Sand-mudstone modeling of fluvial fan sedimentary facies: a case study of Shanxi Formation reservoir in Ordos Basin

Xuecai Zhang · Jialin Fu · Fei Hou · Xugang Zheng · Yuanpei Zhang · Rui Wang · Wei Li · Chenyu Zhai · Wenbin Wang · Ruiwu He · Jin Liu · Siwen Wang

Received: 12 February 2022 / Accepted: 27 March 2022 / Published online: 13 April 2022 © The Author(s) 2022

Abstract

The sand bodies formed by braided fluvial fan deposits have a certain distinctiveness. They not only have the characteristics of fluvial facies sandbodies but also follow the distribution law of alluvial fan sand bodies. The variation law of sandbodies that are present along and perpendicular to a channel is relatively complex. Therefore, constraints in the modeling process of sand–mudstone facies of this type of reservoir are essential. This study selects the second member of the Shanxi Formation reservoir formed by a braided fluvial fan in the middle of Ordos Basin to perform sand–mudstone facies modeling. First, by studying the lithology and sedimentary structure of the area, the sedimentary characteristics and sand body distribution law of braided river fan are analyzed. Then, the original data points are analyzed, the variation function with high convergence is obtained, and the sand–mud facies model under the constraint of sedimentary facies is established using the random modeling method. Finally, the accuracy of the established random model is tested via single-well thinning, multi-well thinning, and random seed model similarity. The test results confirm that the distribution law of the sand and mudstone in the model is highly similar to that of the actual stratum. And it also conforms to the sedimentary model of braided fluvial fan. The accuracy of the model established by this method is reliable, and the method can be used to predict sand body distribution in areas with low well pattern density.

Keywords Braided fluvial fan · Geological constraints · Variation function · Geological modeling

Introduction

As an important sedimentary basin, Ordos Basin has a large number of sandstone reservoirs (Xi et al. 2009). In the northeast of the basin, the Permian strata are mainly composed of clastic rocks, and there are many reservoirs of sedimentary system with braided river as the core (Li et al. 2021a). However, in the actual study, a single braided river deposition can not accurately describe the sedimentary model of an area, or the braided river sedimentary system in this area is very complex (Zhang et al. 2021; Anees et al. 2022b). Through the investigation, it is found that, those formed by fluvial action on a large scale can be referred to as fluvial fans or large fluvial fans (Yuan et al. 2021; Zhang 2021). The sedimentary model of a braided fluvial fan is a type of a fluvial fan system that is derived from alluvial fans. Under normal circumstances, a fluvial fan is considered to be a fan-shaped sedimentary body developed in mountain passes or plains, dominated by river sedimentation, and formed along upstream apexes and downstream areas on geological time scales. The concept of alluvial and fluvial fans was sub-divided in the distributive fluvial systems (DFS) proposed by Hartley in 2010 (Hartley et al. 2010). The plane shape of DFS can be affected by regional relative unloading and sediment supply. When the sediment supply gradient and relative unloading are high, DFS will exhibit the shape of a braided fluvial fan. Braided fluvial fans are usually developed in humid areas and are intertwined with and superimposed by multiple braided fluvial systems, which is similar to the sedimentary characteristics of ordinary braided fluvial fans. There are many fluvial channels and frequent mutual cutting. The internal fluvial channels are often diverted and
highly unstable. Due to the strong hydrodynamic conditions in humid areas, the sand body content is often high in the vertical direction of the formation, with a large number of single sand bodies, which are usually thin. Various parallel and cross beddings under hydrodynamic conditions are also common (Zhang 2021).

In general, the sedimentary phases can be divided into proximal, central and distal subphases. Braided fluvial fans are a new view of sedimentation, and relatively little research has been carried out on them at home and abroad; only a few scholars have mentioned braided fluvial fans in China (Wang et al. 2013). Zhang Xin carried out a sedimentary analysis of the Ningnan fault and the descending disk of the Wunan fault in the western part of the Huimin Depression and found that the sedimentary sequence is a thick coarse clastic system consisting of a series of sand and gravel layers and sand layers of varying sizes that overlap with each other and are often tens of meters thick and concluded that braided fluvial fan deposits are developing in the area (Zheng et al. 2011). It is necessary to use the above three-dimensional geological system for the development of oil and gas fields.

