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A B S T R A C T

Significant breakthroughs of shale gas exploration have been made in Lower Cambrian and Sinian shale in the north margin of the Yangtze Block, South China. The drill wells with industrial gas flow located in the southern margin of the Huangling dome. Base on the geological survey, 2D seismic, geochronological and drill wells data, the tectonic evolution history of Huangling dome was studied, and its control effect on the preservation condition of shale gas was discussed. The result shows that the Huangling dome might undergo four tectonic stages: (1) About 800 Ma, granite intrusion in the Huangling dome basement, primarily of granites replaced metamorphism rocks; (2) 800−200 Ma, no significant tectonic movement with slowly buried history; (3) From 200 Ma, multi-phase uplift and the sedimentary rocks was eroded in the core of the Huangling dome. Shale gas in the Cambrian and Sinian strata was well preserved in the margin of the Huangling dome as the following reasons: (1) The Sinian shale was buried about 7.8 km in-depth during Middle Jurassic, source rocks have a suitable thermal maturity for shale gas; (2) The rigid basement of the Huangling dome was mainly composed by homogeneity granite, without intensive deformation. As the main challenges of the widely distributed Lower Cambrian and Sinian shale are high-maturity and intensive deformation, a geological unit with a dome probably is a favorable zone for the old age shale gas. Therefore, it indicates that the adjacent zone of the Xuefengshan, Shennongjia and Hannan are the geological units with a dome and probably have potentials for the exploration of shale in the Lower Cambrian and Sinian.

1. Introduction

The exploration of shale gas mainly focused on the Ordovician Wufeng-Lower Silurian Longmaxi shales (Dong DZ et al., 2012; Guo XS et al., 2014; Guo TL et al., 2014). However, the Lower Cambrian and Neoproterozoic (Sinian) shale are widely distributed without industrial gas flow (Liang DG et al., 2008; Li YX et al., 2009; Zhang JC et al., 2009; Zhang DW, 2011; Energy Information Administration, 2013; Hao F et al., 2013). Recently, the significant breakthroughs of shale gas exploration have been made in the Lower Cambrian Niutitang Formation and the Sinian Doushantuo Formation in the Yichang City, South China. Drilled wells located in the south margin of the Huangling dome (Fig. 1). This dome was composed of the Proterozoic basement and Cretaceous sediments from the core to outside. As the challenge of the shale gas exploration of Lower Cambrian and Sinian strata are high-maturity and intensive deformation (Zou CN et al., 2016; Chen XH et al., 2018; Bao SJ et al., 2018; Wang YF et al., 2019), this paper aimed at studying the geological evolution history of the Huangling dome and its control effect on shale gas preservation. Based on the geological survey, 2D seismic, geochronological and drilling wells data, the authors analyze the burial history of shale, constructed the history of the geological history of the Huangling dome. The control effect of shale gas was discussed with the evolutionary history of the Huangling dome.

2. Geological background

The Huangling dome is located in the middle Yangtze area and the north margin of the Yangtze Block (Fig. 1a). As

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an exposed area of the oldest basement of the Yangtze Block and its typical sedimentary sequences from Neoproterozoic to Cenozoic, it provides a suitable place to understand the tectonic evolution of this dome (Fig. 1). It primarily consists of the Late Archaean-Early Proterozoic metamorphic gneiss series named the Kongling Group and massively intruded by Neoproterozoic Huangling granites (Ma DS et al., 1997, 2002). The Liantuo Formation of the Nanhua System, a sedimentary caprock, deposited as coverage with unconformity in the basement (Fig. 1b). Sinian-Jurassic sedimentary rocks, from old to young, constructed a dome structure (Zhang HD, 1986; Jiang LS et al., 2002; Li YL et al., 2007; Ji W et al., 2014).

Sedimentary covers, from the core to outside become younger surrounding the Huangling dome, are found in Sinian System through Mesozoic Group. The southern margin is mainly Sinian-Ordovician sedimentary rocks, with the Cretaceous unconformity covering above Paleozoic strata (Fig. 1b).

The sedimentary cover mainly dips southward, with two major faults: Tianyangping Fault and Xiannüshan Fault (Fig. 1b), a thrust fault and a strike-slip fault respectively. There are mainly two sets of organic-rich shales in Lower Cambrian Niutitang Formation and Sinian Doushantuo Formation (Hubei Geological Investigation Agency, 2011), featured by widely distributed, great thickness and high organic carbon content. Two geologic survey wells, namely Well ZD1 and Well ZD2, were drilled (whole-interval coring) to 862 m and 1446 m respectively. Niutitang shales are 104.0 m and 63.3 m in thickness respectively, including 97.0 m and 41.5 m intervals with total organic carbon (TOC) more than 1%. Doushantuo black shales are 142.6 m and 141.0 m in thickness respectively, including 108.0 m and 41.6 m intervals with TOC more than 1%. Field analysis of gas-bearing property indicates that the two layers of shale contain more than 1 m^3/t of gas (Fig. 2). Several hundred-kilometer 2D seismic lines were carried out in the study area (Fig. 1b), to clarify the geometry characteristics of the area. Based on the survey wells and 2D seismic results, a parameter well (EYY1, Fig. 2b) was drilled 3509 m in depth. This drilled well obtained 8.31% and 10.42% in the max total hydrocarbon during drilling in the Lower Cambrian Niutitang Formation and Sinian Doushantuo Formation shales. The gas content in the field of these two shales is up to 4.48 cm/t and 4.80 cm/t respectively. After a hydraulic fracturing in the vertical well, shale gas flow was obtained and the gas production rate up reaches 5460 m^3/day. After drilled horizontal well, the gas production rates are 78×10^3 and 53×10^3 m/day shale gas flow

