Subsalt Structure Identification With Pre-stack Depth Migration

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Summary

Due to the severe ray distortion caused by high velocity salt domes, accurate image of salt dome boundaries and surrounding sediments cannot be achieved with conventional time migration. The irregular shapes of the salt bodies, especially their top and bottom, can greatly impact the seismic reflections of the subsalt and surrounding layers, resulting in the pull-up of underlying strata, imprecise structure image, and distorted amplitude and oil-water contact. Meanwhile, reservoir properties are usually variable, because reservoirs are mainly in subsalt carbonate rocks with multiple pore types resulted from diagenesis and cracking.

This paper analyzes the geological features in central block of eastern margin of the Pre-Caspian basin of Kazakhstan, and demonstrates the successful imaging of subsalt carbonate rocks and the true shape of the underlying structures through the 3D pre-stack depth migration. The depth migration creates high precision data for pre-stack reservoir prediction, and subsalt structures are identified and delineated directly and effectively in depth domain with pre-stack depth migration volumes. The results have proven that 3D pre-stack depth migration is an effective tool for subsalt oil and gas reservoir identification and evaluation.

Introduction

There is variety of salt domes with complex shapes in the central block of eastern margin of the Pre-Caspian basin. , As high-velocity geologic anomalies, subsurface salt domes bring about a series of problems for conventional processing and interpretation in the seismic exploration. For example, false images of subsalt structure, abnormal stack velocity field, and difficult time-depth conversion of structural mapping, are all caused by complex wave-fields from irregular salt bodies.

Pre-stack depth migration is designed for imaging complex structures with strong velocity variations, especially horizontal variation. Complex salt domes are high velocity anomalous zones, which introduce strong velocity variation in horizontal and vertical directions. Consequently, depth migration should be effective in identifying subsalt structural traps. Our applications indicate that pre-stack depth migration produces reasonable seismic images for both salt domes and surrounding sediments. As an illustration, we present both a synthetic example and case study in this paper.

Geological settings

Figure 1 shows a typical subsalt reservoir with carbonate rocks in Middle-Upper Carboniferous formations in the area. The regional cap rocks consist of thick Lower Permian terrigenous sediments composed mainly of sand and shale with some carbonate inter-beds and salt bodies (Zhang et al, 2007). This is an ideal reservoir cap combination in this area.

The data quality on time migration section is sometimes better than that on depth sections. But the thick salt beds, as a high-velocity geologic unit, result in false formations and structures in time domain processing. There are large differences in the structural maps with variable velocity mapping at different research stages (Figure 2). For instance, the pay zone is lower than the depth of structural map; the drilling depth does not coincide with seismic results, leading to increased exploration risks.

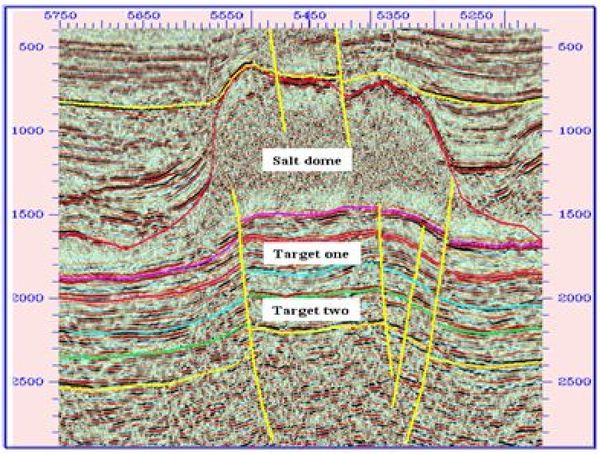

Figure 1. A typical time migration section in the area.

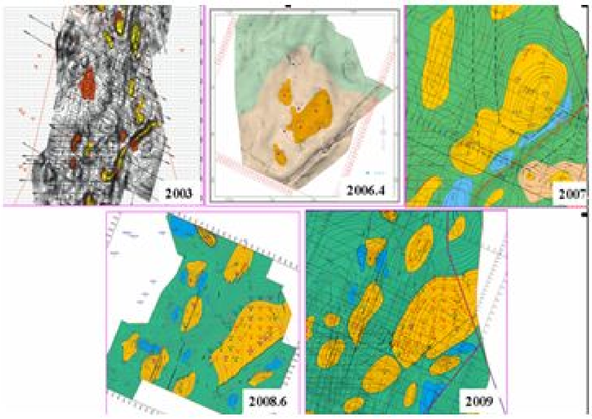

Figure 2. Structural maps at different research stages in the area.

