RESEARCH ARTICLE

# Coupling Mechanisms of Qualitative-Quantitative and Macro-Micro Analyses for Helium Reservoir Characteristics in Northern Huazhou Area, Weihe Basin

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## Abstract

**The North Huazhou area in Weihe Basin, a transition zone between the Ordos Block and Qinling Orogenic Belt, hosts multiple Cenozoic reservoirs critical for helium, geothermal, and tight oil/gas exploration. Based on Well H1 core, logging, and laboratory data, multi-scale analyses of the Sanmen, Zhangjiapo, Lantian-Bahe Formations, and Gaoling Group reveal significant lithological differentiations: the Zhangjiapo Formation is a medium-porosity, medium-permeability reservoir, whereas the Lantian-Bahe Formation exhibits low porosity and permeability. X-ray diffraction confirms dominant siliceous minerals with clay fluctuations reflecting strong hydrodynamic environments. Moderately strong velocity ($D_v = 55.53\%$) and acid sensitivity ($D_{ac} = 57.68\%$) necessitate reservoir-protective development strategies. The Lantian-Bahe gas-water zone (76.5 m, 20.6%) displays dominant positive rhythms macroscopically, while residual intergranular and dissolution pores with sheet-like and necked throats restrict fluid flow microscopically. Noble gas isotopes ($^4He/^{20}Ne = 37{,}164$) confirm anomalous $^4He$ from uranium-rich Qinling granites. A "multi-source supply–fault transport–exsolution enrichment" model is proposed, whereby coal-type gas drives helium exsolution from pore-fracture waters into the free gas phase. The Gaoling Group and Lantian-Bahe Formation are identified as primary targets, providing a geological basis for helium evaluation and multi-energy development in Weihe Basin.**

**Keywords**: weihe basin, qualitative-quantitative evaluation, macro-micro, coupling mechanism, reservoir characteristics.

## 1 Introduction

Weihe Basin is a key geological transition zone between the Ordos Basin and Qinling Orogenic Belt. The basin possesses a Cenozoic fault-depression structural background and complex sedimentary-diagenetic

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evolution processes, forming multiple sets of reservoir systems with important resource potential.

The North Huazhou area is located in the northeastern part of Weihe Basin. The area features complex tectonic activities and diverse sedimentary systems. Multiple types of reservoir systems have developed, such as Cenozoic sandstone thermal reservoirs, Paleozoic carbonate rock reservoirs, and Upper Paleozoic coal-measure unconventional reservoirs [1, 2]. The complex superimposed basin evolution and multi-stage hydrocarbon accumulation processes in such tectonic settings provide important analogues for understanding reservoir development in Weihe Basin [3]. In recent years, with the advancement of the "deep exploration" strategy and the launch of the deep drilling plan in Weihe Basin, the North Huazhou area has become an important target area for resource exploration in the basin. The study of its reservoir characteristics has important theoretical and application value for geothermal resource development, helium resource evaluation and tight oil and gas exploration.

The assessment of resource potential in Weihe Basin has often faced many challenges. Historically, the basin was considered to lack effective source rocks, which restricted the progress of conventional oil and gas exploration. However, recent studies have confirmed that there are Upper Paleozoic coal-measure strata in the basin, mainly distributed in the Xi'an Sag and the North Huazhou area. The coal-measure strata in the North Huazhou area are thicker, and the thicker parts are closer to the south, a distribution pattern linked to the Cenozoic tectono-thermal evolution of the basin [4–7]. These discoveries have opened up a new direction for the study of oil and gas resources in the basin, especially natural methane gas produced by source rocks. The gas can migrate through a large number of faults in the basin to form trap structures sealed by Cenozoic faults, and provide a carrier for helium. In addition, the widely developed Cenozoic sandstone thermal reservoirs in the basin has become realistic target for geothermal resource development, supporting the development of the regional clean energy industry [8, 9].

This study is based on core, logging, and laboratory analysis data from well H1. A systematic characterization of multiple Cenozoic reservoir sets in the North Huazhou area of the Weihe Basin was carried out, followed by a comprehensive evaluation of the reservoirs. The main reservoirs investigated include the Sanmen Formation, Zhangjiapo Formation, Lantian–Bahe Formation, and Gaoling Group. Understanding the reservoir characteristics in this area has significant scientific and practical value for natural gas development and oil and gas exploration in the Weihe Basin. The results are expected to provide valuable guidance and support for the systematic study of the basin's energy geology.

## 2 Geological background of North Huazhou area

### 2.1 Regional geographical location

The northern region is located in the northern part of Huazhou District, and is located in the core area of the eastern Weihe Basin. It is bounded by the Weihe River to the north, facing Dali County, Wei District to the west, Huayin City to the east, Qinling Mountains to the south, and Lantian County to the southwest [10]. The total area of the district is approximately 1,139.5 $km^2$. It belongs to the eastern section of the "Eight Hundred Miles of Qinchuan" in the Guanzhong Plain. There are still large-scale Carboniferous-Permian system and partially residual Mesozoic system in the deep parts of the Xi'an Sag and North Huazhou area.

### 2.2 Sedimentary stratigraphic characteristics

The North of Weihe Fault are mainly Early Paleozoic carbonate rock formations, with Upper Paleozoic and sporadic Mesozoic remnants in some areas; The south of Weihe Fault are mainly Proterozoic shallow metamorphic rocks and Indosinian-Yanshanian granites. The main types of sedimentary facies are alluvial fan, fan delta, fluvial, and lacustrine facies, with the depth of the sedimentary center reaching over 6000 m, consistent with the deep burial conditions inferred from newly discovered crude oil characteristics in the basin [12]. The remaining Upper Paleozoic Carboniferous-Permian coal-measure strata at the base of the basin and the Pliocene Zhangjiapo Formation lacustrine mudstone in the basin are two sets of potential source rocks, consistent with the Cenozoic tectonic framework revealed by crustal structure studies of the Weihe Graben [11].

The North Huazhou area shows a skip-like fault depression shape, which is deep in the east and shallow in the west, steep in the south and gentle in the north, a structural configuration also recognized in the adjacent Gushi Sag where biogenic gas exploration has been conducted [13]. The Huazhou District is located on the southern margin of the North Huazhou area. According to seismic data interpretation, its

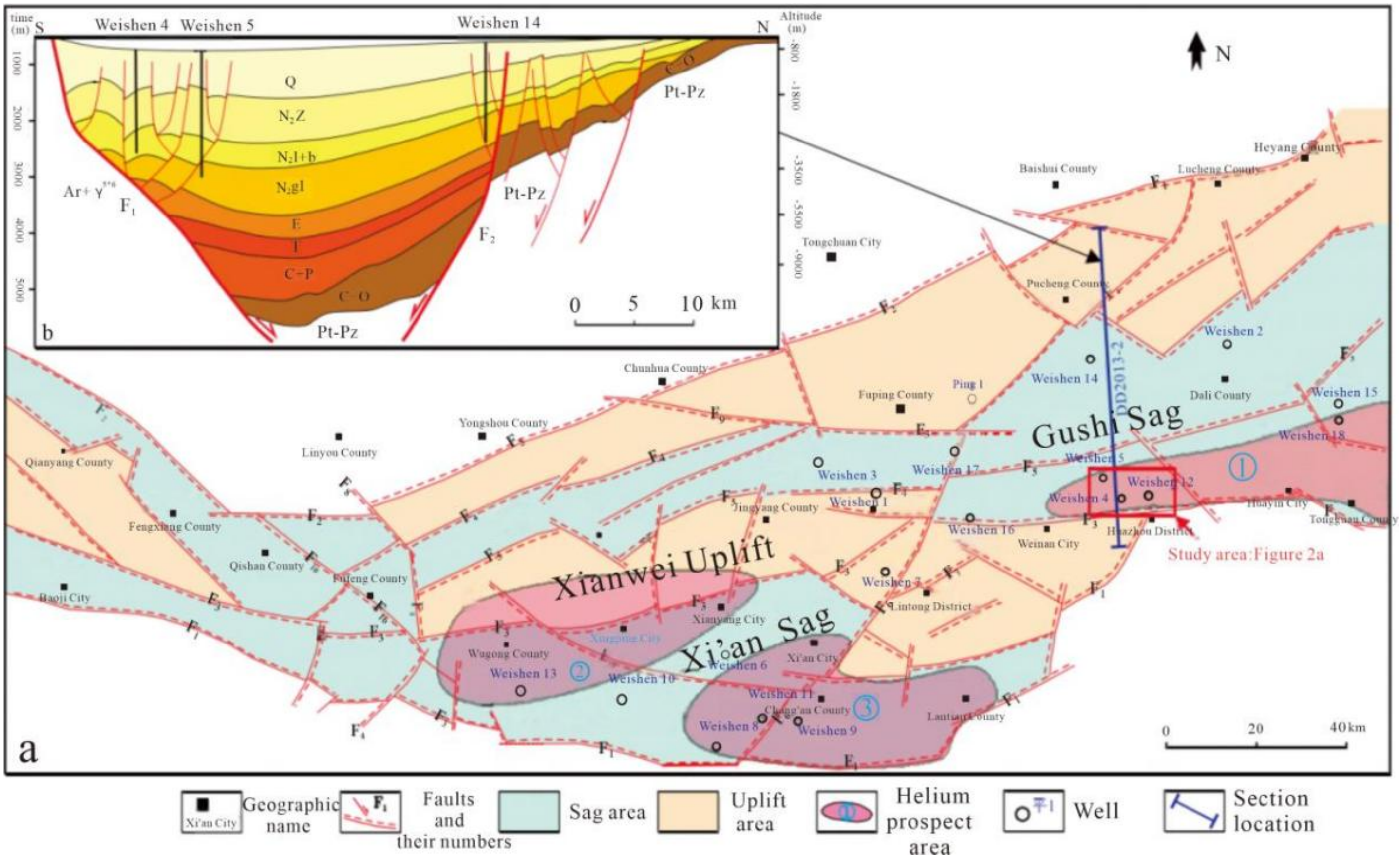


**Figure 1.** The comprehensive geological map of Weihe Basin.

sedimentary cover and basement are bounded by the northern margin fault of the Qinling Mountains. This fault is a basin-controlling fault that deeply cuts through the basement. A series of secondary faults have developed above it, trending nearly parallel to the basin-controlling fault. On cross-sections, these faults exhibit a series of 'Y'-structural styles [14]. The sedimentary cover is controlled by faults at all levels, and takes the form of two faulted anticlines in the east-west direction. The anticlines are cut by secondary faults of different scales, forming a series of faulted blocks, faulted noses and faulted anticline traps [15] (Figure 1).

