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Application and discussion of geological guidance technology for deep coalbed methane horizontal wells: A case study of block X in Shenmu gas field, Ordos Basin

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Abstract: The Ordos Basin is rich in deep coalbed methane resources, with block X of the Shenmu gas field being a key exploration and development area for the Jidong Oilfield in the basin. The deep Benxi Formation the 8th coal seam is an important production resource in this block, mainly produced through horizontal well drilling and large-scale fracturing operations. The Benxi Formation the 8th coal seam is characterized by complex local structures, brittle and soft coal layers, fast drilling rates, and a tendency for collapse, making trajectory control of the horizontal section difficult and posing a challenge to achieving a high rate of reservoir drilling encounter. Therefore, improving the high drilling encounter rate of coalbed methane horizontal wells and achieving rapid drilling and completion have become key technical challenges in the exploration and development of this domain. To address these challenges, multidisciplinary technical research, including geology, seismic analysis, logging, mud logging, and drilling, were conducted. This research led to the development of a deep coalbed methane horizontal well geological guidance technology, which included fine seismic structural interpretation as the foundation and near-bit orientation gamma imaging analysis as the core. This technology involved several key aspects: precise coal seam structural characterization, coal seam feature prediction, landing trajectory control, overall coal seam determination, geological guidance for the horizontal section, and control of drilling engineering parameters. Through the effective integration and proper application of these technologies, precise well landing and fine-tuning of the horizontal trajectory in real time were achieved. In geological guidance practices in the exploration and pilot test wells of this block, the horizontal well geological guidance technology demonstrated significant results, increasing the coal seam drilling encounter rate from 70.4% in the initial risk exploration well to the current average of 94%. Additionally, this technology ensured smooth and seamless wellbore trajectory, facilitating the successful implementation of casing and cementing operations and shortening the drilling and completion cycle. The efficient drilling and completion of deep coalbed methane horizontal wells have laid a solid resource foundation for subsequent large-scale fracturing and economic production, providing valuable insights for geological guidance in deep coalbed methane exploration in other blocks of the Ordos Basin. **DOI:** 10.13809/j.cnki.cn32-1825/te.2025.02.015-en

Keywords: Ordos Basin; Shenmu gas field; deep coalbed methane; the 8th coal seam; horizontal well; geological guidance

The deep coalbed methane resources in the Ordos Basin are abundant^[1-2] and represent another significant production resource for the western exploration area of the Jidong Oilfield, following tight sandstone gas. In block X of the Shenmu gas field, multiple coal seams are developed within the Upper Paleozoic strata, among which the 8th coal seam of the Benxi Formation is well-developed across the entire area. It is characterized by considerable thickness and high gas content, presenting substantial potential for exploration and development^[3]. Currently, exploration and evaluation of the 8th coal seam of the Benxi Formation have entered a phase of rapid advancement in exploration wells, primarily through horizontal well drilling and subsequent large-scale fracturing operations for production^[4-10]. Although the 8th coal seam is

relatively stable, the local structures are complex, and the coal layers are brittle and soft, resulting in fast drilling rates and a tendency for collapse. Achieving high reservoir drilling encounter rates and rapid completion of coalbed methane horizontal wells is fundamental to efficient exploration and economic production of coalbed methane^[11-12].

In conventional tight sandstone gas reservoirs, logging while drilling (LWD) is typically used as the main steering tool during horizontal drilling, with mud logging geologists conducting a comprehensive geological analysis for steering on site. However, this approach leads to extended drilling cycles, and both steering precision and effective reservoir drilling encounter rates cannot be adequately ensured. Compared with conventional sandstone reservoirs, coal

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seams present challenges such as faster drilling rates, shorter collapse cycles, and increased difficulty in casing and cementing operations, rendering traditional steering methods unsuitable. Therefore, there is an urgent need to develop geological steering technologies tailored to coal seams^[13]. To address the geological and engineering challenges in the deployment, drilling, and completion of deep CBM horizontal wells in block X of the Shenmu gas field, research has been carried out in several areas, including fine seismic structural interpretation of the coal seam top, coal seam feature prediction, landing trajectory control, overall coal seam determination, geological steering for the horizontal section, and control of drilling engineering parameters. This has resulted in the development of a relatively mature comprehensive geological steering technology, which has improved the coal seam drilling encounter rate and achieved favorable outcomes in geological steering practices. These advances have laid a solid foundation for effective control of geological reserves and for meeting the requirements of large-scale fracturing operations and production.

1 Regional geological setting

Block X of the Shenmu gas field is located in the northeastern part of the Yishan Slope within the Ordos Basin. The area is characterized by a gently dipping large-scale slope with relatively stable structures and poorly developed faults, creating favorable conditions for the preservation of deep coalbed methane. In this block, multiple coal seams are developed within the Upper Paleozoic strata: the 1st-5th coal seams in the Shanxi Formation (Member 2), the 6th-7th coal seams in the Taiyuan Formation, and the 8th-9th coal seams in the Benxi Formation. Among them, the 8th coal seam of the Benxi Formation, with its considerable thickness and stable development, is the primary target for exploration and development.

The burial depth of the 8th coal seam ranges between 1 800 m and 2 550 m, with an average depth of 2 245 m. The formation pressure coefficient ranges from 0.91 to 1.10, indicating a normal pressure system. The net coal thickness varies between 4.0 and 11.0 m, with an average of 7.1 m. The coal seam exhibits a simple structure, predominantly without interbedded gangue, although a single interbedded gangue layer of 0.5–1.2 m may occasionally occur in the middle part. Macroscopically, the coal lithotype is mainly bright coal, with the coal body structure dominated by primary-structured coal. The vitrinite reflectance (R_o) of the coal ranges from 1.45% to 2.00%. The coal seam is of medium rank, classified as coking to lean coal, which is favorable for gas generation. Besides, it is an ultra-low porosity and ultra-low permeability reservoir, with well-developed cleats and fractures conducive to gas production. The average porosity is 7.71%, and the average permeability is $1.4 \times 10^{-3} \mu\text{m}^2$. The overall gas content of the coal seam is relatively good, ranging from 20.6

to 23.5 m³/t, with an average of 21.9 m³/t. Vertically, the gas content is higher at the top than at the bottom of the seam. Block X of the Shenmu gas field covers an area of approximately 1 090 km². Preliminary volumetric estimates indicate that the reserves of the 8th coal seam exceed $2\,300 \times 10^8 \text{ m}^3$ with an average reserve abundance of approximately $2.1 \times 10^8 \text{ m}^3/\text{km}^2$, demonstrating significant potential for exploration and development.

