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Geophysical prediction and evaluation of lacustrine shale oil and gas: Applications in the Fuxing area

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Abstract

The lacustrine shale reservoirs of Jurassic age in China's Sichuan Basin contain multiple hydrocarbon-bearing intervals and host substantial shale oil reserves, making them promising candidates as a significant replacement resource base for the region's petroleum production. However, the efficient exploration and development of lacustrine shale is confronted with two key geophysical challenges. Specifically, the first challenge involves identifying the location of the "sweet spot" with a primary emphasis on the engineering "sweet spot," characterized by critical parameters such as brittleness index and stress. The second challenge pertains to evaluating the effectiveness of hydraulic fracturing. To address these challenges, we first use engineering "sweet spot" seismic prediction technology to delineate the most favorable engineering zones, which subsequently guide well deployment and the design of horizontal well trajectories. We then use microseismic monitoring to assess the effects of hydraulic fracturing. Finally, we integrate these two technologies to form a complete geophysical workflow and conduct a comprehensive interpretation to understand the primary controlling factor. This integrated geophysical workflow effectively evaluated lacustrine shale reservoirs in the Sichuan Basin of China, providing robust recommendations for subsequent well placement, well trajectory design, and enhancing development efficiency in this complex geological setting. The analysis in this paper indicates that the brittleness index was the primary controlling factor in this geological setting, with higher values consistently corresponding to more microseismic events, and more extensive fracture networks.

Keywords: Lacustrine shale oil and gas; “Sweet spot” prediction; Brittleness; Differential horizontal stress ratio index; Microseismic monitoring; Comprehensive interpretation

1. Introduction

Recently, significant progress has been achieved in the exploration of marine shale gas within China’s Sichuan Basin, leading to the successful commercial development of this resource.¹ In contrast, the Jurassic lacustrine shale oil and gas resources in the same region have not yet reached a comparable stage of development. Marine shale gas deposits are characterized by several distinct geological features that contribute to their commercial viability. These include extensive and stable lateral distributions, considerable burial depths, relatively substantial formation thicknesses, elevated concentrations of total organic carbon (TOC), and quartz content.² The geological characteristics of lacustrine shale formations, however, present a more complex scenario compared to their marine counterparts. Lacustrine shale typically exhibits shallower burial depths, thinner individual layers, intricate lithological associations with greater lithological variability, higher clay mineral content, more heterogeneous stress systems, more diverse fluid properties, and low permeability,³ all of which contribute to the challenges in their exploration and development. Commercial lacustrine shale recovery necessitates extensive hydraulic fracturing treatments to establish adequate reservoir contact and conductivity pathways. Focusing on the complex geological characteristics of lacustrine shale, identifying the “sweet spot,” assessing the effectiveness of hydraulic fracturing, and clarifying the factors that influence fracturing are key geophysical challenges.⁴

As one of the primary geophysical challenges in lacustrine shale studies, accurately identifying the double “sweet spot” is critical for guiding exploration and development efforts. This double “sweet spot” concept refers to formations that simultaneously satisfy the criteria of both geological and engineering “sweet spots.” Specifically, the geological “sweet spot” is defined by high TOC content and optimal thermal maturity, whereas the engineering “sweet spot” is characterized by favorable friability and brittle mechanical properties.^{5,6} In the subsequent analysis, particular attention will be devoted to the engineering “sweet spot” and its distinguishing characteristics within lacustrine shale systems.

The rock physics model is fundamental to the quantitative interpretation of engineering “sweet spots.” Organic-rich lacustrine shale exhibits anisotropic

characteristics, including both intrinsic anisotropy and fracture-induced anisotropy. Specifically, vertical transverse isotropy (VTI) arises from clay lamination, kerogen lamination, and horizontal fractures, while horizontal transverse isotropy (HTI) is induced by vertical fractures. Early theoretical foundations established that thin horizontal layering produces long-wave elastic anisotropy.⁷ Subsequent developments introduced anisotropic effective medium models tailored to shale formations, incorporating the impacts of clay mineral orientation and microstructural anisotropy on elastic properties and anisotropic behaviour.^{8,9} An orthorhombic medium model was later developed to characterize elastic wave propagation in vertically fractured geological formations, in which both VTI and HTI are considered.¹⁰ The lacustrine shale exhibits pronounced orthorhombic anisotropy characteristics; therefore, the adoption of an orthorhombic rock physics model is essential for accurate characterization. More recent advances have integrated the effects of compaction, clay preferred orientation, and stress-dependent anisotropy into rock physics modeling frameworks.^{11,12}

The key to predicting the engineering “sweet spot” of lacustrine shale lies in accurately estimating elastic and anisotropic parameters using an anisotropic rock physics model.¹³ Traditional approaches estimate key parameters, such as brittleness and stress parameters, using elastic parameters derived from isotropic amplitude variation with offset inversion technology.^{14–16} Building upon this foundation, subsequent advancements have integrated anisotropic medium theory with high-quality wide-azimuth seismic datasets to develop pre-stack amplitude variation with azimuth (AVAZ) inversion methodologies. These advanced techniques enable the three-dimensional (3D) spatial characterization of critical engineering “sweet spot” parameters.^{17–19} When combined with geological knowledge and geomechanical principles, these prediction results provide valuable guidance for well placement optimization and horizontal well path planning in lacustrine shale formations.^{20,21}

Focusing on the second critical geophysical challenge in lacustrine shale formations, evaluating hydraulic fracturing effectiveness and comprehending the influencing factors of fracturing play a vital role in achieving efficient development.^{22–23} Microseismic monitoring offers opportunities to re-evaluate fractured

zones and gain insights into the progression of completion performance.^{4,24} We utilize a practical and stable microseismic workflow that includes data acquisition, processing, and interpretation to accurately determine source locations and characterize the geometry of hydraulic fractures.^{25–28} Leveraging real-time interpretation results from microseismic monitoring, we optimize horizontal well drilling designs and fracturing plans, and enhance production efficiency. Collectively, microseismic monitoring stands as a critical technique for the exploration and development of lacustrine shale reservoirs.

To address the requirements for high-quality exploration and development of lacustrine shale formations, we develop a comprehensive workflow by integrating engineering “sweet spot” seismic prediction techniques with microseismic monitoring technologies, thereby enabling detailed characterization of shale reservoirs both before and during hydraulic fracturing operations. This integrated workflow was validated in field applications at the Fuxing lacustrine shale formation in the Sichuan Basin, where it significantly improved well placement, trajectory planning, and fracturing design parameter optimization.

2. Methods

The geophysical workflow for lacustrine shale primarily comprises two key technologies. First, it incorporates “sweet spot” seismic prediction. It is widely recognized that key parameters defining “sweet spot” encompass TOC content, brittleness index, and stress state, among others. In this study, the engineering “sweet spot,” encompassing both the brittleness index and the stress state, was the primary focus of analysis. We conducted quantitative seismic interpretation of the engineering “sweet spot” using pre-stack AVAZ inversion technology, thereby guiding well location deployment and horizontal well trajectory design. Second, the workflow involves microseismic monitoring, where we acquired, processed, and interpreted microseismic data to determine fracture geometry, enabling effective evaluation of hydraulic fracturing outcomes. Ultimately, we integrated “sweet spot” seismic prediction with microseismic monitoring to identify the primary controlling factor of hydraulic fracturing, thereby optimizing the fracturing plan in subsequent stimulation operations and improving the stimulated rock volume.

