Study and Application of Facies-controlled Reef Reservoir Prediction Method in Eastern Sichuan Basin, China

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ABSTRACT. *The upper Permian Changxing Formation in eastern Sichuan has a large reservoir thickness, wide area and high reserve abundance, which has broad prospects for exploration and development. With the continuous development of exploration and development, the prediction accuracy of the distribution of bioreef reservoir is higher. Through a large number of studies and combined with the previous research results, this paper forms a facies-controlled reef reservoir prediction method, it fully integrates Geological understanding and seismic results, and divides the favorable sedimentary facies of reefs based on seismic attribute analysis and ancient geomorphological restoration. Using the effective seismic inversion technique to predict the distribution of bioreef reservoirs in the scope of favorable sedimentary facies. This method can effectively improve the prediction accuracy of reef reservoir and achieve better application results.*

Keywords: *The eastern Sichuan area; Changxing formation;Reefs;Facies-controlled reservoir prediction*

0. Introduction

The marginal zone of the pan Kaijiang-Liangping trough in the Sichuan Basin is a favorable place for the development of the Upper Permian Changxing Formation reefs [1-2]. Its organic reef reservoir boasts large reserves, high yield and good porosity, which makes it a high quality reservoir with great research value in marine carbonate rocks. Exploration works made in recent years have brought to the world the organic reef gas reservoirs such as Yuanba, Longhuichang and Longgang, which demonstrates great exploration potential on it. However, the continuous exploration has also posed great threat to the exploitation of organic reef gas reservoirs economically. And the main reason is that the reef reservoirs are highly heterogeneous, with large differences in vertical and horizontal distribution, which leads to the multiplicity[5-6] of reservoir predictions. Also, the low prediction accuracy of conventional earthquake at reef reservoir further contributes to partial drilling failure , sagging the development benefits.

Setting out from the research results made by predecessors, the author has done extensive researches focusing on the developmental characteristics of organic reef reservoir, and finally forms the ideas of phased bioreef reservoir prediction technology. Based on organic reef deposition model, it organically integrates logging, earthquake and geology, and performs well-seismic calibration to conclude the reflection character of organic reef reservoir. The techniques of seismic reflection intensity and paleo-geomorphology recovery are also adopted to divide the favorable sedimentary facies of the reefs; effective seismic inversion techniques are applied as well to the prediction of the horizontal distribution of organic reef reservoirs in the favorable sedimentary facies of the reef. It turns out that the application of this method in Block W of east Sichuan has yielded good results, which bolsters the exploration and development of organic reef gas reservoir.

1. Seismic reflection characteristics of organic reef reservoirs

Based on previous investigations, the actual data of the eastern Sichuan region and elaborate well-seismic calibration, the seismic reflection characters of the trough facies, platform margin facies and platform facies of the Changxing Formation Trough can be summarized as follows[7-8] : The reflection of the top boundary of the trough facies in Changxing is continuous and strong, with its interior presents parallel or sub-parallel reflection structure; while the amplitude of the top boundary of the platform margin facies (foreslope) is obviously weakened, with poor continuity and chaotic interior reflection. And the time difference between it and the underlying upper permian reflection layer is significant; As to the platform facies, it exhibits continuous seismic reflection, and the time difference between it and the upper permian layer is relatively large and stable, with the lateral change of the reflection layer region presents parallel reflection structure (Fig. 1).

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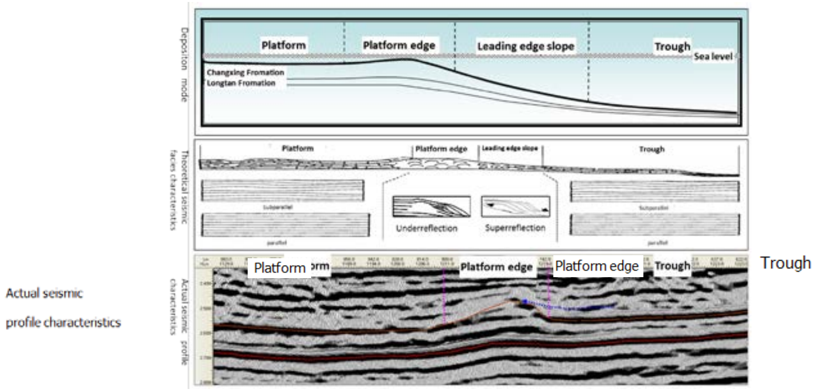


Fig.1 Sedimentary model and actual seismic reflection characteristics of bioreef reservoirs [7,8]

2 Prediction of phased organic reef

The above-mentioned analysis, combined with immense amounts of researches, contributes to the technique of phased organic reef reservoir prediction. The technique makes full use of the differences in seismic reflection characteristics between the trough facies and the platform margin zone, and applies the seismic amplitude properties to identify the boundry between them. Also, it can depict the boundry of the platform margin and the platform through palaeogeomorphic restoration, and divide the distribution of the platform edge facies of the favorable facies zone of organic reef development. Based on this fact, wave impedance inversion technique is adopted to the prediction of the distribution of bioreef reservoirs in the favorable sedimentary facies belt and platform margin facies.

