Characterizing and modeling the Upper Jurassic Arab-D reservoir using outcrop data from Central Saudi Arabia

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ABSTRACT

Outcrop analogs are used to improve the characterization of reservoir stratigraphy, to understand subsurface facies architecture and heterogeneity, and to overcome the limitations associated with large inter-well spacing within individual oil fields. This study characterized and modeled outcropping strata equivalent to the Upper Jurassic Arab-D carbonate reservoir in Central Saudi Arabia. The study presents qualitative and quantitative sedimentological and petrographic descriptions of lithofacies associations and interprets them within a high-order stratigraphic framework using geostatistical modeling, spectral gamma-ray, geochemistry, petrography and micropaleontology. The sedimentological studies revealed three lithofacies associations, which are interpreted as a gentle slope platform depositional environment comprising nine high-frequency sequences. The biocomponents of the study area show a lower degree of diversity than the subsurface Arab-D reservoir; however, some key biofacies are present and provide indications of the nature of the paleoenvironments. The geochemical results show a strong correlation between the major and trace elements and the reservoir facies, and suggest that the concentrations of elements and their corresponding spectral gamma-ray logs follow the same general upward-shoaling pattern. The 3-D geocellular model captures small-scale reservoir variability, which is reflected in the petrophysical data distribution in the model. This investigation increases the understanding of the stratigraphy of the Arab-D reservoir and provides a general framework for zonation, layering, and lateral stratigraphic correlations.

INTRODUCTION

Outcrop analogs have the potential to improve our understanding of reservoir stratigraphy and to provide rock-based data on the vertical and lateral characteristics of their reservoir equivalents (Pringle et al., 2004; Bellian et al., 2005). Integrated outcrop studies provide a higher-order characterization of the lithofacies architecture, highlight sedimentary features and their heterogeneity, thus leading to an improved understanding of reservoir complexity (Girard et al., 2008).

The Arab-D reservoir is one of the most productive intervals in the world (Lindsay et al., 2006) (Figure 1). This reservoir comprises the carbonates of the Arab-D Member of the Arab Formation and the Upper Jubaila Member of the Jubaila Formation, and is assigned to the Upper Jurassic, Kimmeridgian Stage (Powers, 1962; Meyer et al., 1996, 2000; Hughes, 1996, 2004a, b, 2009; Cantrell and Hagerty, 1999; Cantrell et al., 2001, 2004, 2007; Cantrell and Swart, 2004; Cantrell, 2008; Lindsay et al., 2006). The Arab-D reservoir in Ghawar Field has an average thickness of 60 m, an average porosity of 15%, and a permeability of several Darcys (Lindsay et al., 2006).

Sedimentological characterization has been conducted on the major carbonate reservoirs of Saudi Arabia, especially the Arab-D reservoir (e.g. Wilson, 1981; Mitchell et al., 1988; Sahin et al., 1999). These studies encompass many aspects of the characterization of the Arab-D reservoir, but a high-resolution stratigraphic model and correlation, and the main foundation for understanding reservoir heterogeneity are still lacking. These limitations are attributed to the relatively large inter-well spacing in oil fields in which major lithofacies changes could occur (Meyer et al., 2000). In addition, the similarity of the general shoaling upward of the Upper Jurassic System (Lindsay et al., 2006) may also mask the signature of the Arab/Jubaila...
formation boundary. Moreover, the existing 3-D reservoir models have large cell volumes (Douglas, 1996), lack high resolution and neglect large facies changes. With the exception of the electron-microprobe study of the subsurface Arab-D reservoir (Cantrell, 2006), there has not been any published study of elemental analysis carried-out on either the outcrop analogs or the Arab-D reservoir. Elemental geochemistry has been successfully tested for reservoir zonation, paleogeographic interpretation, and lithofacies mapping (Calvo et al., 1995; Cicero and Lohmann, 2001; Vincent et al., 2006). Chemical stratigraphy is useful for reservoir zonation, particularly when it is integrated with outcrop spectral gamma-ray data (SGR).

This study aims to establish a conceptual high-resolution geological and geostatistical model by integrating sedimentological, stratigraphic, paleontological and petrophysical data of the Arab-D reservoir analog. It is anticipated that the model will be capable of displaying small-scale facies heterogeneities that can reflect the spatial continuity of porosity and permeability in the actual reservoir model.

The high-resolution 3-D geostatistical model of the outcrop may act as a norm or proxy for subsurface exploration and production activities. The model will also improve our understanding of the reservoir lithofacies stacking patterns and changes in the lateral facies distributions. The model might also provide solutions to some challenges associated with the correlation of reservoir lithofacies and help in the development of a realistic reservoir facies zonation. The study also explores the utilization of new data from the study area, such as spectral gamma-ray (SGR) logs and geochemical analysis data. These data may contribute to the development of a new data-integration approach to understand the characteristics of the hydrocarbon resources of Saudi Arabia.

The present paper is part of a research project that provides an integrated approach for characterizing facies types and sequences of an outcrop-equivalent of the Arab-D reservoir. The paper proposes a stratigraphic framework for the Arab-D strata based on several stratigraphic methods, including: (1) spatial distribution of lithofacies and their semivariograms (Eltom et al., 2012); (2) outcrop gamma-ray validation and its integration with elemental analysis (Eltom et al., 2013a); and (3) methods to determine microporosity in Wadi Nisah outcrop (Eltom et al., 2013b).

### STUDY AREA

The most representative outcrop-equivalent to the Arab-D reservoir strata is found at the Wadi Nisah area, 90 km south of Riyadh. This section includes the uppermost Jubaila Formation, the carbonate of the Arab-D Member and part of the Arab-C Member. The cliff-forming outcrop faces northwest and is 250 m long and 19 m high. Although some areas of the outcrop are covered by collapsed rocks, the overall exposure is considered to be representative of the reservoir (Figure 2). Meyer et al. (1996) indicated that this outcrop has the same lithofacies stacking patterns as the Arab-D reservoir.

The differences between the Arab-D reservoir and Wadi Nisah outcropping strata was highlighted by Meyer et al. (1996) and could be summarized as the following: (1) The Arab-D Member includes the Arab-D Anhydrite, which is apparently missing at Wadi Nisah, probably due to dissolution.
(2) Zone 1, 3B and 4 of the Arab-D reservoir are not represented in the outcrop at Wadi Nisah. (3) The thickness of the Arab-D in Wadi Nisah is half that of the subsurface. (4) The platy laminated mudstone lithofacies has a greater thickness in the outcrop. (5) Outcrop lithofacies changes include: absence of Cladocoropsis, fragmented Cladocoropsis, mixed skeletal peloidal, and oolitic lithofacies; presence of skeletal-pelecypod lithofacies.

