

Article

Comparative Study of Tectonic Evolution and Oil–Gas Accumulation in the Ri-Qing-Wei Basin and the Jiaolai Basin

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Abstract: The Ri-Qing-Wei basin is located in the central Sulu Orogeny on the eastern side of the Tanlu fault zone in eastern Shandong province. To the north, the Jiaonan uplift separates it from the Jiaolai basin, where drilling in the lower Cretaceous sedimentary rock of the Laiyang group has indicated good oil and gas reserves. Drilling in the Ri-Qing-Wei basin, in contrast, is in the preliminary exploration stage. Lingke 1, the only scientific well, is on Lingshan Island on the basin boundary, and it encountered a large set of source rocks 700 m thick. The two basins were comprehensively compared and analyzed based on comprehensive fieldwork, drilling, core data, seismic profiling, sedimentary filling sequence, tectonic evolution history, basin burial history, geothermal history, and geochemical characteristics of the source rocks. The results showed three things: (1) from the late Jurassic to the early Cretaceous (the Laiyang period), subduction of the paleo-Pacific plate under the Eurasian plate delaminated the lithospheric mantle of the Sulu Orogeny, thus forming a series of passive continental rift basins. Of these, the Ri-Qing-Wei is central and the Jiaolai is its branch. After the active rift stage in the Qingshan period and the depression stage in the Wangshi period, the burial depth of the source rocks in the Ri-Qing-Wei basin was up to 6000 m, while the maximum burial depth in the Jiaolai basin was about 3000 m. The paleogeotemperature of both basins exceeded 125 °C, indicating that the source rocks were very mature. (2) A comprehensive comparison of their geochemical characteristics—organic matter abundance, type, and maturity—showed that both basins have oil-generating potential. It is worth noting that the magmatic activity in the Qingshan period had a positive effect on the evolution of the source rocks but was not the key factor: burial depth was. (3) Oil and gas failed to accumulate in the Jiaolai basin because they were destroyed by the lateral tectonic activities. During the right-lateral strike-slip stage (50 ± 5 Ma) during the late Wangshi, the Jiaolai basin was strongly uplifted over a range of more than 1000 m by the Tanlu and Wulian-Mouji fault zones along the boundary. The Wangshi group, as a cap rock, was eroded, and oil and gas overflowed along the fault that reached the surface. The late Wangshi period uplift of the Ri-Qing-Wei basin was less than 1000 m because the source rock was deeper, and the reverse faults in the basin were sealed well. The uplift did little damage to the oil in the Ri-Qing-Wei basin. Above all, tectonic evolution was the main controlling factor of oil accumulation in the study area, and the layers of the Laiyang group in the Ri-Qing-Wei basin have oil and gas potential, making it a prospective target for unconventional offshore oil and gas exploration.

Keywords: Ri-Qing-Wei basin; Jiaolai basin; tectonic evolution; source rocks; oil–gas accumulation condition



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1. Introduction

Oil and gas exploration has three major oil and gas development areas: deep sea, deep land, and unconventional [1]. The worldwide proportion of unconventional to conventional oil and gas is about 8:2, and since unconventional oil and gas will become necessary to meet future energy needs, the exploration potential is huge. Unlike conventional exploration, the key factor for unconventional geology is determining if the reservoirs are oil-bearing or not [1]. Unconventional oil and gas is not affected by hydrodynamics, which breaks through conventional oil and gas reservoirs and effectively seals them, changing the exploration target from an “external source” to an “internal-” or “proximal-” source reservoir [2]. Therefore, the quality of source rocks is the key to unconventional oil and gas exploration.

The Ri-Qing-Wei, in the Rizhao-Qingdao-Weihai area of the Shandong Peninsula in eastern China, is a recently discovered late-Mesozoic continental rift basin in the Sulu Orogeny at the junction of the Yangtze plate and the North China plate (Figure 1). It was formed similarly to the surrounding basins and extends northeast from land to sea for about 50 km. However, it is the only basin on the peninsula that has not been explored for oil and gas. The recently drilled Lingshan Island (Lingke 1) well encountered huge thick source rocks, which shows great oil and gas exploration potential.

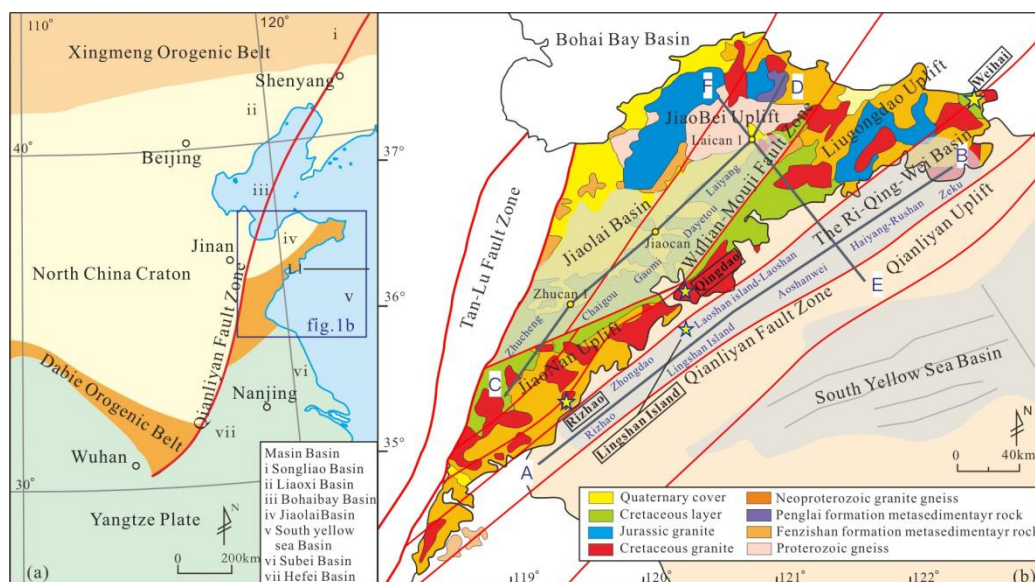


Figure 1. Geological sketch of the study area: (a) tectonic outline map of eastern China (modified from [3]); (b) tectonic outline map of eastern Shandong and adjacent areas (modified from [4]).

The Jiaolai basin is northwest of the Ri-Qing-Wei basin, between the Jiaobei and Jiaonan-Liugongdao uplifts, a Mesozoic fault basin. It comprises three depressions: Zhucheng in the southwest, Gaomi in the center, and Laiyang in the northeast. The thickness of dark mudstone is 200, 200, and 50 m, respectively [5]. The oil and gas from the wells in the Shuinan formation of the Laiyang group in the Laiyang depression have the best hydrocarbon fluorescence. The oil and gas deposits in the Laiyang formation reflect the different characteristics in the sedimentary phases of the basin formation [6].

Among the many studies on source-rock geochemistry [4,7], soft sediment deformation [8–10], basin tectonic evolution [11–14], and deep-water gravity flow sedimentology [15–17], there is no comprehensive analysis on the enrichment conditions of oil and gas resources in the Ri-Qing-Wei basin, let alone a comparison with the Jiaolai basin. In this paper, the main controlling factors of hydrocarbon accumulation in the two basins are analyzed based on structural characteristics and evolution, burial and geothermal history, and the organic geochemical characteristics of the source rocks.

