Ultra-deep Land Seismic Exploration

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Summary

Ultra-deep (deeper than 6,000 m) oil and gas exploration is increasingly critical to global resources supply, while it faces significant geological/geophysical challenges such as complex deep structures and stratigraphy distribution, which, in many cases, make the seismic prospecting possesses low signal-to-noise ratio (SNR), low resolution, poor imaging, and ambiguous interpretation. To address these issues, BGP has made dedicated R&D in four key techniques: energy enhancement and noise reduction, band extension and signal preservation, velocity model building and imaging, and comprehensive geological analysis. Successful applications of these technologies in Tarim Basin and Sichuan Basin, have significantly improved imaging quality and reservoir characterization accuracy, leading to the discovery of more substantial traps and high-yield wells.

Introduction

The definition of “ultra-deep” is various in the industry. According to the China's drilling engineering standard, formations that are buried deeper than 6,000 meters are classified as ultra-deep layers. By the end of 2018, nearly 200 industrial deep oil and gas reservoirs had been discovered globally, while most of them are distributed along the Tethyan domain. Over the past decade, the worldwide proportion of recoverable ultra-deep oil and gas has continued to increase. Ultra-deep oil and gas reservoirs are, and will continue to be, critical components of the global resources supply (Inan R M M et al., 2022; Juboury S A A et al., 2023; Li Z, et al., 2020; Mann P et al., 2003).

However, there are substantial technical challenges for ultra-deep oil and gas exploration. The major challenges for seismic exploration are low SNR and low resolution of ultra-deep seismic data (Fig.1). Since seismic waves must travel through more layers with longer paths, the absorption and attenuation of these waves are more pronounced. The reflections in ultra-deep layers experience strong energy attenuation, which generally keep only less than 10% of their initial energy. In addition, the longer the path, the more complex velocity field the seismic wave may experience, which brings difficulties to achieve the accurate target-oriented migration.

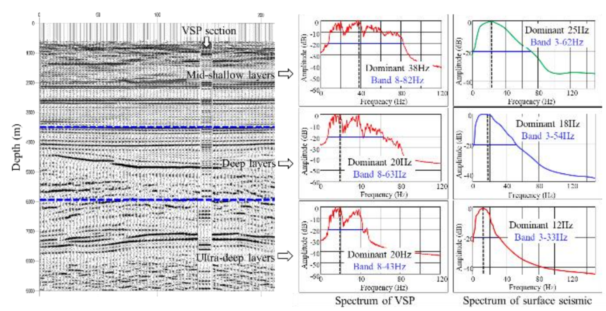

Fig.1 Energy attenuation from shallow to ultra-deep layers

Technical advances

To copy with challenges of ultra-deep exploration, BGP has made many researches and developments from acquisition, processing to interpretation. And progresses of four key aspects are as follows.

1. Energy Enhancement & Noise Reduction

a) High-density 3D acquisition

High-density 3D acquisition can provide sufficient sampling of both signals and noises, which is much helpful to suppress noises in later processing stages.

With the increase of fold and trace density, the seismic imaging quality improved significantly (Fig.2).

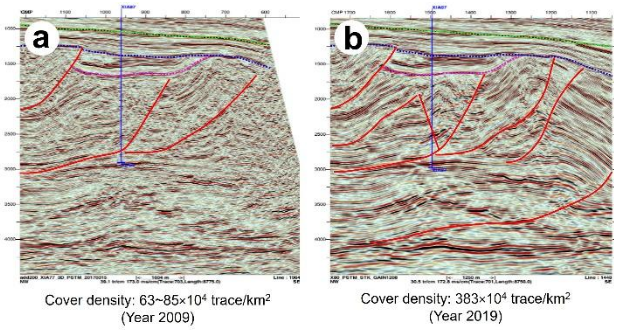

Fig.2 3D seismic sections with different acquisition density

b) Small-array receiving

Low-frequency geophones have better responses to low-frequency components, while small-array can protect high-frequency and increase the energy. Therefore, we use 5Hz low-frequency high-sensitivity geophones or small array in acquisition, which can acquire weak signals of ultra-deep layers.

c) Multi-modal decomposition & compressed sensing

The multi-modal decomposition technique can help to extract weak signals, and compressed sensing can reconstruct and suppress random noises. After these processing, the SNR of ultra-deep layers can be apparently improved.

d) Multiple elimination

When seismic waves penetrate deeper and more complex formations, more multiples develop inevitably. We have integrated conventional multiple prediction algorithms and upgraded to the current multiple elimination method. This technique is particularly suitable for the structures with strong multiples, as it helps to recover weak primary signals from ultra-deep layers.

