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PS Sand Bodies Connectivity Analysis Utilizing Measured Pore Pressure in Normal Pressure, Offshore Bohai Bay Basin, China*

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Abstract

Due to the consistency of pressure system within a uniform reservoir, the pressure-depth plot is currently deemed to be an important criterion to determine the connectivity of sand bodies in normal pressure reservoirs. However, because of the influences of high permeability and fluid heterogeneity in the oil reservoir, the linear rule used to estimate the sand bodies connectivity has its limitations. For instance, there exists relatively lower crude oil density and viscosity as well as higher conversion formation pressure on the top of the oil column and that will influence the linear relationship of the pressure-depth plot resulting in erroneous connectivity identification.

Applying mathematical induction, an advanced method for sand bodies connectivity analysis is proposed. The specific approach is building the relationship of pressure coefficient versus depth through formula derivation transforming the linear relation between the pressure and depth into the inverse proportional function. The properties of inverse proportional function such as intersection, monotonicity, boundedness, and symmetries provide us a new way to explore the relationship between the reservoir depth and pressure system and furthermore determine the connectivity of two or more sand bodies.

We have verified the relationships between the sand bodies connectivity and the properties of inverse proportional function of the pressure coefficient versus depth in more than 50 normal pressure reservoirs out of 7 oilfields in offshore Bohai Bay Basin, where the connection of sand bodies has been confirmed by actual development wells. The conclusions are as follows: 1) the function image being continuous and overlapping, monotonicity and asymptote being consistent, and symmetry axis being unique are the critical criteria for determining the connectivity of the consecutive sand bodies; 2) the pressure coefficient is more sensitive and reliable than the linear function; and 3) the

curvature of the inverse proportional function is affected by the reservoir permeability and fluid properties, thus it overcomes the limitations of linear rule. The prediction accuracy of the sand bodies connectivity has improved significantly utilizing the inverse proportional curve of the pressure coefficients versus depth which also reduces the geological risk and uncertainty, and provides a reasonable support in field development plans design.

Introduction

The pressure-depth plot is currently recognized as an important criterion to determine the connectivity of sand bodies in normal pressure reservoir, based on the consistency of pressure system within a uniform pore network.

Shaker (2001) provided two concepts of the excess pressure (EP) and sealing capacity (SC) from a semi-quantitative point of view to discriminate these pressure systems (Figure 1). The excess pressure (EP) is the difference between the formation pressure and the regional hydrostatic pressure in a reservoir, and the EP window should stay constant in a single wet reservoir. The sealing capacity (SC) represents the pressure shift between two consecutive compartments. The shift from one pressure envelope to a deeper one across the seal defines, and in interconnected pore networks the sealing capacity of the inter-bedded seals does exist.

However, the minimum level of sealing pressure of the inter-bed is recently unknown, when the sealing capacity can be activated. In recent years, the sealing pressure of only 1.6 psi has been identified in non-connectivity state, and it is a too small value that is hard to test and even misleads the determination.

Furthermore, there exists relatively lower crude oil density and viscosity as well as higher measured formation pressure on the top of oil column and that will influence the linear relationship of the pressure-depth plot resulting in erroneous connectivity identification. In this paper, we present an advanced type of analysis for the connectivity of sand bodies in normal pressure reservoirs, within more than 50 normal pressure reservoirs out of 7 oilfields in offshore Bohai Bay Basin. The specific approach is building the relationship of pressure coefficient versus depth through formula derivation transforming the linear relation between the pressure and depth into the inverse proportional function. These conclusions will help improve the prediction accuracy of the connectivity of sand bodies and reduce the geological risk and uncertainty, and provide a reasonable support in field development plans design.

Functional Properties and Connectivity

Pore pressure, P_p, is defined as a scalar hydraulic potential acting within an interconnected pore space at depth. In a hydrostatic regime, the pressures of fluids in sedimentary rock pores increase linearly with depth:

$$H = a \cdot P_p + b \quad \Rightarrow \quad P_P = (H - b) / a \qquad (1)$$

Where *H* is the depth, a and b are constants in a reservoir.

