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PS Application of Unconformity Identification and Evaluation in the Optimizing of Offshore Oilfield Development Plan: A Case Study of CFD Oilfield in Bohai Bay Basin*

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Abstract

CFD is a buried hill drape anticline in Bohai Bay Basin. In the early stages of oilfield development, production wells are designed at each structural high by the overall development plan (ODP) in order to develop the reserves near the top of Paleogene stratum. During the development, it was realized that some of the structural highs do not have any hydrocarbon accumulation. This problem makes our ODP less effective and causes considerable waste of investment. To solve the problem, we take a series of studies to analyze the main controlling factors of hydrocarbon accumulation at structural highs, reevaluate the risk of wells that have not been implemented, search potential reserves and optimize the ODP.

We apply genetic inversion to describe the reservoirs and then identify the two unconformities at the top and base of Paleogene stratum. The sealing ability of unconformities typically depends on the lithology on the two sides. Since the top of Paleogene stratum is a truncated unconformity covered by massive sandstone, the unconformity has poor sealing ability. It means once the cap rock at the top of Paleogene was eroded, the structural high will not get hydrocarbon accumulation. Meanwhile the base of Paleogene stratum is an overlap unconformity covering the dense granite buried hill, thus the unconformity should have good sealing ability. That means sand bodies overlapping on the side of buried hill near the base of Paleogene stratum could be effective traps. Base on this perspective, we build unconformities, structure highs, sand bodies in 3D geological model and describe the spatial composing relations of them to evaluate the possibilities of hydrocarbon accumulation in different positions. After analyzing risk of structural highs and potential of sand bodies, we optimize the ODP and gradually move the well positions which were located in the structural highs with great risk to the sand bodies with greater potential near the base of Paleogene stratum.

The results show that our predictions on hydrocarbon accumulations in the structural highs are accurate; three wells have geological reserves over $400x10^4$ t near the base of Paleogene stratum with high productivity. In the context of current low oil prices, our study optimizes ODP by analyzing effects of different unconformities on hydrocarbon accumulation, effectively avoids waste and increases the return of investment while increasing reserves and production. Moreover it provides new ideas for the exploration of similar structures and development of similar oilfields.

Research Background

CFD is a buried hill drape anticline in Bohai Bay Basin. In the exploration stage, we get some knowledge of geological characteristics according to limited information of a couple of exploratory wells and seismic data. The main structure of this oilfield is a northeast-trending long narrow anticline with a string of local high points distributed along the ridge. Its main oil layer is located near the top of Paleogene stratum which is half-overlapped and half-covered in sequence on the Archaean Group buried hill (Figure 1). The sedimentary type of Paleogene reservoirs are delta front and their properties are all characterized by high porosity and high permeability. Fluid analysis experiments prove that the oil property is so good that the viscosity of crude oil is only less than 10 mPa·s.

Based on the geological characteristics above, the overall development plan (ODP) of this oilfield was designed and implemented in recent years. Several directional wells are arranged at each local high point along the ridge aimed to produce oil from reservoirs near the top of Paleogene. But during the implementation of ODP, a severe problem was exposed that some of the structural highs do have any hydrocarbon accumulation and the wells designed there have no alternative positions and reserves. For example, although the high point B in the north has basically the same elevation depth as other high points in the middle and south of the anticline, it does not contain any oil but only water (Figure 2). This situation seriously increases geological risk and prevents the further implementation of ODP. In the context of low oil prices, the waste of investment caused by geological uncertainties is more unacceptable. In order to avoid further investment waste and recover the damage as much as possible, we need to use existing data to re-evaluate risk and potential, and then optimize the ODP.

Unconformity Identification

Comparing the two geological understandings before and after the ODP implementation, we find that the biggest change of geological understanding is of the unconformity surface. In the exploration stage, on the basis of seismic data and exploratory well data, combined with regional geologic background, we believed the contact surface between Paleogene and overlying Neogene is a parallel unconformity surface and the cap rock covers on Paleogene are wide-spread in the whole anticline. After the development well P2 was implemented, this ideal geological knowledge changes and the structural high B does not have hydrocarbon accumulation (Figure 2). Under the conditions of the same source rock, migration pathway, tectonic position, reservoir continuity, lacking of mudstone cap rock is the most remarkable disadvantage of high point B compared with other high points. The lack of mudstone cap rock means that the top of Paleogene has been subject to erosion at the end of sedimentation and the parallel unconformity in the former understanding is actually a truncated unconformity which had been shown a false appearance by the low resolution seismic data.

