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Gas sand distribution prediction by prestack elastic inversion based on rock physics modeling and analysis

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Abstract: Seismic inversion is one of the most widely used technologies for reservoir prediction. Many good results have been obtained but sometimes it fails to differentiate the lithologies and identify the fluids. However, seismic prestack elastic inversion based on rock physics modeling and analysis introduced in this paper is a significant method that can help seismic inversion and interpretation reach a new quantitative (or semi-quantitative) level from traditional qualitative interpretation. By doing rock physics modeling and forward perturbation analysis, we can quantitatively analyze the essential relationships between rock properties and seismic responses and try to find the sensitive elastic properties to the lithology, porosity, fluid type, and reservoir saturation. Finally, standard rock physics templates (RPT) can be built for specific reservoirs to guide seismic inversion interpretation results for reservoir characterization and fluids identification purpose. The gas sand distribution results of the case study in this paper proves that this method has unparalleled advantages over traditional post-stack methods, by which we can perform reservoir characterization and seismic data interpretation more quantitatively and efficiently.
Keywords: Rock physics, seismic response, elastic parameters, elastic inversion, reservoir characterization, modeling

Introduction

The seismic inversion technique is widely used for oil and gas reservoir prediction. By using different algorithms and methods, it inverts P-waves or converted-wave seismic data and/or gathers into different elastic parameters (acoustic impedance, shear wave impedance, elastic impedance, density, velocity ratio, Poisson's ratio, and etc.) that can be linked to rock properties (lithology, porosity, pore fluids, and etc.), which can be further used for reservoir characterization and fluids identification (Fatti, et al., 1994; Gray, et al., 1999; Avseth, et al., 2005). However, different inversion methods have unique features and suitability and inversion results also have ambiguities. Especially when the impedance difference between the reservoir and adjacent formations is small, the regular post-stack inversion does not work or shows some limitation (Avseth, et al., 2005; Li, et al., 2005).

In the last several years prestack elastic parameter inversion based on rock physics modeling and analysis experienced a quick development (Xu, et al., 2009; Ye, et al., 2009). This technology has a clearer goal and can produce more accurate results efficiently, which can be helpful for realizing seismic data quantitative interpretation.

Seismic rock physics analysis is the critical step in the workflow. Seismic rock physics study is a discipline of analyzing the relationships between rock properties and seismic responses. By integrating core data, well logs,

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and seismic data, the rock physics analysis aims to study the effects of rock physical parameter changes such as lithologic character, porosity, pore texture, fluid type, and saturation on rock elastic properties, from which the theory and methodology of investigating rock physical properties using seismic responses (the related changes of seismic attributes) has been generated. Rock physics analysis can bridge the rock property parameters and seismic responses and is the foundation for seismic data quantitative interpretation. So far, seismic rock physics analysis is one of the most important study areas for reservoir geophysics and gets more recognition from oil companies and research institutes all over the world (Ødegaard and Avseth, 2004; Avseth, et al., 2005; King, 2005; Huang, et al., 2007; Xu, et al., 2009).

The logical and dialectical relationship between rock physics and geophysical responses is elaborated in depth in this paper. The non-replaceable importance and significant contributions of rock physics analysis to quantitative seismic interpretation are also emphasized. Meanwhile, this paper describes in detail the rock physics modeling workflow and analysis, as well as some key points, such as well log quality control and calibration, rock physics model diagnostics, S-wave velocity estimation methods and their suitability, and forward modeling and perturbation to do sensitivity analysis. Eventually the technologies of rock physics analysis and prestack elastic parameters inversion were perfectly combined in a case study using real data from one of northwest China's oil fields. The meaningful and impressive gas sand distribution prediction results proves that the new method introduced in this paper has unparalleled advantages over traditional post stack inversion and can be popularized and applied.

Seismic rock physics modeling and analysis

Generally, rock physics analysis workflows consist of four parts. They are well log analysis and calibration, rock physics modeling and diagnostics, perturbations and "what if" analysis, as well as seismic response (synthetics, AVO models, and attributes) and parameter sensitivity analysis.

Well log analysis and rock physics model diagnostics

The seismic rock physics analysis goal is to establish the deterministic relationship between rock physical properties and seismic attributes that can be used to guide more accurate quantitative interpretation of seismic datasets and reservoir prediction. However, high accuracy of seismic and log data are necessary to get correct rock physics analysis results. Many papers can be found to discuss seismic data accuracy but log data accuracy is usually ignored by geophysicists, which will severely affect the calibration and inversion results.