2.1 Analysis of seismic reflection intensity

As a commonly used amplitude-like seismic attribute ,Seismic reflection intensity represents the lateral strength variation characteristics of seismic reflection interface [9-10]. Numerous forward researches, combined with the results of horizon calibration, unveil that the top boundry of Changxing Formation in the trough facies presents strong peak reflection with mild lateral variation. As to that of the platform margin facies, it generally presents valley reflection with great change in lateral strength; while the long apex in the platform facies shows medium-strong amplitude reflection with insignificant difference to that of the platform margin facies. Based on the above analysis and researches, the seismic reflection intensity attribute (Fig. 2) is extracted for each 10ms time window above and below the Changxing top interface. In the figure,the warm color represents the weak amplitude, indicating the platform margin zone and the platform phase; while the cool tone represents the strong amplitude, indicating the trough facies. As is clearly shown in the figure, the left side of the work area has a north-south strip-shaped amplitude change zone, which is the boundary line of the trough-platform edge, while the line between the platform edge and platform is blurred, which makes the seismic reflection intensity properties fail to work.

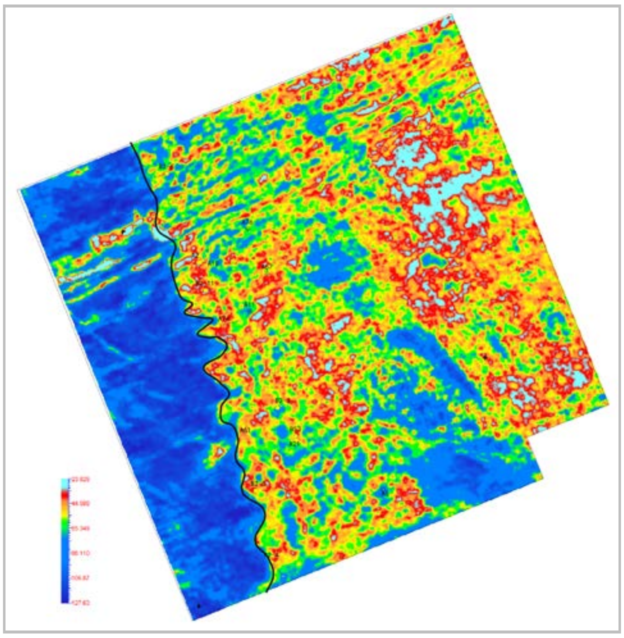


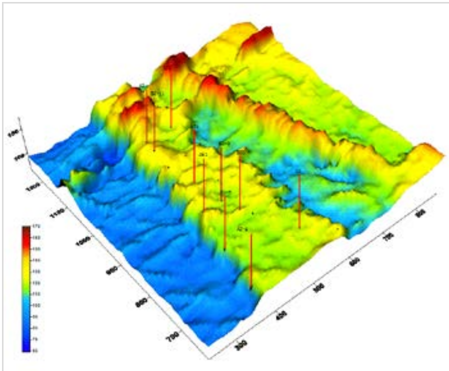
Fig. 2 Schematic diagram of seismic reflection intensity properties

