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Research Article

Classification and Prediction Method for Dolomite Reservoirs in the Permian Maokou Formation in the Sichuan Basin

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Abstract

The Lower Permian Maokou Formation in the Hechuan area is one of the key horizons for natural gas exploration in the Sichuan Basin, showing a low degree of exploration and great exploration potential. The Lower Permian gas reservoir is mainly controlled by the reservoir, therefore it is subject to the development of the Maokou Formation reservoir. However, due to the strong heterogeneity and significant variations in physical properties of the Maokou Formation dolomite reservoir in the Hechuan area, there are significant differences in seismic response characteristics of reservoirs with different porosities. Through comprehensive analysis of gas testing wells in the Maokou Formation, criteria for reservoir classification were established based on lithology, average porosity, plane porosity, and thickness of dolomite reservoirs. The effective reservoirs in the Maokou Formation were divided into two types: high-porosity reservoirs and medium-porosity reservoirs. On the basis of establishing a physical quantity model for the Lower Permian carbonate rock in the research area, the rock physical characteristics and seismic response characteristics of reservoirs with different pores are determined through model forward modeling, and appropriate methods are selected for prediction. By using the optimization processing method of gathers and wavelet decomposition to remove sidelobes, the issue of seismic abnormal response caused by lateral velocity changes in the underlying Maokou Formation has been solved. The relative strength relationship of seismic response amplitude can effectively characterize the true situation of reservoir development. Then, by using post-stack inversion and pre-stack simultaneous inversion methods, the high-porosity and medium-porosity dolomite reservoirs in the Maokou Formation are classified and predicted, thereby to effectively improve the prediction accuracy of reservoirs, ultimately providing a reliable basis for the exploration and development of the Maokou Formation in the Hechuan area in the later stage.

Keywords

Sichuan Basin, Maokou Formation, Dolomite Reservoir Rock, Physical Quantity Version, Reservoir Prediction

1. Introduction

In recent years, the Lower Permian Maokou Formation in the central Sichuan region of the Sichuan Basin has become one of the horizons for natural gas exploration. More and more researchers have conducted extensive research on the karst type

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reservoirs and hydrothermal dolomite reservoirs of the Permian Maokou Formation in the Central Sichuan Basin, clarifying the characteristics of reservoir lithology and geophysical (such as logging and seismic) response characteristics. The main factors controlling the distribution of the Permian Maokou Formation reservoirs were explored and analyzed, laying a good foundation for further oil and gas exploration and development of the Maokou Formation [1-4]. The dolomite in the Hechuan Tongnan area of central Sichuan is mainly a subclass of crystalline dolomite, including small categories such as muddy powder crystalline dolomite, medium-fine crystalline dolomite, and fine crystalline gray dolomite, mostly scattered. Multiple drilling wells, including Well NC7, Well HS4, and Well MX39, have encountered high-porosity dolomite reservoirs during drilling in the Maokou Formation area, and have achieved high gas production. [5, 8]. Through the study of multiple high-yield wells, it has been shown that the Lower Permian is superior to the formation of reservoir. As a lithological gas reservoir controlled by reservoirs, high-quality dolomite reservoirs are the most critical control factor. Therefore, in order to achieve high production, the key is to find high-porosity dolomite reservoirs, which can promote the exploration and development process in this area.

2. Geological Overview of the Research Area

Before the deposition of the Permian, the Sichuan Basin was subjected to long-term erosion due to the uplift of the Caledonian and Yunnan Movements, forming a quasi-plain type sedimentary basement. In the early Permian, a set of carbonate gentle slope sediments were deposited under the background of extensive marine invasion, which respectively overlapped the Carboniferous, Devonian, Silurian, Ordovician and above [9, 10]. On this basis, the Liangshan Formation, Qixia Formation, and Maokou Formation were deposited. The Hechuan-Tongnan area is located in the Sichuan Basin.

2.1. Lithological Characteristics

During the Maokou period of sedimentation in the Sichuan Basin, it was still in the carbonate rock platform facies area, belonging to the period of transgression to highstand system tract. The main sediment was limestone, with only locally developed biogenic reef deposits. From the perspective of regional sedimentary environment, at this time the western part of the basin is the western Sichuan Trough, with steep slope platform edges developed. The northern part of the basin is carbonate rock gentle slope sedimentation, with deeper water bodies. The eastern and western parts of the basin develop local highlands due to the location within the platform. The Hechuan area is located on the eastern part of the central Sichuan region. Within the platform, it is a karst slope-karst valley with relatively low-lying terrain. After the sedimentation of the Maokou Formation, the Hercynian Movement caused the basin to briefly rise. The shoal body of the Mao 2 Member was deposited along the high part the Mao 1 Member, and was developed in a northwest direction as a whole. The geomorphology laid the foundation for the development of reservoir scale and was conducive to the development of the intra platform shoal body.

