The Technical Challenges and Significance on Ultra-Deep Buried Hill Reservoir Exploration in Bohai Bay Basin, China*

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Abstract

The ND buried hill zone is located in the downthrown side of the ND fault in the Jizhong Depression, Bohai Bay Basin, China. Under the control of the ND boundary fault, a series of unidirectional faults in the downthrown side of the ND fault construct a propelling structure that forms fault terrace hills with maximum burial depth of 7,000m. Whether the buried hill reservoirs exist in the ND area of Huabei Oil Field has been the studied for more than 30 years. Since the 1970s, geologists have carried out extensive investigations, focusing on the ND buried hill zone. However, no substantial progress has been made due to the lack of advanced and appropriate exploration technology and equipment.

In the last 10 years, new technology has been developed, such as joint non-seismic and seismic; seismic acquisition with high fold, wide azimuth and high density; anisotropic prestack depth migration, etc. By applying these techniques, higher quality seismic data have been acquired, and meanwhile the geometry and structure of the ND buried hill have been recognized.

Through the drilling of Well ND1, which is the deepest well drilled into buried hill in eastern China at more than 5,000m, excellent highly matured source rocks with more than 2,000m thickness were discovered at the Kongdian Formation of Es4 and a prolific oil and gas flow was obtained in the ultra-deep buried hill. Therefore, abundant hydrocarbons may exist. Reservoirs in the buried hill field possess good petrophysical properties, which are generally not affected by the buried depth. Therefore, the ultra-deep buried hill field is a very important exploration domain in the Bohai Bay Basin.

Introduction

The depth of Buried hill is relatively shallow and is unconformably overlain by younger strata, and known as ultra-deep buried hill if buried at more than 5000 m depth. In this study, buried hill is referred as to the Carboniferous, Permian and Mesozoic strata overlain by the Paleogene and Neogene deposits. Several large-scale buried hill reservoirs have been discovered over the past forty years of exploration in the area of the Jizhong Depression. These reservoirs are widely distributed and varied in form, which can be classified into six types according to the location and pattern (Figure 1).

Over four decades of exploration and exploitation, 3D seismic survey covers almost the whole area of the Jizhong Depression and nearly all the large-scale shallow buried hill reservoirs have been found. For example, CHJ Oil Field is one of the largest Paleogene oil field being exploited. The ND buried hill zone is located in the downthrown side of the ND fault of the Jizhong Depression in Bohaiwan Basin, China, which is the central uplift controlled by both the ND and GJP faults. The anticlines exist in the north-south direction, and the development of fault terrace hills were controlled by a series of step-down faults in the east-west direction at a maximum depth of 7,000m (Figure 2).

The ND buried hill zone is covered by Paleogene strata with fractured fault blocks and fault network (Figure 2). Jixian Wumishan Formation composes the main body of ND buried hill zone while the Qingbaikou and Hongshuizhuang formations of the Jixian System form the low part of this zone. The fractures, caverns and pores are rich in the ND buried hill zone, which are high-quality reservoirs. This area is abundant in oil and gas because of two sets of source rocks. In addition, the mudstone capping bed is distributed in a large region. Buried hill zone is not significantly influenced by tectonics, and traps are well preserved. 2D gravitational, magnetic, electric and seismic survey was conducted from 1976 to 2000, and 2D wide line, conventional 3D survey were accomplished from 2001 to 2005. From the CEMP data, there exists high abnormal resistivity because of high electric resistance of carbonate in buried hill. Based on seismic interpretation, the geological structure was documented and the basic geometry of the ND buried hill was identified. However, due to the low quality of seismic data, top surface and geometry of buried hill as well as fault planes are poorly defined. Therefore, it is difficult to determine the presence of deep burial hill and trap because of the ambiguity of seismic interpretation.

Technical Challenges

Because of the ultra-depth and complicated seismic and geological conditions in the ND buried hill zone, there are two major technical challenges in seismic exploration. First, the ultra-deep buried hill is more than 5,000m deep and poor data quality and how to get good images is a challenge. On the one hand, the interior and top horizon has weak reflection and low signal to noise ratio. The strata have smaller reflection coefficient and the unobvious impedance interface because that the strong absorbing function of capping bed reaching 85% to seismic wave energy. On the other hand, the comprehensive seismic wave field leads to the inferior image. The presence of large amounts of faults in the capping bed brings about a variety of waves. Therefore, the image of the interior and top horizon of the buried hill becomes of poor quality.

Second, the buried hill reservoir is heterogeneous carbonate and how to identify the hydrocarbon is another challenge. Many fractures and caverns often exist in buried hill carbonate reservoirs. The reservoir has average effective porosity of 6% and average permeability of 210mD. Therefore, the characteristics of ultra-deep buried hill carbonate reservoir cannot be predicted easily.

