Lithofacies, diagenesis and reservoir quality of Upper Shu’aiba reservoirs in northwestern Oman

Naima Al Habsi, Mohammed Al Shukaili, Sabah Al Tooqi, Stephen N. Ehrenberg and Michaela Bernecker

ABSTRACT

Core and log data from Lower Cretaceous limestones of the Upper Shu’aiba Member were used to characterize the distribution of lithofacies, clay and porosity within two low-angle clinoforms that form the reservoirs for an oilfield of northwestern Oman. Data from 15 vertical wells, including four with core, and four horizontal well cores were projected into a dip-oriented cross-section derived from a static reservoir model as a basis for visualizing the above variations. Each clinoform consists of a basal “argillaceous zone” and a thicker “reservoir zone” of clean limestone, together reflecting fourth-order cycles of progradation along the margin of the Bab intra-shelf basin. Lithofacies vary in a proximal direction from mudstone and wackestone (mid-ramp) to mud-dominated packstone (slope) to mud-rich floatstone, rudstone and boundstone (ramp crest) and are arranged in a pattern of decreasing water depth and increasing energy both upwards and landward within each clinoform. In contrast, the reservoir zone of a younger clinoform from a nearby oilfield consists of well-sorted grainstone and grain-dominated packstone, illustrating the wide range of depositional conditions that occurred in the ramp-crest facies belt of different units.

Except within the proximal extent of the younger clinoform, where values are transitional toward reservoir zone values, the argillaceous zones have total porosity mostly < 10% and baseline-normalized gamma-ray (GR) activity > 23 API units, reflecting clay contents of around 10–18%. In contrast, most parts of the reservoir zones have GR of 15–23 API units and porosity of 10–35%. Higher clay content is suggested to be linked with lower porosity through facilitation of both mechanical and chemical compaction, the latter providing a local supply of calcite cement. XRD analyses show that the clays are kaolin, illite/smectite and illite, similar to the clays in the overlying Nahr Umr shale. Most former macropores have been filled by blocky calcite cement in the main oilfield studied, but all lithofacies have similar wide ranges of total porosity of 8% to > 30%.

The cores were also studied for evidence of diagenesis related to the contact with the overlying Nahr Umr Formation, but profiles of stable-isotope ratios, bulk-rock strontium, petrography and porosity-permeability data show no trends indicative of upward-increasing meteoric diagenesis below this sequence boundary. Meteoric leaching could nevertheless be pervasive throughout the Upper Shu’aiba reservoirs, at least partially accounting for extensive aragonite dissolution and low Sr and δ^{18}O values. Two of the cores show trends of upwards-increasing bulk-rock uranium, manganese and iron, possibly indicative of sea-floor authigenesis. In addition, saddle dolomite near the tops of these cores may reflect late influx of magnesium derived from clay in the Nahr Umr Formation.

INTRODUCTION

Reservoirs of the lower member of the Shu’aiba Formation have been extensively studied over the past three decades in many giant oilfields throughout the southeastern Arabian Plate (Frost et al., 1983; Litsey et al., 1983; van Buchem et al., 2010). In contrast, the Upper Shu’aiba Member is more restricted geographically (Figure 1) and contains relatively small oil volumes that have only recently
begun to be exploited. Proportionately little information has been published on Upper Shu’aiba reservoirs, other than Boote and Mou (2003) on Safah Field in Oman and the comprehensive study of the Upper Shu’aiba in Abu Dhabi Emirate by Pierson et al. (2010) and Maurer et al. (2010). The present study provides details from Upper Shu’aiba oilfields in northwestern Oman, where exploration and development activities have recently increased. A series of cores were studied together with wireline logs and a reservoir model to characterize the nature and spatial distribution of lithofacies and petrophysical properties in several Upper Shu’aiba depositional cycles.

A particular focus of this study is the hiatus and sequence boundary at the top of the Upper Shu’aiba Member, where the limestones are overlain and sealed by shale from a distant deltaic source. Surfaces representing hiatuses and major paleoenvironmental changes in shallow marine carbonates, termed “discontinuity surfaces” by Immenhauser et al. (2000), are of great scientific and practical interest. They typically form the boundaries of both depositional packages and petroleum reservoirs, as well as being the locus of important diagenetic processes that determine petrophysical properties. Such surfaces are often enigmatic and intriguing: the condensed remnants of possibly complex events of global significance.

**GEOLOGICAL SETTING**

The studied reservoirs comprise several clinoform bodies of the Upper Shu’aiba Member that were deposited in Early Cretaceous time (Late Aptian) as the Bab intra-self basin was infilled by a series of low-angle clinoforms that prograded distances of 20–40 km inward from the basin margins (Figures 1 and 2). Upper Shu’aiba strata are confined within the Bab Basin and formed during a major lowstand of sea level that exposed basin margins and surrounding terrain consisting of Lower Aptian limestones of the Lower Shu’aiba Member (Pierson et al., 2010; Maurer et al., 2010). Successive clinoforms may be recognized in individual wells by alternating intervals of higher and lower gamma-ray activity. Maurer et al. (2010) illustrate examples of well data showing basal argillaceous intervals and overlying clean limestones comprising different Upper Shu’aiba clinoforms. In Oman, each clinoform is described as comprising a basal “argillaceous zone” (herein designated “J-arg” for the J clinoform) and an overlying “reservoir zone” of relatively clean limestone (designated “J-res” for the J clinoform).

Al-Husseini and Matthews (2010) and Maurer et al. (2013) propose that each pulse of Upper Shu’aiba clinoform progradation that is resolvable on available seismic data represents a cycle of glacio-eustatic sea-level fluctuation of approximately 400–500 Kyr duration. Well data show that several of these seismic-scale clinoforms are comprised of smaller clinoform units presumably reflecting higher-order cycles of eustatic fluctuations, as illustrated in figure 8 of Maurer et al. (2010).

Seismic imaging shows that individual Upper Shu’aiba clinoforms in Abu Dhabi have remarkable lateral continuity for tens of kilometers, which Pierson et al. (2010) suggest to result from: (1) a continuous narrow zone of high carbonate productivity paralleling the Bab Basin shoreline during each highstand, and (2) a system of persistent wind- or tide-driven longshore drift of siliciclastic fines. Seismic mapping indicates similar lateral continuity in northwest Oman (Figure 1b).

The Upper Shu’aiba clinoforms in northern Oman are informally identified within PDO by letter symbols A through O from younger to older, and an additional five clinoforms younger than the A clinoform were subsequently identified as comprising the final stages of basin infill. The six cored wells used in the present study are from an oilfield with production from the K and J clinoforms. These therefore represent the fifth and sixth clinoform cycles out of a series of twenty depositional cycles of ostensibly similar magnitude that have been recognized in northwest Oman as constituting the progradational infill of the Bab Basin during sequence Ap 5 of Figure 2. Identification of the exact position of the K and J clinoforms within the series of Upper Shu’aiba clinoform sequences recognized in Abu Dhabi by Pierson et al. (2010) is uncertain. Within the context of Figure 2, the individual Upper Shu’aiba clinoform cycles are schematically represented by the zig-zag contact between the light blue and the brown (Bab Member) colors in third-order sequence Apt 5.
Figure 1: Location of the study area shown on (a) a slightly modified Late Aptian paleogeographic map of van Buchem et al. (2010) and (b) Late Aptian paleogeographic map from figure 25 of Droste (2010). Rectangles in (b) show the general locations of oilfields studied in the present work (labeled by the clinoform reservoirs in each). The dashed arcuate lines in (b) represent trends in Upper Shu’aiba seismic amplitude character thought to follow clinoform depositional trends. Light blue areas around the Bab Basin (prograding carbonate slope deposits) correspond with the distribution of Upper Shu’aiba clinoforms. Outlines and names of oilfields are copied from figure 19 of Boote and Mou (2003).
In addition to the main coverage of the K and J clinoforms, one of the present cores (well 5) includes parts of the younger H and I clinoforms, and one core extends a few meters into the older L clinoform. Two additional cores were also described from nearby oilfields that produce from the A and B clinoforms, respectively. These cores were included to provide additional information on the range of lithofacies and petrophysical properties present in the overall Upper Shu'aiba depositional system.

The main oilfield studied has an area of roughly 12 km along depositional strike by 4 km in the dip direction. The reservoirs are presently at their maximum burial depth of 1.4–1.5 km at 80°C. Most cores are located above the oil/water contact, but one (from well 4) is from the water zone.

The top of the Upper Shu’aiba Member corresponds to a hiatus along which the duration increases from the central part of the Bab Basin towards the edges. The maximum duration, overlying the oldest clinoform along the basin margins, could be as much as 5 million years (Figure 2). The maximum hiatus at the top of the K and J clinoforms of the present study would be somewhat less than 5 Myr because there are an additional four clinoforms (O through L) older than the K clinoform. The K and J clinoforms are thus the fifth and sixth clinoforms out of a total of 20 Upper Shu’aiba clinoforms identified in northern Oman. If these clinoforms each represent uniform time intervals, then individual durations of 250 Kyr are indicated. In this case, the hiatus at the top of the K clinoform may be around 4.75 Myr. Maurer et al. (2013), however, propose that each clinoform may represent a duration of 400–500 Kyr, in which case the top-K hiatus might be around 3.0 to 2.5 Myr.

