REVIEW OF LOWER-PALAEOZOIC RESERVOIR PROSPECTIVITY OF WESTERN IRAQ WITH REFERENCE TO JORDAN

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ABSTRACT

The Palaeozoic basin of Jordan and Iraq occupies the NW part of the Arabian Plate. The Lower Palaeozoic succession is the most under-explored succession in Iraq, particularly in western Iraq where it is the most promising target for future exploration. The western Iraqi subsurface and Jordanian geology are characterized by similar major chrono-stratigraphic rock units. In western Iraq, the Akkas-1 well is the only gas and condensate discovery in sandstone reservoirs of Early Silurian and Late Ordovician age. Lower Silurian sandstones of the Akkas Formation are an oil reservoir characterized by an average porosity of 6.5% and permeability of 0.2 mD. Underlying Upper Ordovician sandstones of the upper part of the Khabour Formation are also reservoir, but for sweet gas and condensate. The latter are comparable to both the Risha and Wadi Sirhan discoveries in Jordan. Several deeper potential sandstone reservoirs (of older Ordovician and Cambrian ages) are also present across the region. Equivalent Ordovician age Jordanian reservoirs are primarily developed in homogeneous, highly mature quartz arenites of storm-dominated clastic-shelf stratigraphies. Within the Risha Field and the Wadi Sirhan area, are also end-Ordovician (Hirnantian) glaciogenic and periglacial sandstones with more variable reservoir quality characteristics compared to the underlying quartz arenites. These often comprise highly immature arkoses (as diamictites), which provide a mineralogically much less stable assemblage in which there is a possibility of developing secondary porosity. Almost similar sandstones were also reported from the upper part of the Khabour Formation in the Akkas Field of western Iraq. Sedimentological and XRD mineralogical studies suggest that diagenesis is an important factor in developing of reservoir quality. Nevertheless, reservoir quality is a major exploration risk where burial was significant that led to quartz overgrowth and clay cementation. It is notable that some sandstone reservoirs have chlorite-clay

coatings, which prevented formation of the quartz overgrowth and preserved good reservoir quality. The widespread occurrence of associated source and seal rocks together with the proven and potential reservoirs, suggests that Lower Palaeozoic prospects below the deserts of western Iraq are promising targets for future hydrocarbon exploration.

Keywords: Lower Palaeozoic; Western Iraq; Jordan; Proven reservoirs; Potential reservoirs

INTRODUCTION

North-western Arabian Plate (Fig. 1A) is considered the most promising exploration region for Lower Palaeozoic reservoirs. The western Iraq and Jordan are characterized by similar subsurface major chrono-stratigraphic rock units (Figs. 2A and 3). The thickest stratigraphic sequence lies on the border area between Jordan and Iraq, whilst to the south, the same stratigraphy thins up against the Arabian Shield (in Aqaba region), as it also thins westwards towards the Dead Sea Rift. Thick Lower Palaeozoic strata crops-out along the Dead Sea road to the Aqaba (Stops 1-5 in Fig. 1B) as well as in most of the Southern Jordan Deserts including the Wadi Ram (Traverse 8), and Hiswah (Traverse 7) and Mudawwara (Traverse 9) locations near the Saudi borders in Fig. 1B. The Lower Palaeozoic succession is thus a primary exploration target with some discoveries in Ordovician and Silurian sandstones (e.g. Al-Haba et al. 1994; Aqrawi, 1998; Al-Hadidy, 2007; Tamar-Agha, 2009; Al-Ameri, 2010; Aqrawi et al. 2010; Al-Khafaji et al. 2015; Al-Juboury et al. 2019; Abdula et al. 2020 and Mohammed et al. 2020) where it is thick in both eastern Jordan and western Iraq (Figs. 2A & 2B).

The main objective of this study is to characterise the proven and predict the potential reservoirs of the Lower Palaeozoic succession of western Iraq. Due to limited subsurface penetration and data availability of such succession in western Iraq as well as at the northern Iraq outcrops, a short review of stratigraphic, sedimentological and mineralogical studies of selected outcrop and borehole rock-samples of Jordan was carried out. The latter characteristics of every rock-unit were then proposed for the potential correlated equivalent rock-unit in the western Iraq succession within a third-order stratigraphic framework (Fig. 3). The latter 3rd order sequences were previously identified by Aqrawi et al. (2010) for each regional Arabian Plate (AP) Megasequence of Sharland et al. (2001 and 2004), particularly for AP2 and AP3.

MATERIALS AND METHODS

During two field trips in March and May 2005, in addition to three visits to the NRA core house in Amman in March, May and September of the same year, outcropping strata and cores were thoroughly photographed and sampled (Table 1). Outcrops at many stops were examined along

the Amman-Dead Sea-Aqaba road and as well as at various stops of the southern Jordanian Desert locations (see stops and traverse locations in Fig. 1B).

Fig. 1. NW Arabia, the study area (A) includes both western Iraqi desert and eastern Jordan subsurface in addition to southern Jordan outcrops and well locations. The inset Google map (B) shows the outcrop sampling stops (1-5) and traverses (6-9)

These photos were analysed later in order to support the analytical results of the 66 collected samples. Representative samples were collected from each Palaeozoic formation at every stop for later analyses (Table 1). Extra core samples were collected from different boreholes across Jordan for correlating the results with the outcropped equivalents (Table 1). More than 50 standard thin sections were prepared for the collected samples. The samples were impregnated with blue epoxy resin to characterise their visual porosity. The thin sections were partly stained in order to differentiate feldspars and clays. All the prepared thin sections were studied using a digitised polarizing microscope in order to classify the reservoir rocks into facies, and to characterise their quality considering the effects of various diagenetic processes. In addition, some 25 selected samples were analysed using an environmental scanning electron microscope (ESEM), FEI Quanta 400, in order to characterise their micro-components and micro-porosity. Secondary and back-scattered images were employed during the analysis, which were supported by the micro-elemental analyser (EDAX) in order to identify the mineralogical components of clays and cements. Thirty-six samples were analysed by X-Ray Diffraction (XRD) for bulk mineral contents and 37 samples for clay mineral content, using Huggett *et al.* (2001) and Aqrawi (1993) methodology for semi-quantitative calculations. The

XRD analyses carried out at the Natural History Museum Laboratories, London, U.K. using the standard methodology described by Huggett *et al.* (2001).

Fig. 2. Composite Infra-Cambrian-Early Palaeozoic subsurface stratigraphy of Jordan with proposed 3rd order stratigraphic sequences (A) and their E-W cross-section in Jafr area of SE Jordan (B) (after Aqrawi *et al.* 2010) data and nomenclature after Andrews *et al.* (1991) and flooding surfaces after Sharland *et al.* (2001)

RESULTS

Arabian Plate (AP) Megasequences of the Study Area

In addition to surface-defined Infra-Cambrian stratigraphy, most work on the Lower Palaeozoic lithostratigraphy in Jordan acknowledges two different nomenclatures for outcrop defined by (NRA) Natural Resources Authority (Fig. 2A) (e.g. Powell, 1989 and Masri *et al.* 2014) and for subsurface by (NPC) National Petroleum Company (Fig. 2B) (e.g. Andrews *et al.* 1991).

Table 1. Rock samples collected from both outcrops and cores during fieldtrips to Jordan in 2005

Sample No.	Stop No./Traverse No.	Well	Depth (m)	Formation	Lithology
1A	1			Burj	Clastics
1B	1			Burj	marly Lst ?
2	3			Umm Ishrin	Clastics
4A	7			Salib	Red fine sst
4B	7			Salib	Red coarse sst
4C	7			Salib	Pebbly yellow sst
5A	6			Disi	white pure sst
5B	6			Umm Sahm	Clastics
6	7			Hiswa	lower shaly part
7A	8			Hiswa	upper sandy part
7B	8			Low. Dubaydib	Sst
8A	10			Middle Dubaydib	Channel Sst