Here, we will contribute an innovative method for the determination of the connectivity of pore networks (Figure 2). Hydrostatic pore pressure, P_P^{hydro}, implies an open and interconnected pore and fracture network from the earth's surface to the depth of measurement using the following formula:

$$P_P^{\text{hydro}} \equiv \int_0^{\text{h}} \rho_w(H) \cdot g \cdot \text{d}h \approx \rho_w \cdot g \cdot H \qquad (2)$$

And, the pressure coefficient in a normal pressure reservoir is

$$\alpha = P_p / P_P^{\text{hydro}} = (H - b) / (\text{a} \cdot \rho_w \cdot g \cdot H) \qquad (3)$$

$$\Rightarrow H = -b/(c \cdot \alpha - 1) \qquad (4)$$

where α is the pressure coefficient as an inverse proportional function of depth, g is gravitational acceleration, and ρ_w is the density of water, c is constant in a reservoir.

The properties of inverse proportional function such as intersection, monotonicity, boundedness, and symmetries provide us a new way to explore the relationship between the reservoir depth and pressure system and furthermore determine the connectivity of two or more sand bodies (Figure 3):

- Intersection: According to the intersection property of the inverse proportion function, the pressure coefficient in the same reservoir can be regressed into only an inverse proportion function versus depth, and vice versa. The regression lines in function images coincidence, if the criterions b and c values are equal with the two in another reservoir, respectively.

- Monotonicity: It is universally observed in the image that the pressure coefficient is seen to increase monotonically as the depth becomes shallower within a single reservoir. The gas-cap pressure is higher than its conversion pressure, when gas-cap or high content of dissolved gas exist at the top of the reservoir, in order to maintain the pressure balance in the reservoir, with the buoyancy, fluid elasticity and the rock skeleton pressure. The monotonicity property of the pressure coefficient increases with depth is the result of the balance on driving forces such as buoyancy, fluid elastic force, and gas cap pressure in the reservoir. And the function curvature are controlled by the oil column height, fluid density, and permeability, moreover the predominant factor has a difference between the deep and shallow strata.

- Boundedness: There are two asymptotes ($\alpha = 1 / c$, $H = h$) for the inverse proportion function in the pressure coefficient-depth plot. The upper limit value of the depth is limited by the maximum oil column height, and the lower value of the pressure coefficient is restricted by the hydrostatic pore pressure. The two of the asymptotes are uniform in the interconnected pore networks and vice versa.

- Symmetries: The inverse proportion function image is a figure of line symmetry, as well as the symmetric axis is also unique in the same reservoir. The presence of different axes in their individual function images indicates that there is no hydraulic connection between them.

The oil column height, fluid density, and permeability are different in the individual reservoirs, which led to a unique balance state to the reservoir, enabling the significance of the inverse proportion function to become the key method to determine the connectivity of sand bodies.

Results and Applications

BZ28-X oilfield is located in the central structural ridge of the Yellow River Mouth depression, southern Bohai Sea of China. This study focuses on Neogene shallow delta system, characterized by high porosity and permeability in the reservoir. Two sets of sand bodies are vertically superposed and penetrated by the 1 well, 3 well, and 4 well. The different oil-water contacts between sand 1&2 have been drilled by development wells, proved that the two sets of sand bodies are separated by the inter-bed and the non-connectivity state (Figure 4).

The pore pressures in the 1 well and 3 well can be plotted on a linear scale with depth, indicating that the interconnectivity of sand 2 is very possible, in contrast with the pore pressure of sand 1 given by 4 well.

Furthermore, these pressure coefficients of sand 2 also can be plotted on an inverse proportion scale with depth, containing the same function property, testified the connectivity of this sand bodies. On the contrary, the pressure coefficient of sand 1 does not provide the same function property with the sand 2, confirming the conclusion of the non-connectivity between sand 1&2 in BZ28-X Oilfield (Figure 5).

Another KL9-X oilfield example for the study also has two sets of superposed sand bodies deposited in Miocene alluvial system, penetrated by wells and proved to be the non-connectivity. It is worth mentioning that the sealing pressure of inter-bed is only1.6 psi, we completely do not have the confidence to determine the connectivity between sand 1&2, if there is lack of drilling.

The inverse proportion function of pressure coefficient versus depth, however, is more sensitive and reliable than the linear function, and avoiding the linear law's limitations. The pressure coefficient in sand 1&2 can be not regressed into only an inverse proportion function with depth. The presence of two asymptotes in sand 1 differs from this property in sand 2. The pressure coefficient is not seen to increase monotonically as the shallower depth, and even they do not have a unique axis (Figure 6). To summarize, the non-connectivity relationship between sand 1&2 has been documented by the differences of function properties.

