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CHARACTERISTICS OF HIGH-FREQUENCY ULTRA-ACOUSTIC WAVE SPECTRUM AND PORE SIZE IN LOW-PERMEABILITY SANDSTONE

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ABSTRACT

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In the study of reservoir geophysics, elastic models of porous medium are commonly used in investigating reservoir geophysics of underground formations. In this work, we investigated the effect of pressure and pore size on acoustic frequency response in low-permeability sandstone. For a 0.5-3 μs pulse width and 725-4351 psi pressure, the dominant frequency and the bandwidth of the transmitted waves are sensitive to the median throat radius, which suggests that the dominant frequency and bandwidth of acoustic log data may depend on microporosity. To characterize the differences between transmitted and incident waves, we defined a new parameter, the spectrum ratio Q, which is the ratio of dominant frequency and bandwidth. Experimental results suggest that the relation between Q and the median throat radius, i.e., the Q-R function, is linear. The spectrum ratio Q also varies linearly with pressure. By establishing relationship between high-frequency ultra-acoustic wave spectra and pore size in low-permeability sandstone, our work suggests acoustic logging data can possibly be used to infer sandstone pore throat size for laboratory studies. Expanded laboratory studies are justified.

KEY WORDS: high-frequency, ultra-acoustic, wave spectrum, pore size, median throat radius, low-permeability sandstone.

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INTRODUCTION

Presently, acoustic logging is widely used in the exploration and development of oil and gas fields (Hu et al., 2004). Besides porosity interpretation, acoustic data is also used in surface, subsurface, and deep imaging (Xu et al., 2010). The concept of 'three instantaneous' attribute spectra of logging data has used to study stratigraphic division and sand bed correlation (Spiess and Mayer, 2003). Several physical models of wave propagation in fluid-saturated and partially saturated porous medium have been reported lot. Numerous papers based on fundamental theories and laboratory experiments, have focused on dispersion and attenuation theories at macro, micro, and meso scales in fluid-saturated porous medium. Approaches include fluid substitution, Biot poromechanics, squirt flow, Biot squirt flow, effective spherical patchy model, and local fluid flow in a double-porosity medium (Aki, 1980; Berryman, 1980a,b,c; Carcione, 2001; Carcione and Seriani, 2001; Carcione et al., 2004; Dvorkin and Nur, 1993; Geerits and Kelder, 1997; Mavko and Jizba, 1991; Mavko and Jizba, 1994; Mavko and Nolen-Hoeksema, 1994; Plona, 1980; Pride et al., 2004; Santos et al., 2004; Smith et al., 2003). In addition, many theoretical models and experiment methods have been developed to describe elastic wave dispersion and attenuation in porous medium, especially media saturated by oil, gas and water (Berryman and Wang, 2001; Biot, 1962a,b; Dutta and Odé, 1979a,b; Dvorkin and Nur, 1993; Mavko and Jizba, 1991; Odé and Dutta, 1980; Pride et al., 2004; White, 1975a,b).

In application, a single-frequency wave is used to measure propagation velocity in media. This monochromatic method ignores several characteristics of sound signals, which when analyzed by Fourier or other transforms can be used to obtain valuable frequency information. It is widely accepted that the propagation of acoustic waves in sandstone is affected by 1) investigating type of waves (P- or S-waves), 2) investigating the wavelength, 3) rock structure, 4) pore fluid, and 5) fractures. Changes in spectrum parameters always occur in the propagation process, which is considered to be the influence of petro-physical properties of a reservoir, especially the complex micro-pore structure of reservoir rocks.

Wave attenuation strongly depends on the distribution of fractures and macro structures in rocks (Hu et al., 2004; Liu et al., 2000; Liu and Zhao, 2006). In addition, fluid saturation in porous media strongly affects the frequency spectrum of transmitted waves. Even methods to identify subsurface reservoir fluids based on earthquake data are being developed (Ba et al., 2013). Typically, acoustic transmission spectra are related to the mechanics properties of rocks and to pore fluids (Li et al., 1999). We designed a series of experiments to study the relation between the pore size of low-permeability sandstone and the frequency characteristics of transmitted waves in dry cores, which allow us to ignore the influence of pore fluid saturation.

