Introduction

When building the rock physics model for clayey sandstones, it is important to know the contact type and the content of cement clay in clayey sandstone for correctly understanding the influence of the cementation on acoustic velocity. The cement effects of the contact cement clay could be described by contact cement theory (CCT model; Dvorkin et al., 1994, 1996; Guo et al., 2016) and little amount of cement could have significant effect on velocities. When using the clay content as input parameters to predict the velocities via CCT model, there will always be large errors and the CCT model over-estimated the velocities (figure 1). The CCT model assumes all the clay behave as cement clay and thus the cementation effect is over-estimated to cause the large errors of predicted velocities. Hence, it’s essential to distinguish the cement clay (contact cement clay) and pore-filling clay (non-cemented clay) to build accurate rock physics model.

![Figure 1](image1.png)

*Figure 1 Model effects of CCT on artificial clayey sands. (a) cross plot of the model velocities and experiment velocities. (b) cross plot of relative errors and porosity.*

The cement clay in this paper has the same meaning of contact cement which is rock physics definition rather than the cement in geology definition because we are more interested in its elastic effects on sandstones. To overcome the over-estimated problems of the CCT model the constant cement model (Avesh, 2005) could be used. The Constant Cement Model assume there exist constant cement and others is pore-filling things and it’s a combination of the Hashin-Strikman lower bound (Hashin et al., 1963) and CCT. However, there is not a method to quantitatively determine the contact cement content, even in laboratory conditions. In this paper, a method for distinguishing cemented clay is proposed by observing the contact relationship and relative distribution between clay and particles in thin sections. The cement clay is used as the input parameter to optimize CCT model and the predicted results are significantly improved.

Experiments

The artificial clayey sandstone have been made for studying the cement effects on the elastic properties(Figure 2).The relevant rock physics experiment have been done in China University of Petroleum (East China) Applied Petrophysics Lab and the porosity have been measured by Boyle law, the velocities have been measured by pulse transmission method and the frequency for P- & S-wave is 1MHz and 0.5MHz, respectively.

Content estimation of cemented clay

The method for distinguishing cemented clay is proposed by observing the contact relationship and relative distribution between clay and particles in thin sections: the clay which distributes at the grain contact area and connects two or more grains is seen as the cement clay, while the clay only distributes around only one grain or distributes in the pore space is seen as dispersed clay(non-contact clay).
The specific recognition method is dye mark and pixel pickup method. We take these artificial samples as an example to show how to identify cement shale. The advantage of using artificial sandstones is that the mineral composition is simple (artificial sandstone is composed of quartz, clays and pore), and it’s easy to identify under the microscope. The workflow is shown as follows:

1. Open the thin section figure with image processing software and mark the cement clay in strong contrast colour (black in Fig3(a));
2. Use image processing software to count the content of the cement clay $V_{cement\ clay}$ by pixel pickup method (Fig3(c));
3. Use software to identify the content of grains $V_g$ and pore space $V_{pore}$ (Fig3(d), Fig3(e)), respectively, and thus the clay content could be calculated by: $V_{clay}=1-V_g-V_{pore}$.
4. The dispersed clay could be calculated via: $V_{dispersed\ clay}=V_{clay}-V_{cement\ clay}$.

The example is shown as follows:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example.png}
\caption{The example to estimate the cement clay. (a) is the concept of the contact cement\cite{Mavoko.et.al.,2009}. (b) is the thin section of artificial samples while the black line represent the cement clay given with user intervention. (c) identify the content of cement clay $V_{cement\ clay}$. (d) identify the content fo grain frame $V_g$. (e)using software to identify the content of pore space $V_{pore}$.}
\end{figure}

The method proposed in this paper could quantitatively estimate the content of cemented mud, which can be directly used as a input parameter in constant cementation model. However, there will be some errors when using this method to determine the cemented shale. It is only a quantitative "estimation" of cemented clay. The error principle of this method is similar to that of the thin section identification for mineral composition, to a certain extent, it depends on the subjective judgment. Especially for artificial sandstone, if the cementation thickness is too large, it should not be identified as cemented clay\cite{Han.et.al.,2014}. In addition, there is no strict boundary between cemented clay and dispersed clay. Due to various factors, it is difficult to give the estimation error quantitatively, so this paper does not give the error analysis of the estimation.

The content of cement clay as well as p- & s-wave velocities are shown in table 1.
Table 1 The content of cement and contact cement of artificial sandstones and its p- and s-wave velocities (dry condition).