Three-dimensional (3D) geological modeling is an important technology in the field of oil and gas exploration. A software is used to analyze the geological body of a region by combining geological interpretation, spatial information management analysis, prediction, and geostatistics to reveal its 3D geological structure, sedimentary distribution, and reservoir characteristics (Thanh et al. 2021). In the geological research of gas and oil fields, the description of spatial development characteristics of a reservoir is crucial; 3D geological modeling is a suitable means toward this aim. In 3D geological modeling, the statistical tool used to characterize the spatial changes in reservoir lithofacies, physical properties, and other attributes is the variation function, which is the mathematical expectation of the incremental square of regionalized variables (Lee et al. 2022). Most advanced reservoir and gas reservoir modeling works are applied to the geostatistical method based on this variation function. In practice, well data are often taken as samples for experimental variogram analysis before fitting with the theoretical model to obtain the azimuth of the variogram in the main direction and the variation range in the main, secondary, and vertical directions to serve as input parameters for geological modeling.

3D geological modeling has been used in various regions. With the passage of time, the use of this technology is constantly improved, and various new modeling ideas appear. Geostatistical modeling using petrel software, a sequential indicator simulation was adopted for facies modeling and then sequential Gaussian simulation and co-kriging approaches were utilized for petrophysical modeling, the above method is used to determine the reservoir potential of an oil field (Thanh et al. 2022). In recent years, there have been more advanced and comprehensive methods for the geostatistical modeling of this clastic sedimentary system (Liu et al. 2011; Dong et al. 2020). First, the geological body is imaged underground, and the three-dimensional reservoir facies model with sedimentary constraints is established through drilling data and three-dimensional seismic data, and then the method of machine learning is introduced. The interaction between the two can effectively improve the accuracy of the model (Ashraf et al. 2021). The above methods have been successfully applied in all regions of the world and achieved good response, which can provide effective guidance for the future development of oil and gas fields.

At present, considerable progress has been made in research on the genesis, configuration, and modeling methods of reservoirs in an areas and abroad (Wu et al. 2007). However, this macro and rough understanding struggles to meet the requirements of tight reservoir characterization. It has gradually become a mainstream research problem to improve the accuracy of geological modeling and solve the coupling difference between the modeling results and geological understanding. According to the relevant literature, geological constraint is important to improve the accuracy of geological modeling (Zheng et al. 2011). At present, there is little research on the selection of a variation function and the adjustment of eigenvalue parameters in geological modeling, especially for tight reservoirs.

Taking the geological modeling of the FX41 block in the FX area of the Ordos Basin as an example, this study applies the geological knowledge base obtained from studying this area to geological modeling, proposes the idea of fine geological modeling combined with geological constraints, and discusses the optimization of variation function and eigenvalue analyses under the braided fluvial fan mode to gain a new understanding of the modeling methods of this type of reservoir. The model established under the sedimentary model in the FX area of the Ordos Basin has broad applications to other regions.

**Regional geological overview**

The FX block is located in the northeast of the Ordos Basin in Central China (Fig. 1a). The FX41 area is approximately 16 km long from north to south and 25 km wide from east to west, covering an area of approximately 400 km² with a well spacing of approximately 2–2.5 km (Fig. 1b). The terrain of the entire study area is flat, and there are no faults or other structural units as a whole. The reservoir in the study area is located in the second member of the Shanxi Formation (S2) of Permian in the upper Paleozoic. The sandstone in this area belongs to the tight sandstone type, with typical characteristics of low
porosity and low permeability, and the sand body exhibits a quasi-continuous distribution (Jiang et al. 2020). Through studying the provenance discrimination and sedimentary characteristics of the study area, we obtain a certain preliminary understanding.