In order to analyze the role that an unconformity plays in hydrocarbon accumulation, we identify it using logging data firstly. The mutation of material composition, compaction and diagenesis on the two sides of the unconformity could be reflected by log data (Li et al., 2007). This conclusion has been verified by the statistics of a large number of log data in this region. In CFD oilfield, it mainly includes several aspects below. Firstly, with the same rock petrophysical property and fluid, the average value of natural gamma ray and resistivity are obviously different in adjacent strata, thus it appears a sidestep around the unconformity. Secondly, for the sedimentary environment is different, the structural characteristics of the reservoir on the two sides of the unconformity surface reflected by well log curve shapes are different. For example, in CFD oilfield the depositional environment of Neogene is a braided river. The reservoirs have huge thicknesses and the well log curves of sandstones are mainly box-shaped. The depositional environment of the Palaeogene is meandering river or delta. Reservoirs are sand-shale interbeds and the well log curve shapes are mainly bell-shaped or funnel-shaped. Thirdly, some specific lithologic layers are contained in some certain strata. For example, the Neogene contains many thin limestone layers with obvious log response such as high resistivity, low gamma and high density. The sudden disappear of high-frequency thin limestone layers could help identifying unconformity. Fourthly, the incomplete stratigraphic cycle caused by erosion indicates a truncated unconformity. According to the log response characteristics above, we identify two unconformities in CFD oilfield. Unconformity 1 is a truncated unconformity between the Palaeogene and overlying Neogene, and unconformity 2 is an overlap unconformity between Palaeogene and underlying Archaean Group buried hill (Figure 3).

After identifying the unconformities in wells, we use seismic data to identify them in 3D space. As we see in Figure 4, unconformity 2 is a strong and clear seismic event in the section for the mutation of lithology. Unconformity 1 is not a strong event for the unstable lithological association and approximate petrophysical property on the two sides of the unconformity (Figure 4).

Unconformity Evaluation

Geologists have considerable knowledge about unconformities. Usually an unconformity is a sealing surface, a migration pathway or both. Actually being a contact surface of adjacent strata, its sealing and migration effects are both limited. We should pay more attention to the combination of the physical properties of rocks on the two sides of the unconformity (Zhang, 2005). In the CFD oilfield, the vertical sealing ability of unconformities typically depends on the lithology on the two sides.

For unconformity 1, as the massive Neogene braided river facies sandstones covers the Palaeogene, we can regard the truncated unconformity as non-sealing vertically. According to the well log data, at the south and middle structural highs, the erosion is not so strong and the cap rock at the top of Palaeogene is basically preserved, thus these highs could be effective traps. While in the north structural highs, the erosion is so strong that the cap rock has been eroded completely, even together with part of the reservoir near the top of the Palaeogene. Without the cap rock those highs could not be effective traps.

For unconformity 2, as the base of Palaeogene is an overlap unconformity surface covering the dense granite buried hill, we regard the overlap unconformity as sealing vertically. Core analysis confirms that the Archaean Group buried hill did not suffer long-term weathering for the fast accumulation of Palaeogene sediments, so that it does not form weathering crust at the top of the buried hill. That means sand bodies overlapped on the slope of buried hill near the bottom of Palaeogene contact with the massive dense granite buried hill on the slope, and we can regard the overlap unconformity as sealing. In this case, we analyze the mechanism of hydrocarbon accumulation of these sand bodies. The relative rise and fall of the Earth's crust always triggers the advance and retreat of the water body. This phenomenon is always shown as overlap and offlap in section. When the water advances, the sedimentary scope expands gradually and the new sediments cover older sediments extending forward to the land. Where the new sedimentary strata contacts the basement, it forms overlap uniformity. For a specified period, porous sandstones with good reservoir properties deposit along the erosion surface in the fringe of a sedimentary sag. With the water face continuing to expand and the water continuing to deepen, mudstones with poor permeability deposit over the sandstones. Containing a lot of organic material, the mudstones could be both good source rocks and cap rocks. So far, stratigraphic overlap traps have formed. After times of water advance and retreat, it could form source-reservoir-cap rock association. Once oil and gas migrates into the stratigraphic overlap traps, it could form stratigraphic overlap reservoirs (Fu et al., 2001) (Figure 5).