Methods

Joint non-seismic and seismic methods

A 1:100000 gravity survey was completed in the mid-1970s in the ND area and a gravity anomaly high was discovered. This indicates that the ND buried hill may exist. Based on the gravitational data, a well drilled to 5,109m was completed with no buried hill strata encountered. 2D seismic survey was finished in the mid-1980s in the ND area and weak reflection from the top horizon of buried hill can be seen. However, the buried hill structure is not obvious according to the 2D seismic data (Figure 3). A 1:10000 gravity survey and a 1:50000 CEMP survey were completed in the late 1990s in the ND area and a bigger gravity anomaly high and magnetic anomaly high value was recorded. This indicates that the ND buried hill exists. A wide line seismic survey was performed in 2001. Though reflection events become more continuous, the geological understanding on buried hill was changed from fault horst hills to fault terrace hills. Traditional 3D seismic survey was finished in 2001 in the ND area and seismic data quality was improved greatly. The top horizon of buried hill can be seen clearly. However, the buried hill structure trap is not obvious according to the 3D seismic data because the fault plane reflection is not continuous. At the time, a well was drilled to 5,500m. Although no buried hill reservoir was encountered, thick matured source rock more than 2000m thick was discovered in the Kongdian Formation of Es4. This fact indicates that there is abundant oil and gas source in this area.

High-resolution secondary 3D survey

From 2008-2009, a high-resolution secondary 3D survey was carried out. High fold, wide azimuth and dense sample acquisition techniques were used in the 3D survey. It is more beneficial to receive reflection from deep and steep horizons due to a large amount of middle and far offset for wide azimuth layout. Hence, wide azimuth acquisition has several advantages in the deep buried hill exploration. On one hand, it is advantageous to improve interior reflection. On the other hand, it can receive better reflection from steep fault plane. It is effective to decrease random noise in data acquisition and migration processing for large shot and trace density. It is necessary to investigate the top and interior of buried hill by using enough shot and trace density. Although the anisotropic prestack time migration technique has played an important role in the seismic exploration, it still has not been used effectively to image the deep buried hill, complex fault and so on due to intensive spatial velocity change. Anisotropic prestack depth migration technique overcomes the problem of intensive spatial velocity change, which makes the better image of complicated structures.

Prestack inversion reservoir characterization

According to the buried hill reservoir characteristics, fine structure interpretation and stratigraphic sequence interpretation were used to structure and fault interpretation. Prestack inversion and fracture prediction methods were used to identify hydrocarbon (Figure 4). From the map, probable hydrocarbon bearing area locates at the northwest, which is the place we hope to drill additional wells.

Results

Over the past 3 decades, adopting the technique described above in this paper in ND buried hill zone, newly acquired sections have clearer features of fault planes, fault terrace hills and the interior of buried hill compared to previous data. By using prestack depth migration technique, the image of buried hill interior has been improved efficiently (Figure 5). Comparing Figure 5 with Figure 2, the new secondary 3D data has more improvement than the previous 2D data. Figure 6 is the structure map of ND buried hill area. Figure 7 is the 3D structure display of ND buried hill area. Figure 8 is the sedimentary facies section corresponding to the location of the section in Figure 5.

In 2011, Well ND1 located at the high place in Figure 7 and marked in Figure 8 was drilled, which recorded a prolific oil flow of 642.9 m^3/d and gas flow of 56.3×104m^3/d and discovered a buried hill field in the Jizhong Depression, Bohai Bay Basin (Figure 9). The reservoir of this field is the deepest in the Bohai Bay Basin and even in Eastern China. Excellent highly matured source rocks with more than 2,000m thickness are developed at the Kongdian Formation of Es4 in the ultra-deep buried hill, so that abundant hydrocarbons could be generated. Reservoirs of the buried hill field possess good petrophysical properties, which are generally not affected by the buried depth. The buried hill trap was formed early and characterized by early charging, sustained charging and overpressured charging. The good matching of timing of hydrocarbon charging and trap formation favored the hydrocarbon accumulation and entrapment. The discovery of Well ND1 is of the milestone significance in promoting exploration of ultra-deep buried hill fields in the Bohai Bay Basin.

Conclusions

The successful drilling in ND buried hill zone has discovered the deepest reservoir in Bohaiwan Basin and even the Eastern China through more than three decades of great efforts, which opens up a new prospect of the oil exploration in Jizhong Depression. The achievement is due to the following techniques: 1) Joint non-seismic and seismic methods; 2) high-resolution secondary 3D survey: high fold, wide azimuth and high-density acquisition; 3) anisotropic prestack time depth and migration technique and 4) prestack inversion reservoir characterization. So the accurate structure of ND buried hill area and hydrocarbon were obtained. Through the drilling of Well ND1, excellent highly matured source rocks more than 2,000m thick were discovered in the Kongdian Formation of Es4 and prolific oil and gas flow was seen in the ultra-deep buried hill. Abundant hydrocarbons may exist. Reservoirs of the buried hill field possess good petrophysical properties, which are generally not affected by the buried depth. Therefore, the ultra-deep buried hill field is a very important exploration domain in the Bohai Bay Basin.

