Journal of Geoscience and Environment Protection, 2022, 10, 101-110
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Research on Pore Pressure-Depth Characteristics in Normal Pressure Reservoir, Bohai Sea Oilfield

Pengfei Mu, Qiongyuan Wu, Mingzhe Cui, Geng Qian, Bo Zhang

Tianjin Branch of CNOOC Ltd, Tanggu, Tianjin, China
Email: mupf@cnooc.com.cn

How to cite this paper: Mu, P. F., Wu, Q. Y., Cui, M. Z., Qian, G., & Zhang, B. (2022). Research on Pore Pressure-Depth Characteristics in Normal Pressure Reservoir, Bohai Sea Oilfield. *Journal of Geoscience and Environment Protection, 10,* 101-110.
https://doi.org/10.4236/gep.2022.104007

Received: March 15, 2022
Accepted: April 17, 2022
Published: April 20, 2022

Abstract

In normal pressure of reservoir, formation pressure and depth can not fully reflect the linear relationship between the formation pressure with depth, the change rule of reservoir measured formation pressure and often reduced pressure, understanding unclear cause fluid properties. By introducing basic principles of hydrostatics. The relationship between pressure coefficient and mathematical depth is discussed by mathematical induction analysis of measured pressure data of nearly 50 normal pressure reservoirs in Bohai Oilfield. The results show that the reservoir pressure data is linearly distributed with depth, and the pressure coefficient is inversely proportional to depth. When the depth becomes shallower, the pressure coefficient increases and approaches the reservoir level. As the depth increases, the pressure coefficient decreases and approaches the hydrostatic pressure coefficient infinitely. The study can more accurately analyze the reservoir pressure changes, which is helpful to study the oil and water distribution, reservoir connectivity and fluid properties of atmospheric pressure reservoirs.

Keywords

Bohai Basin, Normal Reservoir Pressure, Wireline Formation Tester, Pressure Coefficient, Inverse Proportion Function

1. Introduction

Nowadays, the application of Wire-line formation tester which measures formation pressure, such as the tools like MDT made by Schlumberger, FMT by Atlas, RDT by Halliburton and EFDT made by CNOOC, they could all provide data foundation for reservoir stress studies (Schlumberger Land China Operation, 2002; Wang et al., 2008; Qin et al., 2012; Pan, 2012; Ma et al., 1995). The pore data is widely used as an important basis for analysis of fluid properties, however, in actual use, part of the pore pressure data deviate from the linear curve of pore pressure and depth, and the linear curve of pressure data varies greatly in different depth interval. The change of pore pressure data with depth is not clear, and there is a lack of method to accurately understand the relationship between pore pressure and depth, which leads to uncertainty in the fitting scheme of measured pore pressure and depth data. Therefore, it is necessary to fully understand the relationship between measured formation pressure and depth data in order to further guide the study of fluid property distribution in atmospheric pressure reservoirs.

Analysis of characteristics of pressure in more than 50 normal pressure reservoirs by using Cable formation pressure data (Pan, 2012; Ma et al., 1995; The Pressure Log Reference Manual, 1980), can provide the basis of determining water distribution, evaluation of oil and gas formation connectivity, studying the characteristics of reservoir production, making reasonable development program (Shaker, 2014; Kuang, 2005; Zoback, 2007). Pressure points have a concentrated distribution in main oil layer section in Paleogene and Neogene, the pressure coefficient between 0.98 with 1.04, belongs to the normal formation pressure system.

2. Methods and Principles

In this paper, many normal pressure reservoirs in Bohai Sea are taken as the research object. Firstly, the mathematical relationship between measured formation pressure and fluid density is established by hydrostatics theory, and then the influence of fluid property change on measured formation pressure and the trend of formation pressure change are discussed in combination with the analysis data of crude oil physical property. This method can strengthen the research depth of the relationship between measured formation pressure and fluid properties, improve the reservoir description accuracy and the rationality of development plan.

Hydrostatics is the study of the mechanical law of liquid in static or relatively static state and its application. The mass force acting on liquid is only gravity, and the equivalent pressure transfer in homogeneous liquid means the existence of isobaric surface, and the fluid interface is isobaric surface. It is suitable for the study of formation pressure distribution law in normal pressure reservoir. Normal pressure reservoir is a semi-enclosed fluid system, which is shielded by lithology or fault in the trap, and its lower formation water communicates with surface water through permeable layer or fault.