2. Band Extension & Signal Preservation

a) Wide-azimuth 3D acquisition

Wide-azimuth 3D acquisition data can be used to handle the spatial heterogeneity and anisotropy of highly compacted ultra-deep layers and to better identify ultra-deep geological bodies with higher accuracy (Fig.3).

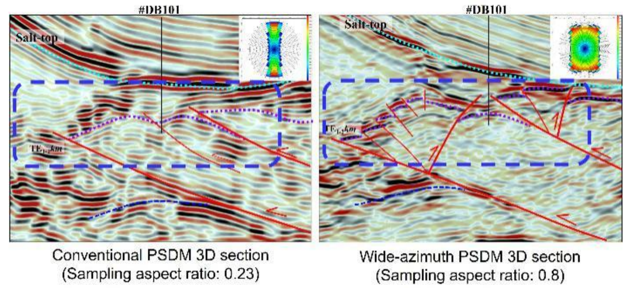

Fig.3 3D seismic sections with different acquisition aspect ratios

b) Broadband (Low-frequency) source

Physically, low-frequency can penetrate deeper horizons and broad frequency band has higher resolution. Taking these advantages, the vibrator (EV56 source) can provide stable low-frequency and broadband output. Compared to dynamite sources, the vibrator offers far stronger ultra-deep energy (Fig.4).

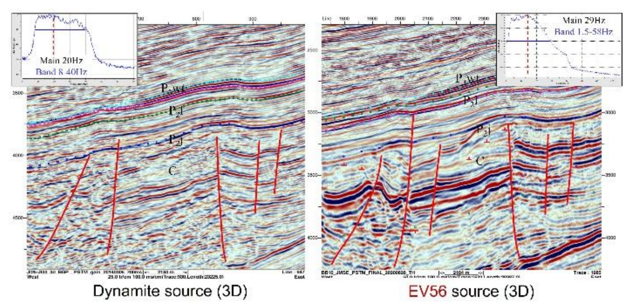

Fig.4 Energy enhancement of ultra-deep signals with broadband and low-frequency EV 56 source.

c) Q-compensation

We have updated a series of algorithms from Q-model building, Q-compensation, to Q-migration, which compensates weak signal, and enhances the ultra-deep energy (Fig.5).

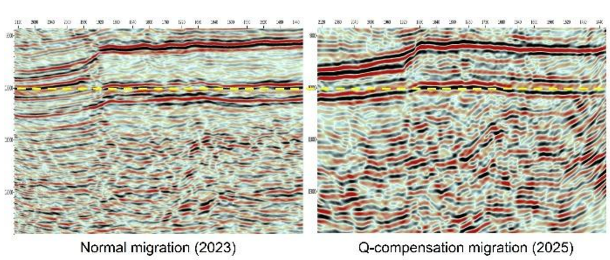

Fig.5 Enhancement of ultra-deep signals energy after Q-compensation

3. Full-azimuth angle-domain tomography & migration

Taking advantages of full-azimuth angle gathers, the full-azimuth angle-domain tomography is adopted to build velocity model (Fig.6-a). It can highly improve the accuracy of velocity model with heterogeneity. Moreover, the angle-domain migration provides clearer imaging results with definite faults and structures of strata (Fig.6-b).

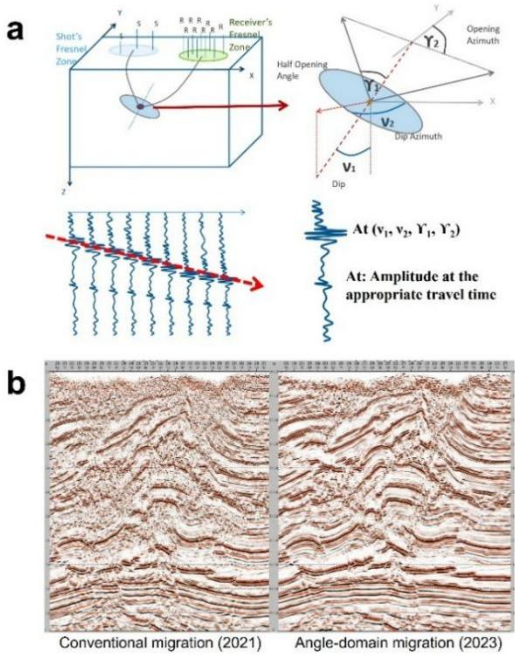

Fig.6 a. Schematic diagram of full-azimuth angle-domain tomography, b. Comparison of imaging performance between conventional and angle-domain migration

4. Geological Analysis

a) Integrated seismic & non-seismic structural analysis

To delineate the ultra-deep structures and stratigraphy, we can combine seismic and non-seismic methods, which can reduce the ambiguity of interpretation. Time-frequency electromagnetic (TFEM) inversion can provide information of large-scale ultra-deep architectures (Fig.7-a). Seismic data (Fig.7-b), reference to TFEM inversion results can further clarify the development and distribution of various geological bodies and structures in ultra-deep layers.