2 Geological steering technology for horizontal wells

The 8th coal seam of the Benxi Formation in block X of the Shenmu gas field is characterized by wide distribution, substantial thickness, and good gas content. Vertical well development cannot fully unlock its potential. Horizontal wells can significantly expand the development control area of coalbed methane underground reserves, increase the scale and intensity of subsequent fracturing operations, and thereby enhance both the daily production per well and the ultimate recoverable reserves per well. This makes horizontal wells the most ideal approach for achieving efficient coalbed methane development with fewer wells in deep coal seams. Once the geological conditions, such as the coal seam's extent, thickness, and gas content, are determined, the coal seam drilling encounter rate becomes the decisive factor affecting the development of the coalbed methane horizontal well.

To improve the coal seam drilling encounter rate of deep coalbed methane horizontal wells in block X of the Shenmu gas field, multidisciplinary technical knowledge has been integrated that includes geology, seismic data, logging, mud logging, and drilling engineering^[14-23] to establish a complete geological steering technology process specifically designed for deep coalbed methane in block X (Fig. 1).

2.1 Precise structural characterization of coal seams

The coal seam serves as both the hydrocarbon source rock and the reservoir with high gas content and well-developed storage capacity. Therefore, precise structural characterization of the coal seam has become the top priority for horizontal well placement and geosteering. Currently, in Block X of the Shenmu gas field, the structural trend of the coal seam roof is primarily characterized and calibrated using 3D seismic data and drilling results from adjacent wells. In areas with low well control, reliance on 3D seismic data is even greater. Through comprehensive analysis of 3D seismic profiles, inversion sections, and drilling data from nearby wells, predictions are made regarding the coal seam landing point, coal seam thickness, and the structural trend of the coal seam top along the horizontal section. These predictions form the basis for designing the drilling trajectory. During actual drilling, continuous corrections to the structural model of the

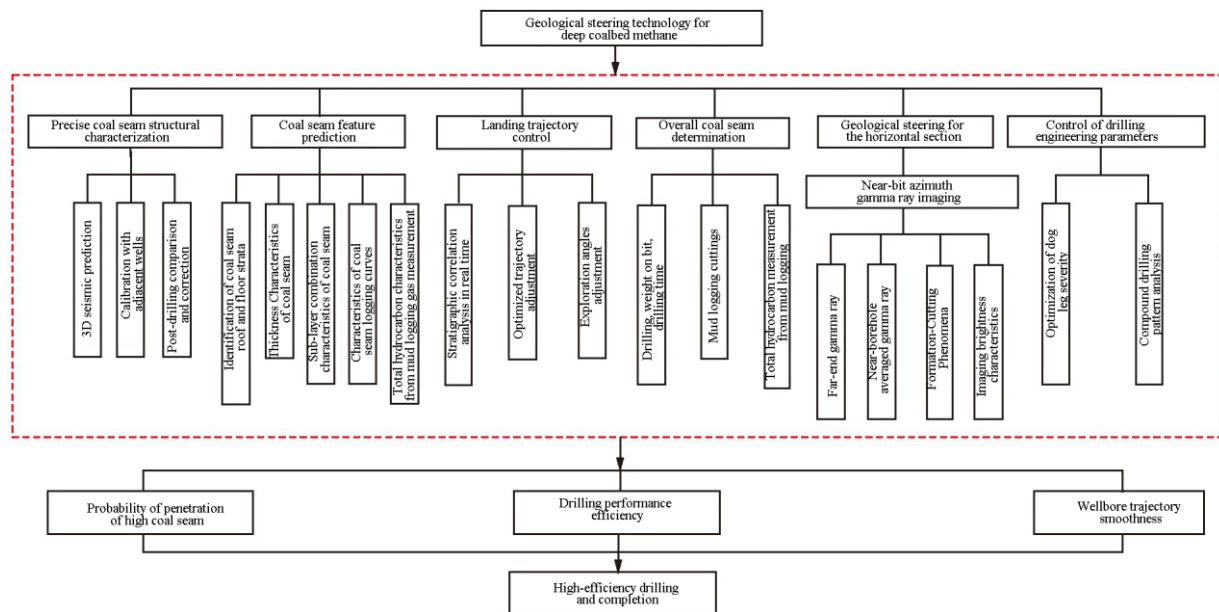


Fig. 1 Workflow of geological guidance technology for deep coalbed methane in block X of Shenmu gas field in Ordos Basin

coal seam top are made based on landing depth, the bit's position and depth within the horizontal section, and other relevant data. This iterative calibration is compared against the designed structural trend to verify the accuracy of the 3D seismic predictions.

From actual drilling results, the combined well-seismic technique applied in block X of the Shenmu gas field provides relatively accurate predictions of the overall structural trend, offering effective steering for the deployment of deep coalbed methane and geological steering operations. However, due to challenges such as the difficulty in accurately capturing seismic velocities in the Loess Plateau region and the limited vertical resolution of seismic data, some issues remain. These include significant discrepancies between predicted and actual coal seam landing depths, inconsistencies between local formation attitudes encountered during drilling and the structural trends predicted by seismic data, as well as notable deviations between the actual formation dip angles and inflection points versus seismic predictions. Therefore, it is necessary to further improve the accuracy of seismic data processing and interpretation. This includes selecting seismic datasets with better matching quality in different regions and revising seismic interpretation results based on actual drilling data to enhance the degree of alignment and consistency. These efforts are essential for further improving the accuracy of structural predictions.

2.2 Feature prediction of coal seam

Before the landing of a horizontal well, it is necessary to analyze the characteristics and differences of the 8th coal seam in adjacent wells. This includes the stratigraphic assemblage of the coal seam roof and floor strata, coal seam

thickness, sub-layer combination characteristics of the coal seam, coal seam logging curves, and total hydrocarbon characteristics from mud logging gas measurement. These features serve as critical references to guide the landing of horizontal wells and the adjustment of horizontal drilling trajectories.

Fig. 2 shows the comprehensive lithological column of Well XX in block X of the Shenmu gas field. According to this adjacent well, the 8th coal seam is relatively thick and can be subdivided into five sub-layers: 8-1, 8-2, 8-3, 8-4, and 8-5. Between sub-layers 8-3 and 8-4, there is a distinct interbedded gangue layer characterized by a high gamma ray value of approximately 140 API and high clay content, which can serve as a clear marker bed. Sub-layers 8-1, 8-2, and 8-3 constitute the upper section of the coal seam, featuring a more intact coal body structure, higher total hydrocarbon values from gas logging, and better gas content. In contrast, sub-layers 8-4 and 8-5 form the lower section, where the coal body structure is more fragmented, and both the total hydrocarbon values and gas content are inferior to those of the upper section. The roof of the 8th coal seam in this well is generally limestone (overlain by approximately 0.5 m of mudstone), and the floor is composed of thick mudstone. These features provide valuable steering for horizontal well landing and geological steering. If there are multiple adjacent wells along the horizontal section trajectory, the coal seam features of each well should be comprehensively considered.

