# Microporosity in Arab Formation Carbonates, Saudi Arabia

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## ABSTRACT

Microporosity occurs throughout Arab Formation carbonates of Saudi Arabia, and affects the log response, fluid flow properties and ultimate recovery of hydrocarbons in these reservoirs. Qualitative examination of Arab samples indicates that microporosity occurs as four major types: (1) microporous grains, (2) microporous matrix, (3) microporous fibrous to bladed cements, and (4) microporous equant cements. Quantitative estimation of microporosity abundance was measured in two ways: (1) thin section point counts, and (2) pore throat size distributions derived from capillary pressure data. Point count data shows that microporosity can vary widely from sample to sample, ranging from 0% to 100% of the total measured porosity of a sample. Capillary pressure data confirms the volumetric significance of pore throats that are 10 microns or less in size. Variations in microporosity abundance and type appear to be controlled by depositional texture, grain mineralogy and grain microstructure. We suggest that microporosity in Arab Formation carbonates formed diagenetically, via three mechanisms: (1) leaching and incomplete reprecipitation of metastable carbonate, (2) crystal growth contact inhibition, and (3) (locally) endolithic borings of grains.

## INTRODUCTION

Microporosity occurs in both sandstone and carbonate reservoirs and affects their fluid flow properties (i.e., productivity) as well as their log responses. In carbonate reservoirs in particular, the presence of micropores increases the capillary attraction to the wetting phase (typically water) and frequently results in abundant bound water in the micropores. Log calculations may then yield high water saturations and cause erroneous hydrocarbon estimates (Kieke and Hartmann, 1974; Keith and Pittman, 1983). Based on log calculations alone, one might not identify a reservoir that would flow little, if any, water. For this reason, it is necessary to consider microporosity in any comprehensive formation evaluation program.

This study documents the occurrence, distribution, abundance and origin of significant amounts of microporosity in Arab Formation carbonates of Saudi Arabia. Information for this study comes from microscopic examination of petrographic thin sections and scanning electron microscope (SEM) examination of fractured rock surfaces and epoxy pore casts, as well as from examination of capillary pressure data. Overall, the emphasis in this study is on the use of standard petrographic techniques to distinguish and quantify microporosity. While we use other techniques to refine our understanding of the fabric and habit of microporosity in these rocks, our focus in this paper is on techniques that would be widely available to a reservoir geologist attempting to recognize and quantify microporosity in any reservoir.

This study uses a three-part approach: (1) microporosity is examined qualitatively throughout the Arab Formation, (2) variations in microporosity abundance in the Arab-D are discussed, and (3) a discussion of several possible mechanisms that could have caused microporosity to form in the Arab-D is included.

# **GENERAL GEOLOGY**

The Upper Jurassic Arab Formation (Tithonian and Kimmeridgian in age, see Al-Husseini (1997) for a discussion) consists of four geographically widespread carbonate-evaporite cycles or members. These members are labeled, from top down, Arab-A, -B, -C and -D (Figure 1a). The Arab-D Member is the

GENE	RALIZED UPP	PER JURA	SSIC-LOWER	ARAB-HITH TERMINOLOGY				
CRETA	CEOUS STRA	TIGRAPH	IC SEQUENC	E	Fm	Member	Reservoir	
ୁ ମ	FORMATION	MEMBER	LITHOLOGY				Manifa	
CRETACEOL	YAMAMA	$\sim$			HITH			
	SULAIY							
	нітн					ARAB-A	Arab-A	
JURASSIC	ARAB	Arab-A			ARAB	ARAB-B	Arob P	
		Arab-B					Alab-b	
		Arab-C				ARAB-C		
		Arab-D					Arab-C	
	JUBAILA					ARAB-D		
	HANIFA							
Figure 1a: Generalized Mesozoic stratigraphic and reservoir terminology of the Eastern Arabian Peninsula.					JUBAILA		Arab-D	Anhydrite Grainstones/ Packstones Wackestone

Wackestones/



Figure 1b: Eastern Saudi Arabian oil fields discussed in the paper.

oldest (deepest) and thickest of these cycles, and is generally interpreted to represent deposition in shallow shelfal to sabkha settings. The Arab-D consists of several (at least four) major upward-shoaling cycles that were initiated in deeper subtidal water and shoaled to near sea-level. These upward-shoaling cycles comprise a variety of skeletal grainstones and packstones with ooid grainstones locally common in the uppermost Arab-D. The top of the Arab-D carbonate is characterized by thin subtidal to intertidal carbonates with sabkha and subaqueous evaporites above. Most of the quantitative data used in this study comes from the Arab-D Member of several large fields in Eastern Saudi Arabia (Figure 1b). For a more complete treatment of the rock types, depositional environments and diagenesis of the Arab-D, see Mitchell et al. (1988) and Meyer and Price (1992).

## **MICROPOROSITY DEFINITION**

Many different definitions for microporosity have been proposed in the literature. Choquette and Pray (1970) defined a micropore as a pore that is less than 62.5 microns in average diameter. Pittman (1971) proposed that only pores less than one micron in diameter in at least one direction be termed micropores. For this study, however, we felt that neither of these definitions were appropriate, since we wanted to develop a microporosity definition that could be used primarily for petrographic characterization. Many petrographically visible pores are less than 62.5 microns in size, yet no pores in the one-micron range are optically resolvable with a standard petrographic microscope.

For this study, we have defined microporosity to be all pores that are approximately 10 microns in diameter or smaller. This definition is empirical and is based on the idea that microporosity is the difference between total measured porosity and porosity visible from microscopic examination of thin sections (point count porosity). Since the optical resolution limit of most petrographic microscopes is approximately 10 microns, by default microporosity includes all pores less than 10 microns in size. As will be discussed later, capillary pressure data reveal that micropores much smaller than 10 microns (as small as 0.01 microns in diameter) are common in most Arab carbonates, although none of these very small micropores are optically resolvable with a standard petrographic microscope.

