A Study of Thermal History Since the Paleozoic in the Eastern Qaidam Basin, Northwest China

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Abstract: Qaidam Basin is the one of three major petroliferous basin in Northeastern Tibetan Plateau, which experienced multiphase superimposition and transformation. A study on thermal history not only plays an important role on analysis the tectonic origin of the Qaidam basin, revealing the forming mechanism and uplift history of Tibetan plateau, but also is available to provide scientific evidence on oil & gas resources appraising. Using balanced cross-sections technique, and combination of analysis of apatite fission track ages with modeling of fission track length distribution, it was infered that eastern Qaidam basin experienced significant tectonic movement in the early Jurassic movement (～200 Ma), which caused the carboniferous uplift and denudation, the geological movement in late Cretaceous, characterized by stretch in the early and the northeast-southwest extrusion in late; Himalayan movement in multi-stage development in the eastern Qaidam basin, Mainly divided into the early Himalayan movement (41.1～33.6 Ma) and the late Himalayan movement (9.6～7.1 Ma, 2.9～1.8 Ma), which large-scale orogeny caused pre-existing faults reactivated in late Himalayan movement. On the basis of burial history reconstruction, thermal history of eastern Qaidam basin was restored, the result show that thermal history in eastern Qaidam basin overall shows slow cooling characteristics, the paleo-geothermal gradient of eastern Qaidam basin was 38～41.5℃/km, with an average of 39.0 ℃/km in late Paleozoic, 29-35.2℃/km, with an average of 33.0℃/km in early Paleogene, the geothermal gradient of Qaidam basin increased in the late Paleogene, and it was similar to present geothermal gradient in the late Neogene. The characteristic of tectono-thermal evolution since Paleozoic in the eastern

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Qaidam Basin was mainly controlled by magmatic thermal events in the study area.

Key words: Thermal history; Balanced cross-sections technique; Fission track; Eastern Qaidam Basin

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0 Introduction

Northeastern Tibetan Plateauis a mosaic of different plates or blocks covered by various basins. Regional tectono-thermal history can provide evidence for studying the intracontinental or intraplate dynamics and also provides the basis for hydrocarbon generation of source rocks in the basin, which can be applied to assess the prospect of petroleum. As an important tectonic unit in the Tibetan Plateau and one of the three oil and gas bearing basins in western China, thermal history research is significant for the research on tectonic origin and palaeogeomorphic evolution of Tibet Plateau and periphery (Yin et al., 2008), which also supports the exploration and development of oil and gas resources in the basin.

Study on thermal history since Paleozoic in the Qaidam basin has been scarce. The temperature distribution up to 3 km below the surface in the western Qaidam basin was studied (Wang et al., 1990), and the terrestrial heat flow in boreholes of the western Qaidam was calculated (Shen et al., 1994; Qiu et al., 2001). The primary methods in previous research for the thermal evolution of the Qaidam basin were used to recover the paleo-geothermal information from fluid inclusions and vitrinite reflectance (Ren 1993). Beside traditional methods, the apatite or zircon fission track method has been used to research the thermal history or the uplift processes of western Qaidam and the peripheral mountains (Qiu et al., 2000; Sun et al., 2009; Gao et al., 2011). The relation between the uplifting of the Qaidam basin and the Eastern Kunlun orogeny was discussed using low-temperature thermochronology (Yuan et al., 2005; Wang et al., 2010). In summary, regional research mainly focuses on the western basin while research on the northern margin and in the eastern Qaidam basin since Paleozoic is scarce. Most research on thermal history has focused on the Cenozoic, while the study on the Paleozoic and Mesozoic has not yet involved. Research on the burial and subsidence of the Carboniferous period has not been studied systematically. Well logging data was used in thermal history research prior to the 1990s and the quality of data today has improved significantly in comparison to the historical low-temperature thermochronology data.

In recent years, the Carboniferous period was intercepted in drill holes such as Chaiye 2, Qingdedi 1, Gaqiu 1, Huocan 1, and Shiqian 1. The data obtained from the samples at the drill cores and outcrops provided prerequisite information for the study of the thermal history of the basin. The primary tectonic stages during the Paleozoic in eastern Qaidam were analyzed using balanced cross-section and apatite fission track methods. The burial processes and thermal histories were reconstructed based on borehole and paleo-geothermal data (from vitrinite reflectance and fission tracks). This study establishes the thermal history during the Paleozoic by analyzing the uplift processes from Paleozoic to Cenozoic. The data were cross-referenced using geodynamical and tectonic principles and methods based on the geothermal evolution history of the basin, which contains important information for understanding the dynamic mechanisms occurring in the thickening lithosphere in western China.

1.Geological setting

The Qaidam basin, which is located in the northeastern Tibetan Plateau, is bounded by the Qilian mountains to the northeast, the Altyn Tagh mountains to the northwest, and the Kunlun mountains to the south (Fig. 1). It is a large Cenozoic intermountain basin with a diamond shaped double crystalline basement. It experienced multiple phases of deformation such as multiple island intercontinental oceans, extensional rifting oceans, residue troughs, and inland basins (Liu et al., 2001; Zheng et al., 2004). The sytudy area in this paper includes the northern edge of Qaidam basin and the Delingha fault depression (Fig. 1B). Proterozoic, Paleozoic, and Mesozoic strata exposed in these areas formed the main body of the pre-Mesozoic terrain of the Qaidam basin (Fig. 2), they were buried to different depths, boundaries of J_3+k/N_1 and C/ J_3+k are regional unconformity (Fig. 2).

