2015 4th International Conference on Environmental, Energy and Biotechnology
Volume 85 of IPCBEE (2015)
DOI:10.7763/IPCBEE. 2015. V85. 1

The Improvement Methods of Pore Pressure Prediction Accuracy in the Central Canyon in Qiongdongnan Basin

Chen Zijian+, Deng Jingen, Yu Baohua, Tan Qiang and Chen Zhuo

State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing, China.

Abstract. The abnormal overpressure developed in the Central Canyon in Qiongdongnan Bain and the drilling is of a high risk. In order to improve the pore pressure prediction accuracy, the responses of the logging data for different abnormal overpressure causes are discussed. The acoustic velocity and the formation density both decrease during the loading process. However, the acoustic velocity reduces but the formation density remains unchanged during the unloading process. Then a judgment method of the abnormal overpressure causes based on the acoustic-density crossplot is proposed. By this means, the choosing of appropriate prediction model is more theoretical. On the other hand, a new conversion method of the pore pressure test results of the drilled well is also put forward to reduce the prediction error. These methods are applied in the Central Canyon in Qiongdongnan Basin. The results show that the overpressure of Huangliu and Yinggehai formation is controlled by the undercompaction which belongs to loading. Meishan and Sanya formation are dominated by the combination of undercompaction, hydrocarbon generation and aquathermal expansion, where the loading and unloading both happens. Lingshui and Yacheng formation is in the control of the hydrocarbon generation which belongs to unloading. The application of a pre-drill well indicates that these methods greatly improve the prediction accuracy and guide the drilling design.

Keywords: pore pressure, prediction accuracy, acoustic-density crossplot, conversion method, Central Canyon, Qiongdongnan Basin

1. Introduction

The Central Canyon in Qiongdongnan Basin belongs to the deepwater continental slope in South China Sea, which is located between the northern Central upwelling area and the southern low upwelling area. The water depth is 1000-1500 m and the stratums include Quaternary, Neogene (Yinggehai formation, Huangliu formation, Meishan formation and Sanya formation) and Palaeogene (Lingshui formation, Yacheng formation and Lingtou formation). The abundant oil and gas resources of the Central Canyon in Qiongdongnan Basin have been proved by Yang Chuanheng [1] and Chen Jianwen [2]. However, the abnormal overpressure exists widely in the Central Canyon, and the highest overpressure could reach 2. 3g/cm^3 [3]. Therefore, predicted pore pressure of a high accuracy is significant for the safe drilling and the further development of oil and gas field.

The choice of appropriate models is extremely vital for the pore pressure prediction. In recent decades, a variety of prediction models have been proposed [4]-[8] and Eaton method and Bowers method are widely used in the pore pressure prediction. Nevertheless, the choices of these models for different areas mostly depend on the researchers' experiences but not the cause of abnormal overpressure. A judgment method of the cause of abnormal overpressure based on the acoustic-density crossplot is proposed in this paper. Then the relationship between the cause of abnormal overpressure and appropriate prediction models is discussed. In addtion, a conversion method by which the pore pressure test results of the drilled well could be corrected as the predicted pore pressure of the pre-drill well is built. These methods are applied in the Central Canyon

---

[+] Corresponding author. Tel.: +86 18612312023; fax: +010-89733911.
E-mail address: 13488780158@163.com.

in Qiongdongnan Basin. The applied results indicate that these methods highly improve the pore pressure prediction accuracy and effectively guarantee the drilling safety.

2. Geological Background

Table 1: The geological tectonic description of Qiongdongnan Basin

Era	System		Period	Geological tectonic movement	Sedimentary Sequence	Tectonic stage and structural system
Cenozoic	Quaternary		Pleistocene	The depression period, namely post-rift thermal subsidence stage, with high sedimentary rate.	Ledong	Depression period; the upper structural system
	Tertiary	Neogene	Pliocene		Yinggehai	
			Miocene		Huangliu Meishan Sanya	
		Paleogene	Late Oligocene	Faults were motivated again, and some new EW faults formed.	Lingshui	Faulting period and the period transformed from fault depression to sag; the lower structural system
			Early Oligocene Late Eocene	With the development of basin extension, the earth's mantle upwells and the base rock is uplifted, and some NEE faults developed.	Yacheng	
			Eocene	Some NE fault depressions formed from the east to the west, then the fault subsidence lake developed. The hydrocarbon source rock is of a high quality.	Lingtou	
			Paleocene	Early tensional tectonic movement began along with the first-phase extensional movement of the northern basin in South China Sea. Some NW fault depressions formed, mostly presented as half-graben, half-graben assembly and graben.	Basement	Basement
Mesozoic	Cretaceous		Late Cretaceous			

