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A critical review on the occurrence of and its implications of natural hot springs in continental China

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ABSTRACT

Hot springs are surface displays of the Earth's internal heat as it travels through the lithosphere. Here, we reviewed the occurrence of hot springs in continental China. We choose six typical places, includes Gulu-Damxung-Yangbajing-Angang rift zone, Kongur Shan extension system, Gonghe-Guide basin, Chuan-Dian area, North China, and East Guangdong province in South China, to decipher the implication of occurrence of hot springs. A comprehensive study of topographic features, characterize of faults, seismic catalog, GPS velocity field, and total strain rate show the first order controlling factors of the occurrence of hot springs are the active faults, water pressure, and deep cycling. The relationship between hot springs distribution and deep thermal background was examined. The results show that the deep thermal background can be used as a secondary factor to control the distribution of hot springs. The role of caprock is relatively limited except of the granite distribution area of South China. In South China, the caprock overlying high heat-producing granite can generate hot springs under with the presence of water pressure. Further, the distribution of hot springs is strongly coupled with the lithospheric/crustal extensional region, implying a relationship between stress released area and the occurrence of hot springs. Such relationship can be used to interpret the tectonic evolution of continental China since the Cenozoic era. Moreover, Integrating the factors of hot spring distribution, we can comprehensively predict the occurrence of hot springs.

1. INTRODUCTION

A hot spring is a natural discharged spring with a temperature higher than the local annual average temperature (White, 1957). Hot springs are widely used in heating and breeding with ground source heat pumps, geothermal greenhouse planting and aquaculture, crop drying, bath, medical care, etc. (Lund and Toth, 2021). Serving as surface manifestations of the geothermal system, the occurrence and distribution of hot springs were commonly used as an indicator to explore the potential energy resources at depth (Craig et al., 2013). Terrestrial hot springs typically develop in tectonic/structural active areas. This feature can be a sign of ongoing tectonic activities. For example, an observation of outburst of hydrothermal fluids inferred a volcano-tectonic earthquake swarm (Ingebritsen et al., 2015); the occurrence of hot springs may be due to the existence of an active magma chamber or ongoing upwelling magma in the uppermost mantle (Hua et al., 2019). Hot springs are also spatial closely related to epithermal mineralization (Moreira and Fernández, 2015). Moreover, studies on hot springs demonstrated the biochemical action of organisms in an 'extreme environment' (Lindsay et al., 2019). All of these are of global interest in hot springs that have stimulated the focus of geologists and hydrologists for more than half a century (Brock, 1967; Jolie et al., 2021).

There are over 2,000 hot springs in continental China (Fig. 1). Although extensive local and limited regional studies have been carried out, insufficient awareness regarding the distribution of hot springs in continental China remains. Most studies focus on local areas. These studies typically calculated the recharge source and circulation depths using hydrogen/oxygen isotopes (Peng et al., 2010) and hydro-chemical geothermometers (Wang et al., 2015), respectively. According to the geological background of the specific study area, which is mainly the distribution of faults, studies established various distribution models of the hot springs. These models with local limitations consist recharged source to the meteoric water, infiltrating/upwelling flow in the faults, water heated by the heat source, and hot springs distributed along the faults. This research paradigm has been carried out in NE China (Zhao et al., 2019), North China (Wang et al., 2015), South China (Luo et al., 2022), Weihe basin (Luo et al., 2017), Chuandian area (Li et al., 2018), Tibetan plateau(Zhang et al., 2021), Pamir plateau (Li et al., 2017), etc. Some studies dissected the factors of the regional distribution of hot springs. The distribution of hot springs was attributed to the combined effect of active tectonics and heat sources through the analysis of the relationship with faults, earthquakes, features of fold belt, basin and range, crustal structure (e.g., Li et al. (2021)). A few studies have summarized the distribution of hot springs across continental China. These studies suggested the distribution of hot springs is related to the distance from the active plate boundary, but not to the distribution of volcanoes (Chen, 1992); to the seismic activity (Zhang et al., 2004); to the increase of mantle heat flow (Jiang et al., 2019); to the lithospheric thickness, Moho discontinuity, lithospheric thermal structure, and Currie point isotherm (Qiu et al., 2022).

All the insufficient awareness rises from the lack of a comprehensive understanding of the distribution of hot springs in continental China. Most explanations can only be applied to a certain region due to the limitations of previous surveys or research. In general, assessing the hot springs distribution of an area requires regional multidisciplinary approaches combining hydrologic geology, hydrochemistry, isotopes, structural geology, geophysics, and drilling. Over the past 60 years, various research has accumulated a wealth of multidisciplinary data on hot springs in continental China. An increasing number of studies indicate that the distribution of hot springs in continental China is related to the distribution of faults, crustal-mantle structure, and the thermal regime of crust-mantle

(Jiang et al., 2019; Qiu et al., 2022). This paper attempts to provide a comprehensive review by interactively synthesizing these available data to give a reasonable explanation for the genesis of distribution. We posit that the resulting controlling factors of hot springs distribution will help guide future hydrological and geological research in continental China.

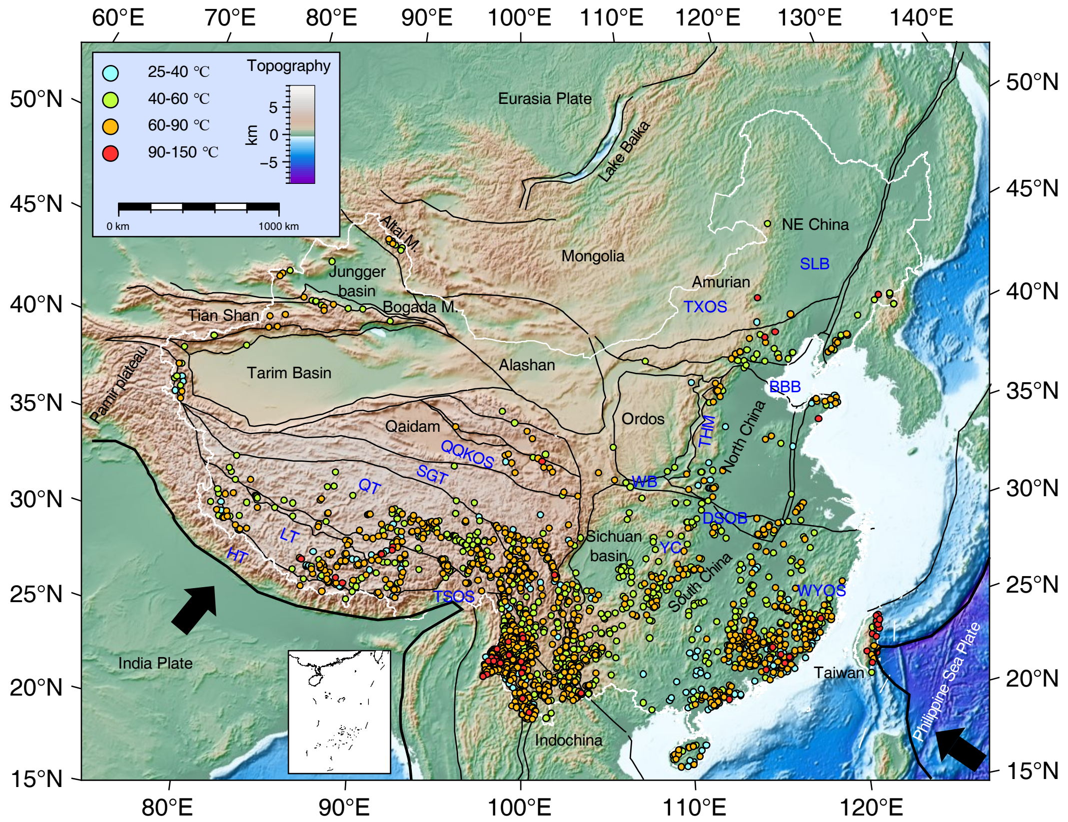

Figure 1: Topography and tectonic background of China and its adjacent area. Color shows the surface topography. Circles with colors are the distribution of hot springs in China. Black curved line shows the large fault zone or/and tectonic block boundaries. Abbreviation: SLB, Songliao Basin; TXOS, Tianshan-XingMeng Orogenic System; BBB, Bohai Bay Basin; THM, Taihang Mountain; WB, Weihe Basin; DSOB, Dabie-Sulu Orogenic Belt; YC, Yangtze Craton; WYOS, Wuyi-Yunkai Orogenic Belt; QQKOS, Qinling-Qilian-Kunlun Orogenic Belt; SGT, Songpan-Ganzi Terrane; QT, Qiangtang Terrane; LT, Lhasa Terrane; HT, Himalaya Terrane; TSOS, Tibetan-Sanjiang Orogenic Belt; M., Mountain.

