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Genesis of high-temperature geothermal resources in the central-eastern part of North China

Baojian Zhang[1,2,3], Siqi Wang [1,2,3], Fengxin Kang [4,5,6*], Yanyan Li[1,2,3], Jun Gao[1,2,3], Shanming Wei[5], Yifei Xing[1,2,3]

1.Chinese Academy of Geological Sciences, Beijing 100037, China;
2. Technology Innovation Center of Geothermal and Hot Dry Rock Exploration and Development, Ministry of Natural Resources, Shijiazhuang 050061, China;
3. Laboratory of Deep Earth Science and Exploration Technology, Ministry of Natural Resources, Beijing 100094, China;
4. College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China;
5. 801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology and Mineral Resources (SPBGM), Jinan 250014, China;
6. School of Water Conservancy and Environment, University of Jinan, Jinan 250022, China
* Corresponding author: Kang Fengxin, kangfengxin@126.com

Abstract: In recent years, high-temperature geothermal resources with temperatures above 150 °C have been successively discovered at the depths of <4000 m in the Matouying and Tianzhen areas of Tangshan City and Datong City, North China. Nevertheless, the heat source, genesis, and geodynamic processes of these high-temperature geothermal formations have not been clearly understood. In this paper, we analyze the deep geological background, crust-mantle structure, deep-large fractures, magmatic activity, as well as motion, upwelling and geodynamic mechanism of asthenosphere in the study area. Combining with the research of geophysics and geochemistry, to elaborate the problem that the effects of internal and external forces on shaping of the Earth's shallow geothermal field and thermal anomaly. The results show that: 1) under the interaction of far-field effect of the collision of Indo-European plate and the subduction and retreat of the western Pacific Ocean, deep geological processes, e.g. lithospheric demolition, sinking and thermal erosion of asthenosphere, occurred in the east-central part of the North China Craton. As a consequence, the destruction, lithospheric thinning, lithospheric induced extension, oblique tensional slip, extrusion and deformation, basin fracture and uplift occurred. These geological activities creates a favorable geological background for the upwelling of mantle-derived thermal materials; 2) the tectonic environment, caused by the relative movement between the blocks, and deep-large slip fractures cutting through the lithosphere constitute the main channels for the upward invasion of mantle-derived thermal materials; 3) the high-conductivity and low-velocity bodies, geochemical evidence and the location of high-temperature geothermal resources have formed a good correspondence. Hence, it is believed that the upward invasion of mantle-derived thermal material caused the shallow thermal anomalies. The lithospheric tectonic weak zones such as block combination zone and deep-large slip fractures constitute the upward invasion channels of mantle-derived thermal material. The concave-convex tectonic pattern and the flow field of groundwater dominate the distribution of heat in the shallow part of the earth's crust. The suitable tectonic parts of Fenwei rift valley, Zhangjiakou-Bohai fracture zone are favorable target areas for finding high-temperature geothermal resources in 2,000-4,000 m depth.

Keyword: High-temperature geothermal resources; deep heat source; upwelling channel; genesis; central eastern North China Block

0 INTRODUCTION

Up to now, the high temperature (>150℃) geothermal resources discovered in China are mainly distributed in western area and Taiwan area. These geothermal resources are especially concentrated in the southern Tibet and the west part of Yunnan and Sichuan Provinces belonging to the Mediterranean-Himalayan geothermal belt, and in Taiwan area belonging to the Pacific rim geothermal belt [1]. Researches about the formation mechanisms of the Chinese high temperature geothermal resources are mainly focus on Tibet and its surrounding areas. Duo (2003) described the geological characteristics of the typical high temperature geothermal system on Tibet -Yangbajing geothermal field [2]. Sun et al. (2015) analyzed the geochemical features of the Tibetan high temperature geothermal fields [3]. Zhou and Luo (2022) provided the distribution of the Tibet high temperature geothermal resources [4]. Tang et al. (2020) and Lin et al. (2021) analyzed the formation mechanisms and distribution features of the hot dry rocks (HDRs) and high temperature geothermal resources in Gonghe Basin, which is located in the northeastern Qinghai-Tibet plateau [5-8]. Shangguan (2000) and Guo (2014) analyzed the geothermal reservoir structure and formation mechanism of the high temperature geothermal field in Tengchong city of Yunnan Province [9-10].

Benefited from the development in the researches and detecting depth of geothermal resources，discovery breakthroughs of the high temperature geothermal resources in eastern China are achieved recently. A high temperature rock of 150 ℃ was encountered at the depth of 3 965 m in 2019 in Matouying of Hebei Province. In 2020, the highest temperature of the geothermal water of 160.2℃ was obtained at the well head in the Tianzhen county of Datong city, Shanxi Province. In 2021, a carbonate thermal reservoir with a temperature of 155 °C was discovered at a depth of 4701.68 meters in the Subei Basin, Jiangsu Province. As the breakthroughs in high temperature geothermal exploration are more and more, researches about the formation mechanisms of the high temperature geothermal resources area also approached. Zhang et al. (2020) analyzed the formation mechanism of the geothermal resources in Matouying, Hebei Province [11]. Wang et al. (2021) studied the thermal accumulation mechanism of the buried hill in the northeast of Gaoyang geothermal field in Xiong’an New area [12]. Lu (2022) studied the geological characteristics of the high temperature carbonate thermal reservoirs in Subei Basin [13].

Herein, we take the high temperature goethermal field in Tianzhen county of Datong city and the HDRs in Matouying as examples to analyze the regional crust-mantle structure and the influence of deep geological processes on high temperature anomalies in shallow crust. These deep geological processes include the upwelling of crust-mantle thermal matter and uplift of Moho. The two example not only help us to interpret the key scientific problem that how the inner and outer geological forces shape the shallow geothermal field and restrict the thermal anomalies, but also help us to explore the formation mechanism of the high temperature geothermal resources in the typical areas and analyze its examplary significance for high temperature geothermal exploration in central and eastern North China.

1 GEOLOGICAL SETTING

Tectonically, the central and eastern North China is located in the east of the North China Plate. From west to east, it includes the Shanxifault-depression belt, Taihang Mountainuplift, Yan Mountain uplift, North China Plain, and Bohai Bay Area (Fig. 1).

1.1 Main tectonic zones

（1）**Shanxi fault-depression belt.** Shanxi fault-depression belt is located in the interaction area of Indian Plate, Pacific Plate, and Eurasian plate. It is the tectonic division belt and decoupling belt of the east and west China, and the adjustment zone of differential movement of Ordos, North China, and other tectonic blocks. The tectonic structure is relatively complex. The north pat of the Shanxi fault-depression belt is featured by basin-range structure and composed of a series of basins and mountain ridges. Fault-depression basins are controlled by the NW-dipped normal fault and mainly include Datong, Yangyuan, Xinzhou, and some other basins. In the Yangyuan and Datong basins, which are located in the north part of the Shanxi Province, the Middle Pleistocene mantle-derived basic volcanic rocks are developed, mainly consisting of olive basalt and basalt, and the volcanic cone landform is very clear.

（2）**Taihang Mountain uplift.** This uplift is a NNE trending giant tectonic belt goes through the central North China. It is bounded by the front fault of Taihang Mountain and adjacent to the subsidence area of North China Plain in the east. The crystalline basement is composed of the Archean and Early and Middle Proterozoic rock series. Because of the strong Quaternary extension, fault-depression basins developed in the north part of Taihang Mountain and became a composition of the northern section of the Shanxi graben system.

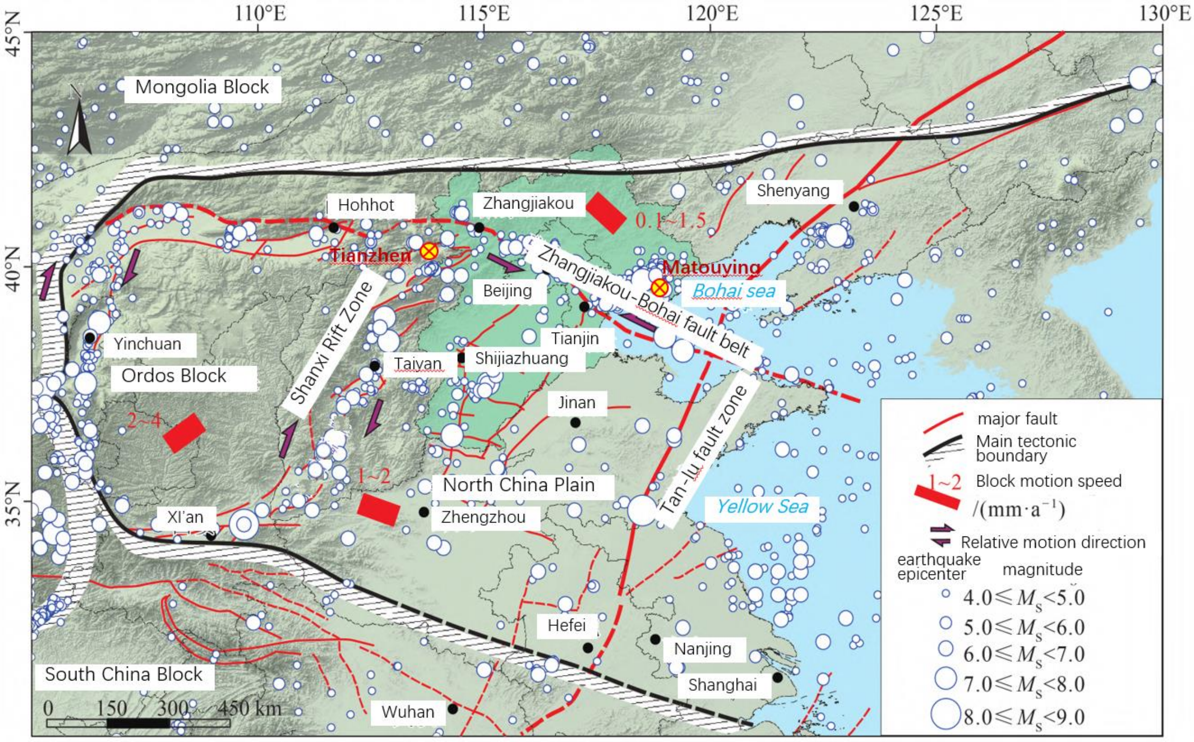

Figure. 1 Active tectonic map of North China area (modified from Wang et al., 2022[14])

（3）**The Yan Mountain uplift area.** This area is located in the south of the uplift area of Yinshan Mountain and its southwest end is connected with the Taihang Mountain uplift at Zhuozhou zone. The Archean crystalline basement is widely exposed here. During the Late Proterozoic, the basement subsided rapidly and the cap rocks developed, leading to a deposition of nearly ten thousand meters thick Sinian strata. In addition to the second-order planation surface developed in the northern region, there are still a third-order planation surfaces with an altitude of 500-600 m, which was formed from the end of the early Pleistocene to the beginning of the middle Pleistocene and reflects the ascending activity since the Quaternary.

