

Article

A Multi-Constraint Integrated Zoning Method for Redevelopment of Mature Shale Gas Well Areas

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Abstract

Mature shale gas areas commonly retain substantial remaining resources after long-term depletion, but their redevelopment potential is governed by pressure redistribution, present-day stress evolution, natural-fracture stability, and target accessibility. Taking the HuangJinBa YS108 shale gas area as an example, this study proposes an integrated redevelopment zoning workflow that couples geological conditions, geomechanical constraints, and fracture-slip risk. Two types of remaining targets are identified: inter-well remaining resources and wellbore-control blind-spot resources. A geological-condition evaluation index (GCEI) is then constructed using remaining gas content, effective reservoir thickness, and remaining pressure. The zoning results are further constrained by the Anderson stress-regime index, horizontal stress difference, maximum horizontal stress orientation, and a Mohr–Coulomb-based natural-fracture-slip-risk index. Results indicate that L113 and L112 are the main depleted layers, whereas L114, L111, and the Wufeng Formation retain further redevelopment potential. Favorable zones are mainly distributed around platforms H24, H1, H3, H23, H13, and eastern H20. Long-term depletion reduces the minimum horizontal stress in densely developed areas and generally improves fracture stability, although local fracture intersections still present elevated slip risk. The final zoning provides a practical basis for redevelopment decision-making: platforms H24, H1, H3, H23, H13, and eastern H20 can be prioritized for near-term screening; inter-well targets should be developed using conservative infill strategies with controlled fracture length; and wellbore-control blind-spot targets can be stimulated more intensively under controllable fracture-slip risk.

Keywords: mature shale gas; redevelopment zoning; remaining resources; present-day in situ stress; natural-fracture stability; infill drilling; hydraulic fracturing



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1. Introduction

The target area of this study is the HuangJinBa YS108 shale gas well area, which is structurally located at the southern margin of the low-steep fold belt in southern Sichuan, China, near the uplifted western limb of the Jianwu syncline. The synclinal core is close to the northeastern part of the work area. The target interval is generally buried at a depth of

2500–3000 m and consists of high-quality marine shale with a favorable resource base and sustained development potential [1,2]. Since commercial-scale development began in 2013, the YS108 well area has been developed with 16 horizontal-well platforms. By March 2025, cumulative shale gas production had reached $41.3 \times 10^9 \text{ m}^3$. However, as the development period has lengthened, production decline from old wells has accelerated. Current deliverability evaluation indicates that the predicted annual production from existing wells may decline to less than $2.6 \times 10^8 \text{ m}^3$ within the next decade. The area has therefore entered a late development stage, in which the remaining resources have shifted from relatively continuous and easily drained sweet spots to inter-well areas, wellbore-control blind spots, and locally under-stimulated zones. The spatial distribution of remaining resources has become increasingly heterogeneous. Therefore, under the constraints of production history and present-day reservoir state, re-identifying redevelopment sweet spots and designing rational infill-well deployment schemes have become key issues for improving the recovery efficiency of the remaining reserve [3].

Existing shale gas sweet-spot evaluation studies have mainly focused on static geological screening during the early development stage. Typical evaluation systems use total organic carbon, mineral composition, pore structure, gas content, brittleness index, reservoir thickness [4–6], and related parameters to characterize geological or engineering sweet spots [7–9]. These methods are effective for new-area screening and initial well placement, but they are less capable of capturing the effects of long-term depletion on reservoir pressure, present-day in situ stress, natural-fracture stability [10], and inter-well remaining-resource heterogeneity [11]. In parallel, in situ stress studies are commonly used for single-well hydraulic-fracturing design and wellbore-stability analysis, with emphasis on horizontal stress magnitude, stress orientation, fracture initiation, and fracture propagation [12–14]; Natural-fracture stability studies are mostly applied to slip-risk identification, fracture activation evaluation, and hydraulic-fracturing risk assessment [15–17]. Overall, three limitations remain: (1) geological sweet spots, present-day stress state, and fracture stability are rarely coupled in a unified evaluation system, making it difficult to describe dynamic differences in reservoir stimulability after long-term production [18]; (2) sweet-spot results are often presented only as classification or zoning maps and are seldom converted into well-placement priority, platform ranking, or target feasibility; and (3) the constraints imposed by fracture stability and stress contrast on stimulation mode, treatment intensity, and redevelopment strategy have not been fully embedded in decision workflows. Reservoir-development simulation in fractured reservoirs is challenging because fluid flow is strongly affected by reservoir heterogeneity, fracture distribution, fracture connectivity, and nonlinear coupling between pressure and transport processes [19,20]. A late-stage redevelopment method is therefore required to integrate present-day geological conditions, in situ stress state, and natural-fracture stability, so that the evaluation can move from sweet-spot identification to engineering feasibility and differentiated development decisions.

In this context, this paper proposes a comprehensive zoning method for mature shale gas well areas with long production histories. The method is applied to the HuangJinBa YS108 well area to support late-stage shale gas redevelopment. The proposed workflow integrates present-day geological conditions, stress state, stress heterogeneity, and natural-fracture stability to establish a redevelopment-oriented evaluation framework for remaining-resource mobilization. Rather than simply delineating static sweet spots, this study aims to identify differences in the implementation feasibility of different targets under current reservoir conditions; clarify priority deployment zones, conditional deployment zones, and risk-control zones; and develop recommendations for platform priority and differentiated hydraulic-fracturing strategies. The proposed method can support infill-well

sequencing, treatment-parameter optimization, and efficient mobilization of remaining resources in mature shale gas fields.

2. Methods

2.1. Development Status and Redevelopment Potential

The HuangJinBa YS108 well area has entered the middle-to-late production stage and currently has approximately 10 years of continuous production history. The target intervals mainly include four sublayers of the Longmaxi Formation, from L114 to L111, with burial depth gradually increasing downward. To clarify the differences in resource utilization among different sublayers under the existing well pattern and fracturing conditions, this study statistically evaluated the proportion of resource-utilized volume, the utilization proportion of adsorbed gas within each layer, the utilization proportion of free gas within each layer, and the utilization proportion of reserves within each layer, as shown in Figure 1. The extraction ratios shown in Figure 1 were calculated using the initial gas reserves of each corresponding sublayer as the denominator. In other words, the free-gas extraction ratio and adsorbed-gas extraction ratio of L114, L113, L112, L111, and the Wufeng Formation represent the proportion extracted from the initial free-gas and adsorbed-gas reserves within each individual layer, respectively, rather than from the total initial reserves of the whole study area. This treatment allows the depletion degree of different layers to be compared while avoiding bias caused by differences in the initial occurrence proportions of free gas and adsorbed gas among layers.

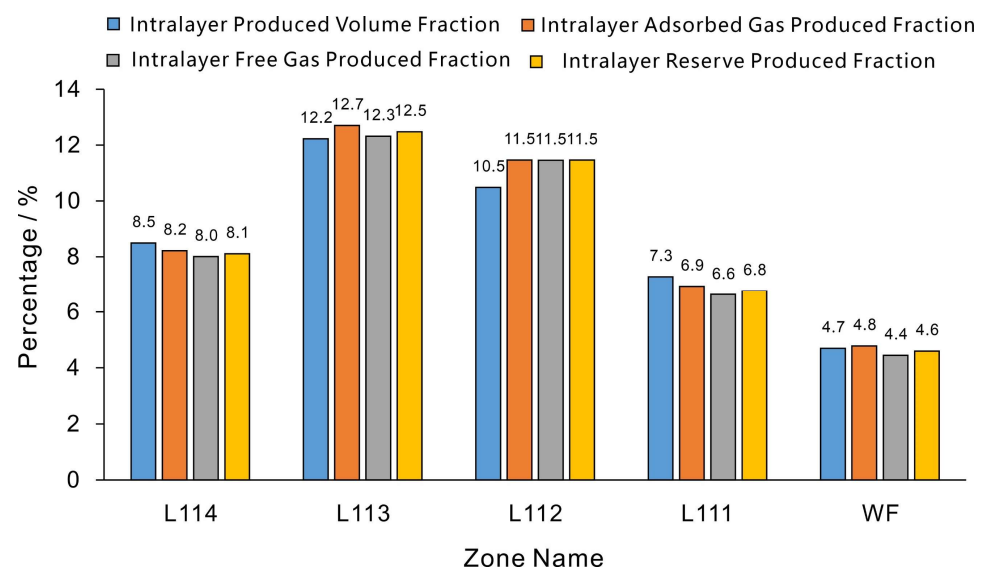


Figure 1. Statistics of the resource-utilization proportions of different sublayers in the study area.

The variation range of each evaluation indicator within the same sublayer is small, indicating that the utilization of gases in different occurrence states during the existing development process has good consistency. No obvious preferential utilization of a single gas type or abnormal over-stimulation of an individual layer is observed. In terms of interlayer differences, L113 and L112 are the main currently depleted sublayers. Among them, L113 exhibits the highest values in resource-utilized volume, adsorbed-gas utilization, free-gas utilization, and reserve utilization, reaching 12.2%, 12.7%, 12.3%, and 12.5%, respectively. L112 ranks second, with each indicator ranging approximately from 10.5% to 11.5%. In contrast, L114 and L111 show relatively low utilization degrees. The indicators of L114 are approximately 8.0–8.5%, and those of L111 are approximately 6.6–7.3%. The Wufeng Formation has the lowest utilization degree, with all indicators only 4.4–4.8%.

These results indicate that existing development has mainly focused on L113 and L112, both of which have formed relatively stable main production contributions under the current well-pattern control and hydraulic-fracturing stimulation conditions. By contrast, L114, L111, and the Wufeng Formation still retain certain remaining-resource potential, especially low-utilization intervals, which may serve as important targets for subsequent mature-area redevelopment and supplementary stimulation.

To further clarify the spatial distribution characteristics and redevelopment potential of remaining resources in the study area, this study used production history and pressure-field evolution results to equivalently characterize the depleted resource range by the wellbore-controlled pressure-depletion region. On this basis, two main types of remaining resources were identified: wellbore-control blind-spot remaining resources and inter-well remaining resources. As shown in Figure 2, the wellbore-control blind-spot remaining resources are mainly distributed in local areas where the control capacity of the existing well pattern is weak and pressure-depletion sweep is insufficient. Their planar distribution range is indicated by the white boundary in Figure 2a, with an area of approximately 5.61 km². This type of remaining resource has a relatively limited overall scale, but it is relatively concentrated, has clear spatial boundaries, and shows strong target orientation. Therefore, it can be regarded as a key target for subsequent local supplementary well deployment or directional stimulation.