2. TECTONIC ACTIVITY FACTOR IN THE OCCURRENCE OF HOT SPRINGS

The hydrothermal activity was tectonically juxtaposed with tectonic activity in continental China, which produced a remarkable Himalayan Geothermal Belt and numerous hot springs (Fig. 1; Hochstein and Regenauer-Lieb (1998); Jiang et al. (2019)), comparable to the most spectacular of the Circum-Pacific Geothermal Belt. The accumulated tectonic activity studies in continental China, including seismic activity, fault distribution, stress and movement of blocks, crust-mantle structure, etc., constitute a tectonic activity database. Such a substantial dataset provides a clear tectonic framework for the distribution of the hot springs in continental China. The relationship between various tectonic activities and the distribution of the hot springs indicates a specific tectonic genesis of the hot springs' distribution, as we will follow up with a regional and localized description. The local area described here contains six major and typical geothermal zones within continental China: Gulu-Damxung-Yangbajing-Angang rift zone, Kongur Shan extension system, Gonghe-Guide basin, Chuan-Dian area, North China, and East Guangdong province in South China.

2.1 Relationship to the regional tectonic activity

2.1.1 Active faults

The distribution of hot springs is spatially related to active faults (Fig. 2A). The hot springs with hot temperatures are all located in the fault zone. The hot springs with low-, medium-, and medium-to-high-temperature are spatially associated with active faults on a broad scale. The role of an active fault in the generation of hot springs is principal to a provide channel (Keegan-Treloar et al., 2022). The generation process of geothermal hot springs is the infiltration of the recharge source into the deeper part of the crust where be heated, and the subsequent upwelling of hot springs along the fault to the shallow surface due to the hydraulic head difference (Luo et al., 2022). Besides, the friction of the active fault generates heat, which promotes the generation of hot water (Ai et al., 2021). Notably, the occurrences of some of those hot springs in parts of inland South China do not appear to be spatially related to active faults.

The distribution of hot springs is not entirely coupled with active faults (Fig. 2A). Faults have occurred in the northern and western parts of the Tibetan Plateau, the southeastern part of the Pamir Plateau, the southern part of the Tianshan Mountains, the eastern part of the Altai Mountains, North China, and Northeast China, where without the occurrence of hot spring. The decoupling relationship between active faults and the distribution of hot springs in North China and Northeast China is due to the lack of hydraulic head difference within the plains to form springs. In the northern and western parts of the Qinghai Tibet Plateau, a large number of strike-slip faults (e.g., Altyn Tagh fault, Kunlun fault) and thrust faults (e.g., Haiyuan fault) were formed under the compression of the Indian Plate and the resistance of the Eurasian Plate (Ye et al., 2021). In the southeastern part of the Pamir Plateau, faults whose nature is mainly strike-slip and thrust formed during the northward movement of the Pamir (e.g., the Karakoram fault and western Kunlun thrust belt; Robinson et al. (2004)). Similarly, thrust zones were formed in the southern part of the Tianshan Mountains and the eastern part of the Altai Mountains (Cunningham, 2010). In addition, the highly active Longmenshan thrust fault belt, where several significant earthquakes have occurred (Jia et al., 2010), has no hot springs. Therefore, the decoupling relationship between active faults and the distribution of hot springs attributes to the performance of thrust faults. The thrust fault does not generate channels, resulting in the inability of hot springs to upwell to the shallow surface.

The distribution of hot springs is associated with the extensional active fault (Fig. 2A). Numerous rifts and strike-slip faults in central and southern Tibet were formed in the Quaternary (Ratschbacher et al., 2011). In these areas, hot springs are widely distributed. A typical example is the YGR (Chevalier et al., 2020), with a spectacular distribution of hot springs. In the Sanjiang region, the East Pamir Plateau, and the central Tianshan Mountains, a few rift zones or transtension basins have formed within the widely developed strike-slip faults and thrust faults (Tang et al., 2022), and these rift zones or transtension basin are where hot springs are located. In South China, many hot spring sites are distributed along the regional strike-slip normal faults. Furthermore, the rift valley system around the Ordos block (Weihe Basin, Shanxi Basin, Hetao Basin, and Jilantai Basin) has plenty of hot springs. All these extensional tectonics provide channels for the upwelling of hot springs to the shallow surface.

2.1.2 Earthquakes

There is a positive relationship between earthquake incidence and the number of hot springs (Fig. 2B). An earthquake is a record of fault activity (Salditch et al., 2020). Its relationship with the distribution of hot springs is identical or comparable to that of active faults and the distribution of hot springs. The seismic activity is significant in areas where hot springs are widely distributed, including East Pamir Plateau, Tianshan Mountain region, Altai Mountain region, southern Tibet Plateau, Sanjiang region, the circum-Erdos block area, and North China. Focal mechanism beach ball of earthquakes in continental China (Fig. 2C) indicates that the coupling sites of hot springs and earthquakes mostly prefer to occurre in the normal fault. These sites comprise the southern Tibet Plateau, east Pamir Plateau, where numerous hot springs are distributed, the Sanjiang region, and North China. Besides, seismic activity is weak in stable areas, including the Ordos block, the Tarim craton, and the site from the Yangtze craton to Sichuan Basin. Accordingly, hot springs are not available in these areas.

The incidence of earthquakes and the distribution of hot springs are not necessarily coupled (Fig. 2B). Seismically active without the matched distribution of hot springs in the Altyn Tagh Mountain, Qilian Mountain, Kunlun Mountain, Alashan region, Longmenshan region, Northeast China, and southern North China. Hot springs cannot be formed in North China and Northeast China due to the lack of hydraulic head differences within the plains. In the Altyn Tagh Mountain, Qilian Mountain, Kunlun Mountain, and Longmenshan region, strike-slip faults with compressional properties and thrust faults are extensively developed. Similarly, the focal mechanism beach ball of earthquakes displays that most earthquakes in these areas have occurred in thrust faults and strike-slip faults with the compressional properties (Fig. 2C). In the Alashan region, the factors of the topographic differences, fault activity, and seismic activity seem to satisfy the origin of hot springs. We speculate that the absence of hot springs is the lack of recharge sources, as the Alashan region has scant precipitation and extreme water shortage. Notably, there are few seismicity records in South China. However, there are many hot springs occur.

2.1.3 Crustal deformation

GPS observation is the essential means of studying tectonic deformation. The GPS velocity field reflects the kinematic and geometric characteristics of tectonic activity (Fig. 2D). Tibetan Plateau and its adjacent areas, eastern Pamir, and Tianshan regions, where the hot springs occurred, have high motion rates. Among these regions, the northeastern and east margins of the Tibetan Plateau have a dramatic decrease in the rate of motion, implying the formation of large-scale strike-slip faults and thrust tectonics (Wang and Shen, 2020). This situation is also reflected in the total strain rate (Fig. 2E). High total strain rates in the Himalayas, Kunlun Mountains, Altyn Tagh Mountain-Qilian Mountains, Xianshuihe fault zone, Pamir Plateau, and the western Tian Shan. These areas are mainly compressional settings characterized by the development of thrust faults, folds, and strike-slip faults (Robinson et al., 2004). The compressional setting is not favorable for tectonics to form hot springs. Thus, no hot springs occur on the northeast and east edge of the Tibetan Plateau. The Xianshuihe fault zone is unique in that it is a large-scale strike-slip fault. Correspondingly, the Xianshuihe fault zone is the only place where a large number of hot springs are located in these areas. However, the distribution of springs shows a positive relationship with the total strain rates. With the exception of hot springs in South China, hot springs in the rest of the region occur in areas where the total strain rate is not too high. Further, the low total strain rates areas contain almost no hot springs, including Tarim craton, Junggar Basin, Alashan region, Ordos Block, and Yangtze craton-Sichuan Basin.

As part of the total strain rate, the dilatation rate for continental China displays that the positive relationship between the distribution of hot springs and the total strain rate is dominated by the dilatation rate (Fig. 2F). There is a strong relationship between the intensity of hot springs distribution and dilatation rate in the Tibetan Plateau, the Sanjiang region, the Eastern Pamirs, and North China. Although the distribution of hot springs in South China does not show such a strong relationship, most of the hot springs in this area have a spatial relationship with the dilatation rate. In general, dilatation is expressed as an extension in a direction. Therefore, the main factor of crustal deformation in the distribution of hot springs is the formation of extensional structures. Crustal deformation factors, combined with active tectonics and seismic records, suggest that one of the controlling factors in the distribution of hot springs is the presence of extensional structures in tectonic activity.

