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ORIGINAL ARTICLE

# Microporosity evolution and destruction in the Jurassic Arab D reservoir, Qatar

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**Abstract**
Core samples were collected from three wells, one onshore and two offshore, from Qatar's Upper Jurassic Arab D reservoir. The samples were subjected to multiproxy petrographic and chemical analyses to identify their micro- and nanoporosity types and understand their evolution and destruction. Based on the petrographic and petrophysical properties of studied rocks, the Arab D succession was divided into seven rock types. Primary microporosity includes intergranular and interplanar, while secondary types include vuggy, intercrystalline, moldic, dissolution, pyrite displacement, microfracture, and microbial boring. Primary micropores were found mainly between the micrite grains in the lime mudstone facies, between the grains or the plates of clay minerals. Secondary micropores result from open and closed diagenetic systems. The open diagenetic system led to the development of dissolution and moldic micropores, while the closed system created pyrite displacement and boring porosity. Mechanical stress due to crystal growth or displacement generated microfractures. Micropores were destroyed either by cementation, clay minerals growth, dolomitization, or microbial pustular overgrowth. Microporosity was important in quantity and varied in nature in the mud-supported rocks. They are similar to macropores in grain-supported sediments but of less importance. The complex lithology of the studied rocks has significantly influenced the development and destruction of the porosity system of the Arab Formation.

**Keywords** Microporosity · Carbonates · Arab Formation · Jurassic · Qatar

## Introduction

Carbonate reservoirs with significant microporosity are common in the geologic column of the Middle East. These are formed of rocks deposited in shallow tidal shelves or coastal lagoons. They were dominant during the Triassic and Jurassic, where evaporites represented a major lithologic component. Although up to 25% of macropores characterize these reservoirs, micropores (with an average size of 10 μm) have been increasingly recognized over the last few decades for their importance in enhancing the poroperm systems of these rocks. In an early study by Moshier (1989a) on microporosity in the Shuaiba Formation in Saja Field, UAE, the development of these pores was attributed to the nature of the micritic limestone rather than to the diagenetic processes as considered at first. However, in a review paper, Moshier (1989b) stated that the solution of the micro versions of molds, vugs, and channels might primarily enhance microporosity. Volery et al. (2009) investigated the relationships between the development of microporosity with the stratigraphic distribution of strata in some Middle Eastern carbonates and variation in the Mg/Ca ratio in seawater. They divided these reservoirs into three packages: the Late Carboniferous to Triassic strata deposited in aragonite seas, the Cretaceous sediments formed under calcite sea, and the Cenozoic deposits precipitated under the transition from calcite to aragonite seas. They suggested that no significant microporous carbonates existed in the Late Carboniferous to Triassic strata. This assumption lacked support due to extensive microporous carbonate reservoirs in the Triassic strata of the northern parts of the Arabian Plate (Sadooni and Alsharhan 2004). Mehrabi et al. (2020) used integrated sedimentological, geochemical, and reservoir data to characterize the microporous intervals of the Sarvak-Ilam Formation in ten oil and gas fields in SW Iran. Micropores in the

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studied strata were determined to occur under either an open diagenetic system near the surface, where meteoric water modified the sediments and created micro molds, vugs and channels, or under a deep closed diagenetic system with limited water flow and reactivity. In this case, the most dominant micropores types were interparticle and intraparticle.

In their study of the Arab Formation in Saudi Arabia, Cantrell and Hagerty (1999) recognized four types of micropores in these strata: microporous, matrix, fibrous, and bladed and equant cement. They suggested that the microporosity counts for 0–100% of the total porosity. They attributed the porosity types to their primary texture, grain mineralogy, and microstructure. They concluded that microporosity might develop through leaching, inhibition of crystal growth, and microbial boring. Eltom et al. (2013) studied the microporosity of the Arab D member in outcrops in Wadi Nisah, Saudi Arabia. Three micropore types were identified, including micropores occurring between macro- and microsparry calcite cement, between micrite grains, and within macrodolomite rhombs. They suggested that the distribution of these micropores was affected by the distribution of cement, the presence or absence of dolomite, and variation in micrite size, shape, and sorting. They reported a weak correlation between microporosity and permeability in the total samples, but the correlation was improved within specific rock types.

## Geologic setting

The Arab Formation is an important hydrocarbon reservoir in central parts of the Arabian Plate, including Saudi Arabia and Qatar. It is the main reservoir at Ghawar Field, Saudi Arabia, the most prominent and prolific field globally (Powers 1962). In addition, the Formation represents a significant play in Qatar's offshore (Bul Hanine and Eid Al-Shargi) and onshore (Dukhan) oilfields (Fig. 1). The Formation was described for the first time by Steineke et al. (1958) from the Dammam well 7, Saudi Arabia, which has since been selected as its type locality. The same terminology was imported, through regional correlation, to Qatar by Sugden and Standring (1975). The Arab Formation is assigned to an Upper Jurassic (Kimmeridgian) age based on the ammonite and benthonic foraminifera population (Lindsey et al. 2006). Although the Formation has been divided into four members (A-D), the basic lithologies are the same. In general, the Arab Formation consists of three persistent lithologies: limestone, dolomite, and anhydrite (Fig. 2). The limestone is divided into either oolitic or skeletal grainstone/ packstone or microbial mudstone with dolomite and anhydrite. The Formation is underlain by the Jubaila Formation, which comprises algal limestone and dolomite. The Arab Formation consists of a series of shallowing-upward, third-order sequences, with the final phase of each younger sequence becoming shallower and more evaporitic. Its depositional system was terminated by the deposition all over the region of thick, widely distributed evaporites of the Hith Anhydrite Formation that signaled the end of the Jurassic depositional system (Moore and Wade 2013).

The Arab Formation was thought to represent a giant sabkha during the Late Jurassic all over eastern Arabia (Leeder and Zeidan 1977; Alsharhan and Kendall 1994). However, the depositional model of the Formation was revised by Al-Saad and Sadooni (2001), who suggested the development of local coral, algae, sponge, and stromatoporoid-bearing buildups in the Late Jurassic shelf that differentiated it from the open Tethys to the east. This configuration led to the development of many local basins, where low stands gypsum wedges were deposited. In addition, halite was precipitated in depressions such as the Gotnia Basin in southern Iraq. Slight variations in water depth caused the flooding or exposure of such buildups, resulting in the cyclic nature of the sediments and forming shallow-water carbonates on the flooded tidal flats (Fig. 3).

## Materials and methods

Rocks samples of the Arab Formation were collected from two offshore (Bul Hanine and Eid Al-Shargi) and one onshore (Dukhan) fields of Qatar, with some logs, porosity, and permeability data provided by *Qatar Energy*. Thin sections were prepared from the samples and subjected to XRD, XRF, and ICP analyses. These analyses were conducted at the *Gas Processing Center (GPC)* and *The Center of Advanced Materials (CAM)* at Qatar University. Selected samples were also examined under SEM coupled with EDX at the *Central Laboratories Unit (CLU),* Qatar University, to identify their major forming minerals, depositional and diagenetic features, and microporosity types and distribution. Collected data were plotted on Gamma Ray, Density, and Sonic logs from the three fields to trace the lateral changes in the reservoir units across the studied oilfields.

With the recent advances in resolution and analytical capabilities, a considerable amount of microporosity (Up to 10%) was reported from some parts of the carbonate reservoirs of the Middle East. Such reservoirs have been producing hydrocarbons for nearly a century from conventional pores (e.g., production in Kirkuk Field started in 1926) (Aqrawi et al. 2010). This discovery meant that some of the lithologic units of these reservoirs formed of lime mudstone, wackestone, and aphanitic dolomite and were considered compact and impermeable rocks representing potential reservoir rocks. With a porosity cutoff of around 8% in some Middle East carbonate reservoirs, such microporous units will significantly add to the netpay thickness. This also encourages exploration of such mud-supported rocks outside