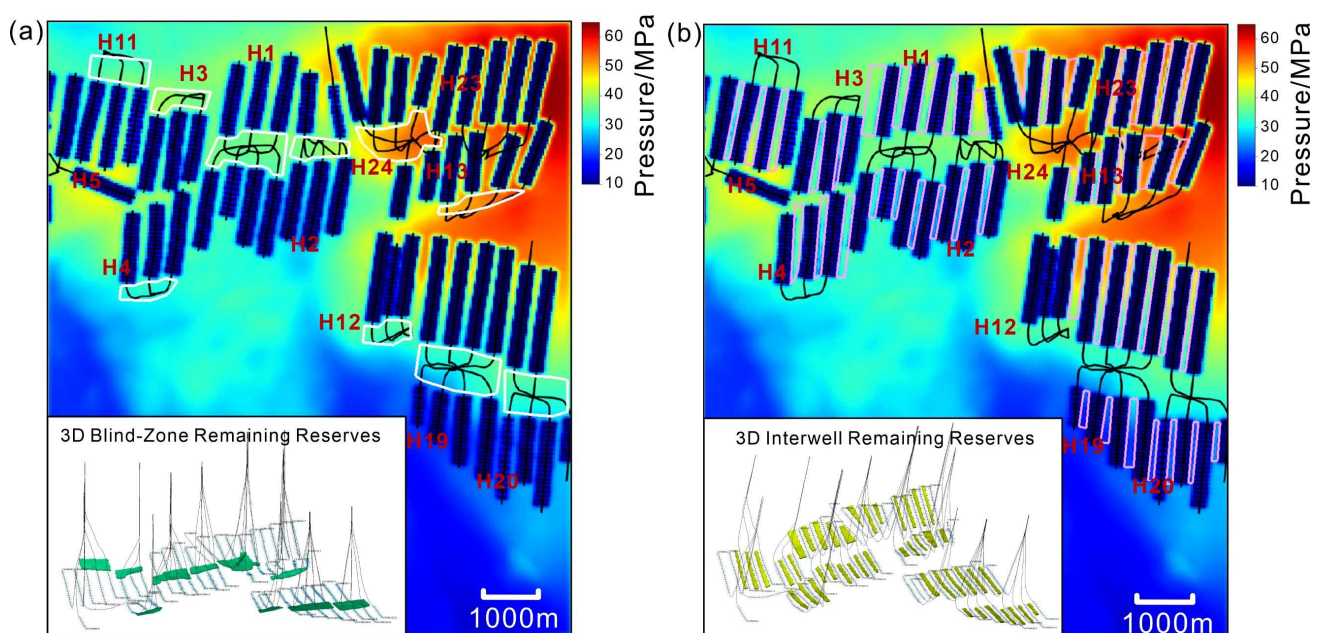


Figure 2. Spatial distribution characteristics of remaining resources in the study area. (a) Planar distribution and three-dimensional resource-body display of wellbore-control blind-spot remaining resources; (b) planar distribution and three-dimensional resource-body display of inter-well remaining resources.

Inter-well remaining resources are mainly distributed in areas between different well groups that have not been fully depleted. Their planar distribution range is indicated by the pink boundary in Figure 2b, with an area of approximately 6.89 km². Compared with wellbore-control blind-spot remaining resources, inter-well remaining resources have a wider distribution range, but they are relatively scattered in space and are jointly controlled by existing well spacing, well-trajectory distribution, hydraulic-fracture-network extension capacity, and interlayer heterogeneity. Therefore, the re-mobilization of this type of remaining resource depends more strongly on well-pattern infill, three-dimensional

well-placement optimization, and differentiated hydraulic-fracturing stimulation methods [21,22].

On the basis of the three-dimensional reserve body, this study further quantified the free-gas and adsorbed-gas resource potential within the two types of remaining-resource bodies. The results show that the Huangjinba YS108 well area still retains considerable remaining-resource potential after approximately 10 years of continuous production, particularly in inter-well areas and wellbore-control blind spots. However, the specific recoverable scale requires further evaluation through dynamic production forecasting, recovery-factor assessment, and economic analysis. This understanding provides the resource basis for the subsequent integrated evaluation of geological conditions, present-day stress state, and natural-fracture stability. It also indicates that redevelopment of mature areas should not determine priority solely on the basis of remaining-resource scale; rather, the engineering implementability and suitable stimulation strategy for different remaining-resource types under present-day geomechanical conditions must be further clarified.

2.2. Basic Input Data

To conduct zoning evaluation for remaining-resource re-mobilization in the HuangJinBa YS108 well area, this study comprehensively used present-day geological-resource attributes and in situ stress-field attributes as basic input data. The key input parameters mainly include the three-dimensional remaining-pressure body, the three-dimensional reservoir-thickness body, the three-dimensional remaining gas content body, and the present-day three-dimensional in situ stress field. Among them, remaining gas content is used to characterize the resource-scale basis of remaining resources. Remaining pressure reflects the current formation-energy level and the degree of depletion. Reservoir thickness characterizes the vertical development scale of the target interval and the suitability for three-dimensional development. The present-day in situ stress field provides mechanical constraints for subsequent stress-state identification, natural-fracture stability evaluation, and engineering-stimulation suitability analysis. The remaining gas content body used in this study is a three-dimensional property model that describes the spatial distribution of remaining gas in both the vertical and horizontal directions. The contour maps presented in the following figures are planar projections or sublayer-averaged slices extracted from the 3D property model. Therefore, these maps are used only for visualization and spatial comparison of the 3D results, rather than representing two-dimensional simulation results.

Because the target interval in the study area consists of multiple sublayers from L114 to L111, this study integrated the attributes of each sublayer on the basis of single-sublayer three-dimensional attribute modeling to obtain a comprehensive characterization of the target interval. This characterization was used to describe the planar distribution characteristics of overall remaining resources and in situ stress conditions. Figure 3 shows the planar distributions of average reservoir thickness, average remaining gas content, present-day minimum horizontal principal stress, and present-day maximum horizontal principal stress for the target interval in the study area.

From the perspective of reservoir-thickness distribution, the target interval in the study area is generally stable in thickness. The main thickness is at a moderate level, and thinning occurs only locally near faults and structurally complex zones, reflecting the influence of faults and stratigraphic-distribution variations on effective reservoir continuity. Remaining gas content shows obvious spatial heterogeneity. High-value areas are mainly distributed in local parts of the northern and northeastern study area, whereas low-value areas are mostly located in zones with a high degree of existing well-pattern control or sufficient pressure-depletion sweep. This indicates that long-term production has significantly affected the distribution of remaining resources around wells and in local inter-well areas.

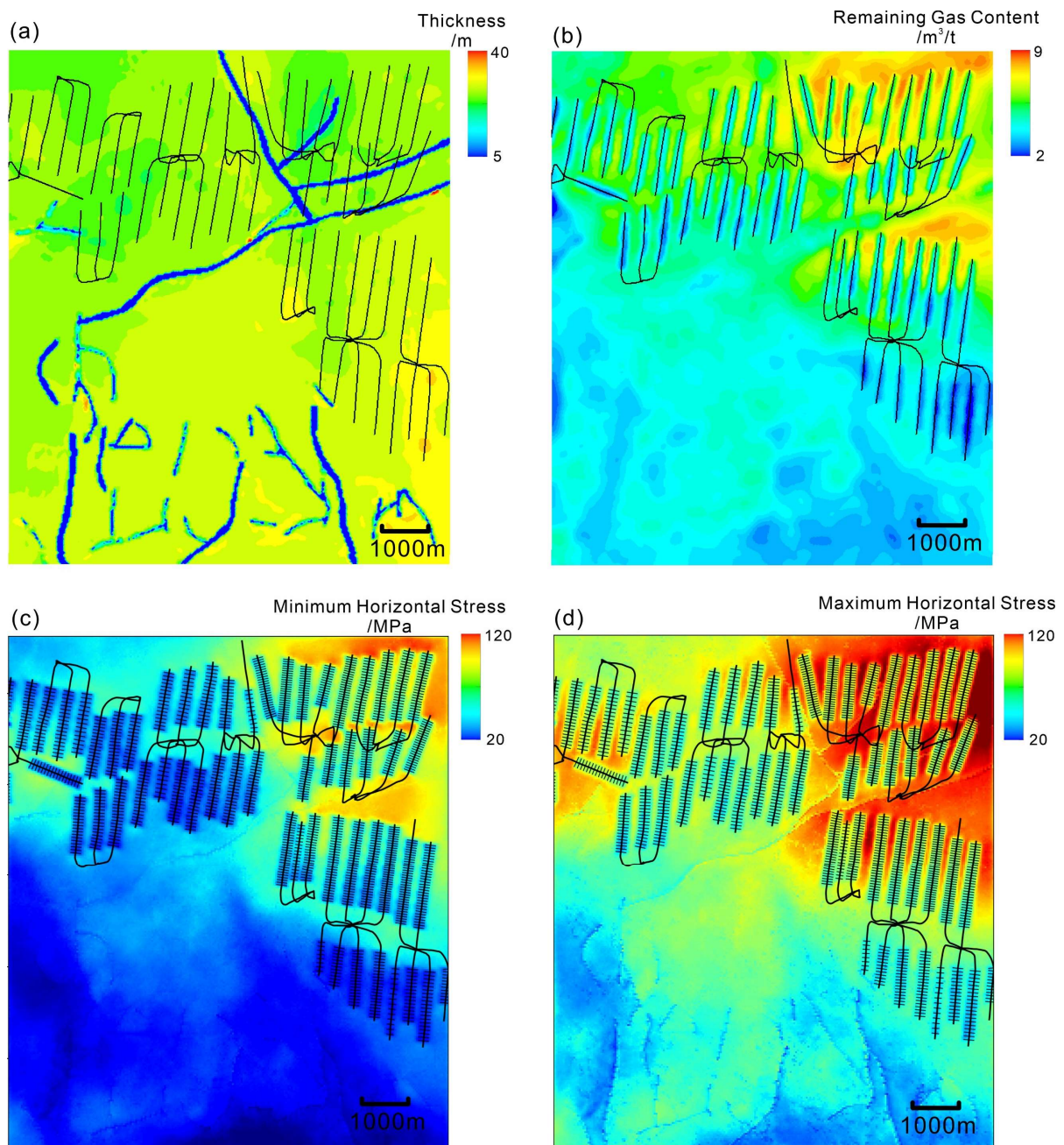


Figure 3. Planar distribution of key input parameters of the target interval in the study area. (a) Average reservoir thickness of the target interval; (b) average remaining gas content of the target interval; (c) present-day minimum horizontal principal stress of the target interval; (d) present-day maximum horizontal principal stress of the target interval.

The present-day in situ stress field also shows strong spatial variability. The minimum horizontal principal stress generally increases from low values in the southwest to high values in the northeast. A certain low-stress response can be observed near existing well patterns and hydraulically stimulated areas, reflecting the modification effect of long-term production depletion and reservoir-pressure redistribution on the present-day stress field. The maximum horizontal principal stress shows a regional variation trend similar to that of the minimum horizontal principal stress, but its high-value areas are more widely distributed and are more pronounced in the eastern and northeastern parts of the study area. The above stress-field differences not only affect subsequent hydraulic-fracture propagation

direction and stimulation difficulty but also further control natural-fracture stability and its opening/closing response during redevelopment [23].

