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Evaluation of representative elementary volume for a vuggy carbonate rock—Part: Porosity, permeability, and dispersivity

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A B S T R A C T

This work highlights variation in petrophysical properties of a macroporous vugular carbonate rock. The macroporosity consists of vugs and moldic pores with sizes ranging from mm to cm scale. Carbonate rocks exhibit multi-scale heterogeneities that make the understanding of fluid flow and recovery a challenge. Properties such as porosity and absolute permeability often vary within a volume and sampling at the representative elementary volume (REV) is needed to determine the appropriate continuum properties for reservoir characterization and prediction.

A classical approach to examine the variation with rock sample size and the REV is through analysis at different scales. Measuring petrophysical properties at various scales has therefore been a part of the REV investigation for the studied material. To study the variation with sample size and the effect of heterogeneities on fluid flow, laboratory tests were conducted at different scales, ranging from cm to m scale. Totally 37 sub-samples of a large outcrop block with different sizes and shapes have been included in this work. The main objective has been to determine porosity, effective permeability and dispersivity as function of rock sample size. Porosity–permeability correlations for heterogeneous material can be inadequate and strongly scale dependant. Thus, we also investigate the variation of the porosity–permeability ratio with sample size.

The experimental results show that the variance and coefficient of variation decreases with increase in sample size for all investigated properties. Based on the reduction of variation with increased rock sample size a representative volume for measurement is proposed for the studied material. The results also indicate less variation for the porosity–permeability relationship with increased sample volume. It is shown that a single measurement at traditional laboratory scale can lead to erroneous interpretation of a measured property for the vuggy carbonate material. However, multiple measurements at laboratory scale can be used to determine the representative properties.

1. Introduction

Large part of world's oil and gas reserves are found in carbonate formations. Still, the average recovery for carbonate reservoirs is lower compared to sandstone fields. In general, the heterogeneous nature of carbonate reservoirs makes it difficult to generate predictive models, resulting in significant uncertainty in the hydrocarbon production forecast. Accordingly, the design and implementation of enhanced recovery methods for carbonate reservoirs is a challenging task, particularly as such expensive decisions usually require underpinning laboratory core flooding work.

The heterogeneity of rock masses is a result of many geological factors of varying orders of magnitude ranging from crystallographic to regional geology (Matula, 1969). In reservoir characterization, heterogeneity specifically applies to the variability that affects fluid flow (Jensen et al., 1997). The classical concepts of fluid flow in porous media are not valid for heterogeneous media. From theoretical point of view, heterogeneity is a challenge in terms of deriving general analytical solutions while from practical point of view, heterogeneity is a challenge in terms of characterizing and modelling reservoirs. The determination of the heterogeneity can be classified into numerical and experimental measures. Numerical measures require flow model simulations to interpret the effect of variability on flow. Experimental measures use a flow experiment and are a direct measure of how the heterogeneity affects the flow. Permeability varies more than other properties that affect fluid flow in porous media and is difficult to characterize because of its highly variable nature over relatively short distances.

Traditionally, petrophysical properties used in reservoir models are determined from laboratory experiments on reservoir core

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samples. Thus, the petrophysical description of a reservoir depends on proper and representative laboratory data. However, for material sampled below the scale of the heterogeneities, the petrophysical properties tend to vary and the question about appropriate sampling size and upscaling scheme arises.

Representative elementary volume (REV) denotes a volume of the property field that is large enough to capture a representative amount of the heterogeneity (Bear, 1988). When the sample volume is small compared to the correlation length of heterogeneity, a measured property will vary with small changes in the sample volume (Nordahl and Ringrose, 2008; Corbett, 2009). At the REV, the fluctuations are absent and a representative amount of heterogeneity can be averaged in the measurement.

REV is considered to be the volume for which a macroscopic property (e.g., permeability) is relatively insensitive to small changes in volume or location (Corbett et al., 1999). Location here means that the REV is the largest quantity insensitive to small changes in volume throughout the entire medium. Further, the REV may differ for the various petrophysical properties. Therefore, the proper representative scale depends also on which property is considered.

The REV is essential to effective medium approximation and the fundamental size volume for measurement, simulation and averaging. When the scale of measurement does not encompass the REV, the resulting measurements show variations. In geostatistical terminology, this indicates a problem of insufficient sample size (Corbett et al., 1999).

The aim of this study is to investigate the existence of such REV by studying the variation of properties with sample size. Secondary aim is to compare the variability of the different petrophysical properties as porosity, permeability, dispersivity and porosity–permeability ratio.

