penetration depth.

We acquired a 600 m-long 2D seismic profile in the study area (Figure 2B). Due to terrain and logistical issue, we separated the profile into three-line segments with different source and receiver intervals. The most extended segment was a 300 m-long 120 shots-120 receivers line with a 5 m shot and receiver interval. The shortest line was a 144 m 96 shots-96 receivers line with a 1.5 m shot and receiver interval. The geophones utilized were vertical P-wave geophones with 30 Hz resonance frequency, while the seismic source was a 500 kg accelerated weight drop mounted on a 4x4 extreme utility vehicle. The recording length was 1000 ms with a 0.5 ms sampling interval. The dominant frequency of the data was ~120 Hz with a vertical resolution of ~6 m. We performed colored inversion (Lancaster and Whitcombe 2000) using the acoustic velocity of the core to utilize acoustic impedance (AI) to image the stromatoporoid/coral facies instead of the regular seismic reflection amplitude.

Depositional Facies and Stratigraphy

We identified eight distinct depositional facies in the study area (Figure 3) based on their sedimentary structure, depositional texture (Dunham and Ham 1962; Embry and Klovan 1971), skeletal and non-skeletal components (Hughes, Varol, and Al-Khalid 2008), and gamma-ray response. These depositional facies are modifications from the Hanifa depositional facies identified by Al-Mojel, Razin, and Dera (2020) and the subsurface Hanifa reservoir facies (including documented porosity and permeability) by Kompanik et al. (1993) and Al-Khalifah and Makkawi (2002).

Figure 3. Thin sections and outcrop examples of eight facies identified in the study area.

Bioturbated foraminiferal wackestone to packstone (FC1)

This facies is characterized by highly bioturbated wackestone to packstone with a high diversity of lagoonal benthic foraminifera such as *Nautiloculina oolithica*, *Kurnubia palastiniensis*, *Redmondoides lugeoni*, and *Quinqueloculina sp.* Deposition of this facies is interpreted to have occurred in the lagoonal

setting. Subsurface equivalent average porosity and permeability of this facies is 14% (standard deviation 2%) and 22 mD (standard deviation 30 mD), respectively.

Sharp-based intraclast peloidal skeletal grainstone (FC2)

This facies is characterized mainly by cross-bedded grainstone with poorly-sorted muddy intraclasts and peloid grains as the dominant components. Deposition of this facies is interpreted to have occurred in the proximal-shore setting above the fair-weather wave base. Subsurface equivalent average porosity and permeability of this facies are 28% (standard deviation 2%) and 515 mD (standard deviation 116 mD).

Oncoidal packstone to grainstone (FC3)

This facies is characterized by cross-bedded grainstone with an abundance of granule to pebble-sized oncoid grains. Deposition of this facies in Wadi Birk is interpreted to have occurred in the high energy backreef to bar/shoal environment. Subsurface equivalent average porosity and permeability of this facies are 27% (standard deviation 2%) and 315 mD (standard deviation 77 mD), respectively.

Stromatoporoid/coral floatstone with wackestone-packstone matrix (FC4A)

This facies is a part of the highly heterogenous stromatoporoid/coral complex. FC4A is characterized by stromatoporoids (domal, encrusting, and branched) and corals detritus floating within wackestone to mud-lean packstone matrix. This facies is associated with the flank of stromatoporoid/coral buildups and interpreted to be deposited in low energy back-barrier patch reef environment. Subsurface equivalent average porosity and permeability of this facies are 28% (standard deviation 1.5%) and 1000 mD (standard deviation 420 mD), respectively.

Stromatoporoid/coral floatstone with grainstone matrix (FC4B)

This facies is a part of the highly heterogenous stromatoporoid/coral complex. FC4B is mainly characterized by stromatoporoids (domal, encrusting, and branched) and corals detritus floating within skeletal grainstone matrix with minor peloidal components. This facies is associated with the flank of stromatoporoid/coral buildups and interpreted to be deposited in the high-energy back-barrier patch reef environment. Subsurface equivalent average porosity and permeability of this facies are 29% (standard deviation 1.3%) and 1100 mD (standard deviation 385 mD), respectively.

