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Novel Understandings and Applications of Azimuthal Gamma-Ray Logging of Horizontal Wells in Sedimentary Sandstones with Grain Sequence Features

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Abstract

The theory and practices of logging facies have confirmed that the grain sequence in sedimentary sandstones is closely related to the amplitude and morphological characteristics of vertical well logs. However, the corresponding studies of logging responses of horizontal wells in sedimentary sandstones with grain sequences have not been publicly reported, especially lacking the corresponding response characteristics of fundamental gamma-ray logging. This situation leads to difficulties in geosteering and reservoir evaluation of horizontal wells. To address it, the grain sequence characteristics of traditional sedimentary sandstones are systematically reviewed. Combining geological features of sandstones and the geometric characteristics of grain size logs, the core features of different grain sequences are extracted. In sandstone reservoirs, semi-quantitative ideal grain sequence models, i.e., cylindrical-shaped, bell-shaped, funnel-shaped and egg-shaped grain sequences, are proposed, and the corresponding formation models with horizontal wells are constructed. Then, the Monte Carlo method is employed to establish the forward model of azimuthal gamma-ray logging (AGR) of horizontal wells in sandstones with different grain sequences. The AGR responses of these formation models are calculated. The results show that the AGR response of the formation model with cylindrical-shaped grain sequence is consistent with that of traditional three-formation models. However, the AGR responses of the formation models with bell-shaped, funnel-shaped and egg-shaped grain sequences are characterized by "double left-handled spoons", "double right-handled spoons" and "double inverted isosceles triangles", respectively, which are significantly different from that of traditional three-formation models. Based on the geological and engineering characteristics of horizontal well drillings, eight different basic spatial relationships between horizontal wells and formations are systematically reviewed. By combining the forward models, the AGR response characteristics and modes of formation models with different grain sequences under the eight spatial relationships are established and abstracted through geometric morphology. After clarifying the application scheme, the research understandings are applied in two typical horizontal wells with different grain 2 sequences to verify the reliability and convenience of the above response characteristics and modes. In addition, the adaptability, advantages, disadvantages and limitations of this study are discussed in detail. The study can provide fundamental understandings and supports for geosteering and reservoir evaluation of horizontal wells in different grain sequence sandstones.

Full Text

Preamble

Novel Response Understandings and Applications of Azimuthal Gamma-Ray Logging of Horizontal Wells in Sedimentary Sandstones with Grain Sequence Features

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Abstract

Logging facies theory and practice have established that grain sequences in sedimentary sandstones are closely related to the amplitude and morphological characteristics of vertical well logs. However, corresponding studies on logging responses of horizontal wells in sedimentary sandstones with grain sequences have not been publicly reported, particularly lacking fundamental research on azimuthal gamma-ray logging (AGR) response characteristics. This gap creates significant challenges for geosteering and reservoir evaluation in horizontal wells. To address this issue, we systematically characterize the grain sequence features of traditional sedimentary sandstones and extract the core attributes of different grain sequences by integrating geological characteristics of sandstones with geometric features of grain size logs.

For sandstone reservoirs, we propose semi-quantitative ideal grain sequence models—cylindrical-shaped, bell-shaped, funnel-shaped, and egg-shaped grain sequences—and construct corresponding formation models with horizontal wells. The Monte Carlo method is then employed to establish a forward model for azimuthal gamma-ray logging of horizontal wells in sandstones with different grain sequences, and the AGR responses of these formation models are calculated. The results demonstrate that the AGR response for the cylindrical-shaped grain sequence formation model is consistent with traditional three-layer formation models. In contrast, the AGR responses for bell-shaped, funnel-shaped, and egg-shaped grain sequence formation models exhibit characteristic patterns of "double left-handed spoons," "double right-handed spoons," and "double inverted isosceles triangles," respectively, which differ significantly from traditional three-layer models.

Based on the geological and engineering characteristics of horizontal well drilling, we identify eight fundamental spatial relationships between horizontal wells and formations. Combining these with forward modeling results, we establish and abstract the AGR response characteristics and modes for formation models with different grain sequences under these eight spatial relationships through geometric morphology. After clarifying the application scheme, we validate the reliability and convenience of these response characteristics and modes using two typical horizontal wells with different grain sequences. Additionally, we discuss in detail the adaptability, advantages, disadvantages, and limitations of this study. This research provides fundamental understanding and support for geosteering and reservoir evaluation of horizontal wells in sandstones with varying grain sequences.

Keywords: Grain sequence; Azimuthal gamma-ray logging; Horizontal well; Logging-while-drilling; Sedimentary sandstones

Highlights:
- AGR forward models for horizontal wells in four ideal grain sequence sandstones are established.
- AGR response characteristics of horizontal wells in different grain sequence sandstones are clarified.
- AGR response modes for eight spatial relationships between formations and horizontal wells are established.

