

Article

Hydraulic Fracturing Effectiveness Evaluation in Tight Sandstone-Type Uranium Deposits Under a High Horizontal Stress–Low Vertical Stress Regime

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Abstract

Hydraulic fracturing is a key stimulation technique for enhancing the permeability of tight sandstone-hosted uranium deposits. However, existing hydraulic fracture network evaluation methods are primarily applicable to stress regimes in which the vertical principal stress exceeds the horizontal principal stress, making them unsuitable for evaluating low-angle or subhorizontal hydraulic fractures formed under high-horizontal-stress and low-vertical-stress conditions. To address this limitation, this study develops a semi-quantitative method for evaluating hydraulic fracturing effectiveness under stress regimes characterized by high horizontal stress and low vertical stress. The proposed method introduces a Stoneley-wave attenuation index and combines it with Stoneley-wave chevron-apex responses to identify hydraulically fractured intervals. By further integrating conventional well-log data to reduce interference from borehole enlargement, lithological boundaries, and natural fractures, the method supports the identification of hydraulically induced fractures and provides a semi-quantitative assessment of their development. The method was applied to a hydraulic fracturing pilot test for in situ leaching uranium mining in the Bayingobi Basin, Alxa, China, where it supported the identification of hydraulically induced fractures and fractured intervals in both stimulation and monitoring wells. Field application results support the engineering applicability of the proposed method and provide preliminary validation of its effectiveness. The results indicate that this method provides an effective logging-based approach for evaluating hydraulic fracturing performance and investigating fracture propagation in tight sandstone-hosted uranium deposits.

Keywords: hydraulic fracturing effectiveness evaluation; array acoustic logging; electrical imaging logging; in situ stress; tight sandstone-type uranium deposits; in situ leaching (ISL)



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1. Introduction

Sandstone-type uranium deposits have become the primary uranium deposit type with the greatest economic value and exploitation potential in China [1–3]. The western Inner Mongolia Plateau has become an important strategic reserve and alternative base for uranium resources in China [4,5]. However, some sandstone-type uranium deposits in this region exhibit highly compact ore-bearing lithologies [6] and extremely low natural

permeability, meaning that conventional natural groundwater hydrodynamic conditions struggle to satisfy the process requirements of in situ leaching (ISL) [7].

For tight sandstone uranium layers, implementing artificial ore-bearing formation stimulation remains the only viable path to enhancing their permeability [8]. Following hydraulic fracturing stimulation, the morphology, propagation direction, network connectivity, and effective conductivity of the induced fractures directly dictate the sweep volume of the leaching solution within the subsurface strata as well as the ultimate efficiency of the ISL uranium recovery [9]. Fracture propagation is governed by the triaxial principal stresses, which comprise two horizontal principal stresses and one vertical principal stress [10,11]. Horizontal stresses are primarily derived from regional tectonic dynamics (such as plate compression or extension), whereas vertical stress is jointly determined by the overburden weight of the overlying strata and the pore pressure [12,13]. Following fracturing operations, the high-precision, reliable, and non-destructive detection of induced fractures within uranium-bearing aquifers—along with the subsequent evaluation of reservoir stimulation effectiveness—remains a critical, unresolved geo-engineering bottleneck critical to guiding injection-production well network design and optimizing subsequent ISL operations [14].

Within the engineering workflow, fracturing evaluation is systematically categorized into three distinct phases: pre-fracturing frackability assessment, real-time dynamic monitoring during execution, and post-fracturing fracture geometry evaluation. Specifically, rock brittleness indices are widely employed prior to stimulation to characterize the frackability of uranium-bearing formations [15]. During execution, the wide-field electromagnetic method is utilized to monitor the diffusion distance, extent, and orientation of fracturing fluids in real time, thereby evaluating the dynamic effectiveness of the stimulation treatment [16]. Post-fracturing evaluation typically leverages array acoustic logging to detect and characterize fracture geometry, focusing primarily on key parameters such as vertical fracture height and radial propagation extent [17]. This study falls within the scope of post-fracturing fracture characterization, specifically focusing on the evaluation of induced fracture networks generated by hydraulic fracturing within tight sandstone-type uranium formations.

Within the domain of post-fracturing fracture geometry evaluation, geophysical well logging techniques represent the most direct and effective diagnostics for acquiring subsurface in situ data [18]. Among these techniques, array acoustic logging and electrical imaging logging represent the state-of-the-art technologies for fracture identification and characterization. When the vertical stress exceeds the horizontal stress in a fractured formation, rock failure preferentially propagates in the vertical direction, resulting in the development of high-angle or near-vertical hydraulic fractures. Such fractures can be effectively identified using array acoustic logging anisotropy analysis and deep-directional imaging techniques [19,20]. Electrical imaging logging employs an array of electrode pads pressed against the borehole wall to scan the formation and acquire microresistivity measurements. After appropriate processing, these measurements can be converted into color-scaled or grayscale images that reflect variations in formation microresistivity. Such images provide an intuitive visualization of lithological changes and reveal the geometric characteristics and occurrence attributes of fractures [21]. Array acoustic logging not only provides compressional-wave and shear-wave information but also, more importantly, records Stoneley waves propagating along the borehole wall. When encountering acoustic impedance discontinuities, such as open fractures, Stoneley waves undergo significant reflection and attenuation. This characteristic enables Stoneley-wave measurements to serve as an effective means for fracture detection and evaluation in boreholes [22,23].

At present, geophysical logging techniques for the evaluation of hydraulically induced fractures are primarily focused on applications in the oil and gas industry. Li et al. [24]

combined a dispersion analysis method based on linear prediction theory with hierarchical clustering and utilized array acoustic logging data to achieve rapid evaluation of hydraulic fracturing effectiveness in shale oil and sandstone reservoirs. Sun et al. [25] conducted a multiscale evaluation of hydraulic fracturing in a reservoir located in western China using radial acoustic velocity tomography based on compressional waves and far-field acoustic imaging based on reflected acoustic waves. Qi Xiao [26] employed compressional-wave tomography and dipole scattered-wave techniques to achieve a comprehensive evaluation of hydraulic fracturing effectiveness in both the near-wellbore and far-field regions of the reservoir. Li Ning [27] employed reflected Stoneley-wave extraction and imaging techniques to quantitatively characterize near-wellbore hydraulic fractures, thereby enabling high-resolution imaging of fractures in the far-field region. Conventional hydraulic fracturing evaluation techniques are generally limited to formations where the vertical principal stress is greater than the horizontal principal stress. However, in situ leaching boreholes are typically located in formations where the vertical principal stress is lower than the horizontal principal stress [28]. Under such stress conditions, hydraulic fracturing tends to generate low-angle or subhorizontal fractures. Moreover, these fractures are generally characterized by narrow apertures and do not exhibit distinct fractured zones [29], thereby increasing the difficulty of fracture identification.

In the field of uranium recovery by ISL, Jamet et al. (2024) [14] integrated acoustic slowness logging and nuclear magnetic resonance logging to comprehensively evaluate small-scale geological structures and reservoir properties, including porosity and permeability, within ore-bearing aquifers intersected by uranium boreholes. Their approach enabled the effective identification and characterization of natural fractures. However, this method is primarily designed for the analysis of natural fracture systems and is not suitable for evaluating hydraulically induced fractures or the effectiveness of hydraulic fracturing treatments. Yarmohammadi et al. [30] employed the Stoneley-wave reflection coefficient as an indicator of fracture connectivity and fluid transmissivity, enabling a qualitative evaluation of fracture connectivity within the reservoir. To date, systematic studies on the detection and evaluation of hydraulically induced fracture networks in tight sandstone-hosted uranium deposits remain absent. To overcome this limitation, this study proposes, for the first time, an integrated semi-quantitative evaluation method for hydraulic fracture networks based on the combined interpretation of array acoustic logging and electrical imaging logging. The proposed method provides a reliable approach for evaluating hydraulic fracturing effectiveness in tight sandstone-hosted uranium reservoirs.

2. Hydraulic Fracturing Evaluation Method

In vertical wells where the vertical principal stress exceeds the horizontal principal stress, hydraulic fracturing predominantly generates vertical or high-angle fractures [31]. High-angle fractures readily induce pronounced shear-wave splitting and acoustic anisotropy, allowing hydraulic fracturing effectiveness to be evaluated using the conventional methods described above.

The study interval comprises the upper mudstone member (K_1b^{2-3}) and the middle sandstone member (K_1b^{2-2}) of the Upper Member of the Lower Cretaceous Bayingobi Formation (K_1b^2). The K_1b^{2-3} member has an average thickness of approximately 200 m and an average bulk density of 1.94 g/cm^3 , whereas the K_1b^{2-2} member has an average thickness of approximately 370 m and an average bulk density of 1.85 g/cm^3 . Based on the formation thicknesses and bulk densities, the vertical stress at a burial depth of 500 m was estimated to be approximately 9.25 MPa. Combined with the interpretation of conventional well logs, the maximum and minimum horizontal principal stresses at the same depth in borehole TZ-4 were determined to be 12.95 MPa and 9.33 MPa, respectively. Comparison

of the calculated stress magnitudes indicates that the vertical principal stress is lower than the minimum horizontal principal stress, suggesting that the in situ stress regime in the study area is dominated by horizontal principal stresses.

According to the general distribution pattern of the in situ stress field in shallow formations, the horizontal principal stress generally exceeds the vertical principal stress at burial depths of less than 500 m [32]. Under such stress conditions, hydraulic fracturing predominantly generates low-angle or subhorizontal fractures, whereas the development of vertical fractures is relatively limited [33,34]. Because conventional cross-dipole acoustic logging is primarily designed to identify high-angle or near-vertical fractures, its response to low-angle and subhorizontal fractures is relatively weak, resulting in a significant reduction in detection capability. Therefore, conventional cross-dipole acoustic logging has limited capability for effectively detecting hydraulically induced fractures in the shallow formations of the study area [35].

To address the challenge of evaluating hydraulic fracturing effectiveness in tight sandstone-hosted uranium deposits under stress conditions where the vertical principal stress is lower than the horizontal principal stress, this study develops a novel integrated hydraulic fracture identification method based on Stoneley-wave attenuation characteristics, Stoneley-wave chevron-apex response features, and the exclusion of interference from non-fracture-related geological and borehole factors.

2.1. Stoneley-Wave Attenuation

Stoneley-wave energy attenuation refers to the gradual decrease in Stoneley-wave amplitude as the wave propagates along the borehole. Under otherwise identical conditions, formations with higher permeability facilitate fluid flow more readily, resulting in stronger Stoneley-wave attenuation. In addition, fractures and pronounced formation anisotropy provide additional pathways for wave energy dissipation, further enhancing Stoneley-wave attenuation. Therefore, comparison of Stoneley-wave energy attenuation characteristics before and after hydraulic fracturing can be used to evaluate hydraulic fracturing effectiveness [36].

