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Pore pressure prediction using geophysical methods in carbonate reservoirs: Current status, challenges and way ahead

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ABSTRACT

Reliable prediction of pore pressure (PP) is critically important to petroleum engineering at different stages. Currently PP prediction in carbonate reservoir is still far from satisfaction, and there is no specific method widely accepted. This paper discussed the current status, challenges, and way ahead of the PP prediction in carbonate reservoirs, and focused on the geophysical models related to the prediction, aiming to provide a valuable reference and promote its developments. With better understandings of the complicated physical properties resulting from the complex pore system and heterogeneity, PP prediction in carbonates with more confidence and higher resolution can be acquired.

1. Introduction

Pore pressure (PP) is defined as the pressure of fluids within the porous rock (Sayers, 2006). Reliable prediction of PP is critically important to petroleum engineering at different stages (exploration, drilling, and production). It is the basic data for the casing program optimization and the design of the drilling fluid density. And satisfactory PP prediction helps to reduce the risks of drilling incidents and protect the pay formation, which provides an important guarantee for the safe, scientific, and efficient drilling works (Dutta, 2002; Zoback, 2007). Carbonate reservoirs contain nearly 60% of the world total oil and gas reserves (Chopra et al., 2005). But carbonate rocks display significant heterogeneity at different scales (Sayers and Latimer, 2008), which results in great uncertainties in PP prediction and challenges the oil and gas exploration.

For clastic sedimentary rocks, the disequilibrium compaction is the main mechanism and origin of abnormal PP (Chen and Guan, 2000). Rocks with different compactions directly have different densities and porosities, and such differences can be reflected from their rock physics properties, such as sonic velocity (or transit time), electronic resistivity, etc., which is the bases for the prediction of undercompaction-induced abnormal PP (Chopra and Huffman, 2006). Unfortunately, the effects of chemical process and cementation post diagenesis on porosity is more important than the mechanical compaction in most carbonate rocks, so the conventional PP prediction methods implicitly or explicitly using the normal compaction trend fail to give reliable results (Wang et al., 2014). Currently, the PP prediction for carbonate reservoir is still not properly solved, which puts our industry activities, especially drilling and completion, at great risk, and constrains the efficiency of exploration and production in carbonate reservoirs.

Generally speaking, PP prediction based on elastic wave data includes the following steps (Dutta, 2002): (1) Acquire and process the elastic wave data (seismic reflection and sonic logging); (2) Choose a proper geophysical model that links elastic wave attributes (velocity, attenuation, etc.) to either effective stress (PE) or PP; (3) Calculate PE or PP using the processed data. Therefore, the geophysical model and acquiring proper data set are two key contents of PP prediction, which are also the main sources of errors and uncertainties in the prediction (Dutta, 2002). Chopra and Huffman (2006), and Dutta (2002) have given good reviews on how to acquire and process the elastic wave data to make them adequate for PP prediction. In this paper, we will focus on the geophysical models of carbonate rocks related to PP prediction, aiming to provide a valuable reference for PP prediction in

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carbonates and promote its developments.

2. The current status of pore pressure prediction

There are no widely accepted methods for PP prediction in carbonate reservoirs. The existing methods and theories in the PP prediction community are almost all based on the shale properties. Although these methods are not the proper way to predict PP in carbonates and may probably lead to dangerous errors, they are still used in the field practice of carbonate reservoirs. Therefore, these models basically about PP prediction in shales are reviewed in this part, especially in Section 2.1 and 2.2. Section 2.3 is mainly about the current attempts of PP prediction by some new ideas in carbonate reservoirs.

Methods for PP prediction can be classified into two categories. First is the direct prediction method. PP is directly related to the measured physical quantities, which is the most simple and old style, such as cross-plots and overlays (Pennebaker, 1968), and Fillippone's (1982) method. The others are effective stress method which is the most popular nowadays. According to the Terzaghi's (1943) effective stress principle, the effective stress can be calculated by:

$$PE = PO - \alpha \cdot PP \tag{1}$$

where, *PE* is the effective stress, *PO* is the overburden pressure, *PP* is pore pressure, and α is the effective stress coefficient which is less than 1. The overburden pressure can be satisfactorily estimated either by empirically regional relations (e.g. Traugott, 1997), or from the density logging data by (Chen and Guan, 2000; Dutta, 2002):

$$PO = g\int_0^h \rho(z)\mathrm{d}z \tag{2}$$

where, g [9.8 N/kg] is the gravity acceleration, ρ [kg/m^3] is the rock bulk density at the depth z [m]. Therefore, the key issue of PP prediction is how to calculate PE properly. It should be noted that the differential pressure (confining pressure minus PP) used in rock physics experiments is not the same as the concept of PE. For detailed discussion on this difference, readers are directed to Hofmann et al. (2005). Currently, geophysical models used to calculate PE can be mainly divided into three types: porosity-PE relations, velocity-PE relations, and elastic moduli-PE relations.