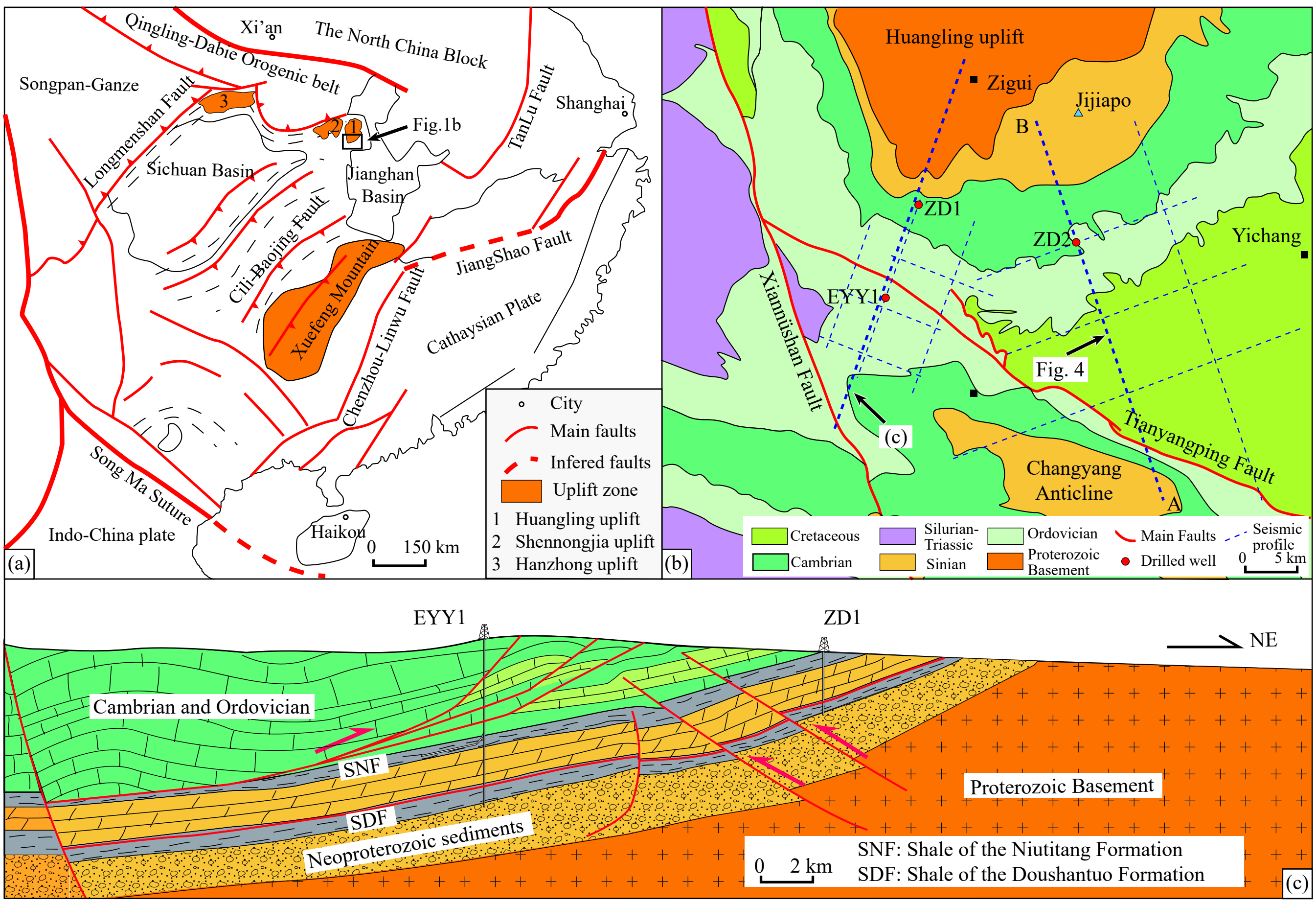

Fig. 1. The geological map of Huangling dome. a–tectonic position of the Huangling dome (modified from Ji W et al., 2014); b–geological map of Huangling dome southern wing (after Hubei Geological Investigation Agency, 2011); c–geological section of Huangling dome southern limb (based on 2D seismic sections).

in the Lower Cambrian and the Sinian shale.

3. Geological evolution of the Huangling dome

3.1. Burial history analysis

Two drilled wells ZD1 and ZD2 are selected to reconstruct sedimentary burial history and hydrocarbon generation history, with PetroMod software (Piñero et al., 2016; Bücker et al., 2008). Combined with previous studies (Lu QZ et al., 2007; Liu HJ et al., 2009; Li TY et al., 2012), regional geology survey and drilled wells (Hubei Province Bureau of Geology and Mineral Resources, 1996; Liu HJ et al., 2009; Guo YF, 2010; Xiao ZH, 2010), the parameters of modeling are listed at Table 1. Paleogeodetic heat flow shows a low-high-low trend since the Early Paleozoic (Xu ES et al., 2015). The previous reconstruction of the thermal history indicates that the middle Yangtze area had a steady increasement from 50 mW/m^2 to 68 mW/m^2 start at Early Paleozoic to Late Permian. While from Late Permian to present, paleo heat flow has been decreasing, to 42 mW/m^2 (Lu QZ et al., 2007). Li TY et al. (2012) calculated the adjacent Jianhan basin has 63–43 mW/m^2 in heat flow from Late Triassic till now. Liu J (2008) calculated the heat flow of the middle Yangtze area is between 46–42 mW/m^2 at present. In this paper, the authors set heat flow values of the two wells are 42 mW/m^2 and 46 mW/m^2 respectively (Table 1), which represent the characteristic heat flow values of this area.

