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Integrated Rock Typing of the Grainstone Facies in a Sequence Framework: a Case from the Jurassic Arab Formation in the Persian Gulf

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Abstract: The late Jurassic Arab Formation, a significant carbonate-evaporite reservoir rock in the Persian Gulf, is characterized by frequent grainstone facies. For rock type identification and reservoir characterization, core description, petrographic studies and pore system evaluation are integrated for Balal oil field in the Persian Gulf. The grainstone facies are developed into three shoal subenvironments on a carbonate ramp platform: leeward, central and seaward. Compaction, dissolution, cementation, anhydrite mineralization and dolomitization are the main diagenetic processes affecting the depositional pore system. Considering depositional and diagenetic features and pore types, the grainstones are classified into six rock types (RT 1 to RT6). Rock types 1, 2 and 5 have large pore throat sizes with inter-granular and touching vug pore types. In rock type 3, moldic pores lead to high porosity and low permeability. Rock types 4 and 6 are cemented by anhydrite, calcite and dolomite. Generally, RTs 1, 2, 3 and 5 are related to late Transgressive systems tract (TST) and early Highstand systems tracts (HST) and show fair to good reservoir quality. In contrast, RTs 4 and 6 of late HST system tract show lower poroperm values, due to evaporite mineralization. Characterization of the grainstone facies provides a comprehensive understanding of the reservoir zones of the Arab Formation.

Key words: grainstone facies, pore system, rock type, reservoir quality, Arab Formation, Kimmeridgian–Tithonian, Iran

1 Introduction

The late Jurassic Arab Formation is among the most prolific hydrocarbon reservoirs in the Persian Gulf and adjacent areas (Al-Silwadi et al., 1996; Cantrell and Hagerty, 2003; Swart et al., 2005; Ehrenberg et al., 2007; Morad et al., 2012; Daraei et al., 2014; Al-Awwad and Pomar, 2015). Development of thick grainstone shoal facies as a result of high-water agitation on a stable (intra-cratonic) carbonate platform is typical in this formation (Ehrenberg et al., 2007). During the long history of these calcite-dominated sediments (Heydari, 2003; Cantrell, 2006; Ehrenberg et al., 2007), miscellaneous diagenetic processes (dissolution, dolomitization, evaporite mineralization, calcite and dolomite cementation, recrystallization and compaction) forged the present pore system properties and heterogeneities.

On the whole, the grainstone facies played an important role in the development of reservoir zones in many hydrocarbon-bearing intervals of Middle Eastern reservoirs including in the Permian–Triassic and upper Jurassic (Cantrell and Hagerty, 2003; Ehrenberg et al., 2007; Daraei et al., 2014; Esrafili-Dizaji and Rahimpour-Bonab, 2013, 2014). Due to deposition in high-energy conditions and high inter-grain porosity, generally the shoal facies show higher reservoir quality than the other carbonate facies (Lønøy, 2006; Lucia, 2007; Ahr, 2008; Honarmand and Amini, 2012; Rahimpour-Bonab and Aliakbardust, 2014; Martin et al., 2017). However, their ultimate pore types and reservoir characteristics are determined by several factors including constituent allochems, original mineralogy, paleoclimate, platform geometry, tectonic setting and diagenetic history. Generally, the original mineralogy of allochems is the

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main parameter that controls the final fate of carbonate reservoirs (e.g. the pore system). Extensive moldic pore development, or filled types, is considered for the identification of aragonitic mineralogy of allochems (Sandberg, 1983; Cantrell, 2006). Carbonate 'factories' of the late Jurassic were dominated by calcitic non-skeletal grains (such as calcitic ooids), which, seemingly, was due to eustatic sea-level rise and suitable conditions for low Mg calcite deposition (Cantrell, 2006).

A rock type characterizes parts of the reservoir in which there is an interpretable relationship between the geological concepts and the petrophysical data (Amaefule et al., 1993; Al-Tooqi et al., 2014; Ghadami et al., 2015; Skalinski and Kenter 2015). For rock type identification, facies analysis and diagenetic studies associated with pore system analysis are the essential steps. The mercury injection test is one of the methods used to measure the capillary pressure curves of a rock by which valuable information regarding the parameters related to pore throats can be provided (Bliefnick and Kaldi, 1996; Cranganu et al., 2009; Chehrazi et al., 2011; Aliakbardust and Rahimpour-Bonab, 2013; Rashid et al, 2015; Skalinski and Kenter 2015). In other words, classifying carbonate reservoir rock samples based on their pore geometry characteristics can be accomplished using mercury injection capillary pressure (MICP) curves. In comprehensive studies on the geological-petrophysical attributes of a reservoir, a sequence stratigraphic framework is required for the interpretation and correlation of rock types (Assadi et al., 2016; Enayati-Bidgoli and Rahimpour-Bonab, 2016). In such 'layer-cake' carbonate-evaporite reservoirs, petrophysical logs can also provide good correlations (Al-Silwadi et al., 1996).

The objective of this study is to investigate the reservoir characteristics of grainstone intervals of the Arab Formation in Iran and to introduce a rock typing scheme using the integration of the facies/diagenesis and pore type properties. Then, by correlation of the resulting reservoir zones, or rock type packages using petrophysical logs, the spatial distribution of rock types in the sequence stratigraphy framework is evaluated. Regarding the reservoir importance of grainstone facies in the Arab Formation, the results from this research can provide a better understanding of their reservoir characteristics and distribution in the studied field and neighbouring areas.

2 Geological Setting and Stratigraphy

The Arabian Plate is surrounded by the Red Sea rifting in the southwest, the Dead Sea in the northwest, the passive margin of the Indian Ocean (Indo-Australian Plate) in the southeast and the crushed zone of the Zagros–Taurus mountains in the northeast (Sharland et al., 2001) (Fig. 1a). The north-eastern part of this plate hosts a huge amount of hydrocarbon reserves in several areas such as the Persian Gulf, Zagros mountains and Mesopotamian basin (Konyuhov and Maleki, 2006, Farzadi, 2006). The Persian Gulf, as one of the most proliferous hydrocarbon basins in the world, is subdivided by major structural lineaments into troughs and highs. Since the Precambrian, the NE–SW trending Qatar–Fars structural high has

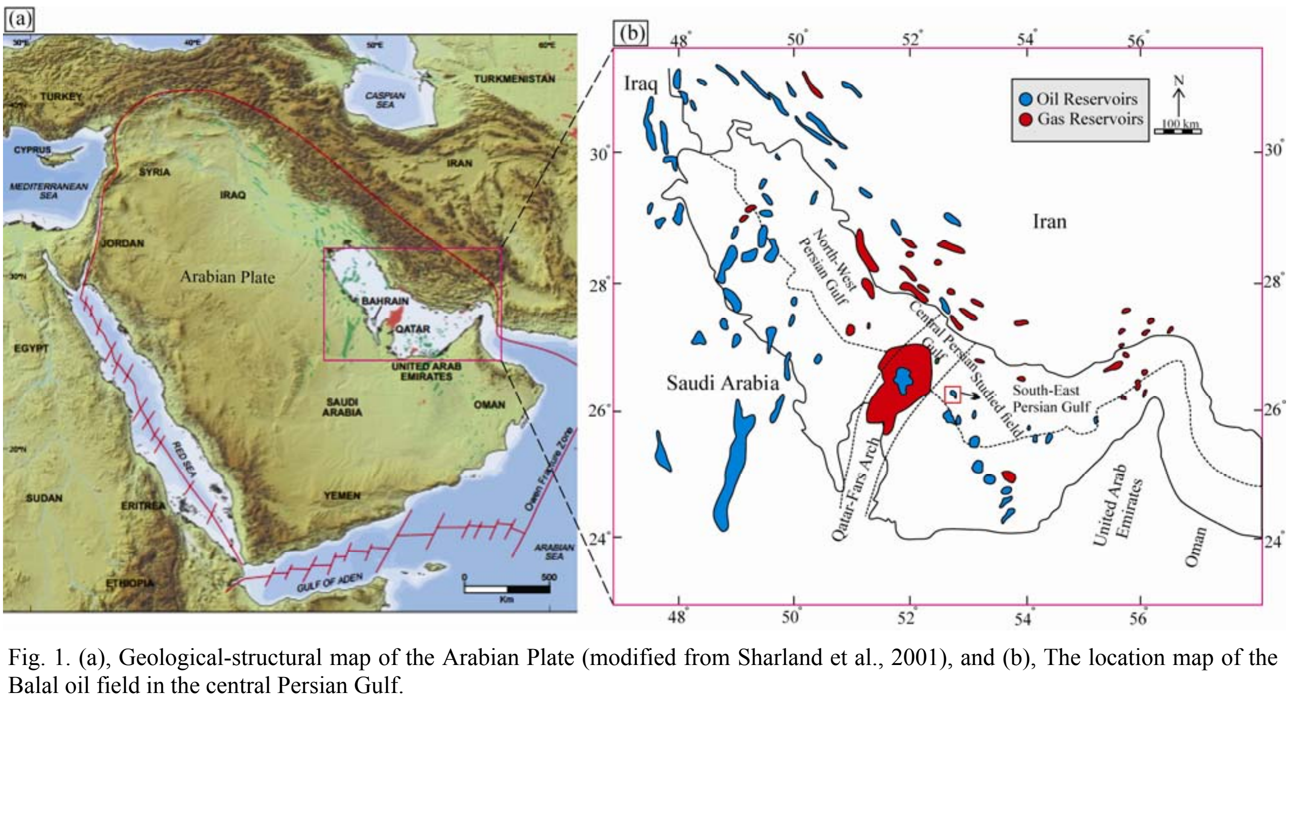

Fig. 1. (a), Geological-structural map of the Arabian Plate (modified from Sharland et al., 2001), and (b), The location map of the Balal oil field in the central Persian Gulf.

divided the Persian Gulf into two NW and SE troughs (Enayati-Bidgoli and Rahimpour-Bonab, 2016). The Hormuz salt domes and their related movements have played an important role in the deformation and formation of hydrocarbon-bearing structures, especially in the south-eastern part of this area (Koop et al., 1982). In this part, similar to most of the structures on the Arabian Plate, the fields are structurally shaped and oriented by the basement faults and salt tectonics, and are generally characterized by simple and gentle folds. The Balal oil field is located in the southeast of the Persian Gulf and show an approximate NW–SE trend (Fig. 1b).