Through the identification of the cycle interface based on seismic, logging, core data, and some previous studies such as the sequence division of Shihezi Formation (Anees et al. 2022a). According to the logging curves of marker wells and core observation in this area, the second member of the Shanxi Formation is divided into three sand groups, namely S21, S22, and S23. S23 is the target interval of this study (Table 1), and it is subdivided into three layers: layer 1, layer 2, and layer 3.

Data and methods

Based on the logging data, core photos and other basic data of FX area in Ordos Basin, combined with the previous research results, this paper obtains a new understanding of sedimentary facies in this area, and describes the distribution of several sedimentary microfacies in detail. Then, according to the relevant research, the corresponding relationship between GR curve and sand mudstone in this area is obtained, the logging data of sandstone and mudstone are calculated, and these data are coarsened. Then, the analysis of geological modeling is carried out, including the vertical adjustment of sandstone content and the multidirectional adjustment of variogram. The modeling process is constrained by the research results of early sedimentology.

| Chronostratigraphy | Lithostratigraphy | Sublayer division scheme | Main lithology |
|---------------------|-------------------|--------------------------|---------------|
| System | Series | Formation | Upper Shihezi Formation | Lower Shihezi Formation | S1 | S11 | S12 | S13 | S2 | S21 | S22 | S23 | Taiyuan Formation | Upper subsegment | Lower subsegment | T1 | Limestone |
| Permian | Lopingian | Shiqianfeng Formation | Red gravelly sandstone |
| | Guadalupian | Shihezi Formation | Light gray, grayish green gravelly coarse sandstone |
| | | Lower Shihezi Formation | Siltstone and fine sandstone |
| | Cisuralian | Shanxi Formation | Light gray medium sandstone and coarse sandstone |
| | | S1 | |
| | | S2 | |
| | | Taiyuan Formation | Upper subsegment |
| | | Lower subsegment | T2 |
and finally a sand-mudstone geological model of the study area is obtained. Finally, a variety of model testing methods are used to test the model to determine the accuracy of the model and strive for the objectivity of the model, so as to guide the exploration of sandstone reservoir.

### Preliminary research results

#### Lithologic characteristics and sedimentary structure

The content of sandstone in the S2 section in the FX area accounts for 60% of the total sedimentation (Xie et al. 2020a, b; Li et al. 2021a), mainly comprising medium sandstone, coarse sandstone, and fine conglomerate. The thickness of the entire S2 section is approximately 60 m (Cui et al. 2013). The middle and upper parts are mainly composed of light mudstone and medium sandstone, and the lower part is mainly dark gray–black mudstone or carbonaceous mudstone, coarse sand, and fine conglomerate. The average thickness of a single sand body is approximately 4 m (Li et al. 2021b). Through the analysis of rock samples in this area, the sandstone types are mainly quartz sandstone and lithic quartz sandstone, lacking feldspar.

Through the core observation of this area, there is generally more oxidized mudstone, indicating that this area is in an oxidation-weak reduction environment during the deposition process. After observing the sedimentary structure (Fig. 2), many typical phenomena of strong hydrodynamic action are found. Bottom scouring significantly developed throughout the entire S2 section. There is substantially large trough cross bedding, much plate cross bedding, and parallel bedding, which reflects the sedimentary environment under the river system, providing a strong hydrodynamic force.

