Advances in Geo-Energy Research

Vol. 14, No. 1, p. 4-7, 2024

Perspective

Future potential research hotspots on the precise integration of geology and engineering in low-permeability oil reservoirs

Shuheng Du[1,2]*, Lei Bai[3]

[1]*State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, P. R. China*

[2]*School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, P. R. China*

[3]*Research Institute of Experiment and Detection, Xinjiang Oilfield Company, Karamay 834000, P. R. China*

Keywords:
Integrating geology and engineering
low-permeability oil reservoirs
sedimentary facies
start-up pressure gradient
advantageous displacement paths

Cited as:
Du, S., Bai, L. Future potential research hotspots on the precise integration of geology and engineering in low-permeability oil reservoirs. Advances in Geo-Energy Research, 2024, 14(1): 4-7.
https://doi.org/10.46690/ager.2024.10.02

Abstract:
While petroleum scientists and engineers have increasingly acknowledged the significance of integrating geology with engineering for efficient petroleum development, the precise integration of above two aspects still requires substantial enhancement. This study identifies several potential future research hotspots in the precise integration of geology and engineering within low-permeability oil reservoirs. These include the accurate identification of sedimentary facies, which is constrained by horizontal wellbore logging, the three-dimensional continuous distribution modeling of heterogeneous start-up pressure gradients, and the determination of advantageous oil displacement paths driven by geomodels. The recommendation for future research is to employ advanced data analysis techniques to determine the correlation between experimental data at a small core scale indoors and multifunctional logging data. Additionally, fine geological modeling methods should be utilized to develop heterogeneous continuous distribution models of diverse reservoir geology and development attributes. This work offers several fresh perspectives for the efficient exploitation of China′s continental low-permeability oil reservoirs in subsequent stages.

1. Introduction

As global petroleum exploration and development continue unabated, low-permeability reservoirs, representd by the sixth member of the Yanchang formation in the Ordos Basin, remain a significant component of China′s petroleum resources (Ji and Fang, 2023). Despite multiple rounds of development, the primary challenge lies in enhancing our geological understanding at macro, meso, and micro scales to more precisely guide engineering practices. This is crucial for achieving further efficient exploitation of these low-permeability reservoirs.

As the oilfield development process advances into its fourth recovery stage, the integration of geology and engineering has emerged as a prominent concept in recent years. This primarily entails the close integration of geology and engineering technology to optimize reservoir development and management. Prior studies have demonstrated that comprehensive consideration of multidisciplinary knowledge encompassing geology, geophysics, rock mechanics, and fluid dynamics can achieve several key objectives (Jolie et al., 2021; Olierook et al., 2021): 1) A more profound understanding of the geological characteristics, fluid behavior, and reserve distribution of low-permeability reservoirs, thereby establishing a reliable theoretical foundation for reservoir development; 2) The creation of reservoir models with high precision and reliability, providing an accurate basis for engineering decision-making and production optimization; 3) The formulation of more rational injection-production schemes, stimulation measures, and enhanced oil recovery methods to maximize the economic development of low-permeability reservoirs; 4) A more accurate assessment of the potential impact of factors such as groundwater, artificial earthquakes, reservoir pressure changes, etc., on reservoir development, and the implementation of corresponding risk control and management measures. In fact,

Yandy Scientific Press

*Corresponding author.
E-mail address: dushuheng@imech.ac.cn (S. Du); bailei@petrochina.com.cn (L. Bai).

Received June 7, 2024; revised June 22, 2024; accepted July 2, 2024; available online July 4, 2024.

the development practice of low-permeability reservoirs in China has demonstrated that integration will play a pivotal role in both current and future development trends (Hu, 2017).

While petroleum scientists and engineers have increasingly acknowledged the significance of integrating geology with engineering for efficient petroleum development, there remain several potential research areas and challenges that warrant further investigation. Addressing these issues will not only enhance China′s consistent growth in petroleum production but also bolster energy security.