The Jurassic sequence in the Middle East is characterized by an AP7 stratigraphic-tectonic mega-sequence, which is limited by two unconformities of late Toarcian and early Tithonian age at the base and the top, respectively (Sharland et al., 2001) (Fig. 2a). The Arabian Plate was stable during the Jurassic, and located at 5 to 10 degrees south of the equator (Al-Fares et al., 1998). Different tectonic events, global sea-level fluctuations and climate changes have led to the formation in late Jurassic strata in the Middle East of one of the best hydrocarbon systems in the world (Alsharhan and Magara, 1994; Al-Husseini, 1997; Ziegler, 2001). The Kimmeridgian–Tithonian age Arab Formation is considered the reservoir rock of the late Jurassic petroleum system in the Persian Gulf and surrounding areas. As a classic layer-cake carbonate-evaporite sequence, this formation is divided into four members, from A to D, each of which are considered as a retrogradational or shallowing upward

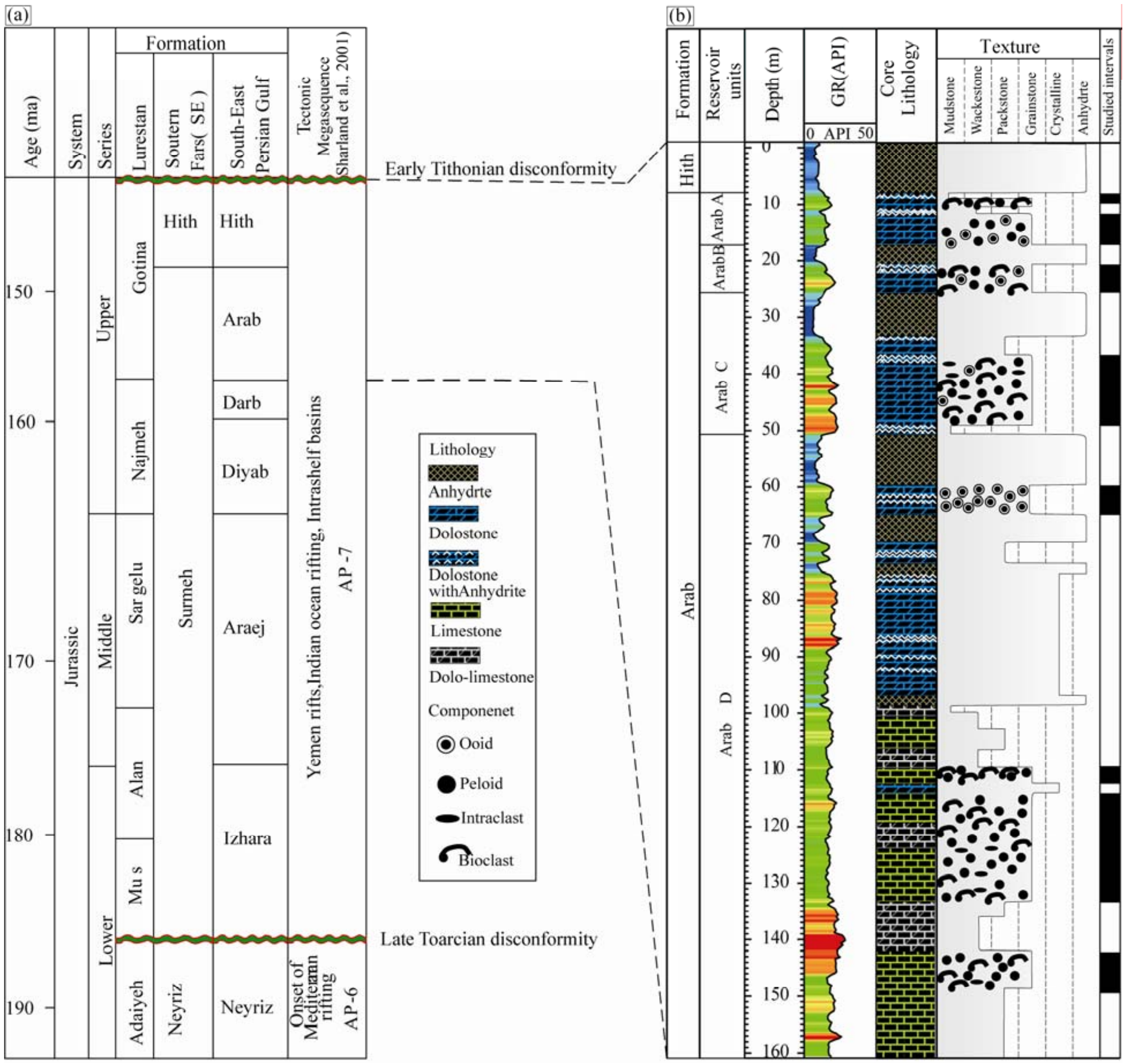

Fig. 2. (a), The lithostratigraphic units of the Jurassic period in some parts of the Zagros and Persian Gulf (modified from Sharland et al., 2001). (b) lithology of the Arab Formation associated with its zonation in a key well from the studied field. Location of the studied grainstone intervals in the Arab Formation is shown.

cycle that is characterized by a gradual change from shallow marine carbonates to the marginal sabkha evaporates (Powers, 1962; Hughes, 1996; Al-Husseini, 1997). The uppermost member is capped by the Hith anhydrite, and this is the last cycle in the late Jurassic secession (Powers, 1962). In the studied field area, the Arab Formation is about 150 m thick and, in contrast to most areas in the Persian Gulf, has been significantly affected by dolomitization. Lithologically, members A, B, C and the upper part of D are totally composed of dolomite and anhydrite, and limestone and dolomitic limestone are found in the lower part of member D (Fig. 2b). Grainstone facies in the Arab Formation have significant thickness, and this study focuses on the geological-petrophysical characteristics of these facies.

3 Data and Methods

In this study, in order to investigate the reservoir characteristics of the grainstone facies of the Arab Formation, data and information from four key wells are used from the Balal oil field in the southeast of the Persian Gulf. In this respect, the results from the description of 130 m of cores and petrographic studies of 300 thin sections collected from NIOC repository in association with analysis of 160 mercury injection capillary pressure (MICP) curves-, 350 core plug porosities and permeability data as well as petrophysical well logs were integrated. Several well logs including gamma ray (GR), density (RHOB), acoustic transmit-time (DT) and calculated log porosity (PHI) were used. To differentiate calcite and dolomite mineralogy, all thin sections were stained with Alizarin Red-S solution (Dickson, 1965). In addition, in order to determine pore types and their properties, blue-dyed epoxy resin was injected into the samples, and all thin sections were scanned in a high-resolution (up to 10000 DPI) scanner (CREO-IQSMART3) at the Research Institute of Petroleum Industry of Iran. Helium porosity and gas air permeability measurements were performed on the core plugs under the standard conditions using Boyle's Law. High-pressure tests (up to 60000 psi) of mercury injection were performed using an automatic system (Micromeritics Autopore II 9220 porosimeter) to detect smaller pore throat sizes. Petrographic studies were carried out to identify different types of grainstone facies, using the allochemical constituents and frequencies and their relative location on the shoal bodies. Furthermore, the important diagenetic processes affecting the grainstones were identified. Finally, rock types were determined using the integration of facies and diagenetic analyses and pore system characteristics, and then these were interpreted in the sequence stratigraphic framework discerned from the field. The direct identification of rock type is limited to the core intervals. Therefore, the petrophysical well log data were utilized for the correlation at field scale. The workflow used in this study is shown schematically in Figure 3.

4 Facies Analysis

In previous studies, a carbonate ramp model with a tidal -flat to open-marine setting has been suggested for the

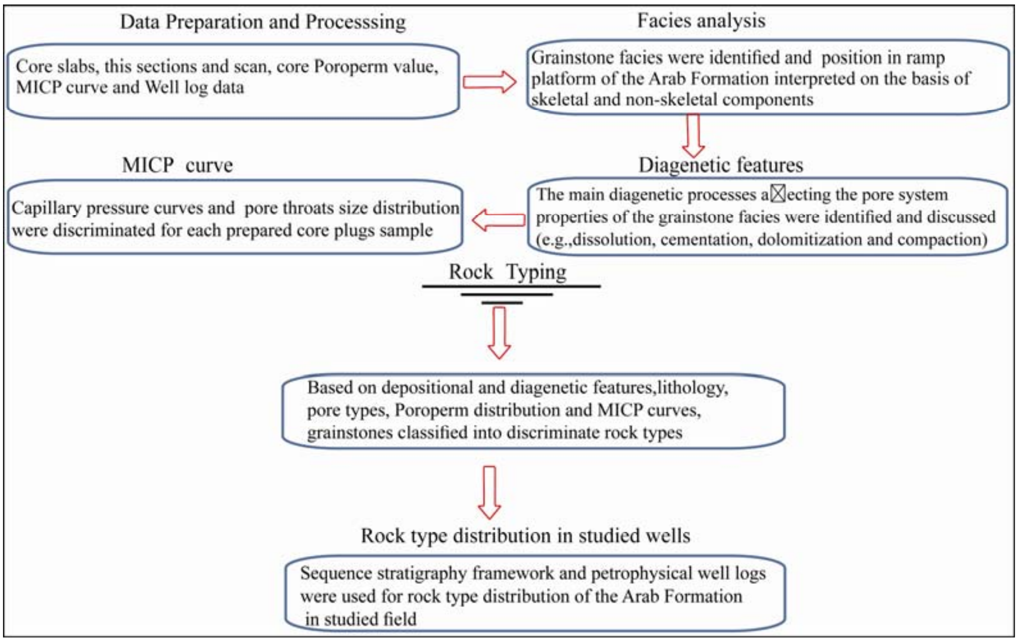

Fig. 3. Schematic diagram display rock typing workflow, which consists of main sequential steps that were used to the define, determine and show distribution of the rock typing model in the Arab Formation.