According to the principle of Hydrostatic Pascal, the internal pressure of liquid is equivalent to the existence of isobaric surface. The isobaric surface of the atmospheric pressure reservoir intersects with mass force. From the perspective of the reservoir, the isobaric surface is horizontal, and the interface of the different fluids is isobaric. The interface between the oil layer and the edge (bottom) water is the isobaric surface of the pure oil zone and the pure water which has equilibrium pressure (Figure 1(a)).

For single oil area:

$$P_1 = P + \rho_o \cdot g \cdot h \tag{1}$$

For pure water area:

$$P_2 = \rho_w \cdot g \cdot H_{\text{OWC}} \tag{2}$$

Formation pressure at some point in single oil area:

$$\begin{aligned} P &= \rho_w \cdot g \cdot H_{\text{OWC}} - \rho_o \cdot g \cdot h \\ &= \rho_w \cdot g \cdot H_{\text{OWC}} - \rho_o \cdot g \cdot \left(H_{\text{OWC}} - H\right) \\ &= \left(\rho_w - \rho_o\right) \cdot g \cdot H_{\text{OWC}} + \rho_o \cdot g \cdot H \end{aligned} \tag{3}$$

Pressure coefficient in single oil area:

$$\alpha = \frac{\left(\rho_w - \rho_o\right) \cdot H_{\text{OWC}}}{\rho_w \cdot H} + \frac{\rho_o}{\rho_w} \tag{4}$$

In the formula: P_1 is formation pressure in depth of oil-water interface in single oil area (psi); P_2 is formation pressure in depth of oil-water interface in pure water area (psi); P is the point for formation pressure in single oil area (psi); P_0 is the atmospheric pressure (psi); ρ_o is the crude oil density in pure oil region (g/cm^3); ρ_w is the average density of formation water; h is the vertical distance from the point to oil-water interface in single oil area (m); H_{owc} is the depth of the oil-water interface (m); H is the depth of the point in single oil area (m); g is acceleration of gravity (m/s^2).

Functional relationship is inverse function which related to the pressure coefficient as independent variable, depth as variate (Figure 1(b)). Its function has nature of two aspects: 1) elevation becomes shallow depth, pressure coefficient is monotone increasing; 2) reservoir pressure coefficient increases, altitude depth

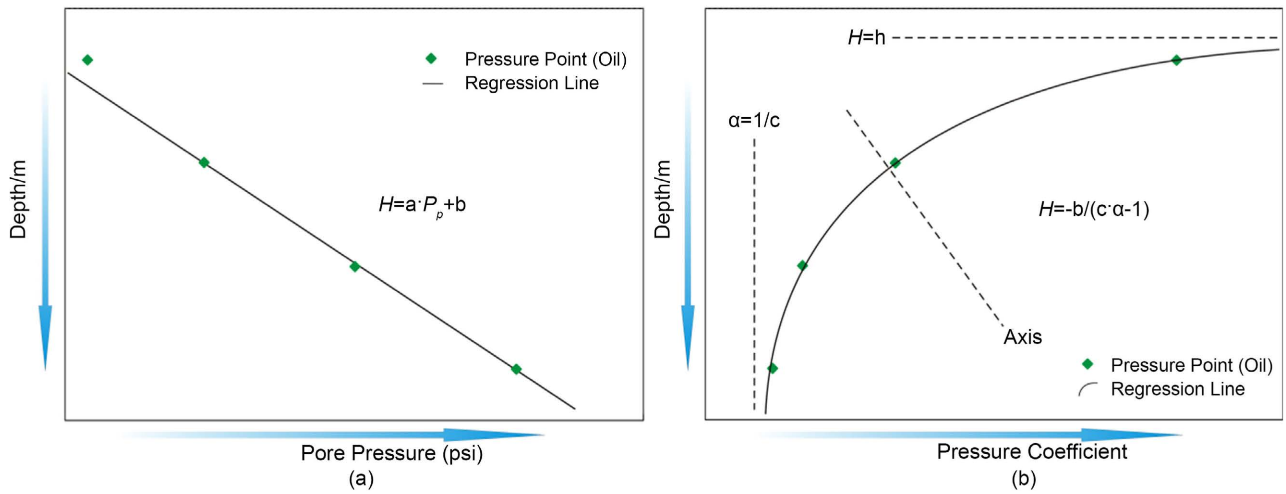

Figure 1. Pressure (pore pressure and pressure coefficient)—depth plots exhibit the linear function and (a) inverse proportional function (b) in conceptual model. (a) The linear function of pore pressure—depth plot; (b) the inverse proportional function of pressure coefficient—depth plot.

becomes shallow, infinite approaching to a constant depth; altitude increases, the pressure coefficient decreases, then infinite closing to a fixed value.

