

Diagenetic and Depositional Impacts on the Reservoir Quality of the Upper Jurassic Arab Formation in the Balal Oilfield, Offshore Iran

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Abstract: The Kimmeridgian-Tithonian aged Arab Formation, as the main reservoir of the Jurassic succession in the Balal oilfield, located in the offshore region of the Iranian sector of the Persian Gulf, is investigated in this study. The formation is composed of dolomites and limestones with anhydrite interbeds. Based on detailed petrographic studies, six microfacies are recognized, which are classified in four sub-environments including supratidal, intertidal, lagoonal and the high energy shoal of a homoclinal carbonate ramp. The main diagenetic features of the studied succession include dolomitization, anhydritization, cementation, micritization, fracturing and compaction. Based on stable isotope data, dolomitization of the upper Arab carbonates is related to sabkha settings (i.e. evaporative type). In terms of sequence stratigraphy, three shallowing-upward sequences are recognized, based on core and wireline log data from four wells of the studied field. Considering depositional and diagenetic effects on the reservoir quality, the studied facies are classified into eight reservoir rock types (RRT) with distinct reservoir qualities. Dolomitization has played a major role in reservoir quality enhancement, whereas anhydritization, carbonate cementation, and compaction have damaged the pore throat network. Distribution of the recognized RRTs in time and space are discussed within the context of a sequence stratigraphic framework.

Key words: reservoir quality, Arab Formation, Balal oilfield, offshore Iran, Persian Gulf

1 Introduction

The Upper Jurassic Arab Formation is one of the most prolific reservoir rocks of the Arabian Plate (Bates 1973; Beydoun 1991; Murris 1980). In some Iranian literature, it is known as the Upper Surmeh Formation, so these two formations are frequently used interchangeably (e.g., Ghazban, 2007; Daraei et al., 2014; Beigi et al., 2017). Numerous studies on the biostratigraphy and regional correlation (e.g., Al Silwadi et al., 1996; Hughes 1996), facies characteristics and depositional environment (e.g., Al-Saad and Sadooni 2001; Alsharhan and Whittle 1995; Meyer et al., 1996), the impact of diagenesis and depositional facies on reservoir quality (Meyer et al., 2000; Morad et al., 2012) and sequence stratigraphy of the formation in the Arabian Plate (e.g., Nindre et al., 1990;

Azar and Peebles, 1998; Al-Hosseini, 1997; Morad et al., 2012; Al-Awwad and Collins, 2013) have been carried out during the last two decades, but nonetheless the information available on the Iranian part of the Persian Gulf remains scant (e.g., Daraei et al., 2014; Beigi et al., 2017). This study aims to investigate the facies characteristics, depositional environment, diagenetic features, and reservoir quality of this formation in one of the north Persian Gulf oilfields. The identification of major factors affecting reservoir quality is also intended to be achieved by using an integrated approach (facies, diagenetic and petrophysical analyses) within a sequence stratigraphic framework.

2 Geological Setting and Stratigraphy

The studied field is located in the central part of the Persian Gulf (Fig. 1). It is an oval-shaped dome, located

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near the international border between Iran and Qatar, southwest of Lavan Island and southeast of the South Pars gas-field (Fig. 1). The Balal Field was discovered in 1967 with two oil-producing reservoirs (in the Sarvak and Arab formations). Later, three main reservoir levels were identified in this field, within the Sarvak, Dariyan and Arab formations. The Arab Formation (also known as the Arab reservoir) holds about 84% of the total reserves and is being considered to be the main reservoir in this field

(Ghazbhan, 2007).

In the studied area, the Arab Formation overlies the Kimmeridgian Darb Formation and is covered by the Late Tithonian Hith Anhydrite, and is composed of limestone, dolomite and anhydritic dolomite with intercalations of anhydrite (Fig. 2). The Upper Jurassic Arab Formation in the Arabian Plate is subdivided into four informal units, from top to base; A, B, C and D (Al-Husseini 1997; Alsharhan and Nairn 1997) (Fig. 2). The Arab Formation

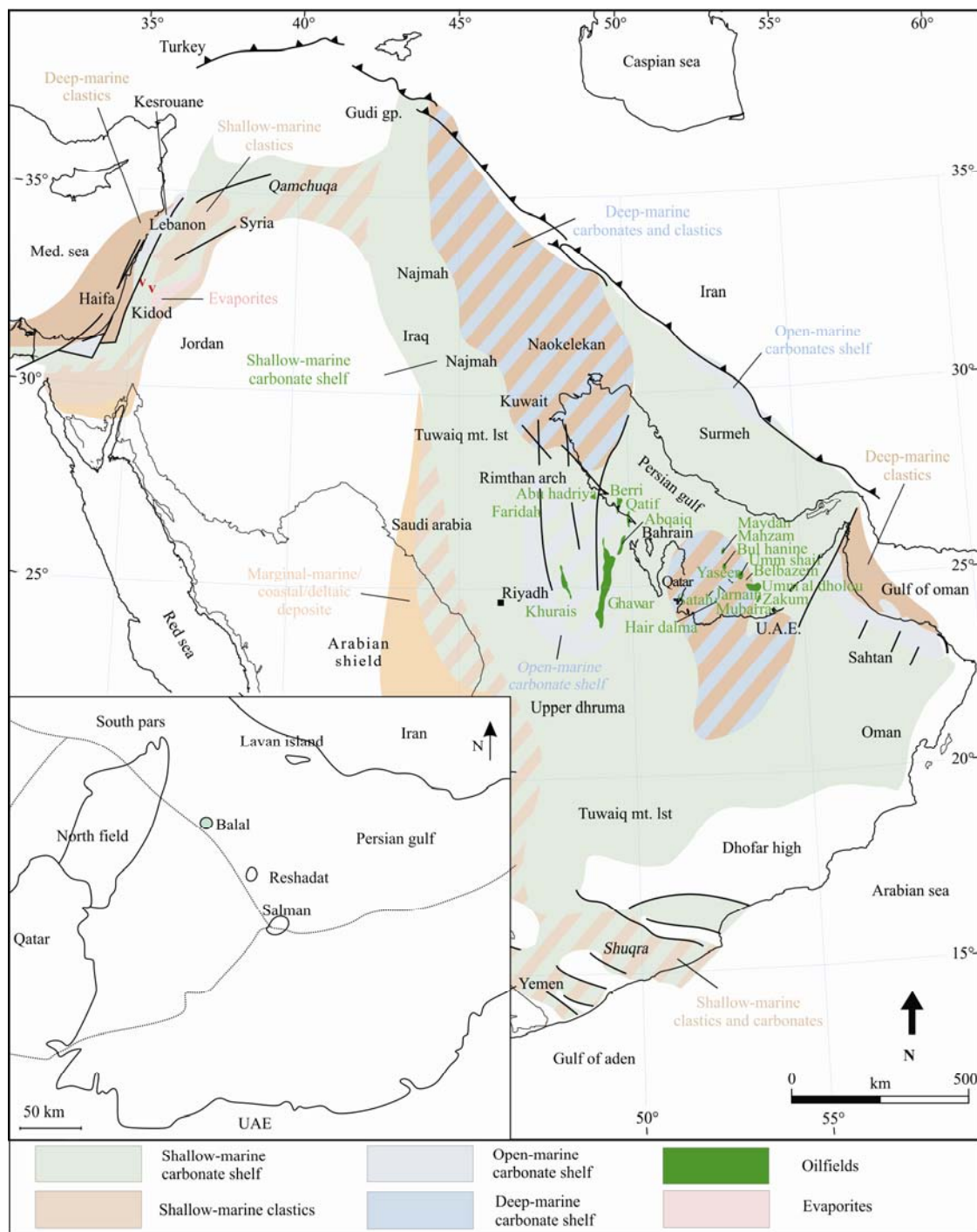


Fig. 1. Paleogeography of the Upper Jurassic in the NE Arabian Plate and location of the Balal Field and neighboring fields (after Ziggler, 2001).

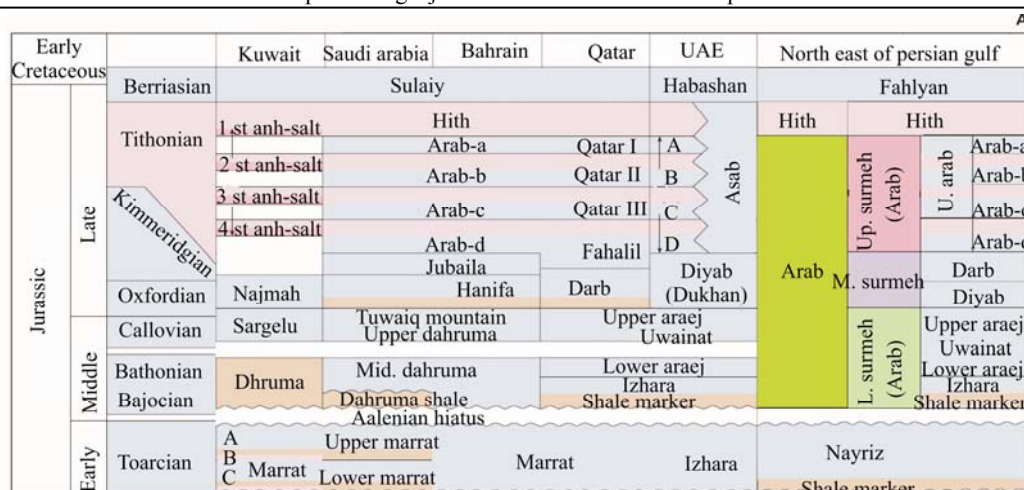


Fig. 2. Schematic representation of the Upper Jurassic units in the Arabian Plate (after Cantrell et al., 2001).

is interpreted as being deposited in a shallow marine carbonate setting on the NE passive margin of the Arabian Plate (De Matos and Hulstrand, 1995; Le Nindre et al., 1990). In petroleum geology studies, this formation is divided into the Lower Arab (unit D) and Upper Arab (units A, B and C) reservoirs (Fig. 2).

3 Materials and Methods

Data from four exploratory wells (B1-1 to B1-4) in the Balal oilfield were available for this study. Some 380 standard thin sections from core samples were prepared for petrographic studies. Microfacies analysis of the rocks was based on the schemes of Dunham (1962) and Flügel (2004, 2010). For pore type analysis and porosity estimation, some 100 blue-dyed thin sections were used. In the petrographic studies, all depositional, diagenetic and reservoir-related features (Choquette and Pray 1970; Lucia 1983) of the samples were investigated in detail. Due to the predominance of dolomite within the studied intervals, the textural classification and crystal size groups of Sibley (1982), Sibley and Gregg (1987) and Lucia (1995) were used. Geochemical data (33 samples of C and O isotopes) from the B1-1 well were adopted from Lotfi (2007) for determination of the dolomitization model.

Routine core analysis was carried out on 400 plug samples from the wells B1-1 and B1-2. To calibrate the initial core depths with those of wire-line logs, natural gamma-ray profiles were measured along the cores then matched with wire-line logs. The plug samples were cleaned to remove residual hydrocarbons, formation brines and salts and other contaminants using toluene and methanol then were dried in a conventional oven. The porosity of the samples was measured in ambient conditions in the ultra porosimeter 200A instrument using the He expansion and the application of Boyles's law. Air permeability was measured in ambient conditions with an

ultra permeameter, which uses Darcy's equation. The reservoir rock types were determined based on the integration of depositional facies, diagenetic imprints and reservoir quality-related petrophysical data. Thereafter, the main controlling factors affecting the reservoir quality (i.e. depositional textures and diagenetic features) were determined. The main depositional sequences and their major elements including systems tracts and stratal surfaces (sequence boundaries and maximum flooding surfaces) were recognized on the basis of defined facies and syn-depositional and subaerial exposure-related diagenetic products. The sequence stratigraphic framework was then used as a basis for the correlation of the proposed reservoir rock types and reservoir quality trends.

4 Results

4.1 Facies analysis

Results from detailed petrographic analysis of the core-based thin sections led to the identification of six microfacies, which were assigned to supratidal, intertidal, lagoonal and barrier/shoal facies belts based on their sedimentological characteristics and fossil content. The main characteristics of the identified microfacies and their related depositional environments are summarized in Table 1.