Arab Formation (Al-Saad and Sadooni, 2001; Lindsay et al., 2006; Morad et al., 2012; Al-Awwad and Collins, 2013a, 2013b; Daraei et al., 2014; Al-Awwad and Pomar, 2015; Beigi et al., 2017). The Upper Jurassic Arab Formation in the Middle East is a well-documented example for preeminent grainstone facies development. This formation was mostly deposited under well-circulated marine conditions near the platform margins, facing deep intratonic basins and characterized by grain-dominated fabrics and to a lesser extent interbedded mudstone facies (Ehrenberg et al., 2007). A prevailing warm and arid climate during the Late Jurassic exerted a major control over depositional patterns and dominant skeletal and non-skeletal components (Morad et al., 2012). Generally, the supratidal and intertidal facies associated with nodular dolo-mudstones and stromatolite boundstones, make a major portion of the successions, representing deposition on a platform dominated by an arid climate (Mehrabi et al., 2015). Shoal-building components in the Arab Formation are mainly bioclasts (e.g., benthic foraminifera, coral, green algae, gastropods and echinoderm debris) and non-skeletal grains such as ooids, peloids and intraclasts.

The integration of the results from core description and petrographical studies has led to the identification of six main grainstone facies named here GF-1 to GF-6 (Fig. 4). The frequency analyses indicate that Bioclast grainstone (GF-6) and Ooid/peloid grainstone (GF-3) are the most frequent facies in the four studied wells. The sedimentary characteristics of the grainstone facies of the Arab Formation are shown in Table 1. Shoal bodies can be subdivided into three parts based on allochemical and textural properties including leeward, central, and seaward (Fig. 5). In the leeward shoal, the skeletal components are mainly gastropods, green algae and benthic foraminifera, and the main non-skeletal grains are peloids. In contrast, grainstone facies related to the central shoal are characterized by the frequency of non-skeletal grains, especially ooids and peloids. Echinoderms, coral, green algae, brachiopods, and benthic foraminifera are the most important skeletal components of the grainstones in the seaward shoal. In these facies, non-skeletal grains predominantly include peloids and intraclasts.

5 Diagenetic Processes

The effects of diagenetic processes on reservoir characteristics of the Arab Formation have been the subject of previous studies (e.g., Cantrell et al., 2004; Morad et al., 2012; Daraei et al., 2014; Beigi et al., 2017). In our research, those diagenetic processes affecting the grainstone facies during and after its deposition and their pore systems have been investigated in detail. They include compaction, dissolution, cementation, dolomitization and evaporite mineralization, all of which affected the pore system properties and porosity–permeability distribution within the Arab reservoir. Fractures with low frequency are often filled by anhydrite cements (Rahimpour-Bonab and Kalantarzadeh, 2005; Aleali et al., 2013). The other diagenetic processes such as micritization, bioturbation, recrystallization, chemical compaction, silicification and phosphatization have no significant effect on reservoir quality. The major diagenetic processes are described as follows:

5.1 Dolomitization

Dolomites of the Arab Formation, on the basis of their characteristics, can be divided into two fabric-retentive - and fabric-destructive groups (Cantrell et al., 2001, 2004). In the fabric-destructive, the primary texture is not detectable, and it is observed as a crystalline texture. In the dolomitic grainstones, fabric-retentive dolomites are

Table 1 The identified grainstone facies in association with their sedimentary characteristics and different sub-environments in the Arab Formation

Facies code	Name	Frequency	Lithology	Grain size	Components		Depositional environment
					Skeletal	None-skeletal	
GF-1	Gastropod/foraminifera grainstone	11.25	Dolomite-limestone	Calcirudite-calcarenite	gastropod (a), green algae (c), benthic foraminifera (c), bivalve debris (c)	Peloid (c)	Leeward shoal
GF-2	Peloid grainstone	14.44	Dolomite-limestone	Calcarenite	gastropod (c), green algae (c), benthic foraminifera (c)	Peloid (a), intraclast (c)	Leeward shoal
GF-3	Ooid/peloid grainstone	19.28	Dolomite	Calcarenite	benthic foraminifera (c)	Peloid (a), ooid (a)	Central shoal
GF-4	Ooid grainstone	8.11	Dolomite	Calcarenite	-	ooid (a), Peloid (r)	Central shoal
GF-5	Bioclast/peloid grainstone	13.69	Limestone	Calcarenite-calcirudite	Echinoderm (c), benthic foraminifera (c), coral (c), brachiopod (c), green algae (r)	Peloid (a) intraclast (c)	Seaward shoal
GF-6	Bioclast grainstone	33.20	Limestone	Calcarenite-calcirudite	Echinoderm (a), benthic foraminifera (c), coral (c), brachiopod (r)	intraclast (r), Peloid (r)	Seaward shoal

(a: frequent, c: common, r: rare)

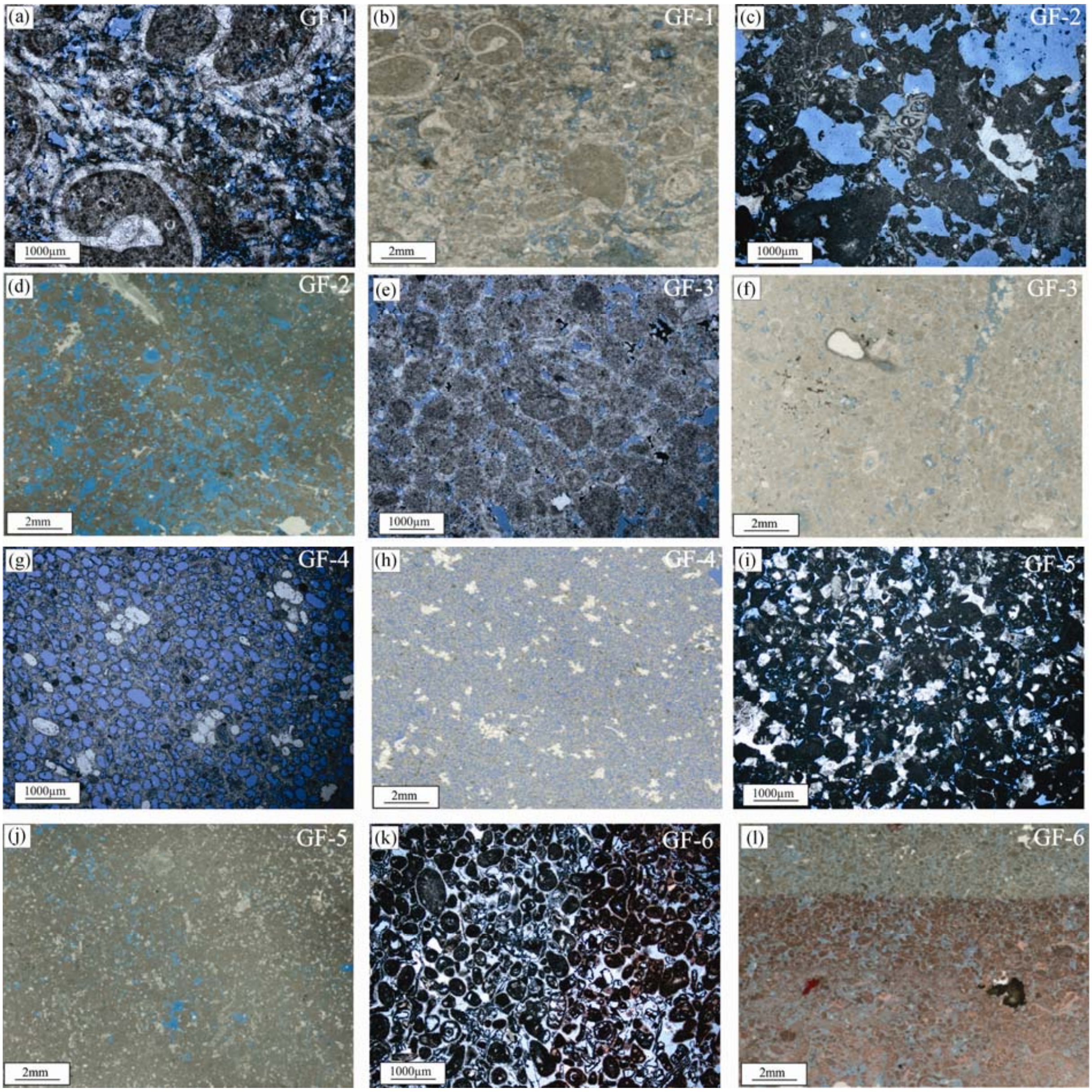

Fig. 4. Photomicrographs of thin sections (b, d, f, h, j and l) and their scans (c, e, g, i, k and m) of grainstone facies. (b–c) Gastropod-foraminiferal grainstone, d-e) Peloidal grainstone, f–g) Peloidal-ooid grainstone, h-i) Ooid grainstone, j-k) Peloidal-bioclast grainstone, (l–m) Bioclast grainstone. GF: Grainstone Facies.

common (Fig. 6a). In these latter facies, the main factors controlling reservoir quality are the nature of the primary texture, and the diagenetic processes associated with dolomitization such as dissolution and evaporate mineralization. Therefore, in these facies, dolomitization has no significant effect on reservoir quality or their pore system properties. Dolomite cements are mostly observed as pore-filling cements, which in some facies have entirely occluded the pore throats (Fig. 6b).