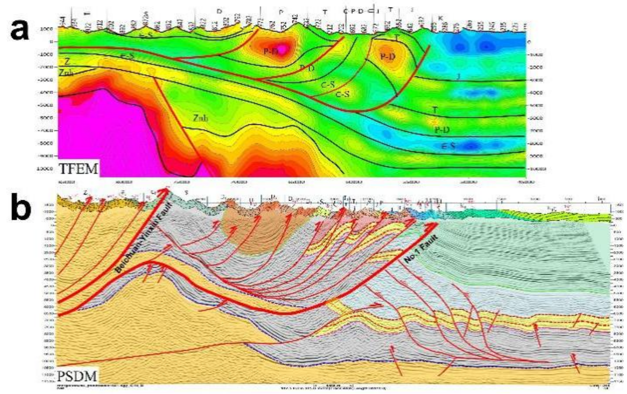

Fig.7 Integrated geological analysis combining non-seismic data (a, TFEM) and seismic data (b, PSDM)

b) Ultra-deep lithology prediction

Additionally, based on measurements of outcrop resistivity and well-controlled TFEM inversion results of inverted resistivity. The conversion formula from inverted to outcrop resistivities can be established, accordingly forming a regional conversion template of lithology in outcrop and inverted resistivity. This transformation template is helpful in inferring lithology distribution in ultra-deep formations (Table.1).

Table.1 Conversion template of outcrop and inverted resistivity

Lithology	Outcrop resistivity (Ω·m)	Inverted resistivity (average) (Ω·m)
Cambrian	1,516	69
Sinian carbonate	5,000	205
Mud shale	1,175	55
Pre-Sinian mud shale	1,167	55
Pre-Sinian sandstone	2,001	89
Pre-Sinian conglomerate & tillite	3,747	158
Pre-Sinian carbonate	9,220	358
Pre-Sinian metamorphic rock	5,603	228
Purplish-rhyolite porphyry	3,105	133
Gray acidic lava	1,718	78
Black basalt	4,871	200
Gray-white diorite	13,041	490
Granite	18,900	687

c) Multi-attribute fusion & AI fault identification

In ultra-deep layers with strong compaction, the development of fracture zones is favorable to improve reservoir physical properties. Actual production data indicates that fracture zones in ultra-deep carbonate reservoirs can increase productivity by 5% to 10%. In the past, the coherence attribute was commonly used to identify faults, which worked well for macro-faults, but it was not capable to identify smaller-scale faults.

Nowadays, multi-attribute fusion and AI identification can identify smaller-scale faults. Combined with symmetric illumination attribute, we can find smaller-scale fracture zones (Fig.8), thus improving the characterization accuracy of ultra-deep oil and gas reservoirs.

d) Three-pressure prediction

To ensure drilling safety, three-pressure prediction (pore pressure, collapse pressure, and fracture pressure) are introduced. Scientific prediction of these three pressures helps to guide the selection of drilling fluid, which ensures safety and efficiency with a reasonable cost.

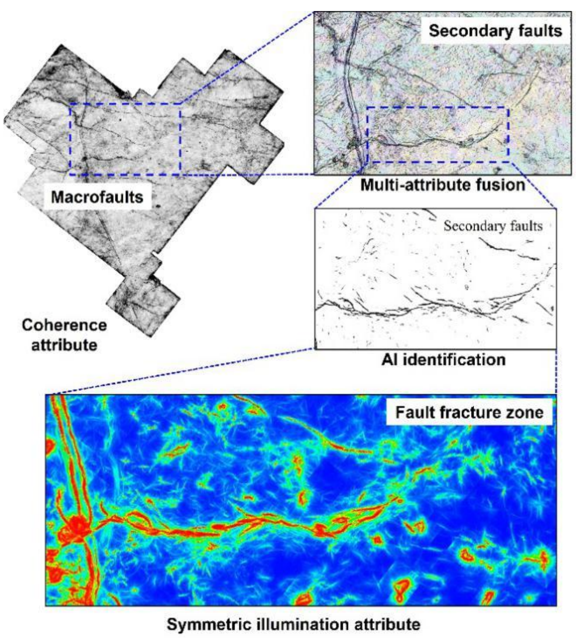

Fig.8 Application of multi-attribute fusion & AI fault identification

Applications

This section presents comprehensive case studies from two major basins in China (Fig.9).