Fig. 1 A Tectonic map of the Qaidam basin; Fig. 1 B Sketch map of the geology and samples sites in the eastern Qaidam basin (Revised after Wang et al., 2005); Fig. 1 C The Geologic cross section across the Delingha fault depression

Fig. 2 Synthetic strata histogram of the eastern Qaidam Basin

2. Main tectonic stages of the eastern Qaidam basin

Research on the main tectonic stages is prerequisite for recovering the burial and thermal evolutionary history. The burial history can be recovered by back stripping the remaining strata along with using the overpressure analysis technique. The thermal evolution history of the basin was reconstructed through the study of the burial history, heat flow at the bottom of the basin, the change in thermal physical parameters of the formation, and denudation. The main tectonic stages of eastern Qaidam were analyzed using balanced cross section and fission track thermochronology methods based on the regional background.

2.1 Balanced cross section technique

The balanced cross section technique is a method used to reconstruct the tectonic evolutionary process of a basin (Chamberlin 1910; Judge et al., 2011; Zhang et al., 2012; 2015; Hu et al., 2008; Fang et al., 2018). The SE-NW seismic profile was chosen to display and represent the tectonic evolution. The profile running from south to north comprises the Yongjia fault terrace, the Huobuxun depression, the Aimunike hill, the Ounan depression, and the Oulongbuluke hill, and the corresponding strata are Carboniferous, Jurassic, Neogene, and Quaternary. The profile (Fig. 3 C aa'cross section) displays the tectonic features of the studied area in north to south direction. At the end of deposition of Paleozoic, it was a wide-sea sediment in entire basin. It experienced lower Carboniferous transgression, which developed from terrestrial fan deltan to carbonate platform, and from costal shore tidal flat, barrier island to carbonate platform in upper Carboniferous transgression.

The faults which controlled mountains and the sags were formed due to the Indo-China movement. For example, the Yongjia and Aimunikeshan faults in front of the Kunlun Mountains and the Ainan and Ounan faults in front of the Oulongbulukeshan, formed a series of NW trending uplifts, which are the prototypes of the ranges today. Traces of the Carboniferous on the Yongjia fault terrace and the Aiding low uplift, which are on the hanging wall of the faults, were completely eroded, as denoted by the drill holes intersecting Devonian and Proterozoic metamorphic rocks. Folds controlled by NW and NS faults formed in depressions. During the Carboniferous period, the hanging wall was uplifted and eroded to various degrees as a result of the faulting activity. The relatively thicker residue strata on the footwall formed a series of dustpan like depressions, such as small residue depressions in the Huobuxun depression and east to west trend depressions in the Ounan sag, which were affected by this phase of tectonic movement.

In the Early and Mid-Yanshanian, a weakly faulted-depression lake basin characterized the Early Jurassic-Late Jurassic basin (Shang et al., 2014). The Early-Middle Jurassic was in a relatively weak extensional stage with relatively limited distribution mostly in the Huobuxun sag.

On the other hand, the present-day Ounan sag is characterized by uplift and received no sedimentation during the Middle-Jurassic. During the Late Jurassic-Early Cretaceous, the whole region received sedimentation, with depression basin characteristics.

During the late Yanshanian large-scale tectonic movement, and under the intense northeast-southwest compression, the Oolongbuluke and Emnik uplifts formed. The lack of evidence of the whole Mesozoic indicates that the uplifted areas, once again, suffered from strong erosion.

Large-scale mountain building activity in the Late Himalayan activated ancient faults such as the Ainan and Ounan, which controlled the mountains and depressions. Two uplifts continually developed with the Oulongbuluke Mountain being thrusted to the surface.

2.2 Apatite Fission track

2.2.1 Technical principle

Fission track (FT) thermochronology is a dating analysis technique based on the radiation damage characteristics of the ^{238}U nuclear fission in minerals (Gleadow et al., 1983; Yang et al., 2017). The density and length of fission tracks are controlled by time and temperature (Yang et al., 2017).

Fig. 3 Tectonic evolution sections in the eastern section of Qaidam

The apatite fission track thermochronology method has proven to be a mature approach to define low temperature evolutionary history and has been widely applied to determine time limits of orogenic uplift, the analysis of material source, paleo-morpholygy, paleothermal evolution, and fault movements (Armstrong 2005; Yu et al., 2013; Chen et al., 2014; Gao et al., 2014; Li et al., 2014; Wang et al., 2008).

2.2.2 Sampling and modeling

Three drill core samples were collected from coal drill holes in the eastern Qaidam basin, composed of sandstone in the Upper Carboniferous Keluke formation. Four outcropping gabbro samples of the upper Ordovician Tanjianshan formation were collected from the Tanjianshan Lianhegou - Xiaosaishitengshan section. The analysis results can be referenced to the author's published paper (Li et al., 2015). The preparation and assays were completed in the fission track labrotary of the State Key Larboard of Geological Process and Mineral Resources, China University of Geosciences following procedures detailed in the references (Gallagher et al., 1998). The neutron-fluence measurements were calibrated using CN5 uranium glass (Bellemans et al., 1994). Fission track age values were calculated using the ζ-constant method and the standard fission track age equation with a Zeta（ζ）value of 353 ± 18 (Hurford et al., 1983; 1992). The ages of the four outcrop samples (C1203-10, C1203-12, C1203-18, and C1203-39) ranged from 39 Ma to 58 Ma, which is much younger than the strata age (about 440 Ma). The average length of the fission tracks is between 10.3 μm and 11.4 μm, which is much smaller than the initial track length（16.3 ± 0.9 μm). The apatite fission track ages of the three drill core samples (Zk3-1-19, Zk3-1-74, Zk3-1-81) ranged from 61 Ma to 72 Ma and were much younger than the strata's age (about 300 Ma). The average length of the closed fission was between 11.8 and 12.7 μm, which is smaller than the initial fission tracks and is distributed in a single peak shape (Galbraith 1984).

Apatite fission track age and length data of the samples indicate that the above samples all underwent moderate annealing. The $\chi 2$ values of fission track age of the seven samples were more than 5%, indicating that apatite fission track age of the samples was a single age, and there were no multiple age groups.