2.1. Porosity-PE relations

In the normal compaction process, the rock matrix (grains) deforms due to the increasing load of accumulated sediments, resulting in the decrease of pore volume (Swarbrick and Osborne, 1998). Researchers investigated the porosity-PE relation in shales under normal compaction. Among these works, the followings are famous and widely used:

Terzaghi (1943):

$$\phi = 1 - \phi_0 PE^{C/4.606} \tag{3}$$

Athy (1930) and Dutta (1983):

$$\phi = \phi_0 e^{-K\cdot PE} \tag{4}$$

Dutta (1988):

$$PE = PE_0 e^{-\frac{\phi}{1-\phi}\beta(T)} \tag{5}$$

Palciauskas and Domenico (1989):

$$\phi = 1 - \phi_0 e^{-\beta\cdot PE} \tag{6}$$

where, ϕ is the porosity, ϕ_0 is the porosity at the mudline, and C, K, PE_0, β are empirical coefficients. The corresponding PE can be calculated once the porosity is known according to any one equation from (3) to (6), and then PP can be calculated according to Equation (1). Therefore, all physical properties, such as acoustic velocity (or transmit time), electronic resistivity, density and so on, that can reflect the changes of porosity can be used for PP prediction. This calculation clue for PE is shown in Fig. 1.

As shown in Fig. 1, this kind of method is limited to predict abnormal PP dominantly generated from disequilibrium compaction because the normal compaction trend is applied. In field application, normal trend between rock physical properties and PE is directly developed by eliminating porosity through mathematical derivation, which can help to reduce uncertainty in porosity interpretation and is more convenient for practice. The amount of abnormal PP is related to the amount of measured properties deviated from the normal trend (Fig. 2), such as effective depth method (Foster and Whalen, 1966; Ham, 1966) and Eaton's (1975) model.

Recently, Researchers made some innovative extensions in Eaton's model when addressing practical problems in field applications. For example, Ebrom et al. (2003), and Kumar et al. (2006) used PS-wave velocity (the arithmetic square root of the product of P-wave velocity and S-wave velocity) in the Eaton's model, and discussed the variation of Eaton's coefficient with depths. Ke et al. (2009) addressed Eaton's coefficient as a random variable, investigated the distribution characteristic of Eaton's coefficient, and developed a PP prediction method with credibility based on Eaton's model.

In fact, similar exponential relation between the porosity and the burial depth as Equation (4) also exists. By combing these two kinds of relations, Zhang (2011) proposed a new PP prediction model dependent on the depth:

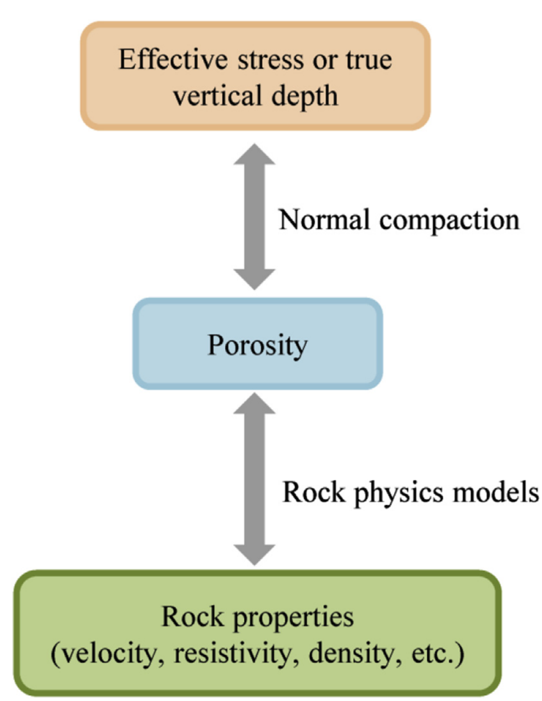

Fig. 1. Relations used for effective stress calculation based on equilibrium compaction.