METHODOLOGY

The methodology used in this study includes the following: (1) sedimentological, stratigraphic and paleontological investigation; (2) $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$ analysis; (3) elemental analysis; (4) spectral gamma-ray logging; and (5) 3-D geostatistical modeling.

Sedimentological, Stratigraphic and Paleontological Investigation

A detailed sedimentological and stratigraphic investigation was conducted at the Arab-D reservoir outcrop analog at Wadi Nisah. The analysis included a description of the outcrop facies and the subdivision of the outcrop into beds, bed sets and high-frequency sequences (HFS). Thin sections were prepared from all field samples and analyzed using optical microscopy for microfacies and micropaleontology. Here, we used the work of Meyer et al. (1996) as a guide for the lithofacies description and interpretation.

Lithofacies were correlated across 14 outcrop sections spaced ca. 15 m laterally (Figure 2). The relatively small spacing of the sections was planned to maintain a high degree of stratigraphic resolution. The outcrop sections were considered as virtual vertical wells that penetrate the Arab-D reservoir zones 1, 2A, 2B and 3A.

Each of the 14 outcrop sections was stratigraphically logged and sampled. The sampling system depended on the bed thickness, which ranges from 10 to 30 cm in the thinner beds, and from 60 to 100 cm in the thicker ones. A single sample was collected from beds less than 30 cm thick. For beds thicker than 30 cm, samples were collected every 30 cm. Facies logging was performed using the following criteria: Dunham classification, grain-size description, carbonate components, sedimentary structures, bed thickness, bed contact and fossil content.

$^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ Analysis

A total of 22 selected samples from section N-1 (Figure 2) were analyzed for bulk $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios. These samples fully covered the stratigraphic section and encompass both the Upper Jubaila and Arab-D members. We also performed dissolution tests for four samples, as follows: (1) The samples were cleaned three times in water to remove all water-soluble salt components. (2) The carbonate was dissolved in 1N HCl. Weak HCl dissolves the carbonate but leaves most of the silicates undissolved. (3) After removing the carbonate fraction by centrifugation, there was a significant silicate residue for all four tested samples. (4) The mineral phase of the silicate fraction was determined using X-ray diffraction (XRD). (5) The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of the 22 samples were also measured to help interpret the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio distribution in the outcrop. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data are reported in delta notation in parts per thousand (%) variations relative to the VPDB (the Vienna Peedee belemnite isotope standard). The expanded analytical uncertainty of the $^{87}\text{Sr}/^{86}\text{Sr}$ analysis is 0.00008 and was calculated using seawater standard.

Spectral Gamma-Ray Logging (SGR)

Gamma radiation is naturally emitted from radioactive-rich sediments that contain the elements uranium (U), potassium (K) and thorium (Th). The radiation was measured in the field using a 512-channel portable SGR spectrometer (Gamma Surveyor model manufactured by Geofyzika, Czech Republic). This spectrometer is equipped with a 3 x 3 inch NaI (TI) scintillation detector and was used to measure the total SGR emissions and the individual levels of each of the three radioactive elements. The SGR spectrometer records counts per second (CPS) within a distinct time window. The SGR readings were collected vertically every 20 cm up the face of the outcrop for each
Figure 2: (a) Map showing the study area in the central area of Saudi Arabia; (b) map showing Wadi Nisah; (c) base map showing the location of the 14 stratigraphic sections, with the complete black filling indicating that the stratigraphic section encompasses both the entire Upper Jubaila and the Arab-D members, the partial black filling indicating that only a few beds of the Upper Jubaila and the Arab-D members are present, and the circles without filling indicating that only the Arab-D Member is present; and (d) photomosaic, viewed looking toward the south, showing the three stratigraphic units of the studied outcrop with locations of 11 stratigraphic sections. Two cars in white box for scale.
section. The sampling time window was selected after testing time durations of 10, 20, 30, 40, 50, 60, 120, 180, and 240 seconds to evaluate the reading variability among these time windows (Eltom et al., 2013a, b). Sixty seconds proved to be the best time interval to obtain the SGR counts in the field.

**Elemental Analysis**

A total of 131 samples representing six outcrop profiles in which a complete individual section was sampled and logged by full SGR spectrometry were selected for the elemental analysis. The samples were selected to cover the whole range of lithofacies in the study area. The major, trace and rare chemical elements were determined using inductively coupled plasma-mass spectrometry (ICP-MS).

**Geostatistical Modeling**

The global positioning system (GPS) was used to locate the 14 sections and their lithofacies were logged, digitized and assigned a code of 1 to 8 (Table 1). A total of 18 indicator semivariograms were computed using pairs of facies codes to evaluate the lateral and vertical variability of the lithofacies and SGR data. Because the dolomitic mudstones and dolomitic wackestones lithofacies are intercalated they were included in a single semivariogram. The same practice was applied to the burrowed fossiliferous wackestones and peloidal fossiliferous grainstones lithofacies. Therefore, our results include 18 indicator semivariograms instead of 24. A total of 12 semivariograms were computed for K, Th, U, and SGR total counts in the major, minor and vertical directions. Three-dimensional geostatistical modeling was conducted using “Sequential Indicator Simulation” (SIS) for the facies model and “Sequential Gaussian Simulation” (SGS) for SGR 3-D modeling.

Table 1

| This Study | Facies Code | Meyer et al., (1996) | Depositional Environment | Equivalent Subsurface Lithofacies | Permeability Equivalent Subsurface Lithofacies (Meyer et al., 2000) | Porosity Equivalent Subsurface Lithofacies (Meyer et al., 2000) |
|------------|-------------|----------------------|--------------------------|---------------------------------|-------------------------------------------------|---------------------------------|
| Stromatoporoid Lithofacies Association | Dolomitic Mudstones | 1 | Burrowed | Open-marine environment (Lower slope) | Dolomitic Mudstones | 10.2 | 0.2 |
| | Dolomitic Wackestones | 2 | Stromatoporoid | Open-marine environment (Upper slope) | Dolomitic Wackestones | 16.9 | 692.8 |
| | Stromatoporoid Wackestones and Packstones | 3 | Stromatoporoid | Open-marine belt of stromatoporoid banks | Stromatoporoid Packstones | 12.7 | 4.2 |
| Skeletal Bank Lithofacies Association | Burrowed Fossiliferous Wackestones | 4 | Burrowed Mixed Skeletal Peloid | Offshore submarine environment | Mixed Skeletal Grainstones | 25.95 | 527.25 |
| | Peloidal Fossiliferous Grainstones | 5 | Skeletal-Pelecypod | Skeletal bank in a marginal marine setting seaward of tidal flats. | Mixed Skeletal Grainstones | 25.95 | 527.25 |
| Tidal Flat Lithofacies Association | Laminated Mudstones | 6 | Thinning-Upward | Millimeter Laminations | Interval and supratidal carbonate | Micritic | 13.4 | 0.9 |
| | Wavy Ripped Sandy Grainstones | 7 | Millimeter Laminations | Interbedded storm deposits in tidal flat environments | Mixed Skeletal Grainstones | 25.95 | 527.25 |
| | Breccia and Mud-Clasts | 8 | Limestone Flat-Pebble Conglomerates | Channel lag deposits or supratidal storm layers | Micritic | 13.4 | 0.9 |
RESULTS