#### Logging response and single-well facies

The sedimentary microfacies in the study area can be divided into the following four types: lacustrine swamp, floodplain, braided channel, and channel bar. The lakes and marshes mainly comprise mudstone and carbonaceous mudstone, and the gamma ray curve (GR) exhibits no obvious low-amplitude characteristics. The overtopping is dominated by fine sandstone and siltstone, mostly with sand–mud interbedding and very few developed parallel beddings, and the GR curve is serrated or linear. The sand body thickness of the braided channels generally varies between 2 and 5 m. The lithology consists of mainly medium sandstone, coarse sandstone, and fine conglomerate. Parallel bedding, oblique bedding, and large trough cross-bedding are developed. In general, grain size change of sand body shows a positive rhythm and the GR is bell shaped (Anees et al. 2019). The thickness of the heart beach is mostly greater than 4 m. The lithology is also dominated by medium sandstone, coarse sandstone, and fine conglomerate. Parallel and cross beddings are developed, and there is an appearance of sudden change in particle size. In general, it is dominated by a positive rhythm and the GR curve is of a serrated- or smooth-box type.

Based on the abovementioned research, a vertical analysis of a key well in this area was conducted, as demonstrated by the single-well phase diagram of S2 of well FX41 in the study area (Fig. 3). The coring depth is 2800–2890 m. The sandstone lithology of the coring section is mainly medium and coarse sandstone and fine conglomerate. The sedimentary microfacies are lacustrine...
swamp, braided channel, and channel bar. The thickness of the lacustrine swamp ranged from 1 to 3 m, owing to the many coal seams and abundant carbonaceous mudstone at its center. The braided channel is developed with light-gray medium sandstone, coarse sandstone, and fine conglomerate, with oblique and parallel bedding. There is trough cross bedding at the bottom of the braided river channel, with a thickness of 2–3 m. The thickness of the channel bar is approximately 2–3 m, with well-developed large sandstone.

**Sedimentary facies distribution**

During the deposition period of the S2 member, most of the northern Ordos Basin was mountainous and canyon-like. After the fluvial flowed out of the canyon, it formed a braided fluvial fan intertwined with many large braided rivers. The study area is located in the middle of the basin. Based on the analysis of the data mentioned above, combined with the sedimentary background and environment of the Ordos Basin, it is concluded that the area is a central fluvial fan subfacies. With the decrease in the hydrodynamic intensity and slope, the river channel disappears at the end of the braided fluvial fan (Fig. 4).

**Result**

**Data source and processing**

The 3D stratigraphic grid was established by delimiting the boundary. To ensure the accuracy of modeling, the plane grid size was 20 m × 20 m, the longitudinal size was less than 0.5 m. Three layers in the longitudinal direction, each divided into 30 parts. So, the number of grids (x × y × z) was 1642 × 800 × 90, and the total number was 118,224,000. Then, according to the stratification results of the area and the constraints of the bottom structural map of the Shan 2 (S2) member in the area, a structural model was formed.

Generally speaking, the GR curve value can roughly characterize the distribution of sandstone and mudstone in this area. The GR value of mudstone is high, whereas that of sandstone is low. Based on a previous study in this area (Ashraf et al. 2019, 2021), mudstone has a GR > 80 and sandstone a GR ≤ 80, generating facies in Petrel (Fig. 5). This is the result of the division of sand–mud facies.

After discretizing the calculated curve, the corresponding sandstone and mudstone facies data after upscaling of each well are obtained. They are evenly distributed. Such
data points are helpful in establishing an accurate random model (Fig. 6). By analyzing the data in the figure, we conclude that the calculated data are not different from the actual statistical data of the sand and mudstone. The average sandstone content in the discrete data of the model is 60%, and that of small layer 1 is the highest, reaching 69.8%, which is consistent with the actual sand and mudstone data in the study area.

Optimization of modeling methods and data analysis

(1) Selection of modeling methods

The establishment of a geological model needs to be based on an understanding of geology; hence, it is necessary to select an appropriate modeling method. At present, many random modeling methods exist. In the modeling for the sand–mud facies model, we use the discrete modeling sequential indication simulation method. The model in a 3D space has good continuity, can maintain data correlation and a spatial structure, and can better simulate the distribution law and heterogeneity in the reservoir (Chen et al. 2020).

