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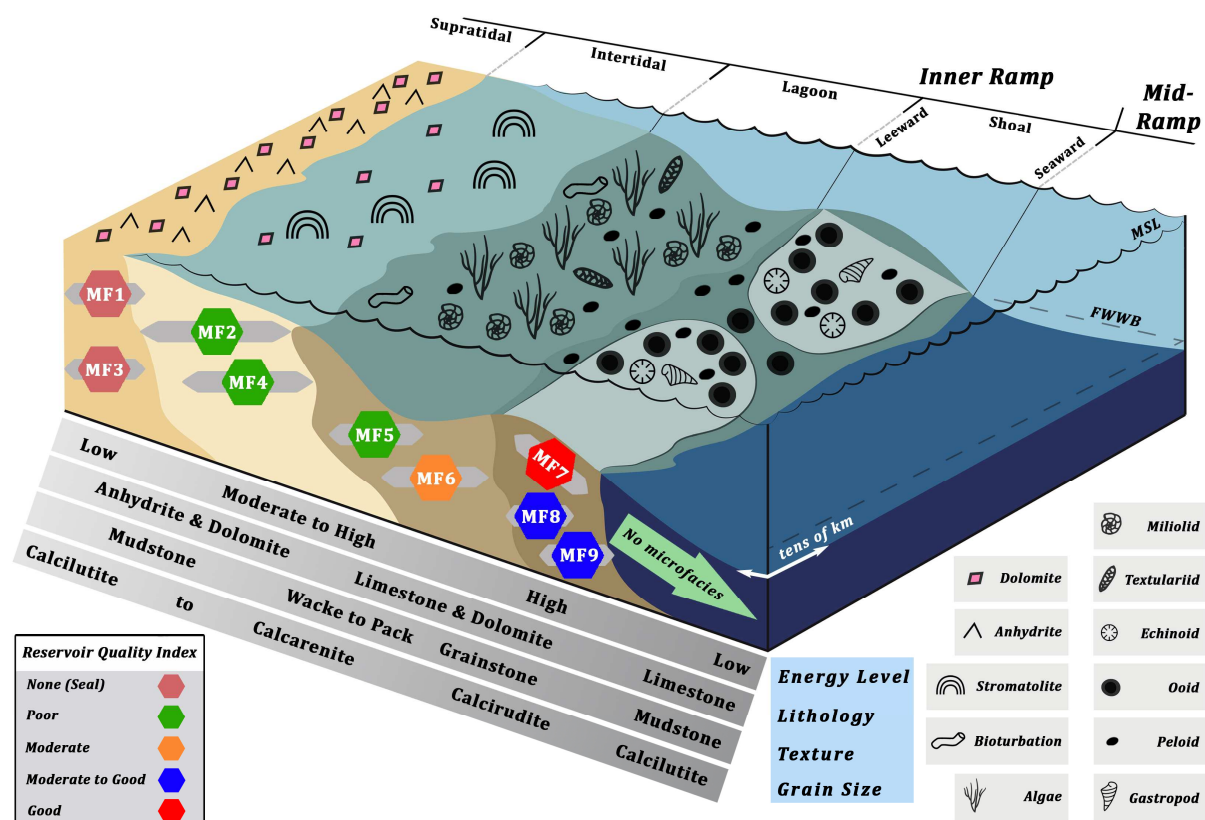
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Facies analysis, diagenesis and sequence stratigraphy of the carbonate-evaporite succession of the Upper Jurassic Surmeh Formation: Impacts on reservoir quality (Salman Oil Field, Persian Gulf, Iran)

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Abstract

This study aims to determine the depositional facies, diagenetic processes and sequence stratigraphic elements of the subsurface carbonate-evaporite succession of the Upper Jurassic (Kimmeridgian-Tithonian) Surmeh Formation of the Salman Oil Field (the Persian Gulf, Iran), in an attempt to explore their impacts on reservoir quality. The Surmeh Formation consists mainly of carbonate rocks, intercalated with evaporite layers. Petrographically, the Surmeh Formation consists of nine microfacies (MF1-MF9). These microfacies are grouped into three facies associations related to three depositional environments (peritidal flat, lagoon and high-energy shoal) sited on the inner part of a homoclinal carbonate ramp. The recorded diagenetic processes include dolomitization, anhydritization, compaction, micritization, neomorphism, dissolution and cementation. Vertical stacking patterns of the studied facies reveal the presence of three third-order depositional sequences, each of which consists of transgressive systems tract (TST) and highstand systems tract (HST). The TSTs comprise intertidal and lagoon facies whereas the HSTs include supratidal and shoal facies.

In terms of their impacts on reservoir quality, the shoal facies represent the best reservoir quality, whereas the peritidal and lagoonal facies exhibit moderate to lowest reservoir quality. Also, poikilotopic anhydrite cement played the most significant role in declining the reservoir quality, whereas the widespread dissolution of labile grains and formation of moldic and vuggy pores contributed in enhancing the reservoir quality. In addition, the HSTs have a better reservoir quality than the TSTs. This study represents an approach to use the depositional facies, diagenetic alterations and sequence stratigraphic framework of carbonate –evaporite succession for a more successful reservoir characterization.

Keywords: Surmeh Formation; Upper Jurassic; Diagenetic processes; Reservoir quality; Sequence stratigraphy; Salman Oil Field; Persian Gulf

1. Introduction

The Surmeh Formation is one of the geographically most widespread formations in the Zagros and Persian Gulf basins including the Salman Oil Field. Approximately two thirds of the Salman Oil Field lies in Iranian waters, whereas the remaining third falls into territorial waters of

Abu Dhabi, U.A.E. (Fig. 1). The Surmeh Formation contains gigantic oil reserves. In the Salman Oil Field, the Surmeh Formation reaches up to 150 m in thickness, and it is made up of limestones and dolostones with several evaporite interbeds (Figs. 2 and 3). It is equivalent to the Arab Formation of Saudi Arabia, Bahrain, Qatar and U.A.E. (Al-Husseini, 2008). The Surmeh Formation was originally introduced by James and Wynd (1965), to describe the lowermost section of the Early Jurassic to Early Cretaceous Khami Group of the Zagros Basin (Fig. 3).

Reservoir quality is one of the key controls on well efficiency (Taylor et al., 2010). The evaluation of reservoir quality in siliciclastic rocks attracted the attention of many authors (e.g., Ketzer and Morad, 2006; Mansurbeg et al., 2009; Deschamps et al., 2012), and is controlled by the distribution of depositional facies, diagenesis and the sequence stratigraphic framework (e.g., Lan et al., 2016; Zahid et al., 2016, and references therein). In contrast, less attention has been drawn to study the impact of depositional facies, diagenesis and sequence framework of carbonate and evaporite successions regarding reservoir quality (e.g., Lucia, 2007; Ahr, 2008; Koehrer et al., 2010; Moore, 2013; Daraei et al., 2014; Shen et al., 2015; Amel et al., 2015; Enayati-Bidgoli and Rahimpour-Bonab, 2016). Therefore, this paper aims to recognize and describe the depositional facies, diagenesis and sequence stratigraphy of the carbonate-evaporite succession of the Upper Jurassic Surmeh Formation (Salman Oil Field, Persian Gulf, Iran), in an attempt to investigate their influences on the reservoir quality. To achieve these purposes, a detailed petrographic investigation was carried out on both the carbonate and evaporite rocks of the Surmeh Formation.

2. Regional geology

The Salman Oil Field is located in the central part of the Persian Gulf. It lies between longitudes 53° 14' to 53° 20'E and latitudes 25° 37' to 25° 38'N. The structural closure of the Salman Oil Field is documented by well and 2D seismic data (Fig. 4). The geology of salt structures in the Persian Gulf and adjacent areas has been addressed by many authors (e.g., Stöcklin, 1968; Kent, 1970; Kent, 1979; Nasir et al., 2008; Bruthans et al., 2010; Mukherjee et al., 2010; Arian and Noroozpour, 2015; Perotti et al., 2016). A steady diapiric rise during the Early Paleozoic was described slightly north of the study area, as well as several main phases of salt movement, namely during the Permo-Triassic, Cretaceous, Eocene–Oligocene and Neogene

(Carruba et al., 2007 in Perotti et al., 2011; Perotti et al., 2016; see also Edgell, 1996). Formation of the Salman Oil Field is related to migration of the Precambrian Hormuz Salt Series, which created a salt structure. The structural shape of the Salman Oil Field is roughly circular to elliptical with gentle flanks dipping 3 to 7 (Fig. 4). It measures ~15 by 16 km horizontally and about 600 meters of vertical closure. Several minor faults trending NW-SE were detected on the southern and northern flanks. These faults are located in the northern parts of the field and in the area close to the Iran/Abu-Dhabi border. Faults of these trends define three grabens dropping the central/crestal parts of the Salman structure by some 15-20 meters in successive steps from both sides (Fig. 4).

During the Early to Late Jurassic, the relative sea level rose and fell several times in the Persian Gulf Basin and in other adjacent basins (Alsharhan and Nairn, 1997), concurrent with the widening and subsiding Neo-Tethys Ocean (Stampfli and Borel, 2002). The Surmeh Formation conformably overlies the Neyriz Formation (Early Jurassic) and is in its turn conformably overlain by the Hith Formation and/or by the Fahliyan Formation in the coastal area of the Fars region (Fig. 3). The equivalent facies of the Surmeh Formation have been reported from Lorestan to Central Iraq as the “Mus Formation” (James and Wynd, 1965) and from Saudi Arabia and Kuwait (Steineke et al., 1958). The prevailing arid conditions of Saudi Arabia extended as far as the Fars region towards the end of the Jurassic and resulted in widespread accumulation of anhydrite sabkha deposits (Hith Formation) throughout the Persian Gulf, costal and central Fars (Alsharhan and Nairn, 1997) (Fig. 3).