2.1. Rock physics modeling

The rock physics model establishes a quantitative correlation between reservoir properties and elastic parameters. The lacustrine shale has complex characteristics, including rapid facies transitions, heterogeneous lithological composition, high clay content, well-developed complex fractures, and the coexistence of

oil and gas accumulations. To characterize the complex petrophysical properties of the lacustrine shale, we constructed an orthorhombic rock physics model, as illustrated in Figure 1, taking into account key influencing factors. The implementation process involved the following steps: first, we computed the equivalent modulus for each mineral in the matrix using the isotropic differential effective medium (DEM) model. Second, we computed the elastic matrix of the VTI background medium using the Backus average method.⁷ Third, we added the horizontal fractures using the anisotropic DEM model.⁸ Fourth, we added the vertical fractures into the model through the linear slip theory of Schoenberg.¹⁰ Fifth, we computed the elastic modulus of pore fluid using the Voigt–Reuss weighted average. Sixth, we computed the orthorhombic elastic matrix of saturated rock matrix using the Brown–Korringa anisotropic fluid substitution formulation. Finally, an orthorhombic rock physics model specifically designed for lacustrine shale was established, enabling the computation of both elastic and anisotropic parameters for the study formation.

The orthorhombic rock physics model was successfully and effectively applied in the Fuxing area of Well-A. The input well logs included porosity, TOC, and mineralogical data (clay, quartz, and carbonate) (Figure 2). The predicted P- and S-wave velocities showed excellent agreement with the measured data, with an overall accuracy of 95%.

2.2. Stress prediction

Given the background of shale oil and gas exploration and development, the stress indicators included the magnitude and orientation of the differential horizontal stress ratio (DHSR), which serve as critical parameters for guiding well placement strategies and optimizing horizontal well trajectory design. The DHSR index is critical for hydraulic fracturing design because it controls fracture complexity and height growth. Low DHSR values indicate near-isotropic stress conditions favorable for complex fracture networks, while high values promote planar, bi-wing, and simple fracture networks.

In the present study, we analyzed stress magnitude and orientation predictions based on the pre-stack AVAZ inversion. The magnitude of the DHSR is defined as Equation 1:

$$\text{DHSR} = \frac{\sigma_H - \sigma_h}{\sigma_H} \quad (1)$$

where σ_H is the maximum horizontal principal stress and σ_h is the minimum horizontal principal stress, respectively.

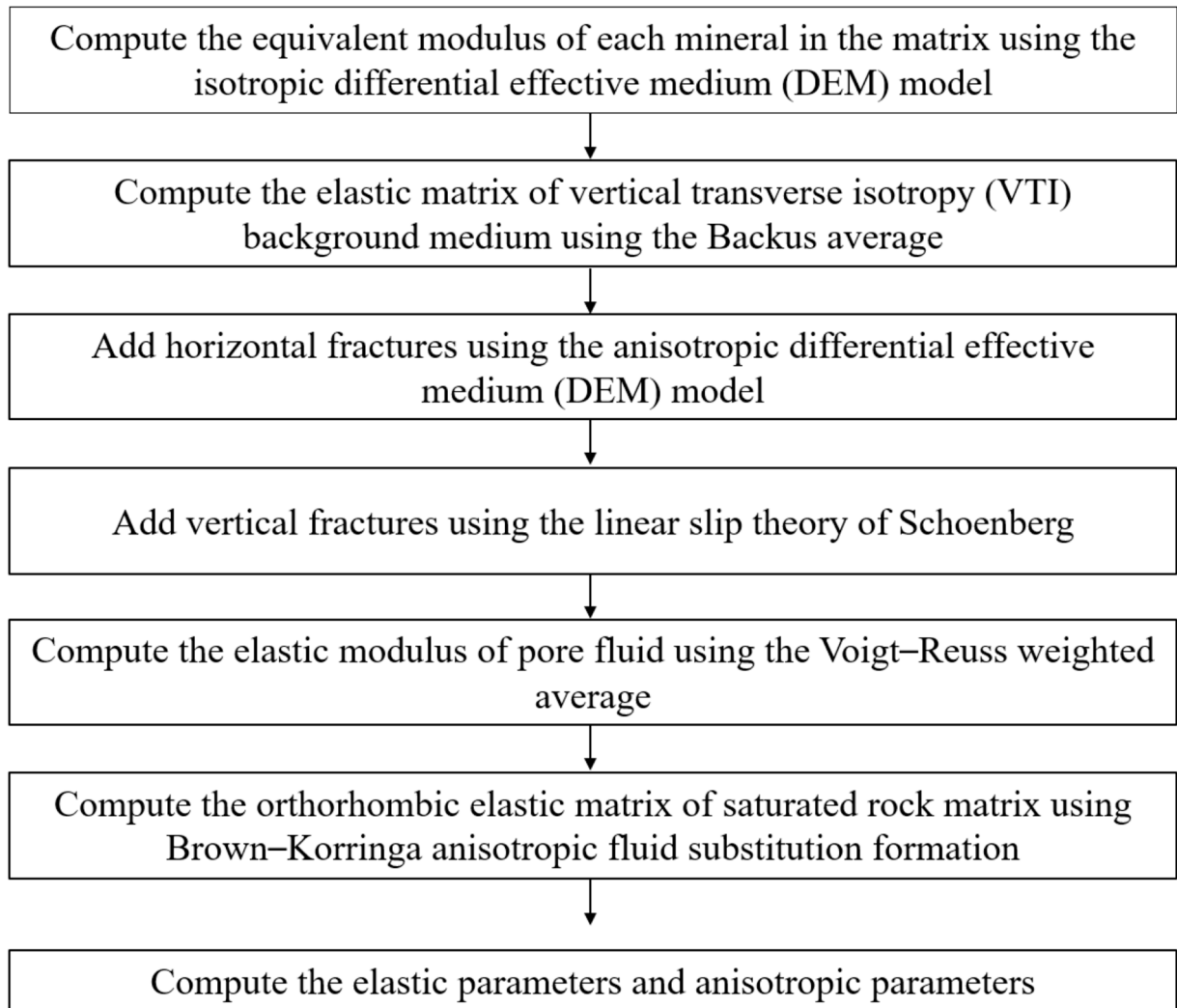


Figure 1. The lacustrine shale rock physics modeling workflow

Under the assumption of HTI anisotropy caused by vertically aligned fractures, DHSR can be related to seismic anisotropy parameters. To derive the DHSR formulation, we first adopted the HTI medium framework as proposed in previous studies,^{29,30} which is specifically defined as **Equation 2**:

$$\text{DHSR} = \frac{2I_p^2 \Delta N}{I_p^2 (1 - \Delta N) + 2I_s^2 \Delta N} \quad (2)$$

where I_p represents P-wave impedance, I_s represents S-wave impedance, and ΔN denotes the normal weakness parameter characterizing fracture compliance.