The Relative Stoneley Attenuation Index (RSAI) is defined as the normalized increment in Stoneley-wave attenuation after hydraulic fracturing relative to the pre-fracturing baseline. It is calculated as follows:

$$RSAI = \frac{\Delta A_{post} - \Delta A_{pre}}{A_{bg,pre}} \times 100\% \quad (1)$$

or equivalently, or equivalently,

$$RSAI = \frac{(A_{bg,post} - A_{f,post}) - (A_{bg,pre} - A_{f,pre})}{A_{bg,pre}} \times 100\% \quad (2)$$

where

ΔA_{pre} and ΔA_{post} denote the Stoneley-wave attenuation amplitudes before and after hydraulic fracturing, respectively. $A_{bg,pre}$ and $A_{bg,post}$ denote the local background Stoneley-wave attenuation values selected from intervals on both sides of the anomalous response, where no anomalous responses are observed and the lithology is consistent, before and after hydraulic fracturing, respectively. $A_{f,pre}$ and $A_{f,post}$ denote the local background Stoneley-wave attenuation values selected from intervals on both sides of the anomalous response, where no anomalous responses are observed and the lithology is consistent, before and after hydraulic fracturing, respectively.

$A_{f,pre}$ and $A_{f,post}$ denote the Stoneley-wave attenuation values of the target interval before and after hydraulic fracturing, respectively. denote the Stoneley-wave attenuation values of the target interval before and after hydraulic fracturing, respectively.

Figure 1a presents the Stoneley-wave attenuation curve. Based on the Stoneley-wave attenuation values, the RSAI can be calculated using the method described above. An RSAI value greater than zero ($RSAI > 0$) indicates that anomalous changes have occurred at the formation interface following hydraulic fracturing, whereas an RSAI value less than zero ($RSAI < 0$) indicates that no anomalous changes are detected at the formation interface after hydraulic fracturing.

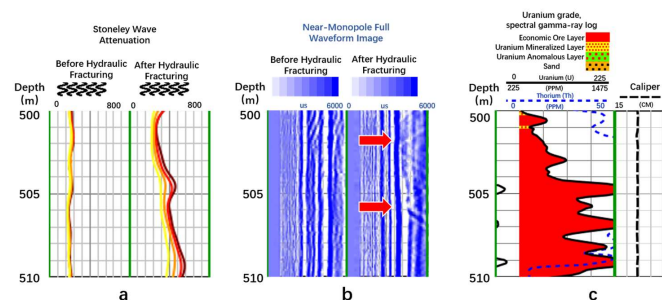


Figure 1. Schematic illustration of logging results for a representative borehole interval. (a) Stoneley-wave attenuation; (b) near-monopole full waveform image; (c) uranium grade, spectral gamma-ray log, and borehole enlargement ratio.

2.2. Validation Using Chevron-Pattern Signatures

In the waveform variable-density image acquired from array acoustic logging, Stoneley waves undergo reflection and transmission upon encountering a fracture. The downward direct Stoneley wave intersects the upward reflected wave generated at the fracture, producing intersecting coherent wavefronts that form a characteristic V-shaped (chevron-shaped) pattern in the waveform variable-density image. The intersection of the coherent wavefronts, referred to as the chevron apex, corresponds to the depth at which the fracture plane intersects the borehole. Therefore, the depth of the chevron apex can serve as a reliable indicator for identifying the location of hydraulically induced fractures [30].

The chevron apex determination procedure is described as follows.

Assume that an acoustic source is located at a fixed position within the borehole, and that a receiver array is deployed both above and below the source. The waveform variable-density image is displayed with receiver position on the horizontal axis and travel time on the vertical axis. Stoneley waves propagate upward and downward along the borehole wall from the source.

For a receiver located at a distance of (x) from the acoustic source,

$$t = \frac{|x - x_0|}{V_s} \quad (3)$$

where

t is the arrival time.

x_0 is the distance between the receiver and the acoustic source.

V_s is the Stoneley-wave velocity.

The two linear travel-time trajectories intersect at the source location, thereby forming a characteristic chevron pattern.

$$t = \begin{cases} \frac{|x - x_0|}{V_s}, & x_0 < x \\ \frac{|x_0 - x|}{V_s}, & x_0 > x \end{cases} \quad (4)$$

Figure 1b presents the waveform variable-density image. The chevron apex, indicated by the red arrow, corresponds to the intersection of the fracture plane and the borehole, thereby identifying the fracture depth.

2.3. Exclusion of Interference Using Conventional Logging Data

Stoneley-wave attenuation characteristics and chevron patterns observed in waveform variable-density images can effectively indicate the presence of fractures or fractured zones in the formation after hydraulic fracturing. However, these response characteristics alone are insufficient to reliably determine the origin of the anomalies. In addition to hydraulically induced fractures, borehole enlargement, lithological boundaries, and interlayer reflections may also generate Stoneley-wave reflections and interference, producing similar chevron patterns and thereby increasing the uncertainty of hydraulic fracture identification.

To address the above limitations, this study integrates electrical imaging logging with conventional logging data to identify and eliminate interference factors associated with anomalous responses observed in array acoustic logging, thereby improving the accuracy of hydraulic fracture identification. First, electrical imaging logging is employed to identify geological features exposed on the open borehole wall, including natural fractures, bedding structures, and the orientation of the present-day in situ stress field (Figure 2), providing a basis for distinguishing and excluding natural fractures. Second, natural gamma-ray logging data are used to eliminate anomalous responses associated with lithological boundaries, while the borehole enlargement ratio is employed to exclude false chevron-pattern anomalies caused by abrupt borehole enlargement (Figure 1c). Finally, the above multi-source logging data are jointly interpreted with waveform variable-density images acquired from array acoustic logging, effectively eliminating interference from non-hydraulic-fracturing factors, including borehole enlargement, lithological boundaries, and natural fractures. This integrated approach supports the identification of hydraulically induced fractures and hydraulically fractured borehole intervals and provides a semi-quantitative framework for evaluating hydraulic fracture networks in tight sandstone-hosted uranium deposits.

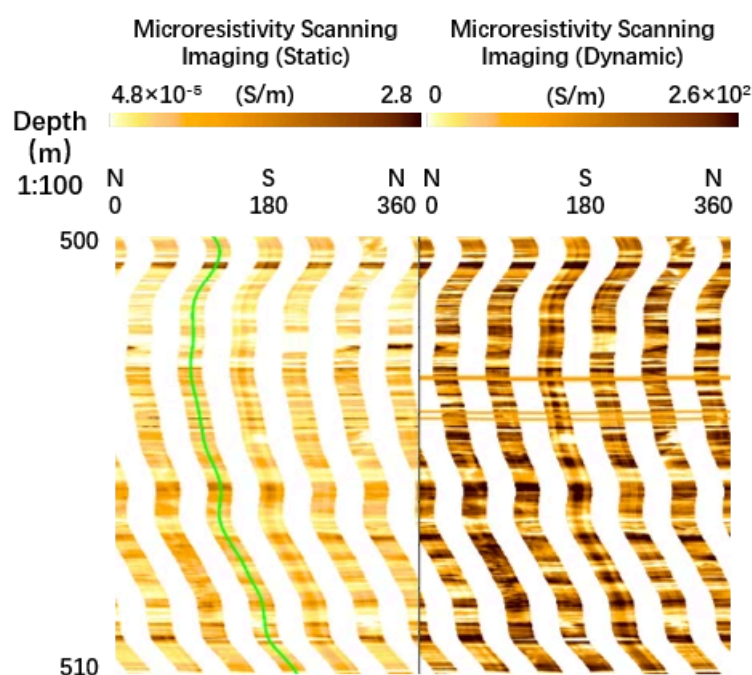


Figure 2. Schematic illustration of electrical imaging logging results from a representative borehole interval.

2.4. Methodological Summary

The proposed workflow first identifies potential anomalous intervals by analyzing Stoneley-wave attenuation characteristics and chevron patterns in waveform variable-density images acquired from array acoustic logging before and after hydraulic fracturing. Subsequently, natural gamma-ray logging data collected before and after hydraulic fracturing are used to eliminate anomalous responses associated with lithological boundaries, while borehole enlargement ratio data are employed to exclude false chevron-pattern anomalies caused by abrupt borehole enlargement. Meanwhile, pre-fracturing electrical imaging logging data are used to identify the locations of natural fractures, thereby enabling their interference with post-fracturing logging responses to be effectively excluded during the interpretation process. Based on these procedures, a workflow for the identification of hydraulically induced fractures was established, as illustrated in Figure 3.

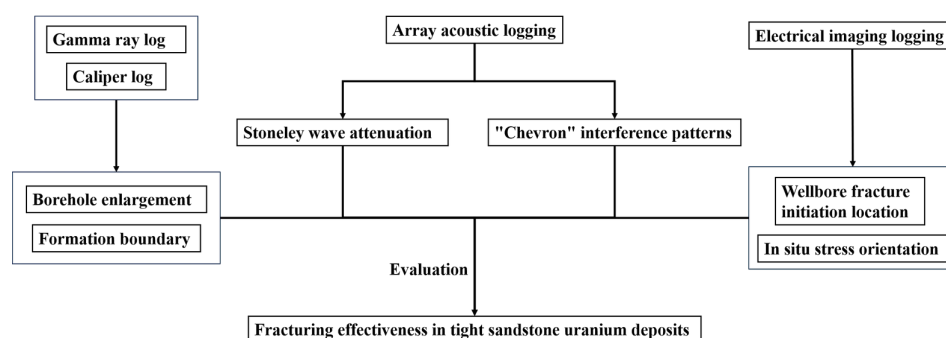


Figure 3. Flowchart of the proposed fracture evaluation methodology.

3. Pre- and Post-Fracturing Geophysical Logging Experiments and Results

This study was conducted at an ISL uranium mining site in the Bayingobi Basin, Inner Mongolia, China.

3.1. Geological Setting of the Study Area

The study area is located southwest of Tamusu Town, Alxa Right Banner, Inner Mongolia Autonomous Region, China, along the eastern margin of the Badain Jaran Desert within the Bayingobi Basin. The Bayingobi Basin occupies a complex tectonic position at the intersection of four major tectonic domains, including the Tarim, Kazakhstan, Siberian, and North China plates. This region constitutes an important Paleozoic continental collision and accretion zone resulting from the convergence and amalgamation of these continental blocks [37].