Stromatoporoid/coral boundstone (FC4C)

This facies is a part of the stromatoporoid/coral complex. FC4C is characterized by “living” in-situ stromatoporoids and corals boundstone to framestone that develops a buildup complex. FC4C represents the buildup “core” within the back-barrier patch reef environment. Subsurface equivalent average porosity and permeability of this facies are 29.5% (standard deviation 1%) and 1800 mD (standard deviation 790 mD), respectively.

Cross-bedded composite-grain and peloidal grainstone (FC5)

This facies is characterized mainly by cross-bedded grainstone with medium-sized composite-grains and peloids as the main components. Deposition of this facies is interpreted to have occurred in a back-shoal washover environment. Subsurface equivalent average porosity and permeability of this facies are 29.5% (standard deviation 1%) and 1800 mD (standard deviation 790 mD), respectively.

Cross-bedded skeletal-foraminiferal grainstone (FC6)

This facies is characterized by cross-bedded poorly-sorted grainstone with a rich diversity of skeletal fragments components such as benthic foraminifera, gastropods, brachiopods, echinoid spines, and crinoids. This facies is intercalated with oncoidal packstone to grainstone (FC3), forming larger-scale foresets and interpreted to be deposited in the high energy backreef to bar/shoal environment. Subsurface

equivalent average porosity and permeability of this facies are 27% (standard deviation 2%) and 290 mD (standard deviation 120 mD), respectively.

During early transgression, the deposition of intraclasts peloidal skeletal grainstone facies (FC2) in the proximal-shore setting initiates the HCS-2. The gamma-ray response of this facies at the base of HCS2 is relatively high (~30-40 API), which indicates a higher influx of argillaceous materials. Bioturbated lagoonal facies (FC1) intercalated with FC5 and FC6 grainstones overlay this early transgressive FC2 grainstone. In this lower part of HCS-2, we utilized the relative trend of gamma-ray to proxy for the relative distance from the proximal shoreline and defined higher frequency sequences within otherwise homogenous FC1 facies. West-east correlation panel between sections and core show more layer-cake parallel bedded geometry with limited lateral variations of facies in the lower ~20 m of HCS-2 (Figure 4). The upper ~25 m of HCS-2 is characterized by a laterally heterogenous stromatoporoid/coral facies complex (FC4A, FC4B, and FC4C) capped by oncoidal skeletal-foraminiferal grainstone (FC5 and FC6). The first appearance of stromatoporoid/coral facies is characterized by a negative shift in gamma ray value, indicating a clean, shallow marine carbonate environment with almost no argillaceous content.

Figure 4. Correlation panel through measured sections and core in the study area. Extreme lateral facies heterogeneity and low gamma-ray value characterize the stromatoporoid/coral complex. Low gamma-ray value also indicates a cleaner and more distal shallow carbonate depositional environment away from the influence of argillaceous contents

Stromatoporoid/Coral Facies Mapping

It is almost impossible to define the geometry and lateral distribution of the stromatoporoid/coral facies solely based on measured sedimentological sections. Hence, we performed a 3D deterministic facies mapping from the digital outcrop model and geophysics data (Figure 5). We utilized a drone-based digital outcrop model and spatially referenced measured sections for a continuous stromatoporoid/coral facies outcrop mapping. We extended this interpretation into the three-dimensional domain “behind-the-outcrop” using GPR and AI profiles calibrated with the core. The stromatoporoid/coral buildup core facies