4.1.1 Anhydrite (MF1)

This is an anhydritic facies, characterized by coalesced nodules, a 'chicken-wire' structure and parallel lamination. It is visible in a spectrum from clean to dirty dolomitic anhydrite. Some diagenetic features such as stylolites and fractures can be locally observed (Fig. 3a and b). This facies occurs in different horizons of the studied succession, which ranges from 1 centimeter to 7 meters in thickness. This facies has no reservoir quality

and typically acts as a seal for the studied shallowing-upward successions.

The nodular anhydrites were most likely formed in a ‘cut-off’ lagoon (see Azar and Peebles, 1998), whereas those with a massive fabric and chicken-wire structure represent a sabkha environment (cf. Alsharhan and Kendall, 1986; Morad et al., 2012 and Beigi et al., 2017). The presence of anhydrite along with supratidal evaporates indicates the predominance of an arid climate during the deposition of the Arab Formation (see Alsharhan and Magara, 1994; Alsharhan and Whittle,

1995; Lindsay et al., 2006).

4.1.2 Dolomitic mudstone to wackestone (MF2)

This is a dolomitized lime mudstone with scattered allochems in places (wackestone) (Fig. 3c and d). Dolomite crystals with non-planar to planar-s and planar-e textures (see Sibley and Gregg, 1987) were identified. Dolomitization affected this microfacies in two ways: the muddy matrix is replaced by finely crystalline dolomites producing a dolo-micrite, whereas coarse crystalline dolomites (with cloudy cores and cement rims) occur as

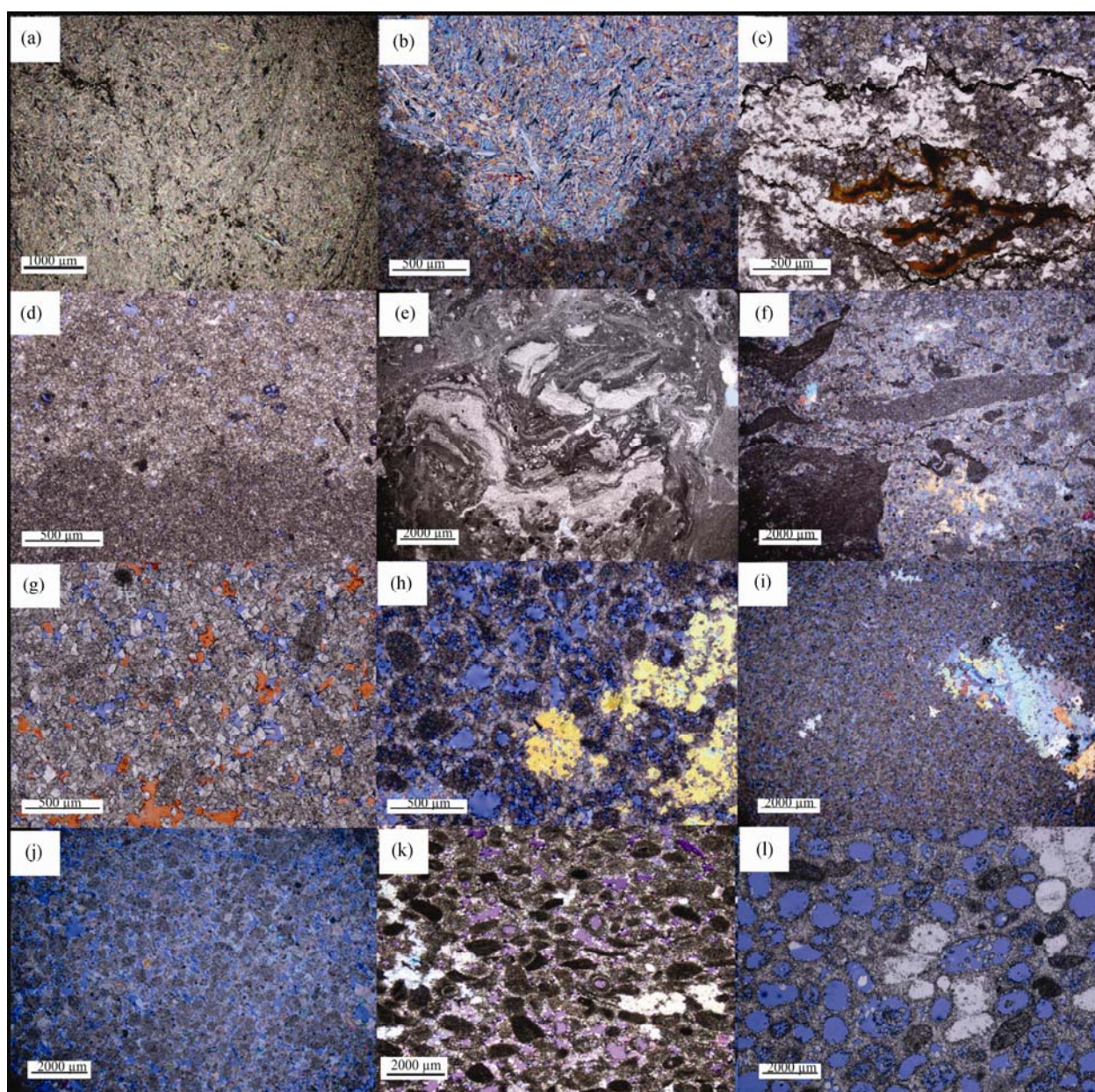


Fig. 3. Photomicrographs showing the principal identified microfacies of the Arab Formation.

(a-b), MF 1: Anhydrite with massive and chicken-wire fabric; (c-d), MF 2: dolomitic mudstone-to-wackestone, having stylolites filled with iron oxides and organic matter; E-F, MF 3: dolomitic algal wackestone to packstone, with both patchy and poikilotopic anhydrite textures; (g, h, i), MF 4: dolomitized bioclast packstone, pore spaces mainly contain interparticle, vuggy and some moldic types and anhydrite observable as pore filling (i) and some poikilotopic (h); (j-k), MF 5: dolomitized bioclast grainstone with high poroperm values, mainly moldic and vugs; (l), MF 6: dolomitized ooid grainstone representing well-sorted and dissolved ooid molds.

Table 1 The main characteristics of the determined microfacies and their related depositional environments

Microfacies name	Microfacies code	Main allochems		Sub-environment
		Skeletal	Non-skeletal	
Anhydrite	MF1	-	-	Supratidal
Dolomitic Mudstone to Wackestone	MF2	-	peloid	Intertidal
Dolomitic algal Wackestone to Packstone	MF3	Clypeina, Gastropod, Echinoids, Benthic forams	Peloid,	Lagoon
Dolomitized bioclast Packstone	MF4	Gastropod, Echinoids	Peloid, Ooid	Lagoon
Dolomitized bioclast Grainstone	MF5	Bioclast, Benthic forams, Algae	-	Back shoal
Dolomitized ooid Grainstone	MF6	-	Ooid	Shoal

pore-filling cement. However, fine crystalline anhydrite dolomites formed tightly inter-locked mosaic cement in some pore spaces. Dispersed anhydrite patches are present in this microfacies. Stylolites are common diagenetic features of this facies.

The sedimentological characteristics of this microfacies indicate a supratidal to intertidal setting that was affected by hypersaline brines (see Flügel, 2004). This microfacies is similar to the 'barren facies' of the Arab D member, which is related to the peritidal environment (Meyer et al., 1996). The high stress setting is reflected in the virtual absence of an *in situ* fauna in this microfacies (see Meyer et al., 1996).

4.1.3 Dolomitic algal wackestone to packstone (MF3)

This is a dolomitized algal wackestone to packstone, the main allochems of which are green algae (Clypeina; Dasycladacean), benthic foraminifera, bivalves, gastropod and ostracod debris, and peloids. (Fig. 3e and f). Micritization, bioturbation and a fenestral fabric are other characteristics of the microfacies. Anhydrite patches are common (Fig. 3f). Fenestral, intercrystalline and interparticle pores are the main pore types in this microfacies. The porosity and permeability of the microfacies are mostly resulted from intercrystalline, moldic and some isolated pore spaces. Anhydrite cements exist as poikilotopic forms in some parts.

Microbial bonding, as a stromatolitic fabric, is the most common feature of a lagoonal to peritidal setting (Flügel, 2004). The existence of anhydrite patches indicates the influence of sabkha-related brines (see Azar and Peebles, 1998; Lucia, 2007). Micritized skeletal components suggest deposition in a low-energy, shallow lagoon sub-environment (see Flügel, 2004; Wanas, 2008).

4.1.4 Dolomitized bioclast packstone (MF4)

This is a dolomitized bioclast packstone with allochems of green algae, echinoderm shell fragments and peloids (Fig. 3i). Anhydrite patches are locally observed in the facies (Fig. 3g and h). Interparticle and vuggy (separated and touching) pores are the main pore spaces (among all pore types) in this microfacies. Dissolution and dolomites are observed in most places (Fig. 3g and h), whereas anhydrite cement is recorded in some (Fig. 3i).

This microfacies is similar to standard microfacies #20, reported from a lagoon sub-environment by Flügel (2010).

4.1.5 Dolomitized bioclast grainstone (MF5)

This is a dolomitized bioclastic grainstone, marked by a grain-supported fabric. Constituent allochems are the whole fossils and fragments of benthic foraminifera, gastropods, green and red algae and bivalves of sand-to gravel-sized (Fig. 3j and k). Anhydrite patches occur in some parts (Fig. 3k). Interparticle and moldic pores are prevailing pore types in this facies.

This facies is similar to standard facies #13, attributed to an intermediate-to-high energy back shoal setting, between lagoon and shoal (Flügel 2010; Sallam et al., 2015).

4.1.6 Dolomitized ooid grainstone (MF6)

This is a dolomitized ooid grainstone that forms the main body of the Arab Formation in the studied field. It is characterized by well-sorted ooids, a mud-free fabric and prevalent cementation (Fig. 3l). Micritization of ooids led to the creation of mineralogically-stable (micritic) grains with primary intergranular pore spaces. However, dissolution of non-micritized grains (ooids) produced frequent moldic porosity in places (Fig. 3l). An abundance of well-sorted ooids and the lack of matrix indicate that it developed in high energy shoal and bank sub-environments (cf. Flügel 2010).

4.2 Depositional Model

The distribution of sedimentary facies in time and space, along with their interpreted depositional conditions, indicates a gradual change from peritidal to shoal sub-environments of a carbonate ramp. Facies associated with reefs and shelf margins, turbidites, off-shore and open marine settings are not common in the studied formation. The results of this study, taken in conjunction with discoveries on the sedimentological and lithostratigraphic properties of the Arab Formation in the Middle East (e.g. Alsharhan and Kendall, 1986; Alsharhan and Nairn 1997; and Alsharhan and Whittle 1995), indicate the environment to have been an inner part of a homoclinal carbonate ramp (see Burchette and Wright, 1992; Buxton and Pedley, 1989; Pedley, 1998; Wanas, 2008; Sallam et

al., 2015; Beigi et al., 2017).

The inner ramp was embracing tidal flat, lagoon and shoal facies belts (Fig. 4). The peritidal facies belt is marked by anhydrite and anhydritic dolomudstone (MF1, MF2), and the lagoon by dolomitized wackestone to packstone with a distinct lagoonal fossil content (MF3, MF4). The shoal facies belt is characterized by well-sorted grainstones (MF5, MF6) (Fig. 4).

4.3 Diagenesis

Micritization, cementation, compaction, dolomitization, dissolution and the development of fractures are the main diagenetic processes, which modified the primary reservoir quality of the Arab reservoir in the Balal Field. Distribution of the processes is interpreted to be a function of their stratigraphic position, depositional environment and sedimentary texture.

4.3.1 Micritization

Micritization is a dominant marine diagenetic process (syn-depositional) in most grain-dominated facies (MF4 to MF6) and occurs both as thin micritic envelopes around carbonate grains and as wholly micritized allochems (Fig. 5a). This process caused the allochems to gain more mineralogically-stable grains, which were resistant to dolomitization and dissolution. Anhydrite, calcite and dolomite are the dominant cement types that fill some moldic, vuggy, fracture and interparticle pore spaces. They are more common in the upper part of the formation. The isopachous marine calcite cement is identified in grain-supported shoal facies (MF5, MF6) (Fig. 5b). Anhydrite cement is observed in pore- and fracture-filling forms (Fig. 5i and j).

