This is a pre-print version of this article:

Al-Fahmi, M.M., Hooker, J.N., Al-Mojel, A.S., Cartwright, J.A., New scaling of fractures in a giant carbonate platform from outcrops and subsurface, *Journal of Structural Geology*(2020), doi: <https://doi.org/10.1016/j.jsg.2020.104142>.

New scaling of fractures in a giant carbonate platform from outcrops and subsurface

M. M. Al-Fahmi*, John N. Hooker, Abdullah S. Al-Mojel, and Joe A. Cartwright

*Corresponding author

Abstract

We scale properties of fractures in the Late Kimmeridgian carbonate platform of the Arabian Shelf from outcrop and subsurface strata. The platform is flat-lying undeformed except from low-relief anticlines and domes, at which the strata hosts the world's most prolific petroleum reserves. The strata exhibit stylolites and veins, besides the dominant fractures. The fractures are opening-mode, steep, and forming major sets of NW–SE and NE–SW orientations. Faults are uncommon. Fracture abundance varies significantly across the platform, but it is constrained spatially by inherent variation in mechanical stratigraphy and temporally by anticlinal growth and isotope geochemistry. In early burial stages, the platform strata were slightly deformed by bed-parallel stylolites and mutually crosscutting veins. The strata fracturing increased by the anticlinal growth in the Late Cretaceous. Fracture spacing is an average of 2m in the horizontal-bedded outcrops in Central Arabia and 0.30m in the equivalent subsurface in a dome in Eastern Arabia. The dome is an end member in the deformation spectrum of the platform interior, with up to c. 5° structural dip and 2% dilational strain expressed in the doming and a few major faults. This finding indicates that carbonate platforms can reach fracture oversaturation under such a subtle tectonic extension.

Introduction

The Late Kimmeridgian carbonate platform (hereinafter the platform) of the Arabian Shelf interior is among the world's giant carbonate platforms (Fig. 1). It is also the richest in petroleum, which is prolifically produced from several supergiant fields of anticlinal structures in Eastern Arabia (e.g., Al-Husseini, 1997). Outcrops and subsurface of the platform have been studied over the past seven decades for lithostratigraphy and petrophysics (e.g., Steineke et al., 1958; Powers et al., 1966; Al-Husseini, 1997; Al-Awwad and Collins, 2013; Al-Mojel et al., 2020) and references therein. Research on the platform fractures, veins, and faults is relatively sparse and only fairly recent. It has been motivated by the business drivers and advancing technology of subsurface reservoir engineering (Al-Fahmi, 2018).

The platform fracturing had been debated with respect to three main topics. Firstly, it is deduced from the passive tectonics of the Arabian Shelf interior that it is less susceptible to tectonic fracturing than the shelf

margins (e.g., Alsharhan and Nairn, 1997). Secondly, fractures are absent in core, which is typically acquired from vertical wells in the petroleum-bearing zones (e.g., Meyer et al., 2000; Swart et al., 2005). Thirdly, 3D petrophysical modeling relates high rates of fluid flow to the matrix porosity alone (e.g., Clerke, 2009). These reasons were additional to the “fracture denial” and shortage of technology in the petroleum industry (e.g., Nelson, 2001). The fracture denial was often countered in the industry by the admonition: “*all reservoirs should be considered fractured until proven otherwise.*” (e.g., Narr et al., 2006).

But advent and increasing use of horizontal drilling and borehole imaging technology in the last two decades has changed our understandings. Images of non-vertical boreholes reveal details of the fractures in the oil-producing carbonate intervals in Eastern Arabia (e.g., Luthy and Grover, 1995; Ameen, 2014). Furthermore, the borehole imaging and caliper tools allow the identification of the present-day maximum

horizontal principal stress (S_{Hmax}) in Eastern Arabia. The S_{Hmax} is estimated between $\sim 60^\circ$ and 100° azimuth and with magnitudes higher than the vertical stress (S_v) of the sediment load (e.g., Ameen, 2014). The findings were mostly reported from the Late Permian Khuff carbonates, but the shallower Jurassic intervals are also influenced by the S_{Hmax} (Al-Fahmi, 2018). The region is currently subject to a strike-slip stress regime due to the far field tectonic compression of the Arabian-Eurasian plate collision and the emplacement of the Zagros orogenic belt.

Here, we synthesize recent data on the fractures in the platform, from outcrop and subsurface areas, and

attempt to derive the fracture systematics. The outcrop data was collected from outcrops in Central Arabia (Fig. 1). The subsurface data includes sub-horizontal core aligned with borehole images (Formation MicroImager, FMI) from extended reach wells in a dome structure, described in (Al-Fahmi, 2018). The paper has two main aims: 1) provide the first scaling of fracture abundance in outcrops and subsurface of a carbonate platform, as a typical case of gently deformed and tectonically passive terrains, and 2) establish a framework for fracture properties in the carbonate platform to be integrated in 3D property modeling of subsurface reservoirs (e.g., Nelson, 2019).

Fig. 1. **a)** Maps displaying the study areas and the outcrop of the Jurassic carbonates in Central Arabia. **b)** Stratigraphic column of the Late Jurassic sequences in the outcrops, modified from Al-Mojel et al. (2020). **c)** Cross sections (XS-1 and XS-2 in the map) display that the Arabian Shelf interior is nearly flat and gently deformed by low-relief anticlinal structures, contrasting with mobile platform margin at the Zagros Fold and Thrust. XS-1, XS-2, modified from Al-Fahmi (2018).

Background

Late Kimmeridgian Platform

The platform formed in shallow marine regions of the Neo-Tethys on the stable margin of Gondwana (e.g., Powers et al., 1966) (Fig. 1b). The platform is interbedded dolomite and limestone with a wide range of lithofacies, from grain- to mud-dominated; porosity, from 5 to 30%; and bed thicknesses, from 0.1 to 3.5m (e.g., Al-Mojel et al., 2020; Al-Fahmi, 2018). The varying mechanical properties are primarily functions of porosity, and they do not change significantly with the dynamic conditions in areas of oil production and water injection (e.g., Ameen et al., 2009). The carbonates are capped by the Tithonian Hith Anhydrite, which is the cap rock of the Jurassic petroleum system in Eastern Arabia (e.g., Al-Husseini, 1997) (Fig. 1b). The platform was buried to shallow depths (< 2Km) in Eastern Arabia, and exhumed in Central Arabia with the eastward tilting of the Arabian Shelf (Fig. 1a, c). Like the shelf interior, the strata remained flat-lying undeformed under prevailing passive tectonics, except in the low arches of the Interior Homocline and in the anticlines and domes that developed by differential compaction or subtle reactivation of buried basement faults and Hormuz Salt (Fig. 1c). The stable tectonics of the platform contrasts with the mobile margins in the Taurus, Zagros, and Oman Mountains (Fig. 1c).

Interior Homocline

The Arabian Shelf in Central Arabia forms a subtle structure called the Interior Homocline (e.g., Powers et al., 1966) (Fig. 1). The homocline extends from the splendid escarpments of Central Arabia to the west of Ghawar Field (Fig. 1c, d). The platform dips gently and uniformly eastward, with dips too small to be measurable from outcrops. The dips are around 0° 30', and slightly greater than 1° 00' in older Paleozoic intervals (e.g., Powers et al., 1966). The term “homocline” was used in reference to the eastward tilting of the shelf strata. But subtle changes in strike make the homocline of north-dipping and south-dipping hinges separated by the Central Arabia Arch (CAA) and the Central Arabian Graben (CAG) (Fig. 1a). The homocline is, therefore, a giant gentle anticline.