Weihe Basin, which includes the North China and Qinling stratigraphic areas, developed at the junction of the Ordos Platform and the East Qinling Orogenic Belt. The exposed strata from oldest to youngest include Archaean, Cambrian, Ordovician, Devonian, Carboniferous, Permian, Triassic, Cretaceous and Cenozoic. Pre-Paleogene and granite constitute the base of the basin and finally the periphery of the basin. The extremely thick Cenozoic sediments form Weihe Plain, within which newly identified internal faults further reveal the complex structural architecture of the graben [16] (Table 1).

## 3 "Qualitative-Quantitative" reservoir characteristic analysis

### 3.1 "Qualitative-Quantitative" analysis of reservoir petrology

It affects the quality of the reservoir at the current stage, so it is the premise for studying the diagenesis of the analytical formula of rock types. The impact of particle size, rounding and sorting on the porosity and permeability of the reservoir is slightly lower than that of the rock composition. However, they are equally important for judging the quality of the reservoir, especially its impact on the heterogeneity of the reservoir.

The study focuses on the helium reservoirs in the North Huazhou area of Weihe Basin, including four layers: Sanmen Formation, Zhangjiapo Formation, Lantian-Bahe Formation, and Gaoling Group.

#### 3.1.1 *Qualitative analysis of cores*

Through the analysis and statistics of the cores (Figure 2) of the four layers from the Sanmen Formation, Zhangjiapo Formation, Lantian-Bahe Formation, and Gaoling Group, a fan-shaped statistical diagram of the lithology classification of the four layers was obtained (Figure 3).

**Table 1.** Sedimentary stratigraphy of Weihe Basin.

| Stratigraphic unit | | | Stratigraphic lithology | Remarks |
|---|---|---|---|---|
| Eonothem | Erathem | System | | |
| PhanerozoicEon | Cenozoic Era | Quaternary | Mainly loess and sandy gravel | Widely distributed, complex contact with underlying Neogene |
| | | Neogene | Sandy mudstone and sandstone interbeds | Exposed in Lishan and surrounding areas |
| | | Paleogene | Massive sandstone with mudstone intercalations | Exposed in Lishan and surrounding areas |
| | Mesozoic Era | Cretaceous | Mainly conglomerate, sandstone, shale | Mainly exposed in Baoji area,western basin |
| | | Jurassic | Stratigraphic hiatus | Stratigraphic hiatus |
| | | Triassic | Sandstone,shale,etc | Parallel unconformity with Permian |
| | Late Paleozoic Era | Permian | Lower coal-bearing strata, upper mudstone and shale | Conformable with Carboniferous;distributed in northern basin margin |
| | | Carboniferous | Shale, marl, locally coal interbeds | Paralic strata,angular unconformity with underlying Ordovician |
| | | Devonian | Stratigraphic hiatus | Stratigraphic hiatus |
| | Early Paleozoic Era | Silurian | Stratigraphic hiatus | Stratigraphic hiatus |
| | | Ordovician | Limestone, shale, locally conglomerate | Parallelunconformity with Cambrian,mainly in Weibeilow mountains |
| | | Cambrian | Limestone and dolostone | Unconformity with underlying Proterozoic, mainly in Weibei low mountains |
| ProterozoicEon | | | Schist, marble, phyllite | Mainly in south-central basin margin, adjacent to East Qinling |
| Archean Eon | | | Gneiss and related metamorphic rocks | Distributed in Lintong-Lishan and Lantian-Tongguan, the oldest basement of East Qinling |


**Figure 2.** Reservoir core photos. (a) Sanmen Formation (well depth 1035.77 m–1040.12 m); (b) Zhangjiapō Formation (well depth 1708.07 m–1711.59 m); (c) Lantian–Bahe Formation (well depth 2678.74 m–2689.42 m); (d) Gaoling Group (well depth 2950.03 m–2954.18 m).

The top of cores were gray-green mixed with gray-white mudstone from Sanmen Formation , and the below is a thin layer of gray siltstone. The middle part was gray-green mixed with gray-brown mudstone. The middle and lower parts are gray-green siltstone, and the bottom was brown mudstone.

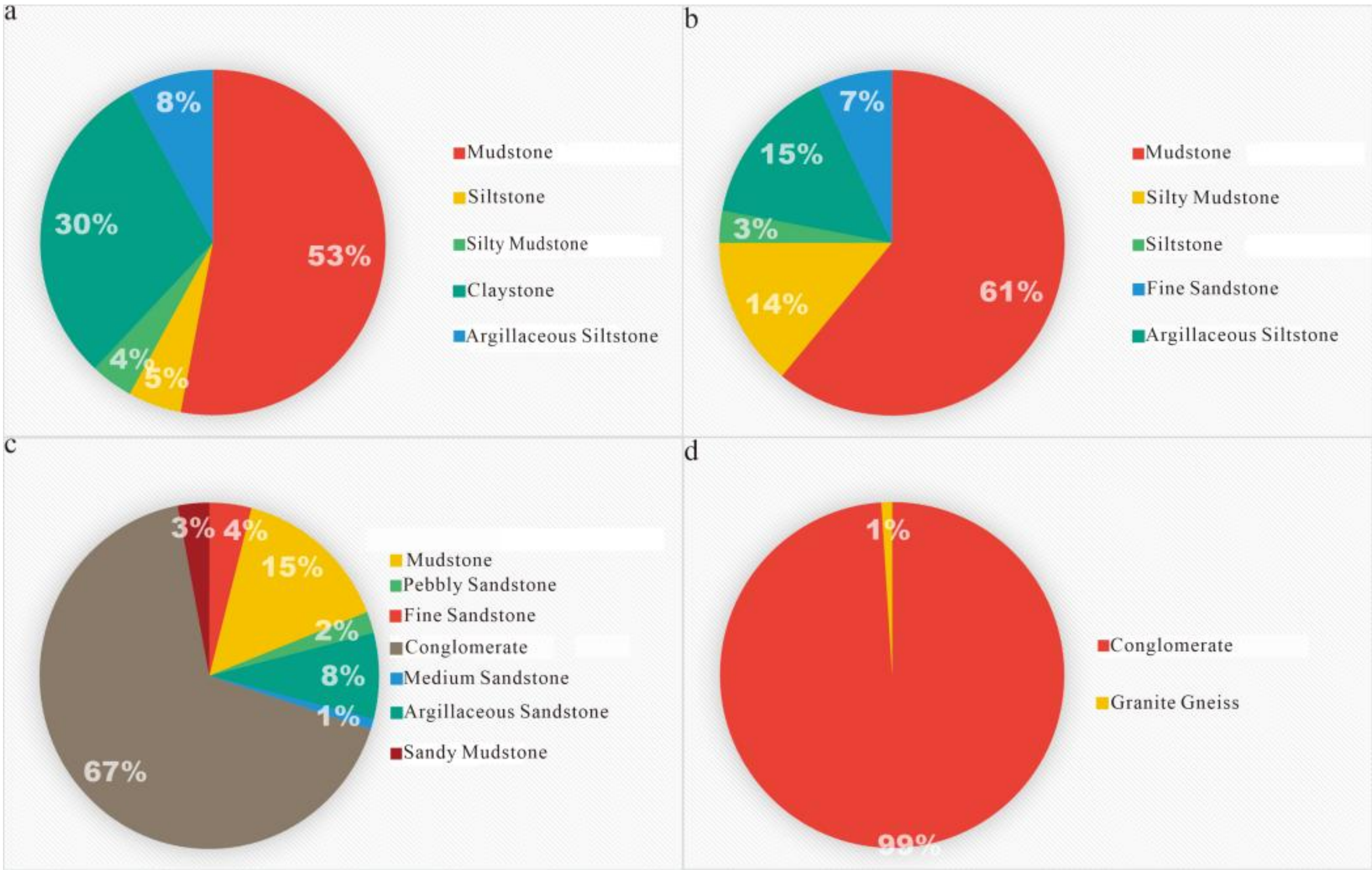


**Figure 3.** Reservoir lithology classification pie chart. (a) Pie chart of lithology classification of the Sanmen Formation; (b) Pie chart of lithology classification of the Zhangjiapo Formation; (c) Pie chart of lithology classification of the Lantian-Bahe Formation; (d) Pie chart of lithology classification of the Gaoling Group.

According to the lithology classification fan chart of the Sanmen Formation, the lithology was mainly mudstone (54 %) and claystone (30 %), with others such as silty mudstone (4 %), argillaceous siltstone (8 %), and siltstone (5 %) accounting for a smaller proportion. The Zhangjiapo Formation core was most gray fine sandstone, and the bottom was gray mudstone. According to the lithology classification fan statistical chart, the Zhangjiapo Formation was mainly mudstone (61 %). And the remaining lithology was silty mudstone (14 %), argillaceous siltstone (15 %), siltstone (3 %), and fine sandstone (7 %). The upper part of the cores of the Lantian-Bahe Formation was brown sandy mudstone, gray gravelly, medium-coarse sandstone, and brown intercalated gray-green mudstone. And the lower part was gray-brown sandstone and conglomerate. The main lithology was conglomerate (67 %), and the remaining six types of lithology were sandy mudstone (3 %), gravelly sandstone (2 %), argillaceous sandstone (8 %), medium sandstone (1 %), fine sandstone (3 %), and mudstone (15 %). The cores of the Gaoling Group were composed of conglomerate as a whole, with granite gneiss at the bottom. The main lithology was conglomerate (99 %), with granitic gneiss accounting for only 1 %.

### 3.1.2 *Qualitative analysis of mineral thin sections*

By observing and analyzing the mineral thin sections of Sanmen Formation, Zhangjiapo Formation, Lantian-Bahe Formation and Gaoling Group (Figure 4), the qualitative analysis of each reservoir was further carried out.