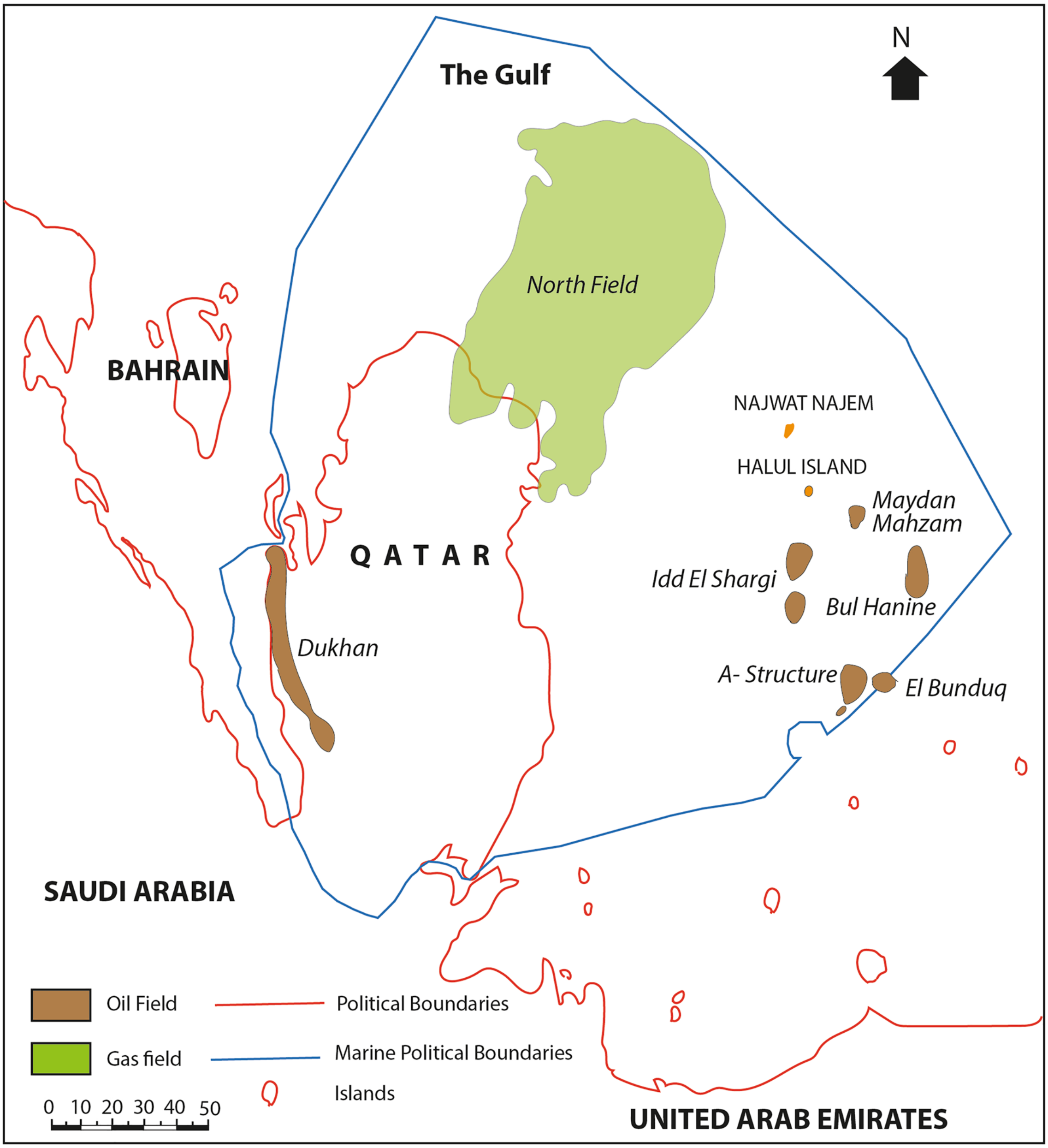


**Fig. 1** Location map showing the studied oilfields in Qatar (modified from Focke et al. (1986)

the usual oil provinces, such as the Triassic evaporitic tidal flats of northern Iraq and the Levant.

## Results

### Geochemical characterization

X-ray diffraction analyses of cored intervals of the Arab D reservoir (Fig. 4) showed that the studied rocks consisted of three major minerals, calcite, dolomite, and anhydrite, with minor amounts of pyrite and Quartz. The main lithologies formed by these minerals are dolomitic limestone, limestone with low amounts of quartz, and pyritic anhydritic dolomite. These lithologies are commonly found in the Arab Formation and reported in other countries in the region, such as Saudi Arabia. Plotting the major minerals versus their relative depths shows that calcite is the main component, forming up to 99%, while dolomite is the second component reaching up to 94% in some cases. Anhydrite is present in most studied sections ranging from 1 to 21% in the anhydritic dolomite. Anhydrite is present either in beds or as cement. Quartz is present only at specific depths, at less than 3%. Pyrite is found as traces only (Fig. 5a).

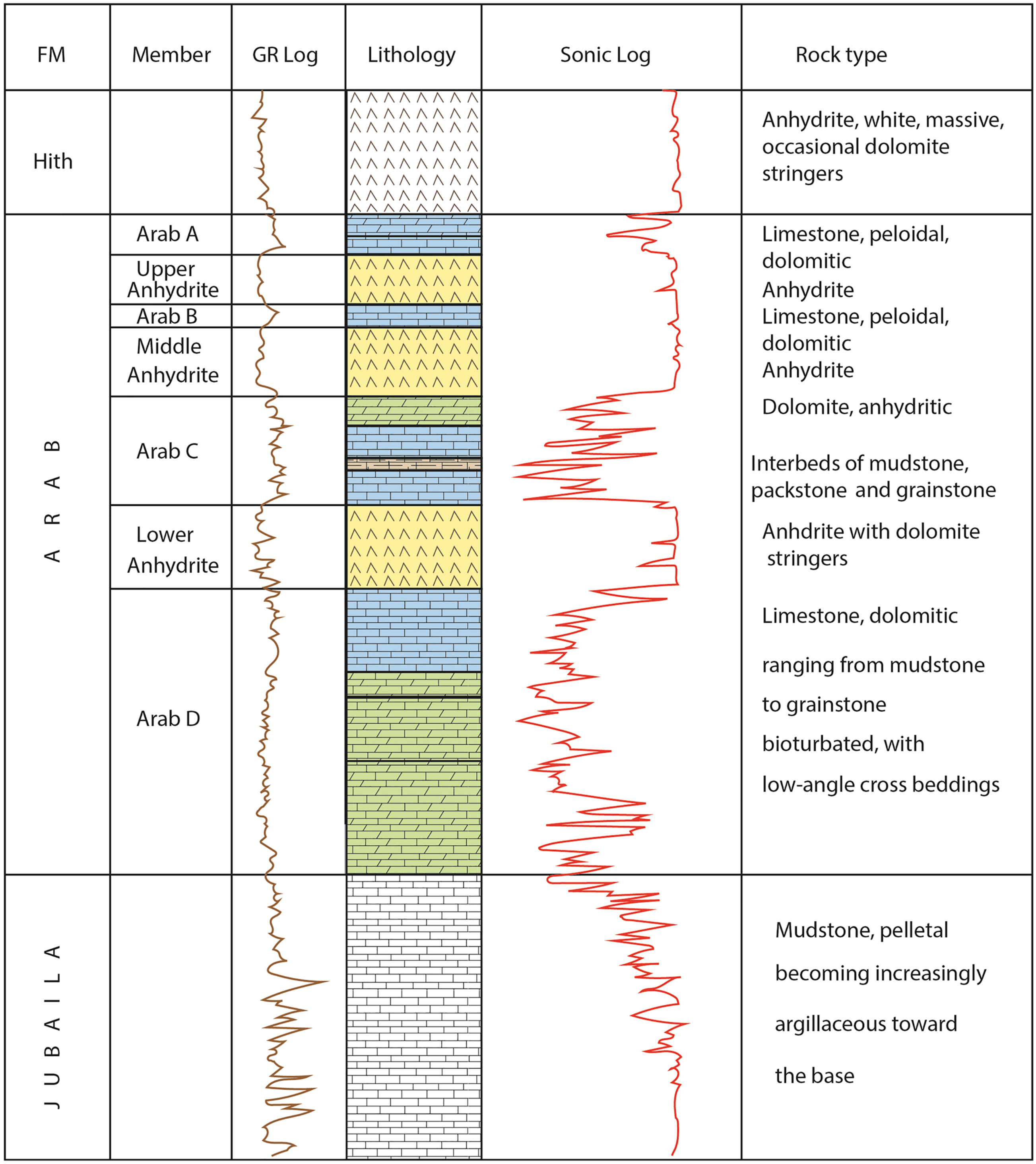


**Fig. 2** General lithologic column of the Arab Formation in the subsurface of Qatar

The elemental composition of the same interval showed some interesting lithologic variations in what appeared to be a homogeneous dolomitic limestone succession (Fig. 5b). Calcium (calcite) and magnesium (from dolomite) remained the predominant elements, as expected at 94 and 34%, respectively. However, samples containing up to 5.2% silicon were also associated with relatively high aluminum, potassium, and titanium contents. This mineral assemblage may suggest the presence of clay minerals indicating argillaceous limestone. Iron (up to 0.2%) and sulfur (up to 8.4%) were