The origin of the homocline is not well constrained. Variations in thicknesses and lithofacies in the shelf sequences in Central Arabia were attributed to eustasy and passive tectonics (e.g., Powers et al., 1966; Al-Mojel et al., 2020). The Paleozoic strata were uplifted by reactivation of faults in the underlying basement during the Devonian to early Triassic Hercynian Orogeny (e.g., Powers et al., 1966). The uplift continued in the Mesozoic and Cenozoic periods, causing extensional structures such as those of the CAA and the CAG. The CAA is a ridge extending eastward from the Arabian Shield toward the Qatar Peninsula and separates the homocline into northern and southern regions (e.g., Hancock et al., 1984). Although the CAA has very gentle dips, it marks the area of maximum curvature of the homocline. The CAA was slightly positive during Early Paleozoic, because pre-Permian strata pinch out against it (e.g., Powers et al., 1966). The CAG is a 560-km *en echelon* graben that cuts about 1800 m of the Mesozoic-Cenozoic sequences (e.g., Powers et al., 1966; Hancock et al., 1984) (Fig. 1a). The CAG may have developed due to: i) regional tension over the crest of the CAA (Powers et al., 1966), ii) left-lateral shear along a buried fault zone in the crystalline basement (Brown, 1972), or iii) northward stretching and separation above an arcuate basement fault of an East Arabian block (Hancock et al., 1984).

Petroleum-bearing Structures

The petroleum-bearing structures are low-amplitude folds of two styles: anticlines and domes (e.g., Konert et al., 2001). Their structural dips are very gentle, ranging from 2° to 6° on average (Fig. 1c). The anticlines are of mostly a north-south (N-S) trending axis, but some have northwesterly (NW) and northeasterly (NE) trends (e.g., Powers et al., 1966; Al-Husseini, 1997). Notable example of the N-S anticlines is Ghawar, the world's largest onshore petroleum field. The domes are much fewer than the anticlines in onshore. They concentrate in the northern and southern basins of the Arabian Gulf (e.g., Al-Fahmi et al., 2016).

The early evolution of the anticlines and domes is poorly constrained for lack of drilling data and

reliable seismic images to model the deepest sediments and underlying basement. The anticlines were interpreted to have formed along major bounding basement faults (e.g., Konert et al., 2001). The anticlines grew during the Carboniferous, coinciding with the Hercynian Orogeny (e.g., Faqira et al., 2009). The faults propagate in the lower Paleozoic section, but do not rise above the Permian sequences (e.g., Khuff Formation) (e.g., Faqira et al., 2009). Subsequent tectonic events produced additional growth in the Late Cretaceous and Neogene, making up the anticlinal traps for petroleum.

The domes, including the one covered by our study area, developed by the movement of Eocambrian Hormuz Salt. The salt was not confirmed by drilling, but deduced from: (i) elliptical planforms coinciding with negative anomalies of gravity survey, (ii) regional seismic interpretations (e.g., Dyer and Hussein, 1991); and (iii) style of the deformation in the sedimentary cover, as the case of our studied dome (Al-Fahmi et al., 2014, 2016) (Fig. 1c).

The initial doming stage of the study area is not obvious for those sequences that are older than Permian (Al-Fahmi et al., 2016). For younger sequences, the dome was formed by slow episodes of deeply seated and rising salt that deformed the overlain sequences (Al-Fahmi et al., 2016). Several faults, including three master faults, were interpreted from the 3D seismic reflection to cut through the platform (Al-Fahmi et al., 2016). The growth episodes of the dome resulted in the bending of the platform mostly during the Late Cretaceous, coinciding with the amplification of many anticlines in Eastern Arabia (e.g., Faqira et al., 2009). A subsequent doming episode occurred during the Oligocene that bent and fractured the Rus carbonates, which are outcrops in the present day (Al-Fahmi et al., 2014).

The structural dips of the platform are very gentle, of up to 5.5° and about 2% volumetric strain dilation in the dome crest (Al-Fahmi et al., 2016). The structural arch, curvature, and strata dips of the dome are relatively higher than those of the anticlines such as Ghawar and Khurais, whose

structural dips are up to 3° . Table 1 summarizes notable aspects of the homocline and the dome.

	The homocline	The dome
Map area	About 150,000 km ²	About 150 km ²
Shape	East plunging anticline	Oval, with N-NW axis
Structural dips	0° - 1°	0° - 5°
Folded rocks	Paleozoic, Mesozoic, and Cenozoic	Paleozoic, Mesozoic, and Cenozoic
The platform burial level	Poorly constrained, but shallower than the 1.6 km burial in Eastern Arabia.	Around 1.6 km
Origin	Reactivation of deep-seated basement faults	Rising of deep-seated salt pillow

Table 1. Comparison of the homocline and the dome.

Data and Methods

We use the following common terms of deformational discontinuities: veins, stylolite, fractures, and faults (Peacock et al., 2016). The veins include any fracture whose walls are bonded, bridged, or coated by mineral crystals that differ from those of the host rock (e.g., Al-Fahmi and Cartwright, 2019). Stylolite refers to serrated surfaces formed as compaction structures of localized carbonate mineral dissolution. Fractures refer to the opening-mode fractures which include layer-confined fractures (joints) and throughgoing fractures (Fig. 2). The fractures exist in two hydromechanical modes under the subsurface confining stresses: open, and hence hydraulically conductive, and closed (Al-Fahmi et al., 2018). Faults refer to the fractures along which the rock layers were displaced (Fig. 2).

The platform outcrops were studied from two regions (Fig. 1a). Site A ($N 25^\circ 09' 14'' N$, $46^\circ 12' 28'' E$) and Site B ($25^\circ 09' 50'' N$, $46^\circ 13' 50'' E$) are located in Wadi Malham, which is about 80 km north of Riyadh City. Site C and Site D ($23^\circ 28' 19'' N$, $46^\circ 52' 11'' E$) are located at Howtat Bani Tamim, 150 km south of Riyadh. The two regions are located on the northern and southern limbs of the homocline and both include complete intervals for the Arab-D and Upper Jubaila carbonates.

Fig. 3. Examples of fractures in core and a corresponding interval of electrical borehole images from X-03.

Well ID	Deviation (from vertical)	Azimuth	FMI interval	Cored interval
	Degrees	Degrees	m	m
X-01	71	55	174	91.4
X-02	76	42	495	
X-03	48	16	198.1	189
X-04	70	16	331.3	
X-05	between 77 and 88	76	4752	
X-06	between 79 and 88	between 87 and 95	3550	
X-07	86	62	710	
X-08	80	70	270	

Table 2. Information of borehole datasets.

Details on the study methods, descriptions of fracture displacement modes, roughness, apertures, widths of veins, and comparison of data are presented in (Al-Fahmi, 2018). The analyses here are focused on fracture mineralization, orientations, and abundance. New observations were added from new four wells (X-05 to X-08) that were drilled in the 2017-2019 period. We also examined repositories of unpublished fault interpretations from seismic reflection surveys.

Veins, stylolites, and their host rock were sampled from the core of X-01 and X-03 for petrographic and chemical analyses. The petrography allowed us to identify fill-mineral types, degree of fills (i.e., microporosity), and associations of filling minerals. Stable isotopes ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) were measured using standard lab methods, described in (Al-Fahmi, 2018). The mechanical stratigraphy was constructed based on sonic and density logs as well as core lithologic descriptions, following the Dunham classification (Dunham, 1962).

Fracture abundance was estimated using two methods. The first method quantifies fracture spacing along boreholes, from the core and borehole images. The second method calculates fracture spacing parallel to mechanical strata, according to the length of the horizontal distance traversed by the borehole (Fig. 2). This method is called a “corrected fracture spacing”, and is analogous to direct measurements of fracture-perpendicular spacing which can be made in outcrops.

The spacing was corrected to the angle between the borehole azimuth and the azimuth of the fractures.

In the framework of relating the host layer thickness (T) to fracture spacing (S), the latter is qualitatively divided into three categories: (i) undersaturated for $S > T$, (ii) balanced saturated for $S \approx T$, and (iii) oversaturated for $S < T$ (Fig. 2). The fracture abundance is correlated and discussed from the context of the dataset (core and borehole images), lithofacies, borehole orientation, and structural setting in the shelf interior.

Outcrops

Wadi Malham region

The surveyed outcrop is not a sharp straight transect in the erosional feature (Fig. 4a). The rock sequences are exposed along sections of about 70° azimuth for Site 1 and 290° azimuth for Site 2. Fractures exist as opening-mode barren fractures (joints).