1. Introduction

Research and practice demonstrate that sedimentary rocks commonly exhibit vertical sequence characteristics of grain size (also known as grain sequence order or rhythm), such as cylindrical-shaped, bell-shaped, funnel-shaped, and egg-shaped grain orders. These patterns typically reflect different paleoclimatic conditions, depositional environments, depositional processes, and other sedimentary features (Serra, 1992; Wang and Guo, 2000). Geosteering with logging-while-drilling (LWD) represents one of the key methods for ensuring horizontal well productivity (Meehan, 1994; Meador, 2009). Among various LWD logging methods, azimuthal gamma-ray logging (AGR) is widely employed in geosteering and reservoir evaluation as a fundamental technique (Martin et al., 2013; Qin et al., 2017; Zhu et al., 2023). Numerous scholars have conducted studies related to AGR logging evaluation and geosteering in sedimentary rocks with different grain sequences.

Some researchers have investigated sedimentary rock particles and logging facies. Serra (1992) initially established a framework correlating logging responses with grain sequence characteristics of sedimentary rocks, forming the foundation of logging facies theory. Wang and Guo (2000) further refined the correlation system between sedimentary reservoirs and logs, enriching the logging facies theory. Building upon these theoretical foundations, subsequent researchers conducted extensive studies on grain sequences and formation sequences in sedimentary rocks. Bauer et al. (2015) processed and classified nuclear magnetic resonance logs using self-organizing maps to analyze lithological grain characteristics, pore size features, and lithological controls on gas hydrate saturation. Lai et al. (2017) applied logging facies theory to conduct detailed sedimentary characteristic studies of braided deltas in the Upper Triassic Xujiahe Formation in the central Sichuan Basin, China. Clift (2019) combined coring and conductivity logging to determine lithology and grain size characteristics in different parts of a sand dam system on the Mississippi River. Ashraf (2019) analyzed electrofacies characteristics of sandstone reservoirs in the Sawan Gas Field, revealing funnel, bell, and cylindrical trends, and employed logging facies theory with 3D seismic data to predict sweet spot areas.

Ogbe (2021) utilized logging facies theory to study and analyze logging probability maps, facies sequences, and heterogeneity characteristics of sandstone reservoirs in the onshore Otovwe Field. Souza et al. (2023) analyzed depositional facies of tidal point sand bars and their associated hydrodynamic control processes using millimetric logging of 31 cores from the Georgia coastal plain, USA. Other scholars have focused on gamma-ray logging research. Huang (1985) derived the gamma-ray integral formula along the well axis for homogeneous formations in vertical wells based on gamma-ray propagation theory. Yin et al. (2008) employed the non-uniform block accumulation method to simulate logging responses of AGR instruments with a single probe in 2D parallel formations. Researchers have also introduced AGR geosteering applications in unconventional reservoirs such as shale gas/oil, coalbed methane, thin layers, and low-resistivity contrast reservoirs, where the confidence level of resistivity methods in geosteering has declined significantly (Pitcher et al., 2009; Harris et al., 2009; Wheeler et al., 2012; Martin et al., 2013). Using the integral method, Shao et al. (2013) developed a fast forward model to study responses of conventional LWD GR in 2D space. Yuan et al. (2015) applied the Monte Carlo method to simulate upper and lower gamma-ray logs when the AGR tool traverses 2D parallel formations and estimated formation dip angles. Wang (2016) developed a mining AGR instrument and tested its 2D geosteering effectiveness in coal seams. Wang et al. (2020) studied forward modeling and inversion of AGR in horizontal wells and its geosteering applications in 2D parallel formations. Zhang et al. (2021) developed an automated interpretation method for subsurface structure in horizontal wells using GR logs, applicable to both post-drill structural interpretation and real-time geosteering in 2D parallel formations. Based on the Monte Carlo method, Qin et al. (2021) proposed a qualitative characteristic scheme for AGR in horizontal wells and a fast prediction method for the distance between well paths and formation boundaries.

Both logging facies and AGR studies have yielded valuable insights. However, previous research on horizontal well logging responses has generally been limited to cylindrical-shaped sequence formations or their interlayer models, such as uniform layered formations and vertical transversely isotropic (VTI) formations. Studies on well logging responses of horizontal wells in sedimentary sandstones with different grain sequences remain unreported, particularly regarding commonly used AGR responses, creating challenges for geosteering and reservoir evaluation in these sedimentary sandstones. This study addresses this gap by systematically characterizing grain sequence features in sedimentary sandstones and corresponding logging facies, constructing formation models with different grain sequences and AGR forward models for horizontal wells. We simulate and analyze AGR response characteristics in sandstones with different grain sequences and establish AGR response modes under various spatial relationships between horizontal wells and formations for different grain sequence conditions. Applications in two horizontal wells with different grain sequences demonstrate the reliability of these AGR response characteristics and modes. Additionally, this work discusses and concludes application conditions, influencing factors, and other issues in detail.

2.1. Sedimentary Characteristics of Grain Sequence

During sedimentary processes, sandstones typically form longitudinal ordered arrangements of particles, commonly referred to as grain sequences or grain size rhythms. Generally, grain sequences can be divided into four main categories: cylindrical-shaped, bell-shaped, funnel-shaped, and egg-shaped grain sequences (Fig. 1 [Figure 1: see original paper]). Cylindrical-shaped sequences form under stable hydrodynamic conditions when water body transport capacity remains unchanged and sediment grains are uniform (Fig. 1a). Bell-shaped grain sequences develop when hydrodynamic conditions change from strong to weak, water body transport capacity decreases, and sediment grains become finer from bottom to top (Fig. 1b). Funnel-shaped grain sequences form when hydrodynamic conditions change from weak to strong, water body transport capacity increases, and grains become coarser from bottom to top (Fig. 1c). Egg-shaped grain sequences develop under unstable hydrodynamic conditions that first strengthen then weaken, causing water body transport capacity to first increase then decrease, resulting in sediment grains with coarse middle sections and fine top and bottom sections (Fig. 1d).