Lithofacies Associations

The sedimentological and stratigraphic analysis of the studied outcrop succession indicated the presence of eight lithofacies that correspond to those described by Meyer et al. (1996) and Eltom et al. (2013a, b). Those lithofacies are grouped into three lithofacies associations (Table 1), as follows:

Stromatoporoid lithofacies association, comprised of dolomitic mudstones and dolomitic wackestones (Figure 3), is interpreted to have been deposited below wave-base in an open-marine environment on a lower to upper slope of a ramp platform, and stromatoporoid wackestones and packstones interpreted as an open-marine stromatoporoid bank on an upper-slope to ramp-crest environment.

Skeletal bank lithofacies association, comprised of burrowed fossiliferous wackestones (Figure 4), is interpreted to have been deposited in relatively low-energy conditions below the wave-base, and peloidal fossiliferous grainstones interpreted as relatively higher-energy, more proximal marine deposits seaward of the tidal flat.

Tidal flat lithofacies association, comprised of subtidal-intertidal laminated mudstones and wavy rippled sandy grainstones (Figure 5), is interpreted to have been deposited in a channelized tidal-flat setting; and supra intertidal breccia and mudflat deposits with rip-up clasts.

High-frequency Sequences (HFS)

By logging the measured sections of the Arab-D reservoir analog, nine high-frequency sequences (HFS) were recognized (Figures 3b, 4b and 5b). Four HFSs occurred in the Upper Jubaila Formation at the base of the outcrop succession (Figure 3c) and showed coarsening- and shallowing-upward cyclicity. Lithofacies comprised of burrowed dolomitic mudstones and wackestones passed up to stromatoporoid wackestones and packstones (rudstones and floatstones). The four HFSs show similar lithofacies arrangements, biofacies components and thicknesses. The HFSs could be correlated laterally between the measured sections.

The remaining five HFSs occurred in the overlying Arab-D Member. At their base, two coarsening- and shallowing-upward HFSs are composed of burrowed and fossiliferous wackestones that pass upwards to the peloidal fossiliferous grainstones of the skeletal bank lithofacies association (Figure 4b). At the top of the Arab-D succession are three fining- and shallowing-upward HFSs comprising distal and proximal tidal flat deposits (Figure 5b), including rippled sandy grainstones passing up to laminated mudstones.

Biofacies Zonation

The boundary between the Jubaila and Arab formations is defined by the last appearance of stromatoporoids (Powers, 1962; Hughes, 1996, 2004a, b, 2009). This boundary is clearly defined in the outcrop and will be referred to in the further interpretation and discussion in this study. Compared to the Arab-D reservoir, the studied samples from this outcrop generally show low degrees of biofacies diversity. However, some key biofacies are present and provide paleoenvironmental indicators. Figure 6 shows some microbiocomponents identified from the thin sections. The stratigraphic distribution of biofacies assemblages is shown in Figure 7. The lower section of the exposed Upper Jubaila Member contains a very limited biofacies component in the dolomitic wackestones and mudstones but exhibits good biofacies diversity in the stromatoporoid wackestones and packstones. This section is characterized by the appearance of stromatoporoid fragments, coral fragments, *Lenticulina* ssp. and *Valvulina* ssp.

Large fossils include stromatoporoid, echinoid, and bivalve fragments. The upper section of the outcrop (Arab-D Member) contains limited biofacies in the platy laminated mudstones. In contrast, the peloidal fossiliferous grainstones and wavy rippled sandy grainstones exhibit a relatively high diversity of biofacies components. In these lithofacies, the dominant biofacies components are
Figure 3: Stromatoporoid lithofacies association. (a and b) Slabbed samples and thin-section photomicrographs showing the stromatoporoid lithofacies association (shallowing and coarsening upward). Depositional interpretation of this lithofacies association is illustrated in the bottom left of (a). (c to e) Field photographs illustrating the stratigraphic position of the stromatoporoid lithofacies association in the outcrop succession with high frequency cycles (red triangles). (Eltom et al., 2013a).
Figure 4: Skeletal bank lithofacies association. (a and b) Slabbed samples and thin-section photomicrographs showing the skeletal bank lithofacies association (shallowing and coarsening upward). Depositional interpretation of this lithofacies association is illustrated in the bottom left of (a). (c to e) Field photographs illustrating the stratigraphic position of the skeletal bank lithofacies association in the outcrop succession (Eltom et al., 2013a).
Figure 5: Tidal flat lithofacies association. (a and b) Slabbed samples and thin-section photomicrographs showing lithofacies comprising the tidal flat lithofacies association (shallowing and fining upward). Depositional interpretation of this lithofacies association is illustrated in the bottom left of (a). (c to f) Field photographs illustrating the stratigraphic position of the tidal flat lithofacies association in the outcrop succession (Eltom et al., 2013a).
Figure 6: Photomicrographs of microbiocomponents of studied stratigraphic sections.
Pseudocyclammina lituus, echinoids, ostracods, Quinqueloculina spp., gastropods, numerous bivalve fragments, and a few agglutinated foraminifera. Microbiocomponents such as Nautiloculina oolithica, Kurnubia palastiniensis, spicules, brachiopod fragments, and bivalve fragments are distributed widely in both the Upper Jubaila and Arab-D members.

**Paleoenvironmental Interpretation**

Stromatoporoid, coral fragments, and Lenticulina ssp. are restricted to the Upper Jubaila Member and not present in the Arab-D Member. This assemblage indicates an open-marine unrestricted regime (Hughes, 2004a, b, 2009). The possible paleoenvironment in the studied outcrop succession is the upper and lower slope to ramp crest where the Upper Jubaila Member was deposited.