Veins, stylolites, and faults were not observed. The fractures typically cut the layers from the base to the top, terminating at the layer contacts. Plan view exposures of layer tops show that fractures either proceed and disappear under the overlain layers or terminate at other fractures. The fractures dip vertically (mostly around 85° – 90°), and are thus effectively normal to the flat strata exposed at the outcrops. The fractures display orthogonal pattern of two sets.

Fracture strikes and spacing were measured from seven layers at Site A and eight layers at Site B (Table 3). The thicknesses of the scanned layers range between 0.4 m and 1.1 m. The scanned layers are not on top of each other; they are separated by other fractured layers that were not measured for strikes and spacing. Fracture spacing is irregular with a wide range, from about 0.5 m to 5 m at Site A, and 0.5 m to 8.5 m at Site B.

The spacing is generally greater than 2 m at both sites. A few cases of large spacing (> 5 m) are due to lateral changes in lithofacies: a reef buildup at Site A, and heavily burrowed lithofacies at Site B. Such lateral changes in lithofacies are uncommon for these carbonates because their layers are mostly laterally continuous in the field.

Howtat Bani Tamim region

Like Wadi Malham, outcrops at Howtat Bani Tamim are flat-lying and fractured by joints (Fig. 4b). Veins, stylolites, and faults were not encountered. The fractures are bed-confined with a few clusters that traverse multiple layers. The fractures are typically of vertical planes that are normal to the flat and horizontal strata.

Fracture strikes and spacing were measured from seven limestone layers: two mudstone layers, three wackestone-packstone layers, and two grainstone layers. The layers at Site C are the same as those at Site D (Table 3). The layer thicknesses range between 0.3 m and 1.1 m, with slight changes between Site C and Site D.

Fractures of NW–SE azimuth are rarely observed at Site C, but observed in the same layers at Site D. E–W fractures are also observed in small numbers at Site D. The orientation of the outcrop axis at Site C is NW–SE, about 290° azimuth. The orientation of the outcrop axis at Site D is E–W, about 90° azimuth. Measurements of fracture strikes were affected locally by the orientation of the outcrop wall, although made on the same layers. Fracture spacing exhibits a wide range, from a few centimeters to about 5 m. The spacing between the outcrop fractures is irregular; the average fracture spacing is nearly 2 m.

Systematics of the outcrop fractures

The outcrop fractures in the two regions display similar properties. The fractures are barren and exhibit subnormal dips to the host horizontal layers (Fig. 4c). The compiled strikes of the fractures display two primary sets of NE–SW and NW–SE fracture systems, in addition to a secondary E–W fracture system (Fig. 4c) (Table 3).

About 85% of the fractures are confined to a layer, and the remaining cut through several layers to terminate above and below the host layers (Fig. 4d). The spacing of the fractures is larger than the thickness of their host layers, with a few exceptions such as thin mudstone layer (of less than 30 cm) (Fig. 4e). Fracture spacing is not linear to the host layer thicknesses (Fig. 4e).

Fig. 4. **a), b)** the platform outcrops at Wadi Malham (looking west), and Howtat Bani Tamim (looking northeast). **c)** All measured fracture strikes from the outcrops at Wadi Malham and Howtat Bani Tamim, displaying two primary sets of NE–SW and NW–SE fracture systems, in addition to a secondary E–W fracture set. **d)** Measurements of the fracture heights and thicknesses of host layers in the outcrops. Most fractures (85%) are found to be layer-confined fractures (joints). **e)** plots of fracture spacing versus layer thicknesses, displaying no linear relationships but displaying that fractures are undersaturated in these flat outcrops in the northern and southern limbs of the homocline

I D	Locati on	Lithology	Thic knes s (m)	No. of fractur es	AVG Spaci ng (m)
1	Site A	Mudstone	0.6	15	1.71
2	Site A	Grainstone	0.8	13	1.57
3	Site A	Wackstone	0.6	17	2.61
4	Site A	Mudstone	0.5	18	1.29
5	Site A	Grainstone	1.15	21	1.71
6	Site A	Dolomite	1	29	1.23
7	Site A	Rudstone	0.7	35	1.02
8	Site B	Mudstone	0.7	6	4.6
9	Site B	Mudstone	0.8	11	3.46
10	Site B	Packstone	0.6	8	5
11	Site B	Grainstone	0.9	11	3.6
12	Site B	Grainstone	0.6	8	5
13	Site B	Mudstone	0.4	14	2.92
14	Site B	Dolomite	0.4	27	1.45

Subsurface

Trend of stylolite and calcite veins

The stylolites are parallel, and their teeth normal, to the strata bedding planes (Fig. 5). The veins are opening-mode with mostly small to micro widths of less than 2mm (Al-Fahmi and Cartwright, 2019). They are sub-vertical, with dips between 70° and 90°. Microveins are of inclined branches, with low dip angles, in the range of 50° and 60°.

The calcite fills are complete, leaving no apertures or pores in the veins and adjacent rock walls. The crystals of calcite veins vary in shape and size, ranging from small (10 micron) equant crystals to elongated 100-micron crystals (Fig. 5b). The observed elongated crystals are not fibrous. They do not exhibit alignment to the orientations of veins or host rock walls. Furthermore, variations in shape and size of calcite crystals exist in the same vein and within the small dimension of a thin section (<40 mm). The textural features do not seem to display any correlation with host rock lithofacies. The veins exist in all carbonate intervals, but with an obvious increase in the water-bearing intervals below the oil. In addition, the veins are

15	Site B	Packstone	0.8	21	1.88
16	Site C	Packstone	0.35	10	1.17
17	Site C	Packstone	0.35	14	1.63
18	Site C	Grainstone	0.63	15	1.38
19	Site C	Mudstone	0.2	16	1.4
20	Site C	Mudstone	0.1	10	2.44
21	Site C	Grainstone	1	15	1.46
22	Site C	Wackstone	0.9	16	1.35
16	Site D	Packstone	0.35	3	3
17	Site D	Packstone	0.4	15	1.74
18	Site D	Grainstone	0.7	16	1.75
19	Site D	Mudstone	0.1	19	1.55
20	Site D	Mudstone	0.3	9	3.3
21	Site D	Grainstone	0.4	24	1.15
22	Site D	Wackstone	0.6	27	1.054

Table 3. Surveyed carbonate units in the outcrops.

strongly associated to, and mix with, the stylolites. Also, the veins were observed in the core to terminate at bed-parallel stylolite planes (Fig. 5a). The vein spacing ranges from 3 cm to 30 m, making it difficult to predict using statistical distributions.

Geochemistry of Stylolites and Veins

The $^{87}\text{Sr}/^{86}\text{Sr}$ values of the calcite veins are mostly between 0.7069 and 0.7071, which is the same range of values as those of their host rocks and stylolite material (Fig. 6a). The values indicate a common strontium reservoir. The range of values cluster around the $^{87}\text{Sr}/^{86}\text{Sr}$ curves of the Late Kimmeridgian seawater (McArthur et al., 2012; Wierzbowski et al., 2017).

The value variations reflect the depths of the samples, with a trend that decreases with an increasing depth. A similar trend, although much weaker, appears in a previous study on the Hith and Arab Formations in Abu Dhabi (Azer and Peebles, 1998). The depth relation is expected, with deep rock strata are old and of low $^{87}\text{Sr}/^{86}\text{Sr}$ values. The low values suggest the age of some veins is Middle

Kimmeridgian, which is a possible age for the lower carbonate intervals. Some high values may reflect a diagenetic event before the deposition of the Early Tithonian Hith Anhydrite. The calcite veins display negative (light) values of oxygen isotopes (-3.5 to -8.3 ‰ $\delta^{18}\text{O}$) and positive (heavy) carbon isotope values (2.1 to 3.1 ‰ $\delta^{13}\text{C}$) (Fig. 6b). The values are

similar to those of the host rocks and stylolite material, indicating a single closed system of dissolution and precipitation (Fig. 6b). Furthermore, the $\delta^{13}\text{C}$ values of the calcite veins are similar to those of the platform strata in Ghawar and Abu Dhabi and differ from those of the platform outcrops (Fig. 6b).