8B	10			Middle Dubaydib	Sst Reservoir rocks
9A	11			Upper Dubaydib	Sst
9B	11			Low. Mudawwara	Shale
10	Petra site			Umm Ishrin	stained Sst
11	NRA Core House	RH-2	3201.1	Hiswa	Shale
12	NRA Core House	RH-2	3209	Hiswa	Shale
20	NRA Core House	WS-6	1398.1	Batra	hot? Shale
21	NRA Core House	WS-6	1403.2	Batra	Sst between two hot? shales
22	NRA Core House	WS-6	1422.1	Batra	hot? Shale
23	NRA Core House	WS-6	1426.7	Dubaydib	Sst- Poor Reservoir Quality
25	NRA Core House	WG-2	2367	Disi	Sst with Good Res. Quality
26	NRA Core House	WG-2	3540.7	Burj	marly Lst
28	1			Burj	
29	3			Umm Ishrin	Sst
30	3			Umm Sahm	Sst
31	4			Hiswah	Clyst
32	5			U Hiswah	Sst
33A	2			L Mudawwara	Sst
33B	2			L Mudawwara	Sst
33C	2			L Mudawwara	
34	3			U Mudawwara	Clyst
35A	1			U Mudawwara	
35B	1			U Mudawwara	
36	NRA Core House	AJ-1	2980.6	Salib	
37	NRA Core House	DH-1	2579.5	Salib	
38	NRA Core House	DH-1	3131.8	Hiswah	
39	NRA Core House	NH-1	1962	Umm Ishrin	
40	NRA Core House	NH-1	2096.9	Burj	
41	NRA Core House	NH-1	2313.7	Burj	
42	NRA Core House	NH-1	2314.4	Burj	
43	NRA Core House	NH-1	2399.5	Salib	Sst
44	NRA Core House	NH-1	2400.5	Salib	Sst
45	NRA Core House	RH-5	2613.4	Risha	Sst
46	NRA Core House	RH-5	2693.1	Risha	
47	NRA Core House	RH-5	3019.2	Dubaydib	
48	NRA Core House	RH-5	3232.55	Dubaydib	Sst
49	NRA Core House	RH-13	2687.4	Dubaydib	
50	NRA Core House	RH-16	2610.5	Risha	
51	NRA Core House	RH-16	2611.5	Risha	
52	NRA Core House	WG-2	3534.5	Burj	Lst
53	NRA Core House	WG-2	3534.8	Burj	
54	NRA Core House	WG-2	3537.5	Burj	
55	NRA Core House	WG-2	3540.15	Burj	
56	NRA Core House	WG-2	3541.9	Burj	Lst
57	NRA Core House	WG-2	356.,8	Burj	
58	NRA Core House	WG-2	3562.9	Burj	
59	NRA Core House	WS-3	453.8	Khushsha	
60	NRA Core House	WS-3	113.9	Mudawarra	
61	NRA Core House	WS-3	1137.05	Mudawwara	Clyst
62	NRA Core House	WS-3	2112.8	Umm Sahm	
63	NRA Core House	WS-3	3430.7	Umm Ishrin	Sst
64	NRA Core House	WS-3	3646.6	Burj	
65	NRA Core House	WS-3	3650.53	Burj	
66	NRA Core House	WS-3	4213	Salib	Sst

In addition, the western and southwestern Iraqi deserts (Aqrawi, 1998; Al-Hadidy, 2007), Syrian (e.g. Best et al. 1993) and Saudi Arabian stratigraphies are different yet again (see Konert 2001 for general regional review). Collectively these Lower Palaeozoic formations of NW Arabian Plate (AP) are developed within the three lowest chronostratigraphic Megasequences namely; AP1, AP2 and AP3 by Sharland et al. (2001, 2004), which have been subdivided into 3rd order sequences by Aqrawi et al. (2010) (Figs. 2A and 3). In this study we have used such Megasequences together with the subdivided third order sequences in order to correlate the stratigraphic units (Formations) of each sequence across the eastern Jordanian border to western Iraq within a best chronostratigraphic framework with available data.

Fig. 3. Rock unit nomenclature used for outcrop and subsurface formations in Jordan (based on NRA Bulletins), correlated to western Iraq rock units within a proposed sequence stratigraphic framework (modified from Aqrawi et al. 2010)

Precambrian Crystalline Basement

The Precambrian crystalline basement is composed of metamorphosed rocks. In Jordan, this is known as the Aqaba Complex (e.g. Jarrar et al. 1993). The basement consists primarily of old high-grade gneisses intruded by calc-alkaline granitoids of the Aqaba granite complex. In addition, there are sporadic mafic and ultramafic intrusives. The top of this interval across the plate marks the Pan African Orogenic event and is variously referred to as the Araba or Sub-Jibala unconformity, which has been dated at approximately 605Ma (Al-Husseini, 2014). In the subsurface, granites equivalent to the Aqaba Complex are noted at T.D. of the Safra-1 well 42 km ESE of Amman (Bender, 1974), and in Al-Jafr-1 well, where they are described as very coarsely crystalline granites in which are visible quartz, feldspar and mica (Andrews et al. 1991). The Al-Jafr-1 granites are unconformably overlain by granite wash/sandstones

(Andrews *et al.* 1991). Elsewhere the Umm Gaddah Formation may rest directly on Basement (Amireh *et al.* 2008). The Aqaba Complex is clearly more complex than indicated by the above summary, but McCourt and Ibrahim (1990) reported more details. However, there is no 'strong' geological data on this stratigraphic interval reported from western Iraq subsurface and northern Iraq outcrops, which could confidently constrain those areas.

Megasequence AP1

The Megasequence AP1 post-dates the crystalline basement. True post-basement covers in NW Arabia commenced with Late Infra-Cambrian stratigraphy exposed in southern Jordan. Sediments of AP1 were generated through intensive erosion of the exposed basement rocks and transported northwards throughout the NW Arabian plate region (Fig. 4A). This Megasequence can be subdivided into four 3rd order sequences and their maximum flooding surfaces (mfs) such as:

Sequence 1: including Saramuj Fm. and Hayyala Volcaniclastics of probably Pc05 mfs,

Sequence 2: including Humrat-Feinan and Aheimir Volcanic Suite, of Pc10 mfs,

Sequence 3: including Umm Gaddah Fm. and Unassigned Clastic Fm. of Pc20 mfs, and

Sequence 4: including uppermost unit of Umm Gaddeh Fm. of Cm10 mfs.

Detailed sedimentological and palaeontological studies are required to characterize each sequence. It is important to mention that no active petroleum system has been reported in any above-mentioned 3rd order sequences of the Megasequence AP1 as there are no viable source or reservoir rocks available. So, these sequences were considered out of the scope of the current study. Stratigraphically they are time-equivalent to the Ara play of Oman. The latter could exist in other basins detected on gravity-magnetic data by Jassim and Goff (2006). Such basins are as near as SW Iraq such as in the Nukhaib Basin (Fig. 4B), which is interpreted to contain thick salt from gravity anomaly (e.g. Bassam *et al.* 1992), if not too deeply buried (Aqrawi *et al.* 2010).

In addition, parts of SE Iraq where Hormuz salt exists may also have potential for plays similar to the Ara petroleum system of Oman (see Aqrawi *et al.* 2010 for details); however, thick overburden is the main risk in that area too. The importance of this interval may lie in the development of deep-seated structures that may play a very important role in the exploration of the younger reservoirs throughout the geological succession because these basins have a long history of repeated reactivation (e.g. Buday, 1980; Jassim and Goff, 2006; Aqrawi *et al.* 2010).

Fig. 4. North-South cross-section showing the Lower Palaeozoic onlap onto Precambrian basement in Jordan (A) from localities on the Dead Sea Rift margin (after Aqrabi *et al.* 2010), data after Powell (1989) and flooding surfaces after Sharland *et al.* (2001). In (B) the map of Iraq shows the possible extent of Infra-Cambrian basins and their evaporitic infills such as the Nukhaib Basin (after Aqrabi *et al.* 2010 modified and simplified after Jassim and Goff, 2006)

Megasequence AP2

The Megasequence AP2 in Jordan comprises the whole Ram Group (including sequences of maximum flooding surfaces; C20-O20 mfs of Cambrian and Ordovician ages) and the lower part of Khreim Group (including sequences O30 – O40 mfs of Ordovician age) (Powell, 1989). The latter encompasses the basal part of the Khabour Formation of Iraq, which is the stratigraphically oldest known unit in the Iraq's western subsurface and northern outcrops (Dunnington *et al.* 1959; Al-Haba *et al.* 1994; Aqrabi, 1998; Al-Hadidy, 2007). This Megasequence can be subdivided regionally into six 3rd-order sequences (Figs. 2 and 3), and each sequence is bordered by regional unconformities across NW Arabian Plate region.

Sequence: S1-AP2

This rather a complex sequence in NW Arabia consists mainly of the Salib, and Burj Formations of Cm20 mfs (e.g. Powell *et al.* 2014). The Salib Formation is reviewed in detail by Abdulhamid (1990). In general, the formation fines upwards, with grain size decreasing from very coarse to medium grained sandstone. Sandstones are yellow, pink and purple-brown, cross-bedded, arkosic and sub-arkosic (Figs. 5A and 6A). Pebbles to cobble clast conglomerates are locally present. Rounded to sub-rounded pebble beds near base are clearly derived from the underlying Aqaba Complex.

