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Petrophysical Analysis and Distribution Prediction of Asphaltene Reservoir of Longwangmiao Formation in Longnusi Area, Central Sichuan

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Abstract: Taking the asphaltene carbonate reservoir of Longwangmiao formation in the longnusi area of the Sichuan Basin as an example, the petrophysical analysis and seismic prediction methods of the asphaltene reservoir are discussed. Asphaltene in the actual formation mainly exists in the reservoir in liquid form, with complex spatial distribution, which makes it easy to block the pore throat channel and reduce the practical space of the reservoir, resulting in poor reservoir connectivity. The asphaltene petrophysical characteristics are quite different from the surrounding rock. Still, the content is only about 1 ~ 4%, which leads to the weak influence of asphaltene on the petrophysical characteristics of the reservoir and the difficulty of asphaltene reservoir prediction. In this paper, a set of integrated research ideas and methods based on core and logging data interpretation, petrophysical analysis, and prestack inversion prediction are formed: the logging response characteristics of the asphaltene reservoir are analysed based on the comparison of the core and logging curve, the logging evaluation process of asphaltene reservoir is formed, and the relative asphalt content is calculated by using conventional porosity curve and nuclear magnetic porosity; The petrophysical analysis of reservoir section is carried out, and it is considered that VP / vs. can effectively partition asphaltene reservoir; Finally, pre-stack inversion technology is used to predict asphaltene reservoir. The actual drilling proves that the prediction results of the asphaltene reservoir by this method are in good agreement, indicating that there is a set of asphaltene carbonate reservoirs with asphalt content of more than 2% and an average thickness of 20m in the study area, which realises the quantitative evaluation of asphaltene carbonate gas reservoir and has reference value for the prediction of such asphaltene reservoir.

1. Introduction

Asphaltene carbonate reservoirs are commonly developed in the Longwangmiao Formation in Longnusi area of the Sichuan Basin. Asphaltene severely affects the reservoir pore structure, leading to poor reservoir physical properties and gas content and reducing gas reservoir production capacity (Ji., Y. et al., 1995). Acid fracturing is commonly used to exploit deep carbonate gas reservoirs in the

Sichuan basin. This production enhancement measure will lead to asphalt shedding in the reservoir space, blocking the pore-roaring channels and reducing connectivity. Studies have shown that the effective porosity of the formation decreases significantly when the asphalt content reaches 1%. Therefore, the distribution and range of asphalt in the reservoir seriously affect the prediction accuracy of the favourable zone of the reservoir as well as the calculation of the storage volume (Zhou., J. et al., 2015). To ensure the accuracy of exploration and development of asphaltene carbonate gas reservoirs in the Longwangmiao Formation and the development success rate, effective geophysical techniques should be used in reservoir prediction to find favourable zones with low asphaltene to guarantee the need for increased storage and production in oil fields.

Asphalt is mainly formed by the oil of transport or aggregation process through thermal cracking, bacterial degradation, etc. It is primarily in high-viscosity liquid and solid state within the formation, ranging from extractable to insoluble under laboratory conditions, and is usually rich in N, S, and O (Hu., S., et al., 2007; Zhang., C. et al., 2009). Researchers at home and abroad have focused on the geochemical characteristics of asphalt, its influence on reservoir storage space, and formation factors. Zhang Chengguang (2009) mainly used core experiments before and after dissolution to study the impact of asphalt on reservoir physical properties and to establish an interpretation plate of rock electrical parameters and pore permeability; Lai Qiang (2017) and others conducted core experiments on the Longwangmiao Formation in central Sichuan, carried out geochemical characteristics analysis of bituminous reservoirs as well as genesis analysis, and proposed to establish a volumetric model based on nuclear magnetic porosity curve as well as a three-porosity curve to calculate the relative content of asphalt in the reservoir (Sima., L and Shu., Z, 2008). Asphalt content calculation methods have played an important role in oil and gas exploration in asphaltene formations. They have made positive progress, but the disadvantage is that the core data and the number of single wells are small, the research results are limited to a single point or single good information, no research on the prediction of the spatial distribution of asphaltene carbonate reservoirs has been carried out, and the research on the comprehensive evaluation of asphaltene carbonate reservoirs is still lacking (Gu., Z., et al., 2015).