Fig. 5. **a)** Examples of barren fractures and calcite veins in core, **b)** calcite veins in thin sections under the microscope. The veins are strongly associated with stylolite and terminate against them. The crystal sizes and shapes of the calcite vary. **c)** Number of barren fractures, veins and stylolite in the core of X-01 and X-03.

Fig. 6. **a)** Measured strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) of calcite veins, host rock, and stylolite materials, projected against the $^{87}\text{Sr}/^{86}\text{Sr}$ global curves of McArthur et al., 2012; Wierzbowski et al., 2017. The measurements agree with the Late Kimmeridgian seawater $^{87}\text{Sr}/^{86}\text{Sr}$ curves, and the previous measurements on the Hith and Arab Formations in Abu Dhabi (Azer and Peebles, 1998). **b)** $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of calcite veins display negative (light) oxygen isotope values and positive (heavy) carbon isotope values. The values are similar to the isotopic signatures of the Arab-D in Ghawar and Abu Dhabi (Cantrell et al., 2001; Morad et al., 2012; Rosales et al., 2018), and different to the platform outcrops in Central Arabia (Eltom et al., 2014; Al-Mojel et al., 2018).

Fractures

The fractures dominate in the platform subsurface, regardless of borehole orientation, lithofacies, and method of observation (whether core or borehole images). We recorded 103 stylolites, 153 calcite veins, and 665 fractures in the 259.4-m core of X-01 and X-03 (Fig. 5c). The fractures make up more than 80% of all encountered fractures and veins. This ratio of open-barren fractures to veins is similar to what was interpreted from the borehole imaging databases of other fields in Eastern Arabia. Fractures are mostly of subnormal dips, greater than 80° (Fig. 7). The fracture strikes widely vary. The rose histograms in Fig. 7b display little or no fractures sub-parallel to the azimuth of the imaged borehole sections (Fig. 7). But there are two dominant orientations of NE-SW and NW-SE fractures, and only a few north-south fractures. Furthermore, many of the fractures were not detected from the borehole images. Fracture

detection was dependent on several factors including size of fracture apertures under the tectonic stress, namely the S_{Hmax} (Al-Fahmi and Cartwright, 2019). The fractures perpendicular to the S_{Hmax} are closed or narrow, and therefore hard to see in the borehole images.

Fracture spacing also varies because of the fracture spatial distributions and sampling methods. The fracture spacing plots from the borehole images generally reveal small spacing, with a peak around 30 cm (Fig. 8a). But the plots in Fig. 8a are not identical. The mostly divergent plots are the four boreholes X-05 to X-08 (Fig. 8a). This divergence is related to the imaged borehole azimuths with respect to the intersected NE-SW fracture set as well as the length and inclination of the imaged sections. It is not resolvable from the spacing plot shapes whether these boreholes are able to indicate different fracture spacing toward the dome crest.

Fig. 7. **a)** Map of the dome drilled area showing structure and locations of the extended-reach (sub-horizontal) wells from which borehole images and core were obtained, **b)** Rose histograms of the strikes of conductive (open) fractures measured from the borehole images. The fracture strikes reflect the traversing borehole orientation (green line), the detection level of borehole imaging that misses closed fractures, and the spatial distribution of fractures.

Fig. 8. **a)** Plots of fracture spacing along core and borehole images obtained from the sub-horizontal boreholes in the dome, **b)** plot of corrected fracture spacing from the core, c) the abundance of fractures according to the carbonate lithofacies described from the core of X-01 and X-03.

The spacing is dominantly less than 1 m along the core, with 80% of the fracture spacing less than 50 cm in X-01 and 70 cm in X-03 (Fig. 8a). The mean value of fracture spacing is 35 cm. The obtained values are typical for a core that is traversing interbedded thick and thin layers with inclination between 50° and 70°. This means that it is unlikely to drill a borehole and encounter unfractured carbonate intervals greater than 1 m, except if the boreholes are subvertical (<25° from the vertical reference, 0°). The skewing of the statistical distribution is expected if larger fracture spacing was obtained from a horizontal core in thick layers.

The corrected spacing values have an arithmetic mean of about 31 cm and standard deviation of 24 cm (Fig. 8b). The fractures exist in all carbonate lithofacies, from muddy to grainy, and from tight to porous rock layers. The fracture abundance clearly increases toward the muddy lithofacies (Fig. 8c). Along a hypothetical 10-m scanline traversing the lithological units; mudstones, which dominate the lithofacies would display 28 fractures (~0.3 m of fracture spacing), and rudstones would display 13 fractures. The dolomite lithofacies displays a median value of about two fractures per meter (Fig. 8c).

Synthesis of the fracture properties

Mineralization and mode of displacement

Joints are clearly visible at outcrop, and these are universally opening-mode and unmineralized. Previous reports interpreted faults from lineaments in the satellite images of the CAG and Wadi Al-Batin (Hancock et al., 1984). The CAG is bounded by high-angle normal faults, subsidiary antithetic faults, and multiple folds (Hancock et al., 1984). Away from the CAG, folds and faults are uncommon in outcrops, except southeast of Riyadh City, where there are some low-amplitude folds (Hancock et al., 1984; Al-Mahmoud et al., 2009). But the faults and calcite veins were subordinate besides the dominant (90%) systematic joints in the CAG region (Hancock et al., 1984; Abdmutalib and Abdullatif, 2017).

The platform in the dome include stylolites, calcite veins, and fractures resembling joints (Fig. 5c). The

fractures and veins are commonly documented, from sub-horizontal borehole images, from the Late Jurassic carbonate intervals in the region (Al-Fahmi, 2018).

The stylolites are commonly observed from the vertical core as bed-parallel in trend, reflecting compaction and fluid pressure solutions in the Arabian Shelf interior (Alsharhan and Sadd, 2000; Paganoni et al., 2016). No part of the shelf interior seems to include tectonic stylolites, which typically form by a prevailing non-vertical stress. The stylolites are of non-porous minerals, like the veins. Their capacity as barriers of fluid flow in the subsurface is however unknown, prompting a need for further research on their lateral continuity and attributes.

The fractures and veins are of opening-mode displacement. They were observed to cut the rock lamina in the core and borehole images without shearing (Al-Fahmi, 2018). The veins are a minority system beside the dominant barren fractures (Fig. 5c). The occurrences of fracture mineralization are small in number and size. The percentage of calcite veins varies along deviated core like those of X-01 and X-03 (Fig. 5c). The calcite veins may drop below 5% of all fractures in the top intervals and increase (up to 20%) in the lower intervals, below the oil-water contact and toward the flank of the anticlines (Paganoni et al., 2016).

In the subsurface, the faults were rarely observed, or validated, in the seismic survey to cut the Jurassic sequences (Faqira et al., 2009). There were a few exceptions of measurable faults (of > 10m shear displacements) in the 3D seismic images of some domes in the Gulf region, like our studied area (Fig. 7a), (Sims et al., 2013; Al-Fahmi et al., 2016). In general, faults did not seem to have breached the cap rock of the Hith Anhydrite, which provides the top seal for the vast oil in the Late Jurassic carbonates. But further research is needed to characterize abundance, geometry, and sealing capacity of the faults detected in seismic reflection surveys.

In summary, the majority (>90%) of the platform fractures are barren, resembling joints. It is not unusual to encounter veins, or faults in the

platform, but with relatively small and random occurrences that defy statistical predictions. The vast subsurface flat areas between the anticlines are less explored, but most likely jointed like the flat

outcrops. Lack of faulting reflects the passive setting of the Arabian Shelf interior, although may partly reflect a lack of good data on some subsurface areas.

Fig. 9. Comparisons of fracture abundance from core and borehole images and measurements of fracture apertures. Modified from Al-Fahmi and Cartwright (2019).