Technical solutions

Subsalt seismic imaging in time domain is extremely difficult because of the insufficient illumination under the salt when seismic wave travels through the salt domes (Wang, 2008). Pre-stack depth migration can partially compensate for the lack of illumination, therefore offer better images of salt domes and surrounding sediments.

Pre-stack depth migration

Pre-stack depth migration generally uses Kirchhoff integration method to solve wave equation. For any subsurface image point, the record amplitudes are summed along the diffraction curve. The impulse response of the image point depends on velocity field and the geometry of sources and receivers.

Kirchhoff pre-stack depth migration can be summarized into a mathematical function:

$$out(x, y, z) = \sum \frac{z}{f(r_s, r_g)} in'(\bar{s}, \bar{g}, t_s + t_g)$$

where (x,y,z) are the output positions, (s,g) are surface positions of sources and receivers, t_s and t_g represent respectively travel times from a shot point to the reflection position and from the reflection position to a receiver position, variable r_s and r_g indicate the distance from an output position to the shot and receiver positions, respectively. The function f (r_s, r_g) is amplitude related to r_s and r_g.

Recently, there have been many new methods and improvements for Kirchhoff migration, such as spectrum decomposition migration and anisotropy migration. For amplitude preservation during the Kirchhoff summation, the input samples are multiplied by true amplitude weights that enable us to recover the reflection amplitude of subsurface horizons. The final equation for the weights is:

$$A = (t_S + t_R)\left(\frac{t_{0,S}}{t_S^2} + \frac{t_{0,R}}{t_R^2}\right)$$

where t_S is the travel time from the shot location to the image point, t_R is the travel time from the receiver location to the image point, and $t_{0,S}$ and $t_{0,R}$

are the vertical times from the image point to the shot and receiver elevations, respectively.

Kirchhoff pre-stack depth migration is usually divided into three steps: velocity modeling, travel time calculation, and depth migration. Among these, the velocity modeling is the key procedure. In fact, velocity model and geological imaging depend on each other. In other words, precise imaging depends on accurate velocity model, while precise image helps obtain accurate velocity model.

Theoretical model

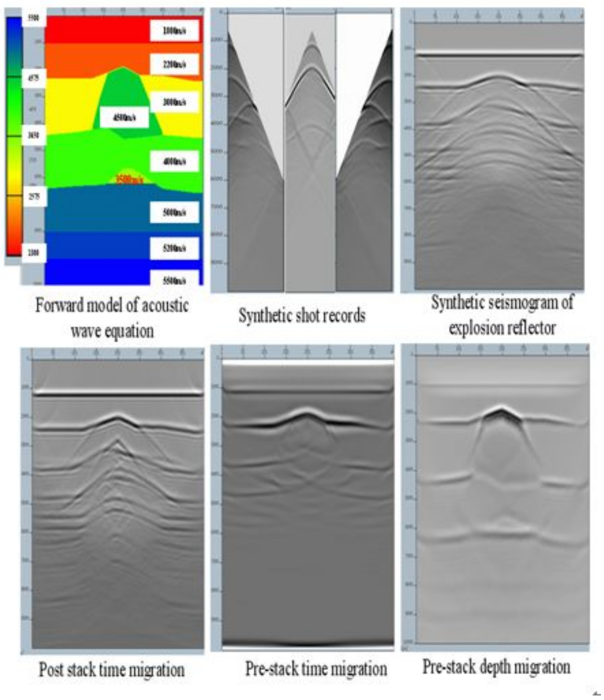

Figure 3. The forward modeling and different migrations.

Figure 3 shows the forward modeling with acoustic wave equation over a salt dome similar to that under study. In the model, the top and bottom of the salt dome is relatively complex; and the salt velocity is 4500 m/s. There are two formations overlying the salt dome with velocities of 1800 m/s and 2200 m/s, respectively. There is a layer of 3000 m/s intersecting the flanks of the salt dome, a complicated layer of 4000 m/s underlying the salt dome that hosts a reservoir with a velocity of 3500 m/s, and three flat strata beneath.