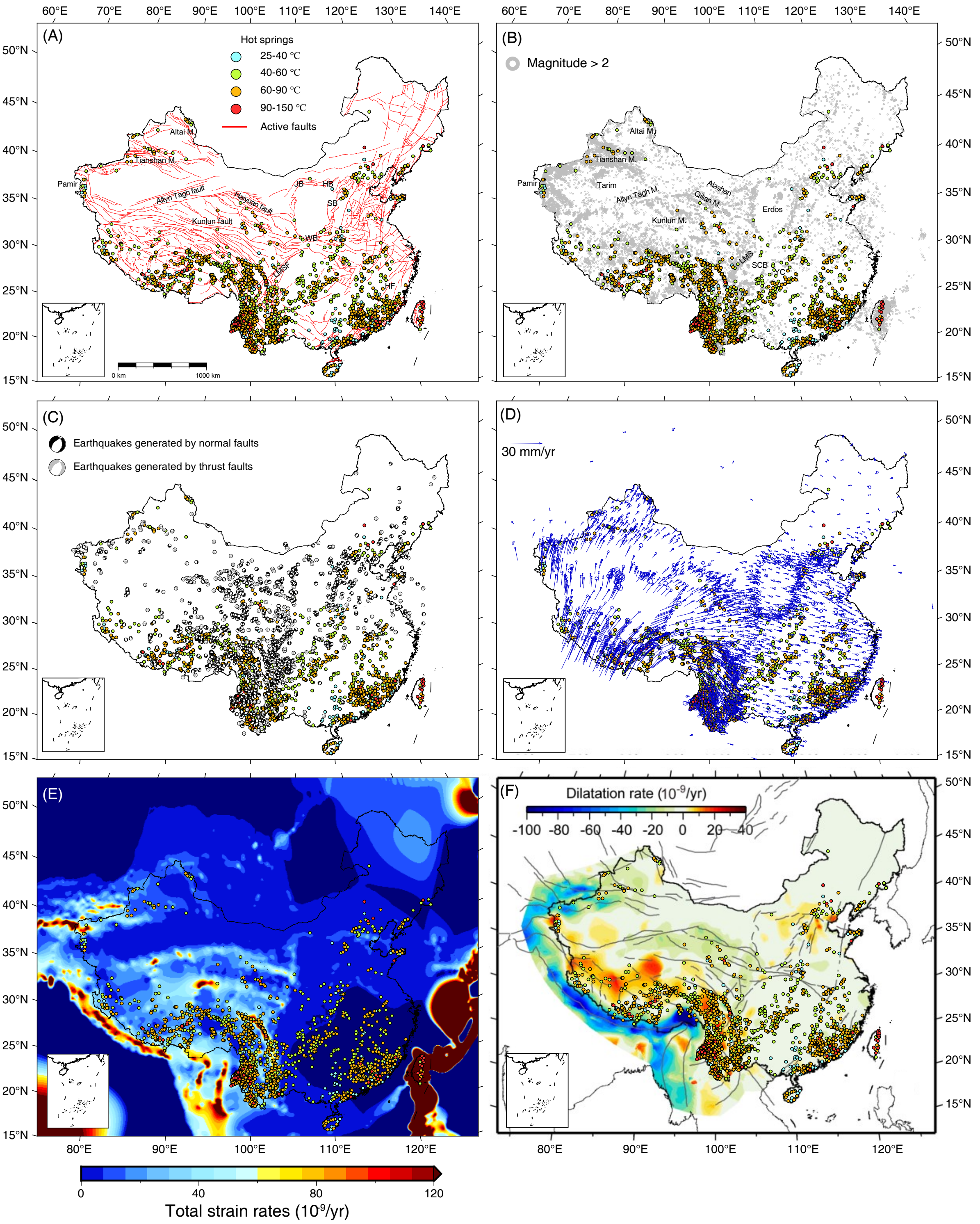

Figure 2 Various tectonic activity records in continental China. (A) Active faults and distribution of hot springs in China. Abbreviation: JB, Jilantai Basin; HB, Hetao Basin; SB, Shanxi Basin; WB, Weihe Basin; LMSF, Longmenshan Fault; HF, Heyuan Fault; M., Mountain. (B) Earthquake records in China with magnitude greater than 2 from year 2009 to present. The data set is provided by China Earthquake Networks Center, National Earthquake Data Center（http://data.earthquake.cn). (C) Focal mechanism data set of continental China and its adjacent areas from year 2009 to 2021. We classify earthquakes with seismic slip angle less than zero as those caused by normal faults and earthquakes with seismic slip angle greater than zero as those caused by thrust faults. Abbreviation: LMS, Longmenshan; SCB, Sichuan Basin; M., Mountain. (D) GPS velocity field with respect to Eurasian plate. (E) Contour map showing total strain rates of China and adjacent area based on the Global Strain Rate Model. (F) Dilatation map of continental China and its adjacent area.

2.2 Relationship to the localized tectonic activity

2.2.1 Gulu-Damxung-Yangbajing-Angang rift zone

The YGR is one of a series of roughly north-south oriented rift valleys formed by the Indo-Eurasian collision in the southern Tibetan plateau. The YGR is a relatively younger structure (7-1 Ma, Chevalier et al. (2020)) and consists of a series of normal faults and grabens. The Gulu-Damxung-Yangbajing-Angang rift zone is the north part of the YGR, including the Gulu half-Graben, Damxung corridor, Yangbajing Graben, and the Angang Granben from north to south (Fig. 3A). This rift zone possesses abundant geothermal resources, which are characterized by extensive distributed hot springs.

The tectonic deformation of the rift zone determines the distribution of hot springs of different temperatures. The entire rift valley has a high rate of north-eastward motion (Fig. 3B) due to the continuous collision between the Indian Plate and Eurasian Plate (Wang and Shen, 2020). Tectonic activity has contributed to the widespread occurrence of earthquakes. Earthquakes mainly occur in the Yangbajing Graben and the Nyainqentanglha range. Seismic beach ball of several significant earthquakes indicates most of the earthquakes in the rift valley occur in normal faults and partial earthquakes in the adjacent area are due to strike-slip fault activity. Regardless of the nature of the earthquake, they all occur in high total strain stress zones. The high total strain rate at the southwest end of the rift is due to the northward motion of the Indian Plate, and the high total strain rate at the northeast end of the rift may be due to the resistance of Eurasia Plate to the northward motion of the Indian Plate (Liang and Song, 2006). High strain rates in both areas contribute to the high dilatation rates (extension rates) in the central Damxung corridor and Gulu half-graben (Fig. 2F, 3C). These places have high levels of hydrothermal activity, accordingly, the hot springs in these places have higher temperatures.

The ultimate tectonic driving force determining the distribution of hot springs in the YGR is the tearing of the Indian subduction plate and the upwelling of mantle material (Fig. 3D). YGR is located above the tearing position of the subduction plate. Hot asthenospheric material surges up through the tear window. The hot upwelling material heats the crust below the YGR, and the crustal structure is deformed under the action of heat. Local mantle convection triggered by asthenosphere upwelling provides a driving force for the northwest-southeast trending extensional stress. Therefore, the YGR was formed under the extensional setting.

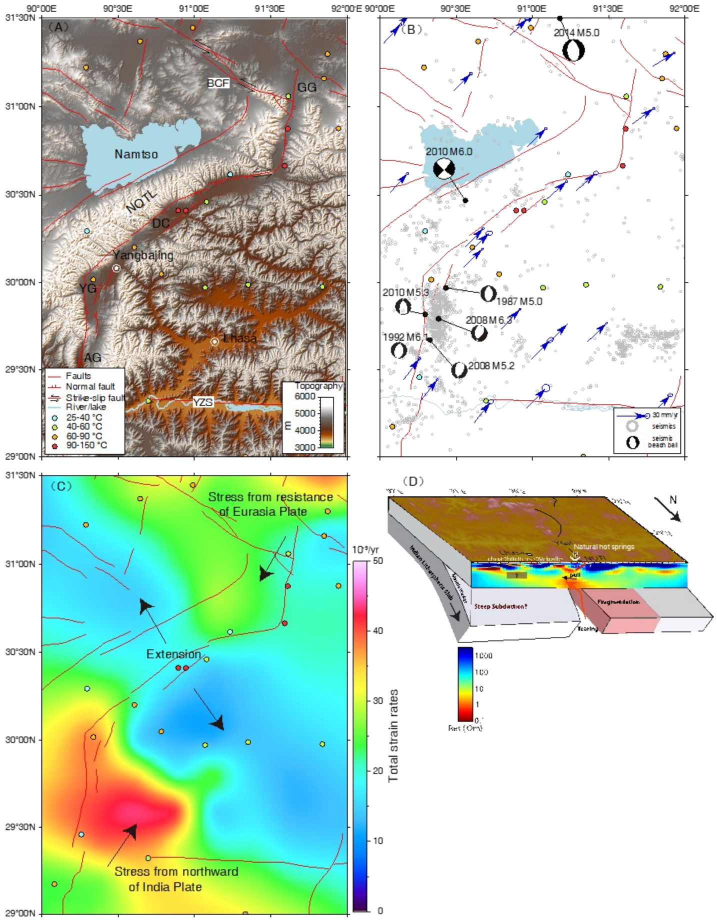

Figure 3 Tectonic map of the Gulu-Damxung-Yangbajing-Angang rift zone. (A), topography and active faults in the Gulu-Damxung-Yangbajing-Angang rift zone. (B), GPS velocity field with respect to Eurasian plate, focal mechanism, and seismic records from year 2009 to present. (C), Contour map showing total strain rates of the Gulu-Damxung-Yangbajing-Angang rift zone based on the Global Strain Rate Model. The black arrow shows the direction of stress. (D), Tearing model for the formation of the YGR. Abbreviation: NQTL, Niahqentanglha Range; BCF, Banco Fault; GG, Gulu Garben; DC, Damxung Corridor; YG, Yangbajing Garben; AG, Angang Garben; YZS, Yarlung Zangbo Suture.