# **QUALITATIVE EXAMINATION OF MICROPOROSITY**

The first steps in understanding microporosity were to catalogue variations in types of microporosity and to document their occurrence. This study recognizes four major types of microporosity, namely: microporous grains, microporous matrix, microporous fibrous to bladed cements and microporous equant cements. Figure 2 schematically illustrates these four important micropore types. Of these, microporous grains and microporous matrix are the most volumetrically significant micropore types in the Arab Formation.

# **Microporous Grains**

Microporous grains are common throughout the Arab carbonates (Figure 3) and constitute the most volumetrically significant microporosity type. SEM examination of pore casts and fractured rock surfaces reveals that a variety of skeletal and non-skeletal grain types are microporous. The microporosity-forming process transforms different grain types into grains that are similar with respect to their internal fabrics. Micritized grains (Figure 3), foraminifera (Figures 4a, 4c to 4f), ooids (Figures 4b; 5a and 5b) and composite grains (Figures 5c, 5d and 5e) can all be readily distinguished from each other both with a petrographic microscope and at low magnifications with the SEM. However, at higher magnification with the SEM, all four grain types have similar internal fabrics. This similarity suggests that the process is ultimately controlled by original grain mineralogy and microstructure, not by grain type.

The internal fabric of microporous grains consists of uniform-sized, subhedral crystals of micrite ranging from 1 to 4 microns. SEM examination of pore casts of microporous grains shows that microporosity occurs as pores that are typically 0.3 to 3.0 microns in size between these micrite crystals (Figures 3c and 3d; 4d, 4e and 4f; 5a, 5b, 5d and 5e). Microporosity thus consists of a network of highly



### **Microporous Fibrous to Bladed Cement**



### **Microporous Equant Cement**



Figure 2: Important micropore types in the Arab-D.



**Figure 3:** Microporosity in Arab Formation carbonates. In thin section, porosity is filled by blue-dyed epoxy, calcite is stained pink to red, other minerals are unstained. **(a)** Thin section photomicrograph of skeletal-oolitic grainstone. Interparticle (BP) and moldic (MO) macropores are abundant. Microporosity (MC) occurs within micritized grains and foraminifera (F). Isopachous fringing calcite cement (arrows) coats most grains in this sample (plane-polarized light, Saudi Arabia, Abqaiq field, Arab-D). **(b)** SEM photograph of epoxy pore cast of sample shown above. Carbonate has been etched away by dilute hydrochloric acid, leaving epoxy replica of pore space. Interparticle (BP) and moldic (MO) macropores are present as solid epoxy, while microporous grains (MC) display fine network of hair-like micropores. **(c)** Detail of area outlined in sample shown in (b). Microporosity (MC) occurs as tortuously interconnected fine pores, while large moldic (MO) and interparticle (BP) pores are completely filled by epoxy. Note the thin, straight micropores between cement crystals that surrounded the grain before being etched away during sample preparation. **(d)** Higher magnification view of area outlined in previous example. Prior to leaching, this micritized grain consisted of well-sorted calcite crystals 1 to 4 microns in size; microporosity occurs as highly interconnected pores generally 1 micron or less in diameter.



**Figure 3:** (e) Epoxy pore cast of microporous grain (M). Density of microporosity is so high that the grain resembles a sponge (SEM image, Saudi Arabia, Berri field, Arab-C). (f) SEM image of fractured rock surface of ooid-skeletal mud-lean packstone. Large sparry calcite cement crystal (C) is non-microporous and distinct in appearance from surrounding micritized and microporous grains (Saudi Arabia, Khursaniyah field, Arab-D).



**Figure 4:** Microporous grains in Arab Formation carbonates. In thin section, porosity is filled by bluedyed epoxy, calcite is stained pink to red, other minerals are unstained. **(a)** Thin section photomicrograph of microporous peloids (P) and microporous miliolid foraminifera (M). Microporosity appears as a blue haze within grains (plane-polarized light, unspecified Mesozoic reservoir, Middle East). **(b)** Thin section photomicrograph of microporous ooid. Microporosity in this grain is denoted by a blue hazy appearance resulting from infiltration of blue-dyed epoxy into micropores in the grain (plane-polarized light, Saudi Arabia, Qatif field, Arab-C).



**Figure 4: (c)** SEM image of fractured rock chip showing internal fabric of a microporous foraminifer (F). Foraminifer consists of subhedral crystals of micrite ranging from 1 to 10 microns in size. Foraminifer is recognizable by a distinctive chambered pattern of intraparticle porosity (arrows) (Saudi Arabia, Berri field, Arab-C). **(d)** Higher magnification view of foraminifer shown in (c) (SEM image of fractured rock chip).



**Figure 4:** (e) SEM image of epoxy pore cast of microporous foraminifer (F). Intraparticle (WP) pores within the foraminifer are partially occluded by microporous cements (arrows). Interparticle (BP) macropores are common (Saudi Arabia, Ghawar field, Arab-D). (f) Higher magnification view of foraminifer shown in previous example. Network of highly interconnected micropores usually 1 micron or less in diameter is visible in foraminifer test wall.



**Figure 5:** Microporous grains and microporous matrix in Arab Formation carbonates. In thin section, porosity is filled by blue-dyed epoxy, calcite is stained pink to red, other minerals are unstained. (a) Epoxy pore cast of microporous ooid. Note radial and concentric distribution of porosity in ooid cortex (arrows) (SEM image, Saudi Arabia, Berri field, Arab-A). (b) Higher magnification view of epoxy pore cast of same microporous ooid shown in previous example. Again, microporosity consists of a maze of highly interconnected pore throats (arrows) and larger, more equant micropores (MC). Pore network of micritized grain (Figure 3e), foraminifer (Figure 4f) and ooid are essentially identical.



**Figure 5:** (c) Thin section photomicrograph of microporous composite grain (plane-polarized light, Saudi Arabia, Qatif field, Arab-C). (d) Epoxy pore cast of microporous composite grain (plane-polarized light, Saudi Arabia, Berri field, Arab-A). (e) Higher magnification view of epoxy pore cast of same microporous composite grain shown in (d) above. Microporosity consists of a maze of highly interconnected pore throats (arrows) and larger, more equant micropores (MC). Note similarity between microporous network of composite grain and foraminifer (Figure 4f), ooid (Figure 5b) and micritized grain (Figure 3e). (f) Thin section photomicrograph of microporous micritized grains in microporous matrix (plane-polarized light, unspecified Mesozoic reservoir, Middle East).

interconnected, uniform-sized straight tubular to laminar pore throats that intersect with less elongate, more equant (often tetrahedral-shaped) pores (Figures 3d; 4f; 5b and 5e). In many cases, the amount of microporosity within microporous grains is so high that the grains resemble sponges (Figure 3e).