During this time, the tops of the K and J clinoforms could have been subaerially exposed, alternately exposed and reflowed by seawater, or continuously submerged below shallow seawater. The clinoform tops may have been eroded, or may have accumulated minor additional sediment, or both, or may simply have been preserved with no loss or addition. Although the climate is reported to have
been warm and humid during Early Cretaceous time, the Late Aptian is interpreted to have been relatively cooler, with evidence for major glaciation in high latitudes and 400–500 Kyr glacio-eustatic fluctuations that caused the Upper Shu’aiba clinoform cyclicity (Maurer et al., 2013).

METHODS

The database for the present study includes 15 vertical wells from the main oilfield studied, four of which have a total of 127.9 m of whole core, plus 4 horizontal wells having a total of 38.4 meters of core. Wells A and B from two nearby oilfields are vertical and recovered 8.9 m and 7.4 m of core, respectively. Conventional core analyses (CCA) of helium porosity, gas permeability and grain density were performed by commercial laboratories using industry-standard methods.

A series of 195 core samples, mostly corresponding with CCA plugs, was selected to cover the ranges of depth and lithofacies in each of the cored intervals. The samples were examined to remove any material of extraneous origin, such as mud cake. All samples were analyzed for bulk chemical composition by SGS Minerals Services of Toronto, Canada, using a combination of x-ray fluorescence (Si, Ti, Al, Fe, Mn, Mg, Ca, K, P, Rb, Sr, Zr, Ba), neutron activation (Na, Cr, As, Br, Sb, REE, Hg, Th), coulometry (CO2), specific ion (Cl) and Leco instrument (S and C). Uranium was determined by delayed neutron counting (detection limit = 0.1 ppm; Aldayel et al., 2002). A selection of 28 of these samples were also analyzed by bulk-rock X-ray diffraction (XRD) at Macaulay Scientific Consulting Ltd. of Craigiebuckler, Aberdeen, Scotland.

Bulk-carbonate oxygen- and carbon-isotope ratios were analyzed by the Environmental Isotope Laboratory of the Department of Earth and Environmental Science, University of Waterloo, Canada. Finely ground bulk-rock samples were reacted with 100% phosphoric acid in sealed vials for more than one hour at 90°C to dissolve all calcite and dolomite present. The CO2 was extracted, purified and then analyzed with a GV1 IsoPrime continuous flow isotope ratio mass spectrometer. Standards were run throughout each 60 sample batch, and duplicates were run approximately every tenth sample.

Thin sections were impregnated with blue epoxy to facilitate identification of pore spaces and are polished on both top and bottom surfaces for optimal petrographic resolution. Thin sections containing more than a few percent carbonate cement (thus excluding most mudstone, wackestone and shale samples) were stained over half their surface with alizarin red and potassium ferricyanide. The thin sections were described using a set of standard categories of information recorded in spreadsheet format. Biotic assemblages, cements and stylolites were noted by a system of numerical scoring. Percentages of visible porosity and total cement were estimated using comparator charts.

Cores were described on A3 sheets at a scale of 3.5 cm = 10 cm (roughly 1:3). Data from available thin sections, including 195 prepared for the present study and 118 older thin sections available from PDO, were posted on the core-description sheets, and an atlas of photomicrographs at standardized scale was consulted during core description.

RESULTS

Clinoform Geometry

The K and J reservoirs of the main oilfield studied were examined in a digital reservoir model in order to visualize their geometry with respect to the top-Upper Shu’aiba surface and the well locations. This model was made by PDO using data from wells and a three-dimensional seismic survey and was not altered for the present study. Using this model, a subcrop map was made showing where the different clinoform units and the vertical wells intersect the top-Upper Shu’aiba surface (Figure 3).

A series of dip-oriented cross-sections was made through the model showing the well and core locations with respect to the clinoform geometries (Figure 4). The cross-sections were then flattened on the base of the Nahr Umr Formation to better show depositional geometries (Figure 5). Data for
Figure 3: Subcrop map of the top-Upper Shu’aiba surface showing areas where clinoform strata are in contact with the base of the Nahr Umr Formation in the area of the main oilfield studied. Cross-sections and 15 vertical wells are labeled and shown in Figure 5.

Figure 4: Cross-sections of the K and J clinoforms from the reservoir model. Locations of cored vertical and horizontal wells are shown, projected into the cross-section lines with approximate positions of cored intervals marked by thick black lines.

The cored intervals and wireline log curves for gamma ray (GR) and total porosity were plotted at true vertical depth so that hole deviations would not affect apparent stratigraphic thicknesses (Figure 6). In most of the reservoir model area, the K clinoform is roughly twice as thick as the J clinoform. However, this relationship varies laterally, with the J clinoform becoming thicker than the K clinoform in the eastern part of the area.
Figure 5: Cross-sections of the K and J clinoforms in the reservoir model, flattened on the base of the Nahr Umr Formation. Locations of vertical wells are shown, projected into the cross-section lines as shown in Figure 3. Simplified representations of core descriptions are shown in their approximate positions.
Figure 6: Profiles of wireline-log gamma-ray (brown) and porosity (blue) in vertical wells penetrating the J and K clinoforms. Wells are arranged in approximate dip direction from basinward (top left) to landward (bottom right). Depths vary from well to well, but vertical scale in meters true vertical depth is constant. Dashed vertical lines mark 20% porosity value. Tops of "argillaceous zones" (intervals of higher gamma-ray activity marked by thicker black vertical lines) are correlated.
To illustrate the main features of the K and J clinoforms, the individual cross-sections were combined into a composite dip-oriented cross-section, with model artifacts like apparent faults and folds removed (Figure 7). The 15 vertical wells from which log data are available were projected laterally into the composite cross-section in their approximate relative positions from distances of 0 to 8.5 km along strike.

Depositional Facies

Nine core-scale limestone lithofacies were defined in the Upper Shu’aiba Member based on study of thin sections and slabbed cores, and two siliciclastic lithofacies were defined in short intervals of core in the Nahr Umr Formation (Table 1; Figure 8). Distinctions between the limestone lithofacies are determined by the textural classification of Dunham (1962), as modified by Embry and Kloven (1971) and Lucia (1995), and by biotic assemblages. Care was taken to use the terminology of Lucia (1995) to

Figure 7: Composite dip-oriented cross-section through a reservoir model of the two clinoform units studied, flattened on the base of the Nahr Umr Formation. The margin of the Bab Basin is toward the right, and the basin center is to the left. (a) Laterally projected positions of 15 vertical wells and 4 horizontal well cores. Simplified core descriptions show the main lithofacies, used to interpret three main lithofacies belts.

Figure 7: (b) Intervals of higher porosity (red) and lower porosity (blue), correlated from log profiles. White areas have porosity mostly between 10% and 20%. Well numbers are shown at top of panel.
Table 1: Lithofacies recognized in the Upper Shu'aiba cores.