Conclusion

- Sand bodies connectivity discussion using inverse proportional function properties has been put into practice in more than 50 normal reservoirs out of 7 oilfields of the Bohai Sea, and authenticated that these function properties of intersection, monotonicity, boundedness, and symmetries lead a critical role on the sand bodies connectivity determination.
- The function image being continuous and overlapping, monotonicity and asymptote being consistent, and symmetry axis being unique are the critical criteria for determining the connectivity of the consecutive sand bodies.
- And it is more sensitive and reliable than the linear function, even avoiding the linear law's limitations.
- Inverse proportional function properties are affected by oil column height, fluid properties, and reservoir permeability.

Discussion

We will continue to strive for the study on the sand bodies connectivity and application of Wireline Formation Testing in a challenging business landscape. Please contact me at email qiangeng@outlook.com if you have any thoughts about these, looking forward to hearing from you.

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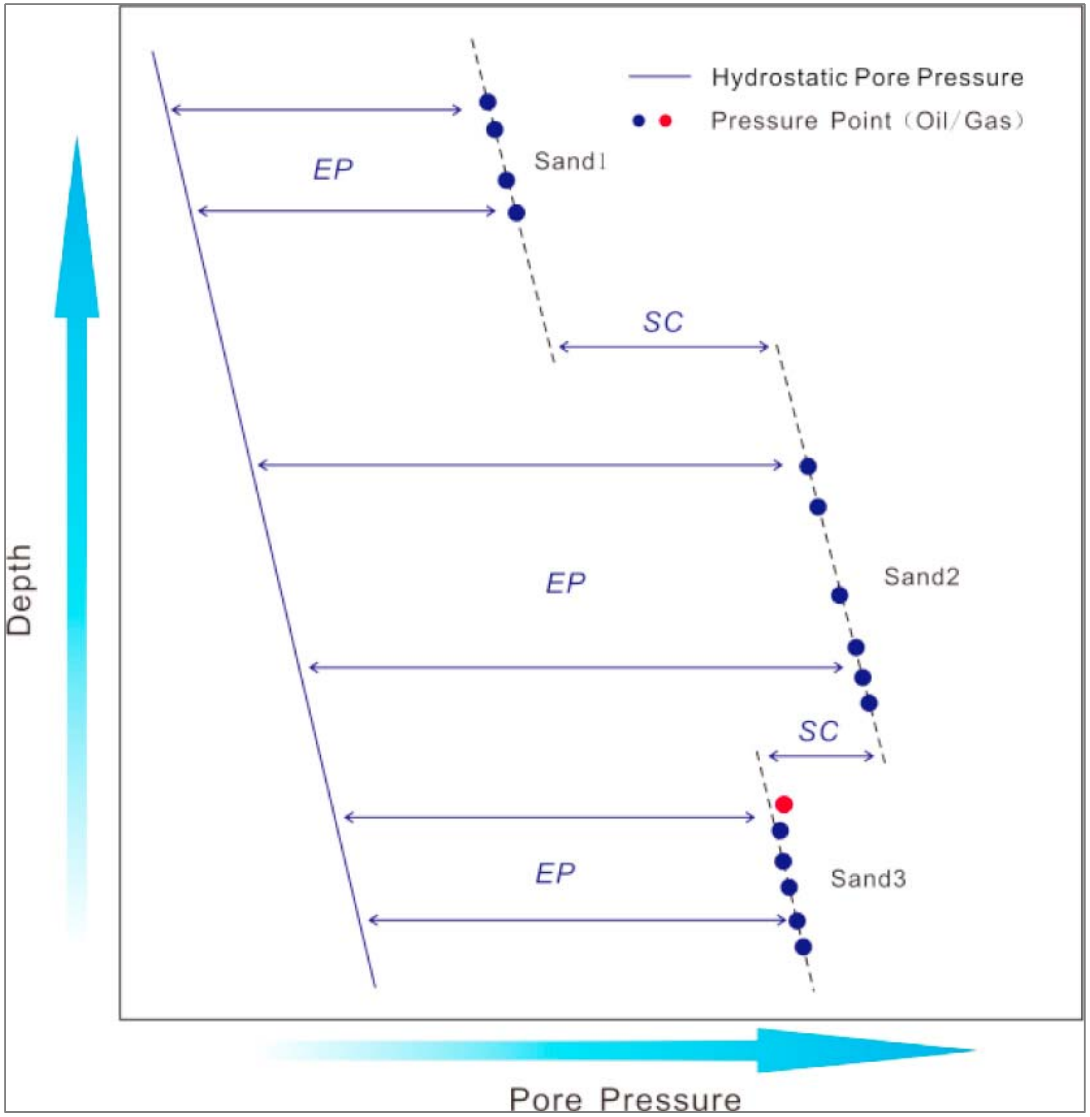