Detailed petroleum operations established reservoir layering in both hydrocarbon bearing reservoirs of the Lower Cretaceous Gadvan (U.A.E.: “Buwaib”) and the Jurassic Surmeh (U.A.E.: “Upper and Lower Arab”) formations in the Salman Oil Field. In this field, the Kangan (U.A.E.: “Khuff”) Formation is a condensate gas reservoir. The gases may have originated from shale deposits and/or intraformational carbonates of the Kangan and Dalan formations (Bordenave and Burwood, 1990). The Surmeh oil-bearing interval is divided into two main reservoir bodies of the Upper and Lower Arab formations. In this paper, the upper part of the Surmeh Formation has been subdivided into nine units (U1, U2, U2A, U3, U4, U5, U6, U7 and U8), and its lower part is made up of two main units (L1 and L2) with some minor subunits (Fig. 2). The Jurassic Surmeh Formation consists mainly of coarse-crystalline, porous dolostones and

limestones, separated from the succeeding and superseding layers by anhydrite or anhydrite-rich carbonates. Furthermore, the most prominent feature between the Lower and more productive Upper Arab Formation are the frequent changes from anhydrite-bearing dolostone to limestone with thin dolostone layers. Terrigenous clay is virtually absent.

3. Methodology

Petrophysical (gamma ray) evaluation of the reservoir units indicate that the main lithologies are limestone and dolostone with anhydrite interbeds. Three hundred thin sections (sample spacing about 30 cm from well core) were prepared and 100 of them were stained with Alizarin Red-S solution and potassium ferricyanide using the Dickson (1965) method to distinguish calcite from dolomite. The carbonate microfacies (Table 1) were classified according to Dunham (1962). Textures of dolomites were described following the terminology and classification of Sibley and Gregg (1987), but we also considered other schemes such as those of Friedman (1965), Mazzullo (1992) and Shukla and Friedman (1983). Porosity and permeability investigations were carried out by a combination of visual percentage estimates from thin sections impregnated with blue epoxy resin and data taken from 1.5 inch diameter plugs (one per foot) to measure air permeability. Porosity types were quantified based on image analysis of 250 thin-sections, with 300 point counts per thin-section. Data gained from aforementioned sources were gathered in order to describe and define facies, diagenetic stages and assess on reservoir quality. The determined reservoir qualities (none, poor, moderate and good) correspond to certain porosity and permeability ranges shown in Table 2.

4. Depositional facies and interpretations

Petrographic investigations led to the identification of nine microfacies (MF1-MF9). These microfacies are grouped into three facies associations that are assigned to three depositional environments (peritidal flat, restricted inner lagoon, and high-energy shoal) sited on the inner part of a homoclinal carbonate ramp. Facies analysis was carried out mainly by using the standard facies model for ramps by Flügel (2010). The description and characteristics of the

main individual sedimentary facies, as well as facies associations recognized within the studied intervals are summarized in Table 1 and presented in the following paragraphs.

4.1. Peritidal flat facies association

The peritidal area refers to supra-intertidal flats (Shinn, 1983). The peritidal flat facies association includes four microfacies types (MF1-MF4): anhydrite, dolomudstone, mudstone and dolostromatolite boundstone.

4.1.1. Massive, nodular and chicken-wire anhydrite (MF1): Massive anhydrites are milky white in color and do not display internal structures (Fig. 5A). The anhydrite beds range from 3 cm to several meters in thickness and occur at various horizons. Anhydrite nodules (crystals smaller than 20 microns) are enclosed within the dolomudstones. They occur as spherical to oval-shaped nodules ranging from millimeters to a few centimeters in size (Fig. 5B). The chicken-wire anhydrites occur as closely-packed nodules with thin stringers of sediment and/or organic material in-between (Figs. 5C and D).

Interpretation: The anhydrite deposits are indicative of supratidal (sabkha) or highly evaporative saline environment (Warren and Kendall, 1985; Kasprzyk and Ortí, 2002; Alsharhan, 2006; Lucia, 2007). It seems that the nodular anhydrites formed in the first stages of diagenesis as indicated by their association with dolomudstone and stromatolite boundstone (Rahimpour-Bonab et al., 2010). Anhydrites with chicken-wire fabric are interpreted to have formed in supratidal deposits (Alsharhan and Kendall, 2003; Insalaco et al., 2006). The anhydrite facies (MF1) lacks reservoir quality (Table 2). Anhydrite is also seen in irregular veins in MF2 and as sporadic nodules in MF3, which led to a decrease of the reservoir quality in these facies.

4.1.2. Dolomudstone (MF2): The dolomite occurs as anhedral and subhedral crystals of very fine to fine size (5 to 16 microns) (Fig. 5E). Recrystallization of the dolomicrite to dolosparite is locally recognized. Some irregular cracks are noticeable in a variety of directions that were filled locally or completely by anhydrite.

Interpretation: The dolomudstone is barren of fossil remains and interpreted as a peritidal carbonate (Wanas, 2008). The facies is similar to the RMF22 (supratidal-intertidal facies) of Flügel (2010). The anhydrite filling of some irregular cracks led to a decrease in reservoir quality of deposits with this microfacies (Table 2).

170 4.1.3. *Mudstone with sporadically occurring anhydrite nodules (MF3)*: This facies is made up of
 171 dark-colored micrite (calcite), enclosing light-colored anhydrite nodules (Fig. 5F). The anhydrite
 172 nodules commonly display felted and lath textures.

173 *Interpretation*: The local occurrence of anhydrite nodules in the mudstone is genetically
 174 related to the upper parts of tidal flat environments (sabkha) (Alsharhan and Kendall, 2003;
 175 Warren, 2006). The facies is similar to the RMF25 of Flügel (2010). The sporadic anhydrite
 176 nodules in MF3 led to a decrease of the reservoir quality (Table 2).

177 4.1.4. *Dolostromatolitic boundstone (MF4)*: In this facies, wavy lamination is seen together with
 178 algal filaments. The laminates range from one to a few millimeters in thickness (Fig. 5G).
 179 Fenestral fabrics, mud cracks, and some amount of small skeletal fragments (ostracods, bivalves,
 180 and gastropods) are also observed.

181 *Interpretation*: Based on the existence of the stromatolitic structure, mud cracks, fenestral
 182 pores and the scarcity of small skeletal fragments of ostracods, bivalves, and gastropods a
 183 supratidal to intertidal environment (Shinn, 1983) is suggested as the origin of this microfacies,
 184 which is similar to the RMF25 of Flügel (2010). The low faunal diversity exhibited by this
 185 microfacies points to a restricted setting with above-normal salinities that facilitated
 186 cyanobacterial blooms and the preservation of laminated and/or stromatolitic structures (Husinec
 187 and Read, 2011; Husinec, 2016). The reservoir quality of this facies is poor (Table 2).

188 4.2. Restricted inner lagoon facies association

189 This facies association includes two microfacies types: bioclastic packstone/wackestone, and
 190 peloid-bioclastic packstone.

191 4.2.1. *Bioclastic packstone/wackestone (MF5)*: In this facies, major allochems are foraminifera
 192 (10-15%) such as miliolids, textulariids and dasycladacean algae (16-20%). Others (9-15%) such
 193 as pellets, intraclasts and bioclasts (bivalves and gastropods) are also observed. Bioturbation is a
 194 main feature of this facies. The intraclasts and bioclasts display intense micritization (Fig. 5H).
 195 This microfacies contains some dolomicrite.

196 *Interpretation*: The presence of micritized skeletal fragments in association with micrite
 197 suggests of sedimentation in a low-energy, shallow lagoon environment (Wanas, 2008; Amel et

al., 2015; Sallam et al., 2015). The facies is similar to the RMF17 of Flügel (2010). The prevailing pore types in this facies are intergranular pores and fracture cavities.

4.2.2. Peloid-bioclastic packstone/wackestone (MF6): Allochems in this facies are mainly fine-grained peloids (25-30%). Other allochems include green algae (13-15%) (Fig. 5I), miliolids (8%), and other bioclasts (10-16%). All allochems are embedded in micrite. The peloids are well-sorted. Bioclasts often show well-developed micrite envelopes. Secondary dissolution and dolomitization features are present in this facies. The dominant porosity is mainly of the moldic and vuggy type.

Interpretation: Abundance of peloids and green algae in micrite with low diversity of fossils indicates deposition in restricted shallow subtidal (lagoonal) water as well as a slow sedimentation rate (Wilson, 1975; Flügel, 2010). The facies is very similar to those described by Wanas (2008) and Amel et al. (2015) for lagoon environments around the margin of carbonate shoals. The facies is also compatible with the RMF20 of Flügel (2010). The facies has moderate reservoir quality (Table 2).

4.3. High-energy shoal facies association

This facies association includes three microfacies types: peloidal-oidial grainstone, ooidal grainstone, and intraclastic grainstone.

4.3.1. Peloidal-oidial grainstone (MF7): The main allochems of this facies are micritized ooids (28-30%), peloids (20%) and skeletal fragments (5%) (Fig. 5J). Peloids form most of the nuclei of ooids. All allochems are embedded in sparry calcite. Porosity types are mainly intergranular, moldic, and vuggy cavities. Moreover, this facies lacks anhydrite, which is advantageous for reservoir quality.

Interpretation: Lack of micrite and occurrence of ooids are indicative of high energy shoal environments (Wilson, 1975). The facies is similar to the RMF29 (shoal environment) of Flügel (2010) and displays moderate to good reservoir quality (Table 2).

