

Article

Petroleum System Analysis and Burial History of Middle Permian Source Rock in Turpan–Hami Basin, NW China

Zhiyong Li ¹, Hongguang Gou ², Xiongfei Xu ^{2,3,4}, Xiao Li ⁵, Ke Miao ^{3,4}, Jing Zhang ¹, Zaiguang Li ¹, Zhiming Li ¹ and Wei Yang ^{3,*}

- ¹ Northwest Branch, Exploration and Development Research Institute, PetroChina Co., Ltd., Lanzhou 730020, China; li_zhiyong@petrochina.com.cn (Z.L.); jing_zhang@petrochina.com.cn (J.Z.); li_zg@petrochina.com.cn (Z.L.); l_zm@petrochina.com.cn (Z.L.)
- ² Research Institute of Exploration and Development, PetroChina Tuha Oilfield Company, Hami 839009, China; gouhongguang@petrochina.com.cn (H.G.); xuxfyjy@petrochina.com.cn (X.X.)
- ³ National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum (Beijing), Beijing 102249, China; 2022216632@student.cup.edu.cn
- ⁴ Unconventional Petroleum Research Institute, China University of Petroleum (Beijing), Beijing 102249, China
- ⁵ China National Logging Corporation, Xi'an 710000, China; lixiaocq@cnpc.com.cn
- * Correspondence: yangw@pku.edu.cn; Tel./Fax: +86-10-89739051

Abstract: The pre-Jurassic in the north depression of the Tuha depression is the most favorable replacement strata to obtain new reserves in the Turpan–Hami Basin. (Pre-Jurassic, in this paper, refers to the Permian and Triassic.) The main source rocks are the Taodonggou Group, of which the burial history and hydrocarbon generation potential remain unconfirmed. The investigation of the burial and thermal history is vital for the basin analysis and hydrocarbon exploration. Therefore, in this paper, by using the acoustic time difference method, vitrinite reflectance method, stratigraphic trend method and PetroMod-1D software, the differential characteristics of denudation thickness, burial history and thermal evolution history of different tectonic units in different periods of Taibei Sag in the Turpan–Hami basin are studied, and their influence on the petroleum system is analyzed, and then the zones with exploration potential are optimized. The results show that the Taibei Sag has experienced multiple tectonic uplift events. The Late Indosinian movement has profound effects on the Taodonggou Group source rocks. The rather large uplift amplitude postpones the maturation of source rocks. In addition, the Turpan–Hami Basin is a typical cold basin. Therefore, the thermal maturity of the source rocks is relatively low, with respect to the relatively deep burial. The thermal histories of the different sub-sags in the study area are slightly differentiated from each other. The Taodonggou Group source rocks in the Taibei Sag generally became mature during the Mid–Late Jurassic epoch, except for those in the Central–Southern Shanbei sub-sag, represented by Well LT-1, which reached the mature stage during the Late Triassic epoch. The study area has well-developed reservoir rocks, and effective reservoir bodies are formed in the slope zone and near the Tainan Sag, due to the higher porosity and permeability of reservoir rocks. The statistics related to the faults and an analysis of the structural styles of oil reservoirs indicate that the structural slope and anticline of the Huobei, Lianbei and Shanbei sub-sags are favorable for increasing reserves and production of hydrocarbons.

Keywords: Turpan–Hami Basin; Taibei Sag; pre-Jurassic; Taodonggou Group; burial history; thermal history; favorable area; petroleum system



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1. Introduction

The burial history and thermal history evolution process of the hydrocarbon source rock series have become the research focus in the field of earth science. The burial history includes the sedimentary burial and uplift denudation of the strata and the thermal evolution history experienced in the geological history period [1]. These two aspects are particularly

important for the study of source rocks because they not only restrict the generation time of oil and gas but also control the equivalent of oil and gas discharge. This study has been carried out in many petroliferous basins in the world. Examples include a study of the Upper Cambrian and/or Temadokian, Upper Ordovician and Lower Silurian source rocks in the Western Baltic region; a study on the thermal history of burial history of Cretaceous source rocks in the Villa Cruz Basin, Mexico; and the Phanerozoic burial and erosion model inside the North American Craton. Therefore, the development of this work is particularly important [2,3]. The petroleum systems in the Tabei Sag are completed. The petroleum systems of different sub-sags are varied, and the processes governing hydrocarbon accumulation are unclear. Therefore, it is necessary to construct the differential burial–thermal history of the Permian Taodonggou Group to clarify the differentiation characteristics of the petroleum systems of different sub-sags [4–6]. By far, over 10 exploration wells have been deployed for the pre-Jurassic of the Tabei Sag, and among them, fewer than 6 wells encounter the Taodonggou Group source rocks. The Taodonggou Group source rocks in the Taibei Sag are identified as mature source rocks having high hydrocarbon generation capacities—the content of TOC (Total Organic Carbon), chloroform bitumen A and hydrocarbon generation potential are 0.67%–8.54%, 0.075%–0.8767% and 0.62–66.92 mg/g, respectively, and the organic matter is predominantly Type-II₂ and III, with the vitrinite reflectance (Ro) of 1.04 Ro%–1.38 Ro% [7,8]. The restoration of erosion thickness is the basis and key to studying the thermal history of the basin. Many effective methods have been developed by predecessors [9]. The methods used in the early stage are mainly the stratigraphic correlation method, deposition rate method, acoustic time difference method, vitrinite reflectance method and wave equation method. Through repeated modifications, these methods have been further expanded and improved [10]. Hence, in this research, the structural uplifting and erosion thickness of the Taibei Sag during each period of the geologic history were quantified, and the burial–thermal history of representative exploration wells in the Taibei Sag was restored using PetroMod (Schlumberger) [11,12]. Burial history and thermal history control the time of hydrocarbon generation and expulsion of hydrocarbon source rocks. They are the most important parameters for hydrocarbon source rock evaluation and dynamic hydrocarbon accumulation in petroliferous basins, and they also point out the direction for further oil and gas exploration [13,14].

2. Geological Setting

The Turpan–Hami Basin is an important petroliferous basin in China, located in the eastern part of the Xinjiang Uygur Autonomous Region. Structurally, it lies in the Southwestern Central Asian Orogenic Belt, sandwiched by the Bogeda Mountain and Jueluotage Mountain. Since the Jurassic Period, the basin evolution is closely related to the Bogeda Mountain, and now, the basin presents the characteristics of the foreland basin [15–21]. The study area, Taibei Sag, mainly lies in the Turpan Depression of the basin. The Taibei Sag extends from the Kalawucheng Mountain in the west to the Taoergou in the east, and from the Bogeda Mountain in the north to the Jueluotage Mountain in the south. The sag, generally a square, covers about 2.5×10^4 km² [22].

By the end of 2018, the Turpan–Hami Basin obtained industrial oil and gas flow in five sets of strata in the Permian, Triassic, Jurassic, Cretaceous and Paleogene. Eight plays were identified in the Tabei, Tuokexun and Sanbao Sags, including Qiuling–Wenjisang, Pubei–Yanmuxi, Shengbei–Honglian, Hongtai–Gedat, Qiquanhu–Shanle, Huoyanshan (the Mountain of Flames)–Kegitai, Lukeqin, Yilahu and Sidaogou. Twenty oil and gas fields have been discovered and proved, and the proved oil and gas equivalent is about 5.4×10^8 tons [23–25]. The proved rate of oil and gas resources in Taibei Sag is more than 40%, and the proved rate of remaining oil and gas resources in Permian is only 16.72%. The maturity of Taodonggou Group in Tainan sag is low, and the maturity of Taodonggou Group in Taibei Sag is mature (Figure 1), which has a strong hydrocarbon generation ability [26]. The maturity of the Taodonggou Group in the Tainan Sag is relatively low, and yet the Taodonggou Group in the Taibei Sag is mature and possesses a high hydrocarbon generation

capacity. The Permian Wutonggou Formation and the Triassic Karamay Formation are the main reservoir rocks for the lower petroleum system. The cap rocks are predominantly the Jurassic coal-forming rocks and mudstone (Figure 2) [27,28].

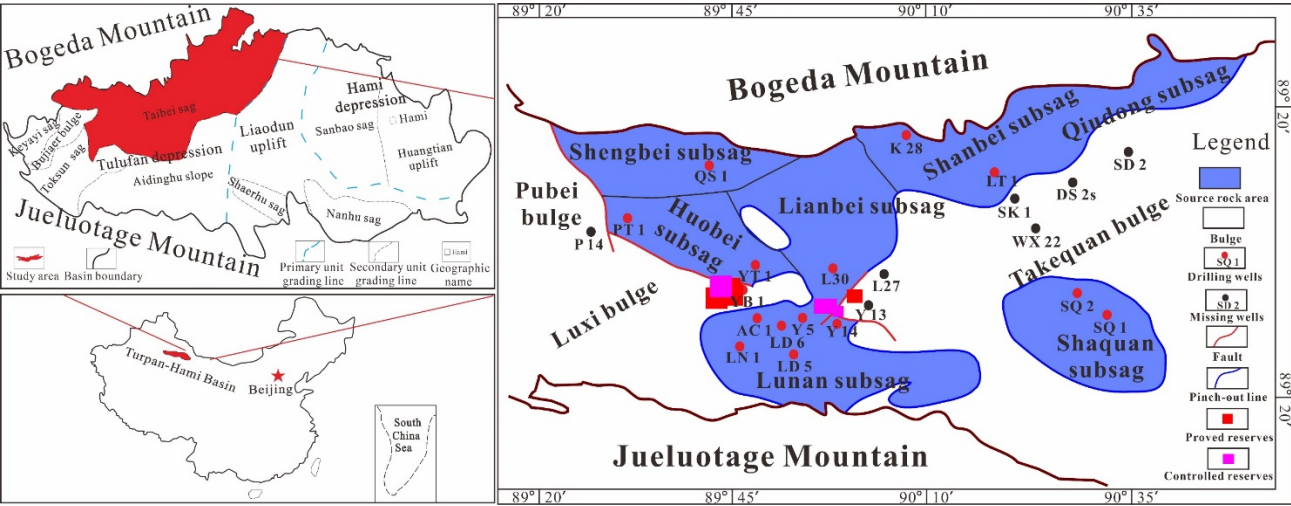


Figure 1. Location of the Taibei Sag and distribution of the Permian Taodonggou Group source rocks in the Turpan–Hami Basin.

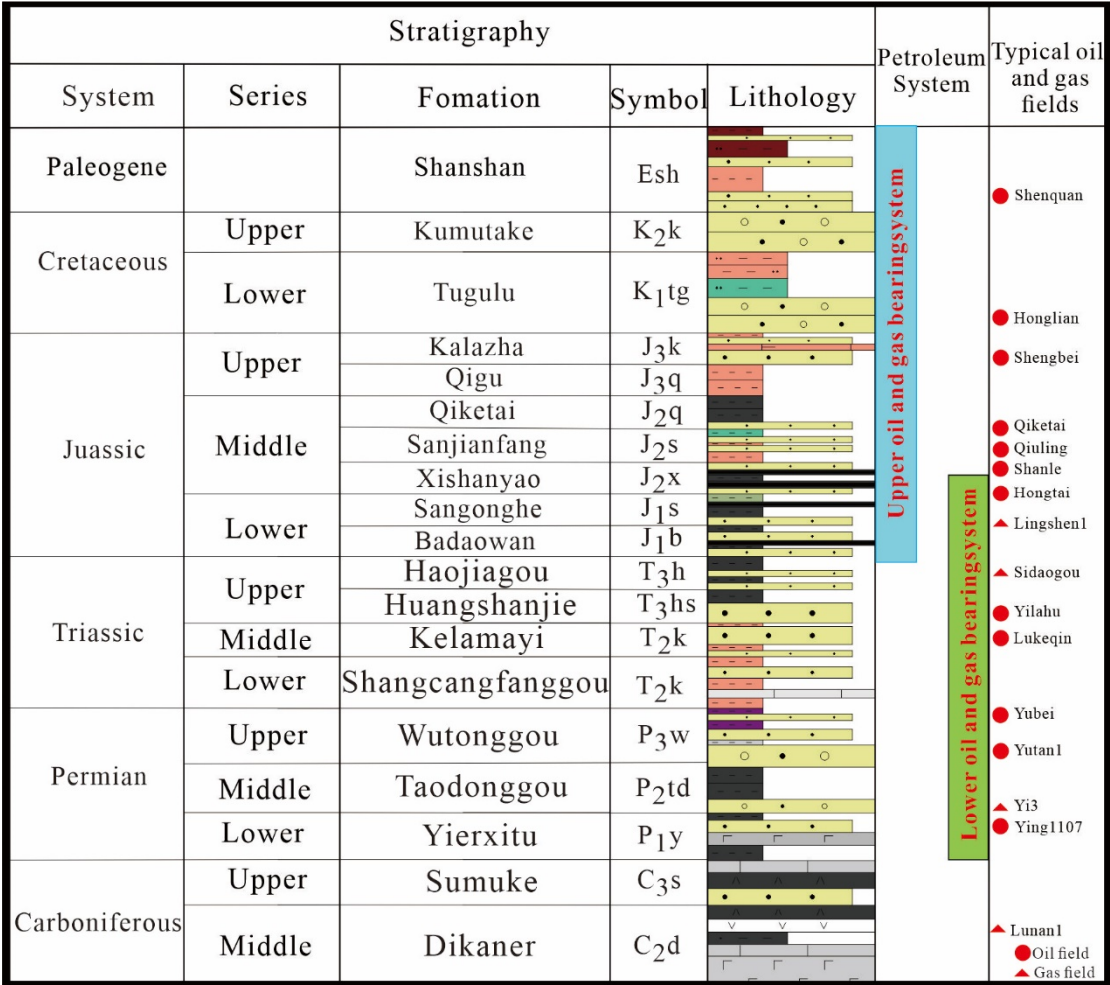


Figure 2. Stratigraphic column of the Turpan–Hami Basin.

3. Methodology

The data of this research included seismic data, well logging data and core data. Specifically, the well logs and geochemical data of eight wells and data of six two-dimensional (2D) seismic survey lines related to the wells of interest were incorporated. Numerous approaches have been developed to calculate the erosion thickness. Given the data of the study area, the erosion thickness was calculated mainly via the seismic horizon trend correlation approach, assisted by the mudstone interval transit time approach and the vitrinite reflectance approach [29,30].

The general strategy is shown as follows: The erosion thickness of each layer in a well was restored using the vitrinite reflectance approach and mudstone interval transit time approach. Then, with the known erosion thickness of a specific period for a well, the formation erosion thicknesses of other wells during the same period were inferred via the seismic stratigraphic trend correlation approach [31]. On the basis of the clarified conformity/unconformity and erosion types, the formation erosion thickness across the study area was restored by extending the trend of the formation erosion thickness [32].

3.1. Acoustic Interval Transit Time Approach

Formations are eroded, and yet the standard exponential correlation between the interval transit time of rocks and depth remains unchanged. Therefore, the corresponding profile can be fitted and plotted by analyzing the related interval transit time data. This method is suitable for the estimation of denudation thickness of unconformity surface with shallow burial depth and small denudation strength. Another premise of this approach is that the overburn pressure imposed on old formations by new sediments is lower than that before denudation, meaning that the compaction of formations below the unconformity remains the same [33,34].

3.2. Vitrinite Reflectance Approach

The principle of this method is based on the difference of vitrinite reflectance (R_o) between the upper and lower strata of the unconformity surface. The specific method is to make the stratum R_o line under the unconformity surface intersect with the unconformity surface and extend the line to the depth where the R_o value is equal to the bottom interface value of the underlying stratum. [35,36]. The difference in height is the erosion thickness (right in Figure 3). The R_o change between this point and the unconformity surface is discontinuous. This method is quantifiable and easy to perform, so it is widely used in erosion thickness restoration. However, Dow's vitrinite reflectance method ignores the influence of secondary burial, which is the factor affecting the vitrinite reflectance. Therefore, the calculated denudation thickness is the minimum denudation thickness of the formation [17–41].

3.3. Stratigraphic Trend Correlation Approach

Regionally, a specific sedimentary layer features a certain pattern in terms of its planar distribution of deposition thickness. As shown in Figure 4, wells in which the sedimentary layer is not denuded or the erosion thickness of this layer is easy to calculate, in accordance with drilling data and seismic data, are selected as the reference wells. Then, the formation erosion thickness is tracked and computed as per the stratigraphic trend. As long as a seismic profile is available, this approach is practicable, with high applicability and yet a flaw of high lateral variation of the calculation results [32,42–44]. In Figure 4, H_0-H_0' represents the erosion thickness in the B zone, and H_0-H , that in the C zone.