The lithology of Maokou Formation is mainly dark gray, limestone, and black gray limestone, with local dolomitization. The Mao 2 Member is mainly a highstand system tract, and the bottom of the Maokou Formation is in integrated contact with the top interface of the underlying Qixia Formation. The Mao 2 Member is further divided into two sub members, namely the Mao 2 upper submember and the Mao 2 lower submember. The average thickness of the Mao 2 upper submember is about 45 m, and the average thickness of the Mao 2 lower submember is about 60 m. The practical drilling results indicate that the development of dolomite is the key to achieving high yield. From the well connection profile, it can be seen that the high-porosity dolomite reservoir of Maokou Formation is mainly concentrated in the lower Mao 2 Member (Figure 1).

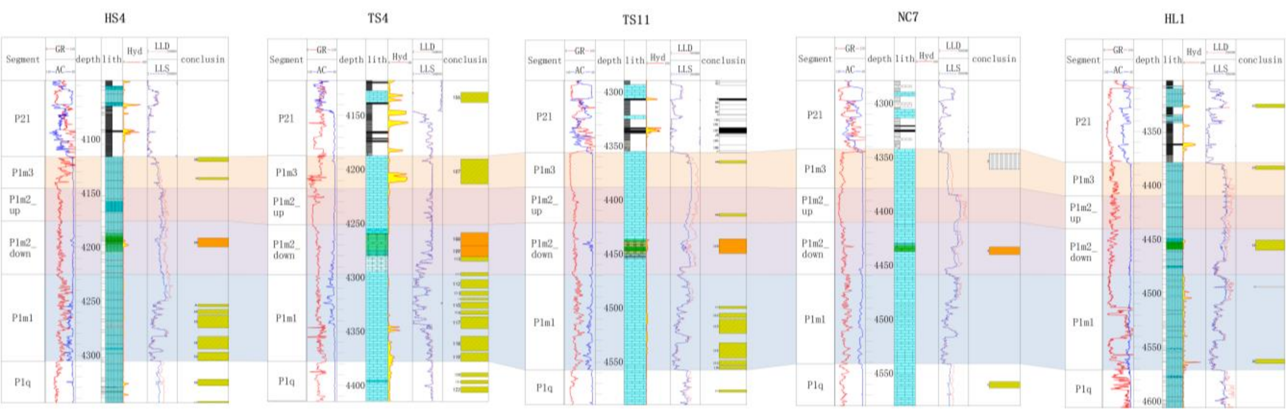


Figure 1. *HS4-TS4-TS11-NC7-HL1 Well Connection Profile.*

2.2. Characteristics of Physical Properties

The Maokou Formation has developed karst reservoir, the reservoir thickness of the Maokou Formation top at Well TT1 was about 5m. The seismic reflection is characterized by serrated weak amplitude valleys, which are overlaid with a stable strong amplitude valley.

The interior dolomite reservoirs of Mao 2+3 Member can be further divided into two categories: hydrothermal zone dolomite reservoirs and granular shoal reservoirs. Drilling reveals the development of hydrothermal dolomite reservoirs in the second and third members of the Maokou Formation, corresponding to strong amplitude peak characteristics in seismic profiles. In addition, in the Well TT1, the core section represents the development of a Class III fractured porous reservoir, with an average porosity of 1.93% and an average permeability of 0.107 md, which is a granular shoal reservoir (Figure 2).

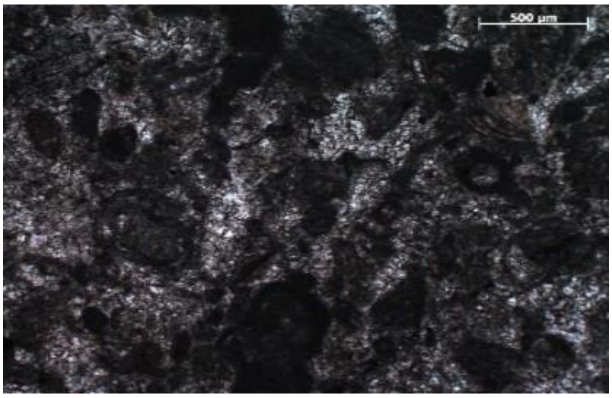


Figure 2. Core photographs of Well TT1 (2-37/424157.58-4157.61m).

3. Reservoir Classification Prediction Methods

Due to the development of large shoal bodies and clear seismic characteristics of reservoirs in the Mao 2 Member of the study area, it is the main target layer for implementing the Lower Permian with a volume of 100 billion cubic meters. Through comprehensive analysis of gas testing wells in the Maokou Formation, reservoir classification criteria were established based on lithology, plane porosity, porosity, and thickness of dolomite reservoir. The effective reservoirs in the Maokou Formation were divided into two categories: one is the high-porosity reservoir in the Maokou Formation, which is composed of dolomite, with an average porosity of >4%, a plane porosity of>10%, a thickness of the dolomite reservoir>8m, and a proportion of high-porosity intervals>60%. The other type is the medium-porosity reservoir in the Maokou Formation, which is judged based on its lithology of dolomite or calcareous dolomite, with an average porosity of 3%~4%, a plane porosity of 5%~10%, and a thickness of 4~8m. This study predicts the classification methods of reservoirs through the Maokou Formation, starting from inversion, and completes the quantitative prediction of reservoirs.