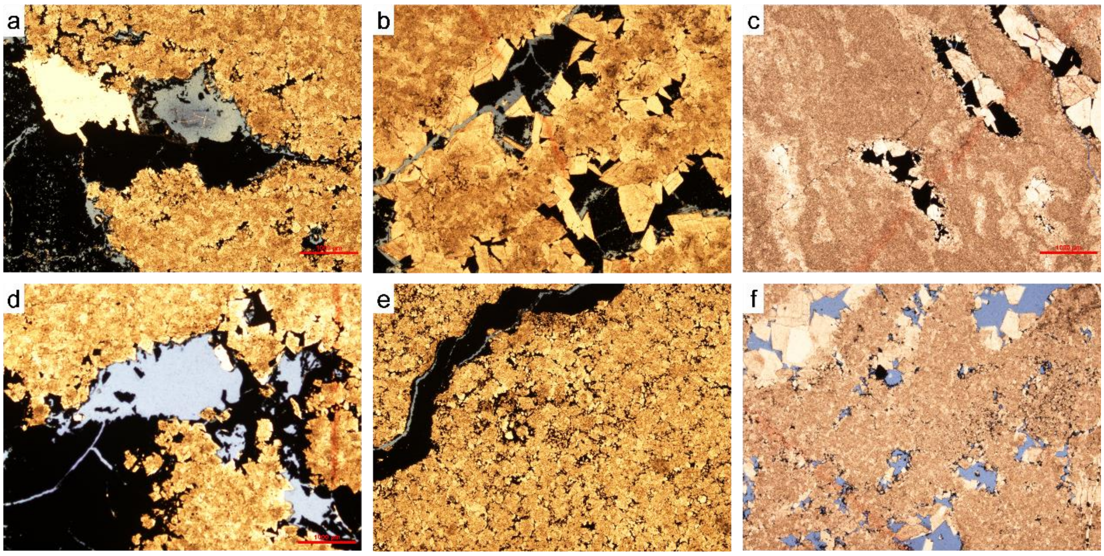
The reservoir in the study area is laterally discontinuous, with solid spatial anisotropy and poor physical properties. The asphalt is widely distributed, so the excellent prediction of a favourable reservoir is the focus and difficulty of exploration and development in the study area. In this paper, a set of research ideas and methods of pre-stack inversion prediction based on core, logging data, and seismic data are developed: based on the analysis of geological characteristics of asphaltene carbonate reservoirs, core experiments are carried out to obtain the petrophysical response characteristics of asphaltene reservoirs, combined with the reconstruction of logging curves, a petrophysical map plate of asphaltene reservoirs is established, and it is found that Vp/Vs. [1-4]

2. Geological characteristics of gas reservoirs

2.1 Asphaltene reservoir characteristics

The Longnusi area in central Sichuan is located in the eastern part of the Leshan-Longnusi paleo-uplift tectonics in the Sichuan basin. The site is influenced by multi-phase co-deposition and denudation uplift. The basal uplift of the South China System causes the natural gas of the Cambrian Longwangmiao Formation to accumulate in higher parts. The Longwangmiao Formation is a set of marine carbonate formations. The reservoir is in the granular beach phase and is also influenced by the epigenetic karst of the Garidonian, with pore development (Zhang., S. et al., 2021).

The reservoir of Longwangmiao Formation is mainly dominated by beach-phase dolomite, and the lithology is especially sand-chip dolomite, residual sand-chip dolomite, and fine-medium crystal dolomite. The reservoir space is primarily dominated by dissolution pores, followed by intergranular pores, and fractures exist in some formation sections. The reservoir type of Longwangmiao Formation is especially a suture-hole type reservoir, with a reservoir thickness of 5-40m and strong anisotropy in spatial distribution; porosity ranges from 2.0% to 10.9%, with an average porosity of 4.28%, showing mainly low porosity and low permeability characteristics. The core data and fluorescence thin section analysis show that asphalt is commonly present in the Longwangmiao Formation reservoir in the Longnusi area, especially in the top reservoir of wells MX202, MX16, and MX41, where the asphalt content is relatively high. The thin section data visualises the asphalt distribution in intergranular pores, particle edges, and intra-granular pores (Figure 1).