(2) Variogram data analysis

Based on the research on the longitudinal section of early sedimentation, the cycle characteristics of sand bodies in this area are obtained by drawing the single-well facies of standard wells. The single-well profile of braided fluvial fan deposits has characteristics typical of fluvial facies, which is a positive rhythm model with fine upper and coarse lower, reflected in the presentation of data via the software. On this basis, the distribution of sand bodies is further adjusted according to the abovementioned single-well facies research (Fig. 7).

Geological constraints simply mean that the established geological knowledge base and relevant qualitative and quantitative relationships are used to constrain the results of geological modeling, determine the approximate boundaries of sand and mudstone on a plane, and draw a distribution map of sand and mudstone of each small layer according to previous studies on the distribution of their sedimentary facies (Lv et al. 2009; Wang et al. 2014). Taking geological constraints as the constraint condition, the results of argillaceous facies calculated by the variogram are constrained. The variogram refers to the variance of the increment in attribute variables, which reflect the variability between regional variables with respect to distance (Bohling 2005). The expression formula is as follows:

\[ y(h) = \frac{1}{2}E[(Z(x) - Z(x+h))^2] \]

where \( Z(x) \) and \( Z(x+h) \) are the values of variable \( Z \) at position \( X \) and position \( x+h \), respectively, and \( E \) is the mathematical expectation. The variation function is irrelevant to the position and is related to the distance \( h \), called the search step. The variation function is finally formed by counting the variation function values corresponding to...
several steps (Wang et al. 2015, 2018). When establishing the geological model, the value of the variation function is directly related to the reliability of the results. Therefore, it is necessary to set a reasonable variation range. The sand body in the study area is formed by braided river fan sedimentary facies. The interior of this type of fan is composed of multiple cross-braided channels. Therefore, the scale of the sand body is mainly constrained by the facies boundary. The
step length of the variogram fitting is set to approximately 1000 m (Fig. 8), and the scale of each microfacies is used to set the corresponding range value of the sand–mudstone facies.

Modeling results

According to previous studies and the above analysis, the sedimentary facies in the study area are distributed from the northeast to the southwest and the provenance direction is basically from the north to the northeast. Therefore, according to the distribution law of sand bodies in each layer, the main variation direction of the three small layers is set along the northeast–southwest direction. After the search for all sand–mudstone facies data points is completed, data analysis is carried out and the variogram value of each small layer is obtained (Table 2). The modeling results were obtained through the above parameter input, and the sand–mudstone facies model is shown in (Fig. 9). It should be noted that there is only a small part of conglomerate in this area, and the main body is sandstone. In this study, it is only to find the location of sand body reservoir, so it is not necessary to represent conglomerate in actual modeling.

Table 2 Variation function values of three small layers in the study area

| Variogram range value | Layers |       |       |       |
|-----------------------|--------|-------|-------|-------|
|                       | Layer 1 | Layer 2 | Layer 3 |       |
| Search direction (°)  | 63      | 65     | 60     |       |
| Major range           | 1234.1  | 1532.1 | 1860.1 |       |
| Minor range           | 880.4   | 793.5  | 936.3  |       |
| Vertical range        | 2.56    | 2.91   | 2.06   |       |

Fig. 8 Variogram analysis scatter diagram (a part of analysis)
Sand–shale facies model and its verification

Based on the analysis of the variation function of each small layer, the sedimentary facies model is used for constraint modeling, the sand–mudstone distribution model of the entire region is established, the model quality is tested, and a high-quality braided fluvial fan sand–mudstone facies model is obtained.

Quality and inspection of the single-well model

Eighty-seven wells are used in this modeling process, and there are nearly 1000 single-layer data points. The reliability of the data volume and data analysis results is relatively high. The single-well model is verified using the thinning method, which is randomly selecting one or more wells, removing them from the interpolated data points, and then re-establishing the model with the same variogram value. We then compare the actual lithology data (coring or logging curve data) of the well with the facies attributes of the section of sand and mudstone passing through the well in the model. Finally, the analysis and comparison results show that if the difference between the two is very small, then the accuracy of the model can be proven to be very high; otherwise, it is very low. The single-well verification results are shown in Fig. 10.