3.1. Rock Physical Model

On the basis of establishing the classification criteria for reservoirs in the Maokou Formation, a rock physical quantity plate for the Lower Permian carbonate rocks was created through the setting of rock physical parameter characteristics (Figure 3). Through the map of rock physical quantities, it can be seen that as dolomitization intensifies, the ratio of longitudinal/transverse wave velocity decreases. High-porosity dolomite reservoirs are catheterized by low longitudinal wave impedance and low transverse/longitudinal wave velocity ratio, therefore effective prediction can be achieved through post stack wave impedance inversion. The medium porous reservoir has a relatively low transverse to longitudinal wave velocity ratio compared to the low-porosity reservoir, which can be predicted through pre-stack inversion methods, making it easier to classify and predict the Maokou Formation reservoir.

3.2. Model Forward and Inversion

Forward modeling methods were used to further clarify the differences in seismic response characteristics between high-porosity and medium-porosity reservoirs in the Maokou Formation of the study area, and to determine the threshold for reservoir prediction [11]. By referring to the actual thickness and porosity characteristics of reservoirs and formations, several forward models are set up, mainly considering the changes in pores.

The first forward model is to set the reservoir thickness to 8 m. Through the results of forward modeling, it can be seen that when the reservoir thickness remains unchanged, the internal amplitude energy gradually increases with the increase of porosity, and the amplitude intensity in actual seismic profile is greater than 3000. On the basis of forward modeling, we also conducted inversion, and the inversion results showed that as porosity increased, the impedance of seismic reflection waves decreased (Figure 4). On the actual impedance profile, the impedance value was less than 16500. It is believed that wave impedance inversion can quantitatively predict high porosity reservoirs in the Maokou Formation. The second model set the reservoir thickness to 15 m, and the forward modeling results showed that when the reservoir thickness was large, the amplitude energy of the Mao 2 Member are more significantly enhanced (Figure 5). Therefore, the forward modeling results indicated that as the porosity and thickness of the reservoir increase, the seismic amplitude energy will be enhanced, and the high-porosity reservoir of the Maokou Formation can be predicted through the post-stack bright spot attribute. The third model sets the reservoir thickness to 4 m, and the forward modeling results showed that when the thickness of the Maokou Formation reservoir is small, the changes in internal amplitude energy were not significant with changes in porosity (Figure 6). Therefore, it is difficult to effectively predict the porous reservoir in the Maokou Formation through bright spot attributes and wave impedance inversion, and it is necessary to use pre-stack methods for prediction.

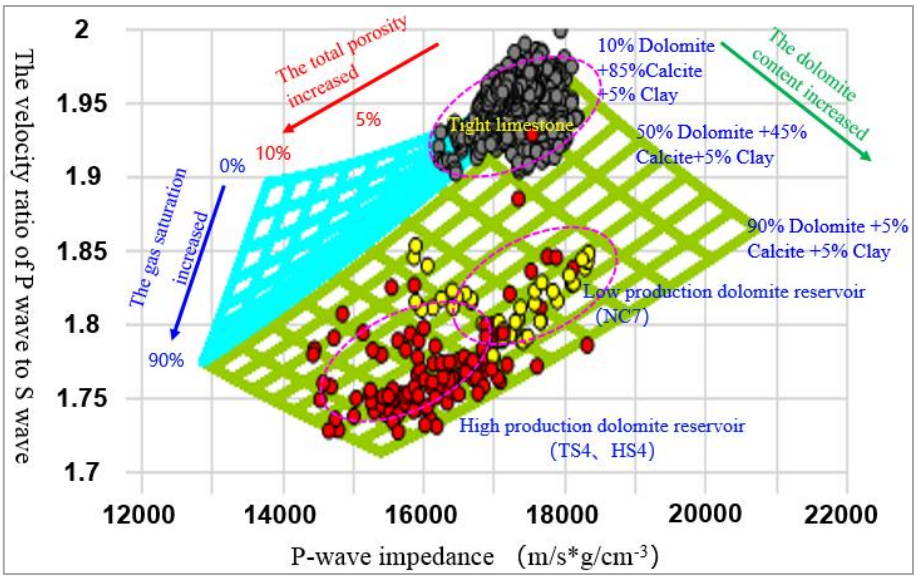


Figure 3. *Physical quantity plate of Lower Permian carbonate rocks in the study area.*