SEM examination is not always necessary to recognize microporous grains, since both a blue hazy appearance in thin section and complete grain micritization usually indicate the presence of microporosity (Figures 3a; 4a and 4b; 5c). This blue hazy appearance in thin section results from the infiltration of blue-dyed epoxy into micropores in grains and matrix (lime-mud or micrite). Also, since microporous grains are composed of micrite crystals, complete grain micritization usually reflects the presence of microporous (for example, compare the non-micritized and non-microporous cement crystal with the microporous micritized grain in Figure 3f).

# **Microporous Matrix**

Microporous matrix consists of 1 to 10 micron, subhedral calcite crystals that are randomly packed to yield a continuous network of micropores that are connected by smaller (1 micron maximum) pore throats. These micropores are found between crystals of lime-mud matrix (micrite or microspar) (Figures 5f; 6a to 6d). SEM examination of pore casts shows that the pore geometry of microporous matrix is similar to that of microporous grains. Pore throats tend to be laminar and tortuous, while micropores are generally subequant.

## **Microporous Fibrous to Bladed Cements**

Microporous fibrous to bladed cements are common in Arab grainstones that contain significant amounts of early marine, isopachous calcite cement. The crystals of calcite cement are approximately 30 to 40 microns long and 5 to 10 microns wide (Figures 6e and 6f). SEM examination of epoxy pore casts of these cements reveals thin (0.1 to 1.0 micron in diameter) straight, tubular-shaped micropores occurring between cement crystals (Figures 7a and 7b). These "intercrystalline" pores apparently result from the inhibition of further crystal growth and preservation of a thin film of water along crystal faces during crystal growth (Wardlaw, 1976). These pores are probably slightly larger than the actual, molecular water film that originally filled them, and represent the terminations of growing crystals as they approached and began impinging upon each other.

Although these "intercrystalline" pores are volumetrically insignificant in the Arab-D, they are important in that they provide a pathway connecting microporous grains to one another and to macropores. These cements isopachously coat and connect microporous grains, and separate microporous grains from larger interparticle pores. Micropores in these cements thus could play an important role in communication between microporous grains and macropores.

# **Microporous Equant Cements**

Microporous equant cements are less common than the microporous fibrous to bladed cements described above, primarily because sparry equant calcite cement itself is not as common in Arab-D reservoir rocks in Eastern Saudi Arabia. Equant cements are composed of subhedral to anhedral crystals of calcite approximately 30 to 40 microns in size (Figure 7c). These micropores occur between cement crystals; similar to the microporous fibrous to bladed cements discussed previously, they probably result from the contact inhibition of adjacent growing crystals (Wardlaw, 1976). Pore throats are flat, platy to laminar in shape and up to 3 microns thick, and intersect to form tetrahedral-shaped pores 2 to 6 microns in diameter (Figures 7d to 7f). Pore throat diameters are extremely uniform in size. Where equant cement occurs in interparticle pores, these micropores serve as possible pathways connecting microporous grains to one another and to interparticle porosity.

# QUANTITATIVE ASPECTS OF MICROPOROSITY

The next aspect of this study was to quantitatively evaluate the abundance of microporosity, and this was accomplished in two ways. First, thin section point counts were used to determine microporosity



Figure 6: Microporous matrix and microporous cements in Arab Formation carbonates. Porosity in thin section is filled by blue-dyed epoxy, calcite is stained red to pink, other minerals are unstained. (a) SEM view of fractured rock surface of chalky microporous matrix. Microporous matrix is composed of well-sorted calcite crystals generally 1 to 4 microns in size; microporosity occurs as small pores between these micrite crystals (unspecified Mesozoic reservoir, Middle East). (b) Thin section photomicrograph of packstone with abundant moldic (MO) porosity and common microporous matrix (arrows). Moldic porosity is the result of leaching of the dasycladacean algae Salpingoporella (DS) which forms characteristic circular pores. Minor interparticle porosity is present (plane-polarized light, Saudi Arabia, Berri field, Arab-C). (c) SEM image of epoxy pore cast of packstone sample in (b). Moldic pores (MO) are interconnected via a microporous matrix (arrows). This epoxy pore cast was prepared from same sample as the thin section shown in the previous photograph. (d) SEM view of epoxy pore cast of rock with microporous matrix. Tortuous network of laminar pore throats (arrows) intersect to form larger, tetrahedral micropores (Saudi Arabia, Berri field, Arab-C). (e) Thin section photomicrograph of grainstone with abundant fibrous to bladed isopachous calcite cement (arrows). Note leached bivalve (B) that is infilled with later equant sparry calcite cement (plane-polarized light, Saudi Arabia, Qatif field, Arab-C). (f) SEM image of fractured rock surface. Isopachous cement composed of euhedral to subhedral bladed calcite crystals (arrows) partly surrounds micritized grain (M). Cement morphology suggests precipitation within the marine phreatic zone (Saudi Arabia, Ghawar field, Arab-D).



**Figure 7:** Microporous cements in Arab Formation carbonates. Porosity in thin section is filled by blue-dyed epoxy, calcite is stained pink to red, other minerals are unstained. **(a)** SEM image of epoxy pore cast of three microporous grains (M) that are enveloped by microporous isopachous bladed calcite cement (MC-FC). Note the presence of abundant, thin tubular pores within the isopachous cement (arrows). Microporosity developed within micritized grains is interconnected via the microporous isopachous cements (Saudi Arabia, Berri field, Arab-C). **(b)** Higher magnification view of epoxy pore cast shown in the previous example. Note thin, tubular micropores (arrows) developed within the isopachous bladed calcite cements (SEM image).



