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Basin-mountain Coupling Relationship in the Northeastern Tibetan Plateau: Evidence from the Thermal History of Hot dry rocks in the Gonghe Basin

Xiaorui Yun[1,2], Bizhu He[1]*, Xijie Chen[3], Shun Yu[1], Zhihui Cai[1], Ruohan Liu[1], Shengsheng Zhang[4], Zhenyu Li[1], Haifeng Chen[5], Yanming Qu[6]

1. Key Laboratory of Deep-Earth Dynamics of Ministry of Natural Resources, Institute of Geology, Chinese Academy of Geological Science, Beijing 100037, China; 2. Petroleum Exploration and Production Research Institute, Sinopec, Beijing 100083, China; 3. Development and Research Center of China Geological Survey, Beijing 100037, China; 4. Qinghai Survey Institute of the Hydrogeology and Engineering & Environmental Geology, Xining 810008, China; 5. No.313 Geological Team, Bureau of Geology and Exploration of Anhui Province, Luan 237010, China; 6. N0.3 Bureau of China Metallurgical Geology Bureau, Taiyuan 030000, China

Corresponding author E-mail address: hebizhu@cags.ac.cn

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ABSTRACT

The Gonghe basin is located within the interjunction of the Qinling, Qilian, and Kunlun orogenic belts, records complex tectonic, magmatic, metamorphic and sedimentary events, and is an ideal area for studying basin-mountain coupling process and tectono-thermal evolution in the northern part of the Tibetan Plateau. In recent years, the discovery of high-temperature hot dry rocks (HDR) in Gonghe basin makes this area a strategic base of new geothermal resources. In order to study the thermal history processes and heat source mechanisms of HDR in the Gonghe basin, we carried out systematic low-temperature thermal chronology study using deep drilling cores and outcrop samples from the northeastern part of the basin, and combined the results of petrology, zircon U-Pb geochronology, mineral thermobarometer and obtained the tectonic-thermal evolutionary history of the basin during Mesozoic-Cenozoic. The thermochronology results of deep drilling core samples record rapid heating process and slow heating process from the middle Miocene to present, which may be the main reason for the formation of high temperature hot dry rocks in the Gonghe basin. The Indosinian granites in the deep of the Gonghe basin and outcrops have experienced obvious thermal events during the Middle Miocene-Late Miocene (15 Ma~5 Ma), and show completely different thermal history, with cooling uplift in the outcrop area and heating in the deep of the basin. The thermal history of HDR suggest that the heating process is related to basin development process. Combined with the tectonic events around the Gonghe basin, the tectonic thermal events of HDR experienced responded to the stronger tectonic activities in the northeastern margin of the Tibetan Plateau and related to the NE-direction expansion and deformation of the Tibetan Plateau during this period. The heat source mechanism of hot dry rocks in the Gonghe Basin is related to mantle upwelling, which resulted in the middle and lower crust partial melt bodies. They constitute the regional and local heat source of HDR and formed a short-path and multi-source heating model.

1. INTRODUCTION

Hot dry rocks (HDR) are generally high temperature rocks with temperature greater than 150°C, buried at depths of several kilometers, and containing no or only a small amount of fluid inside (Mortensen, 1978; Laughlin et al., 1983; Genter and Traineau, 1992; Barbier, 2002; Brown et al., 2012). The lithology of hot dry rocks is dominated by metamorphic and igneous rocks, usually biotite gneiss, granite, and granodiorite (Genter and Traineau, 1996; Cocherie et al., 2004; Duringer et al., 2019). As an important component of renewable and new global clean energy, hot dry rocks geothermal energy is in the initial stage of exploration and exploitation tests in China, and relevant basic geological studies are particularly important. Material composition, spatial distribution and the tectonic-thermal events of hot dry rocks are the keys to geothermal reservoir identification and development.

