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Estimation of compressional seismic wave attenuation of carbonate rocks in Abu Dhabi, United Arab Emirates

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ABSTRACT

The subsurface geology of Abu Dhabi in the United Arab Emirates is primarily composed of carbonate rocks. Such media are known to be highly heterogeneous. Very few studies have attempted to estimate attenuation in carbonate rocks. In Abu Dhabi no attenuation profile has been published. This study provides the first seismic wave attenuation profiles in Abu Dhabi using dense array of VSP data. We estimated three attenuation profiles: the apparent, the scattering, and the intrinsic attenuations. The apparent attenuation profile was computed using amplitude decay and spectral-ratio methods. The scattering attenuation profile was estimated using a generalized reflection–transmission matrix forward model. It is usually estimated from the sonic log, but to be more consistent with the apparent attenuation, we succeeded in this paper to estimate it from the VSP data. We subtracted the scattering attenuation from the apparent attenuation to deduce the intrinsic attenuation. The results of the study indicate that the scattering attenuation is significant compared to the published studies that are mainly based on clastic rocks. The high scattering attenuation can reach up to 0.02. It can be explained by the strong heterogeneity of the carbonate rocks. This study demonstrates that the Simsima and Rus Formations have considerable scattering and intrinsic attenuations. These formations are considered aquifers in Abu Dhabi; we therefore interpreted this high intrinsic attenuation zones to be due to the heterogeneity and to the fluids contained in these formations. The Umm-Er-Radhuma Formation is a more homogenous formation with limited aquifer potential. Hence, scattering and intrinsic attenuations of the Umm-Er-Radhuma Formation are low.

1. Introduction

The intrinsic attenuation of seismic waves mainly results from the friction between the particles and fluid diffusion of the medium during the passage of the seismic wave. Due to this friction, the mechanical energy is converted into heat. The intrinsic attenuation is usually quantified as the inverse of the quality factor, Q, which is directly related to the inverse of the energy loss per cycle, (φ) divided by the total energy (W) at the same cycle:

$$\frac{1}{Q} = \frac{\phi}{4\pi W} \tag{1}$$

The intrinsic attenuation can be also quantified through the absorption coefficient α, which is related to the amplitude $A(x)$ of the attenuated waves at the distance x:

$$A(x) = A(0)G\exp(-\alpha x) \tag{2}$$

where $A(0)$ is the amplitude at the source and G is a coefficient combining the geometrical spreading and reflection/transmission coefficients.

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The mechanism behind the intrinsic attenuation is very complicated and it is still not very well understood. However, several laboratory and in situ studies have attempted to characterize intrinsic attenuation. These studies showed a clear dependence of intrinsic attenuation upon the physical properties of the media, such as grain size and porosity (Hamilton, 1972; McCann, 1969; Shumway, 1960), as well as upon the presence of fluid and the amount of saturation in the sediments (Bouchaala and Guennou, 2012; Nur and Simmons, 1969; Toksöz et al., 1979).

The time necessary for the system perturbed by wave passage to attain its equilibrium is called relaxation time. At high frequency, the relaxation time is bigger than the wave period, so during the wave passage the system has not enough time to return to its equilibrium; therefore, the internal friction caused by the relative movement of the fluid toward the solid has a significant contribution to wave attenuation. However, at low frequency, the relaxation time is smaller during the wave passage than during the wave period; therefore, the system has enough time to return to its equilibrium. In this case, the contribution of the internal friction to wave attenuation is not significant. The close relationship between the physical properties of the media and the attenuation makes this parameter very useful for characterizing and investigating the natural media. The estimation of the attenuation is also useful for amplitude correction, which enhances the quality of seismic images.