(FC4C) in the digital outcrop model was seen as a massive, bulbous, and “chaotic” weather-resistant feature compared to the surrounding relatively smooth-texture well-layered strata. The flank facies (FC4A and FC4B) were characterized by bedded strata exhibiting small-scale internal granular bulbous features corresponding to the floating stromatoporoid/coral detritus. The oncoidal grainstone/packstone (FC3) and skeletal foraminiferal grainstone facies (FC6) were seen onlapping towards the stromatoporoid/coral “core” in the upper part of the stromatoporoid/coral complex. Convex, domal, or chaotic reflection patterns within otherwise concordant reflectors characterize the radargram facies of the stromatoporoid/coral buildups (FC4C). In the 3D GPR depth slice, the stromatoporoid/coral buildups were circular to pseudo-ellipsoid anomalies that outlined chaotic reflection patterns. In the AI profiles, anomalously high AI features ($\sim 10000 - 11000$ m.g/cc.s) with tabular to convex geometry characterize the stromatoporoid/coral buildups. The radargram facies of flank strata (FC4A and FC4B) were seen as reflectors with distinct downlap and onlap stratal termination towards the buildups. The downlapping flank strata were highly asymmetric towards the northwestern side of the buildups. In AI profiles, the flank strata were seen as high AI envelopes (~ 9000 m.g/cc.s) extending from the buildup anomalies. The “tail” of this envelope was also longer to the northwest of the buildup.

Figure 5. (A) 3D display example of select datasets utilized for facies mapping. (B) The expression of stromatoporoid/coral facies in the radargram. (C) Stromatoporoid/coral buildup imaged as circular to pseudo-ellipsoid anomalies in GPR depth slice. (D) 3D GPR image of flank strata where black arrows are pointing the direction of downlapping surface. (E) The expression of stromatoporoid/coral facies in the AI profile. Dashed lines are the buildups, while arrows show the flanks. (F) An example of a digital outcrop model utilized for facies mapping in the stromatoporoid/coral complex.

A simple statistical summary of the stromatoporoid/coral facies (Figure 6) shows that the stromatoporoid/coral buildups (FC4C) morphology is pseudo-ellipsoid preferentially oriented towards northwest-southeast. The flank strata (FC4A and FC4B) are an asymmetric extension of the buildups

towards the northwest. The type of flank facies associated with a buildup depends on the background facies. In the lower part of the stromatoporoid/coral complex, the background strata are dominated by FC1. Therefore, the flanks are FC4A. In the upper part of the stromatoporoid/coral complex, the background strata are FC6. Hence, the flank strata in this region are likely to be FC4B.

Figure 6. (A) Simplified morphology of a stromatoporoid/coral buildup and its associated flank characterized by pseudo-ellipsoid with a preferential orientation towards northwest-southeast. (B) Roseplot of the buildups orientation. (C) Roseplot of flanks orientation color-coded by maximum extent of flank length showing preferential orientation towards the northwest. (D) Histogram of buildup long axis length. (E) Histogram of buildup short axis length. (F) Histogram of buildup thickness.

Outcrop-Based Depositional and Static Reservoir Modeling

The detailed 3D statistical analysis of the stromatoporoid/coral buildup and its' associated flank that we presented in this study is analogous to typical Late Jurassic supergiant hydrocarbon carbonate reservoirs in the Middle East (Al-Khalifah and Makkawi, 2002; Afifi, 2004; Lindsay et al., 2006; Fallatah and Kerans, 2018; Al-Mojel et al., 2020). Evaluating the net influence of these facies on field development decisions (e.g., reservoir drive mechanism and well construction) requires Integrated Reservoir Modelling (IRM) methodology involving dynamic simulation. This type of analysis was not performed in this work, as it could warrant an individual study by itself. Instead, we presented an analysis of the impact of stromatoporoid/coral facies heterogeneities on the 3D distribution of static reservoir properties, uncertainty in volumetric calculations of hydrocarbons in-place, and static reservoir connectivity.

This section presents a brief modeling methodology to construct the 3D depositional and static reservoir model of the HCS2 outcrop that honors the distribution of the stromatoporoid/coral facies. The model size was 1.2 km x 1 km x 28 m, representing the extent of our study area and the thickness of the stromatoporoid/coral complex. We utilized four stratigraphic surfaces that we deterministically mapped from the sedimentological sections, the digital outcrop model, and geophysics data as the basis. These surfaces represent the base of the stromatoporoid/coral complex and three cycles identified within this complex. After making a slight structural correction, these surfaces were almost flat on the scale of the model. Hence, we implicitly constructed the model in a stratigraphic coordinate system (simbox). Any reservoir connectivity analysis will reflect insights on the intrinsic heterogeneity of the stromatoporoid/coral buildups architecture, independent of heterogeneity caused by post-depositional deformation.