| Lithofacies                  | Constituents                                                                 | Sedimentary texture and structures                                                                 | Depositional environment                      |
|-----------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| LF-1 Mudstone and wackestone | In many cases, the dominant or sole bioclast type is ooid or grainstone assemblages. Additional (sparry) assemblages include peloids, miliolids, sponge spicules, echinoids, green algae, crab legs, and fragments likely originating from various molluscs. | Although distinct beds of either mudstone or wackestone can be recognized on the core surfaces, these are grouped as a single lithofacies because the two textural divisions are commonly intimately associated (kisses or thin layers of one in the other), and petrographic observations indicate gradational and overlapping characteristics. Common bioerosion. | Upper to middle slope, below fair-weather wave base. |
| LF-2 Mud-dominated packstone | Peloids comprise the dominant volumetric component (Figure 8b). Bioclasts, of generally larger size than the enclosing peloids, include variable assemblages of ooids (both discoidal and conical shapes), miliolids, other benthic foraminifers, sponge spicules and fragments of various molluscs, green algae, echinoids and crab legs. | Many samples are gradational into wackestone, but with the peloids recognizable throughout most of the area of the thin section. Subordinate intervals classified as LF-2 or LF-3 are technically floatstone in that somewhat more than 10% of clasts, especially ooids, slightly exceed 2 mm in maximum dimension, but these have been recorded as packstone to avoid artificial semantic distinctions. | LF-3 reflects conditions of higher current energy with respect to LF-2. |
| LF-3 Poorly sorted grain-dominated packstone | The bioclast assemblages are similar to LF-2, except that peloids and coated grains tend to be more abundant; LF-3 is gradational with LF-2, but is distinguished by coarser grain size, with predominance of robust (conical) ooids contrasting with surrounding smaller bioclasts and peloids, typically resulting in a distinctly bimodal grain-size distribution (Figure 8c). | Thin sections and core surfaces have massive, non-laminated appearance. | A shallow-water shoal setting similar to LF-5, but with lower current energy. |
| LF-4 Laminated grain-dominated packstone | This lithofacies, present only in well A, consists of relatively sorted grains mainly 0.03–0.4 mm in diameter of peloids, miliolids and green algae with sparse ooid (Figure 8d). Many grains have single coatings of radially oriented, fibrous marine cement or micritized edges. | Thin sections of intervals of LF-4 and LF-7 include a few samples with wackestone or packstone between the larger clasts. | Thin sections reflect variations in grain size, mud and miliolids. LF-4 is gradational into LF-5. |
| LF-5 Grainswaste | The large clasts in LF-6 (Figure 8e) include variable combinations of rudists and serpuloids and subordinate corals, bivalves, gastropods, echinoids and encrustations of Lithocodium/Bacinella, red algae and probable miliolids. A common bioclast seen in this section is crab legs (Schlagintweit et al., 2003; 2007), with cross-sections generally 1–3 mm in maximum dimension. The matrix consists of either mud or fine pebbles with varying content of fragments of the above plus ooids, miliolids, other benthic foraminifers and sponge spicules. | The core surfaces show that larger clast types are in places highly variable over short vertical intervals. | A shallow-water shoal setting similar to LF-5, but with lower current energy. |
| LF-6 Floatstone with bioclasts mostly <2 cm | This lithofacies is present only in well A, consists of well sorted grains mainly 0.1–0.3 mm in diameter of peloids, miliolids and green algae (Figure 8e). Many grains have single coatings of radially oriented, fibrous marine cement or micritized edges, overain by isopachous fine mosaic calcite. | Laminations reflect variations in grain size, mud and miliolids. LF-4 is gradational into LF-5. | LF-5 formed near the crest of a shallow-water sand shoal or in a tidal channel, where currents winnowed and reworked the sand to remove most mud and form simple ooidal coatings on a large proportion of grains. This setting contrasts with the more mud-rich environments of the other cores. |
| LF-7 Floatstone and rudstone with large (3–10 cm) bioclasts | The thin sections from intervals of LF-6 and LF-7 include a few samples with wackestone or packstone texture, apparently due to location of plug samples between the larger clasts. | The core surfaces show that larger clast types are in places highly variable over short vertical intervals. | Ramp crest. |
| LF-8 Lithocodium/Bacinella boundstone | This lithofacies comprises one 8.0 m-long interval in horizontal well 3H2 (2,483.0–2,491.0 m). The core surface shows clasts of sponges, rudists, corals and Lithocodium/Bacinella with patches of muddy matrix containing finer clasts. All of the above are bound by an intricate framework of Lithocodium/Bacinella (Figure 8f), and irregular, undulose bedding surfaces are defined by anastomosing layers/censes of darker, apparently angular grain intraclasts. | The core surfaces show that larger clast types are in places highly variable over short vertical intervals. | Ramp crest. |
| LF-9 Rudist boundstone | Two short core intervals (well 2, 1,466.9–1,468.5 m core depth and well 4, 1,512.0–1,513.1 m) are composed dominantly of whole rudists 5–10 cm in diameter, many of which appear to be in life position. The shells provide mutual support, are in places bound by encrusting material, and thus baffle the packstone matrix. Thin sections from these intervals include either only matrix or part of a single large shell. Subordinate sponges and corals are present in places, such that the bioclastic assemblage is similar to that of LF-6 and LF-7. | The core surfaces show that larger clast types are in places highly variable over short vertical intervals. | Ramp crest. |
| LF-10 Shale | Short intervals of clay shale with minor quartz silt and sparse pyritized bioclasts were recovered from the lowest Nahr Umm Formation in wells 1 and 4. | Intense bioerosion. Because of the abundant clay matrix, there is no macroporosity, and transmissibility and permeability are likely to be very low. In places, the texture is matrix-supported. This rock is likely to contribute to the seal rather than being reservoir. | Condensed sedimentation in a shallow marine setting. Similar lithology is described as part of a more diverse range of lithofacies forming a condensed fanglomerate siliciclastic unit 15 to 18 m thick at the base of the Nahr Umm Formation in Qatar (Raven et al., 2010). |
| LF-11 Goethite-ooid sandstone | An interval 0.4 m thick was recovered at the base of the Nahr Umm Formation in well 4. The rock consists of medium to very coarse sand size goethite ooids, subordinate lithoclasts of goethite-rich rock, and minor quartz concentrated in lens-shaped patches in clay matrix containing euhedral siltite crystals. A few % of the ooids have nuclei of glauconite pellets. An XRD analysis of one sample reports 39% goethite, 25% illite/muscovite, 20% kaolinite, 9% siderite and minor quartz and K-feldspar. | Intense bioerosion. Because of the abundant clay matrix, there is no macroporosity, and transmissibility and permeability are likely to be very low. In places, the texture is matrix-supported. This rock is likely to contribute to the seal rather than being reservoir. | Condensed sedimentation in a shallow marine setting. Similar lithology is described as part of a more diverse range of lithofacies forming a condensed fanglomerate siliciclastic unit 15 to 18 m thick at the base of the Nahr Umm Formation in Qatar (Raven et al., 2010). |
differentiate between packstones which are “mud-dominated” (all intergranular space filled by mud) and “grain-dominated” (intergranular space filled partly by mud, but with significant proportions of open space or cement). The distribution of lithofacies and the textures determined in the thin sections are shown for each core in Figure 9. This figure may be compared with Figures 10 and 11 to see how lithofacies variations are expressed in the wireline-log curves and CCA data.

Lithofacies LF-7 and LF-9 are not readily distinguishable from LF-6 in thin section because their diagnostic fabric elements are much larger than the 2 to 3.5 cm dimensions of the thin sections used, and because of highly heterogeneous fabrics. In plots of plug-scale petrographic and petrophysical data, therefore, most samples from LF-7 and LF-9 are included with LF-6, except in a few cases where the material included in the thin section has entirely missed the larger fabric elements, resulting in a packstone or wackestone fabric at plug scale (LF-1, LF-2, or LF-3).

The positions of three main lithofacies belts in the clinoforms were interpreted from the core descriptions (Figure 7a). Lithofacies in the reservoir zones vary in a proximal direction from mudstone/wackestone to mud-dominated packstone (shown by comparison of the cores from wells 5 and 5H2 in zone J-res) and from mud-dominated packstone to floatstone, rudstone and boundstone (shown by comparison of well 5H2 versus wells 2H4, 4 and 1 in zone J-res and by comparison of wells 4 and 1 versus wells 1H4, 3H2 and 2 in zone K-res).

The distal-proximal core comparisons possible for the argillaceous zones are more limited. Zone J-arg varies from mudstone/wackestone in well 5 to mud-dominated packstone and floatstone in wells 4 and 1. This landward-coarsening trend is consistent with the wireline-log trends of decreasing GR and increasing porosity in the proximal direction in zone J-arg (Figure 6). In zone K-arg, however, no such landward trends are apparent. Mudstone/wackestone comprises the K-arg core intervals from both well 4 and well 2, and the wireline logs show no evidence of distal-to-proximal variation in this zone (Figure 6).

Vertical facies relationships observed in the different cores show overall patterns of upward increase in depositional energy and decreasing paleo-water depth from the argillaceous zones into overlying reservoir zones. Within the argillaceous zones, the same general direction of upward changes in facies is observed in some cores, but not in other locations:

- Zone J-arg shows upward transition from mud-dominated packstone to dominantly floatstone in wells 1 and 4.
- Zone J-arg also shows upward transition from mudstone to wackestone in well 5.
- Zone K-arg shows no apparent vertical facies trend in well 2.
- Zone I-arg shows no apparent vertical facies trend in well 5.
- Zone H-arg, corresponding to the top 8.8 m of the core in well 5, comprises two distinct facies trends. The lower 5.4 m of this 8.8 m interval shows an upward-shoaling trend from wackestone to packstone to a thin bed of floatstone. The upper 3.4 m of the core consists of mudstone and wackestone apparently representing a deeper-water setting than the floatstone and packstone.

No distinctive back-shoal lithofacies were identified in the present study, although back-shoal deposits consisting of bioturbated mudstone, wackestone and mud-dominated packstone are likely to be an important feature of these clinoforms, as was documented in Upper Shu’aiba cores from Abu Dhabi (Pierson et al., 2010). A back-shoal facies belt was not delineated in the present study, however, because of the limited core coverage of the most landward parts of the K and J clinoforms and because the cored intervals most likely to represent such deposits do not appear to have such distinctive characteristics as to support a separate classification.
Distinction between Reservoir and Argillaceous Zones

In general, the K and J argillaceous zones are recognized by wireline-log character as having baseline-normalized GR values mostly > 23 API units and total porosity mostly < 10% (Figure 6). In contrast, the K and J reservoir zones have porosity mainly > 10% and comprise large volumes of rock with porosity of 20–30%. In addition, hydrocarbon saturations tend to be much lower in the argillaceous zones, although these values, of course, vary widely depending on position with respect to the oil-water contact.