The target interval in the test area is located within the upper member of the Bayingobi Formation (K_1b^2), which can be subdivided into three lithostratigraphic units from top to bottom. The first unit (K_1b^{2-1}) is dominated by thick successions of dark gray to gray mudstone. Horizontal bedding is commonly developed, with local occurrences of fissile structures. Reducing media, including carbonaceous debris and pyrite, are well developed within this unit. The second unit (K_1b^{2-2}) mainly consists of light red, purplish-red, brownish-yellow, yellow, and gray sandstones and siltstones, interbedded with thin layers of mudstone and marl. This unit is characterized by relatively coarse grain size and thick sandstone intervals, in which both cross-bedding and parallel bedding are commonly observed. The third unit (K_1b^{2-3}) is generally characterized by fine-grained sediments. On the lacustrine basin side, thick gray to dark gray mudstones predominate and contain abundant reducing media, such as carbonaceous debris and pyrite. Toward the basin margin, facies transitions result in the development of siltstone and fine-grained sandstone, with minor occurrences of conglomeratic sandstone [37,38].

The target interval investigated in this study is located within the second lithostratigraphic unit of the upper member of the Bayingobi Formation. Its stratigraphic characteristics are shown in Figure 4.

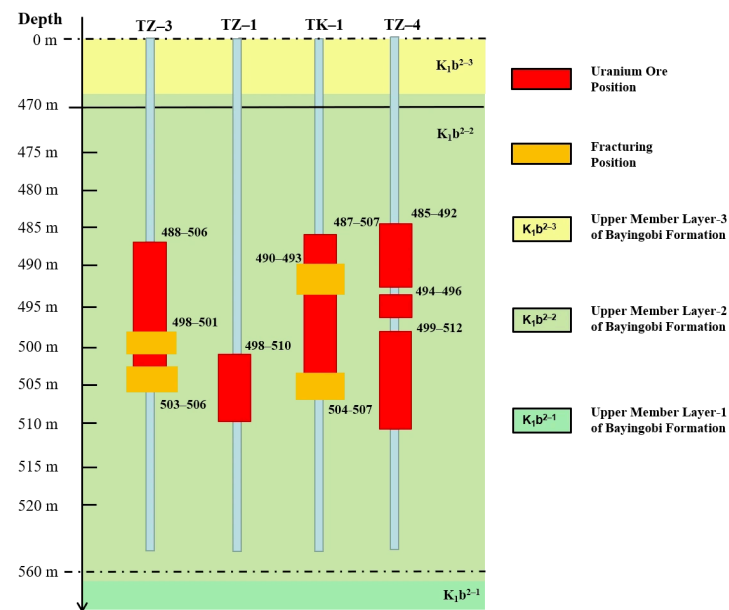


Figure 4. Schematic vertical profile of the borehole stratigraphy and ore-bearing interval in the test area.

3.2. Data Acquisition and Preprocessing

3.2.1. Data Acquisition

The experimental boreholes investigated in this study are located at an in situ leaching (ISL) pilot test site, and their locations are shown in Figure 5.

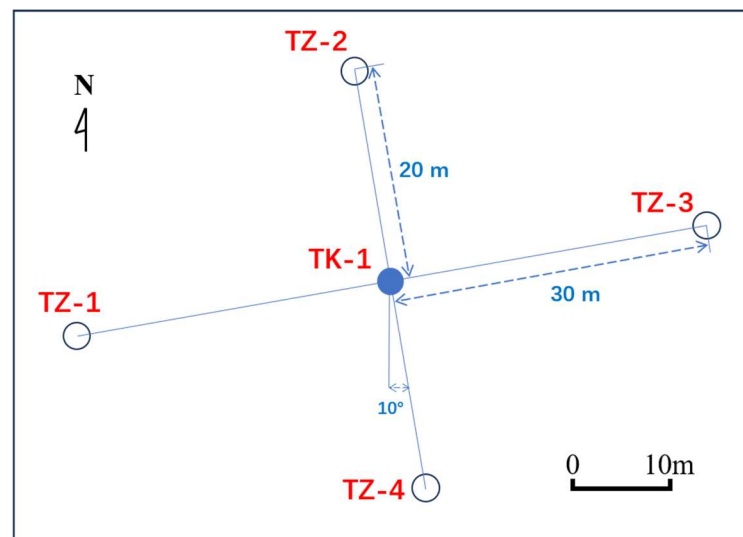


Figure 5. Spatial distribution of the ISL boreholes.

TK-1 and TZ-3 were selected as the hydraulic fracturing wells. The hydraulic fracturing intervals were 490–493 m and 504–507 m in well TK-1 and 498–501 m and 503–506 m in well TZ-3 (Figure 4).

Array acoustic logging was conducted in wells TK-1, TZ-3, and TZ-4 both before and after hydraulic fracturing to acquire Stoneley-wave attenuation curves and waveform variable-density images. The pre- and post-fracturing logging results were subsequently compared to

evaluate the hydraulic fracturing effectiveness. In addition, electrical imaging logging was performed in wells TK-1, TZ-1, and TZ-4 after hydraulic fracturing to obtain information on the in situ stress field and formation characteristics. The hydraulic fracturing operations and logging program for the ISL boreholes are summarized in Figure 4 and Table 1.

Table 1. Summary of fracturing operations and logging programs for the ISL boreholes.

Well No.	Hydraulic Fracturing Performed	Electrical Imaging Logging	Pre-Fracturing Array Acoustic Logging	Post-Fracturing Array Acoustic Logging
TK-1	yes	yes	yes	yes
TZ-3	yes	no	yes	yes
TZ-4	no	yes	yes	yes

3.2.2. Data Preprocessing

The conventional logging data and electrical imaging logging data were processed and interpreted using the LEAD logging data processing platform [39] developed by China National Logging Corporation (CNLC). Cross-plot analysis was performed to evaluate lithological and petrophysical parameters, and appropriate processing parameters were selected according to the lithological characteristics of the formations. The electrical imaging data were processed to generate static and dynamic images, identify formation dip, interpret sedimentary structures, and detect fractures. The pre-fracturing array acoustic logging data were also processed and interpreted using the LEAD platform. Compressional-wave (P-wave), shear-wave (S-wave), and Stoneley-wave slowness were extracted from the full-waveform acoustic data, while dipole shear-wave data were used for shear-wave slowness extraction and acoustic anisotropy analysis.

The electrical imaging data were subjected to static and dynamic normalization to enhance fracture-related features. The full-waveform array acoustic logging data were filtered and denoised to extract high-quality Stoneley-wave signals. Using the natural gamma-ray (GR) log as the depth reference, the array acoustic logging data were precisely depth-matched with the electrical imaging logging data to ensure that both datasets represented the same geological features at corresponding depths.

3.3. Electrical Imaging Logging Results

Figure 6 presents the electrical imaging logging results acquired in the open-hole sections of wells TK-1 and TZ-4. The logging survey was conducted to evaluate the hydraulic fracturing effectiveness within the target interval of the Lower Bayingobi Formation. The logged formations mainly comprise the Upper and Lower Bayingobi formations of the Cretaceous, with a sandstone–mudstone lithological succession.

For well TK-1, no fractures were identified within the interval of 478.2–512.3 m based on the electrical imaging interpretation. In the static microresistivity image, the azimuth of Pad 1 is marked by a green line, whereas bedding planes are highlighted by orange lines in the dynamic microresistivity image.

For well TZ-4, the electrical imaging interpretation over the interval of 482.0–520.0 m identified one conductive fracture with a dip angle of 71.5° and a NE–SW strike, which is marked by a red curve, and one resistive fracture, which is marked by a yellow curve. In the static microresistivity image, the azimuth of Pad 1 is indicated by a green line, while bedding planes are highlighted by orange lines in the dynamic microresistivity image.

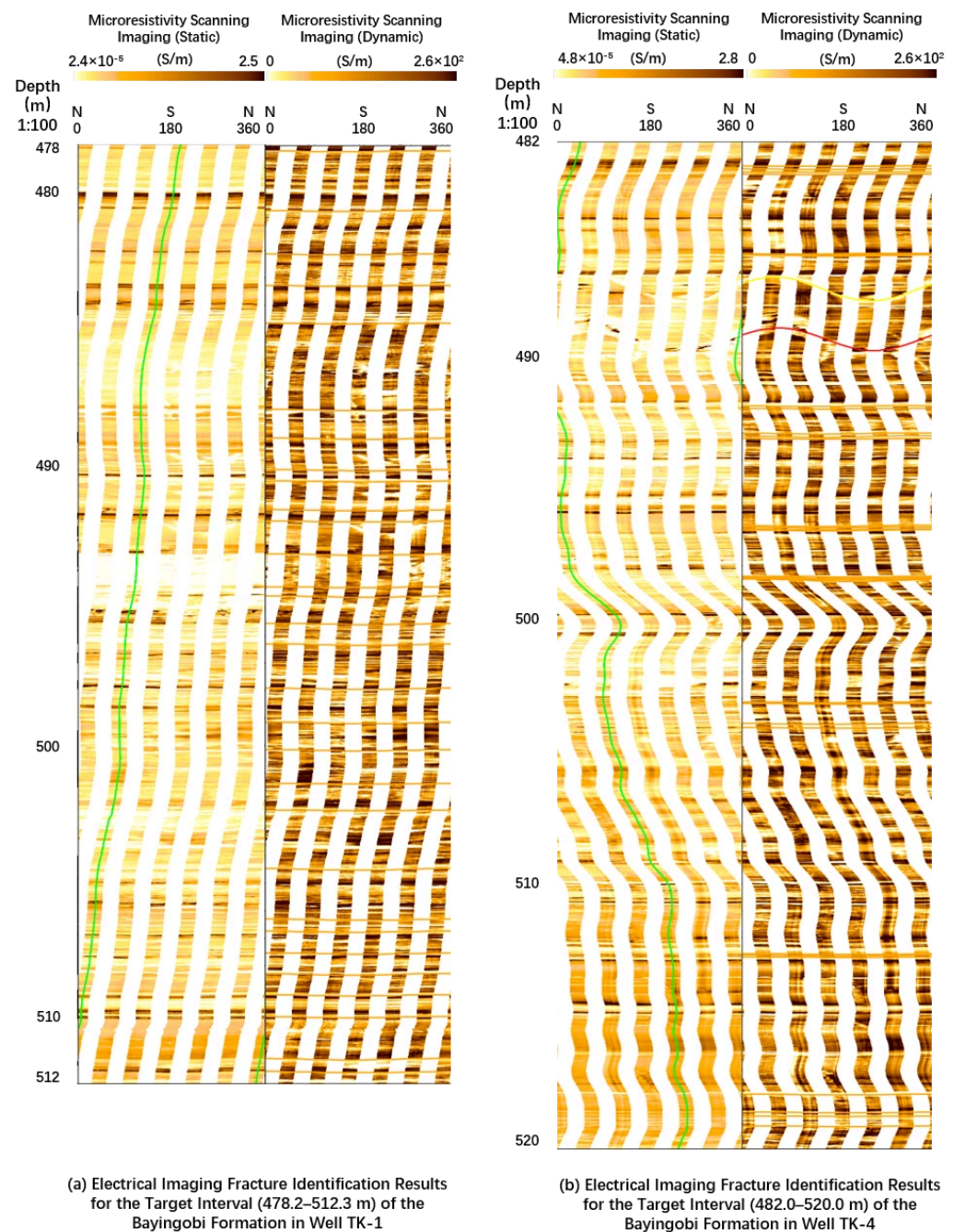


Figure 6. Fracture interpretation from pre-fracturing open-hole electrical imaging logs: (a) TK-1; (b) TZ-4.

