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Modeling of Diagenetic Controls on Reservoir Characteristics

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Abstract

Diagenesis plays a big role in controlling the reservoir storage and flow properties. Modeling the effects of dominant diagenetic processes on petrophysical properties is of importance in reservoir characterization in order to convert a static geologic model into a dynamic reservoir flow model. This paper presents a study on modeling of microstructure and porosity/permeability evolution controlled by three end-member diagenetic processes, namely mechanical compaction, cementation and chemical compaction. Initial pore scale microstructure is modeled by assuming unit cell of uniform spheres with loose simple cubic packing (SC). Mechanical compaction leads change in packing styles from simple cubic packing (SC) to denser face-centered cubic (FCC) packing, while keeping grain size and shape fixed. Cementation is modeled as a process of grain-growth by precipitation while keeping the initial grain center-center distance fixed. Chemical compaction or pressure solution allows grains to dissolve at grain-grain contacts and reduces bulk volume of the unit cells. In a chemically closed system, pressure solution leads grain growth via precipitation of material derived from grain contacts. In a chemically open system, dissolved material by pressure solution is taken away from the system. Porosity is treated as the degree of diagenesis and is independent to grain size. Permeability is modeled using Kozeny-Carman equation for each end-member diagenetic microstructure and normalized to initial grain size. The relationships between porosity and universal permeability for different diagenetic processes are compared. Two diagenetic paths can be distinguished from the modeling results. Mechanical compaction is a more efficient mechanism for permeability reduction than cementation and chemical compaction. Other petrophysical parameters such as pore throat radius, specific surface area and tortuosity are also given.

Introduction

Diagenesis is one of the most important geological processes which control the hydrocarbon reservoir properties. Diagenesis includes both physical and chemical processes altering the primary depositional porosity, microstructure and petrophysical properties. The most common end-member diagenetic processes which lead porosity and permeability reduction during burial are cementation, mechanical compaction and chemical compaction or pressure solution. Depending on the geological variables, one or more diagenetic processes may dominate. Petrographic observations show that these end member diagenetic processes modify not only the porosity but also the pore geometry in different ways. The most common form of calcite and quartz cement is an overgrowth, a syntaxial rim of the detrital grain

(Waugh, 1970; Molenaar et al., 1988; McBride, 1989, Hendry et al., 1996 Mørk & Moen, 2007) (Figure 1a). Mechanical compaction occurs during shallow burial, aided by seismic (including microseismic) shocks. Vibration causes the packing of sediment to tighten as the fabric adjusts and grains snuggle up close to each other. Figure 1b shows a photomicrograph of sandstone with well sorted and rounded grains. Chemical compaction or pressure solution is the most important ductile compaction (deformation) mechanism operating in reservoir conditions (normally deep burial). In a chemically closed system, pressure solution reduces porosity both by dissolution at grain-grain contacts and by precipitation at pore walls (Figure 1c) (Mullis, 1992; Zhang & Spiers, 2005; Zhang et al. 2010, 2011). In an open system, the dissolved materials are taken away from the system and this process results in microstructure of sutured grain contacts but lack of precipitation at pore walls (Figure 1d). These end-member diagenetic processes modify the rock microstructures in different but predictable ways.

Diagenetic microstructure is an important input for permeability modeling, alongside the porosity. Permeability modeling is primarily driven by the need of using log measured porosity to predict the reservoir permeability in order to convert a static geologic model into a dynamic reservoir flow model (Rushing et al., 2008; Chekani and Kharrat 2009). They have been done in three ways, 1) the semi-empirical method 2) the statistical method or by 3) neural network supervised classification (Balan, 1995, Kale, et al., 2010). However, only the first group models consider both the porosity and rock microstructure and hence have a physical base. The most successful and widely used permeability model is the Kozeny-Carman equation. In essence, the Kozeny-Carman equation relates the permeability not only to the porosity but also to the hydraulic radius of pore throat and the tortuosity (Pape et al, 2001). Other frequently used models are those ones which incorporate the hydraulic radius in indirect ways—normally a parameter such as residual water saturation, which can be derived from log data (Tixier, 1949; Wyllie and Rose, 1950; Timur, 1968; Coates and Dumanoir, 1974). Incorporating the diagenetic microstructures into the Kozeny-Carman equation, the diagenetic paths in the porosity and permeability space can be expected.