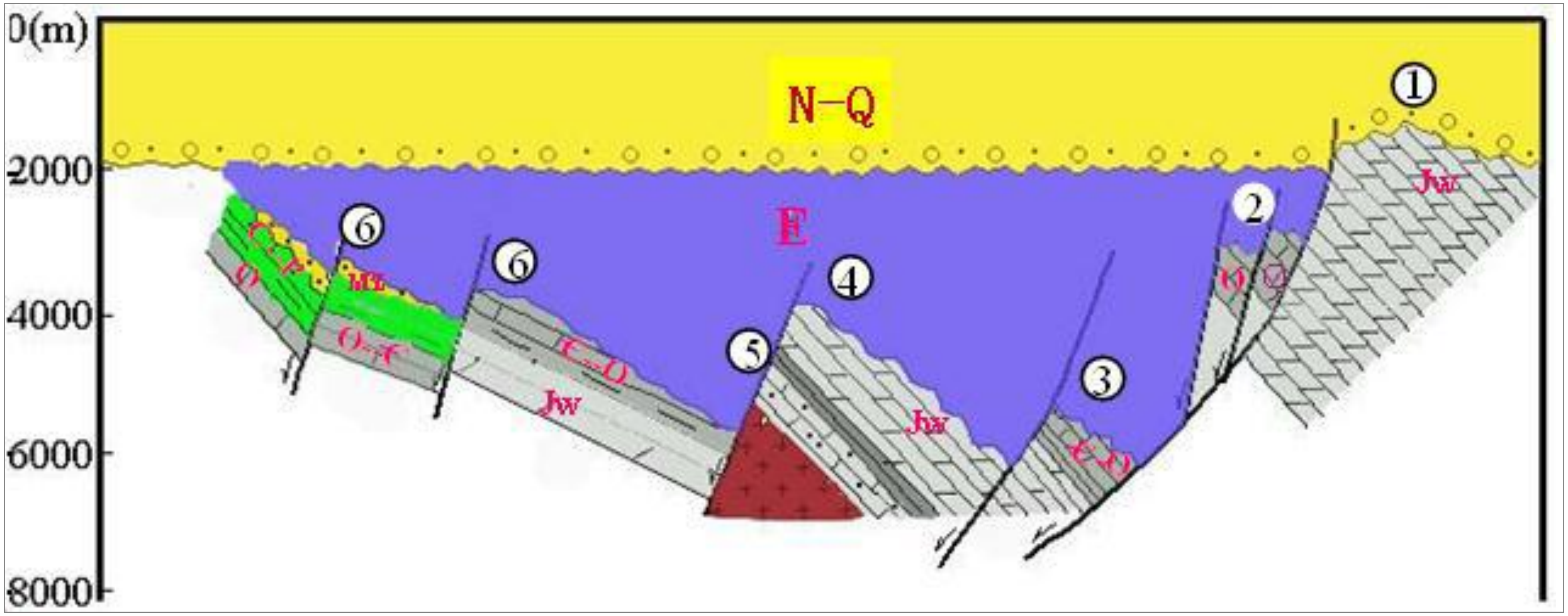

Figure 1. The trap type and distribution pattern of buried hill reservoir in Jizhong Depression. 1. Salient buried hill; 2. Shallow fault terrace hill; 3. Deep fault terrace hill; 4. Fault terrace hill in central depression; 5. Interior buried hill; 6. Buried hill in upper part of incline.