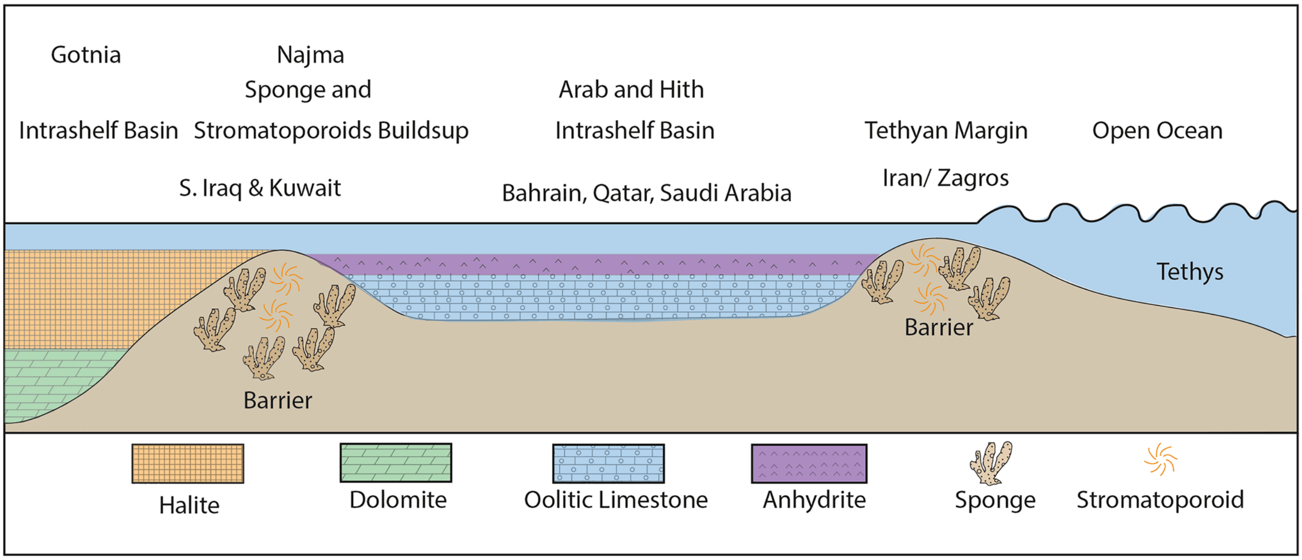


**Fig. 3** Depositional model of the Arab Formation (Modified from Al-Saad and Sadooni 2001)

the two most common minor elements. These two elements reflect the presence of the mineral pyrite ($FeS_2$). In addition, strontium could be found as celestine ($SrSO_4$) and reported from evaporitic environments in other areas (Carlson 1987). Finally, the presence of barium (1.5% in one sample) may have indicated the presence of either baryte ($BaSO_4$) or witherite ($BaCO_3$). Such heterogeneous minerals have different susceptibilities to diagenetic processes, making the system more vulnerable to compaction, dissolution, and cementation.

## Rock types

Rock types were identified based on criteria that included their depositional texture, diagenetic signature and porosity, and permeability nature and amount. Accordingly, the studied rocks were classified into the following rock types:

### Mudstone–wackestone

This rock type is widely distributed and has a lime mudstone or wackestone texture that may be dolomitized at parts with a considerable amount of argillaceous materials (Fig. 6A). It contains a fair quantity of microbial threads, bioturbation, and dwarfed echinoderms. These rocks are deposited under shallow lagoons with hypersaline waters that limit their biodiversity. The presence of microbial mats may indicate upper intertidal conditions. The main diagenetic processes comprise hard grounds, selective and extensive aphanitic and euhedral dolomitization, nodular anhydrite, and anhydrite cementation and dissolution. Dolomite may be microbially mediated similarly to the dolomite found in the intertidal zone of the present sabkha sediments. The relatively high amount of evaporites is associated with low water circulation and increased evaporation. Porosity types include small vugs and both intercrystalline and matrix porosity. Porosity is between 5 and 30% with 1–60 mD permeability. The relation between porosity and permeability was nearly linear, particularly at the lower permeability values (Fig. 7). Matrix porosity is the major form of porosity, and intercrystalline porosity is the dominant type in dolomitized sections. Other types were related to the dissolution of the unstable lithologic components by meteoric water. Bioturbation may have also contributed to porosity.

### Dolomitic mudstone and wackestone

This rock type is restricted to the upper few meters of the succession and consists of euhedral, medium-sized dolomite rhombs replacing what seems to be a peloidal wackestone and featureless mudstone. It was heavily bioturbated and leached. There was also a considerable amount of blocky anhydrite cement filling some pores (Fig. 6B). The facies lithology may indicate a lagoonal depositional environment. The major porosity types were dissolution, intercrystalline, and burrowing. Porosity values ranged between 6 and 30%, with a permeability of 1–80 mD. There was no clear relation between porosity and permeability values, which may be attributed to the selective dolomitization process (Fig. 7).

### Microbial dolomite

This rock type is also found in the upper part of the studied section and may be related to the above rock type.