2. Stratigraphic Correlation

Strata development controls the distribution and structure of the basin. The secondary tectonic units of the Ri-Qing-Wei basin from south to north can be divided into the Rizhao depression, Zhongdao uplift, Lingshan Island–Laoshan depression, Aoshanwei uplift, Haiyang-Rushan depression and Zeku uplift (Figure 1). The strata can be divided into the Laiyang, Qingshan, and Wangshi groups from bottom to top. The Laiyang group can also be divided into three developmental periods. The bottom represents the initial formation of the late Jurassic basin and is characterized by bottom conglomerate and upper sandstone, siltstone. The middle section represents the early Cretaceous basin, characterized by siliceous siltstone (siltstone–mudstone–turbidite), which represents deep-water sedimentary facies. The top section represents the shrinking stage of the basin at the end of the early Cretaceous and is characterized by gravel-bearing sandstone (siltstone–mudstone), which reflects deep-water turbidite fan facies. The Qingshan group is characterized by thick sandstone and igneous rock that represents fan delta deposits. Overall, the deposition of the Laiyang to Qingshan groups from bottom to top show evidence of inflow-water recession. Wangshi group deposits were not found in the upper part of the Ri-Qing-Wei basin.

The strata of the Jiaolai basin can also be divided into Laiyang, Qingshan, and Wangshi groups. The secondary tectonic units from south to north are the Zhucheng depression, Chaigou uplift, Gaomi depression, Dayetou uplift, and Laiyang depression (Figure 1). The regional sedimentary feature is the strata overstepping westward from old to new. The subsidence and fault depression development of the Jiaolai basin in the Mesozoic and Cenozoic is similar to that of the Ri-Qing-Wei basin. The main subsidence and fault depression period is Cretaceous, and it has been mainly uplifted and eroded since the Paleogene. The Laiyang group is a set of typical fluvial and lacustrine deposits; the Qingshan group has fluvial–lacustrine sedimentary facies and a lithology that changes greatly from piedmont alluvial to fluvial facies to create lacustrine facies. The lithologic association of the lower segment of the Laiyang group in the Jiaolai basin is basically consistent with that of the lower segment of the Laiyang group in the Ri-Qing-Wei basin. The lithology is mainly conglomerate and gravel-bearing coarse sandstone. The Laiyang group can be divided into six formations from bottom to top: Xiaoxianzhuang, Zhifengzhuang, Maershan, Shuinan, Longwangzhuang, and Qugezhuang. The Xiaoxianzhuang formation was deposited in the early stages, but distribution was limited. The lower part is mainly gray conglomerate, glutenite, and coarse sandstone. The upper part shows gradual layering of medium sandstone, fine sandstone, fine black shale, carbonaceous shale, and sandy “oil shale”, reflecting the reduction environment. The sedimentary range of Zhifengzhuang is slightly expanded, and the lithology is coarse in the northeast, mainly composed of purple-red fine conglomerate, giant conglomerate, and sandstone. The south is mainly fine conglomerate, medium sandstone, and fine sandstone with thin mudstone belonging to piedmont alluvial facies and fluvial facies under dry climate.

The sedimentary period of the Maershan expanded that of the Zhifengzhuang formation. The strata of the Shuinan formation were widely over-accumulated during the peak period of the basin development. The medium-coarse clastic lithofacies with obvious characteristics of sediment gravity flow reflect the characteristics of short-distance transport, rapid deposition of high-density bottom flow, and gravity flow deposition in a deep-water sedimentary environment. The Laiyang depression is one of the most developed areas of dark shale in the Jiaolai basin. The sedimentary range of the Longwangzhuang formation continues to increase compared with that of the Shuinan formation, but the water is shallow, so it belongs to shore-shallow lake facies.

The Qugezhuang formation is characterized by coarse debris deposition and has a color that reflects the oxidizing environment. The lithology of the Qingshan group changes greatly in both vertical and horizontal directions. It is a set of complex volcanic and pyroclastic rocks, with a small amount of exhalative sedimentary sandstone and siltstone. The main lithology is rhyolitic tuff, breccia, andesite volcanic breccia, and block rock, which is angularly irregular and is in contact with the underlying Laiyang group. The Wangshi

group deposited in Jimo, Jiaoxian, Zhucheng, Gaomi, and other places. The main lithology is a set of dark-purple, brown-red sandstone, siltstone, and conglomerate deposited in fluvial facies that have parallel or micro-angle unconformity contact with underlying strata.

To determine the stratigraphic sequence of the two basins, the horizontal stratigraphic correlation of the Mesozoic strata was studied. The research degree of the Jiaolai basin was relatively high. Three wells, Zhucan 1, Jiaocan 2, and Laican 1 (Figure 2), pass through three depressions: Zhusheng, Gaomi, and Laiyang. From Zhucheng to Laiyang, the Mesozoic thickness decreased, and the lithology changed from coarse to fine. The Laiyang group of the Zhucan 1 well is interbedded conglomerate, conglomerate-bearing sandstone, and sandstone. The size of the conglomerate gravel is mixed, and the sorting and roundness are poor, indicating that the transport distance is very close. Because of the rapid gravity-flow deposits it can be inferred that the provenance was from the south Jiaonan uplift. The Laiyang group in well Jiaocan 2 is mainly composed of sandstone and siltstone along with thin mudstone and thin gravel sandstone; well Laican 1 is dominated by dark mudstone and silty sandstone.

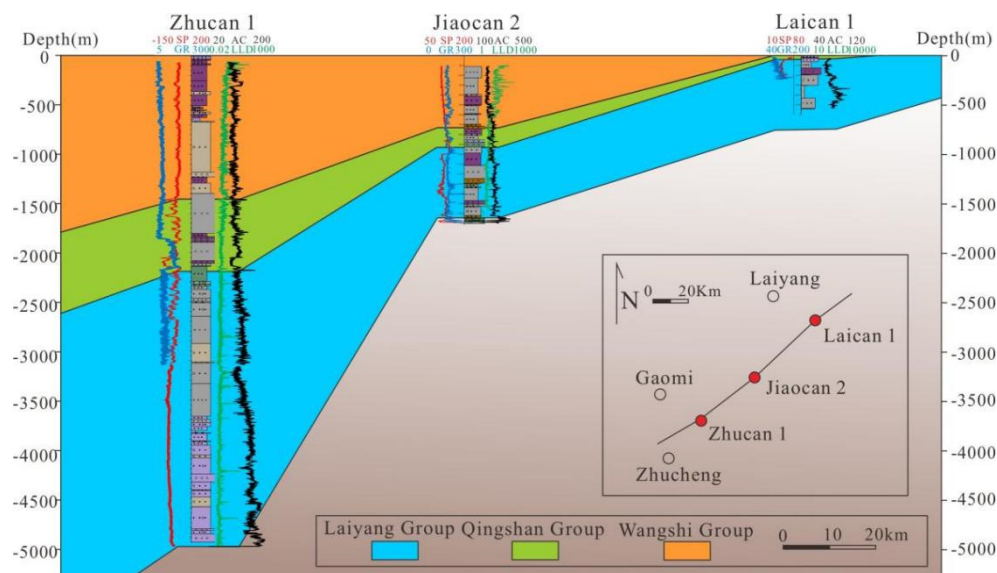


Figure 2. Comparison of Mesozoic SW–NE trending strata across Zhucan 1–Jiaocan 2–Laican 1 wells in the Jiaolai basin.