Figure 10 shows that there is little difference between the sand–mudstone facies model generated in the absence of a well and the original model, which indicates that the variation function used in the modeling has high convergence, and the 3D lithofacies model established with it has high reliability.

Quality and inspection of the multi-well model

Using the same method as the single-well model test can also further deepen the degree of validity of the test. In the cross section of multiple wells, several wells are randomly removed from the difference calculation. If the new model is considerably different from the original model, it proves...
that the stability of the model is poor and cannot meet the required accuracy.

The multi-well verification results, shown in Fig. 11, indicate that after randomly removing the two wells in the model, the connectivity of the sand body is not greatly affected and the accuracy of the model can still meet the modeling requirements. Therefore, the variation function used in the modeling is not applicable to a small number of data points, and it exhibits high convergence.

**Reliability test of the stochastic model**

The characteristic of stochastic modeling is the uncertainty of the model; that is, when using the same set of variation functions for modeling, the distribution law of sand and mudstone facies of the generated stochastic model is inexpressible and countless random seed models will be generated in each modeling process (Thanh et al. 2021). The high correlation of these random seeds proves that their convergence degree is high and the random seed model is more stable.
and reliable. If the correlation of the generated random seed model is poor, then the variation function used is inconsistent with the actual geological situation and the reliability of the generated sand–mudstone facies model is low (Ashraf et al. 2020, 2021).

To verify the correlation of the random seed models, we first select a target seed (the model with the highest reliability) and then select 200 random seed models for observation and statistical analysis before finally analyzing the similarity of these models (Wang et al. 2020a, b). The statistics show that the random seed similarity of the braided fluvial fan sand–mudstone facies model in the study area reaches 70%, with a high degree of convergence, indicating that the established model is reliable (Fig. 12). It should be noted that the six seed model plans in Fig. 12 are the six plane slices of the total model. It can also be seen from the figure that the sand body shape in each figure is roughly heart beach, and the sand body trend is northeast southwest, which is basically in line with the understanding of sedimentology in the previous text. All plane slices are superimposed to form a total sand body thickness diagram, which can be seen from the diagram (Fig. 13). The distribution of braided channel in Fig. 4 is basically the same in the area with sand body thickness greater than 6 m, and the area with sand body thickness greater than 8 m basically conforms to the distribution of channel bar in sedimentary facies map. This shows that the Sand-mudstone model made by using the modeling method in this paper corresponds to the research results of early sedimentary facies and has high reliability.

Conclusions
(1) By analyzing the characteristics of a braided fluvial fan sedimentary model and the sand body distribution law in the S2 member of the Ordos Basin. The original data points are analyzed, the variation function with high convergence is obtained, a sand–mud facies model is established using the variation function with high convergence and under the constraints of sedimentary facies.

(2) After the model is established, its accuracy is tested using several methods, including single-well thinning, multi-well thinning, and random seed model similarity. The final test results show that the distribution law of the sand and mudstone in the model basically conforms to that in the actual stratum and has a high degree of similarity. Finally, it is proved that the sand–mudstone facies random model established by this method has a high accuracy and is feasible; and it also conforms to the sedimentary model of braided fluvial fan.
**Fig. 12** Random seed model and its similarity test

![Random seed model and its similarity test](image)

**Fig. 13** Total thickness of sandstone calculated by the model

![Total thickness of sandstone calculated by the model](image)
more, it can be used to predict the distribution of sand bodies in areas with a low well pattern density.

**Funding**  This work was supported by the Natural Science Foundation of Shandong Province (ZR2020MD035) and the National Natural Science Foundation of China (51504143 and 51674156).