Gastropods, ostracods, Pseudocyclammina lituus, and Quinqueloculina spp. dominate in the Arab-D Member. This assemblage indicates a shallow to very shallow lagoon setting. The corresponding lithofacies for this paleoenvironment is a skeletal bank association.

Nautiloculina oolithica, Kurnubia palastiniensis, echinoid fragments, and brachiopod fragments are distributed equally in both units. These might either have a very wide paleoenvironmental tolerance (Hughes, 2004a, b, 2009) or were transported by channelized flow.

**$^{87}$Sr/$^{86}$Sr, $\delta^{18}$O, and $\delta^{13}$C Isotopes Analysis**

Table 2 and Figure 7 show the results of $^{87}$Sr/$^{86}$Sr analysis of 22 bulk samples and their corresponding $\delta^{18}$O and $\delta^{13}$C signatures. The analysis revealed that the $^{87}$Sr/$^{86}$Sr ratios vary between

Table 2

| Sample No. | $^{87}$Sr/$^{86}$Sr Bulk Sample | $^{87}$Sr/$^{86}$Sr Carbonate | Sample for HCl Leaching (g) | Weight Silicate (g) | Calculated Weight % Silicate | Quartz | Kaolinite | Pseudosilicate-Feldspar | Goethite | Gibbsite |
|------------|-------------------------------|-------------------------------|-----------------------------|---------------------|-----------------------------|--------|-----------|------------------------|---------|----------|
| 35         | 0.707420                      |                               |                             |                     |                             |        |           |                        |        |          |
| 33         | 0.707445                      | 0.707185                      | 15.05                       | 0.53                | 3.5                        | Dominant | Clearly identifiable | Clearly identifiable | Clearly identifiable | -        |
| 32         | 0.707358                      |                               |                             |                     |                             |        |           |                        |        |          |
| 31         | 0.707334                      |                               |                             |                     |                             |        |           |                        |        |          |
| 30         | 0.707340                      |                               |                             |                     |                             |        |           |                        |        |          |
| 29         | 0.707442                      |                               |                             |                     |                             |        |           |                        |        |          |
| 28         | 0.7071224                     |                               |                             |                     |                             |        |           |                        |        |          |
| 27         | 0.707553                      |                               |                             |                     |                             |        |           |                        |        |          |
| 21         | 0.707881                      |                               |                             |                     |                             |        |           |                        |        |          |
| 20         | 0.707291                      | 0.707174                      | 15.1                        | 0.4                 | 2.6                        | Very much | Clearly identifiable | Clearly identifiable | -       | Possible |
| 19         | 0.707464                      |                               |                             |                     |                             |        |           |                        |        |          |
| 18         | 0.707428                      |                               |                             |                     |                             |        |           |                        |        |          |
| 17         | 0.707464                      |                               |                             |                     |                             |        |           |                        |        |          |
| 16         | 0.707552                      |                               |                             |                     |                             |        |           |                        |        |          |
| 15         | 0.707417                      |                               |                             |                     |                             |        |           |                        |        |          |
| 14         | 0.707527                      | 0.707183                      | 15.05                       | 0.38                | 2.5                        | Very much | Much                      | -         | -         | -        |
| 13         | 0.707514                      |                               |                             |                     |                             |        |           |                        |        |          |
| 12         | 0.707896                      | 0.707622                      | 12.42                       | 0.14                | 1.1                        | Very much | Much                      | Clearly identifiable | -       |          |
| 11         |                               |                               |                             |                     |                             |        |           |                        |        |          |
| 10         | 0.707360                      |                               |                             |                     |                             |        |           |                        |        |          |
| 9          | 0.707286                      |                               |                             |                     |                             |        |           |                        |        |          |
| 8          | 0.707510                      |                               |                             |                     |                             |        |           |                        |        |          |
| 7          | 0.707167                      |                               |                             |                     |                             |        |           |                        |        |          |

$^{87}$Sr/$^{86}$Sr isotope data. Four samples were selected for dissolution by HCl. The dissolution method produced carbonate fraction and silicate residual. $^{87}$Sr/$^{86}$Sr ratio was determined for the carbonate fraction and XRD phase minerals were determined for the silicate residuals.
Figure 7: Biocomponents variation of selected forms, $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$ isotope data within section N-1 in the study area. Note that the boundary between the Upper Jubaila Member and Arab-D Member is defined by the last appearance of stromatoporoids. The numbers in the blue squares indicate the abundance of biocomponents (1 is low, while 5 is very high). The vertical elevation assumes zero elevation at the bottom of the outcrop and 1,885 cm at the top.
Upper Jurassic Arab-D reservoir model, Central Saudi Arabia

Samples from the Upper Jubaila Member have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.707167 and 0.707894, with an average value of 0.707481, while samples from the Arab-D Member have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.707224 and 0.707881, with an average value of 0.707466. The $\delta^{13}\text{C}$ values range from -3.62‰ to 1.26‰, with a nearly equal distribution of negative and positive values in both the Upper Jubaila and Arab-D members. The $\delta^{18}\text{O}$ values range from -6.40‰ to -2.09‰, with totally negative values for all samples. The vertical component of the outcrop shows much lighter (more negative) $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ for the upper Jubaila Member than for the Arab-D Member.

Table 2 shows the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio after performing a dissolution method that preferentially dissolves the carbonate and separates the siliciclastic material from the samples. For the four samples analyzed, the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio of the HCl soluble carbonate fraction was lower than the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio of the whole rock. The results of the XRD mineral phase characterizations of the silicate fraction of the four samples are shown in Table 2 and Figure 8. The identified peaks are highlighted by color: quartz (blue), kaolinite (green), potassium feldspar (grey), goethite (brown), gibbsite (pink). Quartz is the most abundant mineral in all four samples. Kaolinite occurs in all four samples. Potassium-feldspar occurs in samples S1-10, S1-20 and S1-33. Goethite occurs in samples S1-10 and S1-33. In sample S1-20, small amounts of gibbsite may be present.