4.3.2 Dolomitization

In the upper part of the Arab Formation, dolomitization is the most common process, which directly controls the

type, distribution and origin of the pore types (Fig. 5c, d and e). Dolomitization of the Arab A, B and C units most likely occurred during reflux of highly saline brines representing the sabkha and seepage-reflux models (see Adams and Rhodes, 1960; Hardie, 1987; McKenzie, 1991) (Fig. 6).

Generally, the near-surface and low temperature dolomites, including supratidal to sub-tidal, seepage reflux and mixing zone dolomites, have the heavy (positive) $\delta^{18}\text{O}$ values (Lohman, 1988). The sabkha dolomites represent a heavier amount of $\delta^{18}\text{O}$ values than the seepage reflux ones due to evaporation (e.g., Lohman, 1988; Morad et al., 2012). This is confirmed by oxygen and carbon isotopic signatures (Fig. 7). In addition, the $\delta^{18}\text{O}$ isotopic composition of the Upper Arab reservoir in the Bala Field has been somewhat changed into negative (light) values as a result of meteoric diagenetic processes (i.e., the effect of meteoric waters). Seepage reflux medium-to-coarse crystalline dolomites indicate more negative $\delta^{18}\text{O}$ values due to the presence of diluted fluids and lower evaporation (which might be related to the higher poroperm and consequent fluid circulation through these facies). These observations are in accordance with the $\delta^{18}\text{O}$ signatures presented by Bouroullec and Meyer, 1994; Morad et al., 2012.

The distribution of oxygen and carbon isotopes of the studied formation (Fig. 8) suggests that dolomitization of lagoon and tidal flat settings occurred in conditions of low temperature (25 to 35°C) and depth, through the pumping of evaporate brines that were enriched in magnesium and sulphate ions, whereas dolomitization of shoal bodies occurred at medium temperature (35 to 42°C) conditions (Fig. 8). As illustrated in Figure 7, the distribution of O and C stable isotopes represent two distinct areas and consequently different dolomitization conditions. The shallower part of the Arab dolostones are characterized by $\delta^{18}\text{O}$ values of -0.9‰ to -2.3‰ (ave. -1.6‰) and $\delta^{13}\text{C}$

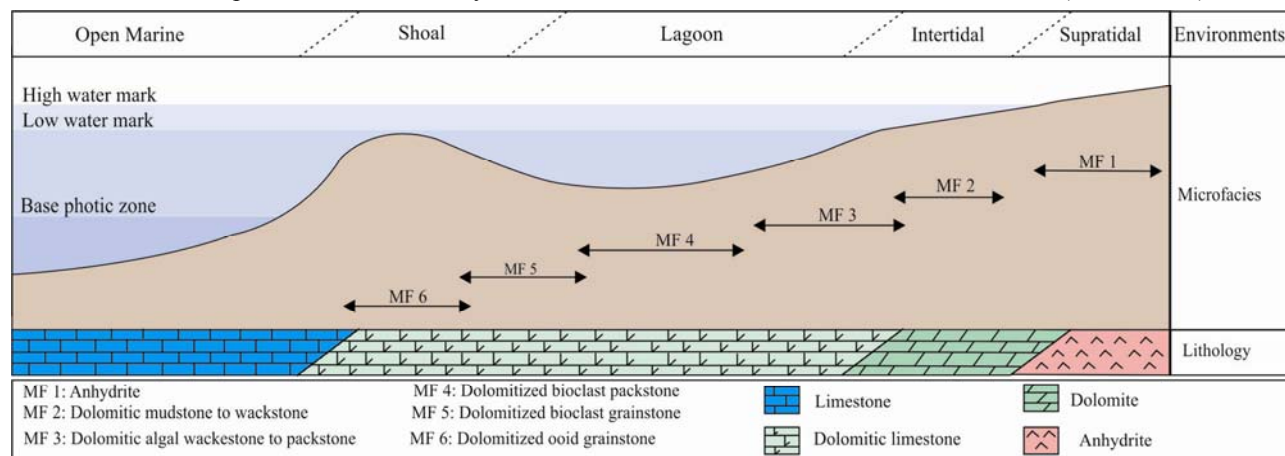


Fig. 4. The proposed carbonate ramp model for the Upper Arab Formation in the studied field with the location of the determined microfacies.

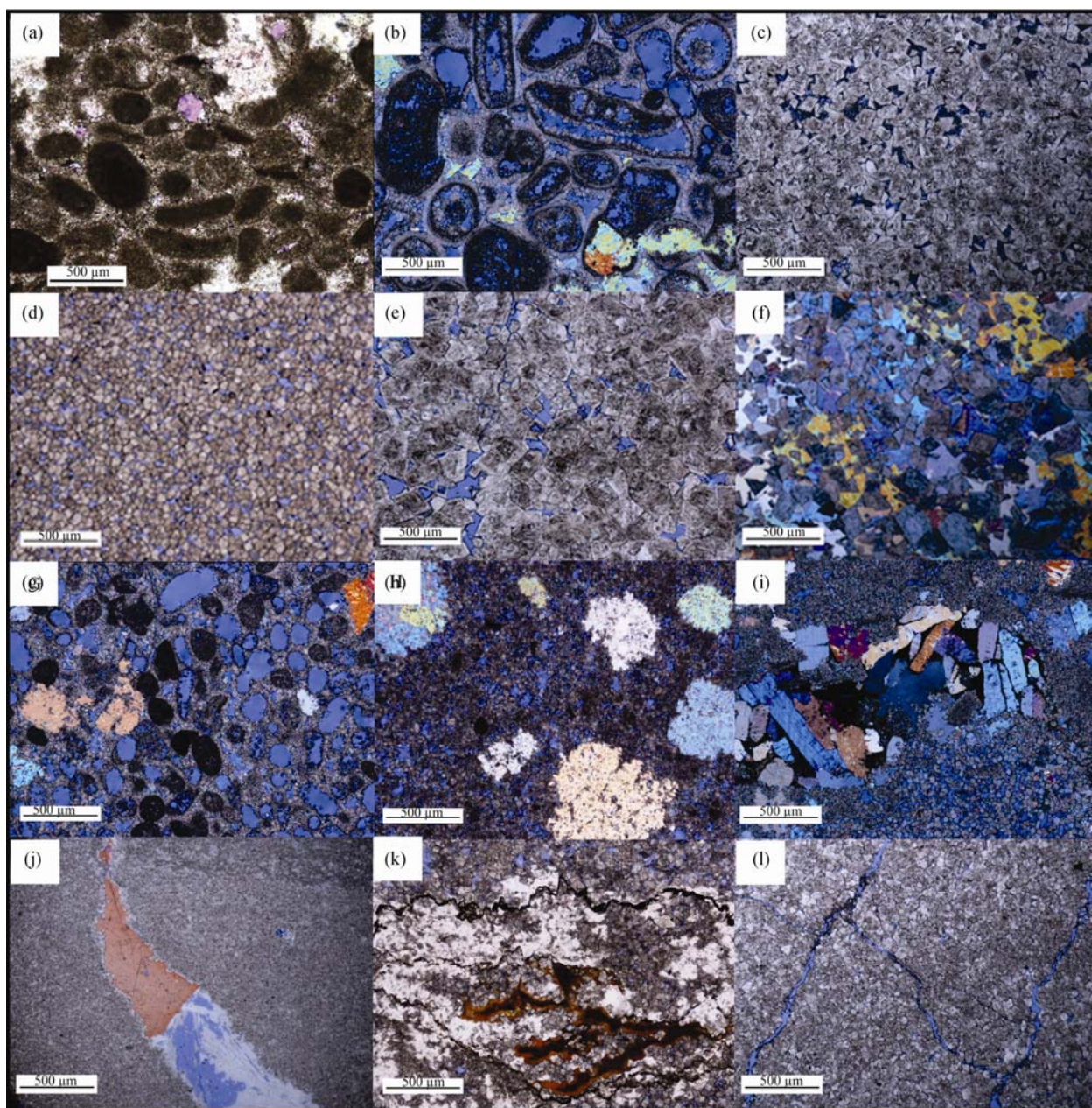


Fig. 5. Photomicrographs showing the main diagenetic features of the Arab Formation in the studied field.

(a), Wholly micritized allochems; (b), an isopachous marine cement in the shoal microfacies; (c-e), dolomitization and intercrystalline porosity; (f-j), different fabrics of anhydrite cement (poikilotopic, pore filling, fine nodules and fracture filling). (g), fabric selective dissolution and ooid molds; (h), stylolites; and (l), open micro-fractures in a mud-dominated facies.

values of +1.1‰ to +3.3‰ (ave. 2.1‰), the slight depletion in the $\delta^{18}\text{O}$ values of the sabkha-related dolomites being due to post-depositional modifications (i.e. the isotopic composition of the early dolomites), which indicates a temperature range of 25°C to 35°C, was very similar to the original brines. Accordingly, the basinward part of the Upper Arab carbonates are defined by $\delta^{18}\text{O}$ values of -2.8‰ to -4.7 ‰ (ave. -4.1 ‰) and $\delta^{13}\text{C}$ values of +2.5‰ to +3.1‰ (ave. 2.85‰), resulting from diluted (under-saturated) dolomitizing fluids at temperatures of 35°C to 42°C (Fig. 7).

The sabkha dolomites can be identified by their fine-grained crystal sizes (10 to 20 μm), reflecting relatively rapid nucleation. Lower saturation towards the basin resulted in fewer nuclei and coarser dolomite crystals (greater than 20 μm) due to the more stable pore fluid chemistry (see Warren, 2000). These coarse crystalline dolomites, known as 'sucrosic', are most likely formed by the reflux of dense brines.

Replacement of calcite by dolomite occurs in various forms, including incomplete replacive dolomitization, replacement of grains and/or early circumgranular fringing

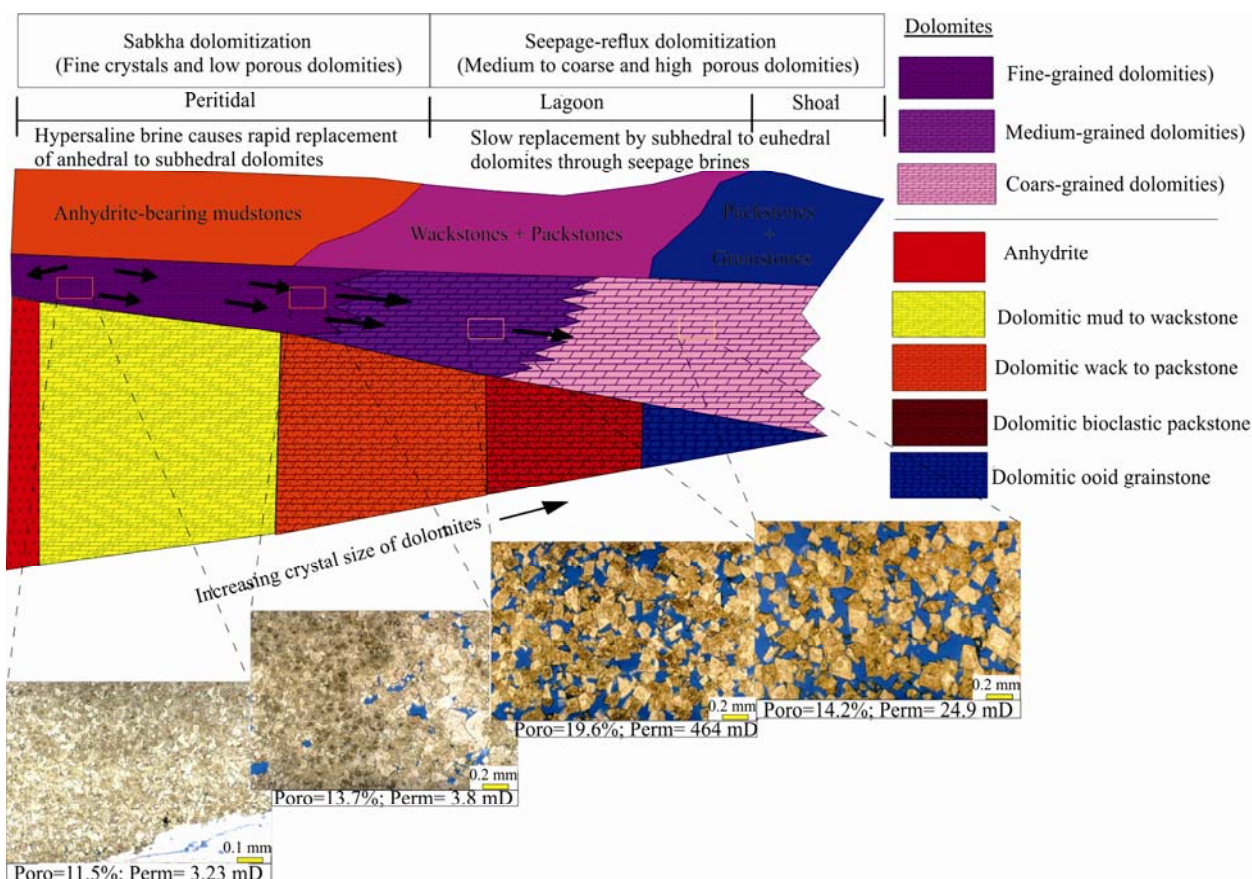


Fig. 6. Dolomitization models of determined depositional microfacies in the Upper Arab Formation.