This middle Yangtze area has significant erosion during Yanshanian and Himalayan tectonic events since the Jurassic. Lu QZ et al. (2007) calculated the denudation thickness between the unconformity Mesozoic and Cenozoic with 2800 m, in a Jian28 well located about 100 km west to the study area. Guo YF (2010) calculated the denudation thickness of seven typical wells in the middle Yangtze area and the result

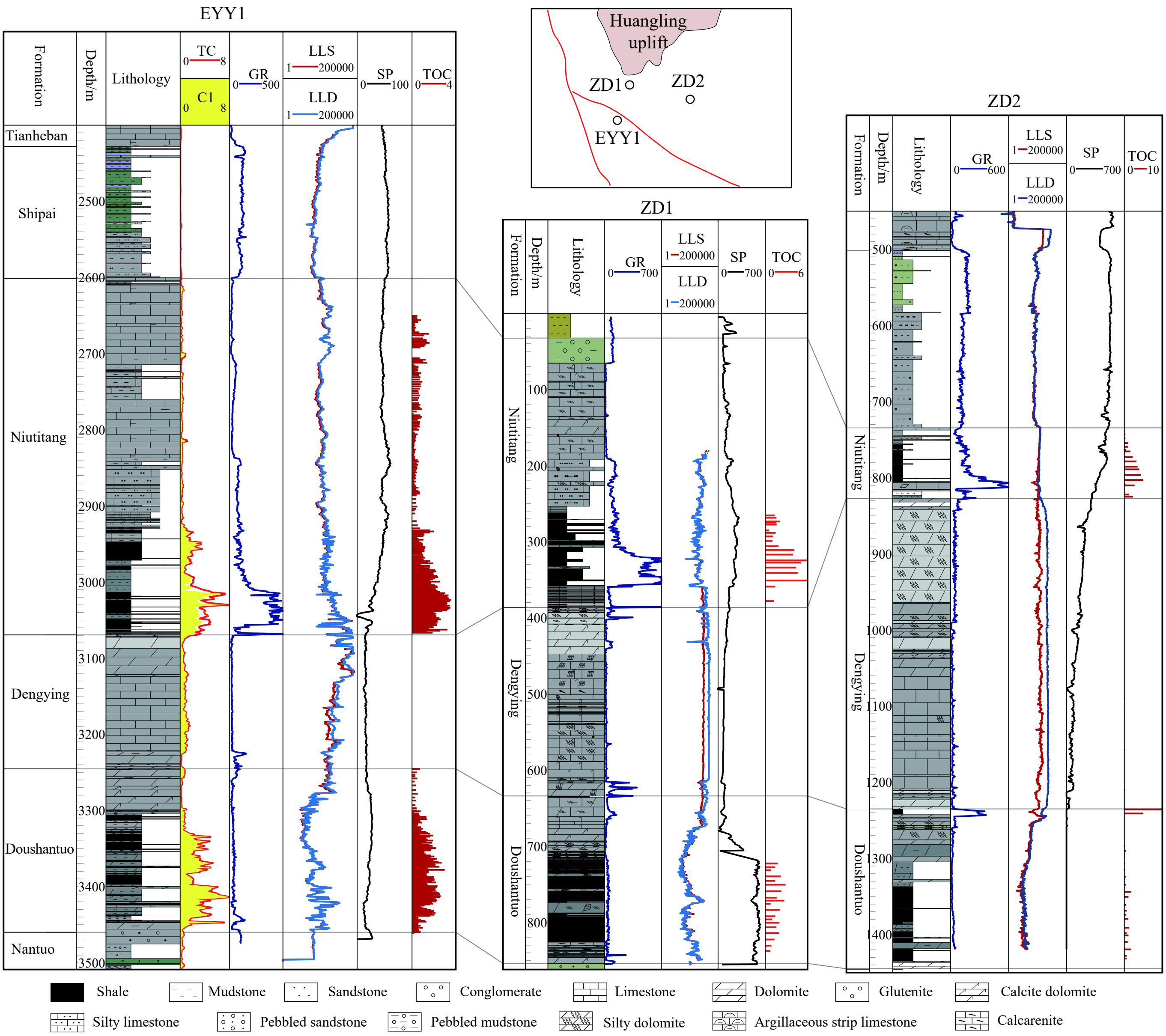

Fig. 2. East-West comparison of drilled wells EYY1, ZD1 and ZD2 (refer to Fig. 1b for the position).

Table 1. The table of the burial-hydrocarbon generation history simulation key parameter of the Well ZD1 and Well ZD2 (partial data from Lu QZ et al., 2007; Liu J, 2008).

Well No.	Depth/m	*Ro*/% (mean)	TOC/% (mean)	Denudation layer	Denudation time/(Ma B. P.)	Denudation thickness/m	Heat flow value /(mW/m^2)
ZD 1	861.86	1.69	2.95	Cam_1–J_3	153–0	5300	42
ZD 2	1445.81	2.59	2.67	Cam_3–J_3	155–0	5600	46

indicates that in the Yanshanian Period, the denudation thickness is 4145.2 m to the maximum. Li TY et al. (2012) studied zircon and apatite fission-track and vitrinite reflectance data in the western Jianghan Basin. The result shows that two significant buried depth heating processes and two major tectonic uplift-denudation cooling events, with the maximum denudation thickness being 4800 m and 2400 m respectively. This study calculates denudation thickness by Well ZD1 and Well ZD2 with the paleothermometer vitrinite reflectivity method, the result shows that during the Caledonian Period, the denudation of this study area was small and negligible. Obvious denudation occurred in Hercynian Period and slight denudation occurred in the Indosinian Period, while denudation thicknesses were up to the maximum in Yanshanian and Himalayan periods, totaling to 5300–5600 m (Table 1). Basin modeling program indicates that paleo surface temperature averages at 22.5℃ and paleo water depth ranges between 0–225 m. The burialhistory and hydrocarbon generation evolution history are reconstructed for two wells using the Easy%*Ro* model (Fig. 3).

As indicated by the burial history reconstruction of the Well ZD1 and Well ZD2 wells, the study area is characterized by early period sustained subsidence –middle period uplift–late period deep denudation, consistent with the drilling thermal simulation result of Jianshi 100 km west to the study area (Xiao ZH, 2010). Before the Caledonian Period, the study area was in a stable sustained subsistence and burial process. During the Indosinian Period, subtle tectonic deformation and obvious differential lifting and subsiding occurred in this area, with the Zigui Basin beginning to form.

