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A combined Parzen-wavelet approach for detection of vuggy zones in fractured carbonate reservoirs using petrophysical logs

Asgari Nezhad Yousef[a,*], Tokhmechi Behzad[a], Kamkar Rouhani Abolghasem[a], Sherkati Shahram[b], Kavousi Kaveh[c], Jamali Amin[b]

[a] School of Mining, Petroleum and Geophysics Engineering, Shahrood University of Technology, Shahrood, Iran
[b] Exploration Directorate of National Iranian Oil Company, Tehran, Iran
[c] School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

Vuggy porosity which is the most important type of porosity in carbonate rocks, significantly affects permeability, pressure drop and recovery factor of the rocks. As a result, its identification and modeling are essential for reservoir characterization and history matching. Image logs as well as RCAL and SCAL tests are main methods to determine vugs. However, these methods are costly and usually unavailable. Therefore, developing a generalized approach for recognizing vugs appears to be necessary. In this paper, a combined Parzen-wavelet based algorithm is developed for identifying vuggy zones in wavelet coefficient domain using gamma ray (GR), neutron porosity (NPHI), bulk density (RHOB) and sonic (DT) logs. Compatibility between core tests and the results of the developed method revealed the capability of the method.

1. Introduction

Vuggy fractured reservoirs are known as important oil production reservoirs in the world. These types of reservoirs are commonly found in Middle East and the Gulf of Mexico (Perez-Rosales et al., 2002).

Choquette and Pray introduced three conditions for definition of vugs (Choquette and Pray, 1970): a. somewhat equant, or not markedly elongate, b. large enough to be visible to the unaided eye, and c. not specifically conformable in position, shape, or boundaries to particular fabric elements of the host rock. Lucia defined vugs as visible pores that are significantly larger than adjacent grains. This definition is more general (Lucia, 1983, 1995). Lucia (1983) also stated that vugs were clearly difficult to be evaluated by wire line logs (Lucia, 1995). The importance of developing a reliable method to identify vugs is quite clear as vugs affect geometrical properties, storage capacity, and flow properties of porous space (Perez-Rosales et al., 2002).

In complex carbonate rocks, pore size distributions, from micro to large vugs, have a large effect on permeability, productivity and estimation of hydrocarbon saturation from resistivity logs. In these reservoirs, it is more difficult to estimate the porosities accurately by conventional wire line logs without calibration against cores (Mengual et al., 2000).

Gomaa et al. (2006) demonstrated that electrical images are useful for detection of vugs. They also proved that NMR log could be used for detection of vugs which were larger than approximately 50 μm and filled with water or light oil (Gomaa et al., 2006).

Hurley et al. (1998) quantified vug fraction from the core slabs by using the general method described. To detect and quantify vugs, Pixel-counting techniques can be applied to borehole images. The purpose of the mentioned study is to calibrate vugs, quantify them on borehole images, and compare them with those quantified from digitally scanned cores. Studying on core slabs showed presence of vuggy intervals, where dimensions of individual vugs ranges from 2–3 mm to 2 cm (Pinous et al., 2007). Towle (1962) noticed a variation in the porosity exponent “m” in Archie's equation ranging from 2.67 to 7.3 for vuggy reservoirs and values much smaller than 2 for fractured reservoirs (Towle, 1962). Aguilera and Aguilera (2004) observed non-connected vugs in the vuggy reservoirs in cores, or deduced from micro-resistivity and/or sonic images (Aguilera and Aguilera, 2004).

In this paper, a novel approach is developed for detection of vuggy zones using petrophysical logs. To evaluate the capability of the approach, core data are used for validation. The core data can also be used for calibration and verification of the model and can indicate the range of applicability of the new approach.

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[*] Corresponding author.
E-mail address: yousefasgari@alumni.ut.ac.ir (A.N. Yousef).

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Nomenclature

GR	gamma ray
RHOB	bulk density
NPHI	neutron porosity
DT	sonic
PLs	petrophysical logs
OMW	optimum mother wavelet
a_1	approximate 1
a_2	approximate 2
d_1	details 1
d_2	details 2

2. Data collection and collation

Data obtained from six wells drilled in two oilfields (A & B) located in the west of Iran have been used in this study. These oil fields or reservoirs are embedded in Sarvak and Illam formations of Albian–Turonian fractured carbonates for which geological and formation properties are available.