In fact, log data accuracy is usually a real problem and the logs do not reflect the actual subsurface geological features because of the effects and limits of log instruments, investigation radius, borehole conditions, mud invasion, and other environmental factors. The logs must be calibrated before use but this calibration can be a little different from the routine environmental correction in two aspects: (1) To pay more attention to acoustic, density, and shear wave velocity log accuracy caused by wellbore breakouts, invasion, cycle skipping, and other reasons from the geophysical point of view; and (2) It is a whole-well calibration rather than a routine interest zone correction and this calibration can give the optimum match between seismic and log data and furthermore is significant to the consequent calibration and inversion.

Two criteria used to examine calibrated log accuracy to judge if the logs imaged the actual subsurface geology features and met the rock physics analysis requirements and inversion: (1) the V_p, V_s, and density calibrated logs and their calculations such as P- and S-wave impedance (Z_p and Z_s), V_p/V_s velocity ratio, or Poisson's ratio must agree with the general rock physics laws and models (that is, model diagnostics). For example, on the interest zone density versus P-wave velocity crossplot of one well (see Figure 1), the blue and red line are the Raymer theoretical model lines for clean sand and pure shale and the color bar shows shale volume. Some data points are off the theoretical model range but after correction the abnormal data points were migrated to their corrrect positions inside the model lines. (2) The synthetic generated by the calibrated logs should have an optimum match with seismic traces near the borehole in both kinematics (travel time) and kinetics (amplitude) features. For example, the calibrations between the synthetic seismogram created by corrected logs and the seismic traces near the borehole in the reflections at 0.70, 0.95, and 1.05 seconds in Figure 2 have a significant improvement compared with the match before correction, especially in kinetics features. This significant matching improvement results from the corrections and migrations of the abnormal data points.

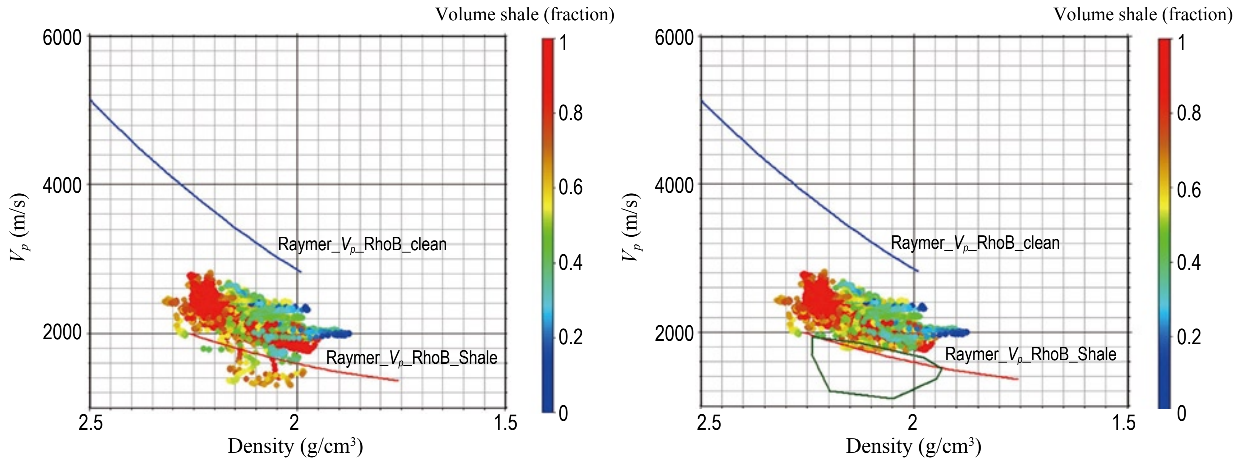

Fig. 1 Comparison of before-calibrated (left) and after-calibrated (right) logs of one well.