Figure 1. The excess pressure and sealing capacity calculations in reservoirs.

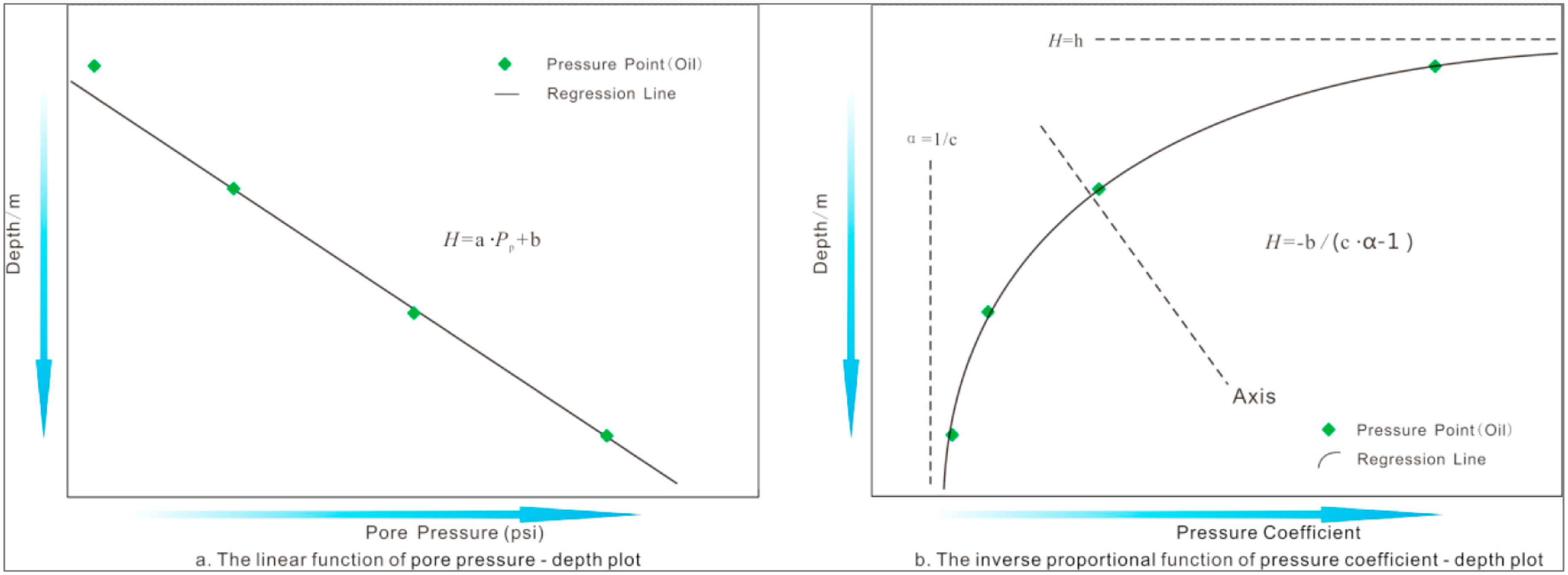

Figure 2. Pressure (pore pressure and pressure coefficient) – Depth plots exhibit the linear function (a) and inverse proportional function (b) in mathematical model.