Statistical analysis shows that in different areas of block X in the Shenmu gas field, the number of sub-layers within the 8th coal seam varies. Generally, based on gamma ray characteristics, the coal seam is divided into 3-5 sub-layers. The gamma ray characteristics of these sub-layers help determine the vertical position of the drill bit within the coal

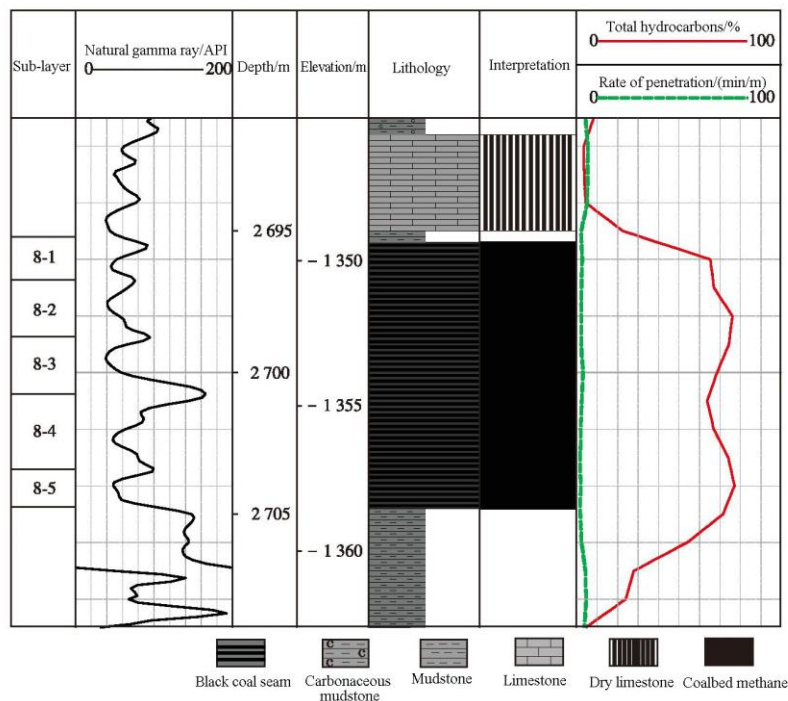


Fig.2 Comprehensive bar chart of well XX in block X of Shenmu gas field in Ordos Basin

seam and guide trajectory adjustments. It is important to note that during the landing and horizontal drilling stages, if few adjacent wells or the offset distance is significant, the thickness of the coal seam, the roof and floor stratigraphic assemblage, and the sub-layer combination characteristics may change. These variations must be analyzed promptly rather than relying solely on data from adjacent wells to avoid making incorrect geological steering decisions.

2.3 Landing interval trajectory control

During the build-up and hold sections of horizontal well drilling, stratigraphic correlation analysis in real time is conducted. By accurately identifying key marker beds such as the “Luotuo Neck Sandstone” of the 8th Member of the Shihezi Formation, the 5th coal seam at the base of the Shanxi Formation, and the limestone of the Dongdayao Member at the top of the Taiyuan Formation (Fig. 3), trajectory control is achieved. In particular, the Dongdayao Member limestone, which is closest to the 8th coal seam, can be preliminarily identified by a high rate of penetration, and further verified by cuttings return using acid drop tests and carbonate experiments to confirm the encountered lithology. These measures enable real-time prediction of the vertical distance from the well bottom to the coal seam. By comparing with the drilling engineering design, the well trajectory can be optimized in advance to prevent the target layer from being reached too early or too late relative to the predicted depth, ensuring a proper landing angle. The goal is to keep the actual well trajectory aligned with the predicted target depth, even if it means sacrificing some horizontal

footage, to avoid prematurely entering the coal seam or landing at too small an angle, which could result in drilling through the coal seam. Typically, the well inclination is maintained at around 85 ° for hold section detection. In actual drilling, the exploration angle should be adjusted upward or downward based on the structural attitudes predicted by seismic data to ensure precise trajectory control^[24-25].

2.4 Overall coal seam determination

In block X of the Shenmu gas field, the 8th coal seam exhibits three types of roof and floor assemblages: mudstone roof and floor, limestone roof and mudstone floor, and sandstone roof and mudstone floor. Among these, the mudstone roof and floor type and the limestone roof with mudstone floor type dominate most areas. Both mudstone and limestone provide strong sealing capacity, offering favorable reservoir-seal conditions. During horizontal section drilling, phenomena such as contacting the coal seam roof, contacting the floor, encountering interbedded gangue, or even drilling out of the seam (roof out or floor out) may occur. Therefore, it is essential to accurately identify the encountered lithology promptly, enabling necessary trajectory adjustments to re-enter and stay within the coal seam. There are distinct differences between drilling through coal seams versus other lithologies such as mudstone, sandstone, and limestone. These differences can be distinguished and assessed based on the following aspects:

1) Weight on bit and rate of penetration. Coal is relatively soft, requiring lower weight on bit and exhibiting faster rate of penetration, typically around 1–2 min/m. Mudstone and