The zone boundaries defined by the above criteria are also correlative between wells based on wireline-log profiles, especially using GR log shape. These correlations show, however, that the J-arg zone becomes poorly defined in the more proximal, up-dip direction, and is an exception to the above GR and porosity criteria in wells 4, 13, 1, 7, and 19. Here the J-arg zone has relatively low GR (around 20–23 API units or even lower in some intervals) and log porosity values somewhat higher than 10%. Well 10 is also in a proximal position in zone J-arg, but has typically “argillaceous” high GR and low porosity (Figure 6). Zone K-arg, on the other hand, does not display any apparent decrease in argillaceous character in the proximal direction, at least as far as the available well coverage shows.
Examination of the core and thin-section descriptions, in comparison with the zone boundaries defined by the above criteria and correlations, shows that textures and lithofacies overlap extensively between the reservoir and argillaceous zones. Floatstone texture, for example, occurs within both the reservoir zones and argillaceous zones. Furthermore, the top of a reservoir zone or an argillaceous zone in any given core commonly occurs within an interval of a particular lithofacies, rather than at the bed boundary between two different lithofacies (Figures 6 and 9).

Nevertheless, the argillaceous zones contain higher proportions overall of finer-grained, mud-supported lithofacies. Also, where zone boundaries occur within beds of the same texturally defined lithofacies, there are subtle, but statistically important petrologic contrasts coincident with the zone boundary. For example, the boundary between zone K-res and the overlying zone J-arg occurs within an interval of mud-dominated packstone in wells 1 and 4 (Figures 6 and 9). However, the K-res packstones tend to have slightly higher bulk-rock alumina, more stylolites, and lower porosity and permeability than the K-arg packstones (Figure 10).

**Clay Content**

Bulk-rock XRD analyses show that clay minerals in the Upper Shu’aiba limestones are kaolin, mixed-layer illite-smectite and illite (Figure 12), with traces of chlorite present in some samples. This assemblage is similar to that of the 3 samples analyzed from overlying Nahr Umr Formation. No consistent differences in clay types or relative proportions are observed between reservoir zones.
Figure 9: Profiles of thin-section textures compared with lithofacies determined from core description. Grain-dominated packstone plots half-way between P and G. Floatstone with packstone matrix plots to the right of F. Red horizontal lines show the position of the top Shu'aiba Formation surface with respect to each core. Dashed horizontal lines mark tops of argillaceous zones (labeled "J-arg" etc.). Black horizontal lines mark tops of reservoir zones (labeled "J-res" etc.).
Figure 10: Profiles of CCA porosity and permeability compared with wireline-log curves of GR and total porosity. Samples with petrologic analyses are marked. Red horizontal lines show the position of the Top Shu'aiba Formation surface with respect to each core. Data boxes compare bulk-rock alumina and thin-section stylolite score (STY; 0 = none; 1 = present; 2 = abundant) in zones J-arg and K-res in wells 1 and 4. Lower porosity and permeability in the J-arg zone corresponds with slightly higher alumina and more abundant stylolites relative to the K-arg zone.
Figure 11: CCA gas permeability (kg) versus porosity. (a) All data, with symbols comparing lithofacies. (b) Data from K and J cliniforms, with symbols comparing reservoir and argillaceous zones. Dashed lines indicate fields of Lucia (1995) rock fabrics 1, 2 and 3.
and argillaceous zones, but samples from the younger clinoforms A and B and from the Nahr Umr goethite-ooid sandstone in well A tend to have higher ratios of illite/smectite to kaolin than the samples from the main oilfield studied (Figure 12a).

The bulk-rock alumina content of the Upper Shu’aiba limestones should mainly reflect clay abundance because clay is the main aluminous mineral present. The bulk-XRD data also show minor feldspar, but in amounts mostly below 1%. The correlation between bulk-XRD total clay and alumina indicates that a bulk alumina content of around 5 to 6 wt% in these limestones should correspond with a clay content of approximately 20% (Figure 13). The most aluminous and clay-rich samples are from zones K-arg and L-arg in well 2.

Figure 12: Bulk-rock XRD illite/smectite versus kaolin. The plot (b) is an enlargement of the dashed outline area in (a).

Figure 13: Bulk-rock XRD clay (kaolin + illite/smectite) versus bulk-rock alumina. The plot (b) is an enlargement of the dashed outline area in (a). The trend line (drawn by eye) is intended to be the same in both plots.
Bulk-rock potassium is a second chemical component that can be expected to provide a measure of clay abundance in these limestones. Non-correlation between alumina and potassium, however, indicates variable contamination with potassium chloride drilling fluid, which was used in several of the wells. Sylvite is also recorded in minor amounts (0.1–0.2 wt%) in the bulk XRD analyses of many samples.

**Gamma-Ray Activity**

GR activity measured by wireline logging is linearly proportional to abundances of the three main elements possessing natural radioactivity (Rider and Kennedy, 2011).

\[
GR = 16.32(\text{wt\% K}) + 3.93 (\text{ppm Th}) + 8.09(\text{ppm U})
\]

GR calculated from the present bulk-chemical analyses, however, shows little or no correlation with wireline-log GR values corresponding with individual sample depths. This poor correlation could result from the plug-size samples being only poorly representative of the heterogeneous distributions of radioactive elements within the larger rock volumes measured by the in-hole logging tool, as well as the presence of extraneous potassium as KCl or other mud additives.

GR activity in the Upper Shu’aiba limestones reflects two independent factors: (1) potassium and thorium within fine-grained siliciclastics (mainly clay) and (2) uranium of unknown but presumed diagenetic origin. Overall linear correlation of bulk-rock alumina with both thorium (Figure 14a) and potassium supports the interpretation that these components mainly reflect siliciclastic fines content. Most of the analyzed limestones fall along trend A in Figure 14a, connecting zero content with the five Nahr Umr shales analyzed, consistent with the alumina and thorium in the limestones being contained in siliciclastic fines similar in composition to the shales. Examination of the more aluminum-rich mudstones indicates that the clay is included as an integral component of the depositional mud matrix. Several samples, however, plot closer to trend B in Figure 14a, connecting zero content with two Nahr Umr goethite-ooid sandstones from just above the top of the Upper Shu’aiba Member in well A. These sandstones have distinctly higher Th/Al than the shales. The limestones closest
Lithofacies, Upper Shu’aiba reservoirs, northwestern Oman

Figure 15: Profiles of bulk-rock uranium (orange), manganese (blue) and total iron as Fe₂O₃ (black) in cores from wells 1 and 2. Red horizontal lines show the position of the Top Shu’aiba Formation surface with respect to each core. Dashed horizontal lines mark tops of argillaceous zones (labeled ”J-arg” etc.). Black horizontal lines mark tops of reservoir zones (labeled ”J-res” etc.).

Diagenesis and Reservoir Quality

Diagenetic processes observed or inferred to have affected the Upper Shu’aiba cores are described in Table 2 in approximate paragenetic sequence. Nevertheless, the timing of several processes, such as calcite cementation and chemical compaction, is uncertain and may well have overlapped over extended intervals of time. Petrographic observations indicate that nearly all former macropores (pores large enough to be visible in thin section) in the cores from the K and J clinoforms have been filled by blocky calcite cement (Figure 16). Therefore, the wide range in total porosity of all lithofacies mainly reflects variations in microporosity of mud matrix. Micropores within micritized bioclasts probably also contribute to the total porosity values. The grainstones and grain-dominated packstones of the A clinoform, however, contain abundant primary macropores that are not filled by calcite cement.

Porosity information was added to the composite cross-section (Figure 7b) by first marking intervals with wireline total porosity generally higher than 20% and lower than 10% on each well profile (Figure 6) and then transferring these intervals to the cross-section. Correlation of these intervals allowed mapping of regions with correspondingly high and low porosity.