**Figure 7: (c)** Thin section photomicrograph of grainstone with abundant equant calcite cement (arrows). This cement fills interparticle porosity between microporous micritized grains (MG) and probable composite grain (CG) (plane-polarized light, Saudi Arabia, Berri field, Arab-C). (d) Epoxy pore cast of microporous grains (MG) that are embedded in microporous interparticle equant calcite cements (MC) (SEM image, Saudi Arabia, Berri field, Arab-C). (e) Detail of epoxy pore cast of microporous equant calcite cement shown in (d). Note the straight, platy to laminar shape of pore throats (arrows). Pore throats intersect to form larger, poorly-defined tetrahedrons (SEM image). (f) Detail of center of epoxy pore cast of microporous interparticle equant calcite cement shown in (e). Pore throats (arrows) are less than or equal to 1 micron in size in at least one direction.



Figure 8: Cross-plot of measured porosity and point count porosity for non-Arab-D calibration samples with minimal microporosity (red circles) and for Arab-D samples (open circles).

abundance and variability; and second, mercury injection capillary pressure analysis allowed the resolution of greater details in the quantitative analysis of microporosity abundance and distribution in Arab-D samples.

# **Petrographic Thin Sections Point Counts**

Petrographic thin sections were point counted to determine optically visible porosity. This visible porosity includes all pores greater than about 10 microns in size (in other words, macropores only). Visible porosity was then compared to the total porosity measured on the equivalent core plug (the thin section was cut from the clipped end of this core plug) by routine core analysis, to derive an estimate of the amount of microporosity in the sample. Sixty-three samples were analyzed in this manner.

Figure 8 illustrates the relationship between measured and point count porosity values for the samples used in this study, as well as for 8 additional (non-Arab-D) calibration samples. For the Arab-D samples (open circles), measured (total) porosity is consistently higher than point count estimated porosity, with a linear regression of Y = 0.68X - 1.37. This plot also shows data for 8 additional calibration samples (red circles) that are included to validate the point count method for porosity determination. These additional samples all have minimal microporosity, yield similar measured porosity and point count porosity values, and tend to fall along a line described by Y = X.

Overall, the petrographic data indicate that microporosity occurs almost universally throughout the Arab Formation (Figures 9 and 10). The abundance of microporosity, however, varies from sample to sample and can account for anywhere from 0% to 100% of the total measured porosity ( $ø_T$ ). In individual samples, both solid non-microporous grains and extremely leached, moldic-appearing grains are seen. Figure 9 illustrates microporosity abundance and variability, and indicates that virtually all samples

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Figure 9: Cross-plot comparing microporosity (as a percent of total pore volume) and total porosity for different depositional textures.



Figure 10: Cross-plot showing variation in microporosity abundance (as a percent of total pore volume) with depositional texture. The total number of samples (n) is 63.

have a significant amount of microporosity. Even the best reservoir quality rocks typically have 25% to 50% microporosity (that is, 25% to 50% of the total pore volume of the sample occurs as microporosity).

While some microporosity typically occurs in all studied samples, the type and amount of microporosity varies systematically. The petrographic data allowed us to identify the three major factors that exercise some control over variations in microporosity abundance and variability: (1) depositional texture, (2) original mineralogy, and (3) grain microstructure.

### **Depositional Texture**

The primary control over microporosity in a rock sample as a whole is depositional texture. This relationship between depositional texture and microporosity abundance (Figure 10) occurs principally because the overall proportion of microporous components (including microporous grains and microporous matrix) increases as depositional texture becomes muddier.

For example, grainstones and mud-lean packstones consist predominantly of grains (which are usually microporous) and large macropores; relatively minor microporous matrix is present. In these rocks, then, microporosity is limited to microporous grains. Some microporous cements and matrix may be present, but they generally do not contribute much quantitatively to overall microporosity. Consequently, microporosity in these rock types is relatively low, averaging 19.8% and 37.6% of the total porosity ( $ø_T$ ) for grainstones and mud-lean packstones, respectively. In muddier carbonates, however, both microporous grains and matrix are present, and macroporosity is less abundant. In these rocks, primary interparticle porosity is filled by microporous matrix, reducing macroporosity yet at the same time increasing the proportion of microporosity. Average microporosity for packstones is 53.8% of  $ø_T$ . In the case of mud-supported rocks (wackestones and mudstones), microporous matrix is dominant. In many cases, no visible macroporosity is present and microporosity accounts for the total porosity of the rock. Essentially 100% of the total porosity in wackestones and mudstones is microporosity.

In general, then, the proportion of total porosity consisting of microporosity increases as depositional texture becomes muddier, due to filling of pore space between microporous grains with microporous matrix. Figure 9 also illustrates this systematic increase in microporosity (as a percent of total porosity) with change in depositional texture. Muddier rocks in the Arab-D tend to have lower total porosity, with more of the total porosity being microporosity.

### **Original Mineralogy**

Microporosity occurs only in grains originally composed of metastable aragonite or high magnesium calcite, whereas grains originally composed of low magnesium calcite are solid and non-microporous. Table 1 summarizes the interpreted primary mineralogies of common grains and cements in the Arab-D. This occurs without regard as to whether grains are skeletal or non-skeletal in origin. Different grain types with different original internal fabrics (e.g., ooids versus foraminifera) may be transformed into microporous grains with similar end-member fabrics (Figures 4a to 4e; 5a to 5e; 11a to 11c).

Aragonite and high magnesium calcite are less stable than low magnesium calcite at conditions typical of the earth's crust (Bathurst, 1975). This difference in stability is responsible for the formation of moldic porosity in aragonite grains and microporosity in most high magnesium calcite grains. As shown by the leaching of aragonitic molluscs, corals and dasycladacean algae, most aragonitic grains in the Arab-D are completely leached; high magnesium calcite grains remain but usually are microporous. In contrast, grains with presumed original mineralogy of low magnesium calcite (brachiopods, ostracodes, and stromatoporoids) never appear leached or microporous. Primary mineralogy thus controls the potential for complete micritization and microporosity development within a grain.