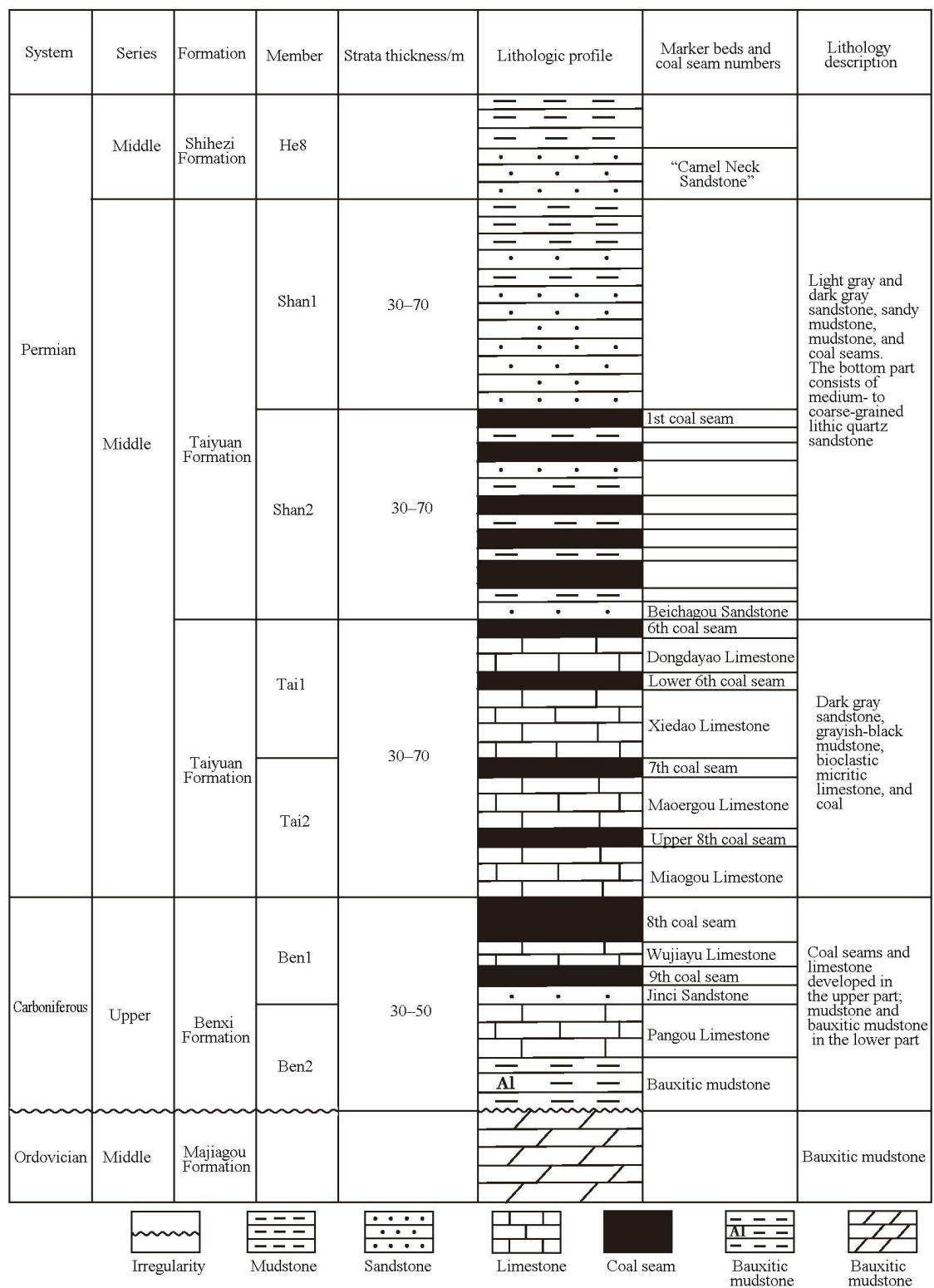


Fig. 3 Characteristics of Upper Paleozoic sedimentary strata in block X of Shenmu gas field in Ordos Basin

sandstone exhibit intermediate weight on bit and penetration rates, with a drilling time of approximately 5 min/m. Limestone, being harder, requires the highest weight on bit and longest drilling time, around 10 min/m. These parameters can help differentiate coal seams from other lithologies in

real time. However, variations in drilling equipment performance may affect weight on bit and drilling time, potentially leading to some misjudgments in lithology identification.

2) Cuttings for visual Lithology differentiation. Coal cuttings are typically black, with higher brightness in structurally elevated zones and at the coal seam top. Mudstone near the 8th coal seam is generally dark gray; sandstone is usually light gray; and limestone appears dark gray to brownish gray, producing strong bubbling when tested with acid.

3) Total hydrocarbons from mud logging gas measurement is the most direct indicator of gas-bearing capacity in coal seams versus other lithologies. In the 8th coal seam of block X in the Shenmu gas field, total hydrocarbons commonly exceed 70%, with a maximum up to 99.99%. Coal seams in structurally high positions usually display higher total hydrocarbons than those in lower structural positions. Likewise, the upper portion of the coal seam typically yields higher total hydrocarbons than the lower portion. Interbedded gangue is generally carbonaceous mudstone, with gas content influenced by clay mineral content: lower clay content results in better gas-bearing capacity and higher total hydrocarbons, whereas higher clay content corresponds to poorer gas content and lower total hydrocarbons. The roof mudstone, limestone, and floor mudstone are typically non-gas-bearing, with total hydrocarbons reflecting baseline levels. The distribution of roof sandstone is limited, and its gas content remains uncertain.

The characteristics of cuttings and total hydrocarbons measurement are the most direct and accurate indicators for lithology identification. When the weight on bit and rate of penetration alone cannot precisely determine the lithology at the well bottom, circulation should be conducted first to bring the cuttings to the surface for lithology confirmation before proceeding with the next geological steering operation.

2.5 Geological steering for the horizontal section

Upon reaching the top of the 8th coal seam, drilling inclination should be adjusted to an appropriate angle for horizontal drilling based on the formation dip predicted by

seismic data. It is important to note that in certain areas, thin coal stringers may develop at the top of the 8th coal seam; during inclination stabilization and exploration, care must be taken to drill through these stringers before leveling off. During horizontal drilling, the known adjacent wells and the structural trends delineated by 3D seismic profiles should be referenced. In combination with steering tools, the bit's precise position within the coal seam should be determined, allowing for continuous updates of the structural trend and timely adjustment of the bit trajectory. This ensures that the bit remains as close as possible to the upper part of the coal seam, where the coal structure is more intact, gas content is higher, and subsequent fracturing operations can be more effective.

2.5.1 Near-bit azimuth gamma ray imaging tool

Currently, the Shenmu gas field block X generally employs the near-bit azimuth gamma ray imaging tool developed by Schlumberger. This imaging tool is capable of capturing various gamma ray data, including far-end gamma ray, near-borehole averaged gamma ray, upper gamma ray, and lower gamma ray measurements.

The far-end gamma ray, measured by conventional LWD tools, has a relatively long detection offset, typically ranging from 16 to 20 m (Fig. 4a), making it unsuitable for real-time lithology identification at the bit. The near-borehole averaged gamma ray represents the average value of gamma measurements from eight azimuthal directions (Fig. 4b). The near-bit tool usually has a diameter of 173 mm, and during horizontal drilling, the upper gamma ray and lower gamma ray measurements can reflect the gamma ray variation between rock layers approximately 173 mm apart vertically. The measurement offset of the near-borehole averaged gamma ray is less than 1 m (typically around 0.8 m), enabling real-time identification of lithology within 1 m of the bit based on gamma ray values (Fig. 4a).