The objective of this paper is to model the porosity-permeability relationships resulting from end-member diagenetic processes of cementation, mechanical and chemical compaction. The depositional porosity is modeled as Simple Cubic packing (SC) of uniform spheres with unit grain radius. The mechanical compaction is then modeled as evolution from Simple Cubic packing (SC) to Face Centered Cubic packing (FCC). Cementation and chemical compaction are modeled in two paths from both originally configuration of a SC packing and from denser FCC packing. Permeability is calculated using Kozeny-Carman equation but normalized to the initial grain radius. The results show that mechanical compaction is more efficient to reduce permeability than cementation and chemical compaction. Two paths of diagenesis can be distinguished from the universal porosity-permeability space. Other microstructural parameters such as pore throat radius, tortuosity and specific surface area are also given.

Methods

The modeling consists of two steps. In the first step, the microstructures are modeled as results of end member diagenetic processes. The microstructural parameters such as pore throat radius, specific surface area and tortuosity, are modeled as changes of geometry of pore and grain as a function of porosity. Permeability is then modeled based on each diagenetic microstructure using the Kozeny-Carman equation.

The start point of modeling is the depositional microstructure of simple cubic packing of spheres with uniform grain size. Two diagenetic paths are followed to model the pore scale microstructure evolutions. The first diagenetic path assumes no mechanical compaction - only cementation and chemical

compaction are involved in changing porosity and permeability. The second path assumes a mechanical compaction applied on the start depositional microstructure and cementation or pressure solution compaction is then followed. Cementation and pressure solution in both close and open system modify the grain shapes from an original sphere into a final cube for a simple cubic packing and into a final 12-faced polyhedron for FCC packing respectively.

Depositional microstructure- the start point

The start point of modeling is the assumption of an ideal configuration of uniform spherical grains with unit radius and has a simple cubic packing (Figure 2a & Figure 3a). The unit cell of this configuration consists of a full grain and circumscribed cube. However, the best way to describe the porosity and pore throat evolution is to use a unit cell cube with 1/8 grain at each corner (Figure 3a). A full pore is formed by eight grains and a pore throat is formed by four grains. The six faces of the cube represent the cross-sections of the pore throats. The bulk volume is the volume of the cube ($V_b=8$) and the grain volume is the volume of a sphere ($V_g=4\pi/3$). Hence the porosity can be easily calculated as:

$$\phi_0^{SC} = \frac{V_b - V_g}{V_b} = 1 - \frac{\pi}{6} = 0.476 \quad (1)$$

The cross-section of pore throat has a star shape as shown in the left figures in Figure 2a and 3a. In this study, the hydraulic radius is defined as the radius of the inscribed circle (r_t) (tube in 3-D) of the pore throat and can be calculated as:

$$r_t^0 = \sqrt{2}r_g^0 - r_g^0 \quad (2)$$

Where r_g^0 is the original radius of the grain which has a unit length (=1).

The specific surface area of the depositional microstructure (to bulk volume of the cell unit cube) is $4\pi/8$ (=1.57).

Porosity reduction and microstructure evolution by end-member diagenesis

The porosity reduction of the start configuration is achieved in four ways, the cementation, chemical compaction (pressure solution) in close system and in open system and mechanical compaction, respectively. The microstructural evolutions from a simple cubic packing are described as follows:

1) Cementation

Cementation is modeled as grain overgrowth as a rim. Rims overlap at grain-grain contacts. As a result, grain contact area grows. The grain-grain contact is assumed to be a circle. The bulk volume of the unit cell is fixed and porosity is reduced by progressively increasing grain volume. This represents the geological scenario where net mass input into the reservoir rock system as cement. The instantaneous grain radius r_g can be calculated as a function of porosity ϕ by solving the following equation:

$$\frac{4}{3}\pi r_g^3 - 6V_{cap} - (1 - \phi)V_b = 0 \quad (3)$$

Where V_b is the bulk volume of the unit cell ($=8$), which is fixed in the case of cementation. V_{cap} is the volume of a spherical cap with height of $r_g - r_g^0$ and sphere radius of r_g .