4.3.2. Ooidal grainstone (MF8): Micritized superficial ooids (30-40%) and bioclasts (10-12%) are the main allochems (Fig. 5K). Bioclasts are mainly bivalves, gastropods, small foraminifera and echinoid remains. They are well-sorted and cemented by microspar and/or sparry calcite.

Locally, ooids occur dissolved though their micrite envelopes are still visible. Sedimentary structures include cross-bedding and graded bedding. Moldic, intergranular and vuggy are the main porosity types of this facies.

Interpretation: The abundance of ooids, lack of micrite and presence of well-sorted allochems are indicative of a high-energy shoal environment above fair weather wave base (FWWB) (Burchette and Wright, 1992; Insalaco et al., 2006). The facies is similar to the RMF29 (carbonate sand shoals and banks) of Flügel (2010).

4.3.3. Intraclastic grainstone (MF9): This facies consists mainly of coarse-sized intraclasts (≥ 2 mm; 25-30%) and bivalve bioclasts (19-25%), cemented by isopachous sparry calcite (Fig. 4L).

Interpretation: The lack of mud and abundance of coarse-grained intraclasts suggest reworking in a high-energy, seaward shoal environment (Reading, 1996). This facies is similar to the RMF27 (carbonate sand shoals and banks) of Flügel (2010). Moldic and intergranular pores represent main cavity types, providing for a moderate to high reservoir quality (Table 2).

5. Depositional model

Vertical and lateral distributions of sedimentary facies and their interpreted depositional environments are indicative of gradual environmental change from peritidal flat to lagoon and to carbonate shoal. Facies associated with rimmed shelves, i.e., reefs, slope break, off-shore slope deposits, slumping apron and oceanic depth-related facies (Read, 1985; Tucker, 1990; Burchette and Wright, 1992) are not represented. Therefore, based on the classification of Burchette and Wright (1992), and the analogous facies types of the studied deposits to other inferred homoclinal carbonate ramp successions (Wanas, 2008) we interpret the studied deposits of the Surmeh Formation as accumulations on the inner part of a homoclinal carbonate ramp setting. In the studied section, the inner ramp depositional environment includes tidal flat, lagoon and shoal facies belts (Fig. 6). This view is substantiated by the following observations: (I) the peritidal flat facies association (MF1 to MF4) is characterized by the lack of allochems, no significant facies change (mainly anhydrite and nodular dolomudstone), common sabkha facies, absence of clastics, occurrence of fenestral fabrics besides stromatolite facies and presence of rhombic dolomites, which are indicative of an inner carbonate ramp system developed under arid

to semi-arid conditions (Wilson, 1975; Read, 1985; Burchette and Wright, 1992), (II) the lagoon facies association (MF5, MF6 and MF7) with specific lagoonal bioclasts such as green algae, benthic foraminifera, especially miliolids, textulariids and gastropods, and also abundant peloids, micritic matrix, and bioturbation is suggestive of sedimentation in a limited zone behind shoals (Brachert, 1992) or a windward shoal environment (lagoon-facing side), and (III) grain-dominated facies, lack of micrite, presence of graded bedding and cross-bedding, and allochems such as ooids, intraclasts, and to a lesser extent oncoids and green algae fragments deposited in a high-energy zone are among the characteristics of the shoal facies belt in an inner ramp setting (Read, 1985; Burchette and Wright, 1992), showing the highest reservoir quality (Table 2). The dolomitization process is generally pervasive. However, it has merely affected ooids and the marine cements in both fabric destructive and fabric retentive forms.

6. Diagenesis

The studied rocks display a variety of diagenetic features resulting from compaction, bioturbation, micritization, cementation, neomorphism, dolomitization and dissolution. Some of these processes led to improve the reservoir quality, whereas some others impaired it. Special emphasis is placed on dolomitization and anhydritization, as these replacements had great impact in shaping the reservoir characteristics.

6.1. Compaction: This process includes mechanical and chemical compaction types. Mechanical compaction is noticed where broken and deformed grains, grain slippage and rearrangement are observed (Fig. 7A). Chemical compaction is identified by the presence of stylolites and pressure dissolution seams (Fig. 7B). Detailed core observation revealed that some of the stylolites are crosscut by fractures.

6.2. Bioturbation: Diagnostic criteria for bioturbation include patchy appearance in color or texture (Fig. 7C). Bioturbation causes heterogeneity in the sediment and led to development of porosity and permeability, finally determining the hydrocarbon migratory direction (Libelo et al., 1994). These features are profusely seen in the lagoonal wackestone and packstone facies.

6.3. Micritization: This is a common diagenetic process in the lagoonal facies. It developed in most allochem rims as in ooids and bioclasts (Fig. 7D). In some cases, micritization enveloped

grains and contributed to increase their stability against further diagenetic changes like dolomitization and dissolution. It also led to retention of the initial form of the grains.

6.4. Cementation: Calcite and anhydrite are the main minerals cementing the studied rocks. These cements have partially or completely filled the fractures and pore throats.

Calcite cement occurs in different fabrics including isopachous rim cement, equant crystals, drusy, blocky and syntaxial overgrowth cement. Isopachous fibrous calcite cement is observed around and inside fossil fragments, for instance around bivalves, ooids and oncoids of ooid grainstones, as well as around intraclasts (Fig. 7A). The cements were completely dolomitized in some facies, thus, creating a strong framework against compaction. This type of cement is indicative of diagenesis under marine phreatic conditions (Tucker and Wright, 1990; Moore, 2013).

Crystal mosaics of equant calcite cement comprise subhedral to anhedral crystals in intergranular and intragranular spaces (Fig. 7A). This cement type is generally found in grainstone facies with moldic porosity and formed in marine conditions. It may reflect meteoric conditions (Tucker and Wright, 1990) but also burial environments (Choquette and James, 1987). This cement type is important in filling the primary intergranular porosity. Blocky calcite cement mainly developed in shoal-related facies and consists of moderate to coarse-grained calcite crystals that usually fill fractures, intraparticle as well as intergranular spaces seen locally in the Surmeh Formation (Fig. 7D). Syntaxial cement overgrew echinoid fragments. This type of cement is rarely seen in the Surmeh Formation. Therefore, it had little effect on the reservoir quality. Drusy cement is not widespread in the Salman Oil Field. However, it fully or partially filled intergranular and vuggy pores in the Surmeh Formation and contributed to reduce the reservoir quality (Fig. 7E). This cement could be early diagenetic in origin, but it is seen in burial phases as well (Flügel, 2010).

The anhydrite cements in the Surmeh Formation are either syngenetic or secondary in origin. Syndepositional anhydrite cement commonly occurs in the lagoon and supratidal facies and fills the primary cavities (anhydrite plugging). The secondary anhydrite cement filled fractures. Pore-filling pervasive anhydrite cement is dominant, while poikilotopic (Fig. 7F) and fracture filling anhydrite (Fig. 7G) are not common. Poikilotopic anhydrite cement in the form of sporadic irregular coarse crystals encloses several grains (Fig. 7F). It mainly formed during burial

conditions. In some cases, anhydrite cement replaced fossils and ooids (Fig. 7H). This cement consequently decreased the reservoir quality (Kendall and Walter, 1977; Amel et al., 2015).

6.5. Neomorphism: Neomorphic features are clearly visible in the micrite-dominated and occasionally grain-dominated facies. It is represented by aggrading neomorphism that led to the transformation of micrite to microsparite and/or sparite (Fig. 7I). This process mainly takes place in meteoric phreatic environments (Budd and Hait, 1993).

6.6. Dissolution: This process led to formation of different types of porosity such as intergranular, intragranular, vuggy, fracture and moldic cavities.

Intergranular porosity is well-developed among peloids, ooids and skeletal fragments (Fig. 7J). This type of porosity is locally found in the empty spaces of large skeletal fragments, like foraminifer chambers and algae, especially in the lagoon facies. Vuggy pores are abundant in dolomitized intertidal facies but are rarely seen in dolomudstone facies (Fig. 7K). This type of porosity is generally not filled by any cement, which is positive for the reservoir quality. Fracture porosity is not common in the reservoir rock; present fractures are filled with anhydrite cement and locally with calcite (Fig. 7G). These fractures mainly developed in dolomudstone and dolowackestone deposits. Fractures are mainly vertical to subvertical, ranging 0.5 to 1 mm in width (Fig. 7B). Formation of channel porosity in the reservoir rocks was closely related to development of fractures in the samples of the shoal facies. Moldic porosity basically occurs in ooid and bioclastic grainstones related to the facies of the central and seaward shoal environments (Fig. 5K). Fenestral porosity has no effects on reservoir quality due to its sparseness. It is mainly observed in dolomudstone facies of intertidal and supratidal environments. Fenestral pores are filled with anhydrite cement (Fig. 7L).

6.7. Dolomitization: Based on the textural classification criteria of Sibley and Gregg (1987), the observed dolostones are divided into four types: dolomicrite, partly sparitic dolomicrosparite, dolosparite and dolomitic limestone.

6.7.1. Dolomicrite: This type is made up of very fine- to fine-grained crystals ranging from 30 to 60 μm (40 μm in average) in size (Fig. 8A). The dolomites are cream-colored to brown, with no porosity but with primary sedimentary features like lamination, intraclasts and peloids. Remains of evaporite minerals, algal filaments and silt-sized quartz grains can also be seen in the

dolomicrite. Based on these features, it is suggested that the dolomicrite formed near the surface under low temperature conditions (Sibley and Gregg 1987; Gregg and Shelton, 1990; Adabi, 2009). The occurrence of dolomicrite together with anhydrite layers and the prevalence of nodular anhydrite are indicative of formation during early diagenetic stages concurrent with and immediately after sedimentation by brine fluids. This type of dolomite is equivalent to the xenotopic-A type of Friedman (1965), xenotopic type of Gregg and Sibley (1984), and the nonplanar-A type of Mazzullo (1992).