3.4. PetroMod Simulation Technique

One-dimensional PetroMod (Schlumberger/Aachen Technology Centre) was used to model the burial history and thermal history of Wells YT-1, LT-1, QS-1, L-30, SK-1, K-28, PT-1 and YB-1. Based on the wells, the process with which the sedimentary basin was modeled to reveal the laws governing the formation and evolution of oil and gas reservoirs and

guide hydrocarbon exploration [45]. The input data include the geochronology, formation thickness, erosion thickness, etc. The ages of sedimentary and denudation events were dated in accordance with the geological timescale developed by Zhou Wenhao and Wu Yanjie et al. [32,41].

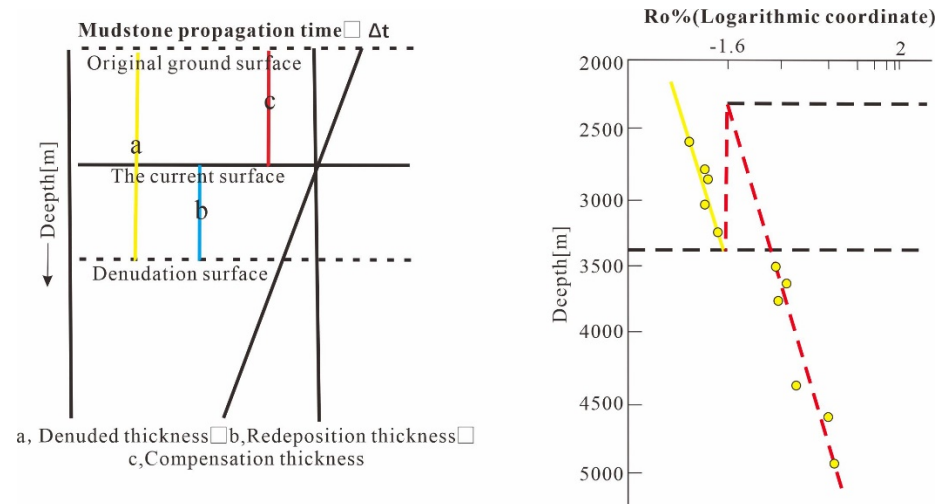


Figure 3. Mechanisms of the interval transit time approach (left) and Dow's vitrinite reflectance approach (right) to restore erosion thickness.

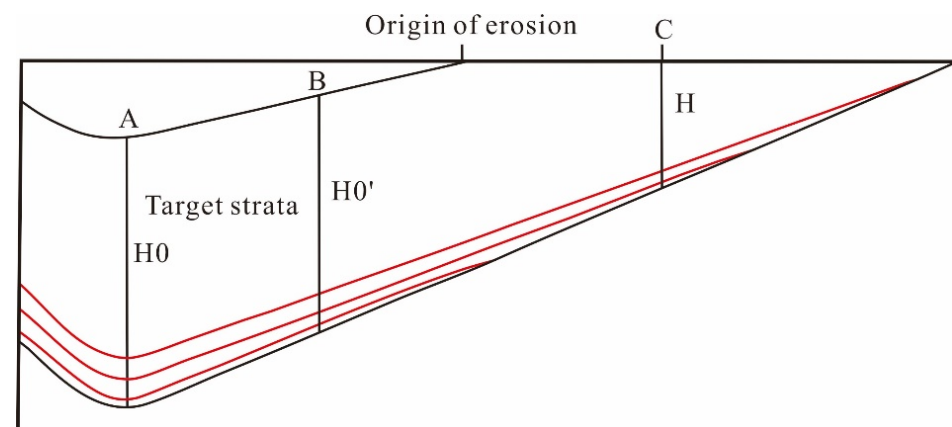


Figure 4. Mechanisms of the stratigraphic trend approach to restore erosion thickness.

The reliability of basin modeling results depends on the selection and input of key parameters. The inputs required by the model include the stratigraphy (lithology, thickness and age), tectonic events (unconformity, denudation and deposition interruption), source rock geochemistry (TOC, HI and hydrocarbon generation kinetic model) and boundary conditions (paleo-water depth, paleo-heat flow and water–rock interface temperature) [46,47].

4. Results

4.1. Restoration Results of Erosion Thickness

The Turpan–Hami Basin is found with three major events of uplift and denudation, namely the Late Indosinian (at the end of the Permian Period), Middle and Late Yanshanian (at the end of the Jurassic and Cretaceous Periods, respectively) and Himalayan (during the Mesozoic Era). These four tectonic movements occur in different locations and have different effects [40,48–50]. The process and results of the erosion thickness restoration are presented below:

The schematic diagrams illustrating the erosion thickness restoration process of some of the wells of interest are presented below. The restoration integrated the mudstone interval transit-time approach, vitrinite reflectance approach and stratigraphic trend approach [51].

Figure 5 shows how the formation erosion thickness is restored using the mudstone interval transit time approach and vitrinite reflectance approach. The erosion thickness of the Middle Yanshanian uplift for Well QS-1 is 200 m (Figure 5a), and the function of the fitting curve is $y = -1.92\Delta t + 1165$. The erosion thickness of the Early Himalayan uplift for Well L-30 is 449 m, and the function of the fitting curve is $y = -1.36\Delta t + 2292$ (Figure 5c). The erosion thickness of the Late Himalayan uplift for Well L-30 is 380 m, and the function of the fitting curve is $y = -2.5\Delta t + 1850$ (Figure 5d). The erosion thickness of the Late Himalayan uplift for Well K-28 is 466 m, and the function of the fitting curve is $y = -1.45\Delta t + 1004$ (Figure 5e). The erosion thicknesses of the Late and Early Himalayan uplift for Well LT-1 are 174 m and 279 m, respectively, and the corresponding functions of the fitting curves are $y = -0.9\Delta t + 732$ and $y = 0.85\Delta t + 1408$ (Figure 5f,g). As per Zhou Wenhao, the interval transit time, Δt , for the uncompacted mudstone in the Taibei Sag is $620 \mu\text{m/s}$. For Well PT-1, the vitrinite reflectance approach was used to calculate the erosion thickness attributed to the Middle Yanshanian uplift (Figure 5b)—the calculated erosion thickness is 402 m, and the function of the fitting curve is $y = 1193.1\text{Ln}(\text{Ro}) + 4816.2$. Similarly, for Well SK-1, the erosion thickness of the Late Indosinian uplift is estimated to be 1129 m, and the function of the fitting curve is $y = 500\text{Ln}(\text{Ro}) + 4520$.

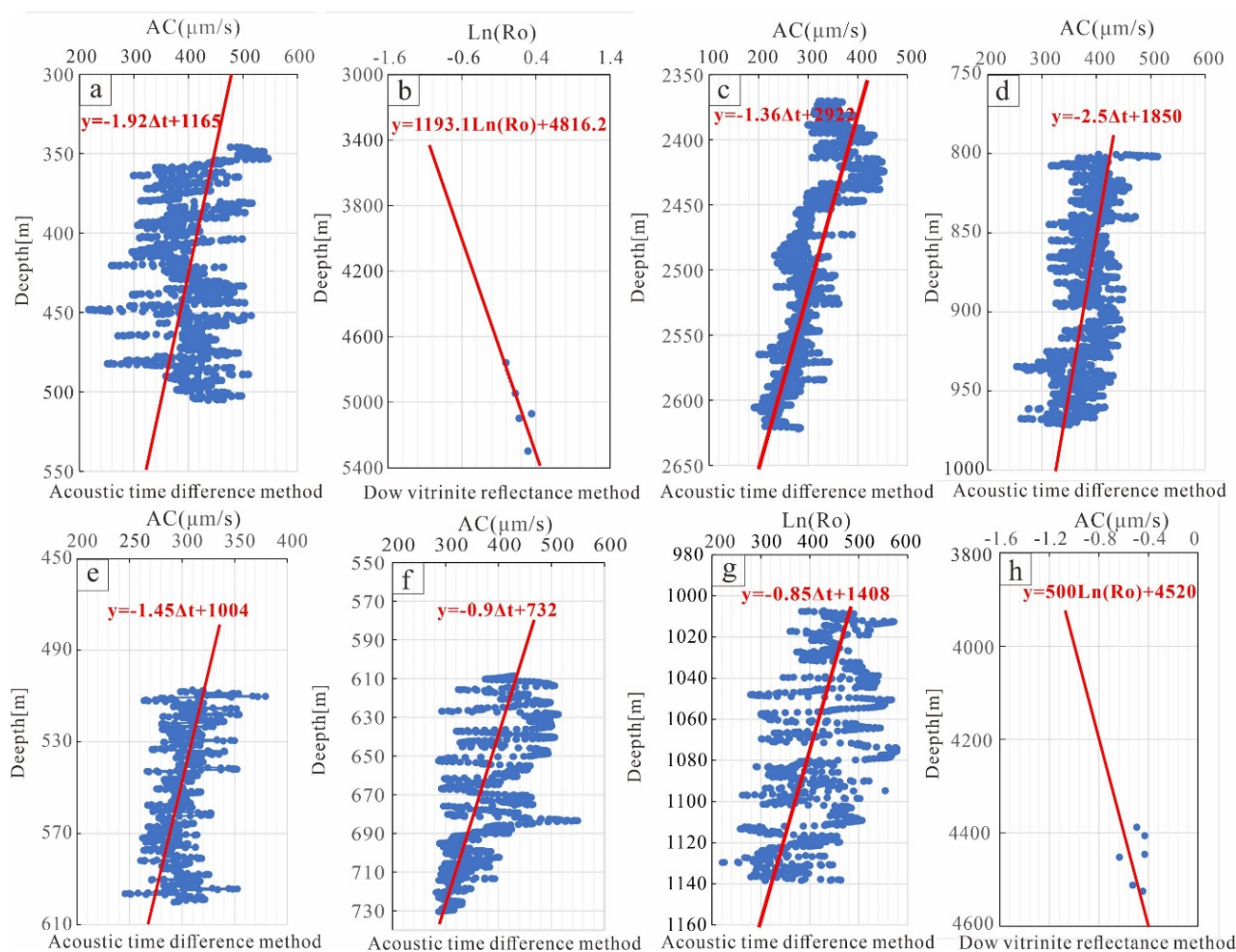


Figure 5. Schematic diagram of restoring the formation erosion thickness via the interval transit time and vitrinite reflectance approaches. (Images were changed in regard to font and clarity.). (a) The erosion thickness of the Middle Yanshanian uplift for Well QS-1 is 200 m. (b) For Well PT-1,

the vitrinite reflectance approach was used to calculate erosion thickness is 402 m. (c) The erosion thickness of the Early Himalayan uplift for Well L-30 is 449 m. (d) The erosion thickness of the Late Himalayan uplift for Well L-30 is 380 m. (e) The erosion thickness of the Late Himalayan uplift for Well K-28 is 466 m. (f,g) The erosion thicknesses of the Late and Early Himalayan uplift for Well LT-1 are 174 m and 279 m, respectively. (h) For Well SK-1, the erosion thickness of the Late Indosinian uplift is estimated to be 1129 m.

Figure 6 illustrates how the formation erosion thickness is restored via the seismic stratigraphic trend correlation approach. Figure 6a is the seismic profile across Well PT-1 (north) to Well YT-1 (south). As the erosion thickness of the Middle Yanshanian uplift for Well PT-1 is known to be 402 m, that of Well YT-1 is estimated to be 499 m. Similarly, for the Late Yanshanian uplift, the erosion thickness of Well PT-1 is 595 m, and that of Well YT-1 is thus estimated to be 450 m. The north–south seismic profile across Well K-28 (projection)–LT-1 (projection)–SK-1 (projection) is shown in Figure 6b. The erosion centers of both the Triassic and Cretaceous are located in the proximity of Well Lingtan-1, and the formations thicken toward both the north and south. Nonetheless, the deposition center of the Jurassic is located at Well Lingtan-1, and the formation thins toward the northern piedmont zone and Well SK-1 (in the south). Accordingly, for the Late Indosinian uplift, the erosion thicknesses along Wells SK-1–LT-1–K-28 are 1129 m (reference well), 1223 m and 958 m, respectively. For the Middle Yanshanian uplift, the erosion thicknesses along Wells SK-1–LT-1–K-28 are 1124 m (reference well), 918 m and 1002 m, respectively. For the Late Yanshanian uplift, the erosion thicknesses along Wells LT-1–SK-1–K-28 are 620 m, 578 m (reference well) and 525 m, respectively. Figure 6c represents a north–south seismic profile along Wells YT-1 (projection)–YB-1. For the Late Indosinian uplift, the erosion thicknesses on the northern and southern sides of the Mountain of Flames (Huoyanshan) are consistent. The erosion thickness of Well YT-1 at this time is 988 m, while that of Well Yubei-1 is 1024 m. For the Middle Yanshanian uplift, the erosion thickness is higher on the southern side of the Mountain of Flames, and the Kalazha Formation is completely denuded. At this time, the erosion thickness of Well YT-1 is 499 m, and that of Well Yubei-1 is 743 m. For the Late Yanshanian uplift, the formations thin southward from the Mountain of Flames, and, therefore, the erosion thickness is increased. At this time, the erosion thickness of Well Yutan-1 is 450 m (reference well), and that of Well Yubei-1 is estimated to be 721 m.

The planar differentiation of the erosion thickness during different tectonic events of the Taibei Sag is shown in Figure 7. During the Late Indosinian movement, the formation erosion across the Taibei Sag was characterized by low intensity in the north and high intensity in the south and low intensity in the east and high intensity in the west. The average erosion thickness of the Shanbei area is up to over 1000 m. For the Middle Yanshanian uplift, the formation erosion across the Taibei Sag is generally weak in the east and strong in the west. The erosion thicknesses of the Shengbei and Huobei sub-sags are lower than 500 m, while those of the Lianbei and Shanbei sub-sags are above 700–1000 m. During the Late Yanshanian movement, the formation erosion across the Taibei Sag was intensive in the southern and northern parts, and it was relatively weak in the central sag. At this time, the formation erosion in the southern sag is stronger than that in the northern sag. For the Early Himalayan movement, the erosion thickness was small across the Taibei Sag, on an overall basis. The formation erosion also features high intensities in the southern and northern parts and low intensity in the central parts of the sag. Except for the piedmont zone, the erosion thicknesses are all below 550 m. During the Late Yanshanian movement, the erosion thickness was generally small across the Taibei Sag and characterized by high values in the east and low values in the west. The erosion thickness of the study area is 100–500 m at this time.

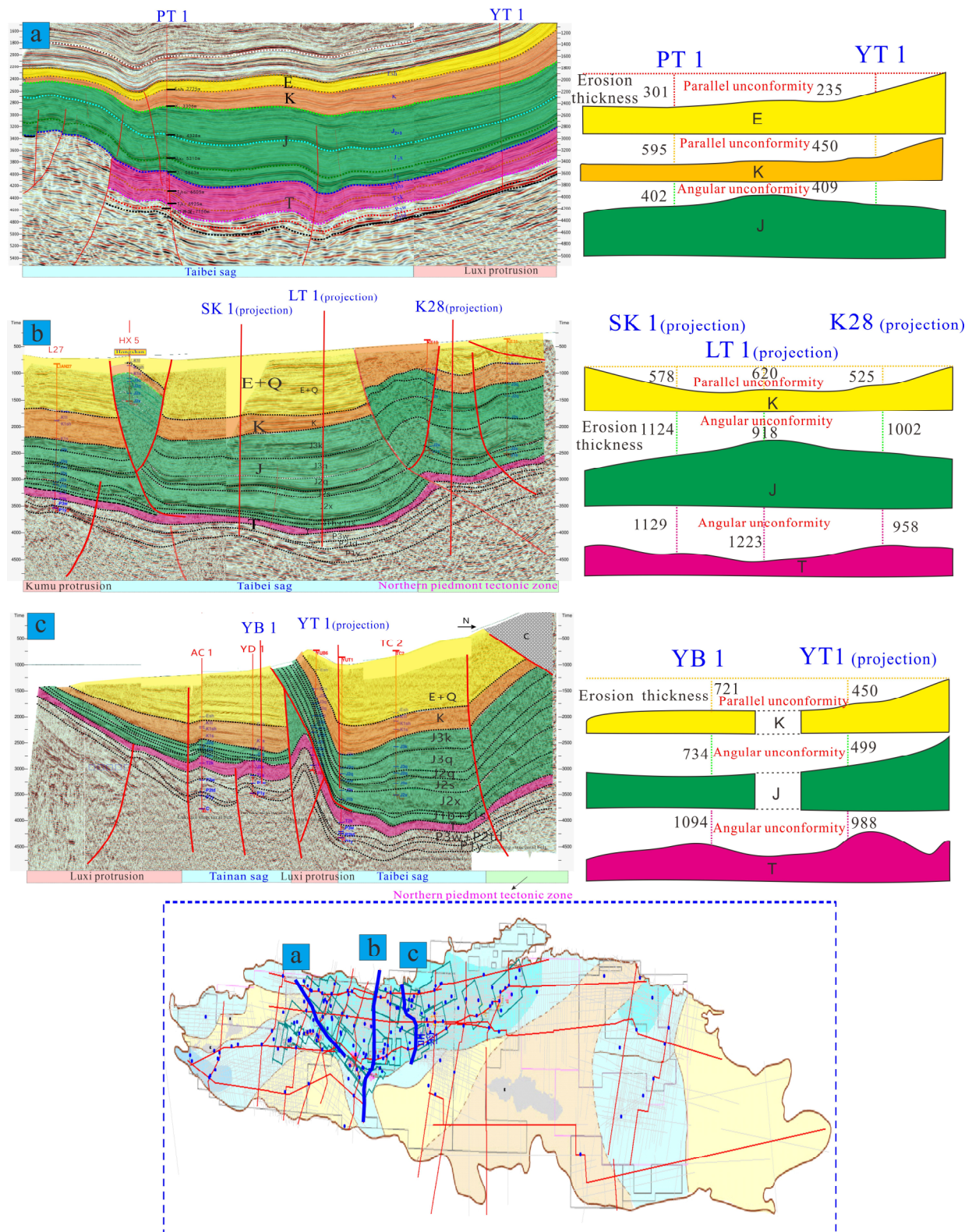


Figure 6. Schematic diagram of restoring the formation erosion thickness across the Taipei Sag via the stratigraphic trend approach. (Images were changed in regard to font and clarity.). (a) Seismic profiles of PT 1 and YT 1 Wells were passed. (b) Seismic profiles of SK 1 (Projection) and K 28 (Projection) Wells were passed. (c) Seismic profiles of YB 1 and K 28 (Projection) Wells were passed.