（4）**North China Plain.** The north part of North China Plain contains the plain in Beijing, Hebei, Shandong, and Henan provinces. The basement experienced extensive crustal extension and fault-depression process during Paleogene, resulted in a series of graben basins controlled by NE-NNE trending shovel normal faults and deposited a set of fluvial and lacustrine sandy mudstone (Kongdian, Shahejie, and Dongying formations). During the Neogene, the post-rift thermal subsidence occurred in the whole rift extension area, and accompanied by strong mantle-derived magmatic activities. Thousands of meters thick fluvial and lacustrine sediments of the Guantao and Minghuazhen formations were deposited. The Quarternary basin evolution generally inherited the regional subsidence tectonic pattern with few rift activities. A set of fluvial and lacustrine sediments were deposited continuously during this period. The northern margin of the basin is connected with the Yan Mountain uplift, which is a part of the Zhangjiakou-Bohai Sea tectonic belt, is composed of a series of NE trending rifting basins and faults controlling basin formations. The Neotectonic combination in the plain area is complex, and the

NWW-SEE trending basin-controlling faults mainly occurred in the early and middle Plesitocene. From the late Pleistocene to Holocene, the main type of fracture is transtensional fault. The NNE trending faults are right-lateral strike-slip fault, while the NW trending faults are lift-lateral strike-slip fault [15-16].

（5）**Bohai bay sea area.** As a composition of North China Basin, this area experienced a similar Cenozoic rifting process as in North China Plain. A graben basin and basement uplift were formed due to the Paleogene strong extensional fault depression. During Oligocene, dextral strike-slip deformation occurred along the Tanlu fault belt, leading to the formation of strike-slip pull-apart basin and strike-slip flower structure. During the Neogene, regional thermal subsidence led to the formation of butterfly depression basin. Since the Quaternary, tectonic evolution in the Bohai bay sea area differentiated significantly, and the tectonic pattern that totally different from that in the terrestrial area appeared. The sea area not only became the center of new tectonic movement, but also accompanied by abundant fold and fault structures. On the margin area of Bohai bay sea area, mantle-derived volcanic activities occurred during the late Middle Pleistocene (600 ~ 800 ka) and the late Late Pleistocene (~ 40 ka). During the Late Pleistocene-Holocene, at least 5 ~ 6 large-scale marine transgression occurred in the Bohai bay sea area, and marine and terrestrial sediments deposited alternatively, which record the crust arching. During the Holocene, fault in this area was poorly developed. The shallow seismic profile and sea bottom topography indicate that two fault groups were to be reactivated [17-18]: one group is the NNE dextral strike-slip activities that parallel to the Tanlu fault belt; the other group is the WNW left-lateral strike-slip activities that parallel to Zhangjiakou-Penglai seismic tectonic belt [19].

1.2 Main fault belts

（1）**Shanxi fault-depression belt.** Based on the Paleozoic tectonic structures, the Yanshan movement changed the crustal tectonic pattern significantly. Due to the NW-SE compression stress field, giant scale of reverse faults and overthrust faults occurred and controlled the boundary of Cenozoic rifted basin. Since the Cenozoic, deep compression led to the occurrence of surface tensile fracture in the axial localities of the uplift area, and a translational normal fault was generated. Besides, a fault basin appeared during the vertical subsidence movement. From Yuncheng in the south part to Datong in the north part, there are a series of ultrabasic rock and basic rock intrusive bodies of different periods. Quaternary basalt is found in Datong area. The Cenozoic faults can be seen on the margin and inner parts of many rifted basins in Shanxi Province.

（2）**Taihang Mountain front fault belt**。This fault belt is the tectonic boundary belt dividing the western uplift and the eastern plain. Northward, this fault belt trends NNE from Handan, Xingtai, to Shijiazhuang. It turns to NE from Shijiazhuang and extends towards Baoding and Zhuozhou direction. The Taihang uplift belt located on the west of this fault belt is mainly composed of the pre-Sinian metamorphic rocks and the Lower Paleozoic duplex anticline. On the top of the anticline, Mesozoic deposits are absent, and fault depression formed due to the continues Cenozoic uplift.

（3）**Zhangjiakou-Bohai fault belt.** This is a famous seismic belt in China, and also a fault tectonic belt goes through North China and eastern China. It starts from the west of Zhangbei county of Zhangjiakou city, goes through Tangshan and other cities, crosses Bohai sea, and finally extends southeast to Yantai, northern Penglai, and the Yellow sea. It is a broad belt trending NW with a total length of 700 km and a largest width of (Fig. 1). This belt is dominated by the NW-NWW trending tectonic units and intersects with NNE trending units. Normally, the NW trending units cut the NE trending units. Since the Neogene, especially the Quaternary, the regional tectonic stress field transformed into NEE compression, and this fault became a left-lateral strike-slip shear fault cutting the NE trending tectonic units. This led to the formation of a large scale regional fault belt, which is a famous seismic belt and controls the north margin of the North China rifted basin.

（4）**Tanlu fault belt**。This fault belt is a strike-slip boundary fault between the North and South China plates, and a series of ductile shear deformation structures developed here. The main part of the Tanlu fault belt was formed during the Late Cretaceous, and suffered a compression reformation during the end of the Late Cretaceous. During the late Neogene, compressional strike-slip activities occurred in the Tanlu fault belt, forming a positive flower-like structure. The strongest activity occurred in the Su-Lu section located in its north part experienced and resulted in the formation of a series of Neotectonic phenomenons such as pull-apart basin, extrusion uplift belt, gully fault, etc. This is a typical seicmic fault. Due to the lateral compression, pre-Cenozoic strata inside this fault belt were folded and uplifted to hills. In the north section, there are also large amount of Cenozoic eruptive rocks.

1.3 Volcanic activities

The eruption of the Cenozoic basalt in North China can be divided into three stages, among which the Neogene eruption is the strongest. In the north uplift area, many basalts and volcanic deposits have been discovered. For example, the Cenozoic basalts, tuffs, and volcanic clastics in Hannuoba. In the Yangyuan and Datong basins in northern Shanxi Province, Middle Pleistocene mantle-derived basic volcanic rocks composed mainly of olivine basalt and basalt developed.

Some Quaternary volcanic rocks exposes in different areas in North China area, including the basalt in Wudidashan of Shandong Province, Nvshan of Anhui Province, Datong of Shanxi Province, etc. According to the comprehensive dating results, the Quaternary volcanic activities in North China can be divided into five stages: early Early Pleistocene (~ 2.36 Ma), late Early Pleistocene (~ 1.34 Ma), early Middle Pleistocene (0.60 ~ 0.80 Ma), late Middle Pleistocene (0.20 ~ 0.13 Ma), late Late Pleistocene (0.07 ~ 0.035 Ma). The volcanic groups in Datong of Shanxi Province (~ 0.68 Ma), the basalt in Wudi Dashan of Shandong Province (~ 0.73 Ma), and the basalt in Penglai of Shandong Province (~ 0.84 Ma) are typical representatives of the former three stages.

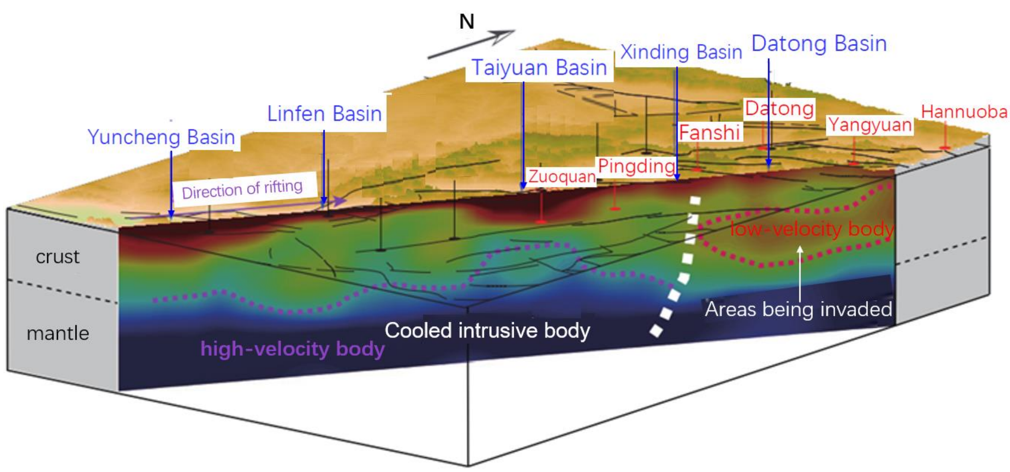

Figure. 2 The deep geodynamic background for the formation of Shanxi fault-depression belt [20]

Blue text, the five basins in this fault-depression belt; Red text, locations where residue of mantle-sourced inclusions were discovered; Red dashed line, the north area being intruded by magmatic rocks; Purple dashed line, the already cooled Early Tertiary underplated magmatic rocks; White dashed line, the boundary between north and south part

In the Taiyuan, Linfen, and Yuncheng basins located in the middle-south part of Shanxi fault-depression belt, the change from the low velocity of the upper crust to the high velocity of the lower crust may be caused by the early Tertiary underplating of basaltic magma before the rift extension, so there is enough time to cool down and lead to the formation of the consistent high velocity lower crust in the three southern basins. The low-velocity anomaly in

Datong volcanic area, located north of 39°N, extends from the top of upper mantle to middle crust, and shows the characteristics of shifting from west to east, which clearly shows the characteristics of mantle magma upwelling. Besides, there are large low velocity areas in north of 38°N, which may be caused by the upwelling and underplating of hot basaltic magma from the upper mantle in Datong volcanic area, resulting in the heating up and even partial melting of crust (Fig. 2).