Second, we derived the pre-stack AVAZ inversion

formula by incorporating minor modifications to Shaw's equation,³¹ and this modified formulation can be expressed as **Equation 3**:³²

$$R_p(\theta, \varphi) = \sec^2 \theta R_p - 8g \sin^2 \theta R_s - (g \cos^2 \varphi \sin^2 \theta)(1 - 2g) \Delta N + (g \cos^2 \varphi \sin^2 \theta) \Delta T \quad (3)$$

where θ denotes the incident angle, φ is the angle difference between the survey line's azimuth and the fracture orientation, g denotes the squared ratio of S-wave to P-wave velocity, R_p denotes P-wave impedance reflection coefficient, R_s denotes S-wave impedance reflection coefficient, ΔN is defined as the normal weakness

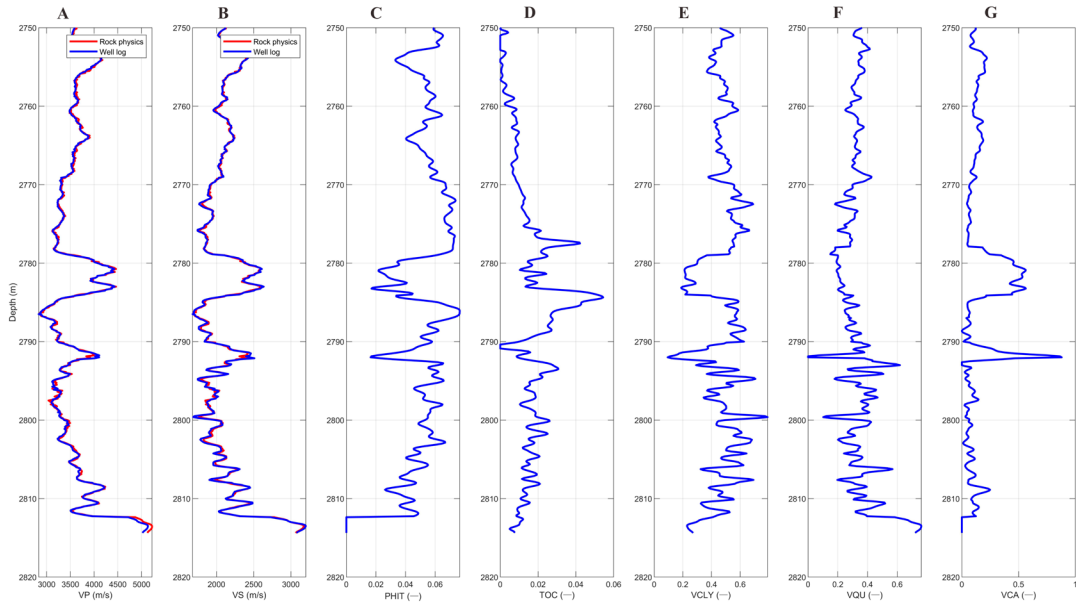


Figure 2. The orthorhombic rock physics modeling results of lacustrine shale. The well logs included (A) P-wave velocity, (B) S-wave velocity, (C) porosity, (D) total organic carbon (TOC), and mineralogical content of (E) clay, (F) quartz, and (G) carbonate. The blue curve indicates the measured well-log data, while the red curve indicates the rock physics-modeled results.

parameter of the fracture, and ΔT is defined as the tangential weakness parameter of the fracture.

According to convolution theory, seismic amplitude response can be represented as **Equation 4**:

$$d = G \cdot m \quad (4)$$

where d represents the observed data, G represents the forward operator, and m represents the model vector.

Assuming that seismic data background noise follows a Cauchy distribution, the correlation between real seismic data and reflection coefficients can be mathematically characterized through a likelihood function of a Cauchy distribution. By adding Cauchy constraints and model-constraint information, the stability and accuracy of the inversion are improved. The inversion estimation values can be obtained by solving the constructed inversion objective function. The specific form of the objective function is shown in **Equation 5**:

$$\begin{aligned} \min J(r') = & J_G(r') + J_{Cauchy}(r'_{lp}) \\ & + J_p(r'_{lp}) + J_s(r'_{ls}) \\ & + J_d(r'_{\Delta N}) + J_d(r'_{\Delta T}) \end{aligned} \quad (5)$$

where the first data misfit term describes the consistency between real seismic gathers and model-generated seismic gathers by the current model, ensuring consistency with measured data. The second term imposes a Cauchy sparsity constraint on the reflection coefficients, utilizing the heavy-tailed Cauchy distribution as a prior probability model, promoting sparse solutions in which significant reflectivity is concentrated at major geological boundaries. The remaining four terms are model-constraint terms that control the added low-frequency components, ensuring that the inversion results honor stratigraphic trends and petrophysical relationships. Taking the derivative of the objective function yields the final inversion equation shown as **Equation 6**:

$$(G^T G + \mu Q + P_3) \cdot m = (G^T d + Q_3) \quad (6)$$

where:

$$G = \begin{bmatrix} W \cdot a(\theta_1) & W \cdot b(\theta_1) & W \cdot c(\theta_1, \phi_1) & W \cdot d(\theta_1, \phi_1) \\ W \cdot a(\theta_2) & W \cdot b(\theta_2) & W \cdot c(\theta_2, \phi_2) & W \cdot d(\theta_2, \phi_2) \\ \vdots & \vdots & \vdots & \vdots \\ W \cdot a(\theta_l) & W \cdot b(\theta_l) & W \cdot c(\theta_l, \phi_n) & W \cdot d(\theta_l, \phi_n) \end{bmatrix} \quad (7)$$

$$P_3 = \alpha_{lp} C^T C' + \alpha_{ls} C^T C + \alpha_{\Delta N} C^T C + \alpha_{\Delta T} C^T C \quad (8)$$

$$Q_3 = \alpha_{lp} C^T \xi_{lp} + \alpha_{ls} C^T \xi_{ls} + \alpha_{\Delta N} C^T \xi_{\Delta N} + \alpha_{\Delta T} C^T \xi_{\Delta T} \quad (9)$$

$$\mu = \frac{2\sigma_n^2}{\sigma_m^2} \quad (10)$$

W is wavelet matrix, $a(\theta_i)$, $b(\theta_i)$, $c(\theta_i, \phi_n)$, $d(\theta_i, \phi_n)$ are model parameter coefficients of AVAZ formula,

$$C = \begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 1 \end{pmatrix} \text{ is the lower triangular summation}$$

matrix, α_{lp} , α_{ls} , $\alpha_{\Delta N}$, and $\alpha_{\Delta T}$ are the coefficient terms corresponding to the four parameters. Accounting for the thin-bed geological characteristic and well-logging responses of the lacustrine shale, we employ k-fold cross-validation to optimal μ and α parameters, thereby obtaining the stable, high-precision inversion results for elastic and anisotropic parameters. ξ_{lp} , ξ_{ls} , $\xi_{\Delta N}$ and $\xi_{\Delta T}$ are the reflection coefficients of the initial model. σ_n^2 is the noise variance, σ_m^2 is the model reflection coefficient variance. Q is the off-diagonal weighted matrix, and it is defined as follows:

$$Q_n = \begin{cases} \frac{1}{\left(\frac{r_n'^2}{2\sigma_1^2} + 1.0\right)^2}, n \leq N \\ \frac{\sigma_1^2}{\sigma_2^2} \frac{1}{\left(\frac{r_n'^2}{2\sigma_2^2} + 1.0\right)^2}, N < n \leq 2N \\ \frac{\sigma_1^2}{\sigma_3^2} \frac{1}{\left(\frac{r_n'^2}{2\sigma_3^2} + 1.0\right)^2}, 2N < n \leq 3N \\ \frac{\sigma_1^2}{\sigma_4^2} \frac{1}{\left(\frac{r_n'^2}{2\sigma_4^2} + 1.0\right)^2}, 3N < n \leq 4N \end{cases} \quad (11)$$

where σ_1 , σ_2 , σ_3 , and σ_4 are the singular value decomposition components of the sparse covariance matrix of the inversion parameters, and r_n' is the initial model reflection coefficient.