The lithology of the Sanmen Formation was identified as mudstone. Thin section microscopic observation showed that its main mineral composition was clay minerals, terrigenous clastic particles and calcite. Among them, the clay mineral component constituted the main body of the rock matrix. It was mainly composed of subtle scaly clay mineral aggregates and was distributed in a chaotic, non-directional manner. The mineral composition of the terrigenous clastic components included quartz, feldspar and a small amount of lithic fragments. The particle shapes were mainly sub-round to sub-angular. The dominant particle size was silt sand, followed by medium-fine

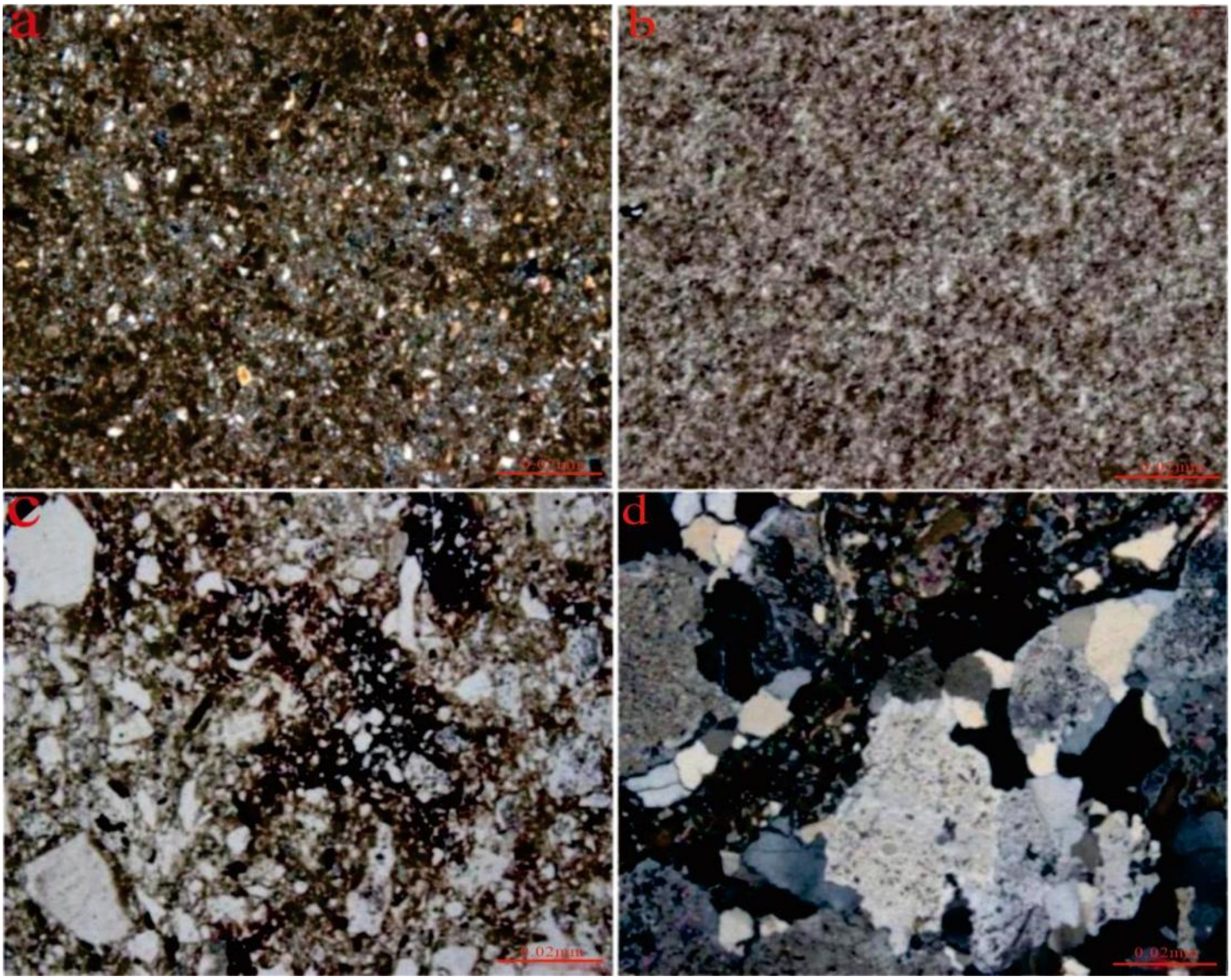

**Figure 4.** The thin sections from Reservoir samples. (a) Mudstone of the Sanmen Formation (well depth 1035.9 m); (b) Mudstone of the Zhangjiapo Formation (well depth 1711.18 m); (c) Coarse sandstone of the Lantian-Bahe Formation (well depth 2001.04 m); (d) Conglomerate of the Gaoling Group (well depth 2953.68 m).

sand particles. The overall distribution was chaotic. Calcite crystals were mostly semi-euhedral to anhedral granular. Their distribution was chaotically dispersed or locally enriched to form aggregates. They were mixed and symbiotic with the clay mineral matrix.

The lithology of the Zhangjiapo Formation was identified as sandstone and mudstone. Microscopic analysis showed that its mineral composition mainly included terrigenous clasts, calcite and interstitial materials. The mineral composition of terrigenous clasts was mainly quartz and feldspar, with a small amount of lithic fragments. The quartz end-member was single crystal quartz, and plagioclase and potassium feldspar could be seen in the feldspar. Among them, plagioclase generally developed sericitization and epidote alteration. The lithic fragments contained biotite, muscovite and other flaky fragments. The structural characteristics were mainly sub-round to sub-angular particles, with the dominant particle size being silt sand, followed by fine sand to medium-coarse sand particles. The clastic particles were chaotically distributed with a heterogeneous support structure. Calcite was semi-euhedral to idiomorphic granular shape and was mixed and symbiotic with the clay mineral matrix. The composition types of interstitial materials include siliceous cement, calcareous cement and zeolite cement. Siliceous cement developed in the form of quartz secondary enlarged edges, with significant recrystallization. The calcareous cement was granular calcite, which increased in particle size after recrystallization. The interstitial material was distributed among the clastic particles in a pore-filling cementation manner.

The lithology of the Lantian-Bahe Formation was identified as sandstone, which was mainly composed of terrigenous clasts and interstitial materials. The terrigenous clastic components were mainly feldspar, quartz and rock fragments. The shapes of clastic particles included angular, sub-angular, and sub-round shapes, all of which were sand-sized particles, and were randomly distributed without sorting. Feldspar mainly included plagioclase and potassium feldspar, with a small amount of granite fragments. Plagioclase generally underwent sericitization and epidote alteration, with varying degrees of alteration. Potassium feldspar was dominated by microcline and striated feldspar. The quartz is mainly single crystal quartz, with a small amount of quartzite fragments. Lithic fragments: Biotite, muscovite, epidote and other mineral debris could be seen. The interstitial material was mainly composed of clayey matrix and a small amount of iron cement. It was distributed between the sand grains as pore fillings. Clay matrix is composed of slightly scaly clay minerals.

Recrystallized structures were less common. The feldspar end-members included plagioclase, potassium feldspar, granite fragments and monzonite debris. Feldspar was generally subject to alteration, mainly characterized by muscovitization, epidoteization and clayification. The lithic end-members included altered rock lithic and other types, and a small amount of mineral fragments, such as epidote, could be seen. The interstitial material was mainly composed of clayey impurities, and its composition was slightly scaly clay minerals. This heterogeneous aggregate often had a stripe-like or line-mark structure, and was oriented and distributed along the intergranular spaces between terrigenous clastic particles.

### *3.1.3 X-ray Diffraction Quantitative Analysis*

From whole-rock X-ray diffraction quantitative analysis, it was found that the core samples of the Sanmen Formation, Zhangjiapo Formation, Lantian-Bahe Formation and Gaoling Group all contained siliceous minerals as the main component. In these formations, the quartz content exhibited significant fluctuations. In terms of plagioclase content, except for the Sanmen Formation, which had relatively small changes, the other layers all showed large changes. The potassium feldspar content changed relatively gently in the Sanmen Formation and Zhangjiapo Formation, but changed to a greater extent in the Lantian-Bahe Formation and Gaoling

