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RESEARCH PAPER

Evolution characteristics and exploration targets of Permian clastic rock reservoirs in Bohai Bay Basin, East China

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Abstract: Based on core observation, thin section examination, fluid inclusions analysis, carbon and oxygen isotopic composition analysis, and other approaches, the structural and burial evolution histories were investigated, and the diagenetic evolution process and genetic/development models were systematically discussed of the Upper Paleozoic Permian clastic rock reservoirs in the Bohai Bay Basin, East China. The Bohai Bay Basin underwent three stages of burial and two stages of uplifting in the Upper Paleozoic. Consequently, three stages of acid dissolution generated by the thermal evolution of kerogen, and two stages of meteoric freshwater leaching occurred. Dissolution in deeply buried, nearly closed diagenetic system was associated with the precipitation of authigenic clay and quartz, leading to a limited increase in storage space. Different structural uplifting–subsidence processes of tectonic zones resulted in varying diagenetic–reservoir-forming processes of the Permian clastic reservoirs. Three genetic models of reservoirs are recognized. The Model I reservoirs with pores formed in shallow strata and buried in shallow to medium strata underwent two stages of exposure to long-term open environment and two stages of meteoric freshwater leaching to enhance pores near the surface, and were shallowly buried in the late stage, exhibiting the dominance of secondary pores and the best physical properties. The Model II reservoirs with pores formed in shallow strata and preserved due to modification after deep burial experienced an early exposure-open to late burial-closed environment, where pore types were modified due to dissolution, exhibiting the dominance of numerous secondary solution pores in feldspar and the physical properties inferior to Model I. The Model III reservoirs with pores formed after being regulated after multiple periods of burial and dissolution experienced a dissolution of acidic fluids of organic origin under a near-closed to closed environment, exhibiting the dominance of intercrystalline micropores in kaolinite and the poorest physical properties. The target reservoirs lied in the waterflood area in the geological period of meteoric freshwater leaching, and are now the Model II deep reservoirs in the slope zone–depression zone. They are determined as favorable options for subsequent exploration.

Key words: Bohai Bay Basin; Permian; clastic rock; diagenetic evolution; reservoir-forming mechanism; secondary pore

Introduction

The Bohai Bay Basin in northern China is a large sedimentary basin with two distinct oil and gas systems. These systems are primarily sourced from the Paleogene lacustrine source rocks [1–4] and the Upper Paleozoic coal-measure source rocks [5–7]. The level of oil and gas exploration in this basin is in the middle-to-high maturity stage [1]. Nevertheless, there are challenges associated with the oil and gas system in the Upper Paleozoic coal-measure source rocks due to its intricate geological history marked by multiple uplift events and disruptions. Recent developments have rekindled interest in this system because significant discoveries have occurred in the Permian clastic rock reservoirs [5–7], underscoring the substantial potential for oil and gas exploration in the

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deeper layers of the basin. The Upper Paleozoic oil and gas system has undergone various tectonic superposition and evolutionary processes, impacting the characteristics and formation mechanisms of clastic rock reservoirs in diverse tectonic zones. The processes governing reservoir formation and the mechanisms responsible for the creation of high-quality reservoirs in Permian clastic rocks remain elusive. This knowledge gap has contributed to a relatively low success rate in oil and gas exploration efforts, posing obstacles to further advancements in exploration endeavors.

In this study, we employed a diverse range of data sources and analysis methods, including drilling cores, rock thin sections, physical property tests, scanning electron microscopy, isotopic analysis, and oil and gas geochemistry. The data were obtained from distinct regions in the Bohai Bay Basin, encompassing the Huanghua Depression, Jiyang Depression, Jizhong Depression, Linqing Depression, and others. Additionally, we conducted comprehensive burial history–thermal history analyses to discern the distinctive characteristics of reservoirs situated in various tectonic zones of the Upper Paleozoic Permian within the basin. We systematically investigated the processes governing reservoir evolution and the mechanisms underlying reservoir formation in response to varying burial–thermal histories. We elucidated the developmental patterns and distribution rules governing different reservoir types. The primary objective of our study was to offer valuable guidance for predicting high-quality reservoirs in the exploration areas with similar tectonic settings.

1. Geological background

The Bohai Bay Basin in northern China encompasses portions of the North China Plain, the Liaohe Plain, and the Bohai Sea area. This extensive basin is encircled by several uplifts, including the Yanshan, Shanxi, Luxinan, Ludong, and Liaodong uplifts. It is subdivided into multiple depressions, such as the Liaohe, Bozhong, Jiyang, Huanghua, Jizhong, Linqing, and Changwei depressions, as well as several uplifts, including the Chengning, Cangxian, Xingheng, and Neihuang uplifts [8] (Fig. 1a).

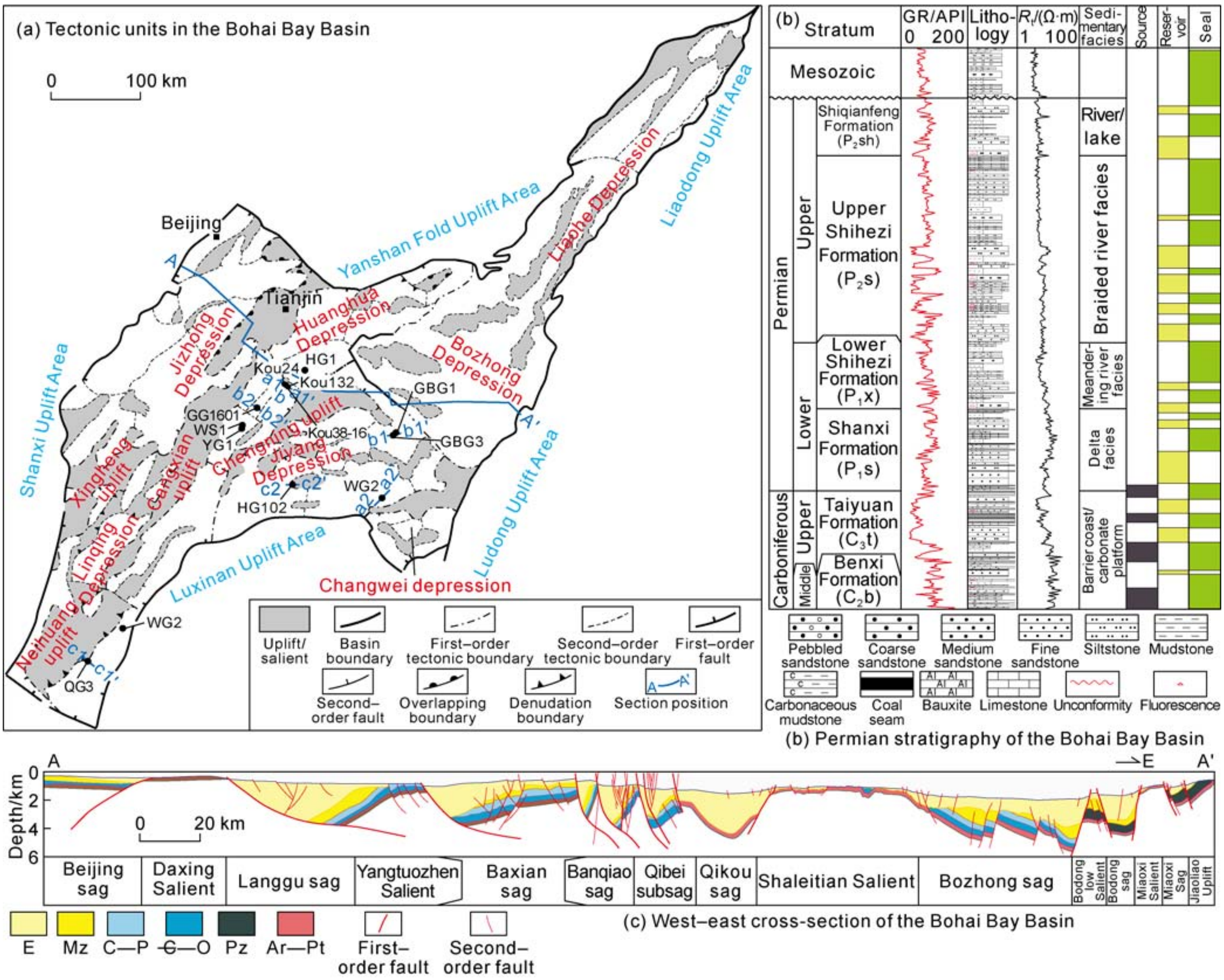


Fig. 1. Location, structure and sedimentary strata of the Bohai Bay Basin. Ar–Archaeozoic; Pt–Proterozoic; Pz–Palaeozoic; Ꞓ–Cambrian; O–Ordovician; C–Carboniferous; P–Permian; Mz–Mesozoic; E–Paleogene.

The Upper Paleozoic strata in the Bohai Bay Basin have experienced multiple tectonic events and underwent exposure erosion processes. Nevertheless, they retain a substantial sequence of Carboniferous and Permian rock formations. These formations, from bottom up, comprise the Carboniferous Benxi Formation (C_2b), Taiyuan Formation (C_3t), Permian Shanxi Formation (P_1s), Lower Shihezi Formation (P_1x), Upper Shihezi Formation (P_2s), and Shiqianfeng Formation (P_2sh) (Fig. 1b). The P_1s–P_2sh interval represents a succession of various depositional environments, spanning from deltaic to meandering river, braided river, and river/lake facies [9–10]. Among these formations, the P_2s braided river sand bodies are particularly significant in exploration due to their substantial vertical thickness, consistent lateral distribution, coarse grain size, and high hydrocarbon potential. The C_3t and P_1s formations serve as coal-measure source rocks underlying the P_2s. They are widespread throughout the basin but have been influenced by multiple tectonic events, resulting in uneven stratigraphic distribution and significant variations in burial depth (Fig. 1c). The vitrinite reflectance values (R_o) of these source rocks, excluding instances of abnormally high values influenced by volcanic activities, typically range from 0.65% to 1.60%. These values indicate that the source rocks are primarily in the mesodiagenesis stage. Over their extended evolutionary history, they have undergone 2–3 stages of acid generation and hydrocarbon generation, serving as crucial sources of oil and gas for the overlying clastic rock reservoirs [11–13].