#### **Grain Microstructure**

One factor that seems to modify the effect of primary mineralogy on microporosity formation is grain microstructure. Certain grains, specifically echinoderm fragments and early marine cement crystals,

Components	Source				
ARAGONITE					
Ooids	Cayeux (1935), Illing (1954), Newell and Rigby (1957), Newell et al. (1960), Taft et al. (1968), Bathurst (1975), Loreau and Purser (1973)				
Fibrous to Bladed Spar Cement	Purser (1969), Longman (1980)				
Green Algae	Johnson (1971), Wray (1977)				
Molluscs	MacClintock (1967), Majewske (1969), Chave (1964), Bathurst (1964, 1975)				
Scleractinian Corals	Chave (1964), Majewske (1969)				
HIGH MAGNESIUM CALCITE					
Ooids	Sandberg (1975,1983), Wilkinson et al. (1985)				
Echinoderms	Chave (1964), Majewske (1969), Bathurst (1975)				
Syntaxial Echinoderm Overgrowths	Meyers and Lohmann (1978), McGill and Walker (1982)				
Red Algae	Johnson (1971), Wray (1977)				
Benthic Foraminifera	Chave (1964), Bathurst (1975)				
Bladed Spar Cement	Longman (1980)				
LOW MAGNESIUM CALCITE					
Ooids	Sandberg (1975,1983), Wilkinson et al.,1985				
Brachiopods	Chave (1964), Majewske (1969), Bathurst (1975 )				
Bryozoans	Majewske (1969), Bathurst (1975)				
Arthropods (restricted to ostracodes in Arab-D)	Chave (1964), Majewske (1969), Bathurst (1975)				
Stromatoporoids (including <i>Cladocoropsis</i> sp.)	Majewske (1969)				
Molluscs (restricted to inoceramid bivalves in Arab-D)	Bathurst (1975)				
Equant Spar Cement	Bricker (1971), Harris (1979), Halley and Harris (1979)				
Syntaxial Echinoderm Overgrowths	Longman (1980)				
MIXED ARAGONITE AND HIGH MAGNESIUM	/ CALCITE				
Micrite	Attributed to post-mortem disintegration of skeletal debris and calcareous red and green algae, Cloud (1962), Lowenstam (1963), Stockman et al. (1967)				
Microspar	Neomorphic after micrite, Folk (1965)				
Molluscs (restricted to bivalves and gastropods)	Chave (1964), Majewske (1969)				
Micritized Grains, Pellets, Peloids and Intraclasts	Composed of aragonite and/or high magnesium calcite (?) micrite				

 Table 1

 Interpreted Primary Mineralogy of Common Grains and Cements in the Arab-D

are not micritized or microporous, in spite of probably being originally composed of metastable high magnesium calcite (Figure 11c). These grains all have single-crystal microstructure and, except for rare micrite envelopes caused by boring activities of endolithic algae or fungi, are devoid of complete grain micritization and microporosity.

While the role of microstructure is not completely understood, large, single-crystal grains (e.g., echinoderms) are probably more stable and less susceptible to dissolution and microporosity formation during diagenesis than fibrous or aggregate-crystalline grains. Fyfe and Bischoff (1965) have shown that very small grains (one micron and smaller) have solubilities that are significantly higher than those of macrocrystalline grains of the same material. Thus, the single-crystal microstructure is a more stable structure and probably inhibits to some degree the formation of diagenetic microporosity within a grain of metastable mineralogy.

# **Capillary Pressure Data**

Capillary pressure data was also used to quantitatively evaluate microporosity in Arab Formation carbonates. For this method, pore size distributions were determined from mercury injection capillary pressure analyses of 138 extracted core plugs. These pore size distributions were obtained by collecting 200 drainage capillary pressure data points from 1 to 30,000 pounds per square inch (psi) for each sample. This high resolution method contrasts with conventional mercury injection techniques (which typically use injection pressures only up to 2,000 psi) and enabled us to better resolve the distribution and relative abundance of microporosity in these samples. Comparison of data from duplicate samples analyzed using both low and high pressure techniques showed similar pore size distributions for the larger pores; however, the high pressure technique also allowed us to "see" the very fine pore throat sizes as well.

Mercury injection data is a measure of pore entry size (diameter), not actual pore size. The pore entry size calculations were made using the equation:

$$D = \frac{0.58 \ (\sigma) \ (\cos \theta)}{P}$$

where: D = Pore entry diameter in microns P = Capillary pressure (mercury injection pressure) in psi  $\sigma$  = Interfacial tension, dynes/cm ( $\sigma$  = 485 dynes/cm for air/mercury system)  $\theta$  = Contact angle in degrees ( $\theta$  = 130° for air/mercury)

The pore entry size distribution functions were calculated by:

$$F(D) = \frac{V \times 10^4}{\Delta D}$$

where: F(D) = Distribution function (as a function of diameter)

V = Incremental volume of mercury injected (fraction of total pore volume)

 $\Delta D$  = Incremental change in diameter over which V was determined

While the percent of microporosity derived from capillary pressure data is not strictly comparable with microporosity determinations from thin section point counts, the capillary pressure data does allow a qualitative comparison of microporosity determined by two very different techniques.

Results from some of the capillary pressure analyses are shown in Figures 12 and 13, and illustrate the complex pore systems present in the Arab-D. Figure 12 is a suite of cumulative pore-size distribution



Figure 11: Microporous grains in the Jurassic and in the Recent. Porosity in thin section is filled by blue-dyed epoxy, calcite is stained pink to red, other minerals are unstained. (a) Thin section photomicrograph of ooid-skeletal mud-lean packstone. Large brachiopod fragment (B) was originally composed of low magnesium calcite and is non-microporous. In contrast, surrounding grains are micritized and microporous (plane-polarized light, Saudi Arabia, Khursaniyah field, Arab-D). (b) Thin section photomicrograph showing micritized and microporous grains originally composed of metastable high magnesium calcite. Original high magnesium calcite components include several types of foraminifera (F), micritized grains (MG) and the red algae Thaumatoporella (TP) (plane-polarized light, Saudi Arabia, Ghawar field, Arab-D). (c) Thin section photomicrograph showing preserved microstructure of several echinoderm grains (E). In spite of their original high magnesium calcite mineralogy, echinoderms are rarely microporous. Algal or fungal borings (B) and micrite envelopes (arrows) are locally common on these grains, although these grains never appear completely micritized (plane-polarized light, Saudi Arabia, Ghawar field, Arab-D). (d) Photomicrograph of a Recent skeletalpeloidal sand. Peloids (P) are completely micritized and microporous, as indicated by their bluish color. Blue appearance results from the infiltration of blue-dyed epoxy into micropores in the grains. In contrast, solid grains are pearly white in color. Note that some grains are incompletely micritized (arrows), and grade from bluish micritized and microporous CaCO, into white, solid CaCO, within the same grain (reflected light, Holocene, North Caicos, British West Indies).

