

# Analysis on Prediction Methods for Formation Pore Pressure under Multiple Pressure Formation Mechanisms

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**Abstract**—There is abnormal fluid pressure widely distributed in Yinggehai-Qiongdongnan Basin, with abnormal zones extending from different depths, and the formation causes of abnormal pressure here are complicated. It is one of the three HTHP offshore regions in the world at present. Hence, drilling in this region is very difficult. It is discovered in drilling practices in recent years that, due to the multiple formation mechanisms of abnormal formation pressure in this region, the conventional pressure prediction model based on under-compaction theory is insufficient to explain the abnormal high pressure suddenly occurring in the middle shallow layer in diapiric structure of Yinggehai-Qiongdongnan Basin, which causes very large deviation of pore pressure prediction before drilling. Based on the basic principle of improved Fillippone method and with the three-dimensional high precision seismic velocity field of geologic modeling inversion, the authors build a three dimensional pore pressure model of target block, extract the pressure slice of horizon and across the target well, analyze the other source pressure transmission possibly caused by formation connectivity, and import them into the mathematical model of pore pressure prediction, so as to attain the purpose of improving the precision of pore pressure prediction. This method has been well applied in pre-drilling pressure prediction for the HTHP block in the South China Sea, reaching a prediction precision above 95%.

## 1 INTRODUCTION

The abnormal fluid pressure in sedimentary basin is formed due to various conditions, e.g. compaction of argillaceous sediment, extrusion of tectonic stress, drastic expansion of pore fluid generated by cracking of organic matters, and hydrodynamic connectivity between formations of different pressure systems caused by fault opening<sup>[1-3]</sup>. The abnormal pressure in Yinggehai-Qiongdongnan Basin in the South China Sea is formed due to complicated conditions of the abnormal high pressure belt formed by under-compaction, hydraulic connectivity between different pressure systems, which makes it very difficult to predict pressure in this region.

## 2 FORMATION MECHANISM AND IMPACT FACTORS OF ABNORMAL PRESSURE

Besides rapid compaction of sedimentary formation and fracturing of organic matters, the abnormal high pressure in Yinggehai-Qiongdongnan Basin in the South China Sea is also formed due to migration of high pressure fluid from deep formation to shallow formation via the active fracture belt. Especially, the abnormal high pressure suddenly occurring in the middle shallow layer in diapiric structure belt of the basin is the external

manifestation of hydrodynamic connectivity between different pressure systems. According to analysis for drilling practices over the years in Yinggehai-Qiongdongnan Basin in the South China Sea, it is considered that the formation mechanisms of sandstone fluid pressure in this region include the following three types.

### 2.1 Self-source high pressure

The abnormal fluid pressure in this formation is formed due to geologic process, physical and chemical actions in the permeable formation. Such abnormal pressure is formed mainly due to rising of reservoir and bubbles, of which, the density differs from that of water largely, in the permeable formation, thermal cracking of crude oil in oil-bearing reservoir, compaction of sandstone and so on.

### 2.2 Adjacent-source high pressure

The adjacent-source high pressure refers to the abnormal high pressure caused by transmission of pressure and fluid in adjacent high pressure mudstone into sandstone in permeable formation. Such type of pressure is mainly formed due to compaction, hydrothermal pressurization, dewatering transformation of clay mineral, tectonic stress, cracking of organic matters and so on. These mechanisms

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and principles are well known and the prediction methods are basically mature.

### 2.3 Other-source high pressure

The other-source high pressure is an important feature of abnormal pressure in Yinggehai-Qiongdongnan Basin in the South China Sea. Due to various geologic and engineering causes in the sand body, hydrodynamic connection occurs between the sand body and the other overpressure permeable formation with higher excess pressure, and the pressure between formations with very different excess pressure varies quickly, thus resulting in abnormal rising of fluid pressure in shallow formation. Such pressure rising process is caused by permeable formation or fracture belt with relatively high hydrodynamic conductivity. The formation with abnormal high pressure may occur in a normal belt or a transitional belt, which is difficult to reflect in the logging and seismic data, or conventional pressure prediction model. Hence, it is difficult to predict such type of pressure.

