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

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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 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 Gassmann’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.

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Combining Gassmann’s equations and Kuster-Toksoz model (Kuster 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.
2.2. Estimation of shear wave

2.2.1. Elastic moduli and density of saturated rocks

According to the theory of elastic medium, the compressional and shear wave velocity of a rock, \( V_p \) and \( V_s \), can be calculated by the elastic parameters of the rock below:

\[
V_p = \sqrt{\frac{K_{sat} + 4\mu_{sat}/3}{\rho_{sat}}}
\]

\[
V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}}
\]

(1)

where \( K_{sat} \) and \( \mu_{sat} \) are the bulk and shear moduli of saturated rock, GPa; \( \rho_{sat} \) is the bulk density of saturated rock, g/cm\(^3\).

The bulk and shear moduli of the rock are both important elastic parameters of rock, which are determined by the composition of the rock. As one of the most valuable rock physical equations, Gassmann’s equation describes the relationship between the rock elastic parameters and the composition of the rock, which assumes that shear moduli of the saturated and dry rock are equal. So, the bulk and shear moduli of saturated rock are saturated by

\[
K_{sat} = K_{dry} + \frac{\left(1 - \frac{\rho_{dry}}{\rho_{sat}}\right)^2}{\frac{1}{K_{sat}} + \frac{1 - \phi}{K_{f}} - \frac{1}{K_{dry}}} - \frac{\rho_{dry}}{K_{dry}}
\]

\[
\mu_{sat} = \mu_{dry}
\]

(2)

where \( K_{sat}, K_{dry}, \) and \( K_f \) is the bulk moduli of the rock matrix, dry rock, and fluid in pores, GPa; \( \phi \) is the porosity of saturated rock, fraction. \( \mu_{sat} \) and \( \mu_{dry} \) are the shear moduli of the saturated and dry rock, respectively, GPa.

It is pointed out that the matrix density is calculated by the weighted average of the individual minerals, and it is same for the fluids. So, the densities of the saturated and dry rock are calculated

\[
\rho_{sat} = \rho_{dry} + \rho_f \phi
\]

\[
\rho_{dry} = \rho_{ma}(1 - \phi)
\]

(3)

where \( \rho_f, \rho_{dry}, \) and \( \rho_{ma} \) are the bulk density of the fluid in pores, dry rock, and rock matrix, respectively, g/cm\(^3\). \( \rho_{ma} \) can be calculated by weighted averaging of various minerals and kerogen,

\[
\rho_{ma} = \sum_{i=1}^{N} \rho_i p_i
\]

(4)
where $\rho_i$ is the density of the $i$-th mineral in rock matrix, g/cm$^3$; $N$ is the number of the minerals including kerogen.

### 2.2.2. Elastic modulus of rock matrix

So far, the spatial averaging model is mainly used to determine the bulk and shear moduli of mineral matrix (solid) in the rock. The most classic method is Voigt–Reuss–Hill (VRH) model (Voigt, 1928), which can be directly used to calculate the bulk and shear moduli of the rock matrix.

\[
\begin{align*}
M_{\text{ms}} &= \frac{(M_V + M_R)}{2} \\
M_V &= \sum_{i=1}^{N} f_i M_i \\
M_R &= \frac{1}{\sum_{i=1}^{N} f_i M_i}
\end{align*}
\]

where $M_V$ is the bulk or shear modulus of mineral matrix including kerogen and other minerals by using Voigt model; $M_R$ is the bulk or shear modulus of dry rock by using Reuss model; $M_i$ is the bulk
or shear modulus of the $i$-th mineral using Voigt model, and $f_i$ is the volumetric concentration of the $i$-th mineral including kerogen in rock matrix. It is pointed that the kerogen is regarded as a special “mineral”, a part of the rock matrix.

2.2.3. Elastic modulus of dry rock

In rock physics modeling, the calculation of elastic moduli of dry rock is a key and indispensable step, but it is the most uncertain in all steps. In fact, because drilling cores were scared and little rock physics experiment were also made, many scholars built some empirical formula models between elastic moduli of solid matrix and porosity of the rock to estimate the elastic moduli of dry rock (“frame” properties). These models include Krief model, Nur model, and Pride model.