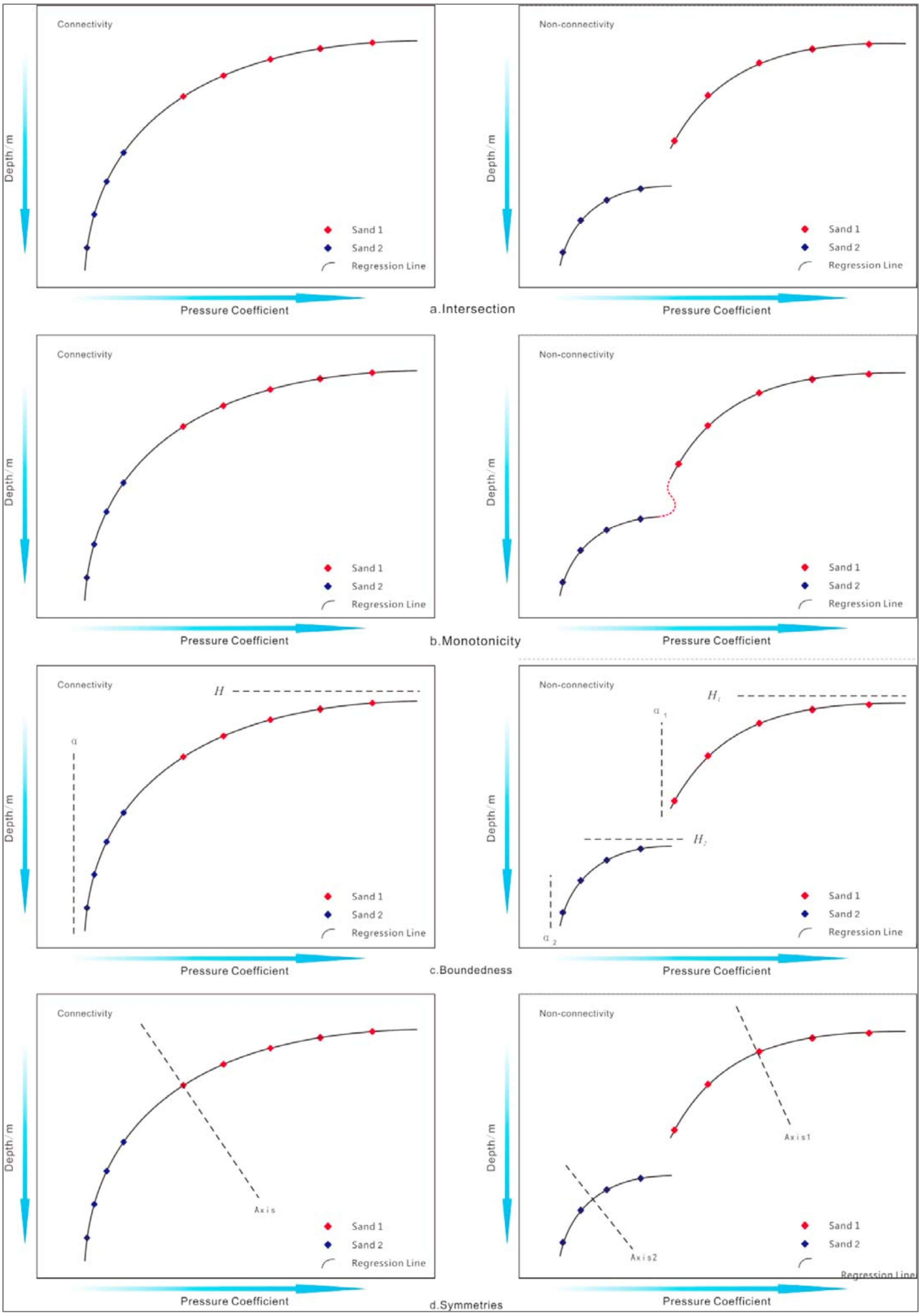

Figure 3. Diagrams of these functional properties (a. Intersection, b. Monotonicity, c. Boundedness, and d. Symmetries) and the connectivity determination.