Fig. 5. (A) The Lower Cambrian Salib Formation main lithologies as exposed at the Wadi Numairah; Arkosic pebbly sandstones characterised by fractures and cross-beds. (B) The Middle Cambrian Burj Formation siliciclastics and carbonates; at eastern Dead Sea stop outcrops (stop 1 in Fig. 1B), showing the cross bedded sandstones (for scale photo width is about 2 m). (C) The Upper Cambrian Umm Ishrin Formation at Petra archaeological site. (D) The Disi Formation at outcrops near Disi village in southern Jordan desert (Traverse 6 in Figure 1B) showing the Disi quartzite has a very good reservoir quality at the outcrops. (E) The Umm Sahm Formation (Lower Ordovician) in the outcropped areas of southern Jordan (Traverse 6 that has a good reservoir quality). (F) The upper sandy beds of the Hiswah Formation have a good reservoir quality at outcrop (Traverse 7 in Fig. 1B). (G) The upper Dubaydib member at this outcrop of southern Jordan (Traverse 8 in Fig. 1B) is thick stacked channel sandstone that keeps a good reservoir quality. (H) The thinly bedded sandstones of lower Dbaydib member (Traverse 8 in Fig. 1B). (I) Sandy beds of the lower Mudawwara Formation of Lower Silurian (Traverse 9 in Fig. 1B) are characterised by high reservoir quality at outcrops

Low angle planar crossbedding of medium to large scale is dominant in the lower part of the formation. Overturned or convoluted trough cross-bedded foresets are particularly common in the middle part. Low angle trough crossbedding, together with medium to large scale tabular/planar sets, often with pebbly basal lags and graded foresets, are common in the middle and upper part of the formation.

The petrographic and mineralogical studies revealed that the Salib sandstone facies are fine grained, angular and poorly sorted sandstones composing of >70-90% quartz, followed by

K-feldspars of up to 16% and clay reaching up to around 40% in muddy sediments (Figs. 6A and 7A) (Table 2). The Salib clastics are also dominated by quartz in the subsurface analysed samples, except in DH-1 well at 2579.5 m depth (sample 37), which is mostly clays (>80%). The clays of the analysed Salib Formation are mostly illite and illite-smectite mixed layers with traces of kaolinite (Table 3).

Fig. 6. Thin sections under plane polarized light of samples collected from previous outcrops locations of Fig. 5 for: (A) Salib sandstone that keeps a very good visual porosity. (B) Burj carbonate grainstones, which are blocked with intensive cementation. (C) Umm Ishrin sandstone that still keeps some good visual porosity. (D) The very porous Disi sandstones, which form the main water aquifer in southern Jordan. (E) The Umm Sahm harder sandstone, but still with good porosity at the outcrops. (F) The Hiswah sandstones of high porosity. (G) Very porous outcropped upper Dubaydib sandstones together with (H) lower Dubaydib sandstones. (I) Highly porous sandstones of the Mudawwara Formation at outcrops

Table 2. Total mineral contents of selected samples using semi-quantitative X-Ray diffraction analysis

Outcrop Formation/well no. and depth	Sample stop No	Illite-Mica %	Kaolinite %	Chlorite %	Quartz %	Kfeldspar %	Plagioclase %	Calcite %	Fe calcite %	Fe dolomite %	Goethite %
Burj	1A	ND	3	3	73	17	0	2	0	2	0
Burj	1B	ND	ND	ND	7	1	0	92	0	0	0
Disi	5A	ND	4	0	95	0	0	1	0	0	0
Hiswa	11	20	0	39	33	0	3	3	0	2	0
Hiswa	12	32	0	27	25	14	1	1	0	0	0
Hiswa	6	6	75	0	19	0	0	0	0	0	0
L. Dubaydib	7B	0	0	0	92	6	0	1	0	1	0
L. Mudawwara	9B	4	71	0	20	5	0	0	0	0	0
M. Dubaydib	8A	0	2	0	89	7	0	1	0	1	0
M. Dubaydib	8B	0	5	0	85	5	0	1	3	1	0
Sahib	4A	7	1	0	74	16	0	1	0	1	0
Salib	4B	6	0	0	84	9	0	0	0	1	0
Salib	4C	3	0	0	90	5	0	1	0	1	0
U. Dubaydib	9A	0	1	0	82	16	0	0	0	1	0
U. Hiswa	7A	0	3	2	91	3	0	1	0	0	0
Umm Ishrin	2	0	6	0	94	0	0	0	0	0	0
Umm IshriPetra	10	3	41	0	56	0	0	0	0	0	0
Umm Sahm	5B	1	0	0	99	0	0	0	0	0	0
WG-2 Disi	25	0	0	2	98	0	0	0	0	0	0
WG-2 Burj	26	0	0	0	7	0	0	93	0	0	0
WS-6 Batra	20	9	0	5	79	2	4	0	0	1	0
WS-6 Batra	21	11	0	7	59	1	7	0	0	15	0
WS-6 Batra	22	33	0	25	36	1	5	0	0	0	8
WS-6 Dubaydib	23	5	0	15	58	9	11	1	0	0	1
Umm Sahm	30	0	1	0	98	0	0	1	0	0	0
L. Mudawwara	33A	6	11	0	66	14	0	1	2	0	0
Up.Mudawwara	34	14	71	0	13	1	0	0	1	0	0
SalibDH 2579.5m	37	41	40	0	15	4	0	0	0	0	0
HiswahDH3131.8m	38	17	21	26	25	4	4	0	0	1	2
Burj NH-1 2096.9m	40	0	0	1	41	8	2	44	3	1	0
SalibNH-12400.5m	44	12	0	0	78	7	0	1	2	0	0
Dubaydib RH-5 2332.55m	48	0	0	14	68	10	4	1	0	3	0
BurjWG-23541.9m	56	8	0	5	52	22	4	4	5	0	0
Khushsha WS-3 453.8m	59	8	18	6	46	18	1	1	2	0	0
Mudawwara WS-31137.05m	61	27	34	13	15	6	2	1	0	0	0
BurjWS 3646.6m	64	10	0	1	8	2	2	45	33	0	0
BurjWS 3650.53m	65	14	0	1	7	3	1	42	31	0	1
SalibWS-4213m	66	5	0	0	82	1	0	2	2	0	8

Table 3. Clay mineral contents of selected samples using semi-quantitative X-Ray diffraction

Formation	Sample/Stop No.	Illite %	Illite-smectite %	Chlorite %	Kaolinite %
Burj	1A	18	0	20	62
Burj	1B	67 %	0	17	16
Disi	5A	0	0	0	100
Hiswa	11	58	21	21	0
Hiswa	12	52	14	34	0
Hiswa	6	13	0	12	75
L. Dubaydib	7B	4	0	11	85
M. Dubaydib	8A	5	0	38	57
M. Dubaydib	8B	12	0	13	75
L. Mudawwara	9B	12	0	15	73
Salib	4A	47	50	0	2
Salib	4B	84	15	0	1
Salib	4C	85	15	0	0
U. Dubaydib	9A	27	8	0	65
U. Hiswa	7A	1	0	23	76
Umm Ishrin	2	0	0	0	100
Umm Ishrin-Petra	10	19	0	0	81
Umm Sahm	5B	0	0	0	100
WG-2 Burj	26	35	0	8	57
WS-6 Batra	20	40	57	3	0
WS-6 Batra	21	74	16	10	0
WS-6 Batra	22	68	17	15	0
WS-6 Dubaydib	23	20	0	80	0
Umm Sahm	30	0	0	0	100
L. Mudawwara	33A	15	0	0	85
Silurian Clayst	34	15	0	0	85
DH-1 2579.5 m Salib	37	41	16	7	36
DH-1 3131.8m Hiswah	38	66	11	19	5
NH-1 2096.9m Burj	40	49	23	18	9
NH-1 2400.5m Salib	44	100	0	0	0
RH-5 2332.55m Dubaydib	48	32	0	68	0
WG-2 3541.9m Burj	56	69	15	16	0
WS-3 453.8m Khushsha	59	21	4	13	62
WS-3 1137.05m Mudawwara	61	60	0	6	34
WS-3 3646.6m Burj	64	5	0	41	54
WS-3 3650.53m Burj	65	71	26	3	0
WS-3 4213m Salib	66	76	14	0	10

Fig. 7. Secondary and backscattered Scanning Electron Microscope (SEM) images of some samples described in Figs. 5 and 6 showing their micro-components and microporosities: (A) Salib sandstones show good micro porosity with the transformation of unstable feldspar grain to clays. (B) Burj highly cemented carbonates with limited micropores. (C) Umm Ishrin sandstones with less quartz overgrowth, but high clay contents filling their micropores. (D) Disi sandstones with both some quartz overgrowth and clay cements partly filling their micropores. (E) Umm Sahm sandstones of high quartz overgrowth cents. (F) Hiswah sandstones of high quartz overgrowth and clay cements filling partly the micropores. (G) Dubaydib sandstones pores are partly occluded by kaolinite clay and partly quartz overgrowth

Yellowish coarse-grained, sub-angular, poorly sorted sandstone is mainly quartzite (of up to 90% quartz), with feldspars and clays making the rest components. Outcropping clastic is mainly sandstone beds of more than two thirds of quartz and rest as feldspars and clays (Table 2) and they are of poor reservoir quality due to clays (chlorite and kaolinite) filling the pores (Table 3), in addition to some quartz overgrowth. The Salib Formation, in Northern Highlands (NH-1 well) at 2096.9m (Fig. 8A), has a very fine grained, rounded, sorted, compacted and

arkosic sandstone as well as in well Wadi Ghadaf-2 (WG-2) at 3541.9m depth. As a result, the Salib sandstones kept a reasonable reservoir quality at the depth over 2000 m having up-to 20% visual porosity (Fig. 8A). All sandstone facies may have well-developed quartz overgrowths in the subsurface, although textures are quite compacted (Fig. 8A) whilst feldspars are transformed to illite and illite-smectite expandable mixed layers forming the two main components of the clayey fractions of the Salib Formation (Fig. 6A and Table 3).