5.2 Compaction

This process has been developed as both physical and chemical compaction in the studied interval. Mechanical compaction is commonly observed in the grainstone facies with limestones and dolomitic limestones, whereas chemical compaction including stylolites and pressure solutions are limited to dolomitic grainstones. In some cases, mechanical compaction of ooid and bioclastic fragments during the early stage of burial (with increasing depth), reduced the porosity–permeability significantly (Fig. 6c). Chemical compaction features as stylolites and solution seems to be limited to the dolograinstone facies (Fig. 6d). Stylolites usually appear as low amplitudes and mainly parallel to the bedding planes.

5.3 Dissolution

This process by creation and development of secondary pore spaces such as moldic, vuggy, intra-granular and

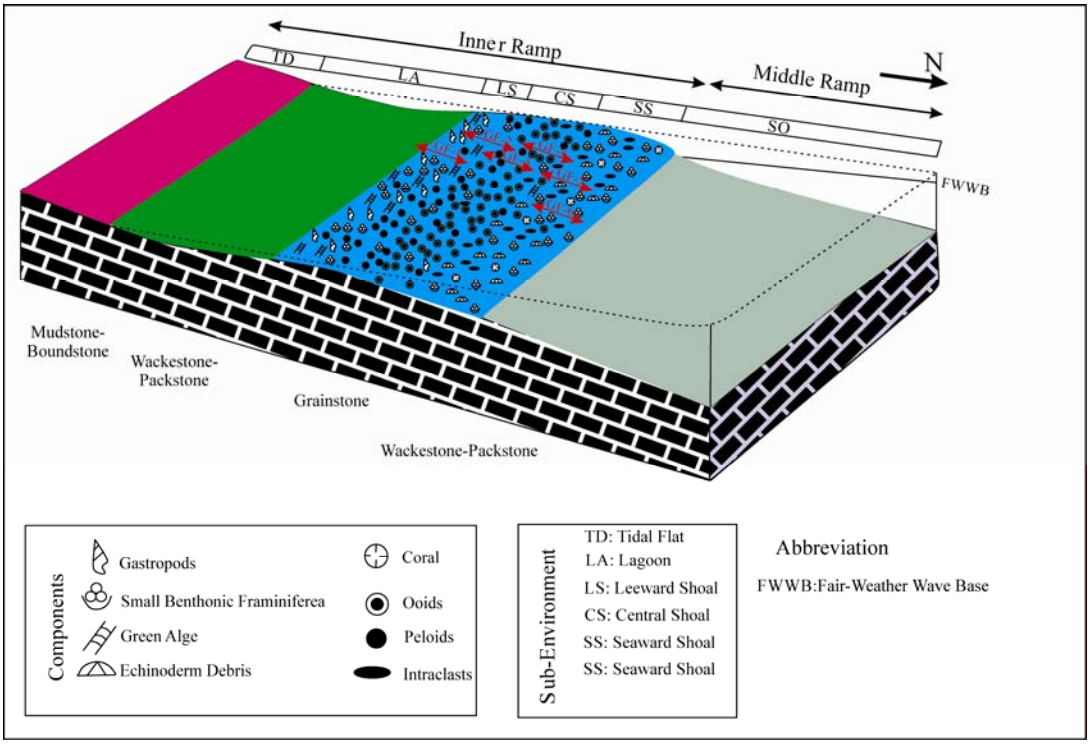

Fig. 5. The conceptual depositional model for the Arab Formation in the studied field, along with the distribution of grainstone facies.

enhanced interparticle pore throat influences reservoir characteristics of the grainstone facies. Interparticle porosity is well-developed between ooids, peloids and skeletal fragments such as green algae and Gastropoda (Fig. 6e). Bioclast fragments, algae, ooids and peloids were commonly dissolved and resulted in the formation of moldic and vuggy pore types (Fig. 6f–g). Dissolution plays an important role in the development of porous and permeable zones of the Arab Formation.

5.4 Cementation

There are three types of cements in the grainstone facies including anhydrite, dolomite and calcite cements. Anhydrite is the most important cement that is observed as uniform and patchy distribution in the reservoir with poikilotopic, nodular, pore-filling and bedding textures. Pore-filling cement shows uniform and patchy distribution in the grainstone facies (Fig. 6h–i). Anhydrite cement has mainly been developed by percolation of sulfate-rich brines into the grain-dominated facies, derived from dissolution of primary evaporates. Calcite cements are observed in three forms of pore-filling in dolograinstones (Fig. 6j) and in isopachous rims (Fig. 6k) and syntaxial cement in non-dolomitic grainstone facies (Fig. 6l). Isopachous rim cement, unlike syntaxial cement, shows significant frequency within the Arab Formation reservoir. This cement does not have an important role in porosity destruction, and by reducing the effect of compaction, it may lead to the preservation of primary porosity during burial (Daraei et al., 2014).

6 Diagenetic Sequence

The occurrence of diagenesis processes within the Arab Formation is presented in terms of diagenetic history. The grainstone facies of the Arab Formation has been affected by diagenesis in three main diagenetic realms, including marine, hypersaline, meteoric eogenetic and burial. The sequence of diagenetic events in the Arab Formation is depicted in Fig. 7. Micritization, bioturbation and isopachous calcite cementation are important diagenetic features of the marine setting. Hypersaline diagenesis is characterized by the precipitation of primary anhydrite nodules, fabric-preserving dolomitization, displacive nodules and pore-filling anhydrite cement. Most of the primary pore spaces are filled by anhydrite cement. The main features of the meteoric realm are recrystallization and preferential leaching of unstable grains as well as rare meteoric calcite cement. Porosity enhancement of the grainstone facies is especially noticeable where dissolution of ooids formed moldic porosity. Dolomite neomorphism, development of fabric destructive dolomites, mechanical and chemical compaction, late anhydrite, calcite and dolomite cementation and fracturing are diagenetic

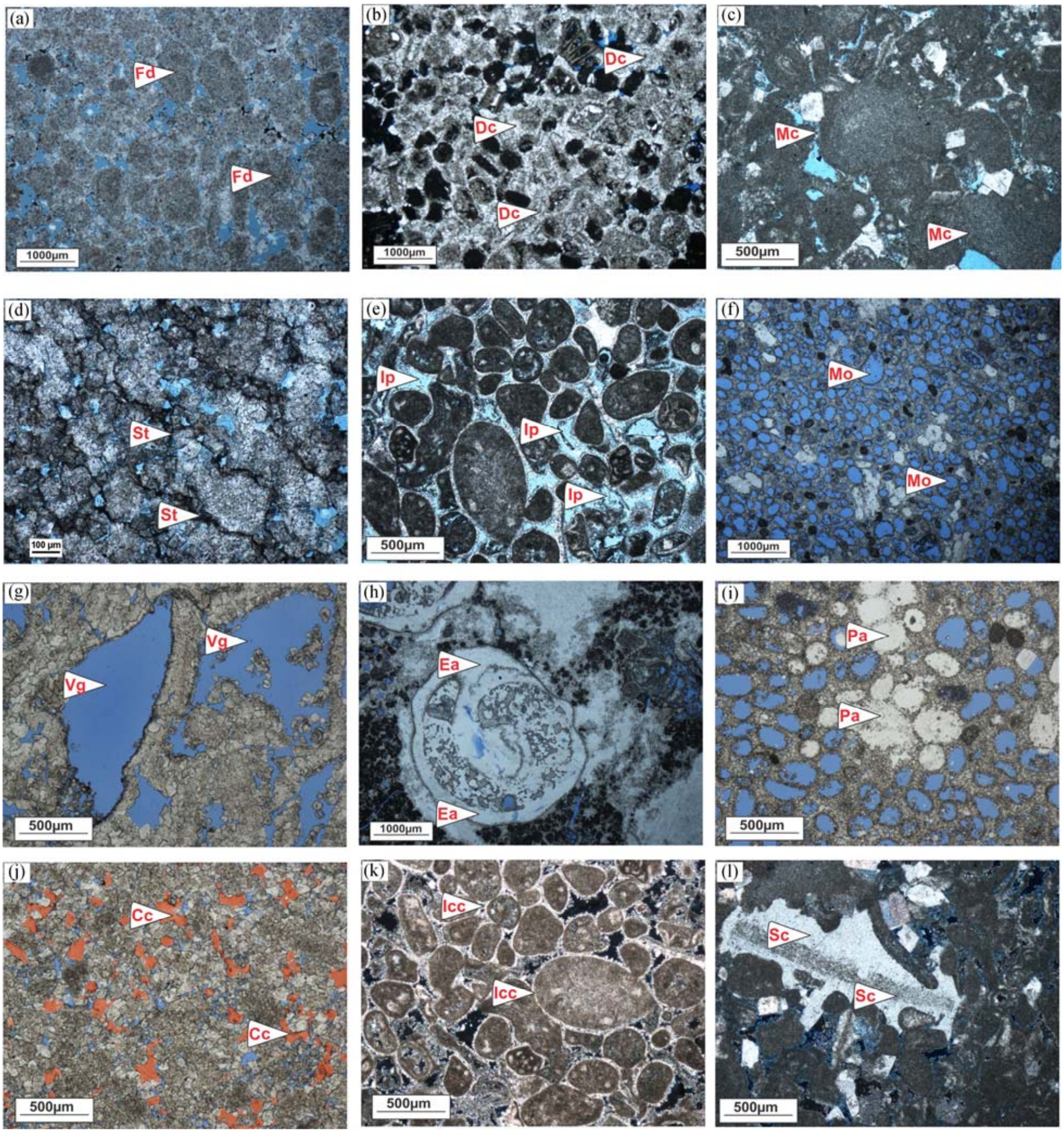

Fig. 6. Thin-section photographs of the main diagenetic processes affecting the reservoir characteristics of grainstones facies the Arab Formation.
(a), Fabric preserving dolomitization (Fd); (b), dolomite cements as pore-filling of inter-granular porosity (Dc); (c), mechanical compaction (Mc); (d), chemical compaction (St); (e), dissolution and development of enlarged inter-granular porosity (Ip); (f), moldic porosity that has been locally occluded by anhydrite cement (Mo); (g), vuggy porosity (Vg); (h), anhydrite cement with even distribution (Ea); (i) anhydrite cement with patchy distribution (Pa); (j) occluding of porosity by extensive calcite cementation (Cc); (k), isopachous calcite cement around the grains (Icc); and (l), syntaxial calcite cement around echinoderm debris (Sc).

processes related to the burial realm.