2. Reservoirs

2.1. Petrological characteristics

The findings from core observations and thin section analyses reveal that the Permian reservoirs in the Bohai Bay Basin exhibit notable lithological variations across different formations. In the P_2s formation, the predominant lithological components comprise medium sandstone, coarse sandstone, and gravel-bearing sandstone. Conversely, the P_1x and P_1s formations are primarily characterized by the presence of fine sandstone. The rock composition is highly mature in the P_2s reservoirs, primarily manifesting as quartz sandstone and lithic quartz sandstone. The framework grains in this context are predominantly composed of quartz, accounting for an average content of 84%, followed by feldspar, mainly potassium feldspar, with an average content of 7%. Additionally, the lithics present in these reservoirs consist primarily of quartzose metamorphic rock fragments, constituting an average content of 9% (Fig. 2). Notably, the matrix content is relatively low, averaging around 2%. On the other hand, the reservoirs in the P_1s–P_1x formations exhibit a lower degree of rock composition maturity, characterized primarily by lithic feldspathic sandstone

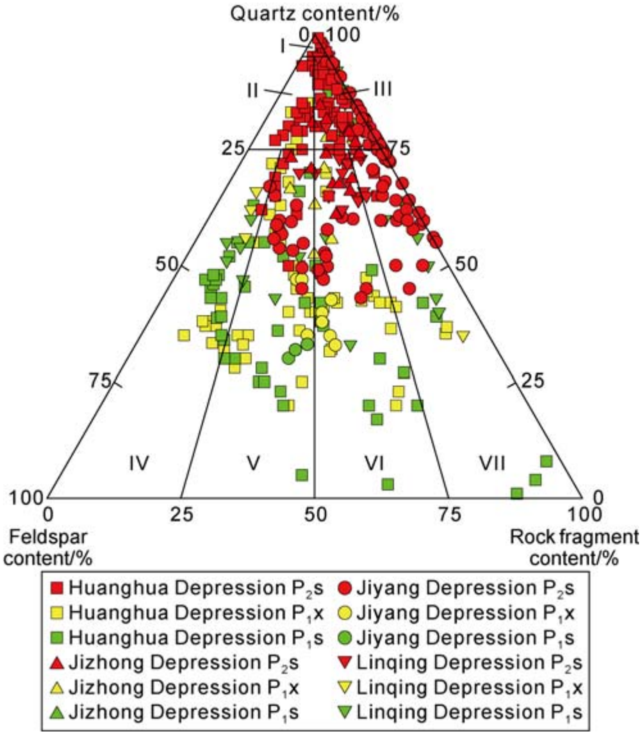


Fig. 2. Lithotype of the Permian clastic rock reservoir in the Bohai Bay Basin (following the classification standard of reference [14]). I–Quartzarenite; II–Subarkose; III–Sublitharenite; IV–Arkose; V–Lithic arkose; VI–Feldspathic litharenite; VII–Litharenite.

and feldspathic lithic sandstone. In these formations, the framework grains comprise quartz, feldspar, and lithics, with average contents of 42%, 35%, and 23%, respectively. Furthermore, the matrix content is comparatively higher, with an average value of 5% (Fig. 2).

2.2. Physical properties and spatial characteristics of reservoirs

The Permian reservoirs in the Bohai Bay Basin are predominantly medium–low porosity, medium–low permeability, and tight reservoirs, with porosity and permeability decreasing slightly with increasing burial depth. The porosity of reservoirs shallower (deeper) than 3500 m is 5%–20% (1%–15%), and the permeability is $(0.1–100.0)\times10^{-3}$ μm^2 $(0.01–10.00\times10^{-3}$ μm$^2)$ (Fig. 3a, 3b).

The Permian clastic rocks in the basin represent porosity-type reservoirs, encompassing various pore types, including primary pores, secondary pores, and micropores, among others (Fig. 4). Primary pores primarily result from residual pores formed after compaction and cementation. They predominantly developed in medium–coarse sandstone reservoirs in the shallow to medium–depth layers (Fig. 4a). In contrast, secondary pores form by the dissolution of feldspar grains and are widely distributed in different layers (Fig. 4b–4d). Micropores, primarily authigenic kaolinite intercrystalline pores, have extensively developed in the medium–deep layers (Fig. 4d–4f). Additionally, some micro-fractures are locally observed in deep-buried reservoirs.

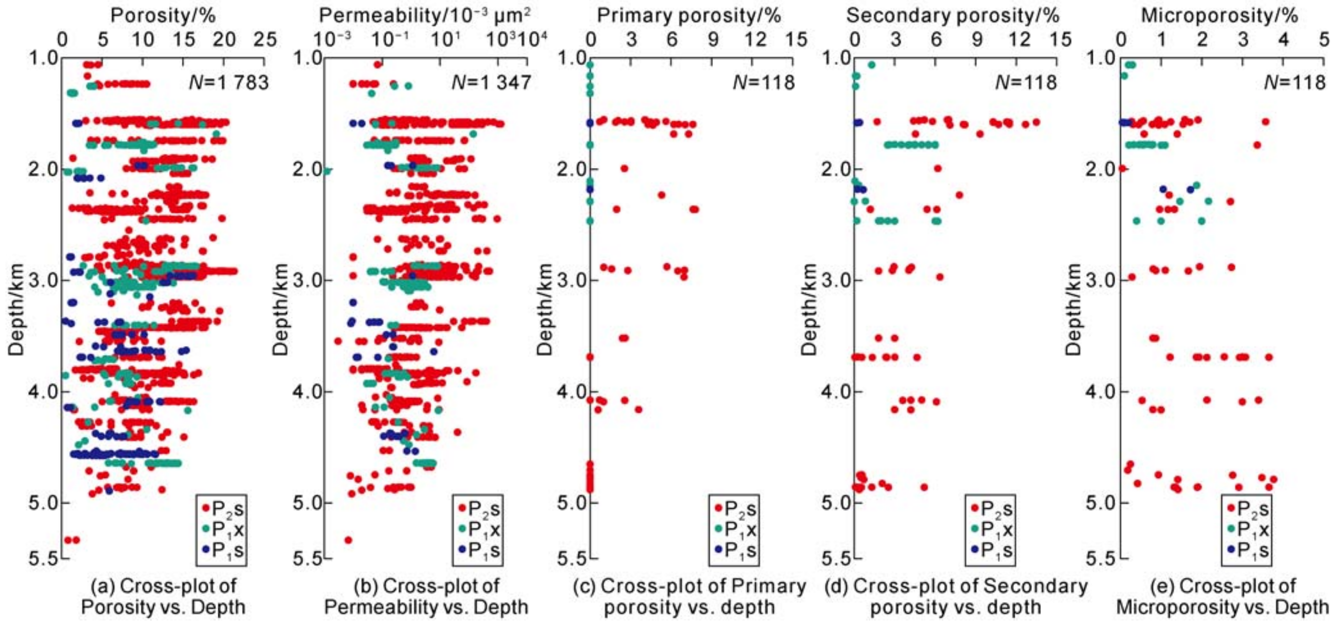


Fig. 3. Physical characteristics of Permian clastic rock reservoirs in the Bohai Bay Basin. N denotes the number of samples.