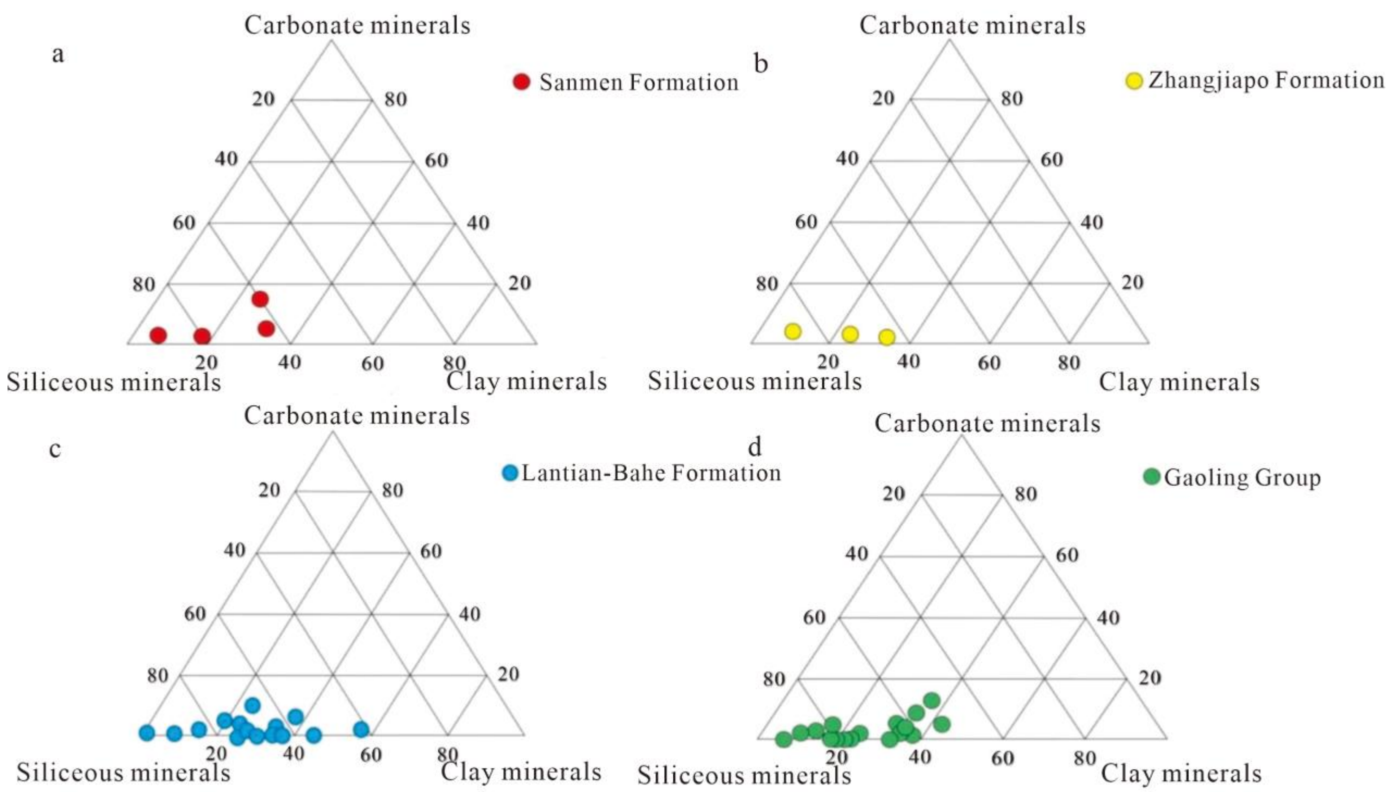


**Figure 5.** The ternary diagram of each layer.(a) Sanmen Formation; (b) Zhangjiapo Formation; (c) Lantian-Bahe Formation; (d) Gaoling Group.

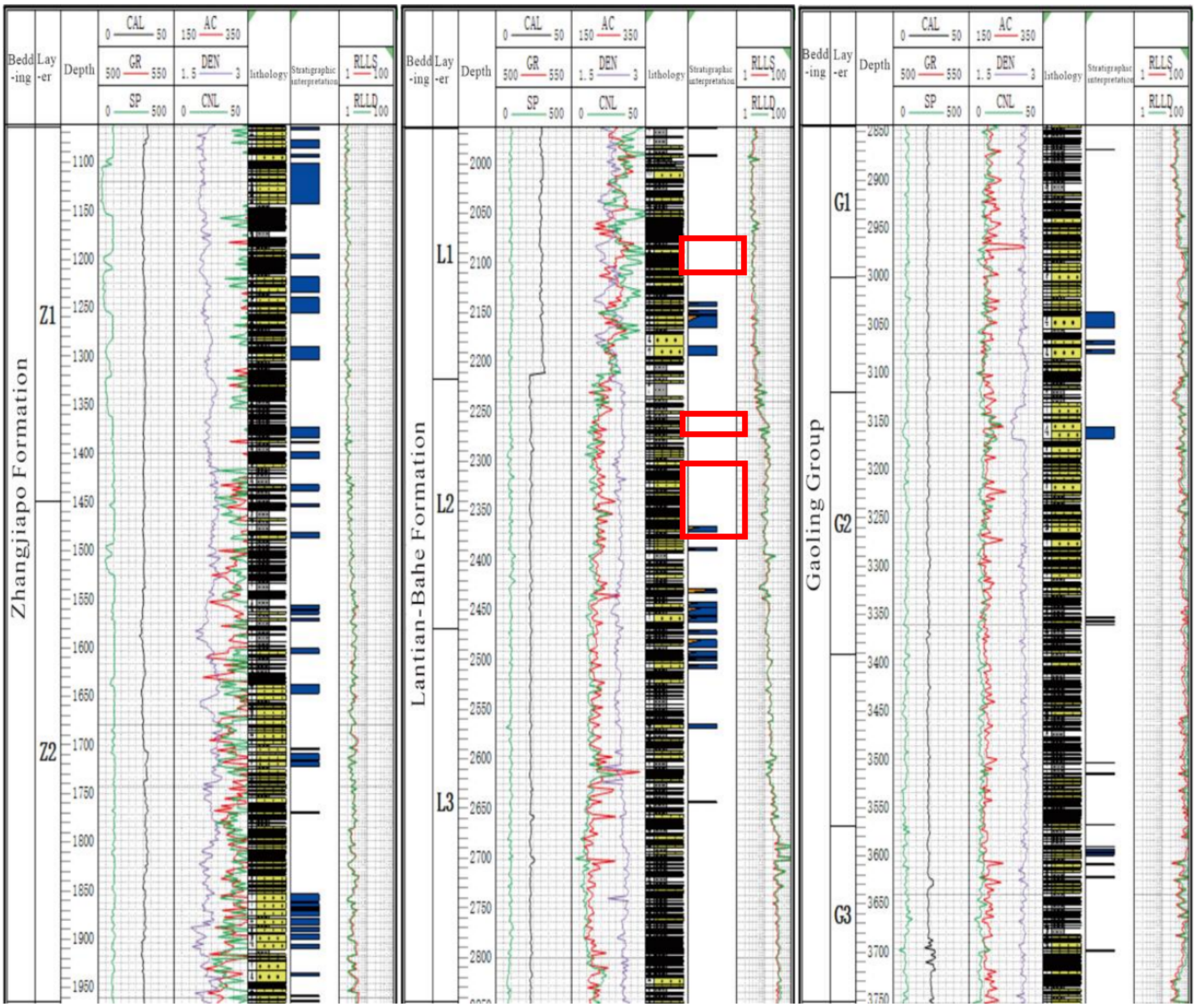


**Figure 6.** The comprehensive histogram of well logging evaluation for the Well H1.

Group. Constructing a mineral triangle diagram for each layer could intuitively and clearly display the proportions of various minerals in rock composition and their changing trends (Figure 5). In addition to siliceous minerals, the clay content in the core had a high proportion and obvious fluctuations. The dynamic changes in the content of siliceous minerals and clay minerals reflected the strong heterogeneity of rocks. The alternating changes of clay content were an intuitive reflection of the alternating changes in hydrodynamic conditions during the deposition process, and also marked the lithology conversion process. In addition, the detection results of pyrite in the Sanmen Formation, Lantian-Bahe Formation and Gaoling Group reflected that there may have been a weak reducing environment at that time.

#### *3.1.4 Quantitative analysis of gas-bearing properties of reservoirs*

A quantitative analysis of gas-bearing properties was conducted on the stratigraphic structure and reservoirs of Well H1 in the North Huazhou area of Weihe Basin, and a complete Cenozoic stratigraphic sequence was established. The Zhangjiapo Formation had a drilled thickness of 900 m, the Lantian-Bahe Formation showed a continuous sedimentary thickness of approximately 1000 m, and the Gaoling Group extended to a depth of about 900 m. Within the interval from the Zhangjiapo Formation to the Gaoling Group encountered by this well, the cumulative reservoir thickness was 371.3 m. The distribution of fluid phases in the reservoirs exhibits significant heterogeneity. Water layers were widely developed, with a thickness of 294.8 m (accounting for 79.4 %), and were present throughout the entire reservoir interval. Gas-water layers were concentrated in the Lantian-Bahe Formation, with a thickness of 76.5 m (accounting for 20.6 %). Gas component analysis showed that the gases in the Lantian-Bahe Formation reservoirs are dominated by methane and helium (Figure 6). The detection of helium is of particular geological significance, indicating possible contributions from mantle-derived fluids or radioactive decay from ancient uranium-rich formations in this interval, which required further verification in light of the regional tectonic setting.

#### *3.1.5 Quantitative analysis of reservoir sensitivity*

Reservoir sensitivity refers to the degree to which various factors cause damage to the reservoir. Tight sandstone rock samples from the North Huazhou area were selected, and the experiments on water sensitivity, velocity sensitivity, acid sensitivity, and stress sensitivity were conducted in accordance with SY/T5358—2010 "Evaluation Method of Reservoir Sensitivity Flow Experiment". Using the reservoir sensitivity experimental evaluation method, the sensitivity degree of this area was assessed, and the damage degree of these four sensitivity factors to the reservoir was determined [17]. In fluid property identification, the sensitivity of conventional logging curves directly affects the accuracy of gas-water layer identification in the North Huazhou area. Accordingly, after a systematic analysis of the response characteristics of conventional logging curves, combined with geological and gas reservoir features, sensitive logging parameters were optimized. The analysis shows that the velocity sensitivity damage rate ($D_{\mathrm{v}}$) reaches 55.53 %, indicating moderately strong velocity sensitivity; the water sensitivity damage rate (D<sub>w</sub>) is 33.72 %, exhibiting moderately weak water sensitivity characteristics, and the critical salinity was determined to be 11,925 mg/L (the threshold point where the permeability change rate exceeds 20 %) through step-down salinity experiments; the acid sensitivity damage rate (D<sub>ac</sub>) is as high as 57.68 %, indicating moderately strong acid sensitivity and potential secondary precipitation risk; the alkali sensitivity damage rate (D<sub>al</sub>) is 45.74 %, classified as moderately weak alkali sensitivity (Figure 7). These results systematically reveal the sensitivity behavior spectrum of reservoir rock samples under fluid action, providing a key experimental evidence for the formulation of reservoir protection strategies during development.

## 4 "Macro-Micro" reservoir characteristics analysis

### 4.1 "Macro-Micro" analysis of reservoir heterogeneity

Reservoir heterogeneity refers to the uneven changes in the spatial distribution characteristics and various properties (lithology, electrical properties, physical properties, etc.) of the reservoir due to sedimentary construction, diagenetic evolution, structural transformation, etc. This change is specifically reflected in the lithological differences of the reservoir, interlayer distribution characteristics, reservoir spatial distribution shape, and internal pore structure characteristics of the reservoir. Studying reservoir heterogeneity is actually to study the anisotropy in the reservoir, describe the reservoir characteristics qualitatively and quantitatively, and provide an accurate geological model basis for subsequent reservoir research.

#### *4.1.1 Research on macroscopic heterogeneity*

Reservoir macroheterogeneity includes inter-reservoir layer heterogeneity and intra-reservoir layer heterogeneity.