Since vertical wells approximate perpendicularity to sedimentary formations, different grain sequence characteristics produce distinct logging response features. Using logging responses to study grain sequence characteristics assists in oil and gas exploration and development. Additionally, based on contact relationships between upper and lower formations at boundaries, sedimentary rocks can be classified as abrupt or gradual grain sequences. Certain logs correlate closely with grain sequence characteristics—for instance, as sedimentary rock grain size increases, its GR value decreases. These characteristics form the research field of logging facies or logging geology (Serra, 1992; Wang, 2000). The four grain sequence categories are illustrated in Fig. 2 [Figure 2: see original paper], where smooth logs typically indicate uniform grain size variation, while jagged curves represent non-uniform variation.

2.2. Ideal Sedimentary Grain Sequences and Log Facies

To establish formation models of sedimentary rocks with different grain sequences, we abstract and summarize ideal sediment grain sequence trends by highlighting the main characteristics of each category (Fig. 3 [Figure 3: see original paper]): ideal cylindrical-shaped, bell-shaped, funnel-shaped, and egg-shaped grain sequences. Based on logging facies theory (Serra, 1992; Wang, 2000), the corresponding GR log morphologies are shown in Fig. 3. The grain sequence characteristics of sandstones correspond to the aforementioned sedimentary conditions. In cylindrical-shaped grain sequences (Fig. 3a), the GR curve exhibits uniformly low values in the main body, corresponding to the cylindrical-shaped grain sequence characteristic. In bell-shaped grain sequences (Fig. 3b), the GR log shows high values at the bottom with uniform upward decrease, matching the bell shape. In funnel-shaped grain sequences (Fig. 3c), the GR curve displays high values at the top with uniform downward decrease, corresponding to the funnel shape. In egg-shaped grain sequences (Fig. 3d), the GR log shows high values in the middle with uniform decreases upward and downward, matching the egg shape. Thus, GR curve characteristics can be formed corresponding to grain sequence characteristics, as GR values increase when grain size in the sedimentary grain sequence decreases.

To investigate correlations between grain size and GR values, we collected median grain size and corresponding GR data from three sandstone reservoirs in different basins (Fig. 4 [Figure 4: see original paper]). The three data types originate from the Quantou 4th Formation in the Songliao Basin, a reservoir in the Beibu Gulf of the South China Sea, and the Chang 8th Formation in the Ordos Basin, respectively. In different sedimentary basins, as median grain size increases, GR values approximate a linear decrease with varying slopes, indicating an approximately inverse relationship between the two parameters. Therefore, field data from different reservoirs support and demonstrate the feasibility of the GR response model for ideal grain sequence formations (Fig. 3), laying the foundation for subsequent logging forward modeling studies in different grain sequence sandstones.

3.1. Formation Model of Grain Sequences

Combining actual engineering conditions of horizontal wells in sandstones, we constructed formation models with horizontal wells and different sedimentary grain sequences (Fig. 5 [Figure 5: see original paper]). To simplify the study, the well deviation of horizontal wells is set to 85°, meaning the angle between the well path and horizontal formation is 5°. The upper and lower formations are identical, homogeneous, isotropic non-reservoir surrounding formations (mudstone) with a GR value of 100 API and thickness of 3.6 m. The middle target formation consists of hydrocarbon-bearing sandstones with low GR values and a thickness of 6 m.

The GR characteristics of target formations with different grain sequences vary (Fig. 5). In Fig. 5a, the target formation has a cylindrical-shaped grain sequence, similar to traditional uniform layered media, with uniform, isotropic grain size and a preset GR value of 0 API. For other grain sequences, the target formation is divided into five small layers (n = 5). In Fig. 5b, the middle target formation exhibits a bell-shaped grain sequence. To reflect grain sequence variation characteristics, the middle formation is divided into five parallel, equal-thickness layers of 1.2 m each. Based on logging facies theory, the GR values of the five layers from bottom to top are sequentially preset as 0 API, 20 API, 40 API, 60 API, and 80 API to simulate the depositional order from coarse to fine grains. In Fig. 5c, the middle formation shows a funnel-shaped grain sequence. Similarly, the middle formation is divided into five equal layers, with GR values from bottom to top preset as 80 API, 60 API, 40 API, 20 API, and 0 API. In Fig. 5d, the middle formation displays an egg-shaped grain sequence, with GR values of the five layers preset as 66 API, 33 API, 0 API, 33 API, and 66 API.