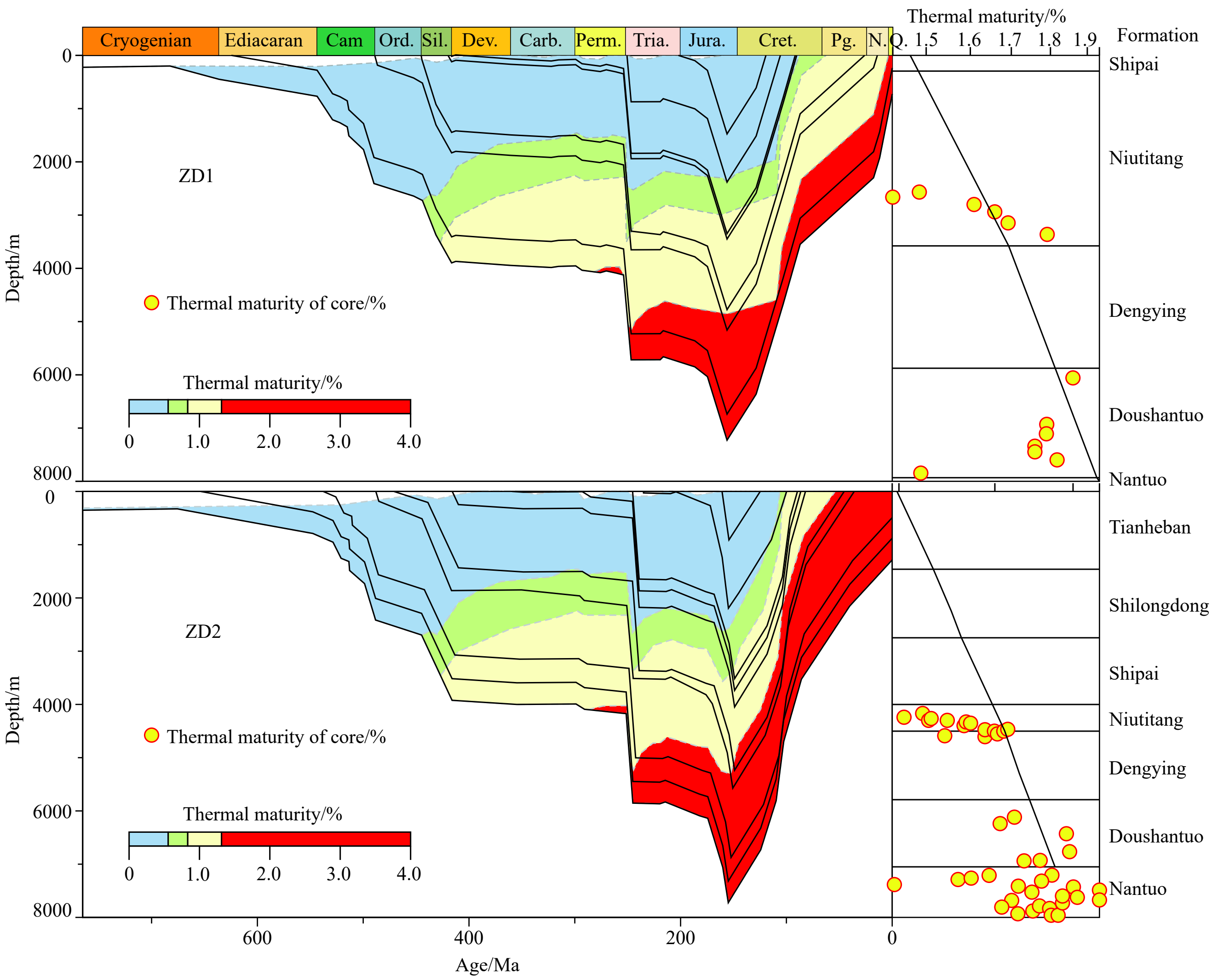

Fig. 3. Sedimentary burial history analysis of Well ZD1 and Well ZD2.

Lower Jurassic–Middle Jurassic were of fast subsiding stage and before the intense uplift at Early Yanshanian Period end, the maximum burial depth was up to about 7800 m. After the Yanshanian-Himalayan periods, the uplift stage followed exposure large-area Lower Paleozoic strata.

According to previous thermal history simulations (Lu QZ et al., 2007; Xiao ZH, 2010), the middle Yangtze area had a small paleogeothermal gradient during Sinian-Lower Ordovician, at about 2.2℃/100 m at Sinian, about 2.3℃/100 m at Cambrian, about 2.4℃/100 m at Ordovician. In Middle Ordovician, tectonic deformation became more intensive in South China, the Silurian geothermal rose to about 2.6℃/100 m. At the end of Silurian, influenced by Guangxi Movement, Carboniferous (C) geothermal gradient rose slightly to around 2.7℃/100 m, around 3.0℃/100 m at Permian, Triassic-Cretaceous (T-K) around 2.4℃/100 m. During the Himalayan Period, thermal subsidence occurred in the South, reducing Quaternary (Q) geothermal rise to around 1.8℃/100 m.

Based on the above parameters, hydrocarbon generation history simulation data of Well ZD1 and Well ZD2 are interpreted. The result shows that for Well ZD1, Niutitang Formation shale entered the oil generation stage during Middle Silurian and stagewise approached its peak of oil generation, reached thermo-cracking-condensate oil and gas stage at the end of Permian, finalizing its thermal evolution during Middle Triassic (Fig. 3). Now, with *Ro* at 1.43% –1.79%, Niutitang Formation shale is at its highly mature thermal evolution stage. The hydrocarbon generation evolution process came slightly earlier in Well ZD2 than in Well ZD1: Niutitang Formation shale entered the oil generation stage at the end of Lower Silurian and stagewise approached its peak of oil generation, reached thermo-cracking-condensate oil and gas stage at the end of Permian. The fast burial process in the Late Hercynian-Indosinian cycle enabled the degree of the thermal evolution of organics to increase quickly. The Niutitang Formation shale reached the thermo-cracking-dry gas stage at the Late Middle Triassic and finalized its thermal evolution at the end of the Jurassic. At present, the Niutitang Formation shale is at its overmature thermal evolution stage, with 1.97%–2.59% in *Ro* value.