The Gonghe basin, located in the northeastern part of the Tibetan Plateau, has high heat flow values, abundant hydrothermal geothermal resources and extensive hot springs, and has also shown potential for hot dry rocks geothermal resources in recent years (Feng et al., 2018; Feng et al., 2020; Jiang et al., 2019; Hu et al., 2000; Wang et al., 2012; Zhang et al., 2018). The high-temperature hot dry rocks at 236°C was drilled at a depth of 3705 m in the bottom of the GR1 well in the Gonghe basin, is the first time with the shallowest burial and highest temperature hot dry rocks was drilled in China (Yan et al., 2015; Zhang et al., 2018). The discovery of high-temperature hot dry rocks in Gonghe basin makes this area a strategic base of new geothermal resources in China, and more than 10 geothermal deep wells have been drilled and implemented, and previous studies have been conducted for the geology, magmatic events, deep structure, thermal reservoir, and geothermal system in the Gonghe basin (Gao et al., 2018; Guo et al., 2009; Feng et al., 2018; Feng et al., 2020; Tang et al., 2020; Chen et al., 2020, 2022; He et al., 2023; Yun et al., 2020, 2021; Zhang et al., 2018; Zhang et al., 2006; Zhang et al., 2019). Previous work has been done on the initial timing and extent of uplift on the northeastern Tibetan Plateau, and related thermochronological studies have been conducted (Mock et al., 1999; Jolivet et al., 2001; Liu et al., 2011; Duvall et al., 2013; Wang et al., 2018; Zhuang et al., 2018; Li et al., 2021; Bovet et al., 2009; Craddock, 2011; Craddock et al., 2014; Cheng et al., 2015, 2019, 2021). However, fewer studies have been conducted on the thermal evolutionary history and basin-mountain coupling relationships within the Gonghe basin, which restrict the exploration and exploitation of geothermal energy and the understanding of tectonic-thermal evolution history in this area.

In this paper, a systematic low-temperature thermal chronology study was conducted on the drilling cores and the adjacent outcrops in the Qiabuqia area of the northeastern Gonghe basin. In combination with the results of petrology, zircon U-Pb geochronology and mineral thermobarometer that have been carried out in our previous work, the tectonic-thermal evolution history of hot dry rocks in the Gonghe basin was obtained, which can provide new evidence for understanding the coupling between basin and mountain on the northeastern margin of the Tibetan Plateau, and the determination of HDR heat source in the Gonghe Basin.

2. GEOLOGICAL BACKGROUND

The Gonghe basin is located in the northeastern part of the Tibetan Plateau where the Qinling, Qilian, and Kunlun orogenic belts are combined, and is a Mesozoic-Cenozoic intermountain basin. The overall direction is NWW-SEE, with a rhombus shape of east-west width, about 210km long and 90km wide at the widest, with an elevation of 2600~3200m. The basin is bounded by Qinghai Nan Shan Fault to the north, Ela Shan-Wenquan Fault to the west, Anyemaqen suture to the south, and Duohemao Fault to the east (Fig. 1A) (Yun et al., 2020, 2021; He et al., 2023).