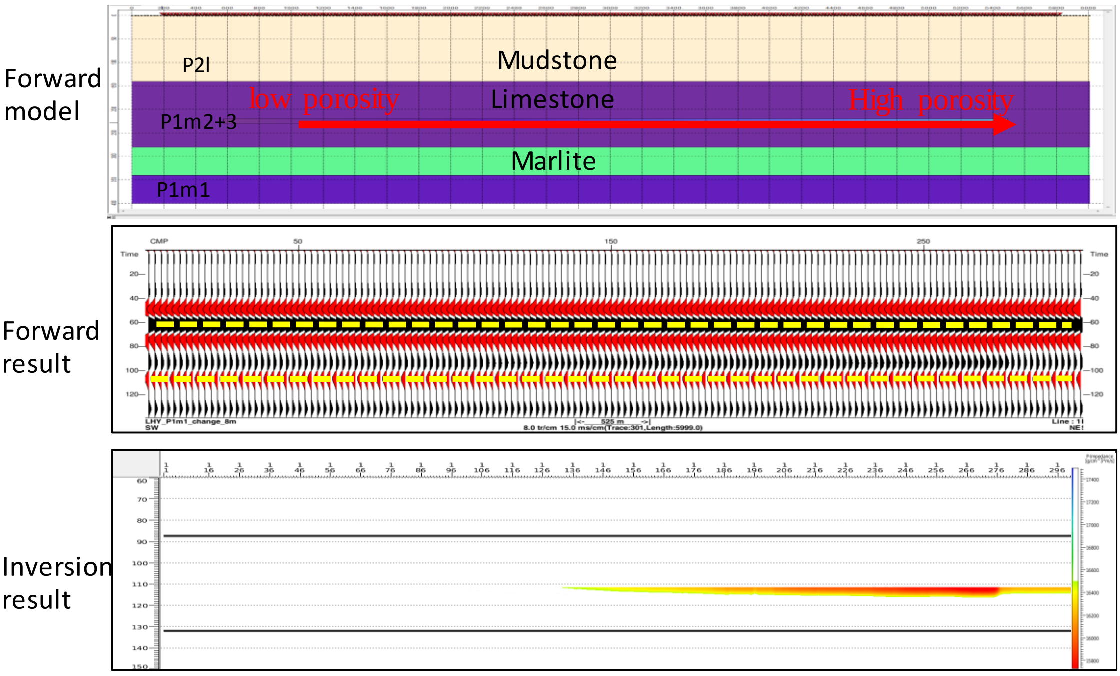


Figure 4. *Inversion results of reservoir model with a thickness of 8 m.*

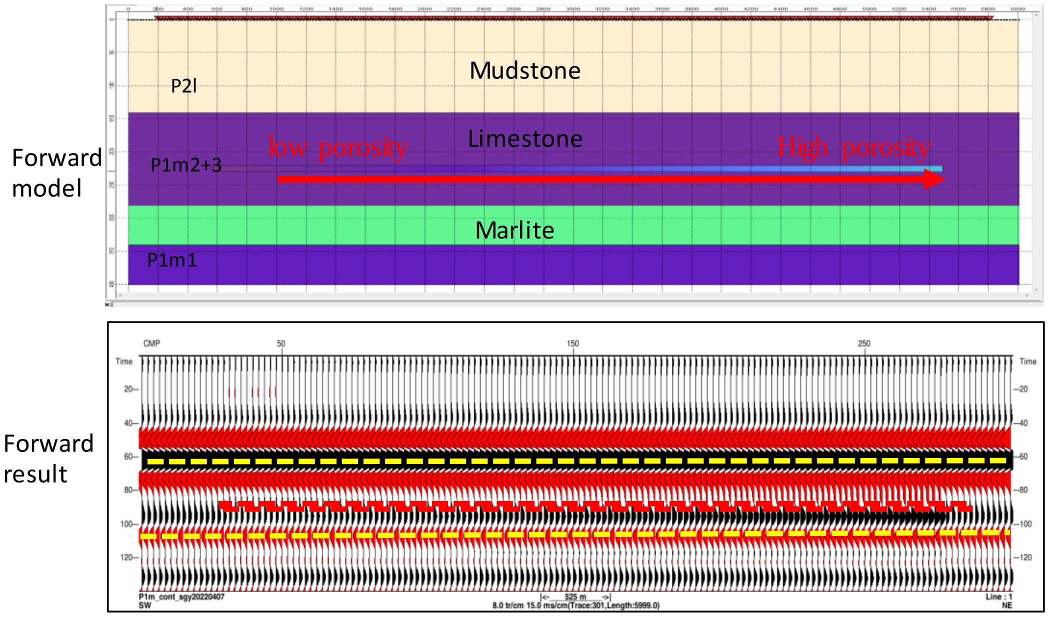


Figure 5. Forward modeling and results of a 15 m thick reservoir.