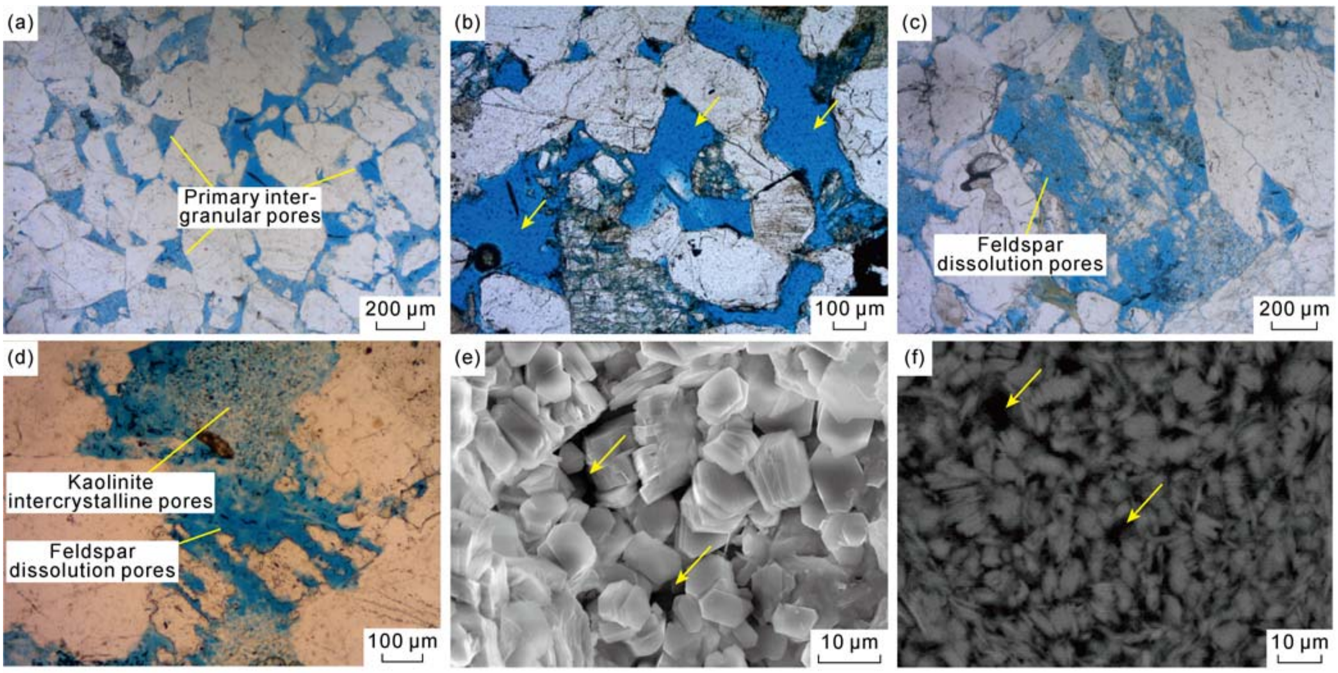


Fig. 4. Reservoir characteristics of Permian clastic reservoirs in the Bohai Bay Basin. (a) Well S18, 2 687.20 m, P_2s, intergranular pores, under plane–polarized light; (b) Well K24, 1 558.50 m, P_2s, super–large dissolution pores, under plane–polarized light; (c) Well S63, 2 331.00 m, P_2s, dissolved pores in feldspar particles, under plane–polarized light; (d) Well GBG1, 4 077.85 m, P_2s, feldspar dissolution pores and kaolinite intercrystalline pores, under plane–polarized light; (e) Well GBG1, 4 123.22 m, P_2s, intercrystalline pores in coarse–grained kaolinite, SEM; (f) Well CG31, 2 233.00 m, P_2s, intercrystalline pores in fine–grained kaolinite, SEM.

The statistics derived from cast thin sections reveal that secondary porosity is dominant in the Permian shallow layers (ranging from 4% to 12%), with locally developed primary porosity (ranging from 4% to 9%). A combination of secondary porosity (ranging from 1% to 6%) and microporosity occurs in the medium–deep layers (ranging from 1% to 5%). Microporosity (ranging from 4% to 5%) is dominant in some areas, followed by secondary porosity (ranging from 1% to 3%) (Fig. 3c to 3e).

3. Diagenesis and reservoir formation

Feldspar represents a significant rock–forming mineral in the Permian clastic rock reservoirs. Its dissolution is critical for secondary porosity, which constitutes the primary reservoir space in the Permian reservoirs (Fig. 4). Consequently, investigating the dissolution of feldspar and its impact on pore formation is crucial for understanding the origin and progression of these reservoirs. It is imperative to analyze the feldspar dissolution in various stages to gain insight into pore formation due to the distinct burial-uplift processes and tectonic evolution scenarios in different zones.

3.1. Multi-phase burial-uplift processes and structural superposition types

The Upper Paleozoic strata in the Bohai Bay Basin have undergone a complex geological history characterized by three burial stages and two uplift stages. These processes have resulted in diverse tectonic superposition types in the Permian strata. Based on the sequence of the uplift, exposure, burial, and deep burial processes in the Permian Upper Shihezi Formation and the current structural characteristics, we have identified three typical structural superposition types (Fig. 5):

(1) Two-stage Unconformity–Exposure Type: In this scenario (Fig. 5a1, 5a2), the P_2sh and Mesozoic layers were entirely eroded, with a regional angular unconformity between the P_2s and overlying Paleogene strata (Fig. 5a3). This type of tectonic region underwent two distinct uplift and exposure phases during the Indosinian–Yanshan period and the subsequent Yanshan late–Himalayan period. These uplift phases caused the erosion of the Mesozoic and P_2sh layers on top of the buried hill. Examples of such regions include the Koucun area in the Huanghua depression and the Wangjiagang and Dawangzhuang areas in the Jiyang depression.

(2) One-stage Unconformity–Exposure Type: In this scenario (Fig. 5b1, 5b2), a significant portion of the P_2sh layer was eroded, and the P_2s was either overlain by a residual thin layer of P_2sh or a thick layer of Jurassic strata, forming a regional angular unconformity beneath the Jurassic layer (Fig. 5b3). This type of tectonic region experienced one uplift and exposure phase during the Indosinian–Yanshan period, resulting in the erosion of

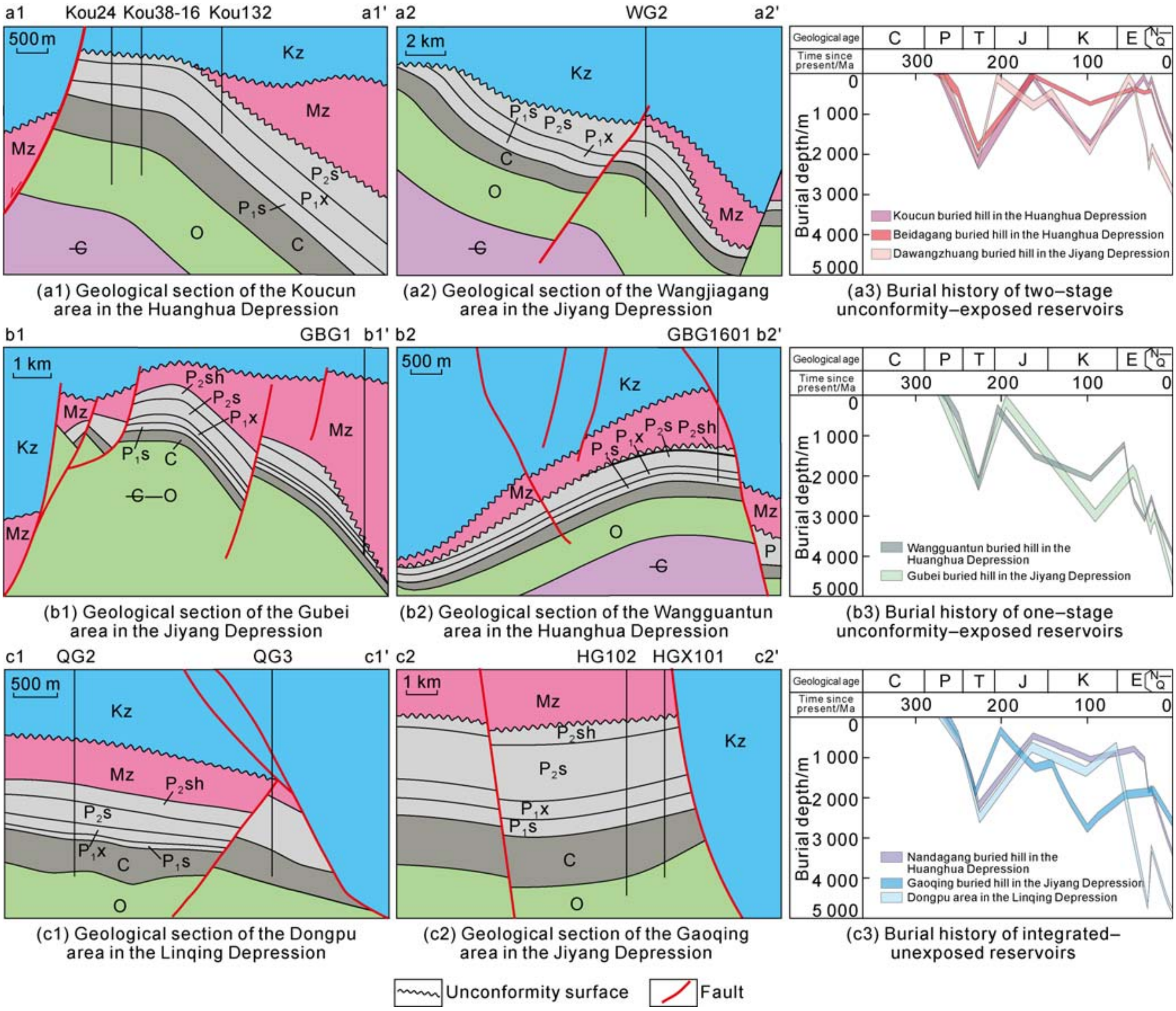


Fig. 5. Typical structural characteristics and burial history of Permian strata in the Bohai Bay Basin (The section position is shown in Fig. 1). C–Carboniferous; P–Permian; T–Triassic; J–Jurassic; K–Cretaceous; Mz–Mesozoic; Kz–Cenozoic; E–Paleogene; N–Neogene; Q–Quaternary.

most of the P_2sh layer. Subsequently, subsidence occurred, followed by uplift during the Yanshan late/Himalayan period, but the Permian strata were not exposed during this phase. Examples of these regions are the Gubei area in the Jiyang depression and the Wangguantun area in the Huanghua depression.