**Declarations**

**Conflict of interest**  The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Open Access**  This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

**References**

Anees A, Shi WZ, Ashraf U, Xu QH (2019) Channel identification using 3D seismic attributes and well logging in lower Shihezi Formation of Hangjinqi area, northern Ordos Basin. China J Appl Geophys 163:139–150

Anees A, Zhang HC, Ashraf U, Wang R, Liu K, Abbas A, Ullah Z, Zhang X, Duan LZ, Liu FW, Zhang Y, Tan SC, Shi WZ (2022) Sedimentary facies controls for reservoir quality prediction of lower Shihezi member-1 of the Hangjinqi area Ordos Basin. Minerals 12:126. https://doi.org/10.3390/min12020126

Anees A, Zhang HC, Ashraf U, Wang R, Liu K, Mangi HN, Jiang R, Zhang XN, Liu Q, Tan SC, Shi WZ (2022b) Identification of favorable zones of gas accumulation via fault distribution and sedimentary facies: insights from Hangjinqi area northern Ordos Basin front. Earth Sci 9:822670. https://doi.org/10.3389/efc.2021

Ashraf U, Zhu P, Yasin Q, Anees A, Imraz M, Mangi HN, Shackle S (2019) Classification of reservoir facies using well log and 3D seismic attributes for prospect evaluation and field development: a case study of Sawan gas field, Pakistan. J Petrol Sci Eng 175:338–351

Ashraf U, Zhang HC, Anees A, Ali M, Zhang XN, Abbasi SS, Mangi HN (2020) Controls on reservoir heterogeneity of a shallow-Marine reservoir in Sawan gas field, SE Pakistan: implications for reservoir quality prediction using acoustic impedance inversion. Water 12(11):2972

Ashraf U, Zhang HC, Anees A, Mangi HN, Ail M, Zhang XN, Imraz M, Abbasi SS, Abbasa A, Ullah Z, Ullah J, Tan SC (2021) A core logging, machine learning and geostatistical modeling interactive approach for subsurface imaging of lenticular geobodies in a clastic depositional system. SE Pakistan Nat Resour Res 30:2807–2830. https://doi.org/10.1007/s11105-021-09849-x

Bohling G (2005) Introduction to geostatistics and variogram analysis. Kans Geol Surv 1:1–20

Chen SZ, Lin CY, Ren LH (2020) Multi-scale geological modeling of meandering river under the control of architectural pattern: taking Shinan block of Shengli Oilfield as an example. J China Univ Min Technol 49(3):552–562

Cui C, Zheng RC, Zhang JW, Qu YL, Wang CY (2013) Sedimentary microfacies and sandbody distribution rule of member 2 of Shanxi Formation in the Yulin gas field, Ordos Basin, China. J Chengdu Univ Technol Sci Technol Ed 9(1):25–33

Dong SQ, Lv WY, Xia DL, Wang SJ, Du XY, Wang T, Wu Y, Guan C (2020) An approach to 3D geological modeling of multi-scaled fractures in tight sandstone reservoirs. Oil Gas Geol 41(3):627–637

Hartley A, Weissmann G, Nichols G, Warwick G (2010) Large distributed fluvial systems: characteristics, distribution, and controls on development. J Sediment Res 80(2):167–183

Jiang ZW, Luo JL, Liu XS, Hu XY, Ma SW, Hou YD, Fan LY, Hu YH (2020) Provenance and implication of Carboniferous-Permian detrital zircons from the upper Paleozoic, Southern Ordos Basin, China: evidence from U-Pb geochronology and Hf isotopes. Minerals 10(3):265

Lee K, Thanh HV (2022) 3D geo-cellular modeling for Oligocene reservoirs: a marginal field in offshore Vietnam. J Petrol Explor Prod Technol 12:1–19

Li J, Zhang X, Tian JC, Liang QS, Cao TS (2021) Effects of deposition and diagenesis on sandstone reservoir quality: a case study of Permian sandstones formed in a braided river sedimentary system, northern Ordos Basin, northern China. J Asian Earth Sci 213:104745

Li W, Yue DL, Colombera L, Du YS, Zhang SY, Liu RJ, Wang WR (2021b) Quantitative prediction of fluvial sandbodies by combining seismic attributes of neighboring zones. J Petrol Sci Eng. https://doi.org/10.1016/j.petrol.2020.107749

