Research Article

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Flow units classification for geostatistical three-dimensional modeling of a non-marine sandstone reservoir: A case study from the Paleocene Funing Formation of the Gaoji Oilfield, east China

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Abstract: Flow units classification can be used in reservoir characterization. In addition, characterizing the reservoir interval into flow units is an effective way to simulate the reservoir. Paraflow units (PFUs), the second level of flow units, are used to estimate the spatial distribution of continental clastic reservoirs at the detailed reservoir description stage. In this study, we investigate a nonroutine methodology to predict the external and internal distribution of PFUs. The methodology outlined enables the classification of PFUs using sandstone core samples and log data. The relationships obtained between porosity, permeability and pore throat aperture radii (r_{35}) values were established for core and log data obtained from 26 wells from the Funing Formation, Gaoji Oilfield, Subei Basin, China. The present study refines predicted PFUs at logged (0.125-m) intervals, whose scale is much smaller than routine methods. Meanwhile, three-dimensional models are built using sequential indicator simulation to characterize PFUs in wells. Four distinct PFUs are classified and located

based on the statistical methodology of cluster analysis, and each PFU has different seepage ability. The results of this study demonstrate the obtained models are able to quantify reservoir heterogeneity. Due to different petrophysical characteristics and seepage ability, PFUs have a significant impact on the distribution of the remaining oil. Considering these allows a more accurate understanding of reservoir quality, especially within non-marine sandstone reservoirs.

Keywords: Flow units, Paraflow units, Classification, Modeling, Non-marine sandstone reservoir, Funing Formation, Paleocene

1 Introduction

Flow units, whose geological and petrophysical properties affect fluid flow, are used to subdivide reservoirs into geobodies appropriate for flow-simulation studies [1, 2]. As a part of a reservoir having lateral and vertical continuity and homogeneous flow and bedding characteristics, flow units can be used to investigate production behavior and to predict reservoir performance [2–4]. Different kinds of methodologies and techniques have been used to characterize flow units: core data [5, 6], depositional and diagenetic overprint [7, 8], reservoir quality index [9, 10], permeability heterogeneity and pore structure on N_2 adsorption [11], and correlated FZI based on a combination of log curves at uncored wells [12–16]. Besides, a mixed approach encompassing neural networks and the multi-resolution graph-based clustering method was reported by Nouri-Taleghani *et al.* [17] to determine flow units.

A geostatistical modeling method at the flow units scale has been developed to provide a better quantitative understanding of the distribution of flow units in recent years. Three-dimensional models of reservoir attributes

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such as porosity, horizontal and vertical permeability, shale volume, FZI and FZIV using Kriging and Gaussian conditional simulation were constructed in shaly sand reservoirs of the Oil Rim of Hassi R'mel field, Algeria [13]. A geostatistical flow units model was built based on the deposition occurred in a wave-dominated delta front [18]. Peng *et al.* [19] establishes flow units models corresponding to different development periods. Geostatistical modeling methods enable the coordination of qualitative and quantitative analysis, which has been of vital importance in the study of flow units.

The concept of PFUs as reviewed by Zhang and Cheng [20] is first investigated for the purpose of studying reservoir heterogeneity in low-permeability sandstones at the detailed reservoir description stage. This concept assumes that PFUs are relatively homogeneous within the flow units due to seepage discrepancy. Therefore, flow units subdivide the reservoir volume into layers or sand bodies, while paraflow units subdivide flow units into homogeneous layers or the so-called instantaneous flow units. Compared with conventional flow units, the concept of PFUs leads to better reservoir description when the target reservoir is non-marine sandstone reservoir due to its extremely heterogeneous nature [20]. However, few attempts have been done to carry out the quantitative recognition of PFUs in the previous studies.

The present paper is devoted to introducing a methodology for PFUs classification predicted from core and calculated log data. Moreover, it provides an opportunity to model PFUs at fine-scale in geostatistical three-dimensions to enhance reservoir description within a non-marine sandstone reservoir.

2 Geologic background

The Subei Basin, eastern China, lies between Subei and the subaerial area of the south Yellow Sea, with a total regional area of about 3.5×10^4 km² [21]. The Subei Basin is tectonically divided into three major units: the Dongtai Depression, Yanfu Depression and Jianhu Uplift (Figure 1) [22]. The Gaoji Oilfield lies along the northwest margin of Dongtai Depression within the Subei Basin in east China, where the Gao-7 fault block is at a structurally faulted nose (Figure 1). Hydrocarbons were discovered in Gaoji Oilfield in 1995, and new reservoirs continue to be discovered in recent years. The Funing Formation (Paleocene) is currently the main oil-bearing strata, which has been described as a typical non-marine sandstone reservoir. The sandstone bodies in this study have been inter-

preted as wave-dominated estuary deposits. The present work deals with 26 wells located in the Gao-7 fault block, separated by faults at Gaoji Oilfield. Log data of all the wells were available. Well G7 and Well G7-7 are partially cored.

3 Materials and methods

A suite of 137 sandstone samples of the Funing Formation from two wells (Well G7 and Well G7-7) located in the Gao-7 fault block were selected for petrophysical analysis. A data set of laboratory generated petrophysical parameters include porosity and permeability for the Funing sandstone core samples from Well G7 and Well G7-7 has been derived.