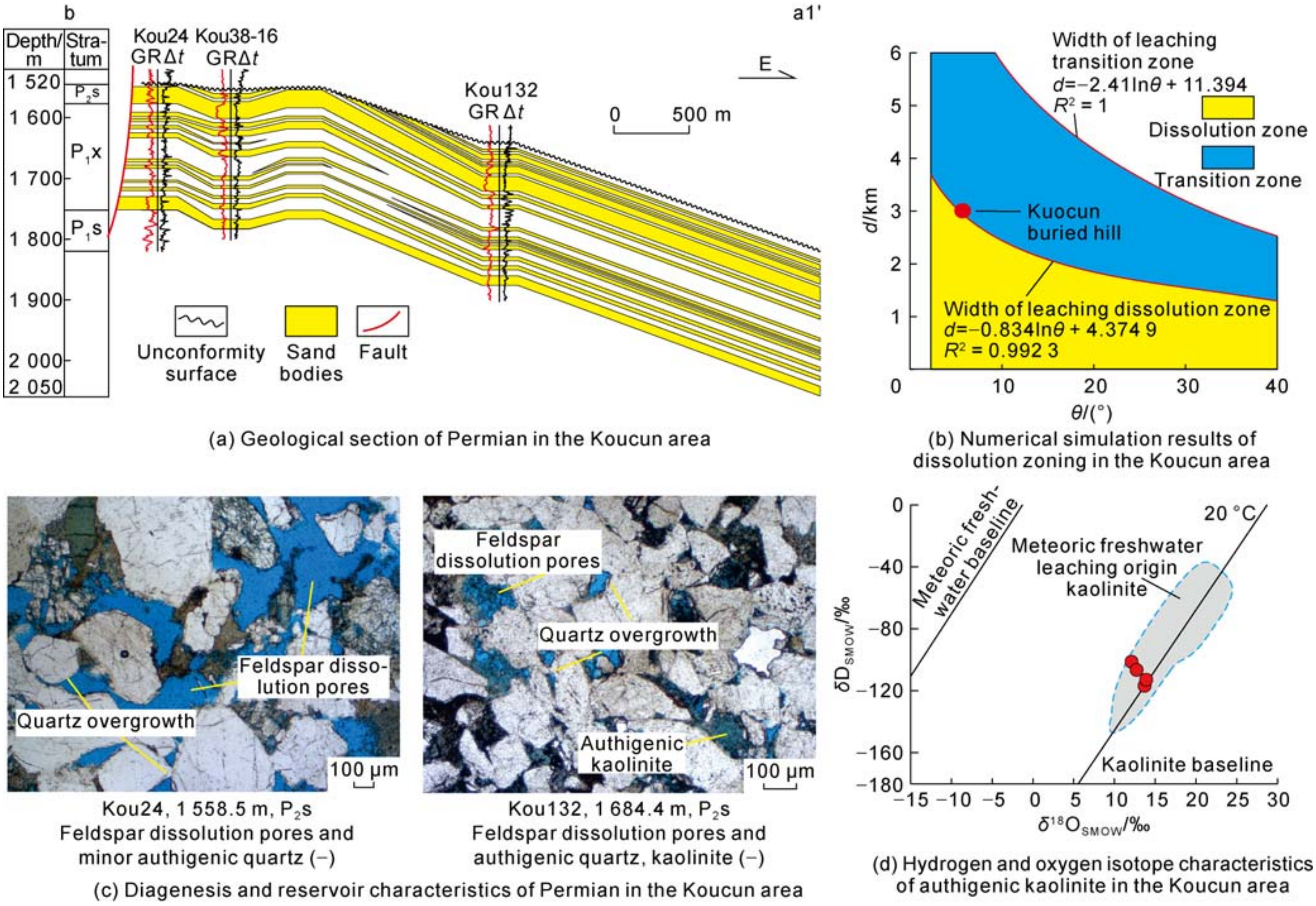
(3) Non-exposure Type: In this scenario (Fig. 5c1, 5c2), the P_2s was overlain by the P_2sh layer over a regional extent, and the Mesozoic layer remained intact without any discernible unconformity above the primary sand body of P_2s (Fig. 5c3). This type of tectonic region underwent two uplift phases during the Indosinian–Yanshan period and the subsequent Yanshan late–Himalayan period. However, neither of these phases exposed the primary Permian sand layer, and the upper strata of the Permian were relatively preserved. Examples of such regions include the Dongpu area in the Linqing depression, the Gaoqing area in the Jiyang depression, and the Nandagang area in the Huanghua depression.

3.2. Feldspar dissolution and pore formation in different stages

3.2.1. Uplift-exposure stage

The Permian strata in the Bohai Bay Basin have undergone multiple exposures to the surface due to tectonic uplift events. During these exposure periods, meteoric freshwater infiltrated the sand bodies along the inclined strata, leading to the leaching and dissolution of minerals, particularly feldspar [15–19]. This process has had a profound impact on the porosity of the reservoirs. For instance, in the Koucun area of the Huanghua depression, an unconformity is observed between the Permian P_2s and the Paleogene Es1 strata (Fig. 6a). Reservoirs in this region exhibit low formation water salinity, with mineralization decreasing as one approaching the unconformity. Meteoric freshwater promotes the dissolution of significant amounts of feldspar in shallow surface rocks in open systems characterized by high fluid flow rates and low salinity. As feldspar dissolves, K^+, Al^{3+}, and aqueous SiO_2 are released from the dissolution zone [19–21]. As the dissolution progresses, the fluid's acidity decreases, whereas the Al^{3+} and SiO_2 concentrations in the fluid increase, resulting in the precipitation of kaolinite in the reservoir.

To simulate feldspar dissolution, dissolved matter transport, and secondary mineral reprecipitation in inclined sand layers under low temperature and high flow rates, we utilized the Geochemist's Workbench and reservoir rocks from the Koucun area as samples. These rocks exhibit a porosity of 20%, a feldspar content of 7%, a quartz content of 72%, and a kaolinite content of 1%. The simulation results reveal the formation of dissolution



(a) Geological section of Permian in the Koucun area

(b) Numerical simulation results of dissolution zoning in the Koucun area

Kou24, 1 558.5 m, P_2s Feldspar dissolution pores and minor authigenic quartz (−)

Kou132, 1 684.4 m, P_2s Feldspar dissolution pores and authigenic quartz, kaolinite (−)

(c) Diagenesis and reservoir characteristics of Permian in the Koucun area

(d) Hydrogen and oxygen isotope characteristics of authigenic kaolinite in the Koucun area

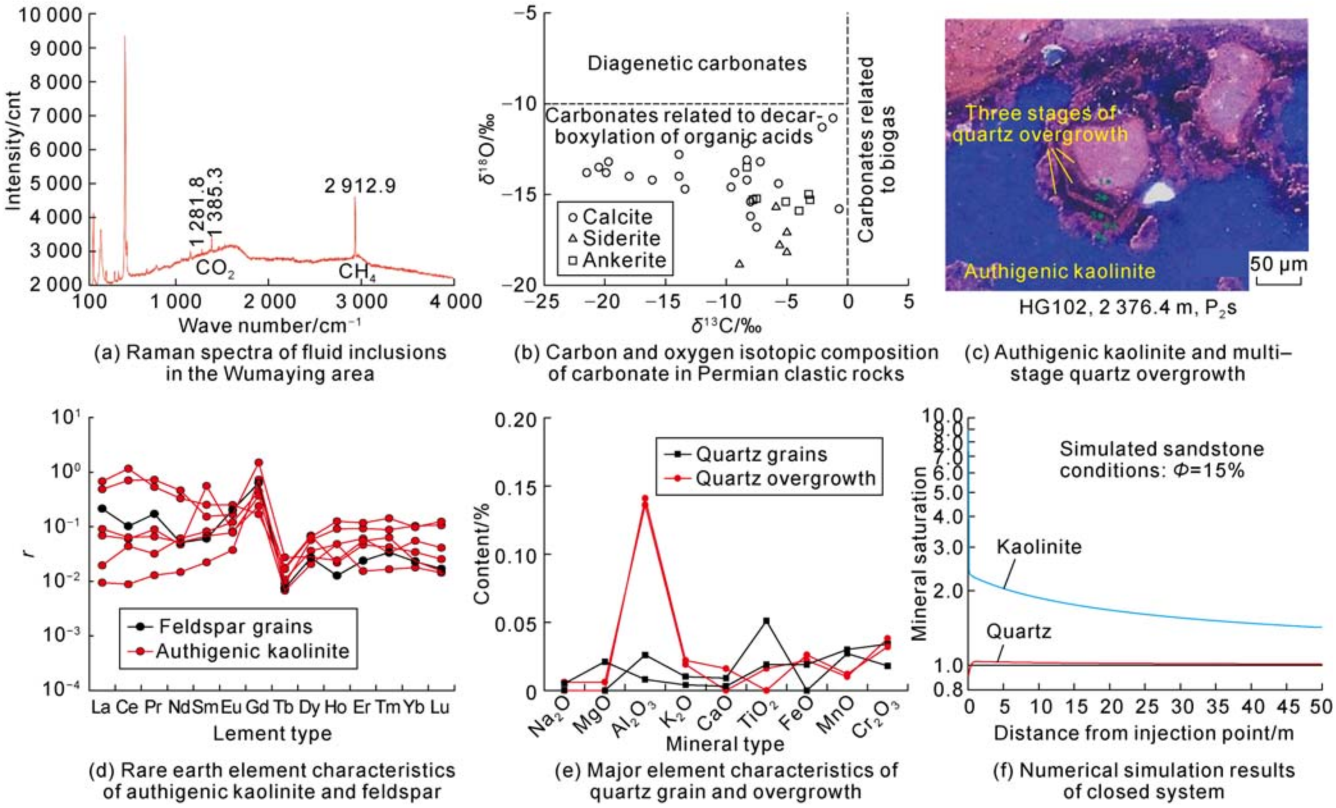
Fig. 6. Case study and numerical simulation of the distribution of the Permian reservoir in the Koucun buried hill belt, Bohai Bay Basin (The section position is shown in Fig. 1; Fig. 6d is adapted from reference [18]).

zones and transition zones in the inclined sand bodies, starting from the water injection zone. Interestingly, the total length of these zones decreases from over 6.0 km to 2.5 km as the stratum dip angle increases from 2° to 40° (Fig. 6b). The simulation results agree with observed geological phenomena, specifically in wells Kou24, Kou38-16, and Kou11 located at the top of the buried hill in the Koucun area. Feldspar dissolution is prevalent in these wells, while kaolinite development is limited. In contrast, feldspar dissolution occurs alongside kaolinite precipitation in well Kou132 situated on the slope of the buried hill. Furthermore, the isotopic composition data of kaolinite in the Koucun area indicate that the δD value relative to the Standard Mean Ocean Water (SMOW) standard ranges from −116.9‰ to −100.0‰, while the δ18O value falls in the range of 11‰ to 14‰. These values overlap with the distribution range of kaolinite originating from meteoric freshwater sources [22] (Fig. 6d). The isotopic data further support the meteoric freshwater leaching process as a contributing factor to the observed mineralogical changes.