3.2. 2D seismic profiles interpretation

2D seismic profiles and interpretations were carried out in the study area, with a 5 km-apart 2D seismic grid (Fig. 1b). A 2D seismic profile (refer to Fig. 1b for its position) across Tianyangping Fault was exhibited in this paper, with an NNW-SSE strike direction. In the north, it shows the contact zone between sedimentary cover and basement. In the south, the section crosses Tianyangping Fault and reaches the Changyang anticline. Well ZD2 is located in the northern slope part of this section. This section shows that the Tianyangping Fault is an imbricate thrust fault, with a large dip angle in surface but a small one in deep (Fig. 4). The thrust displacement is more than 5 km, inferred by the position of sedimentary layers. The hanging wall of the Tianyangping Fault has experienced intensive deformation and long-distance transformation. In contrast, Cretaceous strata deposited above the footwall of Tianyangping Fault, indicating that the fault occurred after the Late Cretaceous. The continuous reflects shows that the deformation has less influence on the footwall of the Tianyangping Fault. The high gas content of Well ZD2 indicates that the footwall area is a favorable shale gas zone.

3.3. Chronological data

Huangling dome is a hot spot of geologic research in South China with Precambrian basement outcrops and arge amount of published chronological data. This study collects chronological data from different methods of different closed temperatures, including U-Pb age, Rb-Sr age and Ar-Ar age, etc (Fig. 5). According to previous studies, the zircon U-Pb age of Huangling granites is 794–837 Ma, peaking at 810 Ma,

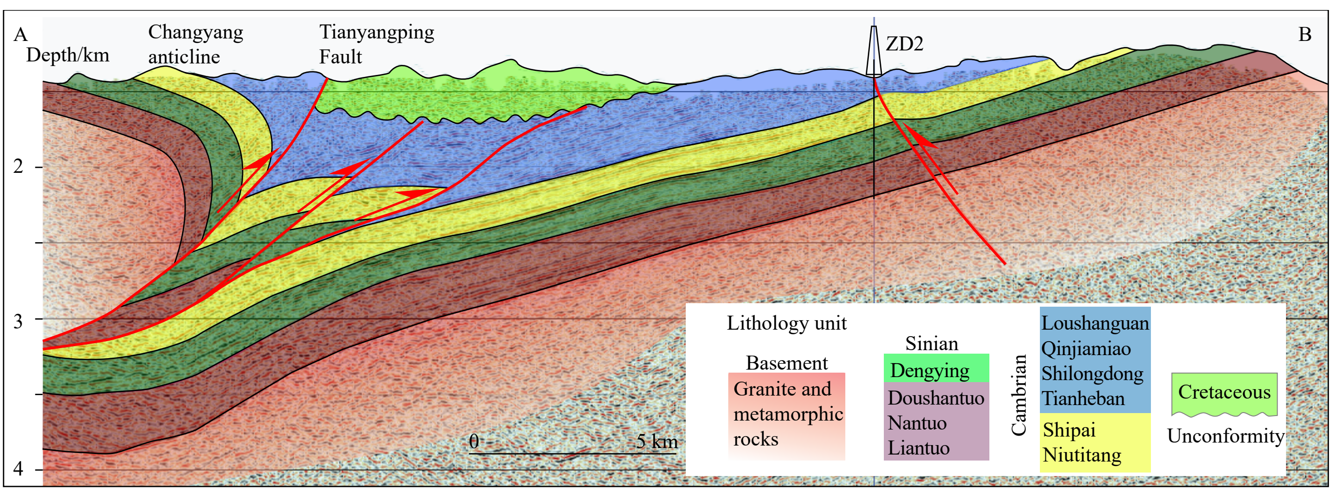

Fig. 4. Geological section of southern margin of Huangling dome across Tianyangping fault according to 2D seismic data (refer to Fig. 1b for the position).

which represent their emplacement age (Fig. 5a; Ma GG et al., 1984; Feng DY et al., 1991; Li ZX et al., 2004; Li ZC et al., 2002; Ling WL et al., 2006; Zhang SB et al., 2008, 2009; Gao W and Zhang CH, 2009). For the diorite-quartz diorite complex, the mineral Rb-Sr isochron age is 805±5 Ma, possibly the initial cooling age of intruded granite (Feng DY et al. 1991). The amphibole and biotite $^{40}Ar/^{39}Ar$ age range 770–900 Ma (Hu SL et al., 1989; Li ZC et al., 2002). To constrain the uplift age of the Huangling dome, low-temperature chronology studies have been carried out (Li ZX and Li XH, 2007; Hu SB et al., 2006; Hu JM et al., 2012; Shen CB et al., 2009; Richardson NJ et al., 2010; Xu CH et al., 2010; Li ZX and Shan YH, 2011; Ji W et al., 2014). Apatite fission-track data ranges between 87–137 Ma and peaks at 120 Ma (Fig. 5c); three sets of zircon fission-track age distributions are 158±50 Ma, 178±34 Ma and 195±14 Ma, respectively, with a large range of errors. Phosphorite's He age spans from 39 Ma to 102 Ma and mainly concentrates on 40–45 Ma. Zircon He age is dispersed, ranging between 121–309 Ma. Moreover, Liu HJ et al. (2009) indicate that Huangling dome uplift in 100–165 Ma by sampling nine apatite fission-track ages from Cambrian, Silurian, Jurassic and Cretaceous clastic rocks in east margin of the Huangling dome.

4. Discussions

4.1. The tectonic evolution history ot the Huangling dome

This study makes a comprehensive analysis of the tectonic evolution data obtained from the three methods: (1) Well ZD1 and Well ZD2 drilling sedimentary burial history. As the two wells exhibit similar drilling analysis structures, data from the deeper Well ZD2 are chosen; (2) Knowledge of the main unconformity and fault contact relationship from field geologic surveys and 2D seismic data; (3) Geochronology statistics obtained using multiple methods. Correspond sedimentary burial history to depth, geochronological data to temperature, use the 2.5℃/100 m linear relation to represent depth *vs.* time (Lu QZ et al., 2005) and mark major tectonic events in a coordinate system. The result indicates that geochronological data and sedimentary burial history data of Well ZD2 match well with major tectonic events (Fig. 6). The zircon U-Pb age of Huangling granites is 800 Ma, indicating the time of magmatic intrusion. Most outcrops at the nucleus of Huangling dome are granites (Hubei Geological Investigation Agency, 2011), and gravity and magnetic data show that below its Sandouping rock mass, there exists a large low-density area (Zhang Y et al., 2012), implying an even larger distribution area of the rock mass deep in the subsurface. This indicates that during the Early Sinian in the