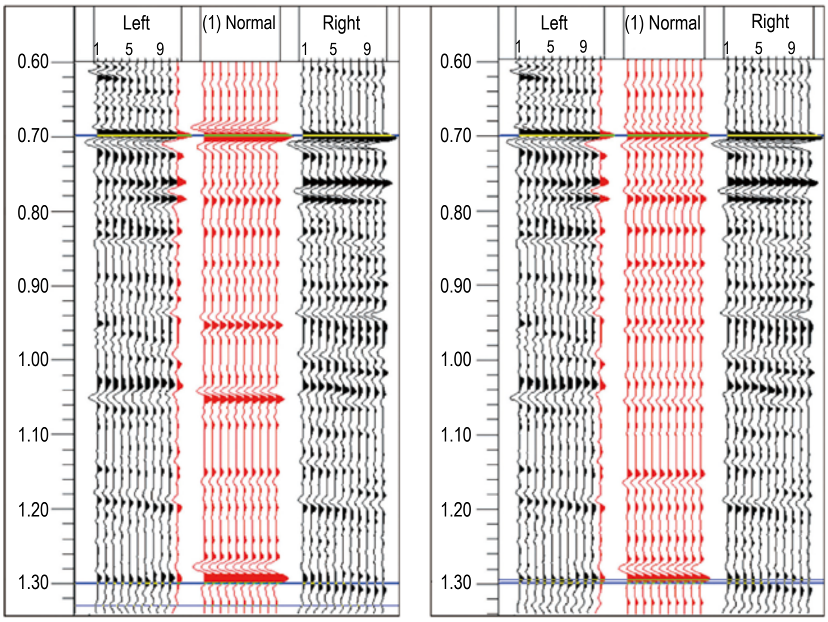

Fig. 2 Comparison of synthetic seismograms generated by before-calibrated (left) and after-calibrated (right) logs with seismic traces near the borehole.

Well log calibration from a geophysical point of view is the critical step for rock physics analysis and seismic inversion and the quality of its results determines whether the seismic quantitative interpretation goal can be achieved. Good calibration results have three important contributions to the whole workflow: (1) If after rigorous corrections, the calibrated logs reflect the actual subsurface geological features, then rock physics analysis and what-if perturbations (forward modeling) can be conducted on the logs to find the sensitive parameters to specific reservoir and fluid types. (2) An optimum match between well logs and seismic, both in kinematics and kinetics behaviors, can be achieved after rigorous calibration. (3) Provide high quality acoustic, density, and shear wave velocity logs to the following seismic inversion.

V_s estimation

V_s data will be used and involved in the rock physics modeling and elastic inversion. However, usually few shear acoustic logs are available. Even when there are shear acoustic logs, the quality and accuracy are poor because the shear wave is the subsequent event in shear acoustic log records and is hard to pick accurately. So V_s estimation is essential in most cases.

Normally there are two ways to estimate V_s, they are: (1) correlating the measured V_p and V_s from well logs and performing statistical regression to get an empirical function to use. This method is valid when there are good quality measured full wave train acoustic logs available in the study area; and (2) using rock physics models for V_s estimation.

Seven rock physics models for V_s estimation are available, such as the Greenberg-Castagna, Cemented, Mud Rock, Unconsolidated, Critical Phi, Krief, and Xu-White models. Usually the first four models are used for Vs estimation for high porosity formations and the other three models are normally valid for formations with medium to low porosity (Castagna, et al., 1985; Greenberg and Castagna, 1992; Xu and White, 1995, 1996; Mavko, et al., 2003). Each model has its suitable conditions and limits and three widely used models are briefly described:

1. Greenberg-Castagna Model

Greenberg and Castagna (1992) have given empirical relations for estimating V_s from V_p in multimineralic brine-saturated rocks based on empirical polynomial V_p-V_s relations in pure monomineralic lithologies (Castagna et al., 1993). The V_s in brine-saturated composite lithologies is approximated as:

$$Vs = \frac{1}{2}\left\{\left[\sum_{i=1}^{L} X_i \sum_{j=0}^{N_i} a_{ij} V_p{}^j\right] + \left[\sum_{i=1}^{L} X_i \left(\sum_{j=0}^{N_i} a_{ij} V_p{}^j\right)^{-1}\right]^{-1}\right\},$$

$$\sum_{i=1}^{L} X_i = 1,$$

where L is the number of pure monomineralic lithologic constituents, X_i is the volume fractions of the lithological constituents, a_{ij} are the empirical regression coefficients, N_i is the polynomial order for constituent i, and V_p and V_s are P- and S-wave velocity (km/s) in composite brine-saturated multimineralic rocks.

To estimate V_s from V_p for other fluid saturations, Gassmann's equation needs to be used in an iterative manner. It includes four steps:

1) Start with an initial guess for V_p-brine (that is, V_p at 100% brine saturation).

2) Calculate V_s-brine corresponding to V_p-brine from the empirical regression.

3) Perform fluid substitution using V_p-brine and V_s-brine in the Gassmann equation to get V_s-fluid (that is, V_s of any other fluid saturation, e.g., oil or a mixture of oil, brine, and gas).