Spectral Gamma-Ray Logging (SGR)

The measured outcrop sections displayed two major SGR profiles of all the logs, U, K, Th, and total counts (TC) (Figures 9a to 9d). These two profiles represent the Upper Jubaila Member in the lower
Figure 9: (a) Cross sections in eight selected stratigraphic sections in the studied outcrop showing spectral gamma-ray logs for (a) uranium (U), (b) potassium (K), (c) thorium (Th) and (d) gamma-ray total counts (TC).
See facing page for continuation.
Upper Jurassic Arab-D reservoir model, Central Saudi Arabia

(c) Thorium Spectral Gamma-Ray

(d) Total Counts (TC) Spectral Gamma-Ray

Figure 9 (continued):

Lithology
- Peloidal fossiliferous intraclastic packstones and grainstones
- Stromatoporoid wackestones-packstones
- Dolomitic wackestones
- Dolomitic mudstones
section and the Arab-D Member in the upper section. The lower section shows general upward increasing in all SGR logs and their TC. The correlation profile throughout the outcrop shows a similar pattern for all of the stratigraphic sections in which the Upper Jubaila was represented. However, in the area with rock collapse there might be some changes in the SGR signatures. The Upper Jubaila Member was subdivided into four subunits of relatively low SGR levels separated by a sharp peak of a relatively high TC of SGR. These high peaks correspond to stromatoporoid wackestones and packstones strata in the stratigraphic section.

The thicknesses of each of the log packages varied and correspond stratigraphically to the HFSs defined in the stratigraphic section in the Upper Jubaila Member. The U SGR has four distinctive troughs corresponding to the TC and Th SGR peaks. It also shows general upward increasing with a generally lower level of emission reading against the high Th SGR emission reading. The upper section, the Arab-D Member, has a serrated SGR log pattern; however, five peaks of relatively high Th, K, and TC SGR readings are recorded. These peaks correspond to relatively low U SGR log troughs. Peloidal fossiliferous grainstones and wavy rippled sandy grainstones were observed in the corresponding intervals of these K, Th, and TC SGR peaks and U SGR troughs. The boundary between the Upper Jubaila Member and the Arab-D Member exhibited sharp break in the SGR log response, especially for the Th, K, and TC logs.

**Geochemical Analysis**

Summary statistics of whole rock elemental analysis are shown in Table 3. A comparison of the three lithofacies associations (stromatoporoid, skeletal bank, and tidal flat) is shown in Figures 10a to 10f. In the petrographic analysis, SiO₂ occurs in the form of silt-size angular to sub-rounded quartz. Therefore, SiO₂ is used here as a proxy for siliciclastic material distribution in the studied samples. SiO₂ showed a remarkably high reading in the tidal flat lithofacies association, followed by skeletal bank and finally stromatoporoid (Figure 10a). This arrangement follows the general trend of upward shallowing of the lithofacies association in the outcrop. The other major oxides show a similar trend except for Fe₂O₃. In contrast to this general trend, the stromatoporoid lithofacies association shows the highest value of Fe₂O₃. Petrographic examination showed that a high concentration Fe₂O₃ in the stromatoporoid lithofacies is associated with dolomitic zones. The trace elements show the same trend of increasing of concentration upward. Figures 10g to 10l show the concentrations per lithofacies association for selected elements. Zr provides evidence of heavy mineral distribution, with approximately 20% of total heavy mineral assemblage (Svendsen and Hartley, 2001). The overall average concentrations of Zr and Zn exhibited higher values in the skeletal bank and tidal flat than in the stromatoporoid lithofacies (Figure 10k and 10l).

**Grid Construction**

Four surfaces were reconstructed from the 14 correlated stratigraphic sections. These surfaces are as follows:

- **Surface-1:** The boundary between Arab-D and Arab-C. This surface is marked by collapsed breccia;
- **Surface-2:** The top of the skeletal bank deposits placed on the transition boundary between the skeletal bank and tidal flat lithofacies associations;
- **Surface-3:** The top of the Upper Jubaila Member defined by the last appearance of stromatoporoid; and
- **Surface-4:** The bottom of the exposed strata. Note that this surface is not a stratigraphic horizon.

Using these stratigraphic surfaces, a 3-D gridding system was reconstructed. It was constrained by the Arab-D/Arab-C boundary (Surface-1) and the bottom of the exposed strata (Surface-4), and surrounded by a polygon extending 200 m in the east-west direction and 100 m in the north-south direction. The four surfaces define three zones, which are from bottom to top, the stromatoporoid,
Figure 10: (a to f) The major chemical elements concentration (SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, K$_2$O, Na$_2$O, and Ti$_2$O) for each lithofacies association (stromatoporoid, skeletal bank, and tidal flat). (g to l) The trace chemical elements concentration (Sr, Pb, Th, U, Zr, and Zn) for each lithofacies associations (stromatoporoid, skeletal bank, and tidal flat).
### Table 3

Elemental analyses results for 131 samples from the studied outcrop. Statistical parameters of the major, minor, and trace elements for each lithofacies associations (stromatoporoid, skeletal bank, and tidal flat).

| Elements | Stromatoporoid (n = 64) | Skeletal Bank (n = 21) | Tidal Flat (n = 44) |
|----------|------------------------|-----------------------|--------------------|
| Fe2O3    | Min: 0.10 Mean: 0.86 SD: 0.31 | Min: 0.10 Mean: 0.86 SD: 0.31 | Min: 0.10 Mean: 0.86 SD: 0.31 |
| Al2O3    | Min: 0.09 Mean: 0.29 SD: 0.17 | Min: 0.09 Mean: 0.29 SD: 0.17 | Min: 0.09 Mean: 0.29 SD: 0.17 |
| SiO2     | Min: 0.27 Mean: 2.78 SD: 0.95 | Min: 0.27 Mean: 2.78 SD: 0.95 | Min: 0.27 Mean: 2.78 SD: 0.95 |
| Na2O     | Min: 0.01 Mean: 0.07 SD: 0.01 | Min: 0.01 Mean: 0.07 SD: 0.01 | Min: 0.01 Mean: 0.07 SD: 0.01 |
| Sr       | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 |
| Ce       | Min: 0.01 Mean: 0.01 SD: 0.01 | Min: 0.01 Mean: 0.01 SD: 0.01 | Min: 0.01 Mean: 0.01 SD: 0.01 |
| Zr       | Min: 0.01 Mean: 0.01 SD: 0.01 | Min: 0.01 Mean: 0.01 SD: 0.01 | Min: 0.01 Mean: 0.01 SD: 0.01 |
| Ba       | Min: 0.01 Mean: 0.01 SD: 0.01 | Min: 0.01 Mean: 0.01 SD: 0.01 | Min: 0.01 Mean: 0.01 SD: 0.01 |
| C        | Min: 11.30 Mean: 12.30 SD: 11.89 | Min: 11.30 Mean: 12.30 SD: 11.89 | Min: 11.30 Mean: 12.30 SD: 11.89 |
| S        | Min: 0.01 Mean: 0.40 SD: 0.26 | Min: 0.01 Mean: 0.40 SD: 0.26 | Min: 0.01 Mean: 0.40 SD: 0.26 |
| Sr       | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 |
| Se       | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 |
| Cu       | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 |
| Pb       | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 |
| Zn       | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 | Min: 0.00 Mean: 0.40 SD: 0.26 |

**Note:** Min = Minimum, Max = Maximum, Mean = Mean, SD = Standard Deviation.
skeletal bank, and tidal flat zones (Figure 11). The average number of bed sets in the outcrop is 20, 10, and 10 for stromatoporoids, skeletal bank, and tidal flat, respectively. Accordingly, these bed sets were represented by layers in each corresponding zone with a proportional separation between these layers. Horizontal grids have spacing of one square meter. This grid dimension allows the capture of small-scale facies heterogeneity in the study area. Table 4 shows the properties of the resulting three-dimensional grid. The thicknesses of each of the eight lithofacies in the stratigraphic sections were up-scaled to match the size of the grid cells in each layer.