The Qiongdongnan Basin is a quasi passive continental margin structure, which developed upon the basement consists of the metamorphic rock of Paleozoic and Mesozoic and the magmatic rock of Mesozoic. The basin experienced three stages: the faulting period, the period transformed from fault depression to sag and the depression period. During the Upper Cretaceous and early Paleogene, the Qiongdongnan Basin experienced the early tensional tectonic movement along with the first-phase extensional movement of the northern basin in South China Sea. The basement rifts developed and some northeast fault depressions formed. After that, the basin came into the period transformed from fault depression to sag and another series of northeast fault depressions came into being with the second-phase tensional movement in the late Eocene and early Oligocene. Then the new structural tectonic movement in the late Oligocene lead to some new NW faults and the basin entered the depression period. In addtion, the sedimentary rate is really high in the depression period [9]. Therefore, the stratums can be divided into two structural systems (as shown in the Table. 1): the upper structural system includes Ying-Huang formation (Yinggehai formation and Huangliu formation), Meishan formation and Sanya formation, which both formed in the depression period; the lower structural system includes Lingshui formation, Yacheng formation and Lingtou formation. The temperature gradient of the upper structural system is higher than the lower structural system [10].

Zhu Jianjun [11] and Zhu Guanghui concluded that the abnormal overpressure of the lower structural system resulted from the hydrocarbon generation, but the abnormal overpressure of the upper structural system mainly induced by the undercompaction, and the aquathermal expansion and hydrocarbon generation also made some contributions. However, these conclusions are mostly based on the geological structural theory but out of the evidence of drilling data.

3. Judgment of Abnormal Overpressure Cause

3.1. Loading and unloading

The causes of pore pressure are related to the loading and unloading process. During the loading process, the rock framework's effective stress increases with the increasing of the overburden stress. When the formation properties change or some tectonic movements occur, the original rock framework's effective stress may reduce, and this progress called unloading [12].

Actually, the responses of the logging data during the loading process and the unloading process are different (as shown in the Fig. 1). During the loading process, the porosity decreases with the effective stress increases, so the interval transit time reduces and the formation density goes up. On the other hand, the formation has been compacted before the unloading happens, even if the effective stress decreases, the porosity can not completely recover because the rock is elastic-plastic. Therefore, the interval transit time which is related to the rock conductive property would increase slowly and the formation density which is affected by the rock bulk property nearly remains unchanged. The Fig. 1 shows that if the rock is perfectly elastic, the loading curve and the unloading curve overlap. On the other hand, the porosity and the acoustic velocity do not change if the rock is perfectly plastic. The actual rock is elastic-plastic, so the typical unloading curve is between the loading curve and the perfectly plastic unloading curve.

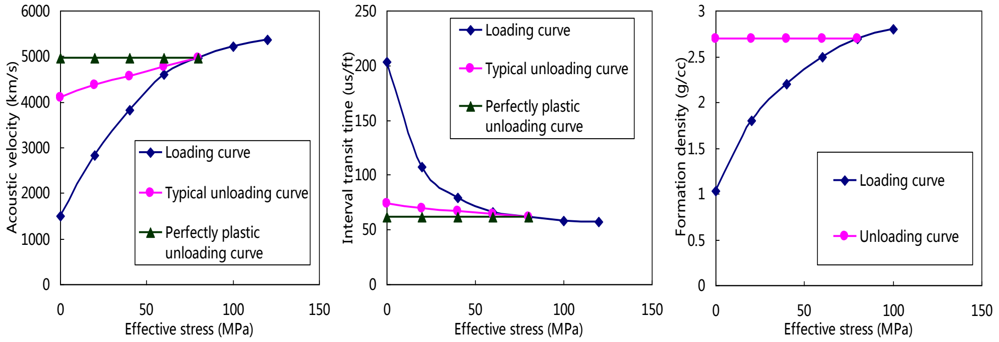

Fig. 1: The response of the logging data during the loading and unloading

3.2. Judgment method of pore pressure cause

Compared to the geological structural data, the logging data can reflect the formation properties more accurately. Besides, the logging data are also more easily obtained. Therefore, if the cause of pore pressure is confirmed by the logging data and the appropriate prediction model is chosen, the prediction accuracy of pore pressure could be improved. According the relationship between the logging data and the loading and unloading process, the causes of pore pressure are concluded in the Table. 2.