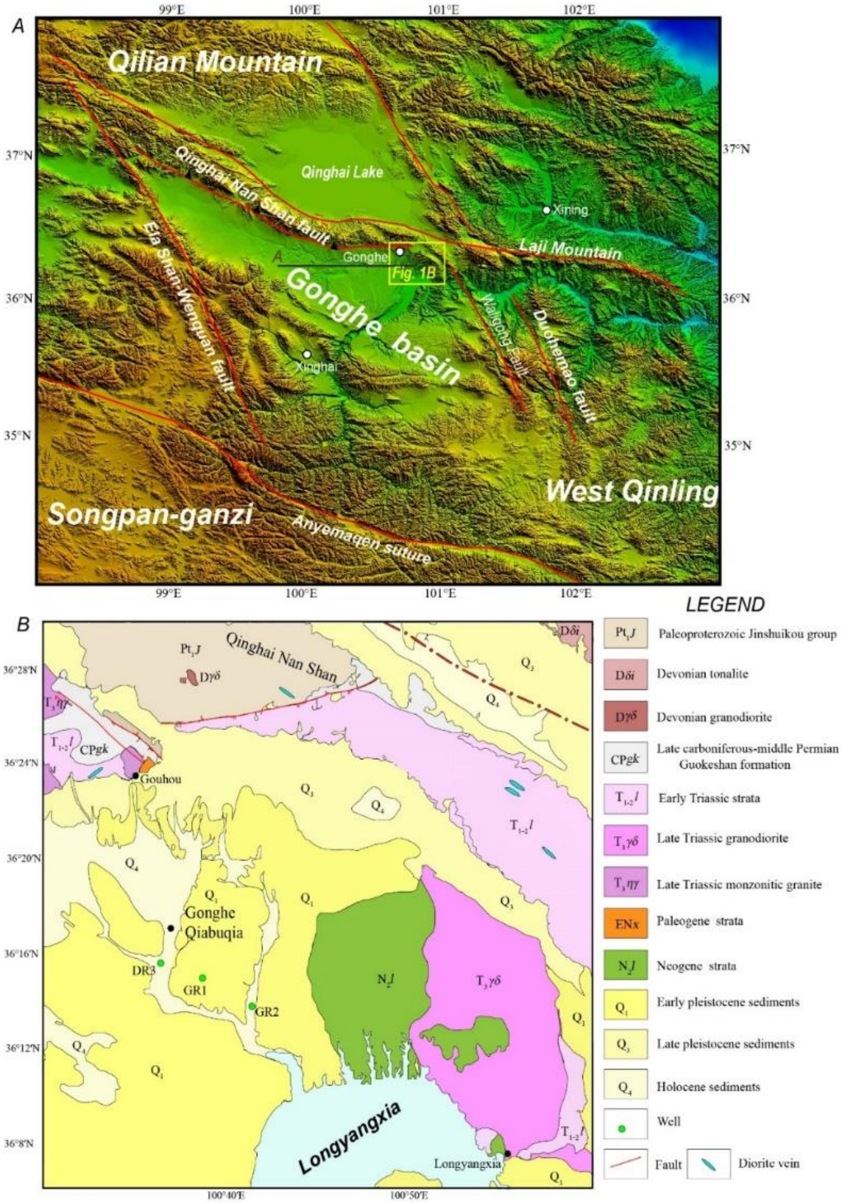

Fig. 1. Geotectonic location of the Gonghe basin (A) and geological map of the northeastern basin (B)）

（Modified after Yun et al., 2020）

In recent years, the exploration and studies of hot dry rocks in the Gonghe basin have mainly focused on the perimeter of the Qiabuqia area in the northeastern part of the basin. The Indosinian granites are widely developed around the periphery areas of the Gonghe basin (Guo et al., 2009; Zhang et al., 2006; Zhang et al., 2019), including the Dangjiasi pluton and the Gouhou complex in the northeastern part of the basin (Fig 1B). The stratigraphy of the northeastern part of the basin is developed with Late Carboniferous-Middle Permian tuffs with sandstones (CP*gk*), Early-Middle Triassic sand slates (Longwuhe Formation, $T_{1\text{-}2}l$), Cenozoic sediments. Cenozoic sedimentary strata including the Xining Formation (EN*x*), the Xianshuihe Formation (N_1x), the Linxia Formation ($N_{1\text{-}2}l$), the Quaternary Early Pleistocene (Q_1), the Middle Pleistocene (Q_2), and Late Pleistocene-Holocene ($Q_{3\text{-}4}$) (Meng, et al., 1999, 2012). The Cenozoic sedimentary rocks is unconformable over the Longwuhe Formation ($T_{1\text{-}2}l$) and Triassic intrusive rocks.

The results of our preliminary study on the granites in the northeastern Gonghe basin show that the hot dry rocks in this area are mainly composed of granodiorite, tonalite, monzonitic granite and syenite granite, with diorite enclave occasionally(Chen et al., 2020). The formation pressure of hornblendes in the hot dry rocks of the Gonghe basin belongs to low medium pressure (1.91~3.52kbar), with low to medium temperature (681~693℃), and the crystallization depth of magma is about 7.2~13.2km. Zircon U-Pb geochronology analysis shows that the protoliths of Qiabuqia area in the northeast of Gonghe basin were mainly formed in

243~236 Ma and 225~210 Ma. There were different periods and different origins of intrusion, which was related to the subduction and closure of the Paleo-Tethys ocean basin in the Northern Qinghai Tibet Plateau during Indosinian (Yun et al., 2020).

