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A New Method for Predicting Well Pattern Connectivity in a Continental Fluvial-delta Reservoir

Yanfeng Liu[1]*, Yuetian Liu[2], Lu Sun[2], and Jian Liu[3]

[1] Sinopec Petroleum Exploration and Production Research Institute, Beijing, China
[2] China University of Petroleum (Beijing), Beijing, China
[3] PetroChina Research Institute of Petroleum Exploration and Development, Beijing, China

ABSTRACT

The features of bad flow unit continuity and multiple layers emphesize the importance of a well pattern design for the development of a fluvial-delta reservoir. It is proposed a method to predict well pattern connectivity (WPC) based on the exploration and evaluation of wells. Moreover, the method helps evaluate the risk of well placement. This study initially establishes the parameters for characterizing the lateral and vertical flow unit distributions. Then, extensive statistics on the mature oil-field sands of synthetic geological models are obtained to generate the prediction model of WPC which will reveal the correlation among WPC, flow unit distribution, and well spacing (WS). Finally, a case study is conducted to validate the proposed method for predicting WPC. The procedure of the method is comprised of two steps. The first step is to calculate the parameters which characterize the vertical sand body distribution of the target formation by using the well drilling and logging information. The second step is to integrate the calculated parameters and designed WS into the proposed formula to forecast WPC. The new method of WPC prediction has the advantage of integrating the static and dynamic information of similar mature oil fields with each other. By utilizing the model, making an important decision on well pattern design and a reservoir production forecast in the newly discovered continental fluvial-delta reservoir would be reasonable.

Keywords: Well Pattern Connectivity, Flow Unit Distribution, Well Spacing Optimization, Reservoir Performance

INTRODUCTION

Well pattern optimization is the key procedure in the reservoir development scheme design. Discontinuous sand bodies and alternate sand–shale sequences are typical characteristics of continental fluvial-delta reservoirs, in which well pattern connectivity (WPC) significantly affects the production performance [1,3]. The optimal well pattern significantly relies on hydraulic flow unit distribution [4,6], whereas a detailed interpretation of reservoir architecture is derived from the available drilling wells [7]. For this type of reservoir, making an important decision on well pattern deployment is a challenging task. Although infill drilling has been a practical choice to reduce the risk of well placement, it is still often deployed at the late development stage, where well pattern and flow unit distribution are mismatched, and it causes irreversible loss [8,9]. Consequently, flow unit distribution and WPC

***Corresponding author**

Yanfeng Liu
Email: yanfeng1022@126.com
Tel: +86 152 1087 9401
Fax: +86 152 1087 9401

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should be predicted as early as possible to derive the optimal well pattern for reservoir development.

Predicting WPC requires the correct understanding of flow unit distribution. A flow unit is defined as a group of reservoir rocks with similar properties, which affects fluid flow. The flow unit provides a means of uniquely subdividing a reservoir into volumes that approximate the reservoir architecture on a consistent scale with well spacing (WS) [10,11]. Based on the definition of flow unit, we observe that wells in one flow unit are connected, whereas wells located in different flow units are not connected. WPC is a measure of well pattern control on flow unit distribution. If reservoir flow unit distribution can be clearly recognized, then a correct prediction of WPC can be achieved.

The flow unit dynamically displays the reservoir internal architecture, which has been the subject of extensive research [12,14]. Outcrop investigation and a seismic survey are the main techniques used to explore the hierarchical heterogeneity of a sandstone reservoir [15,16]. Moreover, the dimensions and scales of individual sand bodies in different types of sedimentary environments are stored as an expert knowledge base [17,18], and they have significant meanings for the optimization of reservoir development. By considering the characteristics of sedimentary elements, the genetic analysis of sand bodies provides an insight into flow unit distribution [19,22]. The scales and shapes of genetic sand bodies significantly control the distribution of flow units. However, within a given facies, the reservoir properties significantly vary, and the flow units do not always coincide with the geologic lithofacies or sedimentary units. Furthermore, a number of techniques identifying flow unit distribution have been proposed in the literature [23,24]. These methods have significance for reservoir characterizations. However, most of these methods rely on detailed geologic and dynamic information of the target reservoir, which can only be used in mature oil fields. The goal of this study is to develop a methodology for the prediction of WPC after the drilling of appraisal wells because only limited data from drilling wells are available.