3.2. AGR Response Simulation

Based on AGR method characteristics (Yuan et al., 2015; Yu et al., 2021; Qin et al., 2021), we established an AGR instrument model in this study (Fig. 6 [Figure 6: see original paper]). Four probes—marked as up (GRU), bottom (GRB), left (GRL), and right (GRR)—are installed in four U-shaped slots and evenly positioned around the instrument. The U-shaped slots form a shielding structure that enables each probe to measure information with a specific orientation. GRU, GRB, GRL, and GRR represent the top, bottom, left, and right azimuthal gamma-ray logging curves, respectively, with the yellow areas indicating schematic detection ranges. The blue hollow cylinder along the axis is designed for drilling fluid circulation. In geosteering and logging evaluation, GRU and GRB are commonly used, while GRL and GRR serve as supplementary information.

To simplify the research process and improve simulation efficiency while considering AGR investigation depth, the simulation model details are shown in Fig. 7a [Figure 7: see original paper]. The 3D two-formation module measures 200 cm × 200 cm × 200 cm. The borehole diameter is 21.59 cm (8.5 in), filled with clean water. The AGR instrument has a diameter of 17.145 cm and length of 20 cm, with a drilling fluid channel of 5.08 cm diameter along its axial line (Fig. 7b). The probes use NaI scintillation crystals measuring 3.05 cm in diameter and 15 cm in length. The instrument body is made of pure lead. The K-40 content of formations is adjusted to achieve different GR values and simulate reservoirs or non-reservoirs.

Based on the Monte Carlo method, the model in Fig. 7 serves as a simulation module for AGR responses. Using the Monte Carlo N-Particle Transport (MCNP) Code (Briesmeister, 2003), we set the counting interruption threshold to 10^7 iterations with an error requirement of less than 5%, enabling calculation of GRU and GRB responses in the formation model.

To test the forward method' s simulation effectiveness, we selected the fast integration method of Qin et al. (2017). Based on the single-boundary formation model (Fig. 7a), we compared simulation results from both methods in Fig. 8 [Figure 8: see original paper]. The suffixes FIM and MCNP represent AGR responses calculated by the fast integration method and Monte Carlo method, respectively. Comparing 17 calculation points from both methods reveals good agreement between GRU and GRB results, with absolute errors of approximately 1.35 API and 1.17 API, respectively. Considering Monte Carlo method randomness and testing errors, we optimized the forward method by implementing double-encrypted simulation points near boundaries and using the average of five Monte Carlo results as the final forward modeling result. After optimization, this forward modeling module can be used for response simulation (Yuan et al., 2015; Qin et al., 2021).

4.1. AGR Response Characteristics in Different Grain Sequences

Based on the formation models (Fig. 5) and forward module (Fig. 7), we simulated AGR responses as horizontal wells pass through reservoirs with different grain sequences from top to bottom. When the instrument traverses the cylindrical-shaped grain sequence target formation (Fig. 9a [Figure 9: see original paper]), GRB first drops steeply to reservoir characteristics (low GR values), followed by GRU. When the instrument is positioned in the middle of the target formation, both GRB and GRU show low values. As it approaches the bottom boundary, GRB first rises to non-reservoir characteristics (high GR values), followed by GRU. The entire curve pattern exhibits a translational "double inverted isosceles trapezoids" shape.

When the instrument passes through the bell-shaped grain sequence target formation (Fig. 9b), AGR responses differ from Fig. 9a. GRB and GRU first decrease to reservoir characteristics then increase to non-reservoir characteristics, with the entire curve pattern showing a translational "double left-handed spoons" shape. For the funnel-shaped grain sequence target formation (Fig. 9c), GRB and GRU responses also differ from the previous cases, exhibiting a translational "double right-handed spoons" shape. For the egg-shaped grain sequence target formation (Fig. 9d), GRB and GRU responses differ from all previous cases, showing a translational "double inverted isosceles triangles" shape. These results demonstrate that AGR response patterns vary significantly when horizontal wells traverse reservoirs with different grain sequences. It should be noted that describing these morphologies as specific shapes facilitates geosteering applications, though the actual curves are smooth.

4.2. AGR Response Modes of Different Spatial Relationships

Due to complex subsurface conditions, numerous spatial relationships exist between horizontal wells and formations. Additionally, geological structures such as lenses, pinchouts, and faults may be encountered. Based on the formation models and simulation modules, we identified and summarized eight common fundamental spatial relationships and corresponding AGR response modes for different grain sequences (cylindrical-shaped, bell-shaped, funnel-shaped, and egg-shaped) in Table 1 . The logging response characteristics in relationship (7) and the pinchout of (8) are similar. These response modes aim to determine whether and how the well passes through formation boundaries (with different grain sequences) or geological structure bodies, and can also qualitatively describe AGR response characteristics.

In Table 1, spatial relationships (1), (2), and (3) show the horizontal well passing from surrounding formation A into the target formation and returning to formation A. The AGR (GRU and GRB) response trends are similar, presenting "large and small inverted isosceles trapezoids" shapes. Due to combined influences of different spatial relationships and grain sequences, GRU and GRB amplitude and separation characteristics vary across grain sequences, with relationship (3) even exhibiting complex W-shaped features.

Spatial relationships (4), (5), and (6) show the well path passing through formation A, entering and remaining in the target formation. The AGR response trends display complex "double Z-shaped" features. Similarly, different amplitudes and separations result from joint influences of spatial relationships and grain sequences, particularly in relationship (6) where logs of different shapes can only be approximately Z-shaped overall.

