Journal of Applied Geophysics 116 (2015) 167–172

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

Seismic response variation of tight gas sand for uniform and patchy saturation patterns

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ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form 5 March 2015
Accepted 6 March 2015
Available online 8 March 2015

Keywords:
Tight sand
Saturation pattern
Velocity trend
Seismic response
Prestack inversion

ABSTRACT

When tight sand reservoir is gas–water saturated the distribution pattern of mixed fluid will lead to different velocity–saturation relationships, which will eventually cause the variation of seismic response. Assuming the gas–water mixed fluid in tight sand is uniform saturation or patchy saturation, theoretical velocity–saturation relationships are calculated by using the Gassmann equation and patchy equation respectively. Based on the two trends of velocity, we built a numerical model and analyzed the variations of AVO response, AVO attribute and prestack inversion by using numerical simulation results. The AVO analysis and prestack inversion results all show that when tight sand reservoir is gas–water saturated patchy saturation is more conducive to the prediction of gas content.

1. Introduction

Gas saturation is a critical parameter for gas-bearing formation which determines whether the reservoir has a commercial exploitation value. The AVO technique has improved the ability of gas reservoir detection, but in actual exploration, gas-bearing sands of different gas saturations or fizz sand are all likely to have strong amplitude reflections and make a similar seismic response. As a result the quantitative prediction of gas saturation is still challenging.

As the bridge to connect reservoir characters and seismic responses, rock physics theories can be applied to reduce the risk in gas saturation evaluation. Much research has been done to understand the effect of fluid on porous media theoretically and experimentally. Domenico (1976) measured the P-wave velocity of unconsolidated quartz sand that contained gas–water mixture fluid and found that P-wave velocity changed obviously near fully water-saturated. Gregory (1976) measured several types of sedimentary rocks and gave typical curves of P-wave velocity with water saturation. The results showed that the curves changed for different porosities. Researches showed that saturation pattern of mixed fluids in pore space may have great influence for velocity when reservoir is partial gas saturation; this phenomenon even appears at seismic frequency band (Knight and Nolen-Hoeksema, 1990; Mavko and Nolen-Hoeksema, 1994; Gist, 1994). Sharma et al. (2013) mapped the seismic rock properties due to mixture of brine and gas at partial and full saturation.

In recent years the tight sands have become the focus of exploration work in China, but due to the low-porosity ($\leq$8%) and low-permeability ($\leq$0.1 mD) of tight sand, the petrophysical characters are different from normal sandstone. Experimental results (Lebedev et al., 2009) show that the relationship between velocity and water saturation for low-permeability samples can be described with Gassmann–Wood relationship at low water saturation. With the increase of water saturation, the trend of P-wave velocity is close to the Gassmann–Hill relationship. Ruiz and Cheng (2010) proposed a new rock physics model for tight sandstone. Their work pointed that the petrophysical properties of tight sandstones have significant difference from traditional high-porosity and high-permeability sandstones.

From the above introduction, we understand that distribution pattern of mixed fluid will cause the different velocity–saturation trends for tight sand. In this work, we focus on (1) the theoretical velocity–gas saturation relationship when gas–water mixed fluids are distributed in uniform and patchy saturation patterns in tight sandstone reservoir; (2) analyze the variations of AVO response and attributes based on numerical simulations; and (3) use prestack inversion result to illustrate the influence of fluid distribution pattern on the prediction of gas content.

2. Velocity–saturation relationship

For the problem of fluid substitution, Gassmann–Biot theory is one of the most widely used theories (Gassmann, 1951; Biot, 1956a,

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http://dx.doi.org/10.1016/j.jappgeo.2015.03.010

1956b). In one-phase fluid substitution, the theory predicts the effective bulk modulus of saturated rock through the following equation:

$$\frac{K_{sat}}{K_0-K_{sat}}=\frac{K_{dry}}{K_0-K_{dry}}+\frac{K_{fl}}{\phi\left(K_0-K_{fl}\right)},\mu_{sat}=\mu_{dry} \tag{1}$$

where K_{dry} is the effective bulk modulus of dry rock, K_{sat} is the effective bulk modulus of the rock with pore fluid, K_0 is the bulk modulus of mineral material making up rock, K_{fl} is the effective modulus of pore fluid, ϕ is the porosity, μ_{dry} is the effective shear modulus of dry rock, and μ_{sat} is the effective shear modulus of rock with pore fluid. For partially saturated rock, there are two or more phase's fluids (for example the gas–water mixture) in the pore space; an effective modulus for mixed fluid can be described by Ruess average:

$$\frac{1}{K_{fl}}=\sum_i\frac{S_i}{K_i} \tag{2}$$

where K_i represents the bulk modulus of the ith liquid phase and S_i represents the saturation of the ith liquid phase. Using this effective bulk modulus of mixed fluid into Eq. (1) can predict the effective bulk modulus of the saturated rock accurately (Cadoret et al., 1995; Mavko and Nolen-Hoeksema, 1994).