EXPERIMENTAL PROCEDURES

The Selection of Parameters Characterizing Flow Unit Distribution

The flow unit is a block of reservoir rock within which the geological and petrophysical properties that affect fluid flow are internally consistent and predictably different from the external properties. Each flow unit has a constant ratio of flow capacity and storage capacity, which indicates that the relationship between permeability and porosity has a constant slope. The wells drilled within one flow unit are connected with each other. Flow units are confined by certain quantitative petrophysical properties such as porosity, permeability, capillarity, and fluid saturation. Flow unit distribution in the vertical direction is usually easier to measure than the one in the lateral direction. Flow units do not have a consistent size, shape, or orientation because of the complex internal architecture of sedimentary units. Therefore, parameters which are independent of the detailed dimensions or scales should be generated to characterize the flow unit distribution, with WPC as the target.

We assumed a theoretical multiple layer of heterogeneous sandstone reservoir with stratigraphy thickness denoted by H, and covered area denoted by S. In the statistical sense, the flow unit number in the vertical direction is N, the total thickness in the vertical direction is h, and the total number in the three-dimensional (3D) space is M. Flow units are randomly distributed in the 3D space. Two pairs of parameters are proposed to characterize flow unit distribution.

The first proposed parameters are flow unit laterally drilled ratio (LR) and vertically drilled ratio (VR). LR is the ratio of wells drilled at any flow unit divided by the sum of the wells in the well pattern, and VR is the proportion of total flow unit thickness to strata thickness. However, LR and VR measure the total volume of all flow units, but they are not able to fully describe the local heterogeneity of flow unit. The other two parameters are flow unit vertically distributed frequency (VF) and laterally distributed frequency (LF). LF is the number of flow units in a layer per square kilometer, and VF is the number of vertical sand bodies per meter (Figures 1 and 2). The parameters of global and local flow unit distributions imply the heterogeneity of the reservoir architecture on different scales. Regardless of the shapes or sizes of the flow units, these two pairs of parameters are capable of determining the distribution affecting WPC.

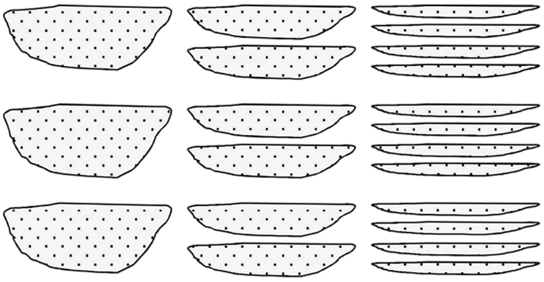


Figure 1: Similar LR and different VF of flow units with a theoretical shape.

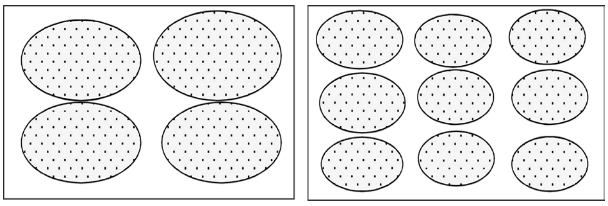


Figure 2: Similar LR and different LF of flow units with a theoretical shape.

WPC is defined as a measure that controls reservoir flow unit distribution. Based on the theoretical model of the continental fluvial-delta reservoir, WPC is expressed as follows:

$$WPC = \frac{\sum_{i=1}^{N}\sum_{j=1}^{NW} C_{ij}}{\sum_{i=1}^{N}\sum_{j=1}^{NW} W_{ij}} \qquad (1)$$

where, W_{ij} is the number of wells adjacent to well j at layer i, and C_{ij} is the number of connected wells in W_{ij}. Then, $W_{ij} \geq C_{ij}$ is a permanent equation (i= 1, 2, 3, ..., N; j=1, 2, 3, ..., NW, where N is the average number of flow units in the vertical direction, and NW is the total number of flow units in a well pattern).