The numerical workflow in this study consists of reservoir dynamic simulation, geomechanical stress-field calculation, and natural-fracture stability evaluation. The reservoir dynamic simulation was conducted using a finite-volume-based reservoir simulation approach, in which the governing flow equations were discretized on the reservoir grid to obtain pressure depletion and remaining gas content after long-term production. The present-day stress field was calculated using a finite-element geomechanical model. In this model, the structural framework, stratigraphic layering, rock-mechanical parameters, pore pressure, and boundary stress conditions were integrated to calculate the spatial distribution of the principal stresses and stress orientation. The geomechanical model was constrained and calibrated using available in situ stress measurements, borehole failure interpretation, and image-logging information. Natural-fracture patterns were characterized using seismic attribute interpretation, ant-tracking results, fault interpretation, and geological constraints and were then used to evaluate fracture-slip tendency under the present-day stress state.

2.3. Evaluation Method for Present-Day Geological Conditions in the Study Area

In the context of mature-area redevelopment, the re-mobilization potential of remaining resources depends not only on the remaining-resource scale but also on formation-energy level and effective development space. Therefore, this study constructed a present-day geological-condition evaluation index to quantitatively characterize the redevelopment priority of different locations in the study area at the current development stage. This index is not a traditional single reservoir-quality evaluation index and does not directly represent the final development-favorable area. Instead, it evaluates the relative potential for further re-mobilization of remaining resources under present-day geological conditions from three aspects: resource basis, formation energy, and staggered-layer development conditions.

Considering that different parameters have different dimensions, value ranges, and spatial variation magnitudes, this study constructed the comprehensive geological-condition evaluation index in a multiplicative form and regulated the relative contributions of different parameters through a logarithmic weighting method. Suppose that a spatial location in the study area is denoted as x , and the remaining gas content, effective reservoir thickness, and remaining pressure are $g(x)$, $h(x)$ and $p(x)$, respectively. To reduce the influence of extreme values on the evaluation results, the 10th and 90th percentiles were first used to truncate each parameter and convert it into dimensionless ratios, as shown in Equation (1):

$$R(g) = \ln\left(\frac{g_{P_{90}}}{g_{P_{10}}}\right), R(h) = \ln\left(\frac{h_{P_{90}}}{h_{P_{10}}}\right), R(p) = \ln\left(\frac{p_{P_{90}}}{p_{P_{10}}}\right) \quad (1)$$

where P_{90} and P_{10} are the statistical percentiles of reservoir parameters and $R(g)$, $R(h)$, and $R(p)$ represent the relative magnitudes of remaining gas content, effective reservoir thickness, and remaining pressure, respectively.

The P_{10} and P_{90} values were selected as the lower and upper truncation thresholds because the P_{10} – P_{90} interval represents the main statistical distribution of reservoir parameters in the study area. Values outside this interval are commonly associated with local geological anomalies, interpolation uncertainty, or non-representative extreme grid cells. The truncation can therefore reduce the excessive influence of extreme values on the normalized index. It should be noted that this operation may slightly compress the absolute contrast among the highest-abundance grid cells, but it does not remove the identification of core favorable areas because the final zoning is based on the relative ranking

and percentile classification of the integrated index. The original parameter values are still retained for resource-scale interpretation, whereas the truncated values are used only for robust index normalization and comparative zoning.

On this basis, the present-day geological-condition evaluation index (GCEI) is defined as shown in Equation (2):

$$I(x) = g(x)^a h(x)^b p(x)^c \quad (2)$$

where $I(x)$ is the present-day geological-condition evaluation index and a , b and c are the weight coefficients of remaining gas content, effective reservoir thickness, and remaining pressure, respectively.

Taking the natural logarithm of the above equation yields Equation (3):

$$\ln(I) = a\ln(g) + b\ln(h) + c\ln(p) \quad (3)$$

It can therefore be seen that the multiplicative form is equivalent to weighted summation in logarithmic space. This method can not only eliminate the influence of dimensional differences among parameters but also reflect the synergistic control of multiple factors. When one parameter is obviously low, the comprehensive evaluation index decreases accordingly, which is more consistent with the practical understanding that remaining-resource scale, formation energy, and effective development space jointly constrain redevelopment in mature areas.

A higher comprehensive geological-condition evaluation index indicates that the location simultaneously has a better remaining-resource basis, better formation-energy conditions, and larger vertical development space and therefore has a higher re-mobilization priority under present-day geological conditions. To convert the continuous evaluation-index results into spatial zoning that is convenient for development decision-making, this study used the percentile method to classify the planar distribution results of the comprehensive evaluation index. Specifically, the I values of all evaluation units in the study area were sorted from low to high, and the 40th, 70th, and 90th percentiles were used as the main zoning boundaries. The evaluation results were divided into four types: core zone, preferred zone, potential zone, and marginal zone, as shown in Table 1.

Table 1. Percentile-based zoning criteria for the comprehensive evaluation index.

Zoning Type	Percentile Interval	Zoning Implication
Core Zone	$I > P90$	The zone with the highest comprehensive evaluation index, representing the most favorable target area for redevelopment under current conditions.
Preferred Zone	$P70 < I \leq P90$	The zone with relatively favorable comprehensive conditions and high redevelopment potential, which can be regarded as a key preferred area.
Potential Zone	$P40 < I \leq P70$	The zone with certain redevelopment potential, but further screening is required by integrating the stress state and fracture stability.
Marginal Zone	$I \leq P40$	The zone with relatively weak comprehensive conditions and low development priority at the current stage.

The remaining gas content and remaining pressure were derived from present-day attribute models constrained by production history, pressure-field evolution, and three-dimensional geological modeling, whereas the effective reservoir thickness was obtained from the three-dimensional geological model and effective-reservoir interpretation of the target sublayers. To reduce the influence of local extreme values on the integrated index, the P10/P90 percentile truncation was applied before dimensionless normalization. This

treatment does not change the general spatial ranking but improves the comparability of different attributes within the same evaluation framework.

This method emphasizes the relative differences among evaluation units within the study area and can avoid the insufficient applicability of fixed thresholds under different indicator combinations or development objectives. In general, the higher the zoning grade, the more favorable the comprehensive conditions of the area under the current evaluation-index system and the higher the re-mobilization priority.

It should be noted that this index only characterizes the relative priority at the level of geological-resource conditions and is not directly equivalent to final development suitability. For areas with high remaining-resource potential but complex stress conditions, poor natural-fracture stability, or high engineering-stimulation risk, further screening and zoning must still be conducted by integrating present-day stress state and natural-fracture stability in the subsequent comprehensive evaluation.

2.4. Evaluation Method for the Present-Day Stress State in the Study Area

The present-day stress state is an important mechanical factor affecting the implementability of mature-area redevelopment and the hydraulic-fracturing stimulation mode [24]. Under different stress states, reservoir-fracture propagation patterns, natural-fracture activation tendency, and fracture stability show obvious differences [25,26]. Therefore, based on the present-day three-dimensional in situ stress field in the study area, this study used the Anderson stress-regime classification method and the continuous Anderson coefficient to quantitatively evaluate the present-day stress state of the study area [27], as shown in Equation (4):

$$A = (n + 0.5) + (-1)^n \left(\frac{S_2 - S_3}{S_1 - S_3} - 0.5 \right) \quad (4)$$

where A is the Anderson coefficient; S_1 , S_2 , and S_3 are the maximum principal stress, intermediate principal stress, and minimum principal stress, respectively; $n = 0$ for the normal-faulting stress regime; $n = 1$ for the strike-slip stress regime; and $n = 2$ for the reverse-faulting stress regime.

The present-day stress-state evaluation is not a direct judgment of development favorability; rather, it quantitatively characterizes the present-day mechanical environment of the study area. For remaining-resource re-mobilization, stress-state evaluation is mainly used to identify differences in hydraulic-fracturing difficulty, fracture-propagation mode, and natural-fracture stability among different areas and to provide a mechanical basis for subsequent comprehensive zoning and differentiated development-policy formulation.

2.5. Evaluation Method for Present-Day Natural-Fracture Stability in the Study Area

Natural-fracture stability is an important factor affecting the redevelopment performance and engineering risk of mature shale gas areas [28–30]. On the one hand, moderate opening or shear slip of natural fractures is beneficial for increasing the complexity of fracture networks and enhancing stimulated reservoir volume. On the other hand, if large-scale sliding instability of natural fractures occurs during hydraulic fracturing, it may lead to fracturing-fluid channeling, enhanced inter-well interference, casing deformation, or instability of fracture zones [31–33]. Therefore, in the zoning evaluation of remaining-resource re-mobilization, it is necessary to quantitatively evaluate natural-fracture-slip risk by integrating the present-day in situ stress field, pore pressure, and natural-fracture occurrence.

According to the Mohr–Coulomb failure criterion [34], slip risk and critical injection pressure can be calculated, and the sliding-instability risk index S of natural fractures is expressed as shown in Equation (5):

$$S = \frac{\tau}{C_0 + (S_n - P)\tan(\varphi)} \quad (5)$$

where S_n and τ are the normal stress and shear stress on the fracture plane, respectively; C_0 is the cohesion of the fracture, which can generally be regarded as 0 because the cementation degree of fractures is weak; φ is the internal friction angle of the fracture plane; and P is the present-day pore pressure.

The natural-fracture occurrence data used in the slip-risk assessment were extracted from the existing 3D geological–fracture model of the study area. This model integrates seismic-attribute interpretation, fault interpretation, well-log interpretation, and geological constraints and provides the spatial distribution and orientation information of natural fractures required for the Mohr–Coulomb slip-risk calculation. In Equation (5), the internal friction angle of the fracture planes was set to $\varphi = 30^\circ$ based on the parameter setting of the 3D geomechanical model and commonly used values for shale fracture surfaces. Since the purpose of this study is to evaluate the influence of fracture-slip risk on redevelopment zoning rather than to present a detailed natural-fracture characterization workflow, the final slip-risk distribution is emphasized in the Section 3.

In this study, the cohesion of the natural-fracture surface was set to $C_0 = 0$ to represent a conservative weak-bonding condition for potentially reactivated fractures in a mature development area. This assumption is suitable for risk screening because it provides an upper-bound estimate of fracture-slip tendency. However, some closed fractures may be strongly cemented by calcite and thus retain finite shear strength. In such cases, setting C_0 to zero may locally overestimate the slip risk. Therefore, the high-risk zones identified in this study should be interpreted as conservative priority areas for engineering avoidance or further calibration, rather than as zones where fracture slip will inevitably occur.

The slip risk of natural fractures under present-day conditions can be identified by calculating the instability risk, and this is used to judge the ease with which natural fractures may be activated during refracturing or redevelopment stimulation. A larger sliding-instability risk index indicates that the fracture is more prone to instability. The evaluation results can provide a basis for subsequently identifying favorable stimulation zones, avoiding high-risk fracture zones, and formulating differentiated hydraulic-fracturing treatment parameters.