## 3 DISCUSSION ON CONVENTIONAL PORE PRESSURE PREDICTION METHODS

### 3.1 Conventional pore pressure prediction method

Pressure prediction is an important reference for drilling design. There are many methods and models for determination of formation pressure. For different prediction time nodes and data sources, there are three types of prediction methods, i.e. pre-drilling pressure prediction, pressure monitoring while drilling, and post-drilling pressure inspection<sup>[3]</sup>. The pre-drilling method is mainly based on the seismic data, and its precision depends on the extraction method and precision of seismic interval velocity. The monitoring while drilling method is mainly based on collection and processing of drilling engineering parameters, including drilling speed, rotary speed, bit pressure, actually used mud specific gravity and others, and the latest LWD, VSP technologies and others. The post drilling pressure inspection method is mainly based on the comprehensive post-drilling data, including acoustic logging, density logging, neutron logging, gamma ray logging, and so on.

Based on the basic principles, both the pre-drilling prediction and monitoring-while-drilling methods can be divided into two categories: normal compaction trend method and direct pressure prediction method<sup>[4-12]</sup>. In the normal compaction trend method based on formation under-compaction mechanism, a compaction trend line equation is built within the normal section using variations of acoustic, density, resistivity and other logging data along with the depth, and the formation pressure is predicted according to deviation of the actually measured value from the trend line. There are empirical relation method (represented by Eaton method), equivalent depth method (also called as balance depth

method), normal compaction trend method (also called as improved equivalent depth method), and so on<sup>[4-10,13,14]</sup>. In the direct pressure prediction method, the empirical relation between actually measured value and formation pressure, instead of a normal trend line, is directly built. This type of method is represented by the effective stress method (Bowers method)<sup>[11]</sup> and Fillippone method<sup>[10]</sup>.

### 3.2 Adaptability analysis of pore pressure prediction method

#### 3.2.1 Empirical relation method

The empirical coefficient method applies to areas with certain amount of actually measured data of pore pressure available. With the data of drill stem test, well completion oil production test, RFT of wells already drilled in this region, the pore pressure is calculated by building a normal trend line equation of interval transit time and regressing of the empirical coefficient equation. Among the methods above, Eaton method<sup>[10]</sup> is currently the most widely used one for determination of formation pressure in the petroleum industry. It is a relational expression between pore pressure and logging parameter built by Eaton according to experiences obtained at Gulf of Mexico and other regions, and relevant theories. Eaton method essentially reflects the abnormal high pressure caused by under-compaction of mudstone, and give consideration to the formation mechanisms of high pressure, e.g. hydrothermal pressurization, dewatering transformation of clay mineral, tectonic stress, cracking of organic matters and others. It can be used for pressure prediction of self-source and adjacent-source pressure effects in Yinggehai-Qiongdongnan Basin in the South China Sea.

#### 3.2.2 Equivalent depth method

The equivalent depth method, also named as the balance depth method, is one of the most effective methods for formation pressure prediction and inspection in most basins of the world. From the principle of rock mechanics, both in the normal compaction zone and the under-compaction zone, the same porosity (or other physical parameters which can reflect the porosity) corresponds to the same effective stress. In the balance depth method, it is considered that the porosity of observed point in under-compaction region is kept since the formation is fully closed in the equivalent depth from the burial depth to the normal section in the formation of this point, all the overburden loads added later are applied onto the pore fluid. This method can be used for prediction for the self-source high pressure belt in Yinggehai-Qiongdongnan Basin in the South China Sea.

#### 3.2.3 Effective stress method (Bowers method)

In Bowers method<sup>[11]</sup>, the acoustic wave velocity and empirical parameters are used for determination of the vertical effective stress, and the pore pressure is worked

out by subtracting the vertical effective stress from the overburden pressure. It can be used for prediction of pore pressure caused by unbalanced compaction or other mechanisms. Only two empirical parameters are needed for prediction of the abnormal high pressure caused by unbalanced compaction. Such two empirical parameters can be determined via compaction trend analysis or selected from the empirical data of adjacent wells. Bowers method<sup>[9]</sup> can be used for prediction of abnormal pressure caused by under-compaction, and that caused by other causes. However, parameters in the prediction equation can be determined accurately only when the historical formation stress is clear.