6.7.2. Partly sparitic dolomicrosparite includes fine- to medium-sized (16 to 64 μm) anhedral to subhedral dolomite crystals. Most of these dolomites display dusty surfaces and contain micrite inclusions (Fig. 8B). Occurrence of the inclusions supports the idea that the partly sparitic dolomicrosparite derived from recrystallization of dolomicrite. The fabric of this dolostone is equivalent to the idiotopic, planar-S type of Gregg and Sibley (1984). They are specific to peritidal/restricted circulation shelf and tidal flat environments. The RMF22 and SMF19 (Flügel, 2010) commonly represent these dolostones.

6.7.3. Dolosparite displays crystal sizes ranging from 70 to 260 μm (220 μm in average). It occurs in two forms: (1) as compact, coarse, anhedral crystals with sutured borders and (2) as coarse, rhombohedral crystals with straight bright and clear borders along with intercrystalline porosity (Figs. 8C and D). The dolosparite shows the same petrographical characteristics as type 3 of Shukla and Friedman (1983), and it is also similar to the matrix dolomite of Qing and Mountjoy (1989). The type 3 dolomite may have formed by crystal growth fed by continuous flow of dolomitizing fluids at low temperatures (Sibley and Gregg, 1987) or as a result of replacement of older limestones and/or recrystallization of dolomite formed in early diagenetic stages below the critical temperature ($<60^{\circ}\text{C}$) (Gregg and Shelton, 1990). Dolosparite is one of the most abundant types of dolomite observed in the lagoon facies of the Surmeh Formation.

6.7.4. The dolomitic limestone displays scattered, fine-grained ($<60\ \mu\text{m}$) rhombohedral dolomite crystals, “floating” in a muddy matrix of calcite. The dolomite occurs as: (1) crystals with cloudy center and limpid rims (Fig. 8E), and (2) clear and bright crystals (Fig. 8F). It is equivalent to the planar-P type (porphyrotopic) of Gregg and Sibley (1984) and the nonplanar-P type of Mazzullo (1992). Dolomite crystals replaced the calcite matrix and probably formed as a result of the entry of less saturated (Mg/Ca) fluids (Sibley and Gregg, 1987).

In the studied samples, dolomite displays two fabrics: (1) fabric retentive and (2) fabric destructive types. The fabric retentive type is widely seen in shoal samples, i.e. from shoal facies where the rocks were partially dolomitized. Only the matrix was selectively replaced by dolomite while the allochems remained unaffected (Fig. 8G). This type of dolomitization has resulted in good reservoir quality in the appropriate facies. This could be due to the moldic porosity and the pore spaces that are interconnected by intercrystalline porosity produced by dolomitization that changed the isolated moldic porosity into effective porosity (Fig. 8H). Pervasive dolomitization was not directly related to particular rock constituents. The whole rock was replaced by dolomite. The primary porosities were not commonly preserved or filled with anhydrite in the latter stages of diagenesis. The general texture influenced by fabric destructive dolomite (pervasive dolomitization) contains two outstanding features: (1) the allochems are still identifiable, and (2) only ghosts of the original fabric remain (Fig. 8I).

In the Surmeh Formation, dolomitization has rarely produced any suitable/appreciable porosity in the mud-supported facies except in dolosparites that formed from euhedral crystals showing some intergranular porosity. The highest porosity occurs in grain-supported facies due to partial dolomitization and dissolution of calcite allochems in late diagenetic phases (Fig. 9).

7. Diagenetic environments of the Surmeh Formation

Based on the aforementioned diagenetic features, two main diagenetic environments, i.e. marine phreatic and meteoric phreatic are distinguished. The diagenetic processes and their related environments are summarized in Fig. 9. The marine diagenetic processes include formation of micrite envelopes, isopachous fibrous calcite cements, early dolomitization and anhydrite cement. Anhydrite cement and dolomicrite developed in supratidal marine phreatic diagenetic environments as a result of evaporation and the corresponding increase in the Mg/Ca ratio. Formation of equant and syntaxial cements, partial dissolution of grains, aggrading neomorphic fragments (aragonite bioclasts fragments inverted into calcite) resulted during the transition from marine phreatic into meteoric phreatic conditions. The latter stage continued with selective dissolution of allochems in ooid-bearing sediments and in bioclastic fragments, which have significantly influenced reservoir quality (moldic and vuggy cavities). The influx of freshwater, unsaturated with “aragonite” and magnesium (but containing some “calcite”) resulted in dissolution of aragonitic grains. The resulting increase in dissolved ions produced saturated

water in the following stage and precipitation of cement with more stable phases such as equant calcite.

8. Sequence stratigraphy

Depositional sequences, systems tracts and parasequences of the Surmeh Formation were recognized, according to the stacking pattern of the studied beds, sedimentary cycles and their relative sea-level equivalents (Vail et al, 1977; Haq et al., 1988; Miall, 2000; Golonka and Kiessling, 2002). Furthermore and importantly, 7.5 million years are considered for deposition of these depositional sequences throughout the Late Jurassic. Three third-order sequences can be substantiated in this study (Fig. 10). It should be stressed that the lagoonal facies are considered to represent the maximum flooding surfaces (mfs) for all depositional sequences due to the lack of other deeper facies (e.g., open marine). In addition, sequence boundaries are indicated based on a combination of methods including core observations, microfacies analyses and presence of evaporite minerals along with gamma ray logs (Fig. 10).

8.1. Depositional sequence 1: This sequence is topped by a sequence boundary type 2 and the same type of sequence boundary at the bottom (Emery and Myers, 1996; Al-Husseini, 1997; Coffey and Read, 2004). The sequence is about 31.8 m thick and composed mainly of lagoonal deposits (MF5, MF6) and rarely of intertidal microfacies (MF4) (Fig. 10). The time span for deposition of the sedimentary sequence is estimated to have lasted about 1.6 million years. The sequence consists of a transgressive systems tract (TST) and a highstand systems tract (HST) (Fig. 10). The TST (11.41 m thick) consists of a lagoonal microfacies (MF5, MF6) which indicates a retrogradational trend. The maximum flooding surface (MFS) was placed at the top of this succession, representing a mud-supported facies of a lagoon environment. The highstand systems tract (HST) is bounded by the maximum flooding surface (mfs) at the bottom (bioclastic packstone/wackestone) and sequence boundary type 2 at the top. This systems tract is 20.4 m thick and it ended with the intraclastic grainstone of MF9.

8.2. Depositional sequence 2: This sequence is subdivided into a transgressive (TST) and a highstand systems tracts (HST) (Fig. 10). Its sequence boundaries that indicate maximum sea level fall is marked by the anhydrite deposits that are located in the respective late HST package. This sequence measures about 22 m in thickness, and deposition of the sequence is estimated to

have lasted approximately 1 million years. The sequence is characterized by lagoon and intertidal facies. The TST (9 m thick) was deposited within in about 0.5 million years. The TST interval is characterized mainly by microfacies MF5 (lagoon) and MF4 (intertidal), indicating a retrogradational stacking pattern. The bioclastic packstone/wackestone (MF5) indicates a maximum sea level rise (mfs). The HST (13.04 m thick) was deposited in a time span of approximately 0.7 million years.

8.3. Depositional sequence 3: This depositional sequence was bounded at the top and bottom by sequence boundaries of type 1 as suggested by the presence of deposits showing microfacies MF1 and MF2, respectively. The upper sequence boundary corresponds to the Surmeh Formation/Hith Formation boundary. This sequence is 96.2 m thick and includes TST and HST. This third sequence was deposited in about 4.8 million years. The TST (39.1 m thick) is composed of lagoonal (MF5) and intertidal (MF4) facies, representing relatively deeper conditions in contrast to the uppermost sequences of the Surmeh Formation (Fig. 10). The MF5 is considered to be the deepest identified facies and consequently representing the mfs. The HST began with deposition of microfacies MF3 and continued with MF1 and MF2 in peritidal environments. This systems tract reaches up to 57.06 m in thickness and was deposited in roughly 2.9 million years.

8.4. Interpretation: Since the Jurassic, the carbonate platform in the Neo-Tethys basin of the Zagros region was covered by water several times, and abundant parasequences formed with different thicknesses. Small-scale shallowing cycles could have been controlled by autocyclic and allocyclic processes (Lasemi, 1995). Both shallowing and deepening third-order cycles of the Surmeh Formation correspond to those outlined in Haq et al. (1988), Ross and Ross (1988) and Sloss (1988). The super-sequence of the Surmeh Formation corresponds to a part of the Zuni I super-cycle. Zuni I (Fig. 10) is a part of a bigger hierarchy, namely the “Zuni Megacycle”. The Upper Jurassic Zuni Megacycle went through a sea-level rise, and the Zuni I super-cycle shows sea-level fall. This may be attributed to the influence of local tectonics, which produced changes in depositional conditions (Zecchin, 2005, 2006; Carpentier et al., 2007; Rosas et al., 2007) and consequently led to formation of third-order successions of the Surmeh Formation.