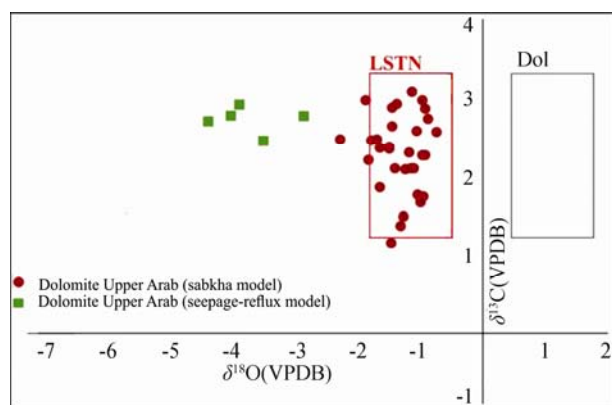


Fig. 7. Carbon and oxygen isotopic values of the studied dolomites. The rectangles DOL and LSTN represent the fields of dolomite and calcite from Jurassic seawater (after Morad et al., 2012).

cement (Fig. 5b). Replacement of aragonite and calcite by dolomite probably occurred under the influence of salina/sabkha brines associated with downward and lateral migration of hypersaline fluids. The process probably started shortly after deposition and continued during early burial (see Warren, 2000).

The Arab Formation dolostones show three main textural varieties, including dolomudstones, dolowackstones to packstones and dolopackstones to

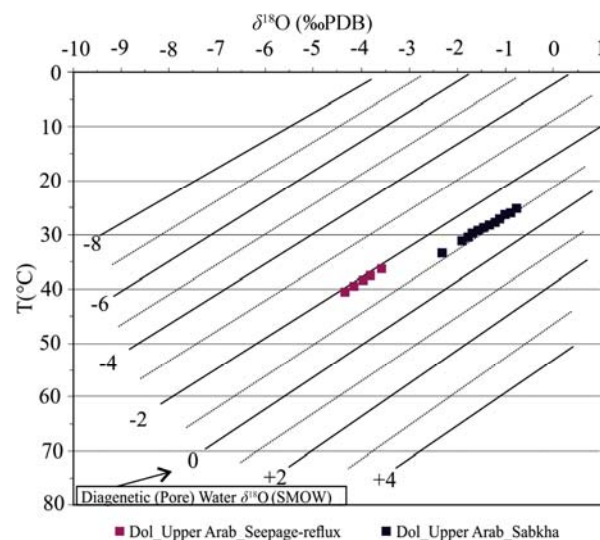


Fig. 8. Cross-plot of oxygen isotope value of various dolomites against the temperature dependency curve for the studied formation (after Lohman, 1988).

dolograinstones (Fig. 6), which provide evidence for the origin of the initial rock fabrics. The dolomudstones are formed by syn- or early post-depositional dolomitization of the peritidal mudstones that are observed in the shallow part of the studied interval, where they are associated with algal-laminated and sulfate layers. Pore spaces are

commonly filled with coarse crystalline anhydrite and medium-to-microcrystalline dolomite rhombs. In some horizons, these dense dolostones may act as barriers to vertical fluid flow because of their low permeability, and therefore lead to reservoir compartmentalization (cf. Morad et al., 2012). Finely crystalline dolomites have a moderately open fabric. Some tiny patches of more densely packed and finer crystals show a wackestone texture. Pore spaces are mostly of fine intercrystalline medium-to-micropores that form a well-connected network. The main pore system in these dolostones resulted from dolomitization of the micritic matrix and development of fractures (Fig. 9a and b).

The dolowackestones to dolopackstones mostly occur in the lagoonal part of the studied deposits. Dolomite crystals in these microfacies are medium in size (20-100 μm), planar-‘e’ to ‘s’ type rhombs (Fig. 10), which replaced both bioclasts and micritic matrix (Fig. 10a and b). Most bioclasts are difficult to identify, due to overdolomitization (Fig. 10a).

The dolopackstones to dolograinstones are mostly fabric-destructive, commonly cemented by scattered anhydrite patches and coarse crystalline dolomites. Partial dolomitization is generally associated with dissolution of peloids, ooids and micritic matrix (Fig. 11a). In terms of size and crystalline texture, the dolomite crystals are medium to coarse, subhedral (planar-s) to euhedral (planar-e), respectively, which form a tightly interlocking mosaic. Many remnants of grains are visible, and most parts of the framework are preserved. Anhydrite is present as cement, which filled intergranular and secondary intragranular/moldic pores after the dissolution of allochems (Fig. 11b).

4.3.3 Dissolution

Dissolution is another diagenetic process that affected

the porosity and permeability of the studied facies. Development of moldic porosity, which is the most common type in the upper part of the formation, is the result of such a process. Dissolution is observed in nearly all microfacies, and led to partial-to-complete leaching of carbonate components (Fig. 5b and g).

4.3.4 Compaction

Both physical and chemical compactions, which resulted in reduction of the porosity and permeability of the facies, can be observed in the studied interval. Mechanical compaction resulted in the reorientation of grains in some mud-supported microfacies (Fig. 5k). Chemical compaction developed as solution seam and stylolite within both grain- and mud-dominated facies (Fig. 5k).

4.3.5 Fracturing

Fracturing occurred on various scales in the studied facies. Fractures are mostly associated with compacted and stylolitized mud-dominated microfacies, i.e. mudstones and wackestones (Fig. 5l). They are also well-developed in the dolomitized microfacies, where they are locally filled with anhydrite and calcite cements (Fig. 5j). This feature seems to be the last diagenetic product in some facies, in which the fractures cross stylolites and cements (Fig. 9a).

On the whole, the identified diagenetic processes took place in marine, meteoric and burial conditions, the paragenetic sequence of which is represented in Figure 12.

4.4 Sequence stratigraphy

The Arab Formation and the overlying Hith evaporites are considered as final stages of the Upper Jurassic shallowing-upward cycle in the Arabian plate (Al-

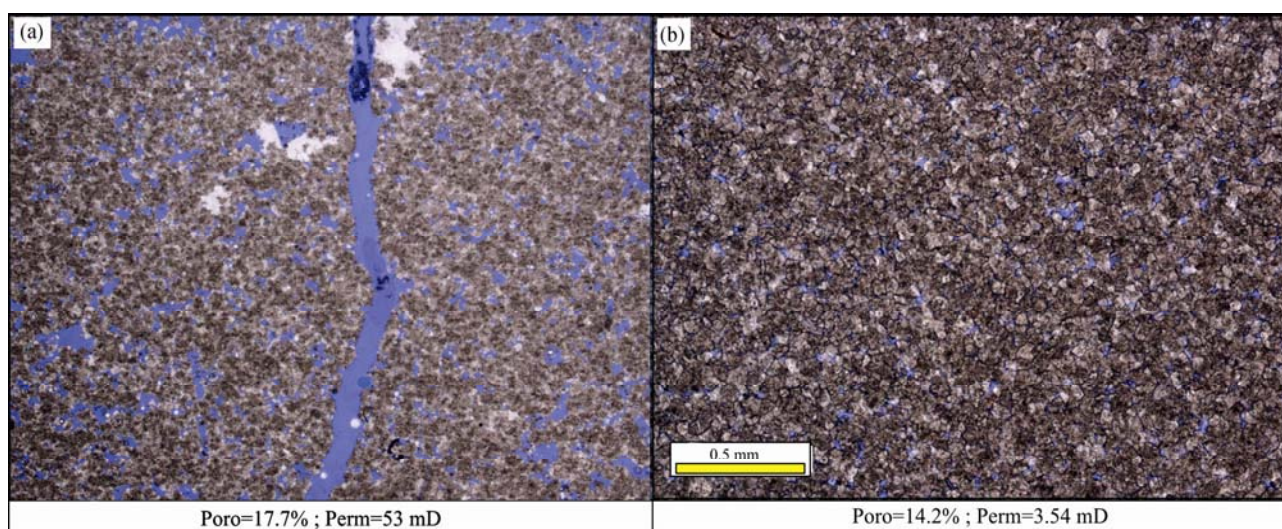


Fig. 9. Photomicrographs showing (A) fracturing, and (B) intercrystalline pore spaces in dolomudstones.

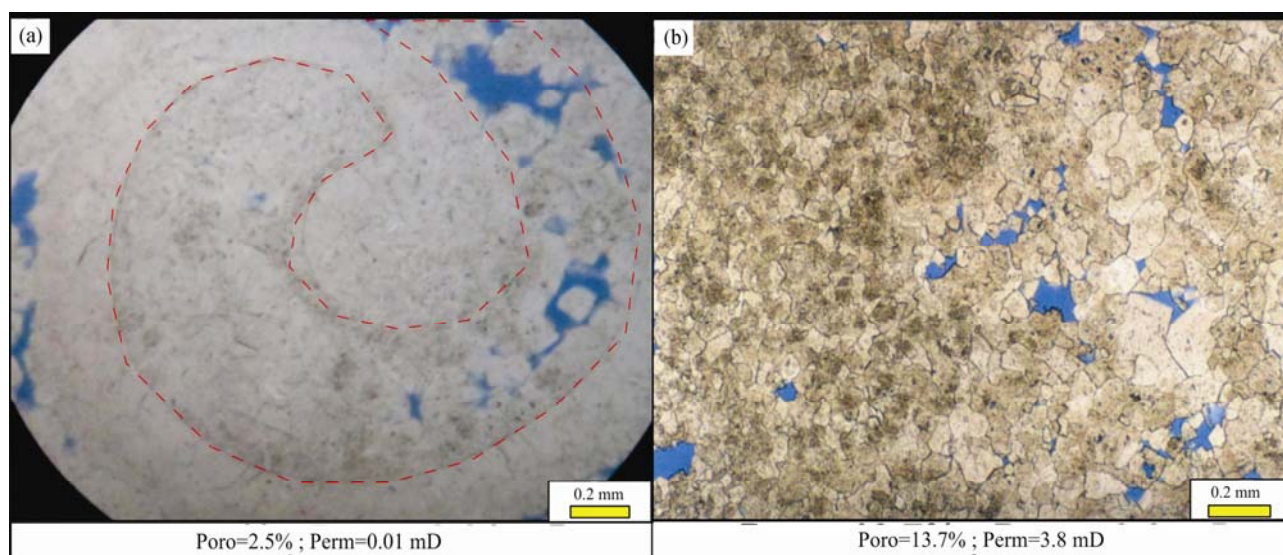


Fig. 10. Photomicrographs of dolomitized wackestone to packstone, representing (a) overdolomitization of bioclasts and matrix that reduces intraparticle porosity and permeability, and (b) medium-size dolomites with good porosity but lower permeability, that resulted from overdolomitization and large crystalline cements.