4) With the calculated V_s-fluid and the measured V_p-fluid, use the Gassmann relation to get a new estimate of V_p-brine. Check the result against the previous value of V_p-brine for convergence. If convergence criterion is met, stop; if not, go back to step 2 and continue.

This method requires prior knowledge of the lithology, porosity, saturation, and elastic moduli and densities of the constituent minerals and pore fluids.

2. Krief Model

The empirical formula of V_p-V_s-ϕ (ϕ is porosity) for water saturated rock from the Krief model is similar to the Critical Phi model.

For dry rock, the V_p-V_s-ϕ empirical formula is:

$$K_{dry} = K_{mineral}(1 - \beta),$$

where K_{dry} and $K_{mineral}$ are the bulk moduli of the dry rock and mineral and β is the Biot coefficient.

Krief et al. (1990) obtained a relation between β and ϕ (porosity) using the data of Raymer et al. (1980):

$$(1-\beta) = (1-\phi)^{m(\phi)},$$

where

$$m(\phi) = 3/(1-\phi).$$

The equation can be rewritten as

$$K_{dry} = K_{mineral}(1 - \phi)^{m(\phi)}, \text{ and } \mu_{dry} = \mu_{mineral}(1 - \phi)^{m(\phi)}.$$

For rocks with any other pore fluid, the equation can be determined by combining the Krief et al. expression $K_{dry}=K_{mineral}$ $(1 - \beta)$ with Gassmann's equations or the following simple approximation:

$$\frac{V_{p-sat}{}^2 - V_{fl}{}^2}{V_{s-sat}{}^2} = \frac{V_{p\text{-}mineral}{}^2 - V_{fl}{}^2}{V_{s\text{-}mineral}{}^2},$$

where $V_{p\text{-}sat}$, $V_{p\text{-}mineral}$, and V_{fl} are the P-wave velocity of the saturated rock, the mineral, and the pore fluid and $V_{s\text{-}sat}$, $V_{s\text{-}mineral}$ are the shear wave velocity of the saturated rock and mineral. This approximate expression can be represented as

$$V_{s-sat}{}^2 = V_{s\text{-}mineral}{}^2\left(\frac{V_{p-sat}{}^2 - V_{fl}{}^2}{V_{p\text{-}mineral}{}^2 - V_{fl}{}^2}\right).$$

3. Xu-White Model

Xu and White (1995) developed a theoretical model for velocity estimation in shaley sandstone. The formulation uses the Kuster-Toksöz differential effective medium (DEM) theories to estimate the dry rock P- and S-wave velocities and the low-frequency saturated velocities are obtained from Gassmann's equation and the high-frequency saturated velocities are calculated using fluid-filled ellipsoidal inclusions in the Kuster-Toksöz model.

The total porosity $\phi=\phi_{sand}+\phi_{clay}$, where ϕ_{sand} and ϕ_{clay} are the porosities associated with the sand and clay fractions and they are related to the volumetric sand and clay content. The properties of the solid mineral mixture are estimated by a Wyllie time average of the quartz and clay mineral velocities and arithmetic average of their densities. Then these mineral properties are used in the Kuster-Toksöz equation along with the porosity and clay content to calculate dry rock moduli and velocities.

The Xu-White model is valid for estimating the elastic properties of medium-to-low porosity, well-cemented, shaley sandstone media. The estimation error will be bigger when used in shallow strata or layers with a high clay content.

Perturbations and sensitivity analysis

After the calibration and rock physics model diagnostics, the well logs reflect the real formation geologic features such as thickness, lithology, porosity, permeability, fluid types, and saturation and also have a good match with the seismic traces near the borehole. We can then use these calibrated logs and the other calculated elastics parameters to do what-if perturbations analysis for analyzing the seismic response changes with vertical and lateral lithofacies variations, porosity, fluid type, and saturation changes, through which the possible reservoir changes away from the borehole and its seismic responses can be studied and evaluated (Avseth, et al., 2005). Sensitive parameters for the lithologies and fluid types for a specific reservoir might be found through this forward modeling process which could provide theoretical foundation and guidance for predicting oil and gas-bearing reservoirs using rock elastic parameters.