Krief et al. (1990) applied the formation data from Raymer et al. (1980) to build the correlations of the bulk and shear moduli between the dry rock and rock matrix

$$K_{dry} = K_{ma}(1 - \phi)^{m(\phi)}$$

$$\mu_{dry} = \mu_{ma}(1 - \phi)^{m(\phi)}$$

$$m(\phi) = \frac{3}{1 - \phi}$$

where $\phi$ is the porosity of the rock; $\mu_{ma}$ is the shear modulus of rock matrix, GPa.

![Graph of predicted compressional, shear wave slowness using XRD measurement and comparison of the predicted P-wave and S-wave slowness and DSI log using (a) Method-I, (b) Method-II, and (c) Method-III. By contrast, the estimated results using Method-III with Pride model is the best.](image)

**Table 4** Comparison of the predicted compressional, shear wave, and bulk density of three models and the errors analysis in well A.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Models for dry rocks</th>
<th>MRE of P-wave (%)</th>
<th>MRE of S-wave (%)</th>
<th>MRE of bulk density (%)</th>
<th>Average MRE of three parameters (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method-I</td>
<td>Krief model</td>
<td>2.707</td>
<td>3.4418</td>
<td>4.5475</td>
<td>3.5654</td>
</tr>
<tr>
<td>Method-II</td>
<td>Nur model</td>
<td>2.596</td>
<td>2.4771</td>
<td>4.5475</td>
<td>3.2068</td>
</tr>
<tr>
<td>Method-III</td>
<td>Pride model</td>
<td>2.677</td>
<td>2.3226</td>
<td>4.5475</td>
<td>3.1823</td>
</tr>
<tr>
<td>Method-III (combined mineral test)</td>
<td>Pride model</td>
<td>2.018</td>
<td>3.591</td>
<td>4.494</td>
<td>3.367</td>
</tr>
</tbody>
</table>

Remark: $\phi_c = 0.30$, $c = 2.50$
Nur (1992) constructed the relationship between rock matrix between the matrix and dry rock moduli of based on the critical relationship between porosity,

\[
\begin{align*}
K_{\text{dry}} &= K_{\text{ma}} \left(1 - \frac{\phi}{\phi_c}\right) \\
\mu_{\text{dry}} &= \mu_{\text{ma}} \left(1 - \frac{\phi}{\phi_c}\right)
\end{align*}
\]

where \(\phi_c\) is the critical porosity.

They thought that different rocks have different porosity, and even for the same lithology, the critical porosity is also different for different interior pore structures. For conventional sand, the critical porosity is about 0.4, and for organic shale with low porosity, it is difficult to determine and need to study further.

Pride et al. (2004) and Lee (2006) modified the bulk and shear moduli of dry rock,

\[
\begin{align*}
K_{\text{dry}} &= K_{\text{ma}} \frac{1 - \phi}{1 + C_0 \phi} \\
\mu_{\text{dry}} &= \mu_{\text{ma}} \frac{1 - \phi}{1 + \gamma \phi}, \quad \gamma = \frac{1 + 2c}{1 + c}
\end{align*}
\]

where \(c\) is the consolidation coefficient, which expresses the consolidation degree of the rock, usually, \(2 < c < 20\) for shaly sandstone.

For Krief model, only the porosity and matrix properties are needed as input. The Nur model needs the critical porosity, and it is a key to choose the suitable values of organic shale. The Pride model depends on both the porosity and consolidation coefficient, but the consolidation coefficient varies in different rocks and different sedimentary environments, and it was related to the shape of the pores in the rock.