In the analysis of age and length distribution, the temperature, and geologic evolution of the fission track samples were simulated using the one-component annealing model of Ketcham et al. (1999), the Monte Carlo method, and Hefty simulation software (Ketcham 2005). Thermal history modeled boundary conditions can be referenced to the author's published paper (Li et al., 2015). The modal age and closed track length of fission tracks were used as basic parameters and the initial value of Dpar was set as 1.65 while the initial fission track length was set at 16.3 μm. The simulation results of thermal evolution denote thermal-time evolutionary history since the late Cretaceous, and the character of the curves tends to be consistent (Fig. 4). Samples taken from the eastern Qaidam boreholes denoted that a fast cooling rate of about 17.2℃/Ma was experienced in the late Cretaceous. The samples began to be buried deeply during the Early Paleogene and experienced a temperature increase period of ~40 Ma. After that, three stages of uplift and cooling during the Late Oligocene (~33 Ma), Late Miocene (~7 Ma), and Pleistocene (~2 Ma), were experienced with cooling rates of 9℃/Ma, 12.3℃/Ma, 11.5℃/Ma, respectively. Four outcrop samples at Lianhegou in the Tanjianshan and Xiaosishiteshan sections of the study area were uplifted and cooled to partial annealing zones in the Late Cretaceous. The cooling rate was ~ 2.1℃/Ma, after which the samples were buried deeply and their temperatures increased. During the Late Eocene, Miocene, and Late Pliocene, the samples were subjected to uplift and cooling at cooling rates of 0.8℃/Ma, 3.4℃/Ma and 6.8℃/Ma, respectively. In summary, the samples from eastern Qaidam experienced cooling during the late Cretaceous, late Eocene, late Miocene, and late Pliocene-early Pleistocene. Analyses of the balanced section and apatite fission tracks indicate that eastern Qaidam experienced significant tectonic movement during the early Jurassic, late Cretaceous, late Eocene, late Miocene, and the late Pliocene-Early Pleistocene.

Fig. 4 Inversed sample results of the thermal history by AFT in the eastern Qadiam basin

1:acceptable paths with GOF between 0.05 and 0.5; 2: good paths with GOF more than 0.5; 3: best fit.

3 Thermal history of the eastern Qaidam basin

Various paleo-thermometers such as vitrinite reflectance, fluid inclusion, and clay minerals can be used to reconstruct the thermal history at a basin scale (Burnham 2005; Bray et al., 1992; lerche et al., 1984). Based on the analyses of the balanced section and apatite fission tracks, the geothermal history was reconstructed with Basinmod 1-D 5.4 software (Hu et al., 1995) using a parallel chemical reaction model (EASY% Ro) and a paleo-thermal gradient method (Hu et al., 1998) using stratified drilling data and vitrinite reflectance (Ro) data. The denudation and heat conductive ratio of individual tectonic periods were referred to, as the newest data (Li et al., 2015) while rock physical properties were set as default values in the software.

3.1 Vitrinite Reflectance ratio (Ro)

The author measured the Ro values of 47 Carboniferous samples from Chaiye 2, zk3-1, and zk3-2 drill holes, 24 Jurassic samples from Chaiye 1 and Ku 1 drill holes, and collected 70 Ro data from 5 drill holes such as Lengke 1 and Shish 3. The scatter diagram of Ro and corresponding depths indicates obvious relevance between Ro and strata (Fig. 5). The general trend is that the higher the Ro, the older the strata are. Ro values of the Paleozoic are much higher than Ro values of the Mesozoic and Cenozoic. The Ro values of the Carboniferous are between 0.99% and 1.74% with an average of 1.30% and occurred in the period of high mature oil generation. The Ro values of the Jurassic are between 0.66% and 1.47% with an average of 0.93% and occurred in the period of moderate mature oil generation. The values of the Tertiary samples are between 0.35% and 0.55% with an average value of 0.41% and occurred in the immature period.

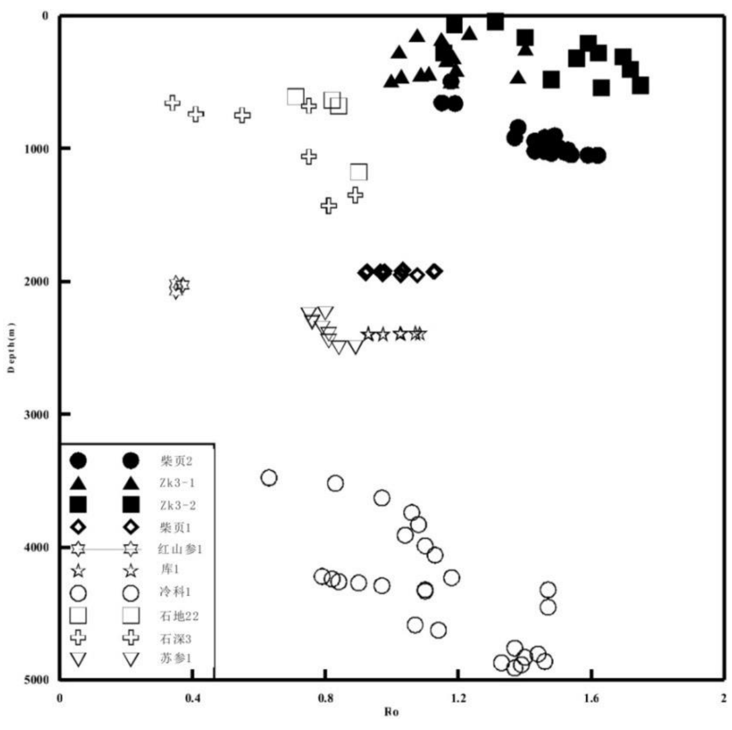

Fig. 5 *R*o measurement distribution with depth from the studied wells in the Qaidam Basin

3.2 Reconstruction of the burial and thermal histories

Eight drill holes, including Chaiye1, Chaiye2, and Lengke 1, were used to reconstruct the burial and thermal histories (Fig. 6). Only Chaiye 2 and Lengke 1 are used to elaborate due to space liminations of the article.