curves for six representative Arab-D samples and reveals that microporosity (as previously defined, all pores 10 microns or less in size) accounts for a significant proportion (from about 50% to over 90% in these samples) of total pore volume. Figure 13 is a series of pore throat size distribution plots which illustrate the range and distribution of pore throats in three Arab-D samples. These pore throat size distribution plots all reveal that Arab carbonates contain a broad range of pore throat sizes and that even relatively mud-free samples have pore throats down into the 0.01 micron range. In general, we interpret pore throats between 0.05 to 0.3 microns to represent microporosity and, while these pore throat sizes are considerably smaller than those identified from the petrographic work, they do compare well with the pore networks observed in SEM and probably connect up to form larger micropores. Pore throats greater than about 5 to 10 microns probably form the larger macropore system.



**Figure 11 continued: (e)** SEM photograph of epoxy pore cast of large Recent microporous peloid (P). Solid components (arrows) within the microporous peloid, as well as other solid grains (SG), were etched away during sample preparation. Interparticle (BP) porosity appears as solid epoxy (Holocene, North Caicos, British West Indies). **(f)** Higher magnification view of previous sample. Micropores in this Recent micritized grain are distinct from typical Arab-D micropores in microporous grains. Whereas Arab Formation micropores in microporous grains are straight tubular to laminar pores usually less than one micron in size, micropores in Recent micritized grains are more massive and equi-dimensional in form.



Figure 12: Typical cumulative pore size distribution curves for representative rock types in the Arab-D from mercury injection capillary pressure data. The samples shown here range from relatively mud-free (solid curves) to mud-rich (dashed curves) rocks, yet all have a significant proportion of their total pore volume contributed by pores less than 10 microns in size. In all samples examined in this study, microporosity (pores less than 10 microns in size) is volumetrically significant.

Figure 13 also illustrates how microporosity - and total porosity - vary with matrix content and depositional texture. As matrix content increases and depositional texture becomes muddier, larger pore throats connecting the macropore system becomes less abundant and microporosity becomes a more significant proportion of total pore volume. By the time matrix exceeds 40% of the rock, microporosity has become the most significant porosity type and larger macropores (especially those with pore throats in the 10 to 100 micron range) are relatively isolated and insignificant.

In general, the capillary pressure data allows us to resolve quantitatively the actual size range and distribution of microporosity. While the pore throats revealed by capillary pressure are generally much smaller than the petrographically-identified micropores, they do confirm the volumetric significance of pores and pore throats less than 10 microns in size. Capillary pressure data also suggest that a significant amount of the pore volume of these samples can only be accessed by very small pore throats (0.03 to 0.3 microns in size) and that microporosity becomes more significant - and conversely that macroporosity becomes less significant - as matrix content increases and depositional texture becomes muddier. Given the limits of resolution of the petrographic microscope, we feel these results generally agree with the observations and conclusions from petrographic data.

## **IMPLICATIONS**

This study has shown how microporosity was identified in Arab Formation carbonates and how its occurrence was related primarily to depositional texture and original mineralogy. This relationship can be extended further and used to predict and map out the spatial distribution of microporosity across a reservoir. This could be done by first constructing maps and cross-sections that show depositional texture variations (using core control), and then, using the microporosity-depositional texture relationship established by this study, predict microporosity amounts and distribution trends across a reservoir. These maps could be effective tools to predict and explain fluid flow, wireline log response and reservoir performance.

It is important to recognize that microporosity can have a significant impact on the fluid flow properties and log response of a reservoir. Typically, water is thought to be the wetting phase in a rock and, consequently, capillary forces tend to draw water up into the very small pores (micropores). Water held



Figure 13: Examples of pore throat size (diameter, in microns) distribution plots for 3 representative Arab-D samples. These plots illustrate the overall distribution of pore sizes, and how the dominant pore sizes (peaks) shift, as mud content increases.

in these micropores by capillary attraction tends to be "bound" (immobile) and may not be producible. Wireline logs record total fluid content of a rock - including bound water in the micropores - thus the resulting calculated water saturations do not reflect the true producible fluid saturations that occur in the macropore system. When no microporosity is present, wireline logs yield fluid saturations that occur in the macropore system and are much more indicative of the true producibility of the reservoir. Zones with significant water-filled microporosity may contain (and produce) water-free hydrocarbons from the macropore system, even though the logs may indicate the zone to be apparently wet. Changes in rock wettability and pore geometry may affect some of these generalizations.

Microporosity can also have a significant impact on a reservoir performance model, for two reasons. First, the actual effective porosity of the reservoir may be significantly less than the total porosity indicated by wireline logs and by core analysis data. Consequently, volumetric calculations using these pore volume numbers may be significantly in error. Second, as detailed above, log-derived saturations may not be indicative of the true producibility of a reservoir. In order to develop an accurate reservoir performance model and volumetric assessment, a systematic effort to recognize and quantify microporosity should be an integral part of any reservoir study.

This study has shown how significant microporosity is, how it varies, and what are some of the controls over its occurrence in Arab Formation carbonates of the Middle East. However, we feel that the techniques developed during this study are applicable to other fields elsewhere, in that they represent a reasonable rapid and cost effective technique for documenting and quantifying microporosity variations within a given reservoir interval.