Statistics on the Sampled Mature Oil Fields

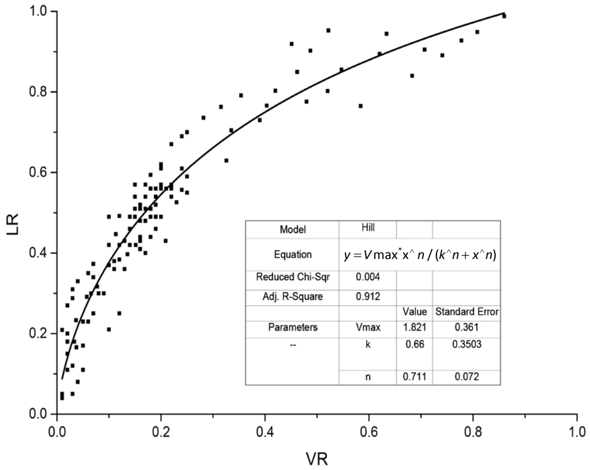
As the main type of continental reservoirs, a fluvial-delta reservoir plays a key role in China's oil and gas industry. Not only expert knowledge and experience, but also static and dynaxmic information of old oil fields are extremely valuable for the well pattern optimization of newly discovered similar reservoirs. Thus, the intrinsic relationship between vertical and lateral flow unit distributions is examined on the basis of the extensively sampled mature oil fields. Then, the correlation among WPC, flow unit distribution and WS is determined. A database containing information on more than 40 reservoirs with the fluvial-delta environment located in the eastern and middle parts of China is generated.

In the database, VR, VF, and LR can be easily obtained from the drilling and logging data. By contrast to VR, VF, Iand LR, the actual LF cannot be detected accurately by any available tools. However, the flow unit distribution of the mature reservoirs which undergo multiple fine characterizations and simulations is presumably clear. We calculate the LF and WPC of each zone based on these previous findings. Then, the relationship between WPC and flow unit distribution is analyzed.

Following the construction of the database of mature oil fields, we analyze the correlation between global flow unit distribution (VR and LR) and local flow unit distribution (LF and VF). LR exhibits a power law correlation with VR (Figure 3), and its mathematical model is expressed in Equation 2. LF varies positively and linearly versus VF according to the relationship of *LF*= 7.62*VF* (Figure 4).

$$AR=1.821\frac{VR^{0.711}}{0.66^{0.711}+VR^{0.711}} \tag{2}$$

Afterward, the intrinsic relationship between lateral and vertical flow unit distributions was examined. The correlation among WPC, flow unit distribution, and WS was determined. Many of the sampled mature reservoirs already have dense WS, the average of which is approximately 200 m. Two histograms are charted to reveal the relationship between WPC and flow unit distribution (Figures 5 and 6). We conclude that WPC has a positive power law function with VR and a negative linear correlation with VF. However, the size of the sample is small because of limited access to the actual reservoirs, indicating unconsolidated discovery. Thus, we attempt to verify and refine the results by other means such as numerical simulation.



Model	Hill		
Equation	$y=V\max^{*}x^\wedge n/(k^\wedge n+x^\wedge n)$		
Reduced Chi-Sqr	0.004		
Adj. R-Square	0.912		
		Value	Standard Error
Parameters	Vmax	1.821	0.361
--	k	0.66	0.3503
	n	0.711	0.072

Figure 3: Regression of LR and VR.

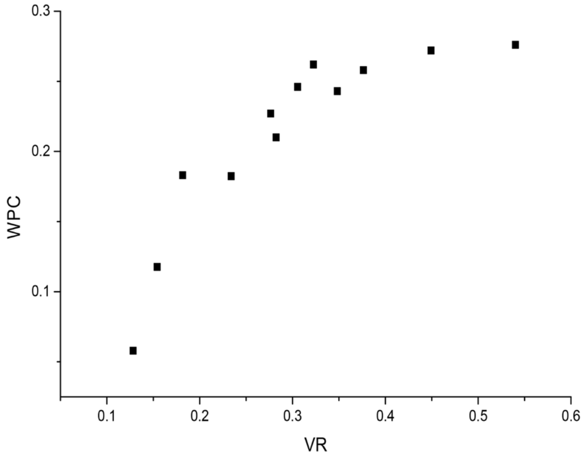
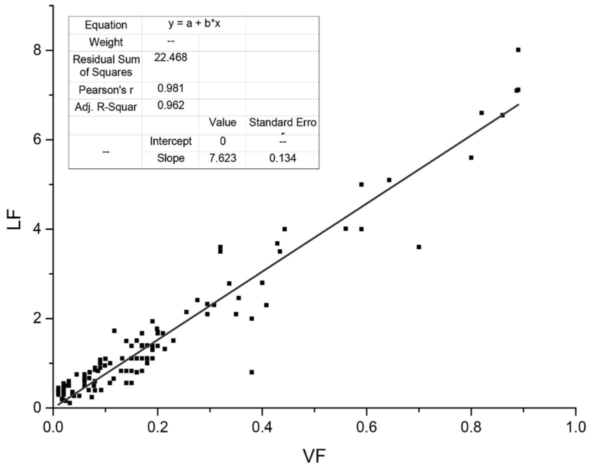