The hydraulic radius of the pore throat can be calculated using equation (2) but replacing initial grain radius r_g^0 with instantaneous grain radius r_g . The specific surface area S_s within a unit cell can be calculated as a function of porosity by:

$$S_s = \frac{4\pi r_g^2 - 6S_{cap}}{V_b} \quad (4)$$

Where S_{cap} is the surface area of the spherical cap.

2) Chemical compaction (pressure solution) in a chemically close system

In a chemically closed system, pressure solution causes dissolution at grain-grain contacts while precipitation at pore walls as shown in Figure 1c. This process is modeled as the unit cell edges reduce as a result of dissolution. At the same time, the dissolved material uniformly precipitates at the surface of free pores. Hence, the grain volume is fixed within a unit cell. The porosity reduction is achieved via reducing the unit cell bulk volume. This represents a geological scenario where sedimentary thickness of reservoir rocks reduces while no net mass input/output to the system.

In this case it is easier to calculate the instantaneous length of edge of the unit cell (Figure 3a) X as a function of instantaneous porosity by a very simple equation:

$$X = \sqrt[3]{\frac{V_g}{1 - \phi}} \quad (5)$$

The instantaneous grain radius is found by solving the equation as follow:

$$\frac{4}{3}\pi r_g^3 - 6V_{cap} - V_g = 0 \quad (6)$$

Where V_g is the grain volume within the unit cell and is equal to the original grain volume in this case. V_{cap} is the volume of a spherical cap with sphere radius of r_g and height of $r_g - X/2$.

With the knowledge of instantaneous grain radius and the length of unit cell edge, other microstructural parameters such as hydraulic radius of pore throat and specific surface area, can be easily calculated for the case of chemical compaction in close system.

3) Chemical compaction (pressure solution) in a chemically open system

In a chemically open system, chemical compaction or pressure solution also leads to grain dissolution at contacts. However, unlike in the chemically close system, the dissolved material is taken away from the system. Since diffusion is a very slow process (Zhang et al. 2011), material is most likely brought out of reservoir rock by fluid convection. In this case, porosity is reduced by reduction both bulk volume and grain volume. However, the grain radius is fixed. The instantaneous length of the unit cell X can be calculated by solving the equation of:

$$\frac{4}{3}\pi r_g^3 - 6V_{cap} - (1 - \phi)X^3 = 0 \quad (7)$$

Where V_{cap} is the volume of a spherical cap with sphere radius of r_g^0 and height of $r_g^0 - X/2$.

4) Mechanical compaction

Mechanical compaction is assumed as a process of microstructural changing from loose simple cubic packing (SC) to dense face centered cubic packing (FCC). Experiments show that vibration can help loosely packed beach sand compacts to densely packed sand. For the FCC packing, the unit cell is a cube with 1/8 grain at each corner and 1/2 grain at each face. So there are four grains within a unit cell and each grain has 12 contacts (Figure 3b). The length of the unit cell is $2\sqrt{2}r_g^0$ (Figure 3b), and the porosity is:

$$\phi_0^{FCC} = \frac{V_b - 4V_g}{V_b} = 1 - \frac{\sqrt{2}\pi}{6} = 0.2596 \quad (8)$$

In the FCC configuration, a pore is formed by four grains and a pore throat is formed by three grains (Figure 2b). The pore throat hydraulic radius for FCC packing of spheres is

$$r_t^0 = r_g^0 \left(\frac{1}{\cos 30} - 1 \right) \quad (9)$$

The diagenetic microstructures of cementation and chemical compaction evolving from an originally FCC packing of spheres can also be modeled by the same way as described in the above sections for the simple cubic packing. Cementation and pressure solution in both close and open system all modify grain shape from original sphere to final cube for simple cubic packing and to 12 faced polyhedron for FCC packing, when porosity approaches zero.