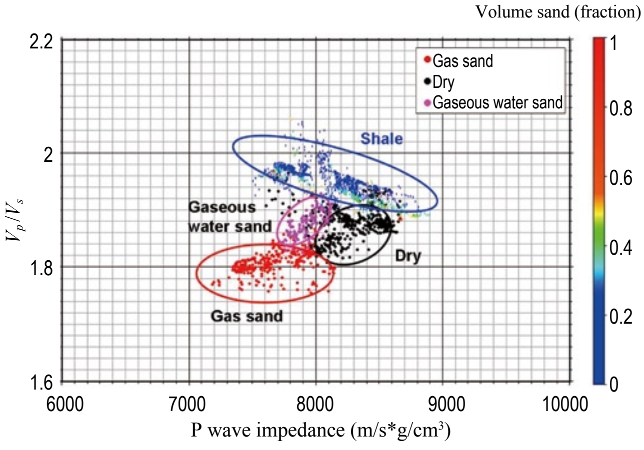

Fig. 3 Lithology differentiation by V_p/V_s - Z_p crossplot.

Generally, it is difficult to differentiate lithology or fluid types by only one elastic parameter. For example, in Figure 3, the impedance range of shale, water sand, dry, and gas sand overlapped each other (7500 to 8500 m/s*g/cm^3), so those lithologies cannot be separated by impedance alone. However, a crossplot of multiple elastic parameters, for example, P-wave impedance (Z_p) and V_p/V_s velocity ratio with a color bar showing volume of sand, shows better separation among those lithologies. We can use multiple elastic parameters with cross-plotting techniques to build the theoretic rock physics templates for differentiating lithologies and fluid types of the specific reservoirs (Figure 3).

Prestack elastic parameters inversion

In contrast to post-stack seismic impedance inversion, which is applied to a zero-offset or near-offset stacked section to estimate the acoustic impedance of sublayers, prestack inversion uses the full recorded seismic information including near, middle, and far offset data to invert for multiple elastic parameters, such as P wave impedance, shear wave impedance, elastic impedance, V_p/V_s ratio, Poisson's ratio, density, Lamé's constant, and etc. Because prestack elastic inversion can produce V_p/V_s-related attributes that are more meaningful for lithologic and fluid identification, it has an advantage over traditional post-stack inversion to handle complicated reservoir characterization.

Prestack inversion is normally started with the Zoeppritz equations (Aki and Richards, 1980). Although the Zoeppritz equations can be used to obtain exact plane wave amplitudes of a reflected P wave as a function of angle, they cannot provide an intuitive understanding of how amplitudes relate to the various physical parameters. Over the years, a number of approximations to the Zoeppritz equations have been made (Aki and Richards, 1980; Shuey, 1985; Gelfand et al., 1986).

The Aki and Richards, Shuey, and Gelfand approximations can be reduced to the simple linear equation

$$R(\theta) = R_P + G\sin^2\theta,$$

where $R(\theta)$ is the reflectivity as a function of incidence angle, R_P is the P-wave reflectivity at zero offset (the intercept) determined by the acoustic impedance contrast across interfaces, and G is the gradient term which is a function of Poisson's ratio or V_p/V_s ratio and can include a density term. The linear approximation is good for AVO analysis with incidence angles of 0° to 30°.

Clearly both Zoeppritz equations and these approximations are related to the angle of incidence. However, seismic data is usually recorded as a function of offset rather than incidence angle. We should first transform seismic data from the offset domain to the angle domain in the processing and analysis procedures and which is called the Amplitude versus Angle (AVA) method. Normally the prestack time migration CRP gathers are transformed to common angle gathers using a proper velocity model generated by log data or seismic processing velocities. Several partially stacked angle gathers will be created to improve the S/N ratio and reduce computations. Each of the stacked gathers covers the seismic data of a certain range of incident angles and has its own estimated wavelet for later inversion. Of course, the gathers must be properly processed to meet the special requirements of prestack elastic parameter inversion. The data should be processed with good amplitude-preservation and noise elimination to get a high signal to noise ratio, event alignment, and, more importantly, the target zone incidence angle should equal or exceed 30 degrees.

Finally, given the partially stacked angle gathers and their estimated wavelets, the initial guess model is built with log data, seismic, and horizon interpretations used as inputs for the prestack inversion computation. The P wave impedance, shear wave impedance, and density can be inverted first using an iterative algorithm under some constraints and then the other elastic properties like P- and S-wave velocity ratio, Poisson's ratio, Lamé's constant, and etc. can be calculated for further lithology interpretation and fluid identification using the inverted P- and S-wave impedance and density results.

However, the inverted parameters can refer to the previous rock physics modeling and sensitivity analysis results and the final interpretation of the inversion volumes can be guided by the theoretical rock physics templates through the multiple parameter cross-plotting technique.