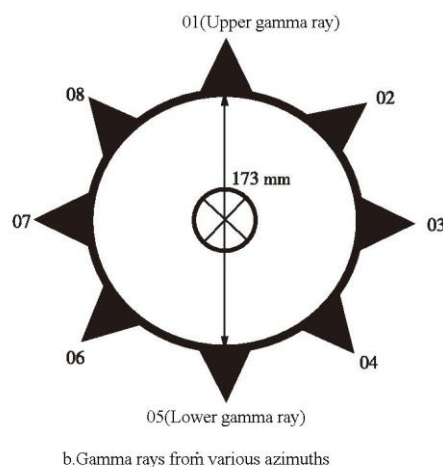
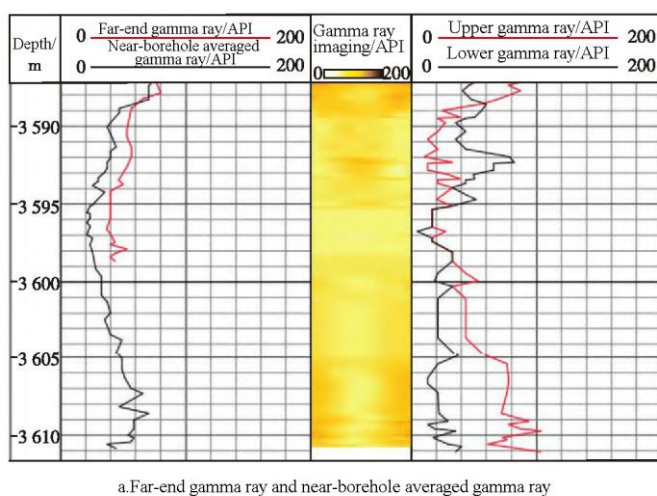


Fig.4 Schematic diagram of the near-bit orientation gamma imaging guidance tool

Statistics show that the gamma ray value of the 8th coal seam in the Shenmu Gas Field Block X generally ranges between 20 and 100 API. In relatively pure coal seams, the gamma ray value is typically below 60 API, although some local coal seams exhibit higher values (100–120 API). In contrast, mudstone exhibits gamma ray values between 100 and 200 API, which is significantly higher than that of coal seams. Thus, coal seams and mudstones can be easily distinguished using the near-borehole averaged gamma ray. Interbedded layers, specifically carbonaceous mudstone, present gamma ray values between those of pure coal and pure mudstone. When the mud content is low, the gamma ray value is correspondingly lower; higher mud content results in higher gamma ray values. Limestone also exhibits low gamma ray values, generally below 60 API, similar to coal seams. However, limestone can be easily differentiated from coal through drilling parameters such as weight on bit and rate of penetration. It is important to note that the gamma ray value range may vary slightly across different regions and wells within the Shenmu Gas Field Block X. Therefore, lithology differentiation and identification during geological steering should be based on the actual gamma ray values measured in each horizontal well.

2.5.2 Formation-cutting judgment method

The guiding principle of the near-bit azimuth gamma ray imaging tool can be summarized as: “averaged gamma ray is used to observe the trend; the formation is cut when the upper or lower gamma ray changes first.” Typically, formation cutting is classified into several types: rapid upward cut, rapid downward cut, slow upward cut, slow downward cut, and no formation cut.

Rapid upward and downward cuts (Fig. 5): During a rapid upward cut, the upper gamma ray value changes first, followed quickly by the lower gamma ray value exhibiting the same trend. The near-borehole averaged gamma ray value

also changes accordingly. Subsequently, the two curves of upper and lower gamma rays intersect, completing a full rapid upward cut process, indicating that the drill bit has rapidly cut upward from the current coal seam into the overlying coal seam. The rapid downward cut follows the same principle, where the drill bit rapidly cuts downward into the underlying coal seam. These rapid upward and downward cut phenomena indicate that the current wellbore inclination angle at the bottom deviates significantly from the actual formation attitude. It is necessary to analyze the drill bit’s position within the coal seam to determine the risk of exiting at the top or bottom and to promptly adjust the inclination by decreasing or increasing the angle accordingly.

Slow upward cut and slow downward cut: During a slow upward cut, the upper gamma ray changes first, and the lower gamma ray follows slowly with the same trend after the drill bit advances a certain distance. The near-borehole averaged gamma ray also slowly changes with the same trend. Eventually, the two curves of the upper and lower gamma rays intersect, completing one full slow upward cut process. The drill bit gradually cuts upward from the current coal seam into the upper coal seam (Fig. 6a). The principle of the slow downward cut is similar, where the drill bit slowly cuts downward from the current coal seam into the lower coal seam. These slow upward and downward cut phenomena indicate that the angle difference between the current wellbore inclination and the actual formation dip is small. Based on the drill bit’s position within the coal seam, decisions can be made whether to reduce or increase the inclination.

Incomplete layering (uncut): During incomplete downward cutting, the lower gamma ray changes first, while the upper gamma ray follows with a smaller change in trend and magnitude. Although the near-borehole averaged gamma ray shows a similar trend, the upper and lower gamma ray curves never intersect. This phenomenon is called incomplete

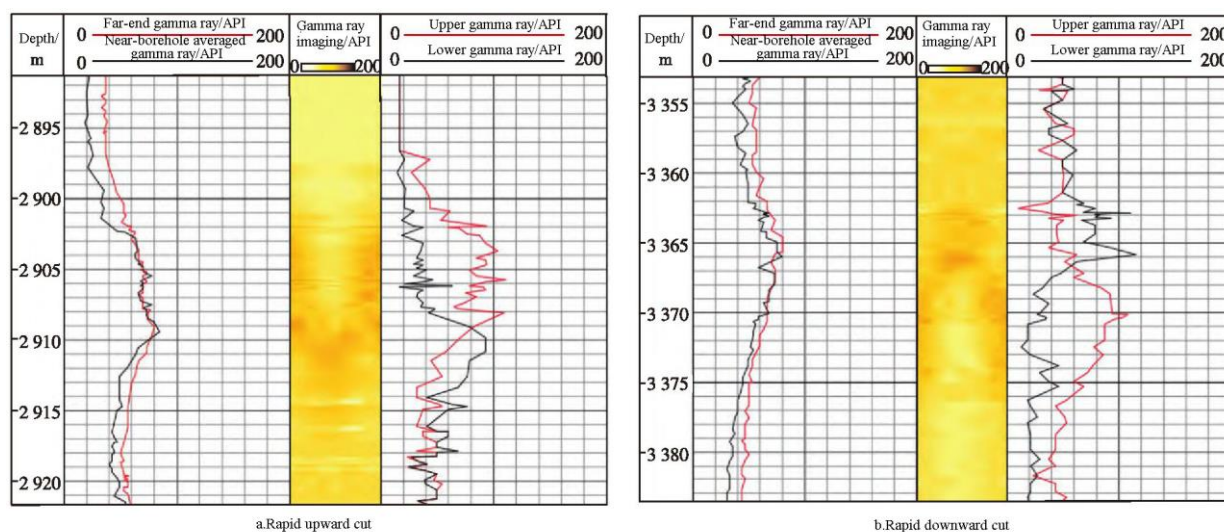


Fig. 5 Schematic diagram of rapid up-cutting and down-cutting using near-bit orientation gamma imaging