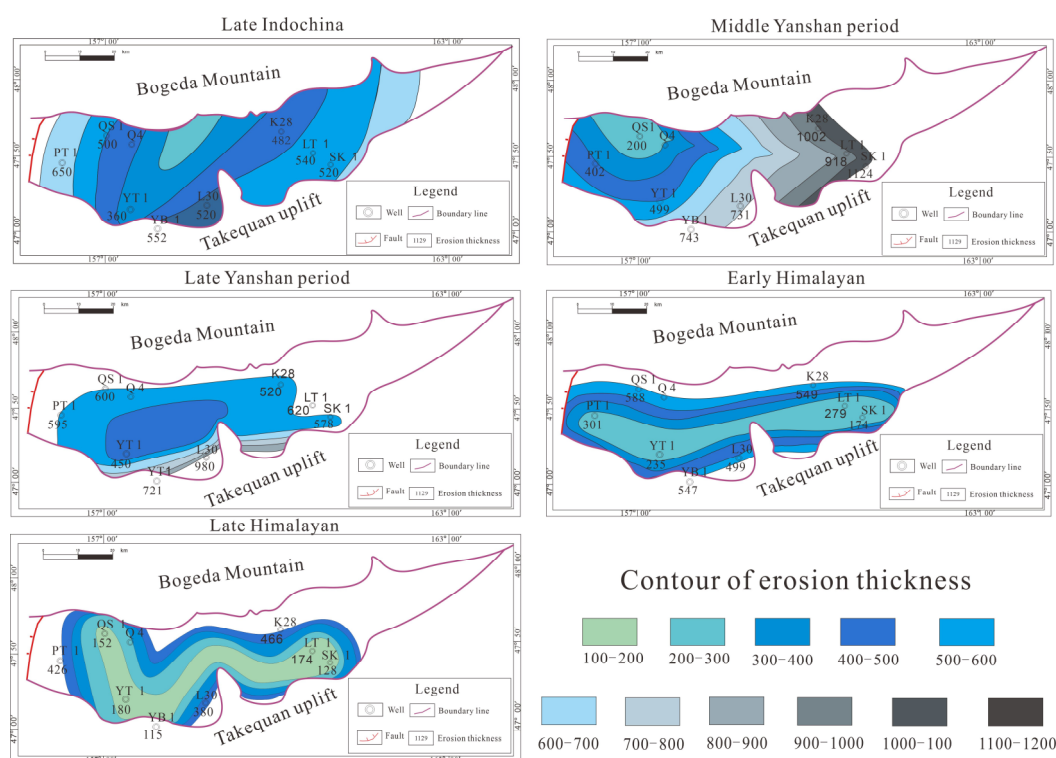


Figure 7. Planar differentiation of erosion thickness across the Taibei Sag during different tectonic events.

4.2. Burial History

The burial history refers to the burial depth variation of sequences/layers in a sedimentary unit or a series of units from the beginning of the sedimentation to now or within a specific geological period. It includes events such as deposition interruption denudation and faulting [48,52,53]. In this research, the back-stripping approach available in the PetroMod software was used for the modeling and restoration of the basin's burial history. The back-stripping technique, based on the sedimentation and compaction theory, is commonly applicable to formations of normal compaction. In accordance with the stratigraphic parameters of wells, it incorporates the effects of geological events such as compaction, over-pressurization, uplift and denudation and faulting, and it restores the formation thickness, layer by layer, up toward to the surface for each geological historic period. Finally, the profile between the geological age and burial depth in wells is obtained. The burial history was reconstructed using the 1D PetroMod simulator, and the necessary inputs are stated above. The modeling results of eight wells in different sub-sags are shown below (Figure 8).

4.3. Thermal History

Thermal history is a very important concept in the field of geology, especially for basin modeling, as it affects hydrocarbon generation. The precision of the thermal history restoration is of utmost importance for understanding hydrocarbon generation. The investigation of the structural–thermal evolution of a basin reveals the characteristics of the geothermal field of the basin at different evolution stages and also effectively constrains the kinetics and structural attributes of the basin during a specific geological evolution stage [18,45]. Previous studies have constituted a thorough study and presentation of the thermal history of the Turpan–Hami Basin. The characteristics of the geothermal field and thermal evolution pattern are basically clarified. It is indicated that the Turpan–Hami Basin has been cooling down since the Carboniferous Period, which is vital for restoring the thermal history of the basin [17,41,49,54,55].

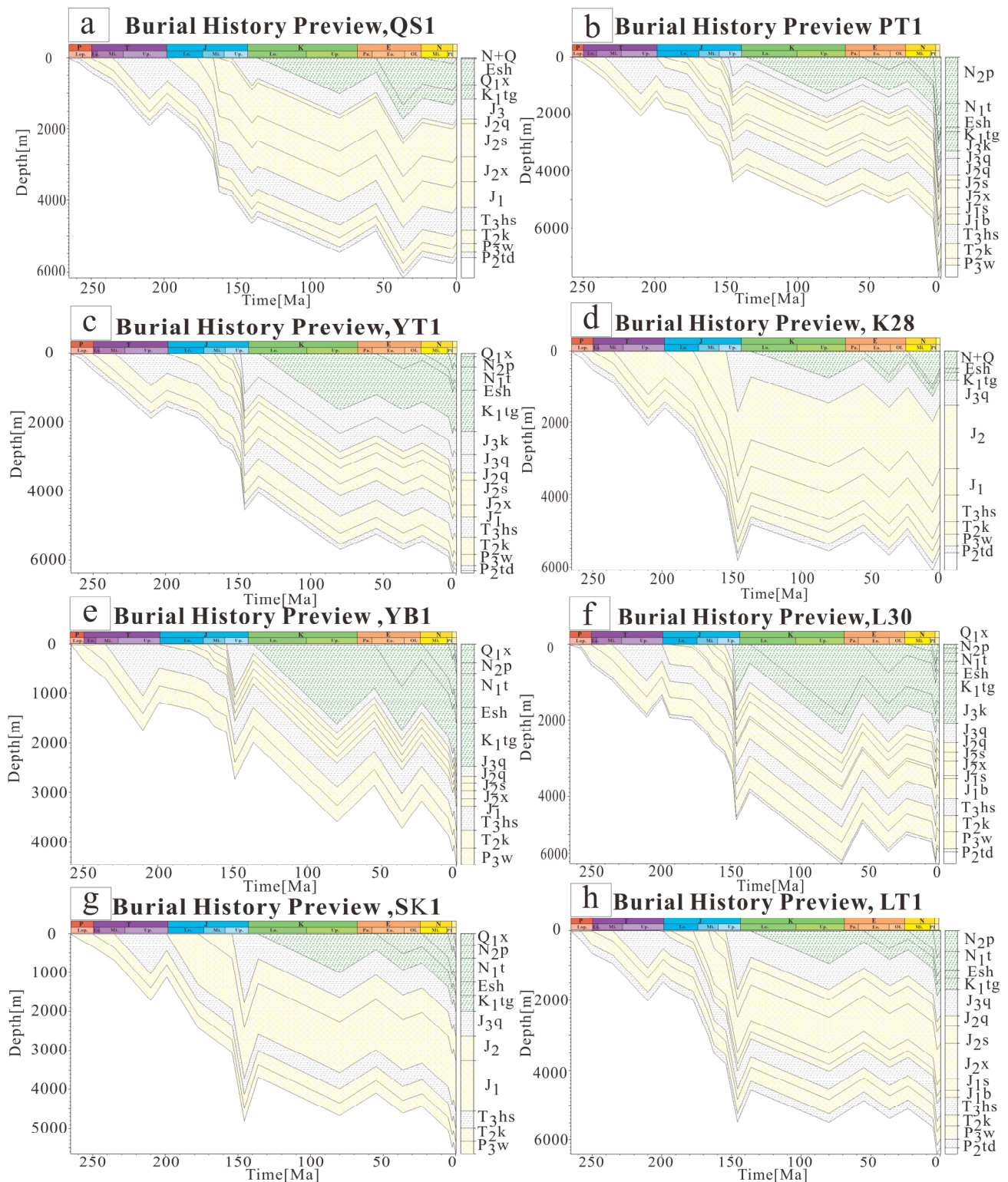


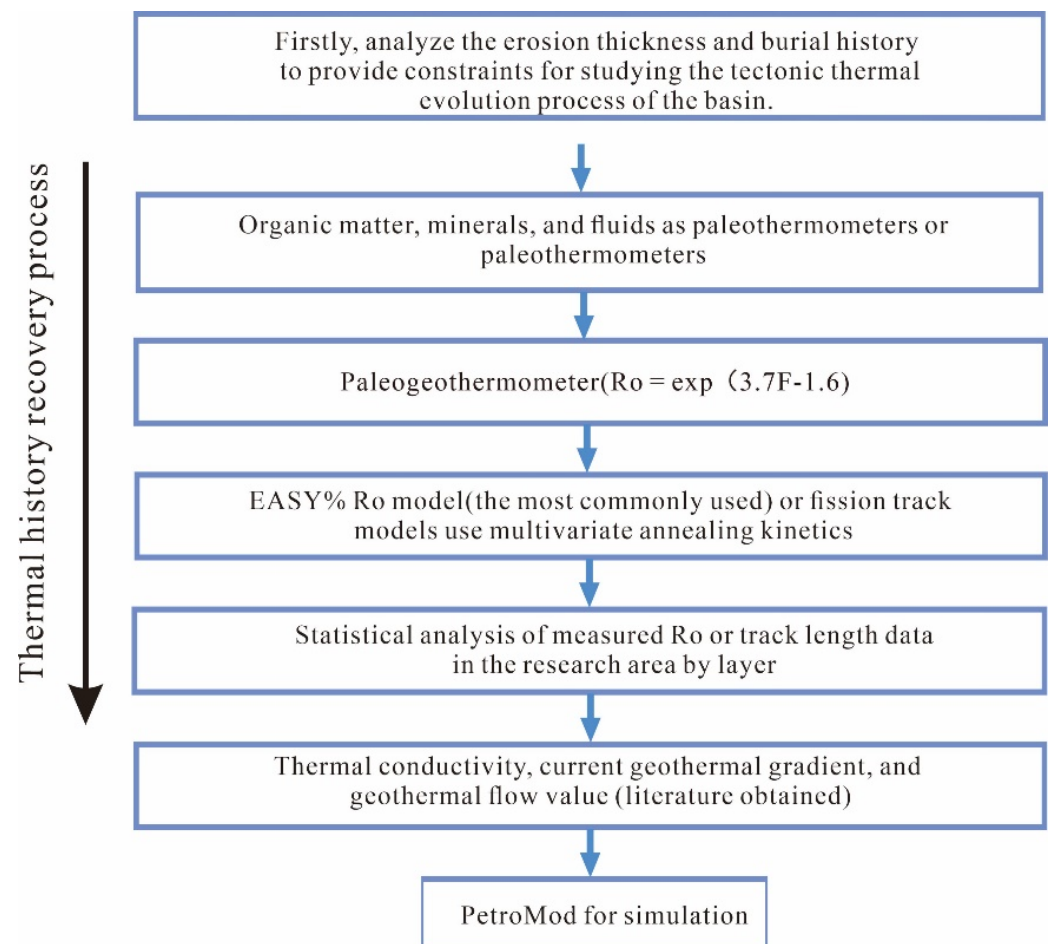
Figure 8. Reconstructed burial history of wells in the Taibei Sag. (a) burial history, QS 1. (b) burial history, PT 1. (c) burial history, YT 1. (d) burial history, K 28. (e) burial history, YB 1. (f) burial history, L 30. (g) burial history, SK 1. (h) burial history, LT 1.

Table 1 summarizes the values of heat flow (densities) in different sags of the Turpan Depression of the Turpan–Hami Basin during different periods. This is based both on previous studies and the findings of this study.

Table 1. Earth heat flow in three major sags of the Turpan–Hami Basin [36] (modified from Chen et al.).

Formation	Heat Flow (mW/m ²)			Time (Ma)
	Toksun	Taibei	Hami	
R + Q (Cenozoic)	29.98	34.50	39.45	65
K (Cretaceous)	34.92	36.48	42.52	140
J ₃ (Upper Jurassic)	32.72	38.44	40.18	154
J ₂ (Middle Jurassic)	38.64	42.81	40.76	175
J ₁ (Lower Jurassic)	39.59	43.76	40.76	203
T (Triassic)	39.78	44.64	45.28	240
P (Permian)	41.08	52.4–56	46.30	260

The workflow to reconstruct the thermal history is presented below (Figure 9). The heat flow (density) is a comprehensive thermal parameter representing the regional geothermal status and defined as the heat released from a unit area of the Earth’s surface per unit time [56–58].

**Figure 9.** Workflow of thermal history restoration.

The Figure 10 is the simulation results of thermal history of typical single wells in different sub-sags:

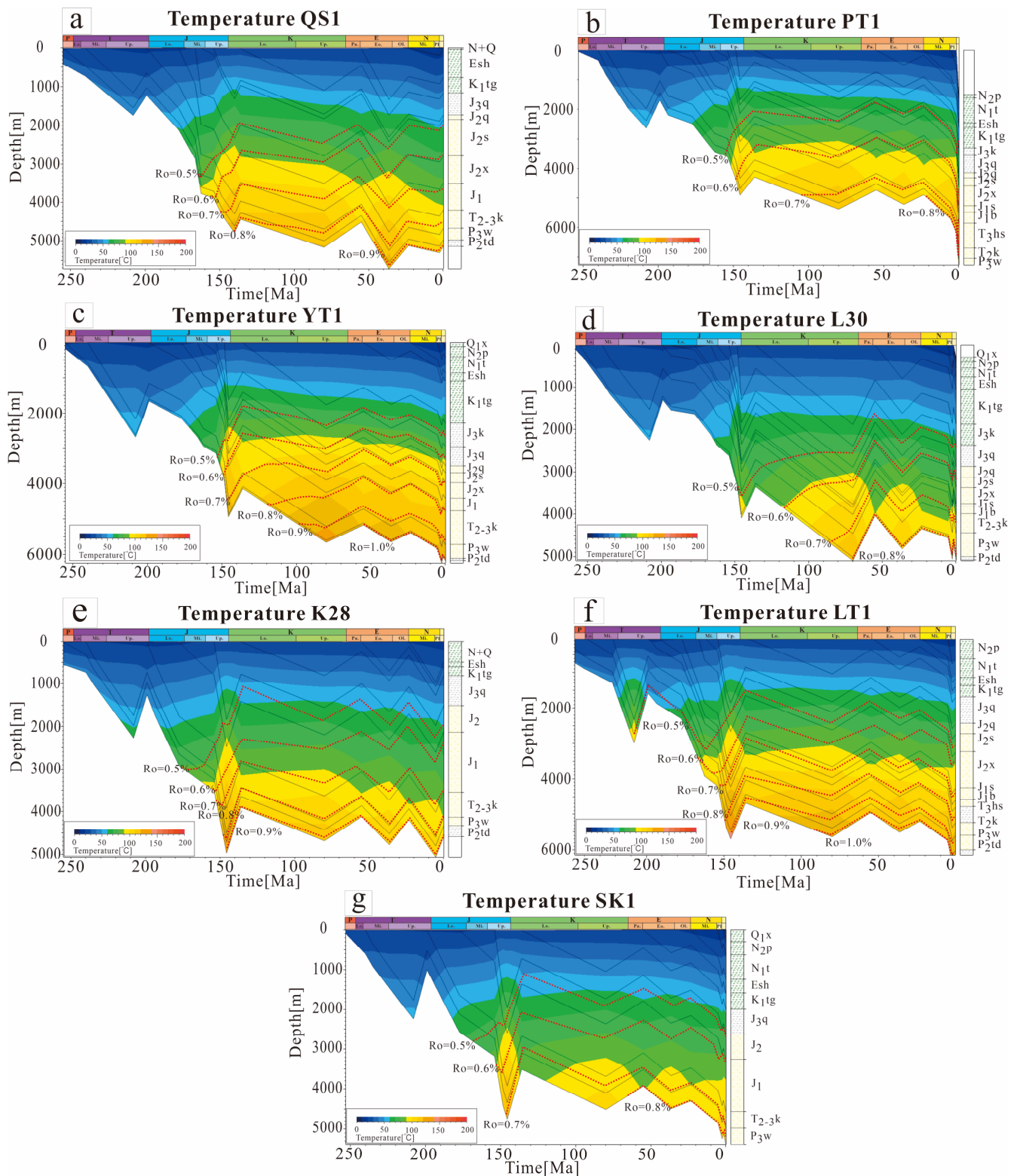


Figure 10. Thermal history of representative wells in the Taibei Sag, reconstructed by PetroMod. (a) thermal history, QS 1. (b) thermal history, PT 1. (c) thermal history, YT 1. (d) thermal history, L 30. (e) thermal history, K 28. (f) thermal history, LT 1. (g) thermal history, SK 1.

