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Research and application of gas detection techniques using full-wave attributes in southwest China

Cai Xiyuan,[1] Xu Tian-ji,[2] Tang Jian-ming,[2] Li Xian-gui,[2] John Tinnin[3] and James Hallin[3] chronicle an application of full-wave interpretation utilizing attributes of full azimuth multi-component seismic which resulted in a significant increase in drilling success at the deep tight sandstone gas reservoirs in the Western Sichuan Depression of southwest China.

The goal of full-wave interpretation is to use the complete seismic wavefield to reduce uncertainty in complex reservoirs. Full-wave interpretation takes advantage of multi-component seismic that captures P-wave and PS-wave data simultaneously. P-wave data provides many PP attributes including waveform, amplitude, frequency, phase, attenuation, frequency dispersion, coherence, curvature, and energy ratio. The PS-wave seismic provides separate measurements of each of these attributes and is more sensitive to rock matrix information. Full-wave attributes are combinations of measured PP- and PS-wave attributes, both pre-stack and post-stack, that provide additional rock properties.

Having been utilized for years, PP-wave attributes are considered mature. By contrast, the slow development of 3D3C seismic acquisition and processing techniques hindered the development and use of full-wave attributes. However, because of the rapid development of 3D3C seismic technology in recent years, it is now possible to calculate, analyze, and combine full-wave attributes. Using the 3D3C seismic data acquired over the Xinchang field in Western Sichuan Depression, the following was possible:

- Identifying gas with P-wave attribute analysis
- Identifying faults and fractures with shear wave splitting
- Determining lithology by joint inversions
- Identifying areas of high quality reservoirs through rock property analysis

Background

Xinchang gas field is located in the Western Sichuan Depression in China. The Triassic gas reservoirs in the 2nd member of the Xujiahe Formation (Xu2) consist of super tight sandstones with porosities less than 4% and rock matrix permeabilities less than 0.06 millidarcies (Guo Zhengwu, 2004). The Xinchang structure, initiated in Indosinian and developed during Yanshan and Xishan periods, is more than 4500 m deep. The high pressure reservoir has original formation pressures of 76.48-80.46 MPa and overburden pressure gradients between 1.57 and 1.70. Complex gas-water interfaces suggest that there is not a single gas-water contact across the structure. Reservoir lithofacies and rock properties also have complex spatial distributions. All of these characteristics make the exploration of Xu2 in the Xinchang gas field difficult.

These tough geologic conditions make it challenging to apply successfully conventional seismic technologies for reservoir identification. Full-wave interpretation techniques applied to 3D3C seismic show great potential to solve these challenges because of the rock property and anisotropy information that they capture along with rock matrix and fluid information.

In 2005, 3D3C seismic data were acquired over the Xinchang field. The 66-fold data had good azimuthal coverage for all offsets to a maximum of 6000 m. Problems that included gas-bearing bed recognition and fracture detection were solved effectively by using the abundant information from multi-component data processing to do joint inversions, multi-component attribute analysis, and integrated interpretation of the target zone in Xinchang gas field.

Seismic response characteristics

Exploring the Xinchang gas field is challenging because of its depth, complex structure, strong anisotropy, limited resolution, and unstable reflections. The first and easiest attribute to analyze is the character of the seismic reflectors in the reservoir units. As per empirical observations, there are three main seismic wave responses to the reservoir:

(1) A PP event that is disordered and weak and a PS event that is continuous and strong (Figure 1, Wells X856 and X851).