MATERIALS AND EXPERIMENT

Rock samples

We collected six natural low-permeability sandstone sample. Five samples were from central North China (T1, T2, T3, T4, and T5), and the sixth was Ottawa sandstone (W1). The sonic pulse was measured in the cores after drying at 120° C for 12 h. The basic physical parameters of the samples are presented in Table 1. For accuracy, we measured the length and diameter of each sample five times, and the relative errors are less than 0.002%.

Table 1. Basic information of rock samples.

Sandstone sample	Length(cm)	Diameter(cm)	Median throat radius(nm)	Porosity(%)*	Permeability(mD)*
T1	2.517(±0.002)	2.513(±0.001)	548.570	19.354	21.136
T2	2.686(±0.001)	2.530(±0.001)	1001.153	12.964	0.653
T3	2.502(±0.003)	2.518(±0.003)	889.249	16.527	0.848
T4	2.515(±0.002)	2.523(±0.001)	157.148	7.803	0.063
T5	2.864(±0.002)	2.535(±0.002)	2554.964	11.347	0.532
W1	2.821(±0.001)	2.524(±0.001)	1599.937	3.431	0.368

* Porosity and permeability were measured at 500 psi.

We used an Autopore 9500 to obtain the pore-size distribution and median throat radius, and an AP-608 automated permeameter-porosimeter to measure the porosity and permeability at different overburden pressures. Fig. 1 shows the cumulative distribution of the throat radius for the Ottawa sandstone sample (W1), and Fig. 2 shows the ratio of permeability and porosity (K/ϕ parameter) with respect to the overburden pressure (725-4351 psi). The data suggest lack of fractures inside the cores.

Experiment

The transmitted waves were measured according to the petroleum and gas industry standard of China (SY6351-2012 Laboratory measurement of acoustic properties on rock). We used the multifunctional acoustic parameter automatic measurement system (YS-HF) to measure P- and S-wave properties at simulated reservoir temperature and pressure conditions. The maximum pressure of the device is 11603 psi, including axial and confining pressure. The ultrasonic pulse transmission method is used to record the P-wave variation at 330 KHz, 500 KHz, 1 MHz, 2 MHz, and 5 MHz (the relative errors are less than 0.1%), and the corresponding width of the incident pulse was 3 μs, 2 μs, 1 μs, 200 ns, and 500 ns. Both ends of the core samples were polished, and white Vaseline was used as the coupling agent.