We populated the stromatoporoid/coral buildup geobodies and their associated flank on each of these stratigraphic surfaces (Figure 7). We placed the buildups and their flank strata deterministically in the area where we achieved a complete 3D data coverage. On the other hand, we performed concept-based modeling using the statistical observations where the data coverage is inadequate. This extrapolation can be summarized as follows:

- We distributed random buildup nucleation points on each stratigraphic surface. Using the buildup density parameter derived from the number of deterministically mapped buildups divided by coverage area at each stratigraphic level, we constrained the maximum number of nucleation points.
- We mathematically constructed a 3D ellipsoid from each distributed nucleation point. Each ellipsoid's long axis, short axis, thickness, and orientation were sampled from the histograms and roseplot of buildup morphology presented in Figure 6B, 6D, 6E, and 6F. These ellipsoids represent the modeled buildups.
- We distributed the flank surface proportional to the size of the modeled buildups. The flank orientation and length were sampled from the roseplot in Figure 6C, resulting in asymmetric flank distribution towards the northwest.

Figure 7. Illustration of four stratigraphic surfaces and the distribution of stromatoporoid/coral buildup geobodies to construct the depositional facies model of the reservoir analog in Wadi Birk. Different colors represent different generations of buildups. (A) The bottom surface (green) shows the first cycle of stromatoporoid/coral complexes. (B) Top of cycle-1 surface (purple) showing the second cycle of stromatoporoid/coral complexes. (C) Top of cycle-2 surface (orange) showing the third cycle of stromatoporoid/coral complexes. (D) Image of all model input data viewed from the south showing the three buildup cycles.

We constructed a 3D high-fidelity outcrop-based geocellular depositional facies model using the four main stratigraphic surfaces, stromatoporoid/coral buildups geobodies, flank surface, outcrop measured sections, and core description as inputs. The resolution of the 3D grid was 4 m x 4 m x 33 cm, which gives rise to a total number of 6.4 million voxels (Figure 8A). We divided the model into three stratigraphic zones based on the four stratigraphic surfaces. We populated the buildups deterministically into these zones by assigning facies code FC4C for all cells that co-located with the location of the buildup geobodies in the grid. We modeled the background facies through the Sequential Indicator Simulation (SIS) facies modeling method (Deutsch, 2006) using measured sections and core descriptions as inputs. We selected the realization that could replicate the measured sections' facies frequency distribution as the definitive background facies model. We then determined the facies of flank strata based on the facies of the background. If the background was FC1, then the facies of flank strata was FC4A. If the background was FC5 or FC6, the flank was FC4B (Figure 8B).

We constructed static reservoir models following the depositional facies model with the assumption that depositional facies control the distribution of properties (Pringle et al. 2006). This study reported subsurface equivalent porosity and permeability distributions of each facies in the HCS-2. Thus, we

utilized this information to populate the depositional facies with properties (Figure 8C and 8D). This 3D geocellular static model represented our best knowledge of the spatial and petrophysical heterogeneity of the stromatoporoid/coral facies.

In the next section, we took this model as the reference model and used it to assess the effect of making a stochastic facies model for calculating the net pore volume of an analog subsurface reservoir. We also investigated the static reservoir connectivity of the stromatoporoid/coral facies and the effect of using different field development concepts on calculations involving the volume of rock connected to a wellbore. We simulated a typical Middle Eastern field development plan where vertical wells with ~1 km spacing were utilized to produce from the reservoir (Vahrenkamp et al., 2019). We performed a brief sensitivity analysis on the field development concept, from which the wellbore connectivity was calculated as a function of each concept. Our final goal was to quantify uncertainties associated with 3D depositional heterogeneity of the stromatoporoid/coral facies that could influence development decisions and associated production behavior for the reservoir in the Middle East.