Complex wave field under the salt dome can be seen in the synthetic seismogram section from the explosion reflector; and the post-stack time migration fails to image the model. The pre-stack time migration improves the images of the top and flanks of the salt dome, but is not effective in imaging the bottom of salt dome, subsalt strata, or the reservoir. In contrast, however, the pre-stack depth migration gives precise images for all units in the model.

Target-oriented salt dome modeling for land data pre-stack depth migration

①Pre-stack-depth-migration-oriented CMP gather processing

The land salt dome data problems, such as serious interference waves, weak energy beneath salt dome, strong lateral velocity variation, etc., has to be solved as much as possible beforehand. Interferences needs to be suppressed, precision of statics has to be improved for energy balance and higher S/N ratio without losing validity. The purpose is to provide high-precision CMP gathers for pre-stack depth migration.

Refraction statics is used to solve the long wavelength statics, while frequency-dependant residual statics is used to solve the short and middle wavelength statics. In addition, noise removing, amplitude compensation and deconvolution are employed to achieve high S/N ratio and high fidelity CMP gathers for pre-stack depth migration subsequently.

②Abnormity analysis of stack velocity spectra in T-X domain

Normally, there is distinct difference between salt dome and surrounding rocks for their velocities and images, especially for velocities, and these differences can be characterized on stack velocity spectra. The thickness and spatial distribution of salt domes can be investigated with these spectra, which help to primarily study and delineate the salt domes (Figure 4).

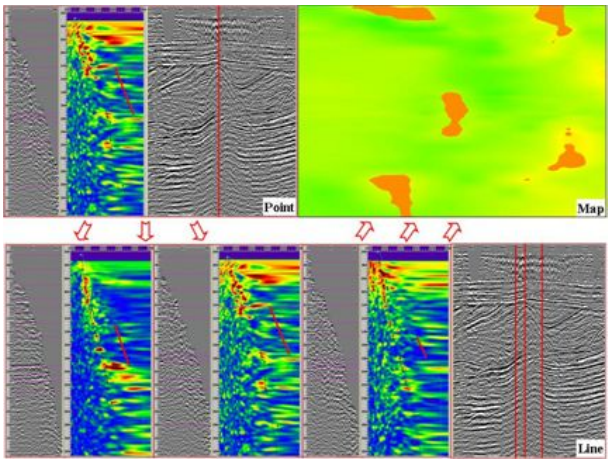

Figure 4. Point-line-map technique for 3D view of complex salt dome with abnormal analysis of stack velocity spectra. The thick red lines indicate the locations of spectra, and the thin red ones are fingered at salt dome.

③Salt dome picks on pre-stack time migration

With better imaging for flanks of salt domes on pre-stack time migration (Figure 5), referring to prior interpretations on post-stack time migration, and based on abnormity analysis on stack velocity spectra, the picks for the flanks of salt domes can be improved in T-X domain.

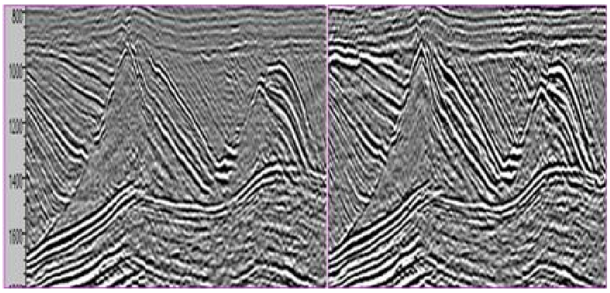

Figure 5. Pre-stack time migration (right) showing better imaging for flanks of salt dome.

Figure 6 shows a salt-dome-crossing section of pre-stack time migration, which is very helpful to track flanks and the bottoms of salt domes efficiently and precisely.

Additionally, pre-stack time migration can remedy, to a certain extent, the lack of low frequencies to improve the imaging at the flanks of salt domes. Dip-corrected RMS velocities of pre-stack time migration can be converted as more precise initial interval velocity for pre-stack depth migration.

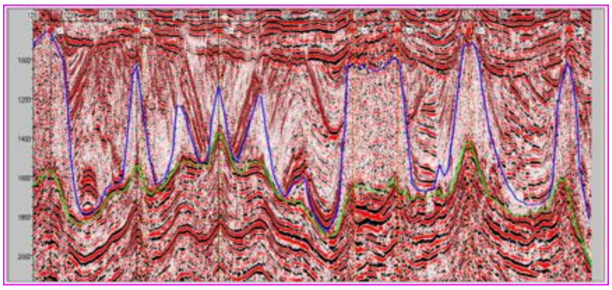

Figure 6. Salt-dome-crossing section of pre-stack time migration helpful to track flanks (blue line) and bottom (green line) of salt domes.