9. Impacts of depositional facies, diagenesis and sequence stratigraphy on reservoir quality

Reservoir quality, reservoir geometry and architecture in carbonate rocks depend on several factors including stacking pattern, spatial distribution of depositional facies, secondary alterations (diagenetic processes) and sequence stratigraphic position (Ahr, 2008; Moore, 2013). The distribution of reservoir quality of the studied Surmeh Formation is highly variable and depends on a combination of multiple factors such as depositional facies, diagenesis and sequence stratigraphy of the studied rocks as will be discussed below.

9.1. Controls of depositional facies on the reservoir quality

Depositional facies is an important factor in controlling the porosity and permeability of non clastic reservoirs (Moore, 2013). In the studied formation, the dominant high-energy shoal facies (MF7-MF9) have the highest average core plug porosity and horizontal permeability (Table 2). The peritidal (MF1-MF4) and lagoonal (MF5-MF6) facies have a moderate to poor/none (lowest) average core plug porosity and horizontal permeability (Table 2).

9.2. Controls of diagenetic processes on the reservoir quality

Diagenetic alterations not only changed the primary detrital composition but also affected the porosities and permeabilities of the rocks because of compaction, neomorphism, cementation, authigenesis, dolomitization and dissolution. These diagenetic processes may enhance and/or reduce the porosity and permeability of the carbonate rocks (Moore, 2013). According to our observations to the diagenetic features in the Surmeh Formation, it is found that the poikilotopic anhydrite cements played the most significant role in decreasing reservoir quality (Table 2). In contrast, widespread dissolution, bioturbation, dolomitization and formation of moldic and vuggy pores contributed to enhance reservoir quality (Table 2).

9.3. Controls of sequence stratigraphy on the reservoir quality

The sequence stratigraphic framework plays a significant role in carbonate reservoir evaluation (Moore, 2013). In the studied section, the HST facies (shoal facies, MF7-MF9) have a higher average horizontal permeability and core plug porosity than the TST facies (intertidal, MF2-MF4, and lagoonal, MF5-MF6, facies), except the HST of the sabkha facies (evaporites) where the reservoir quality is poor (Table 2). The HST facies were principally deposited in shoals, while the TST facies were mostly deposited in intertidal to lagoonal settings. This declared that the HST facies were diagenetically situated in a more exposed environment than

the TST facies which resulted in more leaching by meteoric water during the eodiagenesis than in the TST facies. This may explain the higher porosity and permeability of the HST facies in comparison to those of the TST.

Conclusions

Reservoir quality is one of the most important aspects of the oil industry which dominantly relies on the depositional architecture, diagenetic alterations and sequence stratigraphic framework of the rocks. Therefore, the carbonate-evaporite succession of the Upper Jurassic Surmeh Formation (Salman Oil Field, Persian Gulf) provided an opportunity to systematically study the direct links between the sedimentological properties of carbonate rocks (depositional facies, diagenetic alterations and sequence stratigraphic framework) and reservoir quality. The Surmeh Formation consists of nine microfacies types that include massive, nodular and laminated anhydrite with chicken-wire fabric, dolomudstone, mudstone with crystals and anhydrite nodules, wavy to laminated dolostromatolitic boundstone, bioclastic dolopackstone/dolowackestone, peloid-bioclastic dolopackstone/dolowackestone, peloid-bioclastic dolograinstone, peloidal-oidial dolograinstone, ooid dolograinstone, and bioclastic-intraclastic dolograinstone. These microfacies types indicate that the Surmeh Formation was deposited in three different depositional environments, namely peritidal flats (sabkha and intertidal), restricted inner lagoons and shoals that formed on inner part of a homoclinal carbonate ramp. In the recorded microfacies, the shoal facies have the highest average core plug porosity and horizontal permeability. On the other hand, the peritidal and lagoonal facies have a moderate to poor/none (lowest) average core plug porosity and horizontal permeability.

The Surmeh Formation was subjected to both marine and meteoric diagenetic processes: dolomitization, anhydritization, micritization, neomorphism, compaction and dissolution. In most cases, dolomitization enhanced reservoir quality, whereas anhydritization led to a loss of the reservoir quality. The recorded secondary porosity types include intergranular, intragranular, vuggy and moldic cavities. The highest porosity occurs in grain-supported facies due to partial dolomitization and dissolution, which in turn enhanced the reservoir quality. By sequence stratigraphic analysis three third-order sequences were recognized in the studied formation, each of which consists of highstand systems tract (HST) and transgressive systems tract (TST). The

HST facies show a higher average horizontal permeability and core plug porosity than the TST facies. Consequently, the depositional facies, diagenesis and sequence stratigraphic elements of the studied rocks affected the reservoir quality. This study represents an approach to use the sedimentological characters (depositional facies, diagenesis and sequence stratigraphic elements) of carbonate rocks for a more successful reservoir characterization.

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Figure and table captions

Figure 1. Location map of the Salman and other Iranian oil fields (red) in the Persian Gulf and main geological provinces/structural subdivision of SW Iran.

Figure 2. Generalized Mesozoic lithostratigraphy rock units at the Salman Oil Field in the Persian Gulf. Equivalent names for southern Persian Gulf stratigraphy are also listed (after Setudehnia, 1978). In order to avoid confusion with the past records of the field, southern Persian Gulf stratigraphic names are always referred to in brackets. The Surmeh Formation (Upper and Lower Arab Formations) comprises a major reservoir in the Persian Gulf Basin.

Figure 3. Lithostratigraphic chart of the Mesozoic of the Zagros Basin (after James and Wynd, 1965).

Figure 4. Sketch showing cross-section and contour map of the Salman Oil Field above a salt dome (based on 2D and 3D seismic studies). The cross-section shows the top of the Surmeh Formation. Red lines represent faults. These faults functioned as migration paths and led to the accumulation of hydrocarbons in this giant oil field trap. Abbreviations: W (well), UB (Upper Buwaib Formation), LB (Lower Buwaib Formation), UA (Upper Arab Formation), LA (Lower Arab Formation).

Figure 5. Core photographs and thin-section photomicrographs in the rocks of the studied Surmeh Formation showing: (A) Massive anhydrite, (B) Sparse anhydrite nodules (arrows), (C) Anhydrite showing chicken-wire fabric, (D) Laminated anhydrite, (E) Dolomudstone (MF2), (F) Mudstone containing sparse crystals and anhydrite nodules (MF3), (G) Wavy to laminated boundstone (MF4), (H) Bioclastic packstone to wackestone (MF5), (I) Peloidal bioclastic

packstone to wackestone (MF6), (J) Peloid-oid grainstone (MF7), (K) Ooid grainstone (MF8), and (L) Bioclast intraclast grainstone (MF9). Abbreviations: Pel (peloid), Alg (algae), Opl (peloid as nuclei of ooids), Me (remnant of micritic envelope), and Ght (ghost).

Figure 6. Proposed carbonate ramp depositional model for the Surmeh Formation, with indication of the reservoir quality. MF: microfacies, MSL: mean sea-level, FWWB: fair-weather wave base.

Figure 7. Thin-section photomicrographs showing different diagenetic features. (A) Physical compaction resulted in grain fragmentation in shoal facies, (B) Stylolite cut by a fracture in boundstone facies, (C) Bioturbation in lagoonal facies, (D) Micritized coral, (E) Drusy cement, (F) Poikilotopic anhydrite cement filled pores in shoal facies, (G) Fracture filled with fine- to medium-grained equant crystals of anhydrite, (H) Anhydrite cement plugging most of intragranular pores (arrows), (I) Neomorphism in shoal facies, (J) Intergranular porosity (pores arrows), (K) Vuggy porosity (arrows), (L) Fenestral porosity. Abbreviations: Eqn (equant calcite cement), Iso (isopacheous fibrous cement), Fr (fracture porosity), Sty (stylolite), Blc (blocky calcite cement) and Fn (fenestral porosity).

Figure 8. Photomicrographs illustrating different crystal types of dolomite cement crystals in the studied rocks. (A) Dolomicrite, (B) Partly sparitic dolomicrosparite, (C) Anhedral crystals of dolosparite, (D) Coarse euhedral crystals of dolosparite, (D) Scattered crystals of dolomitic limestone floating in limestone matrix, (E) Scattered crystals of dolomitic limestone in wackestone facies, (F) Partial/selective dolomitization leaving allochems unaffected, (G) Calcitic matrix replaced by dolomite, (H) Dissolution produced moldic porosity, (I) Fabric destructive dolomitization is characterized by the ghost of allochems. Abbreviations: Ps (pore spaces), and Smo (separate ooid molds).

Figure 9. Sketch diagram showing the proposed diagenetic model in the studied Surmeh Formation.

Figure 10. Correlation chart showing microfacies types, depositional environments, relative sea-level changes and third-order sequences determined in the Surmeh Formation. Gamma-ray log and lithological variations are also included. Abbreviations: Supra (supratidal), Inter (intertidal),

790 SB (sequence boundary), TS (transgressive surface), TST (transgressive systems tract), HST
791 (highstand systems tract) and mfs (maximum flooding surface).

792 **Table 1.** Microfacies types, facies associations and depositional environments of the studied
793 rocks in the Surmeh Formation. Dominant sedimentary structures/fabrics and main components
794 of the microfacies are shown.

795 **Table 2.** Reservoir quality of the microfacies and systems tracts in the Surmeh Formation.