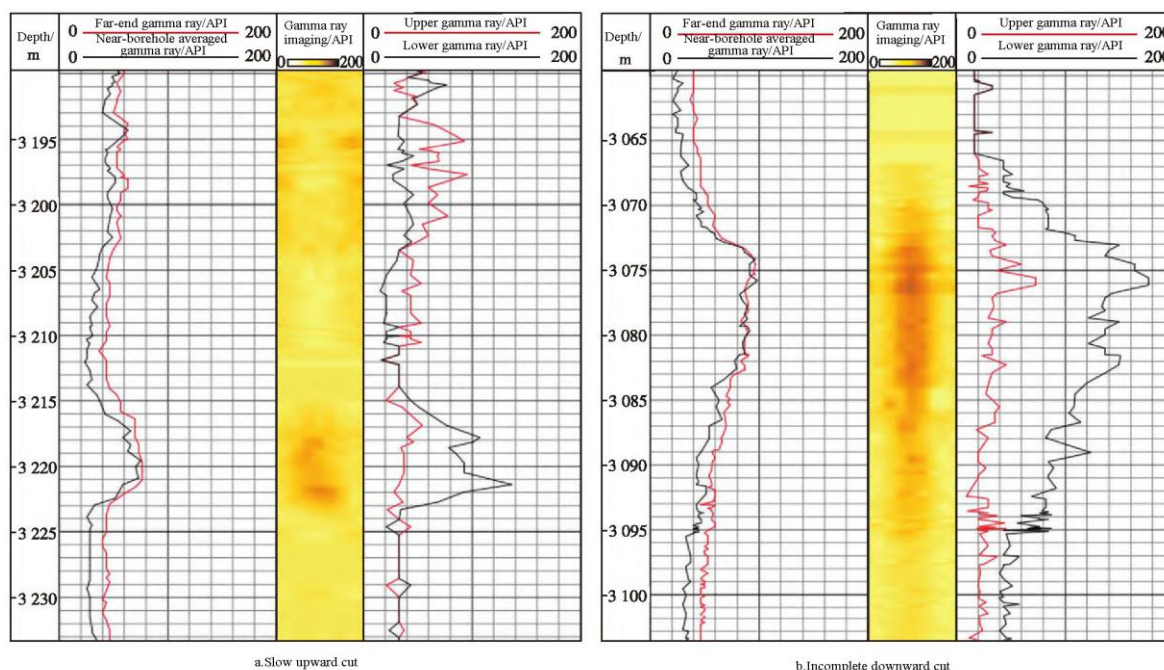


Fig. 6 Schematic diagram of slow up-cutting and unsuccessful down-cutting using near-bit orientation gamma imaging

downward cutting (Fig. 6b). The principle for incomplete upward cutting is similar, where the drill bit remains drilling within the original coal seam. Incomplete layering indicates that the current wellbore inclination is basically consistent with the actual formation dip. The upper gamma ray (or lower gamma ray) reaches the high gamma ray boundary interface, but the lower gamma ray (or upper gamma ray) only slightly touches this interface. The entire drill bit has not fully crossed this boundary and slowly returns to the original coal seam. Incomplete layering is an unfavorable interference to geological steering during drilling, but it is a relatively clear and favorable indicator for predicting formation dip.

2.5.3 Imaging brightness characteristics

During coal seam drilling, the smaller the gamma ray value, the purer the coal seam and the stronger the imaging

brightness (Fig. 7a). When the gamma ray value increases significantly, the imaging brightness correspondingly darkens markedly (Fig. 7b), indicating an increased clay content in the bottom-hole rock, such as encountering partings or even drilling into mudstone. When the magnitude and trend of the upper and lower gamma ray values are basically consistent, the drill bit is not necessarily drilling parallel to the bedding plane within the coal seam. There may be relatively strong lateral and vertical homogeneity in the local coal seam, resulting in little change in upper and lower gamma rays, while the drill bit may still be moving upward or downward within the coal seam. This phenomenon can cause some interference in geological steering judgments.

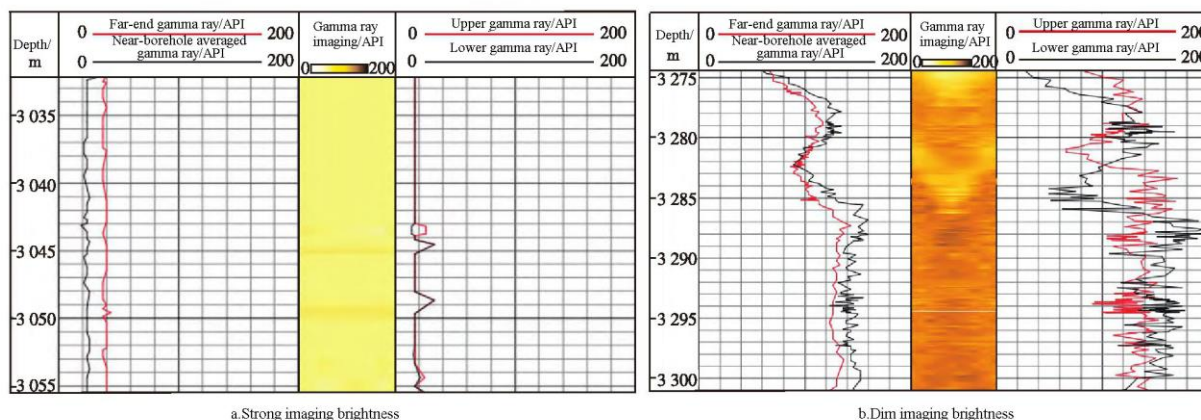


Fig. 7 Schematic diagram of brightness display using near-bit orientation gamma imaging

2.6 Control of drilling engineering parameters

Coal rock is brittle and soft, prone to collapse, making casing running and cementing difficult, which often leads to engineering challenges such as failure to set casing properly and loss of the horizontal section. During geological steering, strict adherence to dog leg severity (DLS) standards is required both in the build-up section and the horizontal section: the build-up section DLS should be $\leq 6\text{ }^{\circ}/30\text{ m}$, the hold section DLS $\leq 3\text{ }^{\circ}/30\text{ m}$, the formation probing section DLS $\leq 5\text{ }^{\circ}/30\text{ m}$, and the horizontal section DLS $\leq 3\text{ }^{\circ}/30\text{ m}$. Especially when adjusting the well trajectory in the horizontal section, within geological requirements, well inclination should be adjusted mainly by controlling dog leg severity, typically less than $1.5\text{ }^{\circ}/30\text{ m}$. To ensure smooth wellbore trajectory, adjustments should be limited to 3–5 consecutive single stands, followed by holding inclination for 1–2 stands before making further adjustments. This approach helps save drilling time in a single run and lays a solid foundation for subsequent casing running and cementing operations.