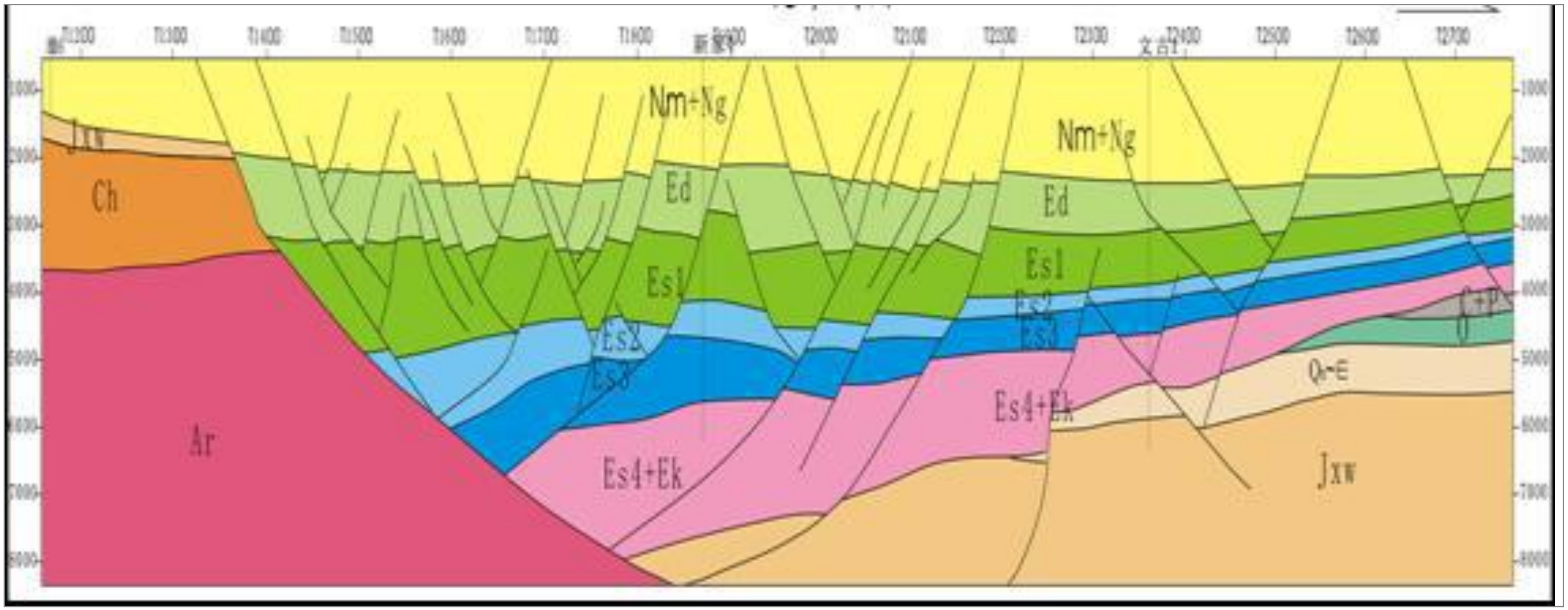

Figure 2. Geological section of ND buried hill zone.

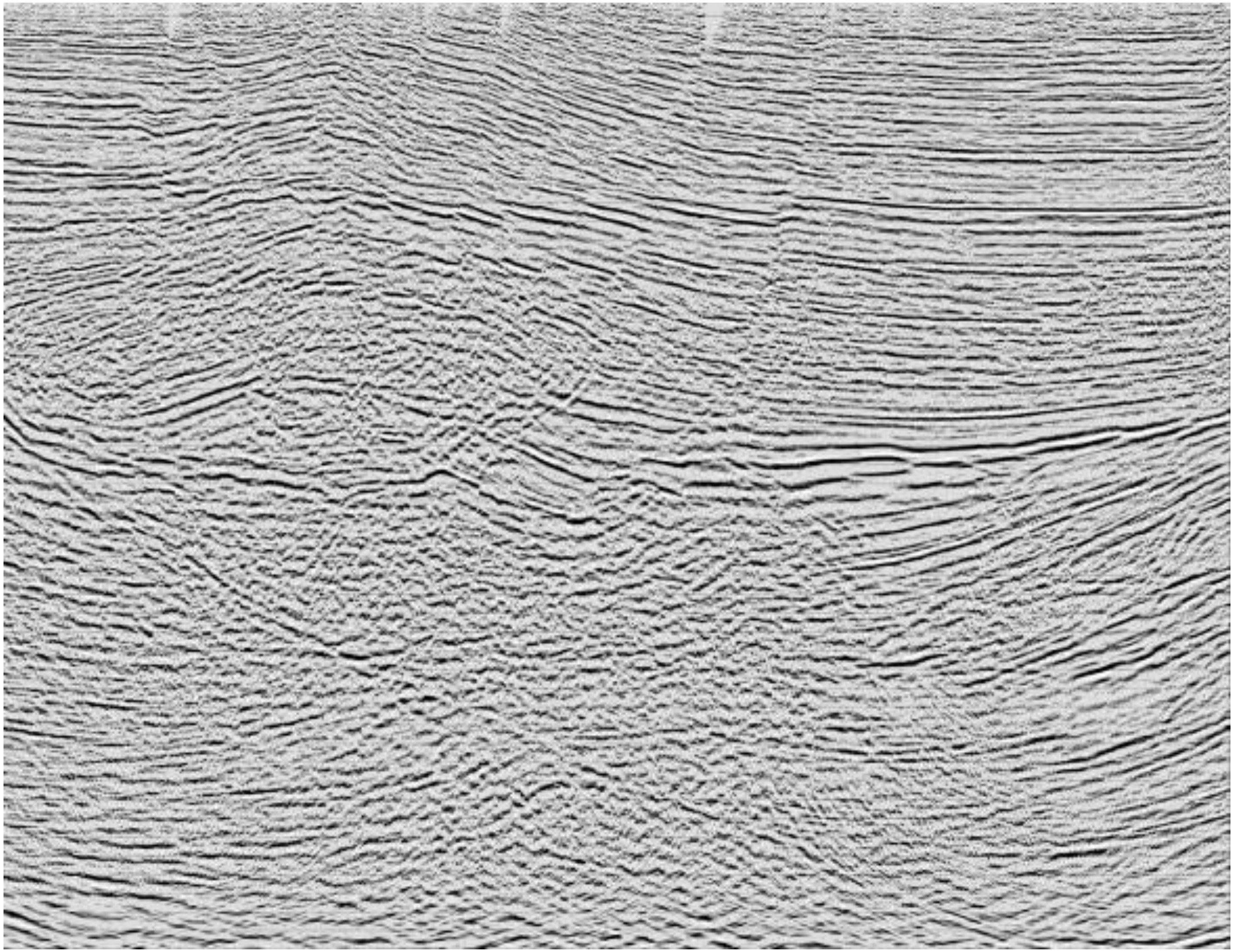

Figure 3. 2D seismic migration section.