Spatial relationships (7) and (8) pinchout show the horizontal well passing through formation A, the target formation, and surrounding formation B or the pinchout. The AGR response trends exhibit translational "double inverted isosceles trapezoids," "double left-handed spoons," "double right-handed spoons," and "double inverted isosceles triangles" shapes, respectively.

Spatial relationship (8) fault shows the well path passing through surrounding formation A, entering the target formation, and encountering a fault. The AGR response trends exhibit complex "large and small trapezoids" features, especially showing a vertical step shape when entering the fault. Overall, different grain sequences and spatial relationships between horizontal wells and formations collectively produce diverse and complex AGR response characteristics and modes.

5.1. Application Scheme

Table 1 presents AGR response characteristics and modes at the horizontal well scale. These can guide horizontal well geosteering. First, relevant geological and seismic data can analyze overall formation distributions. Second, well logs and mud logs from adjacent wells can determine the grain sequence and GR response characteristics of the target formation.

Subsequently, based on AGR response characteristics and modes for different grain sequences (Table 1), horizontal well AGR responses can be predicted, and key information points where the horizontal well trajectory intersects formation boundaries can be identified. Finally, combining these key information points with original formation distribution data enables formation boundary prediction to assist geosteering. The overall application scheme is summarized in Fig. 10 [Figure 10: see original paper].

5.2. Field Applications

Based on the above understanding and application scheme, we processed horizontal wells X (with pilot well X1) and Y (with pilot well Y1), shown in Figs. 11 and 12, respectively. Both target formations are different areas of the Fuyu oil-bearing layer on the Aonan nose structure of the Daqing placanticline in the Songliao Basin, China. The main lithology is siltstone and fine sandstone with an average porosity of 9.5%, and surrounding rock is primarily dark mudstone. The layouts of Figs. 11 and 12 are similar: the left side shows a top view at the top and vertical well X1 logs at the bottom. The first track displays gamma-ray (GR), the second track shows measured depth (MD), and the third track presents deep and shallow laterologs (RD and RS). Compensated neutron porosity (CNL), acoustic travel time (AC), and density (DEN) appear in the fourth track. Horizontal well logs—including GRU, GRB, and caliper (CAL) in the first track, horizontal displacement and measured depth in the second track, propagation resistivities (RP400, RP2M, RA400, and RA2M) in the third track, and porosity logs (DEN, CNL, and AC) in the fourth track—are displayed in the upper area. Well trajectories, formation models, and explanatory diagrams appear in the lower area, with lithology symbols and overall formation model scale shown in the lower right corner. The horizontal and vertical scales are 1:5000 and 1:500, respectively.

In horizontal well X (Fig. 11 [Figure 11: see original paper]), based on prior geological and seismic understanding, the target formation (S1) is thin (approximately 3 m), making AGR more suitable for geosteering than resistivity logs.

According to ideal sedimentary grain sequences (Fig. 3) and GR responses in pilot well X1, S1 is identified as an egg-shaped grain sequence. Using the response characteristics and modes for different grain sequences (Table 1), we analyzed key information points for horizontal well X' s spatial relationships. In Fig. 11, points A, B, and C represent the well trajectory drilling into S1, approaching the upper boundary, and drilling out the bottom boundary, respectively. Section DE is near the bottom boundary. In Figs. 11a1 and 11a2, the enlarged view shows that GRU and GRB logs at point A are similar to those near the upper boundary in Table 5d , corresponding to spatial relationship (5) in egg-shaped grain sequence (d). This indicates the well trajectory encountered the upper boundary of the egg-shaped grain sequence sandstones from the shale layer from top to bottom. At point B in Figs. 11, 11b1, and 11b2, the responses resemble those in Table 4d , indicating the well trajectory is near the upper sandstone boundary. Moderate-amplitude polarization horns in propagation resistivity logs at points A and B confirm this interpretation (Wu et al., 2022; Wang et al., 2023). The GRU and GRB responses at point C in Figs. 11 and 11c1 correspond to those crossing the bottom boundary in Table 7d (Fig. 11c2), showing the well trajectory passing the sandstone bottom boundary, confirmed by low-amplitude polarization horns in propagation resistivities. In section DE of Fig. 11, the responses correspond to those above but near the bottom boundary in Table 6d (Fig. 11d1). The well trajectory re-enters S1 from bottom to top at point D, drills near the bottom boundary, and finally exits at point E. Continuous separation of resistivity logs also confirms the trajectory's proximity to the bottom boundary.

Horizontal well Y and its pilot well Y1 in the Songliao Basin are shown in Fig. 12 [Figure 12: see original paper], along with their well logs. The layout and log types are similar to Fig. 10. Based on geological and seismic data understanding, three hydrocarbon reservoirs (T1, T2, and T3) exist in the 2008–2042 m interval of well Y1. Reservoir T3, the thickest, was designated as the target sandstone for horizontal well Y. According to ideal sedimentary grain sequences and GR logs in pilot well Y1, T3 is identified as a bell-shaped grain sequence. Seismic interpretation shows no faults in this area, with all layers gently sloping southward.