Organic shale has low porosity, and three models look suitable. How are the critical porosity and consolidation coefficient determined? Which is the best one? So, we plan to make some modeling tests using each model, and optimize the best model through comparison of the predicted and measured results.
2.2.4. Elastic moduli of fluids in non-uniform saturation status

In organic shale, the fluids include free gas, adsorbed gas, dissolved gas, and irreducible water. Their distributions are not uniform in the pores of the rock, and the gas is partly saturated. When the acoustic wave translates through the kind of rock, the pressures among different saturated zones are not equal. Therefore, in non-uniform status, total bulk modulus of fluids is between $K_{f,V}$ by Voigt model and $K_{f,R}$ by Reuss model, which can be estimated from

$$K_f = K_{gas} S_{gas} + K_{water} S_{water}$$

$$S_{gas} + S_{water} = 1$$

where $K_{gas}$ and $K_{water}$ are the bulk moduli of gas and water, respectively, GPa; $S_{gas}$ and $S_{water}$ are gas saturation and water saturation, respectively, fraction.

The bulk density of multiphase fluids in pore, $\rho_f$, can be expressed as

$$\rho_f = (1 - S_w)\rho_{gas} + S_w\rho_{water}$$

where $\rho_{gas}$ and $\rho_{water}$ are the density of gas and water, respectively, g/cm$^3$.

Therefore, we may derive the elastic moduli and density of saturated rock from Eq. (4) to Eq. (10), the P-wave and S-wave velocities can be finally obtained from Eq. (1).

2.3. Determination of volumetric concentrations based on logs analysis

According to petrophysical theory, logging response equations about acoustic, density and neutron logs for organic shale are as follow (Thomas, 1991)

$$\Delta t = V_{cl}\Delta t_{cl} + V_{ker}\Delta t_{ker} + V_{pyr}\Delta t_{pyr} + V_{qtz}\Delta t_{qtz}$$

$$+ V_{ca}\Delta t_{ca} + \varphi_f \Delta t_f$$

$$\varphi_N = V_{cl}\varphi_{N,cl} + V_{ker}\varphi_{N,ker} + V_{pyr}\varphi_{N,pyr} + V_{ca}\varphi_{N,ca}$$

$$+ V_{qtz}\varphi_{N,qtz} + \varphi_f$$

$$\rho_b = V_{cl}\rho_{cl} + V_{ker}\rho_{ker} + V_{pyr}\rho_{pyr} + V_{qtz}\rho_{qtz} + V_{ca}\rho_{ca}$$

$$+ \varphi_f \rho_f$$

$$P_E = V_{cl}P_{E,cl} + V_{ker}P_{E,ker} + V_{pyr}P_{E,pyr} + V_{ca}P_{E,ca}$$

$$+ V_{qtz}P_{E,qtz} + \varphi_f$$

$$I = V_{cl} + V_{ker} + V_{pyr} + V_{qtz} + V_{ca} + \varphi_f$$

where $\Delta t$, $\varphi_N$, $\rho_b$, and $P_E$ are acoustic travel time, neutron, density,

![Fig. 6](image_url)
Fig. 7. The comparison of and measured and predicted using three methods: (a) Krief model, (b) Nur (critical porosity), and (c) Pride model. Method-III with Pride model is the most suitable with the lowest average relative error of 5.462%.

Table 5
Comparison of the predicted compressional, shear wave, and bulk density of three models and the errors analysis in well B.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Models for dry rocks</th>
<th>MRE of P-wave (%)</th>
<th>MRE of S-wave (%)</th>
<th>MRE of bulk density (%)</th>
<th>Average MRE of three parameters (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method-I</td>
<td>Krief model</td>
<td>12.991</td>
<td>6.571</td>
<td>4.782</td>
<td>8.115</td>
<td></td>
</tr>
<tr>
<td>Method-II</td>
<td>Nur model</td>
<td>5.239</td>
<td>6.435</td>
<td>4.782</td>
<td>5.486</td>
<td>(\rho_c \approx 0.20)</td>
</tr>
<tr>
<td>Method-III</td>
<td>Pride model</td>
<td>4.953</td>
<td>6.654</td>
<td>4.782</td>
<td>5.462</td>
<td>(c = 5.6)</td>
</tr>
</tbody>
</table>
and photo-electric factor (PE) logs; $V_{cl}$, $V_{ker}$, $V_{pyr}$, $V_{qtz}$, and $V_{ca}$ are volumetric concentrations of dry clay, kerogen, pyrite, quartz, and calcite in the formation; $\Delta t_{cl}$, $\Delta t_{ker}$, $\Delta t_{pyr}$, $\Delta t_{qtz}$, and $\Delta t_{ca}$ are acoustic travel time of dry clay, kerogen, quartz, and calcite, respectively.