Figure 11 shows the comparison and verification of single-well geothermal–thermal simulation results and measured maturity in the Shengbei, Huobei, Lianbei and Shanbei sub-sags of Taibei Sag. Among them, the fitting results of the PT-1 Well, K-28 Well, LT-1

Well and SK-1 Well are good, and the fitting results of the QS-1 Well, YT-1 Well and L-30 Well are good. This shows the reliability of the fitting results.

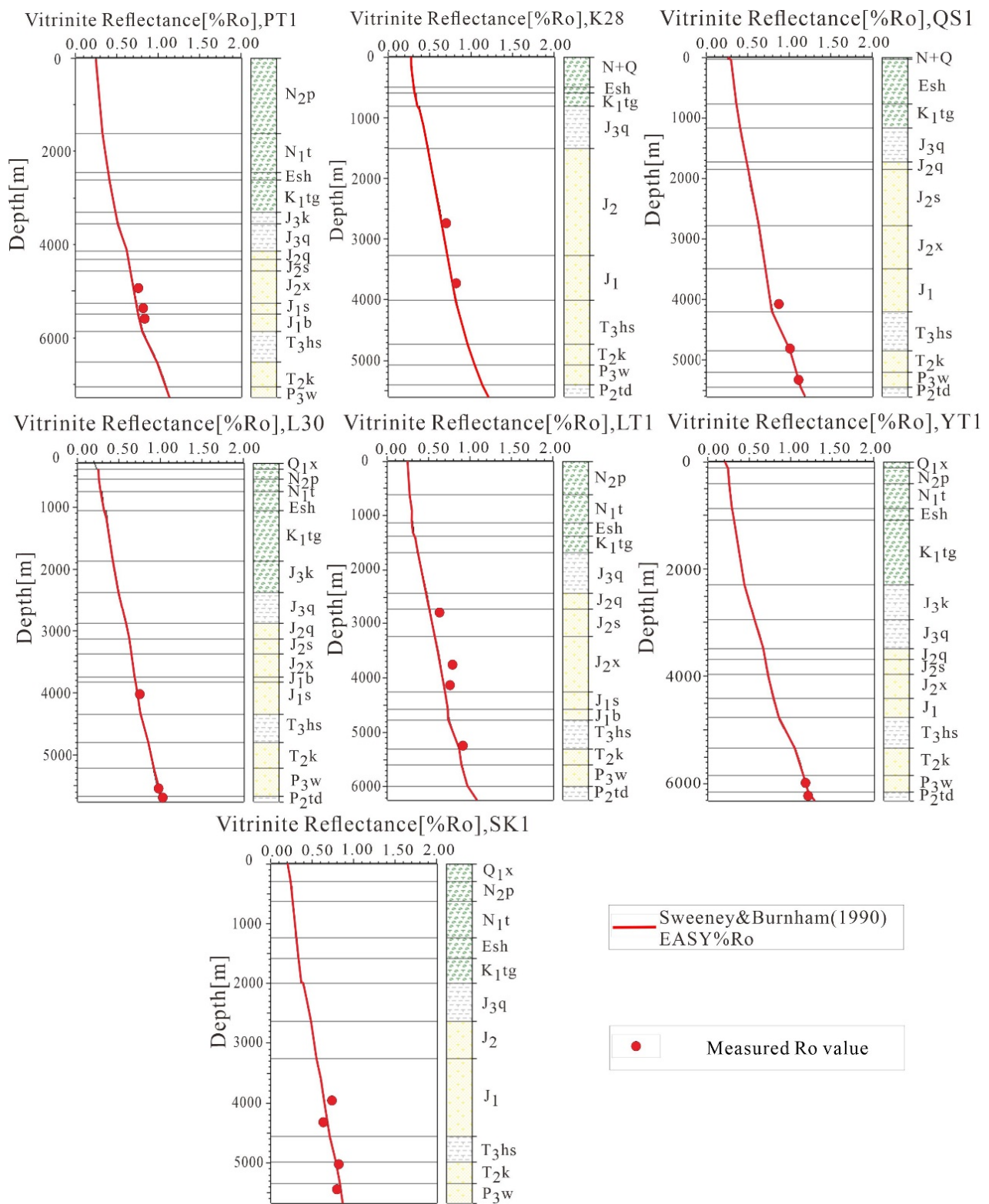


Figure 11. The thermal simulation results of single-well maturity in the study area are compared with the measured maturity.

5. Discussion

5.1. Differentiation of the Burial–Thermal History among Different Sub-Sags

As indicated by Figure 10, the burial history across the Turpan–Hami Basin is fairly identical, with the exception of slight differences. However, the burial history of each sub-sag is differentiated, compared with that of another. With respect to the spatial scale, this research clarifies the characteristics of the burial–thermal history differentiation among different sub-sags in the Turpan–Hami Basin. The formation subsidence and erosion rate can be derived from the slope of the burial plot. Since the Mid–Late Permian epoch, the Taibei Sag has been through several tectonic periods, namely the Late Hercynian, Early Indosinian, Late Indosinian, Yanshanian and Himalayan movements. It should be noted that the effects of the Late Hercynian and Early Indosinian tectonic uplift on the Taibei Sag can be neglected [33,48,50]. Well QS-1 represents the Shengbei sub-sag; Wells PT-1 and YT-1 represent the Huobei sub-sag; Well L-30 represents the Lianbei sub-sag; and Wells K-28, LT-1 and SK-1 represent the Shanbei sub-sag.

5.1.1. Shengbei Sub-Sag

The Shengbei sub-sag is located in the Northwestern Taibei Sag and is represented by Well QS-1. From the deposition of the Permian Taodonggou Group to the Late Indosinian movement, the study area subsided constantly (Figure 10a). During this period, the deposition rate of the Shengbei sub-sag was 30 m/Myr, and the uplift rate during the Late Indosinian movement was 55 m/Myr. From the end of the Late Indosinian movement to the Middle Yanshanian movement, the study area subsided rapidly, and it received ultra-thick sediments during the Jurassic Period. The sediments in the Taibei Sag reach about 5000 m in thickness, and the deposition center is located at the Shengbei sub-sag near the northern piedmont zone (Figure 6). The southern part has evolved into a slope dipping northward since the Indosinian movement. During this period, the deposition rate of the Shengbei sub-sag is about 85 m/Myr, and the uplift rate is 70 m/Myr. Figure 10a shows that the source rocks of the Permian Taodonggou Group in the Shengbei sub-sag became mature ($R_o = 0.5\%$) at about 163 Ma and started early oil generation, corresponding to the threshold depth of about 3500 m. From the end of the Middle Yanshanian movement to the Late Yanshanian movement, the deposited formations were mainly the Cretaceous Tugulu Group and Kumutake Formation. Due to the Late Yanshanian movement, the Kumutake Formation in the Taibei Sag was almost completely denuded, and a part of the Tugulu Group was also eroded. During this period, the deposition rate of the Shengbei sub-sag was about 12 m/Myr, the uplift rate was 25 m/Myr and the deposition rate of the piedmont zone was slightly lower than that of the southern zone. From the end of the Late Yanshanian movement to the Cenozoic Early Himalayan movement, the deposited formations were mainly the coarse-grained clastic rocks of the Paleogene Shanshan Group, with an average total thickness of about 400–700 m. Yet, about 150–550 m of the Shanshan Group was eroded due to the Early Himalayan movement. The erosion intensity varies in different sub-sags. During this period, the deposition rate of the Shengbei sub-sag was about 60 m/Myr, and the uplift rate was about 40 m/Myr. The maturity of the organic matter of the Permian Taodonggou Group in the Shengbei sub-sag reached 0.9%, indicating the arrival of the medium maturation stage. From the Early Himalayan movement to the Late Himalayan movement, the sandstone and sandy mudstone of the Taoshuyuan Formation and the mottled conglomerate of the Putaogou Formation were deposited. Then, the alluvial conglomerates of the Quaternary Xiyu Formation were deposited in a differentiated way after the Late Yanshanian tectonic movement; during this period, the deposition rate of the Shengbei sub-sag was about 10 m/Myr, and the uplift rate was 40 m/Myr.

5.1.2. Huobei Sub-Sag

The Huobei sub-sag is located in the Southwestern Taibei Sag and is represented by Wells YT-1 and PT-1. The regional structural evolution history is characterized using the drilling data and modeling results. As shown in Figure 8b,c and Figure 10b,c, the study

area subsided continuously after the deposition of the Permian Taodonggou Group and up until the occurrence of the Late Indosinian movement, after which the study area uplifted. During this period, the deposition rate of the Huobei sub-sag was 45–50 m/Myr, and the uplift rate was 110 m/Myr. Well YB-1 lies in the southern part of the Huobei sub-sag and shows a deposition rate of over 55 m/Myr and an uplift rate of 150 m/Myr. Therefore, in view of the whole Huobei sub-sag, the deposition and uplift rates are both larger in the southern part, representing a deeper water depth and more intensive uplift of the lake basin during this deposition period. From the end of the Late Indosinian movement to the Middle Yanshanian movement, specifically during the Jurassic rapid subsidence, the deposition rate of the Huobei sub-sag was about 75–80 m/Myr, and the uplift rate was 80 m/Ma. For Well YB-1 in the Southern Huobei sub-sag, the deposition rate is lower than 40 m/Myr, and the uplift rate is 60 m/Myr. The Permian Taodonggou Group source rocks in the Huobei sub-sag became matured ($R_o = 0.5\%$) at 153 Ma and entered the early oil generation stage, corresponding to the threshold depth of about 3200–3500 m. From the end of the Middle Yanshanian movement to the Late Yanshanian movement, the deposition rate of the Huobei sub-sag was about 25 m/Myr, and the uplift rate during the Late Yanshanian movement was 30–40 m/Myr. From the end of the Late Yanshanian movement to the Cenozoic Early Himalayan movement, the deposition rate of the Huobei sub-sag was about 25 m/Myr, and the uplift rate was 25–40 m/Myr. From the end of the Early Himalayan movement to the Late Himalayan movement, the deposition rate of the Huobei sub-sag was about 41 m/Myr, and the uplift rate during the Late Himalayan movement was 80–100 m/Myr.

5.1.3. Lianbei Sub-Sag

The Lianbei sub-sag lies in the Central Taibei Sag and is represented by Well L-30. The study area constantly subsided from the deposition of the Permian Taodonggou Group to the Late Indosinian movement, and the Lianbei, Huobei and Shengbei sub-sags share the same sedimentary history (Figures 8f and 10d). During this period, the deposition rate of the Lianbei sub-sag was about 45 m/Myr, and the uplift rate attributed to the Late Indosinian movement is 100 m/Myr. After the Late Indosinian movement, the study area started to receive sediments again. From the re-deposition to the Middle Yanshanian movement, the deposition rate of the Lianbei sub-sag was about 50 m/Myr, and the uplift rate attributed to the Middle Yanshanian movement is 67 m/Myr. Moreover, the Permian Taodonggou Group source rocks in the Lianbei sub-sag reached the mature stage ($R_o = 0.5\%$) 148 Ma and started early oil generation, corresponding to a threshold depth of about 3250 m. From the end of the Middle Yanshanian movement to the Late Yanshanian movement, the deposition rate of the Lianbei sub-sag was about 25 m/Myr, and the uplift rate during the Late Yanshanian movement was about 20 m/Myr (suggesting a slow uplift process). From the Late Yanshanian movement to the Cenozoic Early Himalayan movement, the deposition rate of the Lianbei sub-sag was about 30 m/Myr, and the uplift rate attributed to the Early Himalayan movement is 40 m/Myr. At this time, the organic matter maturity of the Permian Taodonggou Group source rocks in the Lianbei sub-sag reached 0.8%–1.0%; in other words, the source rocks entirely entered the medium mature stage. From the end of the Early Himalayan movement to the Late Himalayan movement, the deposition rate of the Lianbei sub-sag was about 30 m/Myr, and the uplift rate was 80 m/Myr.

5.1.4. Shanbei Sub-Sag

The Shanbei sub-sag is located in the Eastern Taibei Sag and is represented by Wells K-28, LT-1 and SK-1 in this research. The regional structural evolution was characterized using the drilling data and modeling results. Since the deposition of the Permian Taodonggou Group, the study area continuously subsided until the Late Indosinian movement. The deposition rate in the Shanbei sub-sag is 35–55 m/Myr, and the rate gradually grows from north to south. The uplift rate during the Late Indosinian was 100–140 m/Myr in the Shanbei sub-sag, and this rate, on the contrary, declines from north to south. The period from the end of the Late Indosinian movement to the Middle Yanshanian movement was

characterized by the rapid subsidence during the Jurassic period, in which the deposition rate of the Shanbei sub-sag was 60–75 m/Myr. The uplift rate of the Middle Yanshanian movement was 20–100 m/Myr, and the uplift rate of the piedmont zone was far lower than that of the southern part. The Permian Taodonggou Group source rocks in the Shanbei sub-sag near the piedmont zone became mature about 172 Ma, when they started early oil generation. The corresponding threshold depth is about 2200 m. From the end of the Middle Yanshanian movement to the Late Yanshanian movement, the deposition rate of the Shanbei sub-sag was 12–18 m/Myr, and the deposition rate of the piedmont zone was slightly lower than the southern part of the Shanbei sub-sag. The uplift rate of the Late Yanshanian movement is 20–25 m/Myr. From the end of the Late Yanshanian movement to the Cenozoic Early Himalayan movement, the deposition rate of the Shanbei sub-sag is 24–40 m/Myr, and the uplift rate is 19–45 m/Myr. From the end of the Early Himalayan movement to the Late Himalayan movement, the deposition rate of the Shanbei sub-sag was 30–45 m/Myr, and the uplift rate was 40–60 m/Myr.