2 THE PRESENT SITUATION OF HIGH TEMPERATURE GEOTHERMAL RESOURCES EXPLORATION

2.1 The high temperature geothermal resources in Tianzhen county of Datong city

High temperature and high pressure geothermal fluid has been discovered in Tianzhen county. The GR1 drilling data show that rocks between 0~ 286.5 m are mainly clay cap rocks and the geothermal gradient in the borehole is large with a value of 21.5 ℃/100 m. This may because there are thermal convictions under the cap rock and bake the upper cap rock. Between 285.6~ 1297 m, there is Neoarchean metamorphic rock with a geothermal gradient of 5.15 ℃/100 m. This is also the geothermal resources reservoir. No fracture zone and obvious fracture structures are found in the boreholes in this area, and geothermal fluids are not contained also. All these suggest that no thermal conductive faults are drilled and the geothermal gradient is relatively stable. Thermal gradient increases into 16.01 ℃/100 m between 1297~ 1500 m. In this interval, there are also no faults and geothermal fluids and the geothermal gradient is large. This is mainly because as the drilling depth increases the borehole approaches the deep thermal channels and high temperature fluids, and the deep heat source continuously affects the geothermal gradient in the area [21]. Well GR1 has a temperature of 164 ℃ and meets high temperature high pressure fluids at the depth of 1500 m. Open flow test shows that the well head has a temperature of 160.2 ℃, pressure of 1.12 MPa, and the largest flow rate of 231.15 m^3/h. The high temperature fluid is Cl•SO_4-Na type with total dissolved solids of 1840 mg/l, metasilicic acid content of 282.9 mg/l, and fluorine content of 17.5 mg/l.

2.2 Matouying HDRs in Hebei Province

The HDRs of Matouying area is located on the Matouying uplift, which is 90 km to the southeast of Tangshan city of Hebei Province. The HDRs in the Matouying uplift are Archean metamorphic granites or metamorphic rocks. The cap rocks are the Quaternary loose sediments and Neogene mudstones and sandstones with a total thickness of about 1350 m. The highest regional thermal flow reaches 90~ 100 mW/m^2 [22]. In 2019, HDRs of 150 ℃ was drilled at the depth of 3965m. The preliminary exploration results show that at 4 km depth the area of HDRs is nearly 80 square kilometers and at 5 km depth 500 square kilometers.

3 ANALYSIS OF GEOLOGICAL ELEMENTS OF THERMAL CONTROL

3.1 Geodynamic background

The late Mesozoic subduction of the western Pacific plate not only caused the North China Craton destruction, but also the decarbonization and dehydration of the trapped Pacific plate and the associated melting and intergeneration led to more active convection in the East Asian soft mantle wedge, which is the main driver of basalt formation within the North China plate [23].

Neotectonic movement in North China is controlled by the interaction of two lithospheric structures: the far-field effect of the Indo-European collision and the upwelling of the lithospheric mantle. On the one hand, the eastward tectonic extrusion in the northeastern corner of Qinghai-Tibet also affects the eastern part of North China, and the extrusion slip deformation occurs along the Tanlu fault zone. On the other hand, the deep mantle upwelling caused by the subduction of the Pacific plate dominated the regional thermal subsidence and Quaternary 5 mantle source volcanism in eastern China, and the development of transverse fold deformation and dense vertical shear fault in the middle and late Pleistocene in the Bohai Sea. These two lithospheric tectonic forces alternate and ebb and flow from each other in space-time, controlling the differential evolutionary history of new tectonic features in North China [24].

Pacific plate, Philippine plate, and Indian Ocean plate compress the Chinese mainland and adjacent areas in NWW, NW, and NNE directions, respectively [25]. As a result of the interaction of the above plates, the present large-scale horizontal crustal movement in mainland China and adjacent areas is mainly represented by the movement of Pacific plate to NWW at a speed of 70 mm /a in the global reference frame. Philippines plate moving towards NW at 50 mm / a; Eastern Eurasia, moved towards the SE at a speed of 30 mm /a [26].

The western boundary of the North China block is mainly influenced by NEE tectonic compression, while the western subduction of the Pacific plate may have a restraining effect on the eastward movement of the North China block, which leads to the strong extrusion tectonic activity of the Yanshan tectonic belt, the distinct tectonic movement of the North China plain, and the tensile clockwise twisting of the Shanxi fault belt.

Datong basin is located within the North China block and is the product of tectonic deformation within the plate. The regional dynamic background of the formation and evolution of the Datong Basin may be a combination of the Indo-Eurasian plate and the Pacific-Eurasia plate collisions. Mantle magmatic activity dominated by the Pacific-Eurasia plate collisions persisted throughout the Cenozoic, and the Datong region was continuously stretched throughout the Cenozoic, but the tectonic stress field corresponding to the pre-10~ 8 Ma extension was not as strong as that ruptured the upper crust. Since 10~ 8 Ma, the shallow tectonic stress field has reached the strength of rupturing the upper crust as a result of the long-range effect of the collision of the Indo-Eurasian plates, and the Datong Basin has evolved [27]. Datong basin is located at the intersection of Mongolian block, Ordos block, Taihang mountain uplift and Yanshan mountain uplift. Deep fault and adjacent Zhangjiakou-Bohai fault zone are the transition tectonic belts between several blocks. Under the combination of Indo-Eurasian plate and Pacific -Eurasian plate collision, the tectonic dynamic environment of Batong basin is mainly open, which is conducive to the upwelling of deep mantle thermal material, causes the shallow basin to exhibit high temperature geothermal anomaly.

3.2 Geostructural factors

(1) Lithospheric Structure

Although the exact time, magnitude, spatial distribution, mechanism and structural control factors of lithospheric thinning in eastern North China are still debated in academia, there is little doubt about lithospheric thinning in eastern North China [28]. The consensus is that the Late Mesozoic Western Pacific plate subduction is the primary driver of the North China Craton destruction, with lateral subduction of the lower crust [29] and thermal erosion of the mantle from the bottom up being secondary mechanisms or just different modes of action [30].

The North China Craton disruption caused a significant thinning of the lithosphere (60-80 km thick) and crustal thickness (< 35 km thick) of the eastern continental shelf (Fig. 3, Fig. 4). This is significantly smaller than the western continental shelf lithosphere (200 km thick) and crustal crust (45 km thick) of the eastern Craton. The central of Bohai Sea lithosphere is about 60 km thick and the crust is about 25 km thick, which is the thinnest in the eastern China Sea. The great thinning of the lithosphere caused by the Craton destruction in North China provides good conditions for deep thermal energy to enter shallow layers in the region [31]. The Matouying area is located in the eastern part of North China Craton, which is the most obvious and typical region of the world where ancient Craton was destroyed.

The eastern lithosphere of the north China plate has experienced large-scale destructive activities since the cenozoic era, while the western block Ordos retained a 200km thick lithosphere, basically retaining the structure of the north China craton since its formation and is in a relatively stable state. The lithosphere thickness is about 80 km around Fengzhen in the north of Shanxi fault basin, 80 km to 100 km in Datong basin, 100 km in Hengshan in the south of the basin, and the corresponding LAB in Datong basin is slope to SE. These slopes are the result of lithospheric thinning and mantle activity [27].

The depth of Moho surface in the tensioning area of Shanxi fault is about 32~ 37 km, compared with about 2-3 km in the uplift of Moho on both sides of the fault. In Shanxi fault zone, the mean geothermal flow was measured at 69.49 mW/m^2 with a high geothermal gradient of 2.7 ℃/100 m, while the geothermal flow and geothermal gradient around the fault zone were relatively low. The results of the reception function study show a crust thickness of about 40-43km and a wave velocity ratio of nearly 1.85 in Datong Volcano. It is speculated that the high wave velocity ratio in Datong Volcano may be related to the iron-magnesium volcanics erupting from the Volcano. It is speculated that the upper mantle surged up from Cenozoic period and formed local magmatic activity at the base of the crust, which led to thick crust, high heat flow and high wave velocity ratio in Datong volcano area [33].