Reservoir Description

The key to accurately evade risk and discover potential reserves is describing unconformities, reservoirs, cap rocks and their spatial organization. But the existing geological data quality cannot meet the requirements. So we apply genetic inversion to help identify and explain unconformity surfaces and improve the resolution of seismic data. In this method, multi-layer neural networks as well as genetic algorithms are combined together in order to provide a robust and straightforward seismic inversion. The advantage of this method is that it is not only restricted to conventional acoustic or elastic impedance inversion, but it can be extended to any kind of petrophysical attribute, which is linked in a meaningful and straightforward way to the seismic amplitude or derived attribute data. As the natural gamma ray logging can distinguish sandstone and mudstone better, and can distinguish Palaeogene and Neogene for their different clay mineral content in the sediment, we choose natural gamma as the goal of the inversion. The key points are distinguishing Palaeogene and Neogene in section to identify the truncated unconformity, describing the distribution range of the remaining cap rock on the top of Palaeogene to evaluate the risks and forecasting the thickness and the distribution range of the reservoir overlapped on Archaean Group buried hill slope to forecast potential reserves. As the section shows in Figure 6, the inversion result could help to describe tectonic and reservoir. The truncated unconformity surface between Neogene and Palaeogene is better shown for the obvious different natural gamma ray values in the two strata and interpreted in the inversion section assisted in original seismic data. In the gamma inversion volume, unconformity 1 is identified and explained. At the same time, because of the improvement of resolution, sand-shale interbeds in Palaeogene is better characterized compared with that in the original seismic data. Especially the distribution areas of cap rock on the top of Palaeogene and the thickness of sand layers overlapped on Archaean Group buried hill.

To accurately evade risk and discover oilfield potential, we divide the unconformities, reservoirs and cap rocks into two groups according to spatial location. Group 1 includes the truncated unconformity surface (unconformity 1), the reservoir and cap rock at the top of Palaeogene; Group 2 includes the overlapping unconformity surface (unconformity 2) and sandstones overlapping on Archaean Group buried hill slope. For each group of geological factors we built a geological model to describe their spatial relation and predict risk and potential reserves. Based on the geological models, in structural high A and B the unconformity 1 contacts sandstone directly and no cap rock is present. That means in structural high A and B the cap rock has been eroded completely and the structural high A will not hold any hydrocarbon accumulation just like structural high B, while other structure highs will. Sand bodies overlapping on Archaean Group buried hill slope are encompass by the overlapping unconformity (unconformity 2) in the updip direction, so these sand bodies hold the potential reserves of CFD oilfield.

ODP Optimization and Implementation

According to the newly acquired knowledge about risk and potential in the reservoir characterization study, we made some adjustments to the wells to be implemented on the basis of ODP. Since the cap rock on the top of Palaeogene is in good position in the middle and south of the oilfield, the structural high G does not face the risk of failing to hold hydrocarbon accumulations, thus the pre-existing target point of P12 has no need to be changed. But in order to ascertain the potential reserves of sand bodies overlapping on the south slope of the buried hill basement, we redesigned P12 and add other target points in deeper strata. The actual drilling showed that the high point G successfully holds hydrocarbon accumulation as we predict, since it is covered by the cap rock. Also, the well discovered three oil layers on the buried hill slope with the same sand layer thicknesses as we predicted in inversion and the result of productivity testing of each layer is 30~70 m^3/d. Since the well does not meet any oil-water interface of the three sand bodies, the reserves should be more than the current 400×10^4 t. As the structural high A has already lost the probably of holding hydrocarbon accumulation, we changed P1 together with P2ST (sidetracked well of P2) to the oil layers overlapping the Archaean Group buried hill slope, and they both recovered excellent production.

Due to our study, now the buried hill slope is a key area of CFD oilfield development. In the context of the current low oil prices, our study helped the company avoid the investment waste of millions of dollars and created a good prospect for CFD oilfield development.

Conclusions

The results of this study are summarized as follows:

1) In CFD oilfield, where lacking a weathering crust, the sealing ability of an unconformity mainly depends on the lithology on the two sides, not the unconformity itself.

2) In our study, the gamma inversion could help to identify and explain the unconformity, describe the distribution of mudstone cap rock, and predict the thickness of sand layers. The genetic inversion plays an important role in analyzing risk and potential reserves in CFD oilfield.

3) Unconformity identification and evaluation study plays a decisive role in the process of optimizing the overall development plan of the oilfield. This method can be used by other similar oilfields.