Figure 4. Depth map of hydrocarbon-bearing strata by prestack inversion.

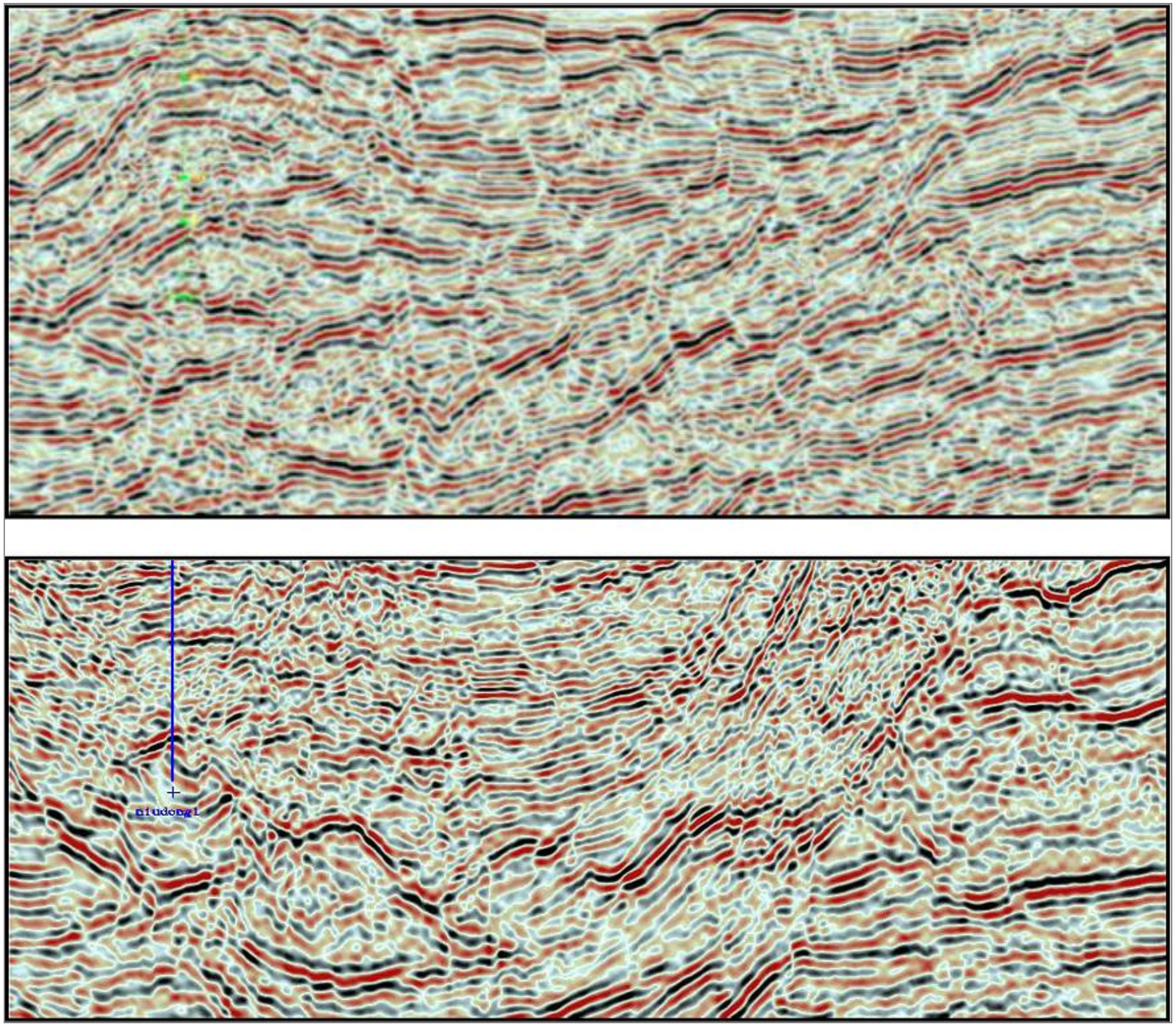

Figure 5. The prestack time (up) and depth (down) migration section of the secondary 3D survey.