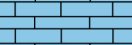
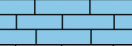
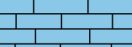
Facies associations	Microfacies code	Microfacies type	Sedimentary structures/fabrics	Main components	Water energy	Depositional environment
Peritidal flat	MF1	Massive, nodular and chicken-wire anhydrite	Anhydrite crystal shapes vary from parallel and sub-parallel crystals to a combination of equant, felted and lath crystals with random and irregular orientation	Anhydrite crystals	None to very low	Coastal sabkha and shallow hypersaline lagoon; RMF25
	MF2	Dolomudstone	Minor amount of anhydrite crystals; dolomudstone is locally laminated and bioturbated	Fine-crystalline dolomite rhombs	Very low	Supratidal; RMF22
	MF3	Mudstone with sporadically occurring anhydrite nodules	Anhydrite nodules with lath and felted textures	Very fine bioclasts, peloids and lithoclasts	Very low	Sabkha; RMF25
	MF4	Dolostromatolitic boundstone	Fenestral fabric and wavy laminae	Commonly peloids and microbial filaments	Low to moderate	Intertidal to supratidal; RMF25
Restricted inner lagoon	MF5	Bioclastic packstone/wackestone	Micrite envelopes and bioturbation	Green algae, foraminifers and bivalves, gastropods, echinoids and ostracods are rarely present	Moderate	Inner ramp (shallow lagoon); RMF17
	MF6	Peloid-bioclastic packstone/wackestone	Bioturbation and micrite envelopes	Peloids and bioclasts also green algae, bivalves and benthic foraminifers	Moderate	Inner ramp (restricted lagoon); RMF20
High-energy shoal	MF7	Peloidal-oidial grainstone	Lack of muddy matrix	Fairly sorted and well-rounded ooids, peloids and bioclasts	Moderate to high	Shoal; RMF29
	MF8	Ooidal grainstone	Cross-bedding and graded bedding	Well-sorted and rounded coarse- and medium-grained ooids, bioclasts; also intraclasts, oncoids and peloids are present	High	Shoal, tidal channel; RMF29
	MF9	Intraclastic grainstone	Cross-bedding and normal graded bedding less developed compared to MF8	Moderately to poorly sorted medium- to coarse-sized bioclasts, intraclasts and ooids	High	Windward shoal, tidal channel lag; RMF27

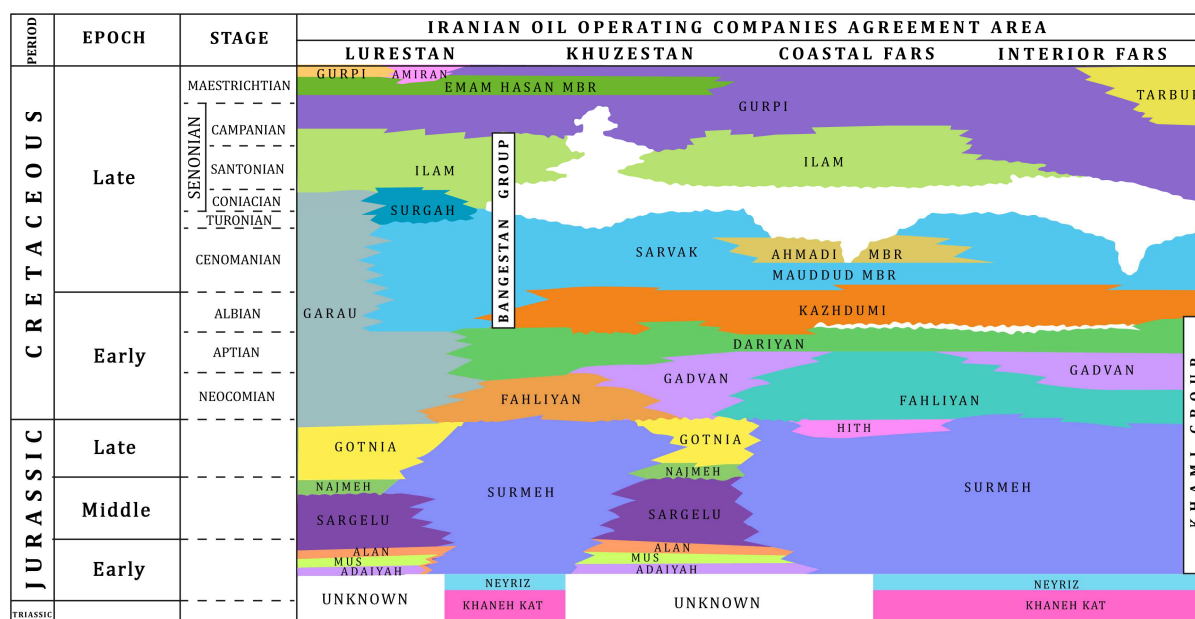
RMF = ramp microfacies type of Flügel (2010); MF = microfacies code

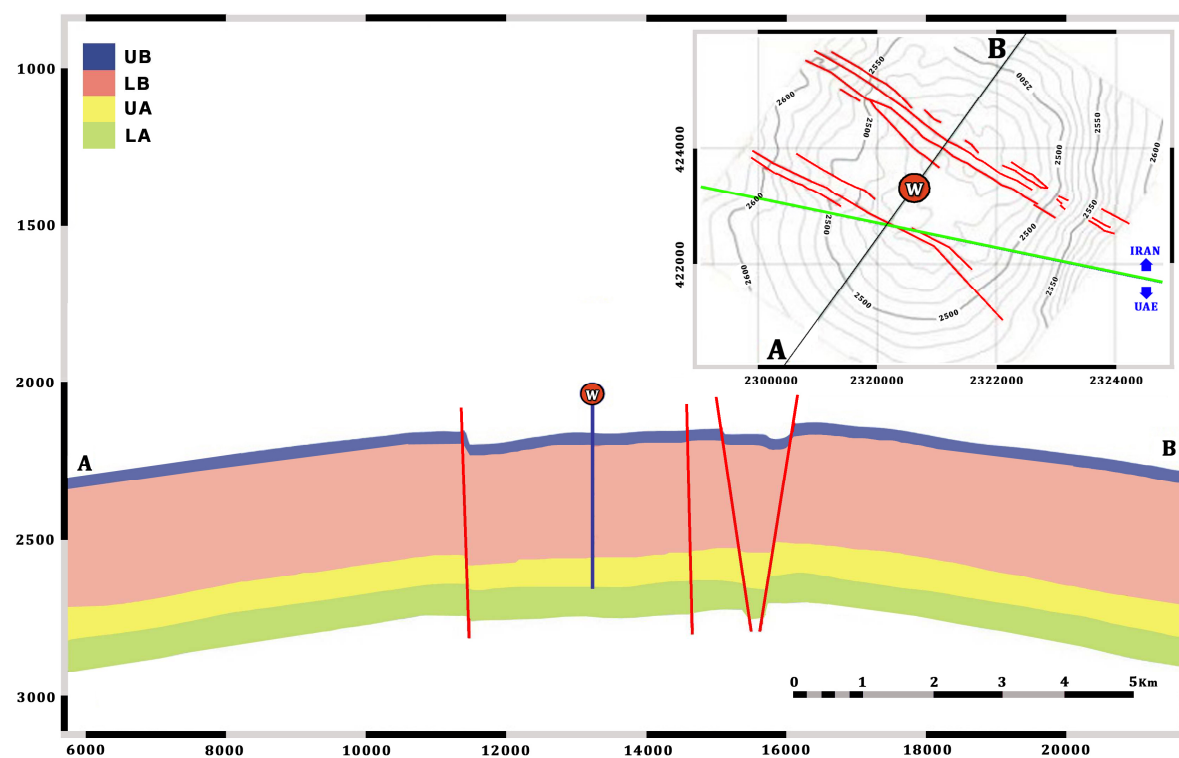
Microfacies code	System tracts	Diagenetic alteration	Porosity type	Reservoir Quality	Helium porosity (%)			Air permeability (mildarcy)		
					Max	Min	Ave	Max	Min	Ave
MF1	HST	Stylolitization; poikilotopic anhydrite fills intergranular porosity	–	None	1.10	0.20	0.64	0.574	0.009	0.292
MF2	HST	Recrystallization of carbonate minerals	–	Poor	30.00	0.50	7.26	511.00	0.001	43.414
MF3	HST	Mud cracks which are filled with anhydrite crystals; dolomitization	Very low amount of fracture porosity	None	4.90	0.80	0.86	10.490	0.002	0.481
MF4	TST	Cementation by poikilotopic anhydrite	–	Poor	12.40	1.10	7.52	13.699	0.009	3.446
MF5	TST	Micrite envelope	Intergranular and fracturing porosities; moldic porosity is commonly plugged by anhydrite	Poor	27.30	0.90	4.49	57.00	0.024	2.336
MF6	TST	Cementation by sparry calcite; replacement by anhydrite; aggrading neomorphism	Moldic and vuggy	Moderate	26.70	1.70	12.63	129.00	0.002	77.896
MF7	HST	Dolomitization	Intergranular, vuggy and moldic	Good	52.50	2.44	33.28	2099.501	0.098	125.368
MF8	HST	Dolomitization; anhydrite cementation; physical compaction	Intergranular, vuggy and moldic	Moderate to good	29.70	1.70	15.66	700.00	0.022	79.444
MF9	HST	Marine fibrous cements around ooid and bioclast grains; blocky cements; dissolution; dolomitization	Intergranular and moldic	Moderate to good	30.45	2.02	15.16	159.00	0.014	52.084

