Marine and Petroleum Geology 79 (2017) 176–187

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Pre-drill pore pressure modelling and post-well analysis using seismic interval velocity and seismic frequency-based methodologies: A deepwater well case study from Mississippi Canyon, Gulf of Mexico

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
2 May 2016
Accepted 1 September 2016
Available online 23 September 2016

Keywords:
Pore pressure
Geopressure
Seismic pore pressure prediction
Seismic frequency-based pore pressure prediciton
Seismic frequencies
Q–factor
Interval velocity based pore pressure prediction

ABSTRACT

Managing and identifying risk and uncertainly involved in drilling operations in unconventional geologic settings starts with improving and correctly applying pore pressure modelling. A relatively new approach, which predicts pore pressure by way of seismic frequencies, has addressed some of the shortcomings seen in seismic interval velocity applications. With the overall goal of reducing operational drilling risk by utilizing multiple pore pressure modelling strategies, a case study will be presented for a near-salt field in deepwater Gulf of Mexico. This study will outline the pre-drill pore pressure modeling, which includes petrophysical, seismic interval velocity, and seismic frequency based approaches. The accuracy of these three approaches will be analyzed both qualitatively and quantitatively for currently existing wells, and from a pre-drill and post-drill standpoint for one prospect well.

1. Introduction

The search for more oil and gas in the Gulf of Mexico has taken operators into increasingly challenging drilling environments. Drilling through salt and/or in near and sub-salt geologic settings to reach reservoir targets has become a standard practice, especially in deepwater. With the industry continuously striving to make drilling operations safer while keeping non-productive time (NPT) to a minimum, there is an ongoing need for improvements in well design. Reaching the goal of reduced risk and uncertainty for any drilling operation starts with improving the methods for modeling the cornerstone of the well design process, pore pressure. Accurate prediction of this one key factor can make the drilling of any well either highly successful or a complete failure.

The current standard practice for modern pore pressure prediction relies on interval velocities obtained through seismic surveys. The methodology for analyzing and interpreting interval velocities for use of predicting pore pressures has come a long way since Pennebaker (1968) first introduced this concept. The transforms utilized for interval velocity based pore pressure prediction, however, are for the most part still heavily reliant on the assumption that porosity trend is directly related to pore pressure. Also, rock velocities are highly dependent on factors such as lithology and porosity, which may have nothing to do with effective stress. Pore pressure modeling from seismic interval velocities has presented major problems for near and sub-salt environments as well.

Terzaghi and Peck (1948) first expressed the fundamental relationship between pore pressure (p), overburden (S), and effective stress (σ). The key factor that all pore pressure models are designed to predict is effective stress. A seismic application for formation pressure prediction has been brought forward that avoids any and all assumed relationships between porosity and effective stress, seismic frequency based pore pressure prediction. The eSeis® patented Q-Based® method has allowed for effective stress estimation based on grain-to-grain contact and independent of factors such as lithology, porosity, or bulk density (Young et al., 2004). This

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http://dx.doi.org/10.1016/j.marpetgeo.2016.09.002
0264-8172/© 2016 Published by Elsevier Ltd.

frequency based model is also substantially less hindered by the presence of salt than interval velocity based approaches.

With the goal of offering a formidable alternative seismic application for pore pressure prediction, a study has been conducted in a near salt field located in Mississippi Canyon (MC), Gulf of Mexico. This study will analyze and compare the accuracy of seismic interval velocity and seismic frequency based pore pressure modeling outputs for three (3) calibration wells, ten (10) control wells, and one (1) prospect well. The prospect well results will be compared on both a pre-drill and post-drill basis.

The accuracy of the two outputs will be assessed both qualitatively and quantitatively. Accuracy will be based on their agreement with petrophysically derived pore pressure curves and well pressure data (mudweights, formations pressures, and well control events) for each well in the study.

2. Seismic frequency based pore pressure prediction

Predicting pore pressures using seismic frequencies has been practiced in the industry since 2004. In order to grasp the idea of pore pressure prediction through seismic frequencies, the concept of attenuation and quality factor (Q) must first be understood. Attenuation can be defined in regard to seismic applications as the progressive loss of energy of an acoustic wave traveling through a medium (Nowick and Berry, 1972). Attenuation will cause a drop in average frequency for a given seismic signal. Q defines the "quality" of the rock, or any medium through which an acoustic wave is passed. A signal that shows a higher average frequency will be associated with a higher Q value than a signal of lower frequency; thus, attenuation is inversely related to Q (Batzle et al, 2005; Nicola et al., 2011).

Attenuation is a fundamental formation property (Batzle et al, 2005). In general, rock formations that transmit a seismic signal well, resulting in low attenuation are considered to have a high Q. Formations that highly attenuate a seismic signal will be characterized as having a low Q.