#### 4 PREDICTION METHODS OF PORE PRESSURE UNDER MULTI-SOURCE PRESSURE MECHANISM CONDITIONS IN THE SOUTH CHINA SEA AND THEIR APPLICATION

From the aspect of causes of abnormal high pressure in Yinggehai-Qiongdongnan Basin in the South China Sea, there is not only self-source and adjacent-source high pressure, but also shallow formation high pressure in the middle of diapiric structure belt caused by other source pressure transmission. Hence, it is very difficult to accurately predict using the conventional single pressure model. According to analysis of abnormal high pressure mechanism in this block, two types of geologic models shall be considered for prediction of pre-drilling pressure in Yinggehai-Qiongdongnan Basin: firstly, a normal compaction trend line equation is built with the interval velocity or the logging data of a temporary well, and the pressure is predicted using the balance depth method, Eaton method<sup>[10]</sup> and others; secondly, a geologic model of other-source high pressure transmission, which causes hydrodynamic connectivity of different pressure zones to fault opening, shall be built. A seismic inversion method under the logging restriction conditions is put forward by building of a high precision three dimensional velocity field model on the basis of previous research and in full consideration of two geologic models.

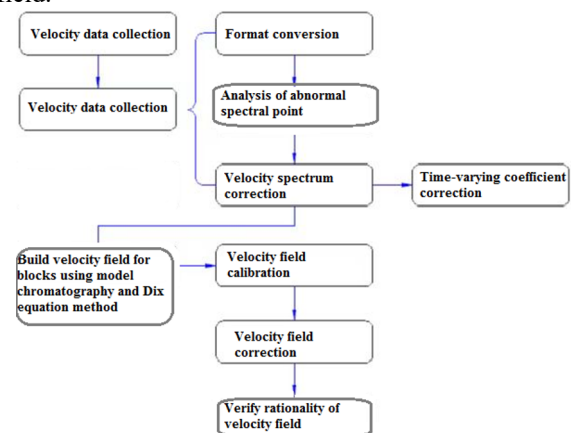
##### 4.1 Basic principle

Prediction of formation pressure with logging data features high resolution. However, due to the restriction of drilling, it is difficult to predict the pressure in a formation not drilled through with this method. It only allows for building of a one-dimensional pressure prediction profile, and fails to consider the impact of multiple formation pressure transmission on pressure in the transverse direction. The seismic data features high planar density, while the parameters used for pressure prediction are usually the average values of the whole region, i.e. spatial restriction of the actually measured parameters is absent. Hence, the shortage of single parameter in the seismic velocity method can be overcome using seismic inversion under logging restriction conditions, thus making the predicted

parameters closer to the actual geologic conditions and reflecting formation pressure variation between wells and formations in a better way. Based on this principle, the logging and seismic data is combined to build a high precision three dimensional velocity field model, the density field is worked out with velocity field based on sparse pulse inversion, the three-dimensional pressure attribute volume is worked out with the improved Fillippone method<sup>[10]</sup>, and slicing in longitudinal and transverse directions are performed based on research of well position coordinate and reservoir position, thus obtaining the pore pressure distribution law with the formation connectivity considered.