For the normal compaction, with the increase of overburden pressure, the rock framework's effective stress increases and the pore pressure remains equal to the hydrostatic pressure. However, the pore pressure would be more than the hydrostatic pressure with the increase of overburden pressure in the undercompaction period, because the formation fluid can not outflow normally. At the same time, the effective stress also goes up but the loading rate is slower than the normal compaction. Therefore, the undercompation also belongs to the loading process, but with slow loading rate. The slow loading rate leads to lower acoustic velocity and lower formation density. The decreasing degree is determined by the undercompaction degree, and the higher the undercompaction degree, the lower the acoustic velocity and the formation density.

For the intense structural tectonic movement, the strong horizontal compression from the horizontal in-situ stress would also result in abnormal overpressure. The mechanical mechanism is the same with the undercompaction, just the loading direction changes from the vertical direction to the horizontal direction. Thus the intense structural tectonic movement is also regarded as loading process.

For the change of formation pore fluid volume, just like hydrocarbon generation, aquathermal expansion, clay diagenesis, etc, the abnormal overpressure develops after the formation compaction, so the pore pressure increases and the effective stress slumps. Hence, the change of formation pore fluid volume belongs to the unloading process. Moreover, the structural shear action caused by the variation of in-situ stress, the pore is shear broken and the effective stress decreases, thus the pore pressure increases. Therefore, the structural shear action is one of the unloading processes.

Table 2: The relation between the abnormal overpressure cause and the logging data response

The cause of abnormal overpressure		Mechanical mechanism	Interval transit time	Formation density	Prediction model
The change of pore volume	undercompaction	Loading	Decrease	Decrease	Eaton model Bowers loading model
The structural tectonic movement	Compression from is-situ stress				
	Shear from in-situ stress	Unloading	Decrease	Remains unchanged	Bowers unloading model
	Uplift of the formation				
The change of formation pore fluid volume	Aquathermal expansion				
	Clay diagenesis				
	Hydrocarbon generation				
	Fluids migration				
	Permeation				
	Hydraulic head				

4. Conversion Method of the Tested Pore Pressure

For the appropriate prediction model, the determination of parameters in the model is also very difficult. The drilled wells' results are usually applied to determine these parameters as reference values without any conversion. However, the pore pressure systems of different wells are different, especially for the deepwater drilling. The lack of conversion of the pore pressure test results of the drilled well could results in a large error.

Zhang Jincai [13] proposed that the conversion of different wells' pore pressure should conform with the principle of hydraulic connectivity in saturated formation, as Equation (1). Aadnoy [14] also put forward a conversion method with the consideration of water depth, as Equation (2). The only difference between these two methods is that the formation fluid density is used by Zhang and the sea water density is in use by Aadnoy.

$$\mathrm{P}_{2\mathrm{p}} = \mathrm{P}_{1p} + \rho_f g\left(H_{2p} - H_{1p}\right) \tag{1}$$

$$\begin{aligned} \rho_{2p} &= \rho_{1\mathrm{p}} \frac{H_{1p}}{H_{2p}} + \rho_{sw} \frac{H_{w2} - H_{w1}}{H_{2p}} \\ H_{2p} &= H_{1p} + \left(H_{w2} - H_{w1}\right) + \left(H_{f2} - H_{f1}\right) \end{aligned} \tag{2}$$

Where, 1 means the drilled well; 2 means the pre-drill well; H_{w} is the water depth, m; H_f is the drilling floor elevation, m; H_{p} is the depth of pore pressure, m; P_{p} is the pore pressure, Mpa; ρ_{p} is the pore pressure coefficient, g/cm^3; g is the gravity acceleration, m/s^2; ρ_{sw} is the sea water density, g/cm^3; ρ_f is the formation fluid density, g/cm^3.