By deriving and calculating using the aforementioned mathematical equation, the desired inversion parameters can be effectively retrieved. The input dataset for this inversion process primarily included the following essential components: well-logging curves characterizing formation properties; azimuth-dependent seismic wavelets capturing azimuthal variation characteristics; prior geological models incorporating key parameters such as P-wave and

S-wave impedances; and azimuthally stacked seismic data volumes encompassing the study area. We had a brief discussion of uncertainty, which indicates that typical pre-stack gathers (signal-to-noise ratio $\sim 3-5$) can introduce $\pm 5-8\%$ relative uncertainty in final DHSR estimates and $\pm 7-10\%$ relative uncertainty in brittleness index estimates. Despite these uncertainties, the overall vertical and spatial trends remained geologically reasonable.

Finally, we used the elastic and anisotropic parameters obtained from the AVAZ inversion to compute DHSR. To address the problem of stress direction prediction, we used least-squares ellipse fitting to estimate orientation from wide-azimuth seismic datasets. By integrating these seismic-derived orientations with dipole acoustic logging measurements, we determined the minimum principal stress direction with enhanced reliability. Subsequently, we obtained the 3D spatial distribution of stress orientation and DHSR, thereby providing quantitative geomechanical constraints for optimal well placement and horizontal trajectory design.

2.3. Brittleness index prediction

The brittleness index is a critical parameter for identifying engineering “sweet spots,” directly governing the feasibility and effectiveness of hydraulic fracturing operations. This study presents a methodology for predicting a brittleness index based on pre-stack seismic inversion. To differentiate brittle from ductile lithologies, we first established the brittleness index through rock physics analysis, defined as the ratio of Young’s modulus to the Lamé constant. Higher values indicate increased brittleness in shale formations, whereas lower values signify greater ductility. The formulation is expressed as **Equation 12**:

$$Bi = E / \lambda \quad (12)$$

where B_i denotes brittleness index, and E and λ denote Young’s modulus and the Lamé constant.

This mathematical formula, represented by P-wave impedance and S-wave impedance, can be formulated as **Equation 13**:

$$Bi = \frac{I_s^2 (3I_p^2 - 4I_s^2)}{(I_p^2 - I_s^2)(I_p^2 - 2I_s^2)} \quad (13)$$

where I_p denotes P-wave and I_s denotes S-wave impedance.

The cross-plot of E/λ and E/σ (Figure 3) shows both of them have good correlation, and E/λ just need P-wave and S-wave impedance, which avoid density term, as we all known, the density inversion is difficult to obtain good

results.

Second, based on the elastic parameter inversion results from the AVAZ inversion analysis, we calculated the 3D brittleness index volume using both P-wave and S-wave impedance data. This approach enabled us to quantitatively characterize the brittleness properties of the target lacustrine shale formation using real data from the Sichuan Basin.

2.4. Microseismic monitoring

Microseismic monitoring is an effective tool for real-time characterization of hydraulic fracture propagation and for evaluating the effectiveness of hydraulic fracturing operations. We developed the technical workflow for surface microseismic fracturing monitoring, as illustrated in Figure 4. First, we developed a radially distributed ground-acquisition system specifically tailored for this work, enabling real-time detection of microseismic signals. It comprised 12 geophone arrays deployed in concentric rings centered on the treatment well pad, each

array consisting of 24 vertical-component geophones. Second, we focused on enhancing microseismic weak signals through a systematic processing workflow that included time–frequency spectral decomposition, strong-noise attenuation, band-pass filtering, amplitude-energy gain, trace balancing, adaptive filtering, and higher-order moment filtering. When microseismic signals were automatically identified using the short-term average/long-term average (STA/LTA) algorithm, the Pwave arrival picking uncertainty ranged from 1–5 ms for high-quality data and from 5–20 ms for moderate-quality data. Third, we conducted microseismic source location and inversion analysis to determine the specific location and magnitude of each microseismic event. Finally, a comprehensive interpretation was performed to characterize the hydraulic fracture geometry and evaluate the effectiveness of hydraulic fracturing. The microseismic data processing workflow is shown in Figure 4.

By integrating “sweet spot” seismic prediction with microseismic monitoring data, this study first evaluates

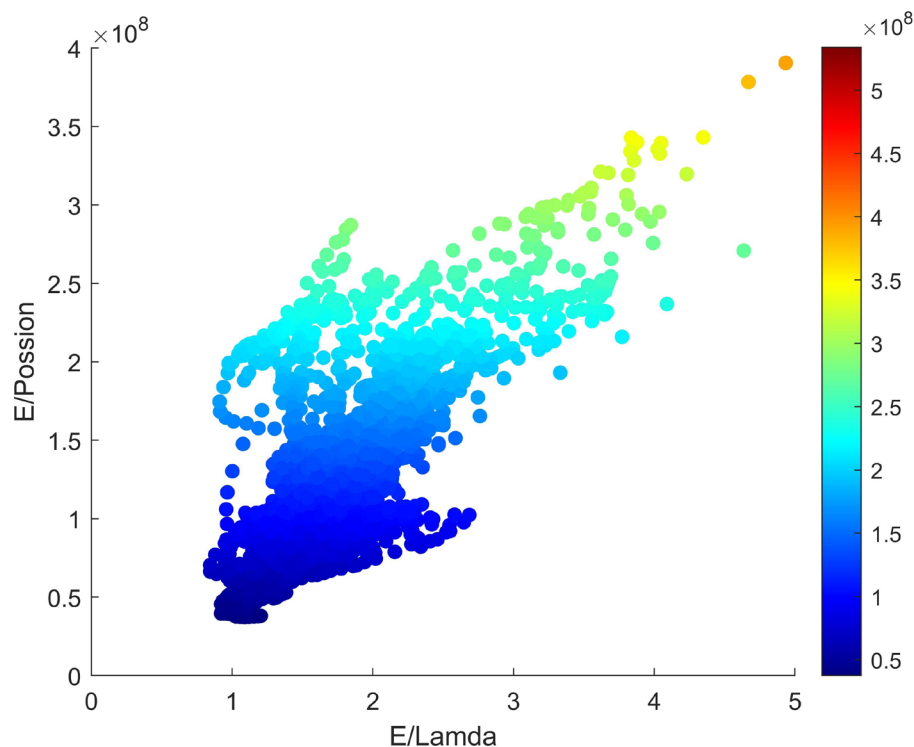


Figure 3. The Well-A cross plot of E/λ and E/σ ; the color bar is E/σ

Note: E is the Young's modulus, which represents the ratio of normal stress to normal strain in uniaxial tension/compression, and measures material stiffness or resistance to axial deformation. λ is the Lamé-constant, which is related to volumetric deformation, and describes material response to hydrostatic pressure. σ is the Poisson's ratio, which is the ratio of transverse contraction strain to axial elongation strain under uniaxial stress, and describes lateral deformation behavior of materials.