2.2.2 Kongur Shan extension system

The Kongur Shan extension system is located at the western end of the India-Eurasia plate collision zone and the eastern part of the Pamir Plateau. The continued northward movement of the Indian plate has led to the formation of thrust faults (main Pamir thrust, Pamir frontal thrust, and south Tian Shan thrust) and strike-slip faults (e.g., Kashgar-Yecheng Transfer System, Darvaz-Karakul fault, and Karakoram fault). An extensional Kongur normal fault system was formed in Cenozoic on the eastern Pamir Plateau under this compressional setting. Such faults system consists Muji fault, Kongur Shan fault, Qiaklak fault, Baoziya fault, Tahman fault, and Tashkorgan fault. The Tashkorgan region in this extensional system has the second-best geothermal resources in continental China, as well as the distribution of hot springs (Fig. 4A).

The distribution of hot springs in the Tashkorgan region is determined by active extensional tectonics. Hot springs are located near active faults, especially where the faults intersect. GPS rates indicate that the Tashkorgan region is tectonic active, and the main body of the block is moving northward (Fig. 4B). The widespread occurrence of earthquakes confirms the intense tectonic activity in the region. Seismic beach ball suggests normal faults caused the occurrence of earthquakes in this region. The total strain rate is the largest in the northern part of the region, where there are medium to high temperature hot springs (Fig. 4C). High total strain rates contribute to the combined action between stress from the northward of India Plate and stress from the resistance of Tarim Craton. The combined action caused the formation of Kongur Shan Mountain, the Kongur Shan normal fault, and the Karakoram normal fault (Fig. 4D). Besides, the northward of India Plate and the resistance of Tarim Craton jointly led the block located in the southeastern part of this region to move in a southeast direction. Such a detachment structure formed the Tashkorgan normal fault. In sum, the Kongur Shan extension system was developed by detachment structures in an active compressional setting. Thus, the distribution of hot springs is controlled by detachment faults.

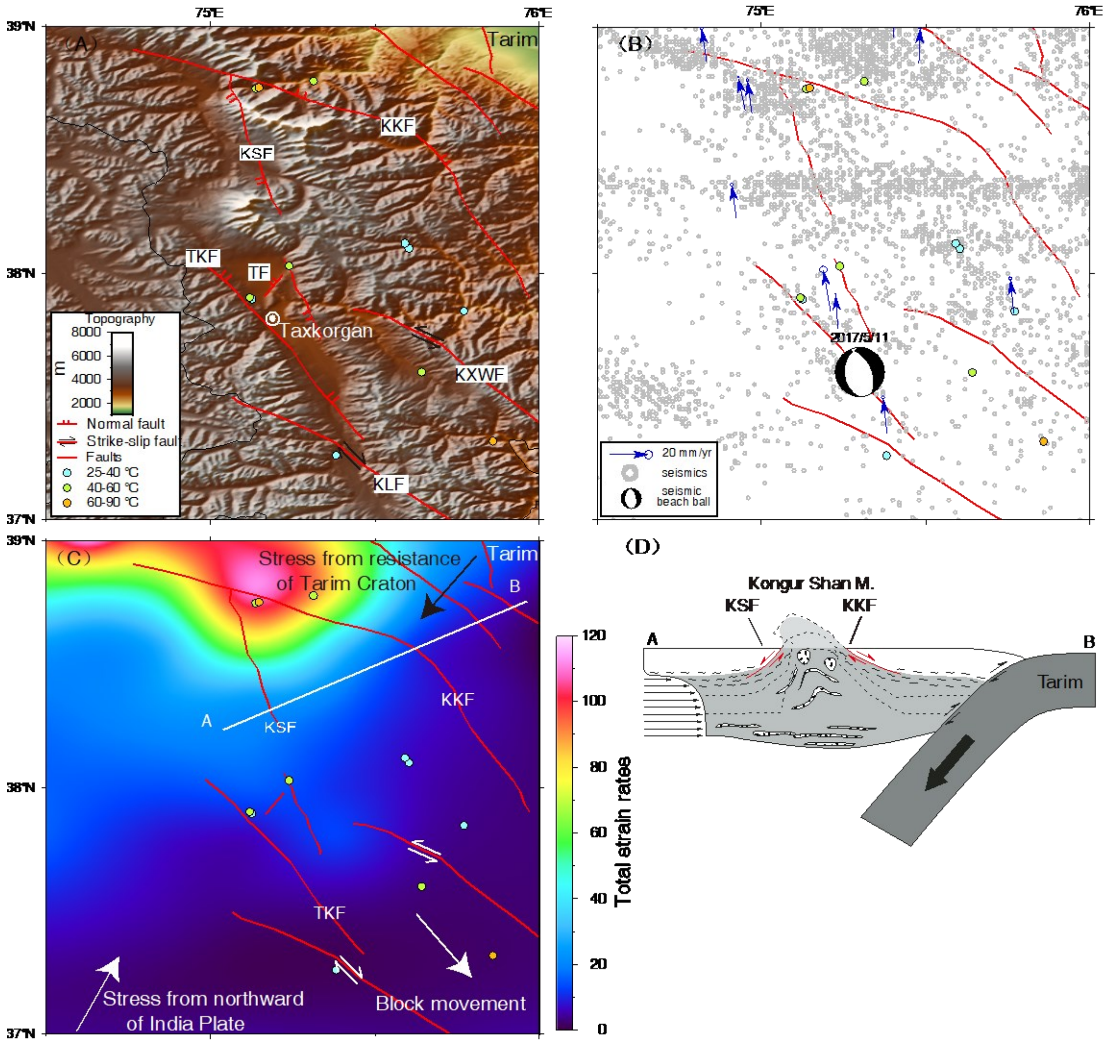

Figure 4 Tectonic map of the Kongur Shan extension system. (A), topography and active faults in the Kongur Shan extension system. (B), GPS velocity field with respect to Eurasian plate, focal mechanism, and seismic records from year 2009 to present. (C), Contour map showing total strain rates of the Kongur Shan extension system based on the Global Strain Rate Model. The black arrow shows the direction of stress. Profile AB is shown in Figure 4D. (D), Detachment model for the formation of the Kongur Shan extension system. Abbreviation: KKF, Karakax Fault; KSF, Kongur Shan Fault; TF, Tahman Fault; TKF, Taxkorgan Fault; KLF, Karakoram Fault; KXWF, Kangxiwar Fault.

2.2.3 Gonghe-Guide basin

Due to the Cenozoic India-Eurasian collision, numerous strike-slip faults (e.g., East Kunlun fault, Haiyuan fault) and thrust faults (Qilianshan fault system) were developed on the northeastern edge of the Tibetan Plateau and in the middle of the Qinling-Qilian-Kunlun fold system. This region is cut by a complex fault system, including the W-NW-trending East Kunlun Fault, Haiyuan Fault, and West Qinling Fault, and the NNW-trending Riyueshan Fault. These active fractures divide the northeastern part of the Tibetan Plateau into several basins (Qinghai Lake basin, Gonghe-Guide basin, Xining basin, etc.). More than 70 hot springs or geothermal anomalies with water temperature exceeding 15 ℃ (annual mean temperature less than 10 ℃) have been found in the Gonghe-Guide basin, of which the outlet temperature of 6 hot springs is greater than 60 ℃. The temperatures of Zacangsi hot springs and Qunaihai hot springs exceed the local boiling point (around 90 ℃). All hot springs are located in the undulating area inside the basin or the strike-slip fault zones at the edge of the basin (Fig. 5A).

The distribution of hot springs in this region is controlled by extensional tectonics. Although the compressional setting has formed thrust tectonics within the Gonghe-Guide basin and its adjacent region (e.g., GHNF and QHNF), the formation of the Gonghe-Guide basin, together with the Qinghai Lake Basin, is due to multiple strike-slip faults. The main control structures are the large-scale East Kunlun sinistral strike-slip fault and the Haiyuan sinistral strike-slip fault (Fig. 5B). The block between the two large-scale faults undergoes counterclockwise rotation due to the sinistral stress. The dextral Riyueshan strike-slip faults (RYSF) and the dextral Elashan strike-slip fault (ELSF) are formed at the boundary of the blocks. Because of the transpressional stress, the block sinks, forming the Gonghe-Guide pull-apart basin and Qinghai Lake pull-apart basin (Tang et al., 2022). The distribution of earthquakes in the region shows there are less seismic activity within basins and there are more near the strike-slip faults. Moreover, the earthquakes located on the primary control fault (HYF) are due to the strike-slip motion. The nature of the earthquakes located on the ELSF and the RYSF is diverse, as the ELSF and the RYSF could be faults with strike-slip, thrust, and tensional properties due to the complex stress (Fig. 5C). The total strain rate is significant at the edge of the block and is negligible inside the block (Fig. 5D). All these pieces of evidence confirm the formation model of the pull-apart basin (Fig. 5B). Therefore, the hot springs located in the basin were formed in the extensional tectonics of the pull-apart basin.