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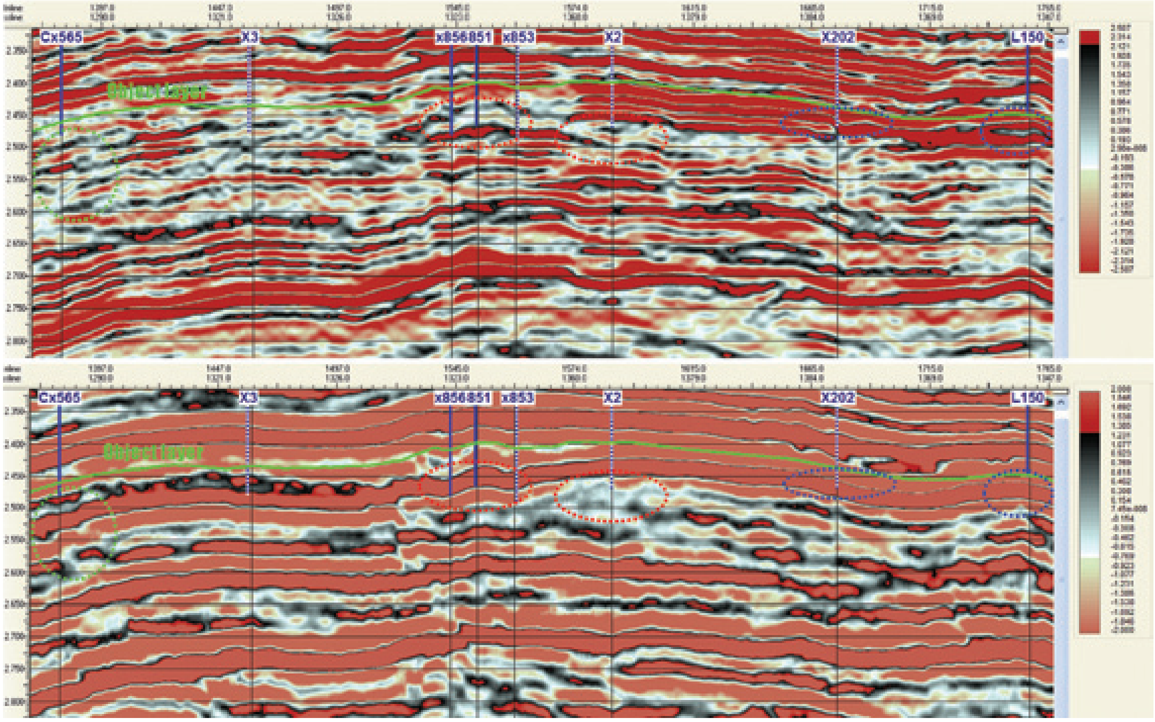

***Figure 1** PP and PS arbitrary seismic sections across known wells displaying three types of seismic responses.*

(2) Both PP and PS events that are disordered and weak (Figure 1, Wells X2 and CX565) .
(3) PP and PS events that are continuous (Figure 1, Wells X202 and L150).

The first two responses indicate the presence of fractures and the third indicates non-fractured reservoir.

P-wave attributes for fluid detection

Absorption and velocity dispersion attributes
Absorption and velocity dispersion (AVD) attributes of P-wave data can be used to indicate gas. AVD is a function of absorption and velocity dispersion expressed as follows:

$$AVD = f(Abs, \Delta V)$$

Where Abs is the absorption calculated from the attenuation of the seismic waves propagating in the earth and ΔV is the velocity dispersion in the target layer.

AVD attributes can effectively identify porous and fractured reservoirs as well as gas layers. When gas is stored in the reservoir, the values of absorption and velocity dispersion are large. Therefore, the anomalously high AVD values indicate areas with gas in porous and/or fractured reservoirs. In Figure 2, wells X2, X856, X851, X853, and X202 are all gas producing wells associated with strong AVD anomalies; wells X11, CX560, and CX565 are dry holes with no AVD anomaly.