7 Reservoir Rock Types

For three-dimensional correlation of rock types in three-dimensional space of the reservoir, all should be connected to a geological model, and especially to facies-diagenetic changes (Hollis et al., 2010; Al-Tooqi et al., 2014; Skalinski and Kenter 2015; Rahimpour-Bonab and Aliakbardoust, 2014). In this study, all fractured samples with low porosity and high permeability were excluded from the data set, because they might have resulted in some errors of conclusion.

The rock types in the Arab Formation are identified by

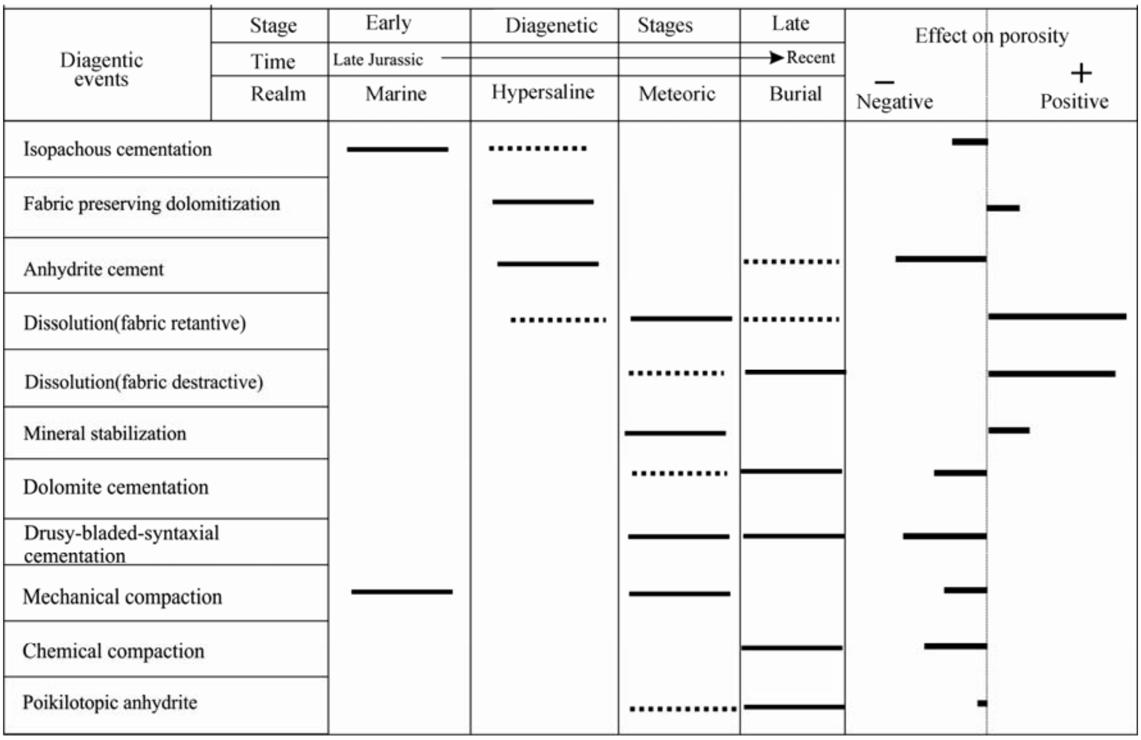

Fig. 7. Paragenetic sequence of diagenetic processes that overprinted the grainstone facies of the Arab Formation. Diagenetic events occurred in marine, hypersaline, meteoric and burial realms and their effects on porosity have been shown.

integration of depositional characteristics, diagenetic overprints, pore system properties and poroperm distribution. To construct a framework for rock type correlation in the studied wells, sequences were discriminated on the basis of facies characteristics and diagenetic features. Six rock types were differentiated in the grainstones of the Arab Formation. Figure 8 shows representative thin section and core photographs of each rock type. Because of their diagenetic imprints, there is a large dispersal on the porositypermeability plot of this facies (Fig. 9a). In these facies, porosity and permeability vary between 2.4 to 37.10% and 0.1 to 1612 mD, respectively. The porositypermeability distribution indicates that the combined method used in this research can effectively differentiate various rock types (Fig. 9bf, h). The facies characteristics, diagenetic features and pore-system properties of each rock type are presented in Table 2.

The shape of the capillary pressure curves and the distribution of pore throats have been used as important parameters for determination of various rock types. The distribution curve of pores throats (uni-, bi- and polymodal) can be a proxy of pore throat heterogeneity in the reservoir. Pore systems with bimodal distribution are more heterogeneous than ones with unimodal distribution. The normalized pore throat size distribution function can be used to group pores as macro (>1.5 ìm), meso (1.5 to 0.5 ìm) and micro pore throats (<0.5 ìm), respectively (Martin et al., 1997; Chehrazi et al., 2011). This curve enables distinction of pore size distributions for the rock types. Regarding the effects of pore geometry on reservoir properties, the shape of mercury injection curves and the

Table 2 Facies/diagenetic characteristics and pore system properties of the identified rock types in the Arab Formation

Rock type	Lithology	Grainstone facies	Main diagenetic processes	Pore type	Average porosity	Average permeability	Reservoir quality
RT-1	dolomite-limestone	GF1-GF2	Dissolution, dolomitization	Interparticle-touching vug	19.91	163.41	high
RT-2	dolomite	GF3-GF4	Dissolution, dolomitization	interparticle	19.42	223.88	high
RT-3	dolomite	GF-4	Dissolution, anhydrite cementation, dolomitization	Separate vug	22.13	5.52	medium-low
RT-4	dolomite	GF1-GF2-GF3-GF4	Anhydrite and calcite cementation, compaction, dolomitization	Interparticle-separate vug	8.35	3.43	low
RT-5	limestone	GF5-GF6	dissolution	interparticle	24.46	329.15	high
RT-6	limestone	GF5-GF6	Calcite and dolomite cementation, compaction, dolomitization	Interparticle-separate vug	15.2	7.31	medium-low

distribution of pore throats in each rock type are demonstrated in Figure 10. These rock types are described as follows:

7.1 Rock type-1 (RT1)

This rock type with dolomite and limestone lithology includes gastropod-foraminiferal and peloidal grainstone facies related to a leeward shoal sub-environment. The pore system of these facies has not been affected by cementation, and consists of inter-granular and touching vug pore types (Fig. 8a–b, m). In this rock type, the effect of meteoric dissolution is associated with the enlargement of pore throats and effective connection of pores. It led to high porosity (19.91% on average) and permeability (163.41 mD on average) in the grainstone facies of this rock type. Dominant pore spaces are greater than 7 μ in size and well-connected pore spaces produce a suitable permeability. The capillary pressure curve and the distribution of pore throats in this rock type indicate low-pressure displacement and predominance of the large pores of facies (Fig. 10a–b).