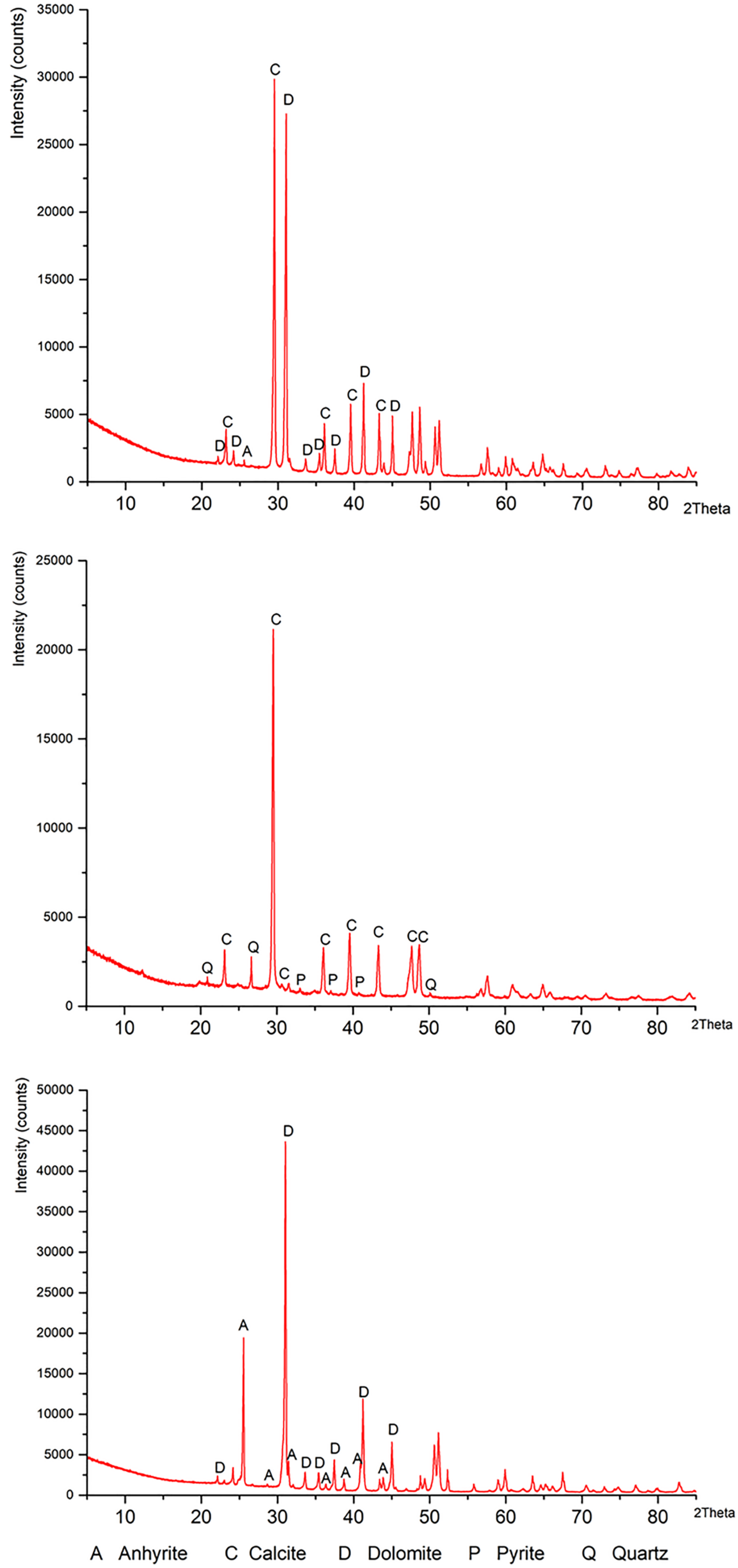


**Fig. 4** XRD graphs show the main minerals forming the studied rocks

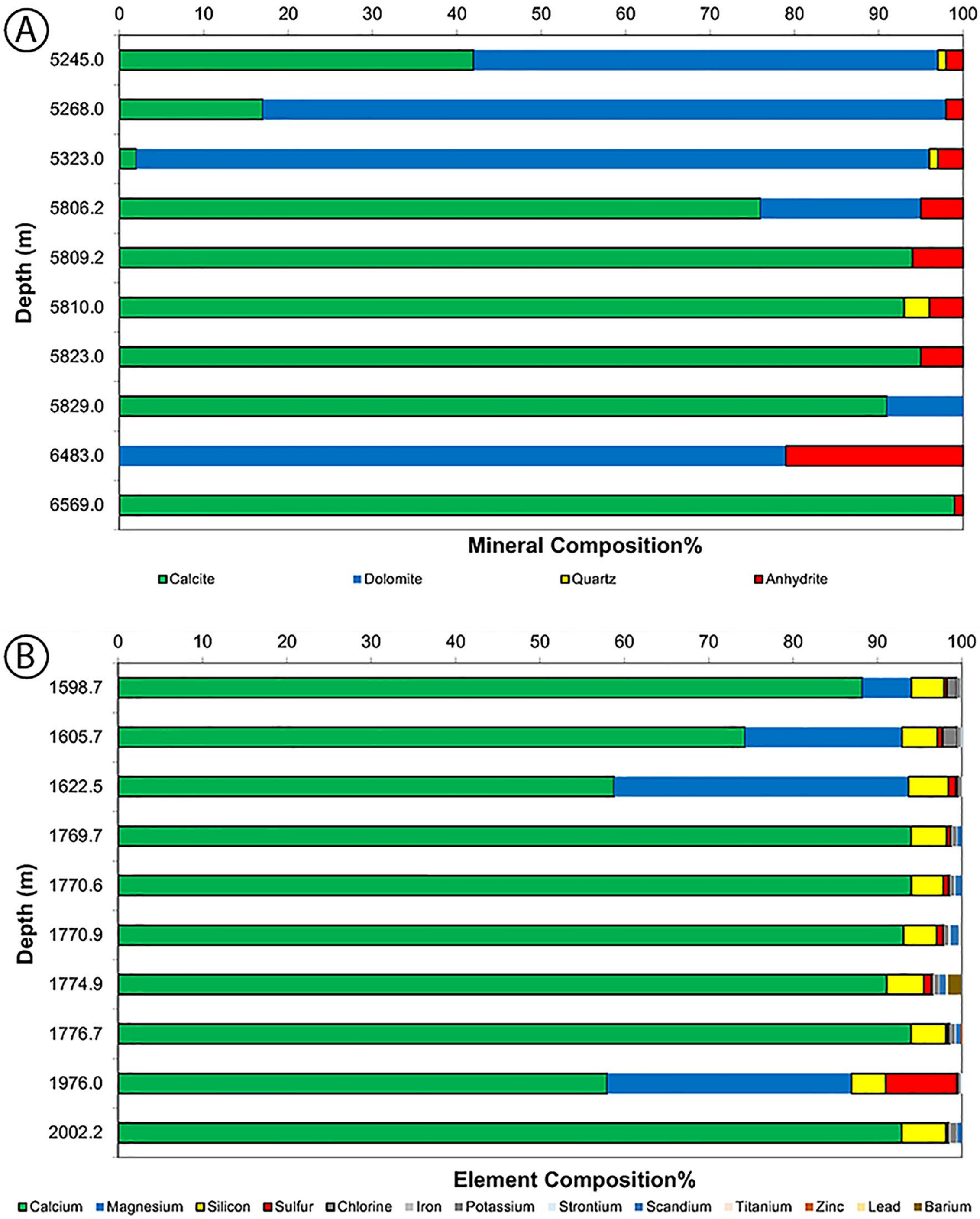


**Fig. 5** (Top) XRD analysis of the major rock-forming minerals, (Bottom) XRF elemental analyses show the main elements forming the studied rocks

It consists of alternating aphanitic dolomite with dark, organic-rich microbial laminations (Fig. 6C and D), with some hardgrounds and burrows. This rock type is probably like the microbial dolomite formed in present-day sabkhas' upper intertidal zone. The major porosity types are dissolution porosity which has resulted from the preferential dissolution of microbial materials, and intercrystalline porosity between fine dolomitic rhombs, with bioturbation porosity being a less important form. A porosity average of 16% has been recorded in this rock type, with permeability values of up to 500 mD. There was a considerable

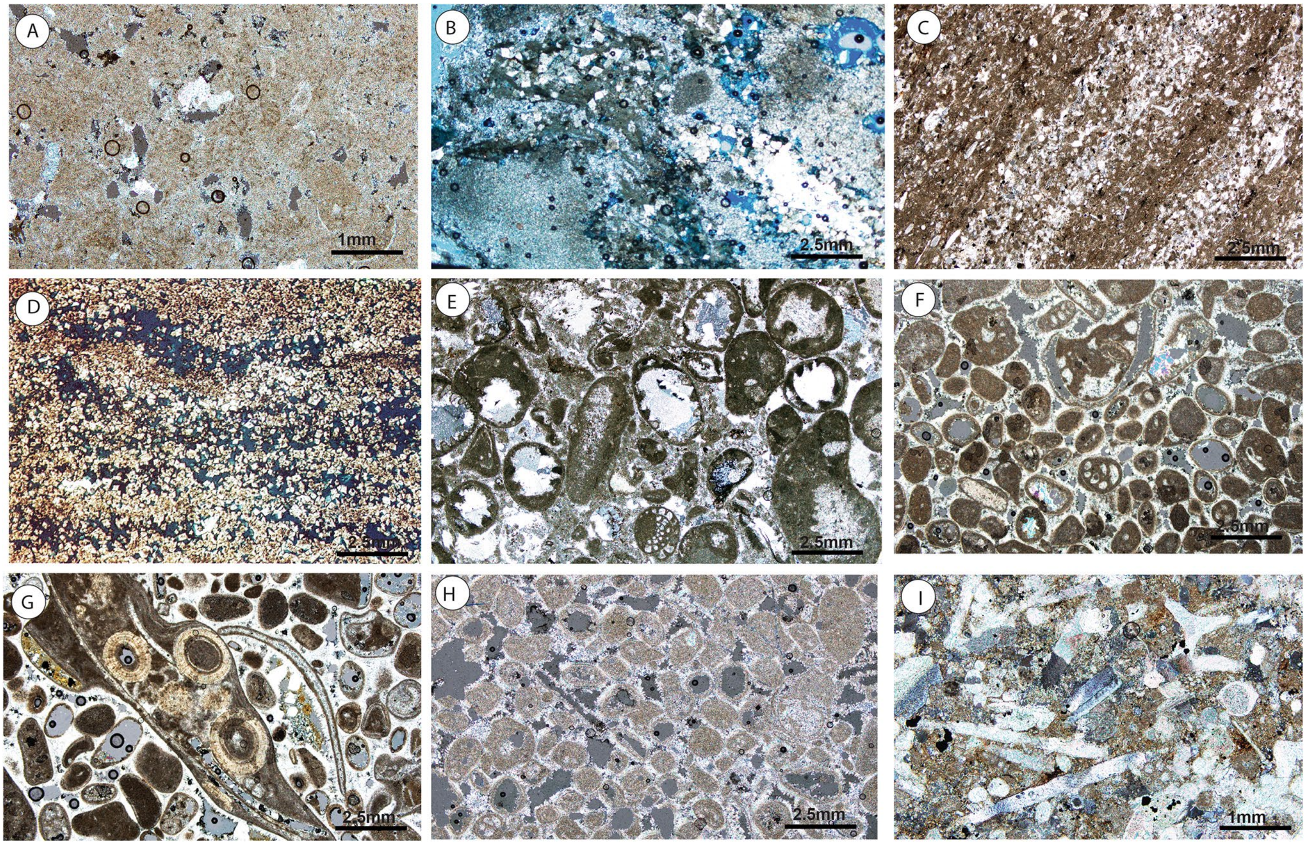


**Fig. 6** The main rock types of the Arab D Reservoir in Qatar are (**A**) mudstone and wackestone (**B**) dolomitic mudstone and wackestone (**C**) and (**D**) microbial limestone and microbial dolomite (**E**) skeletal packstone and grainstone (**F**) and (**G**) skeletal grainstone (**H**) peloidal packstone and grainstone (**I**) buildup boundstone forming of sponge spicules

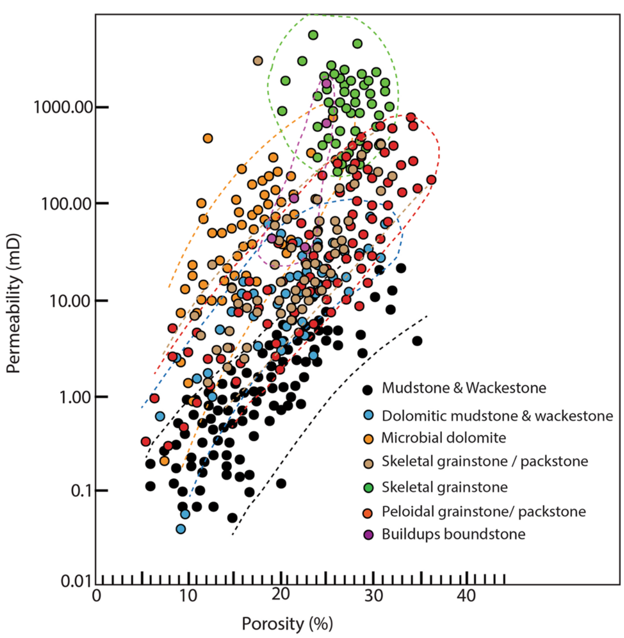


**Fig. 7** Cross plot of porosity and permeability for the main identified rock types (original data from Focke et al. 1986)

correlation between the two parameters (Fig. 7) at the relatively low porosity range and higher permeability.

## Skeletal grainstone/packstone

This is a more common rock type and consists of dasycladacean green algae (e.g., *Clypina jurassica*), a characteristic fossil of the Arab Formation all over eastern Arabia (Sadooni 1997), with stromatoporoids, sponges, benthonic foraminifera, echinoderms, and gastropods. Some ooliths are entrapped inside the shell fragments (Fig. 6 E). This mixed-up rock type indicates two-stage development; first, a high-energy system mixed up these skeletal and non-skeletal components, followed by a low-energy system that led to their extensive micritization. As a result, most of the skeletal elements were heavily micritized and relatively well sorted. The major diagenetic processes include isopachous rim cement and the dissolution of some grains, and the hosting groundmass. Porosity types include intergranular, dissolution, and vuggy porosity, with up to 20% porosity values and permeability ranging up to 100 mD. A narrow range of porosity and permeability readings was concentrated in the middle field (Fig. 7).