A procedure for identifying and characterizing petrophysical flow units was conducted using pore throat aperture radii (r_{35}) values derived from Winland equation [6].

$$\log r_{35} = 0.372 + 0.588 \log K - 0.684 \log \phi \quad (1)$$

The reliability of Equation 1 had been verified in the different regions with different lithology data [23].

Cluster analysis, a mathematical statistical method, was used as a task of grouping a set of objects in such a way that objects in the same group (called a cluster) are more similar (in some sense or another) to each other than to those in other groups (clusters) [24]. It was a quantitative classification of flow units in accordance with the closeness of fit both natural or causal. Cluster analysis itself is not one specific algorithm. A Ward's analytical algorithm was presented to perform cluster analysis on porosity, permeability and r_{35} within the logged interval. This provides an appropriate clustering algorithm that groups flow units parameters. A suite of reservoir parameters which include porosity, permeability and r_{35} for 26 wells has been derived from the Funing sandstones of Gaoji Oilfield.

A geostatistical PFUs model was a direct transformation of the geological model. Three-dimensional model of all PFUs was introduced and built by applying sequential indicator simulation method, which is a widely used technique for categorical variable models. The practical application of this method complies with a conceptual geological model that has proved to be advantageous in most case studies to generate images of the internal architecture of the reservoir adequately [25–29].

Sandstone samples of the Funing Formation were selected from cores from the Well G7-7 of Gaoji Oilfield for thin sectioning within a depth interval from 1768.60 to 1779.60m. Modal analyses were done by counting 300 points per thin section, with four major categories of rock

Figure 1: Mapping showing the location of the Gaoji Oilfield, lying in eastern China. Enlarged solid box in upper diagram shows the location of wells from Gao-7 fault block (indicated in pale-yellow).

volume (grains, matrix, authigenic cements, and pores) recognized by points counting. Rock volume properties were then compared with PFUs prediction results to conform the validity of the predicted PFUs.

4 Results

4.1 PFUs classification

An exponential relationship ($R^2 = 0.823$) between core porosity and core permeability is illustrated by available core-measured petrophysical data (Figure 2). Acoustic log is added to the porosity model as a function of log-porosity,

Table 1: List of criteria for PFUs classification using cluster analysis.

Reservoir parameter	Reservoir parameter interval (Average, Minimum, Maximum)											
	PFUs-1			PFUs-2			PFUs-3			PFUs-4		
Porosity	19.6	13.1	28.1	16.2	12.8	20.9	13.2	8.5	19.8	6.9	0.2	22.1
Permeability	162.9	6.2	2325.5	43.7	24.1	72.6	16.1	4.9	27.9	2.9	0.4	8.5
r_{35}	5.8	1.18	22.9	3.2	2.0	4.2	2.1	1.0	2.9	1.2	0.3	2.3

Figure 2: Cross-plot of core porosity versus core permeability of the Funing sandstone samples of Gaoji Oilfield, indicating a good positive correlation. Core samples are identified into four types of PFUs differentiated with different colors based on the classification criteria of Table 1. **Figure 3:** Three-dimensional fence diagram with the blocked wells used in this study. Blocked PFUs are displayed on the wells consisting of four types of identified PFUs.

log-permeability values are then derived as estimates from the log-porosity curves based on the permeability-porosity transform in uncored intervals. Validity of log-porosity and log-permeability data is checked by available core data for the two cored wells. The r_{35} values are then obtained by the Winland equation, through porosity and permeability determination. The Gaoji Oilfield reservoir is thus classified into several groups by use of the cluster analysis statistical methodology. In order to determine and differentiate different types of PFUs in the reservoir, well log data from the Funing sandstones from all the 26 wells are used. A data set of more than 7000 applied reservoir parameters consisting of porosity, permeability, and Winland r_{35}

values at both cored wells and uncored wells have been chosen by applying Ward's analytical algorithm which is a typical clustering algorithm. Clustering can therefore be calculated and four distinct PFUs (PFUs-1, PFUs-2, PFUs-3, and PFUs-4) have been obtained in this case study. Each PFU has contained its own r_{35} values. Therefore, we have proposed four different categories of PFUs, as shown in Table 1. Accordingly, PFUs acquired from core data based upon the classification criteria of Table 1 are differentiated into four categories with different colors, and the boundaries between PFU types seem obvious when observed in cores (Figure 2). There is an ascending trend in petrophysical data especially permeability values from PFUs-4 towards PFUs-1 (Figure 2). Study of petrophysical characteristics of reservoir rocks in the framework of PFUs indicates that the bigger r_{35} values are, the better seepage ability will be (Table 1).

4.2 PFUs modeling

In this study, the sequential indicator simulation method has been introduced and applied to build PFUs distributions between wells. PFUs zonation is confined to single well as constraints, and within the structural framework. Ten structural layers are used as a framework to reflect the main reservoir intervals of Funing sandstones, with blocked PFUs displaying on the wells at 0.125-m intervals (Figure 3). With mud as background, the PFUs model and its 3-D fence diagram using sequential indicator simulation are constructed (Figure 4a and 4b). By means of the same procedure, each type of PFUs is performed to form the three-dimensional visualization (Figure 4c, 4d, 4e, and 4f). As a result, each of the PFUs has the same properties throughout the model. Hence, four distinct PFUs within the main geological units are identified and located.