Figure 5: Correlation between WPC and VR.



Equation	y = a + b*x		
Weight	--		
Residual Sum of Squares	22.468		
Pearson's r	0.981		
Adj. R-Squar	0.962		
		Value	Standard Error
--	Intercept	0	--
	Slope	7.623	0.134

Figure 4: Regression of LF and VF.

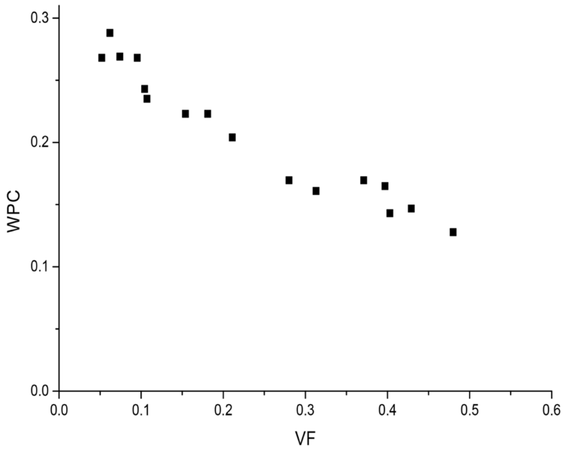


Figure 6: Correlation between WPC and VF.

Regression by Using a Synthetic Geological Model

Although extensive approaches and algorithms have been proposed to characterize discrete reservoir variable distribution [25,29], none of them fulfills the requirement of the aforementioned intrinsic relationship. Relying on the theory of stochastic geometry, a new algorithm combining the philosophies of object-based and pixel-based techniques is created to simulate flow unit distribution. In the procedure, the geometry of the flow unit is similar to the Boolean Simulation, whereas the generating process is analogous to the diffusion-limited aggregation [30]. Flow units with irregular shapes and random sizes are considered the basic volume elements of the model. We call this method the “flow unit growth algorithm” which indicates that a given number of flow units are seeded and then grow thicker and wider simultaneously to conform to the conditions of VR, VF, LR, and AF.

The simulation starts by gridding the reservoir into cells (at a height of *dz* (m) and areas *dx* × *dy* (m^2)). The flow unit generating process contains four steps as follows:

Step 1: The parameters of vertical flow unit distribution (VR and VF) are obtained from drilling data. The lateral flow unit distribution (LR and LF) is determined on the basis of the abovementioned relationship between lateral and vertical flow unit distributions. Flow unit seeds are initiated randomly at the cell grids in 3D, and the seed number is $M = 7.62 \times VF \times H \times S$.

Step 2: Vertical and lateral growth probabilities are calculated and updated to control the direction of flow unit growth in the subsequent step. The real-time average flow unit number (NC) in the vertical direction and the average sand body thickness (hc) control the flow unit generating process. If $\frac{NC}{N} > \frac{hc}{h}$ then the sand body grows vertically; otherwise, the sand body grows laterally.

Step 3: After determining the sand body growth direction, a grid cell is selected randomly and verified whether it is vertically or laterally adjacent to a flow unit. If the growth direction is vertical, then the selected grid cell must be vertically adjacent to the existing flow unit. Otherwise, the selected grid cell must be laterally adjacent to the existing flow unit. A new cell will be selected until it is conditioned.