The Laiyang group in well Lingke 1 in the Ri-Qing-Wei basin has more marine or marine-continental facies deposits compared to the Jiaolai basin. An analysis showed that the Ri-Qing-Wei basin first cracked at this stage and was discontinuously connected with the Pacific plate in an east–west direction. The strata were marine or continental transitional facies. As a rift branch, the Jiaolai basin started cracking relatively late in the Laiyang period. The thickness of the sedimentary strata was relatively thin compared to that of the Ri-Qing-Wei basin, and the sedimentary facies were mainly continental.

3. Comparison of Basin Structure and Evolution

Basin structure and tectonic evolution control the differences in the geological conditions of oil and gas. Based on Jiaolai basin seismic data and data from the South Yellow Sea, 2D Move software revealed northeast- and northwest-trending equilibrium profiles for the Ri-Qing-Wei and Jiaolai basins through depressions and uplifts. The Ri-Qing-Wei basin experienced multi-stage tectonic evolution and a superimposed reformation (Figure 3). From the A–B tectonic evolution profile (southwest to northeast), the axial concave and convex phases of the northeast-trending parabasin were interbedded, and the Ri-Qing-Wei basin experienced large-scale compression tectonic uplift at the end of the Qingshan period (87.5 ± 2.5 Ma) and Wangshi period (50 ± 5 Ma) (Figure 4). A series of thrust faults

developed in the basin because of extrusion, and the Wangshi group developed except for the bulge. The Jiaolai basin is a superimposed half-graben remnant basin composed of three rift prototype basins (Figure 5). The synsedimentary structures of each are controlled by the plane biaxial tensile tectonic stress field. The prototype basins were uplifted or regionally compressed in late evolution, forming inversion structures and unconformity surfaces. Extrusion at the late Qingshan period (87.5 ± 2.5 Ma) and late Wangshi period (50 ± 5) was the strongest.

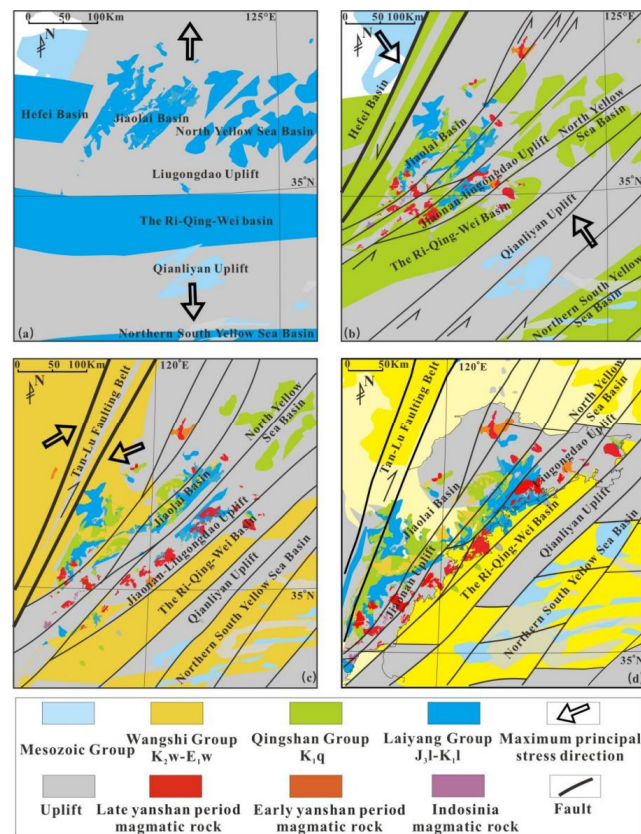


Figure 3. Tectonic outline map of the Ri–Qing–Wei basin and its surrounding area in different periods (modified from [13]): (a) 150 Ma; (b) 90 Ma; (c) 55 Ma; and (d) present.

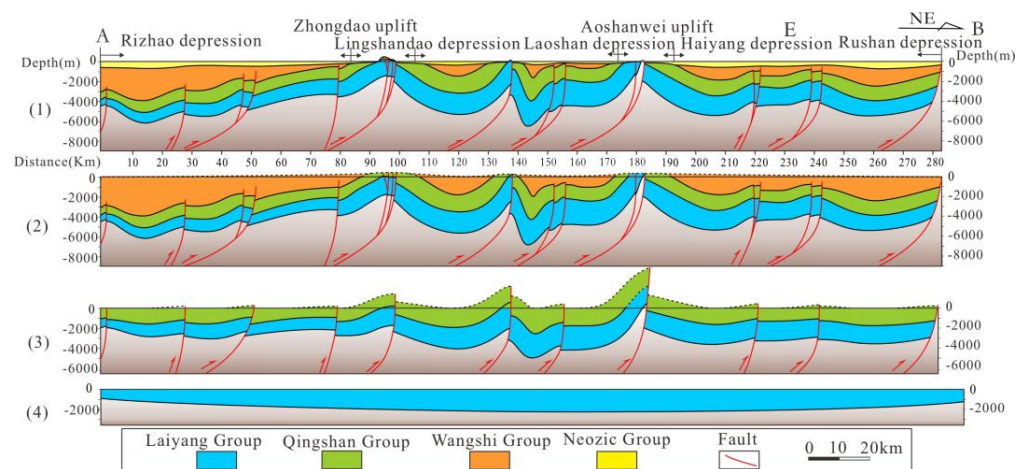


Figure 4. Profile of tectonic evolution map of southwest–northeast trending section in the Ri–Qing–Wei basin (see Figure 1 for the section location): (1) now; (2) late Wangshi period; (3) late Qingshan period; and (4) late Laiyang period.