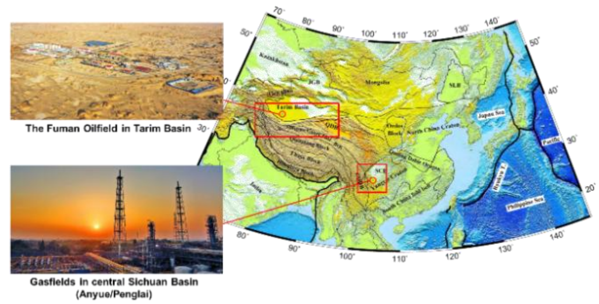

Fig.9 Maps of tectonic units in China and adjoin areas (basemap from Wei W et al., 2016)

1. Fuman Oilfield, Tarim Basin

The Fuman Oilfield is located in the Aman transitional zone in the northern Tarim Basin. Its primary oil-bearing formation is buried at ~6,000 meters depth. It represents the world's deepest fault-controlled karst carbonate reservoir.

With the application of specific techniques for ultra-deep exploration, the seismic data quality is significantly improved. Weak signals are effectively compensated, and the dominant frequency of the target layer is increased from 16Hz to 22Hz (Fig.10). Both the lowest and highest frequencies are extended. The SNR is increased by a factor of 1.9 compared to conventional techniques, and the overall signal energy is also enhanced. Furthermore, seismic imaging sections reveal much more of the intra-layer details, such as progradational reflection configurations.

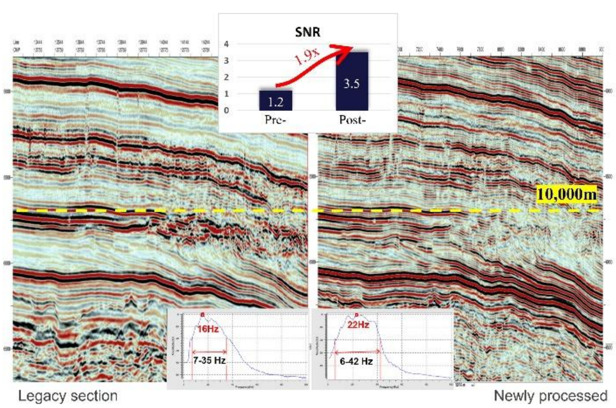

Fig.10 Images deeper than 10,000m in Fuman Oilfield

The application of these new techniques results in enhanced imaging for both profiles and the basemaps.

Faults are delineated more precisely on seismic profiles, and stronger-amplitude beadlike reflections along major fault zones are clearly showed (Fig.11-a). Structural maps also reveal the very details of the main fault systems (Fig.11-b). Breakthroughs in technology have now enabled efficient exploration by directly targeting faults to locate reservoirs. Over the past two years, numerous high-yield wells have been confirmed along these fault trends (Fig.11-c).

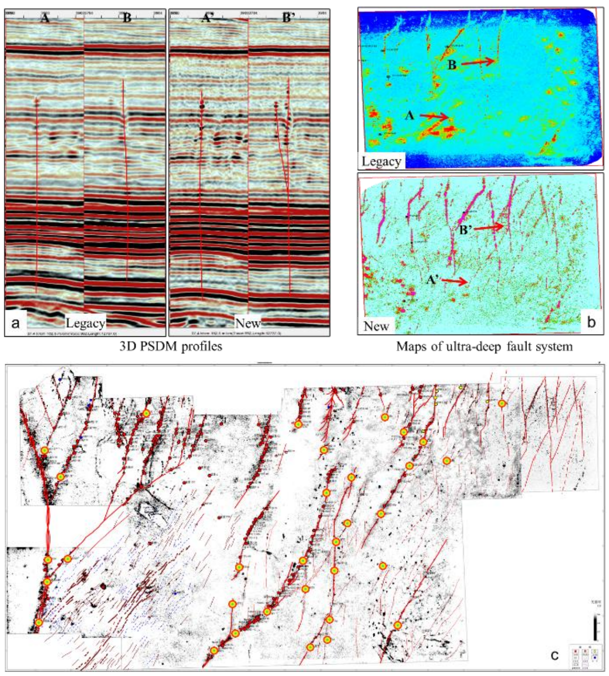

Fig.11. a. 3D PSDM profiles, b. Maps of ultra-deep micro-reservoir, c. Distribution of high-yield wells

2. Explorations in Sichuan Basin

a) Penglai Gasfield, central Sichuan Basin

The Penglai gas field is a major discovery in the central Sichuan Basin where the target reservoir is buried at depths approaching 6,000 meters. Due to complex fault systems and strong attenuation of ultra-deep signals, seismic imaging quality is relatively poor in this area.