1) Interlayer heterogeneity refers to the reservoir heterogeneity within a set of oil and gas-bearing layers, namely, the interlayer differences in the reservoir. Reservoir description at the series scale includes the regularity of the interaction of sand bodies of various depositional environments on the profile, as well as the development and distribution regularity of barriers; systematic characterization of such heterogeneity relies on integrated pore structure analysis methods applicable to tight sandstones [18].

In terms of reservoir lithology, the lithological distribution of strata in the North Huazhou area varies across different periods. This is manifested as differences in the types and grain sizes of terrigenous clasts, as well as differences in secondary minerals. The terrigenous clasts of the Sanmen Formation, Zhangjiapo Formation, and Lantian-Bahe Formation are mainly composed of quartz, feldspar, and rock fragments. The Sanmen Formation is mostly mudstone, with silt grain sizes predominantly ranging from 0.004 to 0.06 mm. The mudstone of the Zhangjiapo Formation is similar to that of the Sanmen Formation, with sandstone grain sizes mainly consisting of medium sand between 0.25 and 0.5 mm. The Lantian-Bahe Formation is predominantly sandstone, with grain sizes mainly of medium

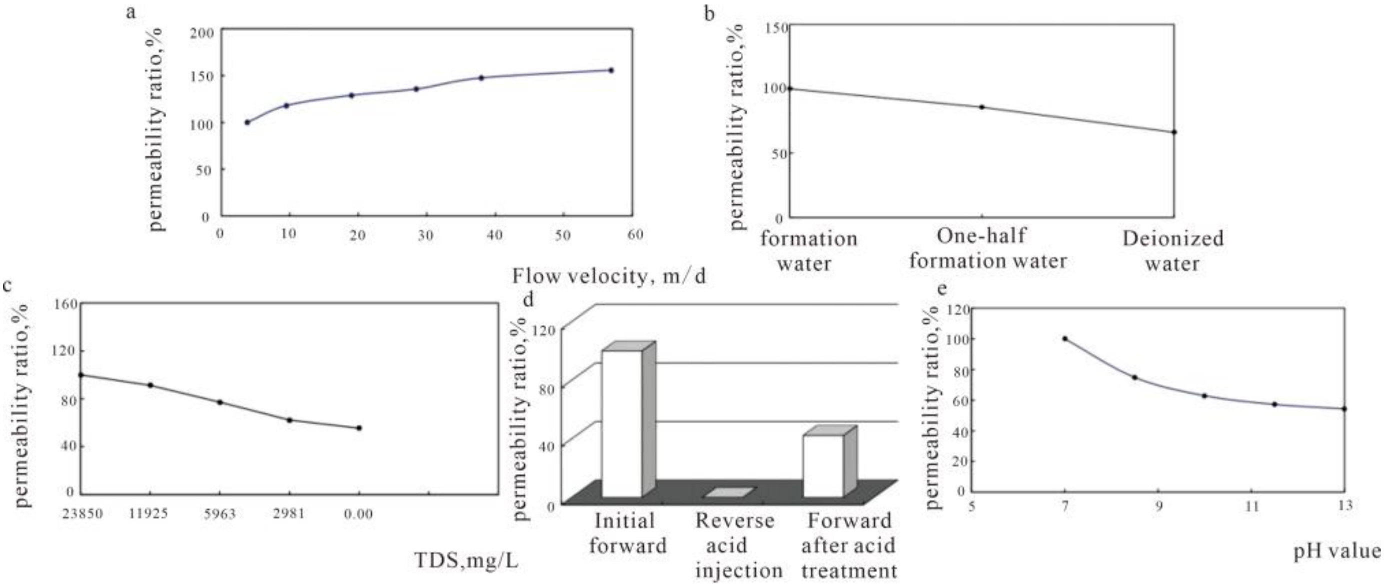


**Figure 7.** Sensitivity experimental curve. (a) Velocity sensitivity; (b) Water sensitivity; (c) Salinity sensitivity; (d) Acid sensitivity; (e) Alkali sensitivity

sand between 0.25 and 0.5 mm, and gneiss and mudstone are observed in the middle-lower part. The terrigenous clasts of the Gaoling Group are mainly composed of feldspar, minor rock fragments, and quartz end-members, with quartz grain sizes ranging from 0.1 to 2 mm, and terrigenous gravels of approximately 2–40 mm are visible in the grains.

Regarding interlayer physical property differences, within a single reservoir interval, The variations in sandbody depositional environments and diagenetic alterations may lead to significant differences in the physical properties of different sandbodies. In the analysis of actual data, the interlayer physical property differences are primarily characterized by differences in porosity and permeability across different sedimentary stages.

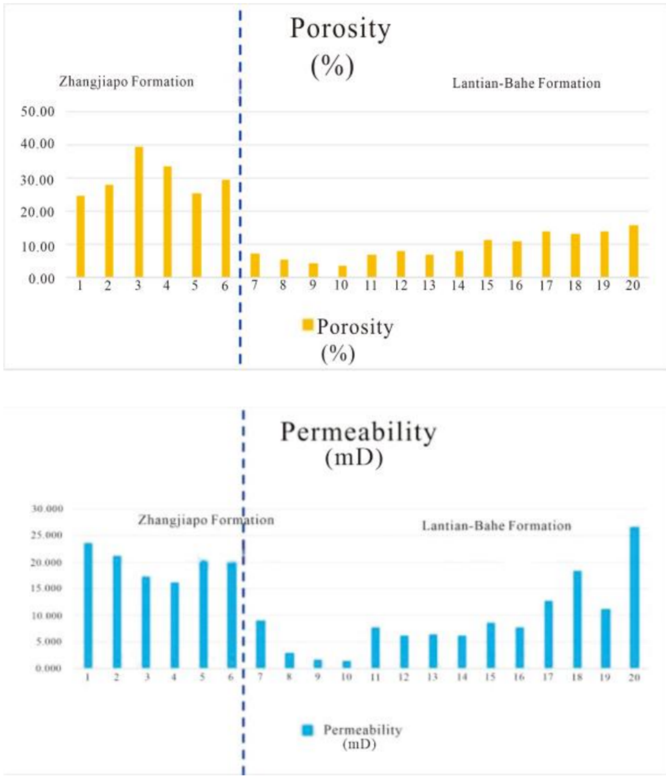


**Figure 8.** The porosity comparison chart and Permeability comparison chart.

Based on production data, the porosity of the sand layers from the Zhangjiapo Formation and Lantian-Bahe Formation in the North Huazhou area ranges from 3.59 % to 39.24 %, and the permeability ranges from 1.247 to 26.71 mD. The overall average porosity is 15.47 %, and the average permeability is 12.18 mD. The Zhangjiapo Formation reservoir in the North Huazhou area is generally a medium-porosity, medium-permeability reservoir, whereas the Lantian-Bahe Formation reservoir is generally a low-porosity, low-permeability reservoir (Figure 8).

There is minimal difference in porosity and permeability within each period; however, the significant differences exist between different periods, reflecting strong heterogeneity in the overall permeability. The greater the interlayer permeability difference, the lower the oilfield recovery factor and the relatively poorer the development performance.

Interlayer reservoir differences are primarily based on a systematic comparison of stratigraphic thickness and reservoir thickness. Taking Well H1 as an example, the Sanmen Formation, Zhangjiapo Formation, Lantian-Bahe Formation, and Gaoling Group exhibit significant differentiation in reservoir development. Specifically, the Zhangjiapo Formation shows a distinctly dominant reservoir thickness proportion, indicating that the reservoir space in this interval is relatively well developed. In contrast, the effective reservoir thickness proportions of the Sanmen Formation and the Gaoling Group are relatively limited, reflecting their relatively weaker reservoir performance. The differential distribution of interlayer effective thickness clearly characterizes the vertical heterogeneity of reservoir development within the studied stratigraphic succession (Figure 9).

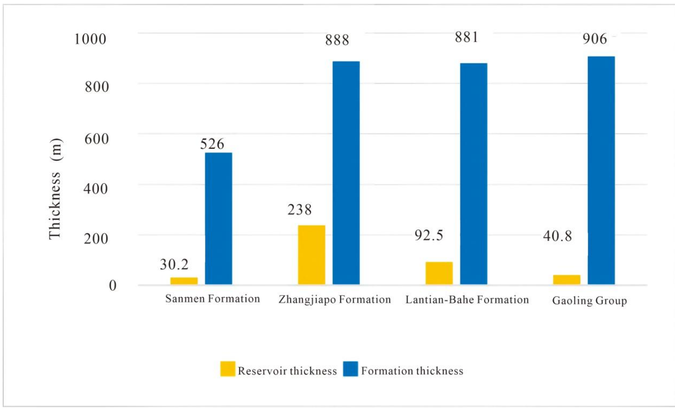


**Figure 9.** Comparison of reservoir thickness and formation thickness.

2) Intra-reservoir heterogeneity specifically refers to the vertical differentiation rules of parameters, such as lithology, physical properties and oil content within the vertical scale of a single sand layer. As a key geological control factor, the heterogeneous feature directly restricts the water flooding thickness distribution and displacement sweep coefficient of a single sand layer. The systematic characterization of intra-layer heterogeneity in North Huazhou area covers three core aspects: analyzing of intra-layer sedimentary rhythmic structure and identifying vertical configuration patterns such as forward rhythm, reverse rhythm and compound rhythm; research on the spatial configuration of interlayers within the layer, quantifying the barrier effect of interlayer density, distribution frequency and lateral continuity on fluid seepage; quantitative characterization of heterogeneity parameters, realizing mathematical modeling through indicators such as permeability variation coefficient, thrust coefficient and step difference, with pore structure measurements such as mercury injection and nuclear magnetic resonance providing the physical property data underpinning these calculations [19].

The intra-layer rhythmic characteristics are mainly represented by the vertical changes in the particle size of clastic particles within a single sand layer. Due to different depositional environments, the particles show different rhythms during the deposition process, and the different rhythms directly affect the vertical differences in the physical properties of the reservoir. Physical rhythm is generally divided into four rhythm types: positive rhythm, reverse rhythm, homogeneous rhythm, and compound rhythm (Figure 10).