2. Carbonate pore classes

Carbonate rocks are generally more challenging for estimation of petrophysical properties and understanding of recovery mechanisms than sandstone material. Because carbonate minerals are susceptible to chemical change, they undergo a far more complicated post-depositional diagenesis compared to siliciclastic material. Compared to sandstone material carbonate rocks differ with aspect of heterogeneity and a wide range of different pore classes. In order to integrate geological and petrophysical information, carbonate pore space must be defined and classified in terms of both rock fabric and petrophysical properties. While geological classification schemes are based on the depositional environments and sequences, the petrophysical classification of carbonate porosity presented by Lucia (1983, 1995) emphasizes petrophysical aspects of carbonate pore space. By comparing rock fabric descriptions with laboratory measurements of porosity, permeability, capillarity, and Archie *m* values, Lucia found that the most useful division of pore types was between pore space located between grains or crystals, called inter-particle porosity, and all other pore space, called vuggy porosity.

The term *vug* and its descriptive forms, *vuggy* and *vugular*, have varied definitions and usage in the literature. Based on petrophysical properties for the various carbonate rocks Lucia (1995) made a classification of different pore types. A vug, as Lucia has stated, can be defined as any pore that is significantly larger than a grain or inside of a grain. Vugs are also characterized by being significantly larger than the typical size of the particles making up the inter-particle porosity.

Vuggy porosity can be subdivided into connected and isolated types. Separate-vug pore space is defined as pore space that is (1) either within particles or is significantly larger than the particle

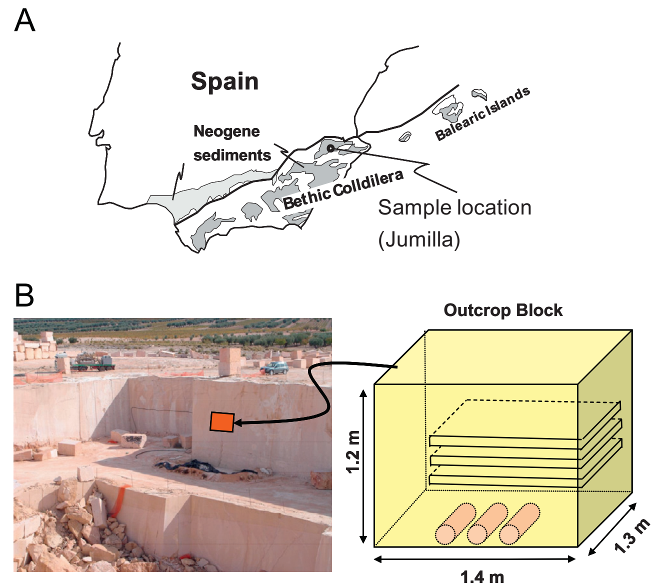

Fig. 1. (A) Map showing Neogene deposits of SE Spain (grey) and the area of Bethic Cordillera with the location of the studied sample. (B) Location of the outcrop block and sampling strategy.

size (generally greater than 2 ×), and (2) is interconnected only through the inter-particle porosity. Separate vugs are typically fabric selective in origin. Intrafossil pore space, moldic pore space, such as dissolved grains, and intragranular microporosity are examples of intra-particle, fabric-selective separate vugs (Lucia 1995). Touching, or connected, vugs are defined as pore space that forms an interconnected system independent of the inter-particle porosity. Touching vugs include interconnected larger cavities, channels, fenestrae, and fractures (Lucia, 2007).

The inter-particle porosity is often referred to as matrix porosity in the literature. While the addition of separate vugs increases the total porosity, it does not significantly increase the permeability. The presence of touching-vugs, on the other hand, increases permeability well above what would be expected from the inter-particle pore system (Lucia, 1983). The petrophysical properties of the matrix pore space relate to particle size, sorting and inter-particle porosity. The permeability and both miscible and immiscible displacements are affected by the connectivity between the vuggy porosity; through the matrix placed between vuggy porosity, via fractures or direct contact.

Martin et al. (1997) proposed a model to identify and characterize petrophysical flow units in carbonates. The flow units can be identified from the calculation of pore throat radii at the 35% pore volume (R35). Four petrophysical flow units: Megaport, Macroport, Mesoport and Microport; all with different reservoir performances are distinguished by ranges of R35. Based on mercury injection data (Djurhuus et al. 2008), the studied material is defined as Megaport flow unit having an R35 above a threshold of 10 μm.

Presumed presence of touching vugs, continuous network consisting of vug-porosity may exist throughout the medium. These channels contribute to permeability increase of several orders of magnitude compared to the matrix permeability. Connected vug channels or high vug density regions leading to preferential flow paths mostly cause the heterogeneous fluid flow behaviour. Reported studies show that classical theories of fluid flow are not applicable for such rocks and make the understanding of fluid flow and recovery a challenge (Archer and Wong, 1973; deZabala and Kamath, 1995; Dabbouk et al., 2002; Zhang et al., 2005).

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