Journal of Petroleum Science and Engineering 86–87 (2012) 27–38

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Creation of a dual-porosity micromodel for pore-level visualization of multiphase flow

M. Buchgraber, M. Al-Dossary [1], C.M. Ross, A.R. Kovscek *

Department of Energy Resources Engineering, Stanford University, Stanford, CA 94305, USA

ARTICLE INFO

Article history:
Received 22 November 2011
Accepted 14 March 2012
Available online 27 March 2012

Keywords:
micromodel
flow visualization
two-phase flow
pore-level
carbonate

ABSTRACT

This paper describes the creation and testing of an etched-silicon micromodel that has the features and characteristics of a dual-porosity pore system mimicking those found in certain carbonate reservoir rocks. This micromodel consists of a two-dimensional (2D) pore network etched into a silicon wafer with a bonded glass cover that permits direct visual examination of pore-level displacement mechanisms and pore-network characteristics during fluid flow experiments. The approach began by creating a mosaic of images from a carbonate thin section of a sample with both high porosity and permeability using a scanning electron microscope (SEM) in back-scattered mode (BSE). Connections based on high-pressure mercury injection data were made to ensure that the 2D connectivity in the imaged pore structure was representative of the three dimensional (3D) pore network of the carbonate sample. Microelectronic photolithography techniques were then adapted to create micromodels for subsequent fluid flow experiments. Micromodel surfaces were made oil- or water-wet by various techniques. One of the main advantages of having a representative carbonate dual-porosity micromodel is the ability to observe pore-level mechanisms of multiphase flow and interpret petrophysical properties. Another advantage is that multiple replicates are available with identical conditions for each new experiment. Micromodel utility is demonstrated here through the measurement of porosity, permeability, fluid desaturation patterns, and recovery factors.

1. Introduction

Microporosity can be a significant porosity type in carbonate reservoirs. Micropores or pores that are 10 μm or less in diameter in the Middle Eastern Arab-D reservoir quality rock comprise 25% to as much as 50% of the total porosity (Cantrell and Hagerty, 1999). The abundance of microporosity has significant implications for fluid flow properties as well as for the distribution of fluids and sometimes leads to misinterpretation of log response. There is also a strong relationship between pore types, their distribution, and sizes as well as pore throat sizes associated with each given pore type (Ross et al., 1995). Direct pore-level observation of displacement mechanisms improves our understanding of two-phase flow behavior and petrophysical properties that depend strongly on the pore network structure (Oren et al., 1992).

This paper reports the creation of a dual-porosity micromodel that simulates typical Arab-D carbonates including microporosity. The task is more difficult with carbonate rocks, in comparison to sandstones. Carbonates tend to show a variety of length scales with some correlation among the pore and throat sizes and pore shapes (Ross et al., 1995). We attempt to understand further the key components of a rock's pore system which impact multiphase flow behavior and, hence, the petrophysical properties.

The paper starts with an overview of microporosity types and their significance. Next, the methodology is given for the creation and development of the carbonate micromodel mask and etched-silicon micromodels. A first step is to mosaic and modify SEM BSE micrographs from an epoxy-impregnated thin section. Next, the apparatus and procedures used during the experiment are presented. The petrophysical characterization of the carbonate micromodel follows. A summary completes the paper.

2. Microporosity

Before discussing the geologic features of Arab-D reservoir rocks and our carbonate thin section, a definition for microporosity is needed as there are multiple definitions. For example, microporosity in carbonate rocks was defined by Choquette and Pray (1970) as any pore less than 62.5 μm in diameter, whereas Pittman's (1971) definition has a threshold less than 1 μm in size. For the design of our carbonate micromodel, however, we use the definition of Cantrell and Hagerty (1999) in which micropores are 10 μm or less in diameter.

The Arab-D Member is part of the Jurassic Arab Formation that consists mainly of skeletal and non-skeletal grainstones and packstones sealed with an impermeable anhydrite layer. Producing from the Arab-D interval, Ghawar is the largest oil field in the world at

* Corresponding author. Tel.: +1 650 723 1218; fax: +1 650 725 2099.
E-mail address: Kovscek@stanford.edu (A.R. Kovscek).
[1] Currently at Saudi Aramco.

0920-4105/$ – see front matter
doi:10.1016/j.petrol.2012.03.012

1260 square miles. It currently produces 5 million barrels of oil per day (6.25% of global production) and its total estimated reserves are around 70 billion barrels of oil (US EIA, 2011).

Microporosity in the Arab-D Member contributes a quarter to half of the total core porosity (Cantrell and Hagerty, 1999). This microporosity exists as microporous grains, microporous matrix, microporous fibrous to bladed cements, and microporous equant cements (Cantrell and Hagerty, 1999). Microporous grains contribute the "most volumetrically significant microporosity type" in the Arab carbonates (Cantrell and Hagerty, 1999). Micropores are observed in most skeletal and non-skeletal grain types. SEM examination reveals that microporosity within grains occurs as pores 0.3 to 3.0 μm in diameter and is highly interconnected by uniform-sized straight tubular to laminar pore throats as determined using epoxy pore casts (Cantrell and Hagerty, 1999). Given the abundance of intragranular porosity in the Arab-D formation, microporous grains and, to a lesser extent, interparticle micropores are incorporated in the micromodel design.