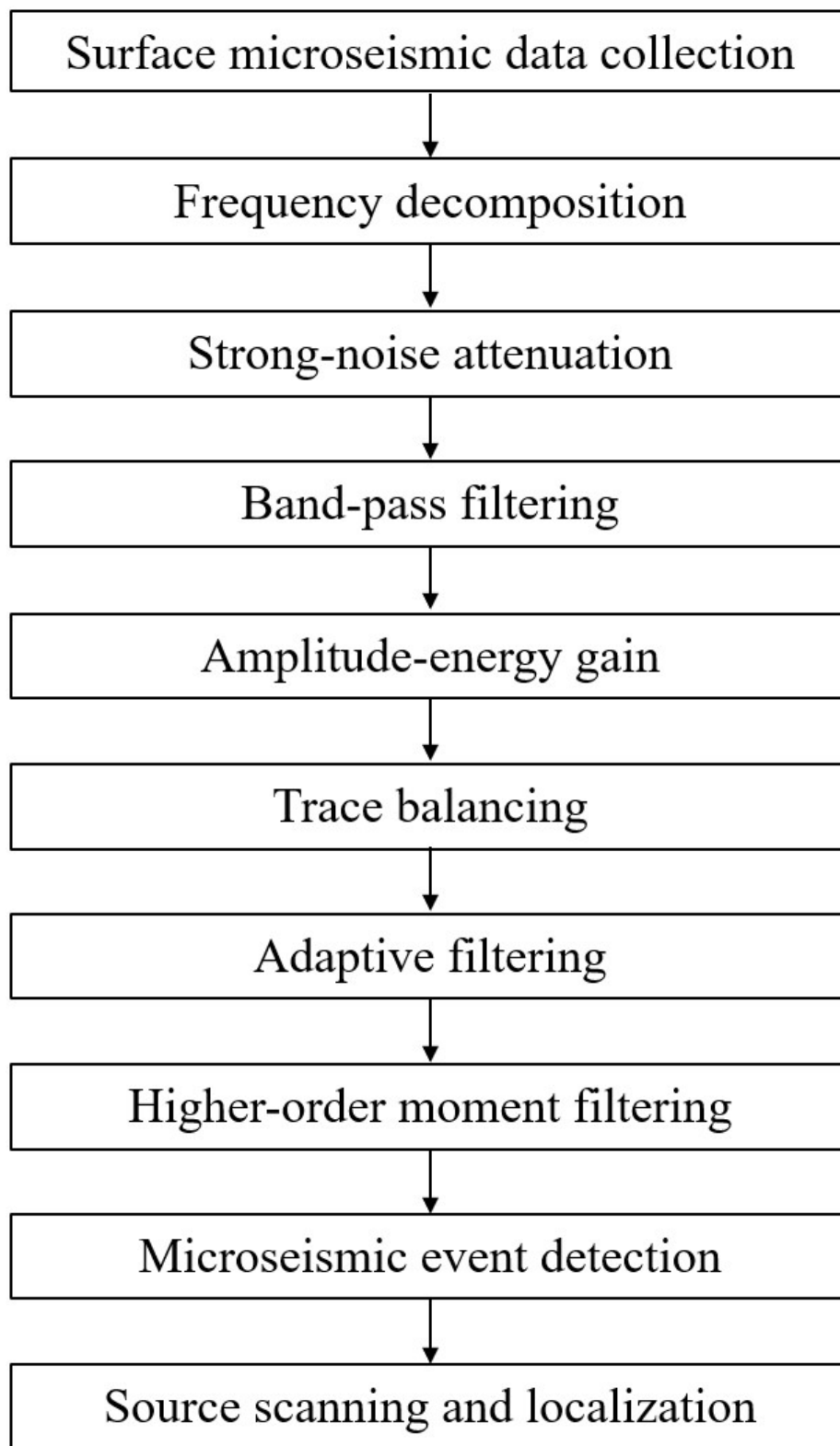


Figure 4. The microseismic data processing workflow

hydraulic fracturing performance and then analyzes the key controlling factors that govern its effects. This closed-loop workflow ensures continuous improvement in characterization accuracy and treatment effectiveness as more data are acquired throughout the oil and gas field exploration and development lifecycle. Building on the valuable insights and practical experiences from prior research and engineering practices, this study enables more precise well placement, optimized horizontal well trajectory design, and refined fracturing strategies tailored to the geological characteristics of the target formation. These comprehensive optimizations significantly enhance both production efficiency and economic viability of lacustrine shale oil and gas development in the Sichuan Basin.

3. Results

3.1. Work area overview

Southern China, particularly the Sichuan Basin, hosts substantial lacustrine shale reservoirs rich in organic matter. In contrast to North American shale systems, the Sichuan Basin's shale formations have undergone complex tectonic evolution involving multiple episodes of deformation, uplift, and erosion, resulting in intricate fracture networks and highly variable reservoir properties.³² The study area encompasses approximately 2,500 km² in the Fuxing region of the Sichuan Basin, where geological structures exhibit diverse features, including both anticlinal and synclinal formations. Specifically, our investigation focuses on a synclinal structure within the high-steep fold belt of the eastern Sichuan Basin, targeting the Jurassic-aged Dongyuemiao Formation (Figure 5). This formation exhibits gentle dip angles and comprises lacustrine shale reservoirs ranging in thickness from 80 to 150 m, at depths of 2,500–3,500 m. Well-A was initially drilled at the syncline center, followed by the deployment of a horizontal well group, comprising Well-A1, Well-A2, and Well-A3, and was subsequently hydraulically fractured. Production data from these wells indicate favorable oil and gas productivity.

A wide-azimuth, long-offset 3D seismic survey was acquired, processed, and interpreted to characterize lacustrine shale reservoirs for exploration and development (Figure 6). The 3D seismic survey was a high-fold (120-fold) wide-azimuth survey with a bin size of 25 m × 25 m. The data were processed using an offset vector tile pre-stack time migration with anisotropic velocity analysis, preserving azimuthal information for AVAZ inversion, and yielded magnitudes of DHSR and a brittleness index from the elastic and anisotropic parameters.

High-quality data were obtained and interpreted,

indicating that the study area lies between the yellow and pink lines, encompassing the main lacustrine shale body. This region contains extensive, laterally continuous shale reservoirs. The seismic data in this area had a high signal-to-noise (S/N) ratio. According to outcrops and logging data, the stable Lgs and J1dy formations were designated as potential reservoirs. The vertical logging data from Well-A, presented in Figure 2D, provide detailed insights into the basin's stratigraphic evolution. Within the target shale interval, TOC content ranged from 2% to 4% (Figure 2) and showed an overall increasing trend with depth. Furthermore, the target shale formation was characterized by well-developed roof and floor lithology that provide effective sealing conditions. These geological characteristics collectively indicate significant potential for lacustrine shale oil and gas exploration and development in this interval.

3.2. Comprehensive interpretation results

Following the offset vector tile pre-stack migration processing of the seismic data, wide-azimuth seismic gathers were generated. Pre-stack AVAZ inversion of these gathers yielded DHSR magnitudes and *in situ* stress directions (Figure 7). DHSR values across the study area ranged from 0.08 to 0.18 (Figure 7). The range of DHSR reflects geological variability; lower magnitudes indicate higher potential for complex fracture network development during hydraulic fracturing, whereas higher values tend to produce simpler fracture geometries. In Figure 8, the minimum principal stress direction derived from seismic data is compared with the maximum principal stress direction obtained from dipole acoustic logging in Well-A. These orientations exhibited a nearly orthogonal relationship, consistent with the observation that microseismic event propagation is approximately perpendicular to the minimum principal stress direction. This multi-source consistency verifies the reliability of the stress field characterization methodology. Building upon these findings, three horizontal well trajectories were strategically designed parallel to the minimum principal stress direction. This placement strategy was expected to reduce mechanical resistance during hydraulic fracturing and enhance fracture propagation efficiency, ultimately improving estimated ultimate recovery.