Chaiye 2 is located in the Shihuigou area of the Oulongbuluke rise and intercepts the Carboniferous Huaitoutala formation (C_1h). The burial history section disclosed the characteristics of the Shihuigou area in the eastern Qaidam basin. The burial history is composed of a fast burial period, a stable period, and a strong uplifting and erosional period. The late Devonian to Late-Early Carboniferous, the early-middle Jurassic to Late Cretaceous, the late Oligocene to Late Miocene, all showed characteristics of fast subsidience, fast deposition and fast burial with subsidence rates of 48 m/Ma, 10 m/Ma, and 45 m/Ma, respectively. The temperature of the strata increased rapidly due to fast burial. The bottom of the Carboniferous strata reached a maximum depth of 3060 m with a temperature of 160℃ in the late Miocene. The late Triassic to late Jurassic, the late Eocene to middle Miocene, and the late Miocene are strong uplifting and erosional periods with uplift rates of 18.7m/Ma, 45 m/Ma, and 241 m/Ma. The late Carboniferous to late Triassic and the early Cretaceous to early Eocene were relatively stable periods.

Lengke 1 is located in the Lenghu tectonic belt. The burial section of this drill hole was divided into a fast burial period, a stable period, and an uplift period. The late Carboniferous to late Triassic, the end of early Jurassic, the late Cretaceous to Early Paleocene, and the late Eocene to late Miocene were fast subsidence and burial periods with subsidence rates of ～18 m/Ma，95 m/Ma, 76 m/Ma, 142 m/Ma, respectively. In the late Miocene the bottom of the Carboniferous reached a maximum depth of 5350 m with a temperature of 160℃. The Middle Jurassic to early Cretaceous was relatively stable. The late Triassic to early Jurassic, the late Cretaceous, and the Miocene were strong uplift periods with rates of 27 m/Ma, 24 m/Ma, and 20 m/Ma, respectively.

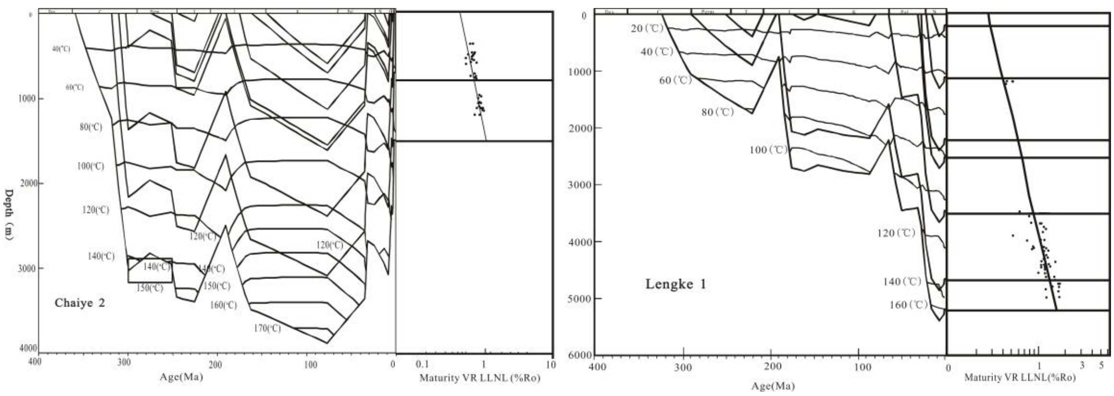

Fig. 6 The modeled results of burial，thermal, and hydrocarbon generation history of Well Chaieye 2 and Lengke 1 in the eastern Qaidam basin. "•" means measured vitrinite reflectance and the solid line means modeled values in the right chart

The thermal simulation shows that the whole eastern Qaidam basin experienced a period of gradual cooling(Fig. 7). The paleo-geothermal gradient of eastern Qaidam is in the range of 38 to 41.5℃/km with an average of 39℃/km. In the Paleogene, the thermal gradient decreased to a range of 29 to 35.2℃/km with an average of ～33.0℃/km and increased again in the late Paleogene. The thermal gradient gradually decreased after the late Paleogene to 22.1 ℃/km-31.4℃/km at the late N_1 and then was similar to the present temperature in the late N_2^3.