5.1.5. Summary

The differentiation characteristics of the burial and structural evolution are investigated for the different sub-sags of the Taibei Sag with respect to the spatial scale and periods of time. During the Triassic Period, the deposition rate was generally higher in the Southern Taibei Sag than in the northern sag. During the Middle Yanshanian movement, the deposition rate of the Taibei Sag was higher in the north than in the south, and also higher in the east than in the west. The maturation time of the Taodonggou Group source rocks is also differentiated. The organic matter maturity of source rocks is subjected to the joint effects of sediment deposition, subsidence, temperature and pressure; thus, the maturation history of source rocks is varied in different regions. On an overall basis, the Taodonggou Group source rocks reached the mature stage during the Mid–Late Jurassic epoch. Nonetheless, those in the central–southern part of the Shanbei sub-sag in the Eastern Taibei Sag, represented by Well LT1, became mature during the Late Triassic epoch, because the geothermal gradient in the Eastern Taibei Sag is higher than that in the western sag and accelerates the maturation of the Taodonggou Group in the Shanbei sub-sag in the east. During the Late Yanshanian movement, the deposition rate in the Northern Taibei Sag was lower than that in the southern sag. The Taibei Sag largely reached the maximum temperature of formations during the Cretaceous period, and the formation temperature gradually declined due to the subsequent Late Yanshanian movement. The maximum formation temperature of the Shanbei sub-sag, represented by Wells K-28, LT-1 and SK-1, is about 150 °C. The maximum formation temperature of the Lianbei, Huobei and Shengbei sub-sags in the west of the Shanbei sub-sag is 120 °C–140 °C. Before the Late Yanshanian uplift, the vitrinite reflectance of the Taodonggou Group source rocks in the Taibei Sag is commonly 0.7 Ro%–1.2 Ro%, and these source rocks are already mature. The Taodonggou Group source rocks in the Shanbei sub-sag generally have higher maturity. During the Early Himalayan movement, the deposition rate in the Western Taibei Sag is higher than that in the eastern sag, while the uplift rate across the sag averages about 40 m/Myr. It is indicated that the Taibei Sag welcomes rapid burial as the Cenozoic Era comes, and the subsequent Early Himalayan movement is associated with commonly small erosion thicknesses. The erosion thicknesses are rather large, over 500 m, on the southern and northern sides of the Taibei Sag, which may be related to the activity of the Bogeda Mountain. The Himalayan structural adjustment since the Cenozoic Era results in complicated faulting of formations and the fault-block structural style. This, on the one hand, may re-adjust the existing oil and gas reservoirs; and, on the other hand, it can cause the escape of hydrocarbons, thus greatly increasing the risks and difficulties for hydrocarbon exploration in this basin [48,59–61]. The intensity of the Late Himalayan movement is generally low in the Taibei Sag, and yet intensive uplift and erosion occur locally, with the erosion thicknesses all above 400 m. Nearer to the piedmont zone, fewer, if any, Quaternary sediments deposit, which leads to high difficulties of well logging identification. This demonstrates the intensive adjustment

of the piedmont zone by the Himalayan movement, which may be directly attributed to the southward thrusting of the Bogeda Mountain [45,51]. In other words, the eastern part of the Huobei sub-sag and the northern piedmont zone of the Shanbei sub-sag are highly adjusted by the Late Himalayan movement, while the maturation characteristics of the Taibei Sag present no considerable changes during this period.

5.2. Effects of Differentiation of the Burial–Thermal History on Petroleum Systems

5.2.1. Effects on Hydrocarbon Generation Evolution

The characteristics of the Taodonggou Group source rocks in the Taibei Sag are described in accordance with the outcrops and cores, respectively. The field outcrop demonstrates that the Taodonggou Group source rocks are more developed in the northern part of the Turpan–Hami Basin, and, therefore, it is an educated guess that the center of the source rocks should be located at the northern deposition center. An investigation of the outcrop sections, such as Taerlang, Kekeya, Zhaobishan and Qialekan, shows that the TOC is 0.53%–2.88%, averaging 1.32%; $S_1 + S_2$ is 0.02–106.14 mg/g (the Taerlang section presents the maximum mean value of TOC of 14.4 mg/g); and the content of chloroform bitumen A is 0.015%–0.28%, with an average of 0.11%. The low content of chloroform bitumen A may be attributed to the weathering leaching [51,62,63]. In the Taibei Sag, dark grey and grey-black Taodonggou Group mudstone with thicknesses of 62 m, 49 m and 106 m are revealed from Wells YT-1 and L-30 newly drilled in the near-sub-sag slope and Well LT-1 in the Shanbei sub-sag, respectively. The drilling data show that the average TOC of the Taodonggou source rocks in the Taibei Sag is 0.67%–8.54%, the content of chloroform bitumen A is 0.075%–0.8767%, and the hydrocarbon generation potential is 0.62–66.92 mg/g. The organic matter is mainly of Types II₂ and III, with the vitrinite reflectance of 1.04 Ro%–1.27 Ro% suggesting mature source rocks (Table 2). The thermal history modeling of wells suggests that the Taodonggou Group source rocks in the Taibei Sag generally became mature during the Mid–Late Jurassic epoch, while those in the central–southern part of the Shanbei sub-sag, represented by Well LT-1, reached the mature stage during the Late Triassic epoch. The sustained sedimentation and deep burial during the Jurassic Period lay down an important basis for the maturation of the Permian Taodonggou Group source rocks. The subsequent tectonic uplift merely adjusts the existing oil and gas reservoirs.

Table 2. Geochemical data for some wells in the Taibei Sag.

Well	Type	Lithology	TOC/%	Chloroform Asphalt A/%	HC/ppm	$S_1 + S_2$ /mg/g	Ro/%	Tmax
YT-1	Debris	Grey-black mudstone	2.34	0.1899	822	4.33	1.08	
YT-1	Debris	Grey-black mudstone	2.29			3.82	1.10	
YT-1	Debris	Grey-black mudstone	5.28	0.3351	1088	4.18	1.10	
YT-1	Debris	Grey-black carbonaceous mudstone	15.23	0.8767		14.95	1.08	
YT-1	Debris	Dark gray mudstone	0.57			0.6		453
YT-1	Core	Dark gray mudstone	1.67			1.96	1.14	454
YT-1	Core	Grey-black carbonaceous mudstone	26.34			43.36	1.01	448
YT-1	Core	Gray carbonaceous mudstone	27.78			66.92	1.20	449
YT-1	Core	Grey-black mudstone	6.08	0.1815	936	7.16	1.04	454
L-30	Debris	Dark gray mudstone	7.44	0.3442	1478	4.66	1.12	
L-30	Core	Grey-black mudstone	2.32	0.059	193	2	1.23	442
L-30	Core	Grey-black mudstone	3.67	0.1175	279	3.72	1.27	443
L-30	Core	Dark gray mudstone	3.24	0.0764	205	3.11	1.10	444
L-30	Core	Grey-black mudstone	5	0.1121	292	5.38	1.24	444
L-30	Core	Grey-black mudstone	4.93	0.0746	258	2.48	1.09	436
LT-1	Debris	Dark gray mudstone	0.41			0.4	1.14	470
LT-1	Debris	Dark gray mudstone	1.79			3.4	1.12	468
LT-1	Debris	Dark gray mudstone	1.19			4.64	1.05	445
LT-1	Debris	Dark gray mudstone	0.97			2.4	1.04	468

5.2.2. Effects on Reservoir Rock Evolution

The favorable reservoir rocks in the study area mainly occur in the Permian Wutonggou Formation and Triassic Karamay Formation, and here this research focuses on the Wutonggou Formation. The sedimentary facies of the Wutonggou Formation reservoir are predominated by the fan delta, and the Wu-I and Wu-III Members (namely the first and third members of the Wutonggou Formation) are the main oil producers [64,65]. The effective reservoir space is mainly composed of dissolved inter-granular pores, dissolved intra-granular pores and residual inter-granular pores (Figure 10). On the basis of the measurements of this research and previous studies, the average, minimum and maximum porosity of the Wutonggou Formation are estimated to be 7.35%, 4.4% and 30.8%, respectively, and the main distribution range of porosity is 5%–12%. Moreover, the permeability mainly ranges from $10 \times 10^{-3} \mu\text{m}^2$ to $100 \times 10^{-3} \mu\text{m}^2$ and averages $1.18 \times 10^{-3} \mu\text{m}^2$. As per China's classification criteria for porosity and permeability of clastic reservoirs specified in the industrial standard DZ/T 0217-2005, the Permian Wutonggou Formation reservoir rocks have ultra-low porosity and low permeability [51,66–70].

The basin modeling of the burial history, trap development and thermal history of the Permian in the Taibei Sag, the Turpan–Hami Basin, clarifies the temporal matching between the diagenesis history and the reservoir rock pore development [54,71,72].

From the Late Triassic epoch to the Mid–Late Jurassic epoch, the underlying Taodonggou Group source rocks became mature and expelled hydrocarbons, and yet, the hydrocarbon expulsion time is somewhat differentiated among different sub-sags, as stated above. The results show that from the Late Triassic to the Middle and Late Jurassic, the source rocks of the Permian Taodonggou Group matured and expelled hydrocarbons, and there was little difference in the hydrocarbon generation time of different sub-sags. Due to the neighboring between the source rocks and the Wutonggou reservoirs, hydrocarbons first enter the Wutonggou Formation reservoirs. The burial depths of different fan bodies are varied, and so are the hydrocarbon emplacement time and experienced diagenetic processes [67]. The Wutonggou Formation sandstone reservoir in the Taibei Sag is highly compacted. The contact among grains is mainly line contact, and the primary pores are mostly destructed, both implying considerable compactions. In the later stage, carbonate minerals occur extensively in the forms of cement and metasomatism, and the quartz overgrowth is identified as the II–III grade [73]. As shown in Figure 12, the diagenesis has reached the meso-diagenetic A phase, and some fan bodies even present the highest diagenesis of the meso-diagenetic B phase, e.g., the Pudong fan group (Figure 13). The modeled porosity curve shows that the porosity of the Yubei fan group is 18%, higher than those of the Lianbei fan body and Qiuling fan group, and the least porosity of 12% occurs in the Pudong fan group. Such an understanding is validated by the observed plane porosity of casting thin sections. The casting thin section plane porosity of the Wu-I Member, Well YB1-3, the Yubei fan group, is 17%, higher than those of Well L-23, the Lianbei fan body; and Well SK-1, the Qiuling fan group (6% and 3%, respectively). The burial depth of the Pudong fan group is the highest and exceeds 7000 m, and the casting thin section plane porosity of the Wu-I Member is 0.3%. It is confirmed that the Yubei fan group has better reservoir physical properties. At present, the burial depth of the Wutonggou Formation in the Taibei Sag is commonly 4000–6000 m, while Wells LN-1, YG-7 and AC-1 in the Tainan Sag reveal that the burial depth in the Wutonggou Formation ranges from 2000 m to 4000 m. In other words, the southern region is located in the higher position of the fan slope. This oil explains why oil and gas reservoirs largely occur in the southern part of the Taibei Sag and Tainan Sag [71–77].

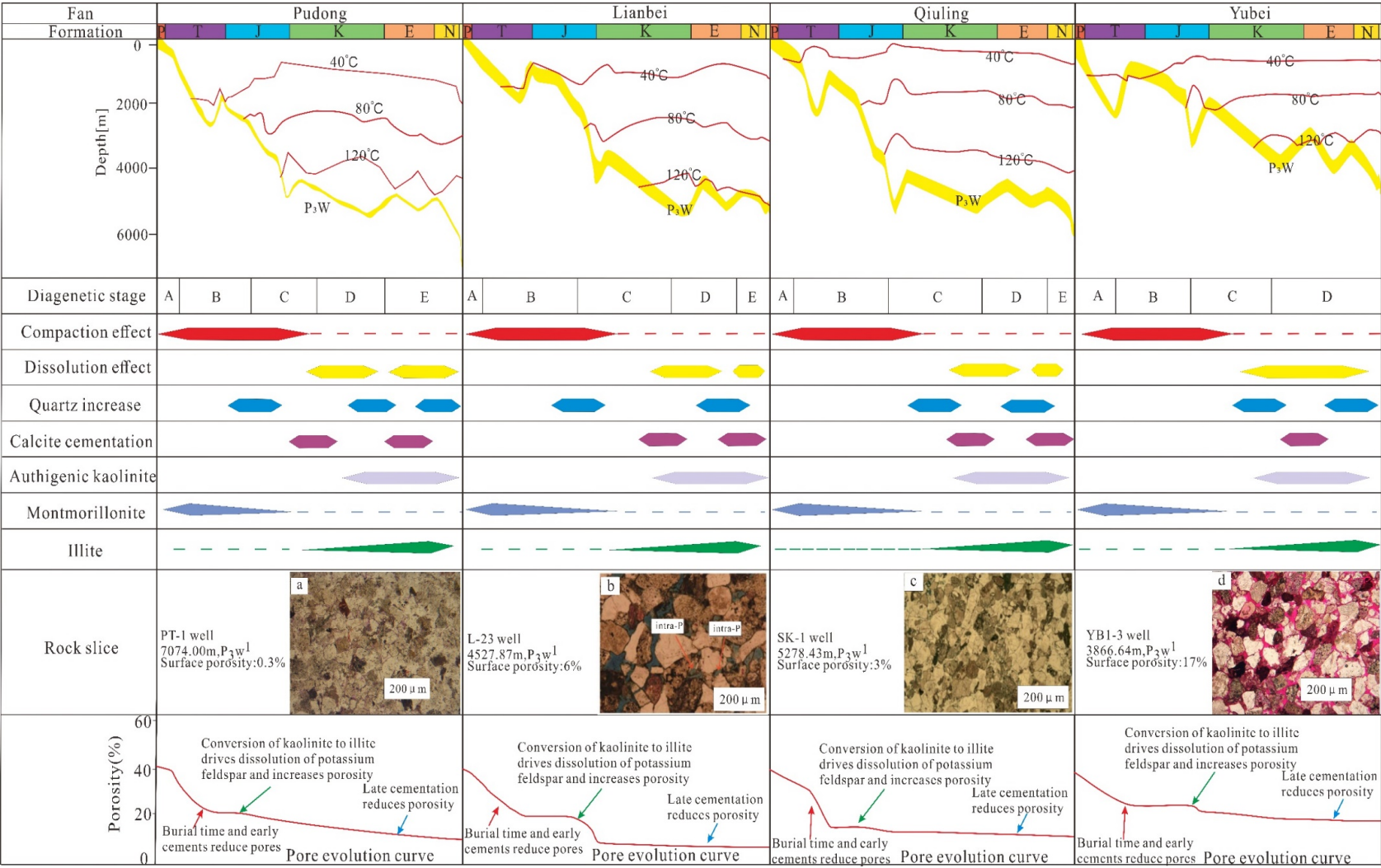


Figure 12. Difference analysis of diagenesis history of different sub-sags [67,78]. (A) Contemporaneous stage, (B) eodiagenetic A phase, (C) eodiagenetic B phase, (D) meso-diagenetic A phase and (E) meso-diagenetic B phase.

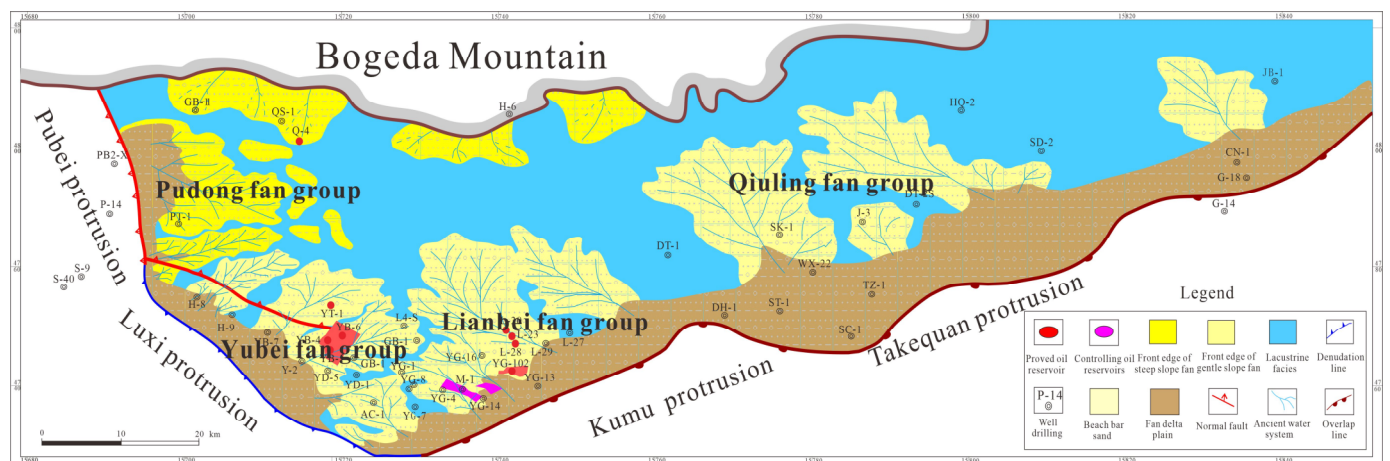


Figure 13. Sedimentary facies map of the Permian Wutonggou Formation in the Taibei Sag.

