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Estimation of shear wave velocity from wireline logs in gas-bearing shale

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ABSTRACT

Gas-bearing shale is one of the most important unconventional reservoirs. Shear wave velocities are essential for prestack AVO analysis, fracture identification, and fluid typing. Moreover, the recent studies of shear wave prediction mostly focused on conventional sandstones, wet shale, sandstone or carbonate rock may not be suitable for gas-bearing shale. Firstly, according to core analysis results of gas-bearing shale, petrophysics model is proposed. Then, shear wave prediction method based on Gasmann's theory, spatial averaging model, and elastic moduli of dry rock were studied in detail. Especially, point to organic shale with low porosity, Krief, Nur, and Pride models are selected to calculate the elastic moduli of dry rock, respectively, and the best critical porosity in Nur model and consolidation coefficient in Pride model are determined, which is virtual to gas-bearing shale. Pride model is finally optimized as the most suitable model through comparison of error analysis. Meanwhile, to implement the estimation of shear wave from well logs, a corresponding log interpretation method for gas-bearing shale is also studied. In case study, calculated volumetric concentrations of minerals are in good agreement with X-ray diffraction (XRD) analysis of cores. The final shear wave velocity also matches well with dipole sonic imaging (DSI) log. Therefore, the whole approach is verified correct and suitable for estimation of shear velocity or slowness in gas-bearing shale.

1. Introduction

Compressional, shear wave velocity are essential to synthetic seismic record, elastic impedance inversion and reservoir prediction, especially to prestack AVO analysis and fluid typing. Moreover, for many reasons such as incomplete logs in old wells, logging tools, and borehole conditions, shear wave log is either incomplete or unreliable in some study area. Therefore, some researchers were always making attempts to find new methods for estimation of shear wave velocities (Castagna et al., 1985; Greenberg and Castagna, 1992; Arild et al., 1999; Bai et al., 2013). However, the present study mostly focuses on carbonate and sandstone formations, and the previous methods are not suitable for gas-bearing shale with complex minerals and low porosity. So it is necessary and meaningful to probe into estimation of shear wave velocity in two unconventional reservoirs.

Shear wave velocity prediction depends on the specific rock physical model. To gain continues shear wave velocity through the borehole, many researchers tried to predict shear velocity from well logs. For studying the relationship between the compressional and shear velocities, Castagna et al. (1985) constructed some empirical formulae through a lot of rock physical experiments. For elastic water-saturated clastic silicate rocks, shear wave velocity was approximately linearly related to compressional wave velocity, and the compressional-to-shear velocity ratio decreases with increasing P-wave velocity. Ideal models for regular packing of spheres and fractured solids exhibit similar behavior to the water-saturated and dry rocks. The dry rigidity equaled to dry bulk modulus, the velocities predicted by Gassmann's equations were in close agreement with laboratory measurement from water-saturated rock. Han et al. (1986) considered the effect of lithology on porosity and pressure coefficient and improved their equations. However, it is necessary to interpret the volumetric concentrations of all minerals and to obtain the regression coefficient before estimation of acoustic velocity. Greenberg and Castagna (1992) developed a general method to predict shear-wave velocity in porous rocks, which was successfully tested with data from several locations, and the estimated shear velocity can improve formation evaluation. Castagna et al. (1985) regarded the wave velocity as a composition-weighted polynomial or linear average of the pore

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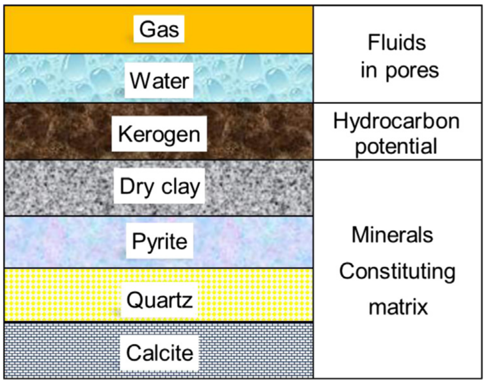

Fig. 1. Petrophysical model of gas-bearing shale.