However, the pore pressure results from the combination of the sedimentary action and the structural tectonic movement. Actually, the pore pressure systems of different wells are different because of different formation sedimentary sequence and structural tectonic movement. But this kind of influence is ignored by Zhang and Aadnoy. In order to reduce the error caused by this influence, a new conversion method considering the formation sequence of different wells is proposed, as shown in the Fig. 2. Firstly, the formation transformation coefficient k is calculated by the formation data and the pore pressure test result of the drilled well. The formation transformation coefficient means the ratio of the pore pressure test depth to the formation thickness, as Equation (3).

$$\mathrm{k} = \frac{H_{1\mathrm{p}} - H_{1\mathrm{t}}}{H_{1\mathrm{b}} - H_{1\mathrm{t}}} \tag{3}$$

Where, H_{t} is the top depth of the test formation, m; H_{b} is the bottom depth of the test formation, m; k is the formation transformation coefficient.

Then the corrected depth of pore pressure test for the pre-drill well according to the predicted formation sequence data can be figured out as follow:

$$H_{2p} = H_{2t} + k\left(H_{2b} - H_{2t}\right) \tag{4}$$

Combined with the Equation (1), the pore pressure coefficient of the corrected depth for the pre-drill well can be obtained as follow:

$$\rho_{2p} = \rho_{1p} H_{1p} / H_{2p} + \rho_f (H_{2p} - H_{1p}) / H_{2p} \tag{5}$$

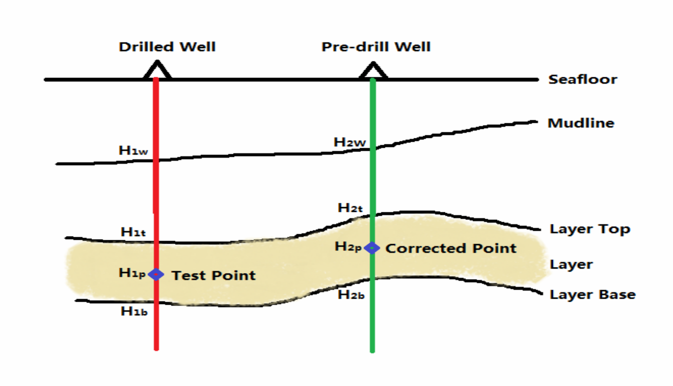

Fig. 2: The conversion method of the pore pressure test result of the drilled well

5. Case Study

According the judgment method proposed above, the causes of abnormal overpressure of the Central Canyon in Qiongdognnan Basin are analyzed by two drilled deepwater wells. One well is LS-1 well, whose water depth is 1335.8 m. LS-1 well was finished in Meishan formation and the abnormal overpressure exists in Huangliu formation and Meishan formation. The other well is YL-1 well, whose water depth is 1695.4 m. YL-1 well was finished in Yacheng formation, and the abnormal overpressure of 1.25 exists in Lingshui formation. The Fig. 3 and the Fig. 4 show the interval transit time and the formation density of the mudstone in LS-1 well and YL-1 well. The Fig. 5 and the Fig. 6 illustrate the acoustic-density crossplot of the mudstone in LS-1 well and YL-1 well. The upper limit curve and the lower limit curve are put forward by Bowers in 2001.

The Fig. 3 indicates that the logging data of LS-1 well become abnormal from the down interval of Yinggehai formation. The interval transit time is higher than the normal value, and the formation density is a little low, especially for Meishan formation. The Fig. 5 illustrates that the data of Yinggehai formation are within the normal range. However, some data of Huangliu formation and Yinggehai formation overlap, which means some Huangliu formation intervals experienced loading process. The transit time is higher and the formation density is lower in Meishan formation, which indicates the loading process. On the other hand, the data of Meishan formation obviously exceed the upper limit curve, this means the interval transit time reduces and the formation density remains unchanged. Therefore, Meishan formation went through loading and unloading process together.