We should note here that the Reuss average assumes that differences in wave-induced pore pressure have time to flow and equilibrate among the various phases, in other words, the mixed fluids are uniformly distributed in pore space. We can define a characteristic scale *Lc* that relates to fluid modulus and seismic wave frequency. If pore pressure heterogeneities caused by saturation heterogeneities will have time to relax and reach a local isostress state over scales smaller than *Lc*, then the effective fluid model mentioned in Eq. (2) can be used, usually sandstone reservoirs with high porosity and permeability will meet this assumption, even a homogeneous carbonate rock can exhibit uniform saturation behavior (Cadoret et al., 1998; Sharma et al., 2013). Spatial fluctuations on scales larger than *Lc* will tend to persist and will not be described well by the effective fluid model (White, 1975; Dutta and Odé, 1979a,1979b). In this case, the effective bulk modulus of rock with mixed fluid can be given by patchy formula (Berryman and Milton, 1991):

$$K_{eff}=\left[\sum_{i=1}^{n}\frac{x_i}{(k_i+\frac{4}{3}G)}\right]^{-1}-\frac{4}{3}G \tag{3}$$

where n is the number of patches with different content, x_i is the volume fraction of ith patch, G is the shear modulus of the rock, K_i is the bulk modulus of the rock completely saturated with ith fluid, and K_{eff} is the effective bulk modulus of the rock. Unlike the effective fluid model, the patchy model predicts a monotonic and almost linear increase in velocity with the increase of water saturation. The velocity versus saturation curves given by the effective fluid model and patchy saturation model represents lower and upper bound respectively. The actual velocity–saturation curves of sandstones change between these two bounds (Mavko et al., 2009).

We measured velocity–gas saturation relationship of several sandstone samples using the ultrasonic transmission method and compared with two theoretical model results. As demonstrated in Fig. 1(a), this sandstone sample has high porosity (24.5%) and high permeability (46 mD). The measured P-wave velocity–gas saturation result fits well with the Gassmann equation calculation. Fig. 1(b) shows a tight sandstone sample with low porosity (8%) and low permeability (0.01 mD); the measured P-wave velocity–gas saturation result fits well with the patchy model calculation.

Combined with the previous research work, we can see that in high-porosity and high permeability sandstone the mixed fluids are more likely to be uniformly distributed therefore the Gassmann equation can give accurate prediction of velocity. But for tight sand, the mixed fluids may not be evenly distributed therefore the Gassmann equation is not practicable but patchy model can give more reasonable result.

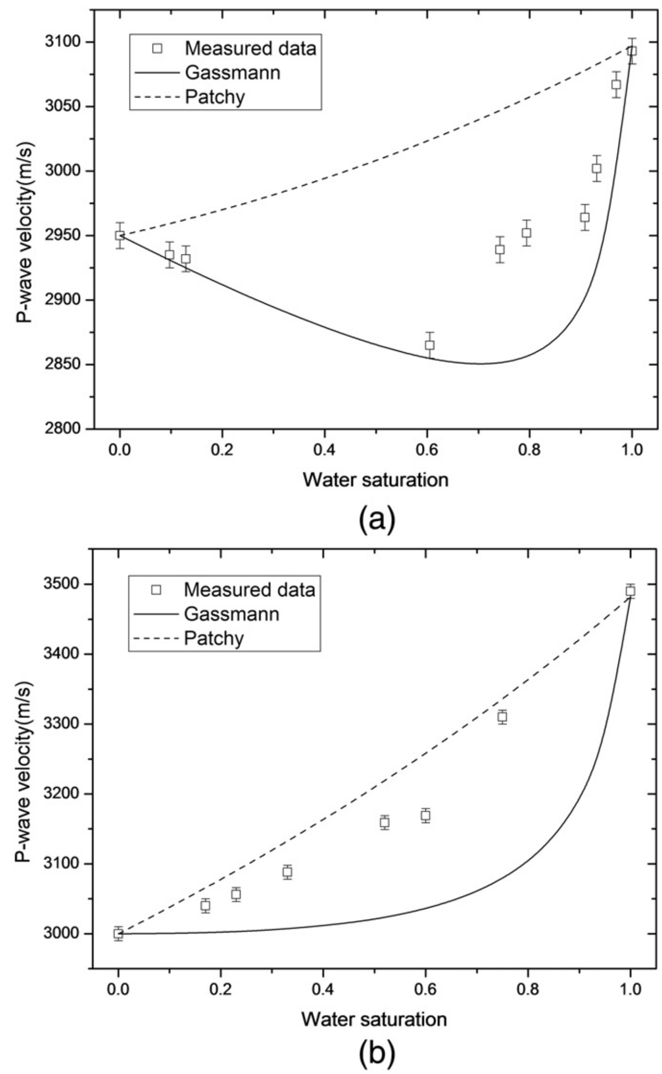

Fig. 1. P-wave velocity–saturation relationship: (a) sample of high porosity (24.5%) and high permeability (46 mD) and (b) sample of tight sand with low porosity (8%) and low permeability (0.01 mD).

3. Numerical model and AVO analysis

Based on above analysis, we built a tight gas sand model; compared the corresponding AVO response and attribute variation when gas–water mixed fluids are uniform or patchy distribution.

3.1. Numerical model

The model is designed as four horizontal layers; Fig. 2 gives the description and parameters of this model. The simulated reservoir is located in layer3 and includes five tight sands, the porosity is 8% and permeability is 0.01 md for each sand. The water saturations of five sands increase gradually, changing from full of gas to full of water.

Table 1 shows parameters of the five sands, P-wave velocity is calculated by the Gassmann equation and patchy model respectively when gas–water mixed fluids are uniform or patchy saturation. We can see the difference of two saturation patterns, as the water saturation increases the Gassmann equation calculation shows that P-wave velocity changes only in a very narrow area near full water saturation; but the