Using response characteristics and modes for different grain sequences (Table 1), we analyzed eight key information points (F, G, H, I, J, K, L, and M in Fig. 12) for spatial relationships between horizontal well Y and formations. In Fig. 12a1, GRU and GRB responses at points F, H, and J are similar to those crossing the upper boundary in Table 7b, corresponding to spatial relationship (7) in bell-shaped grain sequence (b). These response characteristics and modes indicate the horizontal well trajectory drilled downward and intersected the upper boundaries of the three bell-shaped grain sequence sandstones (T1, T2, and T3). Correspondingly, responses at G, I, and M are similar to those crossing the bottom boundary in Table 7b, indicating the well path drilled downward and intersected the bottom boundaries of the bell-shaped grain sequence sandstones. At point L in Figs. 12 and 12b1, GRU and GRB responses correspond to those at point D in Fig. 11, indicating the trajectory returned from the shale layer to T3 from bottom to top. At point K in Fig. 12, GRU and GRB responses are similar to those crossing a microfault in Table 8b , displaying overlapping and steep curve shapes, also demonstrated by the stepwise decrease in resistivity logs. Notably, this microfault was identified by horizontal well logs but could not be detected by prior data, particularly seismic data. The trajectory variation in well deviation shows a process of searching downward for T3 and then moving upward.

Typically, key depth information points of formation boundaries identified by comprehensive logs (CLD) serve as standard boundary depths in the field. Boundary depth ranges (MLD) identified by mud logging during microdrilling can also serve as indicative information, though typically with 1 m resolution. Depth results from these two methods near 13 boundary key points in the two horizontal wells are shown in Table 2 , along with logging depths identified by AGR (ALD). Using CLD as a baseline (value of 0), we analyzed MLD and ALD errors through histogram comparison (Fig. 13 [Figure 13: see original paper]). The ALD identified by the application scheme falls within the MLD range identified during microdrilling. Absolute errors of ALD relative to CLD remain within 0.8 m, with an average absolute error of approximately 0.115 m. The average absolute error of ALD at horizontal well X key points (0.06 m) is better than that at horizontal well Y (0.15 m), while the average absolute error at bottom boundaries (0.06 m) is better than at top boundaries (0.22 m). Additionally, the absolute error at key point K is 0. Considering the well trajectory in the horizontal section is nearly parallel to the formation, this accuracy meets field requirements.

6. Discussions

This study established three-formation models with four ideal grain sequence target formations and horizontal wells, conducting research on AGR forward models, response characteristics and patterns, and geosteering applications. To emphasize the main factors of the four grain sequence types, we assumed smooth grain sequence curves for target formations to avoid additional interference from jagged grain sequence curves on AGR response characteristics. Therefore, the AGR response characteristics (Fig. 9) and patterns (Table 1) in this study are semi-quantitative or qualitative trend insights to some extent. When applied to actual reservoirs, these understandings and schemes are recommended for cases where grain sequences are relatively smooth and formations are relatively stable. For situations where grain sequence curves appear jagged or non-smooth, application should be combined with specific regional conditions.

Additionally, actual data from different basins show varying negative correlations between grain sizes and GR values. Therefore, we recommend clarifying this negative correlation when applying this study' s understandings and scheme in a specific region, then using the methods of this study to establish regional AGR response characteristics and patterns. This approach will yield better results in specific regions.

Analytical and numerical simulation methods are commonly used for AGR forward modeling studies. Analytical methods offer fast calculation speed but poor adaptability to complex formation models, making them suitable for fast calculation and inversion research. Numerical simulation methods such as the Monte Carlo method adapt well to complex formation models but suffer from slow computational speed and result randomness, making them suitable for response characterization, environmental correction, and instrumental characterization research. To avoid Monte Carlo simulation randomness effects, this study employed methods of encrypting simulation points near formation boundaries and averaging multiple simulations to ensure simulation quality. In the formation model, considering forward simulation effectiveness and efficiency, the number of small layers within target formations with different grain sequences was set to five. This number can be adjusted to match different grain sequences, GR gradient features, and regional applications. Additionally, different AGR instruments have different internal structures and detection properties, resulting in different simulated logging responses. In this case, this study' s understandings mainly provide a reference. This study can also provide a research paradigm for establishing response characteristics and patterns of different AGR instruments and conducting specific applications.

After establishing the application scheme for AGR responses and patterns of horizontal wells in sandstone reservoirs with different grain sequences, we analyzed applications in two horizontal wells with different grain sequences in detail. Differences also exist when using vertical well GR curves to determine target formation grain sequences. For example, Fig. 11 shows S1 identified as an egg-shaped grain sequence, where GR logs at the upper boundary in the vertical well are obviously steeper than at the lower boundary. Although not as steep as cylindrical-shaped sequence upper boundaries, this still affects AGR and other logging responses of horizontal wells at both boundaries. For instance, electromagnetic wave logs show medium- and low-amplitude polarization angles at the upper boundary but not at the lower boundary. Additionally, grain sequences in the middle of target formations may not be linear. For example, in Fig. 12, although T3 is ultimately identified as a bell-shaped grain sequence, GR in pilot well Y1 decreases gradually and approximately linearly in the upper part, increases rapidly in the bottom part, and remains at a low, stable value in the middle section (1843–1847 m) rather than being linear. These characteristics indicate that although the overall grain sequence is recognized as bell-shaped, the middle part maintains a higher stable value. Thus, in the enlarged view of Fig. 12b1, the front part of the middle gamma-ray curve does not show obvious separations like the ideal grain sequence response in Fig. 12b2. These conditions also appear in horizontal well X, such as AGR fluctuations in the central BC region of Fig. 11. Analysis suggests this may result from sandstone non-homogeneity, causing actual logs to be less regular and neat than ideal grain sequence responses. Additionally, error analysis shows this study' s understandings and scheme apply better to horizontal well X with more stable formations than to horizontal well Y, again indicating these characteristics and schemes are semi-quantitative or qualitative trend understandings. These understandings and methods are recommended for situations with relatively smooth grain sequences and stable formations, while complicated situations require specific analysis based on actual conditions.