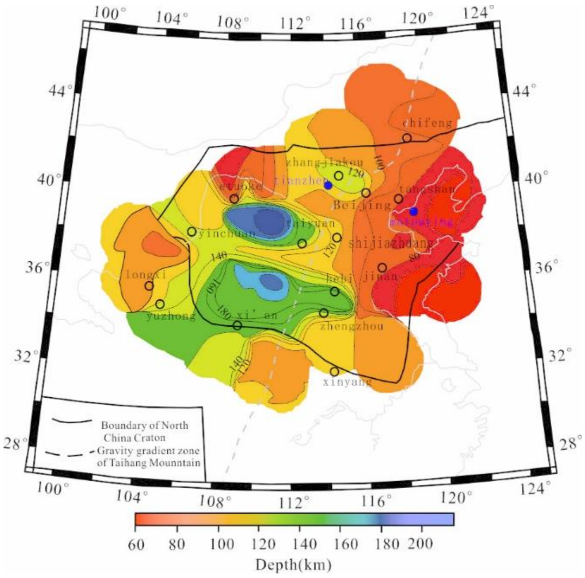

Figure. 3 Lithospheric thickness map of North China [30]

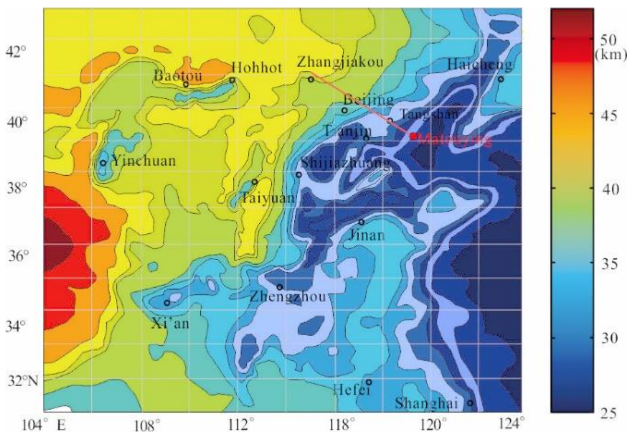

Figure. 4 Contour map of the Moho surface in North China [32]

(2) Thermal structure of lithosphere

The change of lithospheric thickness during the failure of North China Craton has good correspondence with the lithospheric thermal structure of Mesozoic and Cenozoic in Bohai Bay basin. Late Early Cretaceous and early Paleogene were the peak of lithosphere destruction in eastern North China Craton. The present lithosphere has thickened after the Craton destruction, the total lithosphere strength has increased, and magmatic activity has been greatly receded, but the Bohai Bay basin still retains a relatively high thermal background (60~ 68 mW/m^2) from the previous period. As the lithosphere thickness changed, the basin changed from a Triassic-Jurassic lithosphere thermal structure of a "cold mantle thermoshell" to a Cretaceous lithosphere thermal structure of a "hot mantle cold crust" to the present [34].

The North China basin is characterized by a large variation in the buried depth and a shallower internal depth than Tarim and Yangzi basins, revealing that the North China region has undergone intense transformation since the Mesozoic, with the softening of the upper lithosphere and the thinning of the lithosphere, making the crustal thermal structure of the North China land mass particularly complex [35]. The surface depth of Curie isotherm in Bohai Bay and Zhanhua is 16 to 18 km, which is 5 to 10 km lower than the surrounding area (Fig. 5). The rise and fall of Curie isothermic surface are consistent with the rise and fall of Moho surface and the high and low surface heat flux.

The Curie surface axis in Shanxi fault basin, which is generally north-eastward, basically coincides with the basin axis, and the Curie surface axis is buried 18~ 20 km deep. In Datong Basin, the Curie isothermic uplift axis is north-eastward and the shallowest is 20 km. The Mongolian block to its north is 38km deep inside. The Ordos block on the west side is 36km deep inside. Luoyang area in the south is 34km deep inside. The thermal flow value of Shanxi fault basin is relatively high, about 60~ 80mW/m^2, which is obviously lower than that of Ordos block 40~ 50 mW/m^2. Thermal structures display, thin lithospheric mantle beneath the Tianzhen-Yangyuan, while a cold, relatively thick lithospheric mantle lies to the west, corresponding to east-west differences in the thinning of the Craton lithosphere in North China. Based on the higher temperature field of the Yangyuan lithosphere, it is speculated that the lithospheric mantle may be undergoing a soft upwelling and modification of the lithosphere [36].

(3) Deep Fracture and Activity Characteristics

Matouying dry hot rock hole is located in Matouying bulge the northeast of Huanghua depression in Bohai Bay basin, southeast of Bohai depression, and north of Yanshan fold belt (Fig. 6). The Huanghua depression is a Cenozoic sedimentary depression based on the Mesozoic basin. The Matouying outcrop is Cenozoic and the basement is Lower Paleozoic carbonate and Archaean metamorphic rocks. The regional deep fault is very developed, the larger scale of the Tanlu fault belt, Zhangjiakou-Penglai fault belt, Cangdong fault belt and so on.

The Tanlu fault zone of NE-NNE is the largest lithosphere fault zone in eastern China. It is characterized by distinct segmented activity in space and multi-phase activity in time. It is elongated, deeply cut and active. It has cut through the lithosphere [37]. Since the Late Pleistocene, the Bohai Sea section of this fault is characterized by a backlash and a right-hand spin, and there have been many strong earthquakes along or near this section in history.

The Zhangjiakou-Penglai fault zone, which is a complex fault belt of more than 20 discontinuous NW-oriented secondary faults, has been followed by major earthquakes such as magnitude 7.8 in Tangshan in 1976 and magnitude 8 in Sanhe Pinggu in 1679, as well as a large number of small and medium-sized earthquakes. The tectonic belt is also considered to be a new active fault zone [38]. The fault zone corresponds to the crust thickness variation zone, the crust thickness is large in the north and small in the south. Several seismic reflection profiles and magnetotelluric sounding profiles through the Zhangjiakou-Bohai Belt reveal that the fault is a deep fault of a cut lithosphere, some of which control the formation and development of the Quaternary fault basin, thus forming a deep subsidence zone of the Quaternary. High-resolution shallow seismic data confirm that the fault zone in the Bohai Sea has been characterized by strong vertical motion since the Late Quaternary [39]. The latest active age of the faults in the sea is late Pleistocene-early Holocene.

(4) Neotectonic Movement

In addition to the new tectonic movement of the Tanlu and Zhangjiakou-Penglai faults mentioned above, there are two large new tectonic belts in the region: the Miaoxibei-Huanghe estuary fault zone and the Tangshan-Hejian-Cixian fault zone.

Miaoxibei-Huanghekou fault zone: located at the intersection of Tanlu fault zone, Zhangjiakou-penglai fault zone, in the right-hand extrusion shear zone of Liaodong Bay and Laizhou Bay of the Tanlu fault zone, shearing stress is concentrated, along 1 set of maximumshear directions new produced a NE Miaoxibei-Huanghe estuary fault zone with right-rotational translational properties It has become the main new active tectonic belt in the eastern Bohai Sea and also the seismic tectonic belt.

The active tectonic belt of Tangshan-Hejian-Cixian is a new seismic-tectonic belt composed of the Cixian-Handan fault, the Xinhe fault and the Tangshan fault. There are now four earthquakes of magnitude 7 or greater in active tectonic zones, including the magnitude 7.2 earthquake in Xingtai in 1966 and the magnitude 7.8 earthquake in Tangshan in 1976. The source of the rupture is mainly right-hand slip, with steep inclination of the fracture surface [40].

On the basis of lithospheric thinning since late Mesozoic, since 10~ 8 Ma, the soft flow and mantle activity transfer heat to the crust, causing the brittle upper crust to show a certain strength of NW to extend the tectonic stress field, which controls the formation of the Datong rift basin. Because of the continuous thinning of lithosphere and the continuous action of tectonic stress field in Datong area, the boundary fault of Datong Basin is in continuous activity, during the Pleistocene the lithospheric fault in a tensile state was intersected and magma from the mantle was ejected to form the Datong Volcano Group. The formation of the Datong basin is controlled by many faults. The northern boundary of Liulengshan piedmont fault is still active in the Holocene. Four faults occurred between 13.73 and 1.61 ka in the western border estuary fracture. There have been three paleoseismic events since the early Holocene, the most recent of which occurred between 4.37 and 2.26 ka [41].

(5) Magmatic activity

The mid-east region of North China crust is dominated by the collision and jostling of the indian plate, while the deep part is influenced by the westward subduction of the Pacific plate, providing a source of energy for shallow movement and controlling the occurrence of large surface earthquakes. Regional deep walk-slip fractures constitute the main channel for mantle thermal upwelling (Fig. 5) [42]. In general, the newer and larger the magmatic activity, the more residual heat is retained and the greater the impact on the current geothermal field. Cenozoic volcanic rocks from old to new in the region tend to move from the edge of the Bohai Bay basin to the center and then to the edge of the basin, this is mainly restricted by the development and evolution of the deep fault system controlling volcanic activity in different periods.. Since the Neocene, the tectonic activity is weak, magmatic activity is weak and volcanic rocks are scattered, Neogene volcanic rocks are mainly distributed in the north and south of the central part of the basin, Quaternary volcanic rocks are only sporadically visible in Haixing and Wudi counties. These are relatively recent magmatic events that may increase local geothermal field temperatures [43].

According to the joint surface wave and background sound inversion results of Li Shilin（Fig. 6）[44], a low-velocity anomaly is found at a depth of 200~ 250 km below Ordos. The low-velocity anomaly connects to the low-velocity anomaly below the northeastern edge of the Qinghai-Tibet Plateau to the east, and the low-velocity anomaly below Ordos is believed to provide a conduit for magma supply to Ordos [33]. In addition, the stagnation and collapse of the subduction of the Pacific plate in the western boundary of the decompression melt, also conducive to mantle source thermal material invasion; The eastward escape of the Qinghai-Mesosphere (possibly including the southern and northern channels of the Ordos block) meets the greater East Asian mantle wedge in the trapped mantle, which also contributes to the upwelling of the mantle source thermal material. Ma Jinlong determined the Sr-Nd isotope of Cenozoic basalt from the Datong Volcano Group and found that the basalt from the Datong Volcano Group came mainly from the soft Pleistocene mantle [45].

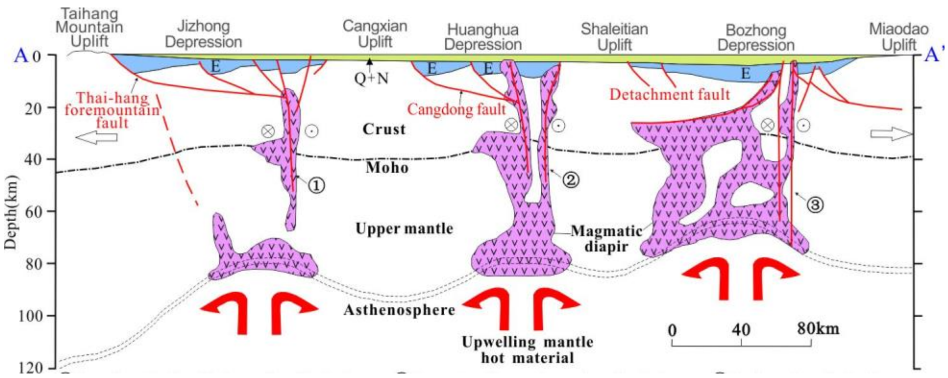

Figure. 5 Schematic diagram of the tectonic section of the Bohai Bay Basin [42]

①Tangshan-Hejian-Cixian strike-slip fault zone; ② Huanghua-Dongming strike-slip fault zone; ③ Tanlu strike-slip fault zone.