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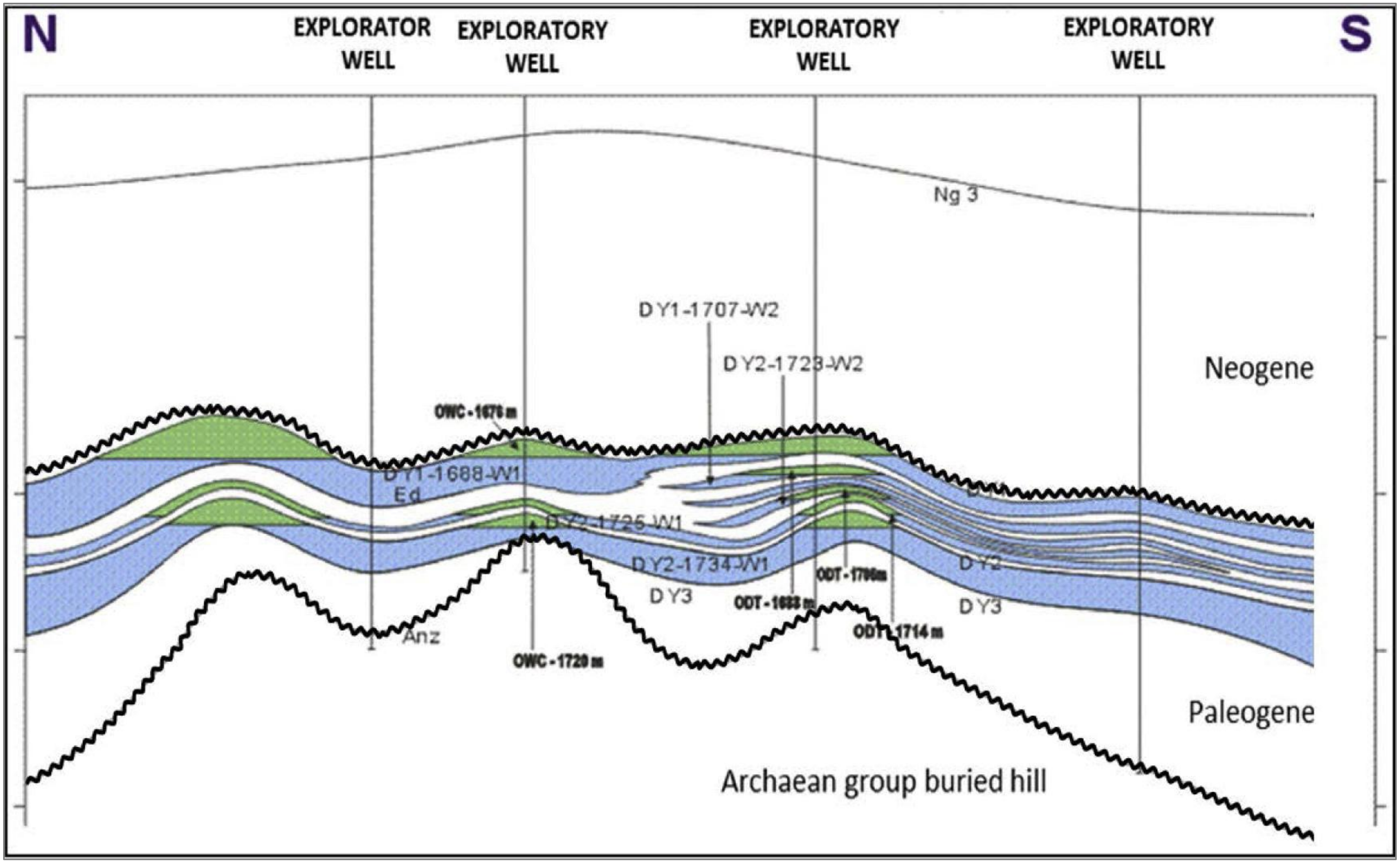

Figure 1. CFD oilfield north-south cross section.