As an important parameter of organic shale, kerogen may be used to characterize the hydrocarbon generation potential. Vernik and Milovovac (2011) thought that kerogen volume is related to total organic carbon (TOC) content, and it can be estimated by

$$V_{ker} = \frac{\rho_{ker} - \rho_f}{\rho_{ker} - \rho_f}(1 - \phi),$$

(12)

where $\rho_{ker}$, $\rho_f$, and $\rho_{ker}$ are the density of the matrix, fluid, and kerogen, respectively, $\phi$ is dependent on the mature of kerogen, which ranges from 0.7 to 0.85 (Vernik and Milovovac, 2011).

TOC content can usually be derived based on wireline logs (Mendelzon and Toksoz, 1985; Fertl and Chilingar, 1988; Passey et al., 1990, 2011; Kamali and Mirshady, 2004; Khoshnoodia et al., 2011). These TOC prediction methods mostly include simple or multivariate empirical regression, $\Delta$logR method, and artificial neural network models such as radial basis function (RBF) method (Huang et al., 2011; Tan et al., 2013).

Generally, gamma ray log (GR) and spontaneous potential (SP) are usually used to calculate the clay content of the formation (Ellis and Singer, 2012). But, in some cases, for example, calculating clay content or shale volume using GR in organic shale is not a good way, it may not work at all in many cases due to the uranium associated with organic carbon, so, we should use the computed gamma ray (CGR or THK).

So, the mineral composition and porosity are accomplished by solving Eqs. (11) and (12) for organic shale, after which the fluid saturation can be calculated from Archie’s model or some modification of Archie’s equation.

### 2.4. Workflow

Fig. 2 shows the whole dataflow of shear wave velocity prediction from wireline logs in detail. Firstly, TOC content is predicted from well logs and kerogen volume is calculated. Then, the porosity, volumetric concentrations of quartz, calcite or other minerals, and gas saturation are derived. Next, the elastic moduli of saturated rock, rock matrix, and dry rock are calculated, and compressional, shear wave velocities or slowness, and bulk density are predicted from Eq. (1). To determine which model of elastic moduli of dry rock is the best and most applicable for organic shale, three methods including Krief model, Nur model, and Pride model are applied to make some prediction tests for the comparison of errors, which is listed in Table 1. Some rock physics parameters of minerals and fluids are listed in Table 2.

### 3. Comparison and validation of methods

For verifying the methods or models, we made some modeling tests in one well with core measurement. Well A is located in South China, whose target formation is organic shale. There are 26 core plugs drilled in the organic shale. TOC content and porosity were measured in the laboratory, and minerals composition was determined via X-ray diffraction (XRD). All measurement results above are listed in Table 3. The XRD data in Table 3 were normalized before they were used to compare with the log-derived minerals compositions.
where $V_i$ is the measured concentrations of this $i$-th mineral from XRD analysis, fraction; $V_{nor,i}$ is the corresponding normalized result, fraction; $\phi$ is total porosity, fraction.

In this study, three methods in Table 1 are used to make some prediction tests. To compare the precisions, we construct a parameter named as the mean relative error (MRE)

$$\text{MRE} = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{E_i - M_i}{M_i} \right|$$

where $E_i$ is the estimated compressional, shear wave slowness, or bulk density; $M_i$ is the corresponding measured result in laboratory or wireline log; $N$ refers to the total number of data presented to the prediction approach.