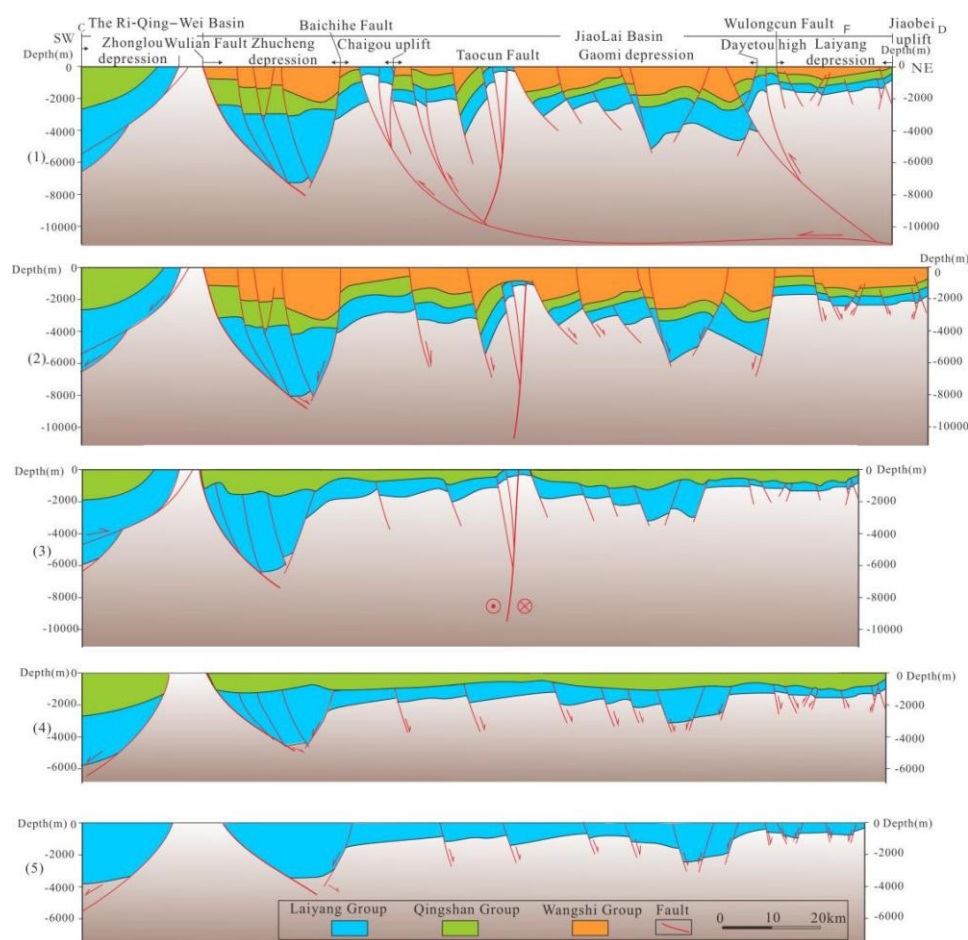


Figure 5. Profile of tectonic evolution map of southwest–northeast trending section in the Jiaolai basin (see Figure 1 for section location): (1) late Wangshi period; (2) Wangshi period; (3) late Qingshan period; (4) Qingshan period; and (5) Laiyang period.

The Laiyang depression is steep in the south and gentle in the north, reaching a double fault on the north–south boundary of the Gaomi depression. Affected by the Tan-Lu fault zone, the buried depth of the nearby Zhucheng depression is the largest in the Jiaolai basin, while the Ri-Qing-Wei basin is deep in the middle and relatively shallow on both sides, conforming to the law of rift basin development. The tectonic activities of the late Mesozoic in the Ri-Qing-Wei and Jiaolai basins can be divided into three stages.

The first was the Laiyang period (150–125 Ma). A series of passive rift basins with the Ri-Qing-Wei basin as the central rift were developed by an orogenic belt because of the subduction of the paleo-Pacific plate and the extension of the paleo-stress field in the north–south direction. The basins were distributed in a long, narrow shape east to west. The Jiaolai basin in the northern part of the Ri-Qing-Wei basin was a subsidiary (branch) rift (Figure 3a). The difference between the Ri-Qing-Wei basin and the surrounding ones at this stage was that the eastern part of the Ri-Qing-Wei basin extended into the ancient Pacific Ocean under the influence of plate cracking. Therefore, marine strata were deposited in the Laiyang period, while the sedimentary environment of the other basins, such as Jiaolai, was continental deposits. The end of the Laiyang period (125 ± 1 Ma) experienced a short paleostress field transformation from the previous north–south extension to a nearly east–west compression. The paleostress field changes caused the angular unconformity between the Laiyang and Qingshan groups, which can be seen by the field outcrop.

The second was the Qingshan period (125–87.5 Ma). The direction of the paleostress field changed to a nearly east–west extension. Because of the retraction of the Pacific plate and the upwelling of mantle material, the thermal uplift and detachment formed an active

rift basin. As a whole, a series of northeast-trending faults developed with extension, and a northwest–southeast compression caused a large-scale left-lateral strike slip at the end of the period (87.5 ± 2.5 Ma; Figure 3b). The Ri-Qing-Wei and Jiaolai basins were distributed northeastward in the Qingshan period, and magmatic rock developed between the basins.

The final stage was the Wangshi period (87.5–50 Ma). The paleo-Pacific plate subducted to the north–northwest, and its velocity was slower. The paleostress field was weak tension in a nearly south–north direction. The thermal anomaly caused by the thermal uplift of the lithosphere gradually cooled and the density increased. The whole lithosphere entered a stage of differential thermal subsidence. Until the end of the period 50 ± 5 Ma, under the dual action of subduction and the remote effect of the Indian plate, a right-lateral strike slip occurred on the west side of the Tan-Lu fault zone and the east side of the western fault zone on the Korean Peninsula. Although the basin strike-slip effect between the fault zones was not obvious, the overall uplift was the main factor. The Ri-Qing-Wei and Jiaolai basins were still generally distributed in a northeast direction (Figure 3c).

Figure 4 shows the southwest–northeast trending structure and evolution profile of the Ri-Qing-Wei basin. A series of high-angle thrust faults shows a progressive southwest–northeast deformation with an overall concave–convex structure. A large number of thrust faults are in the outcrops across the profile on Lingshan Island, indicating that the southwest–northeast extrusion force and secondary depressions in the Ri-Qing-Wei basin were controlled by thrust faults. During the Laiyang period, the basin was cracked by a north–south extension. Under the Qingshan period extension, subsidence was inherited. At the end of the Qingshan period, a series of thrust faults developed in the basin because of northwest–southeast compression. The reverse fault ended activity in the Wangshi period, and differential thermal subsidence occurred with good inheritance superposition.

Figure 5 shows the southwest–northeast trend and evolution profile of the Jiaolai basin. During the Laiyang period, a series of rift basins dominated by normal faults developed. The thickness of the Zhucheng depression near the Wulian fault is the largest and that of the Laiyang depression is the smallest. During the Qingshan period, the faults in the basin that formed in the Laiyang period ended activity. At the end of the Qingshan period, a series of northeast strike-slip faults formed under compression, among which the Taocun fault passed through the Jiaolai basin. In the Wangshi period, active faults from the Laiyang period were activated and reactivated, and differential thermal subsidence occurred in the previous basin.

Figure 6 shows the north–northwest–south–southeast evolution of the Ri-Qing-Wei and Jiaolai basins, which spanned the Jiaonan–Liugongdao uplift. During the Laiyang period, the Ri-Qing-Wei basin was thicker than the Jiaolai. During the Qingshan period, thermal uplift resulted in the slippage of basins near the uplift. At the end of the Qingshan, the northwest–southeast compression caused a left-lateral strike slip, which made the boundary faults on both sides of the basin and the two sides of the uplift zone develop northeast strike-slip faults. The overall thickness of the Wangshi group in the Ri-Qing-Wei basin was thicker than for the Jiaolai basin. At the end of the Wangshi period, the tectonic uplift caused the Laiyang depression of the Jiaolai basin in the study area, and the strata near the Jiaonan uplift in the Ri-Qing-Wei basin were strongly eroded, and the strata were strongly uplifted. The source rocks of the Laiyang group were even exposed to the surface.