**Semivariograms Construction**

Indicator semivariograms were constructed for each of the eight lithofacies in the study area (Figure 12). The experimental semivariograms were computed using the thicknesses of lithofacies in the stratigraphic sections up-scaled to the size of the grid cells. Horizontal experimental semivariograms were computed separately for each zone by considering pairs of points belonging to the same grid layer, with a search radius of 200 m and 100 m for east-west and north-south direction, respectively, tolerance angle of 45°, and a bandwidth of 100 m and 50 m for east-west and north-south directions, respectively. Vertical semivariograms were computed by considering only pairs of lithofacies thickness in the same stratigraphic section. The modeled semivariograms were constructed by fitting a spherical model to the experimental semivariograms.

| Gridging System | Stratigraphic Zone | Thickness of Zone (m) | Number of Layers | Number of Cells | Average Cell Thickness (m) |
|-----------------|--------------------|-----------------------|------------------|----------------|---------------------------|
| 3-D grid of the outcrop | Upper Jubaila and Arab-D | 0.45 | 800,000 | 0.45 |
| Zone-1 grid | Tidal Flat | 6.3 | 10 | 200,000 | 0.60 |
| Zone-2 grid | Skeletal Bank | 2.5 | 10 | 200,000 | 0.30 |
| Zone-3 grid | Stromatoporoid | 11.2 | 20 | 400,000 | 0.60 |
The constructed 3-D facies model has an area nearly the size of one cell of a large-scale subsurface 3-D model of the actual Arab-D reservoir in the Ghawar Field (Douglas, 1996). The model of the study area allows the heterogeneity of the reservoir lithofacies to be examined at a higher resolution than that of the subsurface model (Figure 13). The model in this study is intended to generate a simulation of lithofacies proportions for the Arab-D reservoir at the studied outcrop.

3-D Facies Model

The constructed 3-D facies model has an area nearly the size of one cell of a large-scale subsurface 3-D model of the actual Arab-D reservoir in the Ghawar Field (Douglas, 1996). The model of the study area allows the heterogeneity of the reservoir lithofacies to be examined at a higher resolution than that of the subsurface model (Figure 13). The model in this study is intended to generate a simulation of lithofacies proportions for the Arab-D reservoir at the studied outcrop.
Figure 13: 3-D facies model consists of stratigraphic framework through the studied outcrop. (a to c) Part of this model is truncated laterally due to topographical change at the outcrop site. Facies colors codes are plotted at left corner. Note that the model is truncated by limited outcrop exposure. Scales apply to all. (d) Outcrop picture of Wadi Nisah is compared with the large scale features of the 3-D facies model.
Validation of the 3-D Facies Model

Because the 3-D facies model is based on 14 scattered stratigraphic sections, the model should be validated to test its applicability to simulate the geology of the study area. This section focuses on validation of the 3-D facies model by comparison to the outcrop’s present-day topography and stratigraphic observations. The large-scale features of the outcrop were visually examined to test the match with the 3-D facies model. During this step, it was found that the distribution of the four HFSs and their layering in the Upper Jubaila Member closely resembled their outcrop distribution, and the five HFSs in the Arab-D Member are fairly represented by the model. Despite the fact that the Arab-D Member is more heterogonous than the Upper Jubaila Member in this outcrop, the constructed 3-D facies model adequately reproduces their facies distribution as in the exposed strata (Figure 13d).

The ideal way to check the accuracy of the model is the direct comparison of outcrop high-resolution pictures with the constructed model. This can be accomplished by comparing small-scale features such as small-scale tidal channels in the upper section of the outcrop (the Arab-D Member) with the model (Figure 14). The results show acceptable distribution of these geo-bodies in the model in a pattern similar to the outcrop.

![Figure 14: (a) 2-D slice from the 3-D lithofacies model with outcrop stratigraphy. Outcrop picture of Wadi Nisah was used to compare the small-scale features of the outcrop to the 3-D facies model in this case (the arrow is pointing to the north); (b) is wavy rippled sandy grainstones; and (c) breccia and mud-clasts. See Figure 13 for lithology color code.](image-url)
Upper Jurassic Arab-D reservoir model, Central Saudi Arabia

3-D Porosity and Permeability Modeling

Because of the effects of meteoric diagenesis and the long surface exposure of the studied outcrop, the petrophysical data of the outcrop samples do not reflect the conditions of the Arab-D reservoir. The porosity and permeability measurements of the samples collected from the outcrop have very limited ranges. These petrophysical data are not extensive enough to simulate a subsurface petrophysical model.

Therefore, data from equivalent facies from the subsurface Arab-D reservoir with the same facies component, stratigraphic architecture, and stacking pattern were superimposed on the high-resolution 3-D facies model. Petrophysical data from Meyer et al. (2000) were extracted after the subsurface and outcrop facies were correlated. Average porosity and permeability were extracted for each lithofacies equivalent to the outcrop lithofacies (Table 1). Porosity and permeability 3-D models were generated by assigning the extracted average porosity and permeability values from these lithofacies. The small-scale heterogeneity of the lithofacies created in the lithofacies model was represented by small-scale porosity and permeability variability, which could represent high-porosity zones or permeability barriers (Figures 15 and 16).

