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The effects of gas saturation on the acoustic velocity of carbonate rock

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ABSTRACT

Changes in the P-wave and S-wave velocities (V_p and V_s, respectively) and their ratio at different gas saturations in carbonate rock were investigated experimentally in this study. The results showed the following: (1) Both the P-wave velocity and V_p/V_s tended to decrease as the gas saturation increased, while the S-wave velocity marginally decreased or remained constant. These measured results were in agreement with the theoretical calculations of the Gassmann fluid substitution equation. (2) The acoustic velocity was related to the acoustic frequency. Most rock samples showed the tendency of V_p (1000 kHz) < V_p (50 kHz) < V_p (250 kHz) and V_s (1000 kHz) < V_s (50 kHz) < V_s (250 kHz). The primary distribution domain of V_p/V_s also varied with different frequencies and generally showed that V_p/V_s when $S_g = 0\%$ was larger than that when $S_g = 100\%$. (3) Considering fully saturated rock as the water zone, it was found that V_p/V_s decreases from its initial value as the gas pressure increases; a sharper decline, indicating a transition from the water zone to the gas zone, was also found. Additionally, the integrated use of a cross-plot analysis of V_p/V_s vs. P-wave impedance was used to more accurately identify the gas zone in carbonate rock. This study provides some helpful references for gas-zone identification in carbonate rock using acoustic logging data in practical applications.

1. Introduction

In most cases, the pores of rock contain two or more types of natural fluids such as oil, gas, and water. Understanding the influence of these fluids on the acoustic response characteristics is important for evaluating a reservoir and analysing logged acoustic information about rock structures to determine changes in petrophysical parameters during exploration. The acoustic propagation velocity in rock is useful to determining the rock's properties. As shown in the analysis of geophysical data, the acoustic velocity is closely related to the formation's lithology and the rock's internal structure, depth and geological age. Many studies have been performed to investigate the relationship of the acoustic velocity in rock with the properties of the formations with oil and gas present (Kern et al., 1997; Xin et al., 2008; Zhou et al., 2006). Batzel et al. (1992) studied the influence of fluid type and fluid saturation on the P-wave and S-wave velocities of rocks. Using experimental data, Cheng et al. (2007) found that a change in the gas saturation was an important factor that caused changes in the acoustic travel time under the same axial pressure; the acoustic velocities in sandstones with different porosities were shown to decrease as the gas saturation increased. Wang (2006) studied the rule of acoustic propagation in rocks with three types of pore fluids (oil, gas, water) in different combinations and found that the changes in the P-wave velocity were more complex than expected as the oil saturation increased; the P-wave velocity was shown to increase steadily when the oil saturation exceeded 50% but fluctuated when the oil saturation was less than 50%. These findings showed that the three component fluids in the pore had synergistic effects on the rock's acoustic propagation. The study of Liu (2007) showed that the P-wave velocity of sandstone saturated with gas was significantly lower than that saturated with oil or water; he also showed that the S-wave velocity was nearly unaffected by the type of pore fluid present. The P-wave velocity in rock with a high water saturation was shown to be particularly sensitive to the gas content present; a small amount of gas would result in a significant decrease in the P-wave velocity (Tan et al., 1990; Zhang et al., 2000; Li et al., 2002). Chardac et al. (2003) compared V_p/V_s and the P-wave travel time to identify the properties of the oil and gas present in rock; although those authors used some different parameters than those in this study, the acoustic velocity was essentially used. Based on the

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experiments of Zhang (2004), the relationship between V_p/V_s and the gas saturation in three types sandstone was established. That study also discussed a method to identify the gas reservoir based on V_p/V_s combined with the fluid compressibility factor; it confirmed that using the full-wave acoustic data to identify the gas reservoir in engineering applications was effective.

However, the acoustic response of a carbonate reservoir still requires additional study because there are many differences in the acoustic behaviours of sandstone/mudstone rock with carbonate rock. Regardless of the influence of the pore fluid saturation conditions, the mineral composition, degree of compaction and cementation are key factors that affect the acoustic properties of sand and shale formations that experience continuous deposition and compaction. While the characteristics of the pore structures, including the size and distribution of the pores or caves in the rock, are dominant factors in determining the heterogeneity of carbonate rock with pores, it is currently unknown if the above-mentioned method, which is suitable for sandstone or mudstone with relatively homogeneous lithologies, can be effectively applied to carbonate rocks with complex internal structures (i.e., filled with pores, holes, cracks). In this study, 40 carbonate rock samples from one of the carbonate gas reservoirs in the Sichuan basin were used for experimental research to determine how the gas saturation affects the P-wave and S-wave velocities. Then, based on the test results, the feasibility of whether V_p/V_s can be used to identify a carbonate gas reservoir was also discussed.