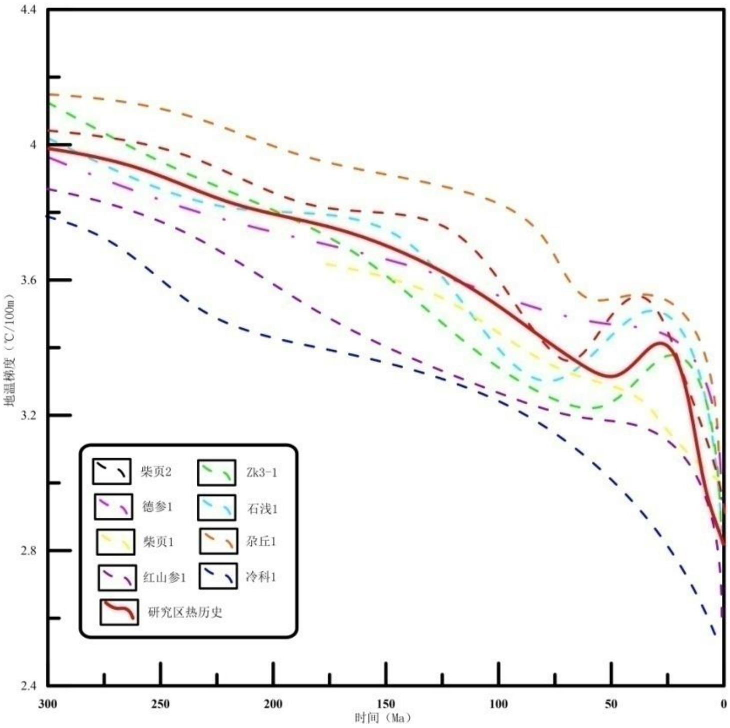

Fig. 7 The thermal history of the eastern Qaidam basin

4. Discussion

4.1 Differential uplift since the Cenozoic in eastern Qaidam basin and its controls

Thermal history of apatite fission tracks, burial history from borehole data, and inversion of thermal history all indicate that the uplift and erosion periods among the Oulongbuluke uplift area, Saishiteng Mountains, and the Tanjianshan differed significantly since the Cenozoic. Obvious uplift events happened at ～40 Ma and ～9 Ma at the Saiteng Mountains and the Tanjianshan with lifting rates of 24 m/Ma and 20 m/Ma, respectively, while lifting in the Oulongbuluke uplift area happened at ～33 Ma and ～6 Ma with rates of 76 m/Ma and 142 m/Ma, respectively. Compared to Oulongbuluke，the Saishiteng Mountains and the Tanjianshan uplifted earlier and more slowly. Two groups of ages (40-33 Ma and 9-6 Ma) recorded in the late Eocene and Miocene tectonic events were related to the convection and collision between the Indian Plate and the Eurasian Plate (Xu et al., 2006; Pan 1999). These presented as conformity between the lower Ganchaigou and Lulehe formations and between the Xiayoushashan and Shangganchaigou formations, as well as thrusts and folds at the margin of the basin, which caused the differential uplift between the Saishitengshan, Tanjianshan, and Olongbulukeshan mountains. This implies that the NE-SW direction gradually-effected remote effect of the Tibetan uplift process on the Qaidam basin is obvious. The sinistral strike-slip movement of the Altyn Tagh range since the Cenozoic developed strike-slip faults and pull-apart basins on both the eastern and western sides of the fault (Yue et al., 2001; 2004; Liu et al., 2012; Zhang et al., 2006). The NE-SW force on the Saishitengshan and Tanjianshan of the eastern section of the fault corresponds with the movement and direction of the Tibetean Plateau uplift. The weakening of the NE-SW force caused the slowing down of the erosional process of the Saishitengshan and Tanjianshan .

4.2 Tectonic-thermal processes in the eastern Qaidam basin

The thermal processes in eastern Qaidam basin presented a trend of gently decreasing temperatures, which were mainly controlled by magmatic thermal events and tectonic movement in the Qaidam basin. The basin was a back-arc rifting basin in the Late Devonian to Early Permian and a back-arc foreland basin in the Late Permian to Triassic, which was related to back-arc extension and orogenic events of the South Kunlun Ocean. The Yuliaokahe-Shaliuhe high pressure-ultrahigh pressure metamorphic zone, the Tanjianshan ophilic–arc and Oulongbuluke terrain were formed in eastern Qaidam and developed an ophiolite complex, arc volcanics, back-arc volcanics, and arc pluton in the 465-435 Ma and 435-400 Ma period(Chen et al., 2006). Paleo-Tethys plutonic magmas dominated by granitic magma were developed in the Late Permian to Middle Triassic and the paleo-thermal gradient was developed in the Late Devonian to Middle Triassic (Wu et al., 2004). Magma activity in eastern Qaidam stemming from the Mesozoic and Cenozoic was not strong (Jin et al., 2004). After extensional depression in the Early and Middle Jurassic, the basin was subjected to compressional depression and reversion with a thickening crust(Xu et al., 2006; Zhao et al., 2006) and decreasing geothermal gradient, after which the basin cooled.

5.Conclusion

(1) Significant tectonic movement happened during the early Jurassic, late Cretaceous, Late Miocene, late Pliocene to early Pleistocene in eastern Qaidam.

(2) The burial history of eastern Qaidam consists of fast burial, followed by stabilization and strong uplifting and erosional periods. Compared to the Saishiteng, Tanjianshan, and Lenghu tectonic zones, the subsiding and uplifting processes of the Oulongbuluke uplift zone differed since the Cenozoic, which were controlled by the far distance effect of the uplifting of the Tibetean Plateau and the sinistrial movement of the Altun fault zone since the Cenozoic.

(3) The overall thermal evolution in the eastern Qaidam basin is characterized by a slow decline. In the Middle to Late Paleozoic (～300 Ma), the paleo-geothermal gradient was in the range of 38.0℃/km-41.5℃/km with an average of 39.0℃/km while in the Late Cretaceous it decreased and was in the range of 29.0℃/km to 35.2℃/km with an average of 33.5℃/km. It increased in the Late Paleogene to some degree and then decreased gradually to 22.1℃/km-31.4℃/km in the Late Neogene. Magmatic-tectonic processes and tectonic movement in the basin controlled the thermal processes in the studied area.

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Figures

Fig. 1 A Tectonic map of the Qaidam basin; Fig. 1 B Sketch map of the geology and samples sites in the eastern Qaidam basin (Revised after Wang et al., 2005); Fig. 1 C The Geologic cross section across the Delingha fault depression