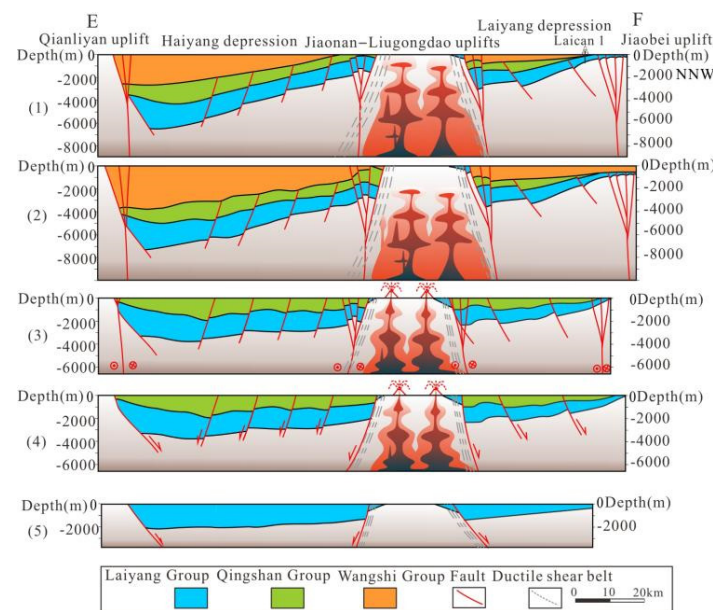


Figure 6. Profile of tectonic evolution map of NNW trending section in the Ri–Qing–Wei basin (see Figure 1 for the section location): (1) late Wangshi period; (2) Wangshi period; (3) late Qingshan period; (4) Qingshan period; and (5) late Laiyang period.

4. Comparison of Burial History and Geothermal History

Because of the differences in burial history of source rocks and geothermal fields in each depression, there are significant differences in how thermal evolution affects organic matter (Figure 7). The Dabie–Sulu Orogeny was formed by the collision of the Yangtze and north China plates in eastern China, during the Indosinian period, followed by the ancient Pacific plate subduction, rollback, and direction change during the Tanzanian period. The Late Mesozoic study area was under extensional tectonic setting and developed multi-stage superimposed basins. The eastern part of China was affected by the subduction of the ancient Pacific plate to the low angle of the Eurasian plate. The Sulu Orogeny collapsed, and the lithosphere underwent large-scale delamination and root removal. The delamination eventually led to large-scale lithospheric thinning. The thickness of the lithosphere decreased from 120–180 km during the Paleozoic to 70–80 km today [18,19]. At this stage, the basin basement rift reached its maximum, the lithosphere thinned, the mantle quickly arched, and lower crust material produced thermal erosion and remelting, resulting in a high geothermal gradient of about $3.1\text{ }^{\circ}\text{C}/100\text{ m}$ at the end of the Laiyang period. The highest geothermal gradient during the Qingshan period was due to the additional geothermal field generated by large-scale volcanic eruptions, about $4\text{ }^{\circ}\text{C}/100\text{ m}$. However, this high temperature caused by volcanic activity soon disappeared with intermittent volcanic action, and the influence on the evolution of organic matter in the basin was relatively limited. By the Wangshi period, the geothermal gradient had gradually decreased, and the geothermal gradient at the end of the Wangshi group sedimentary period was about $3.1\text{ }^{\circ}\text{C}/100\text{ m}$; the lowest current geothermal gradient is about $2.6\text{ }^{\circ}\text{C}/100\text{ m}$ [20]. Therefore, the paleogeothermal went from low to high and then from high to low.

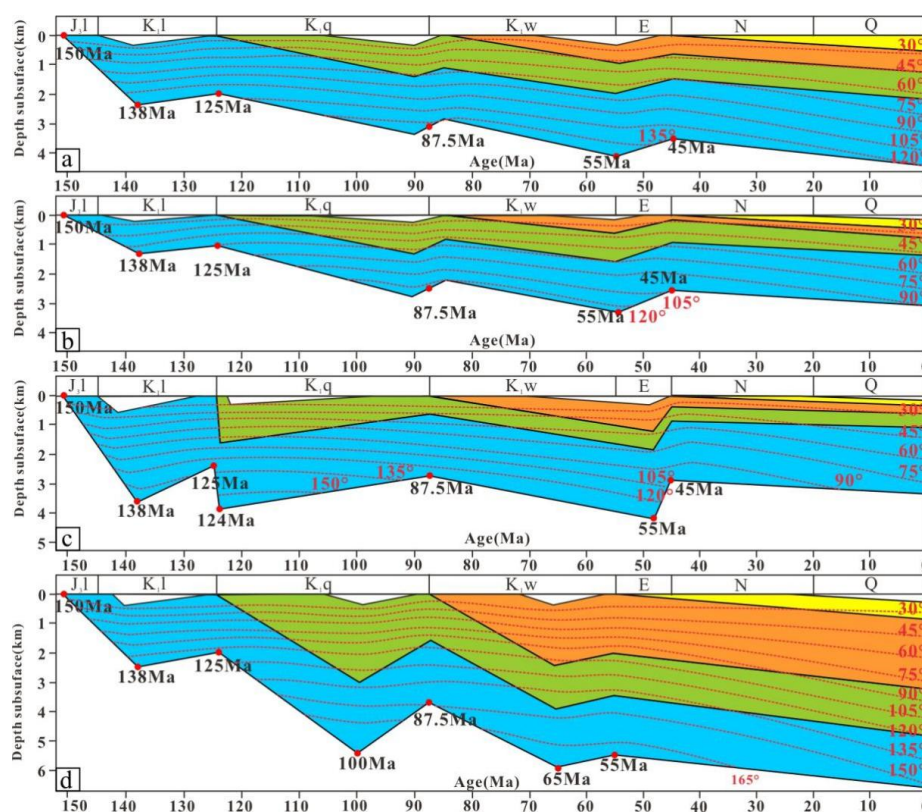


Figure 7. Implication diagram of burial history and geothermal history. (a) Zhucheng depression, western Jiaolai basin; (b) Laiyang depression, eastern Jiaolai basin; (c) Lingshandao–Laoshan depression, Ri-Qing-Wei basin; (d) Haiyang–Rushan depression, Ri-Qing-Wei basin. The western segment of the L1 seismic survey line is shown in Figure 1a.

The buried depth of the Laiyang group in the Ri-Qing-Wei basin is deeper than in the Jiaolai basin, and the paleogeotemperature was relatively high. The paleogeotemperature of the Lingshan Island–Laoshan depression is the highest, followed by the Haiyang–Rushan and Rizhao depressions. According to the distribution of depression paleogeotemperature within the Jiaolai basin during the same period, the Zhucheng was the highest, the Gaomi was second, and the Laiyang was the lowest. For the depressions in the Ri-Qing-Wei basin, the paleogeotemperature reached a maximum value for the entire basin evolution in the Qingshan period and reached the overmature stage in the Laiyang period. Although the temperature gradient at the end of the Wangshi period was not very high, the paleogeotemperature in the Lingshan Island depression even reached 165 °C because of the deep burial of the Laiyang group. For hydrocarbon generation, the geothermal conditions in the eastern Gaomi and western Laiyang depressions of the Jiaolai basin are the best, followed by the central Laiyang depression. The source rocks entered the oil-generation stage at the end of the Laiyang period and then reached 100–130 °C in the Qingshan period when it entered a large oil-generation stage, after which it slowly decreased and was maintained at about 100 °C. The ground temperature in the Zhucheng depression is generally high, and most of the Laiyang period reached the overmature stage, which was unfavorable for oil and gas generation. To evaluate the hydrocarbon generation conditions comprehensively, various organic geochemical characteristics of the source rocks should be considered.

5. Comparison of Organic Geochemical Characteristics of Source Rocks

Only effective source rocks can provide commercial hydrocarbon accumulation in a sedimentary basin, and they are evaluated according to three geochemical characteristics: organic matter abundance, type, and maturity.