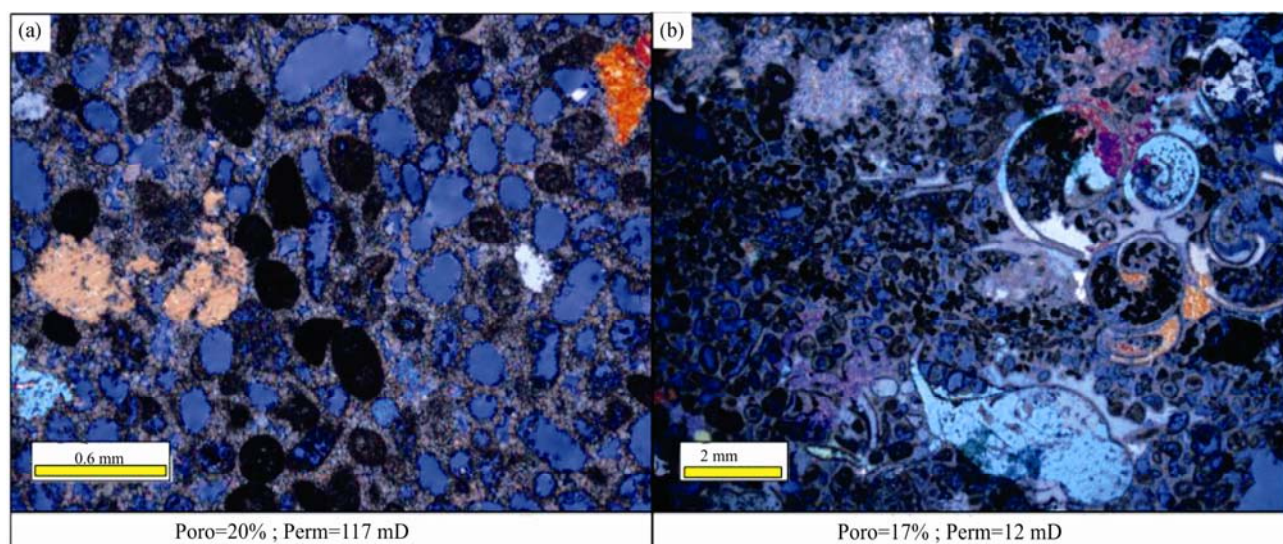


Fig. 11. Photomicrographs of dolopackstone to grainstone microfacies representing: (a) dissolution of ooid and peloid grains along the interparticle/intercrystalline pore spaces, and (b) anhydrite cementation in both bioclasts and matrix.

Husseini, 1997). From the sequence stratigraphic point of view, the Arab Formation is marked by some depositional cycles with bioclastic mud to wackestone in the lower part (Fig. 13), grainstones in the middle and dolomitized mudstone to evaporites in the upper part. The cycles are covered by the Hith Formation (evaporates) in most parts of the Arabian Plate, including the Persian Gulf area (Alsharhan and Kendall, 1986).

Deposition of the Arab Formation in the Iranian part of the Persian Gulf was mainly controlled by sea-level fluctuations in arid climatic conditions (Daræi et al., 2014). The effects of such conditions led to the development of shallowing-up successions of carbonate reservoirs, which are capped by evaporites.

Accordingly, a sequence stratigraphic framework can predict the distribution pattern and relative depositional timing of facies associated with relative sea level changes.

Results from facies analysis on core, cutting and log data, diagenetic studies, and available geochemical data are used here for sequence stratigraphic studies. The main emphasis is put on the recognition of systems tracts and main stratal surfaces (SB, MFS). Three third order sequences with a shoaling-up trend were identified in the studied formation. The major characteristics of these sequences are discussed below (Fig. 13). Comparing with previous studies (e.g. Al-Husseini 1997; Azer and Peebles 1998; Le Nindre et al. 1990), the determined sequences can be considered as part of a second-order long-lasting

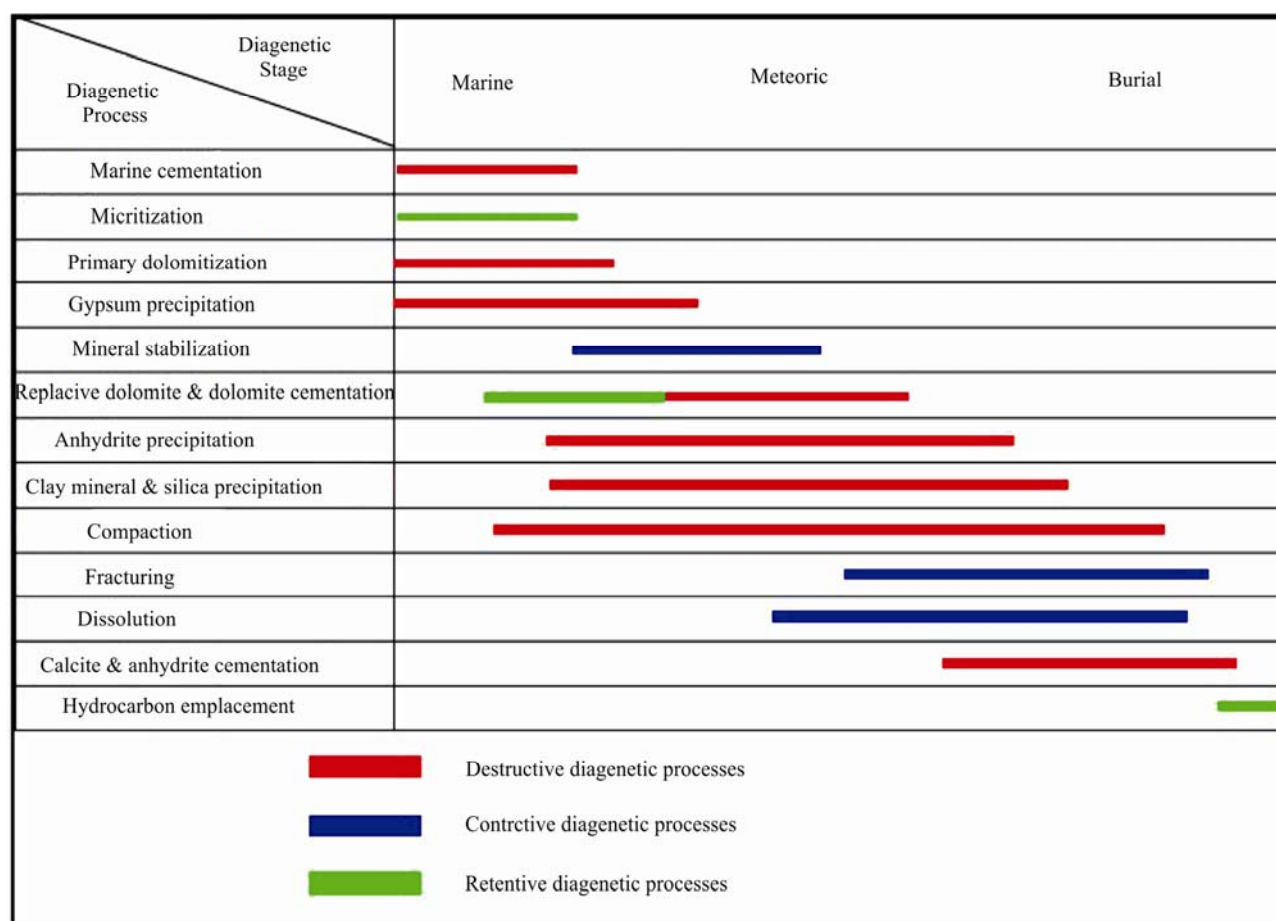


Fig. 12. Paragenetic sequence of the diagenetic processes in the studied interval of the upper Arab Formation.

sequence, which was recorded in most parts of the Arabian Plate.

4.4.1 Sequence I

This sequence is composed of transgressive, highstand and forced regressive systems tracts (TST, HST, FRST) with a total thickness of about 56m. The lower part of this sequence (TST) is dominated by dolomitic mud-to-wackestone (MF2), which is overlain by dolomitic wacke-to-packstone (MF3). The middle part of the sequence (HST) is dominated by packstone-to-grainstone (MF4, MF5) and grainstone facies (MF6), and the upper part (FRST) is dominated by patchy anhydrite (MF1). The upper boundary of the sequence can be traced on an evaporitic layer that is known as the 'lower anhydrite' in the nomenclature of Arabian Plate sequence stratigraphy (Sharland et al., 2001). This boundary is represented by the initiation of a decreasing trend in the density log, and an increasing trend in the transit time of the sonic log, and by local gamma ray log minima (Figs. 13, 14). The entire sequence is equivalent to the C member of the Arab Formation in the Arabian Plate (Fig. 13) (see Sharland et al., 2001).

4.4.2 Sequence II

This sequence is about 27m thick, located on top of sequence I. The TST deposits are mainly composed of dolomitized bioclast packstone (MF4). The MFS is determinable at the base of the shallowing-up packages (Fig. 13) and is marked by a decreasing density log and increasing transit time of sonic log and local maximum gamma ray logs. The HST is characterized by dolomitic ooid grainstone (MF6), dolomitic bioclast grainstone (MF5) and is followed by intertidal deposits (MF2) and the falling stage systems tract (FRST) of supratidal deposits (MF1). The lower boundary of this sequence is determined by a change from anhydrite (MF1) to a dolomitic mud-wackestone (MF2) (Fig. 13) and is marked by low gamma ray, transit time and high density log responses. The entire sequence is equivalent to the B member of the Arab Formation in the Arabian Plate (Fig. 13) (Sharland et al., 2001).

4.4.3 Sequence III

This third order sequence is about 26m thick in the studied wells and is composed of TST, HST and FRST. The TST is mainly composed of intertidal (MF2) to

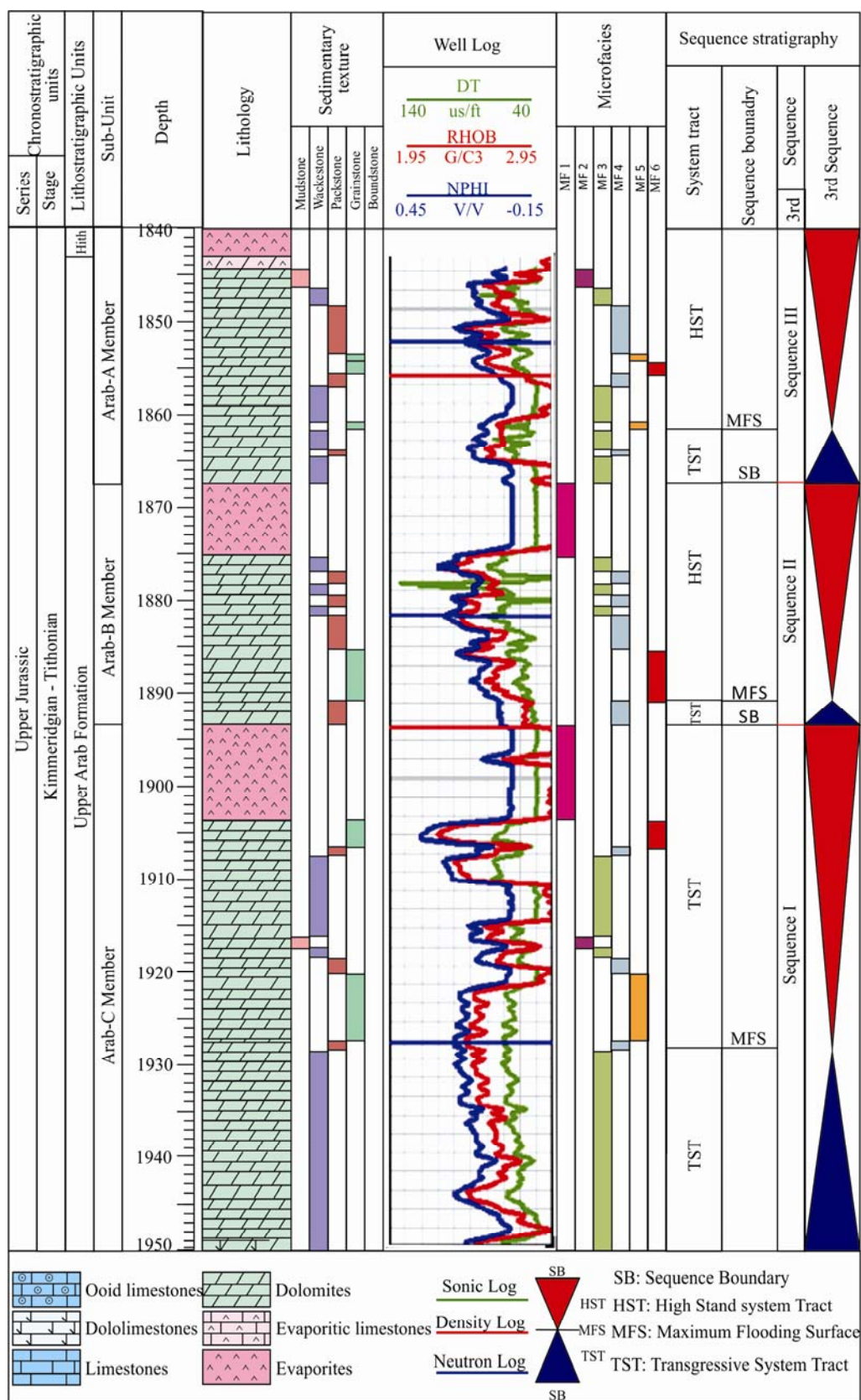


Fig. 13. The three main identified third-order sequences in the Arab Formation of the Balal Field.