Orientation, apertures, and roughness

The veins and fractures are mostly steep, a typical attribute of opening-mode fractures. The fractures

in sedimentary rocks, such as carbonates, are predominantly oriented within 10° of normal to the

bedding plane (Price and Cosgrove, 1990). The high dips ($>80^\circ$) of the fractures and veins explain why they were missed by the abundantly acquired vertical core in Eastern Arabia. Fracture dips in the platform are predictable, and do not present a challenge as fracture strikes.

Predicting fracture strikes require a great deal of data and analyses. The strikes of outcrop fractures seem to vary from one location to another, and from one layer to another (Al-Fahmi, 2018). But the compiled histograms of the two regions display two primary sets of NE–SW and NW–SE fracture systems, in addition to a secondary E–W fracture system (Fig. 4a). These orientations do not seem to be a matter of coincidence. Rather, they indicate an extensive fracturing system in the northern and southern limbs of the homocline, despite differences in location, layer thickness, and lithofacies. Previous studies include similar systematic fracture strikes in the CAG region, although other orientations were also reported (Hancock et al., 1984; Abdmutalib and Abdullatif, 2017). The orientations of veins remain difficult to construct in the platform, because of their small occurrences.

Open fractures appear in the borehole images as conductive features, marking apertures filled (or partially filled) with the drilling water-based mud (Fig. 3). The closed fractures are undetectable in the borehole images but were observed on the core (Fig. 9) (Al-Fahmi and Cartwright, 2019). More importantly, the fractures that are aligned to the S_{Hmax} are open with relatively large hydraulic (e) and mechanical (E) apertures (up to 1.1 mm) (Fig. 9). The apertures diminish in size as the fractures gradually deviate in orientation from the S_{Hmax} (Fig. 9). The non-aligned fractures were undetected, except about 20% of those with partial apertures due to some roughness mismatches in their host lithofacies (Al-Fahmi et al., 2018).

The fracture strikes in Fig. 7b are influenced by three factors: i) the bias of the traversing boreholes (in terms of length and orientation), ii) the impaired

detection of borehole imaging that misses closed fractures, and iii) the spatial distribution of fracture sets in the platform strata. In addition, the measurements have certain ranges of errors that may reach up to 10° . The errors are associated with the accuracy of the imaging tool magnetic field reference, and sometimes related to the precision of fitting sine curves to the borehole structural features (Al-Fahmi, 2018).

Grouping the strikes in one plot can reduce the data bias, given it is based on several sub-horizontal boreholes of different orientations and locations (Fig. 10). The peculiar dominance of the NE–SW set in the imaged carbonates in Eastern Arabia can be explained by their relatively large apertures resulting from their alignment to the S_{Hmax} (Fig. 10). The histograms in Fig. 10 would be different if we account for the closed fractures (i.e., those with matching walls that are normal to the S_{Hmax}).

Identifying the fracture orientations and sets was therefore possible. For example, the reported strikes, from the borehole images of X-01, X-02, X-03, and X-04, were of a dominant NW–SE fracture set due to the borehole orientation biases. The NE–SW fracture set in Fig. 10 was in fact predicted before the drilling and imaging of X-05 and X-06 (see Fig. 6c in Al-Fahmi and Cartwright, 2019). The two boreholes confirmed the prediction.

As it appears, the fractures of the platform in the dome exist mostly with NE–SW and NW–SE orientations. The two sets dominate in the platform in other anticlines in the region (Fig. 10), indicating systems of regional fractures (e.g., Nelson, 2001). The two fracture sets are mostly at right angles; they seem to make up orthogonal patterns like those frequently observed in the carbonate outcrops including those in the dome (Al-Fahmi et al., 2014). But deviations in azimuths of the NE–SW set exist, between 60° and 90° . This may indicate regional patterns of rotations across the homocline. Nonetheless, further work and data are still required to decipher and exclude inherited biases of borehole orientations and imaging.

Fig. 10. **a)** Histograms of the strikes of open fractures in the platform strata, interpreted from borehole images of non-vertical boreholes. The plot of the dome fractures is compiled from the rose diagrams in Fig. 7b. The plot for the anticline is compiled from sub-horizontal boreholes in Ghawar Field. **b)** Models of fracture sets and apertures under the influence of S_{Hmax} in Eastern Arabia.

Fracture abundance

The spacing of fractures in the outcrops is typically larger than the thickness of host layers (Fig. 11). The fracture spacing, between 1 m and 3 m, is apparently representative to the homocline. The CAG region does not seem to be remarkably different, with the most intensely fractured intervals display 1.2 fracture per meter (Abdmutalib and Abdullatif, 2017).

By comparison, the fractures in the subsurface are more abundant than the fractures in the outcrops (Fig. 11). In other words, the platform is fractured in the dome more than in the flat outcrops, or the gentle homocline. In the dome, fracture spacing has an arithmetic means of about 31 cm and standard deviations of 24 cm (Fig. 8). The subsurface strata have a mean fracture spacing mostly smaller than the thicknesses of the traversed mechanical layers (Fig. 11a). The spacing partly depends on fracture height (i.e., unit thickness for confined fractures)

(Fig. 11). Whether all veins and fractures are confined to the host layers of the subsurface remains obscure. Both fracture height and host layer thickness are missing information from core and borehole images. It depends on the rare chances that the core is cut from the intersections of fractures with the layer boundaries. Several possibilities exist for ranges of the mechanical layer thicknesses and fracture spacing. The two extreme scenarios are that fracture spacing is regular and the layer thicknesses are equal. The data indicates neither. The varying abundance of fractures is evidence for their confinement to certain mechanical layers or intervals (Fig. 8c).

The values of corrected spacing partly reflect the tendency of some lithofacies to exist in certain ranges of thickness. If the outcrop observations are to be used to predict the subsurface, the subsurface fractures are expected to be mostly confined to layers ranging from 0.1 m to 1.2 m. About 85% of the outcrop fractures are confined to a layer (Fig.

4). Within this range, fracture spacing is smaller than the thickness of subsurface layers, unless the layers are less than 0.3 m thick. This is unlikely possible, for two reasons. Firstly, modeling of the lithofacies from the core does not indicate this possibility of dominant thin layers (Fig. 11b). Secondly, fractures in layers of 0.3 m could have been partially observed terminating in the domain of boreholes (in core and borehole images), because of their short height and abundance.

Framework of platform fractures

The synthesis of data on fracture properties in the platform is translated into a 3D fracture conceptual model (Fig. 12). The model includes the two major fracture sets in a two-layer scenario with information on fracture mineralization, mode of displacement, orientations, apertures, and abundance, and one possibility for cross-cutting relationships (Fig. 12). The closed “undetectable” fractures in the subsurface are also included (Fig. 12). The model uses the dome and homocline as end members for constraining fracture abundance in the Arabian Shelf interior. It gives a unimodal

distribution for hydraulically conductive fractures and bimodal distribution for the major fracture sets, if the sets were to be intersected by random sub-horizontal boreholes (Fig. 12). The model does not include faults and throughgoing fractures as they exist infrequently in the platform. The platform jointing has possibly evolved into “throughgoing fractures” or corridors for fluid flow in some areas (e.g., Ozkaya, 2019). Faults and fracture corridors are difficult to predict and typically inferred from direct observations of seismic reflection and borehole imaging.

The synthesis contests the view that carbonate strata in the Arabian Shelf interior is less susceptible to the tectonic fracturing. The synthesis also demonstrates importance of the abundance of conductive fractures aligned with the paucity of fracture mineralization and breaching faults. These factors, with the well-known high-porosity intervals, are foremost for making the platform not only ideal for the prolific petroleum accumulations, but for the super permeability and low-cost production

Fig. 11. **a)** Plots of fracture spacing against layer thicknesses from study areas in outcrops and subsurface. **b)** Distribution of typical thicknesses for the platform in the subsurface, obtained from Al-Awwad and Collins (2013).

Fig. 12. **a)** Models showing ratio of veins to barren fractures in the Late Kimmeridgian carbonate platform in the Arabian Shelf interior. **b)** predicted fracture spacing in the carbonate platform structures. **c)** Representative elementary volume of fracture mode of displacement, mineralization, orientations, and abundance in the platform. The models predict fracture abundance in the platform, because the studied areas represent the most and least deformed areas in the Arabian Shelf interior. Arrows point to north.