3. Characteristics of Reservoir Pressure Changes

In order to deeply analyze the matching degree between the theoretical model and the actual characteristics of reservoir pressure, it studies three conditions in single well which drills in pure oil reservoir, top gas bottom oil, top oil bottom water, investigates the linear change of formation pressure data and inverse function change law of pressure coefficient, also the reservoir pressure changes under the control of gas cap energy, bottom water buoyancy and fluid elastic energy.

3.1. Formation Pressure Data and Pressure Coefficient

Single well drilling in pure oil reservoir: KL10-X Well drills in the thickness of 4.4 m single reservoir on the group of ShaHejie in Paleogene, there are four pressure test points (**Figure 2**). Formation pressure has class linear increasing

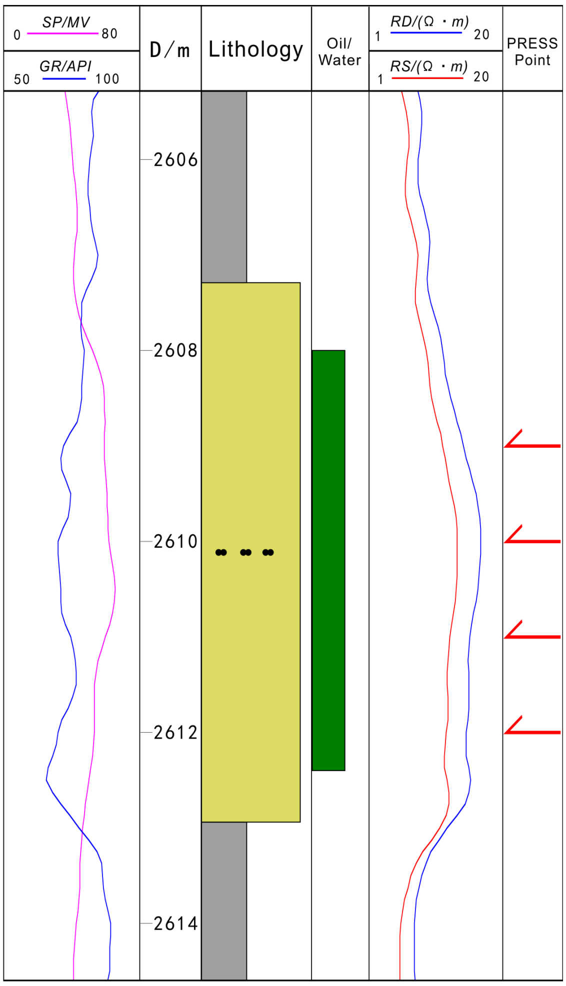

Figure 2. Lithology comprehensive lithogram of KL10-X well in the southern part of Bohai Sea.

with the increase of altitude depth from drilling in the top of reservoir, and pressure coefficient is inverse function declining, exposed function form is relatively complete, confirming actual characteristics consistent with general theory model.

However, the change of formation pressure at the top of reservoir is becoming larger, the first formation pressure data clearly deviates from the main body of stratigraphic pressure trend line, which is estimated to be affected by the energy at the top of gas reservoirs (Figure 3(a), Figure 3(b)).

3.2. Gas-Cap Pressure Effect

The energy of Gas cap refers to the free gas at the top of reservoirs accumulates much energy because of the existence of high formation pressure. When the reservoir pressure drops, gas-cap gas expanded and release energy. The energy of gas cap essentially belongs to the elastic energy, the compressibility of gas is great (at 20˚C, 6.8 MPa pressure, the isothermal compression coefficient of methane is 1645×10^{-4} MPa^{-1}) (Wu, 2004).

KL3-X Well drills in top gas bottom oil reservoir on the group of MingHuazhen in Neogene, it has 3 formation pressure test point on gas and 10 points on oil (Figure 4).

Influenced by the energy of top gas, the pressure test data 1, 2 on gas obviously deviates from the overall formation pressure trend line, the corresponding pressure coefficient changing is also very large. Like drilling in pure oil layer in case, formation pressure presents linear distribution, pressure coefficient is inversely proportional distribution, the function form belongs to the first half of the inverse function (Figure 5(a), Figure 5(b)).