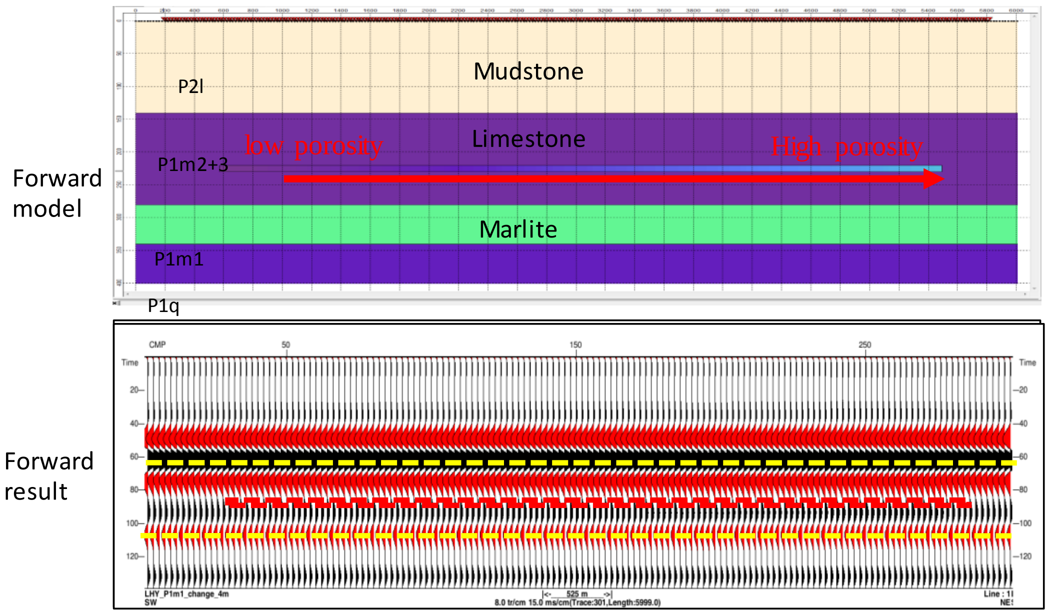


Figure 6. Forward modeling and results of a reservoir with a thickness of 4 m.

3.3. Reservoir Classification and Prediction Methods

3.3.1. Prediction Method for High-Porosity Dolomite Reservoirs

The research results through model forward modeling indicated that in the newly drilled three wells in the bright spot area of Mao 2 Member in this year, TS6, TS10, and TS14 are all bright spot positions but the reservoir is not developed, and there is a contradiction in the well seismic relationship. Through analysis, it is found that although it is feasible to predict high-porosity reservoirs using seismic attributes and impedance inversion, the amplitude intensity may also be affected by the velocity and anisotropy of the surrounding rock. Through analysis, it is believed that there are two main factors: firstly, the lateral variation of velocity in the lower Mao 1 Member has a significant impact on the amplitude energy of the Mao 1 Member reservoir. However, the internal reflection of the Longtan Formation in the overlying strata has little effect on the amplitude energy of the Mao 1 Member. The second issue is that the pre-stack AVO gathers in the Mao 2 Member reservoir are affected by anisotropy, and there are differences in AVO gathers in different directions, as well as issues such as residual time difference and long-distance stretching, which can affect the strength relationship of the stacked amplitude [12].

In the end, the technique of wavelet decomposition were adopted to remove sidelobes [13-15] to eliminate the influence of lateral velocity changes on the amplitude energy of the Mao 2 Member reservoir (Figure 7). Then, the aspects such as gather leveling, advantageous offset stacking, and intercept data calculation were carried out to improve data fidelity as much as possible.

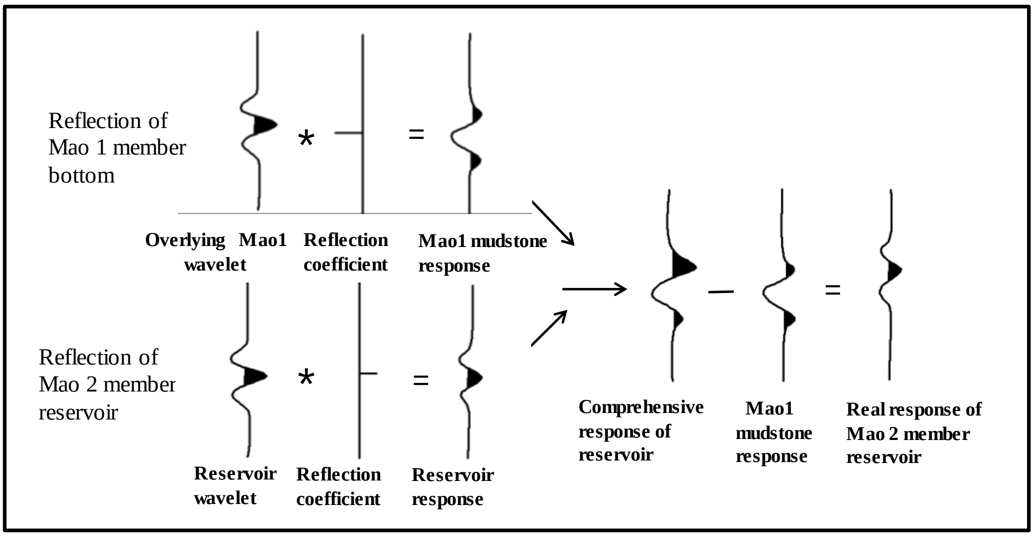


Figure 7. *Principle of wavelet decomposition and sidelobe removal in Mao2 Member reservoir.*