The cross-plot of CCA data in Figure 11a shows how different lithofacies have somewhat different ranges of porosity and permeability. For the entire dataset, log₁₀(permeability) shows broad linear correlation with porosity, but varies by roughly 1.5 log units for any given porosity. Most samples plot within or below rock-fabric field 3 of Lucia (1995), corresponding to limestones where interparticle space occurs mainly within carbonate mud matrix. The lithofacies with larger and more abundant skeletal clasts have statistically higher permeability for given porosity, but there are large degrees of overlap between all lithofacies. The Lucia rock-fabric fields are intended to be used with interparticle
Table 2: Diagenetic processes affecting the Upper Shu’aiba cores studied.

| Process | Evidence | Timing | Effect on reservoir quality |
|---------|----------|--------|---------------------------|
| Micritization | Micritization varies from extensive to none in adjacent grains of the same thin sections. Micritization occurs in warm shallow water as bioclasts are moved about and winnowed by currents (Bathurst, 1966). | Before final sedimentation of grains. | Creation of microporosity, varying from nil to significant, depending on micritized grain abundance. |
| Early calcite cementation | Isopachous to irregular coatings of tiny (<0.05 mm), in places inclusion-rich calcite crystals with fibrous to fine-mosaic morphology occur lining former intergranular and moldic macropores. Syntaxial calcite cement on echinoderm fragments also appears to have formed early. | Early, probably within the upper several meters of the sediment column. | These cements are insignificant in all lithofacies except the grain-dominated packstones and grainstones of the A clinoform (LF-4 and LF-5), where syntaxial cement constitutes a dominant proportion of the 20.30 volume % cement present in various samples. This dominance in the A-res zone reflects both the relative paucity of lime mud and the greater abundance of echinoderm grains in lithofacies LF-4 and LF-5. The early cementation here appears to have been effective in preventing mechanical compaction and preserving high intergranular space, much of which has not been filled by cement. |
| Iron-sulfide precipitation | Minor amounts of pyrite occur in the mud matrix and commonly also within bioclasts in most samples examined. The ubiquitous pyrite is significant because it reflects degradation of organic matter in the sediment column, establishing an oxygen-poor environment (Berner, 1980) within which early processes, such as cementation and recrystallization of the mud matrix, likely took place. | Early, probably within the upper several meters of the sediment column. Continuing pyrite precipitation during burial is suggested by pyrite inclusions also in coarse calcite cement. | No apparent effects. |
| Mechanical compaction | Significant porosity loss by early mechanical compaction may be assumed to have occurred in the Upper Shu’aiba section because carbonate mud has initial porosity around 70% (Einos and Sawoilaki, 1981). Early compaction has been interpreted to vary from none to extensive in other studies of mud-rich limestones (Munnecke et al., 1997; Westphal and Munnecke, 1997). Specific evidence have not been found, however, to indicate which of the present samples have lost more or less original pore space by early mechanical compaction. In particular, it is not apparent to what extend the mud-supported facies have lost original porosity by compaction as opposed to cementation. | Early burial, decreasing exponentially with increasing depth, but inhibited by early cementation. | A potentially major process that reduced both matrix microporosity and intergranular macropores. |
| High-Mg calcite and aragonite | High-Mg calcite and aragonite may have been subordinate components of the original carbonate mud in the studied cores, insofar as Lower Cretaceous muds in general have consisted mainly of low-Mg calcite (Volery et al., 2009). Nevertheless, the presence of abundant aragonitic micromollusks is consistent with production of mud particles of similar composition by mechanical abrasion and bio-erosion. Stabilization can have occurred in the presence of either or both marine and meteoric waters (Munnecke et al., 1997; Richard et al., 2007). | This process is inferred to have occurred soon after deposition. | Early recrystallization and cementation is important for preservation of mud microporosity by inhibiting mechanical compaction (Budd, 1989; Volery et al., 2018). |
| Metagenic stabilization on a bioturbated substrate of mud matrix | Dissolution of aragonite in corals, sponges, green algae, gastropods and rudists is attested by molds, mostly filled by later blocky calcite cement, wherever these fossils occur. Dissolution could have resulted from meteoric water influx or may have been entire a marine phreatic process (Melim et al., 2002). Dissolution took place before the resulting molds were filled by blocky calcite cement (Figure 16). This occurred early because molds are commonly lined by the finely crystalline calcite cement described above and interpreted to be eogenetic. Very few molds were affected by mechanical collapse. | Effects on reservoir quality appear minor because most molds were subsequently filled by coarse calcite spar, but the presence of these molds could have preserved matrix microporosity by providing space for growth of the calcite cement which might otherwise have filled nearby micropores. |

See facing page for continuation

porosity rather than total porosity, but vugs comprise only a minor proportion of total pore space in the present samples because most macropores, whether primary or moldic, have been filled by blocky calcite cement.

Figure 11b shows the contrasting but overlapping ranges of porosity and permeability of the reservoir zones versus the argillaceous zones. Most plug samples from the argillaceous zones have porosity of 10–20%, which contrasts with the observation that the wireline logs show mostly < 10% porosity in

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Table 2: (continued)

| Process                        | Evidence                                                                 | Timing                                                                 | Effect on reservoir quality                                                                 |
|--------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Chemical compaction            | Stylolites are present in many samples, including both high-amplitude    | The timing of the blocky calcite cement is unknown, except that it is   | The blocky cement has greatly reduced macro porosity in lithofacies where larger pores    |
|                                | and low-amplitude “horse-tail” surfaces. As reported by Alsharhan and   | early bioclast dissolution and the early calcite cements described      | were formerly abundant, but is less important in mud-supported fabrics. As a result,      |
|                                | Sadd (2000), the stylolites in the present samples are lined by dark     | above and interpreted to be                                          | total porosity in most samples consists dominantly of microporosity (Figure 16).       |
|                                | material that appears to consist of clay, iron oxides, organic matter,  |                                                              |                                                                                             |
|                                | or all three. Most stylolites are oriented parallel with bedding,       |                                                              |                                                                                             |
|                                | although some stylolites follow the outlines of large clasts.           |                                                              |                                                                                             |
|                                | Petrographic data show that 53% of the 187 thin sections studied        |                                                              |                                                                                             |
|                                | contain stylolites. Floatstones and rudstones contain a higher         |                                                              |                                                                                             |
|                                | proportion of “major” stylolites (59% of 63 thin sections) than        |                                                              |                                                                                             |
|                                | packstones (20% of 60 thin sections) and wackestones/mudstones (14%    |                                                              |                                                                                             |
|                                | of 57 thin sections), whereas the 7 grainstone thin sections           |                                                              |                                                                                             |
|                                | from well A contain no stylolites.                                      |                                                              |                                                                                             |
| Late calcite cementation       | Abundant cement with blocky morphology and fine to coarse crystal      | The timing of the blocky calcite cement is unknown, except that it is  |                                                              |
|                                | sizes (0.05–5 mm) has filled most of the primary and secondary         | early bioclast dissolution and the early calcite cements described    |                                                              |
|                                | macropores previously present in all lithofacies except LF-4 and LF-5. | above and interpreted to be                                          |                                                              |
|                                | Cement crystals typically increase in size from the edges toward the   |                                                              |                                                              |
|                                | centers of former pores, but many former pores lack the finer crystals. |                                                              |                                                              |
| Fracturing                      | Fractures, both open and filled by calcite and dolomite cements, are   | Some fractures cut coarse calcite or dolomite cements, indicating     | The open fractures could be important for enhancing permeability, but appear insignificant  |
|                                | especially common in thin sections of porous floatstones, rudstones    | formation after burial.                                               | for total porosity.                                                                         |
|                                | and boundstones. Fracturing may reflect the heterogeneous fabrics, with |                                                              |                                                                                             |
|                                | rigid skeletal masses in a weakly cemented mud matrix, resulting in     |                                                              |                                                                                             |
|                                | uneven deformation in response to stresses from increasing burial       |                                                              |                                                                                             |
| Dolomitization                  | Dolomitization has affected portions of the cored intervals, commonly   | The saddle dolomite occurs preferentially within areas of coarse-      | Because it occurs mainly within areas of calcite cement, the dolomite probably had minimal  |
|                                | resulting in a few volume % dolomite and as much as 7 weight % of some  | blocky calcite cement that fills former macropores, but textural      | effect on total porosity.                                                                  |
|                                | samples. All dolomite observed in the thin sections is of saddle type   | relationships are ambiguous as to whether it preceded or replaced     |                                                                                             |
|                                | based on observation of curved crystal faces and cleavage, together    | the calcite cement (if Spore 22). Saddle dolomite is known to form    |                                                                                             |
|                                | with sweeping extinction pattern. Staining with potassium ferricyanide  | only at temperatures above 60°C, with most documented temperatures    |                                                                                             |
|                                | indicates an early (inner) iron-rich crystal growth zone (blue stain)   | above 90°C (Spott and Pitman, 1998).                                 |                                                                                             |
|                                | followed by an outer iron-poor zone (no stain).                        |                                                              |                                                                                             |

the argillaceous zones (Figure 6). This apparent discrepancy reflects the relatively high porosity of the particular intervals of the argillaceous zones that are included in the cored intervals: J-arg in wells 1 and 4 and H-arg and I-arg in well 5. As noted above, these J-arg cores are located in the more proximal part of zone J-arg where clay content is relatively lower and porosity higher than elsewhere in the argillaceous zones. The well 5 cores are also located in relatively proximal positions within the H and I argillaceous zones.

Diagenesis at the Top-Upper Shu’aiba Surface

Vertical profiles of petrologic measurements in the cored well sections were examined for evidence of trends that might reveal diagenetic processes related to the top-Upper Shu’aiba surface. For some variables, no trends are apparent. Profiles of porosity and permeability show no evidence of systematic increase or decrease as a function of distance below the top-Upper Shu’aiba surface (Figure 10). Neither are any trends in abundance of calcite cement, vuggy porosity, or other textures indicative of dissolution observed independent of lithofacies variations underlying the top-Upper Shu’aiba surface.
Profiles of bulk-carbonate oxygen- and carbon-isotope composition (Figure 17) reveal no trends of consistent upward decrease immediately underlying the top-Upper Shu’aiba surface, such as have been documented in numerous locations just below the top-Lower Shu’aiba surface (Immenhauser et al., 2000; Vahrenkamp, 2010). A cross-plot of these data (Figure 18) and comparison with published carbon-isotope profiles from the Upper Shu’aiba Member (Figure 19) show the overall similarity between the present values and earlier determinations.