Following well placement and horizontal well trajectory design, microseismic monitoring and integrated interpretation were initiated. Surface microseismic acquisition employed a 12-line array comprising 2,026 active channels, enabling real-time processing throughout hydraulic fracturing operations. A total of 2,640 microseismic events were identified across 88 fracturing stages, with magnitudes ranging from −1.98

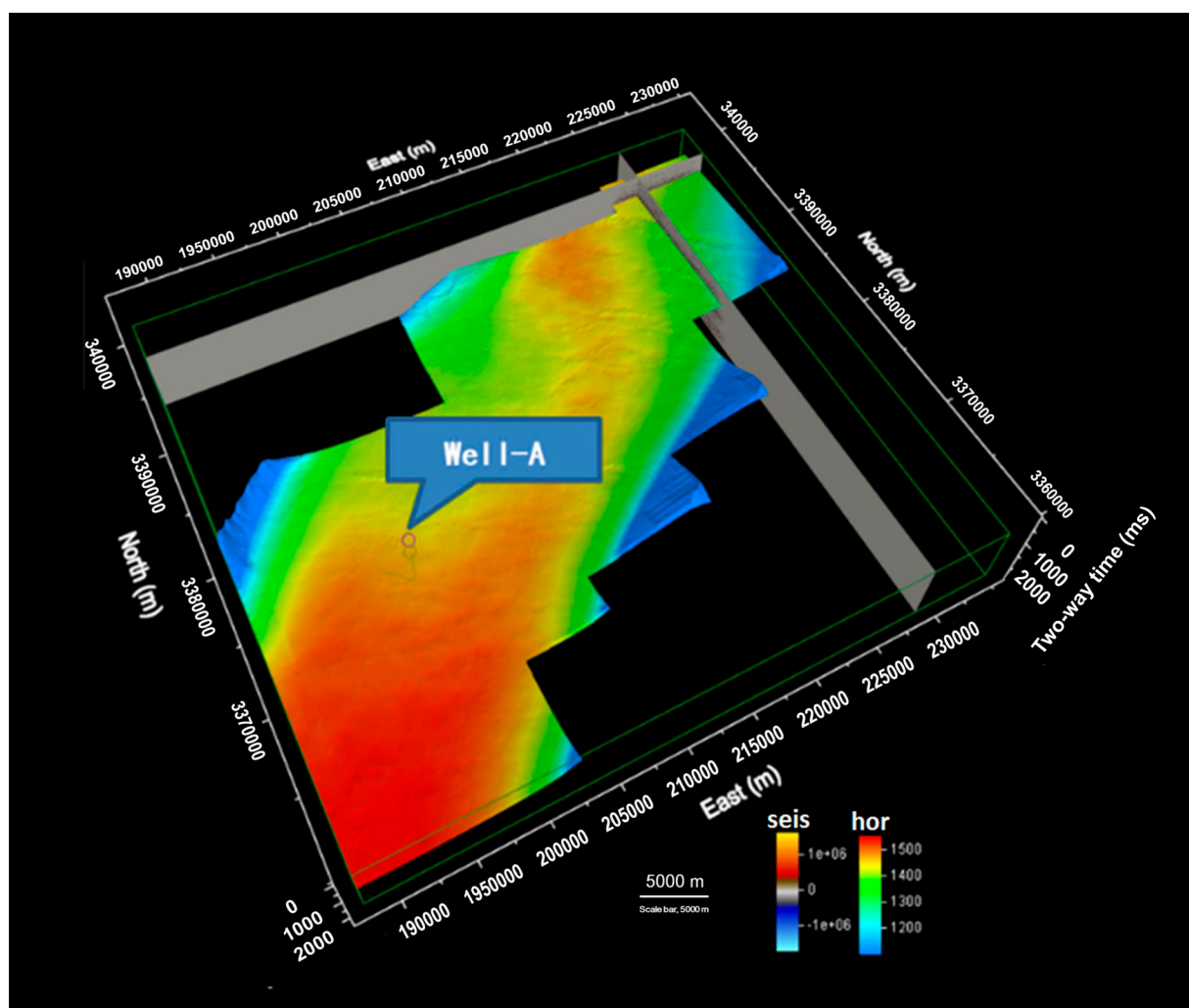


Figure 5. The three-dimensional structural map of the target shale interval. Well-A is positioned at the center. Scale bar: 5,000 m. Abbreviations: seis: Seismic; hor: Horizon.

to -1.08 . Event locations were determined using a robust source-location algorithm. The spatial distribution of microseismic events is shown in Figure 9. Second, based on the observed fracture geometry, there are evident remaining spaces between adjacent wells in the current 300 m well-spacing configuration. Consequently, the fracture spacing in the hydraulic stimulation design for subsequent horizontal well pads in this region may be appropriately reduced to enhance the reservoir utilization rate and optimize development efficiency. Third, based on microseismic event locations, the statistical interpretations of fracture length, width, and height are presented in Table 1. The average fracture lengths were Well-A2 > Well-A1 > Well-A3, and the average fracture heights were Well-A1 > Well-A2 > Well-A3; the average widths of hydraulic

fracture from different wells were broadly comparable.

We conducted an integrated interpretation by correlating the pre-stack inversion-derived brittleness index volume (Figure 10) with microseismic event distributions. Spatial variability analysis revealed moderate planar variations in brittleness across the study area, consistent with the regional geological framework. Microseismic monitoring data from the Well-A platform exhibited distinct clustering on both sides of the wellbore trajectories, with hydraulic fracture propagation orientations approximately orthogonal to the horizontal well paths, thereby supporting the validity of the well deployment design. Stratigraphic brittleness evaluation across the three horizontal wells indicated a descending trend: Well-A2 > Well-A1 > Well-A3. This brittleness gradient correlates positively with both the quantity and

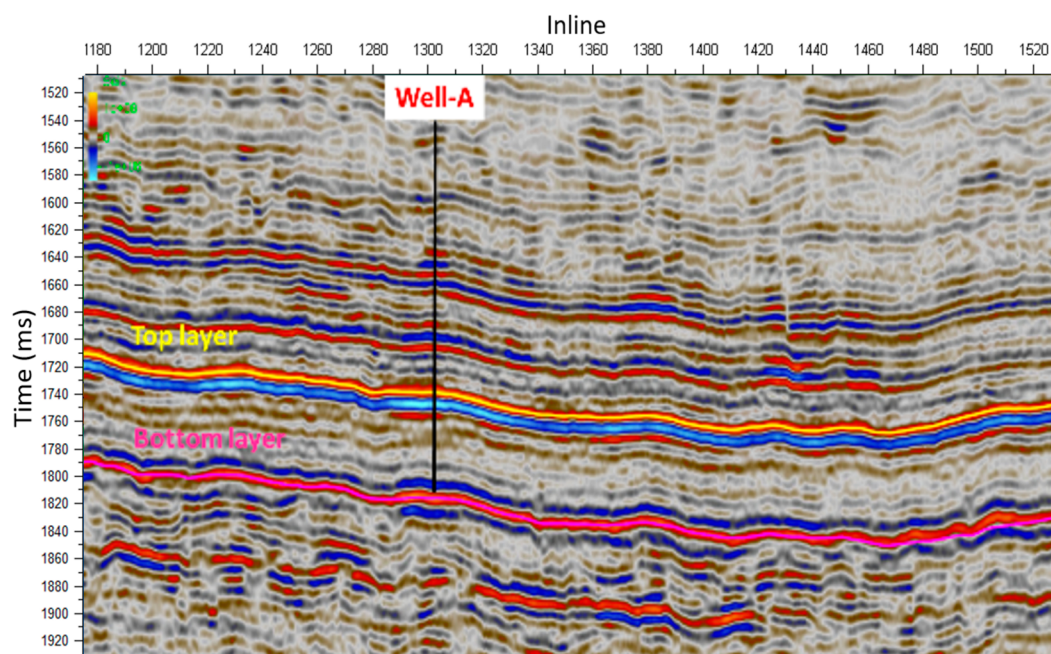


Figure 6. The seismic profile along the inline crossing of Well-A, with the target shale interval bounded by the yellow and pink lines