# **ORIGINS OF MICROPOROSITY**

As Pittman (1971) observed, it is unlikely that any microporosity in ancient rocks can be termed primary, as any primary microporosity associated with metastable aragonite or high magnesium calcite phases must be modified substantially (if not destroyed) during inversion to low magnesium calcite. In a similar manner, most micropores in the Arab-D are probably diagenetic in origin, or at least have been modified somewhat by diagenesis.

As previously noted, microporosity occurs in a variety of forms or types in the Arab-D, implying that several mechanisms are responsible for the formation of microporosity. In the following discussion, similar types of microporosity are treated together, since micropores with similar morphologies probably formed in the same manner. We should note that this discussion applies primarily to possible microporosity-forming mechanisms in the Arab-D Member; while microporosity has also been recognized in other Cretaceous carbonate reservoirs in the area (e.g. Budd, 1989; Moshier, 1989), we have not studied these other units and so conclusions from our study may not be appropriate for them.

Three mechanisms are responsible for the majority of microporosity in the Arab-D: (1) leaching and incomplete reprecipitation of metastable carbonate, (2) crystal growth contact inhibition, and (3) endolithic boring of grains (locally).

# Leaching and Incomplete Reprecipitation of Metastable Carbonate

Post-depositional leaching of metastable  $CaCO_3$  minerals and incomplete reprecipitation of low magnesium calcite is probably responsible for microporosity in micritized microporous grains and matrix. Although grain micritization by boring endolithic algae and fungi is recognized as a significant grain-altering process in modern-day shallow water carbonate environments (Logan, 1974; Kobluk and Risk, 1977) and occurs locally in the Arab-D, several factors argue against an algal/fungal origin for most of the pervasive micritization and microporosity development in the Arab-D.

First, complete micritization is mineralogy-selective in the Arab-D, occurring only in originally metastable components (Figures 11a to 11c). Boring endolithic organisms, however, would not be expected to display any preference in mineralogy of the host grains. Also, the extent of grain

micritization is too pervasive in Arab carbonates to be attributed solely to algal or fungal activity. Although some micrite envelopes and borings of algal or fungal origin do occur, they are readily distinguishable from the completely micritized and microporous grains that are so common in these rocks (Figure 11c). Finally, the habit of Recent micropores of algal or fungal origin are significantly different from those seen in the Arab-D (Figures 11d to 11f). It appears that the pervasive micritization and microporosity development results from partial post-depositional solution of metastable CaCO<sub>3</sub> minerals.

Since the stabilization of metastable carbonate probably occurs relatively early (either during early marine or early fresh water diagenesis (Bathurst, 1975; Longman, 1980; Palmer et al., 1988)), the development of microporous grains and matrix was probably a relatively early diagenetic process. Also, since the appearance of microporosity is dependent on original mineralogy and microstructure, depositional facies controls the architecture of microporosity development. It is the mineralogy and microstructure of the grains typically comprising each facies that determines the appearance and abundance of microporosity present. Depositional facies thus forms the basis for predicting microporosity distribution. All of the rock-types found in the Arab-D in Saudi Arabia contain significant amounts of microporosity; however, the exact amount of microporosity in each rock-type depends on the proportion of grains within each that were originally composed of metastable mineralogy.

There are several diagenetic processes under which the dissolution-incomplete reprecipitation process responsible for most Arab-D microporosity may have occurred. These include: (1) evaporite diagenesis, (2) leaching by carbon dioxide-charged fluids formed during the maturation and migration of hydrocarbons, (3) marine diagenesis, (4) fresh water vadose diagenesis, (5) fresh water phreatic diagenesis, and (6) mixing zone diagenesis. As we will explore in this section, we feel that evaporite diagenesis is probably the most likely process responsible for forming most of the microporosity in the Arab-D.

# **Evaporite Diagenesis**

The presence of a thick evaporite sequence immediately overlying the Arab-D Reservoir influences the diagenesis of Arab-D carbonates. Previous workers (Broomhall and Allan, 1985; Wilson, 1985) have suggested a direct relationship between some of the Arab dolomites and the evaporites. Fluids expelled during the compaction of evaporites or during the transformation of gypsum to anhydrite with burial are usually undersaturated with respect to  $Ca^{+2}$  (Shearman, 1978). Other workers have shown that such fluids typically have high  $Mg^{+2}/Ca^{+2}$  ratios and are capable of dolomitizing limestones (Butler, 1969; Clark, 1980; Moore and Druckman, 1981). Also, these fluids become fairly acidic (pH<5.5) at shallow burial depths (Butler, 1969).

Other workers concerned with the diagenesis of evaporite-carbonate sequences have pointed out the role of evaporite-derived pore waters as a means of producing secondary porosity in carbonate rocks (Oldershaw, 1972; Schreiber et al., 1976; Sarg, 1982). Since evaporite-derived waters are undersaturated with respect to Ca<sup>+2</sup> (Shearman, 1978), they may promote leaching and recrystallization in Arab carbonates. Support for this mechanism for producing secondary porosity in the Arab-D comes from Butler's (1969) observation of the low pH of evaporite-derived waters, as well as the observation that some moldic pores in the Arab-D locally contain minor amounts of anhydrite. Thus, while it is unknown if sufficient volumes of water could be produced by evaporite diagenesis to create the amount of secondary porosity present in the Arab-D, several factors suggest that evaporite-derived fluids may, in part, be responsible for the formation of moldic macropores and microporosity in Arab-D carbonates.

# **Carbon Dioxide-Charged Subsurface Waters**

Carbonic acid may be generated in pore waters through the addition of carbon dioxide derived from the thermal maturation of organic matter during burial diagenesis. Tissot et al. (1974) showed that, with increasing pressure and temperature, the diagenetic transformation of organic matter results initially in the expulsion of water and carbon dioxide and culminates with the generation of oil and/ or gas. Schmidt and McDonald (1979) postulated that most secondary porosity in sandstones originates through the dissolution of carbonate mineral replacements and cements resulting from the

decarboxylation of organic matter during thermal maturation within sandstones or intercalated shales. This process is non-fabric selective and dissolves all carbonate phases. It is a fairly late process in the diagenetic history of a sandstone. As the development of microporous grains and micrite is fabric selective, and because it is believed to be a relatively early process, this model of solution probably is not responsible for microporosity in the Arab-D.