Step 4: Steps 2 and 3 are repeated to confirm the conditions in which the average flow unit thickness reaches h. The simulation is ended when the average flow unit number in the vertical direction reaches N. The results of the simulation are shown in Figure 7. In the model, each flow unit is an ensemble of grid cells surrounded by impermeable shale.

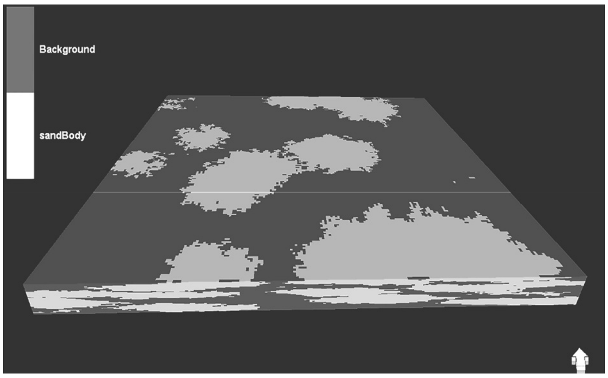


Figure 7: The simulation of flow unit distribution.

The proposed algorithm for 3D flow unit distribution simulation allows us to investigate the influence of flow unit distribution on well pattern. We assumed a reservoir with coverage (S) of 5 km × 5 km, and a stratigraphic thickness (*H*) of 200 m established to forecast flow unit distribution and WPC; the grid cell size is 10 m × 10 m × 1 m. The simulations are conducted in a series of conditions. The flow unit vertically drilled ratios (VR) are 0.2, 0.3, 0.4, 0.5, and 0.6, and the corresponding flow unit vertically distributed frequencies (VF) are 0.02, 0.05, 0.1, 0.2, and 0.3. Each simulation generates 10 realizations to reduce the influence of random error. For every realization, squared well patterns with a WS of 50, 100, 200, 300, 400, 500, 600, and 700 m are arranged to calculate the WPC. Then, an orthogonal experimental design is used to analyze the correlation among WPC, flow unit distribution, and WS.

A single-factor analysis of the simulation results reveals that WPC has a positive power function with VR and a negative linear relationship with VF (Figures 8 and 9). With a given sand body distribution, WPC decreases with an "anti-S" shape, whereas WS increases linearly. The first inflection points on the WPC decrease the curve which denotes the generally recommended reasonable WS (Figure 10). Afterward, we adopt the tools of the multiple nonlinear regression analysis and the orthogonal experimental design to derive the quantitative WPC prediction model. Finally, the well pattern prediction model is expressed in Equation 3, which provides support for well pattern design in the newly discovered fluvial-delta reservoir.

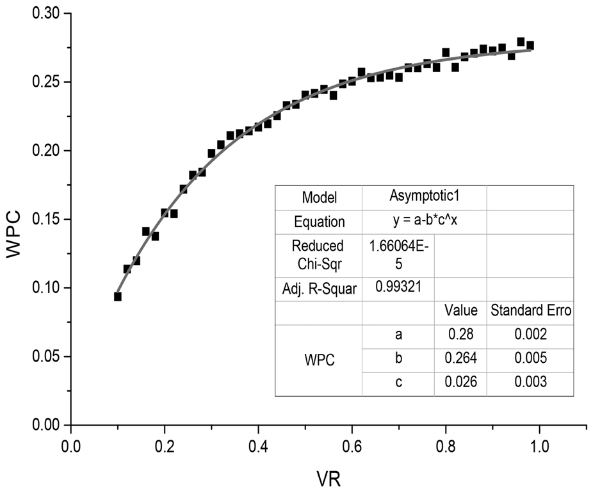


Figure 8: The variation of WPC versus VR.

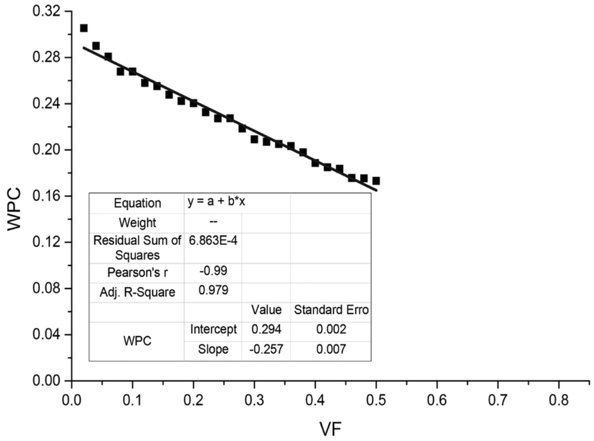


Figure 9: The variation of WPC versus VF.