Case study

We applied the rock physics analysis and prestack elastic inversion technologies and workflow for gas sand distribution prediction in one northwest China oilfield.

All the gathers of 33 2D lines in this project have good amplitude-preserving processing. Demultiple, denoise, and NMO processing have been applied to provide a high signal to noise ratio and aligned events. AVO forward modeling results of these gathers proved that the interest zone (gas layer) CRP gathers have very visible AVO features which agree with the synthetic AVO forward modeling results from well logs. We conclude that these gathers meet the requirements and can be used for further elastic inversion.

In addition, all the logs have been diagnosed and corrected based on the local rock physics model to eliminate the effect of environmental factors and the few anomalous values. Comparison of shear wave velocity estimates with different models showed that the Greenberg-Castagna model gave the best V_s estimation to the specific reservoir in this project and the estimated V_s and measured V_s correlation coefficient can be up to 0.8 (see Figure 4). So the Greenberg-Castagna model was selected to estimate the V_s of the well without measured V_s data in this project.

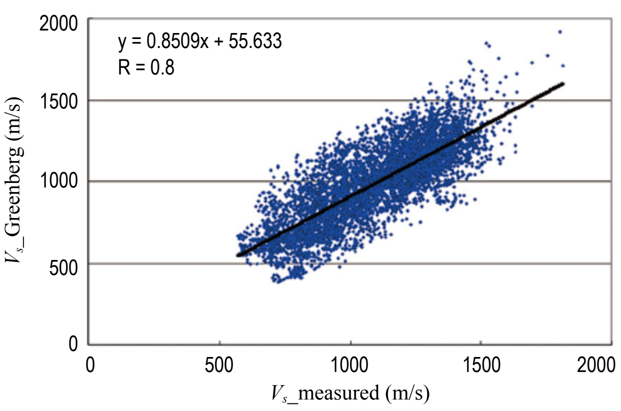

Fig. 4 Crossplot of measured Vs and estimated Vs with the Greenberg-Castagna model.

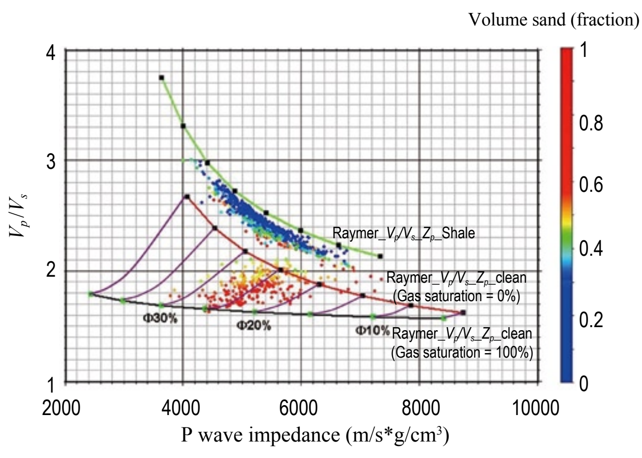

Fig. 5 The study zone rock physic template for this project.

With the P-wave velocity, S-wave velocity, and density data of the available wells, the P-wave impedance (Z_p), S-wave impedance (Z_s), V_p/V_s ratio, and other elastic parameters of each well have been calculated. A V_p/V_s

and Z_p crossplot shows that shale, water sand, and gas sand can be distinguished very well. Figure 5 shows the rock physics template (RPT) of lithology differentiation of the study zone in this project (the color bar represents volume of sand) and it illustrates that gas sand is clearly separated from shale. The gas sand porosity varied from 20% to 30%, V_p/V_s is less than 2.0, and the P-wave impedance is less than 6000 m/s*g/cm^3.

Based on the rock physics and sensitivity analysis, we conclude that the interest zone gas sand distribution in this study area can be differentiated by cross-plotting P-wave impedance (Z_p) and V_p/V_s ratio. So the high quality acoustic travel time, density, and shear wave velocity logs obtained through intensive log calibrations and proper shear wave velocity estimation method have been input into the seismic inversion system, coupled with the related 2D amplitude-preserved seismic data and gathers, the P-wave impedance (Z_p), S-wave impedance (Z_s), V_p/V_s velocity ratio, and density datasets have been inverted.