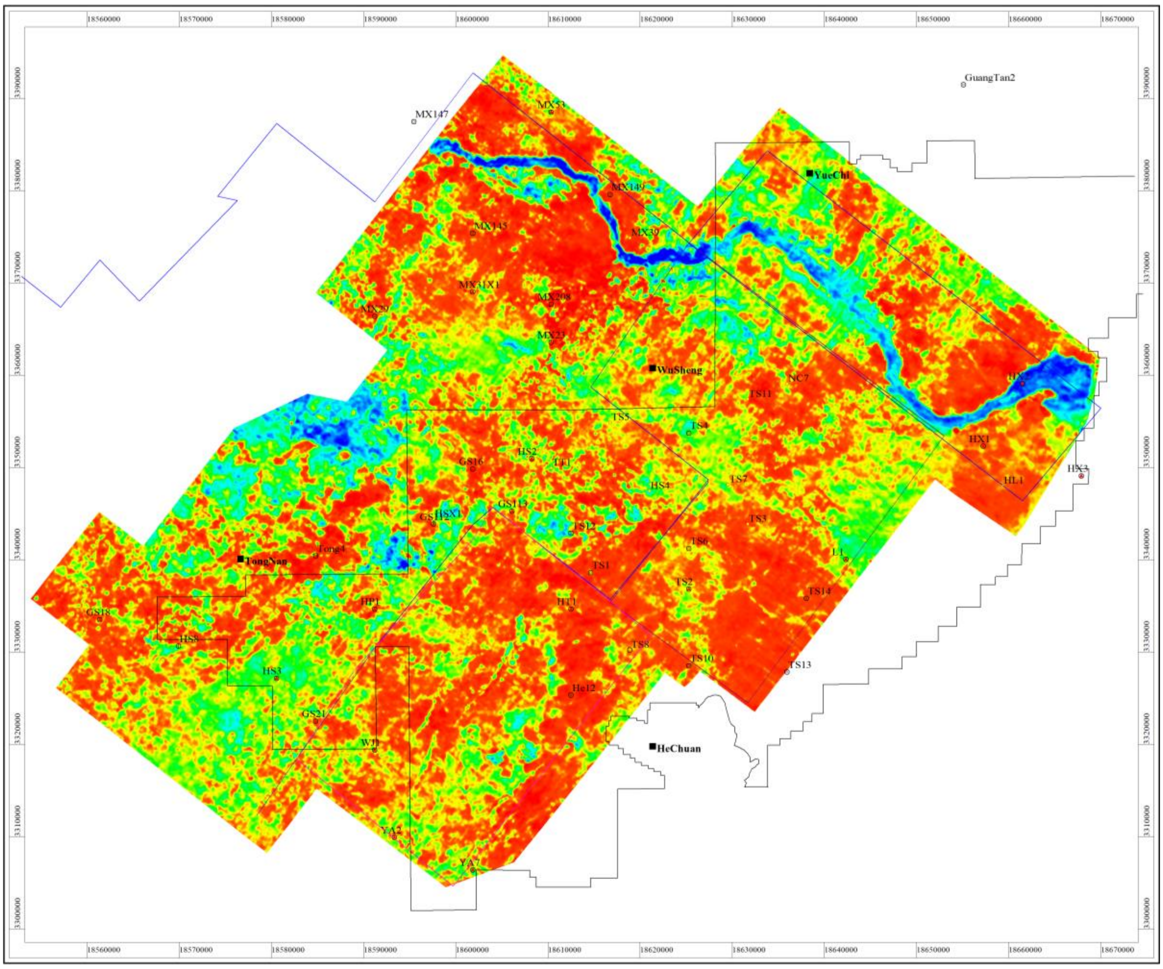
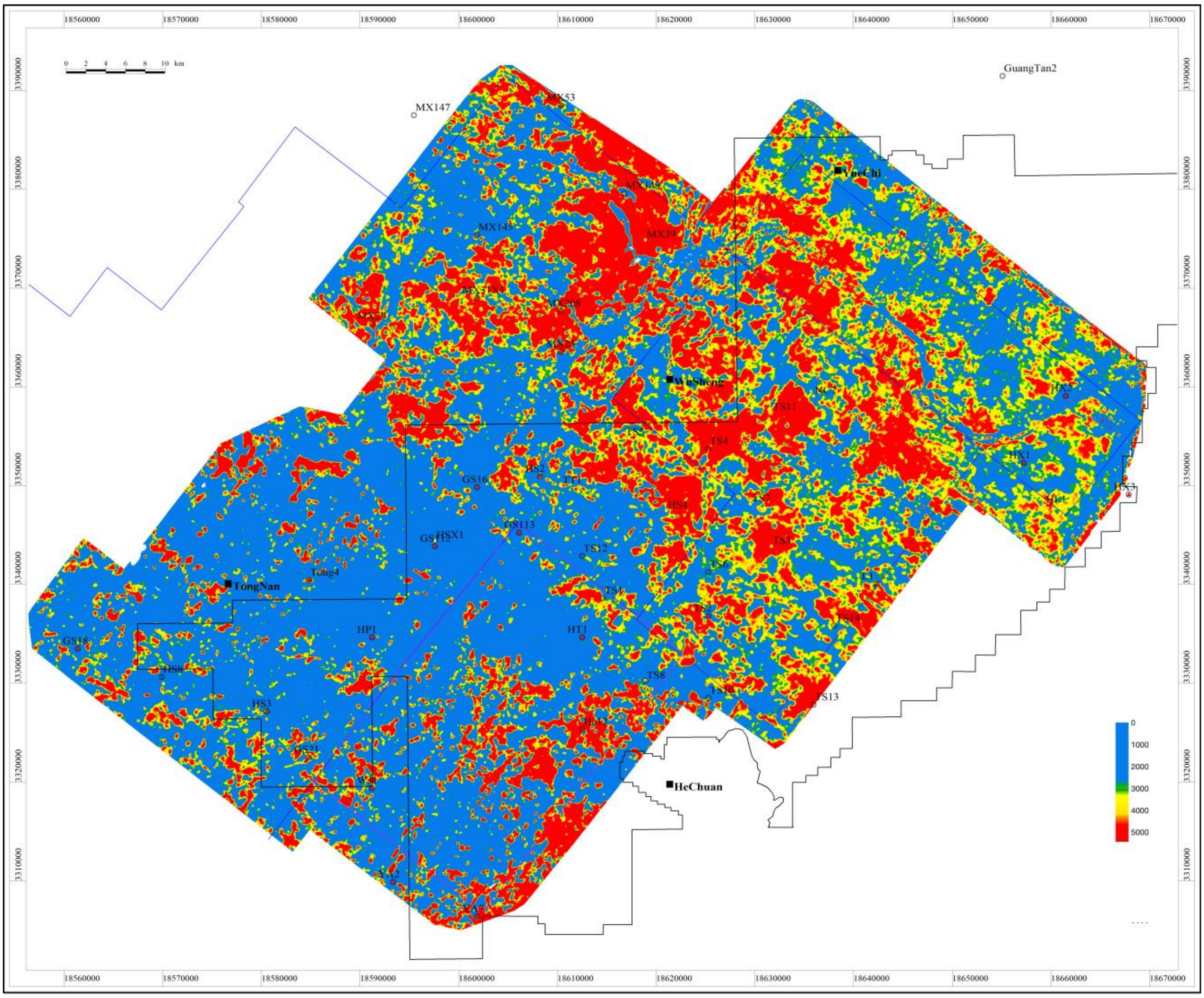