Controls on the Platform Fracturing

We consider burial and tectonic loads as one region of the platform is currently buried and the other is exhumed. The loads, whether compressive or tensile, in rocks result in non-recoverable deformations (i.e., fractures and pressure solution) if the differential loads exceed the rock strengths. The focus here is on the major sources of loads that led to fracturing of a brittle carbonate platform and controlled fracture types and abundance across the platform.

Development of Veins and Stylolites

The calcite veins can be explained from their (i) infrequent occurrences, (ii) association to stylolites, and (iii) chemical, petrographic, and geometric properties. The $\delta^{13}\text{C}$ values of our tested samples are typical of those in modern marine sediments (Azer and Peebles, 1998). The negative $\delta^{18}\text{O}$ values in the platform subsurface are indications of a later rock alteration by warm fluids with the burial, stylolization, and recrystallization in a closed

system of a normal geothermal gradient (Swart et al., 2005). According to Swart et al. (2005), these carbonates would have had positive $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ($\delta^{18}\text{O}$ +2 to +4‰ and $\delta^{13}\text{C}$ +2 to +4‰) of the normal marine fluids during the Late Jurassic period (approx. -1‰ SMOW). The diagenesis in closed systems would have changed the isotopic signatures of the oxygen, but not of the carbon, because the oxygen in the diagenetic pore water is higher than that in the carbonate with which it is in contact (Dodd and Stanton, 1992).

The negative $\delta^{18}\text{O}$ values in the outcrops indicate an open system of meteoric water circulation (Eltom et al., 2014; Al-Mojel et al., 2018) (Fig. 6b). The difference in isotopic signatures between the subsurface and outcrops indicate the role of Hith Anhydrite as an effective barrier for downward fluid migration. The Hith Anhydrite was eroded and the underlain carbonates were subsequently exposed to the meteoric diagenesis in Central Arabia. Midway in the platform in Abu Jifan in Khurais Complex, (Rosales et al., 2018), the platform strata display isotopic excursions from the isotopes of the platform strata in Ghawar, Abu Dhabi, and the herein studied dome (Fig. 6b). The Hith Anhydrite was probably breached in Abu Jifan by fractures or partial chemical dissolutions, because of its shallow depth and proximity to the wadi discharges in Central Arabia. Central Arabia was uplifted and fractured, with the Arabian Shelf tilting and therefore created water drainage systems flowing naturally toward the east.

The stylolites formed under the overburden pressure as compaction structures, or in other terms anti-Mode-I fractures. They were the earliest deformation events in the Late Kimmeridgian carbonates (Fig. 13). The burial depth where stylolitization begins is not well constrained in the Arabian Shelf interior, because the varying effects of water chemistry, clay contents, and organic material (e.g., Alsharhan and Sadd, 2000). Pressure solutions can begin between 300 and 600 m of burial depth and increase with increasing overburden pressure (e.g., Dunnington, 1967).

The stylolites and veins may have stopped developing in the anticlines after the oil migration.

This may explain their relative increase in the water-filled intervals below oil (Fig. 5c). We assume early, and hence shallow-setting for the development of stylolite and veins (Fig. 13). Stylolites were not observed in the outcrops, but it remains unclear if they have never existed, or were simply obscured by weathering. Conceivably, the veins are tension gashes formed with the stylolites. Similar observations were previously reported (Nelson, 2001), including from the lower Arab-D in the Emirates (De Periere et al., 2017).

While the veins may not have developed at once, they must have had spatiotemporal controls that we tried to frame as follows.

- 1) Deposition of the non-permeable Hith Anhydrite prevented penetration of meteoric water into the Late Kimmeridgian carbonates, and hence prevented further diagenesis, from Early Cretaceous onward. The Hith Anhydrite has been an effective sealing rock that contained the vast oil resources in the underlain carbonates.
- 2) Prevalence of pore systems in the Late Kimmeridgian carbonates acted as channels and depositional sites of calcite-rich solutions more than existing fractures during early burial and diagenetic processes.
- 3) Oil emplacement, after growth of the anticlines, in the Late Cretaceous may have halted fracture mineralization in the oil-filled intervals. The oil emplacement and anticlinal growth are believed to hinder the diagenetic processes (e.g., Paganoni et al., 2016). This may be true in porous carbonates because fractures induced by volumetric expansion of organic material in tight shale can nonetheless seal with calcite (Hooker et al., 2020).
- 4) Lack of the tectonic deformations such as breaching faults that could have changed the setting of flat layer-cake stratigraphy. Calcite-rich solutions of connate water are expected to move downward under gravity in the Arabian Shelf interior. The oil and water were segregated in the region

because of their different density, by which light oil tops heavy water.

Development of Fractures

The evolving loads across the platform produced the significant difference in fracture abundance (Fig. 4, Fig. 8). The sediment burial and the vast petroleum resources in the platform raises the role of pore-fluid pressure in fracture development. However, there is no direct or indirect evidence for natural hydraulic fracturing. Data from the Arabian Shelf interior indicates that it is of a normal pressure gradient from outcrops and down to about 4.5km below ground (Al-Mahmoud, 2015). Deeper sequences, like the Triassic Lower Jilh Formation, have some regimes of high pressure due to low permeability, and gas generation from the Early Silurian Qusaiba Shale (Fig. 13).

Fluid overpressure did not develop in the Late Kimmeridgian carbonates because of their shallow burial depths (less than 1.8km) (Fig. 13). The carbonates were neither the product of rapid burial nor did they lack high porosity to accommodate the migrated oil. In general, deeply buried rocks can maintain normal pressure up to 8 km, (Suppe, 2014), making evidence of hydraulic fracturing elusive. For example, the carbonates of Mission Canyon Formation in the Little Knife Field were buried to at least its present depth of 3 km. But fluid inclusions indicate hydrostatic pore-fluid pressure when the fractures formed (Narr and Burruss, 1984). Fracturing by high fluid pressure and volume contraction may happen in rocks but under conditions of rapid fluid expulsion or where fluid flow is hindered by low-permeability sediments (e.g., Narr and Burruss, 1984; Cartwright and Lonergan, 1996). Similarly, unloading of sediment overburden does not indicate how the outcrops in Central Arabia were systematically jointed. Unlike jointed basalt in outcrops, the effects of temperature and strain rate dependences are small for rock brittle behavior (e.g., Suppe, 2014). But again, as the burial is shallow, the thermomechanical effects were negligible. Besides, the outcrops lack the initial overpressured stage, in which the initial compressive stresses are low (e.g., English, 2012).

The fractures formed by tensile stresses that were operative across the platform but at cyclic and of different magnitudes (Fig. 13a). The strata were stretched regionally and locally by the growing anticlines and domes across the Arabian Shelf interior. The strata bending is not an unusual mechanism for fracturing. It has been extensively studied in folded regions, although from highly deformed terrains (Al-Fahmi, 2018). The unusual case of the Arabian Shelf interior is its nearly flat setting, in the spectrum of the folds that were studied from Variscan, Alpine, Alleghanian, and Laramide orogenic belts (Al-Fahmi, 2018). The outcrops represent the flat parts of the platform interior, and the dome represents one of the mostly elevated and bent regions. Yet, the study areas slightly vary in the curvature degrees (Fig. 1). The cross-sections of the dome and other anticlines in the Arabian Shelf typically require a high vertical-scale exaggeration to observe their bending (Fig. 1c).

The first impression is that slight variations in the curvature and elevated structural arches seem to account for these notable differences in fracture abundance (Fig. 11). But fractures did not develop at once. The subtle extension of the homocline probably caused the early and widely spaced regional NE–SW, SW–SE, and E–W fractures. The growth of the dome and other anticlines infilled fractures, whose orientations were controlled by pre-existing regional fractures. The dome grew by multiple episodes of slow rise that produced a higher degree of curvature and therefore strain. Evidence supporting this hypothesis exists in the dome outcrops. The later growth episode produced the jointing of the Cenozoic Rus carbonate in mostly NE–SW and NW–SE fractures (Al-Fahmi et al., 2014). Such infilling process of fractures is expected to have happened in other carbonate intervals and in other anticlines and domes in the Arabian Shelf interior.