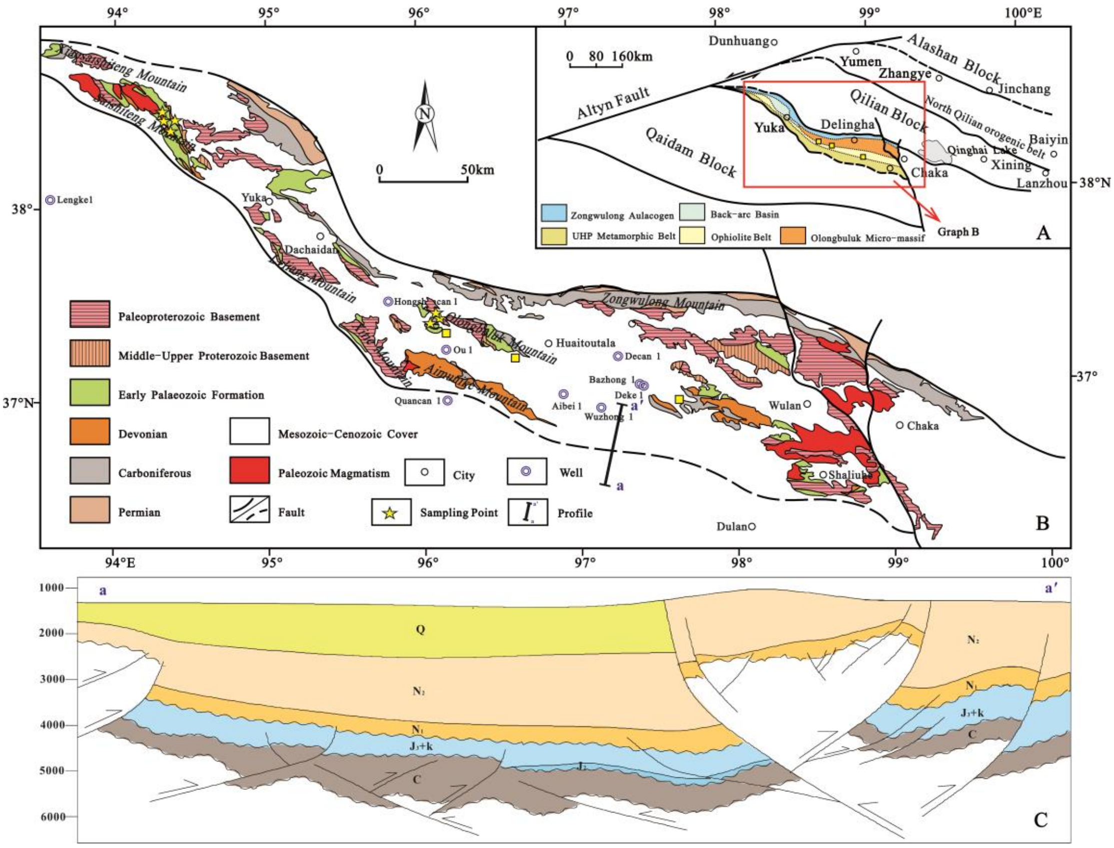

Fig. 2 Synthetic strata histogram of the eastern Qaidam Basin

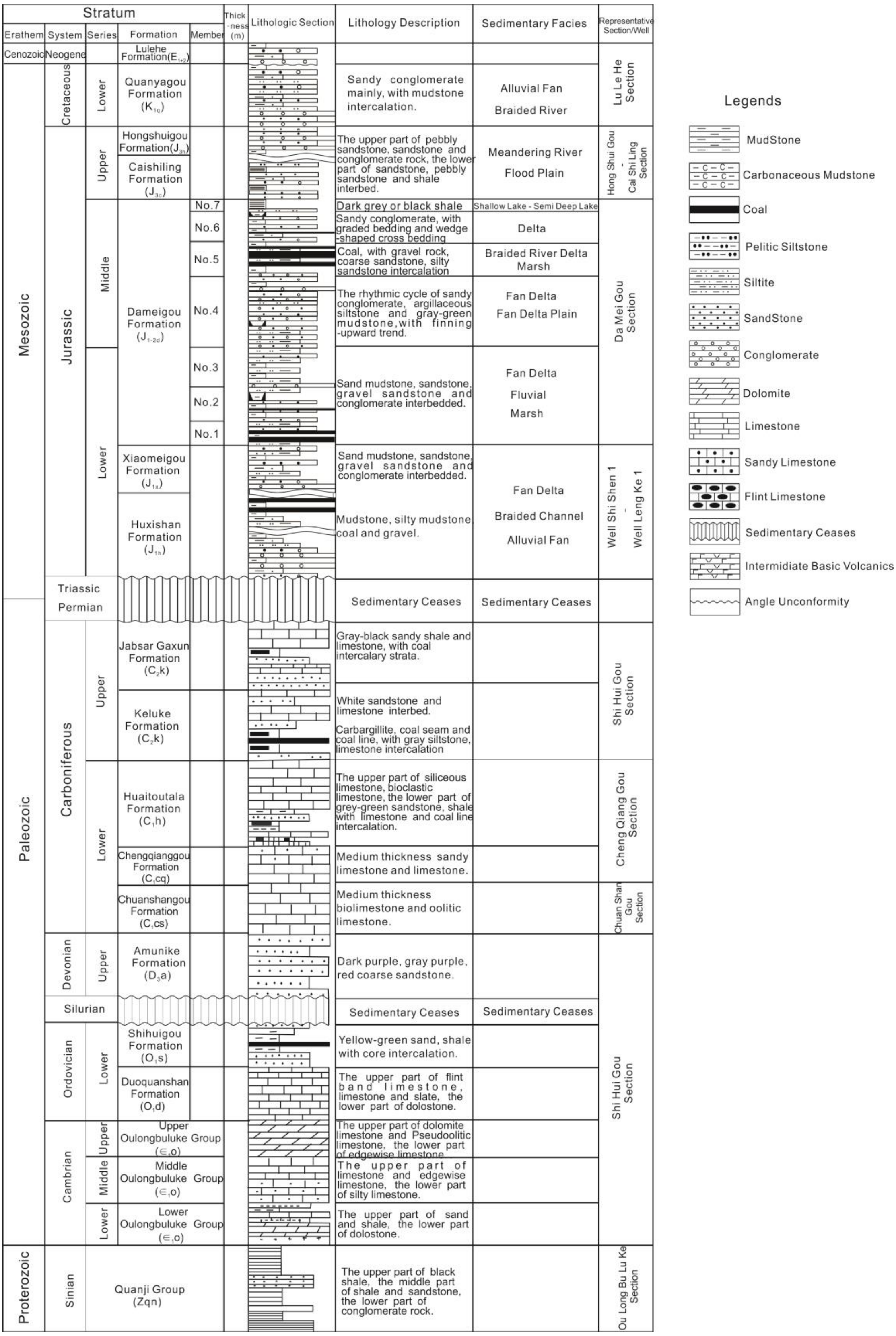

Fig. 3 Tectonic evolution sections in the eastern section of Qaidam