7. Conclusions

Based on grain sequence characteristics of sandstone reservoirs and classical vertical well logging facies theory, we systematically characterized formation features of four ideal sandstone grain sequence types (cylindrical-shaped, bell-shaped, funnel-shaped, and egg-shaped) at logging scale and their GR characteristics, demonstrating ideal grain sequence formation and GR response characteristics using actual field data from sandstone reservoirs in different basins. Combined with geological and engineering characteristics of horizontal wells, we established a three-formation model with different sedimentary grain sequences, where upper and lower formations are identical, homogeneous, isotropic non-reservoir surrounding rocks (high GR values), and the middle formation is a sandstone target formation with grain sequence characteristics. We detailed parameters for cylindrical-shaped, bell-shaped, funnel-shaped, and egg-shaped grain sequence target formations to characterize internal GR values and longitudinal variations of different grain sequences. In conjunction with AGR methods, we established an instrumental model and associated parameter scheme. Using the Monte Carlo method, we developed an efficient AGR forward modeling method, examined and optimized it using analytical algorithms.

Based on the forward modeling method, we simulated and analyzed AGR response characteristics of formation models with different grain sequences. When the horizontal well trajectory passes through the cylindrical-shaped grain sequence target formation, AGR responses inherit traditional three-formation characteristics– "double inverted isosceles trapezoids" response features and understandings. However, AGR responses for bell-shaped, funnel-shaped, and egg-shaped grain sequence formation models differ from traditional understanding, exhibiting "double left-handed spoons," "double right-handed spoons," and "double inverted isosceles triangles," respectively. Considering engineering and geological characteristics of horizontal well drilling, we identified eight fundamental spatial relationships between horizontal wells and formations. Combined with forward modeling methods and results, we established AGR response modes for different grain sequences under these eight spatial relationships. For field geosteering requirements, we established an application scheme for these response modes. We applied the above response characteristics, modes, and application scheme to two horizontal wells with different grain sequence characteristics in the Songliao Basin to verify their applicability, and discussed this study' s adaptability, advantages, and disadvantages in detail. This study provides fundamental understanding of AGR response characteristics and modes for geosteering and reservoir evaluation of horizontal wells in sedimentary reservoirs, and proposes a corresponding optional work program for geosteering.

Considering this study is at a preliminary exploratory stage, subsequent systematic and detailed studies are needed. For example, this study is mainly based on ideal grain-sequence formation models with smooth longitudinal grain-size variation curves, so follow-up work will further investigate more general formation situations such as grain-sequence characteristics containing jagged and interbedded formations, further optimizing understanding of AGR responses in different grain sequence sedimentary rocks.

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References

Ashraf, U., Zhu, P.M., Yasin, Q., Anees, A., Imraz, M., Mangi, H.N., Shakeel, 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. Journal of Petroleum Science and Engineering. 175, 338-351.

Bauer, K., Kulenkampff, J., Henninges, J., Spangenberg, E., 2015. Lithological control on gas hydrate saturation as revealed by signal classification of NMR logging data. Journal of Geophysical Research-Solid Earth, 12(9), 6001-6017.

Clift, P.D., Olson, E.D., Lechnowskyj, A. Moran, M.G., Barbato, A., Lorenzo, J.M., 2019. Grain-size variability within a mega-scale point-bar system, False River, Louisiana. Sedimentology, 66(2), 408-434.

Harris, M., Byrd, D., Archibald, M., et al., 2009. Real-time decisions with improved confidence using azimuthal deep resistivity and at-bit gamma imaging while drilling. In: Proceedings of SPE Offshore Europe Oil & Gas Conference & Exhibition.

Huang, L.J., 1985. Radioactive Logging Principle. Beijing: Petroleum Industry

Press, 22-50 (in Chinese).

Lai, J., Wang, G.W., Fan, Z.Y., Chen, J., Wang, S.C., Fan, X.Q., 2017. Sedimentary characterization of a braided delta using well logs: The Upper Triassic Xujiahe Formation in Central Sichuan Basin, China. Journal of Petroleum Science and Engineering. 154.

Martin, S.J., Thomas, M.G., Hammons, S.D., et al., 2013. Real-Time azimuthal gamma and resistivity LWD data used to navigate complex unconventional reservoir - western US land. In: Proceedings of SPE Asia Pacific Oil & Gas Conference and Exhibition.