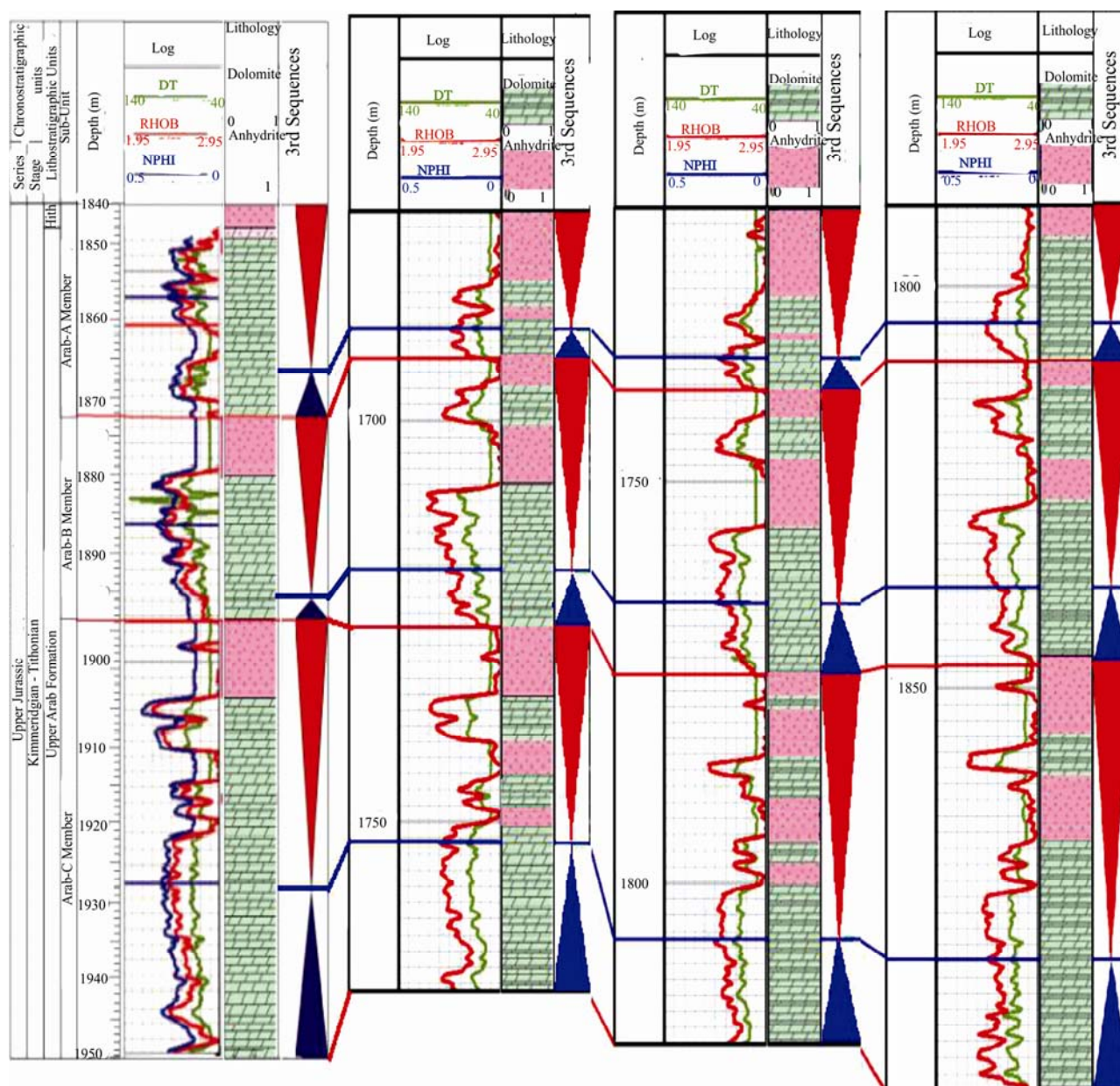


Fig. 14. Correlation of the identified sequences in the studied wells of the Balal Field.

lagoonal facies (MF3, MF4). The maximum flooding surface is determined by gamma ray response and a local minimum density log at the base of the HST. The HST is mostly composed of lagoonal (MF4) to shoal facies (MF5, MF6), and the FRST is represented by supratidal deposits (MF1) (Fig. 13). The upper boundary of this sequence, i.e. the contact of the Arab and Hith formations, shows the last depositional stage of the formation in a homoclinal ramp setting. This sequence is equivalent to the A member of the Arab Formation in the Arabian Plate (Fig. 13) (cf. Sharland et al., 2001).

All of these three sequences are identifiable in the studied wells, so their distribution in time and space is well-understood from their correlation (Fig. 14).

4.5 Reservoir quality

The reservoir quality of carbonate deposits is related to the interaction between primary (texture, grain type, mineralogical composition) and secondary (diagenetic) features (Ahr, 2008; Salman et al., 2018). In this regard, the relationship between porosity and permeability generally represents complex trends (Fig. 15). Various depositional facies of the studied formation experienced different diagenetic processes leading to a variety of porosity and permeability values. Accordingly, in assessing the reservoir quality, the effects of major diagenetic controls (dolomitization, anhydrite cementation, dissolution and fracturing) and depositional characteristics of the facies are taken into account.

Since different facies can lead to various petrophysical classes and a wide range of reservoir quality, a reasonable rock typing seems to be essential, based on the rock fabrics and their petrophysical characteristics. For example, a primary intertidal facies (e.g., rock type 2 in Fig. 16) can be classified into three petrophysical rock types (RRT2, RRT3 and RRT4 in Fig. 16), due to different post-depositional alterations. As such, in this study the specific petrophysical groups for each depositional rock fabric are determined by considering their post-depositional overprints (Fig. 16). In other words, the four depositional rock types (DRT1-DRT4) are rearranged into eight reservoir rock types (RRT) based on their reservoir properties, the characteristics of which follow.

4.5.1 Depositional rock type 1 (DRT1)

Anhydrite (MF1) is the main identified facies of this group in which mean porosity and permeability values are 5.2% and 1.1 md, respectively (Fig. 15). This DRT acts as a seal and leads to vertical reservoir compartmentalization within the studied interval. The poor reservoir quality of the constituent facies is due to their sedimentological characteristics, which had negligible control over diagenetic processes as well. In this regard, one petrophysical rock type (RRT1) is determined in this class as follows:

(1) Reservoir rock type 1 (RRT1): The supratidal anhydrite to anhydrite bearing mudstone (MF1) is the main facies of this reservoir rock type. The mean values of porosity and permeability are 5.2% and 1.1 md, respectively (Fig. 17-A). This RRT is marked by the lowest reservoir quality in the studied interval. In fact, this rock type acts as a seal, capping the reservoir zones of the studied interval.

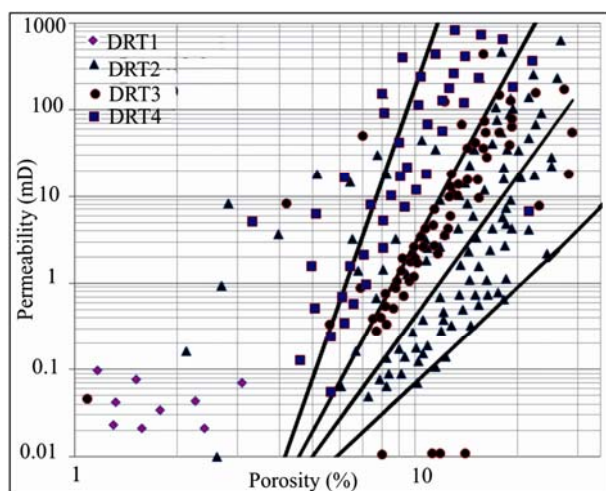


Fig. 15. Poroperm cross-plot for different facies of the Arab Formation in the studied field. As can be seen, the shoal facies show the highest reservoir quality (after Lucia, 1995).

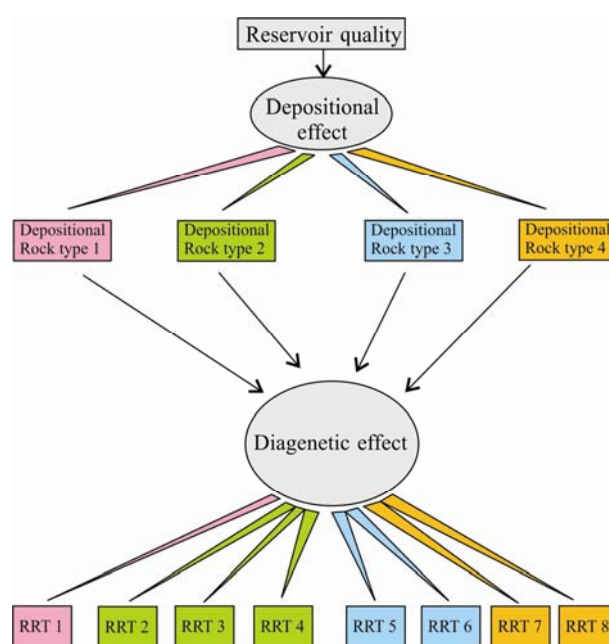


Fig. 16. A schematic chart showing the main reservoir rock types derived from their depositional rock fabrics, following the overprint of different diagenetic processes (see the text for more details).

4.5.2 Depositional rock type 2 (DRT2)

Dolomitic mudstone to wackestones (MF2) is the main facies of this class, which shows variable petrophysical properties and reservoir qualities due to dual diagenetic effects (Fig. 15). The main porosity-permeability controlling factors in this DRT are differential dolomitization intensity, dolomite crystalline texture (euhedral to subhedral), anhydrite cementation, fracturing and stylolitization. Dolomitization increased interparticle porosity in the muddy fabrics through creation of fine subhedral crystals. Recrystallization of dolomite crystals and overdolomitization in the burial setting reduced the porosity and permeability values. Fracturing, especially in fine crystalline dolomites, led to high permeability values. In some cases, fractures are filled with anhydrites without any important effect on the reservoir quality. Accordingly, the dolomitized rock fabrics within this DRT are rearranged into three reservoir rock types (RRT1, RRT2 and RRT3) (Fig. 16).

(1) Reservoir rock type 2 (RRT2): This reservoir rock type is similar to class 3 of Lucia (1995), which includes fine crystalline dolomudstones. The main pore type is intercrystalline. The average values of porosity and permeability are 14.1% and 0.8 md, respectively. MF2 is the main constituent of this RRT (Fig. 17-B).

(2) Reservoir rock type 3 (RRT3): This reservoir rock type is comparable to class 2 of Lucia (1995), and is characterized by intertidal medium crystalline dolomudstone (MF2). The average values of porosity and

permeability are 18% and 62 md, respectively. The high permeability value of the RRT results from interconnected pores between dolomite crystals (Fig. 17-C).

4.5.3 Depositional rock type 3 (DRT3)

The dolomitic wackestone-to-packstone (MF3) and dolomitic bioclastic packstone (MF4) are the main facies of this DRT that show similar reservoir characteristics. Most of the porosity and permeability values are observed in the facies of the distal parts of the lagoon that are highly affected by dolomitization and dissolution. The higher reservoir quality occurs in the medium-sized planar-e to planar-s crystal type dolomites. These porous dolomite crystals are formed through seepage of dense brines refluxing into the mudflats, moving basinward through the sediments (see Adams and Rhodes, 1960; Elliott and Warren, 1989; Saller and Henderson, 1998). The facies of proximal parts of the lagoon represent high porosity but low permeability, which can be attributed to the fine crystal size of dolomites and scattered pore-filling anhydrites. The average values of porosity and permeability are 11.21%, and 30.61 md, respectively (Fig.