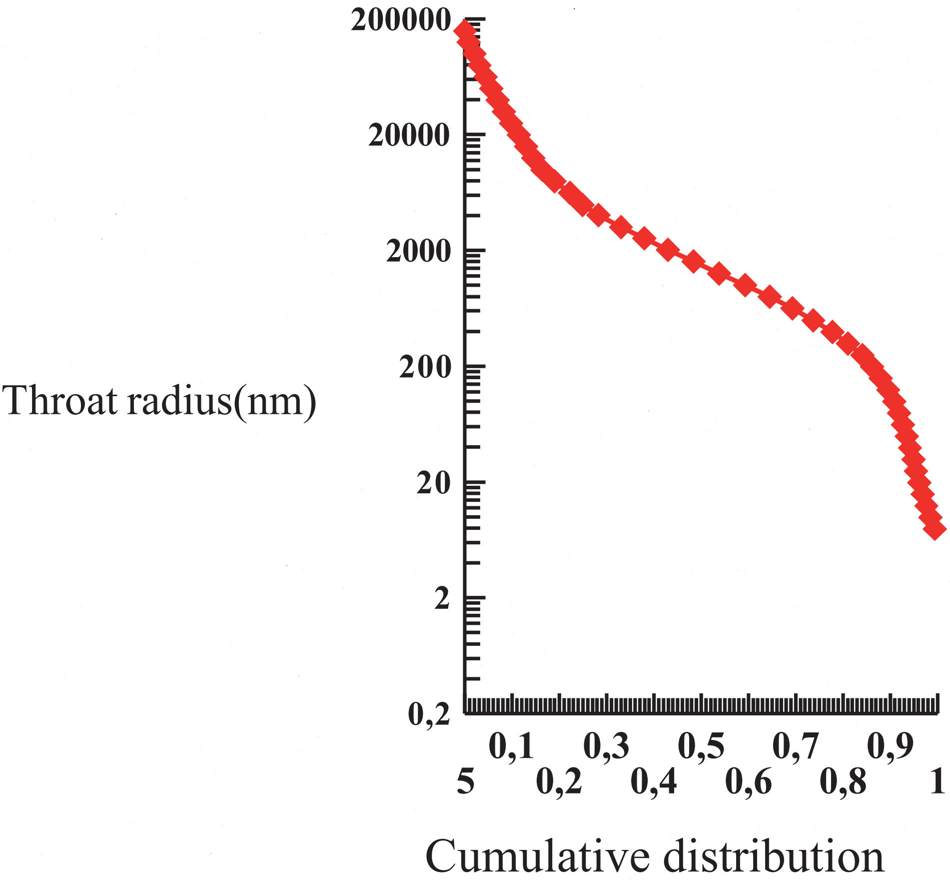

Fig. 1. Cumulative distribution of throat radius (W1).

The experimental apparatus is shown in Fig. 3. The apparatus consists of three parts: the pressure system, the core holder system, and the transmitting/receiving system. Ultra-acoustic waves are transmitted through the core sample from the transmitting and measurement system and we can control the temperature and pressure by temperature controller and pump. The pressure gauge shows axial and confining pressure. A computer is connected to the apparatus to record the wave form data.

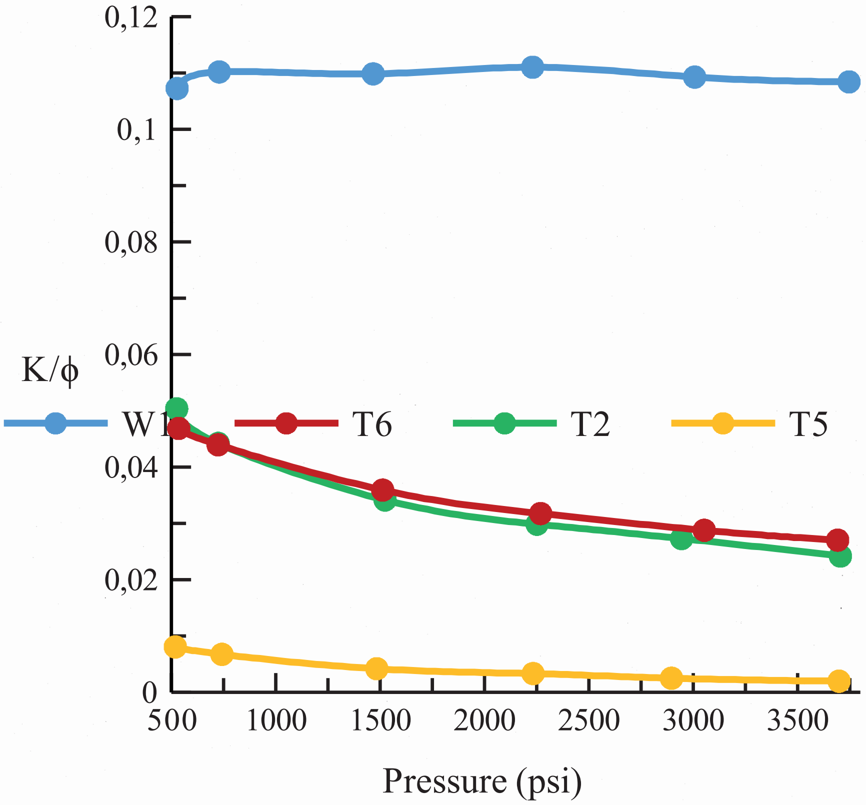

Fig. 2. K/ϕ vs. overburden pressure.

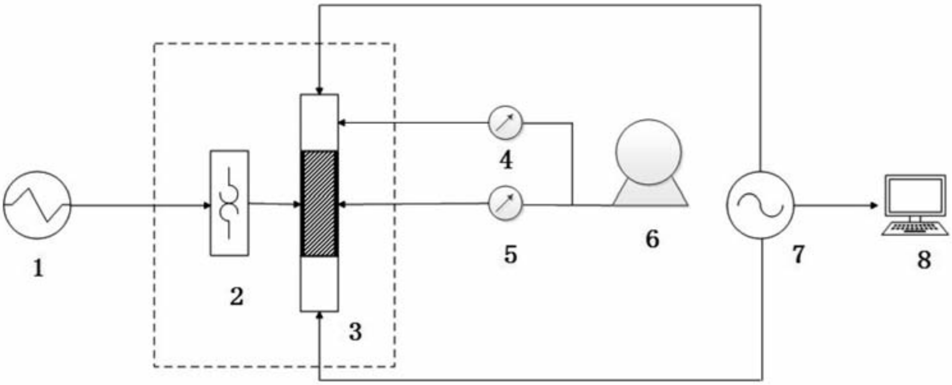

Fig. 3. The experimental apparatus schematic drawing. 1: Temperature controller; 2: Heater strip; 3: Transducer; 4: Axial pressure gauge; 5: Confining pressure gauge; 6: Pump; 7: Ultra-acoustic transmitting/receiving device; 8: Computer.