Fig. 8. Core photos of selected sandstones of formations investigated and sampled at the NRA core house including: (A) Salib Sandstones in well NH-1. (B) Burj Dolomite-Shale in well WG-2. (C) Umm Ishrin Sandstones in well WS-3. (D) Disi (Umm Sahm?) in WS-3. (E) UmmSahm (Disi?) in WS-3. (F) Dubaydib/Risha Sandstone in well RH-5

The overlying Burj Formation (Fig. 5B) in Jordan is subdivided by Powell (1989) and Andrews et al. (1991) into three members namely; upper Hanneh Siltstone Member, middle Numayri Dolomite Member, and lower Tayan Siltstone Member. The three members of the Burj Formation are well exposed to the east of southern part of the Dead Sea in type localities. Carbonates are yellow or grey dolomitic limestone, dolomite and sandy dolomite with chert and sandstone lenses (Fig. 5B). Oncolites, oolites, peloids and bioclasts are present in purer carbonates (Fig. 6B). Cross-lamination is common in the siliclastic lenses. The Numayri Dolomite Member is grey, finely laminated, fine grained quartz arenite with burrows and ripple cross lamination intercalated with green-grey, cross-laminated siltstone. Fine-grained sandstone passes up into oolitic packstone and cross-bedded trilobite grainstone with *Harlania* burrows. The carbonate unit consists of trilobite, brachiopod, hyolithid oolitic grainstone, and is cross bedded in parts. Although the Burj Formation is dominated by carbonates all over NW Arabia, numerous sandstone beds exist and are exposed along the western basin margins such

as those along the Dead Sea, notably at the outcrops near the northern end (Fig. 5B). The carbonates are highly compacted and cemented (Fig. 7B) at the outcrops, as well as the sandstones in the subsurface (Figs. 8B and 9B).

Fig. 9. Photomicrographs (plane polarized) for the sandstone samples collected from the cores described in previous Fig. 8 showing their dominating quartz grains together with pores (of blue epoxy resin) that are filled partly with quartz overgrowth and clay cements, although some other grains such as feldspars might have partly transformed to clays. (A) Salib Sandstone, (B) Burj Sandstone (C) Umm Ishrin Sandstone, (D) Disi/Umm Sahn Sandstone, (E) Hiswah Sandstone, and (F) Duaydib Sandstone

Mineralogically at the outcrops, the carbonate fraction is mainly calcite (>90%) and the clastics are mainly quartz (>70%) (Table 2). In subsurface the Burj carbonate is dominated by calcite in WG-2 well, and the clastics by quartz (>50%) followed by feldspars (>20%) and clays (>10). However, in Wadi Sirhan area, Fe-calcite comprises >30% together with calcite of >40% (samples 64 and 65 of well SW-3 at depths 3646.6 and 3650.53m, respectively) (Table2). The Burj Formation sample in NH-1 well comprises of almost equal amount of calcite and quartz (each around 40%) in addition to fractions of clays, feldspars, Fe-calcite and Fe-dolomite. The clay fraction of the Burj carbonates is dominated by illite (around 67%) followed by chlorite (17%), while the clay fraction in sandstones is mostly kaolinite (62%) and chlorite (20%) (Table 3 samples 1B and 1A, respectively). This assemblage of clays indicates to the marine depositional environment of the Burj carbonates and clastic during the marine transgression that covered all NW Arabia (Sharland et al. 2001).

Potential reservoirs of sequence: S1-AP2

Coarser grained Salib facies in both the reddish and yellowish sandstones (Fig. 5A) have quite good visual porosity of around 20% (Fig. 6A) at outcrops, although their fine-grained sandstones show poorer reservoir quality. It is noted that the Salib sandstone has preserved an acceptable reservoir quality at more than 4000m burial depth in the Wadi Sirhan area and deeper than 2000 m at NH-1 well (Figs. 8A and 9A). This visual porosity of >10% is mostly of secondary origin due to feldspar dissolution (Fig. 9A).

No primary pores are apparent in the subsurface Burj samples. Secondary porosity in the Burj of well Wadi Ghadaf (WG-2 well) is mainly due to the dissolution of feldspars (Figs. 7B and 8B), where quartz is not exceeding 52% in the sandstones (Table 2). On the other hand, Burj carbonates are quite tight due to high calcite cementation (e.g. Figs. 6B and 7B). Depth is a very important factor controlling the reservoir quality of the Burj Formation (Figs. 8B and 9B). So, in areas where Burj exists at more than 6000m depth (Fig. 3) are of very high risk, such as in western Iraq (Aqrawi *et al.* 2010). As a result, most areas of western Iraq, where Burj represents the best reflector (Al-Haba *et al.* 1994), have limited opportunities of a good quality Burj reservoir. However, it can be explored in most areas of Jordan and in SW Iraq, where thinner overburden cover dominates.

Sequence: S2-AP2

Sequence S2 of Megasequence AP2 in Jordan includes the Umm Ishrin and Ajram formations, of Cm30 mfs. The Umm Ishrin Formation at outcrop is shown as coarsening-upwards by Powell (1989). It outcrops along the Dead Sea, at Wadi Rum and throughout Petra (Fig. 5C) where it consists of thick quartzite beds characterised by fractures, mega ripples and cross beds, forming up to 13 stacked cycles. According to the stratigraphic details reported by Lloyd (1969) and Abdulhamid (1990), the sandstone at the type locality (Jabal Umm Ishrin) is red-brown, yellow-pink, grey and mauve-red, medium to coarse-grained massive quartz arenite. These are interbedded with thin beds of mauve red, finely laminated micaceous and/or ferruginous fine-grained sandstone and siltstone. The basal part is mainly composed of reddish quartzitic fluvial sandstones, as seen at the Petra archaeological site (Fig. 5C), where buildings were excavated within these thick compacted sandstone beds. The lower part of the formation is also characterized by large-scale trough cross bedding in erosive base channels. Above, both planar foresets and trough cross bedding within wedge shaped or tabular sets are common (Powell, 1989). The thickness of the Umm Ishrin Formation varies from about 270m at Petra to ~320 m at Jabal Umm Ishrin and up to 350m in the southern Desert and Wadi Numayri, according to Powell, (1989). The subsurface equivalent Ajram Formation (Fig. 3) ranges in thickness from

200 to 370m thick (Andrews et al. 1991). There is no direct evidence for the age of the Umm Ishrin Formation (Powell, 1989). However, the underlying Burj Formation has yielded a late Early to early Middle Cambrian fauna. Accordingly, the Umm Ishrin Formation may range in age from Middle-Late Cambrian.

In thin section, the prominent lithology in the Umm Ishrin Formation is a medium grained quartz arenite of sub-angular to rounded and well sorted quartz grains (Fig. 6C) at Dead Sea road-site outcrops. Quartz mineralogically forms 80-100% of grains with sparse weathered feldspar grains to clays (Fig. 7C). However, the sample analysed by XRD from Petra-site consists around 50% quartz and 40% total clays and the sediment is frequently stained by hematite of around 10% (Table 2). The clays are only kaolinite together with 19% illite in Petra-site sample (Table 3). The sandstones of Umm Ishrin Formation are highly compacted (Fig. 6C), particularly at the subsurface such as in Wadi Sirhan (Figs. 8C and 9C). Quartz overgrowth and clays, such as kaolinite (of blocky and booklet habit) may fill pores (Fig. 7C).