The source rocks in the Ri-Qing-Wei basin, which served as the comparison index, come mainly from well Lingke 1 near the shipyard on Lingshan Island and field outcrop samples. The structural position of the only scientific exploration well is located at the basin margin of the northwest fault boundary in the Ri-Qing-Wei basin. The drilling depth is 1352 meters; the strata are all Laiyang group; and the Laiyang group was not drilled. All types of deep-water gravity flow were developed in the strata, which attests to the fact that the Ri-Qing-Wei basin was a deep-water facies rift basin in the late Jurassic–early Cretaceous, and that the paleomagnetic age of the bottom core is 147 Ma [21]. Well Lingke 1 encountered dark silty mudstone, gravel-bearing mudstone, shale, and multiple sets of intrusive lamprophyre veins. The cumulative thickness of the mudstone accounts for 40.5% of the formation's thickness. The grey–black mudstone is mainly lamellar, and the local texture is developed. There are 17 wells drilled in the Jiaolai basin, and most of them have good indications of oil and gas. Among them, the low-yield oil flow from Laiqian 2 derived from the Shuinan formation. The good oil-and-gas display wells and low-yield oil flow wells are all in the Laiyang depression, and on the horizon is drilling in the Shuinan formation of the Laiyang group. The source rock correlation index of the Jiaolai basin came mainly from well Laikong 2 in the Laiyang depression. Based on field outcrop and core and drilling data, combined with seismic interpretations and analysis of sedimentary facies, the plane distribution contour map of the cumulative thickness of dark shale in the Ri-Qing-Wei basin and Jiaolai basin was drawn.

The source rocks in the Ri-Qing-Wei basin are thicker than in the Jiaolai basin. The dark mudstones in the Lingshan Island and Laoshan depressions are the most developed in the Ri-Qing-Wei basin. The thickness of source rocks in a marine depression is relatively thin, and the thickness of source rocks from the Lingshan Island depression can reach 700 m. The Laiyang and Gaomi depressions in the Jiaolai basin have the most developed areas of dark shale with a cumulative thickness of 200 m. Although the Zhucheng depression has a large lake basin area, deep and semi-deep lacustrine facies did not develop because the deposition rate was greater than the deposition rate of the basement. Although the formation is thick, the thickness of dark shale is small.

5.1. Organic Matter Abundance

Most of the source rock samples in the Ri-Qing-Wei basin come from outcrops and core samples taken from the Laiyang group. The organic carbon content (TOC) of outcrop samples collected from different sections of source rocks changed greatly, with an average of 1.03%. Among them, the TOC on Lingshan Island was higher on the whole. The average TOC value of the Dengta section sample was 1.73%; Chuanchang, 1.62%; Beilaishi, 1.54%; and Qiancengya, 0.75%, all of which met the standard for medium source rock. The TOC of core samples from well Lingke 1 in the western continental part of the Ri-Qing-Wei basin were generally high with an average of 1.3%, putting 61% of the samples in the range of good source rocks, according to pyrolysis evaluation criteria [20]. The average pyrolysis hydrocarbon potential (S1 + S2) of well Lingke 1 was 0.108 mg/g, which belongs in the range of non-hydrocarbon rock. The average content of chloroform bitumen "A" in well Lingke 1 was 0.000119%, which is also in the range of non-hydrocarbon rocks. According to the evaluation results of organic matter abundance in the Ri-Qing-Wei basin, the TOC values pointed to good source rocks, the latter two belonging to the range of non-hydrocarbon rocks. Because of the influence of thermal uplift in the late Laiyang and Qingshan periods, the source rocks were overmature, so hydrocarbon generation potential and chloroform bitumen "A" do not reflect the original source rocks. Therefore, the hydrocarbon generation potential and chloroform bitumen "A" in well Lingke 1 cannot be used as indicators for evaluating organic matter abundance.

The Xiaoxianzhuang and Shuinan formations of the Laiyang group in the Jiaolai basin have thick, dark shale and carbonate rocks. The content of coarse clastic rocks in other formations is high, and the oil generation ability is poor. The distribution of the Xiaoxianzhuang formation is relatively limited, mainly in the piedmont shop area of the

Laiyang depression and some areas of the Zhucheng depression. The mud shale color in the Zhucheng depression is mainly red and purple-red, and the thickness is small. It is said that it does not have the ability to produce oil. The ash-black carbonaceous shale and the shale of the Xiaoxianzhuang formation in the Laiyang depression are about 100 meters thick and have strong oil-generating capacity. The average TOC of well Laikong 2 was 0.81%. Chloroform bitumen "A" is 0.002–0.01%, which is characterized by late and high maturity. The asphalt in the sandstone fractures of the Xiaoxianzhuang formation shows that the oil generation and hydrocarbon migration occurred. The Shuinan formation has a wide range of strata and the best oil generation in the basin. In the Longwangzhuang and Muyudian sections of the Laiyang depression, the thicknesses of oil-generating strata in the Shuinan formation were 215.5 and 102.5 m, respectively, accounting for 60 and 50% of strata thickness [22]. According to drill sample analysis, the samples with a TOC greater than 0.4% accounted for more than 70% of the total, and the chloroform bitumen "A" content was more than 0.01%; the average TOC content of the outcrop sample was 1.02%; and for chloroform asphalt "A" it was 0.004–0.1070%, which is an indicator of good source rock. According to the measurement results of inclusion homogenization temperature in well Laiqian 1, the inclusion temperature of clastic rock in the Shuinan section was between 96.5 and 134.2 °C, which is in the general temperature range for the initial migration of oil and gas. The burial depth should be between 1300 and 1600 m, and the maturity of organic matter should be between the oil generation threshold and the main peak of oil generation. Therefore, it is speculated that a large amount of oil and gas has been generated and the primary migration occurred in this period.

5.2. Maturity of Organic Matter

The maturity of organic matter was studied according to the rock pyrolysis peak temperature (T_{max}) and vitrinite reflectance R_o. The maturity parameters of organic matter of source rocks in the Ri-Qing-Wei basin and T_{max} change with organic matter type, and the maturity of the intermediate (type II) and humic type (type III) was better determined. Pyrolysis peak temperatures of the lighthouse, shipyard, Laohuzui, and Qiancengya profile samples on Lingshan Island were all mature–high-mature stages. The T_{max} values of the reef cave profile (Qingshan group) and the back-clay profile samples were 529 and 513 °C, respectively, and both were over-mature. The T_{max} of the radar station (Qingshan group) sample was 461 °C (high maturity); the Qingshanwan profile sample in Laoshan, 443–455 °C (mature); the Yakou profile sample, 492 °C (over-mature); the Jimo Zhougezhuang section, 457 °C (mature); and the Juxian sample, 481–483 °C (high-mature).

The maturity of organic matter in the Jiaolai basin: the R_o of two samples in the Wawukuang section of Xiaoxianzhuang section was 1.53 and 3.51%, while the R_o of two samples in the Xiaoxianzhuang section were 1.12 and 1.4%, indicating that the evolution of organic matter has reached the maturity stage.