## Skeletal grainstone

This is a significant and most common reservoir unit. It consists of grainstone of mixed skeletal elements, such as benthonic foraminifera, green dasycladacean algae, shell fragments, and echinoderms (Fig. 6 F and G). Many of these materials were micritized, although the general texture of this rock type suggests deposition under a high-energy system, such as an open marine shelf. Most of the groundmass is made of granular calcite cement, with a small quantity of micrite to none. Rim cement and syntaxial rim cement were present, particularly on the edge of some echinoderms or shell fragments. Visual porosity was mainly intergranular, but there were some vugs and moldic porosity. The average porosity was around 27%, with a permeability of more than 1000 mD. The distribution of porosity and permeability did not show any trend. Still, the whole population of the measured samples fell within nearly a circular configuration, with 20–30% porosity and 1000 mD or more permeability (Fig. 7).

## Peloidal grainstone/packstone

This rock type is separated from pure grainstone because of considerable differences in the values and types of its porosity. It consists mainly of peloids with ooliths, small benthonic foraminifera, green algae, and rare echinoderms (Fig. 6H). Most of the peloids were either micritized ooliths or skeletal grains. The peloids were well sorted. Some were totally or partially leached with total or partial mosaic calcite cement. This rock type is distinct in high porosity and permeability due to excellent depositional intergranular porosity, enhanced by extensive leaching. The major porosity types are intergranular, vuggy, and micrite porosity. Porosity values of up to 25% were found in this rock type with a permeability of up to 1000 mD. There was a relatively straightforward linear positive relation between porosity and permeability (Fig. 7), which may be due to the prevalence of intergranular porosity.

## Buildups boundstone and packstone

This rock type is of limited distribution and was found in a single well (A) only (Fig. 6 I). It consists of sponge, stromatoporoids, coral, and algal boundstone with ample sponge spines, probably forming localized mounds in the tidal flat. The major diagenetic processes are the preferential leaching of stromatoporoids and the rim and mosaic cement replacing the sponge spines. The primary porosity was vugs, where the average porosity was around 22%, with permeability up to more than 1000 mD. However, there was no clear relationship between porosity and permeability, probably due to the small number of measurements (Fig. 7).

Correlation of the different rock types discussed above across the studied fields (Fig. 8) was attempted. There was considerable consistency in the principal rock types, such as microbial dolomite, peloidal and skeletal grainstone, and packstone. Still, the relative locations of these rock types within the general succession differed from field to field. The other less essential rock types were inconsistent due to the complicated depositional environments under which these rocks were formed. The Arab D reservoir was deposited in a shallow carbonate shelf punctuated with many minor depositional settings that do not make regional correlation possible.

## Microporosity types

The classification of Choquette and Prey (1970) of porosity in carbonate reservoirs is still a valid classification for microporosity. However, examining these pores under high resolution enabled us to add new micropore types to this classification. Microporosity can be classified as primary or depositional and secondary or diagenetic porosity.

## Primary microporosity

Primary porosity is the porosity inherited by the rock from its depositional system before any diagenetic modifications. The main primary microporosity types recognized in the studied rocks include:

### Intergranular microporosity

Under the standard petrographic microscope, the intergranular porosity in lime mudstone and wackestone is usually challenging to recognize. It is generally described as micrite or matrix porosity, like chalky porosity. The best micrite intergranular porosity is found when the micrite has little or no clay content, and most of the micrite grains are well-sorted and of similar size as in the upper parts of the Arab D member (Fig. 9 A and B). Such conditions are usually found under hypersaline conditions like inland lagoons, where micrite is precipitated chemically due to water evaporation under arid climatic conditions. Such conditions were prevalent during the deposition of the Arab Formation, as reflected by the presence of extensive anhydrite beds and halite in the equivalent Gotnia Formation in Kuwait and southern Iraq (Al-Saad and Sadooni 2001). Micro-intergranular porosity may also be present between grains, such as ooliths or peliods (Fig. 9 C). Porosity sizes range from 287 to 857 microns. Although these are tiny pores, their abundance and connectivity make them essential.

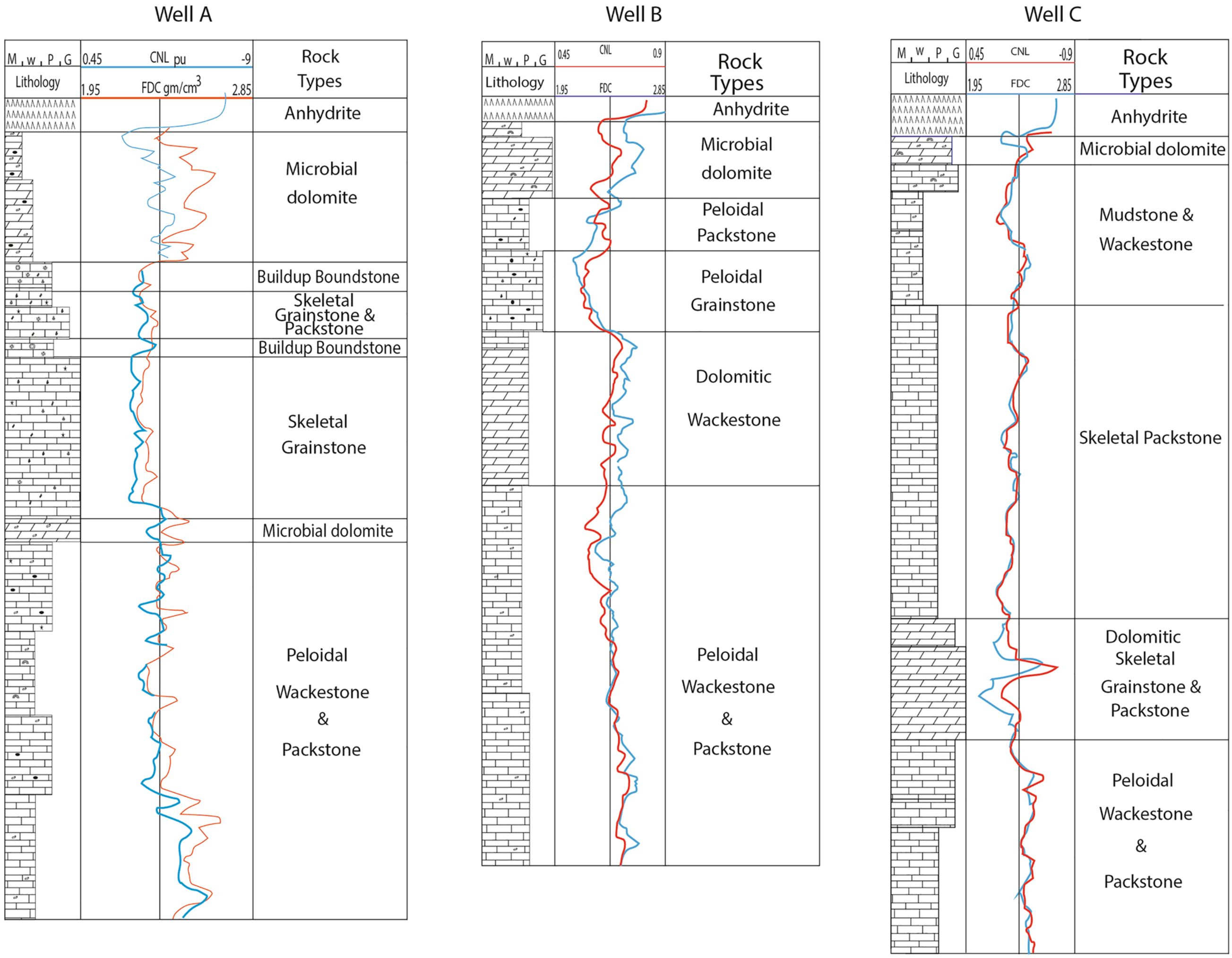


**Fig. 8** Correlation of the main identified rock types across the studied wells

## Interplanar porosity

This microporosity develops in minerals formed of planar or sheet-like structures, such as clay minerals (Fig. 9D). Still, they may be modified by the compaction of the clay minerals. Such porosity is similar to fracture, because it has one long dimension extending along the mineral crystal's length. Although such porosity is not typical but important as permeability conduits, it may enhance the fluid flow between units of shale and limestone where there is no such visual connection.

## Secondary porosity

This porosity results from the different diagenetic processes that affect rocks after their deposition. Some of these start during or directly after deposition, such as micritization, or after a long time, such as dolomitization. Some diagenetic processes, such as dissolution and cementation, may happen within the same time frame. The following describes the major secondary microporosity types.

## Vuggy porosity

Micro-vuggy porosity is similar to the macro type except that these vugs are micron-sized, but their formation mechanism remains the same, i.e., dissolution of the less stable minerals such as aragonite (Fig. 10A). Most of the reported micro-vugs in the studied rocks are found in the lime mudstone, and wackestone rock types and hence are associated with matrix porosity that provides permeability for such pores. The combination of vuggy and matrix porosity generates low to medium-quality reservoir rocks unless these are enhanced by fractures or further dissolution.