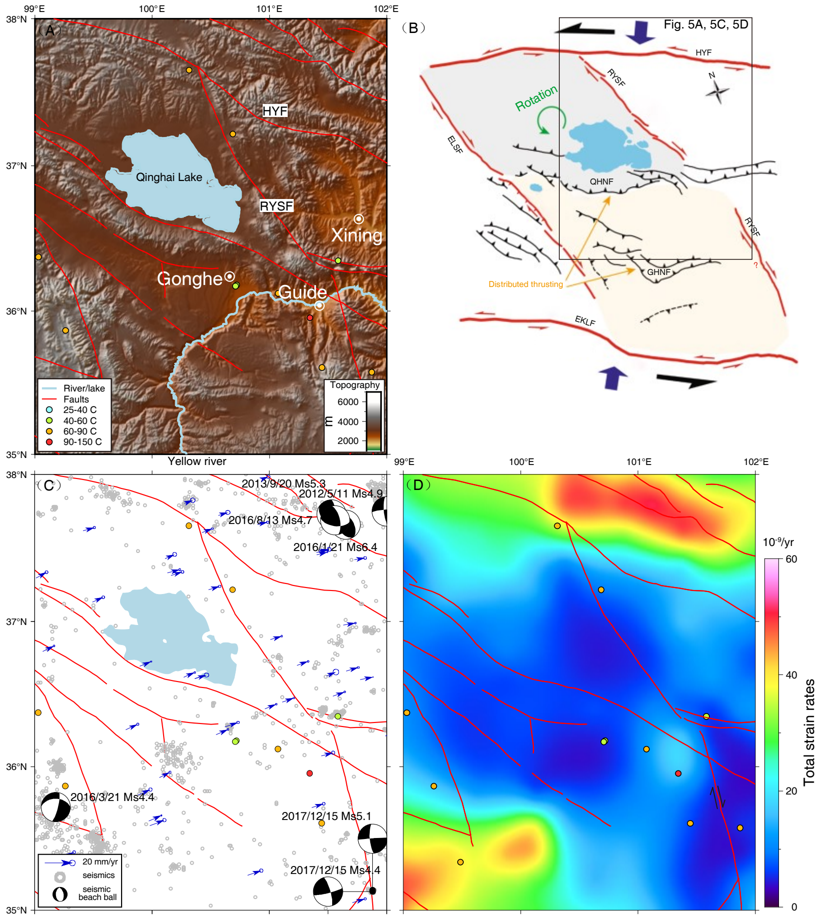

Figure 5 Tectonic map of the Gonghe-Guide basin and its adjacent area. (A), topography and active faults in the Gonghe-Guide basin and its adjacent area. (B), Kinematic deformation around the Gonghe-Guide basin and its adjacent area. (C), GPS velocity field with respect to Eurasian plate, focal mechanism, and seismic records from year 2009 to present. (D), Contour map showing total strain rates of the Gonghe-Guide basin and its adjacent area based on the Global Strain Rate Model. Abbreviation: HYF, Haiyuan Fault; RYSF, Riyueshan Fault; ELSF, Elashan Fault; QHNF, Qiliannanshan Fault; GHNS, Gonghenanshan Fault; East Kunlun Fault.

2.2.4 Chuan-Dian area

The Chuan-Dian area is located on the southeastern edge of the Tibetan Plateau and is one of the most active areas of geothermal activity in continental China. This area contains Songpan-Ganzi Terrain, Chuan-Dian fragment, and multiple strike-slip faults. Two notable faults are the sinistral Xianshuihe strike-slip fault and the dextral Longmenshan thrust fault. There are over 200 hot springs in the area, more than 60% of which are hotter than 40°C and some of which are hotter than the boiling point of the local water (Tang et al., 2017). Most hot springs distribute in the Xianshuihe fault zone and the Litang fault zone (Fig. 6A).

The distribution of hot springs is involved with strong strike-slip tectonics. GPS observations indicated that the block in the area is moving at medium speed in the southeast direction (Fig. 6B). Earthquakes triggered by block movements are concentrated in the Xianshuihe fault zone and the Longmenshan fault zone. The seismic beach ball indicates that earthquakes on the Xianshuihe fault zone were caused by strike-slip fault, and thrust faults caused those on the Longmenshan fault zone. This is consistent with the nature of the two major fault zones. As we described in section 5.1.1, the thrust fault does not meet the conditions for the occurrence of hot springs. Hence, the distribution of hot springs in the Longmenshan fault zone is scarce. Furthermore, the total strain rate is another controlling factor for the distribution of hot springs in this area (Fig. 6C). Bounded by the Xianshuihe fault zone, its eastern side has a low total strain rate and few hot springs, while its western side has a high total strain rate and many hot springs. High strain rate areas are fault zones where hot springs are distributed. Strongly deformed areas are favored sites where hot springs are distributed.

The occurrence of hot springs is determined by the extensional tectonics produced during block rotation (Fig. 6D). Due to the India-Eurasia collision, multi-block movements form crustal flows. An arc-like clockwise rotation pattern was formed from the Xianshuihe fault zone to the Indochina region through the Ailaoshan-Red River fault zone (Todrani et al., 2022). As the outermost end of the arc-like clockwise rotation, the Xianshihe fault zone bears the most significant total strain rate. This process causes detachment between blocks. Such arc rotation and detachment structure form extensional tectonics (normal faults and pull-apart basin) near strike-slip faults in the Chuan-Dian fragment. The Batang Basin, located near the Xianshuihe fault zone, was formed by a detachment structure. In these basins, numerous hot springs occur.

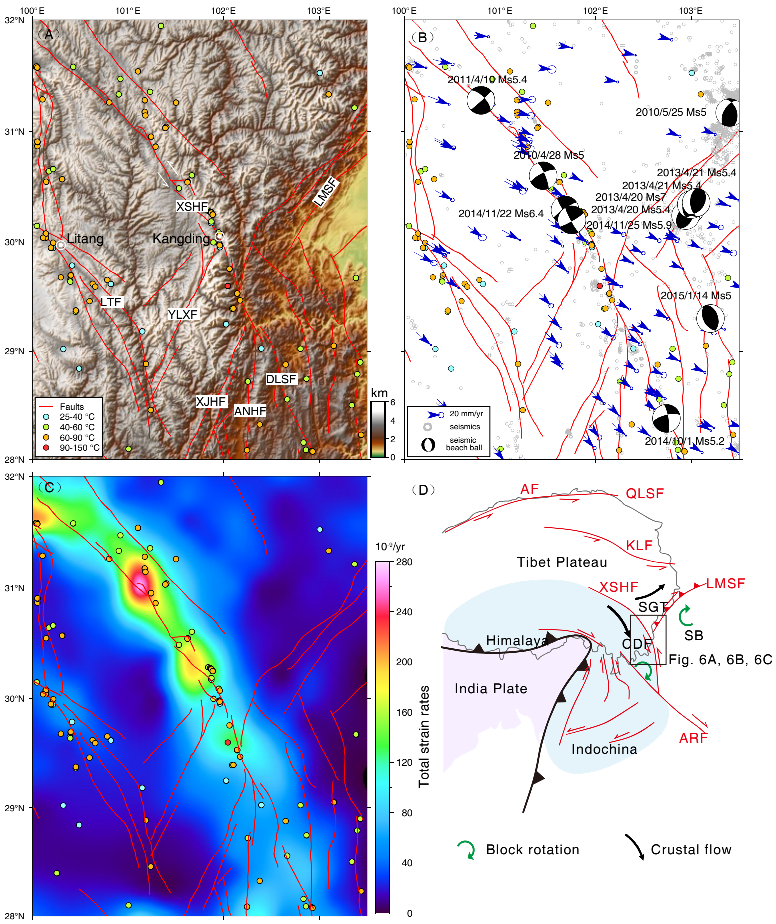

Figure 6 Tectonic map of the Chuan-Dian area. (A), topography and active faults in the Chuan-Dian area. (B), GPS velocity field with respect to Eurasian plate, focal mechanism, and seismic records from year 2009 to present. (C), Contour map showing total strain rates of the Chuan-Dian area based on the Global Strain Rate Model. (D), Crustal flow model for the Chuan-Dian area. Abbreviation: XSHF, Xianshuihe Fault; LTF, Litang Fault; YLXF, Yulongxi Fault; XJHF, Xiaojinhe Fault; DLSF, Daliangshan Fault; ANHF, Anninghe Fault; LMSF, Longmenshan Fault; AF, Altyn Tagh Fault; QLSF, Qilianshan Fault; KLF, Kunlun Fault; SGT, Songpan-Ganzi Terrane; CDF, Chuan-Dian fragment; ARF, Ailaoshan-Red River Fault.

2.2.5 North China

North China contains abundant geothermal resources, and hot springs are located in undulating terrain. These are also placed with the high development of faults (Fig. 7A). These faults mainly contain the Tan-Lu dextral strike-slip fault, Jixian-Tangshan dextral strike-slip fault, Taihang Mountain foreland dextral strike-slip fault, and normal faults distributed along the Shanxi rift valley.

The distribution of hot springs is linked to active structures (Fig. 7B, 7C). Although GPS observations show that the movement rate of the North China Craton to the southeast is low, seismic activity is active where hot springs are located. Seismic beach ball reveals the consistent nature of seismogenic faults and regional faults. In the Shanxi Rift Valley, where normal faults are widely distributed, the seismogenic faults are normal faults. In the North China Plain, where strike-slip faults are developed, the seismogenic fault is also a strike-slip fault. The place where the earthquake occurred matches the high total strain rate, suggesting the coupling of hot springs distribution and active tectonics.

The distribution of hot springs relates to the tectonic window created by the rotation of the block (Fig. 7D). Affected by the collision of the Indo-Eurasian plate, the North China Craton, sandwiched between the Amurian block and South China block, is subject to sinistral shear forces. The fragmentation of blocks forms dextral strike-slip faults in the craton. The block rotates and creates an extensional tectonic window on the north-south edge of the block (Su et al., 2021). Generally, extensional tectonic windows consist of basins and normal faults (e.g., Shanxi Rift Valley). The hot springs in North China are also located in these tectonic windows.