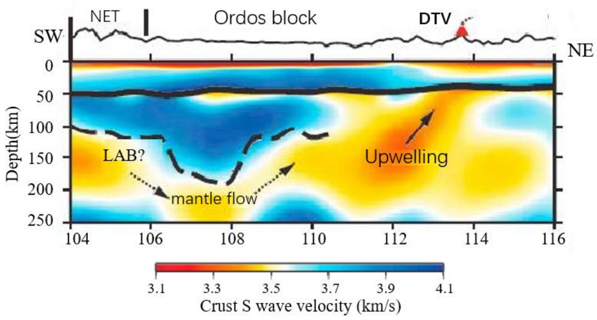

Figure. 6 Three-dimensional shear wave velocity structure in Datong and surrounding areas [33]

The red triangle in the figure represents Datong volcano. Black dotted line denotes LAB interface; The black arrow indicates the direction of transport of the soft rims; NET: Northeast Qinghai-Tibet Plateau; Ordos block: Ordos Block; DTV: Datong Volcano Group

3.3 Geophysical Characteristics

Magnetotelluric (MT) and seismological studies have shown the existence of low-velocity seismic waves [46] in some areas of the lower crust and the top of the soft streamer (50~ 120 km) in the eastern North China region, and have also shown high electrical conductivity anomalies in these areas [47-48]. The convection uplift of the soft sphere has a good correspondence with the distribution of the low velocity high conductors (layers) of the lithosphere at the top of the soft sphere and above it.

The lithospheric structure of different blocks in North China Craton has a strong transverse change. In the lower part of the hinterland of Ordos Basin, the stable Cratonic properties are retained as a whole, except for a small area of local reconstruction in the southeast edge. The lithosphere of the North China basin in the east was severely damaged and thinned, showing a thinner low-velocity crust. The lithosphere at the northern and southern ends of the central orogenic belt and along the north-south gradients was also thinned to varying degrees, with the lithosphere at the northern end of Datong volcano group being the most strongly modified (Fig. 7) and the lithosphere at the southern end relatively weak. The low-velocity bodies at the north and south ends connect through the low-velocity belt below the north-south gravitational gradient line and extend deep into the mantle of the North China Basin, possibly representing the same remodeling thinning mechanism. Heat from the upper mantle of the North China Basin intrudes into the lithospheric mantle below the Taihang orogenic belt and flows to the north and south ends of the central orogenic belt, causing local remodeling thinning. The magmatic activity of the Datong Volcano Group (may have originated from mantle thermal material beneath the North China Basin rising northwestward, invading the crust below the northeastern corner of Ordos, and being blocked by the upper crust from flowing eastward during the upwelling to reach the base of the Datong Volcano Group [49]. Fig. 8 shows that the low velocity high conductors of the middle and lower crust in the Tangshan area tend to flow from the middle crust along the Zhangjiakou-Penglai fault zone through Beijing to Zhangjiakou,which has a good correspondence with the distribution of geothermal resources in Tianjin, Beijing and Zhangjiakou.

The electrical structural profile of the Zhangbo Seismic Belt shows (Fig. 9) that along the middle and lower crust of the Zhangbo Seismic Belt there is a series of highly conductive anomalies upwelling, mainly along deep faults such as the Tangshan Fault, the Xiadian Fault, the Yanqing -Fan Mountain Basin North Rim fracture, the Huai(lai)-Zhuo(lu) Basin North Rim Fault and the Zhangjiakou Fault. The resistivity gradient zone obtained by inversion is consistent with the spatial distribution of faults. The upper crust of the Tangshan fault zone is characterized by high resistance, and there are upwelling high conductivity anomalies at the bottom of the lower crust. The large size of the Zhangjiakou fault zone in the upper and lower crust than in the deeper Huailai basin may suggest that the Zhangjiakou fault zone has a stronger deep material action [51].

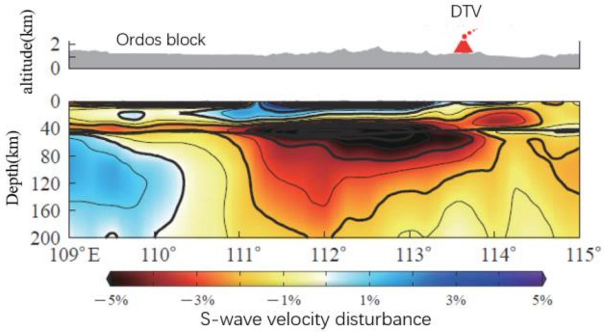

Figure. 7 Vertical sections of the S-wave velocity model，the positions of which are marked with black dotted lines in Fig. 4， the thick black lines denote the Moho depth [49]

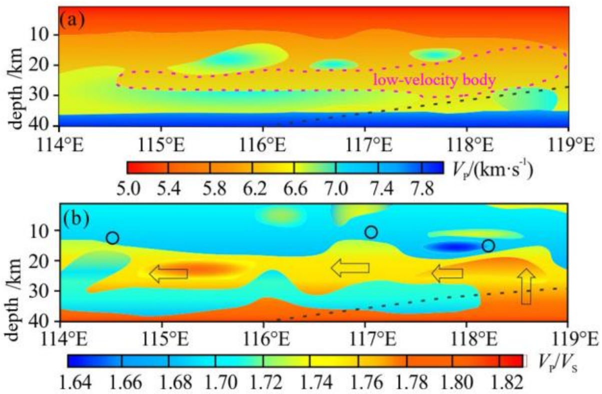

Figure. 8 Section (see Fig. 3 for section) P wave velocity structure (a) and Vp/Vs wave velocity ratio (b) [50]

Hollow circle in the figure from left to right: The 6.2 magnitude earthquake in Zhangbei in 1998; The 8.0 magnitude earthquake in Sanhe in 1679; The 7.0 magnitude earthquake in Tangshan in 1976. ZB: Zhangbei; BJ:Beijing; SH:Sanhe TS: Tangshan. Gray dashed: Moho. Gray arrow: Flowing trend of the low-speed bodies.

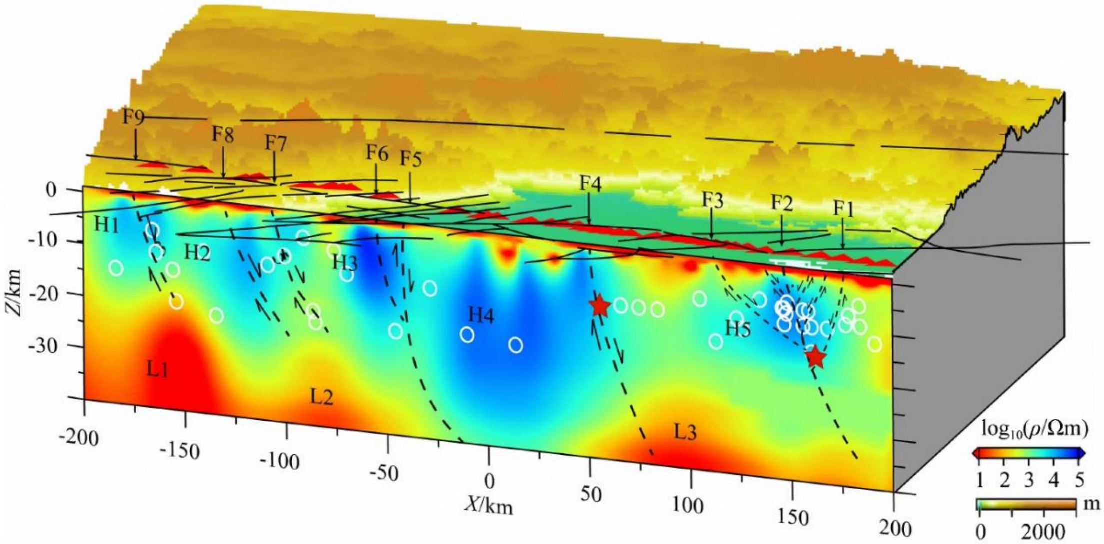

Figure. 9 Electrical structure interpretation diagram of the Zhangbo seismic belt [51]

The white circle represents M > 3.0 earthquakes from 2007 to date (courtesy of China Earthquake Network Center) F1 Ninghe -Changli fault; F2 Tangshan fracture; F3 Fengtai -Yejituo fracture; F4 Xiandian fracture; F5 Huangzhuang -Gaoli Camp fracture; F6 Nankou fracture; F7 Yanqing -Fan Mountain Basin North Rim fracture; F8 Huai(lai)-Zhuo(lu) basin; F9 Zhangjiakou fracture F1-F8 trend to NE or NEE; F9 trend to NW.

3.4 Geochemical Display

Sr-Nd binary isotopic diagrams show that alkaline basalts have more homogeneous isotopic signatures, and labyrinthine basalts have a wider isotopic distribution, suggesting that Datong basalt as a whole has a negative Sr-Nd correlation and falls within the oceanic island basalt (OIB) range, close to the total silicate Earth value (BSE) (Fig. 10a). The ε Nd (t) is -1.5 ~ 6.3 and ε Hf (t) is 5.3 ~ 10.6. On the ε Nd (t) - ε Hf (t) diagram (Fig. 10b), samples of Datong basalt are far from Fangcheng basalt and are positively correlated along the mantle evolution trend line, and also fall within the OIB range. It shows that the main source of Datong basalt is mantle [52].