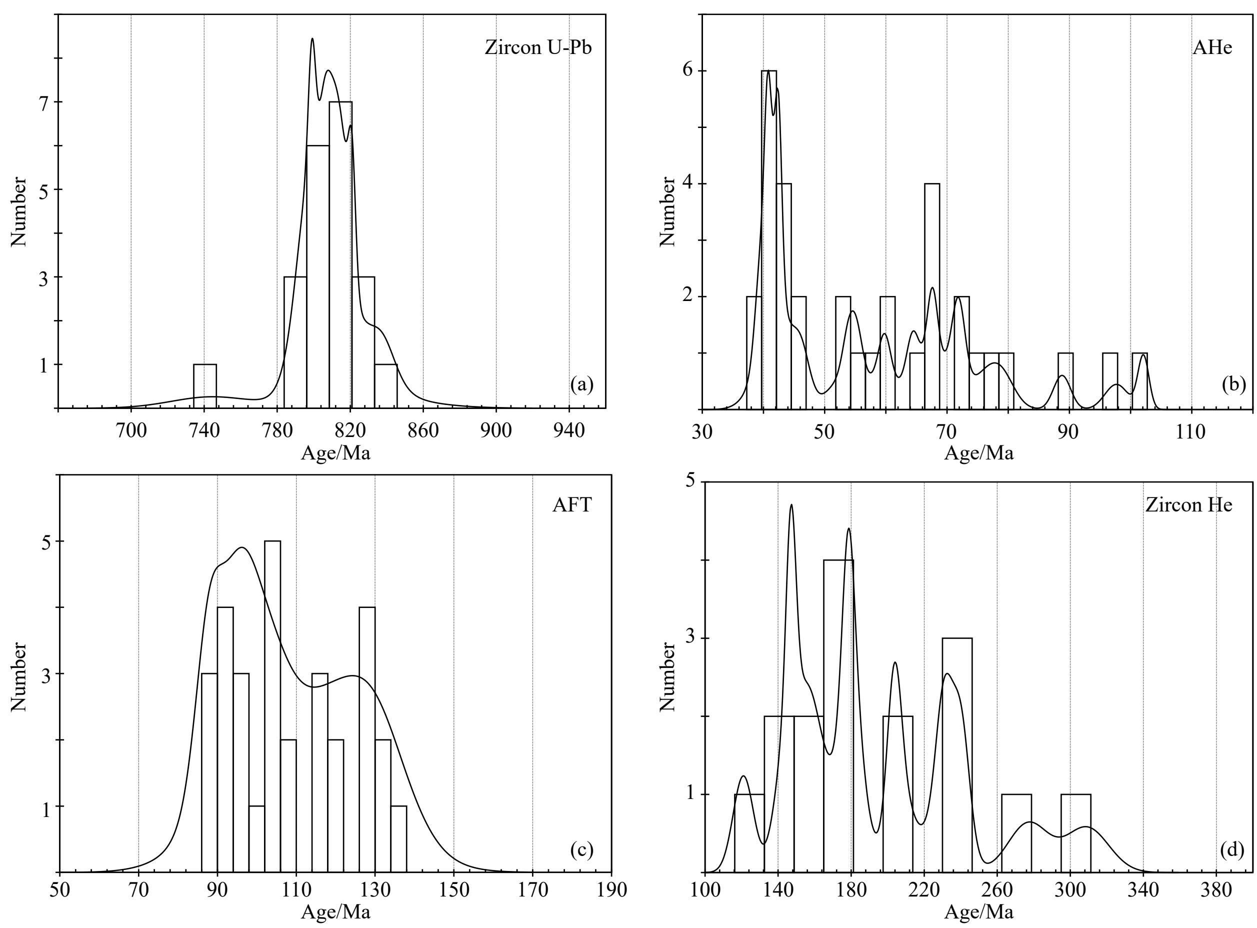

Fig. 5. Chronological data statistical graph of Huangling dome and its surrounding area. a–zircon U-Pb dating data; b–the helium of the apatite dating data; c–apatite fission-track dating data; d–the helium of zircon dating data.

Neoproterozoic Era, Huangling dome metamorphic rock basement was probably transformed into a “rigid basement” of strong homogeneity composed primarily of granites, while after Huangling dome was intruded by granites, the strata above the basement received continuous sediments.

The 800–200 Ma dating data (Fig. 6) is not available for Huangling dome, but due to lack of Devonian–Carboniferous strata, and in combination with the fact that in the whole Western Hunan and Hubei provinces, Devonian and Carboniferous strata are either missing or very thin, it is inferred that the missing of the above dating data is due to regional upheavals or sea-level fluctuations, while in Huangling dome, tectonic reworking activities were not intense. For zircon deposited in about 200 Ma, the temperature corresponding to the He age is around 180℃ and depth around 7.2 km, while according to sedimentary burial history analysis, during this period, the sedimentary strata were burial progressively deeper, up to 7.8 km during Middle Jurassic. However, the chronological results of this period span a large distribution range from 121 Ma to 309 Ma, which is probably related to testing precision, sample lithology and tectonic position (Shen CB et al., 2009).

According to the apatite fission-track test, the age range from 87 Ma to 137 Ma, the corresponding temperature 120℃ and burial depth about 4.8 km, with ages concentrating at 120 Ma. For Well ZD2, the sedimentary burial history analysis matches perfectly with the chronological data in this period (Fig. 6), indicating that a fast uplift event occurred during the Cretaceous and uplift rate changed at about 120 Ma.

The apatite He age spans from 39 Ma to 102 Ma and mainly concentrates at 40–45 Ma that is highly consistent with the sedimentary burial history of Well ZD2 (Fig. 6). As per 2D seismic data (Fig. 4), this uplift tectonic process was accompanied by the NE thrusting of Tianyangping Fault, while Xiannüshan strike-slip Fault activities continued till Neogene (Zhang F et al., 1998).