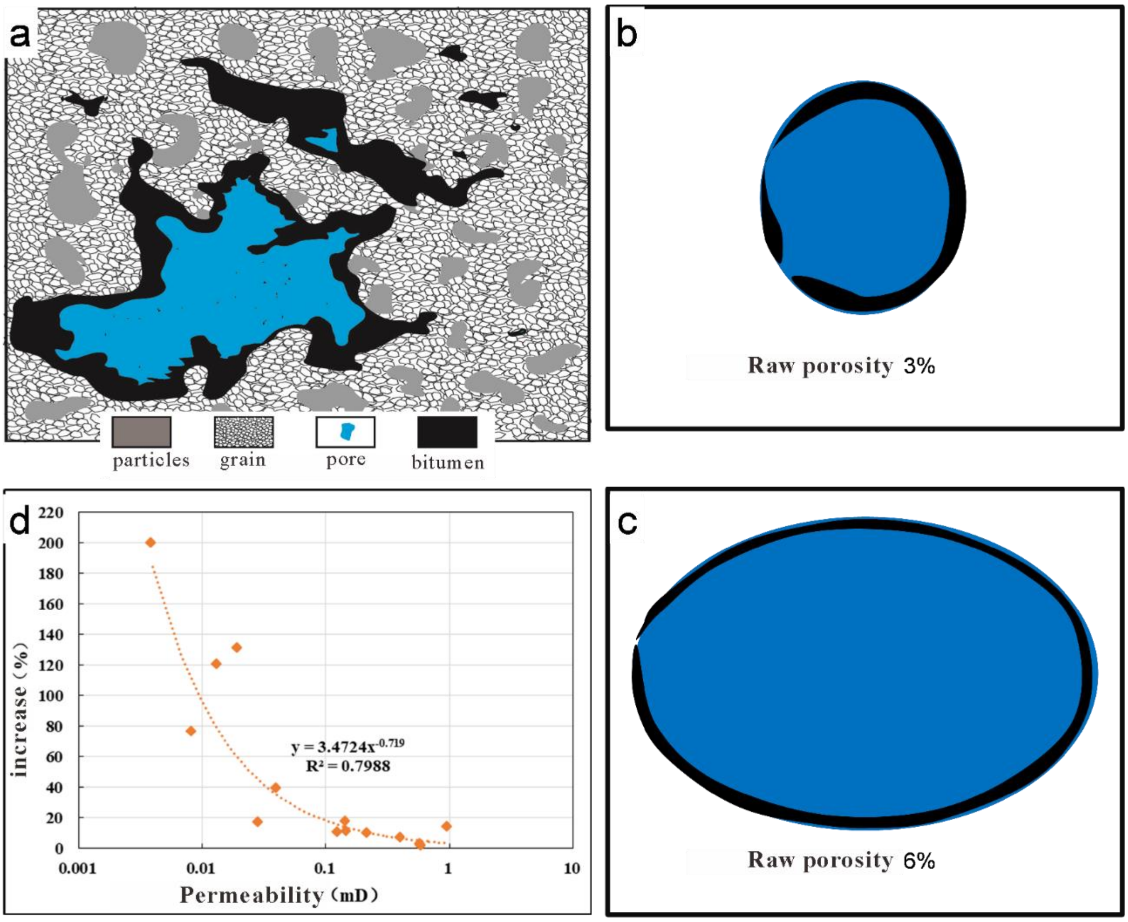


a. MX202, 4646m, fine-crystalline residual sand clastic cloud, dissolution pore development, high asphalt content almost filled with cavities, 20x. Single polarised light; b. MX16, 4771.79, acceptable- to medium-crystalline residual sand clasts with intergranular and intergranular pores nearly filled with asphalt, 20x. Single polarised light; c. MX23, 4802.60, fine crystalline clinopyroxene, solution pores filled with asphalt and quartz, 20x, single polarised light; d. MX 202, 4656.50, fine crystalline residual sand clinopyroxene, solution pores developed, high asphalt content, 20x. Single polarised light; e. MX 16, 4759.70m, fine-crystalline clinopyroxene, fractures filled with asphalt, 20x, single polarised light; f. MX 23, 4805.40, fine-crystalline residual sand clinopyroxene with a small amount of asphalt developing at the edge of the solution pore, 20x, single polarised light.