The low-temperature thermochronological results show that the Dangjiasi pluton and the Gouhou complex had experienced 2 phases (200~150 Ma and 135~100 Ma) rapid cooling and dramatic uplifting during the Jurassic- Cretaceous since they have crystallized in the Triassic, which may be related to the remote effect of the sequential northward collision and splicing of the Qiangtang and Lhasa terrane in the northeastern Tibetan plateau. The Gouhou complex recorded a rapid cooling event in the Late Miocene (15-5 Ma), while the samples from the Dangjiasi pluton in the eastern part of the basin did not record a rapid cooling event in the Neogene. This may be caused by the rapid uplift of the Gouhou complex in the late Neogene due to the reactivation of the north-dipping South Qinghai Nan Shan Fault during Late Cenozoic, while the Dangjiasi pluton in the eastern part of the basin was mainly controlled by the dextral strike-slip Waligong Fault and did not undergo cooling and uplifting events in this period (Yun et al., 2021).

3. SAMPLES AND METHODS

We observed and described the cores of three drilled wells GR1, GR2 and DR3 in the northeastern part of the Gonghe basin, constructed a lithological column, and collected corresponding samples for testing and analysis (Fig. 2). The sample HGR1-11-1 is syenite granite at a depth of 1750m with granitic structure. HGR1-17 is tonalite at a depth of 2753m mainly composed of plagioclase and quartz. HGR2-7 is monzonitic granite at a depth of 1191m with granite structure (Yun et al., 2020).

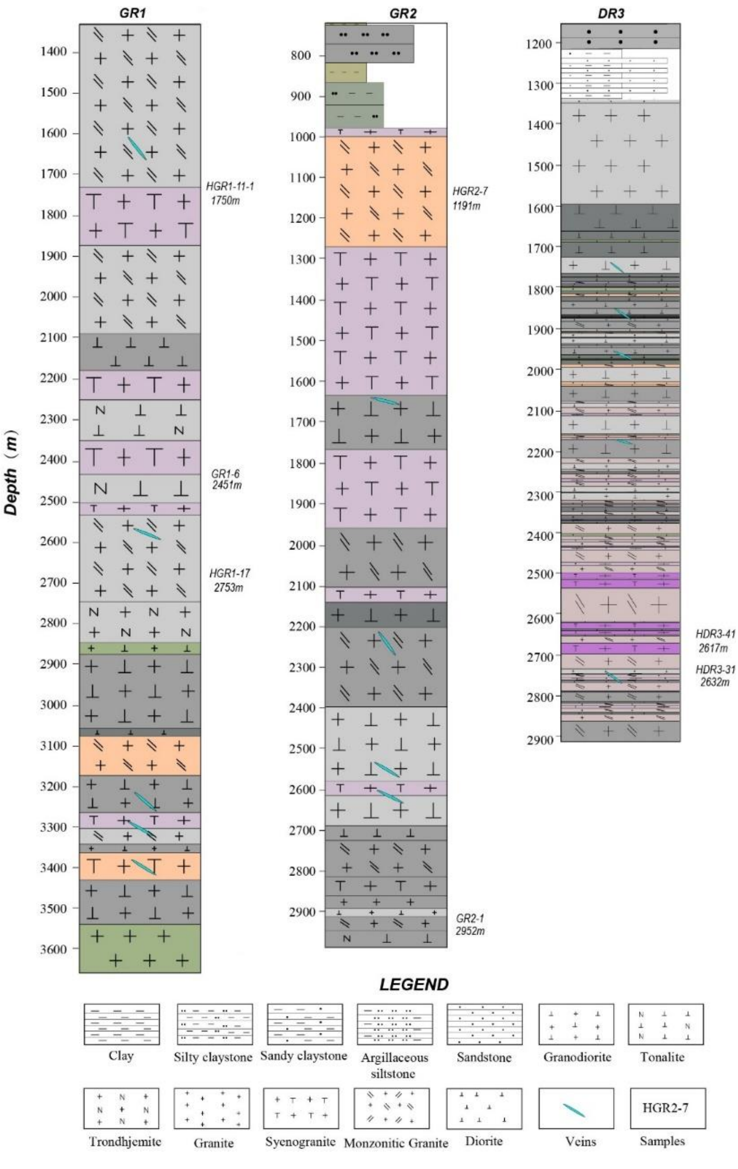

Fig. 2. Simplified lithologic columns and sampling depths of Hot Dry Rock (HDR) drilling cores at the Qiabuqia area in the northeastern Gonghe basin (Modified after Yun et al., 2020)