7.2 Rock type-2 (RT2)

This dolomitic rock type is related to a peloid-ooid

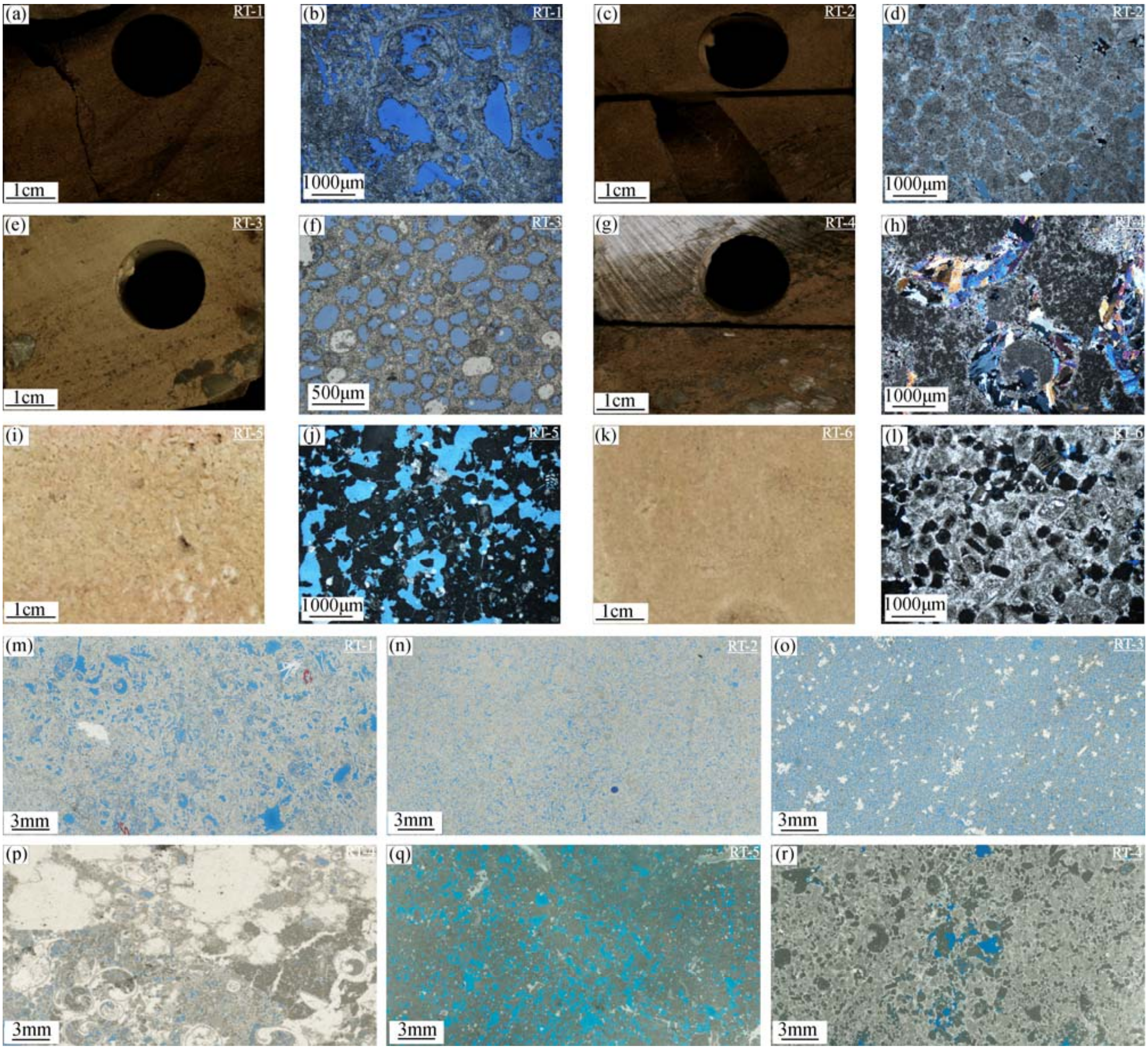

Fig. 8. Photographs of core (a, c, e–g, i, k), thin section (b, d, f, h, j, l) and their scans (m–r) of the identified rock types related to grainstone facies of the Arab Formation. a-b-m) Bioclastic dolograinstone with vuggy and moldic pores. c-d-n) Peloid-ooid dolograinstone with inter-granular pores. e-f-o) Ooid dolograinstone with moldic pores. g-h-o) Dolograinstone cemented by anhydrite. i-j-q) peloidal grainstone with inter-granular pores and high volume of touching vugs. k-l-r) Dolomitic grainstone with dolomite cement.

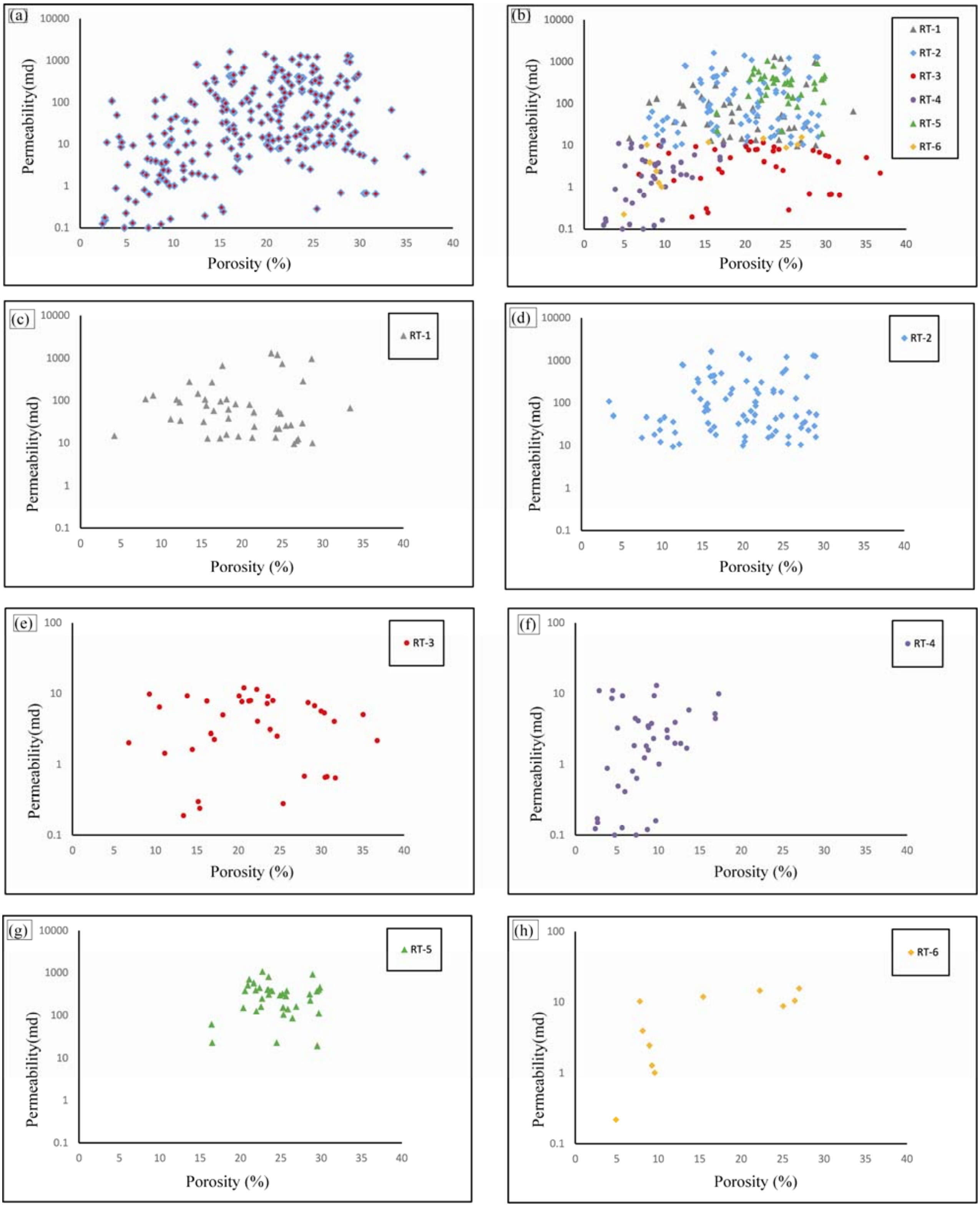

Fig. 9. (a), Core porosity-permeability plot in grainstone facies of the Arab Formation. High scattering pattern is due to the effect of diagenetic processes on pore system of these facies. (b) core porosity and permeability plot of grainstone facies of the Arab Formation based on differentiation of six identified rock types. (c) RT-1, (d) RT-2, (e) RT-3, (f) RT-4, (g) RT-5, (h) RT-6.

grainstone facies deposited in the central part of the shoal environment. Inter-granular pores are dominant pore types, and isopachous rim cement around grains is common (Fig. 8c–d, n). This cement, to some extent, has reduced the effect of compaction and decreased pore throats radius. In comparison with RT-1, the high values