Profiles of bulk-rock strontium were examined (Figure 20) because strontium depletion has been reported as an indicator of meteoric diagenesis below paleo-exposure surfaces in carbonate strata elsewhere (Wagner et al., 1995; Railsback et al., 2003). Well 1 shows a trend of upward-decreasing strontium through the 6.5 m below the top-Upper Shu’aiba surface, and a possible but inconstant trend of overall upward decrease is apparent in zone H-arg of well 5. Similar trends are not seen in the other well cores.

As noted above, uranium displays apparent trends of upward increase just below the top-Upper Shu’aiba surface in the cores from wells 1, 2 and A. These intervals also display possible trends of upward enrichment of iron, manganese and phosphorous (Figure 15).

Saddle dolomite is especially abundant within the upper 7 meters of limestone in well 1, just below the top-Upper Shu’aiba surface (Figure 21). The most Mg-rich of these samples contains 1.48 wt% MgO, which is equivalent to about 7 wt% dolomite having MgO content of 20 wt%, after deduction of a small amount of MgO for minor clay present. Saddle dolomite is also present in most samples from the top 10 m of the Upper Shu’aiba Member in wells 2 and 4, as well as at locations distant from the top surface in wells 1 and 2 and virtually throughout the core from well 4. Bulk-rock magnesium content provides an indication of dolomite abundance, but dolomite is not the only Mg-rich mineral present.

Figure 16: Microporosity % (estimated as CCA porosity minus porosity visible in thin section) versus CCA porosity. Symbols show lithofacies determined from thin sections. Except for the grainstones and grain-dominated packstones of well A, most samples plot along the 1:1 correlation line, where total porosity consists entirely of pores too small to be visible in thin section.
Figure 17: Profiles of bulk-carbonate stable-isotope analyses in the studied cores. Red horizontal lines show the position of the Top Shu’aiba surface with respect to each core. Dashed horizontal lines mark tops of argillaceous zones (labeled "J-arg" etc.). Black horizontal lines mark tops of reservoir zones (labeled "J-res" etc.).

Figure 18: Cross-plot of bulk-carbonate stable-isotope analyses in the studied cores.
Figure 19: Comparison (left panel) of carbon-isotope data from the present study (core profiles shifted to correlate reservoir zones) with Upper Shu'aiba data from Vahrenkamp (2010) and Pierson et al. (2010). To facilitate comparison, the trend line of Vahrenkamp (2010) for sequence Apt 5 (right panel) was squeezed to the same horizontal scale as the left panel and the trend of these data (green dashed line) was then adjusted (arrows) to match the approximate depth range of the cores in the present study, making assumptions regarding age correlation. Similarly, the trend of the data from the one clinoform analyzed by Pierson et al. (2010) was adjusted to match the lower part of the depth scale of the present data, although the Pierson clinoform is probably older than the K clinoform of the present study.

Ideal, pure dolomite has around 22 wt% MgO, but magnesium is also likely to be contained within illite/smectite clay, which comprises around 12 wt% of the most argillaceous mudstones (in zone K-arg of well 2). These mudstones contain as much as 1.1 wt% MgO, but show nearly no dolomite in the one XRD analysis available. Bulk-rock MgO content therefore reflects the combined abundances of saddle dolomite and illite/smectite (Figure 21). In samples with low alumina content, the MgO is mainly held in dolomite, but where alumina is abundant, the MgO is likely to be contained mainly in illite/smectite, especially where no dolomite is observed in thin section.
Figure 2b: Profiles of bulk-rock strontium. Red horizontal lines show the position of the Top Shu’aiba surface with respect to each core. Dashed horizontal lines mark tops of argillaceous zones (labeled “J-arg” etc.). Black horizontal lines mark tops of reservoir zones (labeled “J-res” etc.).
Figure 21: Profiles of bulk-rock total alumina (blue) and magnesium (red). Symbols over weight % MgO points indicate samples where saddle dolomite is present in thin sections. Red horizontal lines show the position of the Top Shu’aiba surface with respect to each core. Dashed horizontal lines mark tops of argillaceous zones (labeled "J-arg" etc.). Black horizontal lines mark tops of reservoir zones (labeled "J-res" etc.).
The most typical mode of occurrence of the dolomite is as euhedral crystals generally 0.2–0.7 mm in maximum dimension enclosed by blocky calcite cement crystals of similar or larger size (Figure 22). Petrographic relationships are ambiguous as to the relative timing of the dolomite and the enclosing coarse calcite cement. Although the calcite surrounds and thus appears to postdate the dolomite crystals, it is also possible that the coarse calcite has been the preferential site for replacement by later dolomite. Similar textures are shown by Scholle and Ulmer-Scholle (2003; p. 386-387), who note the same ambiguity regarding relative timing.

The only calcite inclusions seen within the dolomite appear to have early “dog-tooth” morphology, so these are not diagnostic of the timing with respect to the later coarse calcite spar (Figure 22). In rare cases, dolomite crystals have irregular boundaries with truncated crystal zones against surrounding coarse calcite, but this could result from either dolomite dissolution before later calcite growth or varying replacement of earlier calcite. In only one sample was clear evidence of relative timing observed, where saddle dolomite has grown into a large vug and overlies earlier coarse calcite crystals that partly filled the vug.

Infiltration of clay just below the top-Upper Shu’aiba surface is apparent within the upper one meter of the limestone in well 1, where clay occurs concentrated in a few small (< 1 cm) masses that may fill vugs or fractures. The exact nature of these features is indistinct, however, because of the delicate and crumbly (friable) condition of the core surface. Clay is not observed in the thin sections prepared, except in a highly altered limestone exactly at the top surface, where areas of silty clay are extensively replaced by pyrite. As described above in connection with Figure 14, a second place where clay appears to have infiltrated into limestones just below the top-Upper Shu’aiba surface is in well A, where the top-Upper Shu’aiba surface is overlain by a bed 43 cm-thick of goethite-oolid sandstone having a distinctive potassium/thorium ratio.

**DISCUSSION**

**Clinoform Geometry and Stratigraphy**

The present observations appear entirely consistent with the previous interpretation of the Upper Shu’aiba Member as comprising a series of progradational cycles formed in response to glacio-eustatic fluctuations in sea level (Pierson et al., 2010; Maurer et al., 2010, 2013). In this context, the lesser thickness and volume of the J clinoform, as apparent in Figures 5 and 7, could reflect differences in the magnitude of the sea-level fluctuations responsible for each depositional cycle. As illustrated by Matthews and Frohlich (2002), eustatic sea-level fluctuations driven by orbital dynamics are in general the composite of several interfering frequency oscillations. Some stratigraphic cycles must therefore be of greater magnitude than others. On the other hand, the variation in relative size of the K and J clinoforms along strike (Figure 5) and the limited strike distance included here (Figure 3) indicate that any such inferences within the limits of the present study are highly uncertain.
Insofar as the K and J clinoforms are interpreted as depositional sequences recording fourth-order cycles of sea-level cycles (Maurer et al., 2013), it is of interest to consider how the component transgressive and regressive hemicycles of each clinoform cycle should best be represented; in other words the position of the maximum flooding surface (MFS) within each clinoform. Pierson et al. (2010) show a general cross-section model for Upper Shu’aiba clinoforms in which the MFS is placed roughly in the middle of each package. Although these authors do not use the term “argillaceous zone,” this MFS placement would appear to be approximately at the top of each argillaceous zone. Maurer et al. (2010) in their figures 6–9, however, show transgressive and regressive hemicycles for various Upper Shu’aiba clinoform cores where the MFS position is quite variable with respect to the top of the argillaceous mudstone intervals in each example.

For K and J clinoforms of the present study, placement of the MFS at the top of the argillaceous zone appears inconsistent with the apparent absence of facies trends suggestive of upward-increasing water depth through the argillaceous zones in the studied cores. The J-arg zone of wells 1, 4 and 5 displays a trend of upward-increasing ratio of grains to mud. Neither do any of the vertical wells examined show evidence of a maximum in gamma-ray activity, such as might reflect a flooding event, near the top of any of the argillaceous zones. A possible solution is to place the MFS near the base of each argillaceous zone, such that the transgression initiating each clinoform is represented by only a surface or thin interval, with nearly all sediment volume being deposited during the highstand. This would be consistent with observations from the Pleistocene 100 Kyr sea-level cycles that rising stage of climate-driven sea-level oscillations tends to be more abrupt than the falling stage (Boulton, 1993).

Within the context of the Upper Shu’aiba clinoform model (Pierson et al., 2010), the elevated clay content of the argillaceous zones is consistent with sedimentation following a fall in sea level because each lowering of sea level would increase the gradients of streams draining into the Bab Basin across the exposed Lower Shu’aiba platform, thus increasing their siliciclastic load and the flux of fine suspended detritus entering the Bab Sea. The rather abrupt drop in clay content at the top of each argillaceous zone is suggestive of a threshold effect (non-linear response), whereby the rate of fines influx decreased or the rate of carbonate production increased relatively abruptly after each sea-level highstand was attained.