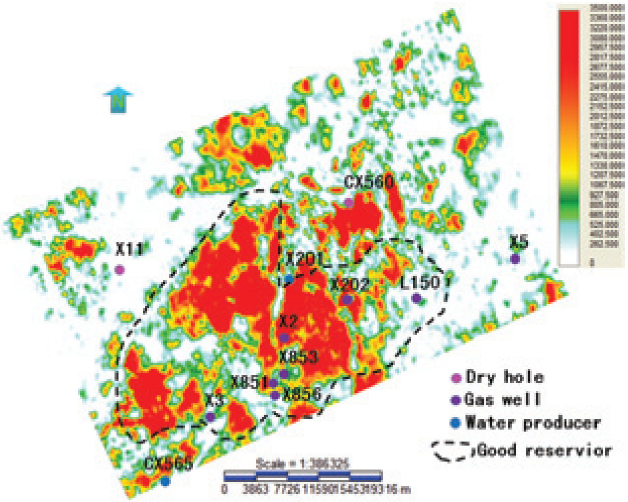

***Figure 2** Distribution of AVD anomalies in the Xu2 target layer.*

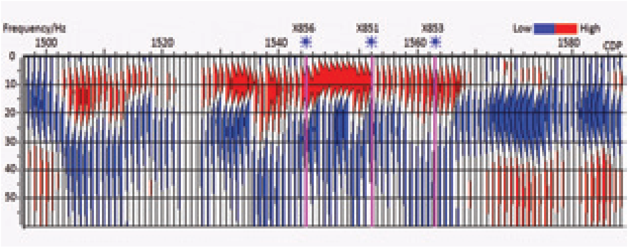

***Figure 3** Arbitrary line of P wave absorption attributes of two-phase media in target layer.*

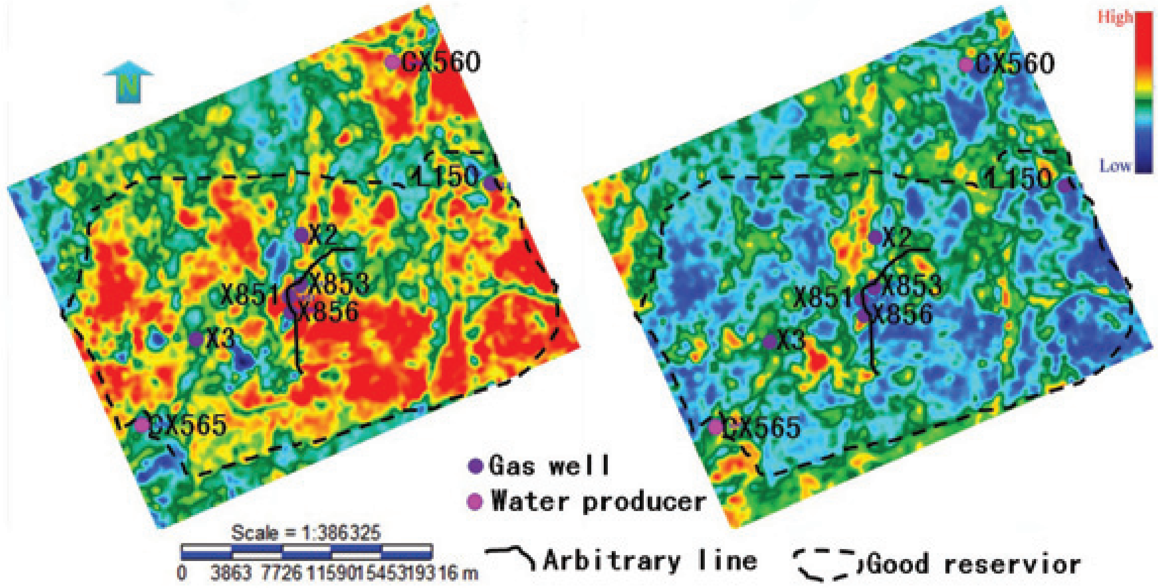

Figure 4 *Distribution of P wave two-phase media absorption attributes in the target layer (left: enlarged in low frequency, right: attenuated in high frequency).*

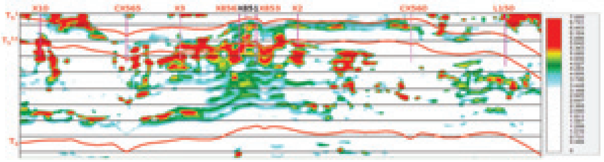

Figure 5 *Arbitrary line with P-wave multi-scale absorption attributes of Xu2.*

Absorption of seismic waves in two-phase media

Theory of two-phase media absorption states that the energy distribution in different frequency bands can change when the P-waves propagate in a low impedance gas layer. Seismic energy moves to the lower frequency, showing an increase of energy in lower frequencies and signal attenuation in higher frequencies. This attribute can be a possible predictor of gas in tight reservoirs. Figure 3 shows a seismic line through three producing wells and Figure 4 shows map views of P-wave absorption attributes of two-phase media for the target layer. In the area of producing wells X856, X851, and X853, the low frequency energy is enhanced and the high frequency attenuation is evident.

Multi-scale absorption attributes

When P-wave propagates in visco-elastic media, the amplitudes attenuate exponentially (Aki and Richards, 1980), typically known as the quality factor (Q). The P-wave multi-scale absorption attribute is the transform of amplitude to obtain the Q value with its variable scale. High P-wave absorption scalars can be used to predict the distribution of gas zones, as indicated in Figure 5. Wells X3, X856, X853, and X2 are good gas producing wells.