In a normal rhythmic layer, grain size coarsens upward from fine to coarse (Figure 11(a)), with well log characteristics showing a bell shape. The highest permeability and porosity values are located at the bottom of the single sand body. During development, normal rhythmic layers are prone to bottom water coning, with the top becoming a residual oil enrichment zone. Moreover, normal rhythmic characteristics account for a relatively large proportion in the North Huazhou area. In a reverse rhythmic layer (Figure 11(b)), sediment grain size becomes coarser upward within a single sand body, with permeability exhibiting relatively small values at the bottom and gradually increasing upward. The type of rhythmic layer was deposited under relatively strong hydrodynamic conditions, with well log characteristics generally showing a funnel shape. Reverse rhythmic characteristics account for a relatively small proportion in the North Huazhou area. In a composite rhythmic layer (Figure 11(c)), normal and reverse rhythms are combined in an upper-lower assemblage, with the highest porosity and permeability occurring in the relatively homogeneous middle section. This is typically caused by rapid changes in water regime or diagenesis. In a homogeneous rhythmic layer (Figure 11(d)), porosity and permeability distribution are relatively uniform with little overall variation, often formed by continuous wave reworking of sediments. The layers are thin, and their well log characteristics commonly display a serrated or finger-like shape. This type of rhythmic characteristic is relatively rare in the North Huazhou area.

#### 4.1.2 *Research on microscopic heterogeneity*

Reservoir microscopic heterogeneity refers to the geological factors within microscopic pore throats that affect fluid flow. This study utilizes data from core thin sections, cast thin sections, and scanning electron microscopy (SEM) to analyze microscopic properties, such as mineral composition of reservoir rocks,

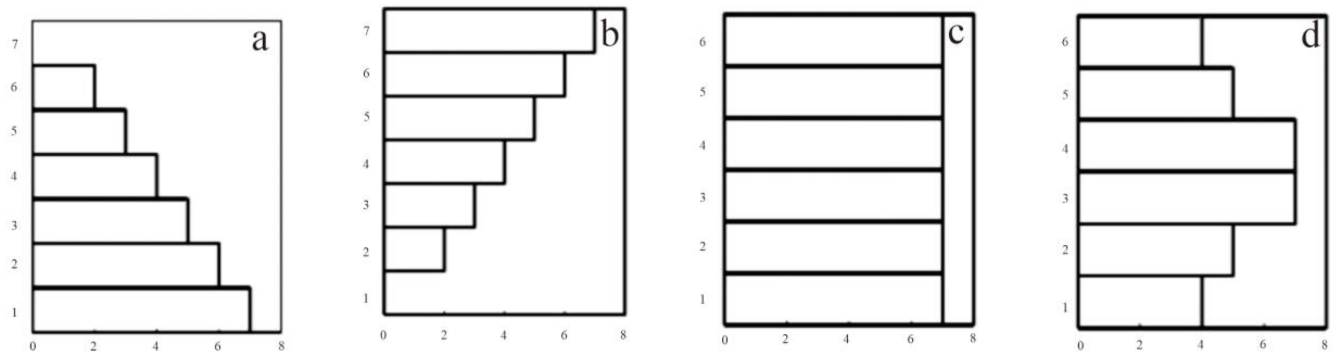


**Figure 10.** Schematic diagram of rhythmic features. (a) Normal rhythm type; (b) Reverse rhythm type; (c) Homogeneous rhythm type; (d) Composite rhythm type.

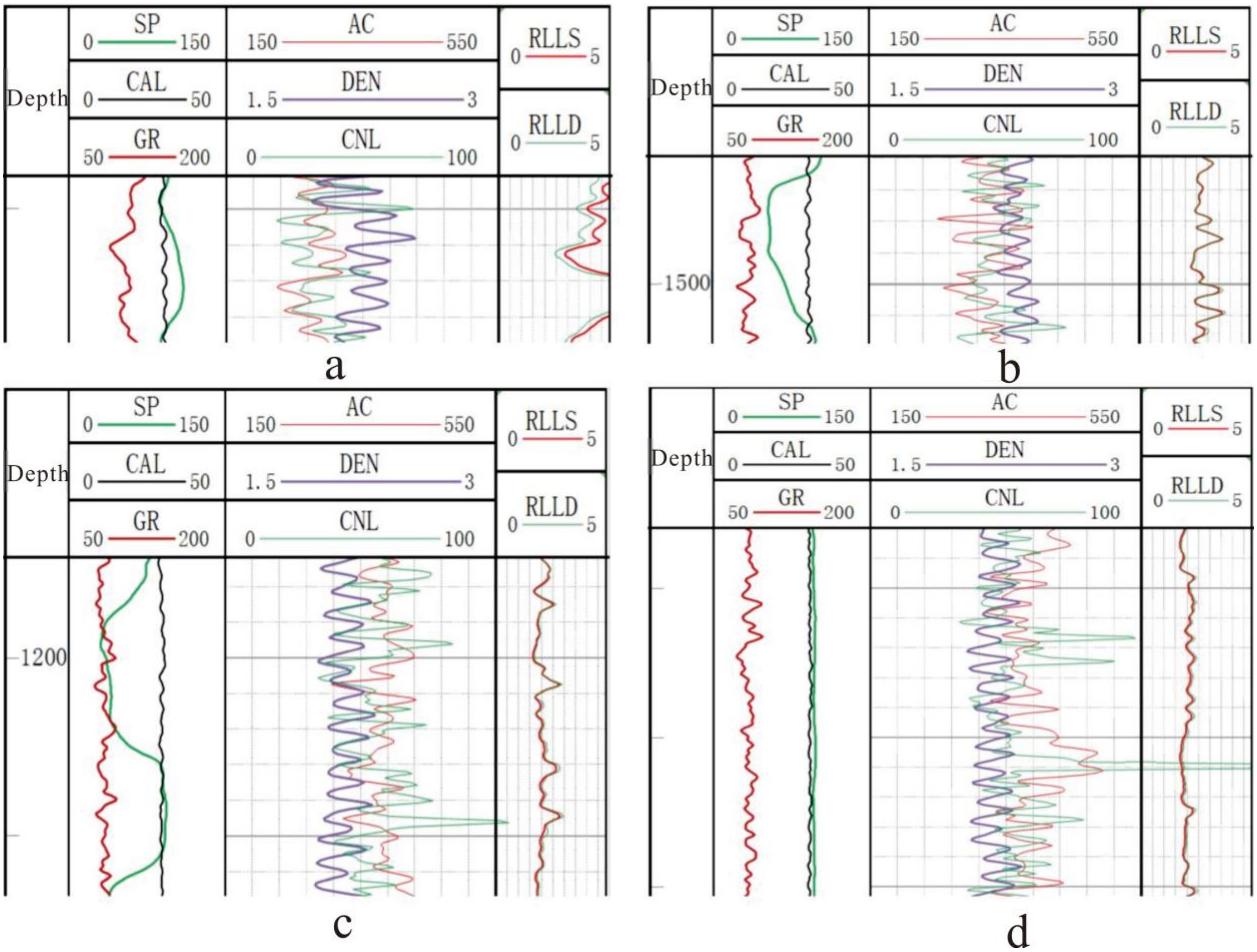


**Figure 11.** Well logging rhythm feature map. (a) Normal rhythm layer; (b) Reverse rhythm layer; (c) Composite rhythm layer; (d) Homogeneous rhythm layer.

intergranular contact relationships, cementation types, pore types, and pore structure characteristics [20].

The pore size and distribution influence the storage space of the reservoir, while throat morphology and pore-throat connectivity constrain fluid flow within the reservoir. Qualitative investigations of reservoir pores and throats mainly focus on the types of pores and throats, pore dimensions, and pore-throat connectivity.

**Reservoir pore types:**
The identification of reservoir pore types is primarily conducted through microscopic observation of cast