2. Hotspots on integrating geology and engineering

From an engineering philosophy standpoint, the crux of petroleum development lies in the continuous collection and integration of geological data from diverse sources, scales, periods, and types. This process aims to comprehensively understand the actual underground conditions, thereby enabling the formulation of targeted development strategies. However, due to the vast volume of geological data and the intricate nature of subsurface conditions, we can never fully comprehend them (Garcia et al., 2020; Guo et al., 2021). This necessitates the utilization of highly accurate geological data to obtain models of various geological and engineering properties at continuous scales. These models serve as powerful tools for oilfield development, akin to a "compass" and a "magnifying glass". Future research hotspots are likely to focus on accurately identifying sedimentary facies, constructing reservoir start-up pressure gradient models at continuous scales, and precisely determining dominant displacement channels. The following section will discuss the current theoretical and technical research status and future prospects of these potential research hotspots.

2.1 Accurate identification of sedimentary facies constrained by horizontal wellbore logging

As to the identification of sedimentary facies, the three-dimensional geological model constructed from logging data of vertical or directional inclined wells often does not accurately reflect the actual geological conditions in development areas that have not yet reached a dense well network level. Actually, the potential to gather pertinent information on the sedimentary facies of a target formation via vertical or directionally deviated wells is markedly constrained. With the advancement and popularization of horizontal well technology, its promising application prospects in the development of low-permeability reservoirs have begun to emerge. However, the logging data from horizontal wells have not been fully utilized in existing studies while research on using regional horizontal well data for fine sedimentary facies division and statistics is even more scarce. For significantly heterogeneous continental low-permeability reservoirs, it is essential to integrate horizontal and vertical wellbore logging data to precisely divide the sedimentary facies.

When compared to vertical wells or directional inclined wells, the horizontal wellbore logging presents several notable advantages. The horizontal section's length is predominantly concentrated within a span of over 1000 m. This significantly enhances the direct contact area with the primary production layer. Furthermore, the detection range in parallel wellbore direction is considerably greater than that of a single vertical well. The detection range for vertical wellbore direction aligns with the standard logging range of several meters. Such characteristics are well-suited to meet the research requirements of low-permeability reservoirs characterized by rapid lateral changes. Using the "An 83" well area in the Xin′anbian region of the Ordos Basin as a case study, numerous horizontal wells have been drilled perpendicular to the mainstream river channel. Consequently, integrating logging data from the horizontal sections of these wells provides a detailed characterization of the lateral swing and migration degrees of the river channel. This data also facilitates the study of the development and patterns of various sedimentary facies, offering valuable insights for the construction of facies models. Such insights are not obtainable from vertical or directionally inclined wells.

Existing sedimentary facies identification results can offer initial guidance during the early stages of development. However, they fall short in meeting the demands for stratigraphic selection and analysis of mine dynamics during the middle and late stages of development (El-Gendy et al., 2022). There is an urgent need for more refined sedimentary facies division results to elucidate development dynamics. The logging data from the horizontal section in the vertical channel direction provides valuable support for this research. In future research, it is imperative to develop a streamlined and precise method for determining sedimentary facies that seamlessly integrates horizontal well data. The new approach should provide precise sedimentological criteria for the stratification and development, elucidate various phenomena observed in development practices, and display the significant benefits of horizontal wellbore logging data in the comprehensive study of unconventional reservoir geology and engineering.

2.2 Continuous distribution modeling of heterogeneous start-up pressure gradient

In the context of terrestrial low-permeability oil reservoirs, the applicability of Darcy flow and the quantitative representation of non-Darcy flow remain critical areas of focus.

Numerous scholars have proposed various equation expressions for non-Darcy flow phenomena, each in a different form but fundamentally consistent. A plethora of laboratory experiments have confirmed the existence of a starting pressure gradient in low-permeability tight reservoirs (Hussain et al., 2023). However, there remain challenges in quantitatively characterizing and providing guidance for this flow property. The value of the starting pressure gradient is, to some extent, related to the mineral composition, pore structure, and macroscopic physical property parameters of the reservoir. Sole reliance on discrete test data is insufficient to meet the requirements of enhanced oil recovery studies. There is a relative dearth of research on obtaining continuous starting pressure gradient values at the three-dimensional reservoir spatial scale and reservoir classification.

In future research endeavors, it is imperative to ascertain the significance of the continuous-scale starting pressure gradient within a three-dimensional reservoir space. This can be achieved by integrating start-up pressure gradient testing with logging parameter sensitivity analysis, multivariate statistical regression, and three-dimensional geological modeling techniques. Subsequently, we should delineate thresholds based on the cumulative probability distribution characteristics of the continuous start-up pressure gradient. Furthermore, proposing reservoir classification and numerical simulation schemes predicated on precise flow attributes will furnish a pivotal scientific foundation for the effective exploitation of low-permeability reservoirs.