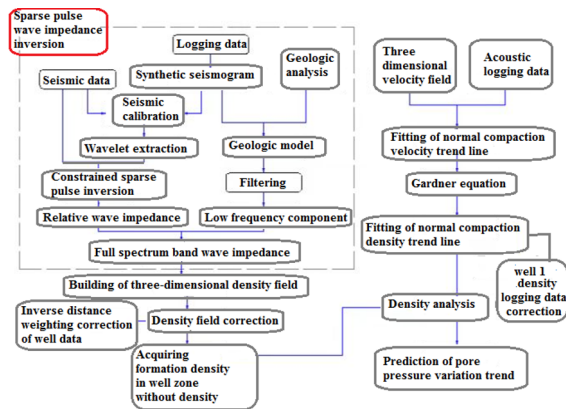
##### 4.2 Prediction process

The whole prediction process includes two parts. In the first part, a high precision velocity field is built. The basic process is as shown in Figure 1. Research on velocity field mainly consists of the following two steps: Step 1, analyze and collect seismic velocity spectrum data and logging data, and obtain a velocity spectrum consistent with the actual logging velocity by combining the seismic velocities. Step 2, work out the interval velocity. Build the initial velocity field using the velocity spectrum obtained in Step 1, perform point-surface-volume correction for the initial velocity field with the logging velocity, and realize secondary correction of the velocity field, thus ensuring the high precision of velocity field.



**Figure 1.** Process of building a three-dimensional velocity field

In the second part, after acquiring a high precision velocity field model, obtain the high velocity field using the sparse pulse inversion method, work out the three dimensional pressure attribute volume with the improved Fillippone method, and perform slicing in longitudinal and transverse directions based on research of well position coordinate and reservoir position, thus obtaining the pore pressure distribution law with the formation connectivity considered. The basic procedure is as shown in Figure 2.



**Figure 2.** Procedure of formation pressure prediction with seismic inversion under logging restriction conditions

### 4.3 Application examples

Both reference well 1 and target well 2 are located in the slope zone of depression in Yinggehai Basin. Target well 2 is arranged at a location 3.0km in the southwest of reference well 1, with water depth about 88.0m. In a downward direction, formations encountered during drilling of reference well 1 are Ledong Formation of Quaternary System, Yinggehai Formation and Huangliu Formation of Neogene System, and the second member of Huangliu Formation in completion horizon in sequence. The main target layers are gas groups II, III and V of Huangliu Formation, and the secondary target layers are gas groups I and IV in Huangliu Formation.

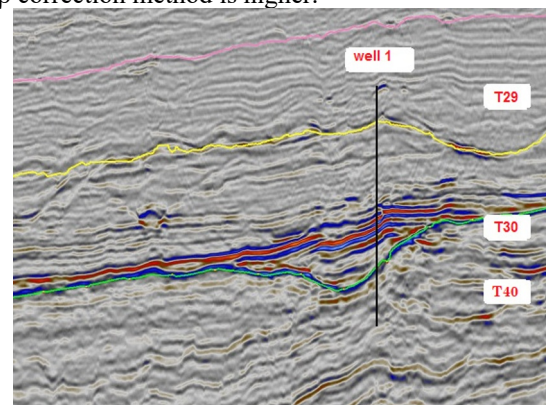
The pre-drilling pressure coefficient of target layer predicted based on the under-compaction mechanism is 1.81~1.98. However, the actually measured pressure coefficient of gas group I is 2.17, that of gas group II is no lower than 2.19, and that of gas group III no lower than 2.23, all of which are much higher than the predicted pressure. Hence, overflow and lost circulation occurred for many times during drilling to the target layer. To analyze the high pressure belt caused by other-source pressure transmission in this block, the seismic inversion method under logging restriction conditions is used for pre-drilling pressure prediction of target well 2, so as to improve the precision of pressure prediction and provide a safe window of drilling fluid density.

#### 4.3.1 Building of three-dimensional velocity field for target well zone

Extraction of interval velocity is the core of improving the pressure prediction precision. Although there are many methods for building a seismic velocity field, the

velocity field must be built in consideration of the actual geologic conditions in the target zone and by taking full advantage of various velocity data. Dix method features high efficiency and easy operation, and applies to the zones with small landform variation and simple geologic conditions. The model chromatography method applies to the zones with large dip angle and complicated structures. Based on analysis for seismic profile of the target block (e.g. Figure 3), with T30 horizon as a boundary, the upper formation features even horizontal layer, small land form variation and simple geologic conditions, which are in compliance with the conditions of velocity field building in Dix method. The formation under T30 horizon features complicated geologic conditions, large dip angle, large lateral variation of velocity and sharp structural variation, which are in compliance with those required for velocity field building with model chromatography. Hence, based on the geologic conditions in this region, with T30 horizon as a boundary, velocity fields are built respectively for blocks in this region, with Dix method for the upper formation and model chromatography for the lower formation, before combination, thus ensuring consistency between the result of velocity field building and the actual velocity distribution.