Results

The Impact of the Heterogeneities of the Stromatoporoid/Coral facies to In-place Volumes

The Net Pore Volume (NPV) of a reservoir is a product of Gross Rock Volume (GRV) with Net-to-Gross (NtG) and porosity. The resolution of our outcrop-based reservoir model is very high, which justifies the assumption of NtG = 1 for the entire model. Thus, in this case, the NPV is dependent on porosity distribution. Assuming the reservoir is completely filled with oil (very low water saturation), the NPV (which now depends on porosity distribution) is also a proxy for the volume of hydrocarbon contained in our analog reservoir. In this study, we calculated the NPV of the reference model and used it as a “ground truth” for the volume of oil contained within the stromatoporoid/coral complex-type reservoir.

A set of pseudo wells at ~1 km spacing were virtually drilled from the reference model, capturing the model’s 1D vertical facies and porosity distribution around the wellbore location. We then stochastically constructed 3D depositional facies and porosity models through SIS using the 1D porosity and facies of the pseudo wells as inputs. We ran the SIS without any external information for variogram parameters such as range, sill, anisotropy direction, and others, as if we did not have any information on the morphology and distribution of the stromatoporoid/coral facies. Hence, the sparse pseudo well data intrinsically drove all variogram parameters. This exercise simulated a typical stochastic reservoir model construction in the petroleum industry. The resulting 3D stochastic porosity model was utilized to calculate the NPV. This stochastic NPV was then compared with the NPV of the reference model. The discrepancies between stochastic model NPV with reference NPV were highly unpredictable. In an extreme case, the stochastic model overestimated the reference NPV by 300% to 500% since one of the SIS realizations resulted in almost all the stromatoporoid/coral complex represented by a single continuous buildup.

Another SIS-based stochastic modeling from pseudo wells that we performed utilized outcrop-based statistical distributions of the stromatoporoid/coral buildups to model the variograms of FC4C. We also honor the distribution of flank strata by forcing the variogram of FC4A and FC4B to perform asymmetric elongation towards the northwest of the buildups. Moreover, we used target facies fractions from the reference model to correct the bias of the input facies distributions from the standard variogram. This process would be similar to a simulation run where we implemented an outcrop analog to the reservoir model. This facies modeling method was much more difficult to construct since we needed to honor many

depositional facies rules, such as the alteration from FC4A to FC4B being dependent on the background facies. However, this method resulted in much more stable NPV discrepancies at ~10% to 30%.

Figure 8. Depositional and static reservoir model presented in screenshots of I = 153, J = 128, K = 85. (A) 3D geocellular grid with a resolution of 4 m x 4 m x 33 cm. (B) Deterministic facies model showing the 3D spatial heterogeneity of the stromatoporoid/coral buildup complexes and flank strata. (C) 3D porosity model where stromatoporoid/coral buildups show the highest porosity. (D) 3D permeability distributions where stromatoporoid/coral buildups show the highest permeability.

Static Connectivity of the Stromatoporoid/Coral Facies

Development planning and integrated reservoir modeling aim to find optimal development concepts that meet selected decision criteria over various uncertainties and risks within an oilfield. In this process, it is essential to quantify how the uncertainties could affect the decision outcomes. One of these development decisions, or acceptance criteria, is on well planning. How many wells do we need to produce the field? What type of wells will need to be drilled? One of the key uncertainties in this course is the 3D connectivity of the stromatoporoid/coral facies. To investigate the uncertainty related to the connectivity, we calculated the number and volume of statically-connected cell clusters that correspond to one or more of the stromatoporoid/coral facies.

We ran two different scenarios for this analysis. In the first scenario, the static connectivity was only associated with the buildups. The stromatoporoid/coral buildups were considered “connected” if they met with other buildups. In other words, stromatoporoid/coral buildups were independent and did not communicate with flank strata. In the second scenario, we included the flank facies (FC4A and FC4B) in the calculation of the static connectivity. With that, we addressed the uncertainty related to the spatial continuity of the buildup complexes through their flanks.