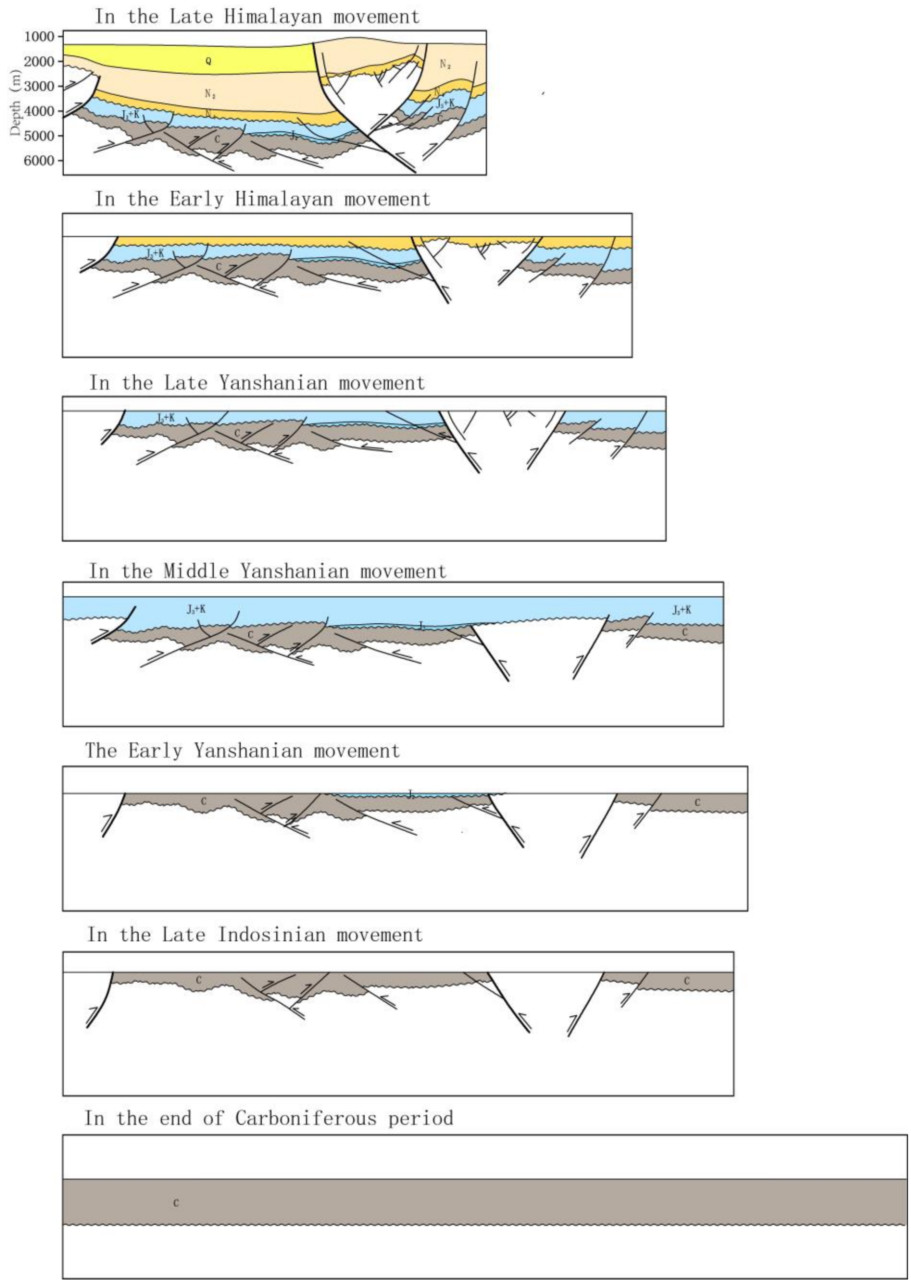

Fig. 4 Inversed sample results of the thermal history by AFT in the eastern Qadiam basin

1:acceptable paths with GOF between 0.05 and 0.5；2: good paths with GOF more than 0.5；3: best fit.