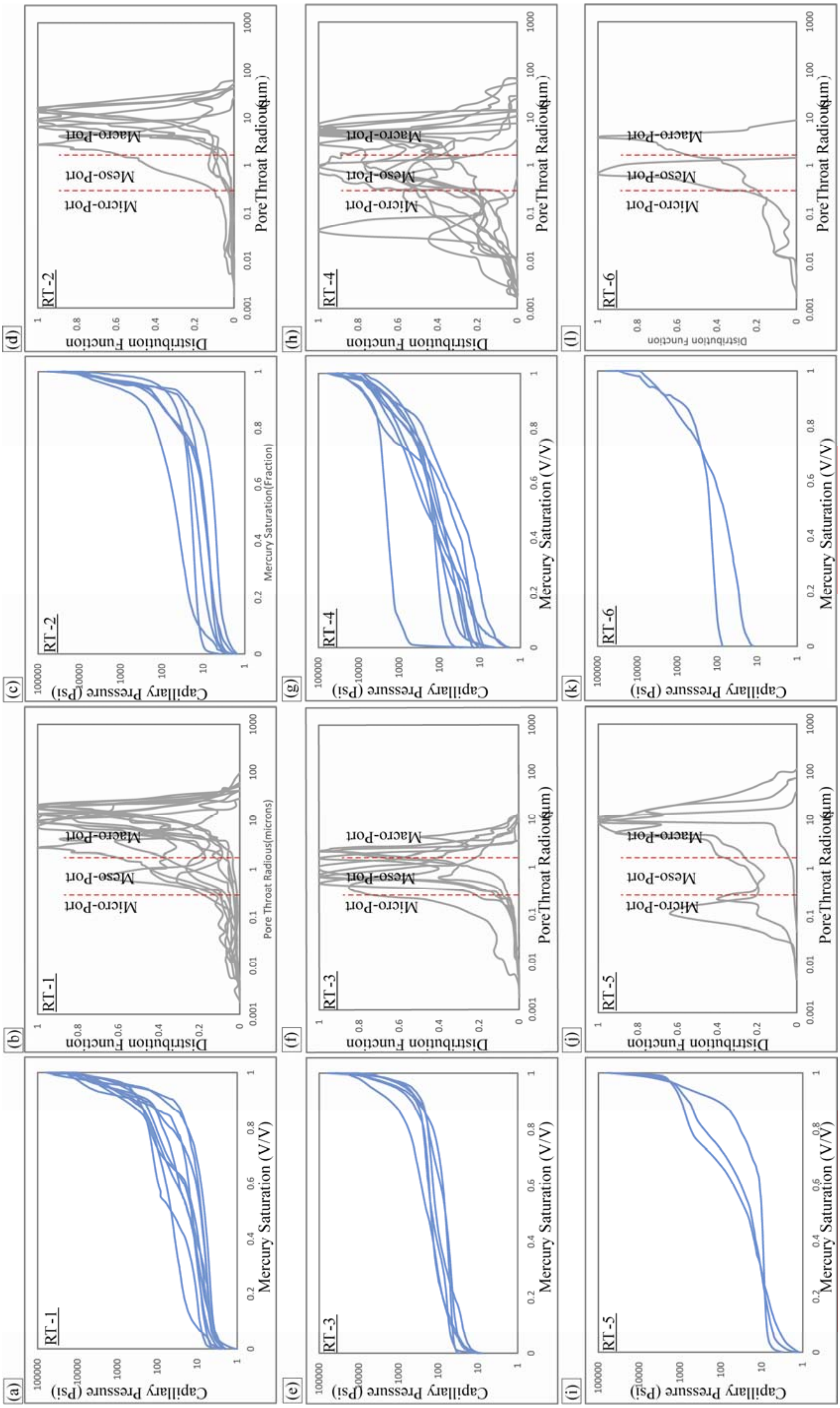

Fig. 10. Mercury injection capillary pressure (MICP) curves (a-c-e-g-i-k) and distribution of pore throats (b-d-f-h-j-l) in six identified rock types related to grainstone facies of the Arab Formation. (RT: rock type; Micro-Port: < 0.5 μm, Meso-Port: 0.5-1.5 μm, Macro-Port: >1.5 μm).

of permeability in this rock type at the same porosity, is attributed to the inter-granular pore types. Pore system analysis of this rock type shows high degree of pore sorting, low displacement pressure and dominance of large pores (Fig. 10c–d).

7.3 Rock type-3 (RT3)

This dolomitic rock type includes ooid grainstone facies with moldic pores (Fig. 8e–f, o). Therefore, these facies, due to the weak connection of pore types, are characterized by high values of porosity (22.13%) and permeability (5.52 mD). The capillary pressure curve and the distribution of pore throats indicate that the pore size sorting is high, but, due to the high displacement pressure, permeability is low (Fig. 10e–f). Most pore spaces are micro size with less than 5 microns.

7.4 Rock type-4 (RT4)

This dolomitic rock type includes a part of the grainstone facies of the Arab Formation in which reservoir quality is relatively low, due to the effect of cementation (anhydrite and calcite and minor dolomite) (Fig. 8g–h–p). Thus, this rock type is characterized by lower values of porosity (8.35% on average) and low permeability (3.43mD on average) compared with the other rock types. This rock type has the highest heterogeneity in terms of pore system properties among all the rock types. Because of low pore sorting, none of the pore types are predominant (Fig. 10g–h).

7.5 Rock type-5 (RT5)

Two facies of peloidal-bioclastic grainstone and bioclastic grainstone with high dissolution and minor cementation belong to this rock type (Fig. 8i–j-q). Pore system of these facies includes inter-granular pores that show the highest values of porosity (24.46% on average) and permeability (329.15mD on average) among all rock types. The pore sorting in this rock type is medium, and the large pores are generally dominant (Fig. 10i–j).

7.6 Rock type-6 (RT6)

This rock type is related to the grainstone facies in which the pore system is affected by compaction and cementation (dolomite and calcite) (Fig. 8k–l-r). Thus, its main pore system is isolated with non-touching pores. Its average values of porosity and permeability are 15.2% and 7.31 mD, respectively. This rock type is characterized by weak pore sorting and high displacement pressure (Fig. 10k–l).

In general, the limy grainstone facies, as compared with the dolomitic grainstone facies of the Arab Formation, is less affected by destructive diagenetic processes, especially cementation. Pore systems in RT-1, RT-2 and RT-5 consist of inter-granular and touching vug with connected and large pore throats. In RT-3, due to the development of non-connected pores, porosity is high and permeability is low. RT-4 and RT-6 that are related to compacted and cemented facies show low to medium porosity and relatively low permeability. Generally, in rock types with the highest reservoir quality, the pore system is dominated by inter-granular pore types. Analysis of the capillary pressure curves and the distribution of pore throats show that RT4 and RT6 have bimodality in distribution of pore throats and higher heterogeneity. Moreover, the size of pore throats is mostly in the macro to mesoport range.

8 Reservoir Controlling Factors

The original sedimentary properties mainly control reservoir quality, but diagenesis may exert remarkable heterogeneity on pore characteristics (Lucia, 2007; Ahr, 2008). Primarily, the grainstone facies of the Arab Formation normally have considerable reservoir potential. However, in these facies, compaction, cementation, dissolution, and dolomitization enhanced or deteriorated reservoir properties. The main negative governing factors are cementation and compaction. In this respect, the lowest reservoir quality is tightly cemented-compacted grainstones (RT4–RT6). Porous-permeable rock types are grainstones with dominant interparticle and vuggy porosity (RT1–RT2, RT5). The grainstone with abundant isolated moldic pores is characterized by high porosity values and relatively low permeability (RT3). In some samples of this rock type intense dissolution improved permeability.

9 Reservoir Rock-types in a Sequence Stratigraphic Framework

The sequence stratigraphic framework of the Arab Formation in various parts of the Arabian Plate has been presented in previous studies based on the stacking pattern, facies distribution and sea-level fluctuations (e.g., Meyer et al., 1996; Al-Husseini, 1997; Azer and Peebles, 1988; Sharland et al., 2001; Al-Awwad and Collins, 2013a; Morad et al., 2012; Daraei et al., 2014; Nowrouzi, et al., 2015). Regional stratigraphic analyses of the Arab Formation on the Arabian Plate (e.g., McGuire et al. 1993; Sharland et al., 2001; Al-Husseini, 2009) indicated four third-order sequences, which are correlatable with four reservoir zones (A, B, C and D). In this study, results of facies analysis and diagenetic examination along with the petrophysical well log interpretations are considered for identification of four third-order sequences of the Arab Formation. The shallow open marine and shoal facies are consistent with maximum flooding surfaces (MFS) and the upper boundary of thick anhydrite layers which are related to tidal flats, are considered as sequence boundaries (SB). In addition, to reach a better understanding of the distribution of the reservoir characteristics of rock types, 10 higher-order sequences (possibly fourth-order) were determined (Fig. 11).

On this basis, five sequences (1-2-3-4-5) in zone D, two sequences (6-7) in zone C, one sequence (8) in zone B and two sequences (9 and 10) in zone A associated with the Hith anhydrite, were recognized. In sequences 1 and 2, RT -5 and RT-6 are related to a HST system tract. In sequences 3 and 4, grainstone facies and their associated rock types are not developed. In sequence 5, RT-3 with high porosity and low permeability is limited to an early HST system tract. In sequence 6, RT-1 and RT-4 have been developed. In sequence 8, RT-2 and RT-4 are observed in the TST and early HST system tracts. Unit A of the Arab Formation associated with the Hith anhydrite is divided into two sequences of 9 and 10, in which RT-3 and RT-4 have been developed in different system tracts, respectively. In the Arab Formation, particularly in the dolomite and anhydrite intervals, the TST parts of the recognized sequences are missing and show a shallowing upward pattern possibly due to the very shallow depositional setting (fourth-order sequences of 4-6.5-6.7) generally not possible.

There are some interpretable relationships between the facies characteristic and diagenetic features, such as the development of moldic porosity is mainly restricted to some ooid grainstone facies. The position of different grainstone rock types of the Arab Formation in each system tract (TST and/or HST) depends on their position in the interval and facies association. In general, rock types with higher reservoir quality are observed in late TST and early HST. In contrast, in late HST, due to the greater impact of destructive diagenetic processes, especially evaporite mineralization, facies show lower porosity and permeability. Petrophysical logs can be used for correlation and interpretation of the geological and - petrophysical characteristics (Aliakbardoust and Rahimpour-Bonab, 2013; Isyaku et al., 2016; Moradi et al., 2017; Lai et al., 2017; Cui et al., 2017). In the Arab Formation, due to the carbonate-evaporite nature of layers, and the minor lateral changes in the reservoir properties, it is possible to use petrophysical logs for correlation of different reservoir zones between the wells (Al-Husseini, 1997). The gamma ray log is utilized in order to reach an understanding of distribution of grainstone rock types within the reservoir. The correlation of the six identified grainstone rock types of the Arab Formation in the studied field in the framework of sequence stratigraphy is shown in Figure 12. Grainstone facies of the Arab Formation are observed in both dolomite-anhydrite and calcareous-dolomitic parts of the formation. The principles of stratigraphic well correlations within the context of static reservoir modeling of heterogeneous carbonate reservoirs was presented in detail by Borgomano et al., 2008. Due to the significant impact of global sea-level fluctuations during deposition of the Arab Formation, there are no major changes in sedimentary characteristics and environment of this formation between the wells. Among the reservoir zones, the highest thickness is related to zone D, and anhydrite layers with the low gamma ray and porosity values can be well-utilized to distinguish and separate the reservoir zones.

10 Conclusions

The Arab Formation is characterized by thick grainstone facies in the Persian Gulf and on the Arabian Plate. In this respect, reservoir rock typing of these facies in the sequence stratigraphy framework has been accomplished based on facies/diagenetic properties and pore system analysis using core data, MICP curves and petrophysical logs in the Balal oil-field in the southeast of the Persian Gulf. The main results can be summarized as follows:

Based on facies analysis, six grainstone facies of shoal bodies were deposited (leeward, central and seaward) on a carbonate ramp platform. These are gastropod-foraminiferal grainstone (GF-1), peloidal grainstone (GF-2), peloidal-ooid grainstone (GF-3), ooid grainstone (Gf-4), peloidal-bioclast grainstone (GF-5) and bioclast grainstone (GF-6).