When Nur model is tested, different critical porosities are used to make some experiments. In Pride model test, different consolidation coefficients are used to make some experiments. The predicted relative errors with different critical porosity in Nur model and consolidation coefficient in Pride model are illustrated in Fig. 3. According to error analysis, we chose the best parameters, $\varphi_c = 0.30$ in Nur model and $c = 2.5$ in Pride model. Fig. 4 illustrates the predicted results of three methods and comparison of the predicted P- and S-wave slowness and DSI log. By contrast, the estimated compressional and shear wave slowness using Method-III with Pride model (Fig. 3c) is in better agreement with DSI log than those using Method-I with Krief model (Fig. 3a) and Method-II with Nur model (Fig. 3b). The errors between the measured and predicted results of three methods are listed in Table 4. For Method-III, the mean relative errors of compressional, shear wave slowness, and bulk density are about 4.547%, 2.325%, and 2.677%, respectively, and the MRE of three parameters averages around 3.182%. These errors of Method-III with Pride model above are all lower than those of other models, which indicate that Pride model is the most suitable in elastic moduli calculation of dry rock in gas-bearing shale.

However, in fact, these cores with XRD experiment are limited,
so TOC content and volumetric concentrations of minerals have to resort to petrophysical parameters prediction from wireline logs. Moreover, log interpretation based on some conventional logs and current petrophysical analysis method unlike laboratory experiment of cores cannot give volumetric concentration of many minerals, it can give the volumetric concentrations of shale, quartz, calcite, and dolomite. For verifying if this method is adaptive to volumetric concentrations of some main minerals, we combine some minerals together. For example, we combine quartz and feldspar as clastic, and consider pyrite and marcasite together. Fig. 5 shows the modeling results of the compressional and shear wave slowness, and bulk density. From this figure, we can see that the estimated results are also in good agreement with DSI log. Total MRE averages around 3.367%, which is similar with the modeling experiments above. Therefore, the test proves again that Method-III correct and applicable, and we may apply the volumetric concentrations of some main minerals from log interpretation to predict the compressional, shear slowness, and bulk density.

4. Case study

Well B is a pilot well for gas-bearing shale of Longmaxi Formation in Sichuan Basin, China. Laboratory XRD analysis results of core samples show that the gas-bearing shale is mostly constituted of quartz, feldspar, calcite, and a little kerogen and pyrite. The reservoir space is mainly dominated by pores among grains. In this case, 65 cores samples were drilled in the target organic shale, and TOC content of core samples was measured in the laboratory. TOC content mainly ranges from 0.5 wt% to 6.0 wt%, which indicates the formation mainly gas bearing shale.

In order to verify the validation and precision of the methods above, Well B is used to carry out the estimation of shear wave velocity or slowness using the cores measurements. We used three methods in Table 1 to make some prediction tests. The predicted relative errors with different critical porosity in Nur model and different consolidation coefficient in Pride model are illustrated in Fig. 6. According to error analysis, we chose the best parameters, \( q_r = 0.20 \) in Nur model and \( c = 5.6 \) in Pride model. Fig. 7 illustrated the comparison of predicted results, and the errors are listed in Table 5. The MREs of compressional, shear wave slowness, and bulk density are all the lowest with 4.953%, 6.654%, 4.782%, respectively, and the average error is about 5.462%, is also the lowest. Therefore, Method-III with Pride model is the most suitable.

For further study, we calculate continues compressional and shear wave slowness by using wireline logs. In this well, geophysical logs include natural gamma spectrum (GR), spontaneous potential (SP), dual laterolog (deep laterolog, LLD, and shallow laterolog, LLS), compensated acoustic log (AC), compensated density log (DEN), and compensated neutron log (CNL), and DSI log. The TOC content, clay content, porosity and water saturation are obtained by log interpretation.