Figure 1: Characteristics of asphalt-filled dissolved holes and cracks

2.2 Effect of asphaltene on reservoir physical properties and production capacity

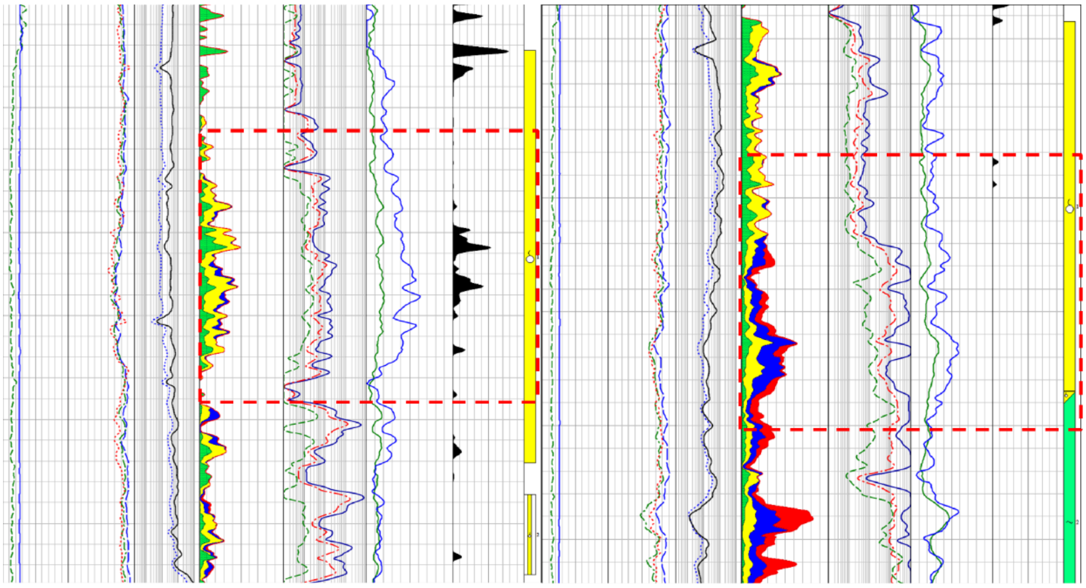
Asphaltene is mainly stored at the edges of reservoir pores (Ji., Y., et al., 1995), and it is easy to fill the pore throat channels and block the reservoir space. The part of the reservoir space where asphalt is removed is the adequate pore space, so the asphalt content significantly influences the reservoir connectivity and physical properties.



a. Pore model filled with the same absolute content of asphalt; b. Original porosity of 3%, asphalt content of 1%, and 33% increase in porosity after extraction of asphalt; c. Initial porosity of 6%, the asphalt content of 1%, and a 16.6% increase in porosity after extraction of asphalt; d. The plot of porosity permeability versus increase after extraction in core extraction experiments.

Figure 2: Impact of asphalt on storage space

The thin section analysis shows that the asphalt is mainly deposited on the surface of the reservoir space, and the middle part is the storage fluid space; the approximate volume model is shown in Figure 2a. In the same asphalt content (1%) formation, when the original porosity is 3% (Figure 2b), the effective porosity of the reservoir is 2%; after extracting asphalt, the effective porosity of the reservoir increases from 2% to 3%, an increase of 33%; when the original porosity is 6% (Figure 2c), the effective porosity of the reservoir is 5%, after extracting asphalt, the effective porosity of the reservoir increases from 5% to 6%, an increase of 16.6%. When the original porosity was 6% (Figure 2c), the effective porosity of the reservoir was 5%. After the extraction of asphalt, the effective porosity of the reservoir increased from 5% to 6%, an increase of 16.6%. It can be seen from the core extraction experiments of multiple samples (Figure 2d) that the original porosity of cores and the growth of effective porosity after extraction are negatively correlated, indicating that when the asphalt content of different reservoir spaces is the same, the more developed the collective pores of the reservoir, the lower the asphalt occupancy, the higher the effective porosity of the reservoir.[5-9]



a.MX202 Single-log histogram b.MX204 Single-log histogram

Figure 3: Comparison of pore structure and asphalt content between well MX202 and well MX204

Figure 3 compares the pore structure and asphalt content between the logging data of MX202 and MX204 wells. In addition, the percentage of layer sections with a porosity of 3-6% in the MX202 well is less than 30%; the portion of layer sections with a porosity of 3-6% in the MX204 well is more significant, reaching 75%, and the rate of layer sections with porosity >6% is 15%, so the pore structure of MX204 well is obviously better than that of MX202 in terms of pore structure parameters. Further verification of the difference between the two wells can also be obtained from the gas test results, with the MX202 well producing 300,000 m3 of gas while the MX204 well produced 1.06 million m3 of gas. Asphalt tends to block the pore throat channels and, therefore, has a more significant impact on the predominantly small pore size of the Mill Creek 202 well, resulting in poorer reservoir connectivity.

The comparison of log interpretation results between asphaltene reservoirs and non-asphaltic sections in typical wells of the Longwangmiao Formation in the study area (Figure 3) shows three characteristics: ① the asphaltene development section is located in the middle-upper section of the Longwangmiao Formation as a whole, and the asphaltene content is between 1-4%; ② the lower the density and lower the velocity, the better the physical properties of the reservoir section; ③ the difference between asphaltene reservoirs and non-asphaltic sections in conventional logging curves is small and difficult to distinguish; ④ asphaltene has a more significant influence on small pore reservoirs.

Longwangmiao Formation in Longnusi area mainly develops low-porosity and low-permeability carbonate reservoirs, and the formation connectivity is greatly influenced by asphalt. Asphaltene will block the pore channels, make the physical properties worse, and significantly reduce the effective porosity and total porosity, resulting in substantially worse pore structure, and finally reduce the reservoir permeability, which is unfavourable to the gas reservoir development, so the high asphaltene content area should reduce the capacity expectation. In summary, the focus and difficulty of asphaltene carbonate reservoir development is the excellent prediction of asphaltene distribution.