The pressure change of the reservoir is directly controlled by the energy of top gas, the buoyancy of bottom water, the elastic energy of the fluid and so on; the shape of the reservoir is affected by factors such as oil column height, fluid density and reservoir permeability. The results show that the reservoir pressure varies with the depth of altitude: 1) the characteristics and the theoretical model

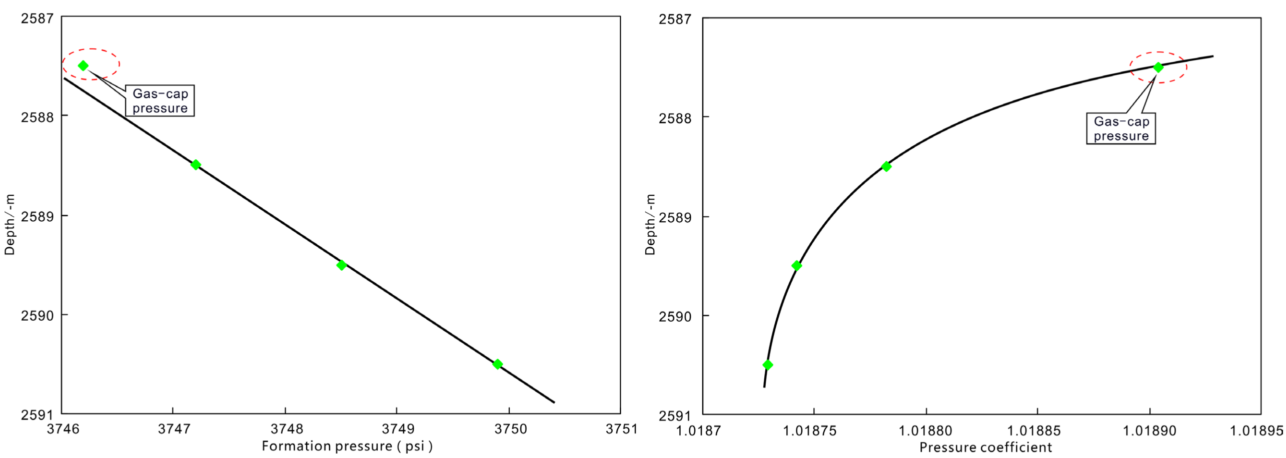

Figure 3. Linear function in pore pressure-depth and inverse proportional function in pressure coefficient-depth plots in KL10-X well.

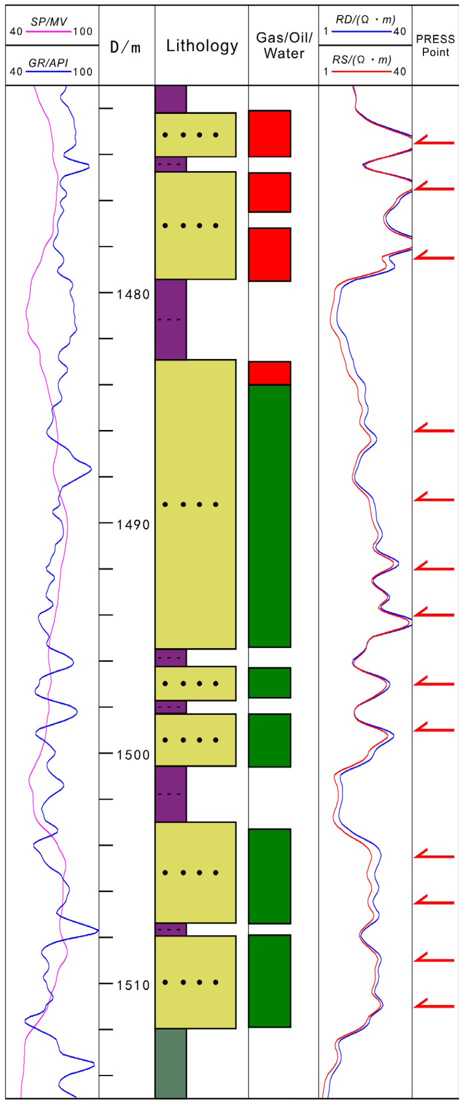

Figure 4. Lithology Histogram of KL3-X well in southern part of Bohai Sea.