The sand layers in the elevated open system exhibit plagioclase dissolution, resulting in a substantial increase in porosity. In addition, secondary minerals precipitate primarily in specific downstream zones. In the proximity of Koucun, plagioclase dissolution cavities in rock slabs typically have contents ranging from 5% to 12%. In contrast, the authigenic kaolinite content is below 1%. Furthermore, the quartz cement content is below 0.2% (Fig. 6c). This observation suggests that the interaction with atmospheric freshwater significantly enhanced the properties of the reservoir rock during the uplift and exposure phase, resulting in vuggy secondary porosity. This process is prevalent in Dawangzhuang and Gubei due to prolonged exposure.

3.2.2. Middle–deep burial stage

The burial history and current R_o data of the substantial coal-bearing source rocks from the P_1s and C_3t underlying the principal Permian sand bodies reveal that the Upper Paleozoic source rocks experienced maximum burial depths of 3000 m prior to the Indosinian uplift. The kerogen had progressed to a low maturity state, with R_o values ranging from 0.6% to 0.8% [11]. This condition led to the generation of substantial amounts of organic acids and CO_2 [23–26]. As these source rocks continued to subside beyond 3000 m, their R_o values increased to 1.6% at depths of 5500 m. Consequently, the source rocks produced more CO_2, organic acids, and hydrocarbons [23–26]. The acidic fluids generated by these source rocks were transported into the Permian reservoirs, evidenced by the presence of CO_2 in fluid inclusions (Fig. 7a), the occurrence of multiple-stage hydrocarbons in the reservoirs, and the isotopic characteristics of carbonate cements (Fig. 7b) [27]. Few of the elements released by the dissolution of feldspar by acidic fluids were rapidly removed from the dissolution zone in this relatively enclosed diagenetic system characterized by elevated formation water temperatures and a low flow rate. Instead, the elements precipitated as authigenic clay minerals and authigenic



(a) Raman spectra of fluid inclusions in the Wumaying area (b) Carbon and oxygen isotopic composition of carbonate in Permian clastic rocks (c) Authigenic kaolinite and multi-stage quartz overgrowth (d) Rare earth element characteristics of authigenic kaolinite and feldspar (e) Major element characteristics of quartz grain and overgrowth (f) Numerical simulation results of closed system

Fig. 7. Authigenic mineral composition and isotope values, inclusion temperature, and composition of Permian clastic rocks.

quartz in situ (Fig. 7c). This process caused the redistribution of diagenetic materials, creating secondary dissolution pores in the feldspar and filling primary pores with authigenic minerals. Consequently, the overall porosity of the reservoirs underwent minimal change [20].

The Permian reservoirs in the Bohai Bay Basin exhibit varying pore formation effects contingent on the diagenetic system. In an almost closed system, these reservoirs undergo a sequence of strong feldspar dissolution, followed by kaolinite cementation and quartz cementation. Notably, feldspar dissolution represents a vital material source for the authigenic kaolinite and authigenic quartz found in the reservoirs [28–30]. This finding is corroborated by several indicators, including the coexistence of authigenic kaolinite and feldspar dissolution (Fig. 4d), the congruence in rare earth element patterns between kaolinite and feldspar grains (Fig. 7d), and the high aluminum element content in the authigenic quartz (Fig. 7e). Additionally, the presence of multiple-stage authigenic kaolinite and quartz (Fig. 7c) suggests the occurrence of several stages of deep burial feldspar dissolution. One example is the Gaoqing area in the Jiyang Depression, where the Permian stratum is relatively intact and overlain by Mesozoic mudstone (Fig. 5c2), indicating the absence of meteoric freshwater leaching. In this setting, the proportion of feldspar dissolution pores in the rock slices ranges from 1% to 3%, that of the authigenic kaolinite ranges from 1% to 7%, and the quartz cement content is 2% to 6%. Under these conditions, the relative increase in the porosity of one unit volume of potassium feldspar after dissolution ranges from 11.91% to 14.47% [31]. However, it is important to note that the precipitation of authigenic kaolinite tends to reduce reservoir permeability. To gain further insights, we employed the Geochemist's Workbench to simulate the feldspar dissolution, dissolved substance transport, and secondary mineral re-precipitation in sand layers under high temperatures and low flow rates. Various deep Permian reservoirs were used as constraints for this analysis. The results indicate that feldspar dissolution in the sand layer is typically accompanied by the precipitation of kaolinite and quartz, primarily occurring within the precipitation zone. In contrast, the development of the dissolution zone is minimal, with very few transition zones (less than 0.5 m) (Fig. 7f).

3.3. Reservoir formation mechanism during multi-stage uplift–subsidence events

We reconstructed the diagenetic and reservoir evolution processes in various tectonic regions by analyzing the tectonic type and feldspar dissolution mechanisms using comprehensive datasets, including the correlations of authigenic minerals, isotopic signatures, inclusions, burial history, and thermal history records.

3.3.1. Shallow development–medium to shallow burial

We used the Koucun area as an example and employed "backstripping" to reconstruct the diagenesis and storage evolution of this reservoir type (Fig. 8). The process can be described as follows: During the initial Subsidence Stage, the Permian strata underwent burial to a depth of 2500 m. The predominant process was compaction, reducing the porosity from 38% to 19%. The first uplift episode occurred in the late Triassic, resulting in the horizontal uplift and exposure of the Permian strata to the surface. Subsequently, the overlying Triassic and Permian P_2sh layers experienced erosion. The P_2s formation was subjected to leaching by meteoric freshwater, dissolving feldspar in the shallow surface rocks and increasing the porosity to 25%. Notably, this process led to the formation of distinct sequential zones: a dissolution zone, a transition zone, and a precipitation zone. In the late Jurassic, the strata once again subsided, with compaction causing a decrease in porosity to 18%. The second uplift episode occurred in the late Cretaceous, leading to the re-exposure of the P_2s strata to the surface. Meteoric freshwater again leached the P_2s formation, contributing to an increase in porosity to 20%. Subsequently, the strata underwent further subsidence from the late Cretaceous period until the present day. Compaction during this phase resulted in a decrease in porosity to 18%. It is worth noting that the subsequent subsidence level of the strata was lower than the initial subsidence. Consequently, secondary pores formed by leaching were preserved because they did not experience intense compaction. This reservoir type exhibits moderate compaction, characterized by line contact between the grains as the dominant feature. Pronounced feldspar dissolution occurred, with a low content of authigenic minerals and a diagenetic profile that comprises strong feldspar dissolution, weak kaolinite cementation, and weak quartz cementation. The reservoir's spatial attributes are primarily characterized by secondary pores, with some locally preserved primary pores. The porosity is 5% to 20%, and permeability typically is $(0.1–100.0)\times10^{-3}$ μm^2, with a high correlation between porosity and permeability (Fig. 9).

3.3.2. Shallow development–deep redistribution and preservation

The diagenesis and storage evolution of this reservoir type are exemplified by the Gubei area in the Jiyang Depression. It consisted of various stages (Fig. 8): During the initial Subsidence Stage, the Permian strata experienced burial to a depth of 2300 m. The prevailing diagenetic process was compaction, which exerted a dominant influence and significantly reduced porosity from 38% to 19%. The first uplift episode occurred in the late Triassic, resulting in the exposure of the Permian strata to meteoric freshwater leaching. This process increased porosity to 24%. Notably, distinct zones emerged in the slope direction, including dissolution, transition, and precipitation zones. The strata underwent subsidence