2.6. Integrated Multi-Factor Evaluation Framework for Remaining-Resource Re-Mobilization

In the context of mature-area redevelopment, whether remaining resources have re-mobilization value depends not only on the remaining-resource scale but also on formation energy, effective development space, present-day stress state, and natural-fracture stability. Therefore, this study constructed an integrated evaluation framework for remaining-resource re-mobilization that combines geological-resource conditions and geomechanical constraints, as shown in Figure 4. This framework takes present-day pore pressure, remaining gas content, reservoir thickness, three principal stresses, and natural-fracture occurrence as basic input data. First, the comprehensive geological-condition evaluation index is calculated to characterize remaining-resource scale, formation-energy conditions, and the suitability of staggered-layer development. Second, the present-day stress state is identified based on the relationship among the three principal stresses to determine hydraulic-fracturing stimulation modes and fracture-propagation characteristics in different areas. Finally, the slip risk is calculated by combining natural-fracture properties and

the Mohr–Coulomb failure criterion to evaluate the stability of the fracture system and engineering risk. On this basis, the remaining-resource re-mobilization targets in the study area are divided into four types and evaluated separately.

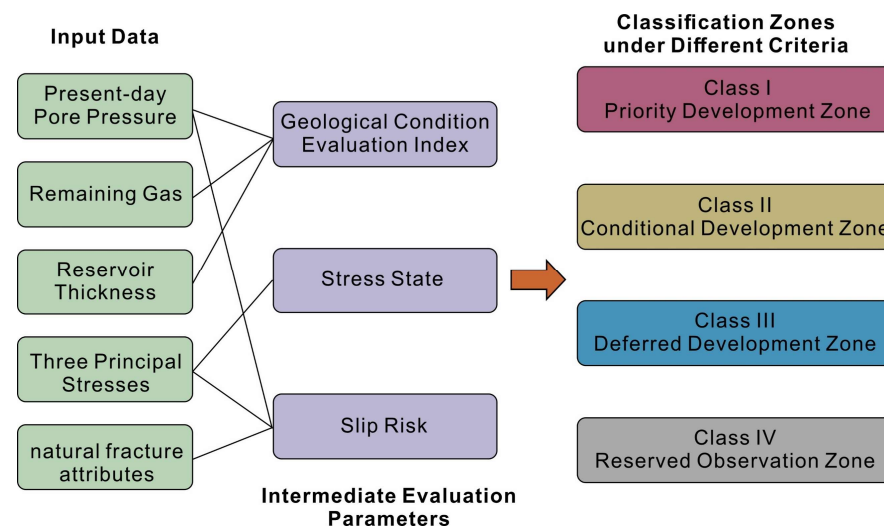


Figure 4. Integrated evaluation framework for remaining-resource re-mobilization.

- **Type I priority zone:** This type of area usually has favorable comprehensive geological conditions, a high remaining-resource basis, favorable formation-energy conditions, and low fracture-slip risk. It has high redevelopment potential and engineering implementability and is the key area for near-term well deployment, hydraulic-fracturing optimization, and production-capacity replacement;
- **Type II conditional zone:** This type of area has a certain remaining-resource basis and development conditions, but its overall advantages are not sufficiently prominent, or local stress constraints and fracture-stability risks exist. For such areas, detailed evaluation should be conducted by integrating specific geological conditions, and conservative infill or pilot utilization should be implemented in selected favorable sections to further verify the development effect;
- **Type III deferred zone:** This type of area usually shows relatively weak comprehensive geological conditions, insufficient continuity of remaining resources, or medium-to-high fracture-slip risk, and the development effect and engineering risk have large uncertainties. Therefore, it is not suitable as a priority development target at the current stage and can be re-evaluated in due course according to subsequent geological understanding and development-technology progress;
- **Type IV reserve zone:** This type of area mostly corresponds to zones with poor comprehensive geological conditions, complex fracture systems, and high slip risk, with limited redevelopment potential and high engineering risk. Such areas should be retained as long-term reserve zones and risk-control zones, and their geological-condition changes and technology adaptability should be continuously monitored to support future development decisions.

Different types of remaining resources correspond to different development strategies. For inter-well remaining resources, areas with relatively large stress differences are more suitable for forming stable and controllable dominant fracture systems. A conservative infill strategy should be adopted, and pumping rate and fracture length should be controlled to reduce mature-well interference risk. For wellbore-control blind-spot resources, if the stress difference is small and fracture-slip risk is controllable, it is more suitable to moderately increase treatment intensity, enhance complex-fracture-network coverage, and achieve

rapid local potential tapping. For wellbore-control blind-spot resources, “moderately increasing construction intensity” does not refer to unconditional high-rate injection. It mainly means that, under the constraints of low fracture-slip risk and acceptable wellbore integrity, the fluid volume per stage, total proppant amount, and/or proppant–fluid ratio can be appropriately increased, and the pumping schedule and proppant-adding program can be optimized to enhance fracture complexity and effective stimulated volume near the blind-spot target. Pumping displacement may be moderately increased only where the stress difference and slip-risk evaluation permit; otherwise, excessive displacement should be avoided to reduce the risk of fracture slip or wellbore interference. Therefore, the integrated evaluation framework can not only identify the re-mobilization priority of remaining resources but also further support well-location deployment sequencing and differentiated hydraulic-fracturing strategy formulation for mature-area redevelopment.

The final re-mobilization zoning was obtained by integrating three types of constraints: geological-condition potential, present-day stress implementability, and natural-fracture-slip risk, as shown in Table 2. The GCEI was used as the primary indicator of remaining-resource potential, whereas the stress-state and fracture-stability evaluations were used as engineering constraints. Therefore, high GCEI alone does not automatically correspond to a Type I zone. If a high-GCEI area is accompanied by high slip risk or unfavorable stress conditions, its priority is downgraded to Type II or Type III depending on the degree of engineering controllability.

Table 2. Zoning decision table.

GCEI Level	Present-Day Stress Condition	Natural-Fracture-Slip Risk	Final Zoning Type	Engineering Meaning
Core/Preferred zone	Favorable	Low to moderate	Type I priority zone	High redevelopment potential and good implementability
Core/Preferred zone	Constrained or locally unfavorable	Moderate to high	Type II conditional zone	Resource basis is good, but stimulation parameters should be constrained
Moderate zone	Favorable or constrained	Moderate	Type III deferred zone	Redevelopment can be considered after Type I/II zones
Low-potential zone	Unfavorable	High	Type IV reserve zone	Low priority under current technical and economic conditions
Core zone	High slip risk	High	Type II or Type III, depending on engineering controllability	High resource potential but risk-dominated; conservative stimulation is required

3. Results

3.1. Present-Day Geological-Condition Zoning Results Under Different Development Objectives

Based on the present-day geological-condition evaluation index established in Section 2.3, this study further set differentiated weight combinations for different redevelopment objectives and carried out resource-dominated, formation-energy-dominated, geological-development-condition-dominated, and balanced zoning evaluations. In each zoning scheme, the index weights correspond to the relative contribution proportions of remaining gas content, effective reservoir thickness, and remaining pressure.

The evaluation objectives and weight settings of different zoning modes are shown in Table 3.

Table 3. Weight settings of present-day geological-condition evaluation under different development objectives.

Zoning Mode	Weight Combination (a:b:c)	Dominant Factor	Main Evaluation Objective
Resource-Dominated Mode	0.55:0.20:0.25	Remaining gas content	To identify areas enriched in remaining gas resources.
Formation-Energy-Dominated Mode	0.30:0.15:0.50	Remaining pressure	To identify areas with relatively well-preserved formation energy.
Geological-Development-Condition-Dominated Mode	0.35:0.45:0.25	Effective reservoir thickness	To identify areas suitable for staggered-layer infill drilling and three-dimensional development.
Balanced Mode	0.40:0.20:0.40	Remaining gas content and remaining pressure	To comprehensively identify priority areas for redevelopment.

The resource-dominated, formation-energy-dominated, and geological-development-condition-dominated schemes emphasize remaining-resource scale, preserved formation energy, and suitability for staggered-layer/three-dimensional development, respectively. The balanced scheme was used to identify comprehensive priority areas. The weight settings were determined by considering field-development objectives, expert knowledge, and comparisons among different evaluation scenarios. The weight combinations in Table 3 were determined by combining expert judgment with scenario-based sensitivity tests rather than by a purely mathematical optimization procedure. In the balanced mode, remaining gas content and remaining pressure were assigned equal dominant weights of 0.40 because redevelopment priority depends jointly on remaining-resource abundance and retained formation energy, while effective reservoir thickness was assigned a weight of 0.20 as a geological-development-condition-controlling target accessibility and fracturing implementability.

Comparison among the four weighting scenarios shows that the main favorable areas remain spatially consistent around H24, H1, H3, H23, H13, and the eastern part of the study area, indicating that the core favorable zones are relatively robust to weight variations.

The resource-dominated zoning result is shown in Figure 5. This scheme increases the contribution proportion of remaining gas content in the evaluation index; therefore, the zoning result mainly reflects the enrichment degree of remaining resources. From the planar distribution of the evaluation index, high-value areas are mainly concentrated in the northern, northeastern, and eastern well-pattern peripheral areas and local inter-well areas of the study area, indicating that these areas still have a favorable remaining-resource basis. The corresponding zoning result shows that the core zones and preferred zones are mainly distributed around H1, H3, H23, H24, H13, and some eastern well groups, indicating that the peripheries of these platforms still have favorable resource re-mobilization potential.

The formation-energy-dominated zoning result is shown in Figure 6. This scheme increases the weight of remaining pressure and is mainly used to identify areas where formation energy is relatively well preserved at the current stage. The formation-energy-dominated zoning result is highly similar to the resource-dominated zoning result overall, and the high-value areas are also mainly concentrated in the northern, northeastern, and eastern parts of the study area. This indicates that remaining gas content and remaining

pressure in the study area have strong spatial correlation, and areas with relatively enriched remaining resources often also maintain a relatively high formation-energy level.