3. Rock Physics Experiments

The carbonate reservoir has a rock skeleton, fluid, and asphalt that differ significantly in physical properties, leading to the specificity of the reservoir logging response. Asphalt is a low-velocity medium with weak acoustic propagation, resulting in high acoustic time differences close to the fluid. Asphalt has a low density, ranging from 0.9 to 1.2 g/cm3, comparable to water. The process of organic matter evolution is the process of dehydrogenation and desulfurisation. As maturity increases, the proportion of carbon elements also gradually becomes more extensive, causing an increase in the density of asphalt. Asphalt rich in hydrogen and carbon elements are good neutron reducer and can be used as equivalent hydrogen content, resulting in higher neutron logging values for asphalt (Zhang., S. et al., 2021). The characteristics of the petrophysical response of bituminous reservoirs in the study area must be further analysed by core experiments.

3.1 Pore Seepage Characteristics

Figure 4 shows the change in pore permeability before and after the dissolution of asphaltene cores. It can be seen that the physical properties of the cores are significantly improved after the abolition of asphalt, and the porosity increases by 0.25 %-2.20 %, an increase of 19%; the permeability increases by (0.002-0.091) *10-3m2, an increase of 67.3%. This indicates that asphalt strongly influences the physical parameters of the reservoir, reducing the effective porosity of the reservoir and decreasing the reservoir connectivity.

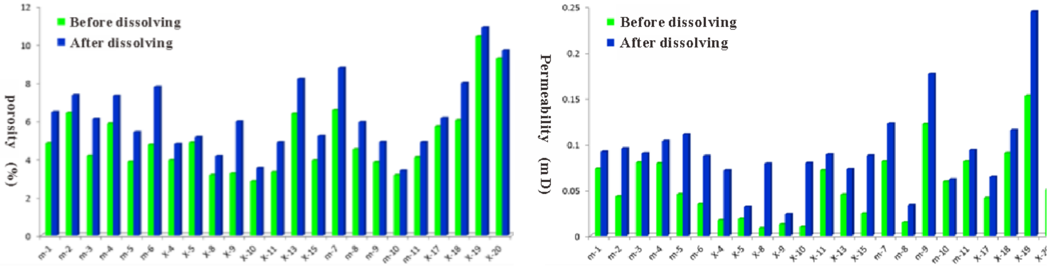


Figure 4: Changes of porosity (left) and permeability (right) before and after the dissolution of core asphalt

3.2 Acoustic time difference characteristics

Figure 5 shows the comparison of longitudinal and transverse wave time differences before and after the dissolution of asphaltene cores; it can be seen that the longitudinal and transverse wave time difference of cores increased after asphaltene dissolution, among which the longitudinal wave time difference increased by 0.43%-2.61% with an average increase of less than 1%, while the transverse wave time difference increased by 3.3%-14.2% with an average of 10%. Therefore, the influence of asphalt on the longitudinal time difference is small, and the impact on the transverse time difference is considerable.[10-13]

3.3 Resistivity, density characteristics

Asphalt is a non-conductive organic material with extremely high resistivity; at the same time, the density of asphalt is low, around 1.3 g/cm3, which is higher than fluid and lower than skeletal density, so asphalt has a more significant impact on the resistivity and density of the reservoir section. Figure 6 shows that the resistivity of asphaltene cores decreases significantly after dissolution, and the resistivity value drops by 10-68.5 Ω.m, with a relative decrease of 24-86%. Figure 5 shows that the density of asphaltene cores does not decrease significantly after dissolution, and the density value decreases by 0.009-0.032g/cm3, with a relative decrease of 0.4-1.2%. In comparison, it can be seen that the resistivity of the reservoir section is more influenced by asphalt than density.