<table>
<thead>
<tr>
<th>No.</th>
<th>Porosity, v/v</th>
<th>$V_p$, m/s</th>
<th>$V_s$, m/s</th>
<th>Clay content, v/v</th>
<th>Cement clay content, v/v</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.31</td>
<td>1897</td>
<td>1219</td>
<td>0.086</td>
<td>0.0057</td>
</tr>
<tr>
<td>2</td>
<td>0.29</td>
<td>1856</td>
<td>1374</td>
<td>0.112</td>
<td>0.0081</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>2521</td>
<td>1384</td>
<td>0.246</td>
<td>0.0039</td>
</tr>
<tr>
<td>4</td>
<td>0.16</td>
<td>2505</td>
<td>1449</td>
<td>0.245</td>
<td>0.0031</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>2320</td>
<td>1525</td>
<td>0.253</td>
<td>0.0012</td>
</tr>
<tr>
<td>6</td>
<td>0.22</td>
<td>2190</td>
<td>1385</td>
<td>0.182</td>
<td>0.0053</td>
</tr>
<tr>
<td>7</td>
<td>0.18</td>
<td>2392</td>
<td>1519</td>
<td>0.224</td>
<td>0.0043</td>
</tr>
<tr>
<td>8</td>
<td>0.17</td>
<td>2436</td>
<td>1425</td>
<td>0.229</td>
<td>0.0060</td>
</tr>
<tr>
<td>9</td>
<td>0.15</td>
<td>2442</td>
<td>1491</td>
<td>0.250</td>
<td>0.0031</td>
</tr>
<tr>
<td>10</td>
<td>0.25</td>
<td>2130</td>
<td>1482</td>
<td>0.147</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

The optimized cemented sand model constrained by cement clay

The figure 1 shows the CCT model effects on these artificial samples and the CCT model fail to describe the elastic properties due to the over-estimation of the cementation. Hence, it’s necessary to know the content of the cement clay which is sensitive to velocities and content of the dispersed clay which is not sensitive to velocities. Then, the constant cement model could be used to describe the effects of the cement clay and dispersed clay, respectively. Due to the limited space of the paper, we only give the final form of the model as follows:

\[
K_{\text{eff}} = \left[ \frac{\phi_0}{K_{\text{CCT}}} + \frac{1 - \phi_0}{V_{\text{cement clay}} \left( K_{\text{CCT}} + \frac{G_{\text{CCT}}}{3} \right)} \right]^{-1} \left[ \frac{4}{3} G_{\text{CCT}} \right] \\
G_{\text{eff}} = \left[ \frac{\phi_0}{G_{\text{CCT}}} + \frac{1 - \phi_0}{V_{\text{cement clay}} \left( G_{\text{CCT}} + \frac{K_{\text{CCT}}}{3} \right)} \right]^{-1} \left[ \frac{4}{3} K_{\text{CCT}} \right]
\]

Where the $K_{\text{eff}}$ and $G_{\text{eff}}$ represents the effective bulk and shear modulus, GPa, respectively. The $\phi$ is the present porosity; $\phi_0$ is the critical porosity and usually range from 0.36 to 0.4. The $V_{\text{cement clay}}$ is the cement clay estimated via our method. $K_{\text{CCT}}$ and $G_{\text{CCT}}$ is the CCT (Dvorkin et al., 1994,1996) model results, GPa, respectively. $K_{\text{VRH}}$ and $G_{\text{VRH}}$ is the matrix modulus calculated by Voigt-Reuss-Hill average (Hill et al.,1962), GPa.

The prediction results of the optimized model are as follows:

Figure 4 The crossplot of the model velocities and experiment velocities while (a) shows the original CCT model effects, (b) shows the model effects in our method.
Figures 4 and 5 show the predictions of velocities by our model and the prediction errors, respectively. According to the prediction error results, the prediction error of P-wave velocity in this paper is 20% lower than that of the original CCT model, and the overall error is within 10%. The prediction results are reliable, and the prediction accuracy is significantly improved compared with the original method. However, for S-wave velocity, there is still a high prediction error. On the one hand, the CCT model itself has the problems of high prediction of shear wave velocity (Avesh et al., 2014), because the CCT model ignores the possible breaking, sliding and recombination of particles during its establishment; on the other hand, for the artificial sandstone, the cementation layer with non-zero thickness will greatly weak the sandstone (Guo et al., 2016). In summary, compared with the original CCT model, the prediction error of our method is reduced by 20%, which shows that the method proposed in this paper is more accurate than the original model.

Conclusion

To overcome the over-estimated of elastic properties for CCT model caused by the over-estimation of the cementation, we proposed a method for distinguishing cement clay and dispersed clay by observing the contact relationship and relative distribution between clay and particles under thin sections. This is an estimation method for the cement clay and it could be used directly in Constant Cement model as input parameters to predict velocities. To assess this method, we made a batch of artificial sandstone and measured its velocities to do the cross-plot. The result show that, compared with the original CCT model, the prediction error of velocity by our method is 20% lower, and the prediction error of P-wave velocity is less than 10%. The prediction result of velocity is reliable, and the prediction accuracy by this method is significantly improved. The method provided in this paper provides an effective and reliable method for the estimation of elastic properties of clayey sandstone formation, which can predict the velocity to identify reservoirs with seismic and logging data and quantitatively evaluate reservoir parameters.

Reference

Avseth P., T. Munkerji, and G. Mavko, [2005], Quantitative seismic interpretation; Applying rock physics tools to reduce interpretation risk. Cambridge University Press.


Figure 5 The relevant errors of P-wave velocities and S-wave velocities and porosity.