3.4. Array Acoustic Logging Results

Hydraulic fracturing operations and pre- and post-fracturing array acoustic logging surveys were conducted in wells TK-1 and TZ-3. Well TZ-4 served as a monitoring well and was also subjected to array acoustic logging before and after hydraulic fracturing. The interpreted acoustic anisotropy results are presented in Figures 7–9. In each figure, panel (a) on the left shows the acoustic anisotropy interpretation of the target interval before hydraulic fracturing, whereas panel (b) on the right presents the corresponding results after hydraulic fracturing.

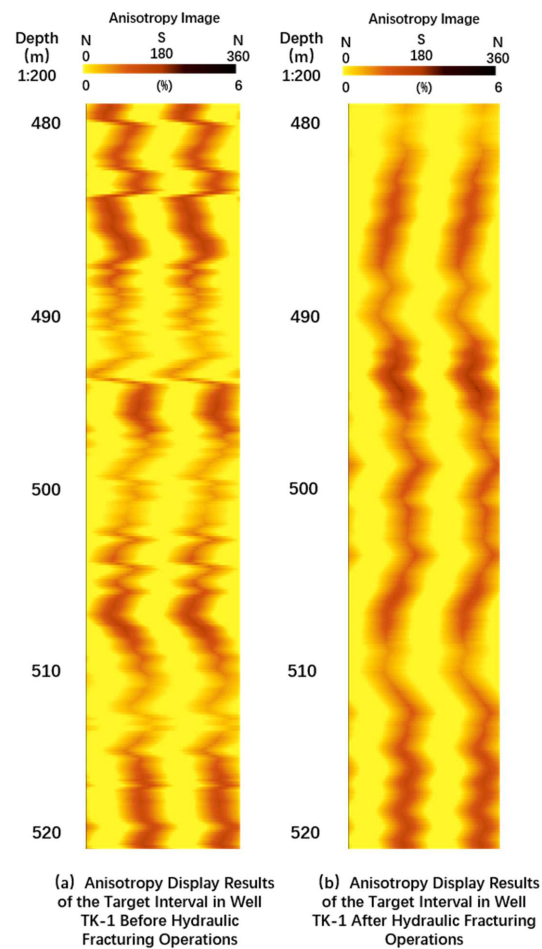


Figure 7. Acoustic anisotropy interpretation results from array acoustic logging for borehole TK-1: (a) pre-fracturing; (b) post-fracturing.

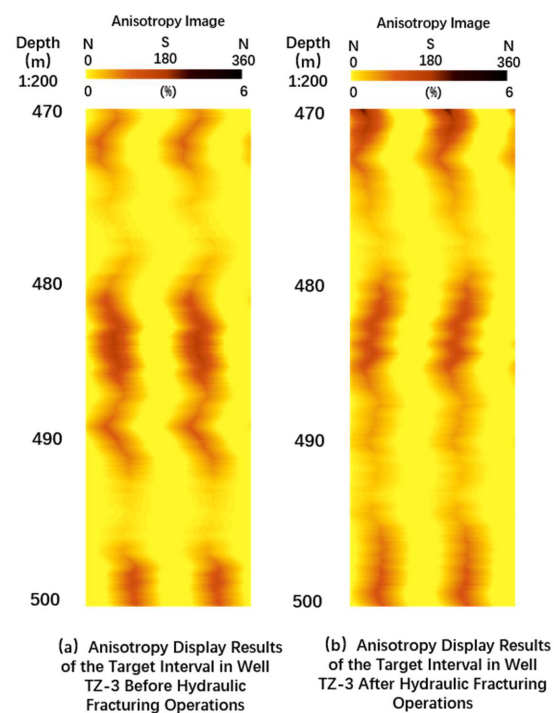


Figure 8. Acoustic anisotropy interpretation results from array acoustic logging for borehole TZ-3: (a) pre-fracturing; (b) post-fracturing.

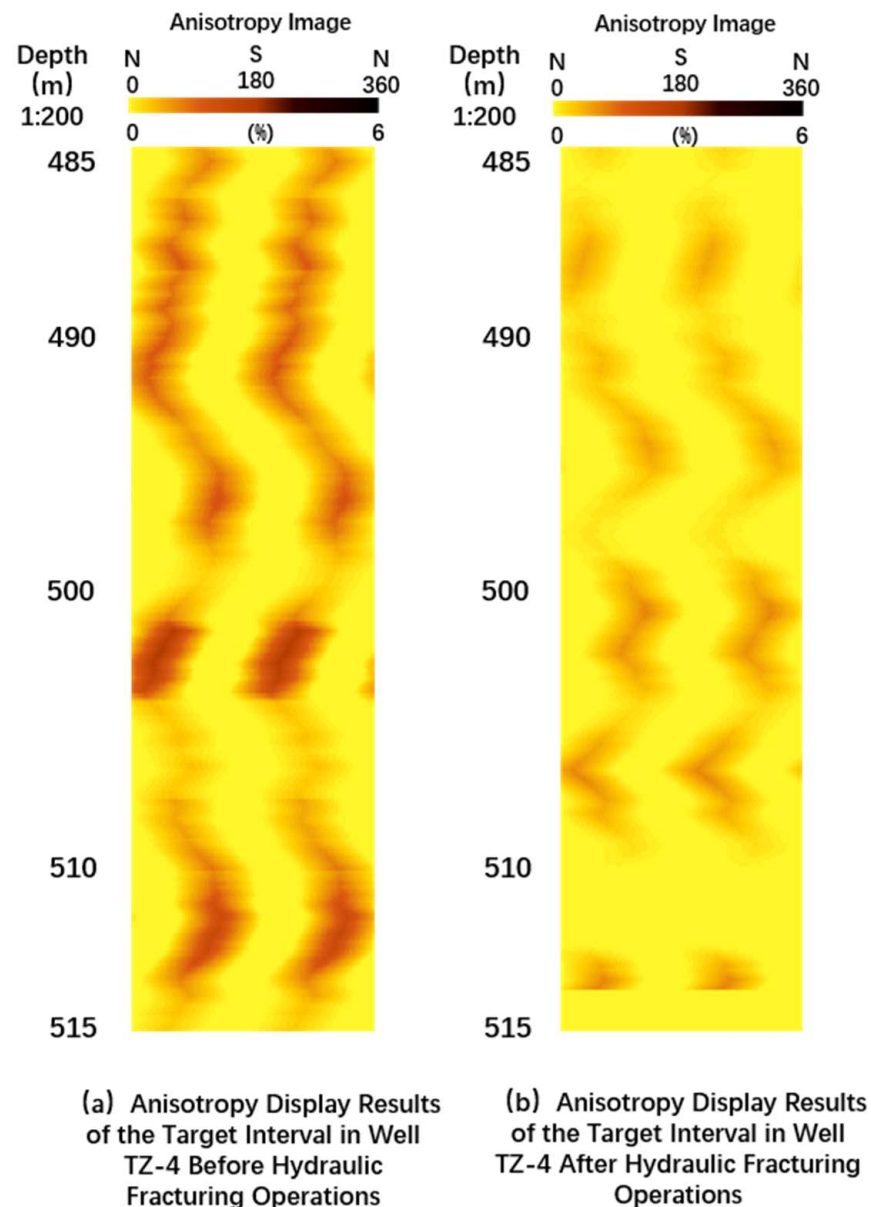


Figure 9. Acoustic anisotropy interpretation results from array acoustic logging for borehole TZ-4: (a) pre-fracturing; (b) post-fracturing.

In conventional oil and gas reservoirs, the in situ stress regime is typically characterized by a vertical principal stress greater than the horizontal principal stresses. Under such conditions, hydraulic fracturing predominantly generates high-angle fractures, which produce significant changes in acoustic anisotropy derived from array acoustic logging. Consequently, the effectiveness of hydraulic fracturing can be evaluated by comparing the anisotropy results acquired before and after fracturing. In contrast, the study area is characterized by a shallow burial depth, where the vertical principal stress is lower than the horizontal principal stresses. As a result, hydraulic fracturing in wells TK-1 and TZ-3 predominantly generated low-angle and subhorizontal fractures. Because such fractures induce only weak acoustic anisotropy responses, no significant differences were observed between the pre- and post-fracturing acoustic anisotropy interpretation results. Therefore, conventional array acoustic logging methods are inadequate for identifying hydraulically induced fractures under this stress regime.

As the hydraulic fracturing monitoring well, well TZ-4 also exhibited only minor changes in the acoustic anisotropy interpretation results before and after hydraulic fracturing, with no obvious anisotropy response attributable to hydraulic fracturing. These results indicate that, under a stress regime characterized by high horizontal stresses and low vertical stress, conventional hydraulic fracturing evaluation methods based on acoustic anisotropy derived from array acoustic logging have significant limitations and cannot reliably characterize the development of low-angle and subhorizontal hydraulic fractures. Therefore, it is necessary to establish a hydraulic fracturing evaluation method specifically applicable to this type of stress regime.

4. Analysis and Evaluation of Hydraulic Fracturing Effectiveness

4.1. Analysis of Hydraulic Fracturing Results

The logging experiment involved three uranium exploration wells. Wells TK-1 and TZ-3 served as hydraulic fracturing wells, whereas well TZ-4 was used as a hydraulic fracturing monitoring well. Array acoustic logging surveys were conducted in all three wells (TK-1, TZ-3, and TZ-4) both before and after hydraulic fracturing to evaluate the fracturing effectiveness. In addition, well TK-1 underwent a comprehensive logging program, including conventional open-hole logging, electrical imaging logging, and pre- and post-fracturing array acoustic logging. Details of the hydraulic fracturing operations and logging program are summarized in Table 1.