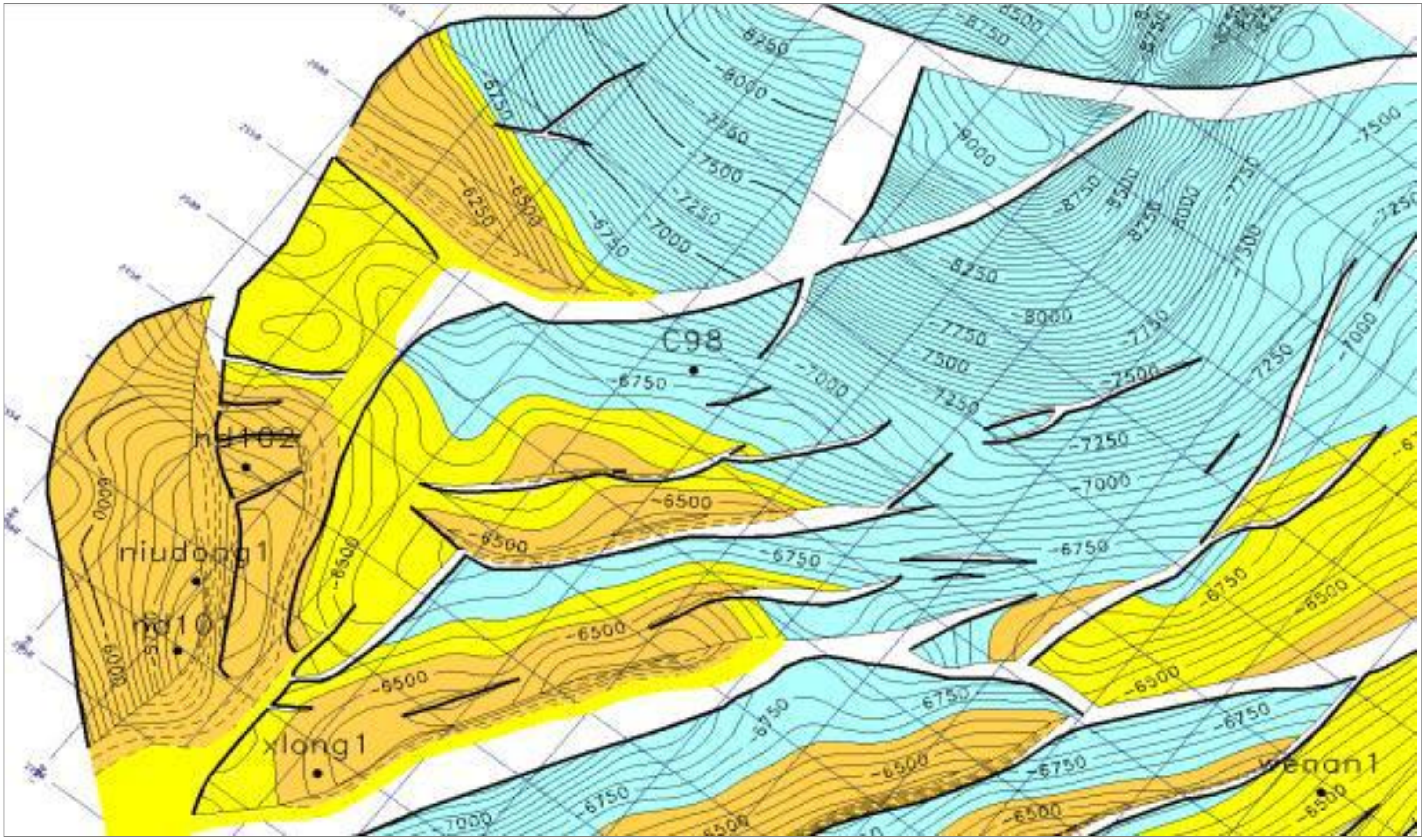

Figure 6. Structure map of ND buried hill area.