Microporosity has direct and indirect implications on fluid flow properties and fluid distribution. Microporosity is also relevant to wireline log interpretation in that calculations of producible water saturations are sometimes too high. For example, micropores are usually filled with capillary-bound water while macropores are filled with oil for mixed-wet reservoir rocks. This gives a high water saturation response and may lead to a decision of not producing the interval, even though most of the water is immobile and only the oil filling the macropores flows (Petricola and Watfa, 1995).

According to Chilinger and Yen (1983), 80% of carbonate oil reservoirs are oil-wet, while 12% are intermediate-wet and 8% are water-wet. Furthermore, literature on Arab-D carbonate wettability found that Arab-D rocks exhibit neutral to oil-wet properties (Clerke, 2009).

3. Micromodels

A typical micromodel consists of a silicon wafer in which the image of a pore network is etched to a certain depth (say 20 μm) and bonded to a glass wafer (e.g., Rangel-German and Kovscek, 2006). The concept of developing micromodels has been around for decades, and most early micromodels were etched glass with uniform mesh pore geometry (Mattax and Kyte, 1961). Due to the drawbacks of such micromodels including concave shaped pore walls during the etching process, a new technique was developed whereby a photoresist was used to coat the glass, a network pattern was exposed selectively removing the photoresist, and the glass was etched where the photoresist was removed (Davis and Jones, 1968). This technique showed better pore geometry representation (Chambers and Radke, 1989). In cross section, however, this technique results in pores that are mainly eye shaped.

The pore networks and structures incorporated into a micromodel are typically created in one of two ways: (1) by analyzing thin section images or (2) by process-based analysis. McKellar and Wardlaw (1982) used a photo-imaging technique of thin sections followed by chemical etching of glass to produce micromodels. The first silicon micromodel replicated the pore body and throat sizes of a Berea sandstone pore network (Hornbrook, et al., 1991).

Currently, micromodels are made from silicon wafers and glass plates. The attraction of silicon is that the etching process is more controllable, more precise, and small-scale pore structures can be represented. This results in the ability to etch more complex and multifaceted pore network structures that are more similar to real pore structures found in reservoir rocks.

3.1. Mask creation

Micromodel fabrication starts by defining a base image that undergoes some digital modification to improve pore network connectivity and allow for seamless overlap of the edges. Once the base image is completed, it is used for mask preparation. The modified base image serves as a unit cell that is repeated or arrayed to fill the pore network portion of the micromodel. The number of repeats used in the array depends upon the size of the base image as well as the desired size of the micromodel. In this case, a three by three matrix was used.

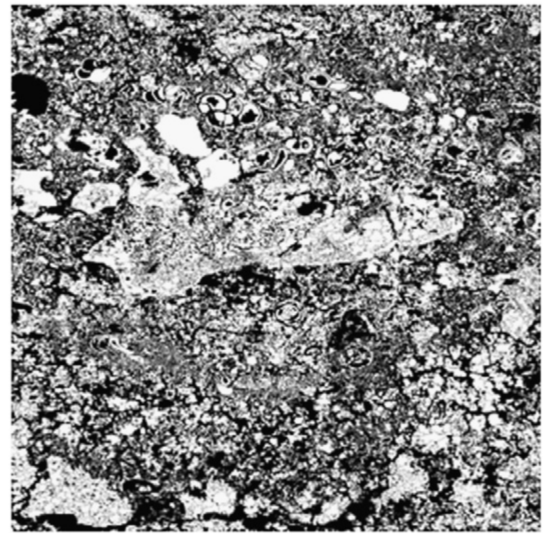

Fig. 1. Carbonate micromodel base image generated by creating a mosaic of SEM EDS gray scale images, 250×. Black represents epoxy-filled pores and white represents rock matrix.

The base image for our Arab-D proxy micromodel was collected using a JEOL JSM-5600LV SEM in BSE mode. An epoxy-impregnated thin section was imaged using overlapping views at a magnification of 250× (Fig. 1). Each SEM image is 2048 by 1600 pixels with a pixel size of 0.235 μm. The resulting composite or mosaicked image has dimensions of 10,065 by 13,407 pixels that represent a thin section area of 2.4 by 3.15 mm. The resulting image is 135 megapixels. The pixel size was increased later during the mask preparation due to resolution limitations of the mask making system.

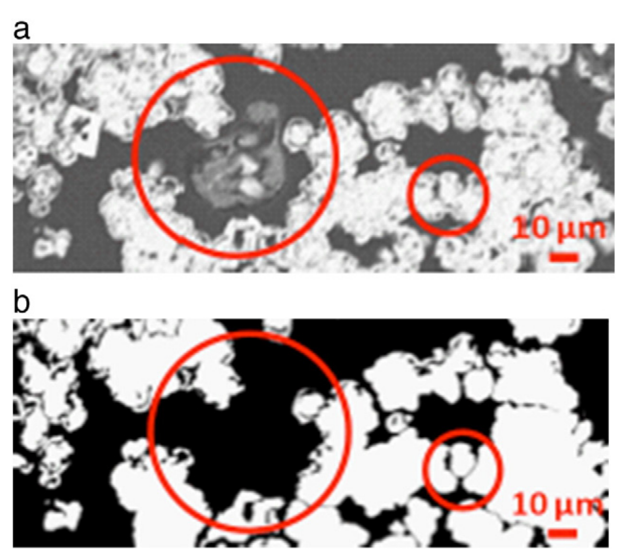

Fig. 2. Example views from (a) carbonate micromodel base image and (b) modified binary image. Red circles highlight where areas of incomplete epoxy impregnation were filled and pores isolated in 2D were reconnected. Black (or gray) represents epoxy-filled pores and white represents rock matrix.