2.2 Paleogeomorphic restoration

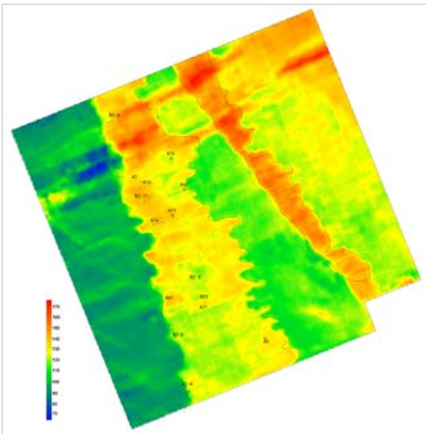
The sedimentary environment of the late Permian in sichuan basin is dominated by carbonate platform facies, platform margin facies and trough facies. Different sedimentary environments determine various water depths, paleogeomorphies and paleotopographic features, which further translate into different carbonate sedimentary characteristics, resulting in significant differences in sedimentary thickness of the strata. The deep-water trough facies has the lowest paleotopography, the slowest carbonate deposition rate and the thinest stratigraphic deposition; while the platform margin facies boasts relatively higher ancient topography and stronger water body energy, which is conducive to the development of organic reef and carbonate sedimentary construction, and its stratum sedimentary is the thickest; The carbonate platform facies terrain is relatively flat with mild variations. In places with relatively low paleoterrains, water body energy is weak, and stratum sedimentary thickness is thin, while in places with relatively higher paleoterrains, the water body energy is stronger, which interprets the local thickening of the stratum sedimentary[7,8]. In view of the development characteristics of Changxing reef reservoir, the application of paleogeomorphologic restoration technology can achieve satisfactory prediction of the platform margin zone.

The impression method and residual thickness method are by far the most commonly used and relatively proven paleogeomorphology restoration technologies [11].The impression method mainly takes advantage of the “mirror “relationship between some overlying isochronous surface and residual-and-thick paleogeomorphy, counting on the semi-quantitative thickness of the overlying strata to restore the paleomorphology. The residual thickness method defines the isochronous surface as the topography to be restored completes erosion and starts deposition of the overlying strata. Then a special layer in the sedimentary stratum is selected as the reference surface and levelled off. The residual thickness above the surface represents the the morphology of the ancient landform. In view of the sedimentary characteristics of the Changxing formation, the residual thickness method is an excellent option to rebuild palaeogeomorpholog during the study. And the bottom layer of the Permian Longtan Formation is used as the marker layer for layer leveling (Its regional sedimentation is relatively stable, and its seismic lateral direction boasts satisfactory comparability and traceability.) The growth and development of the organic reef reservoir leads to the continuous thickening of the Changxing Formation, which explains the increase of the thickness of the

Changxing Formation superimposed with Longtan stratum. Hence, the topographic morphology of the top boundry of Changxing formation falls into the category of paleogeomorphology of Changxing formation. As is clearly shown in the three-dimensional and plan views of the paleo-geomorphology (Fig. 3), the trough-platform boundary line is consistent with the prediction results of the seismic reflection intensity attribute, and the platform margin-platform phase boundary can also be characterized from the paleotopography.



a.Three-dimensional map of ancient landform restoration



b. Two-dimensional plan of paleogeomorphic restoration

Fig.3 Restoration map of the top boundary of the Changxing Formation in the W block of eastern Sichuan

2.3 Division of favorable facies of Changxing Bioreef

Based on the hydrodynamic conditions and sedimentary environment of the Changxing Formation in the eastern Sichuan Basin and the concerning research results made by predecessors, the sedimentary facies of the Changxing Formation in the eastern Sichuan Basin can be divided into open platform, platform margin,foreslope and deep-water trough. Given the boundary between the foreslope and the platform edge zone is blurred and both are bioreef reservoir development areas, this paper includes the foreslope into the platform margin for identification. The open platform refers to the central or outer open area of the platform and the vast shallow sea connected by it and the outer sea. With excellent water circulation, the platform belongs to typical shallow sea carbonate rock shelf deposit environment. The platform edge,as a high-energy environment, refers to the boundary between the carbonate platform and the deep water basin, which is subject to fierce wave and tidal actions. Its main rock types can be categorized as granular limestone, bioreef limestone, sub-facies such as shoals and reefs, and reefs are generally developed at the edge of the platform slope. The existing geological information reveals that the organic reef deposits in the study area are mainly developed in biogenic uplift (reef) area, which is the main reservoir type and belongs to the favorable exploration area; while the trough facies is a sedimentary environment in deep-water basin under the storm wave, with its main types of rock range from siliceous rocks, siliceous limestone to dark mudstone. Figure 4 is a sedimentary facies map of the Changxing Formation based on seismic attribute analysis and paleo-geomorphic restoration. The yellow marginal zone in the prediction map is a favorable sedimentary facies zone for the development of the organic reef reservoir. And as can be seen from the figure, the platform margin zone is distributed in the north-south strip; In addition,within the study area, there are two rows of favorable facies conducive to the organic reef development. In general, the first row on the left is the most favorable area for the development of reefs.