5.2.3. Effects on Hydrocarbon Preservation Conditions

The discovered existing pre-Jurassic oil reservoirs are mostly distributed in the southern part of the Taibei Sag and Tainan Sag, and these reservoirs may store either heavy oil or light oil [79,80]. The generation of heavy oil has been investigated extensively. It is related to the uplift and exposure of the reservoir subject to meteoric weathering and leaching [81–83]. By far, the discovered heavy oil reservoirs mostly occur in the Wutonggou Formation and Karamay Formation, and the oil source correlation shows that such heavy oil is sourced from the Taodonggou Group source rocks in the Taibei Sag [84,85]. The oil reservoir sections of different sub-sags in the study area are presented in Figures 14–16. The section in Figure 14 intersects the Shengbei sub-sag and the piedmont zone of the Shanbei sub-sag. The shown oil reservoir is controlled by the source-connecting fault and underlying source rocks and has good preservation conditions. However, no oil reservoir sourced from the Permian source rocks has been found, due to the low efforts in exploration. The section in Figure 15 cuts both the Huobei sub-sag and Lianbei sub-sag. Well YT-1 presents cores with oil stains and oil patches from both the Wutonggou and Karamay Formations, thus indicating the previous presence of paleo-oil reservoirs in the southern part of the sub-sag. Whether or not such paleo-oil reservoirs are destructed or they serve as part of the migration paths of hydrocarbons remains a puzzle and is under investigation. Nevertheless, the core observations raise confidence in hydrocarbon exploration in the Huobei Sag [86]. Figure 16 is a north–south oil reservoir section intersecting the nose-like uplift in the Central–Southern Shanbei sub-sag. Well SK-1 discovers a light oil reservoir in the Karamay Formation, while Well LT-1 fails. The discovered Permian and Triassic oil reservoirs are predominantly located in the structural slope and anticline zones in the south, which stimulates the confidence in the exploration of oil and gas reservoirs in the piedmont zone. Statistics of the fault amplitude of the oil reservoir sections (Figure 17) suggest high relevance to the last Himalayan movement and also reflect degrees of damage to oil reservoirs [87,88]. The fault amplitude in the Eastern Taibei Sag is larger than in the western part, and the current oil reservoir distribution features the pattern of reservoirs underlain by source rocks. Therefore, faults connecting source rocks are vital for the formation of oil reservoirs. The lowest fault amplitude is found in the oil reservoir section of the Huobei sub-sag, and the Lukeqin large oil reservoir occurs in the south of the Huobei sub-sag. Furthermore, the fault amplitude of the oil reservoir section across the Central–Southern Shanbei sub-sag grows from north to south, and the Karamay Formation oil reservoir found in Well SK-1 lies in the Central–Northern Shanbei sub-sag [89,90]. Comprehensively, a fault amplitude below 80 m is favorable for the formation of oil reservoirs. With a fault amplitude exceeding this threshold, it is increasingly challenging to form or preserve oil reservoirs. The structural slope and anticline zones of the Huobei, Shengbei and Lianbei sub-sags are in favor of raising reserves and production of hydrocarbons.

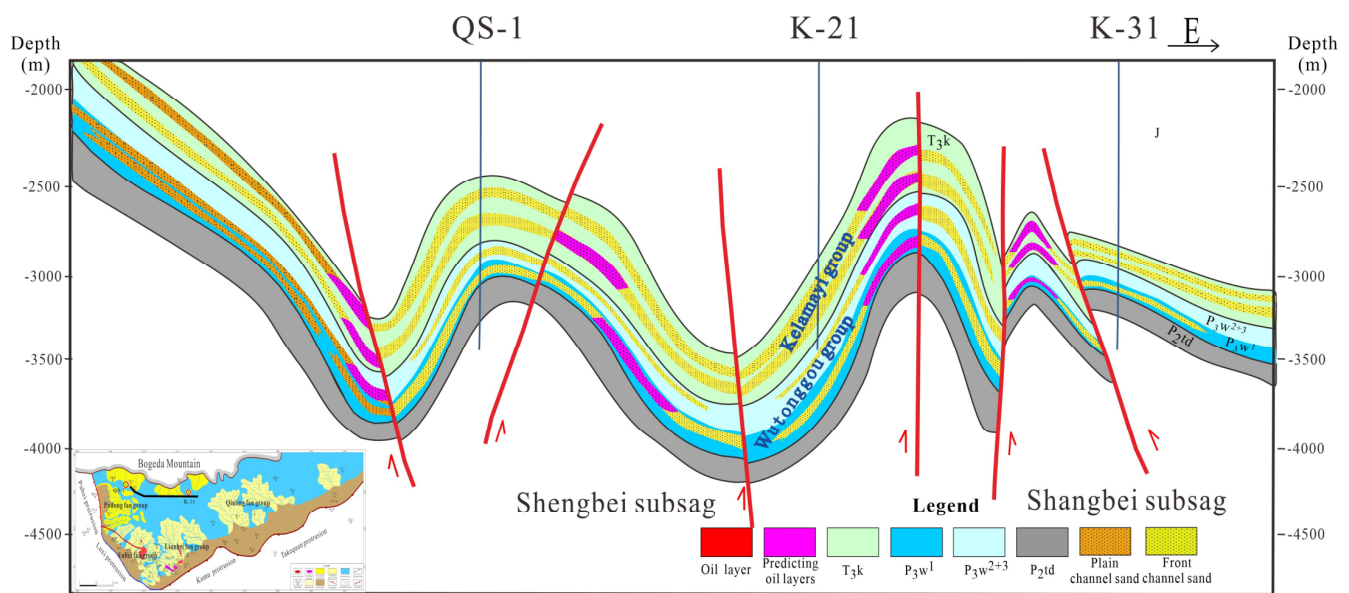


Figure 14. Section of the predicted oil reservoir across the Shengbei sub-sag and piedmont zone of the Shanbei sub-sag.

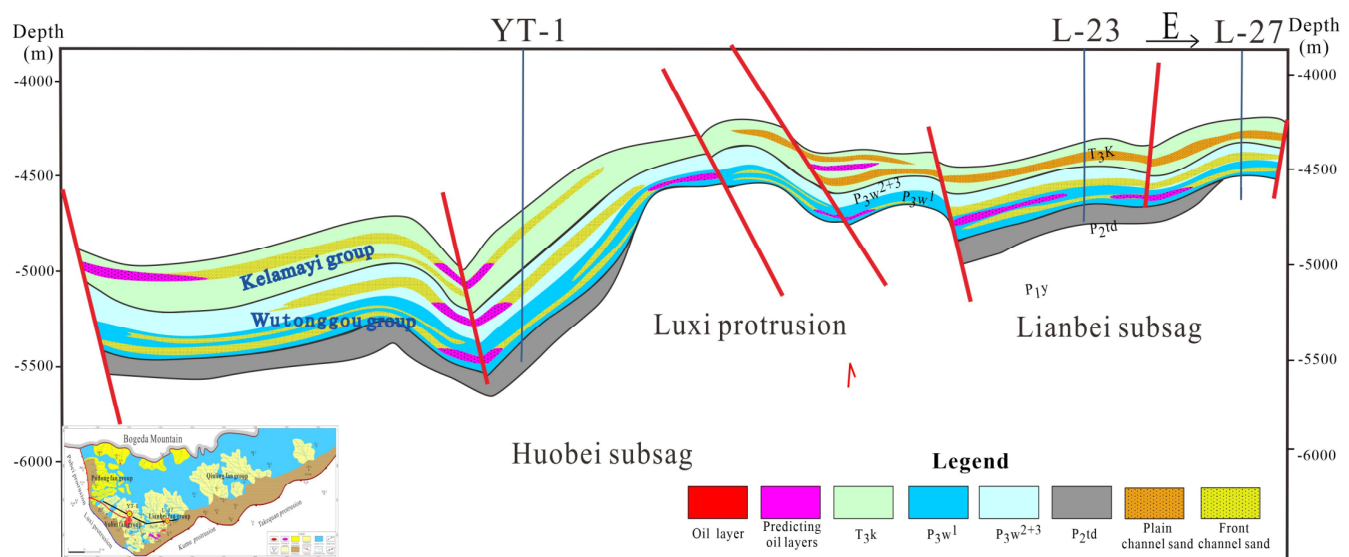


Figure 15. Section of the predicted oil reservoir across the Huobei and Lianbei sub-sags.

5.3. Effects of Differential Burial–Thermal History on Key Reservoir-Forming Elements Corresponding to Characteristics of Petroleum Systems

This research, combined with a systematic literature review of previous studies, compensated for the insufficiency of the studies on the tectonic, burial and thermal history of the Taibei sag, and, moreover, the erosion thickness during each tectonic uplift was systematically quantified. The Permian Taodonggou Group mudstone is commonly mature and can serve as excellent source rocks to provide hydrocarbons for the reservoir rocks of the Wutonggou and Karamay Formations, as per its hydrocarbon generation indexes stated above. The reservoir rocks of the Wutonggou and Karamay Formations, associated with the faults connecting the source rocks, are desirable reservoirs. Their storage capacity and experienced diagenesis are stated above. The porosity is typically above 10% and can locally reach 20% with burial depths over 3000 m (suggesting high-quality reservoirs). The Lianbei sub-sag, the Huobei sub-sag and the nose-like uplift and slope of the Central–Southern Shanbei sub-sag are important predicted oil-reservoir distribution regions (Figures 14–16).

The Cenozoic tectonic movement finalized the structural framework of the Turpan–Hami Basin. The statistics for the fault amplitude of each sub-sag demonstrate that a fault amplitude no longer than 80 m is associated with desirable migration capacity and serves as a communication channel between the source and reservoir rocks [91,92]. An excessive fault amplitude tends to have the migration capacity of the fault greatly reduced by the mudstone blockage [65]. The mudstone/shale of the Triassic Huangshanjie Formation serves as excellent cap rocks immediately overlying the reservoir rocks, while the commonly developed Jurassic thick coal seams are the regional cap rocks [71,93].

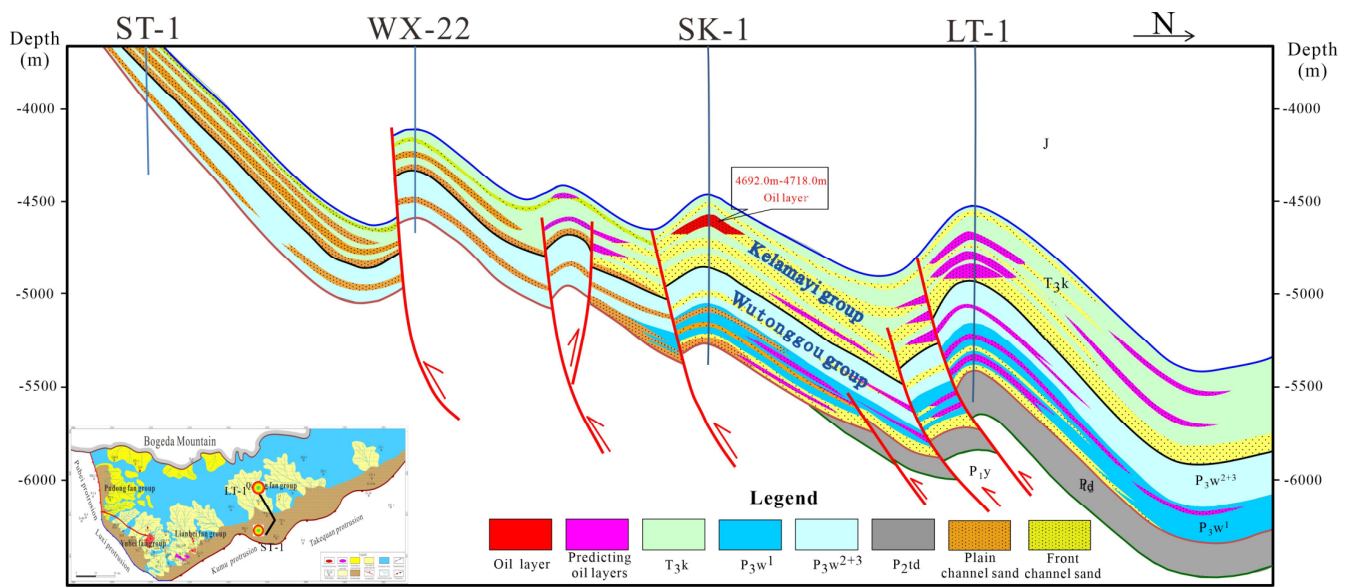


Figure 16. Section of the predicted oil and gas reservoir across the nose-like uplift of the Shanbei sub-sag.

Because the Taibei Sag experienced a large-scale uplift during the Late Indosinian movement, the massive hydrocarbon generation of the Taodonggou Group source rocks was postponed to the Jurassic Period, instead of the Late Triassic epoch. This is validated by the thermal history reconstruction. The pore space of the Wutonggou Formation reservoir, which matches the undone Triassic massive hydrocarbon generation, is subjected to a great loss due to the Triassic rapid deep burial (a major reason for pore loss) [94]. As illustrated by Figure 18, at the end of the Triassic Period, the formation temperature in the Central–Southern Shanbei sub-sag reached 100 °C, and the source rocks in this area first expelled hydrocarbons. The source rocks in the other sub-sags started hydrocarbon expulsion during the Mid–Late Jurassic epoch. The Taodonggou Group source rocks are well-developed in the Shengbei sub-sag and Shanbei piedmont zone, and the maximum source rock thickness averages 150 m, higher than those of the other sub-sags. However, no oil reservoir has been found in the Wutonggou and Karamay Formations. An analysis showed that the oil reservoirs were adjusted during the Cenozoic structural adjustment, and the oil migrated upward to form the Jurassic reservoirs of mixed oil. The oil reservoirs previously in the Wutonggou and Karamay Formations were destroyed by the structural adjustment. The structural styles of the pre-Jurassic oil reservoirs in the different sub-sags were dissected. The oil reservoir section of the Huobei–Yubei–Tuyuke structural zone (Figure 18a) is the current main producing block of the pre-Jurassic oil reservoirs of the Turpan–Hami Basin. The oil reservoirs are located in the structural high and slope, and, hence, attention should be drawn to the slope zone of the Southern Taibei Sag and structural highs and their downdip direction. In view of the oil reservoir section of the Shanbei slope zone (Figure 18b), Well SK-1 discovers the oil reservoir in the Karamay Formation, and, meanwhile, Well LT-1 finds no oil reservoir (Figure 16). The hydrocarbons of the Shanbei sub-sag migrate to Well SK-1 through the southern part of the sub-sag

(Yang et al., 2020) [10], and, therefore, this migration path should be the target for future exploration. As illustrated by the east–west oil reservoir section intersecting the Shengbei and Shanbei sub-sags (Figure 18c), hydrocarbons migrate upward through faults connecting the source rocks buried at 5000–6000 m. Nonetheless, due to the later multiple structural adjustments, the oil reservoirs are destroyed, or hydrocarbons escape upward to form the Jurassic reservoirs of mixed oil. Figure 18d shows the east–west oil reservoir section across the Huobei and Lianbei sub-sags. Below the slope zone of the Southern Taibei Sag, no oil and gas reservoir has been found. The burial depth in this area is relatively high; hydrocarbons tend to flow toward the slope zone in the south.