Newly processed seismic data obtains much better imaging quality (Fig.12-a, b)., and the signal energy has been enhanced with a broader bandwidth, especially the lowest frequency extended from 10Hz to 6Hz. The reflection within the target layers is clearer now. Previously, the platform margin belt can be identified, but its precise location remains uncertain, while it can be precisely delineated now. Supported by the new seismic data, stratigraphic-traps encompassing over 4,000 km² have been discovered within the ultra-deep target layers of the Penglai Gasfield (Fig.12-c).

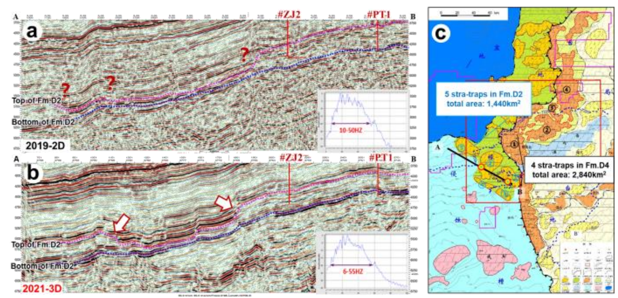

Fig.12 a. 2019-2D seismic profile; b. 2021-3D seismic profile; c. Sedimentary map of paleo-uplift for target formation and new stratigraphic-traps in Penglai Area

Technology for identifying fracture zones plays a crucial role in exploration in the central Sichuan Basin. For example, in Well GSH1 (Fig.13), fracture zones identified from electrical imaging logging show strong correlation with likelihood attributes and seismic profiles. This horizontal well successfully intersects the reservoir and is drilled through a 150-meter-long fracture zone. The test gas flow rate exceeding 1.1 million cubic meters per day in this well; the contribution from this fracture zone is calculated about 16.7%, representing a productivity increase of up to 10% compared to other sections of the reservoir.

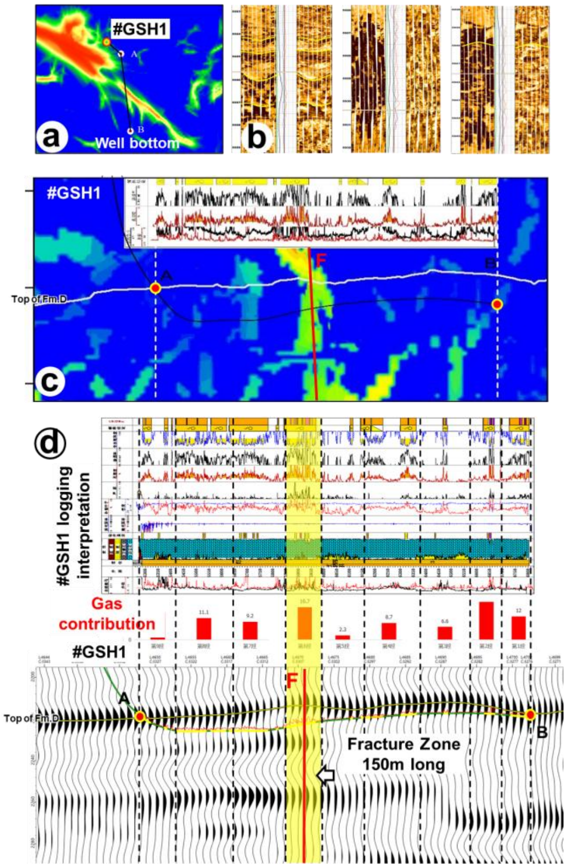

Fig.13 Fracture zone identification of Well GSH1. a. Likelihood attribute map, b. Electrical imaging logs, c. #GSH1 likelihood attribute profile, d. #GSH1 seismic section

Objectively, ultra-deep exploration is still challenging, and BGP's ultra-deep team will continue to carry out researches and development on velocity model building and imaging for complex structures.

Conclusions

Ultra-deep exploration faces many challenges such as low SNR, low resolution, and complex wavefields, which makes poor imaging results. We have proposed four key technique series including signal enhancement and noise reduction; band extension and amplitude preservation; velocity model building and imaging; and geological analysis, covering acquisition, processing, and interpretation.

Acknowledgments

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