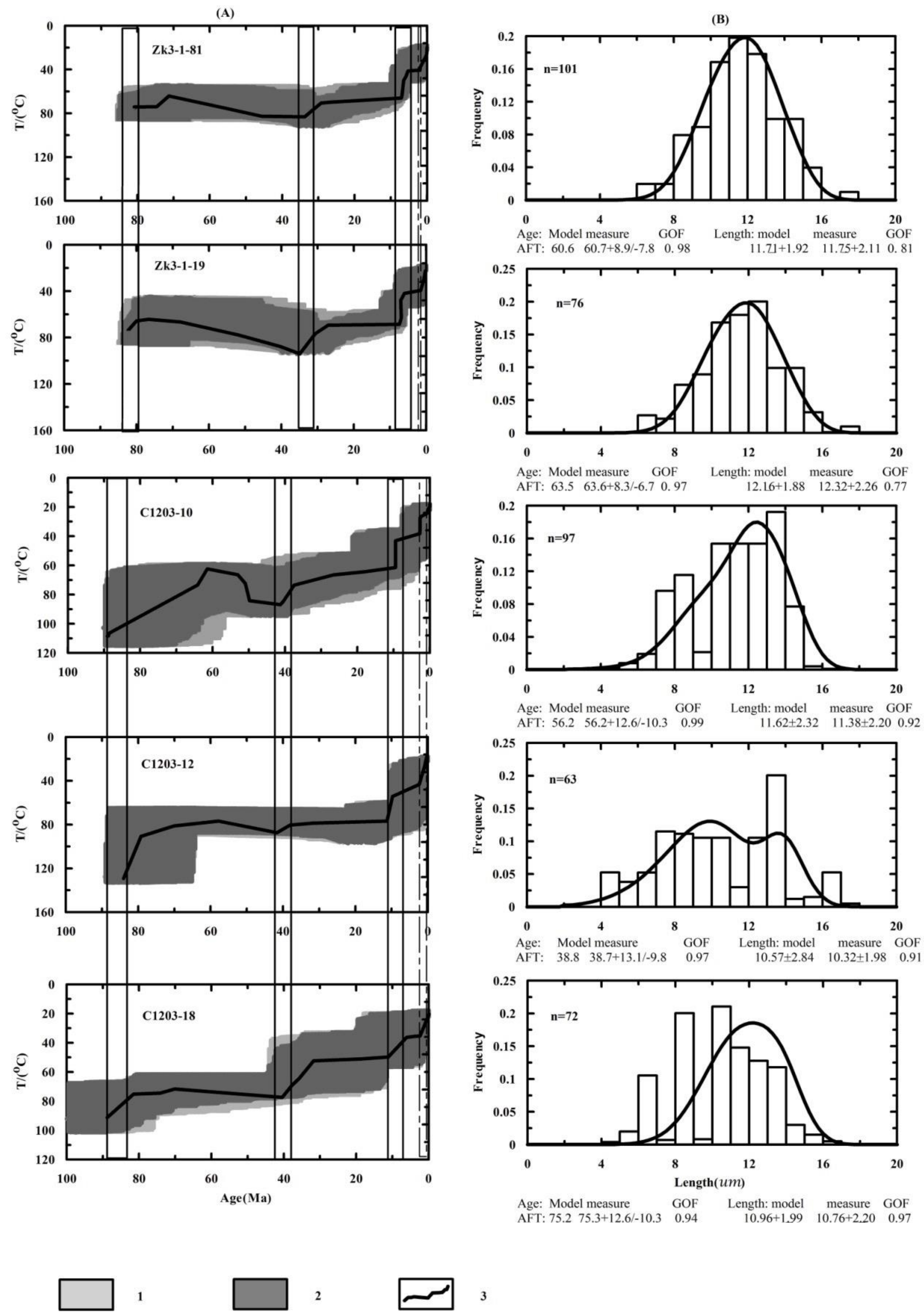

Fig. 5 *R*o measurement distribution with depth from the studied wells in the Qaidam Basin

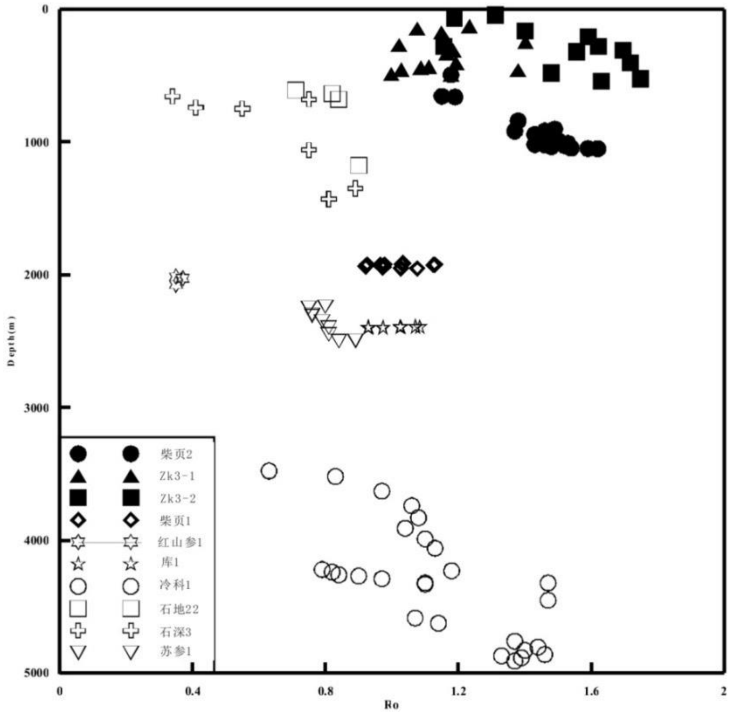

Fig. 6 The modeled results of burial， thermal, and hydrocarbon generation history of Well Chaieye 2 and Lengke 1 in the eastern Qaidam basin. "•" means measured vitrinite reflectance and the solid line means modeled values in the right chart

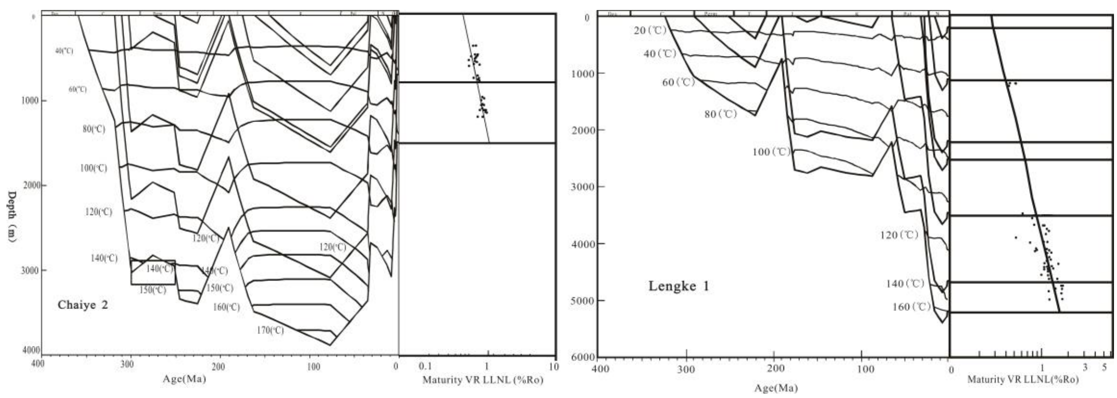

Fig. 7 The thermal history of the eastern Qaidam basin