Compound drilling progresses faster than directional drilling and produces a smoother wellbore trajectory. Therefore, it is possible to explore the patterns of wellbore inclination changes during compound drilling through different lithologies such as coal seams, mudstone, sandstone, and limestone. The goal is to use compound drilling to replace directional drilling for well inclination adjustments, thereby improving drilling efficiency. During most horizontal section drilling, the drill bit tends to reduce inclination while compound drilling within the coal seam. If the later geological objective requires a decrease in inclination, this can be achieved through compound drilling without the need for additional directional drilling to adjust the wellbore inclination.

2.7 Application example of geological steering

Well SM-X-H7 is a pilot coalbed methane test well in this block. The adjacent well's 8th coal seam is relatively thick (approximately 9 m) with high total hydrocarbon gas readings ranging from 85.00% to 99.99%, indicating significant potential for well placement. However, the structural relief in the horizontal section deployment area of this well is highly variable, with a local maximum dip angle of about 3° , posing considerable challenges for achieving a high coal seam drilling encounter rate and smooth drilling and completion of the horizontal well (Fig. 8).

The adjacent 8th coal seam contains four sets of sub-layers, with gamma ray values ranging from 30 to 70 API. A prominent marker layer of about 0.5 m thickness with gamma ray values between 70 and 135 API is developed in the middle as a key reference layer. By applying the integrated geological steering technology described above, real-time decision-making was conducted on site, ensuring rapid drilling and completion. The actual drilled coal seam

horizontal section reached 1 634 m, with a coal seam encounter rate of 100% and an average total hydrocarbon measurement of 93.5%, reflecting excellent drilling results. During drilling, five sets of marker layers (gangue) were encountered, and timely inclination adjustments were made to guide the drill bit into the coal sub-layers above the gangue, ensuring the well trajectory mostly stayed within the upper half of the coal seam. Additionally, careful control of dog leg severity and compound drilling trends contributed to a smooth wellbore, which facilitated subsequent casing and cementing operations for successful completion (Fig. 8).

Comparative analysis between the actual drilled well trajectory and 3D seismic inversion characterization of coal seam roof and floor shows that while 3D seismic accurately predicted the overall structural trend, its prediction accuracy was poorer in the mid and late drilling stages of this well. Ultimately, real-time steering using the near-bit azimuth gamma tool prevented top or bottom exit incidents (Fig. 8).

3 Implementation progress

Since the second half of 2022, the SM X Block of Shenmu Gas Field has been conducting risk exploration in the deep coalbed methane domain. To date, multiple risk exploration, preliminary exploration, pilot test, and evaluation wells have been implemented, all adopting horizontal well designs. Three exploration wells have been put into production and have achieved good production results.

3.1 Drilling encounter situation

At the end of May 2024, 14 horizontal wells targeting the 8th coal seam of the Benxi Formation have been drilled in SM X Block, including 1 risk exploration well, 2 preliminary exploration wells, 8 pilot test wells, and 3 evaluation wells. The average horizontal section length of these 14 wells is 1 432.6 m, with an average coal seam length of 1 346.6 m, and an average coal seam encounter rate of 94.0%, which is relatively high. The average gas-measured total hydrocarbons for these wells are 81.0%, reflecting the good gas content characteristics of the 8th coal seam in this block (Table 1).

3.2 Production situation

As of the end of May 2024, three horizontal wells targeting the 8th coal seam of the Benxi Formation in SM X Block have been put into production, including the risk exploration well SM-X-H1 and the preliminary exploration wells SM-X-H2 and SM-X-H3 (see Table 2). The current daily gas production of these three wells is $16.43 \times 10^4\text{ m}^3$ with a cumulative production of $5\,829.17 \times 10^4\text{ m}^3$. The casing pressure of wells SM-X-H2 and SM-X-H3 remains above 5 MPa with a low pressure decline rate, indicating strong production stability. Overall, the production performance of the three producing wells is good, demonstrating significant development potential for deep coalbed methane in this block.

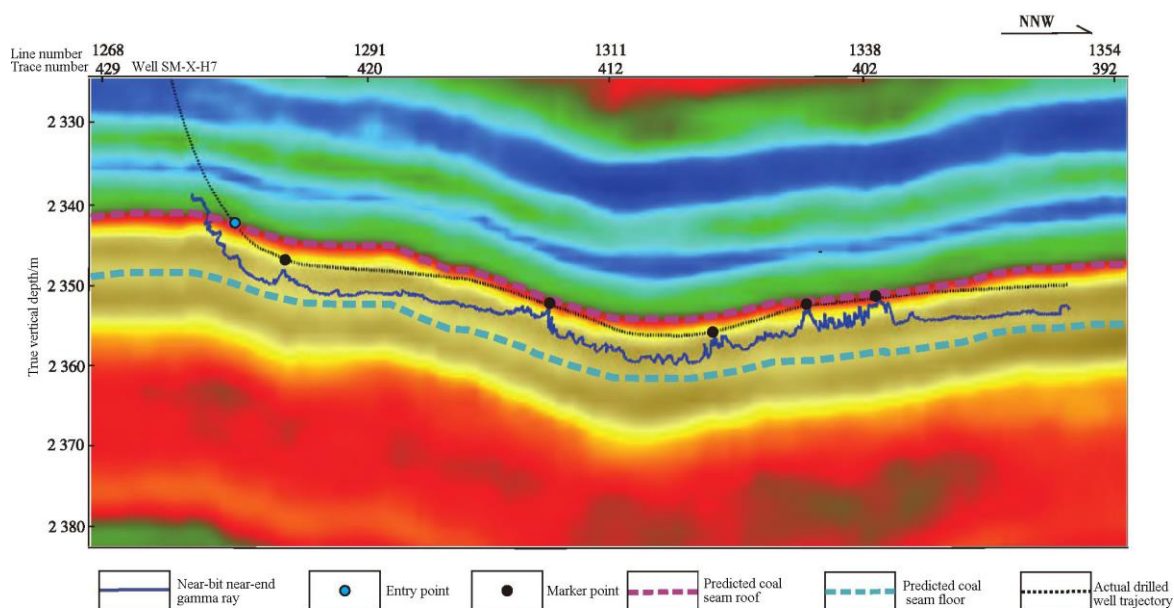


Fig. 8 Schematic diagram of actual drilled trajectory of well SM-X-H7 in block X of Shenmu gas field in Ordos Basin