Different diagenetic processes such as compaction, dolomitization, anhydrite mineralization, cementation and dissolution affected the reservoir quality of grainstone facies. In this respect, dissolution by enhancement of pore system and enlargement of pore throats, and cementation by occlusion of pore system have effectively controlled pore system properties and reservoir characteristics of this formation. The results show that grainstone facies of the Arab Formation due to the effect of diagenetic processes are heterogeneous in their reservoir properties, and can be divided into different rock types.

The pore system of the grainstone facies of the Arab reservoir is dominated by inter-granular, moldic and vuggy pore types. Facies with have high porosity and low permeability. In contrast, facies with inter-granular pores have the highest reservoir quality.

Based on the integration of results from facies analysis

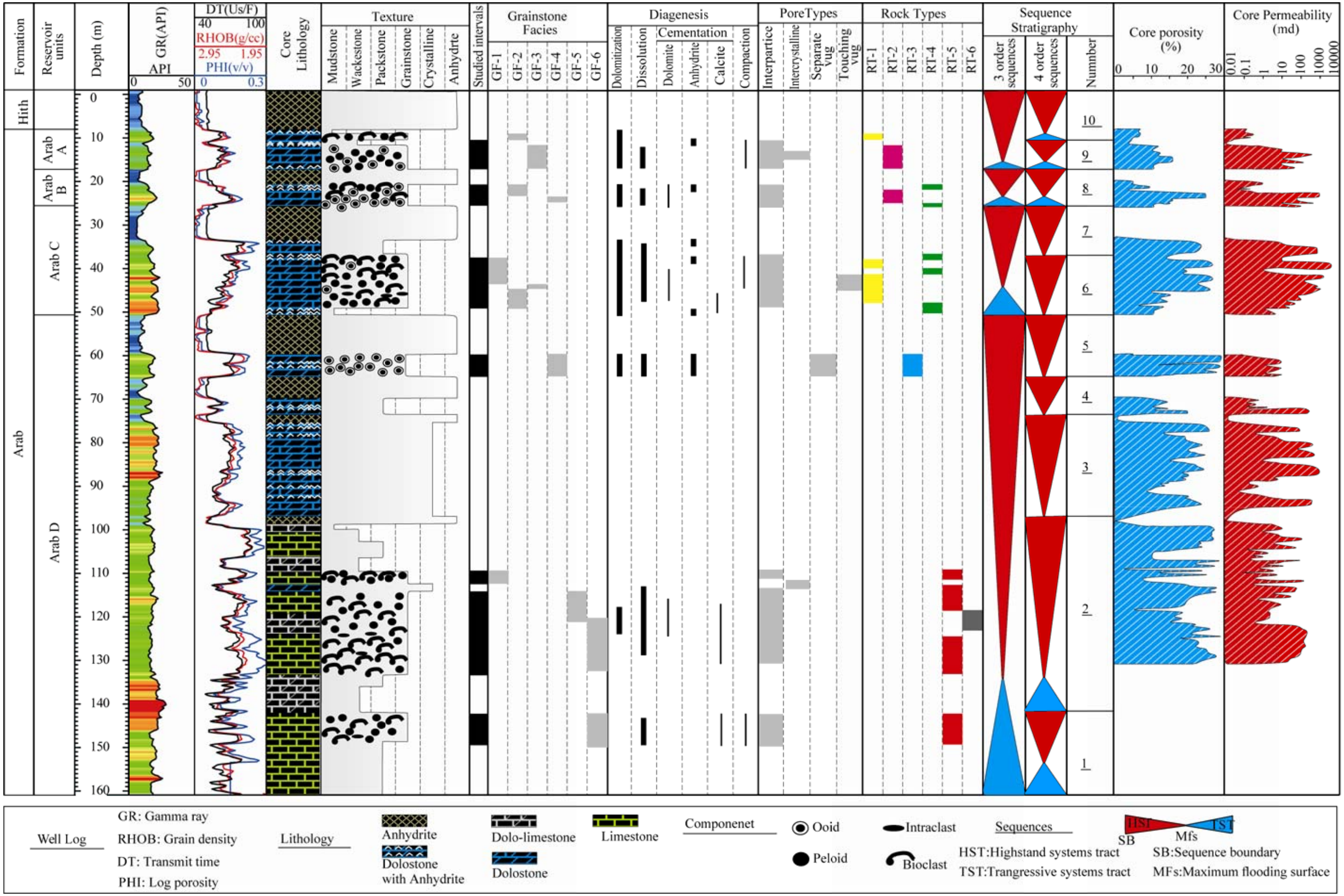

Fig. 11. Distribution of facies/diagenesis characteristics, pore system, rock types and core porosity and permeability related to grainstone facies of the Arab Formation along with their sequence stratigraphic positions in a key well of the studied field.

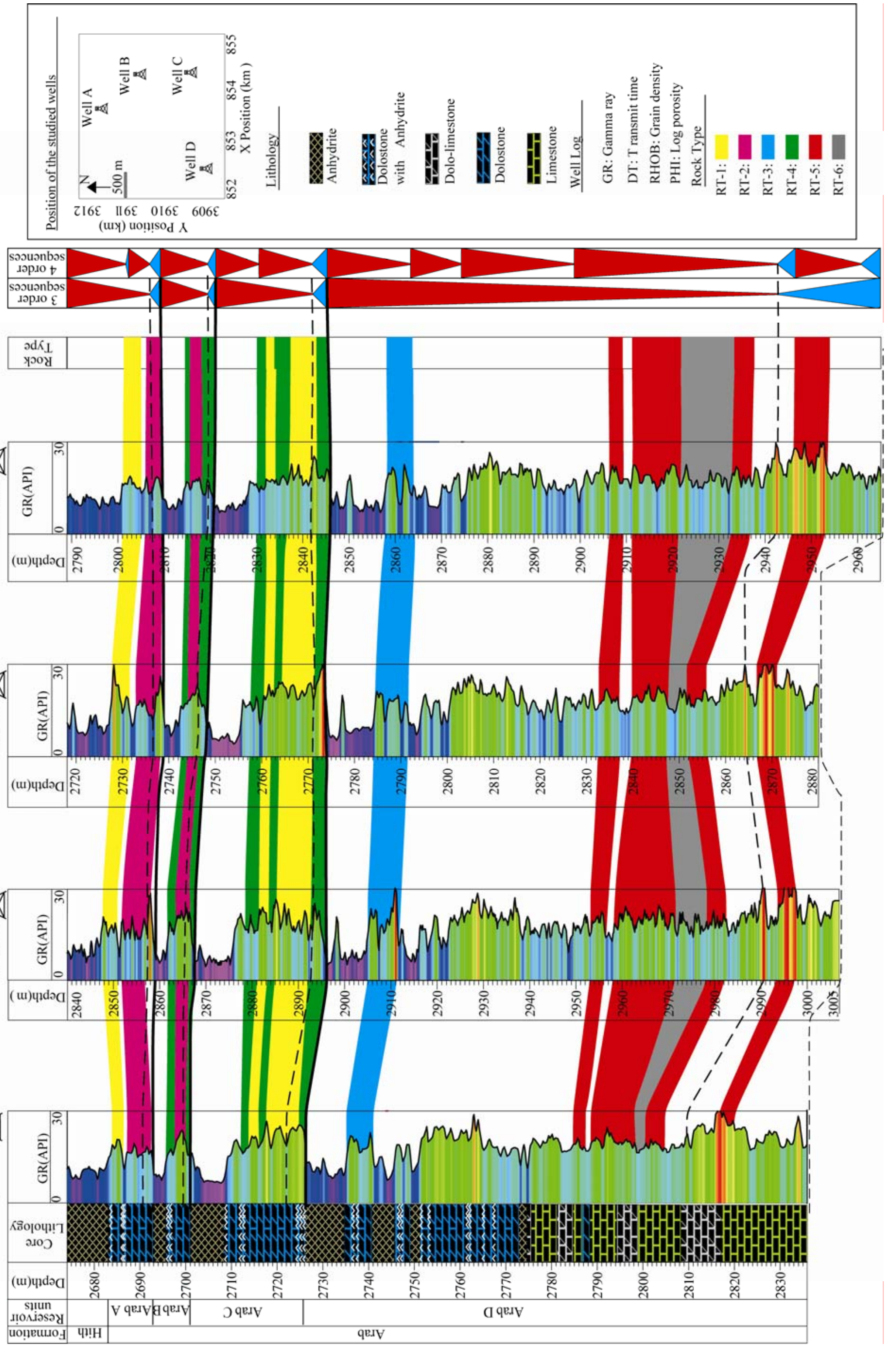

Fig. 12. Correlation of six identified rock types of the Arab Formation in four key wells of the studied field using gamma ray logs in the sequence stratigraphic framework.

and diagenesis studies along with the pore system analysis by core data and MICP curves, six rock types (RT1–RT6) related to grainstone facies were introduced. Accordingly, RT1, RT2 and RT5 show large pore throats with inter-granular and touching vug. In RT3, due to the development of moldic pores, facies have high porosity and low permeability. In RT4 and RT6, due to the effect of cementation and compaction facies show bimodality in their pore system.

Sequence stratigraphic analysis has resulted in the identification of four third-order sequences compatible with the reservoir zones and ten high-order (fourth-order) sequences. In general, reservoir rock types with higher reservoir quality are observed in late TST and early HST system tracts. In contrast, in the late HST system tract mainly due to the significant effect of destructive diagenetic processes, especially evaporite mineralization, facies show lower values of porosity and permeability. Regarding the layer-cake nature of the Arab interval and distinct relationship between different rock types within the identified sequences, as shown in this study, the petrophysical logs can be used for correlation between the four key wells in the studied field.

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