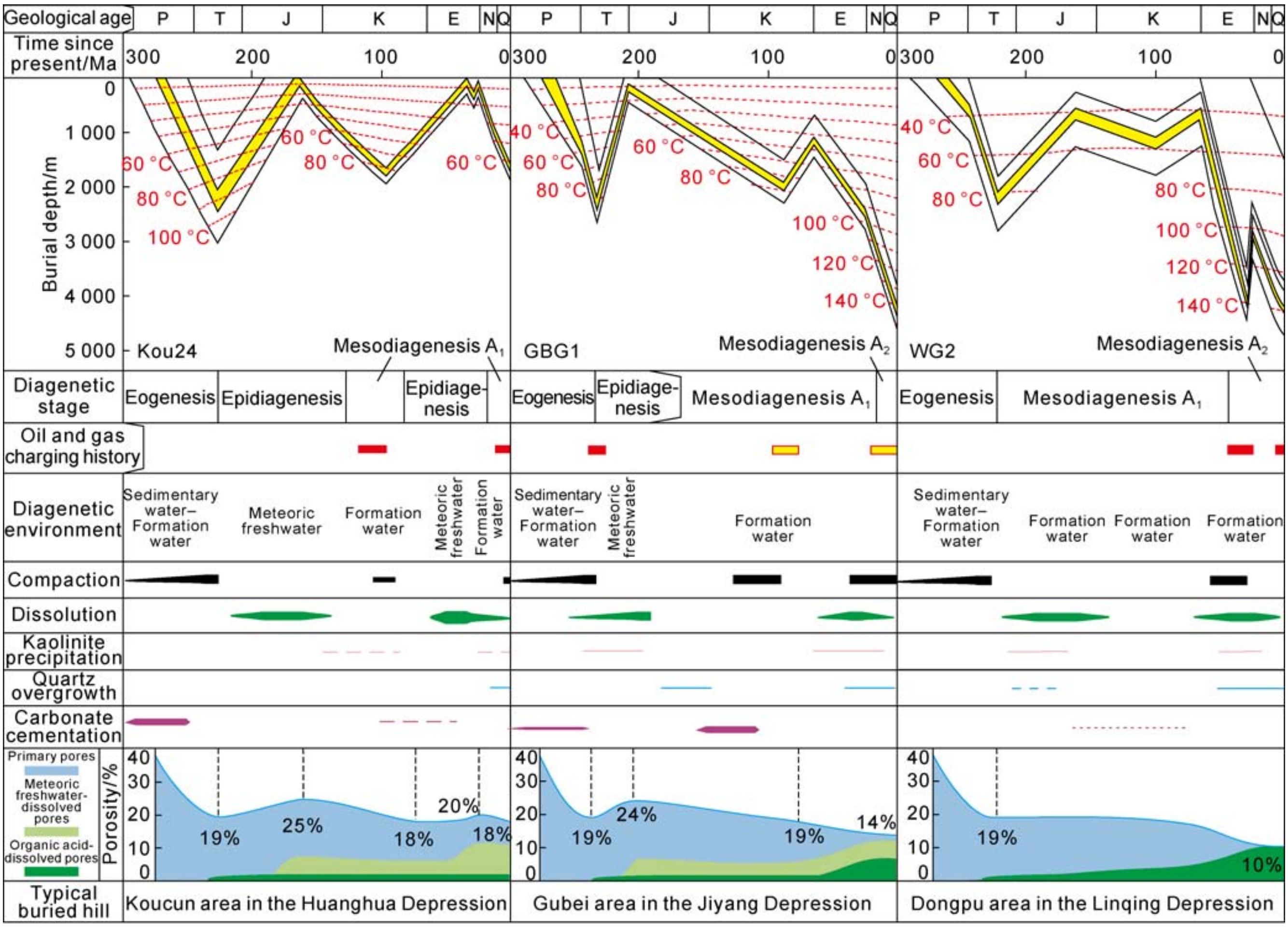


Fig. 8. Diagenetic evolution history of typical Permian buried hill reservoirs in the Bohai Bay Basin.

during the early Jurassic period, and the compaction caused porosity to decrease to 19%. The second uplift episode was caused by tectonic forces and occurred in the late Cretaceous. However, the uplift level was relatively low, and the Permian strata did not reach the surface. Subsequently, the strata experienced burial until the present day, with compaction reducing porosity to 14%. During this stage, the thermal evolution of the source rocks generated acid, facilitating feldspar dissolution. However, this process primarily modified the pore types without a significant increase in porosity. Hydrocarbon filling inhibited carbonate and siliceous cementation, preserving some pores. This reservoir type exhibits a strong compaction effect, with the primary feature being line–concave–convex grain contacts. It exhibits a diagenetic profile of strong feldspar dissolution, strong kaolinite cementation, and moderate to weak quartz cementation. The reservoir space is characterized by secondary dissolution pores in the feldspar and many kaolinite micropores. The porosity range of the reservoir is 5% to 15%, and the permeability range is (0.01–10.00) $\times 10^{-3}$ μm^2. It should be noted that the correlation between porosity and permeability is relatively low in this reservoir type. Dissolution pores are more prevalent than dissolution products in the early dissolution zone, such as the Chenghai area in the Huanghua Depression and the Gubei area in the Jiyang Depression. The opposite pattern is observed in the early transition zone, represented by Wangguantun and Wumaying in the Huanghua Depression (Fig. 9).

3.3.3. Multi-stage dissolution and redistribution

The diagenesis and storage evolution of this reservoir type is exemplified by the Dongpu area in the Linqing Depression (Fig. 8). The following stages occurred. The compaction effect was pronounced during the initial phase of tectonic subsidence, substantially reducing porosity 38% to 19%. The first uplift episode occurred in the late Triassic. However, the Permian strata did not reach the surface, and no meteoric freshwater leaching occurred. The strata were shallowly buried during the Cretaceous period, resulting in a weak diagenetic effect. Subsequently, the Permian strata underwent rapid subsidence during the Paleogene epoch. This phase was characterized by further decreases in porosity to 10%, primarily due to compaction. Additionally, organic acid dissolution occurred during this stage. The sandstone did not become exposed to the surface during tectonic movements. Feldspar dissolution during deep burial was accompanied by significant precipitation of kaolinite and

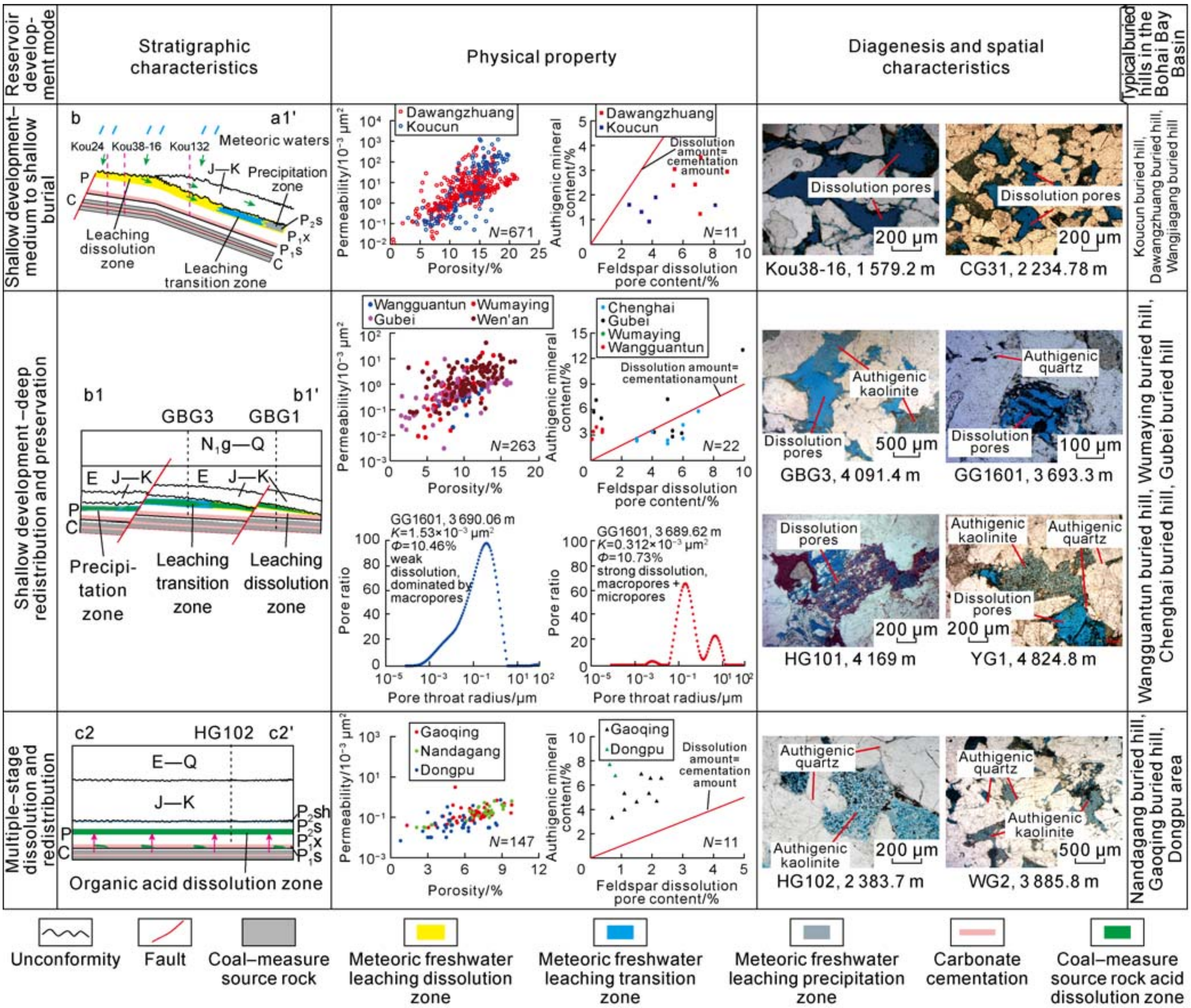


Fig. 9. Classification and diagenesis and reservoir characteristics of Permian Reservoirs in the Bohai Bay Basin (The section position is shown in Fig. 1). N–number of samples; N_1g–Guantao Formation in the Miocene.

authigenic quartz, contributing to pore modification. Diagenesis resulted in strong compaction, with line–concave–convex grain contacts being the primary structural feature. This type exhibits typical diagenetic characteristics, i.e., strong feldspar dissolution, strong kaolinite cementation, and robust quartz cementation. The porosity range is 5% to 10%, and the permeability range is (0.01–1.00) $\times 10^{-3}$ μm^2. It is important to note that the proportion of dissolution pores is lower than the proportion of dissolution products (Fig. 9).

4. Reservoir evolution features and favorable exploration targets

4.1. Evolution features of Permian reservoir development

Different tectonic zones in the Bohai Bay Basin underwent various tectonic superposition processes, leading to varying diagenetic and storage processes in the Permian sandstone reservoirs (Fig. 10). We identified three types of Permian reservoir development according to the tectonic evolution and diagenetic modification (Fig. 11).

Type I reservoirs are shallow development–medium to shallow burial reservoirs. They represent sandstone reservoirs that experienced two distinct uplift episodes to the surface during the Yanshanian and Himalayan periods. This reservoir type was significantly influenced by meteoric freshwater leaching, contributing to the development of secondary pores. The burial depth of this reservoir type did not exceed 3,000 m during the storage process, enabling the preservation of numerous shallowly formed pores. In the meteoric freshwater leaching stage, the reservoir's development led to the formation of a dissolution zone and a transition zone in the inclined sand body from top to bottom. High-quality reservoirs in this category are typically situated close to the water injection areas of the two meteoric freshwater leaching episodes. Notable examples include the Koucun area in the Huanghua Depression and the Dawangzhuang area in the Jiyang Depression (Fig. 11).