### Porosity Controls

The lower porosity of the argillaceous zones with respect to the reservoir zones may be inferred to result from processes whose rates are in large degree dependent on clay mineral abundances, based on the overall inverse relationship between total porosity and bulk-rock alumina shown in Figure 23. Correlation does not, of course, necessarily imply causation, but the effect of clay on promoting porosity loss in carbonates during burial has long been appreciated (Bathurst, 1975; Choquette and James, 1987; Brown, 1997).

The relationship in Figure 23 is not linear, however, as many samples have both low porosity and low alumina content. The widest range of alumina occurs in the mudstone/wackestone lithofacies, but the other, less aluminous lithofacies also show similar patterns. Other possible porosity controls are not apparent in the present set of samples, insofar as comparisons between high-porosity samples and low-porosity samples within the same lithofacies have not revealed any consistent differences in depositional textures, biotic content, dissolution features or in chemical components that are not themselves correlated with alumina.

The overall negative relationship in Figure 23 is envisioned to result from two independent processes whereby compaction and cementation of mud matrix should be accelerated by the presence of depositional clay. At shallow depths, early cement growth around carbonate mud particles may be expected to increase rigidity and thus resistance to mechanical compaction. Where clay occurs between carbonate particles, locking cement bridges cannot form, and thus the presence of clay particles dispersed in the carbonate mud should enhance early mechanical compaction by reducing the frequency of cemented interparticle contacts.
The second way in which clay should accelerate porosity loss is by facilitating “pressure dissolution” of adjacent calcite. The positively charged surfaces of clay crystals tend to locally increase the solubility of calcite, resulting in a concentration gradient that drives diffusion of the dissolved carbonate ions toward sites of cement precipitation in the surrounding rock. Porosity loss thereby occurs by both chemical compaction and precipitation of the dissolved calcite in surrounding pore spaces. Many of the Upper Shu’aiba limestones contain stylolites, all of which appear to be lined with clay minerals. Stylolitic dissolution is thought to occur during burial and is a plausible source for the abundant calcite cement present. Clay content can thus be the principal reason for the low porosity of the Upper Shu’aiba argillaceous zones.

Carbon- and Oxygen-Isotope Compositions

The stable-isotope variations observed in the present study may be compared with the values reported for Upper Shu’aiba cores by Vahrenkamp (2010) and Pierson et al. (2010). Vahrenkamp (2010) constructed a composite carbonate carbon-isotope curve for both the Lower and Upper Shu’aiba members using data from different cored intervals for different age segments. For comparison with this curve, data from the present study were plotted on a common depth scale with depths shifted to match reservoir zone boundaries (Figure 19). Vahrenkamp’s curve was then traced onto this plot (the dashed bright-green line in Figure 19) with the vertical (depth) scale adjusted to match the depth scale of the present cores (as shown by the black arrows in Figure 19). Nevertheless, the depth correlations attempted here are highly uncertain. The upper part of the Vahrenkamp curve is from “Field D” in Oman, which contains clinofoms younger than clinofom A according to internal PDO data. The lower part of the trend is from “Field A” in Abu Dhabi, which contains the oldest Upper Shu’aiba clinofoms, perhaps corresponding with clinofoms O, N and M in the PDO nomenclature. The data from the present study may therefore be more properly correlated as lying somewhere in between the depth ranges of Vahrenkamp’s Field D and Field A.
Pierson et al. (2010; their figures 9 and 12) show a profile of stable-isotope data through an Upper Shu’aiba clinoform cored in a well from Abu Dhabi. According to figure 6a of Maurer et al. (2010), the core analyzed is from the oldest clinoform deposited following the sequence boundary that terminated Lower Shu’aiba deposition. The Pierson et al. (2010) profile shows a trend of upward-decreasing δ13C through the 38 meter-thick basal argillaceous zone (from around 4‰ at the base to around 2‰ at the top), followed by a return to somewhat higher values (2‰ to 3‰) in the overlying 9-meter-thick reservoir zone of clean limestone. These values coincide with the lower part of the range of δ13C in the present data (Figure 19).

According the Vahrenkamp (2010), Shu’aiba diagenesis took place as a closed system with respect to exchange of carbon, but was open with respect to oxygen, as may be expected when diagenesis takes place under conditions of low to moderate water/rock ratios (Lohmann, 1988). The carbon-isotope values should therefore mostly record fluctuations in the isotope composition of Lower Cretaceous seawater. In general the carbon-isotope values of the present study approximately match the Vahrenkamp (2010) composite curve, but show considerably greater variation. The Upper Shu’aiba part of the Vahrenkamp curve ranges from 2.0‰ to 4.5‰, whereas the present data range from roughly 1.5‰ to 6.4‰.

The oxygen-isotope values determined in the present study (mostly -3‰ to -7‰, with a few values in the range -1‰ to -3‰) are similar to the range of δ18O for the entire Shu’aiba Formation shown in figure 4 of Vahrenkamp (2010). Vahrenkamp (2010) noted that most Shu’aiba oxygen-isotope values are distinctly lower than the range expected for Lower Cretaceous marine carbonate (around -2‰ to -3‰ according to Raven and Dickson, 2007) and concluded that this difference reflects diagenetic alteration throughout the formation. Oman was located near 0° latitude in Early Cretaceous time (Sharland et al., 2001), and meteoric water at low elevations near the equator is expected to have oxygen-isotope composition very similar to seawater (Raven and Dickson, 2007). Therefore, near-surface diagenesis, whether involving seawater or meteoric water, would result in calcite having δ18O similar to the Lower Cretaceous marine carbonate values of -2‰ to -3‰. The most plausible explanation for the generally lower Upper Shu’aiba δ18O values (mostly -3‰ to -7‰) is thus precipitation of calcite cement at elevated temperatures during burial.

Diagenesis Related to the Top-Upper Shu’aiba Surface

Uranium, Manganese and Iron

The patterns of upward-increasing uranium and associated GR just below the top of the Upper Shu’aiba Member in wells 1 and 2 (Figure 15) could reflect enrichment by sea-floor authigenesis. This hypothesis is consistent with the apparent enrichment of manganese and iron within the same intervals. Manganese and uranium both have multiple valence states and are least soluble in their relatively reduced state. Fixation from seawater or from the top of the sediment column is therefore facilitated by decay of organic matter in the sediments, which consumes available oxygen. Uranium solubility decreases with transition from the +6 to +4 valence state (Hostetler and Garrels, 1962; Doi et al., 1975; Langmuir, 1978; Murphy and ShocK, 1999). Manganese behaves in a manner similar to U in sea-floor settings (Mangini et al., 2001).

Core and thin-section observations indicate that iron has been concentrated by the formation of pyrite at and just below the top-Upper Shu’aiba surface in well 1 and well A. Iron sulfide can form in marine sediments by reaction between dissolved sulfate from seawater and iron derived from the sediments (Berner, 1980). As dissolved oxygen is consumed by decay of organic matter deposited with the sediments, iron in the sediments is reduced to the more soluble ferrous state and enters the pore water. The dissolved Fe tends to diffuse upwards toward the supply of dissolved sulfate from the sediment/water interface.

Elsewhere, however, localized enrichment of uranium has been interpreted to have occurred by flow of burial-diagenetic fluids (Hassan et al., 1975; Fertl et al., 1980; Hoff et al., 1995; Luczaj, 1998) and, in other cases, by evaporative movement of groundwater upwards toward a subaerial exposure surface (Rawson, 1980; Carlisle, 1983; Carr and Lundgren, 1994). Various alternative processes could
therefore be responsible for the observed patterns. As documented in Figure 21, saddle dolomite is also especially abundant at the tops of wells 1 and 2, so it is possible that late diagenetic fluid circulation formed both the dolomite and the small uranium anomalies.

**Saddle Dolomite**

Because saddle dolomite is known to form only at temperatures above 60°C, with most documented temperatures above 90°C (Spötl and Pitman, 1998), this must be a late burial feature in the present cores. Because the dolomite is of rather minor abundance, and especially if it formed by replacement of earlier calcite cement, dolomitization has likely had insignificant effects on porosity and permeability. The question of relative timing with respect to the enclosing coarse calcite spar cannot be resolved from available information. However, the replacement hypothesis can be explained by the process of “dolomite-growth-driven pressure solution of the calcite host” proposed by Merino and Canals (2011). By this means, dolomite grows as Mg-rich water infiltrates the limestone. The force of dolomite crystal growth causes pressure-solution of adjacent calcite, releasing dissolved calcium to increase the ion-activity product for dolomite and thus promote further dolomite growth.