15). With respect to the diagenetic features, two main petrophysical rock types (RRT5 and RRT6) can be determined in this class (Fig. 16).

(1) Reservoir rock type 4 (RRT4): Coarse crystalline dolomudstones/dolowackestones along with intertidal mud-dominated microfacies (MF2) are the main constituents of this reservoir rock type. It is analogous to class 1 of Lucia (1995). The average values of the porosity and permeability are 7.1% and 10 md, respectively (Fig. 17d).

(2) Reservoir rock type 5 (RRT5): This RRT has average porosity and permeability values of 8.2 % and 1.2 md respectively, and is comparable to class 2 of Lucia's scheme (1995) (Fig. 18a). The main facies of this RRT is related to the proximal lagoon environment (MF3) that is marked by fine crystalline dolomites. Reservoir characteristics of this RRT are affected by compactional features (e.g. stylolites) and anhydrite plugging, which decreased both porosity and permeability values.

4.5.4 Depositional rock type 4 (DRT4)

This DRT includes shoal microfacies of dolomitic bioclastic grainstone (MF5) and dolomitic ooid grainstone

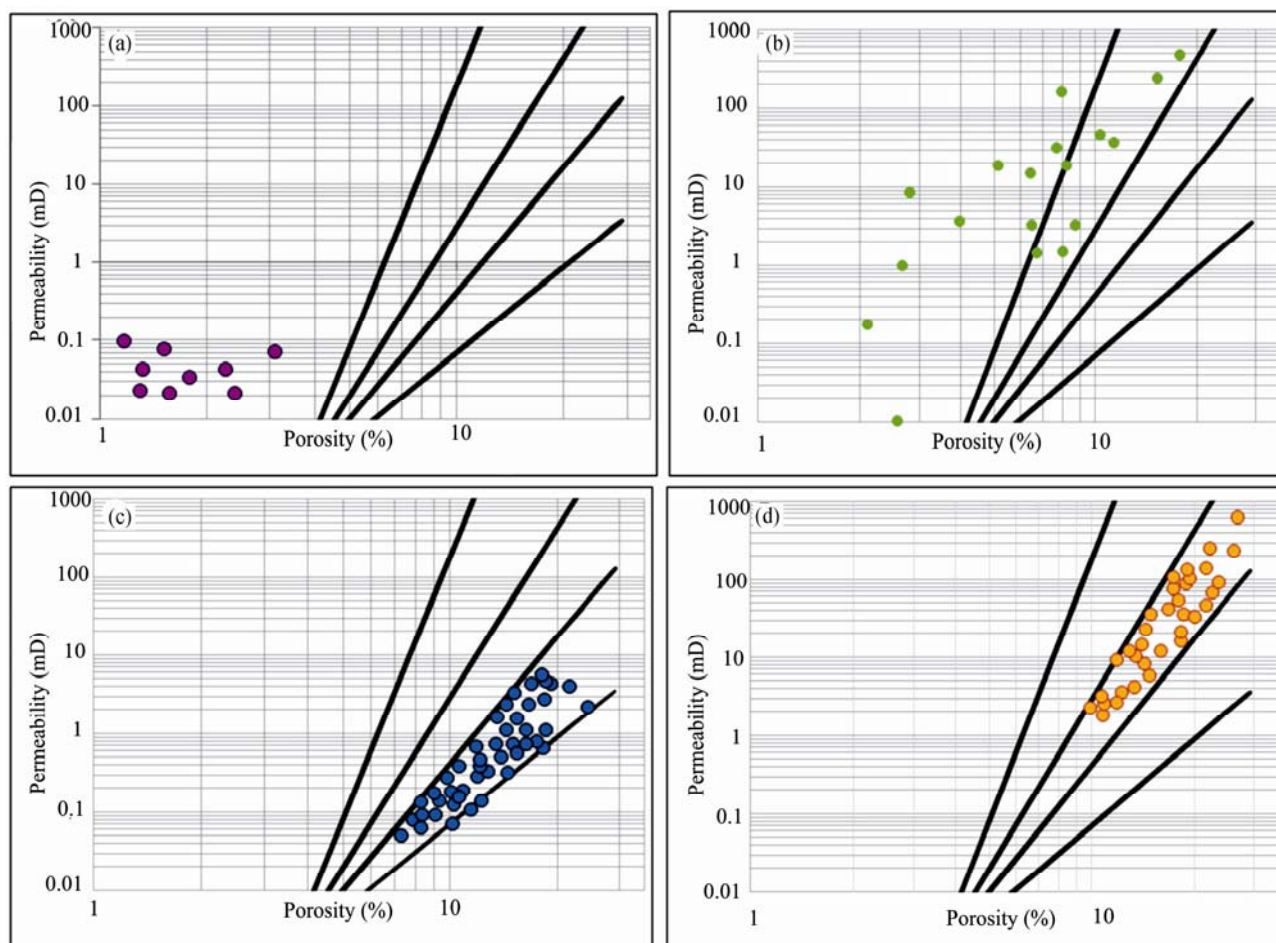


Fig. 17. Cross-plot of porosity against permeability for different reservoir rock types in the upper Arab Formation. (a) RRT1, (b) RRT2, (c) RRT3, and (d) RRT4 (after Lucia, 1995).

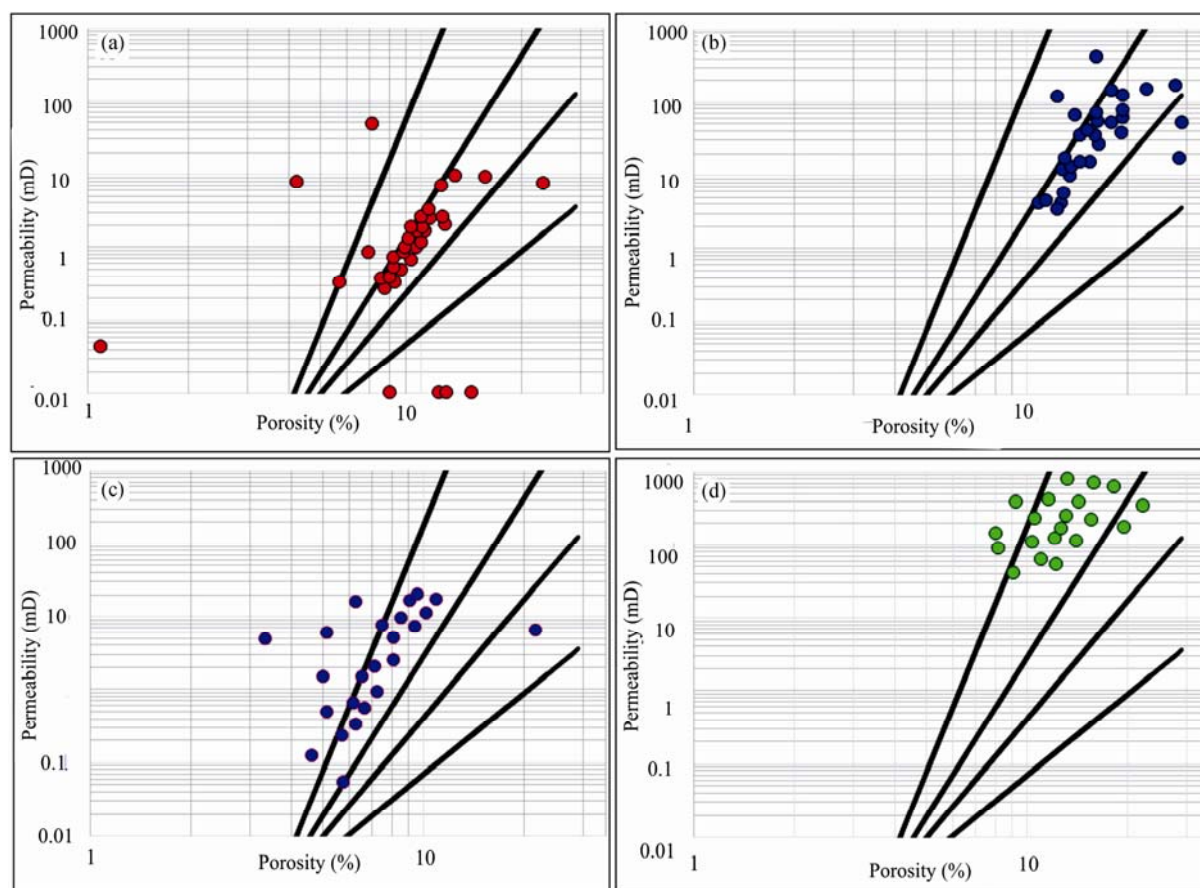


Fig. 18. Cross-plot of porosity against permeability for different reservoir rock types in the upper Arab Formation; (a) RRT5, (b) RRT6, (c) RRT7, and (d) RRT8 (after Lucia, 1995).

(MF6), which represent the best reservoir quality over the studied interval. The main porosity type is interparticle/intercrystalline, along with some intraparticle/moldic type. The moldic porosity is mostly derived from dissolution of ooid and peloid grains and from the interconnected pore spaces from dolomitization with medium-to-coarse planar to planar-s crystals. The porosity in this RRT ranges from 9.6% to 18.9% (ave.: 14.25) and the permeability from 12.88 to 53.55 (ave.: 33.2) md (Fig. 15). Low porosity-permeability values in dolomitized bioclastic grainstones resulted from both poikilotopic and pore-filling anhydrite cement. By including post-depositional features, two petrophysical rock types (RRT7 and RRT8) are determined in this class (Fig. 16).

(1) Reservoir rock type 6 (RRT6): This RRT represents a good reservoir quality due to the medium-sized dolomite crystals, which form interconnected networks. Distal lagoonal facies (MF4) is the main constituent of this rock type. This reservoir rock type is similar to class 2 of Lucia's plot, with mean poroperm values of 10.78 % and 73 md, respectively (Fig. 18b).

(2) Reservoir rock type 7 (RRT7): This reservoir rock type is comparable to class 1 of Lucia's plot (Lucia, 1995)

with mean porosity and permeability values of 9.6% and 1.88 md, respectively (Fig. 18c). The main pore spaces are intercrystalline/interparticle and intraparticle types. Anhydrite cementation (mainly pore-filling) shifted the samples to the left side of the plot (Fig. 18c).

(3) Reservoir rock type 8 (RRT8): This reservoir rock type is similar to RRT7 in its lithology, but has higher porosity and permeability values (12.9%, 85.55 md) (Fig. 18d). The higher reservoir quality of this RRT is due to the selective dissolution of ooids and low anhydrite cementation. The main facies of this RRT is dolomitized shoal ooid grainstone (MF6). This rock type has the highest reservoir quality amongst all of the defined rock types. Distribution of the identified reservoir rock types in time and space (in the sequence stratigraphic framework of the field) is represented in Figure 19.