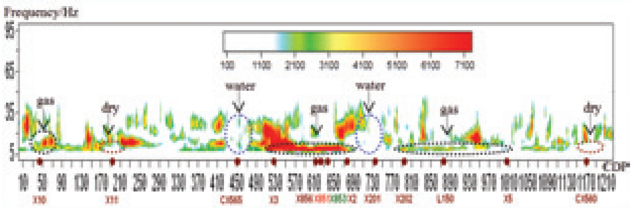

Figure 6 *Spectral decomposition profile along an arbitrary line near the Xu2 target layer.*

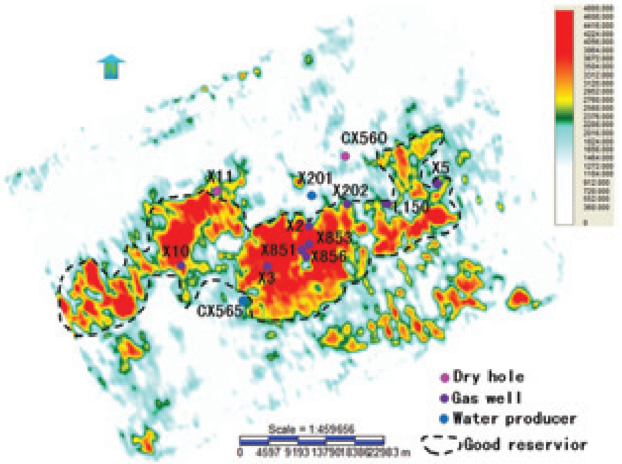

Figure 7 *Map view of the 10Hz spectral decomposition in the Xu2 layer.*

Spectral decomposition attributes

Time domain seismic data can be transformed into the frequency domain using spectral decomposition methods to analyze frequency characteristics of the P-wave at a fixed time. This technique has been used to delineate a wide variety of structure, stratigraphic, and reservoir parameters.

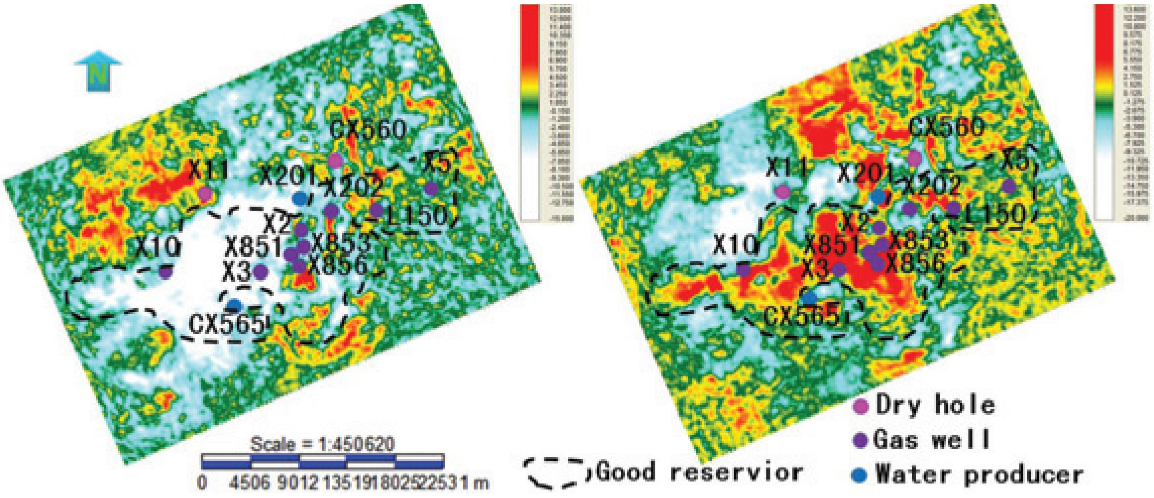

Figure 8 *Fast (left) and slow (right) amplitude distribution in fractured Xu2 target layer.*