Potential reservoirs of sequence: S2-AP2

The subsurface Ajram Sandstone of Jordan and its equivalents in western Iraq are potentially important reservoirs within Sequence 2 of Megasequence AP2 referring to their exposed equivalent Umm Ishrin Formation. The latter formation sandstones are characterised by moderate to good visual porosity (around 10-15%) at outcrops (Figs. 6C and 7C). In addition, at the outcrops along the Dead Sea flammable gas seepages appeared from such porous Umm Ishrin sandstones during road construction (Pers. Communication with Munim Al-Rawi, 2005). Unfortunately, these sandstones lose most of their intergranular primary porosity gradually with depth in the subsurface, mainly due to high compaction and quartz overgrowth cementation (Fig. 8C). Such a reduction is sometimes compensated for by dissolution of limited feldspars and their transformation to kaolinite clay (Fig. 9C) as some secondary visual porosity (of around 5-10%) could be created due to such feldspar dissolution, e.g. as seen in the Wadi Sirhan area in well WS-3 at 3430.7m (Fig. 9C). As result, such equivalent deep sandstones in western Iraq can be considered as potential exploration target.

Sequence: S3-AP2

This sequence in Jordan, includes Disi Sandstone, Lower Umm Sahm Sandstone, and lower Amud Fm, of O10 mfs. The basal part of this sequence consists of the Disi Formation, which is a white quartzite at outcrop in southern Jordan, and the overlying lower part of the Umm Sahm Formation. Disi-Umm Sahm and equivalents are dominated by pebbly quartzite sandstone (Figs. 5 D and 5E) of very good sorting (Figs. 6 D and 6E), but these are sometimes hard to differentiate from each other, particularly in the subsurface cores (Figs. 8D and 8E).

Khalil (1994) reported that the Disi Formation at its type locality (Qa Ad Disa) is composed of white, grey, pale yellow, medium to coarse grained, massive quartz arenitic sandstone with large scale trough crossbedding. Well-rounded rose, pink or milky quartz pebbles are common along foresets and dispersed throughout the sandstone. At outcrop the Disi beds are highly eroded and weathered (having dome shapes), and are characterised by cross beds and ripples, together with pebbly features, which are cemented and dissolved in some places (Fig. 8D). The shallow buried Disi Formation is the main water aquifer in southern desert of Jordan.

The boundary between the Disi and overlying Umm Sahm Formation is gradational over 5-10 m and is set at the upwards transition from white spheroidal weathering sandstone with erosive sets of the Disi, to brown weathering, thin and tabular bedded sandstone with laterally persistent sets and a dense joint/fracture pattern of the Umm Sahm. In addition to the colour, the higher hardness and thinner bedding of the Umm Sahm compared to the Disi Formation is another distinctive feature, particularly at the studied outcrops of southern Jordan (Fig. 5E). The Umm Sahm Formation stratigraphy at the type locality (Jabal Umm Sahm) is characterized by its dark brown weathering patina (Fig. 5E), regular tabular bedded, closely spaced joint pattern, where it develops steep cliffs pyramidal mountain tops (Moumani, 2003). In the subsurface, the likely correlative lower part of the Amud Formation is a monotonous interval of white-buff, fine- to medium-grained sandstone, which is slightly argillaceous (Fig. 8E). An Early Ordovician age (Arenig-Tremadoc) has been indicated for the uppermost third of the Disi Formation based on the trace fossil assemblage dominated by *Cruziana* that includes: *Cruziana furrier*, *C. vilanovae*, and *Merostomichnites* sp. The overlying Umm Sahm Sandstone is likely to be similarly Early Ordovician in age according to Keegan et al. (1990), who considered the Disi and Umm Sahm to be part of one main unit in terms of palynological analysis. Several interpretations of depositional environment have been proposed, ranging from deposition by meandering rivers of intermediate sinuosity to large-scale sub-aqueous dunes in high velocity, and high discharge braided rivers. The O10 mfs is interpreted as being present within the upper part of the Disi Formation, in which brief marine incursions are noted (Powell, 1989). Laterally equivalent Lower Amud Formation of the subsurface is interpreted as distal alluvial plain (Andrews et al. 1991). In petrographic terms, quartz forms up to 99% of the constituents of the outcropped Disi and Umm Sahm formations (Figs. 5D and 5E). The remainder of rock volume is mainly represented by kaolinite (Figs. 7D and 7E) (Tables 2 and 3). In terms of diagenesis, these sandstones show evidence of quartz overgrowth (Figs. 6D and 6E). The Disi/Umm Sahm Formation in subsurface also consists mainly of quartzite (Figs. 8D and 8E). The sandstones of the both Disi and Umm Sahm characterise by very good reservoir quality at outcrop in southern

Jordan (Figs. 6D and 6E) reaching up to 30% of visual porosity. However, Disi-Umm Sahm and equivalents show more quartz overgrowth cementation in the subsurface (Fig. 9D and 9E) that reduces the visual porosity to under 10%.

Potential reservoirs of sequence: S3-AP2

The Disi Formation quartzite shows very good reservoir quality at outcrop and is almost friable sandstone, therefore it represents the main water aquifer in the subsurface of southern Jordan (Figs. 5D, 6D and 7D) reaching some 30% porosity in the analysed this-sections. Also, the sandstones are notably very white and quartz rich, making them ideal for use in the glass industry. However, the reservoir quality of both Disi and Umm Sahm showed a dramatic reduction in the subsurface to less than 10% visual porosity. In Risha 3 well, the Disi/Umm Sahm porosity ranges from 5% to 7.5% and the permeability is between 0.44-0.57 mD at the depth interval of 4191.1-4192.25 m (Sahmoud, 1988). As a result, their equivalents or extensions into the subsurface of western Iraq will probably be similar. This is mainly because of well-developed quartz overgrowths and partly due to the filling of remnant pores with kaolinite clay (Table 3), although the latter does not exceed 1% (Table 2). There are no discoveries reported in the Disi or Umm Sahm and their equivalents in the NW Arabian region yet, but they still can retain some good reservoir quality down to at least 2000m so this sandstone may represent a potential deeper reservoir for exploration in western Iraq and eastern Jordan if covered by not too thick overburden.

Sequence: S4-AP2

This sequence comprises the middle and upper part of the Umm Sahm Formation (Powell, 1989) and the upper part of the subsurface Amud Formation (Andrews et al. 1991) of O20 mfs. In general, this interval of the Amud Formation is much more heterolithic than the lower part of the same formation (Andrews et al. 1991). The texture of this fine-medium grained sandstone is of well rounded, sorted, and compacted grains, consisting of more than 90% quartz, while the rest is either feldspar or feldspars transformed to clays, particularly kaolinite (Figs. 5E, 6E, 7E, 8E and 9E).

The top of the Umm Sahm Formation marking the sequence boundary, is a sharply-defined contact between brown weathering, medium to coarse grained sandstone of the Umm Sahm Formation and the base of the fine-grained ripple-marked micaceous sandstone and red-green buff shales with graptolites including *Didymograptus cf. bifidus* of the Hiswah Formation (Powell, 1989). In the subsurface, the equivalent upper contact is the equally sharp surface between the top of the Amud Formation and the base of the Sahl as Suwwan Formation (Andrews et al. 1991). An abundant and relatively diverse trace fossil fauna has been described

from heterogeneous units in the Umm Sahm Formation of the southern Desert outcrops (Selley, 1970 and Powell, 1989). Selley (1970) records *Cruziana*, *Sabellarifex* and *Harlania*. The youngest age of this sequence is constrained by the Llanvirn age attributed to *Didymograptus* c.f. *bifidus* faunas at the base of the overlying Hiswah Formation. The presence of *Cruziana* sp. in the 'Harlania Shale' of the Middle Umm Sahm is interpreted to indicate a likely Arenig age (Baldwin, 1976). The Umm Sahm is generally shallow marine in character (Powell, 1989); whilst the marine incursion indicated by the Harlania Shale beds, represents the O20 mfs. The top of the Umm Sahm sandstones were rippled by oscillating wave induced currents (Powell, 1989).

Potential reservoirs of sequence: S4-AP2

There are no discoveries in the middle-upper Umm Sahm / Upper Amud or their equivalents in the NW Arabian region, but as in the lower part of the Umm Sahm (in previous sequence 3-AP2), these sandstones can also retain good reservoir quality down to at least 2000m. Subsurface reservoir quality is still good in the Wadi Sirhan area, although compaction has led to quartz overgrowth cementation. This interval is of interest as reservoir because it sits beneath shales of the Hiswah/Sahl as Suwwan formations, which represent a potential regional source and seal (Fig. 3), and hence the upper contact of this sequence should be mapped for regional traps.