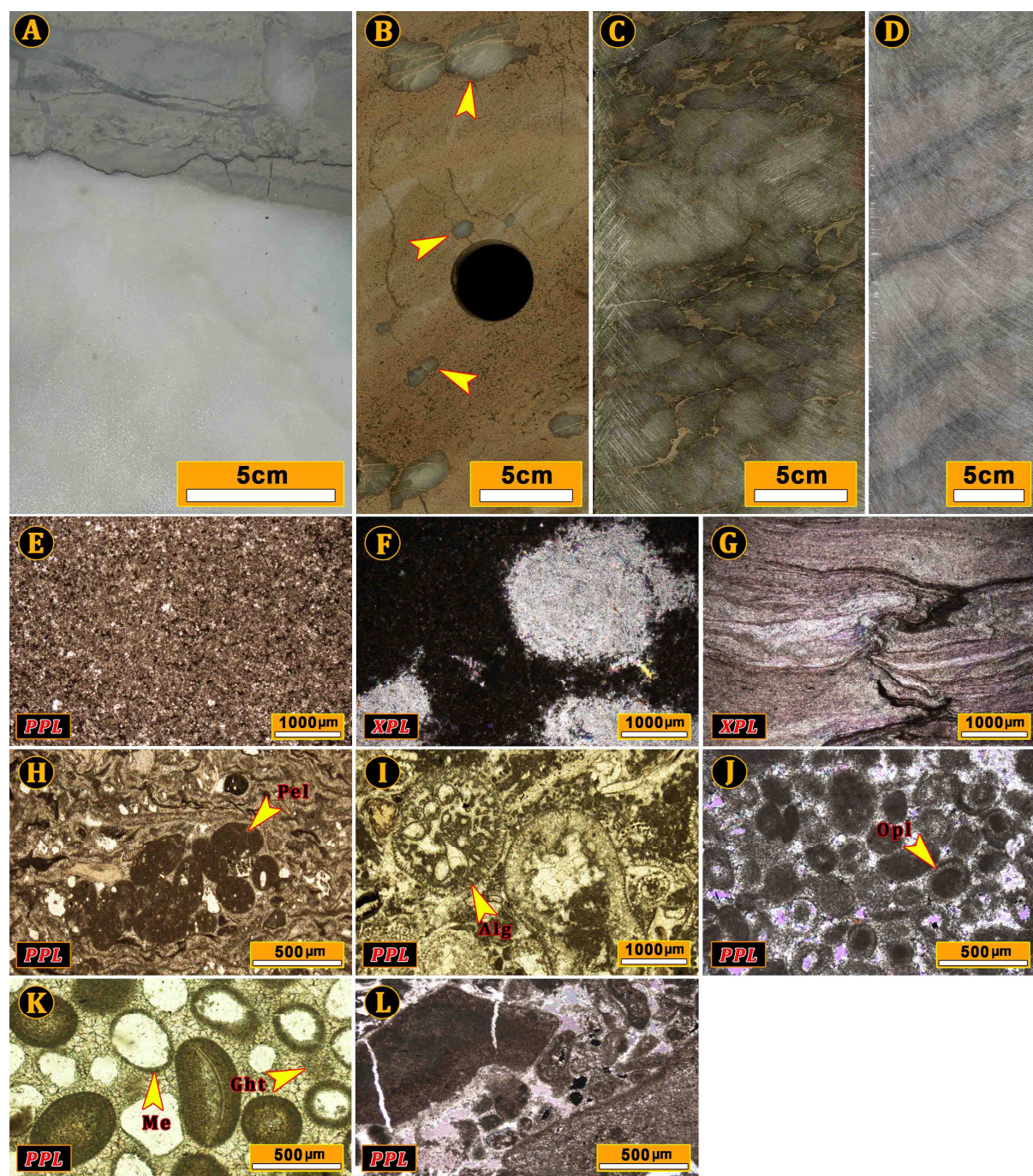
HST = highstand system tracts; TST = transgressive system tracts

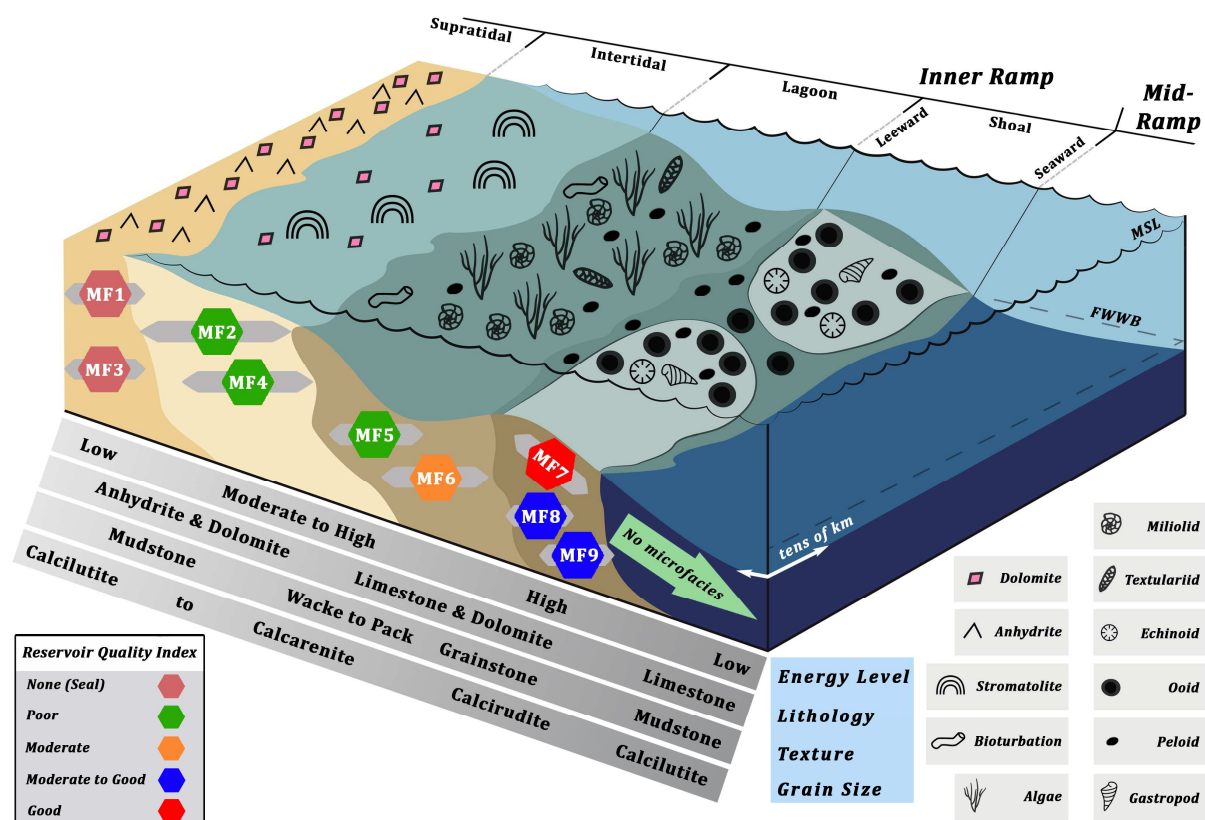


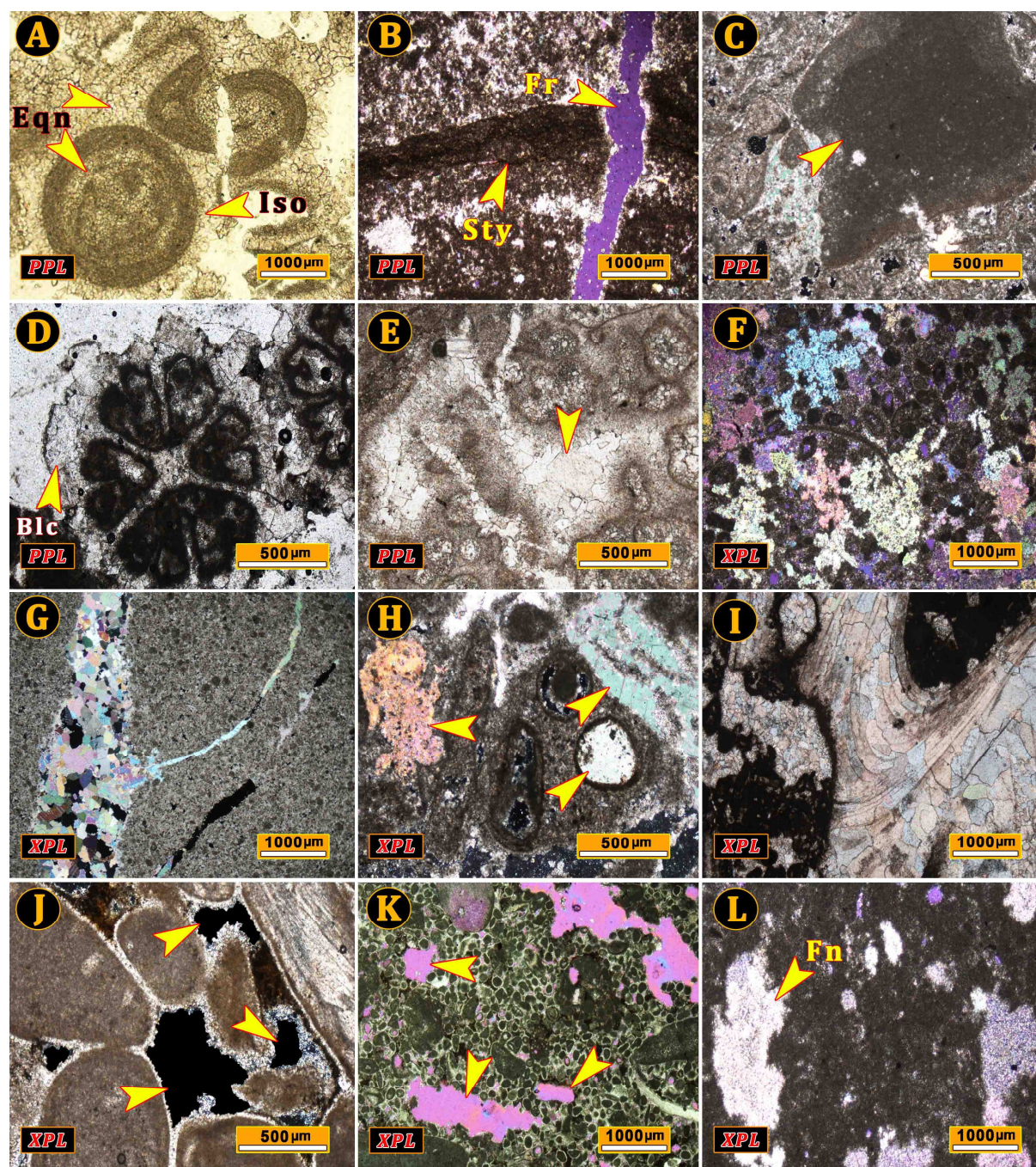
U.A.E./Qatar				Iran		Lithology	
Period	Epoch	Group	Rock Unit	Group	Rock Unit		
Cretaceous	Lower	Thamama	Shuaiba		Dariyan		
			Zubair		Gadvan		
			Upper Buwaib				
			Lower Buwaib (B1-B3)		Fahliyan		
			Yamama				
			Sulaiy				
Jurassic	Upper		Hith	Khami	Hith		
			Upper Arab (U1-U8)		Surmeh		
			Lower Arab (L1-L2)				
			Darb				
			Diyab				
			Upper Araej				
	Middle	Araej	Uwainat				
			Lower Araej				
			Izhara				
	Lower		Marrat		Neyriz		