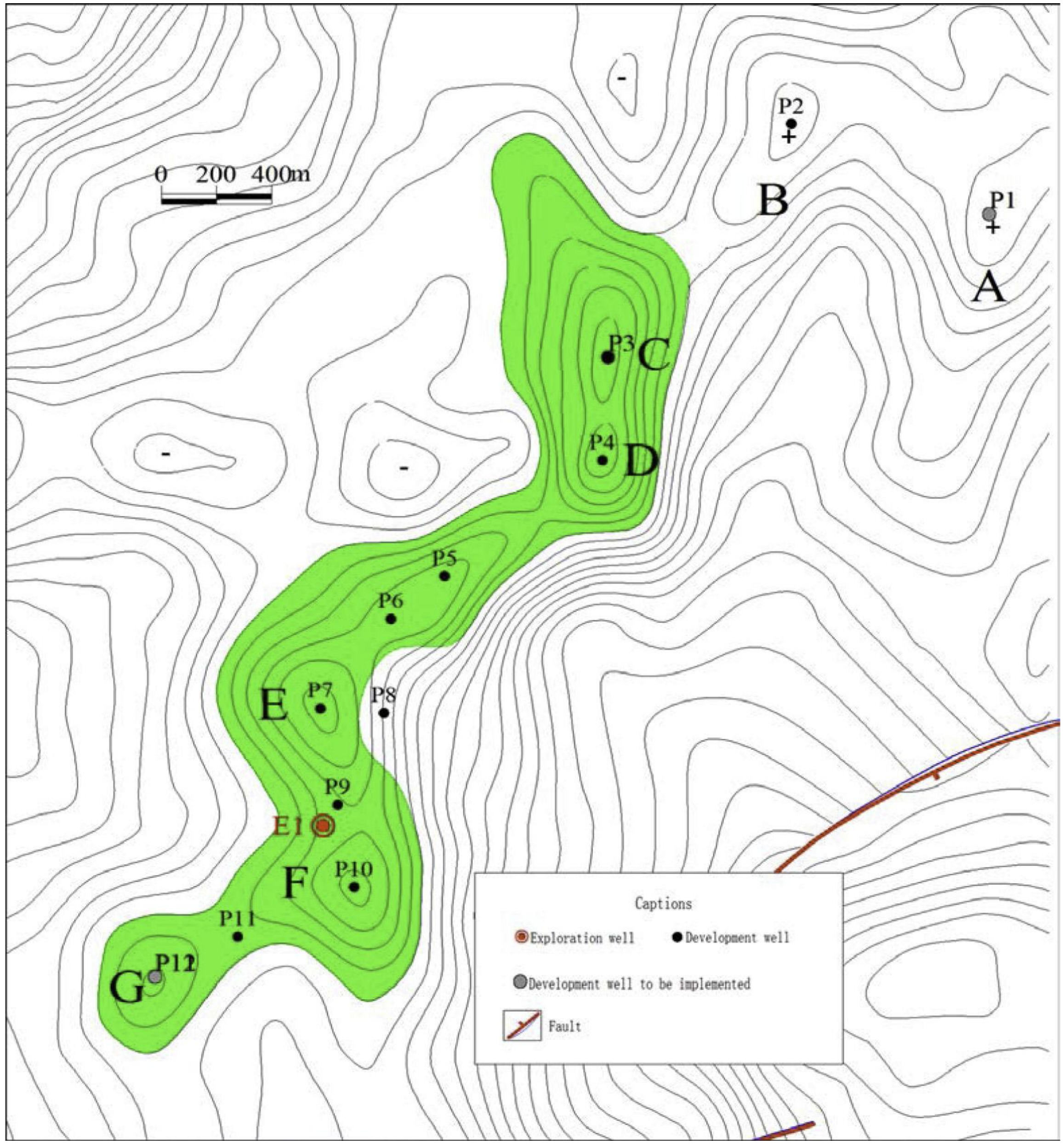

Figure 2. Structure map of top Paleogene in CFD oilfield.