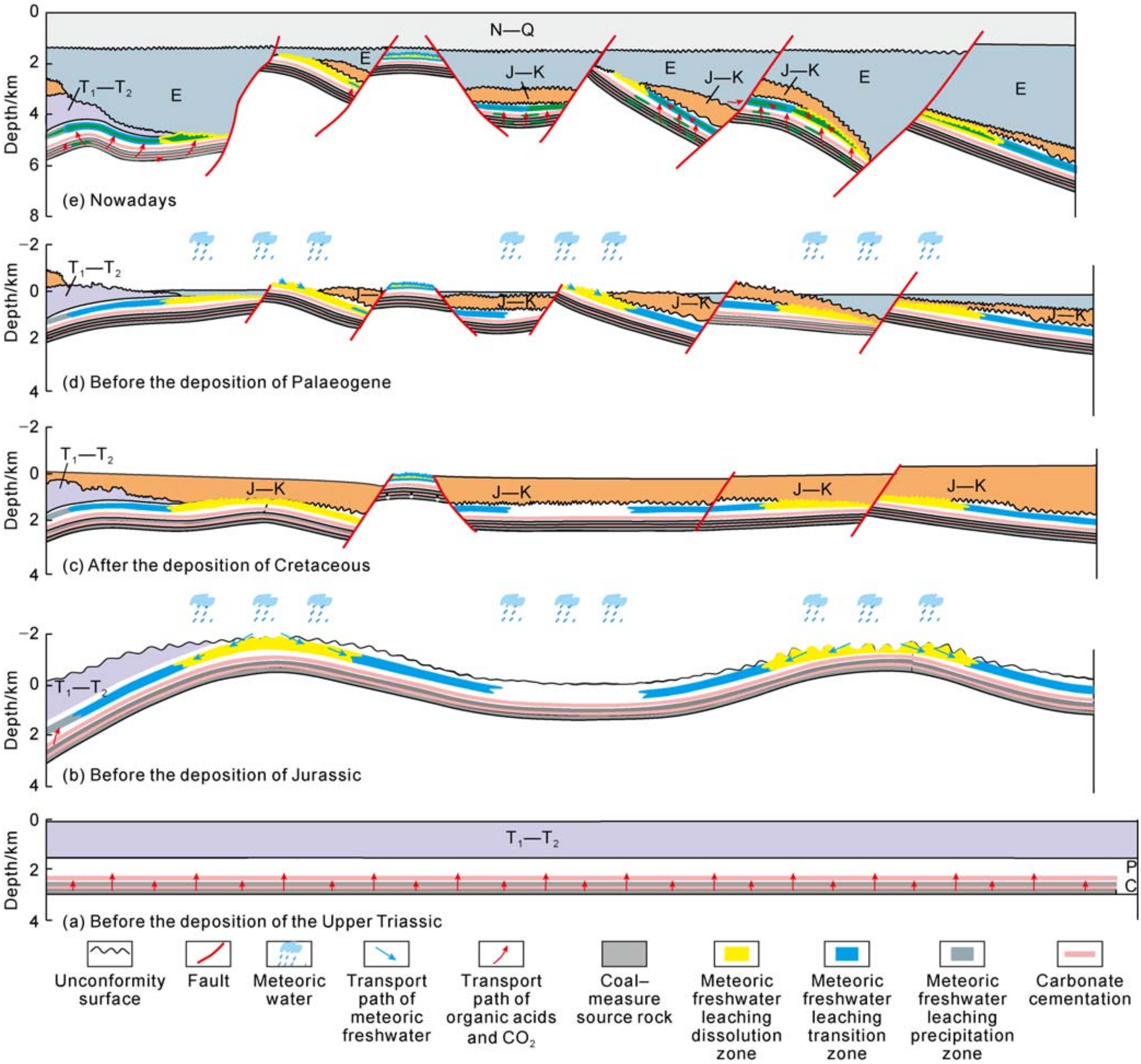


Fig. 10. Comprehensive model of the formation of Permian clastic rock reservoirs in the Bohai Bay Basin (modified according to reference [32]).

Type II reservoirs are shallow development–deep redistribution and preservation reservoirs. They are sandstone reservoirs characterized by shallow development followed by deep redistribution and preservation. Secondary porosity was enhanced by meteoric freshwater leaching during the uplift to the surface in the Yanshan period. The pore types were altered during deep burial due to the influence of organic acid generated by the thermal evolution of organic matter. The sandstone has a high content of rigid particles and quartz cementation stemming from feldspar dissolution, countering the compaction effect during deep burial. Early hydrocarbon was crucial in inhibiting cementation and preserving porosity. This reservoir type underwent continuous burial even after the Late Triassic strata's exposure and erosion. Under closed conditions, the thermal evolution of kerogen produced organic acid and CO_2, which dissolved feldspar. Importantly, this process did not involve the extensive, long-distance migration of dissolution products, enabling the preservation of relatively high porosity and permeability in the early meteoric freshwater leaching injection zone. High-quality reservoirs formed in this zone and persisted at the top of the hill during the subsequent tectonic evolution. Conversely, if the buried hill underwent stratum inversion, the previous dissolution zone was located on the hill's slope, but the reservoir maintained favorable characteristics. Notable examples of this reservoir type include the Gubei area in the Jiyang Depression and the Wangguantun area in the Huanghua Depression (Fig. 11).

Type III reservoirs are multiple-stage dissolution and redistribution reservoirs. This reservoir type is characterized

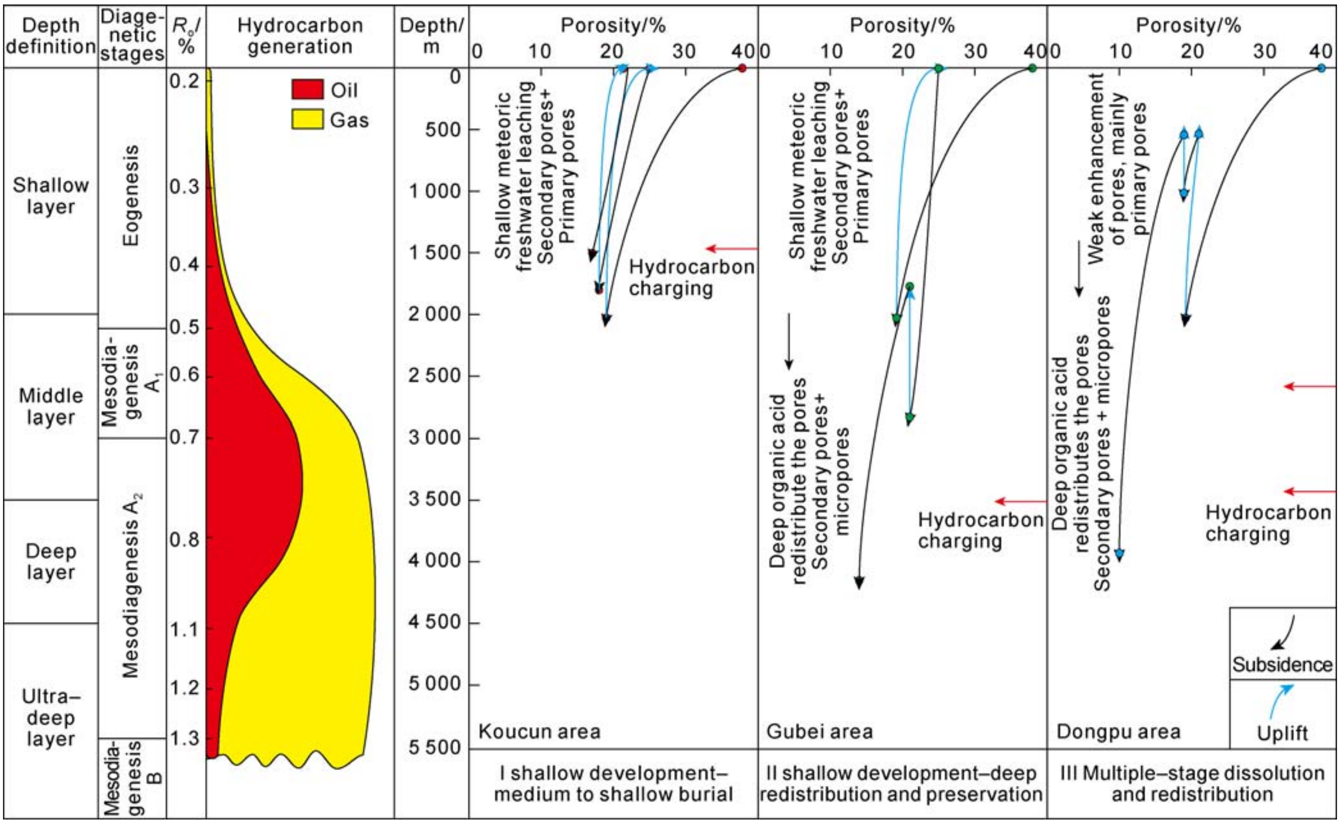


Fig. 11. Typical pore evolution model of Permian reservoirs in the Bohai Bay Basin (the hydrocarbon generation is modified according to reference [33]).

by multiple-stage of dissolution and redistribution of sandstone. The sandstone was not exposed to the surface during tectonic movements and did not undergo meteoric freshwater leaching, which typically increases porosity. Instead, it underwent transformation through multiple secondary organic matter thermal evolution processes, generating acid dissolution and facilitating pore formation. The reservoir space evolved from primary pores to a combination of secondary pores and micropores. Importantly, this reservoir type did not experience uplift and erosion, resulting in the lowest reservoir quality among the three types. Notable examples of this reservoir type include the Gaoqing area in the Jiyang Depression and the Dongpu area in the Linqing Depression (Fig. 11).