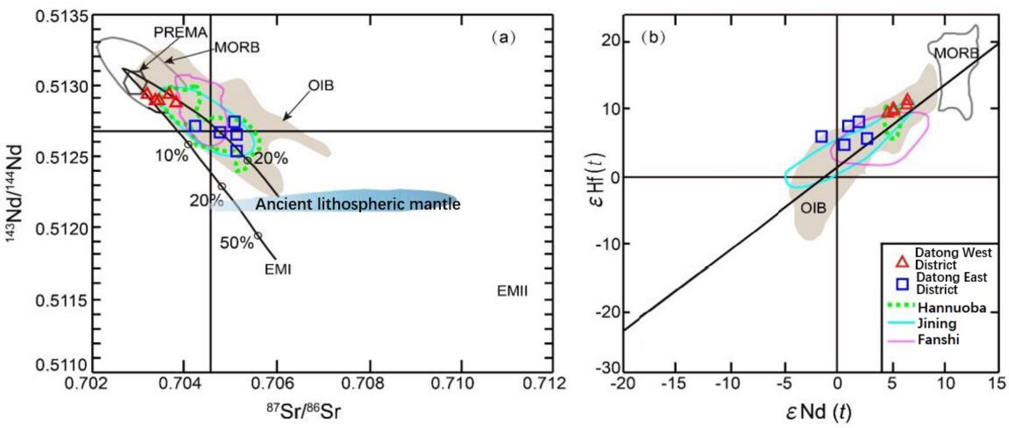

Figure. 10 Datong and surrounding basalt ^{57}Se / ^{85}Sn, ^{145}Nd / ^{144}Nd Illustration [52]

According to zhang yibin(2013) calculation of geothermal helium and neon isotope in Datong [53], the contribution of helium from geothermal water mantle source in Tianzhen-Yanggao is 8% to 13.5%, suggesting that there is a lot of mantle volatilization in the region (Santosh et al., 2010), rising to the surface through weak layer and fracture. Geothermal water R_C / R_A values ranged from 0.64 to 1.10, with ^3He / ^4He being higher (Fig. 11), suggesting that the high heat flux is associated with mantle heat contribution, possibly due to upwelling of the soft mantle and intrusion of mantle source thermal material along deep faults. Soluble silica in the newly constructed Tianzhen High-Temperature Geothermal Portal (DR1) in Datong City reached 217.83 mg/l, and according to the quartz temperature scale, the temperature of shallow thermal reservoir at 2000m is estimated to be 185.85℃, much higher than the temperature of geothermal reservoir at the same depth in North China , indicating the existence of deep abnormal heat sources.

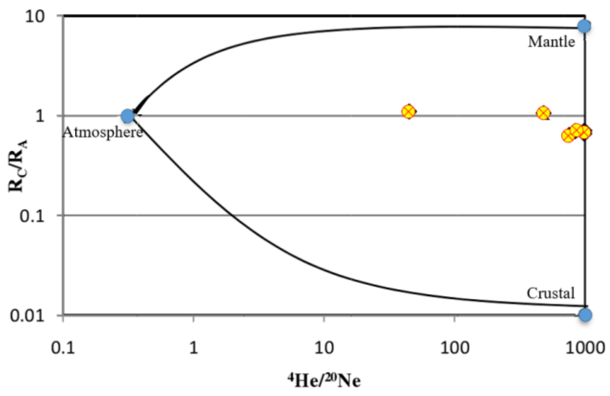

Figure. 11 Tianzhen -Yanggao Area R_C / R_A-^4He / ^{20}Ne Relationship Map [53]

4 ANALYSIS OF "SOURCE, COMMUNICATION, STORAGE AND COVER"

4.1 Heat and fluid sources

(1) Heat source

The hot mantle and cold crust type lithospheric thermal structure of the eastern North China and Shanxi fault basins determines that the heat source from the mantle is the main heat source of the regional heat storage. Quantitative calculations show that 1 g of H_2O from a depth of 100 km can raise 1 ℃ of shallow 1000 g of H_2O, so the injection of a small amount of deep fluid will produce a significant thermal effect. Mantle-derived fluids have strong penetrating ability and have a wide range of influence. The molar enthalpy of CO_2, CH_4 and N_2 is larger than that of H_2O under the same temperature and pressure, indicating that the gas components are good carriers for the heat energy from the earth's interior to the outside [54]. Deep faults that cut through the Moho and even the lithosphere can cause the deep mantle hot material upwell to the crust and migrate to the shallows. Newer mantle-derived magmatic activities and tectonic movements can also bring deep mantle hot materials to the shallows. The deep data show that there are three asthenosphere uplift belts centered on Bozhong (i.e., the direction of Lower Liaohe-Liaodong Bay, the direction of Bohai Bay-Qikou, and the direction of Laizhou Bay-Weibei). These asthenosphere uplift belts are located at and near the intersection of the Tan-Lu fault zone and the Zhangjiakou-Bohai fault zone, indicating that the Bozhong area was the center of the upwelling of Cenozoic mantle materials [55]. Driven by the subduction of the Western Pacific plate, the lithosphere in the eastern part of the North China Craton has thinned significantly, especially in the Bozhong sag and Nanpu sag near the Matouying uplift, which is The Bozhong sag and Nanpu sag near the Matouying uplift have the most obvious thinning, which is conductive for heat conduction and upwelling of deep thermal materials, making the Matouying uplift located in the high heat flow area.

The decompression melting formed by the stagnation and collapse of the western boundary of the subduction of the Pacific plate is also conducive to the upwelling of mantle-derived thermal materials; the eastward escape of asthenosphere materials from the Qinghai-Tibet Plateau encounters the Greater East Asian mantle wedge stranded in the mantle, which is also conducive to the upward intrusion of mantle-derived thermal materials. The mantle-derived thermal materials from the east (Pacific plate) and west (Qinghai-Tibet Plateau) directions may intrude after the convergence of the western boundary of the subduction of the Pacific plate, leading to the formation of Cenozoic basalts in Datong and Hannuoba, and at the same time, bringing the heat flow from the deep to the shallow, which forms a high temperature anomaly in the shallow.

In a word, the heat sources of regional geothermal resources mainly come from the crust and mantle conduction heat in the lower part of the heat storage, the decay heat of radioactive elements in the crust, the upwelling of hot mantle materials along the deep faults, and the shallow geothermal anomalies in tectonic favorable parts formed by relatively new age of mantle-derived magmatic activities, tectonic movement deformation heat and so on.

(2) Fluid source

The He of German scientific deep drilling (KTB, up to 9101 m deep) is caused by the mixture of mantle helium and radioactive helium, indicating that in the lower part of the upper crust and the upper part of the middle crust, there are fluids that are genetically related to the upper part of the upper crust, as well as fluids that are related to the middle and lower crust, and even the upper mantle.

The mantle-derived CO_2 gas reservoirs in Gangxi, Koucun and Beipu in the Huanghua Depression, and Gaoqing and Yangxin in the Jiyang Depression [56-57, 54], indicating that these districts are affected by obvious mantle-derived materials at a depth of several kilometers. The low-velocity and high-conductivity layers in the crust of the Zhangjiakou-Bohai fault zone and the mantle-derived helium in the wells and springs in the Datong-Yanhuai area indicate that the intrusion of mantle-derived materials occurred along the deep fault zone [50]. Before the Tangshan M7.8 earthquake on July 28, 1976, the pressure of Well Zhuang-13 in Dagang Oilfield increased from 2.4 to 2.5 MPa in early July to 3.7 to 4.0 MPa in late July; this phenomenon indicates that the upwelling of deep thermal fluids had already occurred before the earthquake. And the outflow of deep fluids is about 750 million m^3 during and in a short time after the Tangshan earthquake [58].

This shows that the formation water and its temperature, pressure, chemical properties, and mantle-derived gas reservoirs all indicate that the shallow part of the crust is affected by mantle- and crust-derived geological fluids. In addition to the above-mentioned deep fluids, atmospheric precipitation and the earth's shallow surface water are also the sources of fluids that cause shallow thermal anomalies after they circulate and heat up in the deep crust along the crustal fracture zone.

4.2 The process of fluid migration from the deep part of the earth to the shallow

Many research results from tectonic, seismic, oil and gas, as well as geophysics, geochemistry, etc., show that deep fluids migrate to the shallow part of the earth due to deep and large faults, earthquakes, and volcanic-magmatic activities. Deep faults and their activities will inevitably lead to the flow of fluids in the earth, the exchange of materials, the production of new materials, and the transfer and exchange of energy.

Yang Wencai (1998) pointed out that the asthenosphere is a layered body connected by low-density and low-viscosity partially molten materials, and the fluid channel network of the continental lithosphere includes deep faults, collision fracture zones, remelting and deep melting, demolition and subsidence channel, puncture structure of mantle material, etc. through seismic tomography data [59]. Du Letian (1996) analyzed the relationship between crustal fluids and mantle fluids through the study of mantle xenoliths and pointed out that detachment fault systems (including shovel faults, overthrusts nappe, gliding nappe, especially strike-slip faults) are the distribution channel of mantle fluids in the crust [60]. The first- and second-level block boundaries of the destruction area of the North China Craton are mainly composed of two groups of active faults, the NWW-NW left-lateral strike-slip fault and the NNE-NE right-lateral strike-slip fault. These two sets of faults have a conjugate relationship, indicating that the crust in the destruction area of the North China Craton is an environment of horizontal compression and shear deformation [61]. These block boundary strike-slip faults are characterized by steep and straight sections and cut down through the entire crust and even extend into the lithospheric mantle.

Mantle fluid and mantle heat flow will exchange material and energy with crustal rocks during the rising process, and often form a ductile rheological layer (low-velocity layer) with a wide area in the lower part of the lower crust, and a molten magma chamber can be formed in a suitable environment. The fluid and heat flow of the mantle, crust-mantle mixing, or crust continues to rise, and heat energy accumulates again in the ductile rheological layer of the middle crust. The ductile rheological layer contains certain molten components, including gas and water, which increase its chemical energy [62].