Figure 8. *Longitudinal Wave Impedance of Lower Permian Mao 2 Member in Hechuan Area.*

On the basis of conducting targeted analysis and interpretive processing, the sedimentary facies characteristics, stratigraphic distribution characteristics, reservoir characteristics and impedance relationship of the Maokou Formation in the research area were analyzed. Combined with the current status of seismic and logging data, the high-porosity reservoir of the Maokou Formation was predicted through post-stack wave impedance inversion. Based on the previous analysis, the threshold was determined, and finally the body carving function of the software was used to characterize the high porosity reservoir of Mao 2 Member. The results of the post-stack wave impedance inversion profile showed that the post-stack wave impedance inversion can be consistent with the seismic trend. The bright spot area of the Mao 2 Member corresponds to low impedance, which is the response of the high-porosity dolomite reservoir. Finally, the distribution of the high-porosity dolomite reservoir plane is predicted through the longitudinal wave impedance plane attribute plane map of the Mao 2 Member in the Hechuan continuous block (Figure 8).

3.3.2. Prediction Method for Medium-Porosity Dolomite Reservoirs

Through the rock physics data of the carbonate rocks in the Lower Permian, it can be seen that the Maokou Formation has a relatively low ratio of transverse and longitudinal wave velocities (Figure 3) for reservoirs with medium porosity (reservoirs with a porosity of 3%~4%). When the ratio of longitudinal and transverse wave velocities intersects with the impedance of longitudinal waves, it is found that it can be effectively distinguished. Therefore, it is determined to use the method of simultaneous pre-stack inversion to effectively predict the dolomite reservoirs with moderate porosity.