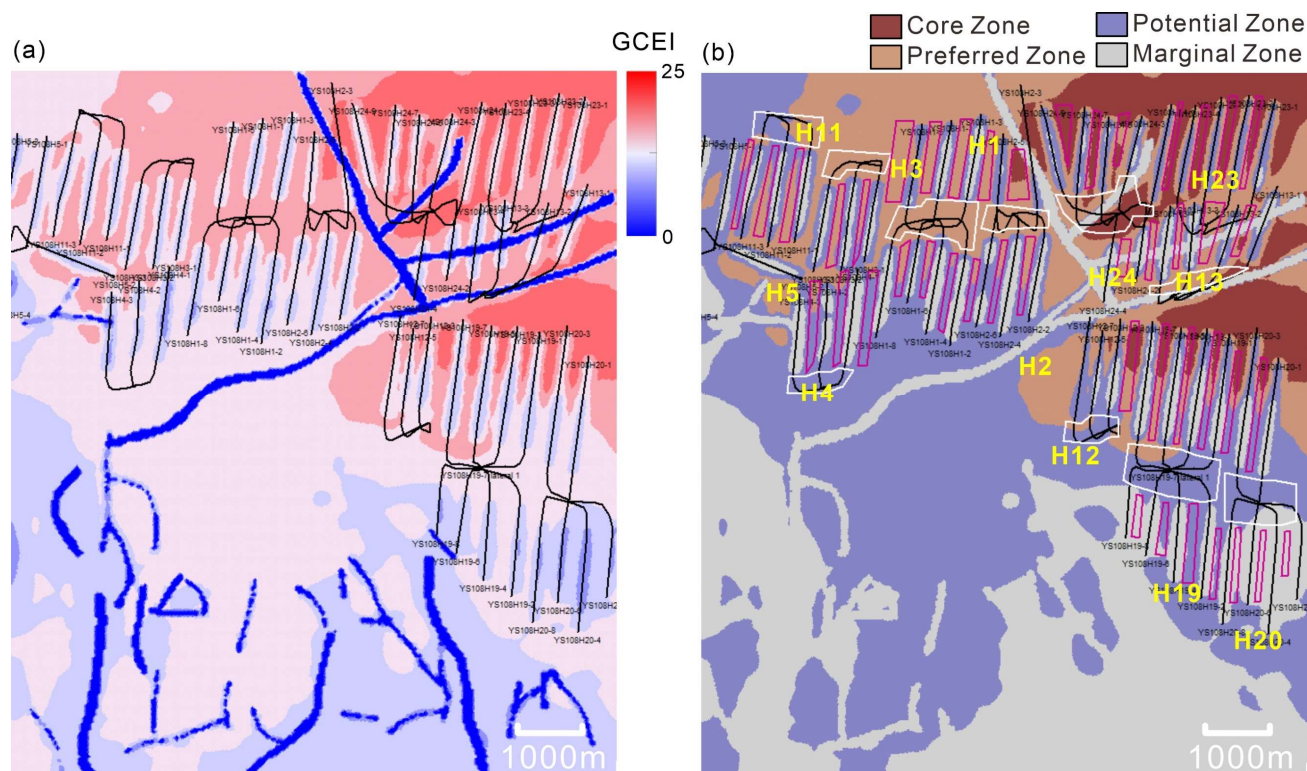


Figure 5. Resource-dominated zoning result: (a) absolute value of the geological-condition evaluation index; (b) zoning type.

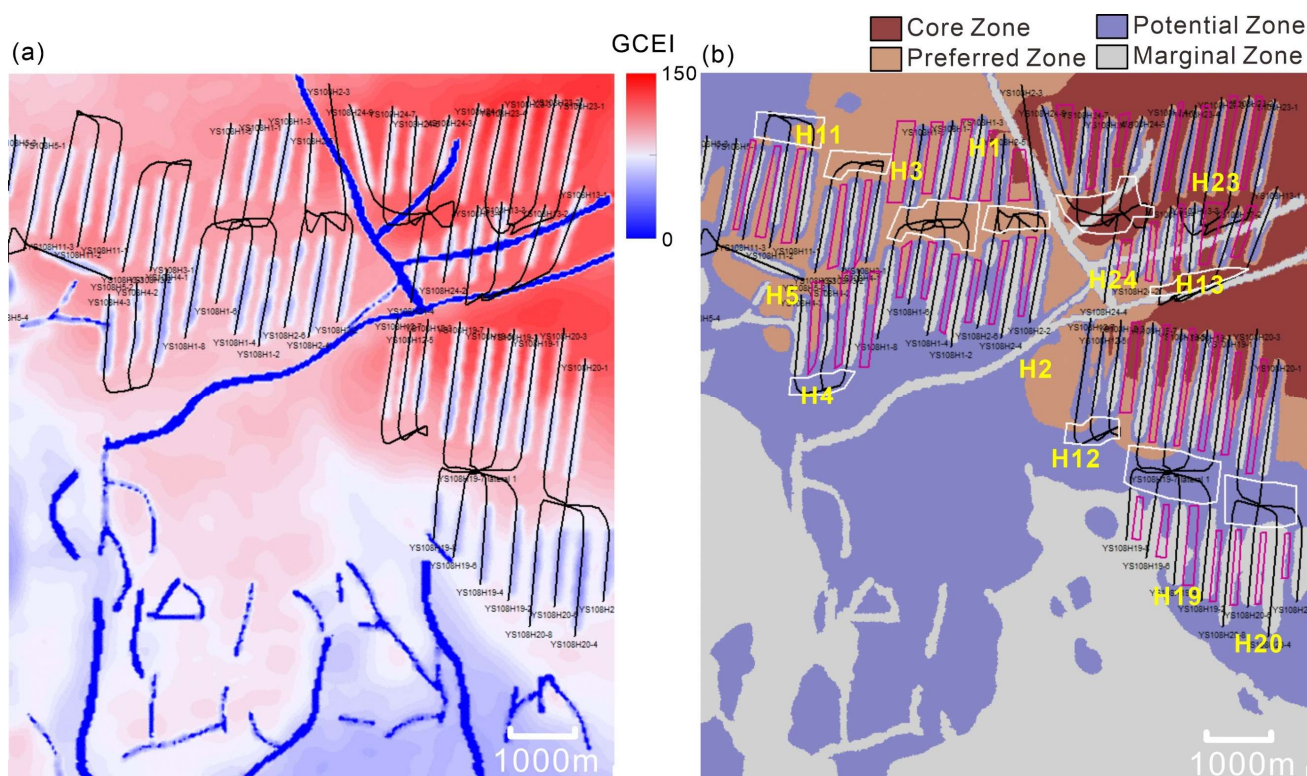


Figure 6. Formation-energy-dominated zoning result: (a) absolute value of the geological-condition evaluation index; (b) zoning type.

The geological-development-condition-dominated zoning result is shown in Figure 7. This scheme increases the contribution proportion of effective reservoir thickness and is mainly used to evaluate the suitability for staggered-layer infill and three-dimensional development. Compared with the resource-dominated and formation-energy-dominated results, the spatial differences in this zoning result are relatively weak, the core-zone range is relatively limited, and most areas are dominated by preferred zones and potential zones. The target interval in the study area has relatively stable overall thickness and does not contain large-scale thick intervals with strong advantages. Therefore, from the perspective of effective reservoir thickness alone, no particularly prominent three-dimensional development advantageous zone exists in the study area.

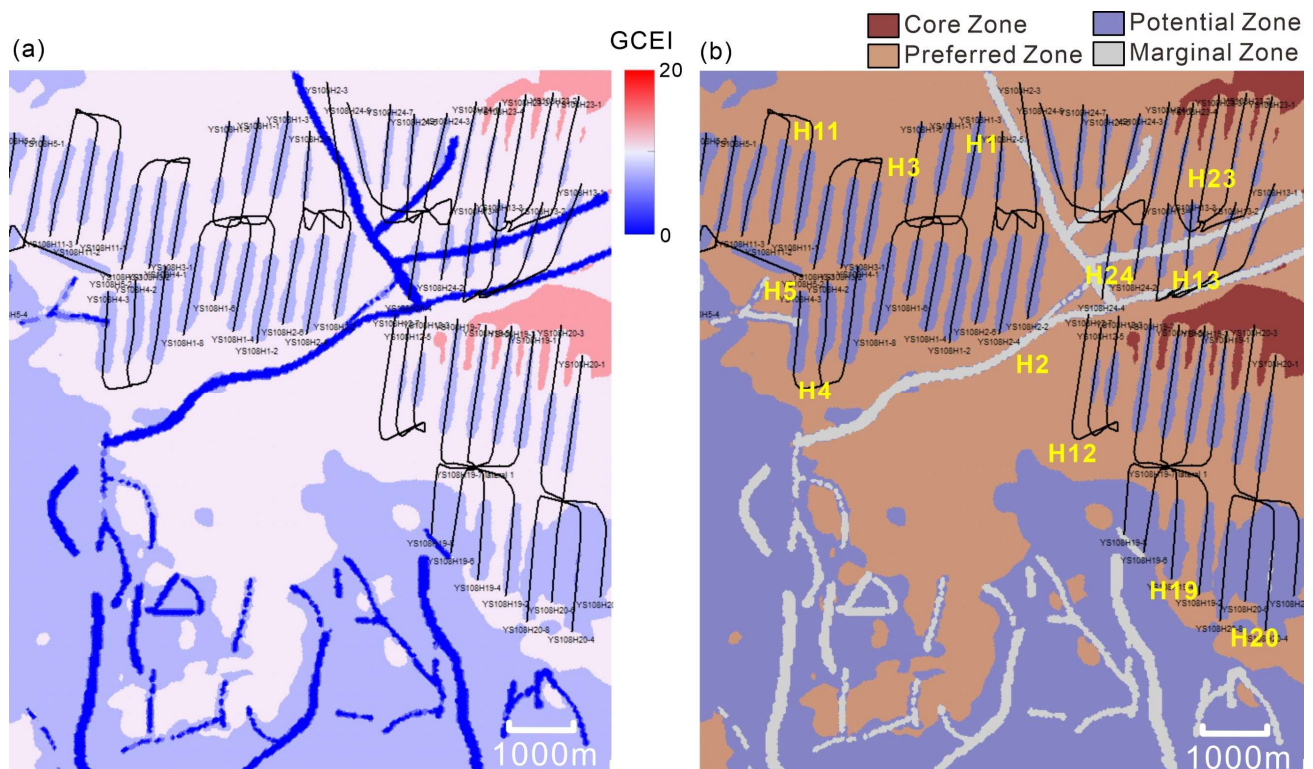


Figure 7. Geological-development-condition-dominated zoning result: (a) absolute value of the geological-condition evaluation index; (b) zoning type.

Integrating the above three types of objective-oriented evaluation, this study further adopted the balanced weight combination to conduct comprehensive zoning, and the result is shown in Figure 8. The balanced zoning simultaneously considers remaining-resource scale and formation-energy conditions while retaining a certain effective-thickness constraint. Therefore, it can more comprehensively reflect the re-mobilization priority of the study area under current geological conditions. The results show that core zones and preferred zones are mainly concentrated in the eastern, northeastern, and northern parts of the study area, especially around H24, H1, H3, H23, H13, and the eastern H20 area. These areas perform well in both the resource-dominated and formation-energy-dominated evaluations, indicating that their remaining-resource basis and formation-energy conditions are relatively well matched and that they should be key areas of concern for subsequent mature-area redevelopment. The southwestern, southern, and some fault-dense zones mostly appear as potential zones or marginal zones, indicating relatively low development priority under current geological conditions.