We also collected and analyzed the field outcrop samples from the eastern section of Qinghai Nan Shan, the Dangjiasi pluton and the Gouhou complex. Sample HQHH5-5-6 was collected from the north side of Qinghai Nan Shan and is Paleozoic black mica gneiss (Fig. 3A) with a semi-directional arrangement of black mica and a gneissic structure. Three samples were collected from the Gouhou complex, HGH3-0 is black mica diorite (Fig. 3B); HGHSK1-1 is altered granite with quartz veins (Fig. 3C); HGHSK1-5-1-2 is plagioclase granite with coarse grain size and sericitization of plagioclase (Fig. 3D). The sample HRDK1-3 obtained from the Dangjiasi pluton is coarse-grained black mica granite (Fig. 3E); HZK6-1 is black mica granite, with dark minerals mostly black mica and plagioclase kaolinization (Fig. 3F).

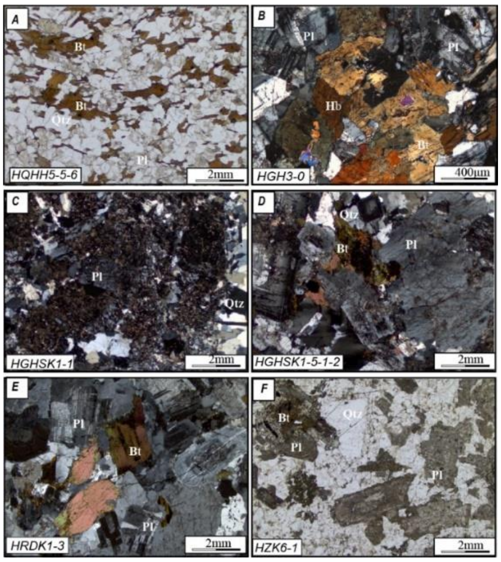

Fig. 3. The representative photomicrographs of the study samples in the northeastern margin of the Gonghe basin

Apatite and zircon (U-Th)/He testing of the samples was carried out at the University of Melbourne and Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Apatite fission track (AFT) analysis was carried out at the University of Melbourne and the Beijing Quick-Thermo Science & Technology Co., Ltd.. Thermal history simulations of apatite (U-Th)/He and fission traces were performed for all samples using HeFTy (1.8.0).

4. CENOZOIC HEATING EVENTS OF HDR IN THE GONGHE BASIN

The AFT test results of granite core samples from well GR2 and DR3 show that the four valid data from samples at depth of 1191m (sample HGR2-7) to 1888m (sample HGR2-12) with fission track ages ranging from 124.64 ± 5.2 Ma (sample HGR2-7) to 70.0 ± 2.8 Ma (sample HDR3-34) have a track length of only 9-10 μm, indicating that this part of the sample is now undergoing annealing, and the apatite fission track of samples at depths greater than 1900 m have been completely annealed.

The deep drilling samples are now at higher temperatures, and the regional geological indicates that Triassic granites in the northeastern Gonghe basin may have been in a near-surface position prior to the deposition of Paleogene strata, followed by rapid subsidence. That is, the granite underwent a heating event since the Cenozoic.

Thermal history simulation results show that the Triassic granite underwent a significant temperature increase since the Miocene, which can be divided into three stages: a heating initiation from 20 Ma to 15 Ma, a sharp heating from 15 Ma to 5 Ma, and a slow heating since 5 Ma (Fig. 4). Combining all the obtained simulation results, we suggest that the granites and overlying deep sedimentary rocks in the northeastern Gonghe basin experienced heating since ~15 Ma (the middle Miocene), which may indicate crustal heating and is the main reason for the anomalously high geothermal gradient in this area.