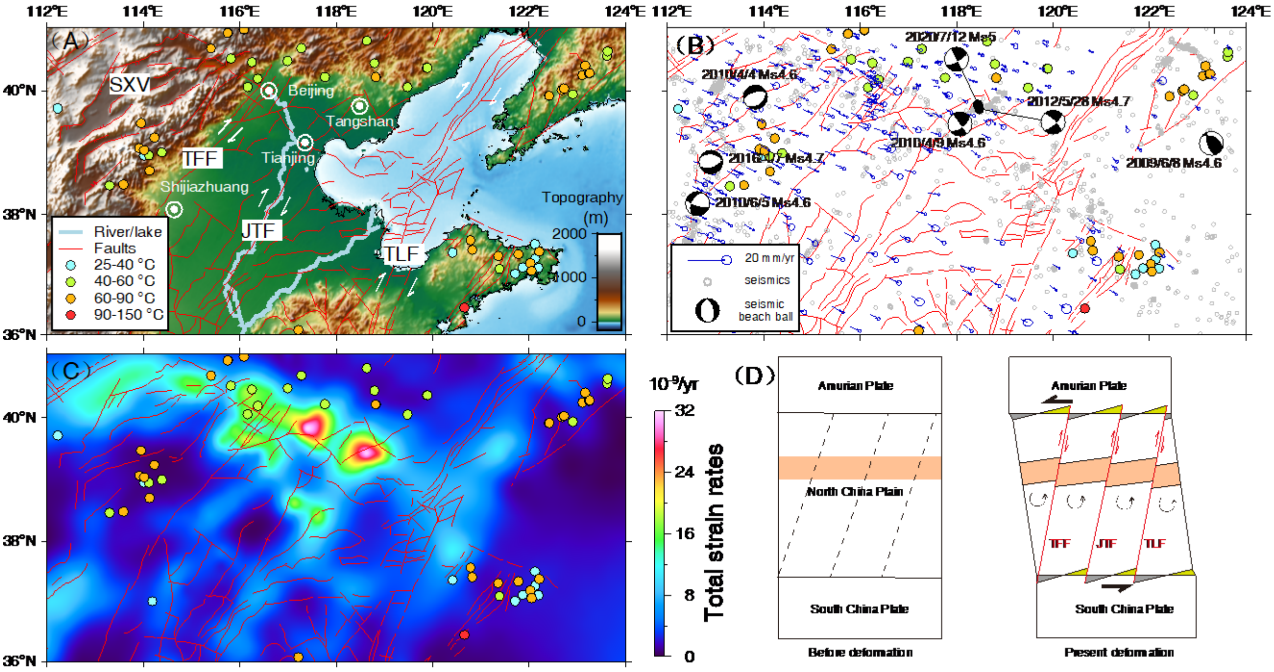

Figure 7 Tectonic map of North China. (A), topography and active faults in North China. (B), GPS velocity field with respect to Eurasian plate, focal mechanism, and seismic records from year 2009 to present. (C), Contour map showing total strain rates of North China based on the Global Strain Rate Model. (D), A deformation model for the formation of tectonic window. Abbreviation: SXV, Shanxi Valley; TFF, Taihangshan frontier Fault; JTF, Jixian-Tangshan Fault; TLF, Tan-Lu Fault.

2.2.6 East Guangdong province in South China

The area is in a tectonically stable region, and GPS observations show that the regional block movement rate is low (Fig. 8A). The low total strain rate determines the weakness of tectonic deformation and seismic activity. However, the area contains rich geothermal resources and many hot springs. The first geothermal power station in continental China is located in Fengshun county.

The occurrence of extensional structures controls the distribution of hot springs in the area. These hot springs are distributed along the northeast-trending Lianhuashan normal fault (south part of the Zhenghe-Dapu fault), formed by the extensional setting of the retreating Paleopacific Plate in the Mesozoic. In addition, the combined action of the far-field effects of the north-westward progression of the west Pacific subduction zones and resistance of Taiwan Island and South China block form a northwest-trending extensional structure in the Cenozoic (Fig. 8B, Chen et al. (2019b)). These northwest-trending extensional structures (e.g., normal faults) are where hot springs are located. The areas where the northeast-trending and northwest-trending normal faults intersect are favorable areas for developing hot springs (e.g., the Fengshun area).

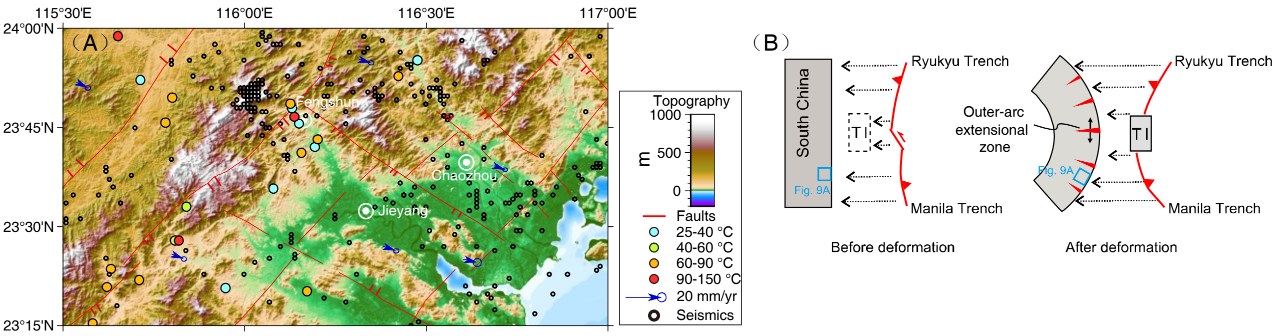

Figure 8 Tectonic map of East Guangdong province in South China. (A) topography, active faults, GPS velocity field with respect to Eurasian plate, and seismic records from year 2009 to present of East Guangdong province in South China. (B) A deformation model for the formation of Northwest trending extensional tectonics.

2.3 The essence of tectonic activity

Analysis of regional and localized tectonic activity implies that tectonic activity is the basis for the occurrence of hot springs. From the perspective of regional tectonic activity, hot springs are basically located in areas of strong tectonic deformation and extensional tectonic windows. The local tectonic activity follows the same pattern as the occurrence of hot springs. Hot springs occur where there are large topographic reliefs caused by extensional structures. Although there are many different types of extensional structures, including normal faults (YGR and East Guangdong, South China), detachment tectonics (Kongur Shan extension system and Chuan-Dian area), pull-apart basins (Gonghe-Guide basin), and tectonic windows (North China), they all collectively create a vertical drop that can be localized or even regionally. As discussed in section 4, the terrain drop provides a hydraulic head for groundwater, which is a necessary factor for the formation of hot springs. This is one of the issues that the distribution of hot springs is influenced by extensional structures, as well as the tectonic activity. The extensional structure also presents a channel for the migration of recharge sources, which is the second issue. Besides, for all of the scenarios, the imbalance in the internal thermal condition of the planet is what drives tectonic movement. As a result of tectonic activity, hot magma, blocks/faults that may produce heat through friction, etc., are formed. The heat sources formed by tectonic activity, which we shall examine in more detail in the next section, are an essential factor for the occurrence of hot springs. Therefore, tectonic activity affects the distribution of hot springs by forming topographic relief differences, tectonic channels, and heat sources.

3. HEAT SOURCES OF THE HOT SPRINGS

The most critical factor determining the formation of hot springs is the heat source. Heat flow is considered to be one of the direct surface geothermal manifestations of subsurface heat energy. Heat flow builds a spatial relationship between hot springs and heat sources. The measured heat flow data has high values in eastern China and the Tibet Plateau region, while it has low values in the Yangtze Craton, Tarim Craton, and North China Craton (Fig. 9A). Heat flow maps (Fig. 9B) show that hot springs in continental China are mostly distributed in areas with heat flow values greater than 60 mW/m^2, suggesting a dependent distribution between hot springs and high heat flow. High heat flow is a manifestation of thermal anomalies in either the crust or mantle or both crust and mantle, revealing the controlling role of heat sources in the generation of hot springs.

The heat of hot springs comes from the sum of the crust and mantle. Generally, the dominant mantle heat source heats the overlying crust mainly through heat conduction. Indeed, hot spots as heat sources are a factor in geothermal anomalies (e.g., Yellow Stone). Considering that only the Hainan plume is currently recognized as a typical Cenozoic hot spot in China (Lei et al., 2009), we only consider the effect of mantle heat conduction on the occurrence of hot springs. Crustal heat sources include local thermal anomalies (magma chamber and volcanoes), friction heat between blocks, and heat from radioactive element decay. These heat sources jointly determine the distribution characteristics of hot springs in continental China.