Permeability and tortuosity modeling as a function of porosity and microstructure

The permeability reduction for each diagenetic process is modeled by using the Kozany-Carman equation in the form of (Kozeny, 1927; Carman, 1938, 1956; Pape, et al. 2001):

$$k = \frac{r_t^2}{8F} \quad (10)$$

where r_t is hydraulic radius, F is the formation factor. It is defined as a function of tortuosity T and porosity ϕ .

$$F = T/\phi^2 \quad (11)$$

For diagenetic microstructures evolved from an originally simple cubic packing, the tortuosity (T) value is taken as 1 at the whole porosity region for the fluid can pass the unit cell straightly (Figure 2a and 3a). For face centered cubic packing related microstructures, fluid has to travel around half grain circumference to pass the unit cell length. For FCC packing, the tortuosity (T) is calculated by

$$T = \frac{\pi r_g}{X} \quad (12)$$

Results and discussions

The modeled microstructural parameters resulted from different diagenetic process are shown in Figure 4, 5 and 6. The denser face centered packing has much smaller pore throat hydraulic radius (0.14) compared to simple cubic packing (0.42). Cementation microstructure from original SC packing has largest pore throat radius. For simple cubic packing the hydraulic radiuses are nearly the same for pressure solution in open and closed system. For FCC packing, all three diagenetic processes of cementation, pressure solution in open and close system result in nearly the same type evolution of hydraulic radius (Figure 4). For both packing styles the hydraulic radiuses approaches zero at porosity about 3.5%. The modeled results of specific surface areas are shown in Figure 5. Cementation results in smaller surface areas compared to pressure solution. Note that the surface areas are not zero at porosity of 3.5 when hydraulic radius is zero. Figure 6 shows the evolution of tortuosity. The tortuosity for microstructures evolved from simple cubic packing by various diagenetic processes takes the value of 1. For the FCC packing related microstructure the tortuosity values are from 1.1 to 1.3 from porosity 26 to 3.5%.

The modeled permeability results are shown in Figure 7a and 7b in semi log and log-log scale respectively. For a certain packing style, the differences permeability reductions caused by various diagenetic processes are not significant. Cementation is the least efficient mechanism for permeability reduction at the same porosity. Mechanical compaction is the most efficient in permeability reduction. Permeability decreases faster at the porosity region <10-4% than at higher porosity region due to drastically reducing hydraulic radius of pore throat. The modeled permeability for both packing styles all approaches zero at porosity about 3.5%. So the pores become isolated at porosity < 3-4%. At this porosity the pore throat radius becomes zero. Hence, the model breaks down when porosity is lower than 3-4%. Two paths of diagenetic processes can be seen in the universal permeability porosity space- faster permeability reduction occurs in the diagenetic sequence including mechanical compaction and slower permeability reduction in diagenetic sequence lack of mechanical compaction.

It is known that grain size plays big role in controlling permeability. In our study, we isolate the grain size effects by using the universal scale microstructural parameters. However, the effect of grain size distribution and start grain shape were not considered. Specifically, the grain size reduction during mechanical compaction can be expected to be very efficient to reduce both porosity and permeability (Ehrenberg, 1989; Schutjens et al. 2004). Other diagenetic processes such as grain leaching, mineral replacement including dolomitization and especially clay generation mineral reaction processes are known very important in controlling reservoir properties (Gluyas & Leonard 1995) and needed to be incorporated in diagenetic modeling. This work provides a start for modeling diagenetic microstructures in clean sandstone and some carbonate rocks which can be used as a basis for kinetic modeling of specific diagenetic process in basin modeling. More sophisticated modeling incorporating grain size distribution especially clay and other diagenetic processes is needed.

Conclusions

In this study the effects of various diagenetic processes on the microstructure and permeability have been investigated. The following conclusions can be drawn.

- 1) Microstructure and permeability modeling for diagenetic processes is a useful method to compare the efficiency of permeability reduction.

- 2) Mechanical compaction is an efficient process to destroy permeability. Cementation is a less efficient permeability reduction mechanism.
- 3) The diagenetic paths can be distinguished for a diagenetic sequence with or without mechanical compaction.
- 4) The modeling results show that the difference of permeability reductions by cementation and chemical compaction is not significant. Permeability decreases faster at the porosity region <10-4% than at higher porosity region due to drastically reducing hydraulic radius of pore throat.
- 5) The modeled tortuosity is at the range of 1-1.3.