4.2. Effect on shale gas preservation

The key tectonic evolution history of Huangling dome is divided into four stages: (1) Huangling dome metamorphic rock basement was intruded by granites at about 800 Ma, shaping a rigid basement composed primarily of granites (Fig. 7a); (2) During Middle Jurassic, Huangling dome and surrounding area were burial to the maximum depth and at Late Jurassic, uplifting started, influencing strata distribution to the east and west of Huangling dome (Fig. 7b); (3) In Upper Cretaceous, Tianyangping Fault activities commenced, Paleozoic strata were thrusted to above Cretaceous strata and subsequently, Xiannüshan Fault began to strike-slip and dislocate Tianyangping Fault (Fig. 7c); (4) Massive denudation occurred to Cretaceous strata and Xiannüshan fault activities continued till Neogene (Zhang F et al., 1998), leading to the current tectonic pattern (Fig. 7d).

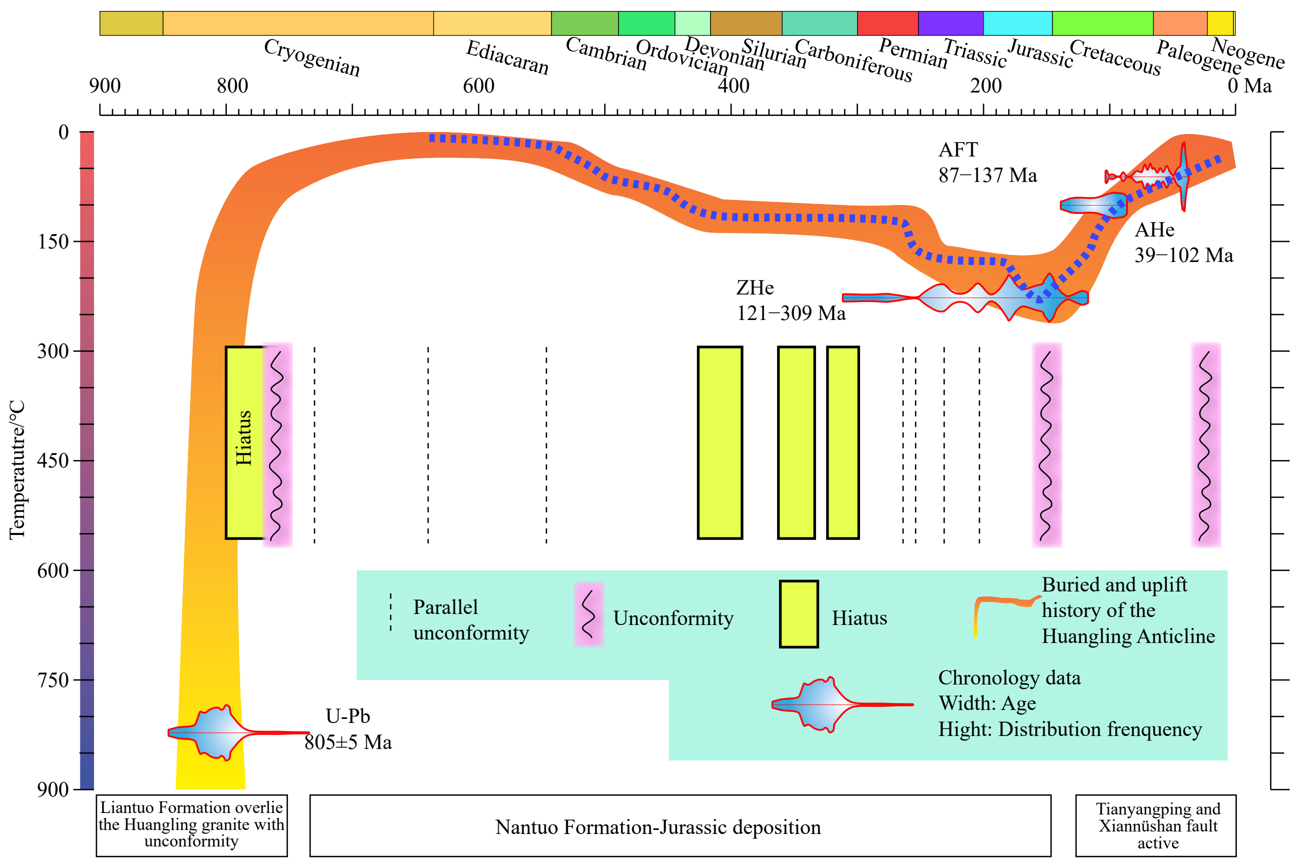

Fig. 6. The tectonic evolution history of Huangling dome basement (Refer to Fig. 3 for sedimentary burial history data; refer to Fig. 5 for geochronological data). U-Pb–zircon uranium-lead age; ZHe–zircon helium age; AFT–apatite fission-track age; AHe–apatite helium age.