Data processing

The Fourier transform is a popular technique for mathematical analysis. It is applicable in almost all areas of science and engineering. The fast Fourier transform (FFT) is a fast algorithm for computing the discrete Fourier transform (DFT) and can provide efficient and exact transformation of a discrete set of data (Cheng et al., 2005; Wu et al., 2013). The Fourier transform and wavelet analysis are commonly used to de-noise well logs and to extract information (Yu et al., 2010). Some theoretical basis and brief reviews of the Fourier transform can be found in Bracewell and Kahn (1986) and Ramirez (1985).

The DFT is a digital approach to Fourier transformation and is applicable only to discrete data over a finite interval. We use the DFT and inverse DFT via the following expressions to obtain the Fourier transform of the wave form data

$$X_d(k\Delta f) = \Delta t \sum_{n=0}^{N-1} x_d(n\Delta t) e^{-i2\pi k\Delta f n\Delta t} \quad , \qquad (1)$$

$$x_d(k\Delta t) = \Delta t \sum_{n=0}^{N-1} x_d(n\Delta t) e^{-i2\pi k\Delta f n\Delta t} \quad , \qquad (2)$$

Using eqs. (1) and (2), frequency-domain data are transformed to time-domain data.

Fourier transforms move data to the frequency domain, where many difficult problems in the time domain become greatly simplified. Performing convolution in the frequency domain is a representative example of applying of the FFT.

RESULTS AND DISCUSSION

Acoustic logging has been used in oil and gas exploration to predict and calculate the porosity of reservoirs. We designed a series of experiments at the simulated reservoir pressure conditions to monitor the transmitted waves that travel through the entire length of the sandstone cores. We then used a FFT to establish the relation between frequency and pore size.

Spectrum parameters vs. median throat radius

First, we explored the relation between single-frequency parameters and median throat radius. The dominant frequency implies the centralized location of propagating acoustic wave's energy in the sandstone samples, and the energy dissipation is described by the bandwidth of the propagating acoustic wave. Figs. 4 and 5 show that the dominant frequency and bandwidth of the transmitted waves are sensitive to rock property variations of the sandstone samples, but a strong correlation is not obvious. The data distribution did not allow predictions of structural parameters such as the median throat radius. Thus, a new parameter needs to be defined to describe transmitted waves.

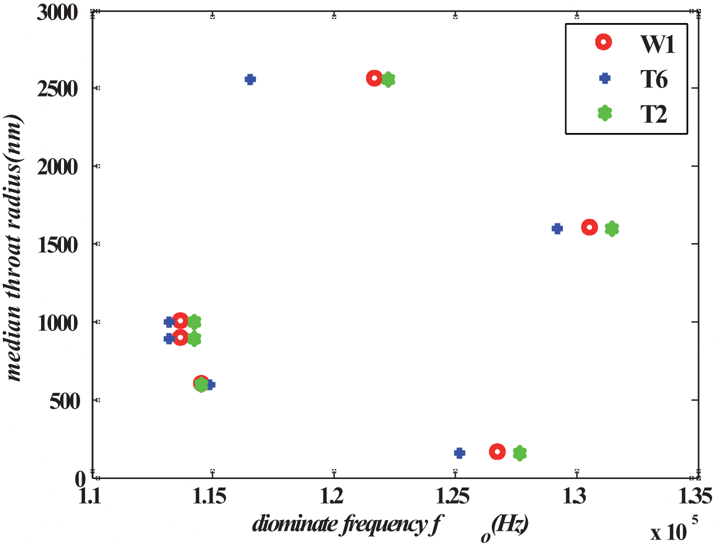

Fig. 4. Median throat radius vs. dominant frequency.