Sequence: S5-AP2

This is the lowest part of the Khreim Group of Jordan (Powell, 1989) which comprises the Hiswah Formation and the overlying Dubaydib Formation at outcrops (Masri, 1988a, b and c), and the Sahl As Suwwan Formation and the overlying lower silty and middle interbedded units of the Umm Tarifa Formation of the subsurface (Andrews et al. 1991) of O30 mfs. In western Iraq, it is represented by the lower part of the Khabour Formation (members K5, 6 and 7 of Al-Hadidy, 2007) (Fig. 10), and the main part of the Khabour Formation as known from outcrops in northern Iraq (Dunnington et al. 1959). At its type locality (Wadi/Jibal Hiswa) the Hiswah Formation has been subdivided into two members (Masri, 1988 b, c; Andrews et al. 1991). The lower member Powell (1989) and Andrews et al. (1991) consists of fissile mudstone/shale that is dominantly a pink, mauve-red, grey and green colour, with occasional thin beds of rippled, hummocky cross-bedded siltstone to fine grained sandstone with oscillation and interference ripples. These sediments are rich in drifted graptolites (*Didymograptus bifidus*) that are common on bedding surfaces; long axes of the graptolites are oriented at right angles to the N-S trending ripple crests. The upper sandy member (Fig. 5F) consists of thin bedded, fine grained sandstones with ripple crossbedding, passing up into hummocky crossbedding and trough

crossbedding. Sandstones become both coarser grained and thicker towards the top of the formation, where vertical and horizontal burrows are common (*Cruziana*, *Harlania* sp. and *Lingula* shells.). The base of the overlying Dubeydib Formation is defined at the base of the first thick bed of pale grey to buff grey sandstone with abundant *Sabellarifex* burrows.

In the subsurface, the Sahl as Suwwan Formation is the correlative of the Hiswah Formation. In well Al-Jafr-1 that is closest to the outcrop locations, this comprises a brownish-grey claystone (Andrews *et al.* 1991). Further to the E and N, lithologies comprise instead, laminated black to dark grey and grey-brown, micaceous silty shales and siltstone. In wells Risha-2 and -3 there is 20m thick, basal, hot or radioactive shale with GR API of up to 200. In addition, in Risha-3, a macrobiota is present of trilobites, orthocone nautiloids, brachiopods and gastropods (Andrews *et al.* 1991). Similar but very thin hot shales are also present in Al-Jafr-1 and Wadi Sirhan-10 wells.

GEOLOGICAL TIME SCALE: GTS 2004			SAUDI ARABIA	IRAQ	JORDAN	SYRIA	Sequence Stratigraphy			
Silurian	Ludlow	Gorstian	Qalibah Formation	Sharawra Member	Akkas Formation	Qaim Member	Kishsha Formation	Tanf or Abba formations		
		Homerian								
	Wenlock	Sheinwoodian								
		Telychian								
	Llandovery	Aeronian								
Rhuddanian										
Ordovician	Late	Himantian	Uqlah Formation							
		Katian	Sarah Formation	Hiatus		Risha Fm	?			
		Sandbian	Quwarah	K1 Member						
		Darriwilian	Ra'an	K2-K4 Member		Dubaydib Formation	Afandi			
	Middle	"Llanvrim"	Kahfah	K5-K6 Member				Swab Formation		
			Hanadir	K7 Member		Hiswah Fm				
	Early	Floian	Saq Sandstone	Sajir		Umm Sahm Formation	Khanaser Formation			
		Tremadocian								
	Late Cambrian			Risha				Disi Fm	Sosink Formation	
									AP3	
								MFS S10		
								MFS O40		
								MFS O30		
								AP2		

Fig. 10. The penetrated lower Palaeozoic formations in western Iraq and their equivalents in the neighboring countries. In western Iraq the Ordovician Khabour Formation and the Lower Silurian Akkas Formation were subdivided in seven and two Members, respectively (modified after Al-Hadidy, 2007) and the Sequence Stratigraphy column (to the right) is adapted from Mohammed *et al.* (2020)

The Dubaydib Formation that overlies the Hiswah Formation at outcrop (Fig. 4G), was subdivided informally by Masri (1988b, c) and Masri *et al.* (2014), into three members:

- Upper – Sandy and silty member with common *Skolithos* burrows (top)
- Middle – Channelled sandstone (middle)
- Lower – *Sabellarifex* sandstone (base)

Masri (1988 b and c) studied this formation in detail. Its morphology at outcrop is of low cuestas and mesas separated by sand-filled or rocky stream wadis. The lower member consists of sheet like grey-weathering beds of fine-grained micaceous sandstone. These are buff to light brown, medium hard, thick bedded and occasionally massive, except for a few ripple marks associated with abundant vertical *Sabellarifex* burrows. These fine up into interbedded silty shales that consist of alternating thin to very thin beds of pale brown siltstone and pale grey sandy siltstone with abundant ripple marks and *Sabellarifex* and *Harlania* burrows. The middle member appears in the field as a prominent cliff overlain and underlain by green to grey, less steeply sloping beds of mudstone and sandstone. It comprises a channelled sandstone facies interfingering with the silty and sandy facies. Large-scale trough cross-bedding, cross-stratification, hummocky cross-stratification, load cast and locally trace fossils (*Cruziana* sp, *Sabellarifex* sp. *Rusophycus* sp.) are all common. The upper member consists of micaceous planar laminated sandstones with abundant *Sabellarifex* sp. overlain by rippled sandstones and siltstones with *Cruziana* sp. traces and *Rusophycus* sp. burrows. These pass up into sandstones with oscillation and interference ripples, containing mudclasts, then an interval of similar sediments with *Lingula*. At the top are thin-bedded, hummocky cross-stratified sandstones, with rippled green micaceous siltstone beds, sparse *Sabellarifex* sp. and *Harlania* burrows (Powell, 1989). In the subsurface of Jordan, the equivalent Umm Tarifa Formation is usually subdivided into a silty lower unit, a middle interbedded unit, and an upper argillaceous unit (Andrews et al. 1991), of which the lower two falls within this sequence. In the wells Risha-3 and Dahikiyeh -1, there are interbedded white to light grey, very fine to fine grained sandstones at the base, but the dominant lithology is a dark grey, micaceous siltstone. In the Wadi Sirhan-3 well, the unit overall lithology is more of a very fine to fine-grained sandstone. The interbedded unit shows grey to dark grey, micaceous siltstone with colourless, fine- to very fine-grained, silica-cemented, silty sandstone. Sandstone beds reach a maximum thickness of about 8m and are numerous, but background sediments are siltstone.

In the subsurface, the boundary between the middle (interbedded) and upper (silty) unit of the Umm Tarifa, is characterised mostly by an abrupt upwards change into much finer-grained lithologies (Andrews et al. 1991). This basal break is evident on logs in both Jordan and Iraq. In western Iraq, the contact between this and the underlying sequence is clearly developed, between low-API GR sandstones at the top of member K5, and high API GR shale of member K4 (Al-Hadidy, 2007 (Fig. 11). In deep exploration wells, the lower and middle members of the Umm Tarifa thicken from 437m in Al-Jafr-1 to a total of 770m in Risha-3 (Andrews, 1991). The lower interval alone thickens towards from 90m in Al-Jafr-1 to 241m in

Risha-19 (Andrews *et al.* 1991). The sharp change in lithofacies (from the Umm Sahm/Amud up into the Hiswah/Sahl as Suwwan) suggests rapid deepening of the shelf, representing the O30 (Llanvirn) mfs of Sharland *et al.* (2001). Iraqi stratigraphies show upwards-cleaning log signatures suggest that these highstand storm dominated shelf sandstones prograded out at least as far as Akkas-1 well location (Fig. 11) of western Iraq (Al-Hadidy, 2007).

Fig. 11. Subdivision of the Ordovician Khabour Formation into seven members in the Akkas Field (well Ak-1) and their electric logs signatures (after Al-Hadidy, 2007)

Petrographically, at outcrop in southern Jordan the Hiswah and Dubaydib sandstones are mainly fine grained quartzites (Figs. 6F, 6G and 6H). Mineralogically these sandstones consist of 82-92% quartz in addition to limited amounts of clays, feldspars and calcite (Table 2). The clays are mainly kaolinite together with chlorite and illite (Table 3). However, in the subsurface

the clay content may reach 38% in Hiswah and 20% in Dubaydib sandstones and the rest is mostly quartz (Table 2). Such clays are dominated by chlorite followed by illite (Table 3). The clays mainly fill pores and do not coat the quartz grains to prevent them from overgrowth cementation at depth.

However, in Well Risha-5 of the Risha Gasfield of Jordan, the Dubaydib Formation (Fig. 12A) is a fine-grained, rounded and well sorted, slightly compacted sandstone (Fig. 12B). Mineralogically, this sandstone is mostly composed of quartz grains (68%), followed by clays (14%), and then K-feldspar (10%) in addition to some traces of carbonate cement (Table 2). The clays are dominated by chlorite (68%) together with illite (32%) with no kaolinite. Chlorite coating of quartz grains (such as at depth 3232.55m in RH-5) has sometimes significantly prevented the quartz overgrowth (Figs. 12 C-E).