Figure 4: (a) Three-dimensional model of all PFUs using sequential indicator simulation, Funing Sandstone; (b) 3-D fence diagram of all PFUs; (c) 3-D fence diagram of PFUs-1; (d) 3-D fence diagram of PFUs-2; (e) 3-D fence diagram of PFUs-3; (f) 3-D fence diagram of PFUs-4.

5 Discussion

In this work, we introduce a new methodology to flow units modeling at a fine scale. Three-dimensional models provide insights into the distribution, which quantifies the external and internal geometry [30]. Because of the limited availability of core, defining PFUs from well logs is a challenge for reservoir characterization at a fine-scale. However, cluster analysis method has been successfully applied to predicted flow units from well logs [5, 31, 32], which infers PFUs distribution statistically at target logged wells in the study area.

Because of the heterogeneous nature, low compositional maturity and low textural maturity of non-marine sandstone reservoirs [33, 34], predicting PFUs encounters several difficulties. However, geostatistical 3-D models can generate quantitatively robust distribution of fine-scale PFUs geometries away from well control [30], beside, they offer boundaries of fluid in this complex continental clastic reservoir. The resulting reservoir models are used to

make economic decisions [35]. Our procedure is an attempt for a better prediction of PFUs, which can be applied to a reservoir at any stage of hydrocarbon production.

Although facies of non-marine sandstone reservoirs change rapidly, the correspondence between the depositional facies and the PFUs is valid. As an example, we observe core plug samples of the Well G7-7. The Well G7-7 offers a good case study that provides the relationship between facies and PFUs (Figure 5). This indicates that four types of PFUs are distinguished by ranges of facies corresponding to trough crossbedding with bottom erosion, low-angle cross bedding containing biological burrow, parallel bedding, and wavy bedding with bioturbation, respectively.

Diagenetic processes have a notable role in fluid movement within reservoir units [36–38], and therefore it is essential to take into account diagenetic effects when differentiating between PFUs. Figure 6 shows a thin section representative photomicrograph of different PFUs (PFUs-2 and PFUs-3, respectively). Figure 6a shows that a majority of pore spaces are maintained, and carbonate pore-fill cementation is relatively limited. In contrast, reservoir rock

Figure 5: Well log suite from the Well G7-7 located in northeastern part of Gao-7 fault block, Gaoji Oilfield, illustrated with gamma ray (GR) and spontaneous potential (SP) in the left track, and acoustic log (AC) and caliper (CAL) in the right track. Selected core photographs showing all PFUs including (a) PFUs-1 (Trough crossbedding with bottom erosion), 1774.7m; (b) PFUs-2 (Low-angle cross bedding containing biological burrow), 1775.5m; (c) PFUs-3 (Parallel bedding), 1776.4m; (d) PFUs-4 (Wavy bedding with bioturbation), 1779.4m.

Figure 6: Thin section photograph of sandstone samples in the Well G7-7. (a) PFUs-2 (The sandstones are moderately to well-sorted with pore-throat well developed), 1779.4m; (b) PFUs-3 (Pore spaces become fewer and discontinuous with higher carbonate content, resulting in poor connectivity), 1775.5m.

of Figure 6b is characterized by enriched carbonate cements, and a certain amount of pore spaces are occluded. In this case, PFUs-2 and PFUs-3 are mostly distinguished in terms of pore spaces and cementation volumes (Figure 6). This reflects the presence of diagenetic effects, which can be a good indicator for verifying the validity of the predicted PFUs.

A flow unit is defined as a reservoir subdivision characterized by a similar pore type [39, 40], which is the same as a paraflow unit. Waterflooding direction is always along the better rock-properties zones (PFUs-1, PFUs-2), while the relative enrichment area of the remaining oil is formed in lower waterflooded zones or none waterflooded zones (PFUs-3, PFUs-4) (cf., [15]). On the same basis, the results demonstrate the obvious control the PFUs exert on the remaining oil. Accordingly, in this research, the characterization of PFUs extends the usage of the proposed model efficiently.

6 Conclusions

This study has contributed to the determination and classification of PFUs. Four categories of PFUs such as PFUs-1, PFUs-2, PFUs-3 and PFUs-4 were identified and located in the Funing sandstones. It has improved our ability to characterize the architecture of a non-marine sandstone reservoir, especially at intermediate and late periods of production. Core and log data provides a basis to conduct fine-scale 3-D PFUs modeling as a new approach to flow units analysis utilizing sequential indicator simulation method. This improves our understanding of the spatial distribution and geometry and results in good reservoir description.

This idea is to focus on geological features and characteristics, generating a model using a fine-scale (log scale). The research of PFUs represents as combinations of static geological body and pore fluid and quantifies heterogeneity and flow difference of fluid within the reservoirs, in order to explore distribution of remaining oil after waterflooding.

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