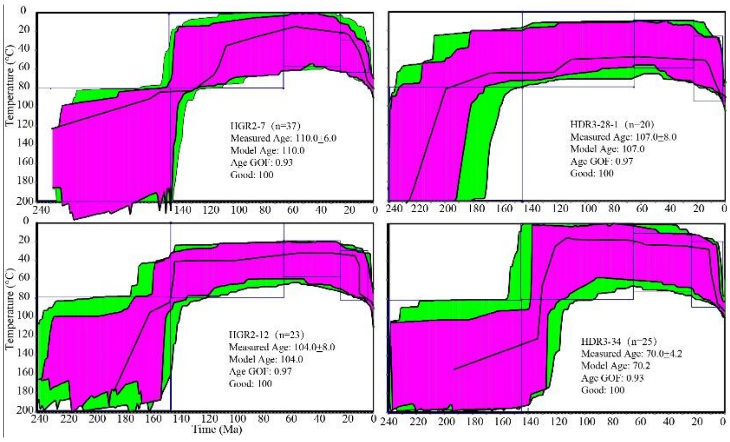

Fig. 4. Time-temperature plot results for samples from drilling cores

5. BASIN-MOUNTAIN COUPLING ON THE NORTHEAST OF THE TIBETAN PLATEAU

5.1 Basin-Mountain Coupling

Numerous published low-temperature thermochronological data indicate that regional uplift occurred in the northern Tibetan Plateau during Cenozoic, with Paleocene and Miocene ages recorded in the Eastern Kunlun, the Altyn-Tagh, and the Qilian Mountains （Mock et al., 1999; Jolivet et al., 2001; Liu et al., 2011; Duvall et al., 2013; Wang et al., 2018; Zhuang et al., 2018; Li et al., 2021; Bovet et al., 2009; Craddock, 2011; Craddock et al., 2014; Cheng et al., 2015, 2019, 2021）。

The timing of fault initiation or mountain uplifting, which indicated by previous thermochronology data at the perimeter of the Gonghe basin based on outcrop samples, is in high agreement with the timing of crustal heating revealed by our simulation results (Fig. 5). Apatite He ages indicate a rapid denudation time of ~26 Ma in the East Kunlun Mountain, which inferred northward expansion since the Late Oligocene at the northeastern margin of Tibetan Plateau (Li et.al., 2021); The deformation and detachment into the middle crust of the Gonghe Nan Shan and Qinghai Nan Shan fault systems in the north and south of the Gonghe basin occurred at 10 Ma ~ 7 Ma and 10 Ma ~ 6 Ma respectively (Craddock et al., 2014); Apatite fission track reveal uplift in the northern Qilian Shan during the Middle Miocene (17 Ma ~ 15 Ma) (Yu et.al., 2019); Detrital apatite fission track indicate fault extension time in the north and south of the Qilian Mountains is 18 Ma ~ 11 Ma and 10 Ma~5 Ma (Pang et.al., 2019).

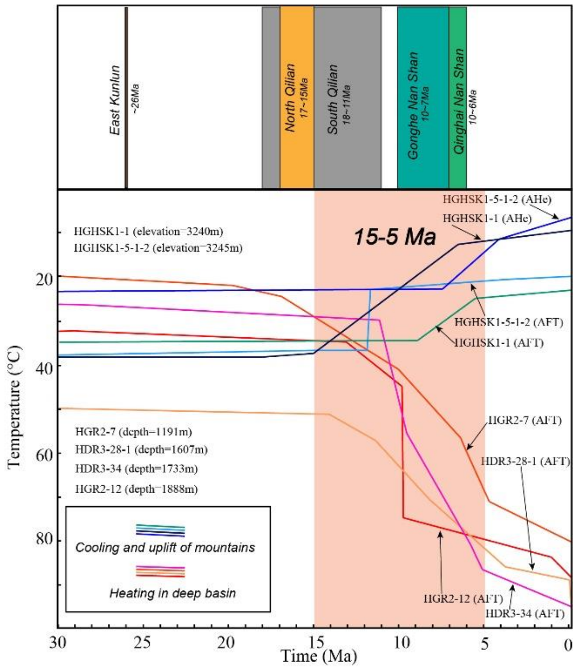

Fig. 5. Thermal history of samples from outcrop and drill cores in the northeastern margin of the Gonghe basin