The Fig. 4 shows that the data of YL-1 well become abnormal from Meishan formation to the upper interval of Yacheng formation. As shown in the Fig. 6, on the one hand, the data of Huangliu formation, Meishan formation and Sanya formation overlap obviously; on the other hand, the data of Meishan formation and Sanya formation exceed the upper limit curve. In conclusion, Meishan formation and Sanya formation experienced loading and unloading process together. For Lingshui formation and the upper interval of Yacheng formation, the interval transit time is higher and the formation density is normal, this means the cause of abnormal overpressure of Lingshui formation and the upper interval of Yacheng formation belongs to unloading.

In summary, Huangliu formation of the upper structural system is controlled by loading. Meishan and Sanya formation of the upper structural system are dominated by loading and unloading together. Lingshui and Yacheng of the lower structural system are in the control of unloading. The conclusions further confirm the results based on the geological structural theory by Zhu Guanghui and Zhu Jianjun. Moreover, the conclusions further distinguish the mechanical mechanism of Huangliu formation from that of Meishan and Sanya formation, which has never been done before.

LS-2 well is a pre-drill well in the Central Canyon in Qiongdongnan Basin, the water depth is 1552 m and the proposed drilling formations are Ledong, Yinggehai and Huangliu. The abnormality of the seismic data occurs from the middle of Yinggehai formation. According the conclusions obtained above, the pore pressure could be predicted by Eaton model and the Bowers loading model. To improve the prediction accuracy, the pore pressure test results of LS-1 well are corrected by the means of the new conversion method proposed in this paper, the conversion results are shown in the Table.3. The parameters used in the models are as follows:

Where, S_p is the overburden pressure coefficient, g/cm^3; Δt is the measured interval transit time, us/ft; Δt_n is the normal interval transit time, us/ft; V is the acoustic velocity, ft/s; σ is the vertical effective stress, Mpa.

The Fig. 7 shows the predicted results. As the pink line shows, the result of Bowers loading model is of a severe variation, and the pore pressure of Ledong formation is higher and that of Ying-Huang formation is lower. By comparison, Eaton model is of a higher prediction accuracy under this condition, which is shown as the blue line. In addtion, the new conversion method gives more accurate corrected pore pressure compared with the other two methods. The predicted pore pressure of LS-2 well by Eaton model is normal in the Ledong formation, and increases from the middle of Yinggehai formation. The predicted pore pressure exceeds 1.10 g/cm^3 in the bottom of Yinggehai formation, and reaches 1.22 g/cm^3 in the top of Huangliu formation. The highest predicted pore pressure is 1.44 g/cm^3 in the bottom of LS-2 well.