A biased estimation of the intrinsic attenuation can result in poor estimation and interpretation of the intrinsic properties of the natural media. An accurate estimation of this parameter requires a good quality of raw data, robust methodology and also the repeatability to confirm the results. The Vertical Seismic Profile (VSP) dataset are known to be nearly ideal for attenuation studies. For example, Q estimation from VSP dataset has been carried out successfully in a number of studies (e.g., Ganley and Kanasewich, 1980; Jansen et al., 1985; Pevzner et al., 2012; Stainsby and Worthington, 1985).

Several methods and techniques were developed to estimate Q from the VSP dataset, either in the time domain or in the frequency domain. For example, in the time domain the rise time (Gladwin and Stacy, 1974) and amplitude decay methods (McDonal et al., 1958; Tonn, 1991) are widely used, and in the frequency domain the spectral-ratio (Bath, 1974) and the frequency shift methods (Quan and Harris, 1997) are popular.

The methods mentioned above give an estimation of the apparent attenuation, which is the sum of the intrinsic and the scattering attenuations (Schoenberger and Levin, 1974):

$$\frac{1}{Q_{\text{apparent}}} = \frac{1}{Q_{\text{scattering}}} + \frac{1}{Q_{\text{intrinsic}}} \tag{3}$$

Unlike intrinsic attenuation, scattering is an elastic phenomenon, which is due to a redistribution of the energy in the space because of the medium heterogeneities without energy loss. We note from equation (3) that as for the intrinsic attenuation, the scattering can be also quantified through a quality factor, $Q_{\text{scattering}}$. Usually scattering attenuation is computed in the elastic domain from the velocity and the density of the medium layers obtained from the sonic and density logs, independently from the apparent attenuation (O'Doherty and Anstey, 1971; Pevzner et al., 2013). Finally, the intrinsic attenuation can be estimated by subtracting the scattering attenuation from the apparent attenuation—see equation (3).

Several studies have been conducted on scattering and intrinsic attenuation in clastic rocks, but very few in carbonate rocks (e.g., Adam et al., 2009). Until now, no attenuation profile has been estimated or at least published in the UAE subsurface formations. Hence, this study provides a first estimation of the attenuation profile of subsurface carbonate rocks in Abu Dhabi. Therefore, we cannot compare our results to those of any previous study. Accordingly, to check the reliability of our results, we estimated the Q_{apparent} profile using two methods, one in the time domain (amplitude decay method) and the other in the frequency domain (spectral-ratio method).

2. Survey area

2.1. Geological setting

The VSP survey was acquired from March to April 2007 over an onshore oilfield in the Emirate of Abu Dhabi in the United Arab Emirates, located about 80 km southwest of Abu Dhabi Island (Fig. 1a). The producing zones of the oilfield are all within a series of stacked reservoirs of the Thamama Group (Barremian to Late Aptian). However, the VSP array extended only up to Simsima and did not reach the Thamama reservoirs.

From the sonic logs (Fig. 1b and c), we defined seven units that vary in thickness from 55 m to 450 m. The first two upper units are Miocene in age and consist of clastic sediments including mudstone, siltstone, and conglomeratic sandstone with some shales and limestone (Alsharhan and Nairn, 1995; Sharland et al., 2004). The third unit is Eocene in age. The upper part of the unit, the Dammam Formation, consists of marly limestone with some dolomite and gypsum. The lower part, the Rus Formation, consists of dolomite and limestone with crystalline anhydrite and some shale (Rizk and Alsharhan, 2003; Whittle et al., 1996). The fourth unit, the Umm-Er-Radhuma Formation, is Palaeocene–Eocene in age. The lower part of the unit consists of thin beds of shales, while the upper part comprises argillaceous and dolomitic limestones (Alsharhan, 1989). The three lower units are all within the Simsima Formation of Maastrichtian age. The units are very heterogeneous and consist of bioclastic packstones, wackestones, grainstones, microcrystalline dolomite and dolomitic limestone (Alsharhan and Nairn, 1990).

2.2. Data acquisition

The VSP survey was acquired from well X-13 (Fig. 1a), which contains a suite of logs including sonic and density