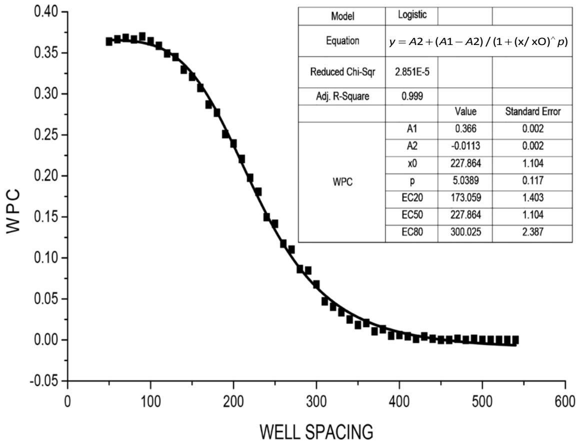


Figure 10: The variation of WPC versus WS.

$$WPC = -1.0226 + 1.1306^{VR} - 0.2012 \times VF + \frac{0.3570}{1+\left(\frac{WS}{243.3456}\right)^{4.5337}} \qquad (3)$$

RESULTS AND DISCUSSION

Case study

A mature reservoir is required to verify the proposed WPC prediction model. Thus, in this section, a fluvial-delta reservoir is selected to determine whether the prediction result at the early stage coincides with the WPC from the actual dynamic production and the static geological information at the late development stage.

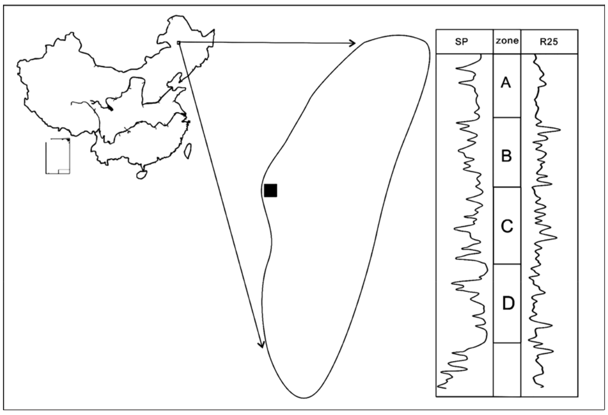


Figure 11: Location of Honggang oil field.

The reservoir is located in the western part of the Honggang oilfield in the Songliao basin of China (Figure 11), which was first discovered in 1965 and utilized in 1973. The block is approximately 4.3 km long and from 3.5 km to 4.2 km wide. Production

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information is obtained from Saertu sandstone at 1,860 m. The maximum sand thickness is 9.6 m, and the average thickness is 2.1 m. The average porosity is approximately 30.2%, and the average air permeability is approximately 105 mD. The reservoir contains (1) black oil with an original bubble point pressure of 10.8 MPa and (2) solution gas to the oil ratio of 53.6 std m^3/(stocktank m^3) (standard cubic meters per stock-tank cubic meters) Previous geological studies reported that the reservoir could be categorized as a delta front subfacies.

The lateral distribution of the flow units has an evident influence on the water flooding performance. During the past 42 years, the well pattern has been altered four times, and WS has narrowed from 1,200 m to 100 m. The reservoir is currently in the high water cut development stage, with a current recovery of 46.4% and a water cut of 94.95. The VR and VF obtained from early deployed wells are 0.544 and 0.136 respectively, which are approximately the same as the average values of 0.550 and 0.134 for all wells at the late development stage. After incorporating VR (0.544) and VF (0.134) into the WPC prediction model, WPC varies with WS as shown in Figure 12. If the WS is 100 m, then the predicted WPC is 0.37. The actual WPC obtained from the dynamic performance is 0.374. Therefore, the prediction model has good reliability.