5 Discussion

Detailed facies analyses resulted in the identification of supratidal-to-shoal facies belts in the proximal parts of a carbonate ramp (i.e. inner ramp to supratidal) with a shallowing-up trend in the studied interval of the Arab

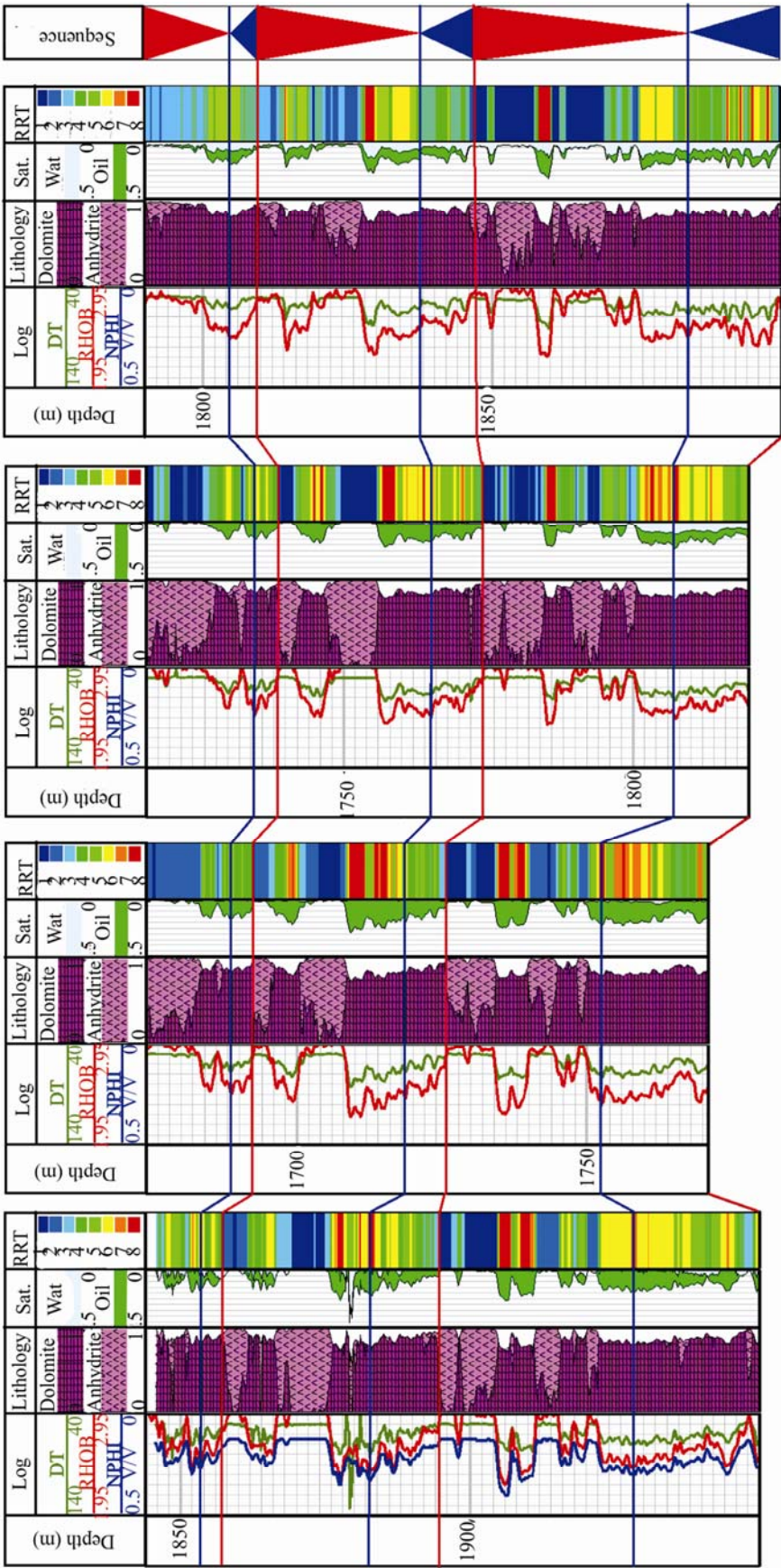


Fig. 19. The main derived reservoir rock types within the sequence stratigraphic framework in the upper part of the Arab Formation.

Formation in the Balal Field. Compared with previous studies on the Arab Formation in southern parts of the Persian Gulf, the inspected interval is deposited under slightly deeper conditions. The shoal facies shows the best reservoir quality, while moderate and least reservoir quality are observed in lagoonal and supratidal facies, respectively. Such a discovery shows the role of the depositional environment in reservoir characterization. Moreover, some diagenetic processes were highly influenced by depositional conditions (eodiagenesis), confirming the greater role of depositional environment on reservoir quality.

The twofold influence of diagenesis on reservoir quality can be addressed as one of the most notable outcomes of this study. Anhydrite plugs, compaction and burial cementation played a negative role, whereas dolomitization and early marine cementation (by preventing further modification during burial) had a positive role on reservoir quality. Among the various dolomitization mechanisms, the seepage reflux and sabkha models were designated for studying the formation, after inspecting both the petrographic and geochemical data. Salinity enhancement of interstitial water in shoal and lagoon-related facies belts during relative sea level fall (lowstands) provided circumstances for the generation of seepage reflux dolomites. Conversely, the sabkha type dolomites were developed in supratidal and intertidal facies belts during a relative sea level rise, with significant water circulation in their constituent facies.

The studied successions are divided into three packages of genetically-related strata (sequences), based on their sedimentological properties and eodiagenetic features. Correlation of the packages with those of previous studies on the Arabian Plate shows that the lowermost package (sequence I) is comparable to zone C, while the other two (II, III) match with the B and A zones of the Arab Formation, respectively. In this regard, the regional sea level changes seem to be responsible for the generation of these packages. Therefore, the identified sequences are considered as 3rd order cycles formed within the higher ordered types (e.g. 2nd order). The relative sea level change is considered to be the third influential factor on reservoir quality in the studied facies. The favorable dolomitization process occurred both during highstand (in shoal and lagoon-related facies) and lowstand (in intertidal and sabkha facies) stages. This result shows that in linking dolomitization and relative sea level changes to the reservoir quality of facies, pinpointing their depositional setting becomes a very critical parameter.

In the studied field, the spatial and lateral distribution of facies and diagenetic processes in the Arab Formation were linked to different systems tracts (TST, HST) and the

main stratal surfaces (MFS, SB). Distribution of the diagenetic alterations in the sequence stratigraphic realm is illustrated by a conceptual model (Fig. 20). Relations between microfacies, depositional environment, systems tract, depositional and reservoir rock types and reservoir quality in the studied field are illustrated in Table 2. Diagenetic alterations along the stratal surfaces and within the systems tracts are highly controlled by rates of sedimentation and relative sea level changes (see Jervey, 1988; Loutit et al., 1988; Sarg, 1988). Diagenesis along the SB and within the HST is typically associated with the circulation of meteoric waters (see Morad et al., 2012; Tucker, 1993). Cementation, in the form of patchy and poikilotopic anhydrites, is the most common diagenetic phenomenon, which occurs below the SB and within the late HST and FRST. These cemented horizons show the lowest reservoir quality (RRT1), and act as a seal to the underlying shallowing-upward deposits. The influx of lagoonal brines caused dolomitization of ooid grainstones in distal parts of the lagoon and shoal deposits (TST). Such dolomitization can be attributed to the seepage reflux model, which led to the development of medium-to-coarse dolomites and intercrystalline pore types within the shoal rock types (RRT7). In some depositional facies (MF2 and MF5), overdolomitization and anhydrite-plugging led to lower reservoir quality rock types (i.e. RRT2 and RRT7). The occurrence of early dolomites and isopachous calcite prevented considerable compaction, and as a result led to porosity preservation within both TST and HST deposits (Fig. 5b, c and e).

Diagenetic alterations along the MFS and within the TST are mainly controlled by low rates of sedimentation, rather than the rate of the relative sea level rise (see Jervey, 1988; Loutit et al., 1988). This is demonstrated by extensive marine pore-water diagenesis and marine bioturbation (see Baum and Vail, 1988; Morad et al., 2012; Tucker, 1993). The most typical diagenetic process in the studied facies is dolomitization of mudstones, wackestones and packstones within TST around the MFS. Dissolution of ooids and peloids and dolomitization along the MFS and within the TST presumably resulted from modification of marine pore waters, which led to the formation of the tight and laterally extensive dolostones (see Poppe et al., 1990; Tucker, 1993; Sanchez-Roman et al., 2009).

6 Conclusions

On the basis of detailed petrographic studies, six microfacies in four facies belts along a hemoclinal carbonate ramp were determined. Distribution of the facies resulted in determination of three shallowing-upward

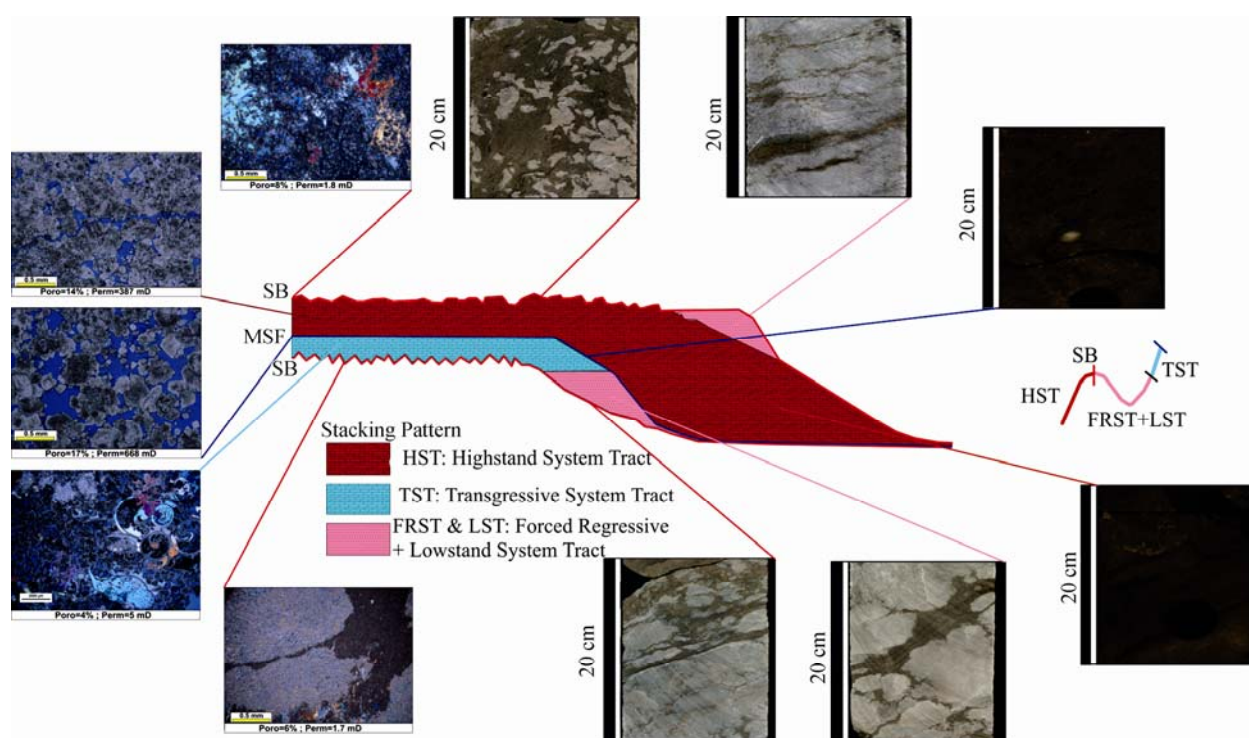


Fig. 20. A simplified conceptual model representing the distribution of diagenetic alterations (in both core and microscopic samples) within the sequence stratigraphic framework in the upper Arab Formation (the base fig. is modified from Bosence and Wilson, 2003 and Morad et al., 2012).

Table 2 Relations between microfacies, depositional environment, systems tract, rock types and reservoir quality in the studied field

Environment	Microfacies	Systems tract	Depositional rock type	Reservoir rock type	Reservoir quality
Supratidal	MF1	FRST	DRT1	RRT1	Bad
intertidal	MF2	FRST, TST	DRT2	RRT2	Bad
				RRT3	Moderate
				RRT4	Good
lagoon	MF3	TST, HST	DRT3	RRT5	Moderate
	MF4			RRT6	Moderate to good
shoal	MF5	HST	DRT4	RRT7	Good
	MF6			RRT8	Good

sequences (I-III), corresponding to third-order cycles, which are correlatable by wireline logs throughout the studied field. Reservoir quality of the formation was mostly controlled by diagenesis, which was in turn influenced by relative sea level changes (depositional conditions). Dolomitization, anhydritization and cementation were found to be the main diagenetic parameters controlling reservoir quality. The sabkha evaporative model is the main dolomitization model occurring in the formation. Dolomitization mostly increased the reservoir quality, but anhydritization and cementation decreased it. The reservoir rock types were determined on the basis of the integration of depositional facies, diagenetic imprints and petrophysical data. In light of the various diagenetic effects on the determined depositional rock type (DRT), we rearranged the DRTs into 8 reservoir rock types (RRT). RRT8 was found to be

the richest and RRT1 the poorest reservoir units within the studied interval.

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