The low-velocity rheology of the middle crust connects the two different fault systems of the upper crust with the middle and lower crust. The middle and lower crustal faults connect the low-velocity bodies with the mantle. The upper-crust faults connect the low-velocity bodies with sedimentary basins and are connected with various traps through the faults in the widely developed sedimentary basins, so that volatiles in low-velocity bodies migrate to shallow parts along the faults. Upper crustal faults are also channels for magma upwelling. Igneous rocks are mostly distributed on both sides of and near these faults, and magma intrusion and eruption will release many volatiles at the same time and later stage [56].

The deep and large strike-slip faults in the NNE-NE trend in the Bohai Bay Basin, such as the Tanlu fault zone, the Tangshan-Hejian-Cixian fault zone, and the Zhangjiakou-Bohai fault zone, all cut through the Moho surface and even the lithosphere, become a channel for the upwelling of hot mantle material or the basic magma [63]. In the extensional tectonic environment represented by the Tan-Lu fault zone, the crustal thickness is small, and the mantle degassing (mantle-derived fluid upwelling) is the strongest [64]. The uplift of the high-conductivity and low-velocity layer of the asthenosphere is mostly located at the lower part of the regional deep and large fault, which indicates that the asthenosphere fluid "chooses" the fractured zone as its upwelling channel. Deep and large faults are not only the main channels for the upwelling of deep mantle-derived thermal materials, but the upwelling of mantle-derived thermal materials can also promote the activation of deep faults or generate new faults. The newly born Miaoxibei-Huanghekou fault zone in the Bozhong area may be related to the upwelling of deep-source thermal materials.

The deep and large fault in the southwest of Tianzhen high-temperature geothermal hole (GR1) connects the deep low-resistivity anomaly and the shallow high-conductivity layer. The deep low-resistance body becomes the heat source of the high-temperature geothermal system. The deep heat source upwells along the deep and large faults in the southwest, intrudes into the surface rock layers, and then migrates eastward along the near-EW-trending shallow fault. The geothermal resources are collected into thermal reservoirs, where the surface water infiltrates in. Heat convection occurs here, forming a typical convective geothermal resource.

4.3 Accumulation of deep heat to shallow high temperature thermal storage

The main factors affecting the geothermal field include tectonic properties, basement relief, magmatic activity, lithology, caprock folds, faults, groundwater activity and hydrocarbon accumulation. Among them, regional geological structure and deep crustal structure play a major role in controlling the distribution of geothermal field; petrophysical properties (thermal conductivity, etc.), volcanic activity, magmatism, rifting, groundwater activity and other factors have an important impact on the local geothermal field distribution.

Many scholars have noticed the mirror image relationship between the depression basement and the Moho uplift [56, 58], that is, in the thin lithosphere area, the asthenosphere and the Moho uplift, the high-conductivity and low-velocity layers in the crust develop and uplift, the differential movement within the fault block is obvious, the basement faults are relatively developed, the magmatic activity is frequent, and the deep activity is strong. Therefore, both the heat flow and temperature in the depression area are higher than the uplift area at the same depth of the basement under the loose caprock, which is consistent with the undulating shape of the Curie isothermal surface. This is the main controlling factor of the geothermal anomaly in the shallow crust. Xiong and Gao (1982) simulated the characteristics of the geothermal field in the shallow crustal uplift and depression area and pointed out that below the heat flow balance line, the heat flow gathered from the depression area to the uplift area; above the line, the heat flow gathered from the uplift area to the depression area [65]. Exploration data in recent years have confirmed this rule. The bottom hole temperature of the deep hole of more than 3,000 meters exposing the Archean metamorphic rock on the Niutuozhen bulge, a well-known shallow-buried geothermal anomaly area, is about 100 °C (unpublished). According to the bedrock geothermal gradient of 2 °C/100 m, to a depth of 6 000m, the temperature is about 160 °C, which is lower than 201 °C at a depth of 6 027 m in Well Niudong 1 in the Baxian Sag on the east side of the uplift [66].

The geothermal gradient in the Huanghua Depression is significantly higher than that in the surrounding uplift belt, which corresponds to the mirror projection of the Moho surface in the depression. The geothermal anomalies in the depression are distributed at the intersection of the NE-trending deep fault and the NW-trending deep fault, which respectively correspond to the anomalous centers of deep source gas [56]. The Matouying uplift is close to the intersection of the Zhangjiakou-Penglai fault zone and the Tangshan-Hejian-Cixian fault zone. The southern boundary fault of the uplift, the Baigezhuang fault, is the Zhangjiakou-Penglai fault zone. It is also a new active fault cutting the lithosphere. In particular, there is a large area of Neogene volcanic rocks near the Matouying uplift, which may still retain a certain amount of waste heat. The upwelling of deep thermal fluids along deep and large faults and the eruption of magma along deep and large faults are the main controlling factors for the formation of deep linear (striped) and beaded thermal anomalies, and the upwelling of mantle-derived thermal materials can also promote the activation of deep faults or the generation of new faults, it is also conducive to the upwelling of deep thermal materials. The temperature of Well Nanpu 3-81 in the Nanpu Sag is 220 °C at a depth of 5 606 m, the temperature of Well Nanpu 1-89 at a depth of 4 700 m is 192 °C, and the temperature of Well 3-81 in the Bozhong Sag at a depth of 5 508 m is 190 °C , the geothermal gradient of these wells reaches 3.30-3.83 °C/100 m [67], which is significantly higher than the average geothermal gradient of 3 °C/100 m in the sag. This indicates that in addition to the normal deep heat conduction, there may be additional heat sources brought by the upwelling of deep thermal fluids and the eruption of magma along the deep and large faults.

The concave-convex tectonic pattern is conducive to the distribution and redistribution of heat flow. Under the effect of "thermal refraction", the heat flow is concentrated from the sag to the bulge. The Matouying uplift is bounded by the Laoting sag, Qinnan sag, Bozhong sag and Nanpu sag in the north, east, south and west respectively. In addition, huge thick Cenozoic loose sediments are deposited in the sags around the Matouying sag. The maximum sedimentary thickness in the Bozhong sag is over 10 000 m [68], the maximum sedimentary thickness of the Qinnan Sag and Nanpu Sag is over 8 000 m [69], and it of the Laoting Sag is also over 3000 m. According to the geothermal gradient of 3°C/100 m, the bases of the Bozhong Sag, Nanpu Sag, and Qinnan Sag can all reach a high temperature of over 250 °C, which provides a heat source for the heat flow from the sag to the

Matouying uplift. The Tianzhen GR1 high-temperature hole is also located in the bulge in the Yanggao-Tianzhen Basin, which is conducive to heat accumulation.

4.4 Reservoir and caprock

The more common hot dry rock reservoirs are dense and impermeable hot rock bodies without water or steam, mainly various metamorphic rocks, or crystalline rock bodies. The main lithology is gneiss, granite, granodiorite, etc.; sedimentary rocks and volcanic rocks containing a small amount of fluid can also be used as thermal reservoirs. The dry-hot rocks in the Matouying uplift and the high-temperature geothermal reservoirs in Tianzhen are both Archean metamorphic granites or metamorphic rocks.

The caprock of the hot dry rock in the Matouying uplift is Quaternary loose sediment and Neogene mudstone and sandstone, with a total thickness of about 1 350m. The caprock of Tianzhen high temperature geothermal field is Quaternary loose sediment and Neogene terrigenous clastic rock, with a total thickness of about 300m. Both are cover layers with good thermal insulation properties.

5 ANALYSIS OF THE GENESIS OF HIGH TEMPERATURE GEOTHERMAL IN TYPICAL AREAS

5.1 The genetic mechanism of high temperature geothermal in Tianzhen, Datong

For the causes of Cenozoic basic volcanic rock activity in eastern China, Niu (2005) put forward a hypothesis: the mantle wedge attraction related to the subduction zone in the western Pacific will cause the asthenosphere in eastern China to flow eastward, which will inevitably lead to the eastward recharge (flow) of the asthenosphere at the bottom of the western plateau in China, and this process will inevitably lead to the decompression and decompression and melting of the eastward asthenosphere, thus leading to the Cenozoic basic volcanic activity in eastern China [70].

In this paper, it is considered that the decompression and decompression melting of the eastward asthenosphere, the stagnation of the subduction of the western boundary of the Pacific plate and the decompression melting formed by the collapse all contributed to the upwelling of mantle-derived thermal materials. The mantle-derived thermal materials intrude the western boundary of the subduction of the Pacific plate, while the Cenozoic basalts of Datong and Hannuoba are formed, the heat flow from the deep part is quickly brought to the shallow. During the upwelling process of hot material in the deep mantle along the Datong volcano, the temperature at the top of the upper mantle increases, and the material melts and dehydrates, thus forming low-velocity anomalies at the crust-mantle boundary and in the crust. Under-invasion or thermal erosion caused the destruction of the lithosphere in the Shanxi fault zone and the "activation" of the entire North China Craton. The upper arch of the upper mantle material led to the eruption and overflow of magma, and the unexploded magma migrated to the upper part of the basin along the crustal fissure and formed a molten or semi-molten magma chamber under the action of open tectonic stress, which provides a stable heat source for the formation of geothermal resources in the region. The magma chambers transfer heat to the shallow surface along the fracture. The shallow surface geothermal heat transfers heat by convection, heating the groundwater, forming high-temperature geothermal resources in the shallow part of the crust (Fig. 12), and forming hot springs on the surface.