5.3. Organic Matter Type

The main parameters of organic matter types in the Ri-Qing-Wei basin are organic maceral analysis and the pyrolysis hydrogen index. Of the 16 outcrop samples of the Laiyang group, 14 were humic type I and humic–humic type II₁, accounting for 87.5%. Among these, 4 samples were humic type I, accounting for 25%, and 9 samples were humic–humic type (II₁), accounting for 56%. One sample was humic–humic type II₂, accounting for 0.06%, and 3 samples were humic type (type III), accounting for 18.75%. In addition, the samples of other profiles were humic type I and humic–humic type II₁. The mudstone samples of the Laiyang group in well Lingke 1 were tested by transmission light-fluorescence kerogen maceral identification. The test results showed that the kerogen was mainly composed of sapropelic and vitrinite. The content of the sapropelic group was 65–88%, mainly the sapropelic type; vitrinite content was 12–35%; and the organic matter type was sapropelic type II₁ and humic–sapropelic type II₂. The test results of organic

matter types of outcrop sections and cores in the basin showed that the hydrocarbon source rocks of the Laiyang group in the Ri-Qing-Wei basin have high oil-generation potential. The mudstone samples in well Lingke 1 were tested by transmission light-fluorescence kerogen maceral identification. The results showed that the kerogen was mainly composed of sapropelic and vitrinite. The content of sapropelic group was 65–88%, mainly sapropelic type, vitrinite content was 12–35%, and the organic matter type was sapropelic type II₁ and humic–sapropelic type II₂. The test results of organic matter types of outcrop sections and cores in the basin showed that the hydrocarbon source rocks of the Laiyang group in the Ri-Qing-Wei basin have high overall oil-generating potential.

The organic matter types of the Xiaoxianzhuang formation in the Laiyang group of the Jiaolai basin are mainly humic–mud type II₂–humic type III. The low abundance of residual organic matter in dark shale may be due to the high degree of thermal evolution and the conversion of most into oil and gas. Therefore, it is speculated that the original organic carbon content may have been higher, meaning that the oil-generating zone should be more favorable. Organic matter types of the Shuinan formation are mainly humic type I and humic–humic type II₁, and some samples are humic–humic type II₂ and humic type III. The organic matter types of source rocks in the Jiaolai basin are good and have a certain hydrocarbon generation capacity.

5.4. Summary

Both the Ri-Qing-Wei and Jiaolai basins have high-quality source rocks with good oil-generating conditions. The thickness of the rocks in the Jiaolai basin is smaller, while the thickness of source rocks for Ri-Qing-Wei was larger. Shale gas in China generally has a large burial depth (>2000 m), an average TOC of 3%, and a Ro of 0.5–2%. The organic matter type is mainly a humic–mixed-humic type. The geochemical characteristics of source rocks in the Ri-Qing-Wei basin meet the evaluation criteria for shale gas. The source rocks in the western land of the Ri-Qing-Wei basin are mostly at the overmature to high mature stage because of thermal uplift, while the source rocks in the eastern sea area are deeper and more conducive to preservation. At the same time, part of the sea area is weakly affected by thermal uplift, which is more conducive to generating oil and gas.

6. Main Controlling Factors of Hydrocarbon Accumulation

The burial depth of the Ri-Qing-Wei basin is deeper than that of the Jiaolai basin, and its relatively high paleogeotemperature made the Laiyang period reach the overmature stage. The Lingshan Island–Laoshan depression has the highest paleotemperature. By comparing the organic geochemistry of the source rocks in the Jiaolai and Ri-Qing-Wei basins, oil-generating conditions in the eastern part of the Ri-Qing-Wei basin are thought to be relatively better. In fact, the Lingshan Island–Laoshan depression has the best hydrocarbon generation potential because the thickness of the source rocks is the largest. Hydrocarbon accumulation is mainly affected by late reformation, in which tectonic uplift and magmatism are the main controlling factors.

6.1. Tectonic Uplift

Most areas of the Jiaolai Basin have strong late-tectonic activities. Oil and gas in the Laiyang group's Shuinan formation are mainly distributed in the piedmontian anticline belt of the Laiyang depression and the Muping–Jimo fault zone to the northeast, which cuts through the basin. The former did not accumulate oil perhaps because compression over 50 ± 5 Ma led to the uplift and denuding of the regional cap rock, including surface exposure of the source rocks, which caused the destruction of the previously formed oil and gas reservoirs. In the latter case, activity from the Muping–Jimo fault zone (formed by the left-lateral strike slip in the 90 ± 5 Ma period) and the regulatory fault (derived from the right-lateral strike slip in the later 50 ± 5 Ma period) caused upward leakage of oil and gas. Although the thickness of the dark shale in the Laiyang group is large, there is a good oil and gas display. Due to the late uplift, the high degree of denudation of the Wangshi group

led to the non-development of the caprock, and the erosion of the exposed strata surface. Although oil and gas were formed, most was scattered and overflowed. At the same time, vitrinite reflectance data show that the area has experienced strong metamorphisms far beyond the oil field death line [23]. On the other hand, because of continuous fault activity, oil and gas continued to spread to the surface. Therefore, exploration for oil and gas in the Jiaolai basin is low.

From the 150 Ma point of the Laiyang period, the central-rift Ri-Qing-Wei basin cracked. The cracking time was early; the scope was large; and the stratigraphic thickness was large. The Jiaolai basin, as a collateral rift, has a thickness and burial depth of the Laiyang group less than that of the Ri-Qing-Wei basin. After the stretching of the Qingshan period, the strike-slip movement of the late Qingshan and the deposition of the Wangshi period, subduction of the ancient Pacific plate and remote compression of the Indian plate uplifted the whole basin 50 ± 5 Ma ago.

The Tan-Lu fault zone has experienced multiple periods of tectonic activity. With the subduction of the ancient Pacific plate to the eastern part of China, the lithosphere is dismantled and the asthenosphere material is upwelling, resulting in the extension activities of the Tan-Lu fault zone and its adjacent basins in the Laiyang period. The fault zones reflect the right-lateral strike-slip movement characteristics. In the Wangshi period, under the dual stress of the eastward extrusion caused by the collision between the Indian plate and the Eurasian plate and the northeastward extrusion of the ancient Pacific plate, the basins in eastern China east of the Tan-Lu fault zone were squeezed and uplifted and subjected to strong erosion.

Among them, the Jiaolai basin was bounded by the Tan-Lu fault zone and the Wulian-Mouji fault zone (Figure 1). The tectonic position of the Jiaolai basin at this stage led to stronger thrust uplifting induced by the right-lateral strike slip of the Tan-Lu fault zone, the uplift of the Wangshi group, and the destruction of the source rock. The Riqingwei basin was far from the Tan-Lu fault zone, and its boundary fault was the northeast-trending Qianliyan fault zone. The uplift of the Ri-Qing-Wei basin caused relatively weak destruction, and the buried depth was larger. Under the compressive stress field at the end of Qingshan period, a large number of thrust faults formed thrust coating structures that formed anticline traps, which are conducive to oil and gas preservation.