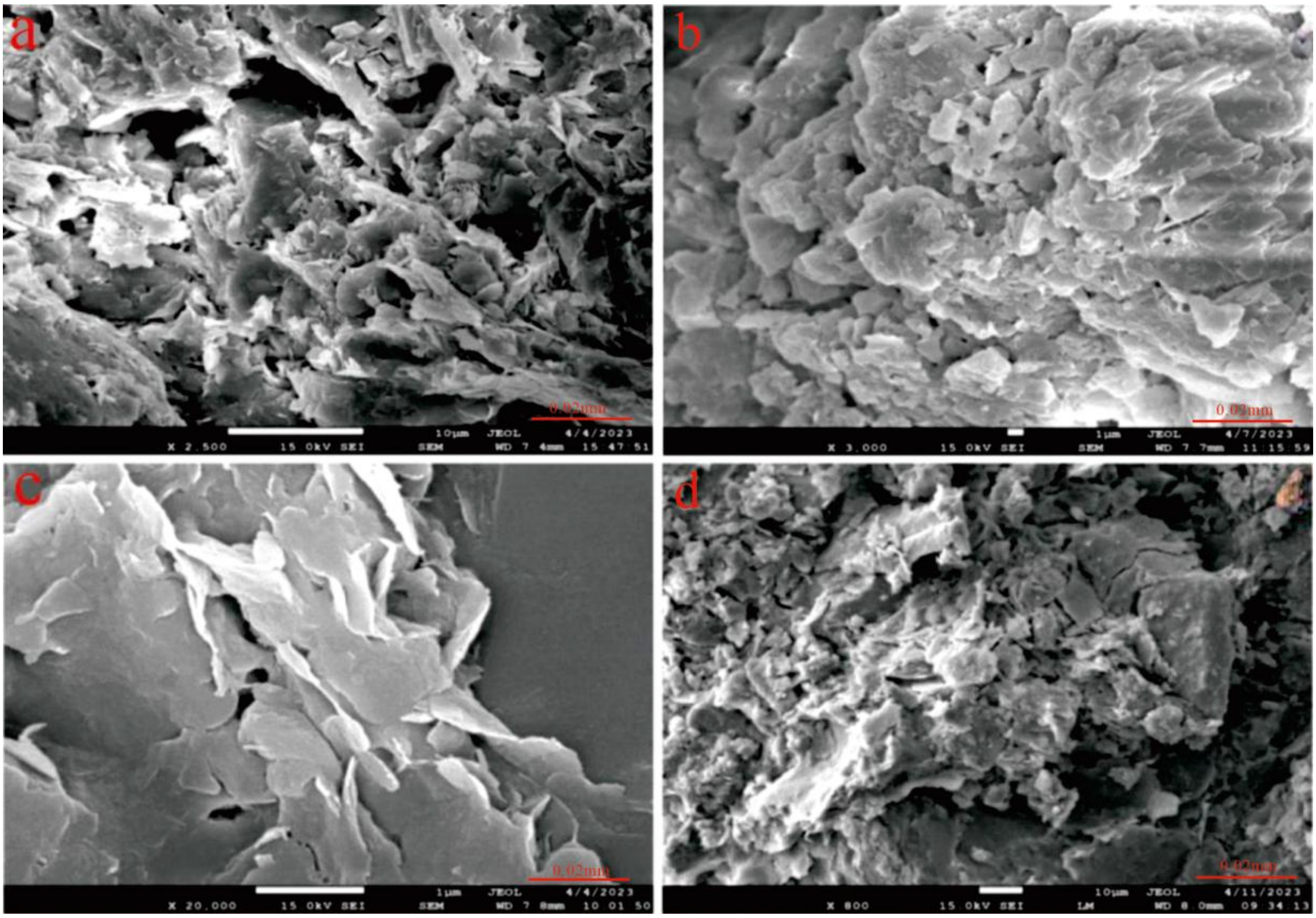


**Figure 12.** Scanning electron microscope pore map of reservoir. (a) Intergranular pore, Sanmen Formation, 1038 m; (b) Intercrystalline pore, Sanmen Formation, 1038 m; (c) Intragranular dissolution pore, Sanmen Formation, 1035.9 m; (d) Microfracture, Lantian-Bahe Formation, 1996.77 m.

thin sections and scanning electron microscopy. Different pore types reflect the various diagenetic processes that the reservoir has undergone, and they can indicate the complexity of the reservoir pore-throat network. Based on statistical analysis of scanning electron microscopy data from the North Huazhou area, four pore types have been identified: intercrystalline pores, intergranular pores, intragranular pores, and microfractures. Among these, intergranular pores, intercrystalline pores, and intragranular dissolution pores are relatively well developed. The identification methodology follows established approaches for clastic reservoir pore classification, informed by diagenetic studies of quartz cementation and porosity evolution in oil field sandstones [21].

**(1) Intergranular pores**

Due to strong compaction, the primary intergranular pores of the reservoir have been destroyed, retaining a variety of morphologically diverse residual intergranular pores. Although intergranular pores gradually decrease with increasing depth, the cast thin section and scanning electron microscopy analyses indicate that intergranular pores remain the most dominant pore type in the study interval, providing favorable space for hydrocarbon accumulation (Figure 12(a)). In the North Huazhou area, the residual intergranular pores mainly exhibit irregular polygonal or triangular shapes, with pore sizes ranging from 1 to 3 $\mu$m, showing strong heterogeneity.

**(2) Intercrystalline pores**

Intercrystalline pores are also widely developed in the North Huazhou area, representing a pore type secondary only to intergranular pores and dissolution pores. Although their areal porosity ratio is very low and small pore radii, they are extensively developed and contribute to connecting pores within the reservoir (Figure 12(b)). Intercrystalline pores mainly refer to the micropores between crystals such as clay minerals and silica.

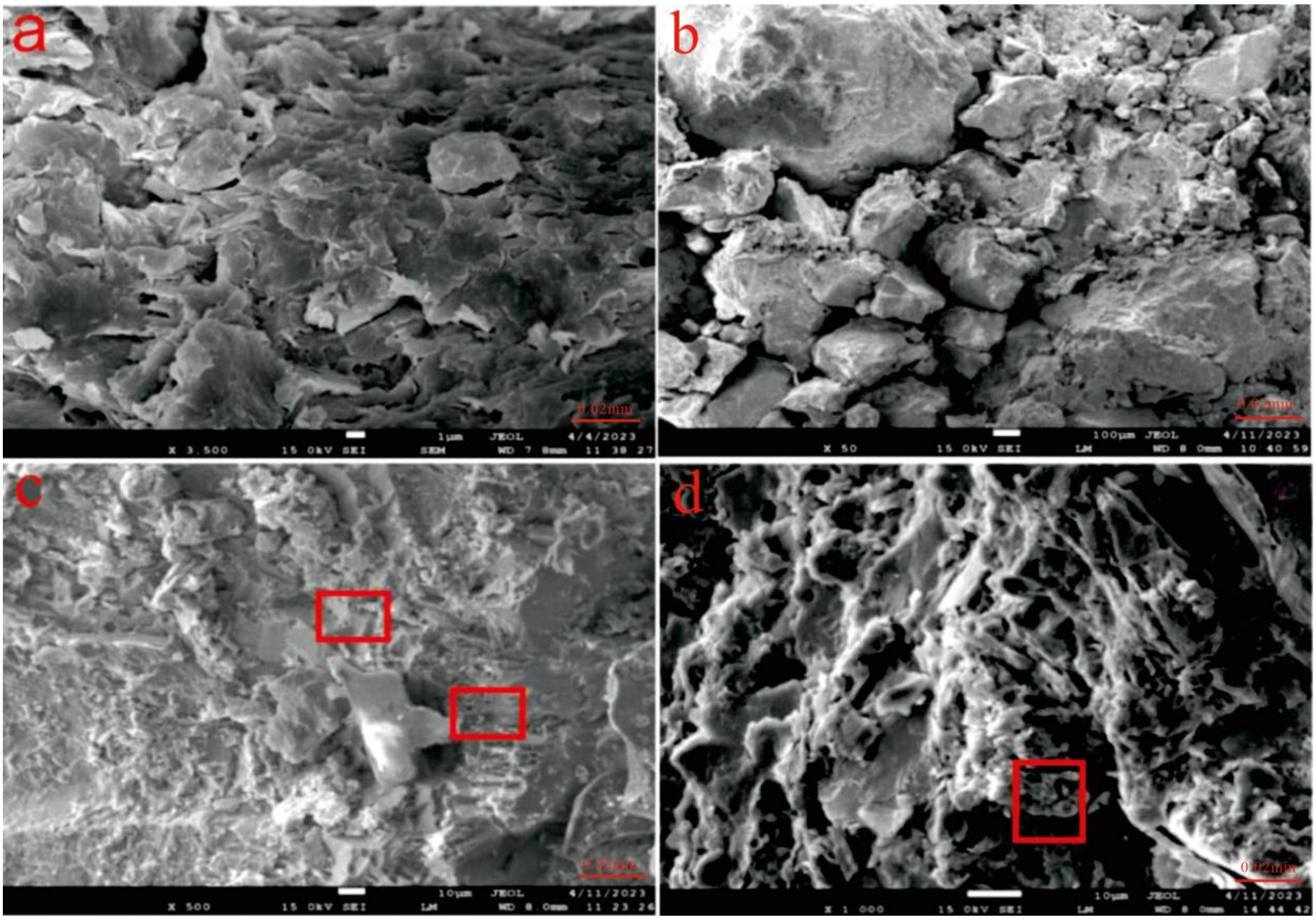

**Figure 13.** SEM throat diagram. (a) Sheet-like throat, Sanmen Formation, 1036.97 m (b) Necked throat, Lantian-Bahe Formation, 1998 m (c) Tube-bundle throat, Lantian-Bahe Formation, 1999.91 m (d)Tube-bundle throat, Lantian-Bahe Formation, 2001.04 m.

**(3) Intragranular dissolution pores**

Microscopic observation reveals that dissolution pores are primarily feldspar dissolution pores and rock fragment dissolution pores, a classification consistent with diagenetic dissolution patterns documented in analogous tight sandstone reservoirs [22]. As noted in the foregoing analysis, the dissolution pores are a major pore type in the North Huazhou area. Dissolution pores in this area exhibit diversity, with varying sizes and irregular shapes, generally developing along cleavage directions. Under severe dissolution, moldic pores are formed (Figure 12(c)). Dissolution pores are often connected to intergranular pores and are not easily distinguishable, but overall they contribute relatively little to reservoir porosity.

**(4) Microfractures**

Microfractures are diagenetic fractures formed by grain breakage or dissolution fractures formed by dissolution, and are very rarely developed in the North Huazhou area (Figure 12(d)). Microfractures mainly include diagenetic fractures formed under compaction and dissolution fractures formed along mineral cleavage directions under dissolution. Although their areal porosity is low, they improve the connectivity of reservoir pore throats to a certain extent and exert a positive influence on fluid flow capacity, analogous to microfracture contributions documented in tight sandstone reservoirs of comparable diagenetic settings [23].

**Reservoir pore-throat type:**

Throats have very small pores in the reservoir, which function to connect the pores to a certain extent and restrict the seepage capacity of the reservoir fluid. Usually a pore is connected to multiple throats. The size and shape of the throats directly restrict the resistance of the reservoir fluid flow. As a vital connecting bridge, the throat plays a non-negligible role in the permeability of the reservoir; this relationship between pore-throat structure and fluid migration has been demonstrated in analogous tight sandstone and carbonate reservoirs through gas-source correlation studies [24]. The size and shape of throats are affected by the properties of sedimentary diagenetic minerals and diagenesis. Various throat types are formed under the influence of different properties of diagenetic minerals and different diagenesis in later stages. Previous researchers studied the contact methods of particles, cementation types, etc., and classified throats into five types based on microscope observation. The throat types in the North Huazhou area include sheet-like throats, curved sheet-like throats, tube-bundle throats, and necked throats.

**(1) Sheet-like or curved sheet-like throats**

The presence of curved sheet-like throats indicates stronger mechanical compaction, with intergranular contacts transitioning to line contacts or concave-convex contacts. The narrow and sheet-like spaces between grains are sheet-like or curved sheet-like throats (Figure 13(a)). The appearance of this type of throat suggests poor physical properties resulting from intense compaction.