Firstly, TOC content and kerogen volume are predicted. For choosing the best method, we chose empirical formula, \( \Delta \log R \) method, and RBF method to make the TOC prediction tests, respectively. From geochemical experiment of some cores, TOC content has the highest correlation coefficients with DEN log (Fig. 8a), whereas, it has lower correlation coefficients with other logs. Fig. 8(b) shows the TOC prediction results using regression equation about density log. In \( \Delta \log R \) method, the TOC predicted result is so bad because of the shale baseline parameters of resistivity and density logs, so we make another experiments using RBF method (Tan et al., 2013), whose result is illustrated in Fig. 8 (c). By contrast, the predicted result is using RBF method is best, the kerogen volume is consequently calculated from RBF TOC content. Then, the calculated gamma (CGR) is used to calculate the clay content. Next, the volumetric concentrations of minerals are calculated by using log interpretation method above, which are all illustrated in the right track of Fig. 9. When TOC content and mineral compositions are ready, the compressional, shear wave slowness, and bulk density are finally estimated using Method-III with Pride model. Fig. 9 shows the predicted TOC content, the estimated compressional, shear wave slowness, and bulk density of well B, which illustrates the estimated results are well consistent with DSI log and compensated density log (DEN). For this interval \( x250\text{–}x440 \) m, the MREs of compressional, shear wave slowness, and bulk density are 7.020%, 6.390%, and 4.127%, respectively. Total MRE of three parameters averages about 5.844%. This suggests again that this approach for estimation of shear wave slowness is applicable and useful.

Recently, Xujiahe Formation in Sichuan Basin, China, is another hotspot for unconventional reservoirs exploration, whose lithology mainly includes gas-bearing shale and tight sandstone, and most layers are laminated. Laboratory XRD analysis results of core samples show that the gas-bearing shale is mostly constituted of quartz, feldspar, calcite, and a little kerogen without pyrite. The reservoir space is mainly dominated by pores among grains. In this area, geophysical logs include GR, SP, LLD, LLS, AC, DEN, and CNL. But, DSI log was measured only in Well C, which is a key well.

In this case study, TOC content is firstly predicted. In the case,
20 cores samples were drilled in the target organic shale, and TOC content of core samples was measured in the laboratory, mainly ranges from 0.39% to 6.33% with an average of 2.75%. The stage of evolution is high maturity with R0 of about 1.02–1.68%. The Organic matter is III kerogen. The correlation coefficients with TOC content and all logs are not so higher. Therefore, we consider using multivariate regression to fit TOC content. Fig. 10 illustrates TOC content prediction results of well C using ΔlogR method and multivariate regression method. Compared with laboratory measurements, the ΔlogR-derived TOC content does not agree better than that by multivariate regression method. So, we chose multivariate regression method to evaluate TOC content, which is illustrated in track “TOC” of well C.

Then, Gamma ray log is used to calculate the clay content because of low TOC in tight sand. Consequently, the volumetric concentrations of minerals are calculated by using log interpretation method above, which are all illustrated in the right tracks of Fig. 11. The predicted results are all in good agreement with XRD of core samples. When TOC content and mineral compositions are ready, the compressional, shear wave slowness, and bulk density are finally estimated using Method-III. The middle tracks of Fig. 11 illustrate that the estimated results are in good agreement with DSI log and compensated density log (DEN). For this interval x000–x100 m, the MREs of compressional, shear wave slowness, and bulk density are 6.788%, 5.181%, and 3.923%, respectively. Total MRE of three parameters averages about 5.296%. This suggests again that this approach for estimation of shear wave slowness is applicable and useful.

When the shear wave log is not available in some other wells, we can use the same methods and steps to estimate the shear wave velocity or slowness. In the estimation, for controlling quality of the estimated results, we use the measured compressional acoustic log and compensated density log to compare and check the estimation quality. Fig. 12 show another example about well D, and the estimated compressional wave slowness and bulk density are both well consistent with compensated acoustic log (AC) and density log (DEN). Total MRE of two parameters averages about 4.801% in well D, respectively (Table 6). Furthermore, we also use the same method to process another two wells, well E and well F. The predicted compressional wave slowness and bulk density are both also match well with wireline logs. The errors between the estimated and measured results of well E and well F are also listed in Table 6. The MREs of compressional wave and bulk density, and total MRE averages all lower than 9.0%, some are even lower than 2.0%, which indicates the estimation approach and error controlling method are both reliable, and the estimated shear wave slowness is also accurate and applicable.