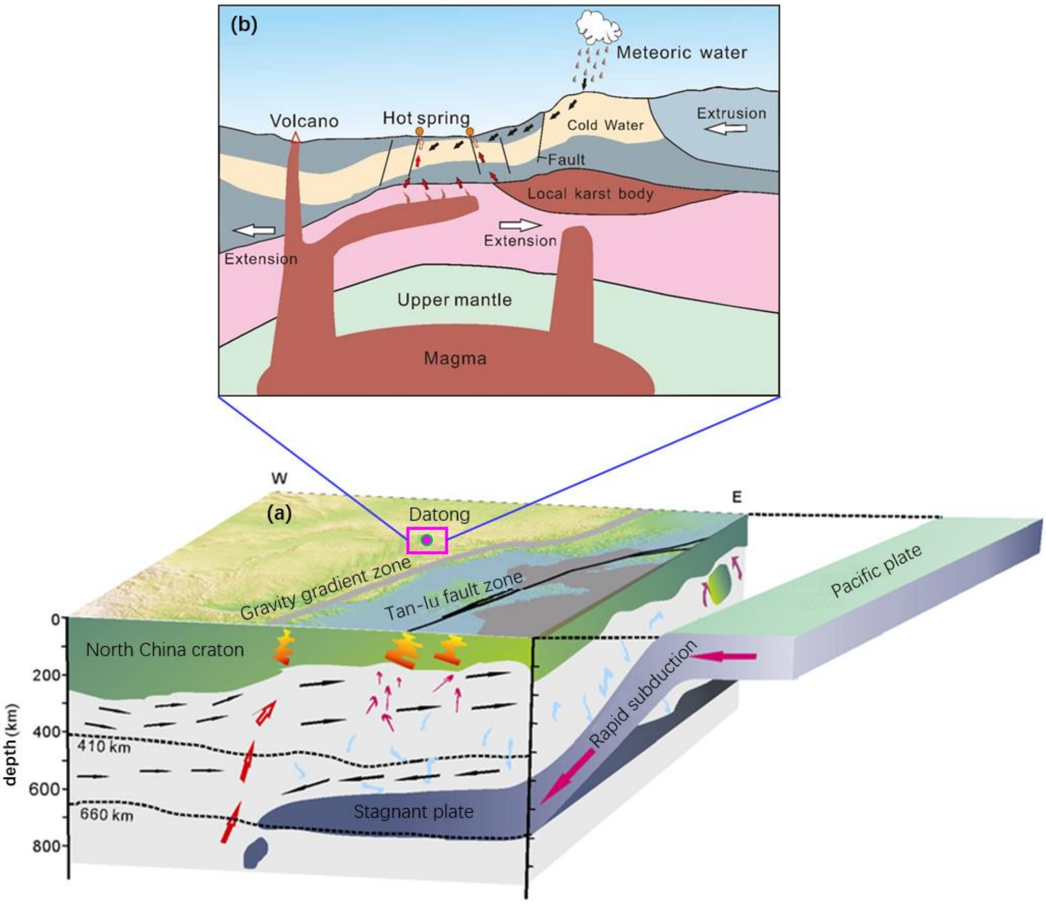

Figure. 12 Genesis of Cenozoic volcanic activity in the gravity gradient zone of the Taihang Mountains (a) [71]; and Genesis conceptual model of high temperature geothermal system in Datong City (b) [21]

5.2 The genetic mechanism of high temperature geothermal in Matouying, Hebei Province

Affected by the destruction of the North China Craton, the lithosphere and crust in the Bozhong sag and Nanpu sag near the Matouying uplift are the thinnest in the region. In this deep tectonic setting, the mantle of asthenosphere thermal material upwells along the lithospheric fluid channel network dominated by deep and large strike-slip faults such as the Tan-Lu fault zone, the Zhangjiakou-Penglai fault zone, and the Tangshan-Hejian-Cixian fault zone. Local melting magma chambers are formed in the lower part of the lower crust in a suitable environment; and it is also formed in the ductile rheological layer (high conductivity and low velocity body) of the middle crust with the participation of gas and water. The upper crustal faults connected the low-velocity bodies of the middle crust, brought deep thermal fluids and magma into the sedimentary basins, and formed high-temperature areas at the bottom of the Under the effect of "thermal refraction", the heat flow gathers from the bottom of the depressions to the uplift area. At the same time, the upwelling of deep thermal fluid and the recent eruption of magma along the deep and large fault, the thermal convection of the fluid in the deep and large fault zone, the migration of compacted hydrothermal fluid from deep parts of Bozhong sag, Nanpu sag and other sags to the uplift area, under the combined effect of factors mentioned above and some not mentioned, the hot dry rock mass was formed in the Matouying uplift bedrock (Fig. 13).

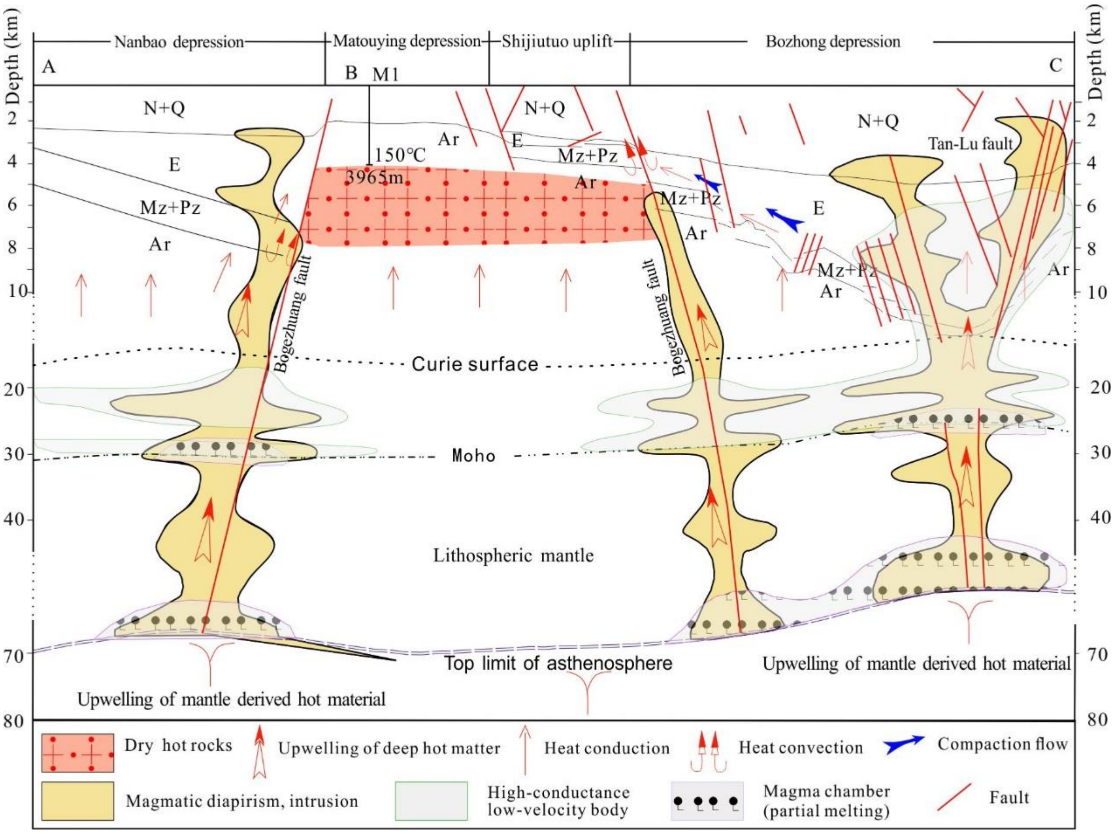

Figure.13 Genetic conceptual model of hot dry rocks in the Matouying [11]

6 CONCLUSION

(1) The subduction of the Western Pacific plate in the Late Mesozoic not only caused the destruction of the North China Craton, but the decarbonization and dehydration of the retained Pacific plate and the associated melting and metasomatism led to more active convection of the asthenosphere in the East Asian Great Mantle Wedge. As a result, the lithosphere in the eastern North China Craton has been significantly thinned, and its continuous influence has also resulted in relatively active basalts in the Cenozoic North China Plate, which has maintained a high geothermal background in the central and eastern North China.

(2) The decompression and decompression segregation of the asthenosphere from west to east and the decompression melting caused by the stagnation and collapse of the western boundary of the Pacific plate subduction cause the mantle-derived thermal materials intrude the western boundary of the subduction of the Pacific plate, while the Cenozoic basalts of Datong and Hannuoba are formed, the heat flow from the deep is also brought to the shallow. Under-invasion or thermal erosion caused the destruction of the lithosphere in the Shanxi fault zone and the "activation" of the entire North China Craton. The upper arch of the upper mantle material led to the eruption and overflow of magma, and the unexploded magma migrated to the upper part of the basin along the crustal fissure and formed a molten or semi-molten magma chamber under the action of open tectonic stress, which provides a stable heat source for the formation of geothermal resources in the area. The magma chambers transfer heat to the shallow surface along the fault, forming high-temperature geothermal resources in Tianzhen area of Datong City.

(3) Affected by the destruction of the North China Craton, the lithosphere near the Matouying uplift is significantly thinned. The mantle of asthenosphere thermal material intrudes up along the deep and large strike-slip faults such as the Tan-Lu fault zone, the Zhangjiakou-Bohai fault zone, and the Tangshan-Hejian-Cixian fault zone. Local

melting (high-conductivity, low-velocity body) is formed in the appropriate environment in the lower part of the middle and lower crust. The upper crustal faults connected the low-velocity bodies of the middle crust, so that the deep thermal fluids and magma were brought into the sedimentary basins, and high-temperature areas were formed at the bottom of the depressions. Under the effect of "thermal refraction", the heat flow gathers from the bottom of the depression to the uplift area, forming a dry-hot rock mass in the bedrock of the Matouying uplift.

(4) The most favorable conditions for the formation of high-temperature geothermal in the Matouying uplift are that the nearby lithosphere thins significantly, the asthenospheric mantle hot material intrudes along the deep and large strike-slip faults, and the heat flow accumulates from the bottom of the depression area to the uplift area, forming high-temperature hot dry rocks. Compared with the formation conditions of Matouying high-temperature geothermal, the lithosphere in Tianzhen area is relatively thick, but driven by the decompression and melting of the eastward asthenosphere and the decompression and melting of the Pacific plate subduction in the west, the recent magma intrusion or eruption caused by the intrusion of mantle-derived thermal material is more obvious, and the molten or semi-molten magma capsule in the crust provides a stable heat source for the formation of high temperature geothermal. Therefore, it is judged that in the Fenwei rift valley, Zhangjiakou-Bohai fault zone and other areas like Tianzhen and Matouying, there are still favorable target areas for high temperature geothermal resources within the depth of 2000-4000 m.

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