4.1.1. Analysis for TK-1

A comparative analysis of Stoneley-wave attenuation was performed for the hydraulic fracturing intervals of 490–493 m and 504–507 m in well TK-1 (Figure 4). Comparison of the pre- and post-fracturing attenuation amplitudes indicates noticeable differences within and adjacent to the uranium-bearing intervals. Relative to the pre-fracturing measurements, the Stoneley-wave attenuation increased consistently after hydraulic fracturing.

(1) Calculation of the Relative Stoneley Attenuation Index

The Relative Stoneley Attenuation Index (RSAI) for well TK-1 was calculated using Equation (1), and the results are presented in Table 2. The Stoneley-wave attenuation values measured within the interval of 345–350 m, located above the hydraulic fracturing intervals and characterized by the same lithology with no anomalous logging responses, were selected as the local background values. Compared with the pre-fracturing condition, the relative Stoneley-wave attenuation at the fracture locations increased by approximately 150% after hydraulic fracturing. The Stoneley-wave attenuation curves in Figure 10 consist of four differently colored curves, each representing the measurement recorded by a different receiver. The Stoneley-wave attenuation curves in Figures 11 and 12 are presented in the same manner.

Table 2. Relative Stoneley Stoneley Attenuation Index (RSAI) for well TK-1. Attenuation Index (RSAI) for well TK-1.

Depth (m)	$A_{bg,post}$	$A_{f,post}$	$A_{bg,pre}$	$A_{f,pre}$	RSAI
489 m	400	125	150	110	157%
498 m	400	90	150	120	187%
507 m	400	110	150	80	147%
513 m	400	100	150	80	153%

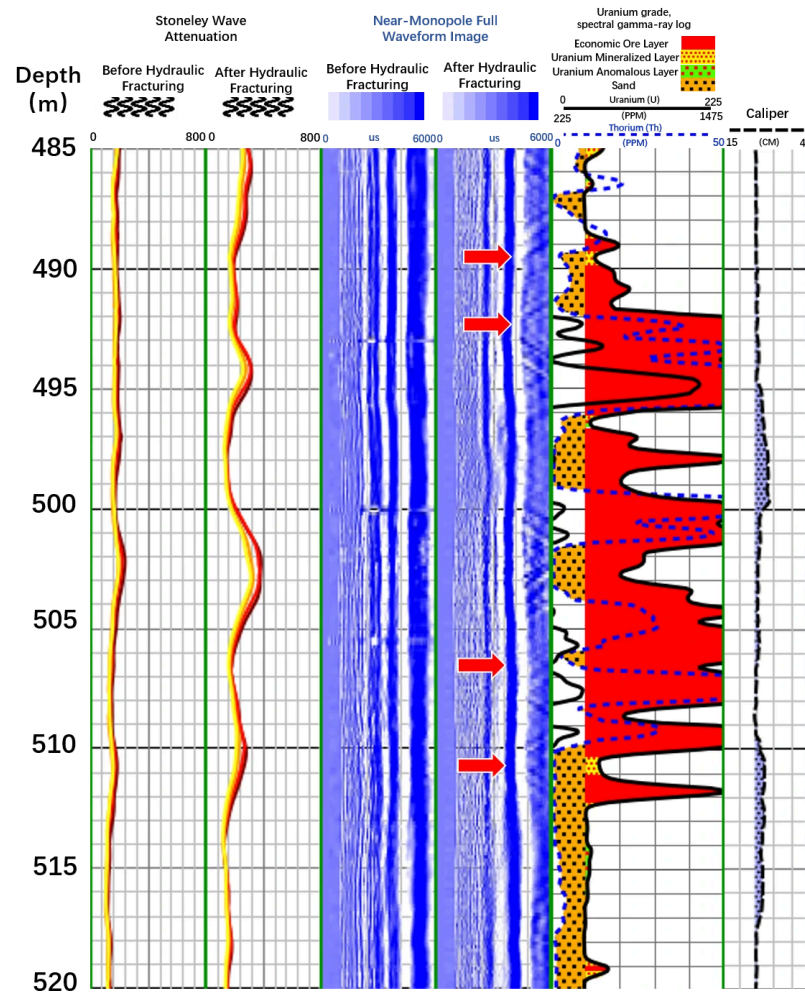


Figure 10. Array acoustic logging and conventional logging results of the hydraulic fracturing interval before and after hydraulic fracturing (TK-1).

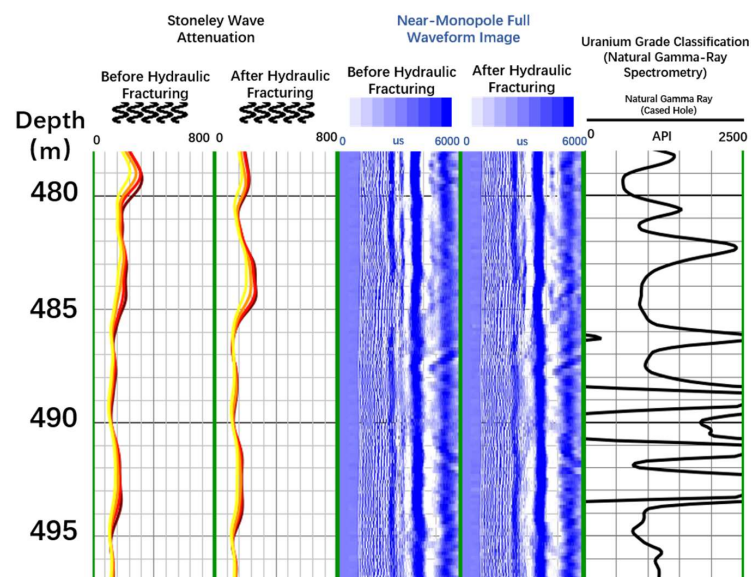


Figure 11. Array acoustic logging and conventional logging results of the hydraulic fracturing interval before and after hydraulic fracturing (TZ-3).

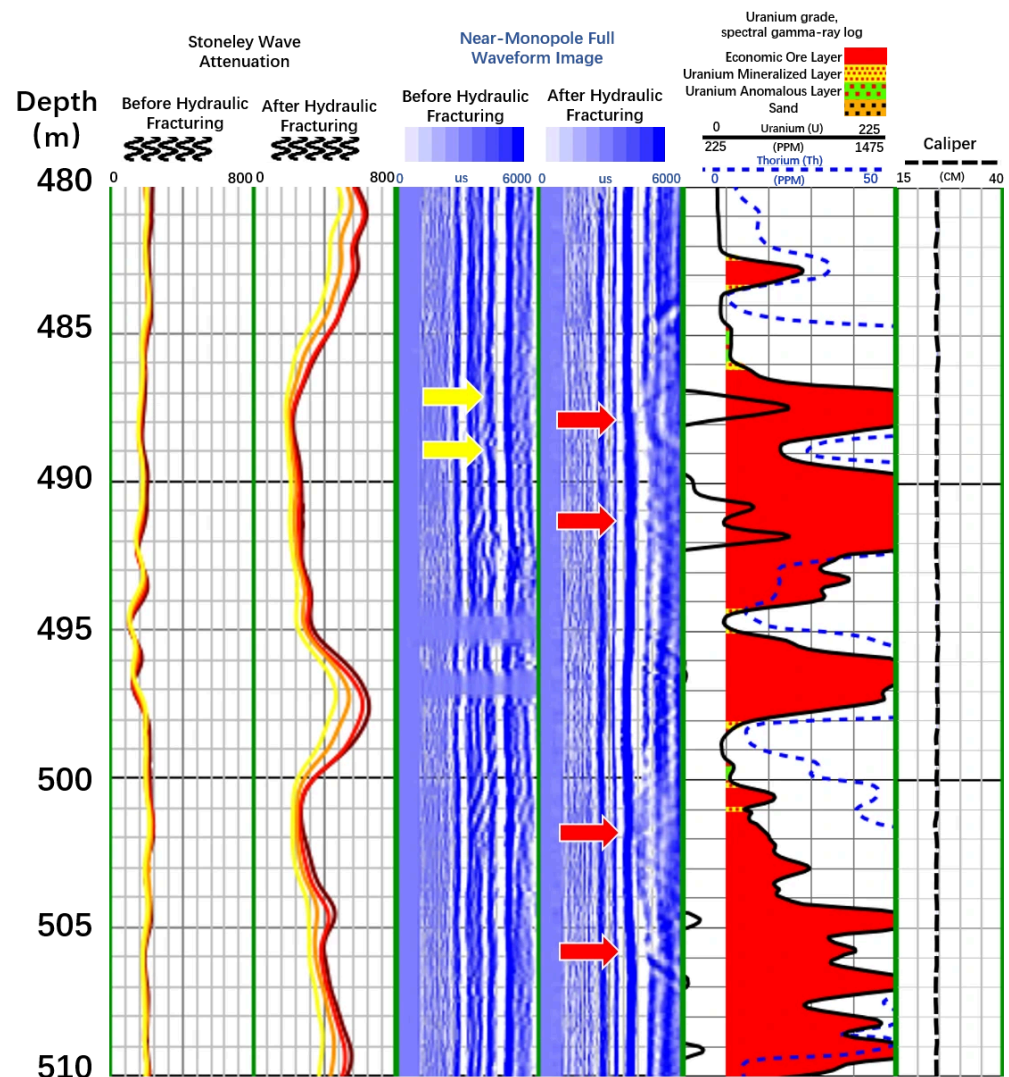


Figure 12. Array acoustic logging and conventional logging results before and after hydraulic fracturing (TZ-4).

(2) “Chevron” Feature Verification

A comparative analysis of waveform variable-density images was conducted for well TK-1. Comparison between pre- and post-fracturing monopole variable-density images indicates that, at the uranium-bearing interval, the post-fracturing Stoneley wave exhibits a distinct “chevron” pattern, suggesting that the uranium-bearing formation has been effectively opened. The upper fracturing interval (Figure 4) shows the most pronounced chevron characteristics, while the lower fracturing interval (Figure 4) and deeper sections also exhibit interface reflection features, although with relatively weaker attenuation.

The apex depths of the chevron patterns are 489.5 m, 492.5 m, 507.0 m, and 511.0 m, corresponding to abrupt changes in formation interfaces (red arrows in Figure 10). The depth intervals exhibiting post-fracturing energy attenuation relative to the pre-fracturing condition are interpreted as fractured and damaged zones, including 487.0–493.0 m, 496.0–499.0 m, 504.5–507.0 m, and 511.0–513.0 m.