④Picks of salt dome with CIP gather

During iteration of pre-stack depth migration, CIP gathers can show some distinct difference at flanks and bottoms of salt domes (Figure 7). Therefore, CIP gathers help confirm where the flank is and where is the bottom of salt domes.

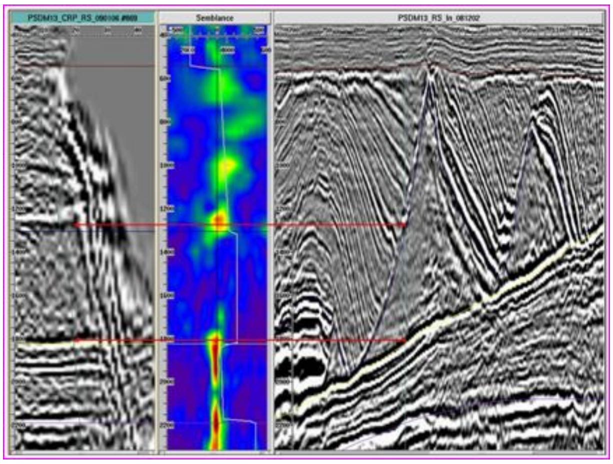

Figure 7. CIP gathers of pre-stack depth migration used to track flanks and bottom of salt dome.

⑤Iterative pre-stack depth migration constrained with geology, well log, and drilling information

Geological concept helps a lot for velocity model building; geological knowledge, well log information, and drilling information are analyzed comprehensively beforehand, in order to improve pre-stack depth migration capability for solving practical geological problems.

As to the multi-step modeling technique, the tendency is to qualitatively constrain the trend of spatial velocity variation with well log information (Figure 8) in order to find and then exclude velocity abnormality for eliminating the deceptive structures, and qualifying more geological concept into velocity model. At this time, pre-stack depth migration focus more on its imaging accuracy, to ensure special imaging, to fulfill quality control of pre-stack depth migration itself, such as flattening CIP gathers as much as possible, and having closed-to-zero residual moveout along horizons as much as possible.

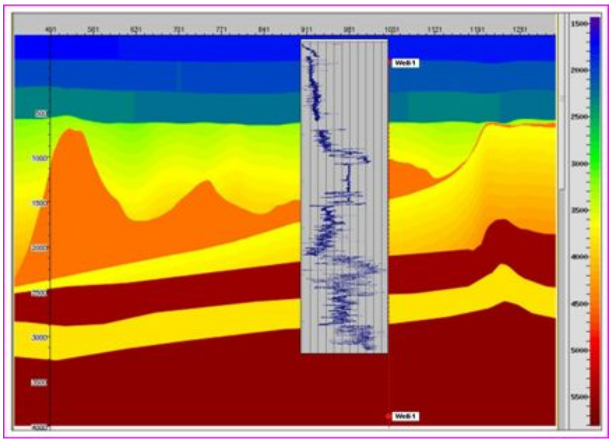

Figure 8. Velocity model constrained by acoustic log data.

As for the overall adjustment on velocity model, the tendency is to quantitatively improve the accuracy of depth imaging by drilling information (Figure 9), so that the imaging of pre-stack depth migration will be close to, but not equivalent to the drilling results and existing geological knowledge as much as possible; at the same time, keeping its advantages and characteristics of imaging accuracy in spatial

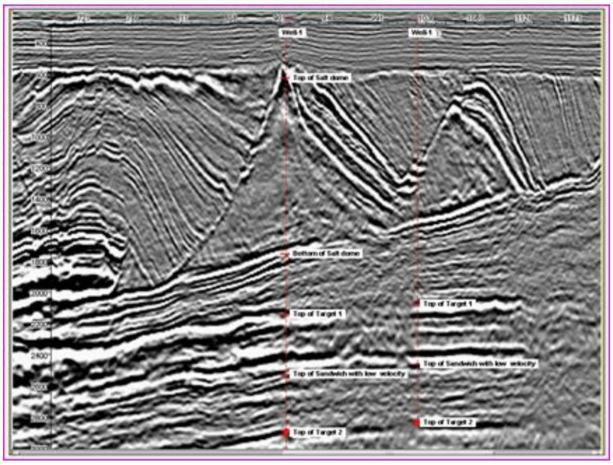

Figure 9. Picks of salt domes and target formations with the help of drilling data.

position. Here, variety of information is used on entire velocity model to perform partial adjustment, and the posterior results are used to verify the prior results. Specially, partial adjustment on velocity model can be done to make it more reasonable and efficient.