In essence, the platform fracturing continued with extension episodes (Fig. 13a). It reached the level of oversaturation in fracture spacing in the dome, which experienced low degrees of strain below 2% of layer volumetric extension (Al-Fahmi et al., 2016). This observation challenges standard

structural models that relate fracture abundance from strain magnitudes and orientations of severely folded strata (Al-Fahmi, 2018). This finding indicates that layered carbonates respond by fracturing under subtle tectonic extension and in flat or nearly flat layers. Producing further fractures gets harder, when layered rocks are broken into smaller blocks. Instead, the fractures in the layered rock ultimately coalesce, leading to strain localization and macro-scale shear failure, in a manner that has been observed from rock mechanics tests (e.g., Hoek and Martin, 2014).

Accordingly, faulting takes place in the jointed carbonate platforms to accommodate continuing loads. This seems to be the case of the Arabian Shelf in Central Arabia, in which the platform was jointed before the region evolved into a graben system, the CAG. Bedding-parallel slip is another process that took place, when layers were uplifted or overturned by sharp-curvature folding like those at the Arabian Shelf margins. Bedding-parallel slip by flexural slip folding is the predominant mechanism in the Asmari carbonates in Zagros Mountains (Stephenson et al., 2007).

Fig. 13. **a)** A timeline graph showing fracturing of the Late Jurassic carbonate platform in the homocline and the dome. **b)** the pressure-depth plot of the Arabian Shelf interior showing a normal pressure regime up to around 2.5 km depth, modified from (Al-Mahmoud, 2015). **c)** The classic strength-depth graph, modified from Suppe (2014), showing linearly increasing brittle strength versus hydrostatic pore-fluid pressures and the shallow burial setting, excluding possibilities of overpressure and hence hydrofracturing as a mechanism for fracture development.

References

- Abdulmutalib, A., Abdullatif, O., 2017. Multi-scale Discontinuities Characterization of the Arab-D and Upper Jubaila Tight Carbonates Outcrop, Central Saudi Arabia. *Arabian Journal for Science and Engineering* 42, 2515–2538. <https://doi.org/10.1007/s13369-017-2522-2>
- Al-Awwad, S.F., Collins, L.B., 2013. Arabian carbonate reservoirs: A depositional model of the Arab-D reservoir in Khurais field, Saudi Arabia. *AAPG Bulletin* 97, 1099–1119. <https://doi.org/10.1306/11051212103>
- Al-Fahmi, M.M., 2018. Controls on fracture abundance in gently deformed carbonates, PhD thesis. University of Oxford.
- Al-Fahmi, M.M., Cartwright, J.A., 2019. Comparison of carbonate reservoir fractures from core and modern electrical borehole images. *Marine and Petroleum Geology* 101, 252–264. <https://doi.org/10.1016/j.marpetgeo.2018.12.006>
- Al-Fahmi, M.M., Cooke, M.L., Cole, J.C., 2014. Modeling of the Dammam outcrop fractures: Case study for fracture development in salt-cored structures. *GeoArabia, Journal of the Middle East Petroleum Geosciences* 19, 49–80.
- Al-Fahmi, M.M., Ozkaya, S.I., Cartwright, J.A., 2018. New insights on fracture roughness and wall mismatch in carbonate reservoir rocks. *Geosphere* 14, 1851–1859. <https://doi.org/10.1130/GES01612.1>
- Al-Fahmi, M.M., Plesch, A., Shaw, J.H., Cole, J.C., 2016. Restorations of faulted domes. *AAPG Bulletin* 100, 151–163. <https://doi.org/10.1306/08171514211>
- Al-Husseini, M.I., 1997. Jurassic sequence stratigraphy of the western and southern Arabian Gulf. *GeoArabia* 2, 361–382.
- Al-Mahmoud, M., Khalil, M., Moustafa, A., 2009. The Jinadriyah anticlines: a surface model for oil fields in eastern Saudi Arabia. *Arabian Journal of Geosciences* 2, 213–234. <https://doi.org/10.1007/s12517-008-0031-z>
- Al-Mahmoud, M.J., 2015. Pressure and thermal regimes and systems in the sedimentary sequence of central and eastern Saudi Arabia. *Arabian Journal of Geosciences* 8, 6249–6266. <https://doi.org/10.1007/s12517-014-1619-0>
- Al-Mojel, A., Dera, G., Razin, P., Le Nindre, Y.M., 2018. Carbon and oxygen isotope stratigraphy of Jurassic platform carbonates from Saudi Arabia: Implications for diagenesis, correlations and global paleoenvironmental changes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 511, 388–402. <https://doi.org/10.1016/j.palaeo.2018.09.005>
- Al-Mojel, A., Razin, P., Dera, G., 2020. High-resolution sedimentology and sequence stratigraphy of the Oxfordian-Kimmeridgian, Hanifa, Jubaila and Arab outcrops along Jabal Tuwaiq, Central Saudi Arabia. *Journal of African Earth Sciences* 103803. <https://doi.org/10.1016/j.jafrearsci.2020.103803>
- Alsharhan, A.S., Nairn, A.E.M., 1997. *Sedimentary Basins and Petroleum Geology of the Middle East*. Elsevier B.V. <https://doi.org/10.1016/B978-044482465-3/50000-0>
- Alsharhan, A.S., Sadd, J.L., 2000. Stylolites in Lower cretaceous carbonate reservoirs, U.A.E. *SEPM Special Publication* 56576.
- Ameen, M.S., 2014. Fracture and in-situ stress patterns and impact on performance in the Khuff structural prospects, eastern offshore Saudi Arabia. *Marine and Petroleum Geology* 50, 166–184. <https://doi.org/10.1016/j.marpetgeo.2013.10.004>
- Ameen, M.S., Smart, B.G.D., Somerville, J.M., Hammilton, S., Naji, N.A., 2009. Predicting rock mechanical properties of carbonates from wireline logs (A case study: Arab-D reservoir, Ghawar field, Saudi Arabia). *Marine and Petroleum Geology* 26, 430–444. <https://doi.org/10.1016/j.marpetgeo.2009.01.017>
- Azer, S.R., Peebles, R.G., 1998. Sequence stratigraphy of the Arab A to C members and Hith Formation, offshore Abu Dhabi. *GeoArabia* 3, 251–268.
- Brown, G.F., 1972. *Tectonic map of the Arabian Peninsula*. US Geological Survey.
- Cantrell, D.L., Swart, P.K., Handford, R.C., Kendall, C.G., Westphal, H., 2001. Geology and production significance of dolomite, Arab-D Reservoir, Ghawar Field, Saudi Arabia. *GeoArabia* 6, 45–60.
- Cartwright, J.A., Lonergan, L., 1996. Volumetric contraction during the compaction of mudrocks: A mechanism for the development of regional-scale polygonal fault systems. *Basin Research* 8, 183–193. <https://doi.org/10.1046/j.1365-2117.1996.01536.x>
- Clerke, E.A., 2009. Permeability, Relative Permeability, Microscopic Displacement Efficiency and Pore Geometry of M_1 Bimodal Pore Systems in Arab-D Limestone. *SPE Journal* 14, 524–531. <https://doi.org/10.2118/105259-PA>
- De Periere, M.D., Foote, A., Bertouche, M., Shah, R., Al-Darmaki, F., Bin Ishaq, W., 2017. Link between microporous limestones and elastic properties in tight carbonates. A case study from the lower arab formation upper jurassic, onshore United Arab Emirates. *Society of Petroleum Engineers - SPE Abu Dhabi International Petroleum Exhibition and Conference 2017* 2017-Janua. <https://doi.org/10.2118/188944-ms>
- Dodd, J.R., Stanton, R.J., 1992. *Paleoecology: Concepts and Applications*, 2nd Editio. ed. John Wiley & Sons.
- Dunham, R.J., 1962. *Classification of carbonate rocks*

