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Characteristics and genesis mechanism of deep geothermal resources in East China: take the North Jiangsu Basin as an example

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ABSTRACT <HEADING 1 STYLE>

Geothermal resources have been considered as an important component of clean renewable energy, and the exploration, development and utilization of geothermal resources are important for achieving carbon capping and carbon neutrality. Eastern China belongs to a high heat flow background area (>60 mW/m^2), which represents a tectono-thermal event that has experienced a certain intensity since the Cenozoic. In this study, we take the North Jiangsu Basin (NJB) as an example and carry out simulations and calculations with the latest geothermal data. The results show that the NJB is a typical "hot basin" with an average heat flow value of 68 mW/m^2. The shallow favorable geothermal resource areas in the NJB are mainly distributed in the Jianhu Uplift, while the deep favorable areas are mainly distributed in depressions, especially in the depressions near the Jianhu Uplift; the genesis mechanism of the deep favorable geothermal resource areas in the NJB can be summarized as "two times, two sources" thermal concentration. This study not only provides an important possible model for the future utilization of geothermal resources, but also provides new ideas for the study of geothermal characteristics and genesis mechanism in East China.

1. INTRODUCTION

In recent years, due to the deepening energy crisis and increasing environmental pollution, solar and wind energy have made great strides, while geothermal energy, which is widely distributed, low-carbon, and sustainable, has lagged behind. In comparison with wind and solar energy, geothermal energy is more stable, universal, and safe; it is cleaner and safer than nuclear energy (Lund and Toth, 2020; Tester et al., 2006). It is possible for clean renewable energy, including geothermal energy, wind energy, and solar energy, to contribute significantly to the country's energy structure and to help it develop a low-carbon economy (Hou et al., 2018; Zhu et al., 2015). During the long term, the Chinese government is committed to adopting strong policies and measures to achieve CO_2 emission peak in 2030 so that carbon will be neutralized by 2060. Geothermal energy will undoubtedly play a very important role in this process.

Located in Jiangsu Province, the foremost created area in China, the North Jiangsu Basin (NJB) may be exceptionally favorable range to carry out geothermal development and utilization in China at present for the following reasons: (1) The NJB is a typical "hot summer and cold winter" area with a strong heating demand market, and considering the high population density and energy consumption in the area, the feasibility of adopting geothermal heating is high; (2) detailed geological data could be a ensure for the advancement and utilization of geothermal resources, and (3) at the same time, it also gives an critical conceivable model for long term utilization of geothermal resources within the Yangtze Waterway Delta region.

The NJB is generally NE-SW trending, with an area of approximately 35,000 km^2. The main body of the basin is located within the northern part of Jiangsu province, adjoining to the Binhai Uplift in the north, associated to the Lusu Uplift in the northwest, adjacent to the Su'nan Uplift in the south, and deep into the South Yellow Sea in the east, which is belonging to the onshore part of the western part of the North Jiangsu-South Yellow Sea Basin (Figure 1). Tectonically, the NJB belongs to the post-arc area of the Meso-Cenozoic West Pacific tectonic domain and is part of the Lower Yangtze Craton. The tectonic pattern of "one uplift (Jianhu Uplift in the middle) and two depressions (the northern Yanfu depression, and the southern Dongtai depression)" in the NJB can be further subdivided into 22 highs and sags (Figure 1).