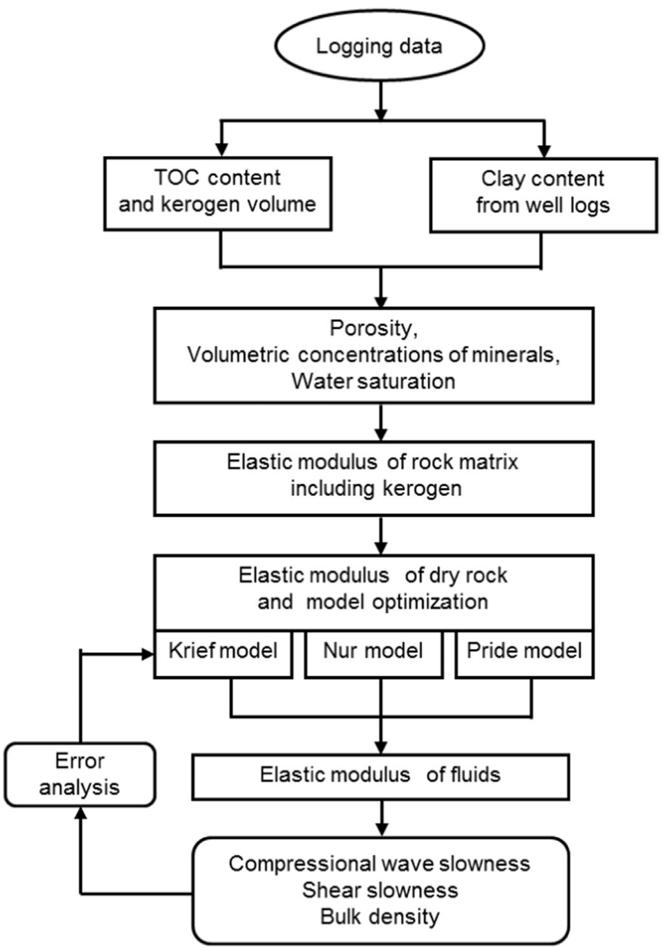

Fig. 2. Workflow of shear velocity prediction from well logs.

Table 1
Three methods and models for shear estimation of gas-bearing shales.

Procedures	*Calculation of elastic moduli*	*Method-I*	*Method-II*	*Method-III*
(1)	*Saturated rock*	*Gassmann's equation*		
(2)	*Rock matrix*	*Voigt–Reuss–Hill*		
(3)	*Dry rock*	*Krief model*	*Nur model*	*Pride model*
(4)	*Fluids*	*The rock is regards as partly saturated.*		

fluids and various minerals.

Combining Gassmann's equations and Kuster-Toksoz model (Kustera and Toksoz, 1974a, 1974b) with differential effective medium theory, Xu and White (1995, 1996) proposed an estimation method of compressional and shear velocities in argillaceous sandstone using the porosity and clay content, which was named as Xu-White model. Keys and Xu (2002) improved the Xu-White model and determined the elastic modulus of the rock matrix by solving linear ordinary differential equations. Lee (2006) applied the consolidation coefficient model proposed by Pride et al. (2004) to calculate shear velocity. Shao et al. (2009) studied shear wave velocity inversion method from conventional well logs based on rock physics and multi-mineral analysis for shaly-sand, and the predicted results were more accurate than the Xu-White model.

In recent years, several researchers studied the intelligent systems to predict rock parameters in general and shear wave velocity in particular (Rezaee et al., 2007, 2008; Rajabi et al., 2010; Asoodeh and Bagheripour, 2012; Ranjbar Karami et al., 2014). But one of the main concerns about these methods is that the number of data points plays an important role in accuracy of the models. For example, Rajabi and Tingay (2013) modeled sedimentary rocks using different types of intelligent systems, which showed that these methods were sensitive to the number of data point, and the reliability of the models decreases in cases of low number of data in modeling stage. However, these intelligent systems are seriously dependent on the laboratory measurement of cores or well logging data in ahead without considering physical concepts of rocks.

However, most of these studies above focused on the sandstone and carbonate reservoirs. Since organic shale is considered as one of the most important unconventional reservoirs, more researches are required to characterize their rock physical properties. In the previous methods, the mineral model of shaly-sand or carbonate formation is so simple, and they did not consider the kerogen. So, those previous methods are not applicable to organic shale.

In this study, the rock physical model is firstly studied for organic shale. Then, the whole theory for estimation of shear wave velocity is derived, in which the kerogen is regarded as a part of the matrix. For gaining some parameters required in the estimation of shear wave velocity or slowness (the reciprocal of velocity), the log analysis method of multiple minerals is investigated in detail. The applications of some cases prove that the volumetric concentrations of several minerals agree well with X-ray diffraction (XRD) analysis of core samples, and the predicted compressional, shear velocity, and bulk density are all well consistent with dipole shear imaging (DSI) log and compensated density log.

2. Theory and methodology

2.1. Geology and petrophysical model of gas-bearing shale

Gas shales unlike other lithologies contain significant quantities of organic matter in various stages of maturation (Sondergeld et al., 2010). From laboratory analysis results of cores in gas-bearing shale, besides kerogen, the target layer contains various clays, quartz, feldspar, calcite as well as a small amount of pyrite or siderite, aragonite. The geometry and nature of the mineralogical components and the organics would be easy to describe in the laboratory (Sondergeld et al., 2010). Moreover, the logging items in most wells are conventional logs, so it is impossible to identify all minerals above from well logging data. Therefore, petrophysical model of gas-bearing shale is simplified as kerogen, clay, quartz, calcite, and pyrite. Fig. 1 shows clearly petrophysical models of gas-bearing shale.