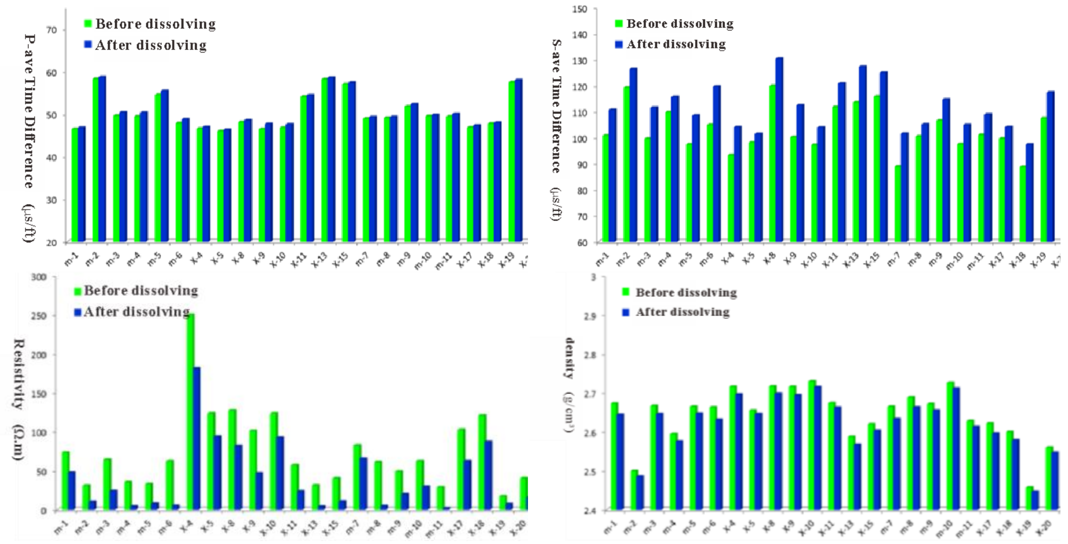


Figure 5: Comparison of core logging response values before and after asphalt dissolution

According to the above-mentioned extensive core experiments, it is shown that the bituminous section has prominent logging response characteristics, which leads to the sizeable transverse wave time difference and resistivity variation but has less effect on the longitudinal wave time difference and density. In conclusion, the petrophysical experimental analysis shows that the high asphaltene reservoir is characterised by low pore and low permeability, high resistivity, and low transverse wave time difference, which is the basis for logging and seismic interpretation for spatial distribution prediction of asphaltene reservoir.

4. Sensitivity analysis of asphaltene reservoirs

4.1 Logging curve reconstruction

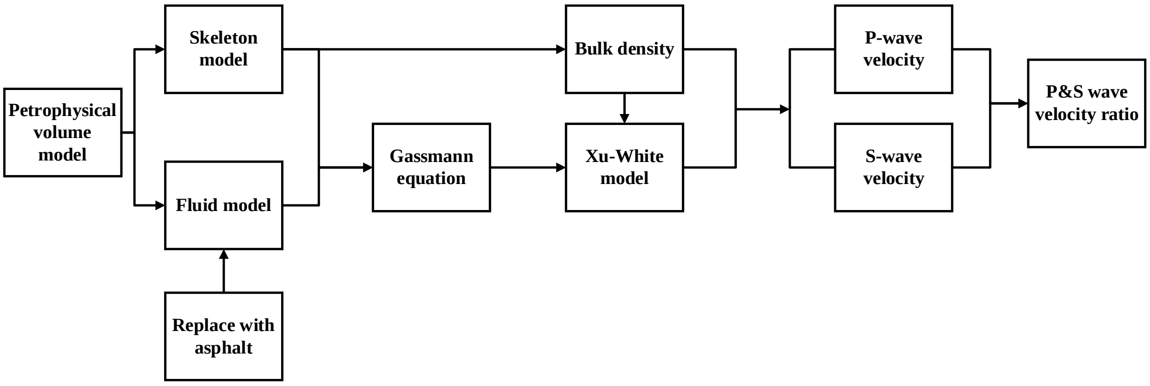


Figure 6: Logging curve reconstruction process

The actual drilling and logging data are limited by the lateral detection depth of the instrument, and the main detection range is the petrophysical characteristics of the flushing zone near the wellbore, which is affected by borehole collapse and mud filtrate, etc. The actual logging curve cannot truly reflect the formation’s physical and elastic parameters, resulting in the curve not reflecting the formation’s lithology and physical characteristics. Therefore, this paper adopts the reconstruction of the logging curve based on the Gassmann theory and Xu-White model to improve the identification ability of the logging curve to the reservoir, reflect the petrophysical response characteristics of the in situ formation, and facilitate the acceptable prediction of fluid, lithology and physical parameters of the reservoir. In this way, it is necessary to conduct the reconstruction operation of longitudinal and transverse wave time differences based on petrophysical experiments to obtain physical and lithological parameters.[14-16]

The logging curve reconstruction is divided into three steps (Figure 6).

1) Establish a solid model and fluid (with asphalt) model of carbonate rocks based on the mineral volume model;

2) Find the bulk density, effective bulk modulus, and shear modulus of the formation based on the different pore properties and fluid properties of carbonate rocks, respectively;

3) Determine the formation's bulk and shear modulus according to the Gassmann theory and the Xu-White model to obtain the original building's longitudinal and transverse wave velocities.