The observed occurrence of saddle dolomite in proximity to the top-Upper Shu'aiba surface in well 1 and to lesser degree in well 2 (Figure 21) is suggestive of a genetic relationship. One possible source of magnesium for dolomitization is from illitization of smectite in the Nahr Umr shales. This mechanism has been proposed to explain spatial correlation between dolomite and clay in other strata (McHargue and Price, 1982). The present reservoir temperature in wells 1 through 5 is around 80°C, which is high enough to have enabled at least partial illitization of smectite in shales. Reaction of detrital smectite to form illite typically starts at around 60°C and is completed by 120°C in shales of the United States Gulf of Mexico and the Norwegian continental shelf (Hower et al., 1976; Peltonen et al., 2009; Nadeau, 2011). Smectite can contain varying amounts of both Mg and Fe, which are partly released upon reaction to form illite (Boles and Franks, 1979). An alternative source of Mg for minor late dolomitization is influx of water derived from a deeper source. In the other cores studied, no relationship between saddle dolomite and the top-Upper Shu’aiba surface is apparent, and the dolomite seems to occur more or less haphazardly at various places.

**Meteoric Diagenesis**

Profiles of bulk-carbonate oxygen- and carbon-isotope composition and bulk-rock strontium content were examined because trends of upward-decrease in these components have been documented as indicators of meteoric diagenesis underlying subaerial exposure surfaces (Allan and Mathews, 1982; Marshall, 1992; Railsback et al., 2003; Theiling et al., 2007). Bulk-rock Sr content of carbonates can be reduced from high marine values when Sr-rich aragonitic components are dissolved and reprecipitated as low-Mg calcite. This can occur under marine phreatic conditions, but is especially rapid during meteoric diagenesis (Friedman and Brenner, 1977; Morrow and Mayers, 1978). Examples of depletion in bulk-rock Sr below paleo-exposure surfaces in carbonate strata are shown by Wagner et al. (1995) and Railsback et al. (2003).

Neither bulk-calcite stable-isotope values nor bulk-rock strontium concentrations show definite trends indicative of upward-increasing meteoric diagenesis below the top-Upper Shu’aiba surface. Well 1 does show a trend of upward-decreasing Sr content in the 6.5 m interval just below the top-Upper Shu’aiba surface (Figure 20), but the range of variation (from around 300 ppm to a minimum of 150 ppm in the topmost sample) seems insignificant in comparison with the range of < 300 to 1,500 ppm in stratigraphic sections elsewhere that have been suggested to reflect meteoric leaching profiles (Railsback et al., 2003).

Porosity and permeability data also show neither increasing nor decreasing vertical trends suggestive of surface-related diagenesis (Figure 10). Neither are vertical trends in CCA values apparent at the top of the K-res zone where it underlies J clinoform beds in wells 1 and 4 (Figure 10).

Despite the absence of evidence for increased meteoric diagenesis immediately below the top-Upper Shu’aiba surface, it is possible that the entire reservoir zone in both the K and J clinoforms has experienced extensive meteoric diagenesis. Virtually all aragonitic skeletal material throughout the
studied cores was dissolved, including corals, sclerosponges, gastropod shells and the inner layer of rudist shells, before the moldic macropores thus produced were subsequently filled by blocky calcite cement.

Comparison with the Top of the Lower Shu’aiba Member

Rameil et al. (2012) describe the surface at the top of the Lower Shu’aiba Member, which has been encountered in wells throughout southeastern Arabia and studied in outcrops in Oman. Immenhauser et al. (2000) presented an earlier version of the same results, but including descriptions of several other, quite similar Cretaceous discontinuity surfaces within and at the tops of the Nahr Umr and Natih formations. The top-Lower Shu’aiba was subaerially exposed by a major fall in sea level at 121–118 Ma and was transgressed between 113–111 Ma by Nahr Umr siliciclastics (Figure 2). The exposure duration should thus be approximately 5–10 million years. This sea-level fall is confirmed by stratal geometries of the Upper Shu’aiba clinoforms in the Bab and Kazdumi basins (Pierson et al., 2010) and by karst fissures and a major siliciclastic-filled incised valley in Qatar (Raven et al., 2010).

Nevertheless, the top-Lower Shu’aiba surface shows a general lack of evidence for karst formation and only subtle indications of meteoric diagenesis. Minor negative excursions in bulk-carbonate stable-isotope profiles are interpreted to reflect soil formation. Vahrenkamp (2010) reports additional occurrences of negative excursions in bulk-carbonate carbon-isotope composition underlying the top-Lower Shu’aiba surface. The top-Lower Shu’aiba surface was also affected by sea-floor diagenesis, as evidenced by a dark brown/black coating a few millimeters thick and borings by marine organisms penetrating the dark coating material. Rameil et al. (2012) note that these effects indicate only relatively short periods of submarine exposure relative to the major duration of the hiatus. Uranium data have not been reported, but possible evidence of uranium enrichment just below the top-Lower Shu’aiba surface is provided by the GR profiles reported by Vahrenkamp (2010), where two locations show patterns of upward increase in GR (well V in his figure 8 and well 2 in his figure 11) that closely resemble the patterns attributed to uranium enrichment in wells 1 and 2 of the present study.

Comparison between the top-Upper Shu’aiba and top-Lower Shu’aiba surfaces thus shows that both show signs of relatively modest and laterally varying sea-floor diagenesis, although this evidence is more ambiguous in the former. The top-Upper Shu’aiba surface shows no evidence of surface-focused meteoric diagenesis in the limited areas examined, whereas the top-Lower Shu’aiba surface shows locally developed negative stable-isotope excursions, root traces, bleaching and vadose cementation.

CONCLUSIONS

The main findings of this study can be summarized as follows.

• The two Upper Shu’aiba clinoforms which are the main focus of this study each consist of a basal argillaceous zone and an overlying reservoir zone, the former having overall higher GR (mostly > 23 API units) and lower porosity (mostly < 10%). Lithofacies vary in a proximal direction from mudstone/wackestone to mud-dominated packstone to mud-rich floatstone, rudstone and boundstone. The reservoir zone of a younger clinoform, cored in a nearby oilfield, comprises well sorted grainstone and grain-dominated packstone, representing a very different, more current-winnodowed depositional environment.

• The higher clay abundance in the base of each clinoform likely reflects both increased influx of siliciclastic fines during periods of lower sea level and lowered carbonate productivity during transgression. Low porosity and permeability in these intervals results from the role of clay in facilitating both mechanical and chemical compaction.

• The top-Upper Shu’aiba surface displays local patterns of upward increase in uranium, manganese and iron in the immediately underlying limestone that may record sea-floor mineralization. However, late formation of saddle dolomite has also especially affected the same intervals, so interpretation of the timing of these elemental enrichments is uncertain.
Profiles of bulk-rock strontium concentration, bulk-carbonate oxygen- and carbon-isotope ratios, petrographic data and conventional core analyses of porosity do not show evidence of increased meteoric diagenesis immediately below the top-Upper Shu’aiba surface in any of the wells examined. Meteoric leaching, forming abundant molds of aragonitic macrofossils, may nevertheless be pervasive throughout the studied reservoir intervals.

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ABOUT THE AUTHORS

Naima R. Al Habsi received a BSc in Geophysics and an MSc in Petroleum Geosciences from Sultan Qaboos University, Oman. She joined Shell in July 2013 as a Reservoir Engineer for the Land East Sour Gas System (GZI). She received best poster award in the EAGE Forum on Students and Young Professionals in Abu Dhabi in 2013. She is a member of EAGE, SEG and SPE.

naima.alhabsi@shell.com

Mohammed Al Shukaili holds a BSc in Geology and an MSc in Petroleum Geosciences from Sultan Qaboos University, Oman. He is currently employed with the Ministry of Commerce and Industry, Muscat, Oman.

mohammedalshukaili@yahoo.com
Sabah Al Tooqi holds a BSc in Geology from Kuwait University and an MSc in Petroleum Geosciences from Sultan Qaboos University, Oman, where she was funded by a scholarship from Petroleum Development Oman. She started her career recently working with static modeling in Saih Nihayda cluster in the Gas Team of PDO. She is a member of SPE.
sabah.sn-tooqi@pdo.com

Stephen Neville Ehrenberg holds a PhD from the University of California at Los Angeles, USA. He is currently working at The Petroleum Institute, Abu Dhabi, UAE. Steve was Shell Chair in Carbonate Geosciences at Sultan Qaboos University, Oman, from 2010 through 2013 and had previously enjoyed a long career with Statoil in Stavanger, Norway. His research concerns reservoir quality in sandstones and carbonates. He is a member of AAPG.
sehrenberg@pi.ac.ae

Michaela Bernecker studied Geology and Paleontology at the University of Erlangen, Germany. For her PhD dissertation on carbonate platforms and reefs (1995) she did field work in the Hajar Mountains on Permian and Triassic formations. She became Assistant Professor at the University of Erlangen and worked on her research project on Paleogene sedimentary environments on the Arabian Shelf funded by the German Research Foundation (DFG). Since 2008 Michaela has been an Associate Professor in Applied Sedimentology and Stratigraphy at the German University of Technology in Oman. Her current projects focus is on carbonate facies characterization and interpretation of outcrop and subsurface data for industrial applications on the Arabian Peninsula.
michaela.bernecker@gutech.edu.om

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