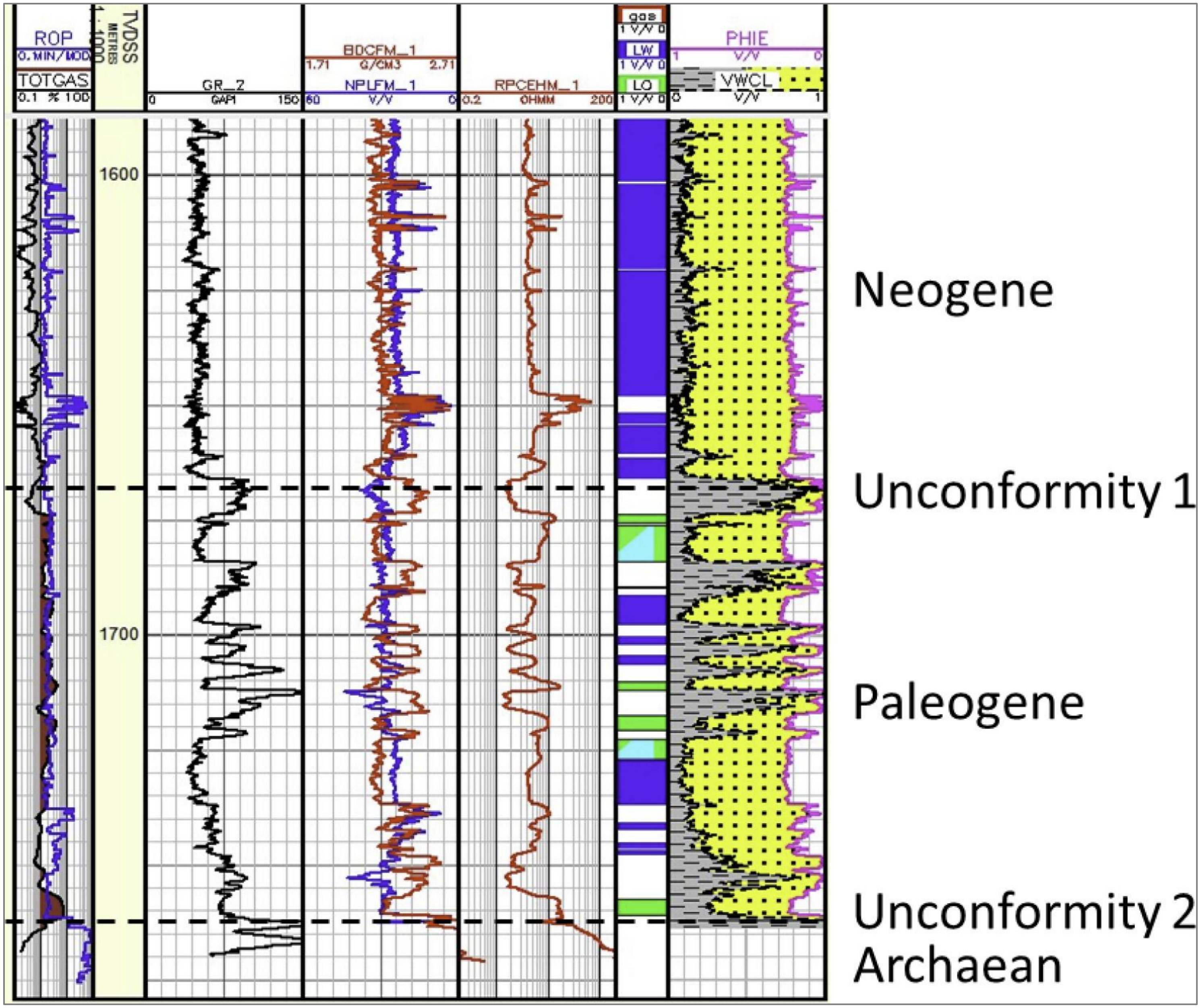

Figure 3. The log curve response to the unconformity surface in CFD oilfield.