Nomenclature

F	Formation Factor
k	Permeability
r_t^0, r_t	Original and instantaneous hydraulic radius of pore throat
r_g^0, r_g	Original and instantaneous grain radius
S_s	Specific surface area per bulk volume
S_{cap}	Surface area of a spherical cap
T	Tortuosity
V_b	Bulk volume of unit cell cube (initial and instantaneous)
V_g	Grain volume per grain (initial and instantaneous)
V_{cap}	Volume of a spherical cap
X	Edge length of unit cell cube
ϕ_0^{SC}	Initial (depositional) porosity of Simple Cubic packing (SC) of uniform spheres
ϕ_0^{FCC}	Initial porosity of Face Centered Cubic packing (FCC) of uniform spheres
ϕ	Instantaneous porosity

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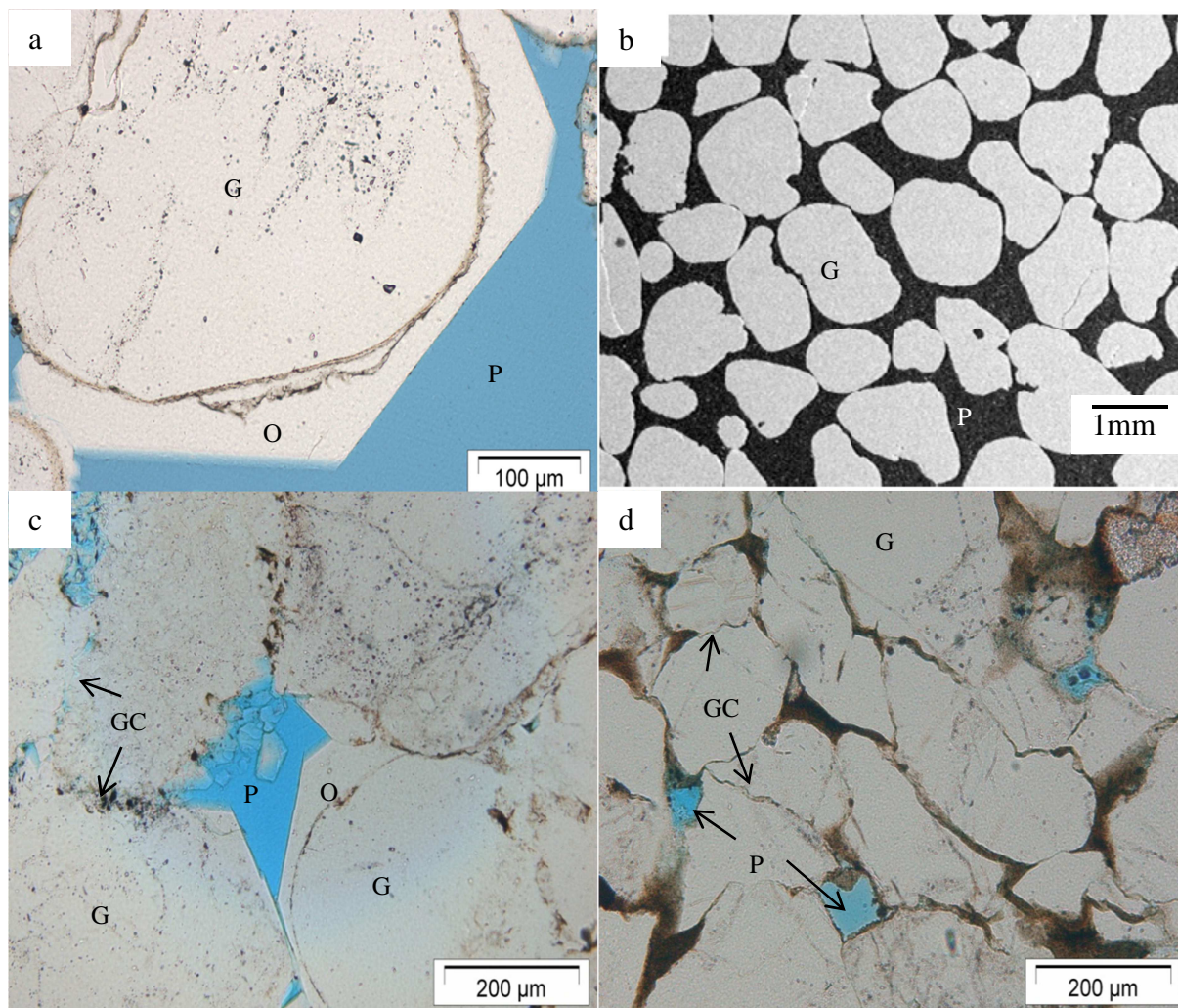