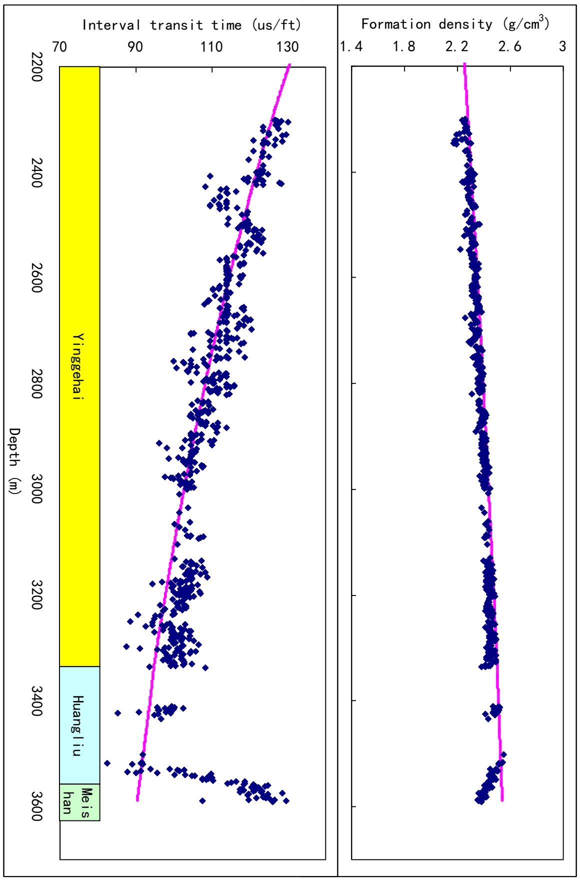

Fig. 3: The logging data of LS-1 well

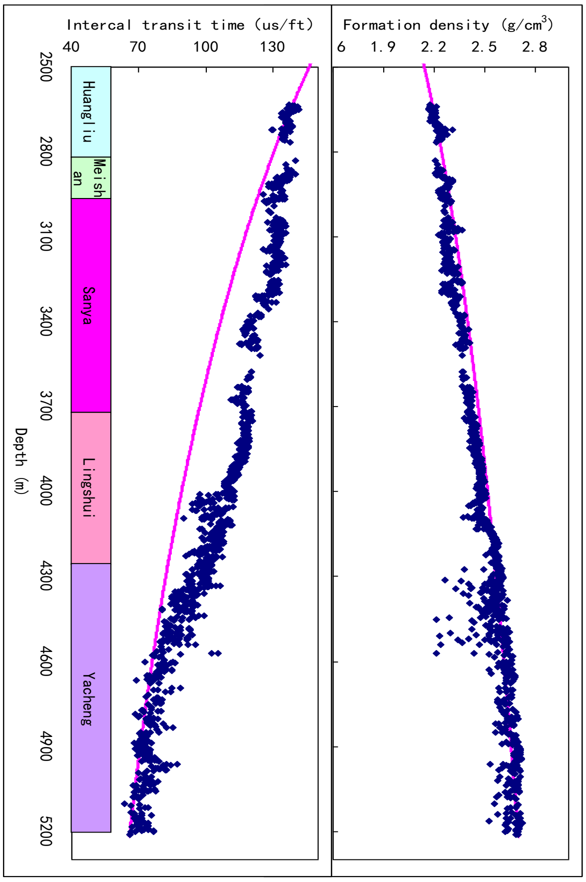

Fig. 4: The logging data of YL-1 well

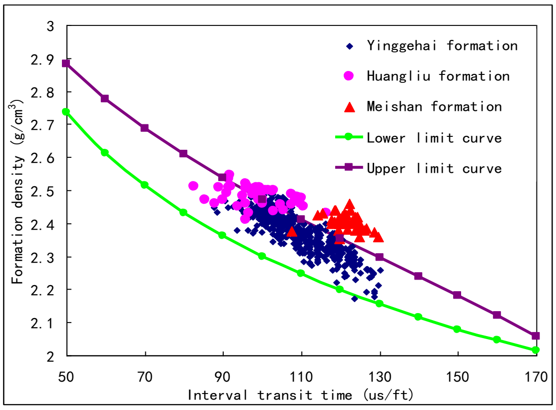

Fig. 5: The acoustic-density crossplot of LS-1 well

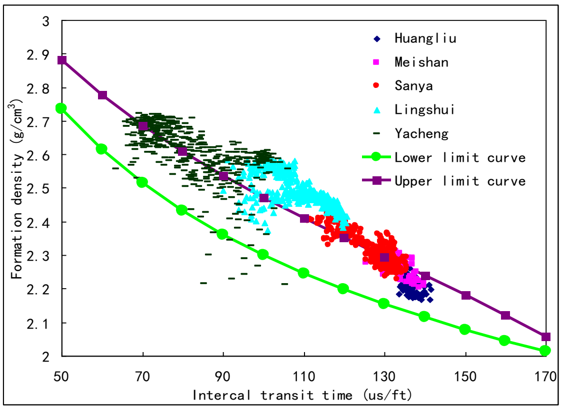

Fig. 6: The acoustic -density crossplot of YL-1 well

Eaton model: $$\rho_p = S_p - (S_p - \rho_{sw})(\frac{\Delta t}{\Delta t_n})^{3.2} \tag{6}$$

Bowers loading model: $$V = 5000 + 503\sigma^{0.775} \tag{7}$$

Bowers unloading model: $$V = 5000 + 503[14.02(\sigma/14.02)^{(1/3.13)}]^{0.775} \tag{8}$$

The Bowers unloading model is also applied in LS-2 well as a comparison. The result of Bowers unloading model is symbolized as the red line. The predicted pore pressure is quite higher and could increases at the high of 1.51 g/cm^3. This verifies the conclusion that the choice of appropriate prediction model is significant for avoiding the large error. Nevertheless, the unbelievable corrected pore pressures by the methods proposed by Zhang Jincai and Aadnoy also explain that the consideration of the formation sedimentary sequence and structural tectonic movement is necessary. For the area with intense structural tectonic movement or with quite different formation sequence, this kind of influence on the results can be enlarged.