3-D Spectral Gamma-Ray (SGR) Modeling

The 3-D model of SGR logs of the Arab-D reservoir in the study area is represented by the same gridding system used for facies modeling. The SGR model was generated using a Sequential Gaussian Simulation stochastic approach (SGS). The resulting 3-D SGR models for U, K, and Th showed differences in the Upper Jubaila Member and the Arab-D Member (Figures 17 to 19). There is an obvious upward increase of CPS in all of the three models following the general shallowing upward trend of lithofacies. The stromatoporoid zone showed the lowest CPS values, and the tidal flat zone showed the highest, while the skeletal bank zone represented a transition zone between the stromatoporoid and tidal flat zones.
Figure 16: 3-D permeability model generated by assigning the extracted average permeability values from Meyer et al. (2000). The small-scale lithofacies heterogeneity created in the lithofacies model was represented by small-scale permeability variability (the green arrows are pointing to the north). (a to c) 3-D permeability model in the 3-D volume of each of the three zones; (d) the completed stacked 3-D permeability model. Scales apply to all.

Figure 17: 3-D model of U-SGR of the studied outcrop. (a to c) U-SGR values distributed in the 3-D volume of each of the three zones; (d) the completed stacked 3-D model for U-SGR logs. Note the increasing upward of U-SGR values in the 3-D model (the green arrows are pointing to the north). Scales apply to all.
Figure 18: 3-D model of K-SGR of the studied outcrop. (a to c) K-SGR values distributed in the 3-D volume of each of the three zones; (d) the completed stacked 3-D model for K-SGR logs. Note the increasing upward of K-SGR values in the 3-D model (the arrows are pointing to the north). Scales apply to all.

Figure 19: 3-D model of Th-SGR of the studied outcrop. (a to c) Th-SGR values distributed in the 3-D volume of each of the three zones; (d) the completed stacked 3-D model for Th-SGR logs. Note the increasing upward of Th-SGR values in the 3-D model (the green arrows are pointing to the north). Scales apply to all.
DISCUSSION

Outcrop studies of hydrocarbon reservoirs are important because they facilitate improvement of the exploration and exploitation of hydrocarbon recoveries (Stoudt and Raines, 2004). Carbonate reservoirs are very heterogeneous because of lateral facies changes and diagenetic alteration and commonly yield far less than their estimated reserves. Thus, any improvement of the description of these reservoirs could result in improved recovery.

Studying outcrops equivalent to the Arab-D reservoir at high-resolution scale helps us to understand the reservoir heterogeneity, reservoir stacking patterns, sequence hierarchy, and lateral facies change. As indicated by Meyer et al. (1996), this outcropping stratum is equivalent and similar in stacking pattern to the Arab-D reservoir and has the following characteristics: (1) the muddy-grainy-muddy stacking pattern of the outcropping facies is similar to that of the Arab-D reservoir and indicates poor vertical connectivity of the reservoir facies; (2) the pinching out of the grain-dominated facies in the upper part of the outcrop (Arab-D Member) may also indicate poor horizontal permeability. This study allows these two observations to be visualized in a 3-D framework and therefore provides more understanding of facies distribution and their effect on petrophysical properties at a higher order of resolution than in the subsurface. When the petrophysical data of the Arab-D reservoir is superimposed on the high-resolution 3-D facies model, the resulting petrophysical model introduces small-scale heterogeneity into the lithofacies model and clearly illustrates the above-mentioned observation about vertical and horizontal permeability.

The subsurface lithofacies of the Arab-D reservoir show lateral changes in the thickness from south to north in the Ghawar Field (Mitchell et al., 1988; Handford et al., 2002). These authors and Lindsay et al. (2006) interpreted this change in thickness as an increase of the evaporite/carbonate ratio towards the north, which was attributed to the change of the depositional environments from a deep intra-shelf basin in the south to a shallower setting in the north. The same scenario may be applicable when comparing the outcropping strata in Central Saudi Arabia to the Arab-D reservoir in the Ghawar Field in eastern Saudi Arabia. The muddier lithofacies and the scarcity of a biofacies component indicated that the outcrop is situated in a more lagoonal and tidal flat setting, especially those intervals within the Arab-D Member (skeletal bank and tidal flat zones).

The accommodation space available for the Arab-D reservoir that did not extend to the outcrop location, is also reflected in the biocomponents diversity of the study area. Although the Upper Jurassic Arab-D reservoir has excellent biocomponents diversity (Hughes, 1996; 2004a, b, 2009), samples from the outcrop succession show very low biocomponents diversity. The scarcity of microfossils and dasyclad algae indicate slightly different environmental conditions from those of the Arab-D reservoir and may be related to environmental conditions such as elevated salinity.

Although there is a limited biofacies component in the study area, key biocomponents are present and support the analogy of this outcrop to the Upper Jurassic Arab-D reservoir. The presence of Kurnubia palastimensis, Nautiloculina olithica, and Quinqueloculina spp. in the outcrop samples suggest a Kimmeridgian age for the succession (Okla, 1986; Hughes, 2004a, b, 2009). During the Kimmeridgian, the seawater $^{87}$Sr/$^{86}$Sr curve shows a minimum $^{87}$Sr/$^{86}$Sr ratio between 0.7068 and 0.7069 (Veizer et al., 1999). The $^{87}$Sr/$^{86}$Sr data of the outcrop samples are clearly higher than the Kimmeridgian age seawater $^{87}$Sr/$^{86}$Sr. The $^{87}$Sr/$^{86}$Sr ratios of the HCl-soluble fractions of the dissolved samples are still higher than expected for the Kimmeridgian age, but exhibited lower values than those obtained by bulk analysis and relatively similar values to the subsurface Arab-D reservoir of Lindsay et al. (2006) and Morad et al. (2012) (Figure 20). Possible reasons for this high $^{87}$Sr/$^{86}$Sr ratio include the following:

(1) Rocks are a mixture of carbonate and a minor amount of siliciclastic components. The siliciclastic components could have no seawater isotope signature if they were derived from a continental source.

(2) Dissolved materials from an overlying Cretaceous interval could have elevated the $^{87}$Sr/$^{86}$Sr ratio in the studied interval.
XRD data show that two of the four identified mineral phases, kaolinite and potassium feldspar, can have relatively high strontium concentrations with radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The occurrence of high amounts of kaolinite and a clearly identifiable potassium feldspar signal is consistent with a relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. This observation supports the assumption of the presence of carbonate mixed with a minor amount of siliciclastic material. The presence of goethite might indicate development of paleosoil, which in turn may indicate the exposure of the corresponding interval of the samples and increased siliciclastic input.