Combining the thermal history results obtained from outcrops and drill cores in the deep in the northeastern Gonghe basin (Fig. 5), the northeastern margin of the Gonghe basin was indicated in a stronger tectonic active area during the Middle Miocene-late Miocene (15 Ma ~ 5 Ma). The granite in the deep basement of the basin and the samples from the outcrops underwent obvious tectono-thermal events and showed completely different thermal history. The outcrop experienced cooling and uplift, while the deeper of the basin experienced heating. The cooling rates and heating rates indicate a nearly coupled characteristics since the Miocene. During the Middle Miocene-Late Miocene (15 Ma ~ 5 Ma), cooling rate of the outcrop area samples and the heating rate of the interior of the basin both experience a pattern of increasing and then decreasing (Fig. 6).

Combined with the tectonic events around the Gonghe basin, the northeastern of the Tibetan Plateau was in a stronger tectonic area, and it indicates that the front of expansion and deformation has been located in the northeastern margin of the Tibetan Plateau in this period.

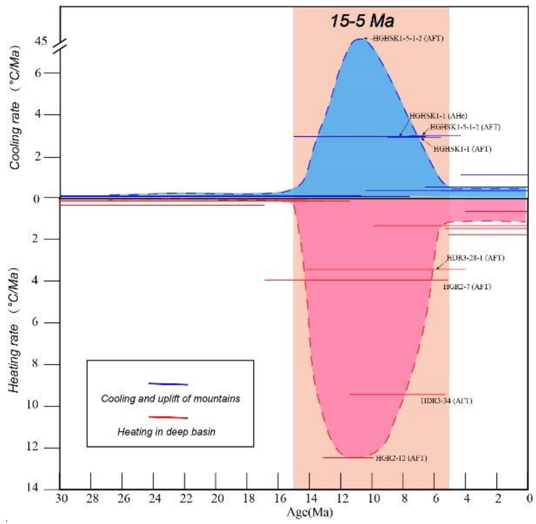

Fig. 6. Cooling rate since the late Oligocene for the samples of outcrops and drill cores in the northeastern Gonghe basin

5.2 Inspiration of thermal evolution on heat source mechanism of HDR in Gonghe Basin

The heat source mechanism of the hot dry rocks in the Gonghe Basin is still controversial. Xue et al., 2013 believes that it may be related to the north-south geothermal belt, border fault, and the radioactive heat generation in concealed pluton; Feng et al., 2018's research shows that it is related to the Qinling asthenosphere channel, the heat source is contributed by the deep mantle and the participation of the earth's crust; Gao et al., 2018 believes that it is related to a partial melting layer in crust under Gonghe Basin; Zhang et al., 2020 believes that the ductile detachment shear zone is the main heat source structure.

This study reveals the Miocene crustal heating event in the northeastern Tibetan Plateau, and proposes a new model for the heat source mechanism of hot dry rocks in the Gonghe basin by combining regional geophysical data. The dynamic mechanism may be the convergence between different blocks in the northeastern part of the Tibetan Plateau, which caused the removal of the deep lithospheric mantle and the upwelling of asthenosphere (Yun et al., 2020; He et al., 2023). The upwelling of mantle leaded to the upward disturbance of each layer in the crust, formed the middle and lower crust partial melt bodies and lost the boundary between the upper and middle crust, and superimposed the strike-slip and extensional tectonic environment, formed a short-path and multi-source heating model. The regional and local heat sources are mantle upwelling and partial melting bodies respectively.

6. CONCLUSIONS

（1）Thermal history simulation results show that hot dry rocks of the Gonghe basin underwent a significant temperature increasing since the Miocene, the major and rapid heating phase has occurred since 15-5 Ma. The cooling rates of the outcrop area samples and the heating rates of the interior of the basin both experience a pattern of increasing and then decreasing. It also shows a well-matched coupling between basin subsiding and mountain uplifting.

（2）The tectonic thermal events of HDR experienced responded to the stronger tectonic activities in the northeastern margin of the Tibetan Plateau and related to the NE-direction expansion and deformation of the Tibetan Plateau during this period.

（3）The heat source mechanism of hot dry rocks in the Gonghe Basin is related to mantle upwelling, which resulted in the middle and lower crust partial melt bodies. They constitute the regional and local heat source of HDR and formed a short-path and multi-source heating model.

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