Table 1 Statistical summary of drilling encounters for deep coalbed methane horizontal wells in block X of Shenmu gas field

Well type	Stratum level	Well category	Well number	Horizontal section length/m	Coal seam length/m	Probability of penetration of coal seam/%	Average gas-measured total hydrocarbons/%
Horizontal well	8th coal seam of Benxi Formation	Risk exploration well	SM-X-H1	2 211	1 556	70.4	65.1
		Preliminary exploration well	SM-X-H2	1 273	1 251	98.3	75.1
			SM-X-H3	1 264	1 216	96.2	88.6
			SM-X-H4	1 574	1 574	100.0	79.3
		Pilot test well	SM-X-H5	1 482	1 307	88.2	72.2
			SM-X-H6	1 043	974	93.4	89.9
			SM-X-H7	1 634	1 634	100.0	93.5
			SM-X-H8	1 609	1 603	99.6	70.6
			SM-X-H9	1 550	1 550	100.0	75.8
			SM-X-H10	1 514	1 462	96.6	89.9
			SM-X-H11	1 430	1 376	96.2	85.1
		Evaluation well	SM-X-H12	1 243	1 144	92.0	90.5
			SM-X-H13	1 253	1 253	100.0	68.6
			SM-X-H14	977	952	97.4	90.2
		Average		1 433	1 347	94.0	81.0

Table 2 Statistical summary of production performance of deep coalbed methane horizontal wells in block X of Shenmu gas field

Well number	Production date	Vitrinite reflectance/%	Carbonaceous layer length/m	Test Production gas Volume/10 ⁴ m ³	Current casing pressure/MPa	Current gas production/10 ⁴ m ³	Current water production/m ³	Cumulative gas production/10 ⁴ m ³
SM-X-H1	2022-11	1.8	1 556	8.16	1.72	2.22	3.5	1 879.55
SM-X-H2	2023-04	1.8	1 251	12.47	5.42	6.17	8.3	2 452.29
SM-X-H3	2023-10	1.6	1 216	6.67	5.06	8.04	13.0	1 497.33
Total						16.43	24.8	5 829.17

4 Understanding and discussions

4.1 Horizontal well deployment

The Benxi Formation 8th coal seam in the SM-X block of Shenmu Gas Field exhibits a structural trend of lower

elevation in the west and higher in the east, with relatively gentle north-south variation. Generally, coal seams in higher structural positions have better gas content. The Ro value gradually increases from north to south; the higher the Ro value, the greater the coal maturity and stronger the hydrocarbon generation capacity. The coal seam thickness is greater in the northern and southern parts and thinner in the

central part; greater thickness corresponds to larger geological reserves. Considering factors such as structure, R_o value, and coal seam thickness, deep coalbed methane horizontal wells should preferably be deployed in areas with higher structural positions, higher R_o values, and thicker coal seams.

Optimized deployment of horizontal wells is a prerequisite for geological steering in horizontal wells. For deep coalbed methane horizontal wells, accurate structural understanding is the most important basis for deployment. From the structural perspective alone, priority should be given to areas with relatively gentle structures and upward-dipping strata for focused deployment. This is beneficial for improving probability of penetration, ensuring smooth well trajectories, and facilitating later water drainage and gas production. Deployment should avoid areas with highly variable strata orientations and locally steep dips.

4.2 Geological steering of horizontal wells

The geological steering technology, which integrates multidisciplinary knowledge from geology, seismic, logging, well logging, and drilling engineering, has currently achieved good coal seam encounter results, with the near-bit directional gamma imaging steering tool playing a core role. However, the near-bit steering tool is expensive, charged daily, and due to the fast drilling in coal seams and short collapse cycles, an on-site steering team must make timely decisions around the clock. Although the exploration and development results are significant, they also require a large investment of manpower, materials, and financial resources.

Thoughts on future geological steering for deep coalbed methane: ① It may be appropriate to moderately lower the requirement for coal seam encounter rate. According to current understanding, when the horizontal well trajectory is within the upper part of the coal seam, subsequent fracturing and production results are better. Therefore, efforts should be made to keep the drill bit running near the top of the coal seam. Even if some encounter rate is sacrificed due to exiting the seam, sufficient fracturing of the out-of-seam section can be achieved by adjusting the perforation method. ② It is advisable to appropriately change the steering mode. The current steering mode imposes significant operational costs and is unsuitable for large-scale promotion. Exploration of remote online steering and using conventional LWD steering tools to replace near-bit steering tools is worth considering. However, this mode requires the development of remote steering technology and imposes higher requirements on the accuracy of structural characterization of the 8th coal seam.

5 Conclusions

1) The 8th coal seam of the deep Benxi Formation in the Shenmu gas field Block X is relatively thick, with highly variable lithologic combinations of the roof and floor along

the vertical direction, as well as complex small-layer combinations within the coal seam. The lateral variation in the roof structure is also rapid in some areas. The coal seam exhibits fast drilling rates and is prone to collapse, imposing strict requirements on drilling and completion cycles. It is difficult to accurately determine the real-time position of the horizontal well during drilling using a single discipline or technology alone, making it challenging to achieve both high probability of penetration and efficient drilling and completion. Geological steering is therefore highly difficult.

2) By deploying well locations based on fine seismic structural interpretation, and using near-bit azimuthal gamma ray imaging analysis as the core guiding technology—combined with integrated data from geology, logging, mud logging, and drilling parameters—a comprehensive horizontal well geological steering technology system has been established. This approach has achieved remarkable results in guiding deep coalbed methane horizontal wells in Block X of the Shenmu gas field and provides valuable reference and applicability for similar reservoirs in the Ordos Basin.

3) The current geological steering technologies for deep coalbed methane incur high human resource and financial costs, limiting their sustainability. In the future, it is necessary to further optimize and improve steering technologies to balance achieving geological targets with reducing manpower and financial input, ultimately enabling the efficient development of deep coalbed methane in the Block X of the Shenmu gas field.

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