Figure 1. Diagenetic microstructures. a) Quartz overgrowth developed as cementation; b) Mechanical compaction leads to dense packing of sand grains; c) Pressure solution microstructure developed in chemical closed system, note grain overgrowth and dissolution feature at grain-grain contacts; d) Pressure solution microstructure developed in chemically open system, note the tight and dissolution feature at grain contacts and lack of cementation in the pores. G-grain; O-overgrowth; P-pore; GC-grain contacts.

a.

b.

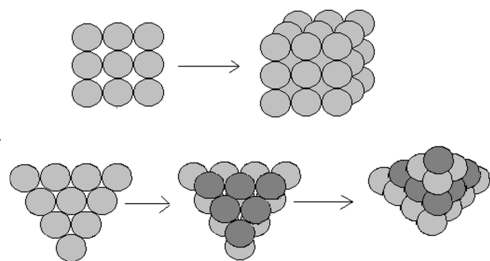


Figure 2. Simple cubic packing a) and face centered cubic packing b). Note the shape of the pore throat in the left and pore in the right. A pore throat is formed by four grains in SC packing and by three grains in FCC packing. A pore is formed by eight grains in SC packing and by four grains in the case of FCC packing.

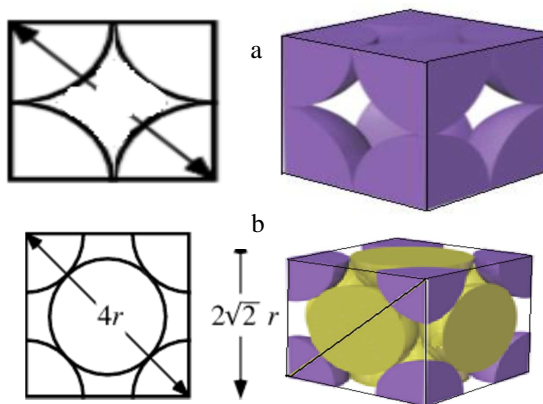


Figure 3. Unit cells for simple cubic packing a) and for b) face centered cubic packing b). Left show faces of unit cells. The relationships between the unit cell edge length and grain radius can be seen. Cementation and pressure solution modify the grain shape from a sphere into a final cubic or polyhedron for SC and FCC respectively. Grain contacts are assumed to be circular and do not interface till porosity of 3.5%.

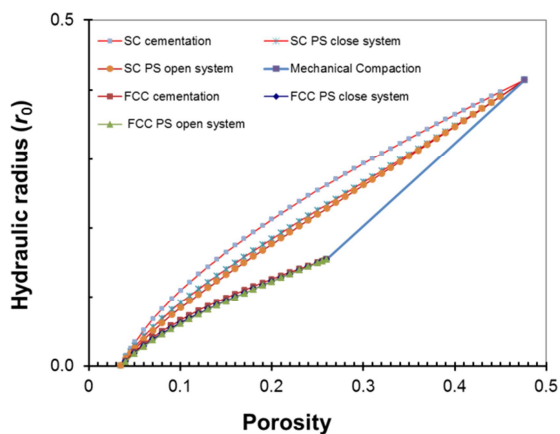


Figure 4. Evolution of hydraulic radius of pore throat for various diagenetic processes. Normalized to original grain radius (r_0).