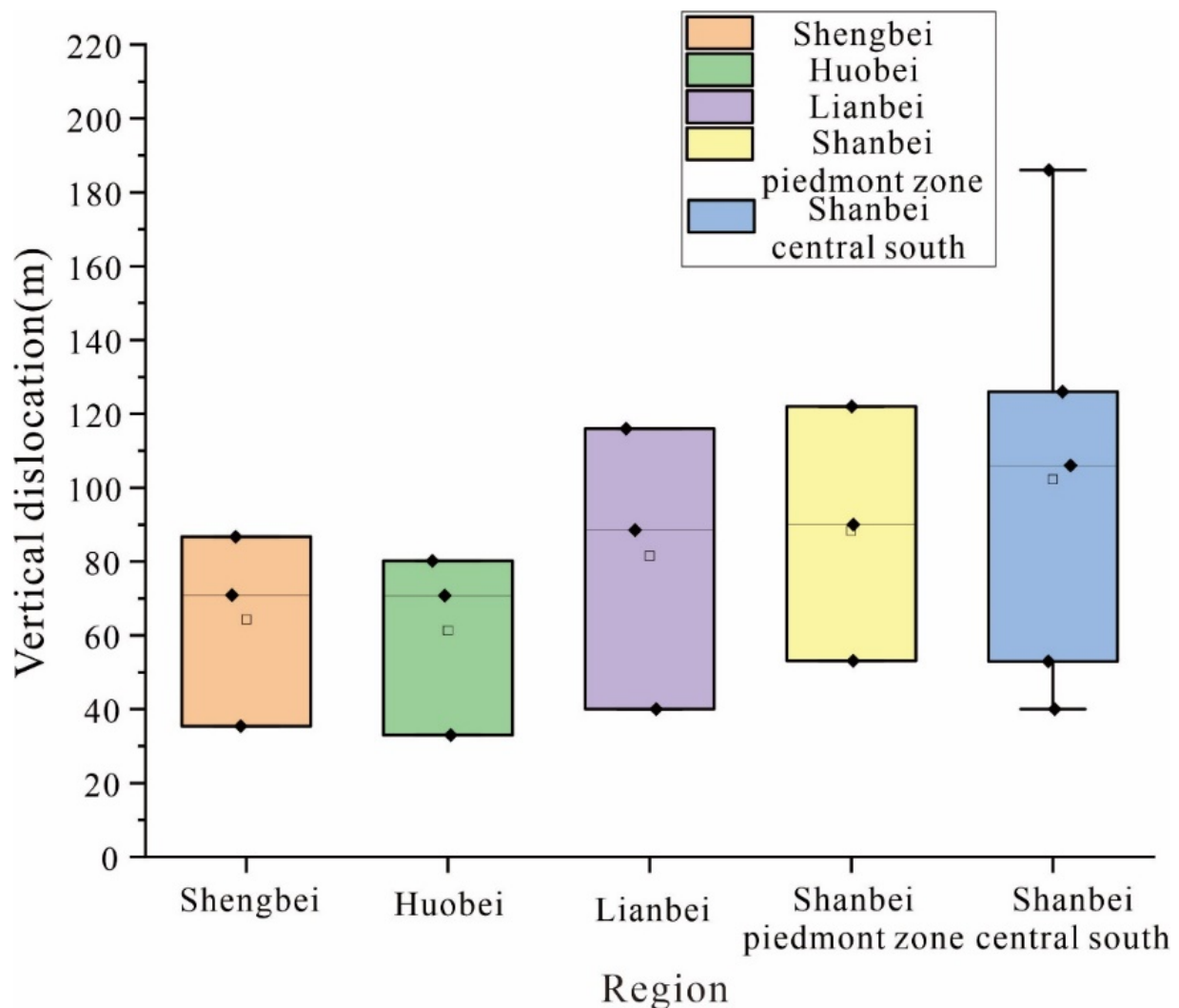


Figure 17. Box diagram of the fault amplitude of each sub-sag in the Taibei Sag.

To sum up, the structural styles of oil reservoirs in Figure 18a,b are rather desirable. Accordingly, confidence remains for hydrocarbon exploration in pre-Jurassic formations, and the main exploration areas include the Southern Taibei Sag and the structural highs, nose-like uplifts and slopes of the Lianbei and Huobei sub-sags and the Central–Southern Shanbei sub-sags.

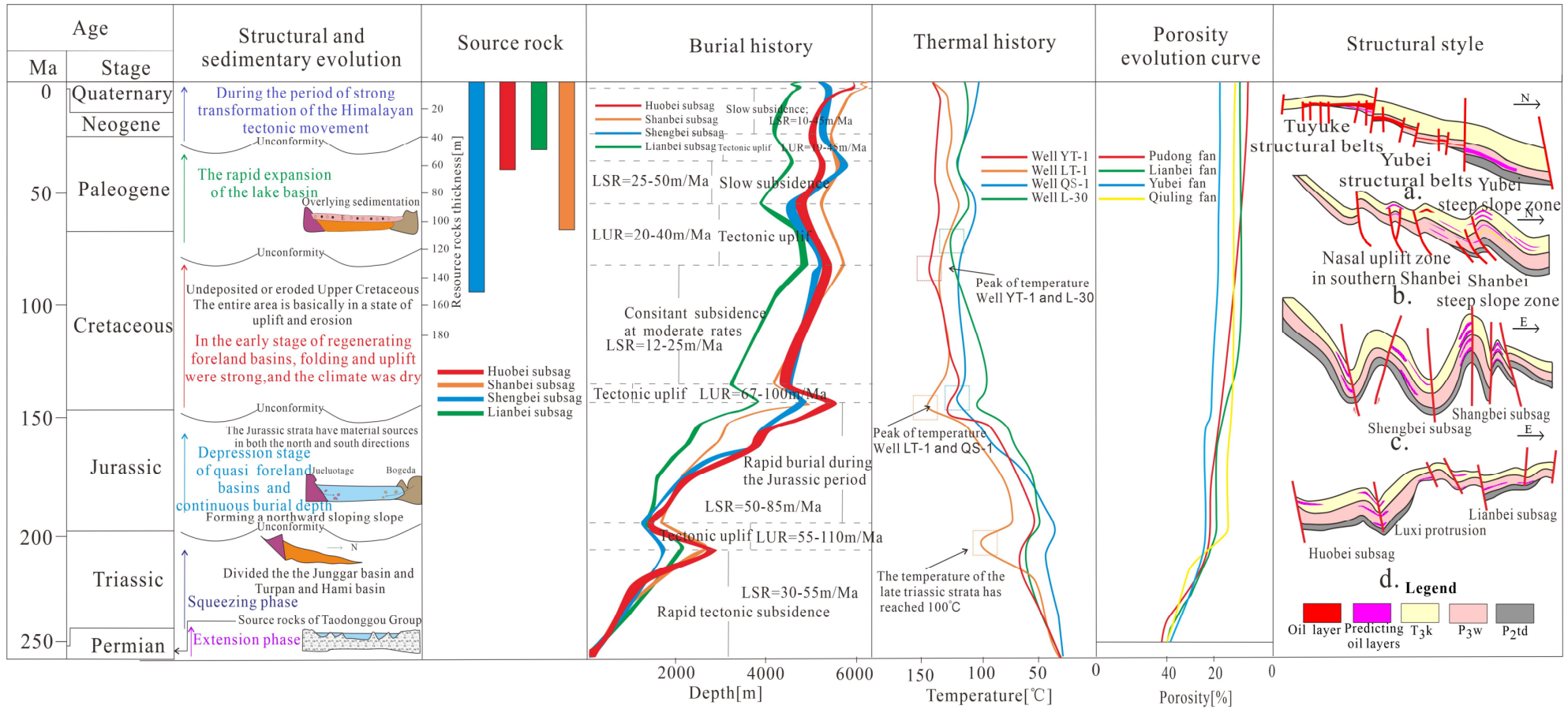


Figure 18. Matching among the burial, thermal, porosity evolution and structural-sedimentary evolution history of each sub-sag of the Taibei Sag, the Turpan-Hami Basin (a–d).

6. Conclusions

Basin modeling was performed to simulate the burial and thermal history of the Taodonggou Group in the Taibei Sag, the Turpan–Hami Basin. The differentiation characteristics among different sub-sags were analyzed, and their effects on petroleum systems were investigated. The following conclusions were drawn:

- (1) The erosion thickness across the Taibei Sag presents the following characteristics. For the Late Indosinian movement, the erosion thickness was generally low in the north and east and high in the south and west, and the average erosion thickness of the Shanbei sub-sag reached over 1000 m. For the Middle Yanshanian movement, the erosion thickness across the sag is generally characterized by low values in the east and high values in the west. The erosion thickness of the Shengbei and Huobei sub-sags is lower than 500 m, and that of the Lianbei and Shanbei sub-sags is over 700–1000 m. For the Late Yanshanian movement, the Taibei Sag generally features low erosion thickness in the central sag and high erosion thickness in both the northern and southern sag. The erosion thickness is below 550 m, except for in the piedmont zone. For the Late Himalayan movement, the Taibei Sag presents small erosion thicknesses of 100–500 m on an overall basis, and yet the erosion thickness of the eastern sag is higher than that in the western sag.
- (2) For different tectonic movements, the average uplift rate of each sub-sag is ranked as follows: Shanbei > Lianbei > Huobei > Shengbei during the Late Indosinian movement, and Huobei > Shanbei $\approx$ Shengbei during the Middle Yanshanian movement. The average uplift rates of the Huobei, Shengbei and Shanbei sub-sags were similar during the Late Yanshanian and Early Himalayan movements, two key periods of structural adjustment. The average uplift rates of the Late Himalayan movement, also a key period of structural adjustment, are ranked as Huobei > Shengbei > Shanbei, showing differentiated uplift and denudation due to the eastward propagation of the regional tectonic event.
- (3) The Taodonggou Group source rocks in the Taibei Sag generally became mature during the Mid–Late Jurassic epoch. Yet, those in the Central–Southern Shanbei sub-sag, represented by Well LT-1, reached the mature stage during the Late Triassic epoch, because the higher geothermal gradient in the Eastern Taibei Sag (where the Shanbei sub-sag lies) accelerated the maturation of the source rocks. The experienced maximum formation temperature of the Shanbei sub-sag is near 150 °C, while those of the Lianbei, Huobei and Shengbei sub-sags in its west are 120 °C–140 °C.
- (4) The Yubei fan group has the best reservoir physical properties, followed by those of the Lianbei and Qiuling fan groups. The reservoir physical properties of the Pudong fan group are the worst, due to its fairly deep burial.
- (5) The piedmont zone of the Northern Shengbei sub-sag, the structural slope and anticline of the Huobei sub-sag and Southern Lianbei sub-sag and the nose-like uplift of the Southern Shanbei sub-sag are favorable for raising reserves and production of hydrocarbons of the Taibei Sag.

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References

1. Poprawa, P.; Kosakowski, P.; Wróbel, M. Burial and thermal history of the Polish part of the Baltic region. *Geol. Quart.* **2010**, *54*, 131–142.
2. Ferket, H.; Guilhaumou, N.; Roure, F.; Swennen, R. Insights from fluid inclusions, thermal and PVT modeling for paleo-burial and thermal reconstruction of the Co'rdoba petroleum system (NE Mexico). *Mar. Pet. Geol.* **2011**, *28*, 936–958. [\[CrossRef\]](#)
3. Sturrock, P.C.; Flowers, M.R.; Kohn, P.B.; Metcalf, J.R. Phanerozoic Burial and Erosion History of the Southern Canadian Shield from Apatite (U-Th)/He Thermochronology. *Minerals* **2024**, *14*, 57. [\[CrossRef\]](#)
4. Kenneth, D.; Angielczyk, A.; Liu, J.; Christian, A.; Sidor, E.; Yang, W. The stratigraphic and geographic occurrences of Permo-Triassic tetrapods in the Bogda Mountains, NW China—Implications of a new cyclostratigraphic framework and Bayesian age model. *J. Afr. Earth Sci.* **2022**, *195*, 104655.
5. Wainman, C.C.; McCabe, P.J. Correlation of fluvial strata in the subsurface—A review. *Mar. Pet. Geol.* **2020**, *122*, 104611. [\[CrossRef\]](#)
6. Thomas, S.G.; Tabor, N.J.; Yang, W.; Myers, T.S.; Yang, Y.; Wang, D. Palaeosol stratigraphy across the Permian-Triassic boundary, Bogda Mountains, NW China: Implications for paleoenvironmental transition through earth's largest mass extinction. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2011**, *308*, 41–64. [\[CrossRef\]](#)
7. Obrist-Farner, J.; Yang, W. Nonmarine time-stratigraphy in a rift setting: An example from the Mid-Permian lower Quanzijie low-order cycle, Bogda Mountains, NW China. *J. Palaeogeogr.* **2015**, *4*, 27–51. [\[CrossRef\]](#)
8. Chen, Z.; Liao, Z.; Liu, L. Correction of two Upper Paleozoic stratigraphic units in the Tianshan Mountains region, Xinjiang Uygur Autonomous Region and implications on the Late Paleozoic evolution of Tianshan tectonic complex, Northwest China. *J. Palaeogeogr.* **2015**, *4*, 358–370. [\[CrossRef\]](#)
9. Welte, H.D.; Horsfield, B.; Baker, R.D. *Petroleum and Basin Evolution: Insights from Petroleum Geochemistry, Geology and Basin Modeling*; Springer: Berlin/Heidelberg, Germany, 1997.
10. Yang, W.; Cai, J.F.; Wang, Q.Y.; Cui, Z.J.; Cui, Z.; Xu, L.; Li, L.; Gu, X.M.; Wang, J.L. The controlling effect of organic matter coupling with organic matter porosity on shale gas enrichment of the Wufeng-Longmaxi marine shale. *Petrol. Sci. Bull.* **2020**, *2*, 148–160.
11. Kumar, S.; Ojha, K. Reaction kinetic, maturity, burial and thermal histories modelling of cambay shale source rocks, Cambay Basin, Western India. *J. Petrol. Sci. Eng.* **2021**, *202*, 10854. [\[CrossRef\]](#)
12. Zielińska, M.; Jirman, P.; Gedl, P.; Botor, D. Burial and thermal history of the eastern transform boundary of the central western carpathians based on 1D basin modeling. *Mar. Pet. Geol.* **2023**, *147*, 106021. [\[CrossRef\]](#)
13. Kim, J.-H.; Martini, A.M.; Ono, S.; Lalk, E.; Grant, G.; McIntosh, J.C. Clumped and conventional isotopes of natural gas reveal basin burial, denudation, and biodegradation history. *Geochim. Cosmochim. Acta* **2023**, *361*, 133–151. [\[CrossRef\]](#)
14. Wood, D.A. Thermal maturity and burial history modelling of shale is enhanced by use of Arrhenius time-temperature index and memetic optimizer. *Petroleum* **2018**, *4*, 25–42. [\[CrossRef\]](#)
15. Tissot, B.P.; Pelet, R.; Ungerer, P.H. Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation. *AAPG Bull.* **1987**, *71*, 1445–1466.
16. Luo, Q.S. Analysis on the relationship between inversion structure characteristics and oil and gas in Taibei sag. *Petrol. Geol. Exp.* **1997**, *05*, 25–28.
17. Zhou, T.S. A Study on the Exploration Foreground of the Permian in the North Structural Belt of Taibei Depression in Turpan-Hami Basin. Master's Thesis, China University of Petroleum (East China), Qingdao, China, 2008.
18. Yang, H.Y. Carboniferous-Permian Tectonic Evolution Analysis of Turpan-Hami Basin. Master's Thesis, Ocean University of China, Qingdao, China, 2015.
19. Lu, X.H. Petroleum Geological Characteristic of Carboniferous-Permian in Turpan-Hami Basin. Master's Thesis, Xi'an Shiyou University, Xi'an, China, 2018.
20. Zhou, S.Y. Analysis of Deformation Characteristics of the Northern Piedmont Belt in the Turpan-Hami Basin. Ph.D. Thesis, China University of Petroleum (Beijing), Beijing, China, 2018.
21. Li, C.M.; Liu, J.T.; Ni, L.B.; Fan, S.W. Characteristics of deep geological structure and petroleum exploration prospect in Turpan-Hami Basin. *China Petrol. Exp.* **2021**, *26*, 44.
22. Li, T.; Jiang, Z.; Li, Z. Continental shale pore structure characteristics and their controlling factors: A case study from the lower third member of the Shahejie Formation, Zhanhua Sag, Eastern China. *J. Nat. Gas Sci. Eng.* **2017**, *45*, 670–692. [\[CrossRef\]](#)
23. Hou, L.J.; Huang, G.H.; Du, Y.B. Geochemical characteristics of Jurassic coal-measure source rocks in the Turpan-Hami basin. *Petrochem. Appl.* **2015**, *34*, 83–87.