High-quality logging reconstruction results: the reconstructed curve in the non-reservoir section should basically overlap with the measured curve, and the difference between the two in the reservoir section should follow the geological law. Figure 7 shows the reconstruction results. When the reservoir contains asphalt, the density of asphalt is more minor than close to the thickness of water, and the viscosity is more significant, which makes it easy to fill the pore space, resulting in the change of longitudinal wave time difference. Still, the magnitude is not large, and the transverse wave time difference becomes smaller. It shows that the longitudinal and transverse wave velocity ratios correlate well with the asphalt content of the reservoir, indicating a high longitudinal and transverse wave velocity ratio, which is consistent with the general understanding of the law.

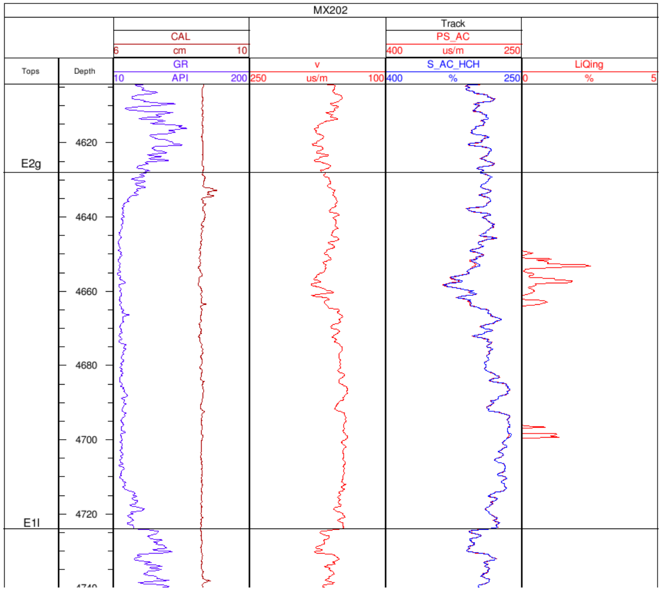


Figure 7: Logging curve reconstruction results

4.2 Elastic parameter curve rendezvous analysis

The analysis of reservoir elastic parameters is the "bridge" between various seismic attributes and flexible rock parameters. It is essential for geophysical interpretation from qualitative to quantitative, post-stack to pre-stack, and lithology to fluid (Yang., F. et al., 2019). The petrophysical model is used to reconstruct the logging curves, calculate the reservoir elastic parameters, visualise the effect of asphalt content changes on the petrophysical parameters, select the combination of flexible parameters sensitive to asphaltene by rendezvous analysis, determine the reliability of pre-stack inversion technique in asphaltene reservoir prediction, and finally analyse the distribution of asphaltene reservoir favourable zones (Shi., L., et al., 2020; Yin., X., X., Liu., and S., O, 2016).

Longitudinal waves are affected by reservoir pores and fluids, and the velocity values are reduced to a certain extent; transverse waves propagate in the formation skeleton and are not affected by the fluids endowed in the reservoir space and are more affected by the distribution and size of the reservoir space. Hence, the reduction of transverse wave velocity is less than that of longitudinal waves (Wen., Z. et al., 2008). Therefore, the transverse wave time difference is more sensitive to asphaltene (Fig. 5), and the reservoir contains asphalt leading to a significant decrease in transverse wave velocity. However, the accuracy of identifying asphaltene using transverse wave impedance alone is still low. Through the rendezvous analysis of Vp/Vs. Asphaltene content (Figure 8), the divergence between high asphalt reservoirs (range greater than 1%) and low asphaltene reservoirs (content less than 1%) on the rendezvous graph is also more apparent. The longitudinal and transverse wave velocity ratio of high asphaltene reservoirs has a rising trend compared with reservoirs with low asphaltene content. Asphaltene-bearing reservoirs' longitudinal and transverse wave velocity ratio is usually above 1.8.

Based on the above analysis, the prediction study of asphalt-bearing reservoirs can be carried out in the central Sichuan area using the pre-stack elastic inversion method.