4.2. Favorable exploration targets in the next stage

Comprehensive studies have revealed that Permian reservoirs in the Bohai Bay Basin were shaped by diverse burial-lifting processes and had different structures. They exhibit notable discrepancies in their diagenetic histories and current reservoir qualities. Consequently, leveraging three-dimensional seismic data from the Bohai Bay Basin, we can systematically ascertain the stratigraphic uplift-subsidence processes and structural characteristics of various tectonic zones in the region. This analysis considers geological factors, such as unconformities, overlying strata, and burial depths in different areas, enabling us to predict the diagenetic alteration processes of reservoirs in undrilled areas and conduct predrilling assessments of reservoir quality by integrating established geological models of reservoir development.

The systematic research results have highlighted distinct reservoir characteristics in various regions: (1) Northeast of the Jizhong Depression, Cangxian Uplift, Northwest of the Jiyang Depression, and similar areas: The P_2s and P_1x formations northeast of the Jizhong Depression are overlain by Paleogene strata, featuring thick sand bodies and robust connectivity. These reservoirs underwent two stages of meteoric freshwater leaching, leading to porosity enhancement. Consequently, they are Class I reservoirs. (2) Bozhong Depression, Central and Southern Huanghua Depression, Northeast of the Jiyang Depression, and similar areas: The P_2s sandstone is covered by Mesozoic strata, characterized by substantial sand bodies and strong connectivity. These reservoirs experienced one stage of meteoric freshwater leaching, porosity enhancement, and dissolution redistribution. As a result, they are Class II reservoirs. (3) P_1s Sandstone and other areas in the P_2s and P_1x Sandstone in the Bohai Bay Basin: The sandstones are overlain by thick P_2sh mudstone layers. They have undergone multiple stages of dissolution redistribution, resulting in Class III reservoirs (Fig. 12a).

Early oil and gas exploration efforts in the Upper Paleozoic of the Bohai Bay Basin predominantly concentrated on the summits of buried hills, with less attention

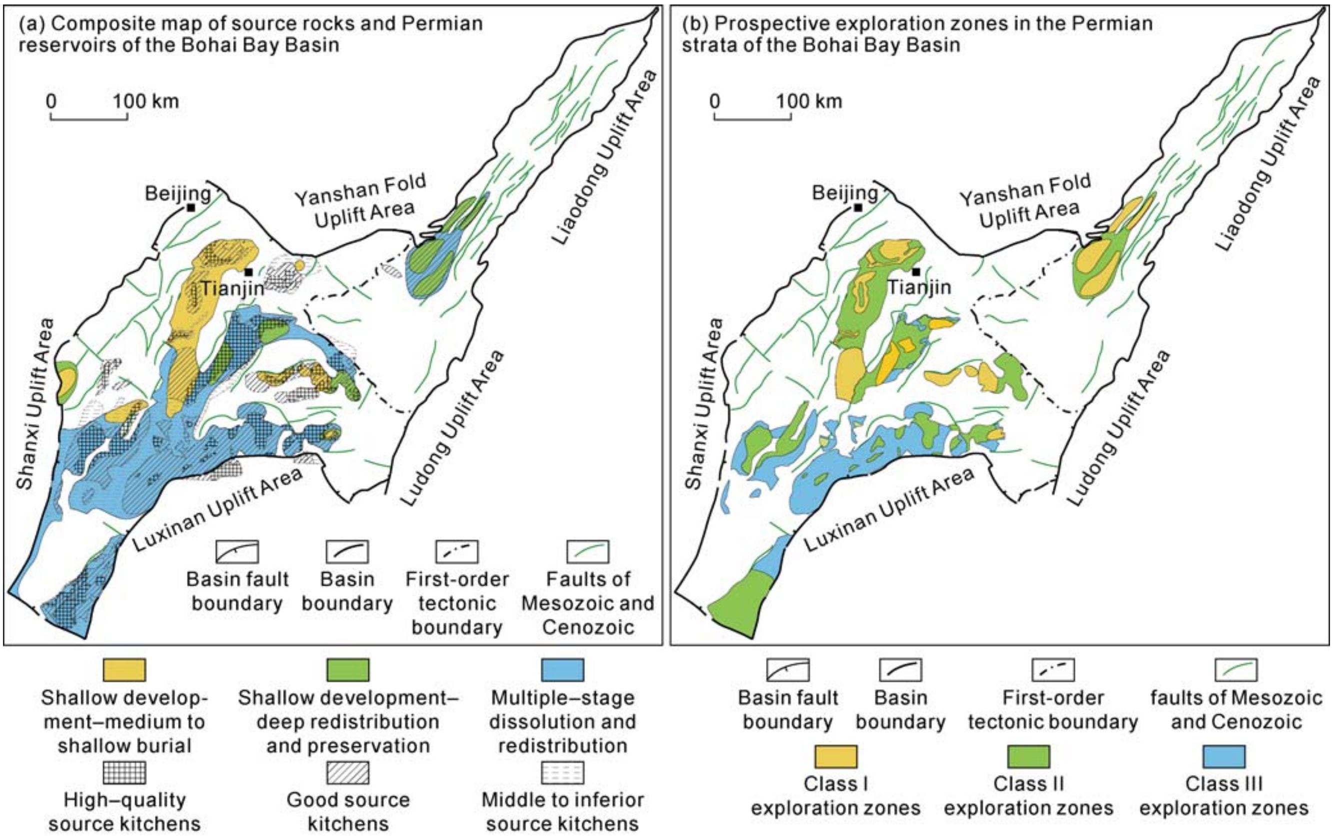


Fig. 12. Permian source reservoir superposition and favorable exploration targets in the Bohai Bay Basin.

on the slopes and sag zones of these hills. However, it should be noted that the shallow development – deep redistribution and preservation reservoir type, which underwent structural inversion following early meteoric freshwater leaching, holds substantial potential for reservoir development in the buried hill slopes and sag zones. In these areas, reservoirs that were previously situated in the meteoric freshwater leaching dissolution zone are now buried, creating new opportunities for exploration and development. Furthermore, the Upper Paleozoic coal-measure source rocks in these regions are currently in the peak stage of oil and gas generation. Consequently, these areas represent highly promising targets for exploration endeavors (Fig. 12b). Exploring and developing reservoirs in the buried hill slope and sag zones, in conjunction with tapping into the oil and gas potential of the associated source rocks, holds significant promise for future endeavors in the Bohai Bay Basin.

5. Conclusions

The P_2s clastic rocks in the Bohai Bay Basin are primarily comprised of quartz-rich sandstones featuring coarse grains and a high level of compositional maturity. In contrast, the P_1x and P_1s sandstones are predominantly quartz-poor, characterized by fine grains and a lower degree of compositional maturity. These Permian reservoirs are generally categorized as tight reservoirs and medium–low porosity and permeability reservoirs. The porosity range of these reservoirs is typically 5% to 20%, and the permeability range is (0.1 to 100.0) $\times10^{-3}$ μm^2. The reservoir space is predominantly occupied by feldspar dissolution pores. Some primary pores are present in the shallow and intermediate layers, and kaolinite intercrystalline pores are widely distributed in the medium and deep layers of these reservoirs.

The Permian clastic rock reservoirs have experienced three burial stages and two uplift stages. Thus, the Permian rock can be categorized into three typical structural superposition types: two-stage unconformity exposure, one-stage unconformity exposure, and relative conformity non-exposure. The enhancement of dissolution porosity primarily occurred in open to semi-open environments in the shallow and intermediate layers during the uplift stages when the dissolution effect was the most pronounced. Conversely, the dissolution transformed primary pores into secondary pores and kaolinite intercrystalline pores in nearly-closed diagenetic systems during deep burial conditions. Additionally, a slight expansion of the reservoir space occurred.

The shallow development–medium to shallow burial reservoirs underwent two stages of meteoric freshwater leaching, leading to porosity enhancement near the surface. They retained the dissolution pores during shallow burial, and the reservoir space is primarily composed of numerous secondary pores, with some primary pores. These reservoirs exhibit the most favorable physical properties. The shallow development–deep redistribution and preservation reservoirs experienced meteoric freshwater leaching, resulting in porosity enhancement near the surface. Subsequently, the dissolution altered the pore types due to deep burial in a closed system. The presence of highly rigid particles and hydrocarbon filling helped preserve the pores. These reservoirs are primarily characterized by a significant number of feldspar secondary dissolution pores and kaolinite intercrystalline micropores. They possess the second-best physical properties. Reservoirs experiencing multi-stage dissolution and pore formation underwent organic acid fluid dissolution modification and pore formation in a nearly-closed to closed environment. Their reservoir space primarily consists of kaolinite intercrystalline micropores and feldspar secondary dissolution pores. They no longer contain primary pores and have relatively poor physical properties. The shallow development–deep redistribution and preservation reservoirs experienced early meteoric freshwater leaching followed by structural inversion. They are currently situated on the slopes of buried hills or in depression zones and represent the next favorable exploration targets.

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Nomenclature

GR—natural gamma, API;

d—the distance from the water injection point, km;

K—permeability, 10^{-3} μm^2;

r—the ratio of the rare earth element content to the chondrite content, dimensionless;

R_t—formation resistivity, Ω·m;

Δt—interval transit time, μs/m;

θ—the dip angle of the formation, (°);

ϕ—porosity, %.

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