The seismic data is of poor quality, which results in a large error of the velocity worked out. Therefore, the velocity worked out must be restricted to eliminate the unreasonable value and improve the reliability of speed. The logging data of reference well 1 is used as restrictive conditions for seismic velocity comparison herein, so as to improve the reliability of velocity. To analyze the error of velocity spectrum and acoustic wave logging curve, the time-varying coefficient method and  $v_0\beta$  correction method is used for correction of velocity spectrum respectively. The analysis result is as shown in Table 1. The precision of velocity spectrum after correction using  $v_0\beta$  correction method is higher.



**Figure 3.** Seismic cross-section of reference well 1

**TABLE 1** COMPARATIVE ANALYSIS FOR P WAVE LOGGING DATA AND SEISMIC VELOCITY SPECTRUM OF REFERENCE WELL

| Form<br>ation | Time | Depth<br>(m) | (m/s)<br>P<br>wave<br>velocit<br>y<br>(m/s) | Uncorrected velocity<br>spectrum                        |                       |                            | Velocity spectrum after<br>correction with time<br>varying coefficient<br>method |                           |                            | Velocity spectrum after<br>correction with $v_0\beta$<br>correction method |                       |                            |
|---------------|------|--------------|---------------------------------------------|---------------------------------------------------------|-----------------------|----------------------------|----------------------------------------------------------------------------------|---------------------------|----------------------------|----------------------------------------------------------------------------|-----------------------|----------------------------|
|               |      |              |                                             | (m/s)S<br>pectru<br>m<br>point<br>velocit<br>y<br>(m/s) | Absol<br>ute<br>error | Relat<br>ive<br>error<br>% | Spectr<br>um<br>point<br>velocit<br>y<br>(m/s)                                   | Abso<br>lute<br>erro<br>r | Relati<br>ve<br>error<br>% | Spectr<br>um<br>point<br>velocit<br>y<br>(m/s)                             | Absol<br>ute<br>error | Relati<br>ve<br>error<br>% |
| T20           | 1381 | 1465         | 2088                                        | 2167                                                    | 79                    | 3.78                       | 1993                                                                             | -95                       | -4.55                      | 2082                                                                       | -6                    | -0.29                      |
| T27           | 1953 | 2336         | 2368                                        | 2452                                                    | 84                    | 3.55                       | 2273                                                                             | -95                       | -4.01                      | 2355                                                                       | -13                   | -0.55                      |
| T29           | 2432 | 3111         | 2539                                        | 2680                                                    | 141                   | 5.55                       | 2434                                                                             | -105                      | -4.14                      | 2570                                                                       | 31                    | 1.22                       |
| T30           | 2728 | 3562         | 2595                                        | 2795                                                    | 200                   | 7.71                       | 2518                                                                             | -77                       | -2.97                      | 2576                                                                       | -19                   | -0.73                      |
| T31           | 2928 | 3939         | 2675                                        | 2862                                                    | 187                   | 6.99                       | 2581                                                                             | -94                       | -3.51                      | 2635                                                                       | -40                   | -1.50                      |

At present, software available for velocity field building in China includes Aroundwave, Hongliu, V2C and others, of which, Aroundwave is the most widely used one in the oilfields since it plays a leading role in analysis of velocity and application for velocity field building at home. The velocity field of a target block is built and outputted by Aroundwave

#### 4.3.2 Building of three-dimensional pressure field for target well zone

Fillippone method combines seismic, logging, drilling and other various data, and is independent of the normal compaction trend line. However, it requires to assume an approximately linear relation or logarithmic relation between formation pressure and P wave velocity, as shown in Equation (1). The precision of pressure calculation mainly depends on the conformity of actual conditions in the target region to the empirically assumed conditions, as well as the accuracy of relevant empirical parameters.