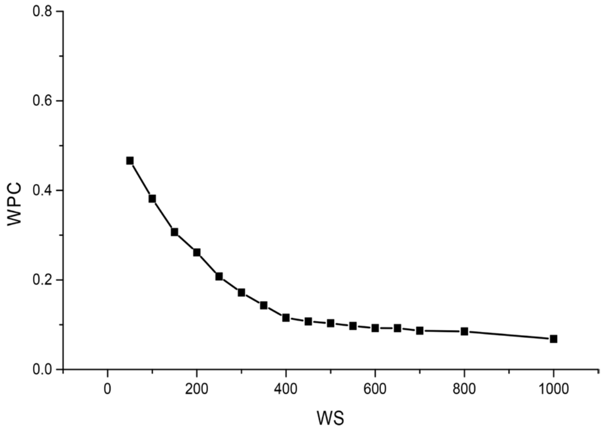

Figure 12: Actual WPC varies with WS.

Volumetric sweep efficiency in the fluvial-delta reservoir is mainly determined by WPC. In this study, we hypothesize that a potential correlation among WPC, flow unit distribution, and WS may exist. In a continental fluvial-delta reservoir, lateral flow unit distribution within sedimentary sequences has a statistical correlation with vertical flow unit distribution. Although bearing certain similarities, flow units and genetic sand bodies essentially differ. The study of a sand body shape or size relies on the hydrodynamic characteristic of the sedimentary process. Meanwhile, the flow unit is a tool used to understand fluid flow during reservoir development. A substantial knowledge of the width to thickness ratio, the length to width ratio, and profile style of sand bodies in braided river, meandering river, and distributed river in the fluvial-delta system has been obtained. Therefore, extensive literature on sand body shape, size, and distribution provides a significant insight into lateral flow unit distribution, but cannot replace the role of flow unit. The irregular shapes of flow units are determined by reservoir architecture and well position, resulting in considerable difficulty when delineating the flow unit distribution. Regardless of the shapes, sizes and variations of flow units, reservoirs would have a similar WPC if their flow unit laterally drilled ratio and laterally distributed frequency are the same.

After evaluating the reliability of areal flow units in predicting WPC, we illustrate and compare the methods used to predict the lateral flow unit distribution on the basis of information on the vertical flow unit distribution. Many geostatistical tools such as Boolean Simulation or sequential indicator simulation are used to evaluate the uncertainty of reservoir architecture at the appraisal stage when only several wells are available. The presumed length, width, thickness and variation of the sand bodies as the main parameters are employed as the input to the simulation. However, previous studies conducted by experts on the lateral flow unit distribution mainly concentrate on the late development stage. These approaches require detailed geologic and dynamic information to identify flow unit distribution in the 3D reservoir. The method proposed in this study has the advantage of predicting flow unit distribution and WPC earlier than the regular procedure. The final well pattern prediction model is a nonlinear function of low unit distribution and WS; in addition, the model can be used easily in a newly discovered reservoir.

If the sedimentary facies of a newly discovered reservoir has been confirmed to be a continental fluvial delta during the exploratory and appraisal stages of a reservoir lifecycle, the proposed prediction model of WPC can then be used. The usage of the method implements two steps, as follows:

Step 1: Calculation of the parameters of vertical flow unit distribution;

After revealing the correlation of stratigraphy, the flow units of each drilled well could be interpreted by using the core and logging data within the target zone. The flow unit is a block of sandstone separated by impermeable shale. Then, the parameters characterizing vertical flow unit distribution (VR and VF) are averaged for all wells.

Step 2: Optimization of WS;

By putting parameters of vertical flow unit distribution (VR and VF) into Equation 3, we can evaluate the variation of WPC versus WS. The optimized WS is located at the place where WPC decreases fastest.

CONCLUSIONS

This study proposes a method of WPC prediction by establishing the relationship among WPC, sand body lateral distribution, and sand body vertical distribution. The method can be used when only exploratory and appraisal wells are available.

The results of this study show that WPC increases with the power function of the flow unit vertically drilled ratio; moreover, WPC decreases linearly with the flow unit vertically distributed frequency; in addition, WPC exhibits an “anti-S”-shaped function versus WS.

The WPC integrating the static and dynamic knowledge of many similar mature oil fields can serve as a guide for well pattern design in newly discovered fluvial-delta reservoirs.

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