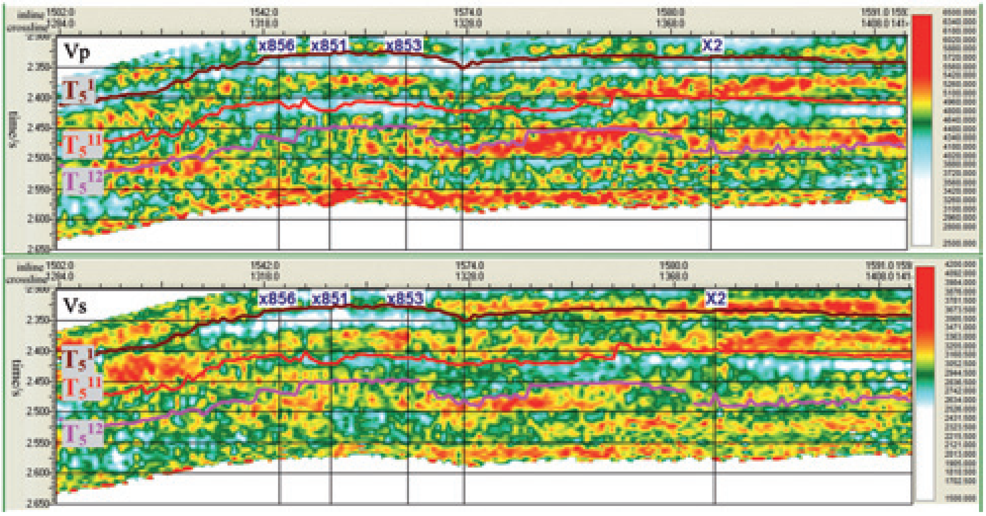

Figure 9 *P-wave (top) and C-wave (bottom) velocity section in Xu2.*

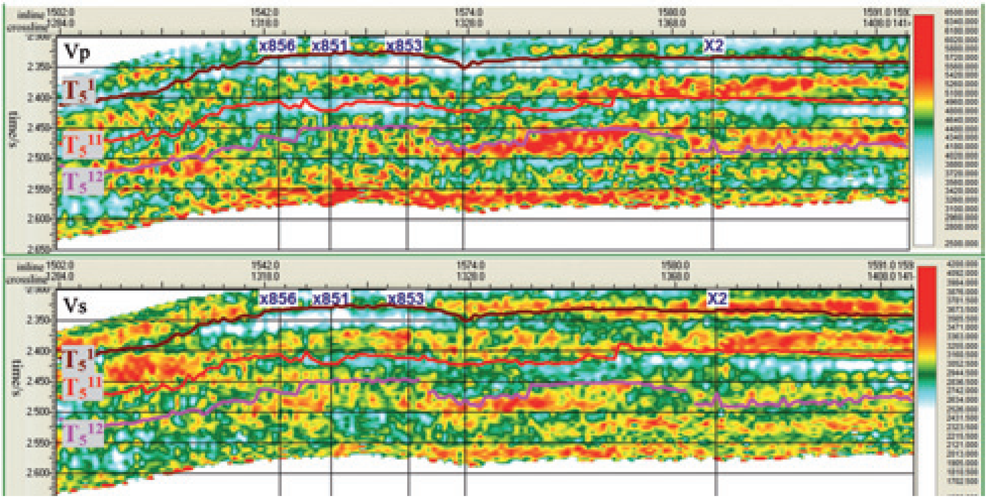

Figure 10 *P-wave (above) and C-wave (below) impedance section Xu2.*

In the XinChang area, this method was used to identify low frequency shadows associated with gas, as shown in Figures 6 and 7. Figure 6 is an arbitrary seismic line across several wells showing low frequency anomalies at the Xu2 target horizon. Figure 7 is a map view of the strong 10Hz anomaly in the target Xu2 horizon.

Shear wave splitting for fracture identification

Converted waves will split to fast and slow waves as they propagate through fractured anisotropic media. Fast waves propagate parallel to the orientation of the fractures and slow waves propagate perpendicular to this orientation. Identification of shear wave splitting in the target reservoir is a tool to locate fractures. For this, fast and slow volumes are created through proper processing (Tang et al., 2009). As a reconnaissance tool, a horizon is selected over the target zone of both volumes to accommodate the time difference between the two volumes. The amplitude envelope of the two volumes at the target horizon level can then be compared. Slow shear waves show different response characteristics when propagating in fractured rock.