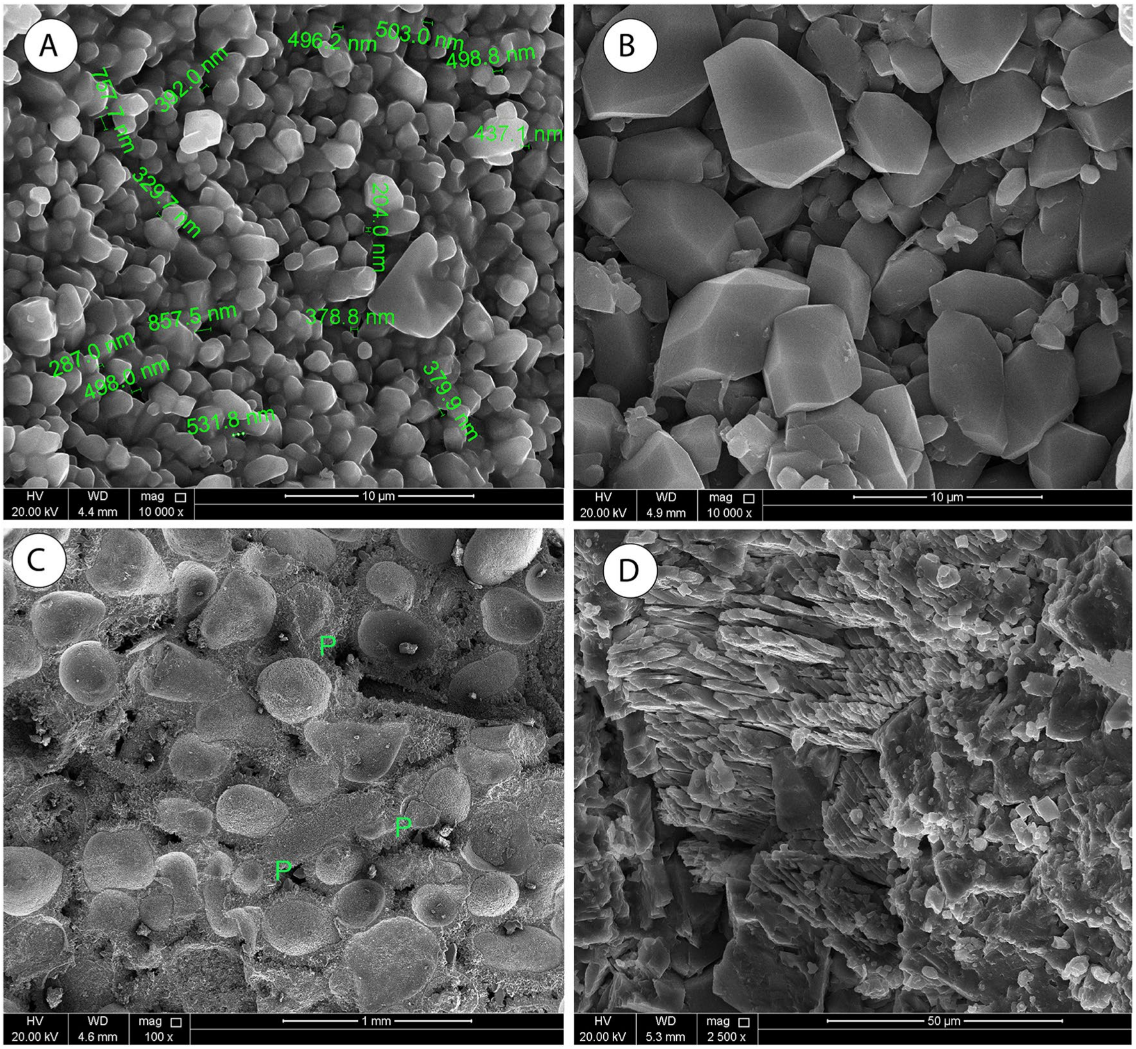


**Fig. 9** Primary microporosity types **A** and **B** intergranular between micrite grains **C** intergranular porosity between peloids **D** interplanar porosity between clay mineral sheets

## Intercrystalline porosity

Micro-intercrystalline porosity is found mainly between the fine rhombs of dolomite (Fig. 10B). Incipient or aphanitic dolomite is characterized by microrhombic crystals that cannot be recognized under the standard petrographic microscope (less than 4 microns in size). Due to the difference in the radius of the Mg ion compared to the Ca ion ($Ca^{+2}$ ion radius is 1.00 angstrom compared to 0.72 angstrom for $Mg^{+2}$), dolomitization is associated with about a 13% increase in porosity. Furthermore, dolomitization is related to expelling clay minerals and organic matter from the rock lattice, creating more porosity.

This porosity is essential in the lime mudstone and wackestone in the upper part of the studied sections. These rock types are usually associated with low porosity and a high percentage of argillaceous or organic materials. Therefore, porosity will add a new reservoir capacity to the typical ones, particularly if associated with other microporosity types.

## Moldic porosity

Moldic porosity results from the dissolution of unstable skeletal or non-skeletal grains in contrast to vuggy porosity, which involves the dissolution of the matrix part of the rock. Such instability is the by-product of two factors. Either the grain is formed of unstable minerals such as aragonite or an easily soluble mineral such as anhydrite or is due to impurities in the lattice such as clays or organic matter, eventually weakening its structure.

The studied rocks have two types of moldic porosity: biomoldic porosity, which occurs in skeletal grains such as gastropods (Fig. 10C), and oomoldic or pelmoldic porosity,

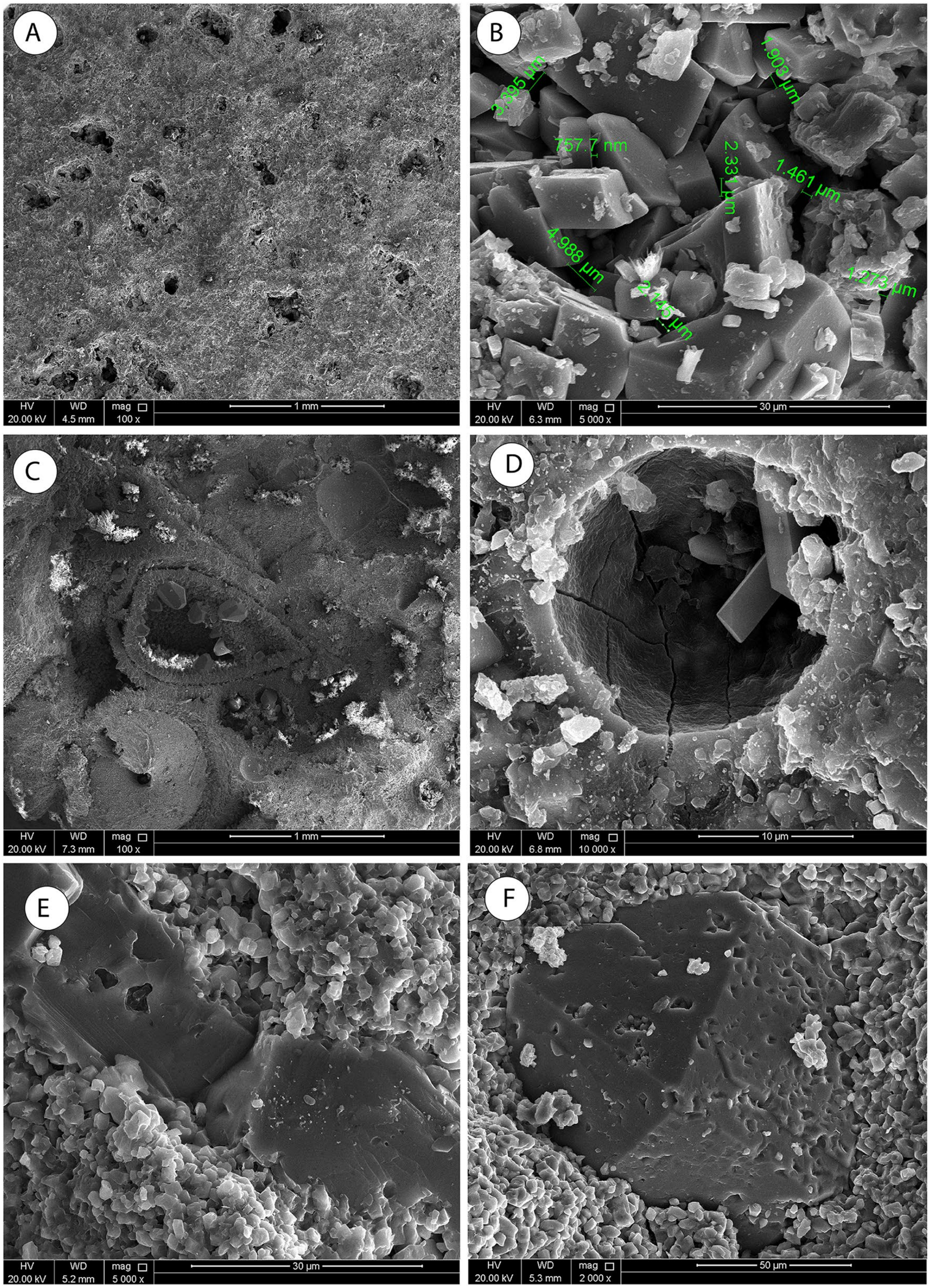


**Fig. 10** Secondary microporosity types **A** vuggy porosity in lime mudstone. **B** intercrystalline microporosity between dolomite rhombs **C** biomoldic porosity in a gastropod shell. **D** oomoldic porosity, micro-fractured, and partially filled with cement. **E** dissolution porosity of anhydrite crystal. **F** dissolution microporosity of Quartz crystal

which can be found in non-skeletal grains such as ooliths or peloids (Fig. 10D).