For example, Figure 6 is the inverted V_p/V_s section crossing wells W9 and W10 and it shows that the well W9 K10 zone is featured by sharply lower V_p/V_s value in contrast with the surrounding rock. Four thin gas sands have been found and tested between 1814.3 and 1827 m inside this zone and the initial production was 42,000 cubic meters per day. A similar lower V_p/V_s feature can be seen in the well W10 K9 zone and one thin gas sand has been drilled between 1705.5 and 1707 m with an initial flow of 14,700 cubic meters per day. The real drilling results proved that this inversion is reliable.

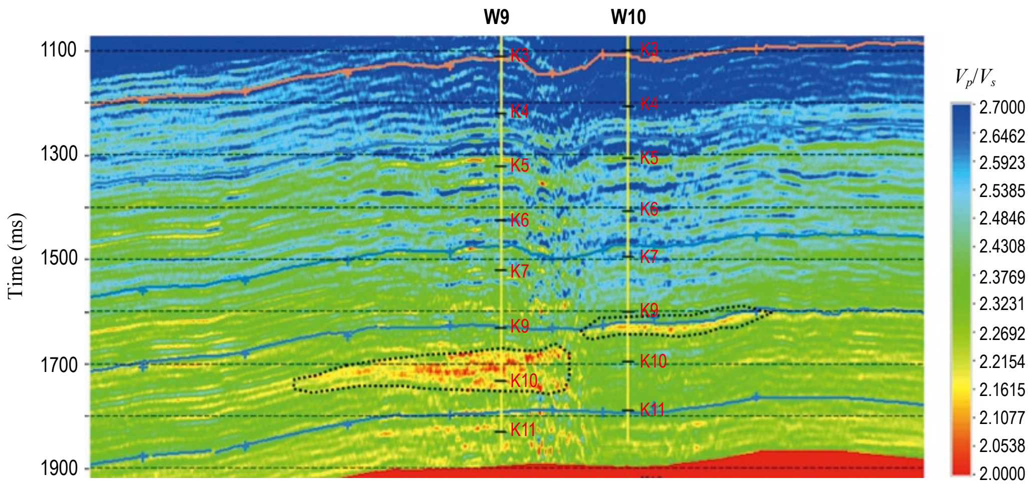

Fig. 6 The inverted V_p/V_s section crossing wells W9 and W10.

Cross plot analysis between inverted *P*-wave impedance and V_p/V_s velocity ratio in the interest zone (K9 to K10) in this area was conducted. The Figure 7 left panel is the crossplot of inverted P-wave impedance and V_p/V_s ratio. Comparison with the rock physics template (RPT) generated by the rock physics analysis workflow with calibrated well data (Figure 7 right panel) shows that the inverted data crossplot has similar features to the standard RPT. So with the guide of the standard RPT, abnormal zones can be delineated on the inverted cross-plot map (the blue zone) that represents the gas sand distribution around wells W9

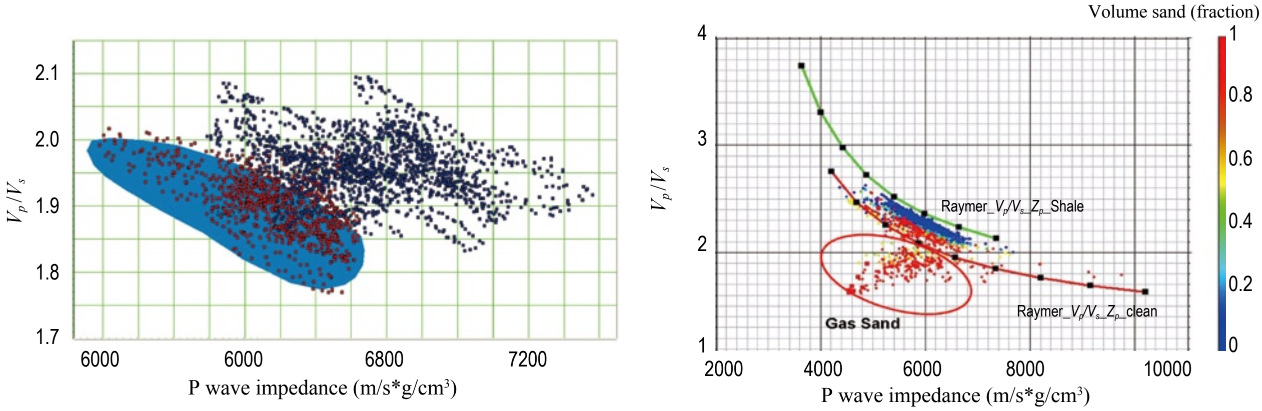

Fig. 7 Comparison of the inverted data crossplot (left) and the standard RPT (right) of zone K9 to K10 near wells W9 and W10.

and W10. The inverted gas sand distribution results are shown in Figure 8.