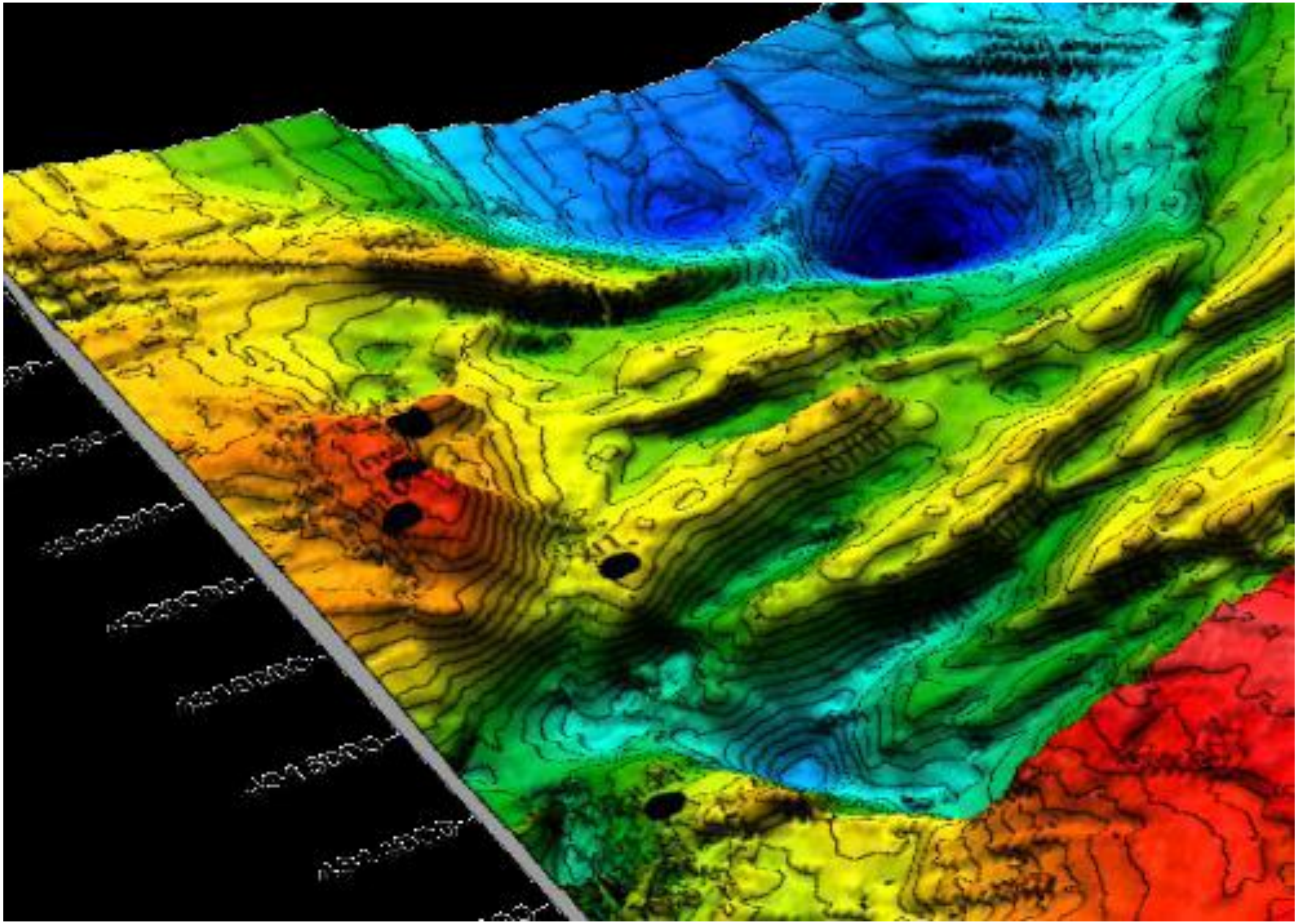

Figure 7. 3D display of ND buried hill area.