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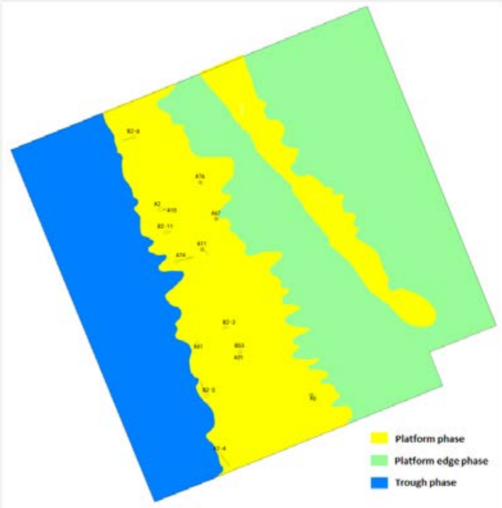

Fig.4 Map of favorable sedimentary facies zone of Changxing organic reef in W block of east sichuan

2.4 Reservoir prediction by seismic inversion

The petrophysical analysis has been conducted on different lithologies in the 10th well of the study area. It can be seen from the longitudinal wave velocity and wave impedance intersection map (Fig. 5) that the range of mud shale wave impedance is between 7000 and 13000g/cm3_m/s, while that of the organic reef reservoir is between 12500 and 17500 g/cm3_m/s, and the dense limestone, greater than 17500. g/cm3_m/s. Generally speaking , the reservoir (gas layer, water layer) and non-reservoir can be distinguished with wave impedance difference. Through the above analysis, it's safe to conclude that optimizing the wave impedance inversion method can improve the prediction accuracy and reduce the prediction multi-solution in the favorable sedimentary facies zone of the organic reef.

Wave impedance inversion is a seismic technique that adopts seismic data to invert stratum wave impedance [12-13]. As one of its branches, the colored inversion is relatively mature and effective. It firstly performs spectrum analysis on the wave impedance of the well, and at the same time conducts the spectral analysis of the seismic data around the well. Then, a matching operator is designed to match the spectrum of the earthquake with the impedance spectrum of the well; the matching operator is also applied to the seismic data, and is added to the low-frequency model to complete the inversion process. The inversion method does not require wavelet extraction during the process, and the establishment of the initial model is also unnecessary which reduces the error caused by inaccurate logging data,and makes the inversion results reflect the geological phenomenon more objectively .

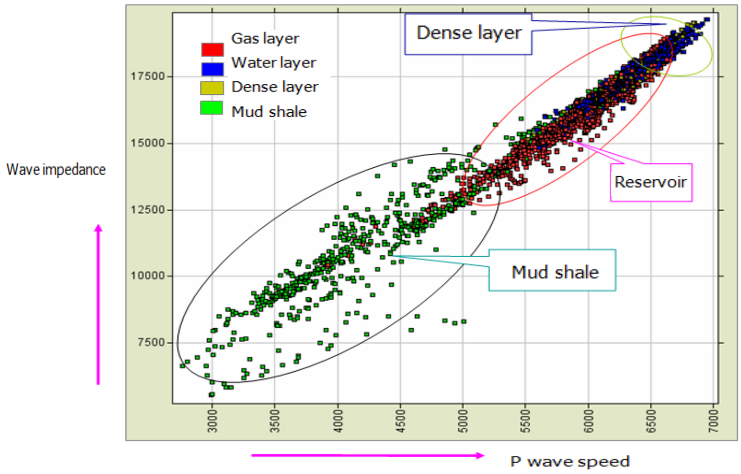

Fig.5 Intersection diagram of longitudinal wave velocity and P wave velocity in different rock layers of Changxing Formation

From the inversion profile of the typical well wave impedance in the W work area of eastern Sichuan (Fig. 6), the results can depict the lateral variation characteristics of the wave impedance in a satisfactory way. Combined with the results of petrophysical analysis, the reef reservoir in the inversion profile boasts distinguished characteristics(Yellow indicates the reef reservoir, while green indicates the mud shale,and blue indicates the dense limestone), and can be clearly distinguished from the trough shale. Based on the seismic inversion, the development law of the bioreef reservoir is predicted on the plane, and it's clearly that there are two organic reef developmental zones distributed in the north - south strips in the work area (Fig. 7). Among them, the first row of reefs on the left side is the main reservoir development area with large thickness, which is the main distribution area of organic reef gas reservoirs. The thickness of the second row is relatively small , and it has not yet been drilled, which makes it a potential exploration area of organic reef gas reservoirs.