Martin, S.J., Thomas, M.G., Hammons, S.D., Wilke, N. Real-time azimuthal gamma and resistivity LWD data used to navigate complex unconventional reservoir–western US land[C]. Paper presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, October 2013.

Meador, R.A., 2009. Logging-While-Drilling A Story of Dreams, Accomplishments, and Bright Futures. In: Proceedings of the SPWLA 50th Annual Logging Symposium. June 21-24, 2009, Paper C.

Meehan, N.D., 1994. Geological Steering of Horizontal Wells. Journal of Petroleum Technology, 10, 848-852.

Ogbe, O.B., 2021. Reservoir sandstone grain-size distributions: Implications for sequence stratigraphic and reservoir depositional modelling in Otovwe field, onshore Niger Delta Basin, Nigeria. Journal of Petroleum Science and Engineering. 203, 1-16.

Pitcher, J., Schafer, D., Botterall, P., 2009. A New Azimuthal Gamma at Bit Imaging Tool for Geosteering Thin Reservoirs. In: Proceedings of the 2009 SPE/IADC Drilling Conference and Exhibition, Amsterdam, The Netherlands.

Qin, Z., Pan, H.P., Wang, Z.H., Wang, B.T., Huang, K., Liu, S.H. Li, G., Konaté, A.A., Fang, S.N.,2017. A fast forward algorithm for real-time geosteering of azimuthal gamma-ray logging. Applied Radiation & Isotopes. 123, 114-120.

Qin, Z., Tang, B., Wu, D., Luo, S.C., Ma, X.G., Huang, K., Deng, C.X., Yang, H.J., Pan, H.P., Wang, Z.H., 2021. A qualitative characteristic scheme and a fast distance prediction method of multi-probe azimuthal gamma-ray logging in geosteering. Journal of Petroleum Science and Engineering. 199, 1-10.

Serra, O., 1992. Fundamentals of well-log interpretation: The interpretation of logging data: Elsevier.

Shao, C.R., Cao, X.J., Chen, G.X., Zhang, F.M, Ji, J.Q, Tang, J.H., 2013. A fast forward algorithm for LWD gamma-ray response and its geosteering application. Chinese J. Geophys., 56(11), 3932-3942 (in Chinese).

Souza, P., Georgiou, I.Y., Fitzgerald, D.M., Hughes, Z.J., Howes, N.C., Kulp, M.A., 2023. Hydrodynamic controls on sedimentary facies of tidal point bars:

A case study in the Georgia coastal plain, USA. Sedimentology, 70(3), 895-926.

Wang, G.W., Guo, R.K., 2000. Well logging Geology. Petroleum Industry Press (in Chinese).

Wang, J.X., Crawford, J., Montgomery, M. Modeling and inversion with azimuthal gamma ray for a better geosteering decision-making[C]. Paper presented at the SPE Annual Technical Conference and Exhibition, Virtual, October 2020.

Wang, L., Qiao, P., Zhao, W.N., Cao, F.H., Fan, Y.R., 2023. A new propagator matrix algorithm to compute electromagnetic fields in multilayered formations with full anisotropy. IEEE Transactions on Geoscience and Remote Sensing, 66, 1-11.

Wang, X.L., 2016. Design and experiment of mine azimuthal gamma logging instrument while drilling. Coal Science and Technology. 44(8), 161-167 (in Chinese).

Wheeler, A.J., Billings, T., Allan, R., et al., 2012. The introduction of an at-bit natural gamma-ray imaging tool reduces risk associated with real-time geosteering decisions in coalbed methane horizontal wells. In: Proceedings of the SPWLA 53th Annual Logging Symposium.

Wu, Z.G., Li, H., Han, Y.J., Zhang, R.R., Zhao, J., Lai, Q., 2022. Effects of formation structure on directional electromagnetic logging while drilling measurements. Journal of Petroleum Science and Engineering, 211, 1-11.

Yin, H.Z., Zhou, J.J., Guo, P.J., 2008. A hybrid solution for fast 3D gamma-ray tool modeling in high angle and horizontal wells. In: Proceedings of the SPWLA 49th Annual Logging Symposium. Edinburgh, Scotland, May 25-28, 2008.

Yuan, C., Zhou, C.C., Zhang. F., Hu, S., Li, C.L., 2015. A novel method for quantitative geosteering using azimuthal gamma-ray logging. Applied Radiation and Isotopes. 96, 63-70.

Yu, H.W., Wang, W.D., Zhang, L., Xiao, H.B., Yang, Q.J., Zhang, Y.X., Yang, Z.C., 2021. Study on the azimuth sensitivity of azimuthal γ ray logging while drilling. Nuclear Techniques. 44(01), 45-50 (in Chinese).

Zhang, T.F.; McCormick, D.; Nandlal, A., Lefranc, M., 2021. The TST3D method for automated structural interpretation in horizontal wellbores. Mathematic Geosciences. 53(5), 925–944.

Zhu, R.X., Jin, Z.J., Di, Q.Y., Yang, C.C. Chen, W.X., Tian, F., Zhang, W.X. et al., 2023. Research and progress of Intelligent Drilling Technology System and related theories. Chinese Journal Geophysics, 66(1), 1-15 (in Chinese).

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