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Modeling and interpretation of *Q* logs in carbonate rock using a double porosity model and well logs

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Abstract

Attenuation data extracted from full waveform sonic logs is sensitive to vuggy and matrix porosities in a carbonate aquifer. This is consistent with the synthetic attenuation ($1/Q$) as a function of depth at the borehole-sonic source-peak frequency of 10 kHz. We use velocity and densities versus porosity relationships based on core and well log data to determine the matrix, secondary, and effective bulk moduli. The attenuation model requires the bulk modulus of the primary and secondary porosities. We use a double porosity model that allows us to investigate attenuation at the mesoscopic scale. Thus, the secondary and primary porosities in the aquifer should respond with different changes in fluid pressure. The results show a high permeability region with a Q that varies from 25 to 50 and correlates with the stiffer part of the carbonate formation. This pore structure permits water to flow between the interconnected vugs and the matrix. In this region the double porosity model predicts a decrease in the attenuation at lower frequencies that is associated with fluid flowing from the more compliant high-pressure regions (interconnected vug space) to the relatively stiff, low-pressure regions (matrix). The chalky limestone with a low Q of 17 is formed by a muddy porous matrix with soft pores. This low permeability region correlates with the low matrix bulk modulus. A low Q of 18 characterizes the soft sandy carbonate rock above the vuggy carbonate.

This paper demonstrates the use of attenuation logs for discriminating between lithology and provides information on the pore structure when integrated with cores and other well logs. In addition, the paper demonstrates the practical application of a new double porosity model to interpret the attenuation at sonic frequencies by achieving a good match between measured and modeled attenuation.

Keywords: Double porosity; Attenuation; Full waveform sonic; Inversion of Q (quality factor)

1. Introduction

Seismic attenuation is a powerful attribute that can be used as an indicator of lithology, pore structure, fractures, and clay and fluid content in a reservoir characterization program. Acoustic attributes

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from full waveform sonic logs effectively relate to petrophysics and core data in a single borehole. The intrinsic and scattering effects at the borehole scale can therefore be determined. Since the early 1980s, many researchers have attempted to develop techniques for the inversion of Q_P from single-hole full waveform acoustic log data; in particular, to obtain depth profiles of intrinsic Q_P^{-1} from the head P-wave of the sonic data. In a popular approach, Q_P^{-1} is calculated from the Amplitude Spectral Ratio (ASR) of the head P-wave measured at two locations (e.g., Cheng et al., 1982; Sun et al., 2000; Dasios et al., 2001). In this approach, the borehole head wave is analogous to a plane wave in a uniform unbounded medium. The degree of success of existing work on Q_P^{-1} varies, but in general is not very satisfactory. The key to success is to be able to fully understand the signal of the head P-wave, and to quantify and account for factors besides Q_P^{-1} that also alter the amplitude of recorded signals. An algorithm that takes into account such factors as geometrical spreading of the head waves, scattering due to heterogeneities (discontinuities), and multiple path and reflections within the borehole has been recently developed (Parra et al., 2004).

In this paper we demonstrate the value of attenuation data extracted from a full waveform sonic log using a processing algorithm given in Parra et al. (2004). For this purpose we evaluate the attenuation data using porosity logs, rock physical properties, and a Q model based on poroelasticity. We use a data set from a south Florida aquifer in which the stratigraphy was characterized at the pore, core, and well log scales (Parra et al., 2003a,b). In addition, we use vuggy and matrix porosity logs obtained by a joint inversion of resistivity and velocity logs by Kazatchenko et al. (2004). We integrate the porosity logs with the lithology to visualize a region that contains different facies that give different acoustic signatures. This integration explains the attenuation ($1/Q$) responses of the zones.

2. Data analyses

The south Florida well is a test site for an aquifer storage and recovery system. The formation of primary interest is a vuggy, high porosity, high permeability carbonate bounded above by sand, shale, and carbonate mudstones; and below by lower-porosity, lower permeability chalky carbonate. The attenuation algorithm was used to estimate Q from a monopole sonic log recorded in well PBF10 in south Florida (Parra et al., 2004). In Fig. 1, we compare acoustic attributes in the micro-seismogram between depths of 1000 and 1250 ft (305–381 m). This figure shows

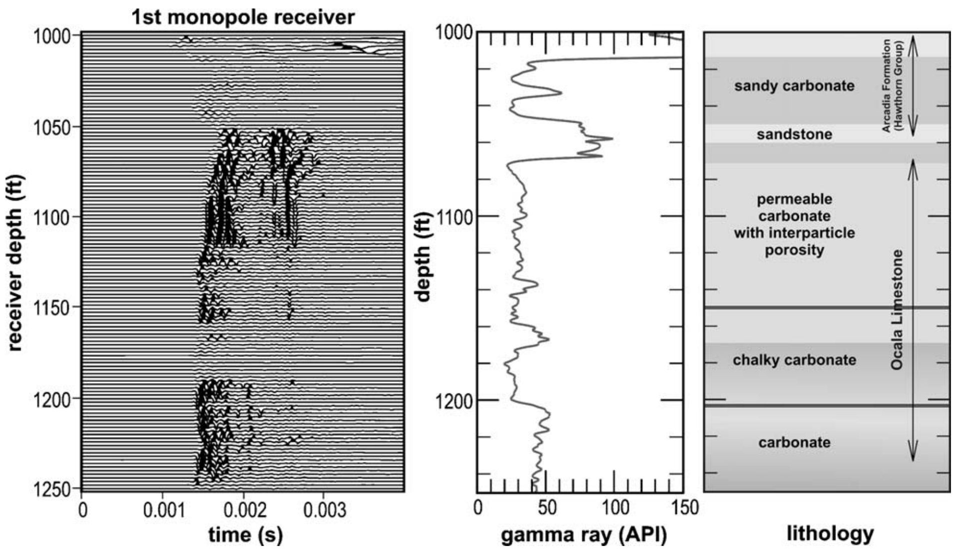

Fig. 1. Comparison between sonic waveforms and lithology at the south Florida aquifer.