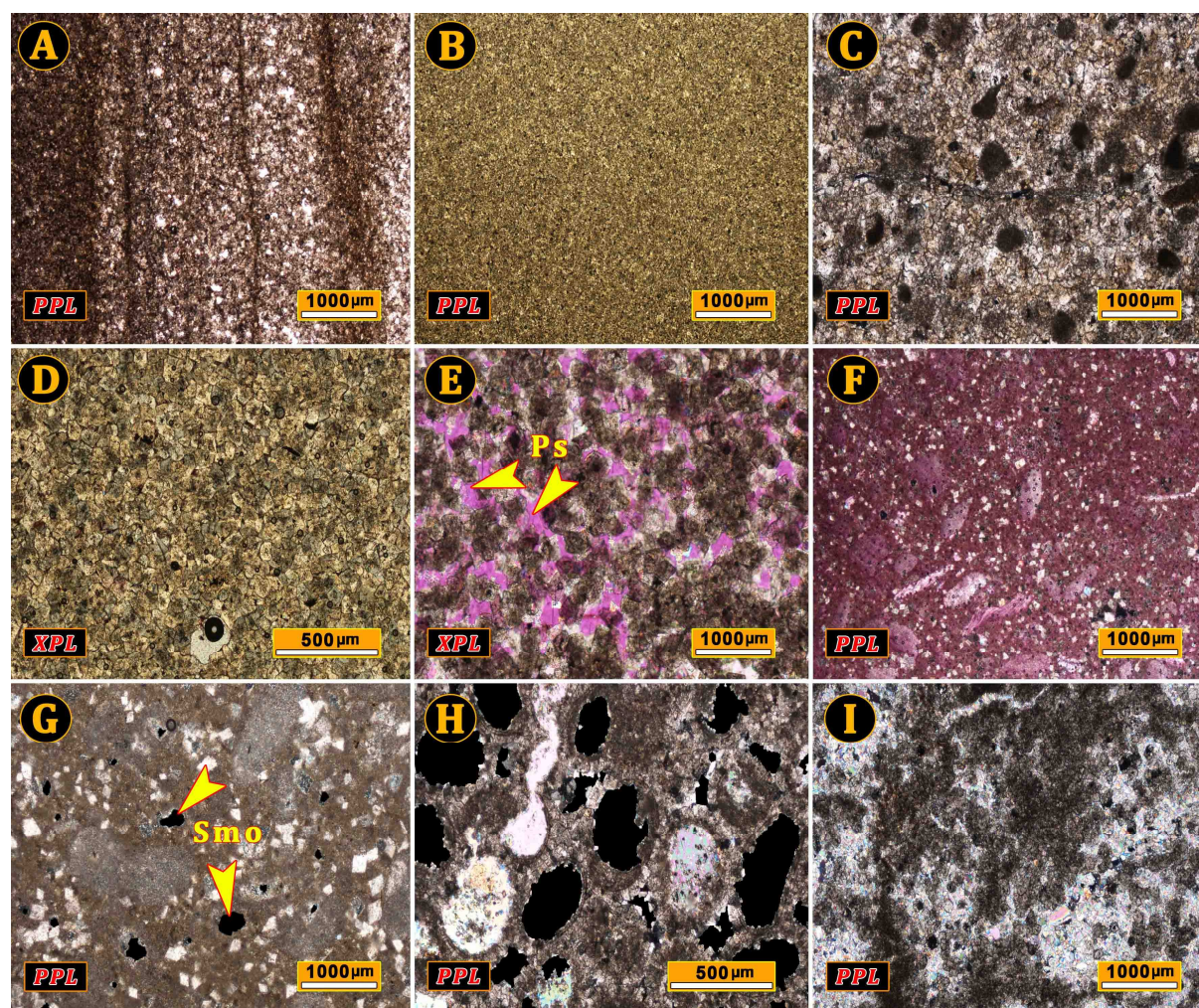


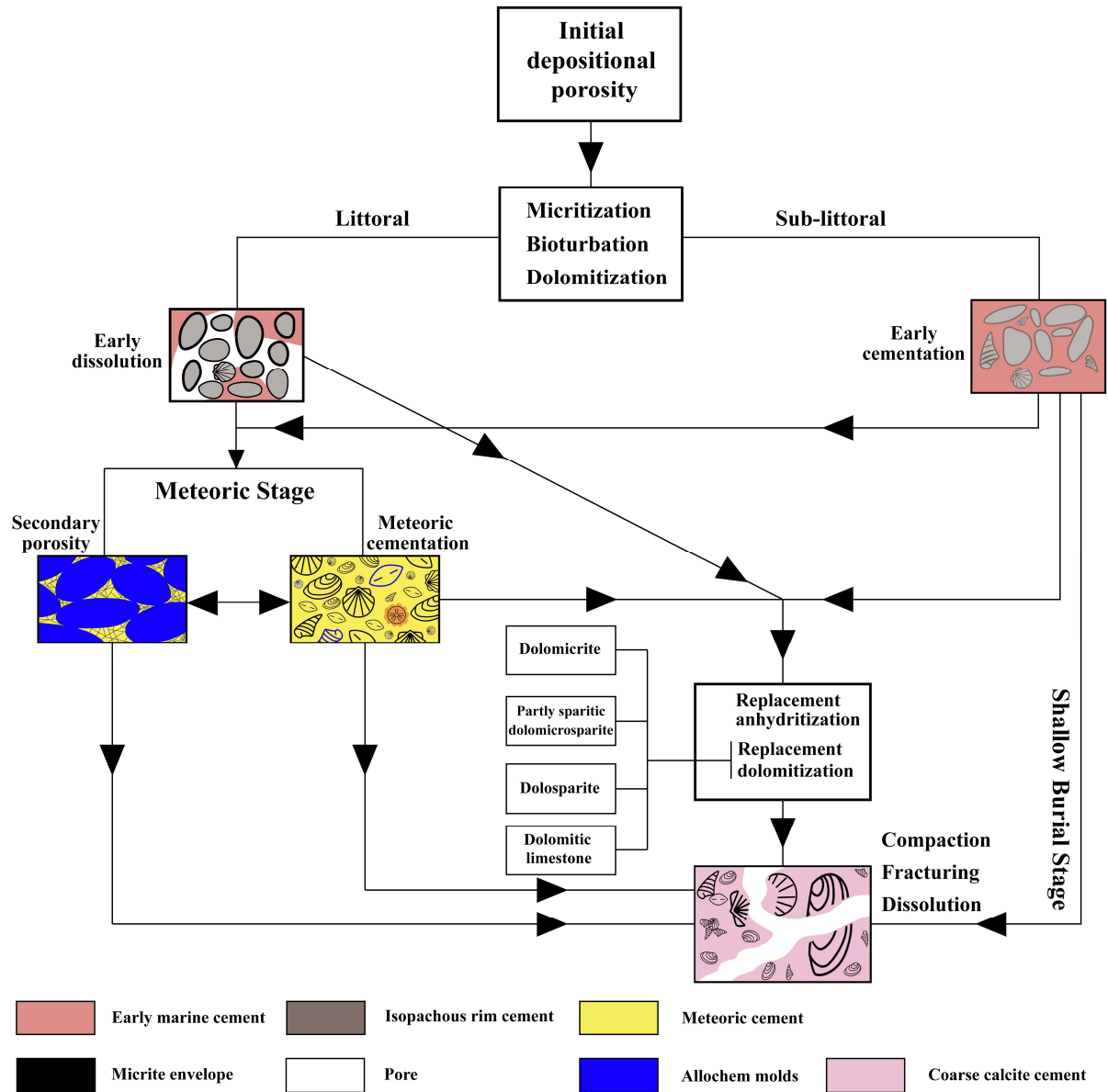














- The Surmeh Formation consists mainly of carbonate rocks, intercalated with evaporite layers.
- The recorded depositional environments are peritidal flat, lagoon and high-energy shoal.
- The studied facies revealed the presence of three third-order depositional sequences.
- The reservoir quality was controlled by the depositional facies, diagenetic alterations and sequence stratigraphy.