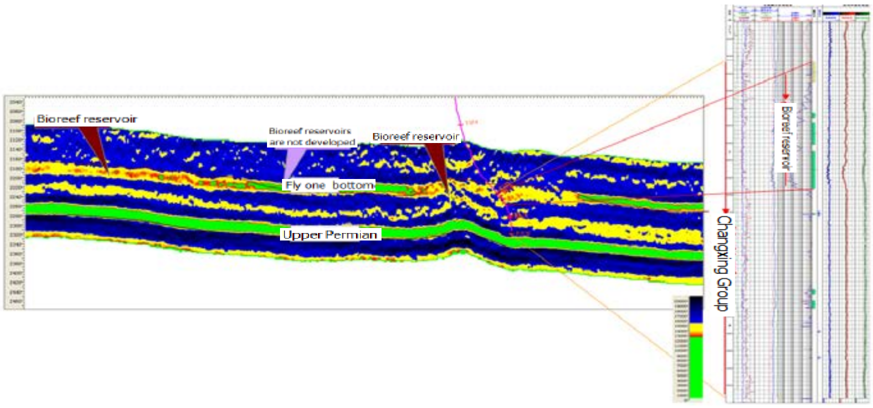

Fig. 6: Wave impedance inversion profile of typical well

3. Application effect

An analysis has been performed on the prediction results of 15 wells (10 known wells and 5 verification wells) in the study area , and it turns out that the10 known wells all have smaller reservoir thickness errors, and the prediction results are consistent with the wells. Among the 5 verification wells, the earthquake predictions error of 4 with their actual drilling results are small, and the total prediction rate is over 90%. The statistical analysis of known wells and verification wells in the study area fully demonstrates that the application of phased organic reef reservoir prediction technology can accurately predict the distribution of bioreef reservoirs and support the exploration of bioreef gas reservoirs.

Table 1 Error Table of Drilling Reservoir Thickness and Predicted Reservoir Thickness

Well Types	Well Name	Reservoir thickness above the well(m)	Reservoir thickness of earthquake prediction (m)	Absolute error (m)	complied

Known well	A11	0.625	2	1.375	Complied
	A21	29	36	7	Complied
	A74	44.8	48.6	3.8	Complied
	A10	42.875	45	2.125	Complied
	A2	50.75	52.8	2.05	Complied
	A61	18.6	20	1.4	Complied
	A67	1.75	2	0.25	Complied
	A76	2.625	3.8	1.175	Complied
	A5	38	41.2	3.2	Complied
	A2-4	33.975	40	6.025	Complied
Verification well	B53	8.875	36	27.125	nonstandard
	B2-6	17.5	18.5	1	Complied
	B2-11	50.75	53.1	2.35	Complied
	B2-3	38.5	40	1.5	Complied
	B2-5	11.25	13.5	2.25	Complied

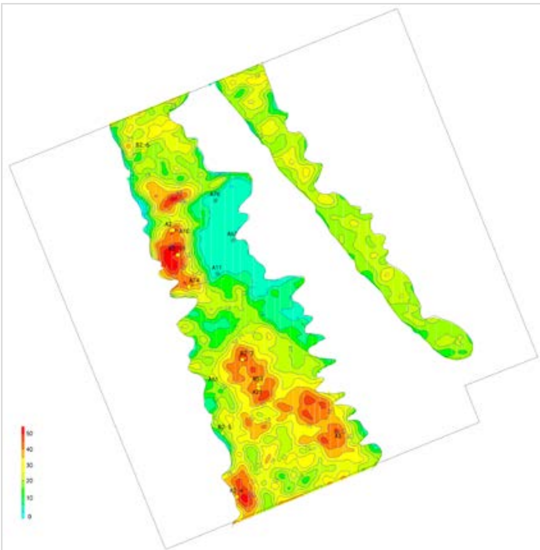

Fig. 7 Plan of thickness prediction of Changxing organic reef reservoir in W block of eastern Sichuan

4. Conclusion

(1) Through the exploration and application of phased organic reef reservoir prediction technology, the accuracy of organic reef reservoir prediction can be improved. The actual drilling method also proves that the technical method enjoys high reliability.

(2) The prediction results of the W-block bioreef reservoir reveals that the thickness of the reef reservoir along the platform margin zone is large and there exists multiple rows of reefs, which further confirms the huge exploration and development potential of the marginal zone on both sides of the trough.

(3) Phased organic reef reservoir prediction technology can be promoted and applied in northeastern Sichuan, thus further fuelling the exploration and development of bioreef reservoirs.

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