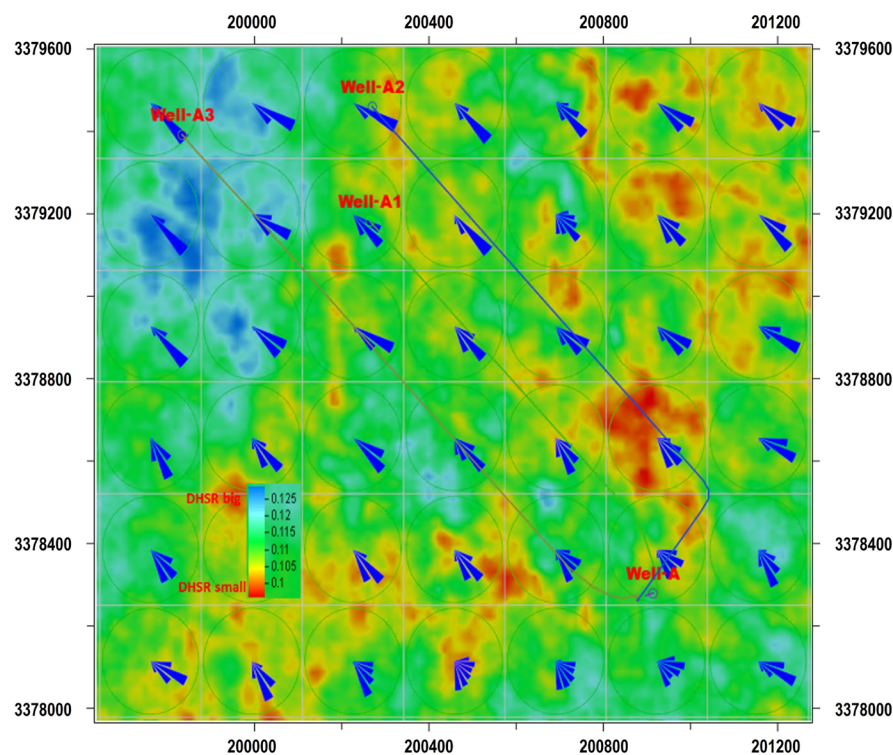


Figure 7. The Well-A platform map, constructed from differential horizontal stress ratio (DHSR) and orientation data, illustrates the minimum principal stress orientation within the target formation and the trajectories of three horizontal wells, with each trajectory distinguished by a distinct color. The warm colors on the map indicate lower DHSR values, and the cool colors indicate higher DHSR values.

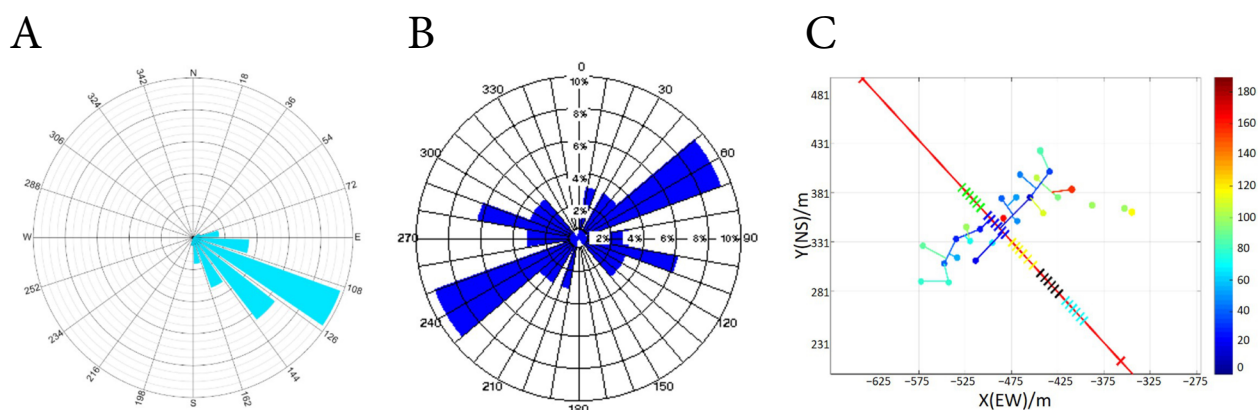


Figure 8. Rose diagrams of stress orientations and microseismic results at Well-A. (A) Minimum principal stress orientation from pre-stack AVAZ inversion. (B) Maximum principal stress orientation from dipole acoustic logging. (C) Microseismic interpretation of hydraulic fractures for the fracturing stage 29 of horizontal well-A3. The red line indicates the horizontal well trajectory, the colored dots indicate microseismic events, and the colored lines between microseismic events indicate the extension trajectories of hydraulic fractures; warm colors indicate higher fracture energy.

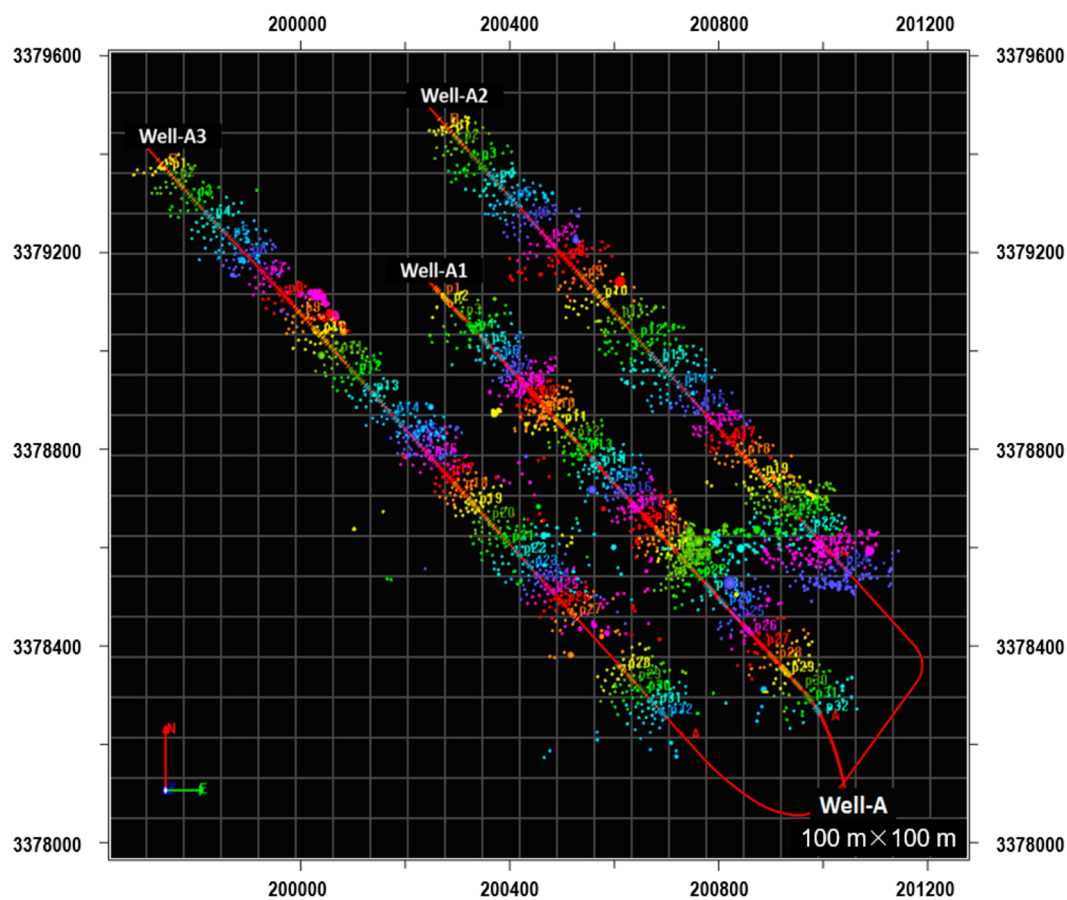


Figure 9. Plan view of microseismic event locations for the Well-A platform. The red lines indicate the horizontal well trajectory, the colored dots indicate the microseismic events at different stages, and the different sizes of dots indicate different fracture energies. The size of each grid square indicates the scale of 100 m × 100 m.