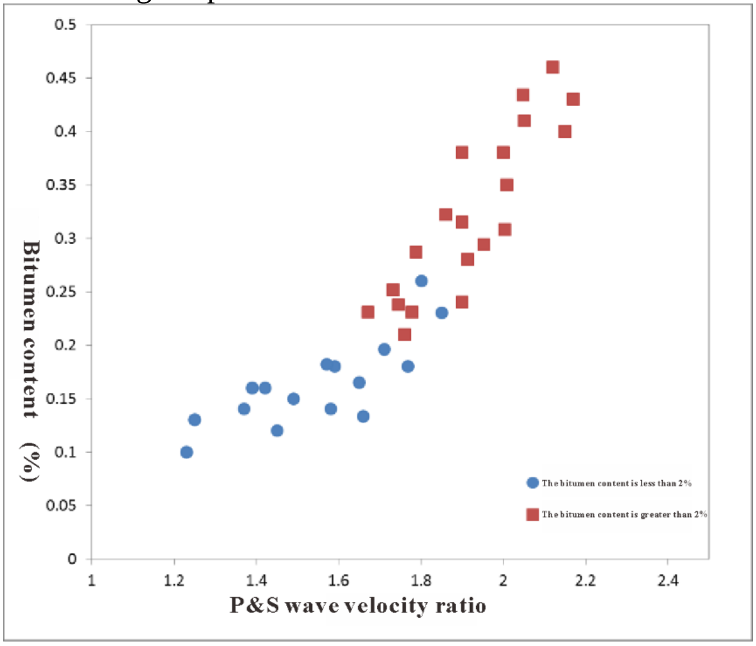


Figure 8: Longwangmiao Formation longitudinal wave velocity ratio and asphalt content rendezvous map

5. Pre-stack inversion

Analysing the appealed petrophysical sensitive parameters shows that longitudinal and transverse wave velocity ratios can effectively distinguish reservoirs from non-reservoirs. At the same time, it also has better results in the identification of high bituminous reservoirs. Therefore, in this paper, the pre-stack geostatistical inversion technique is used. The log data are only used in the inversion to construct the low-frequency model, while the medium- and high-frequency information mainly comes from the seismic data.

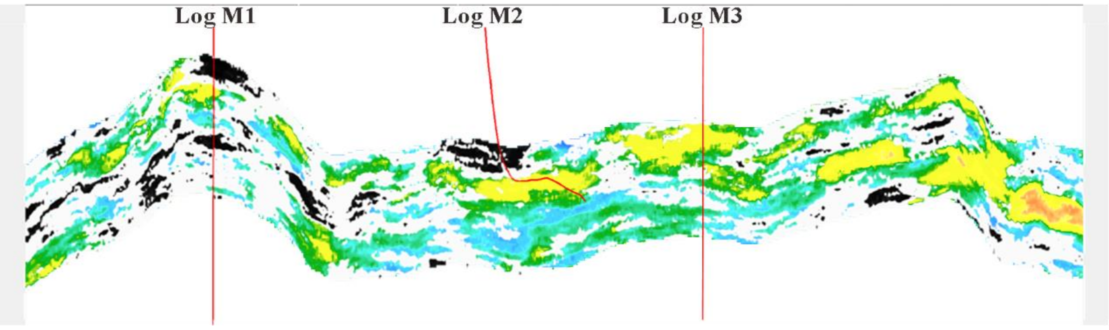


Figure 9: Seismic prediction profile of asphaltene reservoir in Longwangmiao Formation

Figure 9 shows the inversion results of the M1, M2, and M3 wells. M1 well encountered 10 m of the reservoir in the interior of the target formation with good physical properties, and the logs showed gas formation; the top, middle, and lower part of the well-encountered asphaltene with poor physical properties; the seismic prediction distribution of asphaltene reservoir was in good agreement with the log interpretation. The M2 well is a newly completed development well. The seismic prediction of the asphaltene reservoir was used to clarify the distribution of high asphaltene reservoirs in the study area, avoiding the top reservoir with poor physical properties and drilling directly into the middle reservoir with good physical properties and low asphaltene, which eventually produced 1.4 million cubic meters of gas per day. The distribution of high asphaltene reservoirs was predicted by pre-stack geostatistical methods, and the reservoir results directly guided well deployment and optimisation.

6. Conclusion

(1) Asphalt in a high-temperature environment in the actual formation is stored in the reservoir space in the form of fluid, which reduces the effective porosity of the reservoir, destroys the reservoir pore structure, minimises the reservoir permeability, and affects the production capacity of a single well. Because asphalt and fluid in the solid form in the rock physical characteristics are similar, it is difficult to distinguish; core experiments show that asphalt will lead to a decrease in transverse wave time difference, density, and resistivity values increase, and the difference between asphalt and fluid chirality time is noticeable. Hence, the use of three porosity calculations of total porosity and nuclear magnetic porosity difference calculation of asphalt is a more accurate method at this stage.

(2) High-precision core data constrain single-well interpretation conclusions, low-frequency logging data deny high-frequency seismic data, and through reservoir sensitivity analysis, multi-parameter reservoir indicator factors constructed using longitudinal and transverse wave velocity ratios and other petrophysical parameters can effectively identify pore-type dolomite reservoirs. The combination of point line surfaces to carry out asphaltene reservoir spatial distribution prediction is a good promotion for asphaltene reservoir prediction in the Sichuan basin. The combination of point-line and surface can be used to predict the spatial distribution of asphaltene reservoirs.

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