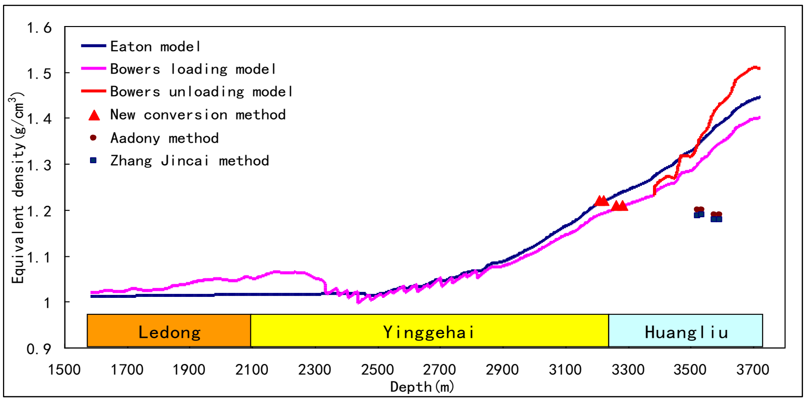

Fig. 7: The predicted pore pressure of LS-2 well

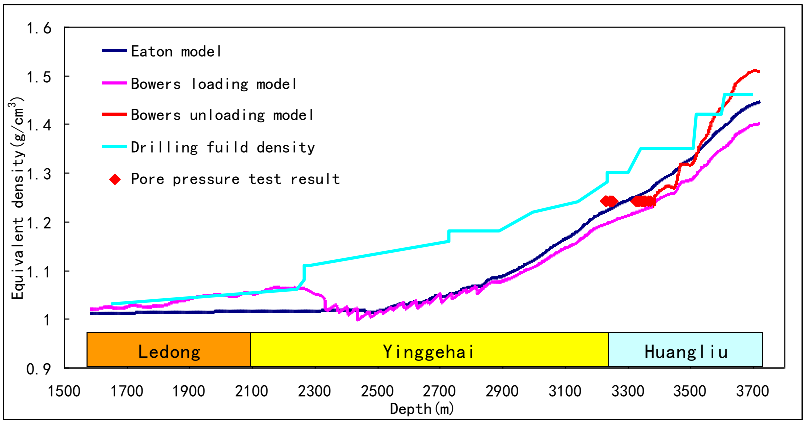

Fig. 8: The comparison of the predicted result and the real test result of LS-2 well

As shown in the Fig. 8, compared with the real pore pressure test results and drilling fluid density, the absolute errors between Eaton model result and the real test result are only ±0.02-0.03 g/cm^3, and the relative errors are lower than 2.5%. The drilling is very smooth without any accident. Compared to Bowers loading model, the result shows that Eaton model is more appropriate for the Ying-Huang formation where the abnormal overpressure is caused by loading. But the pre-drill well does not drill the lower formation where the unloading happens. Although the unloading model is applicable to the lower formation according to this study, it still needs further research and more evidences for the deep formation pore pressure.

6. Conclusions

The acoustic-density crossplot can be applied to judge the causes of abnormal overpressure in the Central Canyon in Qiongdongnan Basin, and the appropriate prediction model can be chosen based on this method. The prediction error can be reduced by this method and this is verified by filed case study.

On the basis of the logging data analysis, the causes of abnormal overpressure in the Central Canyon in Qiongdongnan Basin are further verified. For Ying-Huang formation, the overpressure is due to the undercompaction which belongs to loading. For Lingshui and Yacheng formation, the cause is hydrocarbon generation which belongs to unloading. For Meishan and Sanya formation, the reasons include undercompaction, hydrocarbon generation and aquathermal expansion, this means the loading and unloading both happened there.