This porosity is found in the skeletal, oolitic, and peloidal grainstone and packstone, which form the primary reservoir rocks of the member. As discussed earlier, these rock types already contain a considerable macroporosity. Sometimes, the pores are either wholly or partially filled with a cement of the same lithology (e.g., calcite) or a different lithology, such as anhydrite or silica.

### Dissolution porosity

Is a general term used to describe various cases in which some grain minerals are partially or totally dissolved. Figure 10E shows a partial dissolution of anhydrite crystal in a lime mudstone matrix. The Arab Formation contains many evaporites (anhydrite, gypsum, and some halite). These minerals are susceptible to dissolution by meteoric water. Dissolution can also be seen in quartz crystals (Fig. 10F). Such quartz crystals are probably transported to the carbonate system by eolian or fluvial processes. As indicated by the widespread evaporite sediments, the arid climatic conditions that prevailed during the Upper Jurassic may suggest the presence of nearby dry land that represented the source for such crystals. Dissolution of quartz requires highly alkaline conditions, and probably the crystal has been partially dissolved during the transportation process before landing in the carbonate system.

## Pyrite displacement

There is a considerable amount of framboidal pyrite in the microbial mudstone facies of the studied samples. Pyrite crystals form, at first, inside porous structures similar to raspberry (the word framboid is derived from the French framboise, which means raspberry). Then, the crystals grew larger than their containing vesicles and fell and accumulated in friable porous aggregates, thus forming porosity and permeability conduits (Fig. 11A & B). The vesicles, in turn, got enlarged by dissolution and developed enhanced intra-structural porosity.

### Microfracture porosity

Is similar to typical fracture porosity in carbonate reservoirs. However, it is probably formed more commonly by compaction or displacement due to crystal growth rather than by tectonic stress, as with macrofractures. They are usually associated with molds (Fig. 10D) or cementations (Fig. 11C).

Microbial boring is found in the form of semi-rounded pores in anhydrite crystals. The geometry and distribution suggest a more deliberate mechanism than random dissolution (Fig. 11D).

## Microporosity evolution

The Arab D Member was deposited in a shallow, marine carbonate ramp under arid climatic conditions (Al-Saad and Sadooni 2001). The ramp was punctuated with low relief, coral, sponge, and stromatoporoid buildups, with a vast network of tidal channels where oolites were forming. This depositional system generated two major sediment types: the grain-supported rocks formed mainly of oolitic and skeletal packstone/grainstone. These were deposited in the oolitic shoals, the buildups, and the normal marine shelf environments. The second type of sediment is the mud-supported rocks such as wackestone, mudstone, and microbial aphanitic dolomite associated with anhydrite and even halite in some parts of the basin. These sediments were deposited in the local shallow restricted shelves, lagoons, and coastal sabkhas and salinas (Fig. 3).

The first sediment type is the major reservoir rocks, in which oil was found early in the last century. The porosity of these sediments has been studied thoroughly (Ehrenberg et al. 2007). It is mainly primary intergranular and secondary intercrystalline in the dolomitized sections. Porosity values of up to 26% were reported in some reservoir parts. Microporosity is insignificant in this rock type and is found mainly within their skeletal components.

Microporosity is important in the second type of sediment, where it forms the main type. Most of the primary microporosity was found between the micrite grains forming the lime mudstone, the grains, the crystals of the aphanitic dolomite, and the planes of clay minerals. Different lithologic components such as calcite, dolomite, anhydrite, and clay minerals created a relatively loose packing between these components, leading to intergranular microporosity development.

While the Jurassic of Arabia was mainly arid, the Cretaceous was humid since Arabia moved to the tropical zone (Ziegler 2001). As a result, some parts of the Jurassic strata were subjected to open-system diagenesis by the action of the percolating meteoric water. Closed-system diagenesis was reported in areas where the thick anhydrite sediments of the Hith Formation covered these rocks.

In open-system diagenesis, leaching impacts both grains and matrix and generates a wide range of secondary microporosity, such as micromolds, micro-vugs, and other dissolution porosity. Some components, such as aragonite and anhydrite, are more susceptible to dissolution than others.

The closed diagenetic system encourages microbial activity. The presence of considerable amounts of anhydrite and iron together makes it possible for bacteria to generate a substantial quantity of framboidal pyrite (Zhao et al. 2018).

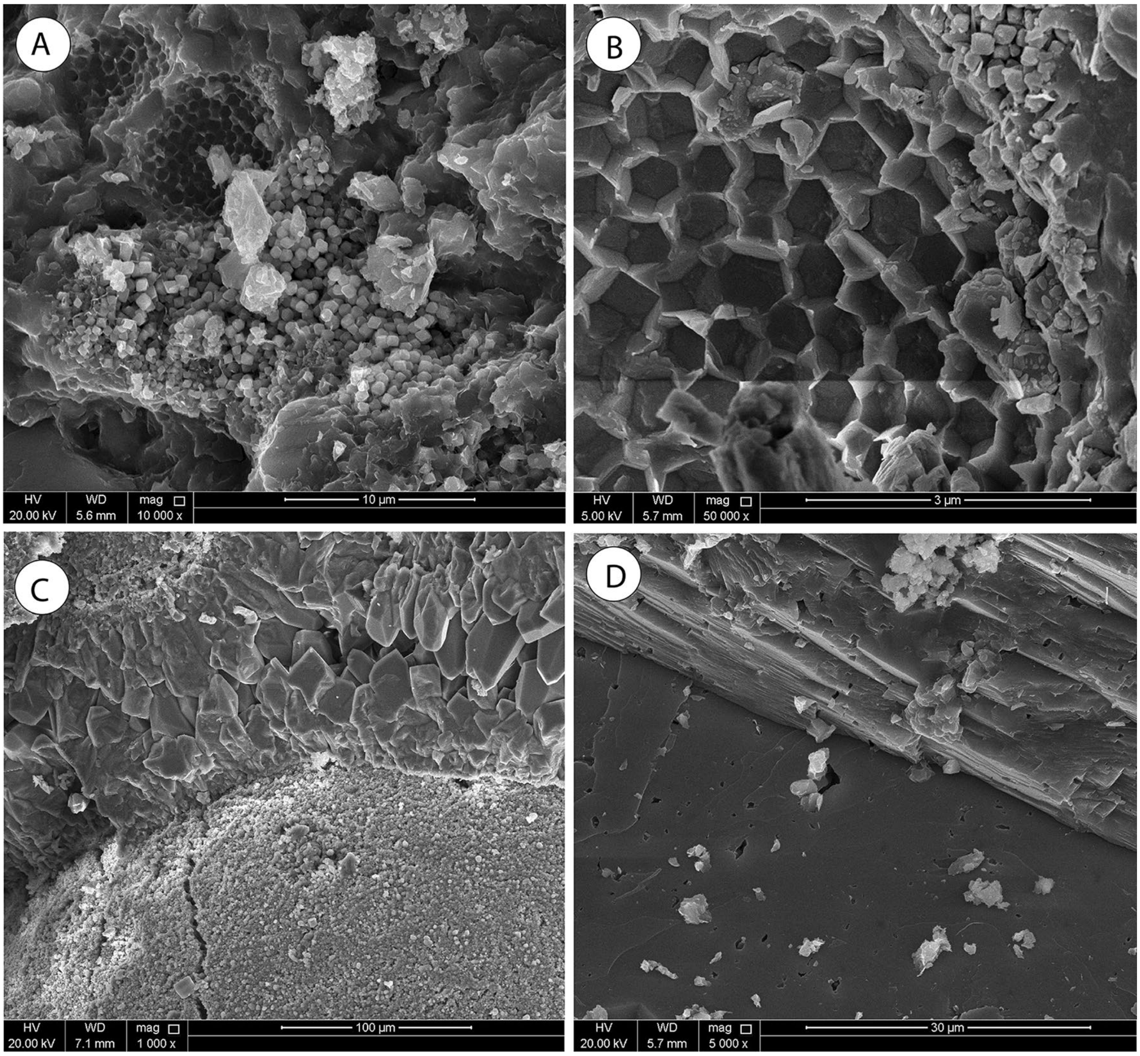


**Fig. 11** Secondary microporosity **A** pyrite displacement resulted from the displacement of pyrite crystals, leaving a spongy, porous structure. **B** a Close-up of the spongy structure resulted from the displacement of pyrite **C** microfracture, probably from cement overgrowth. **D** microbial boring of anhydrite crystals

Microbial activity may also mediate the formation of microbial dolomite (Sadooni et al. 2010). This set of processes creates peculiar microporosity types, such as pyrite displacement and microbial boring, and possibly the intercrystalline porosity in dolomite. In addition, the open and closed diagenetic processes disturbed the original grain packing and created diagenetic dissolution microporosity. Other microporosity, such as microfractures, may be generated due to stress from either displacement or crystal growth rather than of tectonic origin.