The relationship between effective stress and Q has been demonstrated in numerous studies (Prasad and Manghnani, 1997; Khaksar and McCann, 1999; Siggins et al., 2001; Carcione and Helle, 2002; Angus et al., 2007). In each of these studies, Q values were recorded while acoustic signals were passed through pressurized core samples. The studies all show that with higher pore pressure (low effective stress) a lower Q value will result. This relationship can be seen at both ultrasonic frequencies, consistent with rock core testing, and low frequencies, as commonly seen in seismic acquisition (Carcione and Helle, 2002).

Fig. 1 depicts why the inverse relationship exists between pore pressure and Q. A formation that is normally pressured will exhibit stronger grain-to-grain contact than a formation that is abnormally pressured. Seismic energy passing through a normally pressured formation will exhibit lower signal attenuation, and much of the bandwidth of the original signal will be preserved. If this same acoustic wave is transmitted through an overpressured formation the resulting signal will undergone more attenuation and be of a reduced bandwidth. The increased fluid pressure in the matrix decreases the effective stress thereby reducing the grain-to-grain pressure resulting in lower acoustic coupling.

While determining Q from surface seismic is difficult, the influence of Q on the frequency bandwidth can easily be observed. It is a well-known geophysical principle that seismic frequencies will decrease with increasing depth. This is due to the dispersion in the acoustic waves as the energy is transferred through the sediments, further from the source at surface. Average frequencies will attenuate at a normal decreasing rate in the normally pressured interval in a sedimentary basin. Once the abnormally pressured depth interval is encountered, average frequencies begin to decrease at an increasing rate relative to the shallower, normally pressured zones. The increased attenuation rate is caused by increased dispersion of the seismic wave reacting to the reduced grain-to-grain contact in the overpressured formations (Mannon et al., 2014).

Siggins et al. (2001) compared the response of Q to increasing pore pressure while confining pressure was held constant with the response of rock velocity under identical conditions (Fig. 2). Showing a change of approximately 150%, Q was much more sensitive to pore pressure changes under these conditions than velocity which showed only a 5% change.

Seismic surveys will provide both velocity and frequency data. When average frequency is plotted with depth along a wellbore trajectory, it will show a normal decreasing trend until the top of abnormal pressure is encountered. A normal frequency declination trend line (analogous to a normal compaction trend-line (NCTL)) can be plotted along the normally pressured interval, and an equation similar to the Eaton (1975) transform can be applied to determine pore pressure magnitude (Fig. 3) (Young et al.,2004; Mannon and Salehi, 2013; Mannon et al., 2014). The normal frequency declination trend line is not exactly the same as a NCTL, though they serve a similar purpose. Changes in effective stress, and the impact on grain-to-grain contact within a formation that results from such changes, have a greater influence on Q than the formation's porosity.

Eq. (1) shows one possible application of the Q-Based method for predicting pore pressure:

$$p = S - \left((S - p_n) \left(\frac{f}{f_n} \right)^m \right) \tag{1}$$

where (Pn) is normal pore pressure, (f) is average frequency, (fn) is frequency along the normal trend, and (m) is an empirical constant. This is known as the Q-Based method for pore pressure prediction (Young et al., 2004). Please see Young et al. (2004) for other possible approaches for pore pressure from seismic frequencies.

3. Seismic interval velocity based pore pressure prediction

The first attempts to predict pore pressure from seismic interval velocities were made by Pennebaker (1968). Since then, the industry and academic community have worked continuously at improving this application from the initial seismic processing and velocity analysis to the transforms that convert the interval velocities to pore pressure magnitudes. The vast majority of these transforms are still applied using the same "undercompaction principle" first expressed by Hubbert and Rubey (1959).

Pioneered by Hottman and Johnson (1965), the use of a NCTL is still implemented with the assumption that there must be a relationship between porosity declination and pore pressure, and in such environments, this application works well. There have been other methods (Bowers, 1995) that allow for rock velocity – pore pressure conversions when the driving mechanism for abnormal pressure is not related to undercompaction, such as thermal expansion and load transfer through smectite to illite diagenesis (Dutta, 2002) or hydrocarbon generation (Hunt et al., 1994).

If the source of overpressure is indeed being caused by a mechanism other than undercompaction, special modifications have to made to the transforms that will allow these other drivers to be accounted for (Dutta, 2002; Sayers et al., 2006; Khaksar, 2011; Saad et al., 2013a,b). The modifications may require that large amounts of field data be obtained for empirical constant calibration.

One underlying issue with seismic interval velocity applications is that there must be a relationship between rock velocity and