$$P = \frac{V_{\max} - V_i}{V_{\max} - V_{\min}} \times \rho \times D \times 0.12 \quad (1)$$

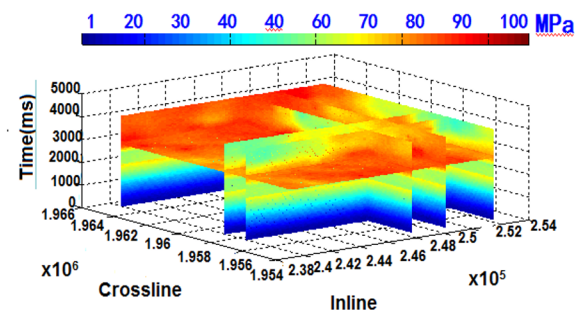
Where,  $v_i$  is the interval velocity of the  $i^{\text{th}}$  interval (m/s);  $v_{\max}$  is the maximum interval velocity (m/s), and is P wave velocity when the effective porosity of reservoir approaches zero;  $v_{\min}$  is the minimum interval velocity (m/s), and is P wave velocity when the rigidity of reservoir approaches zero;  $\rho$  is the formation density ( $\text{g/cm}^3$ );  $v_{\max}$  and  $v_{\min}$  are velocities which rise linearly along with the reflection time, can be calculated using Equation (2).

$$\begin{cases} V_{\max} = 1.4V_{ro} + 3kt \\ V_{\min} = 0.7V_{ro} + 0.5kt \\ V_{r0} = V_r - kt_0 \end{cases} \quad (2)$$

Where,  $V$  and  $t$  are root-mean-square velocity (m/s) and reflection time (s) respectively obtained from the velocity spectrum;  $V_{r0}$  and  $t_0$  are root-mean-square velocity and reflection time (s) on the surface;  $k$  equals  $\Delta V_r / \Delta t$ , and is the slope of  $V_r - t$  in shallow linear relation.

In complicated geologic conditions, the assumption of approximately linear relation or logarithmic relation between formation pressure and P wave velocity is often impossible. Hence, the improved Fillippone method is put forward herein, e.g. Equation (3), and the pore pressure gradient is obtained according to the effective stress principle. The three-dimensional pressure field of target well zone is built as shown in Figure 4.

$$\sigma_{ev} = \frac{v_{\max} - v_i}{v_{\max} - v_{\min}} \times \rho \times 0.12 \quad (3)$$



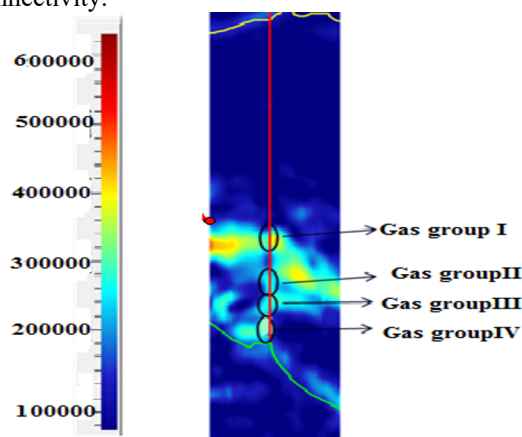
**Figure 4.** Pressure field across well position and gas group slicing