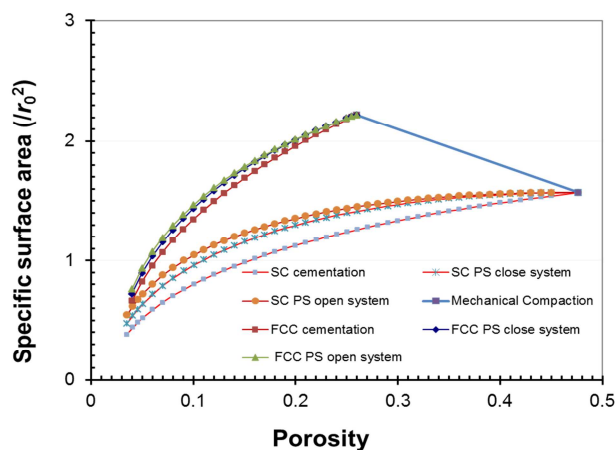


Figure 5. Modeled specific surface areas per bulk volume. Face centered cubic packing has higher specific surface areas. Lowest specific surface areas are found in microstructures of cementation.

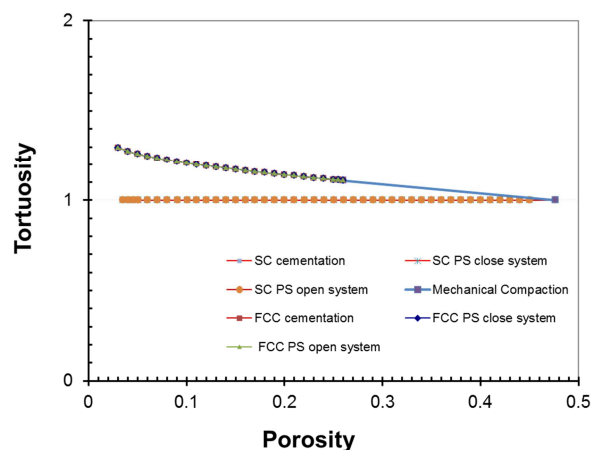


Figure 6. Tortuosity as a function of porosity. For microstructures evolved from original SC packing, tortuosity is kept to a fixed value of 1. For those microstructures evolved from FCC packing, diagenesis modifies their tortuosity values from 1.1 to 1.3.

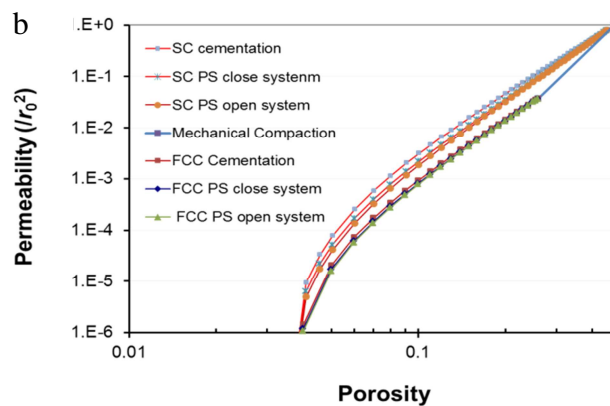
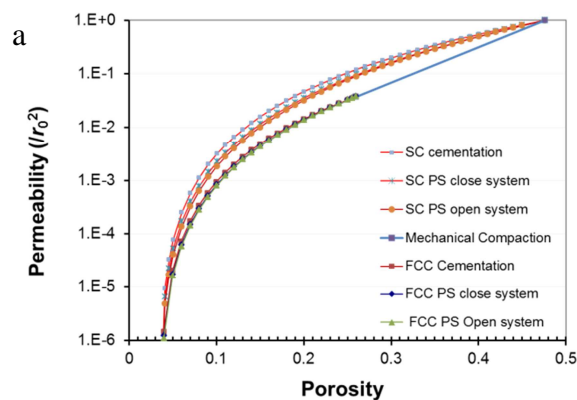


Figure 7. Universal permeability reduction by various diagenetic processes. a) Semi log plot. b) Same data plotted in log-log scale. Two diagenetic paths can be seen from the permeability and porosity space. Absolute theoretical permeability of real reservoir rocks can be estimated from this figure by multiplying a factor of 0.0049 and scale to the square of grain radius.