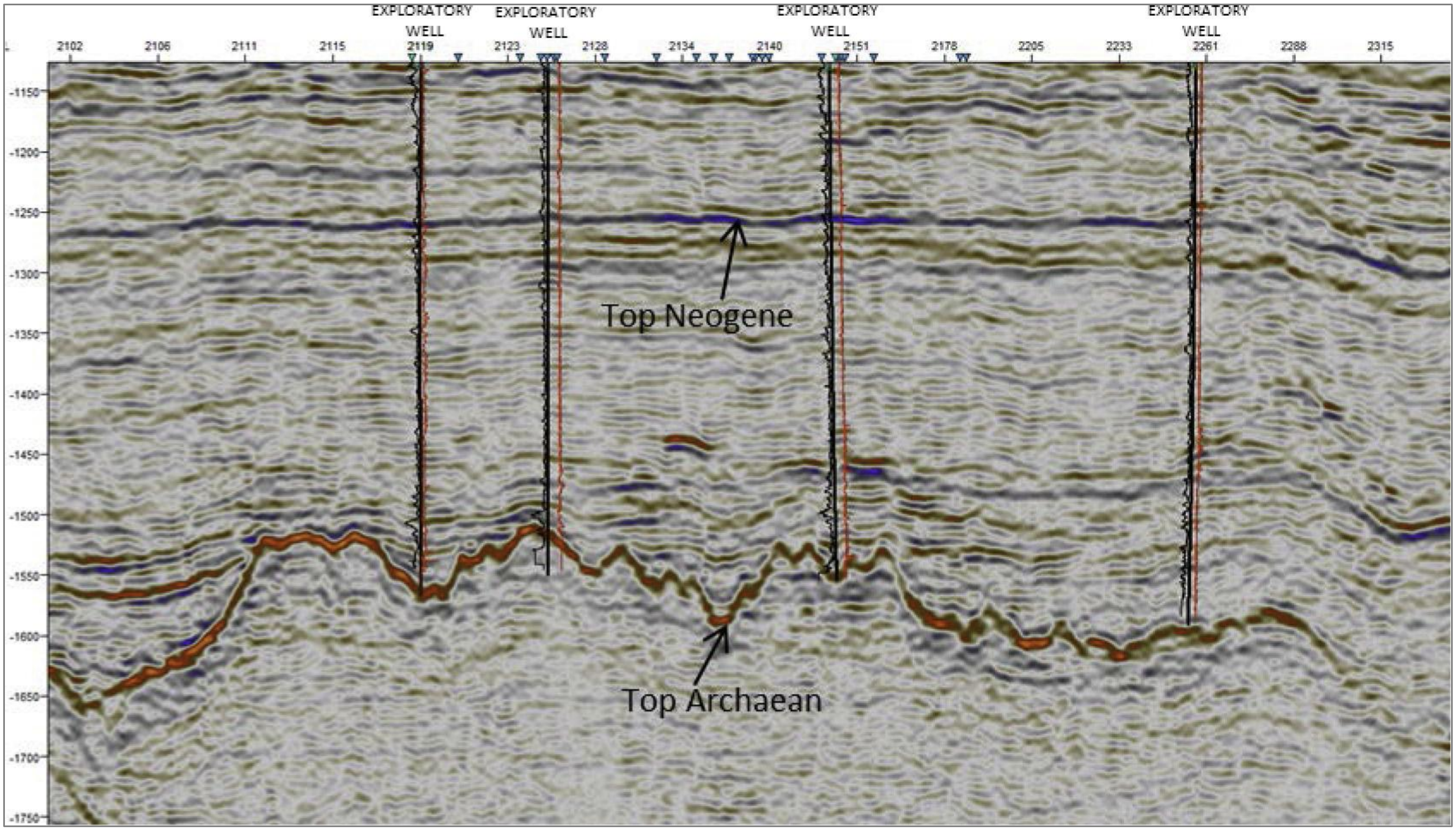

Figure 4. CFD oilfield south-north seismic section.