2.3 Geomodel-driven determination of advantageous oil displacement paths

During the development of low-permeability reservoirs, it is essential to conduct the prediction of advantageous oil displacement paths which are crucial for well location deployment, well pattern design, and development policy adjustments to devise an optimal development plan (Shi and Wang, 2022). Identifying the advantageous flow channel has emerged as a pressing and significant scientific challenge in the realm of water injection development. The main approaches currently focus on the following aspects:

1) Field testing yields firsthand data. Production logging is crucial for identifying the dominant flow channel of a reservoir by examining the production liquid profile of the production well and the water absorption profile test of the water injection well after stable production. However, these results are only applicable near the wellbore and do not predict flow dynamics between wells. The microseismic test of water-flooding front edge determines the flow area by monitoring the energy distribution of microseismic events during the water flooding process. However, due to numerous triggering factors for microseismic events, many non-flow related microseismic events can be included, leading to misjudgments. The tracer test primarily involves injecting a tracer into the water injection well to observe the tracer′s effect time in the production well within the well pattern, thereby determining the flow direction. This method is time-consuming and cannot monitor the dynamic flow of the tracer in the reservoir space, which can cause some degree of reservoir damage. Core analysis of inspection wells involves drilling new wells and coring between the production and injection wells of the original well pattern, and judging the flooding law by analyzing the flooding status of the core. This provides the most direct basis for determining the dominant flow channel. However, due to cost constraints, this method cannot be implemented on a large scale.
2) The physical simulation test primarily involves the collection of large-scale core blocks, the establishment of simulated well locations, and the documentation of water occurrence time and content in each direction through the design of a water injection scheme. This approach aims to determine the dominant flow direction. While this method offers an intuitive advantage, it also presents several disadvantages. Except its lack of representativeness, it is also impossible to truly restore the in-situ conditions underground for testing.
3) Numerical simulation could help to calculate remaining oil saturation and production levels at varying times. While this method can capture the dynamic process of flow to a certain extent, it is constrained by the computational capabilities. Furthermore, the introduction of a geological model necessitates a significant degree of coarsening, which inevitably results in the loss of crucial information pertaining to the actual conditions of fluvial migration and swing in continental low-permeability reservoirs. Therefore, the accuracy of the simulation warrants further discussion.

Numerous studies and practices have consistently demonstrated that dynamic fractures are prone to occur due to the unstable changes in reservoir fluid pressure and hydration damage during water injection (Zhao and Du, 2024). This phenomenon has become a double-edged sword for water injection development. On one hand, the generation of new fractures creates new flow channels, providing an effective pathway for the recovery of remaining oil. On the other hand, the large-scale extension of dynamic fractures caused by water injection can lead to the direct connect between production and injection wells, resulting in water channeling and significantly reducing the recovery rate. In future research endeavors, the authors suggest that there should be a paradigm shift in the study of water injection development. Specifically, from an integrated perspective, the water injection development process can be viewed as a “proppant-free mild fracturing process” with “water” serving as the “fracturing fluid”. The two objective realities of dynamic fracture generation and long-term water flooding caused by pore enlargement provide strong evidence for this view.

3. Conclusions

In order to enhance the exploitation of low-permeability resources, there is an urgent requirement for research that integrates geology and engineering. This integration must aim for a level of refinement that surpasses previous efforts. The identification of sedimentary facies using horizontal wellbore logging data is particularly effective for analyzing low-permeability reservoirs, which are characterized by swift lateral changes. To explore the multi-scale flow mechanism in low-permeability reservoirs, it is necessary to ascertain the continuous-scale starting pressure gradient within a three-dimensional reservoir space. In examining the characteristics and mechanisms of water-flooding development through the paradigm of “proppant-free mild hydraulic fracturing”, it becomes possible to identify more realistically advantageous oil displacement paths than previously thought.

Acknowledgements

This work was supported by Young Elite Scientists Sponsorship Program by CAST and BAST (Nos. YESS20220094 and BYESS2023182), Youth Innovation Promotion Association CAS (No. 2023021).

Conflict of interest

The authors declare no conflict of interest.

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