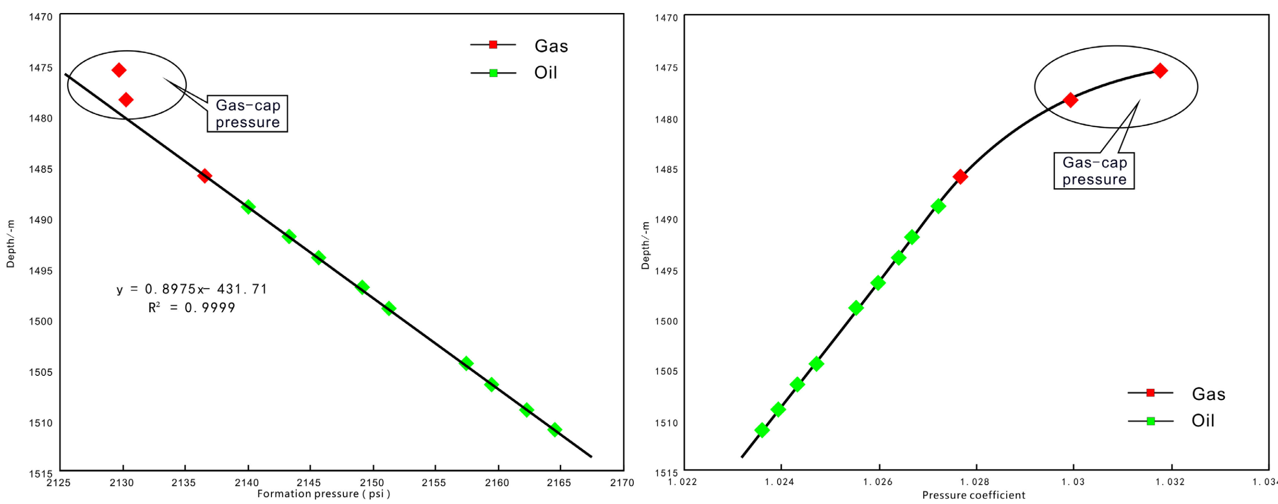

Figure 5. Pressure profile of oil-gas phase reservoirs in KL3-X well in the southern part of Bohai Sea. (a) Linear function distribution of formation pressure—depth; (b) the inverse proportional function distribution of pressure coefficient—depth.

has high degree of agreement; 2) formation pressure has a class linear distribution, pressure coefficient presents the distribution of inverse proportion function curve; 3) the existence of the energy of gas cap causes the formation pressure data at the top of reservoir deviating from the main trend line.

4. Application and Results

KL16-X Well is located in the southern slope of the LaiZhou Bay depression. The main oil-bearing layer is on the group of GuanTao in Neogene. The strata is mainly composed of thick sandstone-coarse sandstone mudstone, it is similar to the braided river sedimentary facies on the group of GuanTao in Bohai Bay Basin. However, in the case of oil-water relationship which is not contradictory, only according to the characteristics of reservoir development and combination can not fully explain the number of sandwiches containing oil which belongs to the same reservoir, and the use of reservoir pressure with altitude changes is precisely solving this question, and it provides critical evidence.

This well drill in five sets of oil, in addition to the failure of the third set of sand bodies, the other four sets of sand bodies are distributed with nine pressure points. In the conventional stratigraphic pressure data-elevation depth profile, the pressure data of four sets sand body are generally poorly fitted, with a fitting coefficient of only 0.9974, equivalent to the ground crude oil density is 0.9267 g/cm^3, which is large different from the relative density of the field test crude oil 0.9549 (20˚C), it was confirmed that this method was not reliable (**Figure 6**).

However, according to the variation of reservoir pressure with altitude, 1) formation pressure line and pressure coefficient has a distribution of inverse proportional function curve; 2) the existence of energy of gas top causes the top of the reservoir pressure data deviates from the main trend line. The data point (−901.6 m) of the first sand body at the top of the reservoir is obviously deviated from the main pressure trend line and is located at the top of the reservoir, and it is analyzed as the data anomaly under the influence of the energy. Therefore, the