Table 1. The statistical geometry shape of hydraulic fracture based on microseismic monitoring

Well name	Well-A1	Well-A2	Well-A3
Geometry shape			
Average number of events per fracturing stage	31	38	23
Average length (m)	176	188	154
Average width (m)	61	62	64
Average height (m)	52.5	37	30

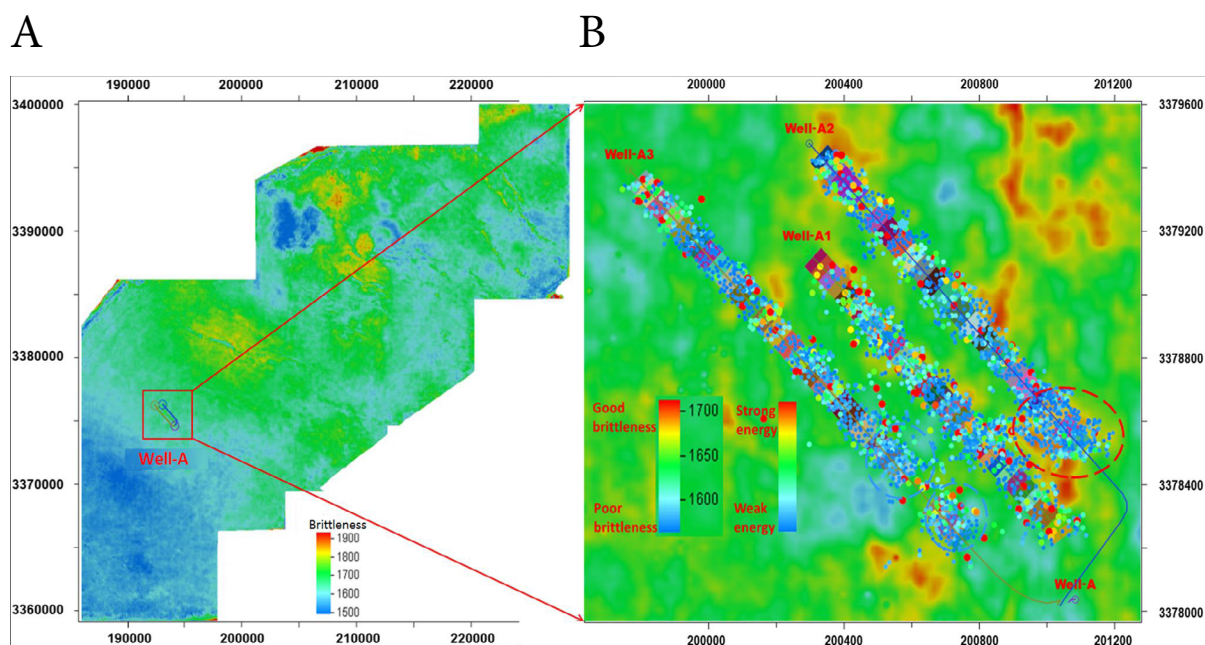


Figure 10. Brittleness index slices along the target horizon. (A) Full three-dimensional survey extent. (B) A detailed view of microseismic events and stage information for three horizontal wells. Colored dots denote microseismic events of varying magnitudes, overlain on the background brittleness index; colored rectangles indicate individual fracturing stages.

the magnitude of recorded microseismic events, suggesting a direct relationship between rock mechanical properties and the intensity of fracture development. Detailed examination of high-brittleness zones (red circles) revealed concentrated microseismic activity with morphologically similar distribution patterns, whereas low-brittleness regions (blue circles) exhibited significantly reduced event counts. These correlative analyses demonstrate strong consistency between brittleness index predictions and microseismic interpretations, confirming the reliability of

the geomechanical characterization approach.

4. Discussion

In this study, the geophysical prediction and evaluation technologies for lacustrine shale oil and gas were successfully applied to real Fuxing data from the Sichuan Basin. First, engineering “sweet spot” prediction technologies based on a rock physics model characterized the compressibility of lacustrine shale in 3D space; the prediction results were in seismic scale, which are tens to

hundreds of meters. Second, the microseismic monitoring technology evaluated the hydraulic fracturing effect in real time; the acquisition method of surface microseismic monitoring technology has a longer propagation and stronger attenuation, whereas the acquisition method of downhole microseismic monitoring technology is close to the source. It exhibited detection thresholds of moment magnitude (M_w) from shear-wave source between -1.0 and -2.0 for surface configuration, whereas downhole configuration typically achieved lower thresholds of M_w -3.0 to -3.5 . Consequently, the microseismic monitoring technology had detection limits of approximate magnitude, and potentially missed small-scale fracture events that contribute to permeability enhancement. This resultant sampling bias introduced systematic uncertainty into the interpretation of fracture network intensity and stimulated reservoir volume estimates; the limitation underscores the necessity of microseismic with complementary diagnostics (e.g., reservoir characterization, distributed acoustic sensing). Third, we performed a comprehensive interpretation that included static and dynamic data. The resulting analysis guided subsequent well placement and optimization of fracturing designs. Additionally, hydraulic fracturing operational parameters were significant factors influencing fracture geometry and production performance, highlighting the importance of this research.

5. Conclusion

This study presents an integrated application of “sweet spot” seismic prediction and microseismic monitoring for lacustrine shale formations in the Sichuan Basin. The research framework comprised three interconnected methodological components. First, engineering “sweet spot” seismic prediction was conducted using an orthorhombic anisotropic rock physics model, enabling 3D characterization of critical reservoir parameters, including brittleness index, DHSR, and *in situ* stress orientation, and guiding horizontal well trajectory optimization. Second, the high-precision microseismic monitoring was implemented to precisely locate hydraulic fracture initiation throughout the stimulation process. Third, comprehensive data interpretation facilitated quantitative evaluation of fracturing effectiveness and identification of the primary controlling factor. Analysis indicates that the brittleness index was the primary controlling factor in this geological setting, with higher values consistently corresponding to more extensive fracture networks. Field application of this integrated methodology in the Fuxing area of the Sichuan Basin yielded promising results, validating the proposed approach. These findings suggest significant potential for broader application in enhancing the efficiency of exploration and development

in unconventional reservoirs.

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Conflict of interest

Xinpeng Pan is an Editorial Board Member of this journal, but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. All the authors have no conflicts of interest.

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Availability of data

The data analyzed in the study can be requested via Sinopec and Sinopec Geophysical Research Institute (xukai.swty@sinopec.com).

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