In the first scenario, we found over 200 individual buildup cell clusters of various dimensions (Figure 9A) within 1.2 km x 1 km x 28 m grid cells. This high number of clusters quantifies the extreme 3D spatial heterogeneity of these stromatoporoid/coral buildup facies. We placed five vertical wells in this scenario as a hypothetical development concept to test the sensitivity on the range of connected wellbore volume. To identify where to plan the location of the vertical concept wells, we made an isochore map for all stromatoporoid/coral buildup facies (FC4C). This map revealed, to some degree, the total vertical thickness of this facies through the projection for all cycles, which indicated where connected clusters could be found.

The “best” development concept for the first scenario (Figure 9B) was where we placed all five vertical wells at the location where the thickest buildup clusters could be found. Surprisingly, even the “best” development concept that we simulated could only access ~12% of the total GRV from the buildups. Moreover, this “best” concept required well spacing of less than ~400 m which is challenging to achieve in the actual field development scenario. Obviously, the “worst” development concept was when all vertical wells did not encounter any buildup at all. However, the next “worse” concept that we simulated was when 3 out of 5 wells encountered buildup facies (Figure 9C). In this concept, we would be accessing only ~2% of the total GRV available.

In the second scenario, we assumed that stromatoporoid/coral buildups and their associated flanks were a single entity. The combined isochore map for this scenario had a more extensive areal coverage (Figure 10). In this scenario, it was more difficult to avoid the stromatoporoid/coral complex rather than encountering it. Hence, the buildup complex will be hit by almost any development well. The static connectivity analysis resulted in a sizeable cluster that contains ~80% of the GRV available. The whole reservoir would act as a tank while the remaining 20% of the volumes were located in various smaller clusters.

Figure 9. (A) Cell clusters presented in different colors computed from the static connectivity of the FC4C facies in the entire field. (B) Isochore map in (m) of the FC4C facies showing the five well plans of the first development concept. (C) Isochore map in (m) of the FC4C facies showing the five well plans of the second development concept.

Figure 10. Isochore map in (m) of the combined reef complex facies (FC4A + FC4B + FC4C). The lateral coverage of this complex is greater and that the stromatoporoid/complex complexes would be encountered by almost any vertical well plan.

Conclusion

We have constructed a 3D high fidelity outcrop-based depositional facies model of the Hanifa reservoir analog from comprehensive datasets, including drone imageries, measured sections, core, GPR, and seismic. We populated this depositional facies model with subsurface equivalent porosity and permeability and constructed an outcrop analog reservoir static model that honors lateral heterogeneity of the stromatoporoid/coral facies.

We have demonstrated the strong influence of 3D depositional heterogeneity of the stromatoporoid/coral facies on the uncertainty associated with hydrocarbon in-place volumes. The SIS's stochastic process will likely be inaccurate on volumetric calculation without any outcrop analog to guide the porosity distribution in a Hanifa-like reservoir. The volume discrepancy due to this inaccuracy can go as high as ~500%. Imposing statistical trends and rules from outcrop analog to the porosity distribution significantly increases volumetric calculation accuracy. The margin of volume discrepancy narrows down to ~10% – 30%. Thus, development decisions should be driven by reservoir models that incorporate data-driven outcrop analogs to reduce the risk of investment decisions significantly.

The static connectivity between the buildup complex is mainly dependent on the connectivity of the flank facies. If the flank and buildups are connected, the reservoir is a sizeable connected cluster where any five wells will access the 80% volume. If the buildups and flank are separated, only 20% of the volume is accessible at most. Furthermore, regardless of whether the flanks are connected, at least the remaining ~20% of the volume is still left within the smaller clusters of stromatoporoid/coral facies.

We obtained the results above based on a small (1.2 km x 1. km x 28 m) analog model. Evaluating the net influence of these facies on field development decisions requires a more thorough study. Therefore, we suggest performing an Integrated Reservoir Modelling (IRM) methodology involving dynamic simulation on a larger model (~ 10 square km area) to capture larger and potentially more significant areal heterogeneity.

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