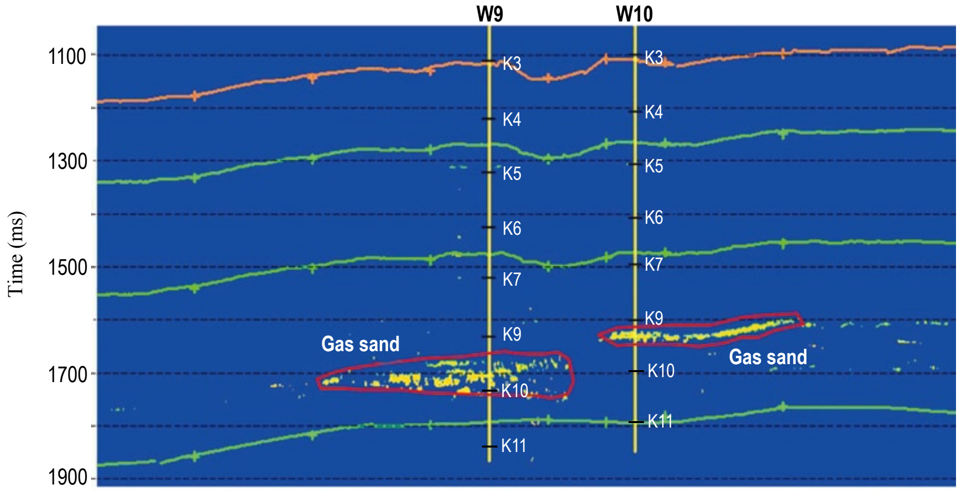

Fig. 8 Inverted gas sand distribution section crossing wells W9 and W10.

Crossplotting the inverted P-wave impedance and V_p/V_s velocity ratio with the guidance of the standard RPT presents a more accurate and well defined gas sand distribution and this prediction coincided with the real geological characteristics, drilling and testing, and production very well.

However, there is a question of scale among seismic, well log, and core analysis that we need to discuss. Geophysicists normally use low frequency surface seismic data to do seismic rock physics study on an oilfield scale, log experts analyze the rock properties with high resolution log data but petrophysicists explore the micro-scale rock physical properties like components, architecture, temperature and pressure conditions, and etc. So how we match and integrate these analyses results at different scales for interpretation is a big problem (Tang, 2008). The way to address this problem in this study is to conduct the rock physics analysis with seismic, logs, and core data at different scales first and then examine the relationships between these elastic parameters at different scales and see if the distribution patterns of the crossplots are consistent or similar. If consistent or similar, the templates built with core and/or logs data could be used to guide the interpretation of seismic inversion results but the parameter data ranges at different scales may be different.

Conclusions

Quantitative interpretation of seismic data for reservoir characterization and oil and gas identification is the ultimate goal of geophysicists. Rock physics analysis is one of the vital technologies to make this dream come true. Dialectically, all the seismic attributes are superficial phenomena (representations) but the intrinsic factor that induce those representations are some changes of rock physical properties, such as rock matrix, pore, fluid content, and even temperature and pressure that can cause the variation of all kinds of moduli and density of rocks. These rock property changes then induce the changes in P- and S-wave velocity of the subsurface layers and eventually generate different seismic attribute representations such as impedance, amplitude (energy), frequency, phase, waveform, and etc. Rock physics modeling and analysis explores the essential factors that induce those various seismic changes and tries to establish a deterministic relationship among these intrinsic factors and seismic attributes which can be used to guide seismic data quantitative interpretation.

Application of seismic prestack elastic parameter inversion based on rock physics modeling and analysis for gas sand distribution prediction in this study proved that this method has unparalleled advantages over traditional methods, which can help to bring seismic data interpretation to a new quantitative (or semi-quantitative) level. By doing rock physics modeling and analysis, the sensitive parameters to the specific reservoir and fluid types of the reservoirs in the study area have been found. This can not only point out clearly which parameter volumes should be inverted, but also the standard rock physics template (RPT) generated with the intensive calibrated logs data can guide the interpretation of the inverted seismic dataset or volumes. Because there are multiple parameters used for reservoir characterization and fluid identification in this workflow, the ambiguity and uncertainty of seismic interpretation will greatly decrease.

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