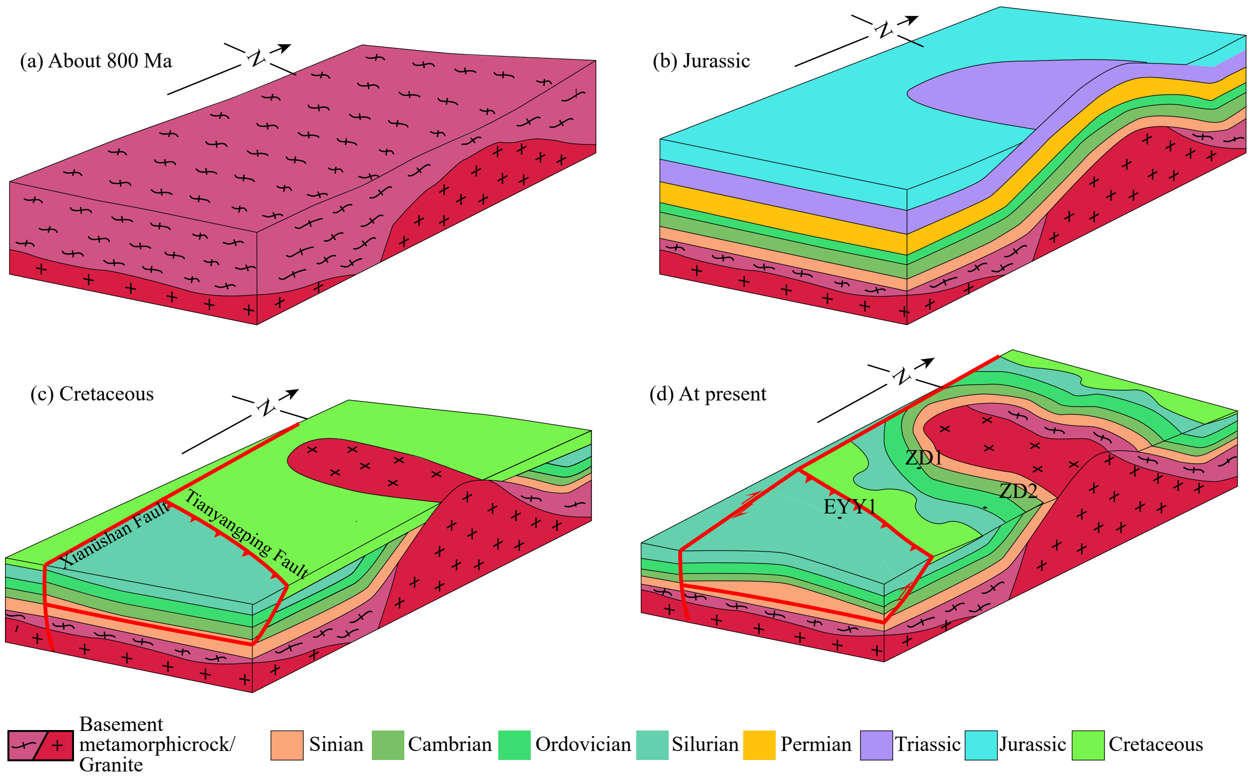

Fig. 7. Schematic illustration showing Huangling dome uplifting. (a–continuous deposition in Huangling dome and its adjacent area during Triassic; b–Huangling dome started to lift during Late Jurassic; c–Tianyangping Fault and Xiannüshan Fault began to take shape during Late Cretaceous; d–the current tectonic geometry takes shape.

When it comes to Well ZD1 and Well EYY1, etc. surrounding Huangling dome, Lower Cambrian Niutitang Formation shale cores are complete, indicative of the anti-deformation effect of Huangling dome rigid basement for the area's tectonic structure; Huangling dome uplifts later, which, to some extent, ensures Sinian and Cambrian strata deposited earlier free of serious damages during the long geological periods, while post-Yanshanian tectonic processes only result in several nappe structures in shallow layers, without any material damages to the preservation of shale gas from Sinian and Cambrian strata in the footwall of the fracture. Shale gas preservation conditions are better in the southern wing of Huangling dome, with breakthroughs made in Lower Cambrian and Sinian shale gas.

Huangling dome peripheral region, the footwall area of the fracture, in particular, boasts favorable shale gas preservation conditions, with moderate-maturity organic-rich shale and simple stratigraphic structures, paving a way for paleo-strata shale gas exploration in South China. Shale gas preservation involves two elements of space and time. In terms of space, there are vertical (top and bottom cap rock conditions) and lateral controlling factors. Oil and gas migrate 2 –8 times faster laterally than vertically (by courtesy of Sinopec Exploration Company), as a result, the distance between shale and the open boundary is the main controlling factor of lateral oil/gas migration, where, the open boundary refers primarily to tension fractures and outcrops. In terms of time, concerns mainly include burial depth (undue burial depth of shale will lead to excessive maturity) and organic-rich shale evolution history (is there any spatial diffusion of the liquid or gaseous hydrocarbon?). The challenge here is how to reconstruct the sedimentary tectonic history of the geological body in question, but the fundamental issues are basic sedimentary and tectonic geological ones.

In Western Hunan and Hubei provinces, Lower Cambrian Niutitang Formation shales of great thickness and high organic content are found surrounding Xuefengshan dome, Shennongjia anticline, Hannan paleo-land and its adjacent areas (Liang DG et al., 2008), with its tectonic characteristics similar to Huangling dome, which is instrumental in shaping moderate-maturity and weak tectonic reworked shale gas preservation conditions, and therefore it is the direction for subsequent shale gas exploration in paleo-strata in South China.

5. Conclusions

The Yangtze basement metamorphic rocks hosting Huangling dome were massively replaced by Neoproterozoic granites, and Neoproterozoic sedimentary rock (Liantuo to Dengying Formation) unconformity covered the paleo-basement, receiving continuous sediments. During Hercynian and Indosinian periods, tectonic uplift activities were weak, and the unconformity surface therein was a result of regional settlement. At the bottom, Middle Jurassic rocks were burial and uplifting began in the Late Jurassic. The nucleus of Huangling dome was lifted to the maximum extent and denuded to Neoproterozoic granites, with a metamorphic rock basement partially remained, resulting in the present tectonic pattern.

In the southern margin of Huangling dome, shale gas preservation conditions are favorable for two reasons. First, the basement is primarily composed of Proterozoic granites with homogeneous mechanical properties and as a basically complete tectonic element in the sedimentary tectonic evolution process, is less reworked by the fracture and fold; Second, the burial depth of the shale gas strata series is moderate, with Doushantuo Formation being the deepest at 7800 m, and the degree of thermal evolution is also moderate, conducive to hydrocarbon generation from organics and accumulation in shales.

In paleo-strata in South China, such as Lower Cambrian Niutitang Formation, Sinian Doushantuo Formation, organic-rich shales are widely distributed in great thickness and, with moderate maturity and favorable tectonic preservation conditions, are keys for shale gas accumulation. Xuefengshan dome, Shennongjia anticline and Hannan paleo-land and other complex tectonic areas in South China, exhibit paleo-uplift tectonic characteristics similar to Huangling dome, with their adjacent areas being favorable targets for paleo-strata shale gas exploration. A study on basic sedimentary geology and tectonic preservation, as well as in-depth exploration, are recommended.

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