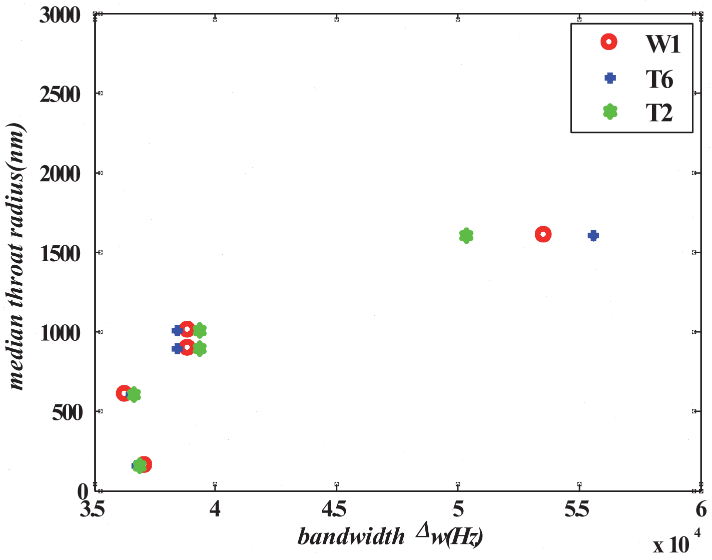

Fig. 5. Median throat radius vs. bandwidth.

Spectrum ratio Q vs. median throat radius

We examined the dominant frequency f_0 and bandwidth $\Delta\omega_0$ to describe variations in the propagating waves. These two parameters are typically considered to be affected by the rock properties, whereas the effect of the incident waves may be ignored. The spectrum ratio

$$Q = f_0/\Delta\omega_0 \quad , \tag{5}$$

is used to monitor energy dissipation and concentration of the propagating acoustic waves in the sandstone samples.

Although dry cores were used in this research, it is well known that water and hydrocarbon saturation have an influence on wave propagation, and that S-waves cannot propagate in liquids and gases. We analyzed the propagation of P-waves only in porous dry cores. The experiment about the influence of water or hydrocarbon saturation on spectrum ratio Q will be conducted in the future. The relation between the spectral properties of the transmitted waves and pore size at different reservoir pressures was investigated and the following results were obtained.

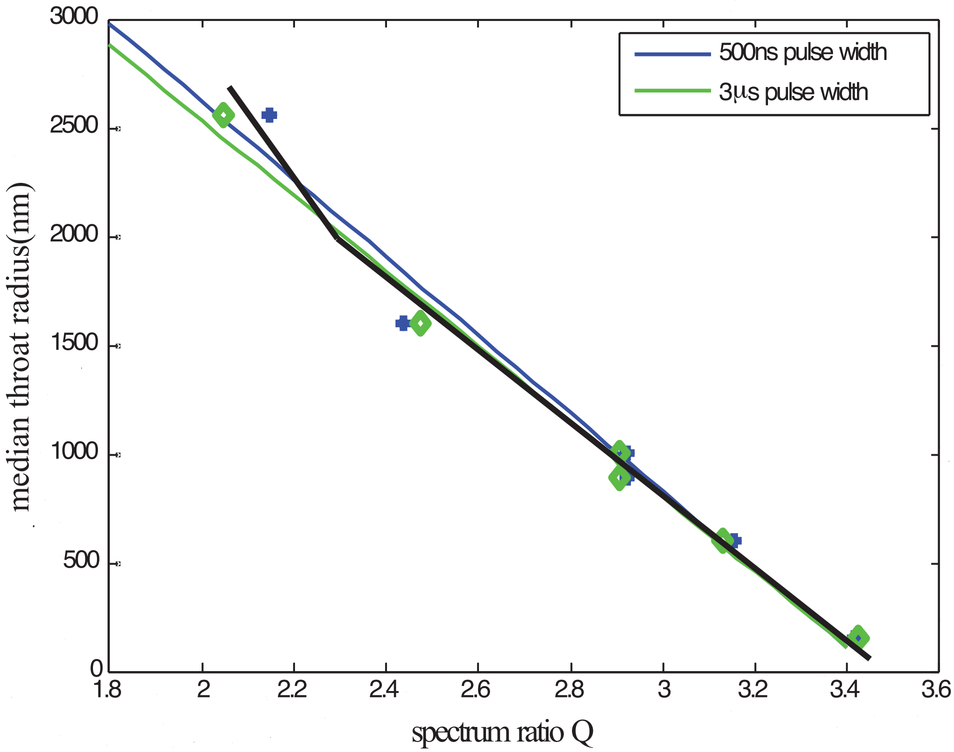

Fig. 6. Median throat radius vs. spectrum ratio Q.