Fig. 12. The Dubaydib (Risha) sandstones in well RH-5 at 3232.55m depth (A) preserve quite good reservoir quality (B), as the chlorite coatings (C) prevent further quartz overgrowth cements (D) and (E)

Deposition of sandstones would appear to have been mid- to inner shelf dominated by wave, storm and tidal effects (Fig. 13), with more silty basal facies being indicative of deeper water and more open marine setting, here interpreted as the O40 mfs of Sharland *et al.* (2001). Western-Iraq stratigraphies and upwards-cleaning log signatures suggest that highstand shelf clastics prograded out at least as far as Akkas-1 well location, and most probably to around Khleisia-1 well location (Al-Hadidy, 2007).

Fig. 13. The core description of the reservoir zone of Upper Dubaydib in well WS-4 show that the main reservoirs are porous shore-face sandstones, which have fractured as that was obvious from the core's description particularly at 1392.95 m Depth

Proven and potential reservoirs of sequence: S5-AP2

The upper sandy member of the Hiswah Formation has good reservoir quality at outcrop of around 25% of visual porosity (Figs. 5F and 6F). However, it is slightly compacted and has limited quartz overgrowth cements (Fig. 7F), which could increase at depth in the subsurface and reduce the porosity and permeability of this potential reservoir. It was thought that the Hiswah shale is a promising source rock in the region; as a result, samples of the shale (from the Risha-2 well and outcrops) were analysed, but the geochemical analyses showed that these shales are lean in source material, with very low TOC and a very low potential of expelling economic hydrocarbons (Aqrawi *et al.* 2006). However, the Hiswah locally in other subsurface areas within further Eastern Jordan and probably western Iraq may have higher TOC contents and consequently becomes better potential source for hydrocarbon generation (e.g. Aqrawi, 1998 and Al-Hadidy, 2007). Further geochemical studies are required to better assess these potential source rocks. The Dubaydib sandstones have similar good reservoir quality at the

outcrops (Figs. 5G and 6G), which is also reduced due to quartz overgrowth, calcite cementation and kaolinite clay filling the pores (Fig. 7G). The Dubaydib Formation porosity in RH-3 is <1% and does not exceed 3.35% while permeability is usually <1 (0.2-0.8) mD for tested core plugs at depth interval of 2856.45-2859.55 m. Except Risha Member where the porosity may reach >20% and permeability up to almost 90mD (Sahmoud, 1988). The latter zones usually tested as gas reservoirs. The porosity analysis from the sidewall cores of Risha-6 ranged 3-6% but showed as high as 8% too with almost half percent as secondary in origin (Davies, 1990). The effective porosity for the Risha sandstone at the Risha Field is considered to be more than 5% (Risha Task Force, 1990). More sedimentological details about the Risha Gasfield reservoir characterisation were reported by Tamar-Agha (2009) for the Risha sandstone member of the Dubaydib Formation.

Upper Ordovician sandstones of the upper part of the Khabour Formation of western Iraq are proven reservoir of sweet gas and condensate comparable to both the Risha and Wadi Sirhan discoveries in Jordan (Figs. 10 and 11) (Mohammed *et al.* 2020). Sandstones are particularly significant when fractured (Fig. 8G). Where subsurface reservoir is very good, it is dominated mainly by intergranular porosity even at depth of 3232.55m such as in Risha-5 well (Figs. 12A and 12B), particularly when the quartz grains are coated with chlorite clays (Fig. 12C). The chlorite clay has been proven through elemental analyses of the backscattered SEM (Figs. 12D and 12E) and XRD analysis of the clay fractions (Table 3). The latter chlorite coating was detected within a limited depth zone of 10-20 m in well Risha-5 (Figs. 12A and 12B), which has prevented quartz overgrowth (Figs. 12C-E). However, such a zone in this well was within a water column. Even though, this Formation can thus be considered as potential reservoir in the subsurface of Jordan and western Iraq. Optimum reservoir quality is also likely where feldspars have transformed to clays and thereby added more secondary porosity. The main remaining risk is still quartz overgrowth cementation at depth; although feldspars started transforming to clays (Table 2) that infill the pores rather than coating the grains. Both sweet gas and condensate have been found in sandstones of the upper part (K1 member) of the equivalent Khabour Formation within the Akkas field of western Iraq (Al-Haba *et al.*, 1994 and Al-Hadidy, 2007), although the risk of quartz overgrowth cementation was noted again because of their significant burial. Other underlying Khabour members of western Iraq, particularly members K 2, 3 and 4 in the Akkas-1 well of the western desert (Al-Hadidy, 2007), fall within this sequence equivalent to the Dubaydib Formation (Fig. 10) too. Al-Hadidy (2007) reported an average porosity of 7.6% for K1 and 6.6% for K2 together with an average permeability of

0.13 mD for K1 and 0.08 mD for K2. As a result, the Ordovician Khabour Formation represents one of the main Paleozoic reservoir targets in western Iraq.

Sequence: S6-AP2

In Jordan, this includes the Tubeiliyat Sandstone member of basal Mudawwara Formation of outcrop (Powell, 1989) and the upper silty unit of the Umm Tarifa Formation of the subsurface of mfs O40 (Figs. 2 and 3) (Andrews *et al.*, 1991). Tubeiliyat Member comprises at its base, a thick (about 15 m) bed of varicoloured (grey, green, mauve and pink) ripple cross-laminated micaceous siltstone, highly fissile green shale, and very fine-grained, micaceous, medium to thin bedded, flaggy sandstone with hummocky cross stratification. Overlying the basal fine clastics are medium-thick bedded fine-grained, micaceous, mostly beige (locally red and olive green) sandstone, with trough cross-bedding and various ripple marks. The correlative upper silty unit of the Umm Tarifa Formation is only known from the Risha and Wadi Sirhan areas, although it is absent in Wadi Sirhan-3 and -4 (Andrews *et al.* 1991). In Iraq, members K 2, 3 and 4 of the Khabour Formation (Fig. 10) in the Akkas-1 well of the western desert (Al-Hadidy, 2007), fall within this sequence. Al-Hadidy (2007) logs-figure shows that these comprise some high-API GR shales at the base that pass up into lower-API sandstones, in a series of stacked cycles (Fig. 11). In both cases (outcrop and subsurface) the upper contact of the formation is a very strong and erosional one. In addition, the overlying units are highly variable, often there are localised glacial facies of the Risha Member in the Wadi Sirhan and Risha areas, but elsewhere such as over much of the outcrop, the contact is directly overlain by the slightly younger and graptolitic Batra Mudstone and its equivalents. In Iraq, the upper contact of member K2 of the Khabour Formation is a very abrupt one, from relatively high-API GR sandstones, up into notably low-API GR sandstones of member K1 (Fig. 11). The Tubeiliyat Sandstone Member is 105 m thick at outcrop (Powell, 1989) whilst the upper silty member of the Umm Tarifa, may reach a thickness of 420m in Risha-2 well (Andrews *et al.* 1991) and the equivalent Khabour Formation stratigraphy is perhaps 650m thick in the Akkas-1 well (Al-Hadidy, 2007).

Deposition would appear to have been mid- to inner shelf dominated by wave, storm and tidal actions, with more silty basal facies being indicative of deeper water and more open marine setting, here interpreted as the O40 mfs of Sharland *et al.* (2001). Western-Iraq stratigraphies and upwards-cleaning log signatures suggest that highstand shelf clastics prograded out at least as far as Akkas-1 well location, and most probably to Khleisia-1 (Al-Hadidy, 2007). Local post-depositional loss in the subsurface of the upper silty member of the Umm Tarifa Formation may relate to the local peneplanation of palaeohighs (such as in the south of the Wadi Sirhan area)

by the end-Ordovician (Hirnantian) glacial event that is associated with the AP2/AP3 Megasequence boundary.

Potential reservoirs of sequence: S6-AP2

Sandstones of this interval show similar reservoir characteristics to those in the underlying HST to O30 MFS. It is also possible that locally, the basal siltstones/shales, may act as top-seal or at least as a baffle horizon, above underlying Umm Tarifa/Dubaydib sandstone reservoirs of Jordan and their equivalents in western Iraq.

Megasequence AP3

This Megasequence consists of the middle and upper parts of the Mudawwara Sandstone Formation, comprising the Batra Mudstone Member (containing the S10 mfs, of Llandovery age), and the overlying Ratiya Sandstone Member/Kishsha Sandstone Formation at outcrops of Jordan (Fig. 2). In the subsurface it includes the Risha Member/Formation or Trebeel Formation overlain by the Batra Formation which contains both a basal and upper 'hot shale' (Andrews et al. 1991) (Fig. 3). These hot shales are correlative with the S10 mfs of Sharland et al. (2001) basal shale, and what can be termed the S15 mfs (i.e. upper shale) of later Llandovery age (see Aqrawi et al., 2010 for its definition in Iraq). In terms of Iraqi stratigraphy, this entire interval falls within the Akkas Formation of the Western Desert area, in which there is basal hot shale, Hoseiba Member and uppermost Qaim Member (Al-Hadidy, 2007 and Al-Juboury et al., 2019).