- according to depositional texture. M 1: Classification of Carbonate Rocks--A Symposium. 23.
- Dunnington, H. V., 1967. Aspects of Diagenesis and Shape Change in Stylolitic Limestone Reservoirs. 7th World Petroleum Congress. World Petroleum Congress.
- Dyer, R.A.R., Hussein, M., 1991. The Western Rub'Al-Khali Infracambrian Graben System. Middle East Oil Show SPE 21396, 2139.
- Eltom, H., Abdullatif, O., Makkawi, M., Al-Ramadan, K., Abdulraziq, A., 2014. Porosity evolution within high-resolution sequence stratigraphy and diagenesis framework: outcrop analog of the upper Jurassic Arab-D reservoir, Central Saudi Arabia. *Arabian Journal of Geosciences* 1669–1690. <https://doi.org/10.1007/s12517-013-1251-4>
- English, J.M., 2012. Thermomechanical origin of regional fracture systems. *AAPG Bulletin* 96, 1597–1625. <https://doi.org/10.1306/01021211018>
- Faqira, M., Rademakers, M., Afifi, A.M., 2009. New insights into the hercynian orogeny, and their implications for the paleozoic hydrocarbon system in the arabian plate. *GeoArabia* 14, 199–228.
- Hancock, P.L., Al Kadhi, A., Sha'at, N.A., 1984. Regional joint sets in the Arabian Platform as indicators of intraplate processes. *Tectonics* 3, 27–43. <https://doi.org/10.1029/TC003i001p00027>
- Hoek, E., Martin, C.D., 2014. Fracture initiation and propagation in intact rock - A review. *Journal of Rock Mechanics and Geotechnical Engineering* 6, 287–300. <https://doi.org/10.1016/j.jrmge.2014.06.001>
- Hooker, J.N., Ruhl, M., Dickson, A.J., Hansen, L.N., Idiz, E., Hesselbo, S.P., Cartwright, J., 2020. Shale anisotropy and natural hydraulic fracture propagation: An example from the Jurassic (Toarcian) Posidonienschiefer, Germany. *Journal of Geophysical Research: Solid Earth*. <https://doi.org/10.1029/2019JB018442>
- Konert, G., Afifi, a. M., Al-Hajri, S. a., Droste, H.J., 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian plate. *GeoArabia* 6, 407–442.
- Luthy, S.T., Grover, G. a., 1995. Three Dimensional Geologic Modelling of a Fractured Reservoir, Saudi Arabia. *Proceedings of Middle East Oil Show* 419–430. <https://doi.org/10.2118/29814-MS>
- McArthur, J.M., Howarth, R.J., Shields, G.A., 2012. *Strontium Isotope Stratigraphy. The Geologic Time Scale*. Elsevier, Boston, 127–144. <https://doi.org/10.1016/B978-0-444-59425-9.00007-X>
- Meyer, F.O., Price, R.C., Al-Raimi, S.M., 2000. Stratigraphic and petrophysical characteristics of cored arab-D super-k intervals, Hawiyah area, Ghawar field, Saudi Arabia. *GeoArabia* 5, 355–384.
- Morad, S., Al-Aasm, I.S., Nader, F.H., Ceriani, A., Gasparrini, M., Mansurbeg, H., 2012. Impact of diagenesis on the spatial and temporal distribution of reservoir quality in the Jurassic Arab D and C members, offshore Abu Dhabi oilfield, United Arab Emirates. *GeoArabia* 17, 17–56.
- Narr, W., Burruss, R.C., 1984. Origin of Reservoir Fractures in Little Knife Field, North Dakota. *AAPG Bulletin* 68, 1087–1100. <https://doi.org/10.1306/AD4616D3-16F7-11D7-8645000102C1865D>
- Narr, W., Schechter, D.S., Thompson, L.B., 2006. *Naturally Fractured Reservoir Characterization*. Society of Petroleum Engineers.
- Nelson, R.A., 2019. *Static Conceptual Fracture Modeling*. Static Conceptual Fracture Modeling. Wiley. <https://doi.org/10.1002/9781119596875>
- Nelson, R.A., 2001. *Geologic Analysis of Naturally Fractured Reservoirs*. *Geologic Analysis of Naturally Fractured Reservoirs*. <https://doi.org/10.1016/B978-088415317-7/50005-1>
- Ozkaya, S.I., 2019. Validating Predicted Fracture Corridors by Statistical Comparison With Well Data. *SPE Reservoir Evaluation & Engineering* 22, 1385–1398. <https://doi.org/10.2118/195582-PA>
- Paganoni, M., Al Harthi, A., Morad, D., Morad, S., Ceriani, A., Mansurbeg, H., Al Suwaidi, A., Al-Aasm, I.S., Ehrenberg, S.N., Sirat, M., 2016. Impact of stylolitization on diagenesis of a Lower Cretaceous carbonate reservoir from a giant oilfield, Abu Dhabi, United Arab Emirates. *Sedimentary Geology* 335, 70–92. <https://doi.org/10.1016/j.sedgeo.2016.02.004>
- Peacock, D.C.P., Nixon, C.W., Rotevatn, A., Sanderson, D.J., Zuluaga, L.F., 2016. Glossary of fault and other fracture networks. *Journal of Structural Geology* 92, 12–29. <https://doi.org/10.1016/j.jsg.2016.09.008>
- Powers, R.W., Ramirez, L.F., Redmond, C.D., Elberg, E.L.J., 1966. *Geology of the Arabian Peninsula Sedimentary Geology of Saudi Arabia*. U.S. Geological Survey Professional Paper 560-D, 154.
- Price, N.J., Cosgrove, J.W., 1990. *Analysis of Geological Structures*. Cambridge, New York, Port Chester, Melbourne, Sydney: Cambridge University Press.
- Rosales, I., Pomar, L., Al-Awwad, S.F., 2018. Microfacies, diagenesis and oil emplacement of the Upper Jurassic Arab-D carbonate reservoir in an oil field in central Saudi Arabia (Khurais Complex). *Marine and Petroleum Geology* 96, 551–576. <https://doi.org/10.1016/j.marpetgeo.2018.05.010>
- Sims, D.W., Morris, A.P., Wyrick, D.Y., Ferrill, D. a., Waiting, D.J., Franklin, N.M., Colton, S.L., Umezawa, Y.T., Takashi, M., Beverly, E.J., 2013. Analog modeling of normal faulting above Middle East domes during regional extension. *AAPG Bulletin* 97, 877–898. <https://doi.org/10.1306/02101209136>

- Steineke, M., Bramkamp, R.A., Sander, N.J., 1958. Stratigraphic relations of Arabian Jurassic oil: Middle East. AAPG 1294–1329.
- Stephenson, B.J., Koopman, A., Hillgartner, H., McQuillan, H., Bourne, S., Noad, J.J., Rawnsley, K., 2007. Structural and stratigraphic controls on fold-related fracturing in the Zagros Mountains, Iran: implications for reservoir development. Geological Society, London, Special Publications 270, 1.2–21. <https://doi.org/10.1144/GSL.SP.2007.270.01.01>
- Suppe, J., 2014. Fluid overpressures and strength of the sedimentary upper crust. *Journal of Structural Geology* 69, 481–492. <https://doi.org/10.1016/j.jsg.2014.07.009>
- Swart, P.K., Cantrell, D.L., Westphal, H., Handford, C.R., Kendall, C.G., 2005. Origin of Dolomite in the Arab-D Reservoir from the Ghawar Field, Saudi Arabia: Evidence from Petrographic and Geochemical Constraints. *Journal of Sedimentary Research* 75, 476–491. <https://doi.org/10.2110/jsr.2005.037>
- Wierzbowski, H., Anczkiewicz, R., Pawlak, J., Rogov, M.A., Kuznetsov, A.B., 2017. Revised Middle–Upper Jurassic strontium isotope stratigraphy. *Chemical Geology* 466, 239–255. <https://doi.org/10.1016/j.chemgeo.2017.06.015>