6.2. Magmatic Activity

The Ri-Qing-Wei and Jiaolai basins are located on the eastern margin of the East Asian plate. Since the late Mesozoic, strong magmatic activity has occurred under the influence of the ancient Pacific plate subducting under the Eurasian plate, reaching a peak in the early Cretaceous. The change of the subduction angle and direction of the paleo-Pacific plate is closely linked with the tectonic evolution and magmatic activity of the Cretaceous in eastern China. For example, the quartz vein-type gold deposit in eastern Shandong province was formed against the tectonic background of compression, and its formation age is consistent with the transformation age of the plate subduction direction, which recorded the time from tension to compression [24]. Subduction of the paleo-Pacific plate can also explain the Cretaceous magmatism in eastern China [25]. As the subduction angle of the ancient Pacific plate increased, the deep asthenosphere material gradually upwelled, melting the lithospheric mantle and crustal material. The magma formed in the late Laiyang period caused large-scale intrusion and eruption. Due to the dual influence of the upwelling of asthenosphere material and crust-derived magma, the study area underwent thermal uplift, and the previously formed Laiyang-period rift basin disappeared, thus ending the passive rift stage. In the Qingshan period (125–90 Ma), the thermal uplift was accompanied by strong volcanic activity and led to the development of a series of active rift basins along the slip surface on both sides of the volcanic arc. During this period, the local highlands were caused by a strong thermal uplift between the Ri-Qing-Wei and Jiaolai basins. Volcanic activity gradually weakened from east to west, and the magmatic rock type was mainly granite intrusion [19]. These magma intrusion and eruption activities were accompanied

by the development of the whole basin, which inevitably affected its structural pattern. As a result of intrusion and eruption, the molten magma had an impact on the history of thermal and organic matter evolution and of hydrocarbon generation. The typical volcanic profiles in the Ri-Qing-Wei basin come mainly from the Lingshan Island, Jimiya, Jimo, Zhougezhuang, and Taolin areas. Intrusive rocks in the Jiaolai basin are mainly distributed in the surrounding Jiaobei and Jiaonan uplift areas. The magmatic intrusion activities in the early Yanshanian period (140–110 Ma) mainly occurred in the Jiaobei uplift, which is represented by Guojialing-type crust-margin intrusive rocks. By the late Yanshanian (110–80 Ma), intrusive rock activities in the Jiaonan uplift increased significantly and invaded the fault zone along the basin boundary, while westward intrusion activities weakened. The eruptive rocks were mainly distributed near the basin margin and the northeast-trending fault zone and erupted in the Qingshan period [26]. This eruption stage occurred in the rift basin expansion (Laiyang) period. Volcanic activity was the strongest in the Qingshan period, while in the Wangshi period it was not obvious. Igneous rock that intrudes into oil-generating strata can bake the surrounding organic matter at high temperatures, abnormally increase maturity, and generate oil and gas earlier [27]. Research results at home and abroad, however, show that the extent of baked organic matter is very limited, only within 20–30 m of the igneous rock.

Large intruders make oil and gas suffer from high-temperature metamorphism, which has a destructive effect on the reservoir because heat generated by small-scale intrusions and volcanic eruptions promotes the maturation of source rocks. For example, those near the Jiaobei and Jiaonan uplifts in the Jiaolai basin were destroyed by high-temperature baking from intrusive rocks, and source rocks in the basin were weakened [28]. Source rocks affected by small intrusive rocks and eruptions in the eastern part of the Ri-Qing-Wei basin were less affected by high-temperature damage, making them more conducive to oil and gas formation. The overland part of the western Ri-Qing-Wei basin was roasted by magmatic rocks, and the Ro of the source rock was above 3.6%, indicating an over-mature dry gas generation stage [29]. Ro increased 1% because of magmatic roasting in the Qingshan period, suggesting that the thermal uplift was more than 3 km, and the magmatic activity improved the overall Ro value in the study area.

The strata drilled by the Lingke 1 well, which is closer to the eastern part of the Ri-Qing-Wei basin, identified a magmatic channel through the core. The Ro value of the samples affected by burial depth gradually increased from shallow to deep. Therefore, even in areas with strong magmatic activities, there are still favorable accumulation areas. At the same time, the magmatic thermal uplift caused the slippage-extension effect, which made the source rock slip deep. The source rock in the eastern part of the Ri-Qing-Wei basin is more conducive to oil and gas formation.

The destruction of hydrocarbon source rocks in the Jiaolai basin caused by tectonic uplift in the late Wangshi period is a key factor for its non-accumulation. The high-temperature destruction of intrusive rocks in the Jiaolai basin and the western continental part of the Ri-Qing-Wei basin is a secondary factor. Thermal uplift caused the detachment and extension of the eastern sea area of the Ri-Qing-Wei basin, which is more conducive to preserving hydrocarbon source rocks and one of the favorable conditions for its accumulation.

7. Conclusions

1. The Ri-Qing-Wei basin is a Mesozoic-Paleogene (Laiyang period) rift-depression basin. Because it is a central rift, its thickness is greater than that of the Jiaolai basin, which is a branch rift. Lingshan Island and the Laoshan depression in the Ri-Qing-Wei basin have large strata thickness. The Zhucheng depression near the Tanlu fault zone in the southwest of the Jiaolai basin has the largest thickness, and the Laiyang depression in the northeast has the thinnest. Due to the change of subduction direction and angle of the paleo-Pacific plate, the study area experienced three stages of extension and three of tectonic evolution accompanied by compression: the early Laiyang period (150–125 Ma) passive continental rift; late Laiyang period (125 ± 1 Ma) thermal uplift shrink closed; the Qingshan period

(125–87.5 Ma) thermal uplift detachment active rift; the Qingshan period (87.5 ± 2.5 Ma) extrusion left lateral strike slip; the Wangshi period (87.5–50 Ma) thermal subsidence; and the Wangshi period (50 ± 5 Ma) extrusion right lateral strike slip.

2. The development horizon of source rocks in the study area is the Laiyang group, and there are some differences in their maturity between basins and different depressions in the basin. In general, affected by burial depth, the source rocks in the Gaomi and Laiyang depressions and in each depression in the Ri-Qing-Wei and Jiaolai basins reached maturity or even high maturity in the Qingshan and late Laiyang periods, and experienced large-scale hydrocarbon generation and expulsion in the Qingshan.

3. The right-lateral strike-slip extrusion uplift in the late Wangshi period was the main factor causing the destruction of the reservoir in the Jiaolai basin. Under the control of the right-lateral strike-slip-derived compression in the late Wangshi period of the Tanlu and Wulian-Mouji fault zones, the overall uplift of the Jiaolai basin was strong, in which the Laiyang depression, with the best source rock condition, was greatly uplifted. The right-lateral compression lifted the source rock up to or near the surface, severely damaging the ancient oil and gas reservoirs. The source rocks in the Ri-Qing-Wei basin are deeply buried, and the faults associated with extrusion in the late Wangshi period rarely extended to the surface, so destruction was weak. At the same time, the reverse fault sealing caused by extrusion in the late Qingshan period was beneficial to oil and gas sealing.

4. The thermal uplift caused by the Qingshan magmatic intrusion was a secondary factor for unaccumulated oil and gas in the western part of the Ri-Qing-Wei basin, where thermal uplift destroyed the source rocks, and the local high temperature caused them to over-mature. In the eastern part of the Ri-Qing-Wei basin, thermal uplift and detachment occurred, and the source rocks were rapidly buried and continuously deposited. The degree of damage from high-temperature magma and tectonic uplift was low, which was beneficial for the preservation of the source rocks. Magmatic activity led the increase in the geothermal gradient in local areas. Shallow source rocks had a reduced hydrocarbon generation threshold, and deep source rocks entered a large-scale gas generation stage. The offshore area in eastern China is important for replacement energy exploration. The Ri-Qing-Wei basin in the Yellow Sea should be explored to strengthen the development of medium-deep unconventional shale gas, and to develop the sea area of the Ri-Qing-Wei basin.

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