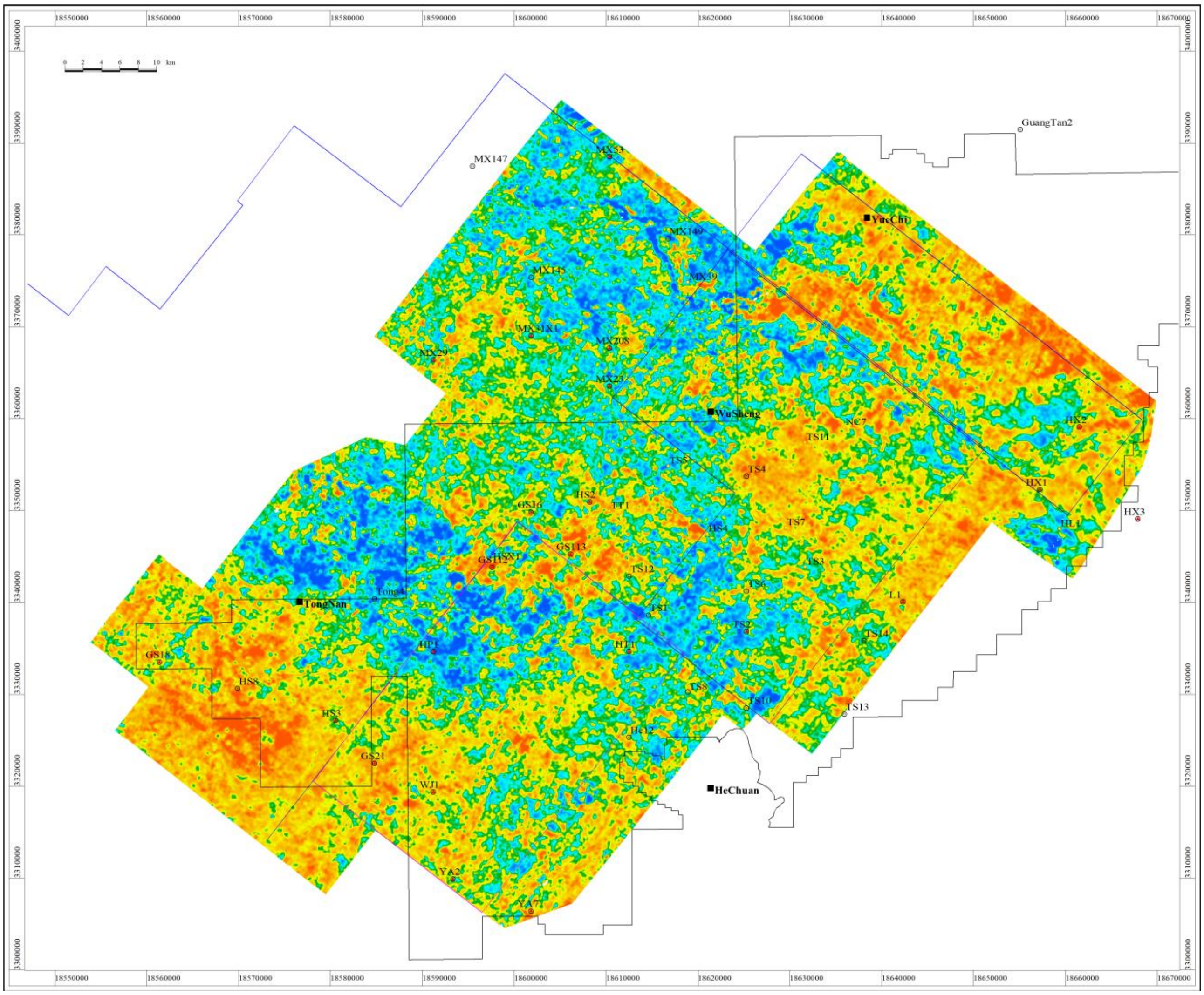


Figure 9. *Maximum peak amplitude attributes (upper) and longitudinal and transverse ave velocity ratio plane attributes (lower) of Mao 2 Member in Hechuan area.*

By using the longitudinal and transverse wave velocity ratios obtained from pre-stack inversion, the overall distribution of high-porosity reservoirs in the Mao 2 Member was characterized (as shown in Figure 9 below), and the distribution of high-porosity reservoirs was predicted based on the maximum amplitude (as shown in Figure 9 above). Finally, the distribution of high-porosity reservoirs in the Mao 2 Member of the Dalian work area was jointly predicted using two methods. Based on comprehensive analysis, it is believed that the overall development of the Mao 2 Member reservoir in the study area, with high porosity reservoirs developed in strong bright spots, and medium porosity reservoirs developed in areas with weak reflection intensity during this period. The prediction results showed that the medium-porosity reservoir is most developed in the southern and eastern parts of Well HSX1 in the central part of the study area, and the distribution area north of WJ1 is also relatively large.

4. Conclusion and Understanding

(1) The Maokou Formation dolomite in the Hechuan area has strong heterogeneity and significant changes in physical properties. There are significant differences in seismic response characteristics of reservoirs with different porosities, and suitable methods need to be selected based on the different physical characteristics of the rocks for prediction.

(2) Based on the establishment of classification standards for reservoirs in the Maokou Formation, a rock physics model of the Maokou Formation reservoir was established and a rock physics quantity plate for the Lower Permian carbonate rocks in the study area was developed. It was found that the high-porosity dolomite reservoir in the Maokou Formation is characterized by low longitudinal wave impedance and low longitudinal to transverse wave velocity ratio. Medium-porosity res-

ervoirs are characterized by relatively low longitudinal and transverse wave velocity ratios.

(3) Through forward modeling analysis, it was found that on the basis of optimizing the gathers and removing sidelobes through wavelet decomposition, the post-stack bright spot attributes can effectively predict high-porosity reservoirs in the Maokou Formation. However, for medium-porosity reservoirs, the method of pre-stack inversion can only be used to effectively predict the ratio of longitudinal and transverse wave velocities.

(4) When studying reservoirs in the Hechuan area, full consideration should be given to the influence of surrounding rocks on the seismic response characteristics of the reservoir, and effective methods should be selected to eliminate interference and highlight the true seismic response of the reservoir in order to effectively predict the seismic response.

Conflicts of Interest

The authors declare no conflicts of interest.

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