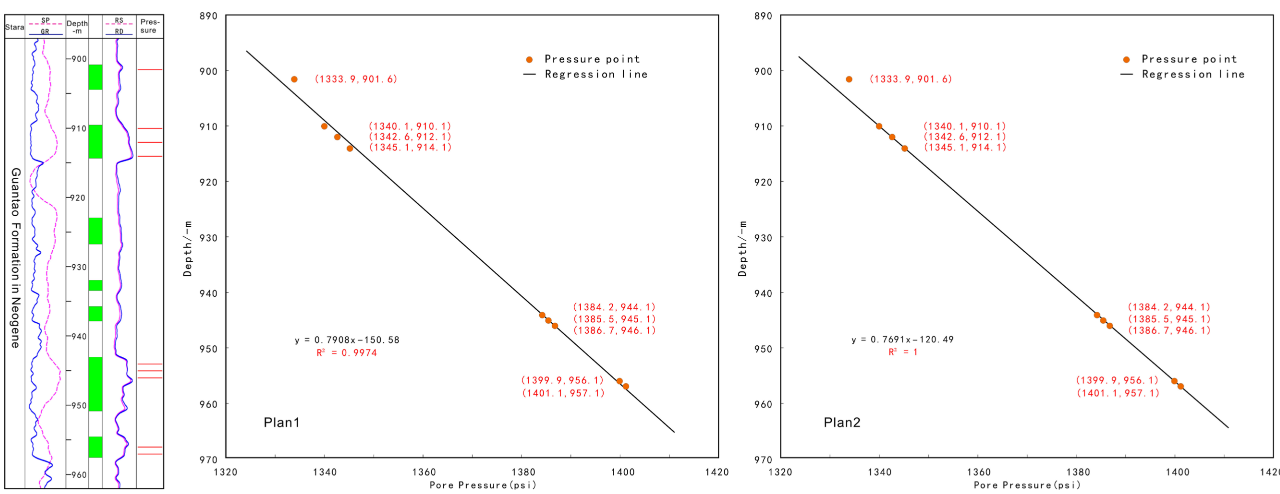

Figure 6. Lithology comprehensive column and two plans for pore pressure-depth characteristics of KL16-X well in the southern Bohai Sea.

interference of the −901.6 m data points is excluded and re-developed. The four sets of sand bodies have a high degree of fitting and a fitting coefficient of 1, the ground oil density is 0.9528 g/cm^3, which is closer to the oil Crude oil physical analysis data (Zhang et al., 2010). Based on the analysis, the five reservoirs of KL16-X well drilled at the top of the Guantao Formation belong to the same reservoir, and the reservoir pressure characteristics can be more real and effective to identify the reservoir model, fluid properties, and evaluate the scale of oil and gas reservoirs reasonably.

5. Geological Significance

The function form of reservoir pressure is controlled by factors such as oil column height, fluid density, reservoir permeability, and so on. Oil column height is larger, and its function on the longitudinal span was greater; the reservoir permeability and the fluid density affect the reservoir pressure changing rate, but because of the difference between the depth and the horizon, the main factors influencing the change of the main control factors is different, resulting in a slightly different function form (especially the inverse proportional function). Selim Simon Shaker (2014) pointed out that the change of formation pressure in the shallow metamorphic zone is affected by reservoir permeability and satisfies Darcy's law $Q = -K/\mu * \Delta P$, that is, when the flow rate and fluid viscosity are constant, The pressure change rate and the permeability are inversely proportional to each other. Therefore, the inverse proportional function of the pressure coefficient in the shallow high permeability zone is relatively gentle, and even the near linear shape appears in the middle of the function. In the deep middle-low permeability zone, the change of reservoir pressure is relatively large because of the fluid density, and the influence of permeability on the shape of the reservoir is limited, so the change rate of reservoir pressure is relatively large under the control of gas pressure, bottom water buoyancy and fluid elastic energy (Finkbeiner et al., 2001; Zhang et al., 2010) (**Figure 3(b)**, **Figure 5(b)**).

The function shape of reservoir pressure and its combination form can be used as a key evidence for the study of connectivity, fluid migration path, sand body configuration analysis (Qian et al., 2016; Liu et al., 2008; Bu et al., 2015) of sand body. In the same lithology sequence stratigraphic framework, which can be fitted to a class of linear and inverse proportional function curve belongs to the same reservoir under the condition of unclear deposition distribution, dubious oil and water relations, poor seismic data quality, pressure data permitted, and the sand bodies which not be fitted to a class of straight and inverse proportional function curve do not belong to the same reservoir, this conclusion has been confirmed in the Bohai Oilfield. In addition, the comprehensive sedimentary model analysis, the inverse proportion function of the pressure coefficient and its combination form can further explore the sand form and the connected mode, that is, the sand body configuration analysis.