Table 3: The correct predicted pore pressure of LS-2 wellLS-1 Well (water depth is 1335.8 m)

LS-2 Well (water depth is 1552 m)									
Formation	H_{1p} (m)	H_{1p} - H_{1t} (m)	ρ_{1p} (g/cm^3)	New conversion method		Aadnoy method		Zhang Jincai method	
				H_{2p} (m)	ρ_{2p} (g/cm^3)	H_{2p} (m)	ρ_{2p} (g/cm^3)	H_{2p} (m)	ρ_{2p} (g/cm^3)
Yinggehai	3306.9	1107.9	1.21	3208.85	1.22	3523.10	1.20	3523.10	1.19
Yinggehai	3320.4	1121.4	1.21	3222.37	1.22	3536.60	1.20	3536.60	1.19
Huangliu	3358.8	22.8	1.2	3262.59	1.21	3575.00	1.19	3575.00	1.18
Huangliu	3374.8	38.8	1.2	3279.85	1.21	3591.00	1.19	3591.00	1.18

A new conversion method of the pore pressure test result of the drilled well is proposed. The result shows that this method can greatly improve the pore pressure prediction accuracy with the consideration of formation sedimentary sequence and structural tectonic movement.

7. Acknowledgments

This work is financially supported by National Natural Science Foundation Project of China (Grant No.51134004), and the project name is "Wellbore Stability Study of Under-Balance drilling".

8. References

[1] Yang Chuanheng, Du Xu, Pan Heshun et al. Advances in Worldwide Deep Water Hydrocarbon Exploration and Oil and Gas Exploration Potential in the Northern Continental Slope in South China Sea. *GeoscienceFrontiers*, 2000, (3): 247-256.

[2] Chen Jianwen, New Exploration Domain for O Oil and Gas in Deep Water Basins. *Marine Geology Letters*, 2003, (8): 38-41+59.

[3] Xiao Jun, Wang Hua, Zhu Guanghui et al. Abnormal Formation Pressure and Deep Reservoir Physical Property in Qiongdongnan Basin. *Journal of Oil and Gas Technology*, 2007, (1): 7-10+30+16.

[4] B. A. Eaton, The Equation for Geopressure Prediction from Well Logs. SPE-5544-MS, 1975.

[5] G. L. Bowers, Pore Pressure Estimation from Velocity Data: Accounting for Overpressure Mechanisms besides

Undercompaction. *SPE Drilling & Completion*, 1995, (2): 89-95.

[6] N. C. Dutta, J. Khazanehdari, Estimation of formation fluid pressure using high-resolution velocity from inversion of seismic data and a rock physics model based on compaction and burial diagenesis of shales. *The Leading Edge*, 2006, 25(12):1528-1539.

[7] Fan Honghai, Zhang Chuanjin. New Methods for Calculation of Pore Pressure in ComPlex Geologic Environment. *Petroleum Drilling Techniques*, 2005, (5): 43-46.

[8] Ye Zhi, Fan Honghai, Cai Jun et al. Investigation And Application Of A Discrimination Method For Abnormal High Formation Pressure Forming Mechanism. *Journal of China University of Petroleum*, 2012, (3): 102-107.

[9] Liu Jun, Wang Hua, Jiang Hua et al. Prospects for Deepwater Oil and Gas Exploration in Qiongdongnan Basin. *Xinjiang Petroleum Geology*, 2006, (5): 545-548.

[10] Zhu Guanghui, Chen Gang, Diao Yinghu. Characteristics of Geotherm-Pressure Field And Its Relationship With Hydrocarbon Migration And Accumulation In Qiongdongnan Basin, South China Sea. *China Offshore Oil and Gas (Geology)*, 2000, (1): 30-37.

[11] Zhu Jianjun, Zhang Xiaobao, Zhang Gongcheng et al. A Study of Abnormal Pressure Distribution and Formation Mechanism in Qiongdongnan Basin. *Natural Gas Geoscience*, 2011, (2): 324-330.

[12] Jin Yequan, Wang Yuezhi, Li Zijun. Undercompaction Causes for Using Seismic Data to Predict Formation Pore Pressure. *Petroleum Drilling Techniques*, 2000, (3): 7-9.

[13] J. Zhang, Pore pressure prediction from well logs: Methods, modifications, and new approaches. *Earth-Science Reviews*, 2011, (1): 50-63.

[14] B. S. Aadnoy, Geomechanical Analysis for Deep-Water Drilling. SPE-39339-MS, 1998.