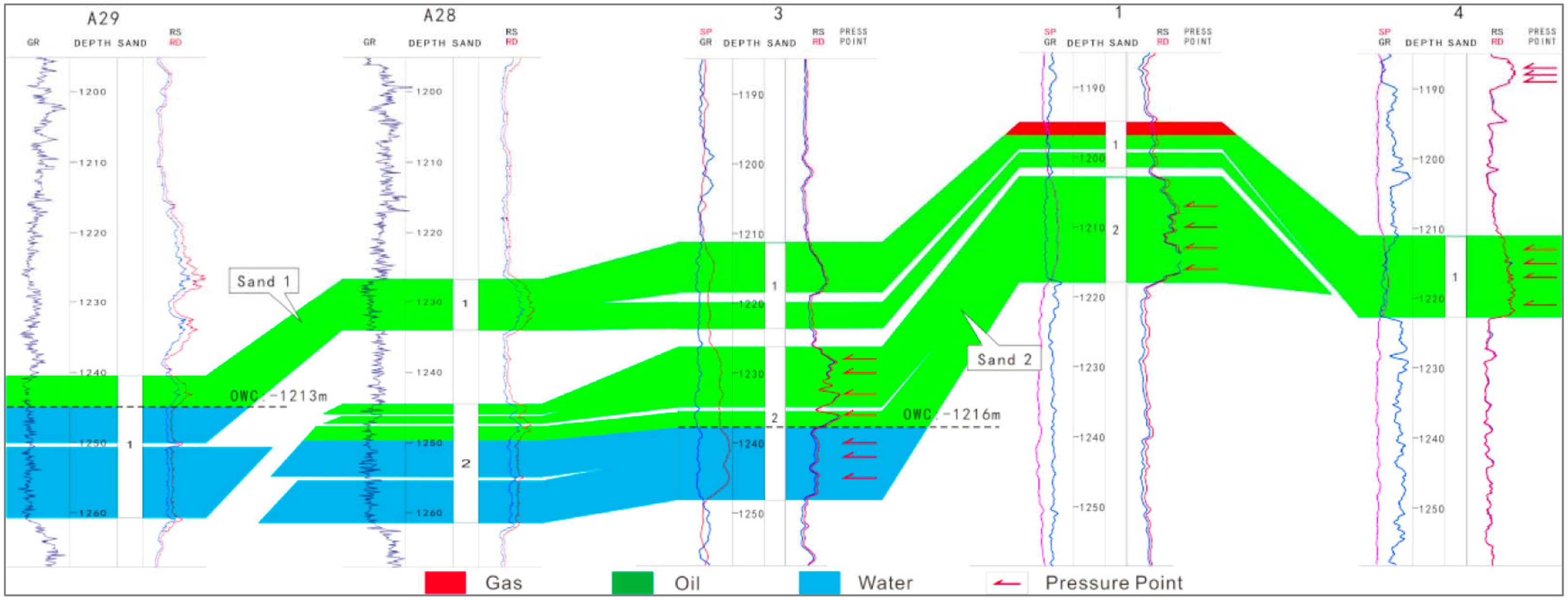

Figure 4. Five-well cross-section, shows the hydrocarbon-bearing properties and pressure measurement locations in Neogene sand 1&2 of BZ28-X Oilfield.