5. Discussions

In this study, we assume the formation is isotropic. But, shale, typically, fractured shale, is often very seismically anisotropic, and the lithology of the case study mentioned in the text are laminated. Moreover, neither the Voigt–Reuss–Hill nor Gassmann’s equation takes into consideration the effect of anisotropy. Therefore, the
Fig. 12. Estimation of compressional, shear wave slowness, and bulk density in well D where shear wave is not available. The estimated compressional and bulk density is compared to the compensated acoustic log and density log, which show they both agree well.

Table 6
The error analysis of the estimated compressional wave and bulk density of another 3 wells.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>MRE of P-wave (%)</th>
<th>MRE of bulk density (%)</th>
<th>Average MRE of two parameters (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>5.121</td>
<td>4.480</td>
<td>4.801</td>
</tr>
<tr>
<td>E</td>
<td>7.378</td>
<td>3.892</td>
<td>5.635</td>
</tr>
<tr>
<td>F</td>
<td>5.607</td>
<td>2.926</td>
<td>4.266</td>
</tr>
</tbody>
</table>
models or methods above should be further modified or probed in. Furthermore, the XRD experiment can provide detailed composition of many minerals, and the estimation method of shear wave based on XRD analysis is verified correct with low error. Log interpretation from conventional logs unlike XRD experiment cannot identify many minerals, but the combined principle minerals test indicates the estimation method is also applicable. Only conventional logs were measured in most wells of study area, and neither natural gamma spectrum logs (NGS) or element capture spectrum log (ECS) was carried out, so log interpretation results cannot determine the composition of all kinds of minerals, but the shear wave prediction in some cases is in good agreement with DSI log. Of course, if NGS or ECS were measured, more minerals can be calculated, it is sure that the estimation of shear wave maybe more accurate.

6. Conclusions

This research aims to study the estimation of shear wave based on mineral compositions from petrophysical analysis of well logs in gas-bearing shale. An integrated approach of rock physical simulation for shear wave in gas-bearing shale is investigated in detail, and the workflow is summarized. Some cases and corresponding tests indicate that the proposed method is correct and suitable for gas-bearing shale.

(1) According to volumetric composition of gas-bearing shale, a suitable petrophysical model is proposed. Gas-bearing shale is different from tight sandstone and conventional reservoirs.

(2) The whole approach of rock physical simulation for shear wave is probed in detail, which is characterized with the kerogen and low porosity. The kerogen is regarded as a specific “mineral”, a part of rock matrix. About elastic moduli of saturated rock, rock matrix, and dry rock, some models are improved and optimized according to the properties of gas-bearing shale. Especially, in estimation of elastic moduli of dry rock, the critical porosity in Nur model and consolidation coefficient in Pride model are optimized for gas-bearing shale. Pride model is finally verified the suitable and useful from the analysis of error three models, and the consolidation coefficient of rock is consequently determined through error analysis. Therefore, the proposed whole method is applicable and suitable for gas-bearing shale.

(3) The comparison of predicted and laboratory measured volumetric concentrations of minerals and porosity proves that the proposed petrophysical interpretation method is correct. Moreover, two estimation tests of shear wave using laboratory measurements and log interpretation results are both in good agreement with DSI log, which indicates the proposed approach is also reliable and applicable for estimation of continuous shear wave slowness from well logs.

(4) In case study, the comparison of estimated shear wave slowness and DSI log indicates the approach estimating shear wave slowness from well logs is accurate. For some wells where shear wave log is not available, the quality of estimation of shear wave is guaranteed through controlling the error between the calculated and measured compressional wave slowness and bulk density. These cases indicate the error controlling method is reliable, and the estimated shear wave slowness could meet the requirements of seismic analysis.

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