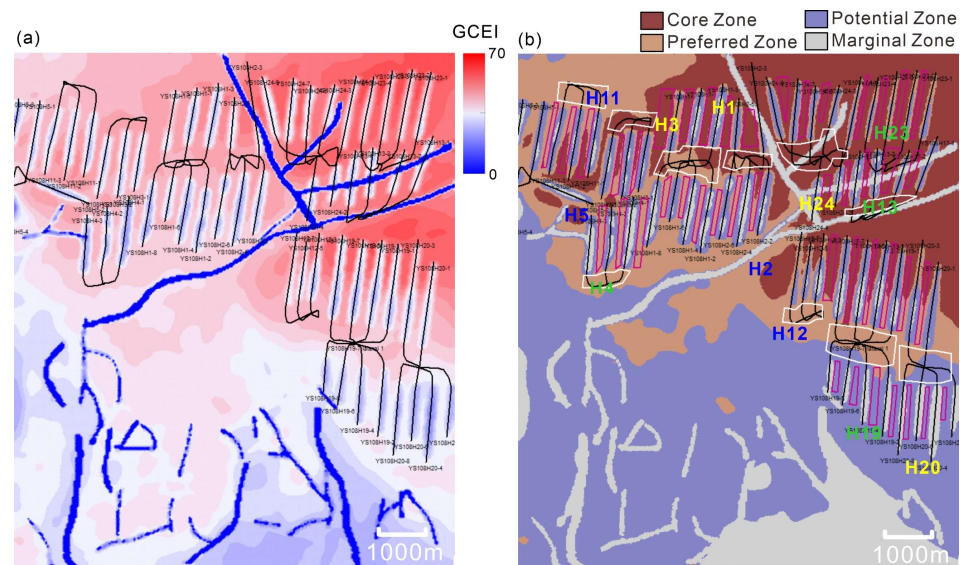


Figure 8. Balanced zoning result: (a) absolute value of the geological-condition evaluation index; (b) zoning type.

This study preliminarily ranked the secondary-development priority of 12 well platforms in the eastern HuangJinBa area. Overall, the core zones and preferred zones around platforms H24, H1, H20, and H3 are well developed. These platforms perform prominently in the resource-dominated, formation-energy-dominated, and balanced evaluations, and the matching degree between remaining resources and formation-energy conditions is relatively high, indicating a favorable redevelopment basis. Platforms H23, H13, H4, and H19 generally have certain preferred-zone and potential-zone foundations, but the scale and spatial continuity of advantageous areas are relatively weak. Some areas are limited by reservoir heterogeneity or local development conditions, and their comprehensive evaluation results are slightly lower than those of the first-tier platforms. By contrast, platforms H2, H11, H12, and H5 show relatively general comprehensive geological conditions, limited development of preferred zones, and relatively weak matching between remaining resources and formation-energy conditions in some areas. Their overall performance is not prominent in the different zoning evaluations, and they are not recommended as key deployment targets for near-term redevelopment.

It should be noted that the above ranking mainly reflects development priority at the level of present-day geological-resource conditions. Subsequent work still needs to integrate present-day stress state, natural-fracture stability, and engineering-implementation risk for comprehensive evaluation, on the basis of which a more reasonable redevelopment deployment plan can be formed.

3.2. Present-Day In Situ Stress State in the Study Area

The present-day in situ stress-state evaluation results of the study area are shown in Figure 9. Overall, the present-day stress state of the study area is dominated by a strike-slip to extensional transitional regime. The Anderson coefficient is relatively high in the northeastern area, and the stress state is more strike-slip-like. By contrast, in the densely developed control area of the existing horizontal-well pattern, the minimum horizontal principal stress decreases overall under the influence of long-term production depletion and reservoir-pressure redistribution, and the stress state gradually evolves toward a normal-faulting regime, generally showing a slightly normal-faulting stress state. This indicates that long-term development has not only changed the reservoir pressure field but also significantly modified the present-day in situ stress state.

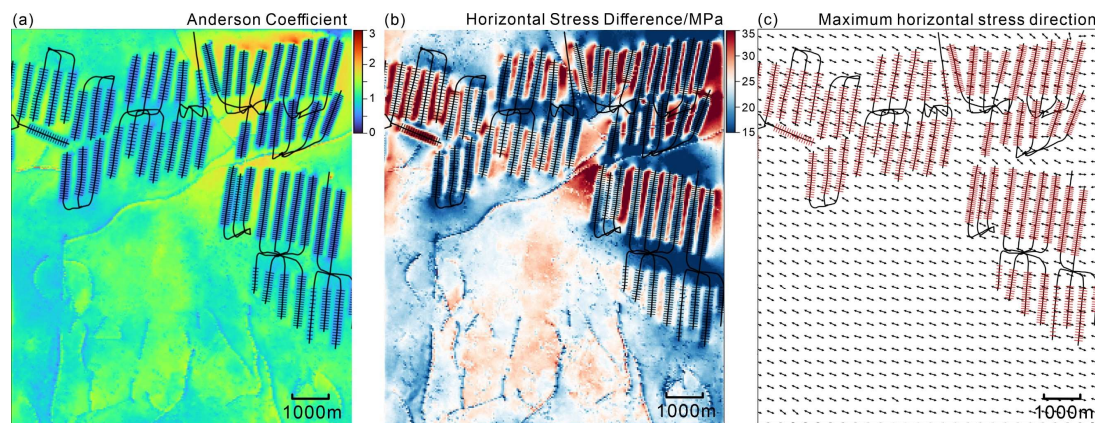


Figure 9. Present-day in situ stress-state characteristics of the study area: (a) Anderson coefficient; (b) horizontal stress difference; (c) maximum horizontal principal stress orientation.

The distribution of horizontal stress difference further indicates that different development locations in the study area have differentiated mechanical conditions for re-stimulation. Overall, the horizontal stress difference in the northern well-control area is lower than that in the southern insufficiently depleted area. However, in inter-well areas among existing horizontal wells, the local horizontal stress difference increases due to production depletion and stress redistribution. A larger horizontal stress difference is favorable for forming directionally stable and controllable dominant fractures but is unfavorable for the development of complex fracture networks. Therefore, subsequent re-stimulation in densely developed well-pattern areas should focus on controlling the fracture-extension scale to avoid excessive hydraulic-fracture propagation that may cause mature-well interference and nonuniform depletion. In contrast, the horizontal stress difference in wellbore-control blind-spot locations within each well group is relatively small, providing more favorable mechanical conditions for forming complex hydraulic-fracture networks. Treatment intensity and fracture-control volume can be moderately increased to improve the utilization degree of undepleted resources near the wellbore.

The orientation of the maximum horizontal principal stress shows only small overall variation, with azimuths mainly concentrated in the range of $100\text{--}115^\circ$, indicating that the present-day regional stress orientation in the study area remains relatively stable. Within local horizontal-well control areas, the maximum horizontal principal stress orientation shows slight deflection toward the direction perpendicular to the well trajectory, with a deflection amplitude of approximately $10\text{--}15^\circ$. This reflects that long-term production and hydraulic-fracturing stimulation exert a certain disturbance on the near-well in situ stress direction. Overall, the present-day stress field in the study area is characterized by “stress reduction in well-control areas, enhanced inter-well stress difference, and slight local directional deflection.” This understanding indicates that subsequent remaining-resource re-mobilization should not adopt a uniform fracturing strategy. Instead, conservative infill and complex-fracture-network stimulation strategies should be formulated separately according to the different stress environments of inter-well remaining resources and wellbore-control blind-spot remaining resources.

3.3. Present-Day Natural-Fracture Stability in the Study Area

The natural-fracture development characteristics and slip-risk evaluation results of the study area are shown in Figure 10. Figure 10a shows the planar distribution characteristics of natural fractures in the study area, where the blue fractures mainly represent relatively single natural fractures and the red fractures mainly represent complex network-like fractures. Overall, natural fractures are highly developed in the study area. Fracture density is

relatively high near fault zones and local structurally complex areas, and the fracture distribution pattern transitions from single dominant fractures to complex network-like fractures. The development characteristics of natural fractures not only affect hydraulic-fracture propagation paths but also further control the degree of fracture-network complexity and potential engineering risk during re-stimulation.

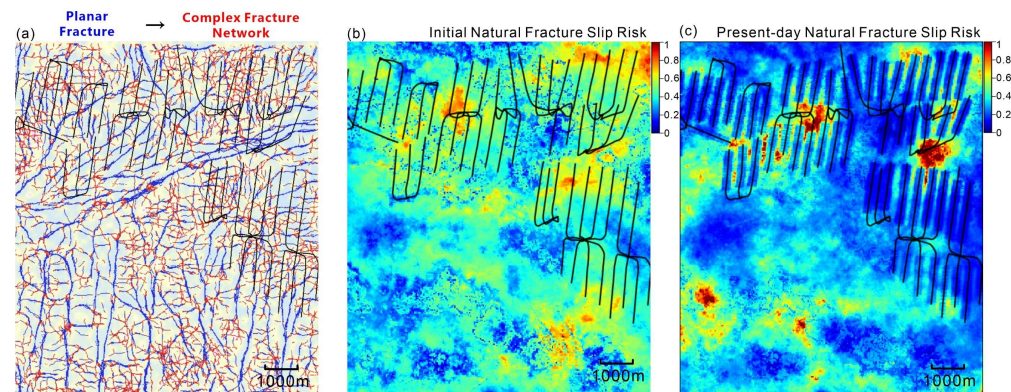


Figure 10. Distribution of natural-fracture stability in the study area: (a) natural-fracture development characteristics; (b) initial natural-fracture stability; (c) present-day natural-fracture stability.

Based on present-day stress magnitude, maximum horizontal principal stress orientation, natural-fracture strike, and pore-pressure conditions, this study further calculated natural-fracture-slip risk. As shown in Figure 10b, under initial stress conditions, natural-fracture-slip risk is relatively high in local areas of the mid-northwestern, northeastern, and mid-eastern parts of the study area, indicating that natural fractures in these areas were closer to the critical sliding state under the original geomechanical conditions. As shown in Figure 10c, with continued long-term production, the overall reservoir pore pressure decreases. Under the normal-faulting stress state in the well-pattern control area, natural-fracture stability is better [10]. Under present-day conditions, natural-fracture stability in densely developed well-pattern control areas is generally improved, and the overall slip risk decreases.

Natural-fracture stability in the study area shows the characteristics of “overall stabilization and local enhancement.” Long-term production increases the effective stress in most well-control areas, making natural fractures generally more stable. However, in local zones where fracture intersections and stress perturbations are superimposed, natural fractures may still maintain relatively high slip risk. This understanding indicates that different fracture-stability areas should be treated differently during subsequent redevelopment. For inter-well remaining-resource areas with low slip risk, relatively conservative hydraulic-fracturing stimulation can be adopted. For wellbore-control blind spots and fracture intersection zones with high slip risk, the complexification potential of natural fractures should be utilized while strictly controlling treatment pressure, pumping rate, and fracture length, thereby reducing fracture instability and mature-well interference risk.