## Microporosity destruction

High-resolution microscopy enabled us also to understand better the processes that were responsible for the destruction of porosity, which included the following:

### Cementation

Is abundant in the grainstone–packstone rock types of the Formation. In some cases, the whole rock mass is extensively cemented. The cement comprises the drusy mosaic or the so-called dog-teeth calcite cement. In some cases, cement fills the spaces between the grains, such as ooliths, clogging the pore-throats, and in other cases, it completely replaces the skeletal grain, such as with fossils. The cement grains also vary in size, eliminating the space between grains (Fig. 12A). In other cases, cement is of different mineralogy, as shown in Fig. 12B, where massive anhydrite cement fills a mold.

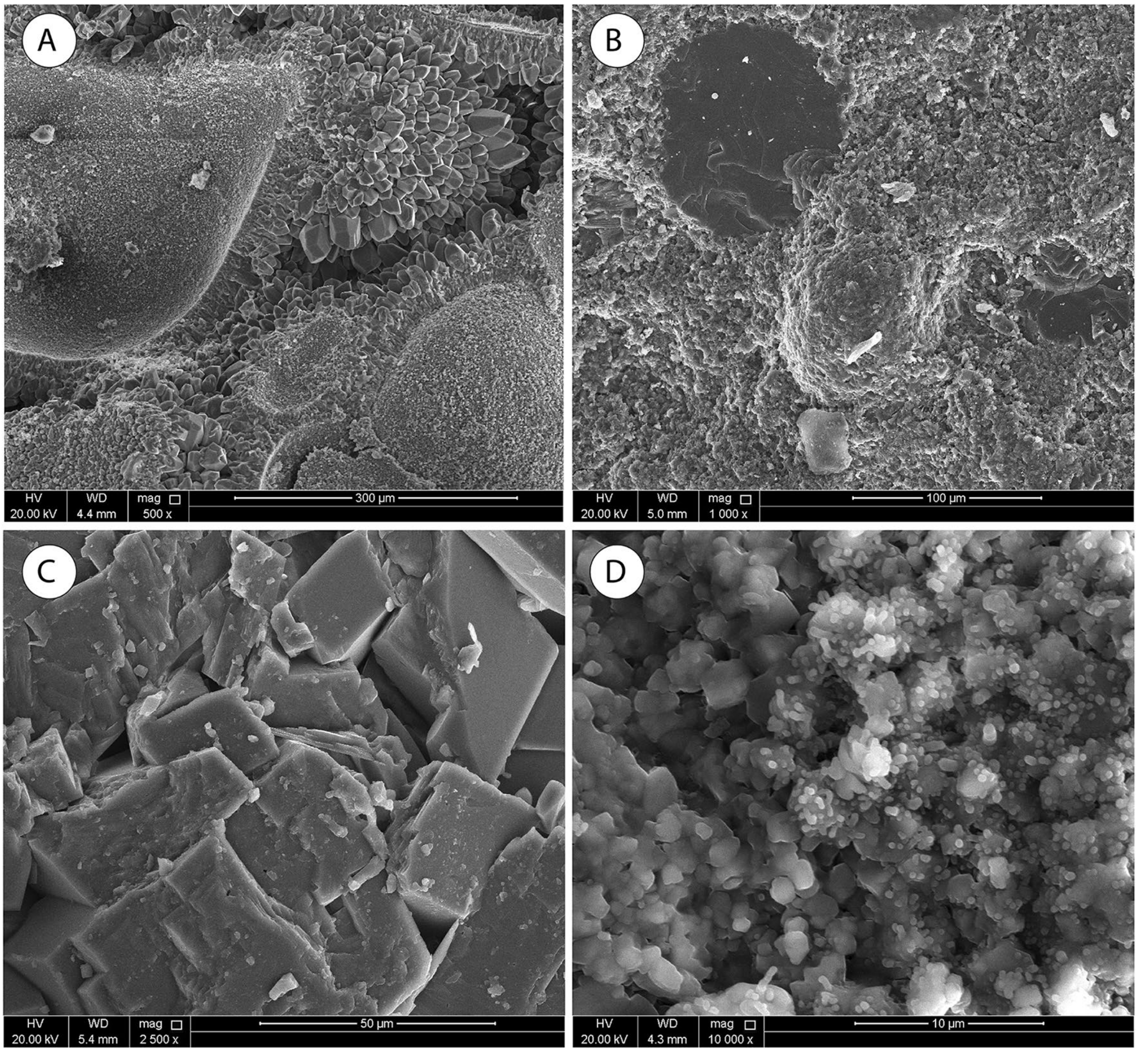


**Fig. 12** Destruction of microporosity **A** calcite "dog-teeth" cement filling the pores between peloids. **B** anhydrite massive cement filling vugs. **C** crystal overgrowth of non-descript interlocked dolomite crystals. **D** microbial pustular overgrowth on clay minerals

### Overgrowth and the growth of new crystals

Were two significant types of overgrowth in the studied samples. The most important is the growth of clay minerals. Such crystals take different textural shapes, such as laths, needles, and a fur-like aggregation. They may grow within spaces or on top of other crystals, such as calcite. The overgrowth of dolomite crystals forms the so-called non-descript or interlocked dolomite (Fig. 12C). This type of dolomitization gradually blocks intercrystalline porosity due to crystal overgrowth.

### Microbial overgrowth

Was noticed on some of the clay minerals forming pustular overgrowth and causing the clay crystals to coalesce with each other, reducing the intergranular or dissolution porosity (Fig. 12D). Such pustular overgrowths are microbial masses reported from the recent sabkha of Abu Dhabi by Sadooni et al. (2010).

## Discussion

The importance of microporosity in the Arab D strata can be viewed from two perspectives. Firstly, it introduces the possibility of new reservoir units comprised of aphanitic dolomite and lime mudstone that were previously overlooked. Secondly, microporosity is a crucial permeability network that enhances fluid communication between isolated macro pores in grain-supported rocks. Table 1 provides an overview of the various rock types, including their average porosity and permeability, macro and visual porosity, and microporosity. The highest macroporosity values are found

**Table 1** Summary of the principal rock types with average Porosity and permeability values, visual Porosity, and microporosity types

| Rock type | Average porosity (%) | Average permeability (mD) | Visual porosity types | Microporosity |
|---|---|---|---|---|
| Mudstone and wackestone | 5–30 | 1–60 | Matrix, bioturbation, dissolution | Intergranular, interplanar, depositional interface, vugs, diagenetic interface, pyrite displacement, microbial boring |
| Dolomitic mudstone and wackestone | 6–30 | 1–80 | Intercrystalline, bioturbation, dissolution, burrowing, bird's eye | Intercrystalline, dissolution, diagenetic interface |
| Microbial dolomite | 16 | 500 | Intercrystalline, bioturbation, dissolution | Intercrystalline, dissolution, vugs, microbial boring |
| Skeletal grainstone/packstone | 20 | 100 | Intergranular, vugs, dissolution | Intergranular, vugs, moldic, dissolution |
| Skeletal grainstone | 27 | 1000 | Vugs, intergranular, moldic | Intergranular, moldic, vugs, micro fractures, |
| Peloidal grainstone/packstone | 25 | 1000 | Intergranular, moldic, vugs, matrix | Intergranular, moldic, vugs, dissolution |
| Buildups boundstone | 22 | 1000 | Vugs | Vugs, dissolution, |

in dolomitic limestone and grain-supported sediments such as skeletal, oolitic, and peloidal limestones, which are common reservoir rocks in the Arab Formation. The presence of microporosity was visually estimated to be around 10% in mud-supported rocks, while it ranged from 3 to 5% in grain-supported rocks. Microporosity is more abundant and diverse in mud-supported rocks. The highest permeability values are found in microbial dolomite and grain-supported rocks. At least, in microbial dolomite, the permeability is linked to microporosity.

The existence of abundant microporosity in mud-supported rocks can be attributed to various factors, including the presence of minerals like dolomite, anhydrite, and quartz and a substantial amount of organic matter. The heterogeneous components underwent diagenetic processes, such as bioturbation, dissolution, and dolomitization, which proceeded at different rates, resulting in the formation of diverse types of microporosity.

In some cases, micropores are filled with irreducible original salt water, while macropores are filled with migrating oil. In these instances, determining log-driven porosity, permeability, and saturation values can be challenging due to the impact of the "background" saltwater on resistivity values generating what is called "low-resistivity" reservoirs (Si et al. 2022).

## Conclusions

A multiproxy approach was utilized based on detailed petrographic and chemical analyses to study cored materials from the Arab D reservoir in three wells from offshore and onshore oilfields in Qatar. The collected data were integrated with the previously acquired petrophysical data. The aim was to identify the micro- and nanoporosity types and understand their evolution and destruction. Primary microporosity was intergranular between well-sorted, clean micrite grains; interplanar between clay minerals sheets. Secondary microporosity was more varied and included types similar to those attributed to the macropores, such as intercrystalline, vugs, moldic, dissolution, fracture, or new varieties such as pyrite displacement and microbial boring. Microporosity was more abundant and varied in mud-supported sediments. The microporosity of the studied sediments was either wholly or partially destroyed by cementation, crystal overgrowth of clay minerals and dolomite rhombs, or microbial pustular overgrowth.

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**Data availability** The datasets generated during and/or analyzed during the current study are not publicly available due to data confidentiality as required by the petroleum industry regulations in the State of Qatar. Still, they are available from the corresponding author upon reasonable request.

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