In sample S1-10, however, the calculated weight percentage of silicates within the whole carbonate sample is only 1.1%, the lowest value of the four samples. The percentage of silicates in the carbonates does not seem to systematically influence the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. The petrographic investigation of this sample indicated that this sample consists of dedolomite facies. The high $^{87}\text{Sr}/^{86}\text{Sr}$ could therefore be related to meteoric processes dissolving the overlying stratigraphic interval with high $^{87}\text{Sr}/^{86}\text{Sr}$ and influencing the underlying section with high $^{87}\text{Sr}/^{86}\text{Sr}$ (the second assumption). The corresponding $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data showed very high values, indicating the influence of meteoric processes and supporting the second scenario as the cause of the high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio.

There is an obvious upward increase of CPS in all the three SGR models (U, Th, and K) following the general shallowing upward trend of lithofacies. The stromatoporoid zone showed the lowest CPS values in the models, and the tidal flat zone showed the highest CPS values in the models, while the skeletal bank zone represents a transition between these two zones. This observation supports the depositional environment interpreted for the lithofacies association (shoaling upward) as well as the paleoenvironments reconstructed from biofacies. The geochemical data showed a similar pattern of having higher concentrations of most elements and oxides in the Arab-D Member than in the Upper Jubaila Member (Eltom et al., 2013a). This suggests that the Arab-D Member received more siliciclastic input than the Upper Jubaila Member. This could be due to the following three possible scenarios:

1. The Arab-D Member may have received more detrital material than the Upper Jubaila Member because of its proximity to land. These materials may have fractionated from silicate minerals brought to the basin by land progradation.

2. The Arab-D and Upper Jubaila members could have received the same amount of detrital material; however, the Upper Jubaila Member had higher solubility due to the deep-water conditions and therefore retained a lower concentration.

3. It is possible that the wind direction changed between the times that the Arab-D Member and the Upper Jubaila were deposited.

Figure 20: A diagram comparing $^{87}\text{Sr}/^{86}\text{Sr}$ ratio data for (a) bulk $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the selected four outcrop samples before HCl dissolution performed; (b) soluble carbonate fraction $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the selected four outcrop samples after HCl dissolution performed; (c) published $^{87}\text{Sr}/^{86}\text{Sr}$ ratio data for Arab-D reservoir in Ghawar Field (Lindsay et al., 2006); (d) published $^{87}\text{Sr}/^{86}\text{Sr}$ ratio data for Arab-D reservoir in a United Arab Emirates Field (Morad et al., 2012); (e) published $^{87}\text{Sr}/^{86}\text{Sr}$ ratio data for Kimmeridgian age rocks (Veizer et al., 1999).
**Study Limitations**

Outcrop studies proved to be a suitable proxy for reservoir characterization and modeling because they provide an approximation of what geologists may encounter in the subsurface reservoirs. In this study, outcrop strata equivalent to the Arab-D reservoir was used to conceptualize the depositional environments, paleogeography, spatial distribution, and petrophysical 3-D distribution of the reservoir equivalent facies. However, as indicated by White et al. (2004), it is not easy to find a perfect outcrop that is completely similar to the subsurface reservoir, and there are always some limitations of outcrop studies. Some geological characters of the hydrocarbon reservoir can be observed both in the subsurface and outcrop while some may not.

The features that can be observed in the outcropping Arab-D strata and the Arab-D reservoir were discussed by Meyer et al. (1996). Several features are present in the Arab-D reservoir that cannot be observed in the outcrop. The porosity and permeability data of the outcrop does not reflect the real characteristics of the Arab-D reservoir because the pore system was completely cemented by meteoric cementation. The lack of sufficient porosity and permeability data from outcrop samples limited the understanding of the pore system distribution, pore system connectivity, and porosity-permeability relationship in the outcrop.

Meteoric cementation also changes the isotopic signature of lithofacies and shifted the oxygen and carbon isotopes toward more negative values. This makes the interpretation of the diagenetic regime of the Arab-D reservoir in the outcrop difficult. The high values of negative oxygen and carbon isotopes also limit the understanding of the dolomitization and dedolomitization processes and occurrence in the Arab-D reservoir outcrop analog (Cantrell et al., 2007). Non-fabric preserving dolomite associated with high permeability (super-K interval) in the Arab-D reservoir was clearly defined from other dolomitic intervals by their isotopic signatures (Cantrell et al., 2001; Swart et al., 2005). Conversely, this dolomitic interval could not be distinguished based on the isotopic signature in the outcrop, although it was petrographically observed. This is also attributed to the long exposure of the outcrop and the heavy meteoric cementation. The Arab-D outcropping strata showed less biocomponents diversity than that of the reservoir. This may limit the process of the reconstruction of reservoir paleoenvironment in the outcrop. The outcrop locations discussed in this study have strike and dip exposures; however, exposures along strike have the best continuity, following the general trend of Central Saudi Arabia uplift. The conceptual and geostatistical facies models discussed in this study are hampered by the limited dip direction exposure of the outcrops. Because there was no proposed shallow drilling program for this study, adding dip direction as an additional dimension to the outcrop models remains an upcoming task.

**CONCLUSIONS**

Sedimentological and stratigraphic analysis of outcropping strata in Wadi Nisah, Central Saudi Arabia, equivalent to the Arab-D reservoir unit, showed that they are composed of three lithofacies associations. At the base is a stromatoporoid lithofacies association, composed of dolomitic mudstones, dolomitic wackestones and stromatoporoid wackestones and packstones. A skeletal bank lithofacies association included burrowed fossiliferous wackestones and peloidal fossiliferous grainstones and a tidal flat association is composed of laminated mudstones, wavy rippled sandy grainstones and mud sheets with rip up clasts.

The biocomponents of the study area show a lower degree of diversity than the Arab-D reservoir; however, some key biofacies are present and provide paleoenvironmental and reservoir zonation indicators.

\[^{87}\text{Sr}/^{86}\text{Sr}\] data showed clearly higher values than Kimmeridgian age (Arab-D reservoir time span) values. This was attributed to the fact that rocks sampled in outcrop are carbonates, contaminated by a minor amount of siliciclastic and dissolved materials from an overlying Cretaceous interval, which contain a higher amount of \[^{87}\text{Sr}/^{86}\text{Sr}\] than primary ratios expected in the studied interval.
Upper Jurassic Arab-D reservoir model, Central Saudi Arabia

Geochemical analyses show strong correlations between major and trace elements in the reservoir facies. The geochemical data also suggest that concentrations of the elements and the corresponding SGR counts follow the same general upward shoaling system.

The stratigraphic sections were used to build a 3-D geocellular model of the outcrop units to visualize the facies variability and distribution over short distances. The 3-D geocellular model was converted to a petrophysical model by assigning porosity and permeability values from the subsurface data. The petrophysical model highlights the small-scale variability of the petrophysical data.

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