4. Discussion

4.1. Key Findings

By integrating the evaluation results of present-day geological conditions, stress state, and natural-fracture stability, this study further carried out re-mobilization zoning for inter-well remaining resources and wellbore-control blind-spot remaining resources and formed the remaining-resource re-mobilization zoning scheme for the HuangJinBa YS108 well area, as shown in Figure 11. The core purpose of this zoning result is to implement the preceding multi-factor evaluation results on specific remaining targets and to clarify

the redevelopment priority and suitable stimulation mode of different locations under present-day geomechanical conditions.

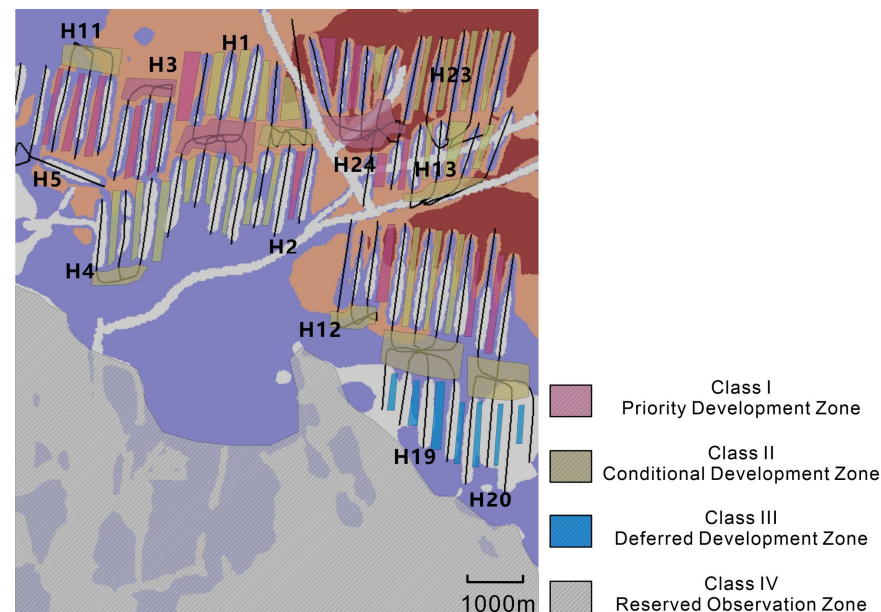


Figure 11. Remaining-resource re-mobilization zoning scheme of the HuangjinBa YS108 well area.

From the perspective of overall distribution, favorable re-mobilization areas in the study area are mainly concentrated within and adjacent to the existing well-pattern control range, especially around platforms H1, H3, H24, H13, and H23, where Type I priority utilization zones are locally developed. These areas correspond well to the core zones and preferred zones in the balanced geological-condition zoning described above. After being constrained by present-day stress state and fracture stability, they still maintain high development priority, indicating a high matching degree among remaining-resource basis, formation-energy conditions, and engineering implementability. By contrast, the southern and southwestern parts of the study area, as well as some areas far from the existing well pattern, are mostly classified as Type III or Type IV, indicating that their current comprehensive re-mobilization conditions are weak and that they are not suitable as near-term development priorities.

From the perspective of remaining-resource type, inter-well remaining resources mostly occur as strip-shaped distributions between adjacent horizontal wells and represent the main targets for subsequent well-pattern infill and inter-well supplementary depletion. Inter-well remaining resources commonly occur as strip-shaped targets between adjacent horizontal wells. Because the local horizontal stress difference is relatively large, these targets are more suitable for forming directionally stable and controllable dominant fractures. Some inter-well areas in Figure 11 are classified as Type I or Type II, indicating that these inter-well targets still have a certain remaining-resource basis. However, their stress difference is relatively large, making them more suitable for forming directionally stable dominant fractures during re-stimulation. Therefore, the development of inter-well remaining resources should mainly adopt conservative infill, with an emphasis on controlling pumping rate, fracture length, and fracture-extension range to avoid excessive communication between hydraulic fractures and mature wells [35], which may otherwise cause inter-well interference and nonuniform depletion.

Wellbore-control blind-spot remaining resources are mainly distributed inside well groups, at the ends of well trajectories, and in local insufficiently swept areas. In Figure 11, they mostly appear as blocky zones within platforms or at the edges of well groups.

Compared with inter-well remaining resources, these targets are usually closer to existing wellbores. If their stress difference is small and fracture-slip risk is controllable, they are more conducive to forming complex fracture networks and are suitable for enlarging the stimulated volume through a moderate increase in stimulation intensity. Wellbore-control blind-spot resources are mostly located within well groups, near well-trajectory ends, or in locally insufficiently swept zones. Where the stress contrast is small and the slip risk is controllable, these targets are more suitable for moderately intensified stimulation to enhance complex fracture-network coverage [34]. For example, some wellbore-control blind spots near H1, H3, H24, and H13 have high re-mobilization grades and can be regarded as important targets for rapid local potential tapping. However, for locations close to fracture intersections or with high slip risk, pressure control and treatment-risk monitoring should be implemented to avoid fracture instability and mature-well interference.

At the platform scale, the re-mobilization zoning grades around H1, H3, H24, H13, and H23 are generally high, indicating that these platforms have both a favorable remaining-resource basis and strong near-term redevelopment value. The areas near H4, H5, H11, H12, H19, and H20 are dominated by Type II and local Type III zones. During development, local sections with better conditions should be preferentially screened to avoid large-scale homogeneous deployment [36,37]. The H2 periphery is strongly influenced by fault zones and stress perturbations. Although certain remaining-resource potential still exists locally, its engineering risk and stimulation uncertainty are high. Therefore, further fine-scale screening should be conducted in subsequent deployment by integrating single-well production dynamics and fracture-risk evaluation.

Overall, the zoning result shown in Figure 11 realizes the transformation from “spatial identification of remaining resources” to “optimization of re-mobilization targets.” Inter-well remaining resources are more suitable for a development concept characterized by conservative infill and controlled fracture scale, whereas wellbore-control blind-spot remaining resources place greater emphasis on increasing local stimulation intensity under risk-controlled conditions to enhance complex-fracture-network coverage. These results can provide a basis for subsequent well-location deployment sequencing, refracturing target selection, and differentiated fracturing-parameter design in the HuangJinBa YS108 well area.

At the present stage, the proposed zoning results have not yet been independently validated by post-redevelopment production data from newly drilled infill wells, micro-seismic monitoring, or long-term production response after implementation. Therefore, the zoning scheme should be regarded as a predictive evaluation based on present-day geological conditions, formation energy, stress state, and natural-fracture stability. Future work will focus on closed-loop validation using production data from newly drilled infill wells, fracturing-treatment curves, microseismic or fiber-optic monitoring, and history-matching results. These data will be used to examine whether Type I and Type II zones show better production response than Type III and Type IV zones and to update the zoning criteria accordingly.

4.2. Limitations and Future Work

The proposed workflow provides an integrated method for redevelopment zoning in mature shale gas well areas by coupling remaining-resource conditions, formation energy, present-day stress state, and natural-fracture stability. However, several limitations should be noted.

First, the current evaluation is based on present-day geological and geomechanical conditions and should be regarded as a static or quasi-static assessment. It captures the current distribution of remaining gas content, remaining pressure, stress state, and fracture-

slip risk but does not forecast the dynamic evolution of pressure, stress, and fracture stability during future redevelopment. Therefore, future work should couple the zoning workflow with dynamic reservoir simulation and geomechanical updating to evaluate how the redevelopment process may further modify pressure and stress fields.

Second, the present workflow mainly focuses on subsurface geological and engineering constraints. Economic and surface factors, such as drilling and completion cost, gas price, surface facilities, platform accessibility, and operational constraints, were not included in the current evaluation [38]. These factors may further affect the final deployment priority of infill wells and should be incorporated in future field-scale decision-making.

Third, the percentile-based thresholds, including P40, P70, and P90, were adopted to classify relative redevelopment potential within the study area. This approach is practical for regional comparison and avoids relying on absolute thresholds that may be difficult to generalize. However, alternative threshold schemes may influence the classification of transition zones and boundary areas. Therefore, future studies should test the sensitivity of zoning results to different threshold combinations.

Fourth, although the proposed workflow is applicable in principle to other mature shale gas fields, its direct application requires recalibration. Different shale gas areas may have different burial depths, structural styles, pressure-depletion patterns, stress regimes, fracture systems, and engineering constraints. Therefore, the weights, zoning thresholds, and geomechanical constraint criteria should be adjusted according to local geological conditions, development history, and data availability before field application.

5. Conclusions

1. This study established an integrated zoning workflow for redevelopment of mature shale gas areas. By incorporating present-day geological conditions, stress state, and natural-fracture stability into a unified framework, the proposed method couples remaining-resource identification with engineering implementability evaluation and provides methodological support for infill-well deployment and differentiated hydraulic-fracturing design.
2. After approximately 10 years of continuous production, the HuangJinBa YS108 well area still shows considerable redevelopment potential. L113 and L112 are the main depleted sublayers, whereas L114, L111, and the Wufeng Formation retain remaining-resource potential. Two major types of re-mobilization targets were identified: wellbore-control blind-spot resources and inter-well remaining resources, with areas of approximately 5.61 km² and 6.89 km², respectively.
3. The present-day geological-condition zoning indicates that favorable redevelopment areas are mainly concentrated in the northern, northeastern, and eastern parts of the study area. Under the balanced weighting scheme, areas around H24, H1, H3, H23, H13, and eastern H20 show relatively good matching between remaining-resource scale and formation-energy conditions and can be regarded as priority screening areas for subsequent redevelopment.
4. The present-day stress-state and natural-fracture stability evaluations show that long-term depletion reduces the minimum horizontal principal stress in densely developed well-control areas and generally improves natural-fracture stability, although local fracture intersections and stress-perturbation superposition zones still present elevated slip risk. The final comprehensive zoning results indicate that H1, H3, H24, H13, and H23 have relatively high near-term redevelopment value. Inter-well remaining resources should be developed using conservative infill strategies with controlled fracture length, whereas wellbore-control blind-spot resources can be stimulated more

intensively under controllable risk conditions, thereby improving remaining-resource utilization while reducing inter-well interference and fracture instability risk.