3.1 Mantle heat

Due to the collision of the Indian-Eurasian plate, the lithosphere thickness of the Tibetan Plateau and its adjacent exceeds 120 km (An and Shi, 2006). The mantle heat, which depends on thermal diffusion and fluid convection, has a limited influence on the distribution of hot springs in this region. In eastern China, because of delamination, the lithosphere thickness was destroyed to about 80 km (An and Shi, 2006). In contrast, the influence of mantle heat in eastern China is more significant than those in the Tibetan Plateau. Mantle heat flow, mantle heat flow/surface heat flow, and mantle heat flow/crust heat flow all increase from west to east (Fig. 9). Therefore, hot springs in eastern China are more influenced by mantle heat conduction than hot springs in western China. Many medium and high-temperature hot springs distributed in North China and the Yangtze Craton region with low surface heat flow may be attributed to a high mantle heat flow and a high ratio of mantle heat flow/surface heat flow. Indeed, these may also be due to magmatism and frictional heat generation in the active structure, as we will discuss as follows.

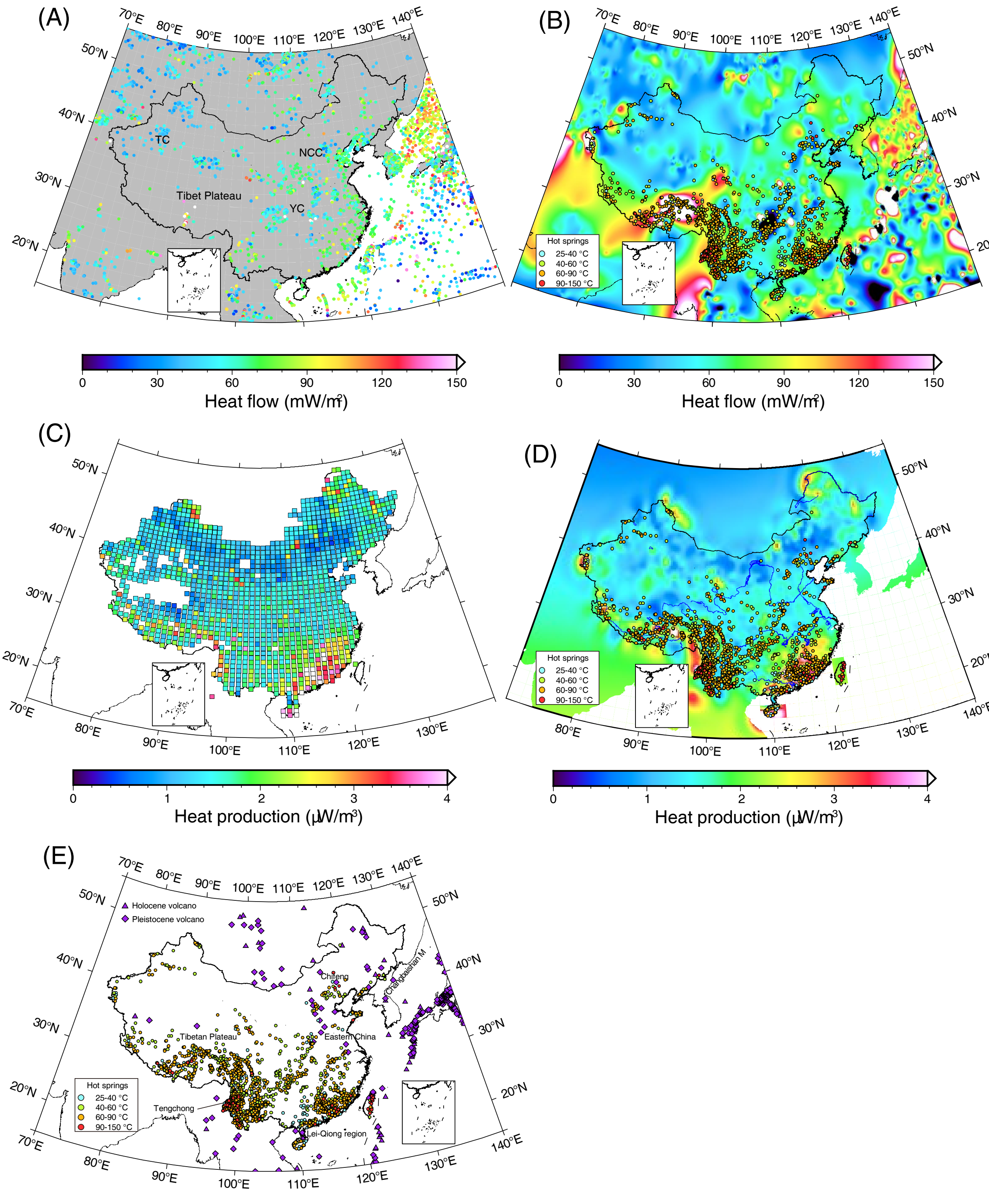

Figure 9 The measured (A) and interpolated (B) values for the surface heat flow. Values are from the International Heat Commission database (http://www.ihfc-iugg.org/products/global-heat-flow-database). Abbreviation: YC, Yangtze Craton; TC, Tarim Craton; NCC, North China. Craton The observed (C) and interpolated (D) values for the radiogenic heat production of surface rocks (with total of 1,518, 1° × 1° cells). (E) Distribution of Holocene and Pleistocene volcanos in China and its adjacent area (data from Global Volcanism Program, https://doi.org/10.5479/si.GVP.VOTW4-2013).

6.2 Radioactive element decay

The heat generated by the decay of radioactive elements in rocks is one of the major heat sources on Earth and the main control factor for the temperature field distribution of the lithosphere. The radioactive heat production of rocks depends on the element concentration of U, Th, and K. The three elements are Th, U, and K in descending order of importance in the history of the Earth's thermal evolution. The radiogenic heat production of the first two elements' accounts for 80% of the total elemental heat production. The heat generation rate determined by an equation based on the content of the three elements is a characterization of the radioactive decay heat.

We employed near-surface radiogenic heat production dataset compiled by Sun et al. (2022) based on radioactive element abundance measurements. Such dataset contains a total of 6,617 samples from 3,382 sites. These samples were eventually gridded into 1518 1° x 1° cells (1405 grids data from China and 113 grids data from Mongolia). The heat production rate map of near-surface rocks in continental China shows that South China, southern Tibetan Plateau, and eastern Pamir Plateau are high heat production rate regions with many hot springs (Fig. 9D). In South China, Mesozoic igneous rocks cover an area of more than 262,920 km2 and occupy one-fifth of the surface area of South China (Zhou et al., 2006). Multiple large-scale Paleozoic and Mesozoic tectonothermal events led to remelting of crustal rocks and enrichment of large ion lithophile elements (Xu et al., 2007). These igneous rocks contain high Th, U, and K concentrations with an average heat production rate of more than 5 $\mu W/m^3$ and some rocks with heat production rates exceeding 10 $\mu W/m^3$ (Zhou et al., 2020). Due to these igneous rocks' high heat production rate, hot springs were found in many tectonically stable areas and adjacent regions of igneous rock distribution areas in South China. This is why, despite being in a tectonically stable zone, South China has a large number of hot springs. In the southern Tibetan Plateau, the high heat production rate area is distributed in a belt with an almost east-west trend. This belt coincides spatially with the Lhasa terrane. Cenozoic rocks contain high Th, U, and K concentrations in the Lhasa terrane. Indeed, the hot springs in the Lhasa terrane are mainly distributed along the rift valley with an approximate north-south trend, for example, the YGR. The distribution of hot springs at YGR is controlled by extensional tectonics and topographic features. However, we do not deny the thermal contribution of radioactive decay of rocks within the Lhasa terrane to the generation of hot springs. Recently, 3-D thermo-mechanical modeling suggested that the widespread low-velocity bodies within the middle crust in the southern Tibetan may be due to crustal melt layers caused by the high heat production rate of rocks (Chen et al., 2019a). In the eastern Pamir Plateau, rocks with high heat production rates may be the dominant factor in the occurrence of hot springs. The thickness of the lithosphere in this region exceeds 120 km, and no low-velocity anomalies were found in the crust (Schneider et al., 2013). Medium total strain rate hardly supports the formation of large-scale geothermal resources. Cenozoic rocks in the eastern Pamir Plateau contain extremely high Th and K concentrations. These rocks have an average heat production rate of over 7 $\mu W/m^3$ and some rocks have heat production rates as high as 20 $\mu W/m^3$. The role of the Kongur Shan extension system in the formation of hot springs is to provide a channel for the recharge source to seep down into the subsurface. The decisive factor in the formation of these hot springs should be the presence of rocks with a high heat production rate. In sum, radioactive heat production plays a vital role in the distribution of hot springs.

6.3 Friction heat between blocks

The nature of frictional heat as a heat source of hot springs is the thermal contribution of active tectonics. The total strain rate map reflects the high strain zone along the Himalayan orogenic belt. This high strain area is distributed with abundant geothermal resources and is known as the Himalayan Geothermal Belt. Shear heating occurs at the crustal thrust interface between the Indian and Eurasian plates beneath the Himalayan Geothermal Belt was proposed to interpret the geothermal anomaly (Hochstein and Regenauer-Lieb, 1998). Plate collisions trigger brittle or ductile deformation within the block and drive block flow. Distribution of hot springs is strongly coupled with high strain rate. Heat generated by friction between blocks in crustal flows is an important source of hot spring heat. Recently, a numerical computational study on the Xianshuihe fault, where has high strain rate, demonstrated that heat flow values from shear friction can be up to approximately 40 mW/m^2, which occupies 30% of the surface heat flow in the Xianshuihe fault (Ai et al., 2021). Therefore, frictional heat between blocks contributes thermally to the generation of hot springs in the high strain rate of Tian Shan Mountain, the Pamir Plateau, the Tibetan Plateau, and North China.