Real data applications

Because of the complex shapes of the salt body and the seismic ray distortion at the junction of the salt dome, accurate imaging of salt dome boundaries can not be achieved by time migration (Zhang and Shen, 2003). Pre-stack depth migration is currently the most effective seismic imaging technology for complex structures. The key issue is to establish reasonable velocity model consistent with underground geological features using up-to-date hardware, the latest software technology, and seismic, geological, drilling, and well log data. In this study, high precision imaging of complex salt body and subsalt strata has been achieved with pre-stack depth migration. New well locations have been planned based on the new depth structural map; and the successful rate has greatly improved. The depth processing not only shortens the exploration cycle, but also reduces the cost.

Clear seismic features on depth sections

Pre-stack depth migration results much more clearly delineate the salt dome boundaries, Characteristics of seismic wave group of the salt dome and subsalt formations are more identifiable. Meanwhile, depth migration also eliminates pseudo faults due to the dramatic velocity changes in the horizontal direction (Figure 10).

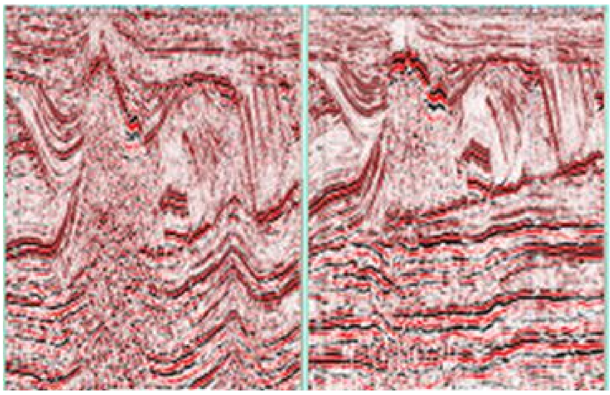

Figure 10. Comparison of pre-stack time migration (left) and pre-stack depth migration (right).

Reliable structures on depth sections

Pre-stack depth migration solves a suite of problems that can occur with ordinary time processing and interpretation. The pull-up effect on the underlying formation due to high velocity salt dome is generally eliminated; the images of subsalt structures become more reasonable. The drilling results confirm that subsalt structures interpreted with pre-stack depth

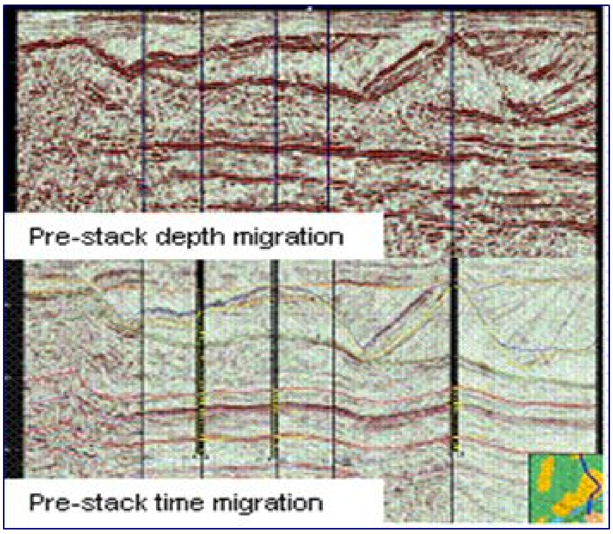

Figure 11. Comparison of pre-stack depth migration (up) and pre-stack time migration (below) of a well-tie seismic section in the study area.

migration is reliable. Figure 11 is a well-tie seismic section in the study area. Pre-stack depth migration result reveals that the structural trap is a large complete anticline.

More accurate oil-water contact on depth sections

Pre-stack depth migration restores the real structure under high velocity salt dome. More importantly, this technology is also more effective in imaging the heterogeneity of the subsalt reservoir caused by multiple types of pores in carbonate, the impact of diagenesis and cracking, and variation in reservoir properties. Pre-stack depth migration preseves relative amplitude for subsalt carbonate reservoir. Consequently, the method is conducive to subsalt structure identification, reservoir prediction, and attribute analysis.