6. Conclusion

Based on hydrostatics principle, the measured pressure data of nearly 50 normal pressure reservoirs in Bohai oilfield are analyzed, and the relationship between pressure coefficient and formation depth is clarified. The reservoir pressure data are linearly distributed with altitude, and the formation pressure coefficient changes with the inverse proportional function with altitude. The function form of Reservoir pressure is controlled by oil column height, fluid density, permeability reservoir and so on. Also, the formation and combination of reservoir pressure could be the key evidence in researching connectivity relationship of reservoirs, fluid migration path, sand body architecture and so on. Fully understanding the relationship between pressure and formation depth can reduce the misjudgment of convection property and reservoir model, which is of great significance for fine evaluation of reservoir size and reasonable planning of oilfield development program.

Acknowledgements

The study of this paper is based on the fund project: the major National Science and Technology project "geological characteristics of large and medium-sized oil and gas field in Bohai Sea area". It mainly thanks to technical personnel's support in Tianjin Branch of CNOOC Ltd, also the recognition and support of Open Journal of Yangtze Oil and Gas, thanks at here.

Fund Project

The major National Science and Technology project "geological characteristics of large and medium-sized oil and gas field in Bohai Sea area" (2011ZX05023-006-002)

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Bu, F. Q., Zhang, Y. K., Yang, B. Q., Gao, B. Y., & Gao, Y. F. (2015). Technique and Application of Fine Connectivity Characterization of Composite Deep Water Turbidite Channels. *Fault-Block Oil and Gas Field, 22*, 309-313.

Finkbeiner, T., Zoback, M., Flemings, P., & Stump, B. (2001). Stress, Pore Pressure, and Dynamically Constrained Hydrocarbon Columns in the South Eugene Island 330 Field, Northern Gulf of Mexico. *AAPG Bulletin, 85*, 1007-1031. https://doi.org/10.1306/8626CA55-173B-11D7-8645000102C1865D

Kuang, L. C. (2005). *An Introduction to Applied of the Wireline Formation Data*. Beijing: Petroleum Industry Press.

Liu, C. Q., Lv, D. Y., & Hou, D. M. (2008). Study of Connectivity of Sand Bodies in Oilfield A, Bohai. *Geophysical Prospecting for Petroleum, 47*, 251-256.

Ma, J.-G., & Fu, Z.-J. (1995). *Principles and Applications of Wireline Formation Tester*

(p. 6). Petroleum Industry Press.

Pan, F. X. (2012). Research of the Erct Wireline Formation Tester Application Examples-tianjin Branch Company of CNOOC. *WWTL, 4*, 45-48+4.

Qian, G., Zhang, J. M., Liu, C. Q., Zhang, L., Yang, H. F., Mu, P. F., et al. (2016). A Study on Sand Bodies Connectivity in Normal Pressure Reservoirs of the Bohai Sea with Hydrostatic Pressure Data. *Oil & Gas Geology, 37*, 584-590.

Qin, X.-F., & Feng, Y.-R. (2012). Research on the Setting Function of Dual Packer on Formation Tester. *Hydraulics Pneumatics ＆ Seals, 12*, 12-13+17.

Schlumberger Land China Operation (2002). MDT Operation Client Manual. pp. 10-16.

Shaker, S. S. (2014). Reservoir vs. Seal Pressure Gradients: Calculations and Pitfalls. *AAPG 2014 Annual Convention & Exhibition*, Omnipress..

The Pressure Log Reference Manual (1980). *Theory and Evaluation of Formation Pressure*. Exploration Logging Inc.

Wang, X.-R., Zhou, C.-C., Wang, C.-X., & Cao, W.-L. (2008). Review on Application of the Wireline Formation Tester. *Progress in Geophysis, 5*, 1579-1585.

Wu, Y. J. (2004). *Reservoir Geology* (p. 2). Petroleum Industry Press.

Zhang, G. Q., Zhang, W. P., Li, X., Su, H. C., & Wang, J. (2010). Application Study Research of Wireline Formation Test in Bohai Oilfield. *Journal of Yangtze University (Natural Science Edition), 7*, 528-530+755.

Zoback, M. D. (2007). *Reservoir Geomechanics*. Cambridge University Press. https://doi.org/10.1017/CBO9780511586477