#### 4.3.3 Formation connectivity analysis

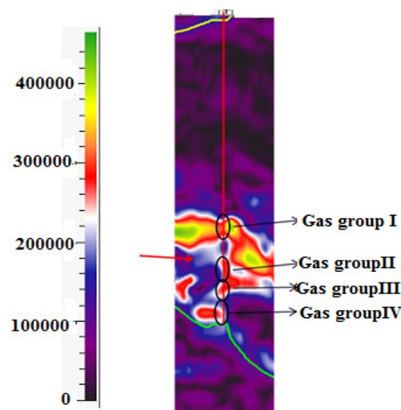
Ultra-high pressure horizon, which is impossible to explain using under-compaction model, occurred during actual drilling in the lower reservoir of reference well 1. According to geologic profile analysis, there may be other-source pressure transmission generated by formation connectivity. A high precision velocity field under the logging restriction conditions is built to obtain

the three dimensional pressure volume data of target block, perform longitudinal and transverse slicing for analysis with reference to the well position coordinate and gas group depth of reference well 1 and target well 2, so as to achieve the goal of qualitative evaluation for formation connectivity as shown in Figure 5 to Figure 10.

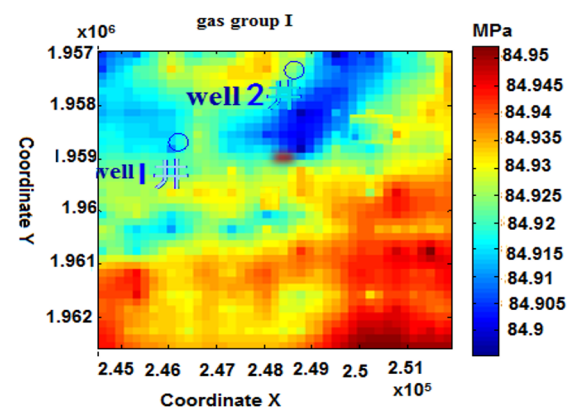
Analysis suggests that in longitudinal direction on instantaneous amplitude attribute drawing of main seismic line of reference well 1, gas groups I and IV show as strong amplitude, and gas groups II and III show as weak amplitude, and the amplitude values are uncontinuous in longitudinal direction, which means there is no connectivity between gas groups I~IV in longitudinal direction. On the attribute drawing of instantaneous amplitude across the seismic line of target well 2, gas groups I~IV show as weak amplitude, and gas groups II and III connect with each other in longitudinal direction. In horizontal direction, pressure distribution of gas groups I, III and IV varies little in transverse direction, the difference between the maximum value and the minimum value is within 0.1 MPa. It can be judged qualitatively that these gas groups connect with each other in transverse direction. However, the pressure of gas group II varies largely, the difference between the maximum pressure and the minimum pressure approaches 5 MPa. Hence, there is no possibility of connectivity.



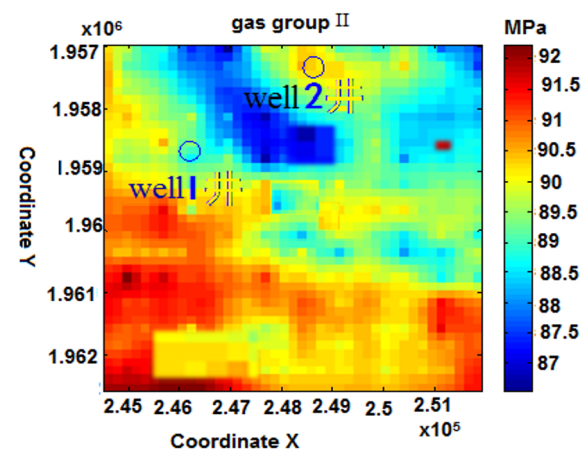
**Figure 5.** Profile of instantaneous amplitude across Inline of reference well 1



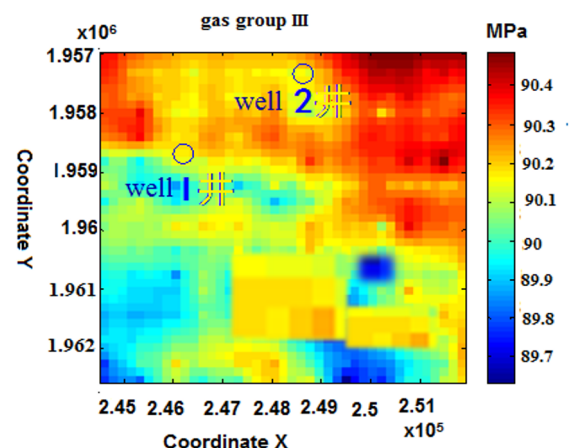
**Figure 6.** Profile of instantaneous amplitude across Inline of reference well