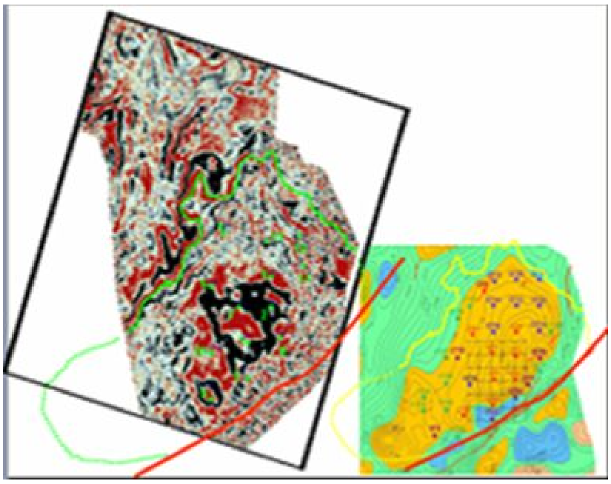

Figure 12. Oil-water contact of pre-stack depth migration (left) and conventional structural map (right).

Figure 12 shows the oil-water contact of a subsalt trap indicated by the green line on the pre-stack depth migration slice and a yellow line on the conventional structural map. Pre-stack depth migration results reveal that the oil-water contact of subsalt traps in carbonate rocks is very complex and larger in size than shown on the conventional structural map. Drilling results have confirmed that the results of pre-stack depth migration are correct.

Detailed structural map from depth migration

Since there are 17 salt domes in our study area, it is difficult to construct a reasonable depth velocity model for pre-stack depth migration. Integrated geological-geophysical salt dome carving makes it possible to build the depth-velocity model consistent with the geological conditions, and to allow pre-stack depth migration to locate complex geological targets to their relatively correct spatial positions. As a matter of fact, pre-stack depth migration images are close to the drilling results and geological knowledge. At the same time, pre-stack depth migration is also effective in resolving horizontal changes in subsalt reservoir. Compared with the structural maps with time-domain variable-velocity mapping, ray tracing mapping and other methods, pre-stack depth migration is more reliable in identifying subsalt structure characteristics.

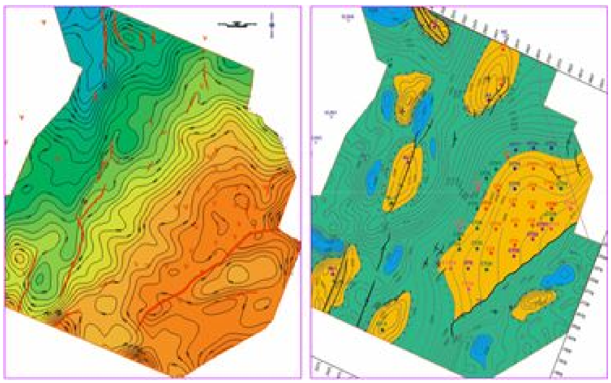

Figure 13. Comparison of structural map with pre-stack depth migration (left) and conventional structural map (right).

Figure 13 shows a comparison of structural map with pre-stack depth migration and conventional structural map .It can be observed that the depth map from variable velocity mapping in time domain exhibits striping from north-east to south-west. For one of the largest traps, the structure contours are very simple, but quite different from the actual drilling results. On the structural map from pre-stack depth migration, there is a feature with a large north-east to south-west structure setting, providing the strongest evidence for further understanding the causes of the reservoirs. Moreover, 18 new exploration wells have been drilled, and depth accuracy of pre-stack depth migration has been confirmed by these subsequent drilling. Compared to the drilling results, average depth errors for the two reservoirs from pre-stack depth migration are 14.86 and 21.56 meters respectively. Both are less than 1%.

Conclusions

1. In this study, high precision imaging of complex salt body, salt dome flanks and reasonable subsalt strata has been achieved with pre-stack depth migration.

2. The depths of the two reservoirs obtained from pre-stack depth migration are consistent with drilling results. The structural map retrieved from pre-stack depth migration shows reliable geological structure in detail.

3. 3D pre-stack depth migration preserves relative amplitude that is important for the prediction and characterization of subsalt carbonate reservoirs.

4. The depth processing not only shortens the exploration cycle, but also reduces the cost.

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