A comprehensive data quality control program has been performed to select the wells with adequate and reliable data. The input data in this study are shown in Table 1.

3. Methodology

The methodology used in this study for the detection of vuggy zones in the fractured carbonate reservoirs is outlined in the following; and it is shown by the diagrams in the Appendix:

3.1. Wavelet analysis of scaling processes

Wavelet transform decomposes a signal into a set of basic functions. These basis functions are called wavelets. Wavelets are obtained from a single prototype wavelet $y(t)$ called mother wavelet by dilations and shifting:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{1}$$

where '*a*' is the scaling parameter, '*b*' is the shifting parameter, ψ is the wavelet function and '*t*' implies the time (Grossmann and Morlet, 1984).

3.1.1. Biorthogonal

Families of orthogonal wavelets are derived from biorthogonal wavelets. Symmetry and perfect reconstruction are incompatible when the same FIR filters are used for decomposition and for reconstruction process; except for Haar wavelet. To circumvent this dilemma, it is recommended to utilize two wavelets, instead of one:

The first one, $\tilde{\psi}$, is used for analysis, and the coefficients of a signal "*S*" are

$$\tilde{C}_{j,k} = \int S(x)\,\tilde{\psi}_{j,k}(x)\,dx \quad \text{and} \quad S = \sum_{j,k}\tilde{C}_{j,k}\psi_{j,k} \tag{2}$$

The other one, Ψ, is used for synthesis:

The wavelets Ψ and $\tilde{\psi}$ are linked by dual relations:

$$\int \tilde{\psi}_{j,k}(x)\psi_{j,k'}\,dx = 0 \quad \text{for } k \neq k' \text{ or } j \neq j' \tag{3}$$

$$\int \tilde{\varphi}_{0,k}(x)\varphi_{0,k'}(x)\,dx = 0 \quad \text{for } k \neq k' \tag{4}$$

Now, it is possible to aggregate contradicting attributes, which are of interest for analysis (the number of zero moments for example) in the wavelet $\tilde{\psi}$, while the required properties for synthesis, i.e. regularity and symmetry could be achieved in Ψ. Fig. 1 presents Biorthogonal wavelets, constructed by Daubechies. For each of them, we find the graphs of the Ψ and $\tilde{\psi}$ functions represented in Fig. 1 (Misiti et al., 2007).

3.1.2. Optimum mother wavelet selection

Optimum mother wavelet (OMW) is a mother wavelet, which has the best function for analysis and decomposition of signals. For Optimum mother wavelet selection, the energy matching method is used, which is based on the mount of coordination of earned signal energy from Fourier transform and wavelet that follows this workflow: (1) Initially well logs are transformed from depth domain to frequency domain using Fourier transform; (2) Log energy is calculated in the identified dominant frequency band; (3) Signals with different mother wavelet analysis and their energies are calculated in the frequency band; (4) Basis of Parsual theory: OMW is the mother wavelet which shows the maximum match between signal energy obtained from Fourier transform and signal energy in dominant frequency bands (Burrus et al., 1997).

3.2. Feature selection

(1) Decomposing of signal by OMW to several levels (approximations & details) (Fig. 2). (2) Classifying vuggy zones by Parzen, using approximations and details. (3) Selection of sub-signals which has the best accuracy in classification.

3.3. Parzen classifier

To estimate the class condition probabilities, the Parzen classifier is used. Parzen estimator can be modeled based on the

Table 1
Input data.

Wells	*W1*	*W2*	*W3*	*W4*	*W5*	*W6*
Depth (m)	*1717.08 –2132.98*	*1657.01 – 1808.13*	*1193.9 – 1344.5*	*914.25 – 1116.94*	*3333.14 –3380.38*	*3382.36 –3470.60*
Utilized Loges	*GR, DT, NPHI, RHOB*	*GR,NPHI RHOB*	*GR, DT, NPHI, RHOB*	*GR, DT, NPHI, RHOB*	*GR, DT, NPHI, RHOB*	*GR, DT, NPHI, RHOB*
Availability of Cores	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Formation	*Sarvak*	*Illam*	*Sarvak*	*Illam*	*Illam*	*Sarvak*
Field No.	*A*	*A*	*A*	*A*	*B*	*B*