We fit a quantity called the Q-R function to the spectrum ratio Q and pore-size data. Fig. 6 shows the variation in the spectrum ratio Q with respect to the median throat radius for different incident pulse widths at 725 psi confining pressure. The goodness of fit is greater than 0.95. The data suggest that the frequency variation at low confining pressure is inversely proportional to the median throat radius, and the less permeable the sandstone samples, the more accurate is the Q-R function.

We also find that as the scattering of the data increase, the throat size or the permeability increases. Hence, the higher the core permeability, the smaller the spectrum ratio Q. However, the spectrum ratio cannot be less than zero. We predict that the relation between the median throat radius and spectrum ratio becomes steeper with increasing throat radius or permeability.

The permeability of the samples varied uniformly with pressure, which suggests that the median throat radius follows similar trends. However, as Fig.7 shows, the spectrum ratio Q varied similar to permeability and median throat radius only when the incident pulse width was less than 3 μs. Thus, we chose 3 μs as the incident pulse width to investigate the relation between transmitted waves and the pore size of the low-permeability sandstone samples.

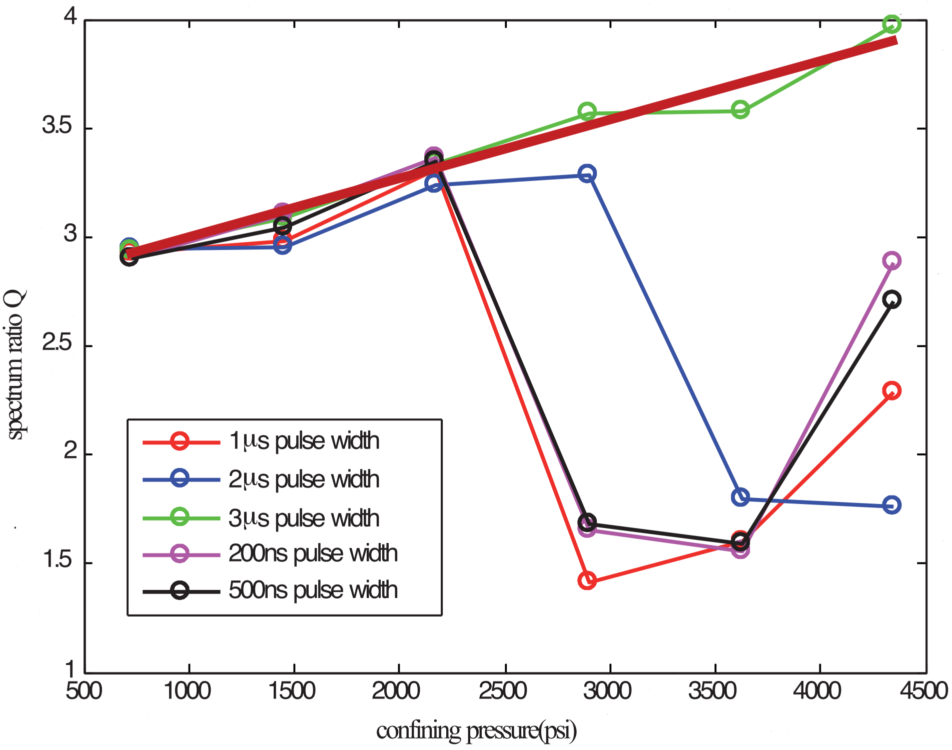

Fig. 7. Spectrum ratio Q vs. confining pressure for different pulse widths in sample T4.

CONCLUSIONS

Experimental results suggest that the spectrum ratio Q defined to describe the relation between spectrum and median throat radius is linearly correlated. This finding may allow acoustic logging data to define low-permeability data and high-permeability zones in unconventional reservoirs. This relationship will also may help develop new nondestructive methods for sandstone samples. An important result is that the lower the sandstone permeability, the higher the accuracy of the predictions.

The relation between the median throat radius and spectrum ratio is much steeper in high-permeability sandstones, similar to an exponential function.

For low-permeability sandstone without fractures, the incident pulse width of choice should be less than 3 μs.

The spectrum ratio Q varies linearly with confining pressure.

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