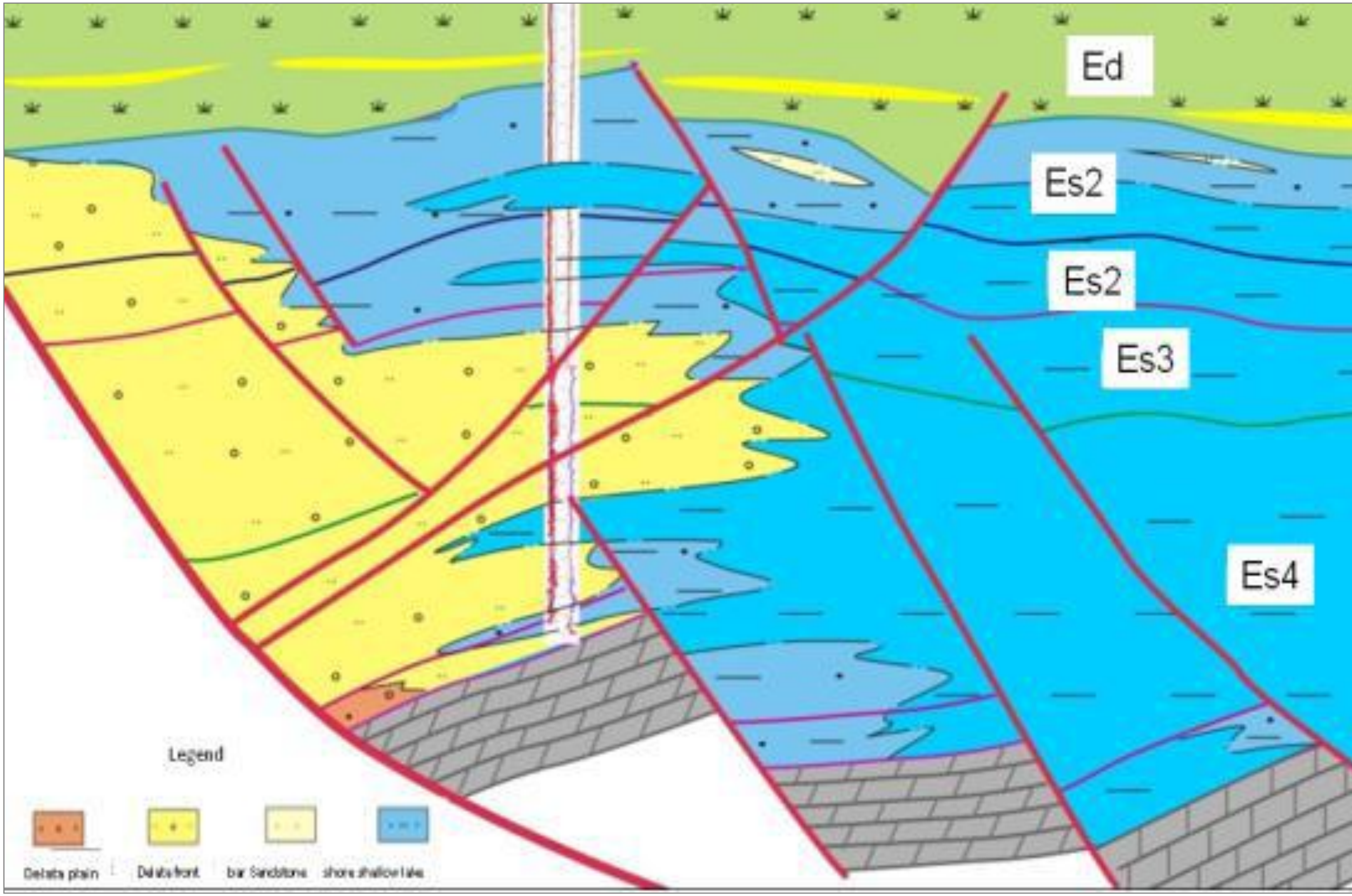

Figure 8. Sedimentary facies section corresponding to the location of Figure 5 section.

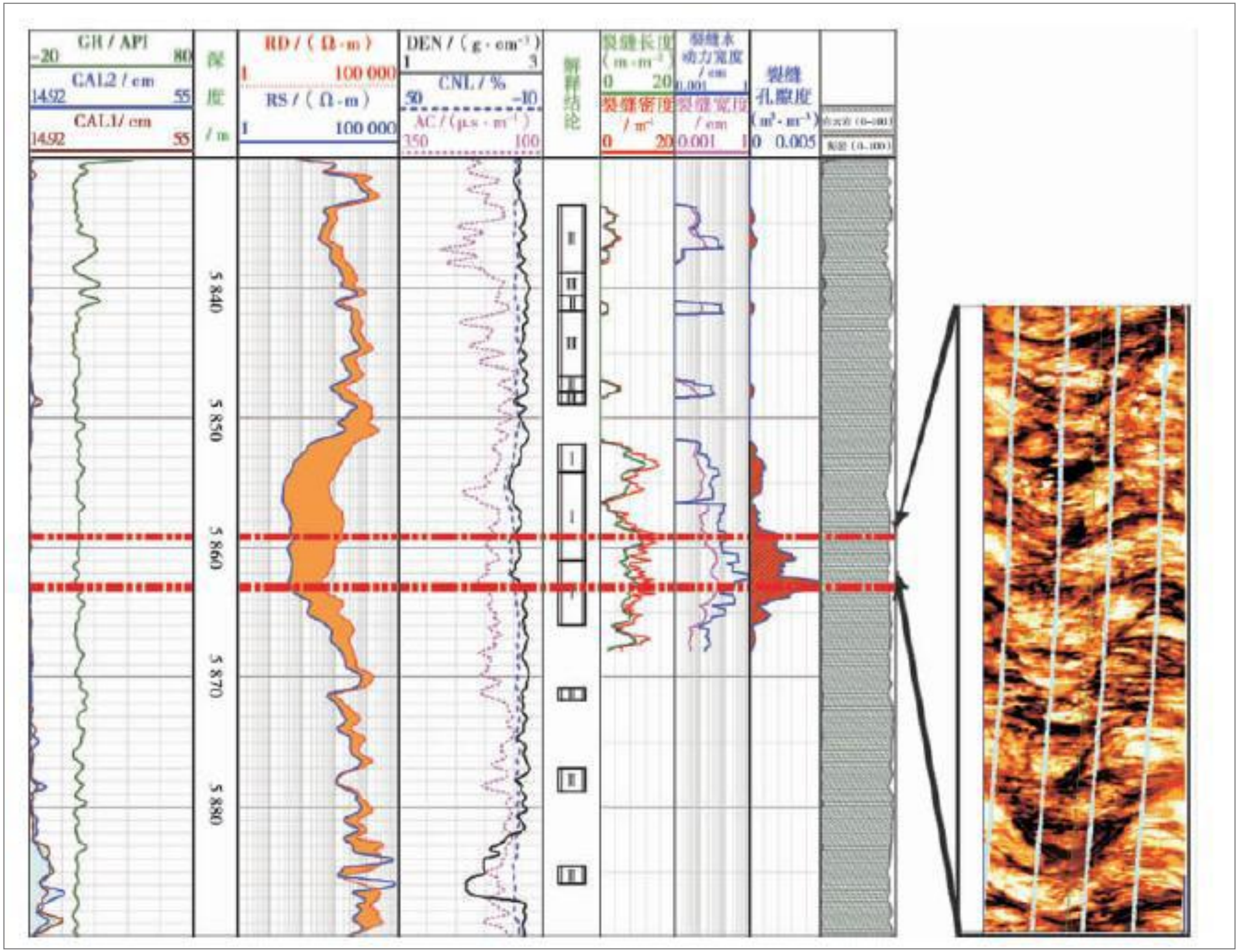

Figure 9. Log data interpretation results for well ND1.