(3) Removal of Interference Factors

The chevron features were further cross-validated with natural gamma-ray spectrometry logs, borehole enlargement (caliper) data, and electrical imaging logging results from well TK-1 (Figure 6a). This comparison was used to eliminate potential interference from lithological boundaries and borehole enlargement effects that could generate false

chevron-like patterns. As shown in Figure 10, combined interpretation indicates that such non-fracturing-related effects can be effectively excluded. Electrical imaging results (Figure 6a) further confirm the removal of formation-related and natural fracture-related interference. Integrated analysis suggests that the uranium-bearing formation has been successfully stimulated by hydraulic fracturing.

4.1.2. Analysis for TZ-3

The TZ-3 well was not subjected to open-hole array acoustic or electrical imaging logging. Because the pre-fracturing data were acquired after perforation, the formation had already been opened at that time; therefore, the pre- and post-fracturing logging responses are generally consistent. As a result, the logging data acquired over the fracturing interval of 503–506 m in TZ-3 are not available for evaluation.

(1) Calculation of the Relative Stoneley Attenuation Index

A comparative analysis of Stoneley-wave attenuation and full-waveform image data was conducted over the fracturing interval of 498–498 m in well TZ-3 (Figure 3). Compared with the pre-fracturing condition, the post-fracturing data indicate energy attenuation over several depth intervals, including 479–482 m, 485–490 m, and 494–496 m.

The Relative Stoneley Attenuation Index (RSAI) for well TZ-3 was calculated using Equation (1), and the results are presented in Table 3. The Stoneley-wave attenuation values from the interval of 343–348 m, located above the fracturing section and characterized by the same lithology with no anomalous logging responses, were selected as the background reference. After fracturing, the relative increase in Stoneley-wave attenuation at the fracture locations ranges from approximately 2% to 17.5%.

Table 3. Relative Stoneley Attenuation Index (RSAI) for well TZ-3.

Depth (m)	$A_{bg,post}$	$A_{f,post}$	$A_{bg,pre}$	$A_{f,pre}$	RSAI
479 m	640	208	640	320	17.5%
487 m	640	96	640	128	5%
494 m	640	160	640	176	2.5%

Compared with well TK-1, the variation in the RSAI for well TZ-3 is minimal, which also reflects the influence of acquiring pre-fracturing data after perforation on the observational results.

(2) Chevron Feature Verification

A full-waveform image comparative analysis was conducted for well TZ-3. Comparison of the pre- and post-fracturing monopole variable-density images indicates that, near the main uranium-bearing interval, reflection interfaces are observed after fracturing, while only minor differences exist between the pre- and post-fracturing responses. The most pronounced features are observed at the top of the upper fracturing interval (Figure 3) and in the overlying fracture zones. A distinct chevron pattern is present in the Stoneley-wave variable-density image, accompanied by significant Stoneley-wave amplitude attenuation.

(3) Removal of Interference Factors

The locations of the observed chevron features were further cross-validated with natural gamma-ray spectrometry logging results from well TZ-3 to eliminate the influence of interference patterns caused by lithological boundaries and other stratigraphic effects. The results are presented in Figure 11. Integrated interpretation indicates that these interference factors can be effectively excluded. The combined analysis suggests that the uranium-bearing formation has been effectively fractured and subsequently reworked by hydraulic stimulation.

4.1.3. Analysis for TZ-4

Well TZ-4, serving as a hydraulic fracturing monitoring well, was subjected to pre- and post-fracturing array acoustic logging, including open-hole logging before fracturing and post-fracturing measurements. A comparative analysis of Stoneley-wave attenuation was conducted over the depth interval of 480–510 m in well TZ-4. The comparison between pre- and post-fracturing data indicates that the relative amplitude of Stoneley-wave attenuation increased after hydraulic fracturing.

(1) Calculation of the Relative Stoneley Attenuation Index

The Relative Stoneley Attenuation Index (RSAI) for well TZ-4 was calculated using Equation (1), and the results are presented in Table 4. The Stoneley-wave attenuation values from the interval of 345–350 m, located above the fracturing section and characterized by the same lithology with no anomalous logging responses, were selected as the background reference. After fracturing, the relative Stoneley-wave attenuation at fracture-related intervals increased by approximately 113–228%.

Table 4. Relative Stoneley Attenuation Index (RSAI) for well TZ-4.

Depth (m)	$A_{bg,post}$	$A_{f,post}$	$A_{bg,pre}$	$A_{f,pre}$	RSAI
487 m	720	272	240	160	153%
488 m	720	224	240	160	173%
489 m	720	256	240	160	160%
501 m	720	172	240	240	228%
506 m	720	400	240	192	113%

(2) Chevron Feature Verification

A comparative analysis of full-waveform images was conducted for well TZ-4. Comparison of open-hole array acoustic logging data and post-fracturing monopole variable-density images indicates that no chevron pattern was observed prior to hydraulic fracturing. After fracturing, however, chevron features appear in the array acoustic logging results at the top of both the upper perforation interval and the lower perforation interval within the main uranium-bearing formation.

The apex depths of the chevron patterns are 488.0 m, 491.5 m, 502.0 m, and 506.0 m, corresponding to abrupt formation interface changes (red arrows in Figure 12). The depth intervals exhibiting relative Stoneley-wave energy attenuation after fracturing include 486.0–495.0 m, 500.0–503.0 m, and 505.0–507.0 m, indicating the presence of induced fractures within these intervals.

(3) Removal of Interference Factors

The locations of the observed chevron features were cross-validated with natural gamma-ray spectrometry logs, borehole enlargement (caliper) data, and electrical imaging logging results from well TZ-4 (Figure 6b) to eliminate the influence of lithological boundaries and borehole enlargement effects that may generate false chevron-like interference patterns. The results are shown in Figure 12.

Based on the electrical imaging interpretation in Figure 6b, formation-related interference was further excluded. The image shows one conductive fracture and one resistive fracture at depths of 487 m and 489 m, respectively; however, no corresponding chevron pattern is observed in the pre-fracturing waveform variable-density image (yellow arrows in Figure 12). In addition, the pre-fracturing Stoneley-wave attenuation curve remains stable without significant amplitude variation, thereby excluding interference from natural fractures.

4.2. Evaluation of Hydraulic Fracturing Effectiveness

4.2.1. Hydraulic Fracturing Effectiveness

A comprehensive analysis of pre- and post-fracturing array acoustic logging data from wells TK-1, TZ-3, and TZ-4 indicates that Stoneley-wave attenuation consistently increases to varying degrees after hydraulic fracturing. In addition, a typical chevron reflection pattern is observed within the fracturing intervals, reflecting the initiation and development of hydraulic fractures.

For wells TK-1 and TZ-4, the relative Stoneley-wave attenuation increased by approximately 150% and 113–228%, respectively, indicating a pronounced fracturing response. In well TZ-3, the pre-fracturing data were acquired after perforation, resulting in relatively minor differences between pre- and post-fracturing measurements. Nevertheless, localized but distinct chevron features and enhanced Stoneley-wave attenuation are still identified within the main fracturing interval, with relative attenuation increases of approximately 2–17.5%, suggesting effective formation stimulation.

Integrated interpretation of natural gamma-ray spectrometry, caliper, and electrical imaging logging data was further conducted to eliminate interference from lithological boundaries, borehole enlargement, and natural fractures. The results confirm that the chevron patterns and Stoneley-wave attenuation anomalies identified from array acoustic logging reliably characterize hydraulic fracture development. These findings demonstrate that the target uranium-bearing formations in all three wells were successfully stimulated to varying extents. A summary of the fracturing effectiveness is provided in Table 5.

Table 5. Summary of hydraulic fracturing effectiveness.

Well ID	Well Type	RSAI	Chevron Apex Depth (s)	Interference Factors Excluded	Hydraulic Fracture Interval (s)	Remarks
TK-1	Hydraulic fracturing well	150%	489.5 m, 492.5 m, 507.0 m, 511.0 m	Interference from formation boundaries and borehole enlargement excluded.	487.0~493.0 m, 496.0~499.0 m, 504.5~507.0 m, 511.0~513.0 m	
TZ-3	Hydraulic fracturing well	2~17.5%	479 m, 487 m *, 494 m	Interference from formation boundaries and borehole enlargement excluded.	479~482 m, 485~490 m *, 494~496 m	* indicates that the influence of natural fractures at this anomalous point cannot be completely ruled out.
TZ-4	Hydraulic fracturing monitoring well	113~228%	488.0 m, 491.5 m, 502.0 m, 506.0 m	Two natural fractures identified in electrical imaging logs.	486.0~495.0 m, 500.0~503.0 m, 505.0~507.0 m	

4.2.2. Validation Using Independent Experimental Evidence

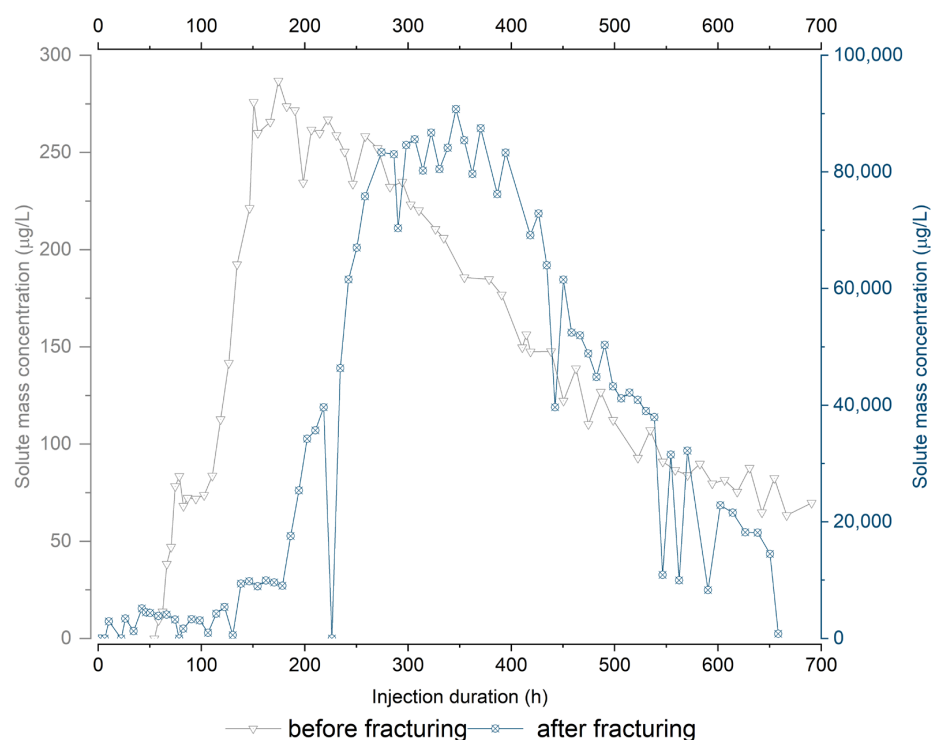
(1) Tracer Test

To verify the effectiveness of hydraulic fracturing, tracer tests using a common source were conducted in the study area before and after fracturing, as shown in Table 6.