Figure 8 shows the map view of fast and slow waves amplitude distribution in the fractured Xu2 target layer, which display marked amplitude differences and thus can be used to highlight possible fracture distribution. Comparing amplitudes of wells CX565 and X201 (filled with water) with wells X2, X3, X851, and X856 (producing gas wells), we observe similar fast wave amplitude energy, but noticeably different slow wave amplitude energy.

Full-wave attributes

PP/ PS pre-stack simultaneous inversion attributes

When elastic waves enter into an elastic interface, the Zoeppritz equation can depict the energy relation of PP and PS data, and the AVA curve reflects changes of lithology parameters and the anisotropic coefficient. Applying this relationship to pre-stack PP and PS data to establish the initial model and then applying generalized linear inversion to iterative fitting of AVA curve, we can obtain PP- and PS-waves velocities, densities, anisotropic coefficients, and elastic impedance used to distinguish lithology, detect gas, and predict reservoir quality. Figure 9 is the result of PP- and PS-wave velocity inversion from pre-stack data. In the Xu2 target layer, the PP-wave velocity of sandstone with gas slows down, but PS-wave velocity is unaffected.

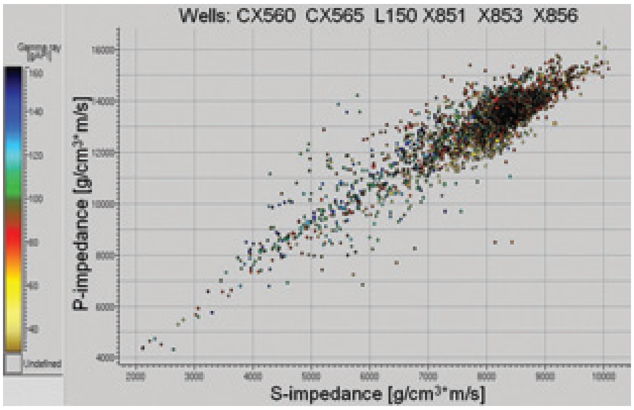

Figure 11 *Crossplot of PP and PS impedance in Xu2 (the orange is sandstone).*

Post-stack joint inversion attributes

We can obtain parameters of PP- and PS-wave impedance, velocity, shear modulus, and Lame constant by applying the AVA relationship of PP-wave and PS-wave, and combining integrated information including full-wave logs, geology, PP- and PS-wave post-stack data to carry out combined inversion. Before inversion, PP- and PS-waves should be registered to eliminate time, energy, and waveform differences. Only when the volumes match can this method be used to predict the presence of gas. Figure 10 shows the PP- and PS-wave impedance obtained by post-stack combined inversion.

Rock property analysis

Results from the joint inversions can be used to generate reservoir parameters such as PP and PS velocity, Vp/Vs ratio, Poisson's ratio, density, Lame constant, and shear modulus. Some of these parameters are related to rock matrix characteristics and others are related to the fluid in the reservoir. Well log analysis is key in identifying which of the available inversion attributes are most sensitive to differentiating reservoir rock from non-reservoir rock.