**(2) Necked throats**

Necked throats are formed by the narrowing of intergranular pores and are typically observed in constricted positions between grains, exhibiting short and thick morphologies. The presence of this throat type indicates relatively favorable reservoir physical properties, where pores and throats are difficult to distinguish (Figure 13(b)). The formation of necked throats is primarily attributed to the presence of rim cements (e.g., readily formed around chlorite coatings) and the modification of grains and fillings by dissolution. The type of throat is commonly found in reservoirs where dissolution pores and intergranular pores are well developed, which is conducive to the preservation of intergranular pores [25].

**(3)Tube-bundle throats**

The occurrence of tube-bundle throats is related to the abundant presence of clay minerals in the reservoir. Clay minerals such as chlorite and illite fill the pores, and due to their inherent tube-bundle characteristics, they partition the original pores into tube-bundle shapes. In most cases, these are essentially the intercrystalline pores of the clay minerals themselves (Figure 13(c, d)). In such cases, pores and throats are very difficult to distinguish. These throat types not only serve as storage space for fluids within the reservoir but also act as fluid migration pathways. The throats are often associated with abundant clay minerals.

## 5 Helium enrichment model under coupling mechanism

### 5.1 Coupling relationship between helium and groundwater

Noble gas isotopic composition serves as a key tracer for subsurface fluid migration and enrichment processes. Among these, $^{20}$Ne is of atmospheric origin, entering original formation water or surface water through the dissolution of meteoric precipitation and migrating underground via the hydrological cycle. The initial concentration in formation water can be quantitatively determined. Given that helium (He) and neon (Ne) have similar Henry's coefficients in both water and oil phases, they are unlikely to undergo significant elemental fractionation during phase transitions. Therefore, the $^{4}$He/$^{20}$Ne ratio can be used as an effective geochemical tracer for assessing helium enrichment and groundwater migration pathways [25].

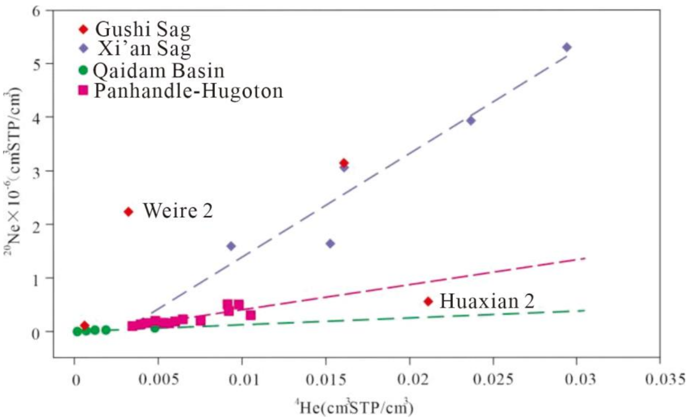


**Figure 14.** Plot of $^{4}$He versus $^{20}$Ne in wellhead gas samples from Weihe Basin.

Zhang et al. [10] analyzed noble gas isotopes in gas samples from ten geothermal wells in Weihe Basin. The results show that the $^{4}$He/$^{20}$Ne ratio of the Huaxian-2 well (37,164) is significantly higher than that of other samples from the same study. This study further compares the $^{4}$He/$^{20}$Ne ratio of this sample with those of typical helium-rich natural gas reservoirs, such as the Panhandle-Hugoton Gas Field in the United States (24,871–46,023) and the Dongping and Mabei gas fields in the Qaidam Basin (38,373–78,190) [25] (Figure 14). The comparison reveals that the ratio of the Huaxian-2 well falls within the typical range of these helium-rich gas reservoirs, confirming its nature as a helium-rich natural gas. This anomalously high ratio may reflect two possible geological conditions near Huaxian: either a significantly elevated deep $^4$He flux or a relatively low groundwater migration rate. The North Huazhou area is adjacent to the Late Mesozoic uranium and thorium-rich Huashan granite pluton on the southern margin of the Qinling Mountains. The helium generation rate of the Laoniushan pluton, located on the southern margin of this area, far exceeds the average crustal value, indicating a significant anomaly in the deep $^4$He flux in this region. Given that groundwater is widely distributed in the pore-fracture systems of rock strata and that helium, due to its low abundance, rarely migrates as an independent phase in geological environments, this study suggests that the pore-fracture water system is the key carrier for helium migration and enrichment in the North Huazhou area.

### 5.2 Helium enrichment model in North Huazhou area

Based on noble gas isotopic analyses and tracer studies of gas samples from geothermal wells in Weihe Basin, previous researchers have preliminarily established a helium-rich natural gas accumulation model for the basin. The key processes include: (1) input of atmospheric noble gases, where atmospheric noble gases (e.g., $^{20}$Ne) dissolve into original formation water or surface water and migrate into the subsurface system with water flow; (2) release and dissolution of crustal-derived gases, where crustal radiogenic gases ($^4$He, $^{40}$Ar, etc.) are released from the rock matrix and dissolve into groundwater; (3) oil-water differentiation, during which groundwater undergoes two-phase fractionation of oil and water; (4) injection of major gases, where gas components dominated by $N_2$ and $CH_4$ are introduced into the subsurface fluid system of the basin; and (5) evolution of accumulation sequences. With increasing methane supply, the system successively forms three types of reservoirs: high-helium, low gas-water ratio water-dissolved gas reservoirs; low-helium, high gas-water ratio water-dissolved gas reservoirs; and high-helium free gas reservoirs. Within free gas reservoirs, continuous water-gas equilibrium promotes the ongoing exsolution of helium into the gas phase. Owing to its extremely low solubility, this process results in secondary helium enrichment. Existing studies indicate that the North Huazhou area hosts free gas reservoirs and exhibits a significantly elevated $^4$He flux [25]. Based on the above characteristics, this area can be identified as one of the favorable target zones for helium-rich natural gas accumulation in Weihe Basin.

Integrating the aforementioned research findings with the regional geological setting of the North Huazhou area, this study preliminarily constructs a helium-rich natural gas accumulation model for the area. The key processes are as follows:

(1) **Migration and cycling of atmospheric-derived neon**: Atmospheric $^{20}$Ne dissolves into original formation water or surface water and migrates through basin-controlling faults and stratigraphic pore systems, establishing a stable hydrological circulation system.

(2) **Generation and migration of deep coal-type gas**: The deeply buried Carboniferous-Permian coal measures in the North Huazhou area generate coal-type methane through thermal evolution, which then migrates along faults and stratigraphic pore networks toward shallow low-potential areas.

(3) **Radiogenic production and supply of basement-derived helium**: Uranium- and thorium-rich granites in the basement continuously generate $^4$He via radioactive decay, which subsequently diffuses and migrates into the overlying strata.

(4) **Helium exsolution and enrichment during migration**: As coal-type methane and other gases migrate upward along faults and pores, they continuously cause the exsolution of radiogenic $^4$He from pore and fracture waters, leading to a progressive increase in helium concentration in the free gas phase.

(5) **Deep gas-water mixing and shallow migration-accumulation**: Downward-migrating shallow recharge water meet upward-migrating helium-rich, high-nitrogen methane free gas at depth, where they undergo thorough mixing and dissolution. The mixed fluid then migrates within the sandstone reservoirs of the Gaoling Group and the Lantian-Bahe Formation, eventually accumulating as free gas reservoirs at local structural highs.

(6) **Continuous helium enrichment within gas reservoirs**: Within the free gas reservoirs, sustained water-gas equilibrium promotes the ongoing exsolution of helium due to its extremely low solubility into the gas phase, achieving further helium enrichment.

(7) **Origin of shallow low-helium biogenic gas reservoirs**: The shallow biogenic gas reservoirs

in the Zhangjiapo Formation are sourced locally, with limited methane migration distance, and thus failed to effectively exsolve and enrich substantial amounts of helium during migration. Moreover, the groundwater hydrodynamic system in this area is relatively inactive. It lacks the conditions favorable for helium exsolution and migration, thereby resulting in the formation of low-helium methane gas reservoirs.

## 6 Conclusion

(1) Through qualitative analysis, the four sets of reservoirs in the North Huazhou area of Weihe Basin, the Sanmen Formation, the Zhangjiapo Formation, the Lantian-Bahe Formation, and the Gaoling Group, have significant lithological differences. The Sanmen Formation is dominated by mudstone (accounting for 84 %), the Zhangjiapo Formation is characterized by mudstone-fine sandstone interaction, and the Lantian-Bahe Formation is dominated by conglomerate and medium-coarse sandstone (conglomerate accounts for 67 %). The Gaoling Group is dominated by conglomerate (99 %). The mineral composition is centered on siliceous minerals, and the content of clay minerals fluctuates significantly, reflecting a strong hydrodynamic alternating depositional environment.

(2) According to the quantitative analysis results, the Zhangjiapo Formation is a medium-porosity and medium-permeability reservoir. And the Lantian-Bahe Formation is a low-porosity and low-permeability reservoir. Reservoir sensitivity experiments revealed moderate to strong velocity sensitivity and acid sensitivity, and the development plan needs to be optimized to protect the reservoir.

(3) From a macro perspective, reservoir development is controlled by sedimentary rhythm (mainly positive rhythm) and fault systems, with significant differences in physical properties between layers, and the Zhangjiapo Formation has the optimal reservoir thickness ratio.

(4) From a microscopic perspective, the reservoir pores are dominated by residual intergranular pores (1–3 $\mu$m) and dissolution pores, while the throat types are characterized by tabular/necked morphologies, which constrain the fluid flow capacity.

(5) Coal-type methane in reservoirs in North Huazhou migrates upward along faults, driving helium exsolution in groundwater, and helium continues to enrich into the free gas phase under the action of water-gas equilibrium. The Gaoling Group and Lantian-Bahe Formation sand body structure are a favorable area for reservoir formation, while the shallow Zhangjiapo Formation forms a low-helium biogenic gas reservoir due to hydrodynamic stagnation.

## Data Availability Statement

Data will be made available on request.


## Funding

This work was supported without any funding.


## Conflicts of Interest

Xinlei Cai, Qianyi Li, Yang Zhang, Zheng Li, Guoqiang Zhang, Mingpu Fan are affiliated with the Shaanxi Gas Group Co., Ltd., Xi'an, Shaanxi 710016, China. The authors declare that this affiliation had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

## AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

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