Liu JH, Zhao CM, Huo CL, Shen CS, Li SB (2011) Application of geological knowledge in while drilling geological modeling of Ed Formation LD27-2 oilfield. J Oil Gas Technol 33(9):28–31

Lv JR, Wang XG, Qian X, Li JP (2009) Sedimentary microfacies constraint in geological modeling. Fault-Block Oil Gas Field 16(3):14–16

Thanh HV, Sugai YC (2021) Integrated modelling framework for enhancement history matching in fluvial channel sandstone reservoirs. Upstream Oil Gas Technol 6:100027. https://doi.org/10.1016/j.upstre.2020.100027

Wang J (2013) Sedimentary characteristics of neogene Shawan formation reservoirs in Chepaizi area. Junggar Basin. Petrol Geol Recovery Eff 20(7):30–36

Wang JK, Zhang JL, Xie J, Ding F (2014) Initial gas full-component simulation experiment of Ban-876 underground gas storage. J Nat Gas Sci Eng 18:131–136

Wang JK, Xie J, Lu H, Pan LL, Li LY (2015) Numerical simulation on oil rim impact on underground gas storage injection and production. J Petrol Explor Prod Technol 6(3):1–11

Wang JK, Liu HY, Zhang JL, Xie J (2018) Lost gas mechanism and quantitative characterization during injection and production of water-flooded sandstone underground gas storage. Energies 11(2):272

Wang JK, Fu JL, Xie J, Wang JM (2020a) Quantitative characterisation of gas loss and numerical simulations of underground gas storage based on gas displacement experiments performed with systems of small-core devices connected in series. J Nat Gas Sci Eng. https://doi.org/10.1016/j.jngse.2020.103495

§ Springer
Wang JK, Zhang YP, Xie J (2020b) Influencing factors and application prospects of CO2 flooding in heterogeneous glutenite reservoirs. Sci Rep 10(1):1839

Wu SH, Li YP (2007) Reservoir modeling: current situation and development prospect. Mar Orig Petrol Geol 03:53–60

Xi SL, Li WH, Wei XS, Meng PL, Feng JP (2009) Study on the characteristics of quartz sandstone reservoir of the neopaleozoic of two gas field in Ordos Basin. Acta Sedimentol Sin 27(02):221–229

Xie J, Hu X, Liang HZ, Li Z, Wang R, Cai WC, Nassabeh SMM (2020a) Experimental investigation of permeability heterogeneity impact on the miscible alternative injection of formation brine-carbon dioxide. Energy Rep 6:2897–2902. https://doi.org/10.1016/j.egyr.2020.10.012

Xie J, Hu X, Liang HZ, Wang MQ, Guo FJ, Zhang SJ, Cai WC, Wang R (2020b) Cold damage from wax deposition in a shallow, low-temperature, and high-wax reservoir in Changchunling Oilfield. Sci Rep 10(1):1–4

Yuan G, Cao Y, Sun P, Zhou L, Li W, Fu L, Li H, Lou D, Zhang F (2021) Genetic mechanisms of Permian Upper Shihezi sandstone reservoirs with multi-stage subsidence and uplift in the Huanghua Depression, Bohai Bay Basin. East China. Marine Petrol Geol 124:104784

Zhang JL (2021) Tight reservoir sedimentology. Science Press, Beijing

Zhang YP, Zhang XC, Cao HF, Zheng XG, Wang JK, Zhang JL (2021) Paleogene lake deep water sedimentary facies in the northern zone of the Chezhen Sag, Bohai Bay Basin, China. J Petrol Explor Prod Technol 11(11):3903–3916. https://doi.org/10.1007/s13202-021-01294-z

Zheng YZ, Liu GL, Ma CQ, Li XT (2011) The application of multiple constraints geo-modeling technology in Qingxi fractured reservoir. Petrol Geol Recovery Eff 18(03):77–80

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.