Table 6. Tracer test information.

	Pre-Fracturing	Post-Fracturing	Remarks
Tracer Injection Well	TK-1	TK-1	
Tracer Type	Methanol	Ethanol	
Tracer Mass Injected	160 kg	160 kg	
Tracer Injection Method	Instantaneous injection	Instantaneous injection	
Tracer Monitoring Well	TZ-2, TZ-3, TZ-4	TZ-2, TZ-3, TZ-4	
Duration of Tracer Test	700 h	700 h	
Injection Rate at Injection Well(s) during Tracer Test	1.6 m ³ /h	1 MPa stage: 1.2 m ³ /h; 3 MPa stage: 2.50 m ³ /h; 5 MPa stage: 2.91 m ³ /h	TK-1 is injection well.
Average Production Rate at Production Well(s) during Tracer Test	4 m ³ /h	4 m ³ /h	TZ-1, TZ-2, TZ-3, and TZ-4 are production wells.

By comparing the tracer migration velocity, breakthrough time, and concentration variation between pre- and post-fracturing conditions, the evolution of hydraulic connectivity between the tracer injection well (TK-1) and the monitoring/production wells (TZ-1, TZ-2, TZ-3, and TZ-4) can be directly evaluated. The solute breakthrough curves of borehole TZ-4 before and after hydraulic fracturing are shown in Figure 13.

**Figure 13.** Tracer breakthrough curves of TZ-4 before and after hydraulic fracturing.

Prior to hydraulic fracturing, the tracer peak concentration in TZ-4 was approximately 280 µg/L, indicating relatively weak hydraulic connectivity between wells TK-1 and TZ-4. After fracturing, the tracer peak concentration at TZ-4 increased sharply to approximately 100,000 µg/L, representing an increase of about 357 times. This significant increase demon-

states that an extremely efficient hydraulic conduit was established between TK-1 and TZ-4 after fracturing.

The tracer breakthrough time remained approximately 200 h both before and after fracturing. However, the pre-fracturing breakthrough at ~200 h was associated with a low peak concentration (280 µg/L), indicating that tracer migration occurred through a long and highly tortuous flow path with limited connectivity. In contrast, the post-fracturing breakthrough at a similar time (approximately 200 h) was accompanied by a very high peak concentration of 90,776 µg/L, suggesting the formation of a near-direct, high-conductivity preferential fracture pathway connecting the injection and production wells.

(2) Validation of In Situ Stress Orientation

The orientation of in situ stress is closely related to the azimuths of borehole breakouts and drilling-induced fractures. During drilling, the release of tectonic stress commonly generates systematic drilling-induced fractures and borehole breakouts. Therefore, the orientation of the maximum and minimum principal stresses can be determined by analyzing the azimuthal distribution of these features on borehole image logs.

Interpretation of electrical imaging logging data indicates that multiple sets of drilling-induced fractures are developed in the logged interval of well TZ-1 (Figure 14). Based on the orientation of these induced fractures, the present-day maximum horizontal principal stress in the study area is inferred to trend in a northwest–southeast direction, with an azimuth of approximately 120.0–300.0°. Since hydraulic fractures preferentially propagate perpendicular to the minimum horizontal stress and parallel to the maximum horizontal principal stress, the induced fracture network in the study area is generally expected to exhibit a northwest–southeast orientation.

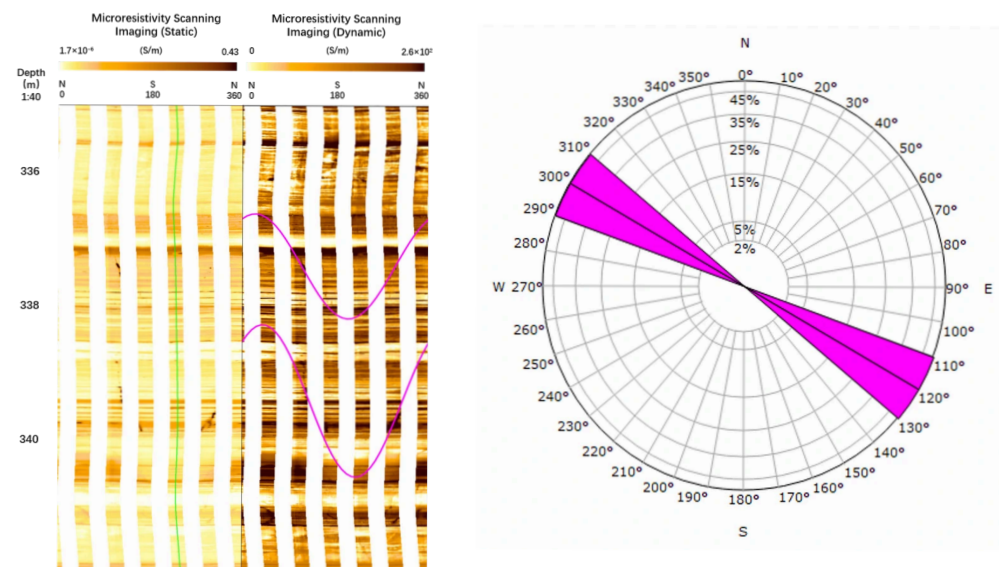


Figure 14. Electrical imaging-based fracture identification results in well TZ-1 (left) and analysis of the maximum horizontal principal stress orientation (right).

The spatial alignment of wells TK-1 and TZ-4 also follows a northwest–southeast trend (Figure 5), which is consistent with the orientation of the regional maximum horizontal principal stress. This stress-aligned well configuration provides a favorable geomechanical condition for hydraulic fractures initiated in well TK-1 to propagate toward well TZ-4, thereby facilitating effective hydraulic connectivity between the two wells.

5. Conclusions

This study addresses the challenge of evaluating hydraulic fracturing effectiveness in tight sandstone uranium reservoirs under a stress regime characterized by high horizontal stress and relatively low vertical stress. A semi-quantitative evaluation method was developed based on the integrated interpretation of array acoustic logging, electrical imaging logging, and conventional logging data, and its effectiveness was validated through field experiments. The main conclusions are as follows:

(1) A semi-quantitative evaluation methodology suitable for high horizontal stress and low vertical stress conditions was established. The method integrates array acoustic logging and electrical imaging logging. First, the Stoneley-wave attenuation index within the fractured intervals is calculated, and anomalous zones associated with hydraulic fracturing are identified using both Stoneley-wave attenuation characteristics and the chevron patterns observed in waveform density images. Subsequently, conventional logging and electrical imaging data acquired before and after fracturing are jointly interpreted to exclude interference from borehole enlargement, lithological boundaries, and natural fractures. The final outputs include the identification of fracture development depth and fractured interval distribution, enabling a semi-quantitative assessment of hydraulic fracturing effectiveness in tight sandstone uranium reservoirs. This approach extends the applicability of conventional logging techniques for fracture evaluation under stress regimes dominated by high horizontal and low vertical principal stresses.

(2) The proposed method has been successfully applied in a field hydraulic fracturing test site for in situ leaching uranium recovery in the Bayingebi Basin, Inner Mongolia. Based on pre- and post-fracturing logging data, fracture networks in the two stimulation wells (TK-1 and TZ-3) were effectively identified, confirming that the fracturing operations achieved the expected reservoir stimulation. In addition, fracture development features were detected in monitoring well TZ-4 along the direction of the maximum horizontal principal stress, indicating that fractures propagated toward the monitoring well and established effective hydraulic connectivity between TK-1 and TZ-4. This interpretation is supported by independent experimental evidence. Field applications demonstrate that the proposed method can reliably identify hydraulic fractures and fractured intervals and provide semi-quantitative estimates of fracture development depth, showing strong robustness and engineering applicability.

(3) The semi-quantitative fracture network evaluation method developed in this study provides a reliable technical approach for assessing hydraulic fracturing effectiveness and investigating fracture propagation behavior in tight sandstone uranium reservoirs. However, the method does not directly yield quantitative geometric or petrophysical parameters such as fracture porosity, dip angle, length, area, or detailed reservoir properties. Moreover, it is not applicable to fracture systems generated under conditions where vertical stress exceeds horizontal stress. Therefore, its applicability is primarily limited to the identification and evaluation of low-angle and subhorizontal hydraulic fractures formed under high horizontal and low vertical stress conditions. Further research is required to achieve quantitative characterization of fracture geometry and associated reservoir parameters.

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Abbreviations

The following abbreviations are used in this manuscript:

ISL	In situ leaching
RSAI	Relative Stoneley Attenuation Index
LEAD	Log Evaluation and Application Desktop
GR	Gamma ray