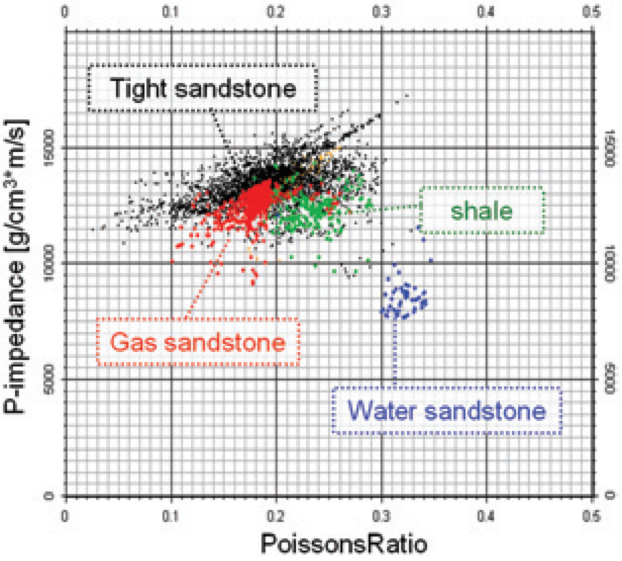

Figure 12 *Crossplot of PP impedance and Poisson's ratio in the Xu2 formation.*

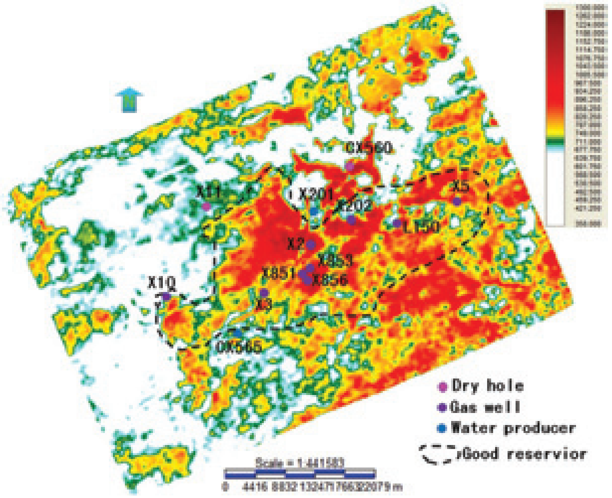

Figure 13 *Gas index parameter map in the Xu2 formation.*

Figure 11 shows a crossplot of PP and PS impedance that does not differentiate the reservoir rock from the surrounding mudstones. Since a single parameter cannot identify the available reservoir distribution, two or more parameters must be used to solve the problem of gas prediction in Xinchang. By analyzing the crossplot of the target layer's rock parameters, we find that PP impedance and Poisson's ratio are the most sensitive parameters for reservoir identification.

Figure 12 is a crossplot of Poisson's ratio and P-wave impedance in the Xu2 target layer showing that the impedance of tight sandstone is high (14000-15000 m/s*g/cm^3) and Poisson's ratio is lower than 0.3. Log parameters show that the gas reservoir has mid to low impedance, with P-wave impedance lower than 14000 m/s*g/cm^3 and Poisson's ratio between 0.1 and 0.2. The Poisson's ratio of mudstones is generally higher than 0.2 and P-wave impedance is lower than 13000 m/s*g/cm^3. The Poisson's ratio of fractured-porous sandstone filled with water is higher than 0.3 and P-wave impedance is lower than 10000 m/s*g/cm^3. By using the crossplot of Poisson's ratio and P-wave impedance, we can identify potential gas-filled reservoirs.

Combined full-wave gas detection

We can use multiple crossplots to identify reservoirs with satisfactory rock property characteristics, and then use full-wave seismic inversion to predict lateral boundaries. By analyzing multiple full-wave attribute crossplots, we can identify effective attribute groups. Using acoustic impedance (AI), shear impedance (SI), and elastic impedance (EI), we can establish the gas index parameters in the Xinchang field (i.e., gas index = AI × EI33/SI), which can reflect gas character of a reservoir. Figure 13 shows the gas index parameter map of Xu2. The commercial gas wells X851, X856, X2, X3, X202, and X5 are all in an area of higher gas index value. Whereas, the non-economic gas wells X11 and CX565 are all in an area of lower gas index value. This indicates that the gas index determined from full-wave attribute crossplots can identify areas with higher gas potential.

Conclusions

Full-wave interpretation techniques for gas detection combine PP-, PS- and full-wave attributes, which can be calculated directly or indirectly from PP- and PS-wave data. Based on sensitivity analysis, the additional information provided by 3D3C seismic allows us to reduce risk by improving reservoir understanding. With the development of full-wave data, we now have ample information and new ideas for addressing unconventional gas reservoir challenges. From this study, we can draw the following conclusions:

(1) P-wave attributes are important because they are clearly affected by gas. There are many established gas detection techniques but most of them cannot eliminate the effect of uncertainty in the prediction results. It is difficult to obtain a P-wave only application of gas detection for the deep tight clastic reservoirs of the Xinchang field, especially because of the subtle difference in the P-wave response between gas and water.

(2) Because PS-waves are sensitive to the rock matrix, PS attributes can be used to determine rock properties and shear wave splitting can effectively detect the fracture orientation and density. Furthermore, research indicates that slow shear waves show different response characters in fluid-filled fractured rocks.

(3) Full-wave attribute techniques for gas detection can provide abundant and sensitive lithology and gas index parameters, from which we can establish approaches to solve the challenges of unconventional tight gas reservoir prediction.

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