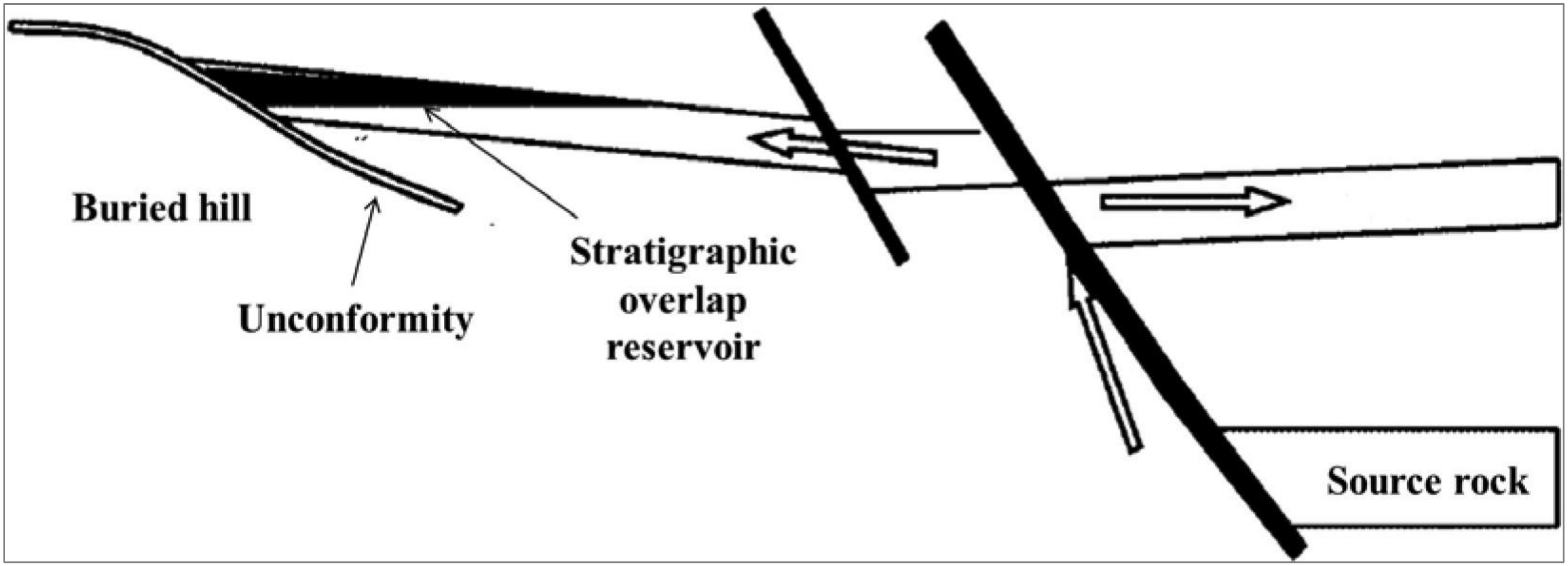

Figure 5. Model of stratigraphic overlap hydrocarbon reservoir in CFD.

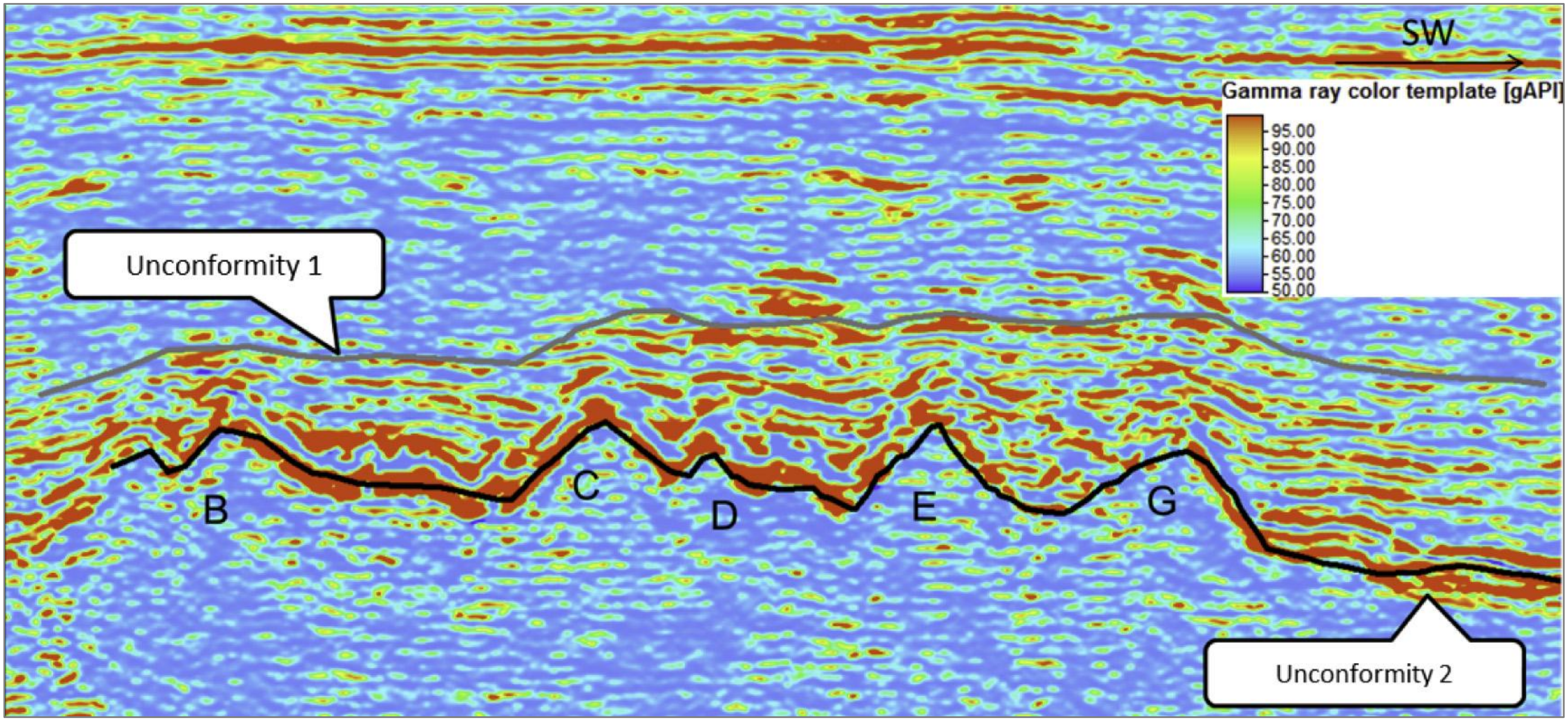

Figure 6. CFD oilfield south-north gamma inversion section.