## Marine Diagenesis

Diagenesis in the marine environment is a common process in many shallow-marine carbonate depositional environments. Typically, products of this environment include cementation, partial grain micritization (micrite envelope formation), some forms of dolomitization and, potentially, grain leaching. This last process is particularly significant in Upper Jurassic sea water. It is thought to have generally been "calcite facilitative" (Wilkerson et al., 1985), and capable of dissolving originally aragonitic grain components. Indeed, recent workers have described the occurrence of aragonite dissolution within the "marine-burial" diagenetic environment of shallow water Neogene carbonates in South Florida and the Bahamas (Melim and Swart, 1998). Such dissolution could have produced moldic porosity in originally aragonitic grains. However, partial dissolution of Neogene originally calcitic grains (to form microporosity) has not been observed, and it is likely that Jurassic originally calcitic grains would have been in equilibrium with sea water and would not have been significantly affected (dissolved) by continued immersion in sea water. Partial dissolution of these originally calcitic grains by sea water during marine diagenesis was probably not responsible for the microporosity observed in the Arab-D.

# Fresh Water Vadose Diagenesis

It seems likely that local small islands could have developed upon subaerially exposed, grain-rich, shoaling sands that reached sea-level during deposition of the Arab-D. This is commonly seen in many regressive carbonate systems (Wilson, 1975). Although several workers (for example, Wilson, 1985; Bray, 1997) have recognized vadose diagenetic products in the Arab Formation in the form of unique cement types and internal peloidal sedimentation, these features are extremely rare overall in the Arab-D (Mitchell et al., 1988). Other features indicative of subaerial exposure of carbonates, such as caliche profiles or karst solution features, are absent in the Arab-D. Thus, the effect of vadose diagenesis was too localized and short-lived to account for the widespread occurrence and abundance of microporosity in the Arab-D.

# Fresh Water Phreatic Diagenesis

The geometry and extent of the fresh water phreatic zone is normally a function of topography, rainfall and the distribution of permeable pathways. In light of the probable low topography and arid climate that prevailed during Arab carbonate deposition (Mitchell et al., 1988), it seems unlikely that fresh water lenses of a sufficient size and hydrostatic head could have persisted. This view is supported by the obervation that interpreted fresh water cements are volumetrically minor in the Arab-D in Saudi Arabia.

### Mixing Zone Diagenesis

This zone is a narrow zone that marks a diffuse boundary between the fresh water (meteoric) phreatic and marine phreatic diagenetic zones. While Runnels (1969) has shown that the mixing of two chemically dissimilar pore waters can result in a mixture undersaturated with respect to calcium carbonate, dolomitization is typically the most important diagenetic process in the mixing zone (Hanshaw et al., 1971; Land, 1973; Wigley and Plummer, 1976). An effective mixing zone would probably be localized and short-lived for the same reasons stated for the fresh water vadose and phreatic diagenetic zone.

# **Crystal Growth Contact Inhibition**

Micropores in microporous cements probably result from the persistence of a thin film of water at crystal interfaces during crystal growth (Wardlaw, 1976). During crystallization, CaCO<sub>3</sub> precipitates

from interstitial waters; as adjacent crystals grow toward each other, a thin film of water is preserved along crystal faces. Contact between adjacent crystals is actually inhibited by this thin water film, and in this manner, thin "intercrystalline" micropores are developed between cement crystals. Since the vast majority of all diagenetic modifications of carbonate sediments occur in the presence of water (Bathurst, 1975), these thin "intercrystalline" micropores survive subsequent diagenetic modifications of crystal mineralogy. Such "intercrystalline" micropores are observed in the Arab-D and probably occur in most carbonate rocks that contain cement.

Although micropores of this type are volumetrically minor, they are significant in that they provide a passage between microporous grains and each other, and to larger macropores. These intercrystalline micropores commonly rim microporous grains, and occur as straight, tubular or laminar pores leading from microporous grains to other microporous grains, or open out into the larger macropore system.

## **Endolithic Boring of Grains**

As previously noted, endolithic algae and fungi produce relatively little microporosity in the Arab-D. Although micrite envelopes and borings are locally common, the microporosity formed in these envelopes is insignificant relative to that developed in micritized grains or matrix.

Grain alteration and micritization is common in Recent sedimentary environments (Bathurst, 1975). In Recent environments, grain micritization ranges from single micrite-filled borings within grains to complete grain micritization. Although such completely micritized grains superficially appear similar to Arab-D micritized grains, detailed examination of micropore sizes and habit reveals them to be very different (Figures 11d to 11f). Micropores in Arab-D grains typically are straight tubular to laminar pores usually less than 1 micron in diameter; micropores in Recent micritized grains, however, are larger and more equi-dimensional in habit (Figure 11f). Such differences in habit are to be expected, since micropores in Recent sediments occur between micrite crystals of metastable mineralogy and would be extensively altered (if preserved at all) by diagenesis.

### CONCLUSIONS

Microporosity occurs almost universally throughout Arab Formation carbonates of Saudi Arabia. Qualitatively, microporosity occurs in four major categories: (1) microporous grains, (2) microporous matrix, (3) microporous fibrous to bladed cements, and (4) microporous equant cements. Quantitative thin section data reveals that microporosity can vary widely, from 0% to 100% of the total pore volume and, even in the best quality reservoir rocks (most mud-free), microporosity typically accounts for 25% to 50% of total porosity. Depositional texture appears to be the major control over microporosity variations, but original grain mineralogy and grain microstructure play important but secondary roles.

Capillary pressure data, while not strictly analogous to the point count data, also suggest that microporosity comprises a significant portion of the total pore volume in Arab-D samples and that pore throats 0.03 to 0.3 microns in size probably connect up to form the micropore system. Pore throats greater than about 5 to 10 microns in size probably form the larger macropore system.

We suggest that microporosity in the Arab-D formed via three mechanisms: (1) leaching and incomplete reprecipitation of metastable carbonate (probably caused by fluids derived from the overlying evaporite); (2) crystal growth contact inhibition; and (3) (rarely) endolithic borings of grains.

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