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References

1. Liang, X.; Wang, G.; Xu, Z.; Zhang, J.; Chen, Z.; Xian, C.; Lu, H.; Liu, C.; Zhao, C.; Xiong, S. Comprehensive evaluation technology for shale gas sweet spots in the complex marine mountains, South China: A case study from Zhaotong national shale gas demonstration zone. *Nat. Gas Ind. B* **2016**, *3*, 27–36. [\[CrossRef\]](#)
2. Liang, X.; Shan, C.; Wang, W.; Li, Z.; Zhu, D.; Xu, J.; Zhang, Z.; Zhang, Z.; Luo, Y.; Yuan, X. Exploration and development in the Zhaotong national shale gas demonstration area: Progress and prospects. *Nat. Gas Ind. B* **2023**, *10*, 44–61. [\[CrossRef\]](#)
3. Gupta, I.; Rai, C.; Devegowda, D.; Sondergeld, C.H. Fracture hits in unconventional reservoirs: A critical review. *SPE J.* **2020**, *26*, 412–434. [\[CrossRef\]](#)
4. Meng, M.; Li, Z.; Hong, Z.; Bao, J.; Jiang, Q. Quantifying pore size distribution by nuclear magnetic resonance method in tight sandstones: Comparison between water-wet and oil-wet saturated fluids. *Int. J. Hydrogen Energy* **2026**, *197*, 152608.
5. Qin, Z.; Xu, T. Shale gas geological “sweet spot” parameter prediction method and its application based on convolutional neural network. *Sci. Rep.* **2022**, *12*, 15405. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Hong, Z.; Meng, M.; Yuan, B.; Ma, C.; Wang, Q.; Deng, K.; Bao, J.; Yuan, M. Nanopore structure characterization of lacustrine and marine shales: Comparison between small angle neutron scattering and nitrogen adsorption methods. *Int. J. Hydrogen Energy* **2026**, *208*, 153565. [\[CrossRef\]](#)
7. Bao, J.; Meng, M.; Wang, Q.; Yu, S.; Yuan, M.; Hong, Z.; Jiang, Q. Comparison of square-root and logarithmic data treatment for pore connectivity by co-current spontaneous imbibition in lacustrine shales. *Int. J. Hydrogen Energy* **2026**, *229*, 154737.

8. Mesdour, R.; Basri, M.; Temizel, C.; Jama, N. Sweet spot identification in unconventional shale reservoirs. In *Physics of Fluid Flow and Transport in Unconventional Reservoir Rocks*; Wiley Online Library: Hoboken, NJ, USA, 2023; pp. 333–349.
9. Liu, S.; Yang, X.; Zhao, S.; Xu, H.; Lei, Y.; Liu, Y.; Cao, L.; Li, B.; He, Y.; Xia, Z.; et al. Evaluation of geological-engineering sweet spots in deep shale gas reservoirs in the North Luzhou Block. *Processes* **2025**, *Epub ahead of printing*. [[CrossRef](#)]
10. Zhang, M.Y.; Zhou, K.R.; Li, C.X.; Cui, H.; Yuan, X.J.; Su, Z.H.; Xian, C.G. Evolution of natural fracture stability in middle-deep shale reservoirs. *Pet. Sci. Bull.* **2026**, *11*, 99–133.
11. Mezzar, A.; Mehdi, K.M.; Nabila, H.; Abdelmadjid, A. Sweet spots identification: Geological and engineering integrated shale gas: A case study of shale gas Ahnet Basin Algeria. *Iraqi Geol. J.* **2024**, *57*, 162–190. [[CrossRef](#)]
12. Ning, W.; Ju, W.; Guo, W. The present-day in-situ stress field and its effect on shale gas development in Zigong area of southern Sichuan Basin. *Unconv. Resour.* **2024**, *4*, 100078.
13. Yong, R.; Wu, J.; Song, Y.; Xu, E.; Xu, B.; Wang, Q.; Wu, L. Investigation of present-day in situ stresses in a shale gas reservoir of Sichuan Basin, China: Field measurement, stress field modeling, and engineering implications. *Arab. J. Geosci.* **2022**, *15*, 14. [[CrossRef](#)]
14. Mandal, P.P.; Sarout, J.; Rezaee, R. Triaxial deformation of the Goldwyer gas shale at in situ stress conditions—Part II: Viscoelastic creep/relaxation and frictional failure. *Rock Mech. Rock Eng.* **2023**, *56*, 7441–7474.
15. Zhang, M.; Xian, C.; Huang, X.; Liu, Y.; Liu, Y.; Liu, M.; Wang, J.; Liu, C.; He, Y. Quantitative assessment method and application of natural fracture risk in shallow shale gas based on geomechanics—A case study of Zhaotong shale gas area in southern China. In *Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference*; SPE: Houston, TX, USA, 2024.
16. Morrow, C.; Moore, D.E.; Lockner, D. The effect of mineral bond strength and adsorbed water on fault gouge frictional strength. *Geophys. Res. Lett.* **2000**, *27*, 815–818. [[CrossRef](#)]
17. Tian, H.; Zeng, L.; Xu, X.; Li, H.; Luo, B.; Dong, S. Factors influencing the in-situ stress orientations in shales: A case study of the Wufeng-Longmaxi formations in the Jiaoshiba area, southeastern Sichuan Basin, China. *J. Nat. Gas Sci. Eng.* **2021**, *94*, 104110.
18. Li, D. Evaluation methods and engineering application of the feasibility of “double sweet spots” in shale gas reservoirs. *Pet. Drill. Technol.* **2020**, *48*, 94–99.
19. Wang, L.; Chen, W.Z.; Zhang, Y.J.; Zhang, X.D.; Vuik, C. Investigating Effects of Heterogeneity and Fracture Distribution on Two-Phase Flow in Fractured Reservoir with Adaptive Time Strategy. *Transp. Porous Media* **2023**, *149*, 175–203.
20. Jiang, J.; Tchelepi, H.A. Nonlinear Acceleration of Sequential Fully Implicit (SFI) Method for Coupled Flow and Transport in Porous Media. *Comput. Methods Appl. Mech. Eng.* **2019**, *352*, 246–275. [[CrossRef](#)]
21. Sun, H.; Cai, X.; Hu, D.; Lu, Z.; Zhao, P.; Zheng, A.; Li, J.; Wang, H. Theory, technology and practice of shale gas three-dimensional development: A case study of Fuling shale gas field in Sichuan Basin, SW China. *Pet. Explor. Dev.* **2023**, *50*, 651–664. [[CrossRef](#)]
22. Gao, J. Three-dimensional development technologies and countermeasures for shale gas in Weiyuan Block of the Sichuan Basin: A case study on Wei 202A Platform. *Nat. Gas. Ind.* **2022**, *42*, 93–99. [[CrossRef](#)]
23. Han, L.; Li, X.; Liu, Z.; Duan, G.; Wan, Y.; Guo, X.; Guo, W.; Cui, Y. Influencing factors and prevention measures of casing deformation in deep shale gas wells in Luzhou block, southern Sichuan Basin, SW China. *Pet. Explor. Dev.* **2023**, *50*, 979–988. [[CrossRef](#)]
24. Zhang, M.; Li, C.; Xian, C.; Wang, H.; Liu, Y.; Huang, X. High-resolution in-situ stress modeling integrating scratch test experiments. *SPE J.* **2026**, *31*, 2105–2120.
25. Zoback, M.D. *Reservoir Geomechanics*; Cambridge University Press: Cambridge, UK, 2010.
26. Zoback, M.D.; Kohli, A.H. *Unconventional Reservoir Geomechanics*; Cambridge University Press: Cambridge, UK, 2019.
27. Anderson, E.M. *The Dynamics of Faulting and Dyke Formation with Applications to Britain*; Oliver and Boyd: Edinburgh, UK, 1951.
28. Chen, Z.; Liao, X.; Zhao, X.; Dou, X.; Zhu, L. Performance of horizontal wells with fracture networks in shale gas formation. *J. Pet. Sci. Eng.* **2015**, *133*, 646–664. [[CrossRef](#)]
29. Deng, Y.; Feng, X.; Wang, X.; Zhao, Z.; Guo, J.; Zeng, J. Risk analysis of casing deformation in shale gas wells: A case study from the Jingyan Block. In *Proceedings of the SPE Advances in Integrated Reservoir Modelling and Field Development Conference and Exhibition*; SPE: Houston, TX, USA, 2025; p. D021S011R007.
30. Huang, H.; Xu, E.; Zhong, G.; Zhang, Z.; Yang, X.; Liu, C.; Yu, W. Analysis of casing deformation in horizontal wells of deep shale gas reservoirs: Causes and mitigation strategies. In *Proceedings of the SPE/AAPG/SEG Unconventional Resources Technology Conference*; SPE: Houston, TX, USA, 2025; p. D031S066R006.
31. Li, Y.; Liu, W.; Yan, W.; Deng, J.; Li, H. Mechanism of casing failure during hydraulic fracturing: Lessons learned from a tight-oil reservoir in China. *Eng. Fail. Anal.* **2019**, *98*, 58–71. [[CrossRef](#)]
32. Licitra, D.T.; Vittore, F.; Espindola, B. Casing deformation in unconventional developments: Case study Vaca Muerta Formation, Argentina. In *Proceedings of the SPE/AAPG/SEG Unconventional Resources Technology Conference*; GeoScienceWorld: McLean, VA, USA, 2025; p. D031S049R004.

33. Wu, J.; Shi, X.; Gou, Q.; Xu, E.; Zhang, D.; Ren, X.; Yu, T.; Wu, K.; Tong, Y.; Wang, L.; et al. Casing deformation risk prediction with numerical simulation during hydraulic fracturing in deep shale gas reservoirs. In *Proceedings of the SPE/AAPG/SEG Unconventional Resources Technology Conference*; URTEC: Houston, TX, USA, 2024; p. D021S032R002.
34. Labuz, J.F.; Zang, A. Mohr–Coulomb failure criterion. In *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007–2014*; Springer International Publishing: Cham, Switzerland, 2012; pp. 227–231.
35. Li, Q.; You, D.; Li, Q.; Wang, F.; Wang, Y.; Yang, Y. Analysis of Sedimentation Behavior and Influencing Factors of Solid Particles in CO₂ Fracturing Fluid. *Processes* **2025**, *13*, 4049. [[CrossRef](#)]
36. Ao, F.; Li, Q.; Li, Q.; Wu, J.; Wang, F.; Yan, C. Numerical Simulation Investigation of Fracture Propagation Behavior Patterns and Sensitivity Factors of Oil Shale Reservoirs in the Xunyi Region Considering the Influence of Natural Fracture. *Geofluids* **2025**, *2025*, 2762142. [[CrossRef](#)]
37. Li, Q.; Li, Q.; Wang, F.; Wu, J.; Wang, Y.; Jin, J. Effects of Geological and Fluid Characteristics on the Injection Filtration of Hydraulic Fracturing Fluid in the Wellbores of Shale Reservoirs: Numerical Analysis and Mechanism Determination. *Processes* **2025**, *13*, 1747. [[CrossRef](#)]
38. Dumitrache, L.; Roy, A.; Bird, A.; Goktas, B.; Sorgi, C.; Stanley, R.; De Gennaro, V.; Eswein, E.; Abbott, J. A Multidisciplinary Approach to Production Optimization through Hydraulic Fracturing Stimulation and Geomechanical Modelling in Clair Field. In *Proceedings of the International Petroleum Technology Conference, Riyadh, Saudi Arabia*; IPTC: Richardson, TX, USA, 2022; p. IPTC-22293-MS.

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