Sequence: S1-AP3

This sequence includes Mudawwara Formation, and Batra Mudstone and Ratiya Sandstone Member of Jordan together with the equivalent Akkas Formation of western Iraq of S10 mfs (Figs. 2 and 3). In outcrops it comprises the Batra Mudstone Member and the overlying Ratiya Sandstone Member (Powell, 1989), which are equivalent to the Trebeel, Batra and Alna Formations of the subsurface, Andrews et al. (1991) and the Akkas Formation of western Iraq (Al-Hadidy, 2007). It should be noted to avoid confusion that the Batra Formation of the subsurface, is the facies equivalent of the Batra Member of Mudawwara Formation at outcrop.

In the Risha Field, NPC (National Petroleum Company) of Jordan has informally defined a Risha Formation (equivalent to the Trebeel Formation of Andrews et al. 1991). In the Risha area, these deposits are thick and complex comprising alternating beds of very low-API GR sandstones, and high-API GR argillaceous facies, as four unconformity-bound units. Variants on these facies are noted in the Akkas-1 and Khleisia-1 of western Iraq (Al-Hadidy, 2007) too. In the latter, the low-API GR 'clean sand' lithologies and associated higher-API GR lithologies can be seen on logs, they are thinner than the examples known from the Risha area. The Mudawwara Formation has a diverse faunal assemblage, among which the graptolite fauna in

the Batra Mudstone Member indicate an Early Silurian (Lower Llandovery) age. The stratigraphic position and presence of *Monograptus cf. sedgwicki* in the Ratiya Sandstone Member also indicate an Early Silurian (Llandovery) age (Masri, 1988a). The suggested depositional environment of the Mudawwara Formation is as an offshore open marine shallow shelf, indicated by the diversity of the acritarch assemblage (Masri, 1988a). Mudstones were deposited in periods with slightly deeper water as the Early Silurian is marked by the most intensive marine transgression across the whole of Gondwanaland, covering most of the Arabian Plate (including the NW region) and North Africa (e.g. Masri, 1988a).

Petrography reveals the Risha/Trebeel Formation diamictites to be poorly sorted sandstones, notably in Wadi Sirhan, locally with whole clasts of granite (Figs. 5H and 5I). These sediments may be rich in angular grains including abundant perthitic feldspars (Figs. 6H and 6I). Glaciogenic sediments of the Jordanian Trebeel Formation and its subsurface equivalent the Risha Member, are often very matrix-rich diamictites that generally have low reservoir quality. In contrary, glacial associated sandstones probably related to outwash deposits are highly microcline-rich and thus have better potential for secondary porosity development in the subsurface, lacking in the quartz-rich Dubaydib Formation of Jordan, and its equivalent Khabour Formation of western Iraq. Glacio-marine shelf sandstones such as in the Jafr area, are commonly both fine-medium grained angular arenites and coarser rounded grain arenite. Such sandy beds are characterised by fine-grained sandstone of sub-rounded and medium sorted grains and may be rich in trilobites (Figs. 6H and I). These sandstones are mainly composed of quartz (66%), K-feldspar (14%), and clays (as kaolinite 11% and illite 6%) (Tables 2 and 3). Diagenesis of the glacio-marine shelf sandstone is dominated by quartz and calcite, with minor chlorite rims to grains. Much porosity is secondary after dissolution of calcite cements; core plug porosities reach 8-9% but average log porosity is 13% at about 2,600m (Andrews et al. 1991). Strong compaction has locally led to quartz overgrowth. As a result, many intervals are commonly quite tight such that almost no visual porosity can be observed. In the Jafr area burial is less such that there is only very limited quartz overgrowth cement resulting textures similar to the underlying Umm Tarifa sandstones.

Proven and potential reservoirs of sequence: S1-AP3

Although the Silurian is an important source succession in the region, it has very good reservoirs too, Al-Hadidy (2007) and A-Juboury et al. (2019), which are proven in western Iraq Akkas Field and NW Saudi Arabia. Typically, shales alternate with porous sandy beds, which are some of the best quality Palaeozoic reservoirs hosting light oils such as those of the Akkas Field of western Iraq (Al-Haba et al. 1994). The Risha Member has quite uniform reservoir

characteristics in wells such as Risha-16 and Risha-25 and especially at deeper levels, where quartz overgrowths are well developed and the clays do not coat the quartz grains, although there may be chlorite present. Contrasting with this, are the diamictites, which show very poor reservoir quality. The subsequent transgression, in addition to providing a shale seal for the underlying reservoir play, resulted in the formation of anoxic intra-shelf environments. These have produced some excellent marine source rocks very rich in organic matter and characterised by graptolites, in the form of the regionally extensive Lower Silurian 'Hot Shales'. As a result, the Silurian is considered as a complete petroleum system having very rich source rocks and quite porous reservoirs and tight seals within a small thickness of stratigraphy.

In the Akkas-1 well, light oil (42° API) was discovered in fractured sandstones and siltstones of the Qaim member, which has been assumed to be sourced from the hot shale of the underlying Hoseiba Member (Al-Habba *et al.* 1994 and Al-Juboury *et al.* 2019). Al-Khafaji *et al.* (2015) concluded that only the Khabour Formation can be regarded as source for the gas and condensate in the Akkas field, whereas the hot shales of the Akkas Formation have not reached a sufficient maturation level in the well investigated. Mohammed *et al.* (2020) concluded that the black shales of Khabour Formation are fair source rocks, highly matured and reached the peak of gas generation. Al-Juboury *et al.* (2019) reported visual porosity in the sandstones from the Akkas-1 and -3 wells ranging from 1% to 10%, but pore connectivity was considered often poor, which might affect the reservoir potential. In the Akkas-1 well, reservoir potential was assessed as good (of 7-10% porosity) to moderate (of 5-7% porosity). They also mentioned that visual porosity estimated using microscopy may underestimate the effective porosity of a sandstone because it may not account for microporosity. Effective porosity would normally be measured using core plugs, but this could not be carried out in the present study due to the limited availability of core material.

MAIN CONCLUSIONS

1. The stratigraphic review of the Lower Palaeozoic formations of Jordan and their sedimentological and XRD mineralogical analyses led to the characterization of their potential and proven reservoirs. The latter reservoirs were correlated to western Iraq Lower Palaeozoic formations within a regional sequence stratigraphic framework of several 3rd order sequences in each of the main Arabian Plate (AP) Megasequence, particularly AP2 and AP3 of Sharland *et al.* (2001), whereas AP1 and the crystalline basement lack any reservoir prospectivity.

2. Most of the clastic reservoir formations of Jordan are characterised by good to very good reservoir quality at outcrop including Salib, Umm Ishrin, Disi, Umm Sahm, Hiswah, Dubaydib and Mudawwara formations, particularly when they are dominated by well sorted and rounded quartz-sand grains with less cementation.
3. Reservoir quality is usually compromised by the risk of thick overburden, where elevated temperature and increased mechanical compaction lead to quartz overgrowth cementation. As a result, most of the reservoir quality is usually destroyed in subsurface by quartz overgrowth cementation, particularly for the more quartzitic sandstone facies.
4. Normally, the deeper the sandstone reservoir, the worse the reservoir quality, except when the sand grains are coated with chlorite clays such as in the middle-upper Ordovician Dubaydib sandstone sample in well RH-5 at 3232.55m depth sample.
5. Several deep sandstone reservoirs are proposed for non-penetrated Cambrian-Ordovician succession of western Iraq based on the study of their Jordanian equivalent formations such as the Salib, Umm Ishrin, Disi, Umm Sahm and Hiswah.
6. Proven reservoirs in the subsurface of Jordan so far are mainly Dubaydib and/or Risha Formation in both the Risha Field that mostly accommodate gas, and in the Wadi Sirhan (Hamza Field) having light oil, but in uncommercial amounts.
7. Glaciogenic sediments of the Jordanian Trebeel Formation and its subsurface equivalent the Risha Member, are often very matrix-rich diamictites that generally have low reservoir quality. In contrary, glacial associated sandstones probably related to outwash deposits are highly microcline-rich and thus have better potential for secondary porosity development in the subsurface, lack in the quartz-rich Dubaydib Formation of Jordan, and its equivalent Khabour Formation of western Iraq.
8. Generally, in NW Arabia, reservoir prospectivity in the Infra-Cambrian-Lower Palaeozoic interval is best at the critical transition from basal sand-dominant (generally Ordovician-Cambrian) stratigraphies, up into clay-dominant (generally Silurian) stratigraphies. Here, there is the greatest opportunity to develop clean shallow marine sandstone reservoirs with good porosities, sealed and sourced by overlying organic-rich shales. Deeper levels tend to lack good source and seal; whilst shallower levels, are commonly fine-grained such that reservoir quality is compromised.

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