24. Bai, G.J. The reservoir characteristics and the influence to waterflood development of Permian Wutonggou formation in block Beiyi, Lukeqin oilfield. *Xinjiang Oil Gas* **2017**, 10–14.
25. Dong, S.X. Analysis of the Sources and Origin of Oil and Gas in the Shuixigou Group, Taibei Sag, Turpan-Hami Basin. Master's Thesis, Northeast Petroleum University, Daqing, China, 2023.
26. Lei, H. Fault characteristics and evolution of Middle-Lower Jurassic in eastern Taibei sag, Turpan-Hami Basin. Master's Thesis, Northeast Petroleum University, Daqing, China, 2023.
27. Wang, X.Y. Main Controls on the Quality Reservoir of Permian-Triassic in Turpan Depression, Tuha Basin. Master's Thesis, China University of Petroleum (Beijing), Beijing, China, 2019.
28. Wei, S.Y.; Wang, J.G.; Cai, L.N. Study on Sedimentary Paleogeography and Sedimentary Facies of the Triassic Karamay Formation in the Midwestern Taibei Sag. *Acta Sedimentol. Sin.* **2023**, 1–26.
29. Wasson, R.J.; Saynor, M.J.; Lowry, J.B.C. The natural denudation rate of the lowlands near the Ranger mine, Australia: A target for mine site rehabilitation. *Geomorphology* **2021**, 15, 107823. [[CrossRef](#)]
30. Mason, C.C.; Romans, B.W. Climate-driven unsteady denudation and sediment flux in a high-relief unglaciated catchment–fan using 26Al and 10Be: Panamint Valley, California. *Earth Planet. Sci. Lett.* **2018**, 492, 130–143. [[CrossRef](#)]
31. Wu, B.; Jin, Z. Application of Milankovitch cycles in the restoration of high-resolution deposition velocity of Neogene strata in Kutei Basin, Indonesia. *Energy Geosci.* **2023**, 4, 100089. [[CrossRef](#)]
32. Burgess, P.M.; Duller, R.A. Autogenic masking of allogenic inputs: Numerical modelling of signal preservation in deep-water fan strata. *Earth Planet. Sci. Lett.* **2024**, 628, 118583. [[CrossRef](#)]
33. Zhou, W.H. Characteristics of Permian hydrocarbon evolution in western area, Turpan Depression, Turpan-Hami Basin. *Fault-Block Oil Amp.* **2017**, 24, 316–319.
34. Li, N.; Zhang, J.L.; Shen, W.L.; Liu, Y. Recovery of the Erosion Thickness and Characterization of the Paleogeomorphology in the Southern Lishui Sag, East China Sea Shelf Basin. *J. Ocean. Univ. China* **2020**, 19, 320–330. [[CrossRef](#)]
35. Green, P.F.; Westaway, R.; Manning, D.A.C.; Younger, P.L. Cenozoic cooling and denudation in the North Pennines (northern England, UK) constrained by apatite fission-track analysis of cuttings from the Eastgate Borehole. *Proc. Geol. Assoc.* **2012**, 3, 450–463. [[CrossRef](#)]
36. Spahić, D.; Šajnović, A.; Burazer, N.; Radisavljević, M.; Jovančičević, B. Neogene subsidence rates of the southern Peri Pannonian realm (1D basin modeling): Constraints on the extensional geodynamic drivers of the asymmetric Toplica basin (central-southern Serbia). *Geoenery Sci. Eng.* **2023**, 226, 211714. [[CrossRef](#)]
37. Dow, W.G. Kerogen studies and geological interpretations. *J. Geochem. Explor.* **1997**, 7, 79–99. [[CrossRef](#)]
38. Shan, X.L.; Yang, L.; Wang, P.J. Calculation of Ordovician Erosion Thickness in Eastern Tarim Basin. *Xinjiang Geol.* **2006**, 389–391.
39. Peng, Q.H.; Zhou, J.Y.; Jie, Y.X. An application of the vitrinite reflectance trend method to the restoration of erosional thickness in the Dongying Formation, Nanpu depression. *Sediment. Geol. Tethys Geol.* **2013**, 33, 89–94.
40. Zhou, H.T. The Research of Stratum Characteristics and Restored Prototype Basin in Hami Depression. Master's Thesis, Ocean University of China, Qingdao, China, 2012.
41. Wu, Y.J.; Wang, S.; He, L. Research on burial history and the thermal evolution history of the Jurassic coal-measure rocks in the Eastern Margin of Xiaocaoahu Sag. *Northwestern Geol.* **2021**, 54, 180–191.
42. Wang, Y.; Jin, Z.J. Progress of the methods on the recovery of the thickness of eroded strata in basin. *Adv. Earth Sci.* **1999**, 14, 482–486.
43. Liang, Q.X.; Liu, Z.; He, X.H. Study of stratigraphic denudation recovery by seismic data in new exploration area. *Xinjiang Petrol. Geol.* **2009**, 30, 103–105.
44. Liu, H.; Wang, Y.M.; Wang, Y.; Liu, M. Restoration of eroded stratal thickness in key periods of tectonic change in a multi-stage superimposed Tarim Basin in China. *J. Palaeogeogr.* **2012**, 1, 149–171.
45. Wang, F. Study on Mesozoic-Cenozoic Structural Characteristics of the Piedmont Belt in the Northern Tuha Basin. Master's Thesis, Northeast Petroleum University, Daqing, China, 2023.
46. Chen, C.S.; Shi, S.Y.; Wang, Y.P. Adsorption simulation based on PetroMod of high-quality shale segment of Wufeng-Longmaxi Formation in Changning Area, Sichuan Basin. *Geochimica* **2019**, 48, 602–612.
47. Yao, X.; Wang, Y. Assessing shale gas resources of Wufeng-Longmaxi shale (O₃w-S₁l) in Jiaoshiba area, SE Sichuan (China) using Petromod I: Burial and thermal histories. *Petrol. Sci. Tech.* **2016**, 34, 1000–1007. [[CrossRef](#)]
48. Jian, J. Basin Analysis on Turpan-Hami Basin. Master's Thesis, North West China University, Xi'an, China, 2001.
49. Shi, Z.G.; Huang, F.X.; Xiao, L.P. Research and application of erosion recovery method in Shanshan arc belt of Turpan-Hami Basin. *J. Oil Gas. Tech.* **2005**, 62–64.
50. Hao, J.R. The Tectonic and Thermal History of Superimpose Basin: The Case of Turpan-Hami Basin and Santanghu Basin. Ph.D. Thesis, North West China University, Xi'an, China, 2006.
51. Wu, C.; Li, H.W.; Sheng, S.Z. Characteristics and main controlling factors of hydrocarbon accumulation of Permian-Triassic in Lukeqin structural zone, Turpan-Hami Basin. *China Pet. Explor.* **2021**, 26, 137–148.
52. Hakimi, H.M.; Al-Matary, M.A.; Hersi, S.O. Burial and thermal history reconstruction of the Mukalla-Sayhut Basin in the Gulf of Aden, Yemen: Implications for hydrocarbon generation from Paleocene potential source rock. *J. Afr. Earth Sci.* **2018**, 14459–14475. [[CrossRef](#)]

53. Yang, X.B. Research on Burial, Geothermal, Hydrocarbon Generation History in Wangfu-Dehui Depression. Master's Thesis, Northeast Petroleum University, Daqing, China, 2015.
54. Chen, M.J. Evolution and numerical simulation of Turpan-Hami Basin. *China Inst. Pet. Explor. Dev.* **1993**, 1–7.
55. Li, X.N.; Li, Z.J.; Wang, J.S. Application and analysis of basin simulation technology in Turpan-Hami Basin. *J. Oil Gas. Technol.* **2005**, 838–842.
56. Sweeney, J.J.; Burnham, A.K. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *AAPG Bull.* **1990**, 74, 1559–1570.
57. Suggate, R.P. Relations between depth of burial, vitrinite reflectance and geothermal gradient. *J. Pet. Geol.* **1998**, 21, 5–32. [[CrossRef](#)]
58. Uwe Ring, U.; Glodny, J.; Hansman, R.; Scharf, A.; Mattern, F.; Callegari, I.; van Hinsbergen, D.J.J.; Willner, A.; Hong, Y. The Samail subduction zone dilemma: Geochronology of high-pressure rocks from the Saih Hatat window, Oman, reveals juxtaposition of two subduction zones with contrasting thermal histories. *Earth-Sci. Rev.* **2024**, 250, 150711.
59. Chen, Z.L.; Li, X.G.; Gong, H.L. Late Cenozoic tectonic movement in the Keyir Mountain area, Kuqa, Xinjiang, and its controls on sandstone-type uranium deposits. *Geol. China* **2006**, 33, 572–581.
60. Sakawat, M.H.; Hossain, S.M.K.; Rashed, A. Late Cenozoic transpression at the plate boundary: Kinematics of the eastern segment of the Dauki Fault Zone (Bangladesh) and tectonic evolution of the petroliferous NE Bengal Basin. *Petrol. Geol. Exp.* **2021**, 131, 105133.
61. Nie, L.S.; Ma, J.H.; Tang, X.F.; Yang, Z.; Zhang, W.J.; Li, H.R. Meso-Cenozoic tectonic events and their petroleum geological significance in Zhangpenggou area, eastern Junggar Basin. *Lithol. Reserv.* **2023**, 35, 81–91.
62. Miao, H.; Wang, Y.B.; Guo, J.Y. Weathering correction and hydrocarbon generation and expulsion potential of Taodonggou Group source rocks in Taibei Sag in Turpan-Hami Basin. *Pet. Geol. Oilfield Dev. Daqing* **2022**, 42, 22–32.
63. Liu, S.J. Study on regional effectiveness difference of source rocks of Taodonggou Group in Tuha Basin. Master's Thesis, China University of Petroleum (Beijing), Beijing, China, 2019.
64. Cheng, J.T. Reservoir Characteristics of Wutonggou Formation in Permian, Taibei Sag, Turpan-Hami Basin. Master's Thesis, China University of Petroleum (Beijing), Beijing, China, 2021.
65. Chen, X.; Wu, C.; Wang, B.; Yang, S.C.; Wang, Y.; Wang, Y.C. Paleo-Geomorphology and Its Controls on Sedimentation of the Permian Wutonggou Formation Taibei Sag. *Xinjiang Petrol. Geol.* **2020**, 41, 642–650.
66. Wang, Y.C. Study on Sedimentary Facies of the Permian Wutonggou Formation in Taibei Depression, Tuha Basin. Master's Thesis, China University of Petroleum (East China), Dongying, China, 2020.
67. Wei, Y.N. Study on Permian Reservoir Characteristics in Taibei Sag, Turpan-Hami Basin. Master's Thesis, China University of Petroleum (East China), Dongying, China, 2020.
68. Bai, L.; Duan, L.; Gao, Z.Y. Controlling Effect of Shale Pore Connectivity on the Adsorption State of Shale Gas: A Case Study of Continental Shale of Jurassic Ziliujing Formation, Sichuan Basin. *Energy Fuels* **2023**, 37, 14891–14905. [[CrossRef](#)]
69. Dongming, Z.; Jianzhong, L.; Xuan, C.; Fan, Y.; Juntian, L.; Hongguang, G.; Hua, Z.; Lin, L.; Bin, L.; Yufeng, S.; et al. New fields, new types and resource potentials of oilgas exploration in Tuha Basin. *Acta Pet. Sin.* **2023**, 44, 2122–2140.
70. Salih, N.; Mansurbeg, H.; Kolo, K.; Gerdes, A. In situ U-Pb dating of hydrothermal diagenesis in tectonically controlled fracturing in the Upper Cretaceous Bekhme Formation, Kurdistan Region-Iraq. *Int. Geol. Rev.* **2020**, 62, 2261–2279. [[CrossRef](#)]
71. Su, C.G.; Li, D.F.; Jiang, X.Y. Hydrocarbon generation potential of Upper Permian source rocks in Taibei Depression, Turpan-Hami Basin. *Xinjiang Geol.* **2002**, 77–79.
72. Zhang, Z.M.; Tu, Q.; Zhao, C.L. The diagenesis characteristics of Jurassic in Taibei Sag of Turpan-Hami Basin and its control on the formation of oil and gas reservoirs. *J. Daqing Pet. Inst.* **2003**, 8–11.
73. Yang, W.; Wang, Y.H.; Du, W.; Song, Y.; Jiang, Z.X.; Wang, Q.Y.; Xu, L.; Zhao, F.P.; Chen, Y.; Shi, F.L.; et al. Behavior of organic matter-hosted pores within shale gas reservoirs in response to differential tectonic deformation: Potential mechanisms and innovative conceptual models. *J. Nat. Gas Sci. Eng.* **2022**, 102, 104571. [[CrossRef](#)]
74. Xiao, D.S.; Chen, X.; Wen, C.J.; Yang, S.; Xu, X.F. New understanding of oil and gas accumulation in Shengbei structural belt of Taibei sag, Turpan-Hami basin. *Spec. Oil Gas. Reserv.* **2016**, 23, 21–24.
75. Luo, J.L.; Shao, H.M.; Yang, Y.F.; Li, M.; Luo, C.Y. Temporal and spatial evolution of burial-hydrocarbon filling-diagenetic process of deep volcanic reservoir in Songliao Basin. *Earth Sci. Front.* **2013**, 20, 175–187.
76. Wang, S.X.; Chen, C.X.; Si, X.Q. Reservoir characteristics and influencing factors of Lower Jurassic, Taibei Sag, Tuha Basin. *J. Yanan Univ. (Nat. Sci. Ed.)* **2017**, 36, 40–46.
77. Xu, H.; Cheng, T.; Chen, A.Q. Calcite cementation of deep sandstone and Its reservoir formation effect in the Turpan-Hami Basin. *Acta Sedimentol. Sin.* **2023**, 1–16.
78. Feng, M.S. Study on the Difference among Deep Sandstone Reservoirs at Different Structures in Foreland Basin. Master's Thesis, Chengdu University of Technology, Chengdu, China, 2016.
79. Song, Y.W.; Mu, J.F.; Liu, Y.M. Study on Accumulation Mechanism and Oil and Gas Enrichment Law of Lukeqin Heavy Oil enrichment zone. *Inn. Mong. Petrochem.* **2009**, 35.
80. Wang, H.X. Research on Hydrocarbon Accumulation of Different Structural Belt the Pre-Jurassic Strata in the Tainan Depression, Tuha Basin. Master's Thesis, Northeast Petroleum University, Daqing, China, 2015.

81. Salih, N.M.; Al-Majmaie, S.M.; Muhammad, Z.A. The Porous-Permeable Zones in Heterogeneous Carbonate Reservoirs: A Case Study from Amara Oilfield-Iraq. *Proceedings* **2023**, *87*, 35. [\[CrossRef\]](#)
82. Salih, N.M. The Impact of Hydrothermal Fluids on Porosity Enhancement and Hydrocarbon Migration in Qamchuqa Formation, Lower Cretaceous, Kirkuk Oil Company. *Minerals* **2023**, *13*, 377. [\[CrossRef\]](#)
83. Salih, N.; Pr  at, A.; Gerdes, A.; Konhauser, K.; Proust, J.-N. Tracking the Origin and Evolution of Diagenetic Fluids of Upper Jurassic Carbonate Rocks in the Zagros Thrust Fold Belt, NE-Iraq. *Water* **2021**, *13*, 3284. [\[CrossRef\]](#)
84. Shen, Y.; Wang, J. Spatial matching relationship and reservoir control effect of Permian oil accumulation factors in Tainan sag. *West-China Explor.* **2017**, *29*, 72–75.
85. Gou, H.G.; Zhang, P.; She, J.C. Petroleum geological conditions, resource potential and exploration direction in Turpan-Hami Basin. *Mar. Orig. Pet. Geol.* **2019**, *24*, 85–96.
86. Yang, Y.T.; Zou, C.N.; Li, W.; Cen, X.C. Oil-accumulating stages of the Triassic trap within the Shanshen structure in Turpan-Hami Basin. *Acta Pet. Sin.* **2022**, *23*, 22–25.
87. Yang, W.; Xu, L.; Chen, D.X.; Jiang, Z.X.; Zhang, Z.Y.; Hao, B.; Zuo, R.S.; Wang, Q.Y.; Chen, R. How argillaceous reservoirs exhibit better quality than silty mudstones? Anomalous behavior of shale gas-bearing properties of continental fine-grained sediments in Southwest China and its possible forcing mechanisms. *Petrol. Sci.* **2021**, *18*, 1589–1610. [\[CrossRef\]](#)
88. Zou, C.N.; Zhao, W.Z.; Long, D.J. Characteristics and analysis of thermal evolution of organic matter in Turpan-Hami Basin. *Nat. Gas Earth Sci.* **1991**, 209–216.
89. Zou, C.N.; Zhao, W.Z.; Long, D.J. Type of source materials in the source formation in Turpan-Hami Basin and their feature of thermal evolution. *Petrol. Geol. Exp.* **1992**, 10–19.
90. Zhang, L.X.; Alvarez, L.V.; Bonthond, G.; Tian, C.M.; Fan, X.L. *Cytospora elaeagnicola* sp. nov. associated with Narrow-leaved oleaster canker disease in China. *Mycobiology* **2019**, *47*, 319–328. [\[CrossRef\]](#) [\[PubMed\]](#)
91. Zhang, L.X.; Meng, F.L.; Ge, W.; Ren, Y.; Bao, H.B.; Tian, C.M. Effects of *Colletotrichum gloeosporioides* and Poplar Secondary Metabolites on the Composition of Poplar Phyllosphere Microbial Communities. *Microbiol. Spectr.* **2023**, *11*, e04603-22. [\[CrossRef\]](#) [\[PubMed\]](#)
92. Liang, S.J. Achievements and Potential of Petroleum Exploration in Tuha Oil and Gas Province. *Xinjiang Petrol. Geol.* **2020**, *41*, 631–641.
93. Zhang, L.X.; Bao, H.B.; Meng, F.L.; Ren, Y.; Tian, C.M. Transcriptome and metabolome reveal the role of flavonoids in poplar resistance to poplar anthracnose. *Ind. Crops Prod.* **2023**, *197*, 116537. [\[CrossRef\]](#)
94. Zhang, Z.Y.; Shao, L.Y.; Zhang, S.H.; Jia, G.L. Distribution of mixed crude in western arc structural belt of Taipei Depression in Turpan-Hami Basin. *Acta Pet. Sin.* **2005**, *26*, 15–20.

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