2. Test methods and principles

2.1. Gas saturation of rock samples

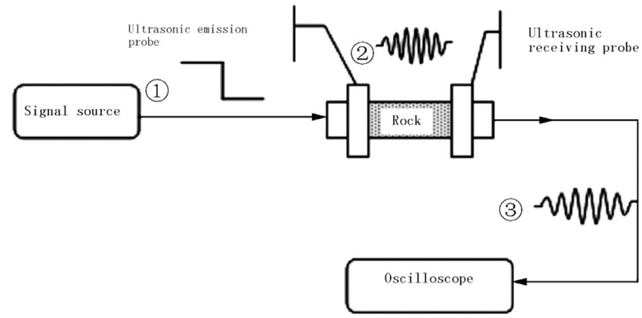
To establish a 100% water saturation point, a vacuum pump was used to pump air from the rock samples, which were placed in a hermetically sealed container until the system reached a negative pressure; concurrently, water was sucked into the rock through a catheter. The fully saturated rock samples were then placed in an incubator, where they were allowed to dry naturally so that the moisture was removed spontaneously. During this process, the changes in weight of the samples were monitored continuously until they reached the corresponding weight of the required saturation. The gas saturation can be expressed as:

$$S_g = 1 - S_W \qquad (1)$$

where S_g is the gas saturation, and S_w is the water saturation.

2.2. Acoustic velocity measurement

We used custom multi-frequency acoustic test devices to measure the travel times of the P-wave and S-wave through the rock samples with different gas saturation. The acoustic velocity is the reciprocal of acoustic travel time. The principle of this instrument is as shown in Fig. 1.



① —voltage of 600 V step pulse; ②—incident wave; ③—transmitted wave

Fig. 1. Measurement principle used to determine the acoustic travel time through the rock samples.

3. Test process and results

3.1. Rock sample preparation and basic physical parameters measurement

First, the carbonate rock samples were processed into 25 mm × 50 mm cylindrical core samples and dried for 72 h at 40 °C. The samples were then placed into a desiccator with moisture-absorbing silicone at the bottom to cool. Because the primary reservoir space types were inter-granular solution pores and intercrystalline solution pores, the lithology of these cores consisted primarily of dissolved-pore dolomite, dolomite lime, and dissolved-pore aplitic dolomite; no significant fractures were present around the core surface. The samples were thus vulnerable to the influence of diagenesis. The largest contribution to diagenesis in the study of reservoirs is dissolution, which can promote the evolution of porosity; thus, the samples formed a large number of dissolution pores and intercrystalline solution pores.

Then, the parameters of length, diameter, and dry-weight were measured, and an analyser of the porosity and permeability of tight rock was used to measure the porosity and permeability of the samples (Table 1). It is shown in Table 1 that the porosity and permeability of these samples were low despite the presence of micropores that were widely distributed around the core surface. After multi-stage cementation, the frame hole was found to be nearly filled with calcite or dolomite; the original larger pores had disappeared, and the existence of a large proportion micro-throats in the scattered remaining pores lead to poor connectivities between the pores.

Finally, we measured the P-wave and S-wave velocities of the original rock at different acoustic frequencies, which was regarded as the acoustic velocity at 0% water saturation.

3.2. Preparation of simulated formation water

To create a different gas and water saturations in the samples, we configured some simulated formations water based on the analysis data of in situ formations with water present, which were used to saturate the dry core samples.

3.3. Saturation and acoustic velocity tests

The dry core samples were placed in a vacuum container for 5 h at pressures reaching −0.1 MPa. Then, the prepared water was slowly added to the container until the samples were totally immersed. When the core surface produced some small bubbles, pumping continued until all of the surface bubbles disappeared; the samples were then set aside for 12 h. They were then removed from the water, their surfaces were dried, and they were weighed on an electronic balance, which had an accuracy of 0.0001 g. The resulting measured masses were considered to be the fully water-saturated (i.e., 100% water saturation) masses of the samples. In fact, it is difficult to fill every pore, particularly those with small apertures, with water; thus, the fully water-saturated masses should be determined based on the measured pore volume. This method is only an approximation, but the parameters are unaffected by this method. Then, the measurement of the acoustic velocity was conducted immediately.

After the completion of the acoustic test at 100% water saturation, the samples were placed into a desiccator to allow them to dry