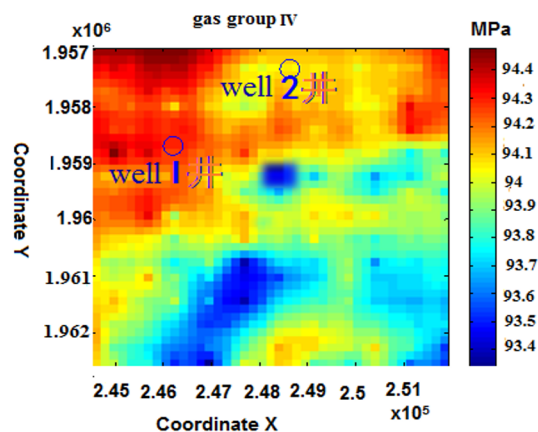
**Figure 7.** Horizon slice of pressure in gas group I (connected)



**Figure 8.** Horizon slice of pressure in gas group II (not connected)



**Figure 9.** Horizon slice of pressure in gas group III (connected)



**Figure10.** Horizon slice of pressure in gas group IV (connected)

**TABLE 2** COMPARATIVE ANALYSIS OF PRESSURE PREDICTION AND ACTUAL DRILLING RESULTS FOR TARGET WELL 2

| Horizon       | Actual drilling pressure (g/cm3) | Connectivity not considered |         | Connectivity considered   |         |
|---------------|----------------------------------|-----------------------------|---------|---------------------------|---------|
|               |                                  | Prediction result (g/cm3)   | Error % | Prediction result (g/cm3) | Error % |
| Gas group I   | 2.15                             | 1.9                         | -11.63  | 2.135                     | -0.70   |
| Gas group II  | 2.26                             | 2.1                         | -7.08   | 2.15                      | -4.87   |
| Gas group III | 2.27                             | 2.12                        | -6.61   | 2.2                       | -3.08   |
| Gas group IV  | 2.28                             | 2.14                        | -6.14   | 2.22                      | -2.63   |

## 5 CONCLUSION

(1) The abnormal high pressure formed due to multi-source pressure mechanisms in Yinggehai-Qiongdongnan Basin in the South China Sea brings great challenge to drilling in this region. Application of conventional pressure prediction model in this region is limited significantly, and this model has shown large problems in previous drilling.

(2) This paper analyzes the formation mechanisms of abnormal pressure in Yinggehai-Qiongdongnan Basin in the South China Sea, confirms that there is not only self-source and adjacent-source high pressure in this region, but also shallow formation high pressure in the middle of diapiric structure belt caused by other source pressure transmission, and puts forward two types of geologic models for the first time, i.e. the geologic model based on self-source or adjacent-source under-compaction mechanism, and the geologic model of other-source high pressure transmission, which causes hydrodynamic connectivity of different pressure zones to fault opening. On this basis, the seismic inversion prediction method under logging restriction conditions is developed via inversion of high precision three-dimensional velocity field.

(3) This method decreases the prediction precision of pre-drilling pressure in actual drilling of a block in the South China Sea to a level within 5% for the first time, and provides accurate fundamental data support for smooth drilling of ultra-high pressure formation in the lower part of this region.

## 4.3.4 Error analysis

As shown in Table 2, pre-drilling pressure prediction and error analysis is made for the gas group of target well 2 using the mathematical model of formation pressure prediction based on the conclusion of analysis in longitudinal and transverse directions of main gas groups of target well 2 and reference well 1. The analysis results show that, in consideration of formation connectivity, compared with prediction using a single mathematical model, the prediction error can be decreased to a level within 5%, which can provide more accurate basis for successfully drilling to the target layer and avoid downhole accident.

## ACKNOWLEDGMENT

The Norteheast Petroleum University on-campus project , project number: 2020YDQ-06.

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