6.4 Magmatism

Magmatism is associated with geothermal resource and is an important heat source for the formation of hot springs. The number of currently active as well as Cenozoic volcanoes in continental China is small and only located in eastern China, on the Tibet Plateau, and in the Lei-Qiong region (Fig. 9E). The impact of volcanic activity on the occurrence of hot springs in mainland China is limited. The Changbaishan Mountain Volcanic Belt and the Tengchong Volcanic Belt are typical volcanic geothermal areas in China, where there are a large number of hot springs. In the Chifeng region, volcanic activity may be a source of heat for high-temperature hot springs, even though the area is located in a low surface heat flow region (Fig. 9A, 9B, 9E). Furthermore, studies show that geothermal resources in Yangbajing and Tengchong are associated with magmatism (Guo et al., 2017). Thus, although magmatism has a small effect on the distribution of hot springs in continental China, it has a decisive effect on the distribution of hot springs in local areas.

4 SYNTHESIS GENESIS OF HOT SPRINGS DISTRIBUTION IN CONTINENTAL CHINA

We provide basic but convincing pieces of evidence for the genesis of the distribution of hot springs in continental China by synthesizing existing studies from regional and localized regions for review. The factors that determine the distribution of hot springs in continental China, including recharge sources, heat sources, and tectonic channels, are summarized in Figure 10.

One necessary condition for generating hot springs is the recharge sources. The recharge source consists of two parts. The first part is that the recharge source must have water. The Alashan region is a typical example. The annual precipitation in this area is less than 100 mm, while the annual evaporation is more than 2,000 mm. A large amount of water loss forms a vast Gobi Desert. Despite the fact that this area is tectonically active and topographically undulating (Fig. 1), no hot springs have ever been recorded here. The second part is hydraulic head differences between the recharge and discharge areas to meet the surface exposure of the hot springs. There are no hot springs in the interior of the great basins of continental China (Fig. 1) because of the lack of hydraulic head difference, even if the tectonic activity and thermal conditions are met that for the occurrence of hot springs.

Another necessary condition for generating hot springs is the heat sources. A hot spring is essentially a spring. If it does not have a heat source, it exists in the discharge area in the form of spring with ordinary temperature or even cold springs. Indeed, even if the heat source meets the conditions, the hot spring may not be formed. The hot water will be cooled by the permafrost during the upwelling process and become cold water in the permafrost area (e.g., Qiangtang region). Furthermore, the heat exchange efficiency between the cold water and the heat source is the key to the formation of hot springs. Hot springs are the result of adequate heat exchange between cold water and heat sources. In summary, the distribution of hot springs is controlled by the nature of the heat source and the adequacy of the heat exchange between the cold water and the heat source.

Tectonic channels are a considerable condition for the distribution of hot springs. The first function of the tectonic channel is to facilitate the infiltration of cold water. The permeability of the Earth's surface layer decreases with depth. The difficulty of cold-water infiltration in areas without tectonic channels is directly proportional to the depth. In geological conditions with tectonic channels, cold water can penetrate to a deeper area. A recent study in orogenic geothermal systems showed that meteoric water could penetrate to a subterranean area with a depth of 9–10 km along the fault (Diamond et al., 2018). In the process of heat exchange between cold water and heat source, cold water that penetrates deeper would be heated to a higher temperature. Correspondingly, the generated hot springs will have a high temperature. Further, the friction of the blocks in the tectonic channel generates heat, promoting the formation of hot springs. In addition, the construction of tectonic channels is frequently associated with extensional tectonics, for example, normal fault and rift valleys. The development of extensional tectonics is accompanied by the subsidence of the block to form topographic differences. The hydraulic head difference caused by topographic difference is a necessary condition for the generation of hot springs. The second function of the tectonic channel is to provide channels for the upwelling of hot water. The hot water formed in a subterranean area flows up to the shallow surface along the structural channel and is coupled with the active extensional tectonics in spatial distribution. Specifically, one of the spatial distribution characteristics of hot springs in South China and North China is that they occur along normal faults. On the Tibetan Plateau and Pamir Plateau, hot springs are located in the rift basin (e.g., the YGR).

Notably, tectonic channels may not necessary for the occurrence of hot springs. South China has a large number of high heat-producing granites (Zhou et al., 2020). Supposing the granite valley area is covered with sedimentary rocks, the recharge source from the hilly area will be heated by radioactive decay heat during infiltration, and a hot spring will be formed at the bottom of the valley. This formation model of hot springs is widely applicable to the Nanling area, South China (Kuang et al., 2021; Zhou et al., 2020).

In summary, recharge sources and heat sources are indispensable for the occurrence of hot springs, as well as for the distribution of hot springs in continental China. Hot springs can be generated in suitable areas where there are no active structures. However, the presence of active structures can affect the formation and spatial distribution characteristics of hot springs. Therefore, the distribution of hot springs in continental China results from a combination of recharge sources, heat sources, and tectonic channels. Since the Cenozoic era, the tectonic development of continental China may be interpreted using this connection. We can also accurately anticipate the existence of hot springs by integrating the elements that affect their distribution. Whereas we acknowledge the distribution mechanism model of hot springs in continental China outlined here is necessarily simplified, the resulting genesis will contribute to deciphering the hydrological and geological processes in continental China. Future research would compile all the influencing components and gain in-depth analysis using big data or deep learning approaches to quantitatively describe the control factors of hot springs in continental China.

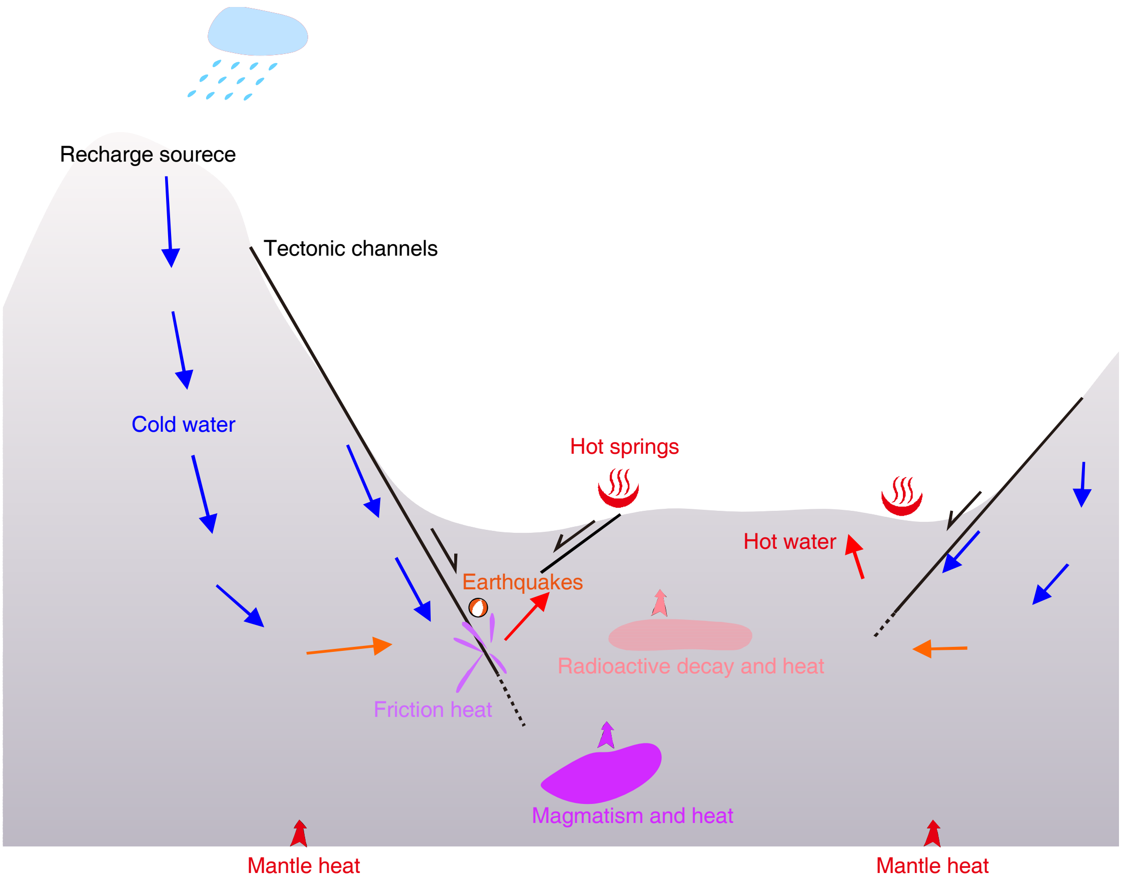

Figure 10 A genesis model of hot springs distribution in continental China. The beach ball shows an earthquake generated by normal fault. This model illustrates the influence of recharge sources, tectonic channels, and four heat sources (mantle heat, friction heat, magmatic heat, and heat from the radioactive element decay) on the formation and distribution of hot springs.

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