References

1. Cai, Y.; Zhang, J.; Li, Z.; Guo, Q.; Song, J.; Fan, H.; Liu, W.; Qi, F.; Zhang, M. Outline of Uranium Resources Characteristics and Metallogenetic Regularity in China. *Acta Geol. Sin.-Engl. Ed.* **2015**, *89*, 918–937. [\[CrossRef\]](#)
2. Li, G.; Yao, J.; Song, Y.; Tang, J.; Han, H.; Cui, X. A Review of the Metallogenetic Mechanisms of Sandstone-Type Uranium Deposits in Hydrocarbon-Bearing Basins in China. *Eng* **2023**, *4*, 1723–1741. [\[CrossRef\]](#)
3. Zheng, F.; Teng, Y.; Zhai, Y.; Hu, J.; Dou, J.; Zuo, R. Geo-Environmental Models of In-Situ Leaching Sandstone-Type Uranium Deposits in North China: A Review and Perspective. *Water* **2023**, *15*, 1244. [\[CrossRef\]](#)
4. Meng, L.; Ning, H.; Jiang, W.; Sheng, Y.; Wang, W.; Tang, C. Comprehensive Study on Hydrogeological Conditions and Suitability Evaluation of In Situ Leaching for Sandstone-Hosted Uranium Deposit in Erlian Basin. *Water* **2024**, *16*, 2785. [\[CrossRef\]](#)
5. Tang, C.; Xu, Z.; Duan, M.; Meng, L.; Liu, H.; Wei, J.; Zhang, C.; Zhao, L. Genetic Model of the Luhai Sandstone-Type Uranium Deposit in the Erlian Basin, Inner Mongolia. *Minerals* **2025**, *15*, 294. [\[CrossRef\]](#)
6. Hu, X.; Yang, X.; Wu, Z.; Ren, Y.; Miao, P. Sedimentological, petrological, and geochemical constraints on the formation of the Beisantai sandstone-type uranium deposit, Junggar Basin, NW China. *Ore Geol. Rev.* **2022**, *141*, 104668. [\[CrossRef\]](#)
7. Li, G.; Yao, J. A Review of In Situ Leaching (ISL) for Uranium Mining. *Mining* **2024**, *4*, 120–148. [\[CrossRef\]](#)
8. Niu, Q.; Hu, M.; He, J.; Zhang, B.; Su, X.; Zhao, L.; Pan, J.; Wang, Z.; Du, Z.; Wei, Y. The chemical damage of sandstone after sulfuric acid-rock reactions with different duration times and its influence on the impact mechanical behaviour. *Heliyon* **2023**, *9*, e22346. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Zhu, W.; Khirevich, S.; Patzek, T.W. Impact of Fracture Geometry and Topology on the Connectivity and Flow Properties of Stochastic Fracture Networks. *Water Resour. Res.* **2021**, *57*, e2020WR028652. [\[CrossRef\]](#)
10. Wang, M.; Gan, Q.; Wang, T.; Ma, Y.; Yan, C.; Benson, P.; Wang, X.; Elsworth, D. Propagation and complex morphology of hydraulic fractures in lamellar shales based on finite-discrete element modeling. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2024**, *10*, 71. [\[CrossRef\]](#)
11. Liu, G.; Zhao, Y.; Cheng, Y. Experimental Study on the Fracture Behaviors Effect of Stress Conditions on the Fracture of Shale by Super-Critical Carbon Dioxide. *Front. Energy Res.* **2021**, *9*, 763052. [\[CrossRef\]](#)
12. Abdiev, A.R.; Wang, J.; Mambetova, R.S.; Abdiev, A.A.; Abdiev, A.S. Geomechanical assessment of stress-strain conditions in structurally heterogeneous rock masses of Kyrgyzstan. *Eng. J. Satbayev Univ.* **2025**, *147*, 31–39. [\[CrossRef\]](#)
13. Obradors-Prats, J.; Rouainia, M.; Aplin, A.C.; Crook, A.J.L. Assessing the implications of tectonic compaction on pore pressure using a coupled geomechanical approach. *Mar. Pet. Geol.* **2017**, *79*, 31–43. [\[CrossRef\]](#)
14. Jamet, M.; Ballas, G.; Soliva, R.; Gerbeaud, O.; Lefebvre, T.; Leredde, C.; Loggia, D. Naturally fractured reservoir characterisation in heterogeneous sandstones: Insight for uranium in situ recovery (Imouraren, Niger). *Solid Earth* **2024**, *15*, 895–920. [\[CrossRef\]](#)
15. Zeng, F.; Gong, G.; Zhang, Y.; Guo, J.; Jiang, J.; Hu, D.; Chen, Z. Fracability evaluation of shale reservoirs considering rock brittleness, fracture toughness, and hydraulic fracturing-induced effects. *Geoenergy Sci. Eng.* **2023**, *229*, 212069. [\[CrossRef\]](#)
16. Gao, S.; Deng, W.; Wang, J.; Xu, M. Wide-field electromagnetic method for deep hot dry rock fracturing monitoring: Penetrating thick low-resistivity overburden. *Front. Earth Sci.* **2025**, *13*, 1579468. [\[CrossRef\]](#)
17. Cai, M.; Wu, H.; Xin, Y.; Liu, P.; Zhang, C.; Tang, J.; Lin, M.; Tan, L. Experimental Study on Shear Wave Transmission in Fractured Media. *Sensors* **2022**, *22*, 4047. [\[CrossRef\]](#) [\[PubMed\]](#)

18. Kang, Z.; Zhang, Y.; Hou, B.; Chen, G.; Hao, X.; Qin, H.; Qin, W. Using the multi-component induction logging data to evaluate the geometric parameters of the hydraulic fracture. *J. Geophys. Eng.* **2022**, *19*, 1163–1179. [\[CrossRef\]](#)
19. Wei, X.; Cai, M.; Kong, C.; Zhao, D. Spatiotemporal evolution analysis of multiscale fracture dynamics in hydraulic shale stimulation via integrated acoustic emission and CT imaging. *Sci. Rep.* **2025**, *15*, 44451. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Huang, Y.; Zhu, J.; Li, Y.; He, L.; Fang, Z.; Chen, X. Experimental Study on Factors Influencing the Propagation of Hydraulic Fractures in Shale Reservoirs with Developed Natural Weak Planes. *Energies* **2025**, *18*, 1100. [\[CrossRef\]](#)
21. Dou, Y.; Qi, X.; Cui, W.; Ma, X.; Wang, Z. The Application of Migration Learning Network in FMI Lithology Identification: Taking Glutenite Reservoir of an Oilfield in Xinjiang as an Example. *Processes* **2025**, *13*, 2095. [\[CrossRef\]](#)
22. Li, N.; Liu, P.; Wu, H.; Li, Y.; Zhang, W.; Wang, K.; Feng, Z.; Wang, H. Development and prospect of acoustic reflection imaging logging processing and interpretation method. *Pet. Explor. Dev.* **2024**, *51*, 839–851. [\[CrossRef\]](#)
23. Qi, X.; Wei, Y.; Wang, S.; Wang, Z. Finite Element Simulation of Stoneley Wave Propagation in Fracture Zones in Wells. *Mathematics* **2024**, *12*, 3511. [\[CrossRef\]](#)
24. Li, S.; Chen, W.; Sun, X.; Jiang, L.; Hou, Y.; Sun, H.; Shi, P.; Wen, R. Method for Evaluating Formation Fracturing Effect Utilizing Array Acoustic Logging. *Well Logging Technol.* **2025**, *49*, 636–642+652. [\[CrossRef\]](#)
25. Sun, X.; Yu, C.; Zhang, H.; Zhou, J.; Liu, X. Application of Multi-scale Borehole Acoustics Imaging Technology to Fracturing Effects Evaluation. *Well Logging Technol.* **2024**, *48*, 157–162. [\[CrossRef\]](#)
26. Qi, X.; Zhang, Z.; Li, D.; Yi, L.; Yu, Y. Evaluation of Fracturing Effects in Offshore Sandstone Reservoirs Based on Array Acoustic Logging Technology. *Pet. Drill. Tech.* **2023**, *51*, 128–134. [\[CrossRef\]](#)
27. Li, N.; Liu, P.; Fan, H.; Hu, J.; Wu, H. Evaluation Method of Downhole Multi-Scale Fracturing Effect Based on Array Acoustic Logging. *Pet. Drill. Tech.* **2024**, *52*, 1–7. [\[CrossRef\]](#)
28. Ju, W.; Shen, J.; Qin, Y.; Meng, S.; Wu, C.; Shen, Y.; Yang, Z.; Li, G.; Li, C. In-situ stress state in the Linxing region, eastern Ordos Basin, China: Implications for unconventional gas exploration and production. *Mar. Pet. Geol.* **2017**, *86*, 66–78. [\[CrossRef\]](#)
29. Garagash, D.I. Cohesive-zone effects in hydraulic fracture propagation. *J. Mech. Phys. Solids* **2019**, *133*, 103727. [\[CrossRef\]](#)
30. Yarmohammadi, S.; Javaherian, A.; Sharifi, M.; Saberi, M.R.; Mahdavi Basir, H. Investigating the source of acoustic anisotropy in the Asmari Formation, a fractured carbonate reservoir, using a well in the Southwest Iran. *Sci. Rep.* **2025**, *16*, 3754. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Arias Ortiz, D.A.; Klimkowski, L.; Finkbeiner, T.; Patzek, T.W. The Effect of Hydraulic Fracture Geometry on Well Productivity in Shale Oil Plays with High Pore Pressure. *Energies* **2021**, *14*, 7727. [\[CrossRef\]](#)
32. Shen, J.; Qin, Y.; Li, Y.; Yang, Y.; Ju, W.; Yang, C.; Wang, G. In situ stress field in the FZ Block of Qinshui Basin, China: Implications for the permeability and coalbed methane production. *J. Pet. Sci. Eng.* **2018**, *170*, 744–754. [\[CrossRef\]](#)
33. Alalli, A.A.; Zoback, M.D. Microseismic evidence for horizontal hydraulic fractures in the Marcellus Shale, southeastern West Virginia. *Lead. Edge* **2018**, *37*, 356–361. [\[CrossRef\]](#)
34. Xiang, Z.; Yu, S.; Wang, X. Modeling the Hydraulic Fracturing Processes in Shale Formations Using a Meshless Method. *Water* **2024**, *16*, 1855. [\[CrossRef\]](#)
35. Huang, B.; Wang, H.; Chen, H.; Li, Q. Applications of cross-dipole acoustic logging for formation fracture and anisotropic identifications. *ASEG Ext. Abstr.* **2007**, *2007*, 1–4. [\[CrossRef\]](#)
36. Li, H.; Tang, X.; Li, S.; Su, Y. Dynamic fluid transport property of hydraulic fractures and its evaluation using acoustic logging. *Pet. Explor. Dev.* **2022**, *49*, 223–232. [\[CrossRef\]](#)
37. Lu, C.; Zhang, Z.; Jiao, Y.; Li, Z.; Yuwen, X.; Zhuang, Y.; Jin, C.; Zhang, C.; Zhong, W.; Wang, Q. Key Ore-Controlling Factors and Genetic Model of the Tamusu Super-Large Sandstone-Type Uranium Deposit, Bayingobi Basin. *Minerals* **2026**, *16*, 357. [\[CrossRef\]](#)
38. Zhang, K.; Liu, R.; Liu, Z.; Li, B.; Liu, G.; Yan, X.; Li, L. Terrestrial records of Early Cretaceous paleoclimate fluctuations in the Yin'e Basin, northern China: Evidence from sedimentology and palynomorphs in lacustrine sediments. *Sediment. Geol.* **2022**, *432*, 106110. [\[CrossRef\]](#)
39. Chen, X.; Zhou, J.; Zhang, J.; Ma, X.; Yu, C.; Fan, Q.; Duan, X.; Du, Q.; Ni, L.; Liu, Y. Logging Data Visualization System: Architecture, Scalability, and Applications. In *Proceedings of the 2025 International Conference on Computer, Internet of Things and Smart City (CIoTSC)*, Suzhou, China, 7–9 November 2025; IEEE: Piscataway, NJ, USA, 2025; pp. 1–7.

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