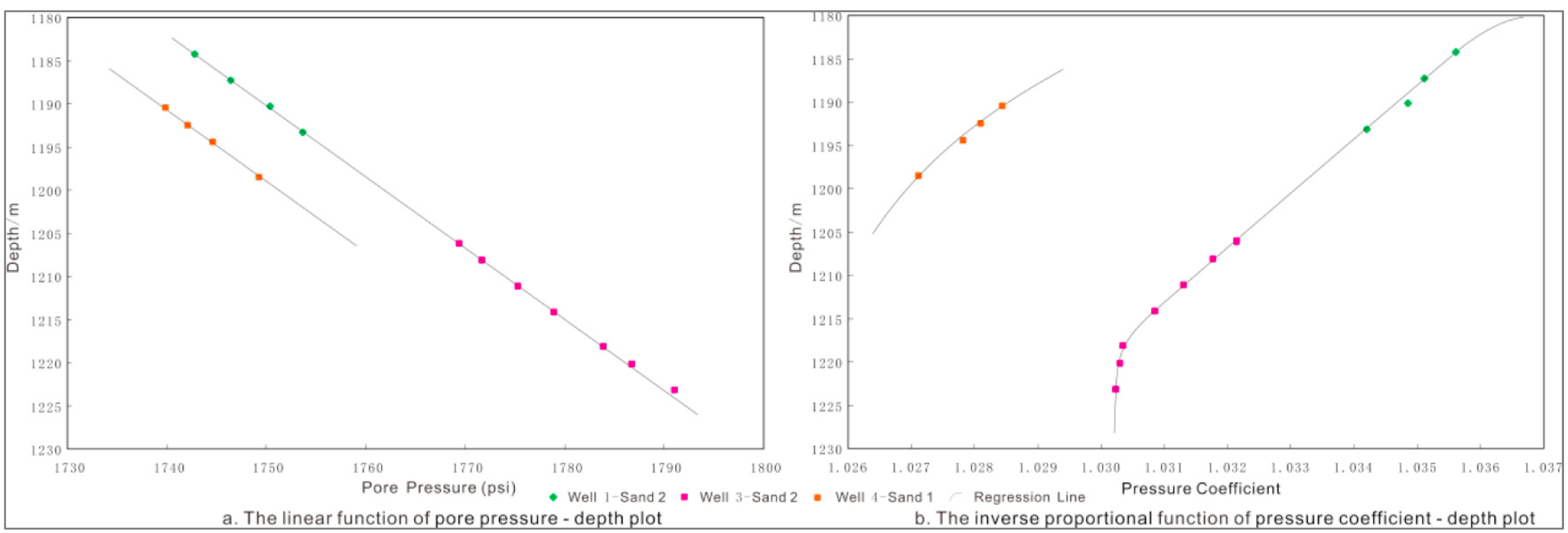

Figure 5. The linear function in pore pressure-depth and inverse proportional function in pressure coefficient-depth plots the non-connectivity between sand 1&2 in BZ28-X Oilfield.

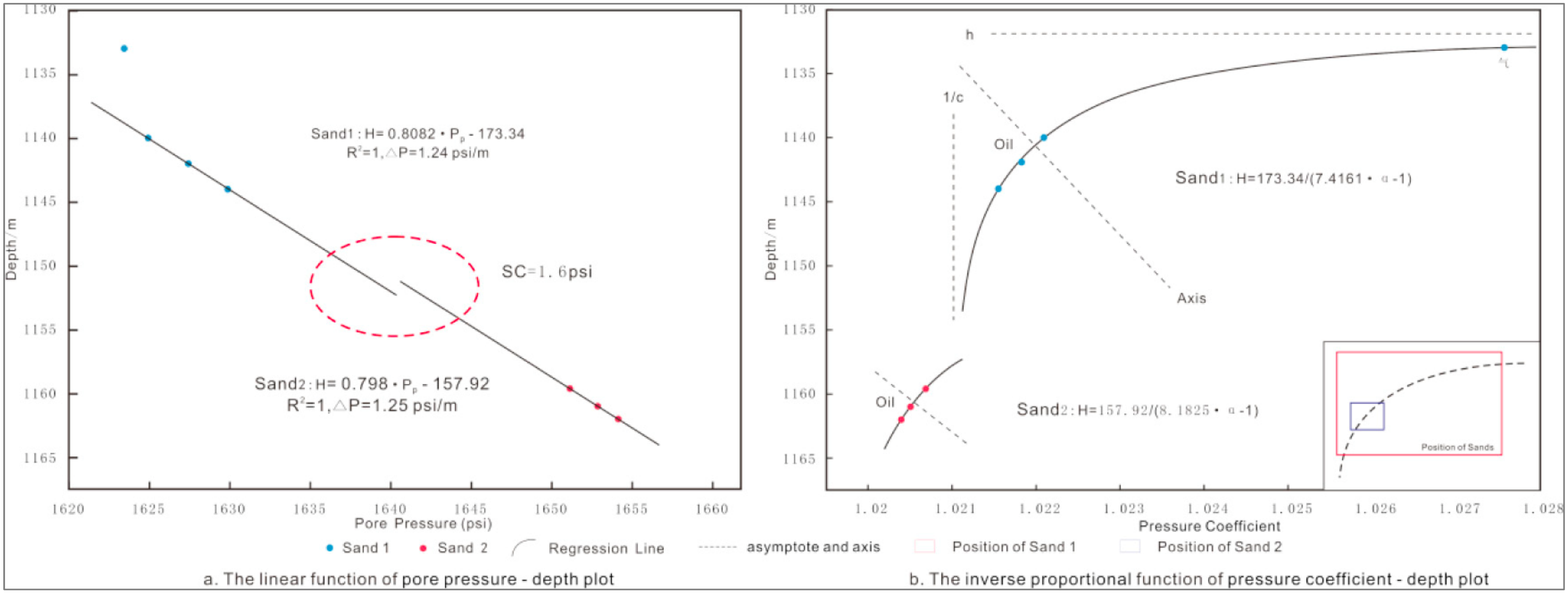

Figure 6. Sand bodies Connectivity analysis by pressure-depth between sand 1&2 of KL9-X well.