Introduction

As sand and shale are composed of different mineral components with different petrophysical properties, they always present as different reflection characteristics (such as seismic amplitude or frequency) on seismic profile. These differences are the basis for geophysical methods to conduct reservoir prediction, and the key is finding the elastic parameters that can distinguish sand from shale, which is usually realized through rock physics analysis. In the early days, P-wave impedance was the most frequently used lithological identification parameter, amplitude attribute and post-stack inversion were therefore widely used by geophysicists for reservoir characterization. With the introduction of Vs, more elastic parameters are available for reservoir identification, such as Vp/Vs, Poisson’ ratio and λρ/μρ, which are more sensitive to lithological variations than P-wave impedance in most cases and are generally calculated by pre-stack inversion. In some cases, a single parameter alone may be ineffective in reservoir identification, then two or more parameters are usually combined in crossplot analysis.

For more complicated areas with large buried depth and complex geological conditions, however, we may find it hard to identify reservoirs effectively neither by a single parameter nor the combination of several parameters. Jinzhou Block of Bohai Oilfield is exactly this situation, reservoirs with different amplitudes are drilled (Figure 1) and all the conventional elastic parameters can hardly distinguish sand from shale. In this paper, detailed crossplot analysis of drilled wells is conducted to reveal the petrophysics characteristics of each elastic parameter firstly. It’s found that Vp is insensitive to lithological variations, density is relatively better but unfortunately affected by compaction effect and still can’t differentiate sand from shale effectively. Therefore, the Vp in “Vp/Vs” is replaced by density and a new parameter is therefore established: ρ/Vs, which is proved to be much more sensitive to lithological variations than other conventional elastic parameters. The lithology factor F is subsequently obtained through crossplot analysis and coordinate rotation, which can differentiate sand from shale effectively. Pre-stack inversion is finally performed and reservoirs with different seismic amplitudes are clearly characterized.

Figure 1 Post-stack section crossing Well J1. Reservoirs associated with different amplitudes are revealed at the same time.

Rock physics and crossplot analysis of well logs

The distinguishing ability of well curves to sand and shale is the precondition of pre-stack reservoir inversion. In order to find the lithological sensitive parameter, rock physics analysis is therefore performed on the drilled wells within Jinzhou Block firstly. Figure 2 demonstrates the crossplot analysis of several conventional elastic parameters, as shown in the figure, gas sands denoted in red color can be easily identified by Vp/Vs and Poisson’ Ratio, or the crossplot of Ip versus Is and λρ versus μρ. However, almost all parameters of oil sand (green), brine sand (blue) and shale (white) overlap with each other, making it hard to differentiate between sand and shale effectively.

In order to find out the reason for poor lithological identification ability of conventional parameters, we compare the original log curves of Well J1 (Figure 3). It’ shown that Vp is not sensitive to lithological variations, just manifesting as slight fluctuations at sand-shale interfaces, significant
changes only appear at two sets of glutenite (in the dashed boxes), which are not treated as effective reservoirs in this block. Fortunately, Vs and density are relatively more sensitive to lithological variations, especially the latter. Sand presents as low density and obvious jump of the curve (denoted with black arrows) can be seen at sand-shale interfaces. However, as the influence of compaction effect, density alone still can’t differentiate between sand and shale effectively, as shown in Figure 2b.

![Figure 2](image)

**Figure 2** Crossplot analysis of conventional elastic parameters. (a)Vp versus Poisson’s Ratio; (b)Density versus Vp/Vs; (c) Zp versus Zs; (d) λρ versus μρ.

**Establishment of the new parameter ρ/Vs and its effectiveness analysis**

In order to improve the reservoir identification ability, density is used to replace the Vp in ‘Vp/Vs’ and a new parameter is therefore proposed in this paper: ρ/Vs. This parameter takes advantage of the favorable reservoir sensitivity of density and adopts the division operation to weaken the compaction effect at the same time. The new parameter is then computed and used in crossplot analysis versus density (Figure 4). It’s demonstrated that sand and shale are distributed at obviously separated areas and can be more easily to be differentiated than using Vp/Vs (Figure 2b). Coordinate rotation is then followed up and a new lithological identification factor F is subsequently obtained, which can distinguish sand from shale clearly (glutenite is not considered). The expression of F is as follows:

\[
F = -0.96 - \frac{282.22}{Vs} + 2.65 \rho
\]  

(1)

Then the correlation coefficients between GR and different parameters are calculated respectively (Table 1), so as to further evaluate the lithological sensitivity of each parameter. It’s shown that ρ/Vs has a much higher correlation coefficient with GR than conventional parameters, and that of the new lithological identification factor F is even higher, reaching 0.65, which indicates the effectiveness of this parameter.

Comparison of the original curves of different parameters also comes into the same conclusion (Figure 5). The new lithological identification factor F is proved to be more superior to other parameters in the following three aspects:

- Better reservoir identification ability. Obvious jump of the curve (denoted with black arrows) can be seen at sand-shale interfaces.
- Weakened compaction effect. The shale baseline of the curve is nearly a vertical line from shallow to deep.
- Better stability. No outliers are detected on the curve (such as the purple arrows on other curves).
Table 1 Correlation coefficients between GR and different parameters

<table>
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<tr>
<th>Parameters</th>
<th>Ip</th>
<th>$\rho$</th>
<th>$Vp/Vs$</th>
<th>$\sigma$</th>
<th>$\lambda/\mu$</th>
<th>$\rho/Vs$</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficients</td>
<td>0.25</td>
<td>0.28</td>
<td>0.30</td>
<td>0.27</td>
<td>0.26</td>
<td>0.49</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Pre-stack inversion and reservoir characterization

Pre-stack inversion is subsequently performed based on the above analysis and Figure 6 demonstrates the comparison of inverted curves (red) with original curves (blue). It’s seen that the inverted curves fit the original curves very well, which indicates the reliability of the inversion process. Then the computation is applied to the whole 3D block. Figure 7 shows the inverted volumes of conventional parameters, it’s shown that all of the conventional parameters are unable to characterize the reservoirs effectively, especially the weak-amplitude gas layer at the bottom of Dongying Formation.

Then the volume of new lithological identification factor $F$ is computed based on the inversion result. As shown in Figure 8, each set of reservoir is clearly characterized on the profile, including the weak-amplitude reservoir at the bottom. What’s more, the drilling result matches the research very well, which is successfully applied in the subsequent exploratory well deployment within this block.
Conclusions
A new elastic parameter ρ/Vs is proposed in this paper based on detailed rock physics analysis and the lithological identification factor is then obtained through crossplot analysis, which is more sensitive to lithological variations than conventional parameters and is proved to be effective in reservoir identification within Jinzhou Block. Reservoirs with different amplitudes are all clearly characterized by the final pre-stack inversion result of F, which provides favorable support for the subsequent exploratory well deployment within this block.

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References


Figure 7 Pre-stack inversion results of conventional parameters. (a) Ip; (b) Is; (c) density; (d) Vp/Vs.

Figure 8 Pre-stack inversion result of the new lithological identification factor F crossing Well J1.