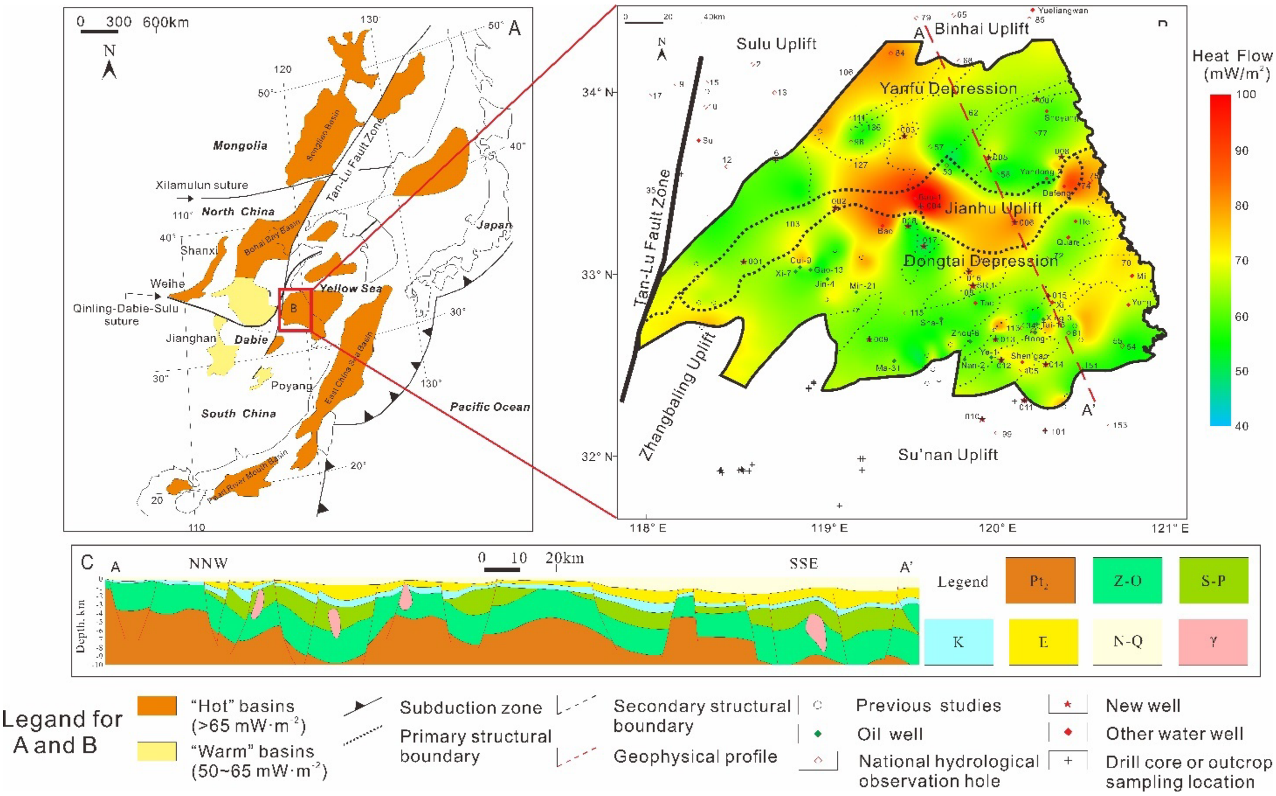

Figure 1. Tectonic, geological interpretation sections and geothermal information of the North Jiangsu Basin. (A is modified after Grimmer et al. (2002); B is modified after Wang et al. (2020, 2021); C is modified from Wang et al. (2020).

This paper updates and summarizes high-quality temperature profiles from boreholes within the NJB, and sets up columns of thermal conductivity, density, and porosity all through the NJB formations (or rocks) of all geological ages. The characteristics of the deep temperature field distribution in the NJB are analyzed, and its geothermal asset potential is discussed. Combining geographical and geophysical information, the genesis mechanism and dynamics of the present-day thermal state of the NJB is discussed.

2. GEOTHERMAL DATA

From 2018 to 2021, we designed and constructed 18 200-m-deep boreholes (numbered 001-018 in Figure 1) and a 4700 m deep well (SR1 in Figure 1(B)). Besides, we carried out steady-state temperature measurements on 104 wells in the NJB and its adjacent area and calculated 78 high-quality heat flow values, based on which heat flow maps of the NJB are shown in Figure 1(B)

2.1 Temperature data

In the NJB and its surrounding regions, temperature records from 104 boreholes were collected from 2018 to 2020. Figure 2 (a-f) shows representative temperature profiles. Temperature records below the water level of the borehole more accurately reflect the true temperature of the formation because air and water have different thermal conductivities. The water level of the borehole, which is typically less than 40 meters in the NJB, can be calculated based on the vertical fluctuation in temperature (Figure 2). The temperature rises linearly or nearly linearly when the depth exceeds 50 m, which is a conduction-type temperature measuring curve. Using the least-squares approach and the temperature data, the temperature gradient of each log was determined, ranging from 22 to 59°C/km, with an average temperature of 32 °C/km for the NJB.

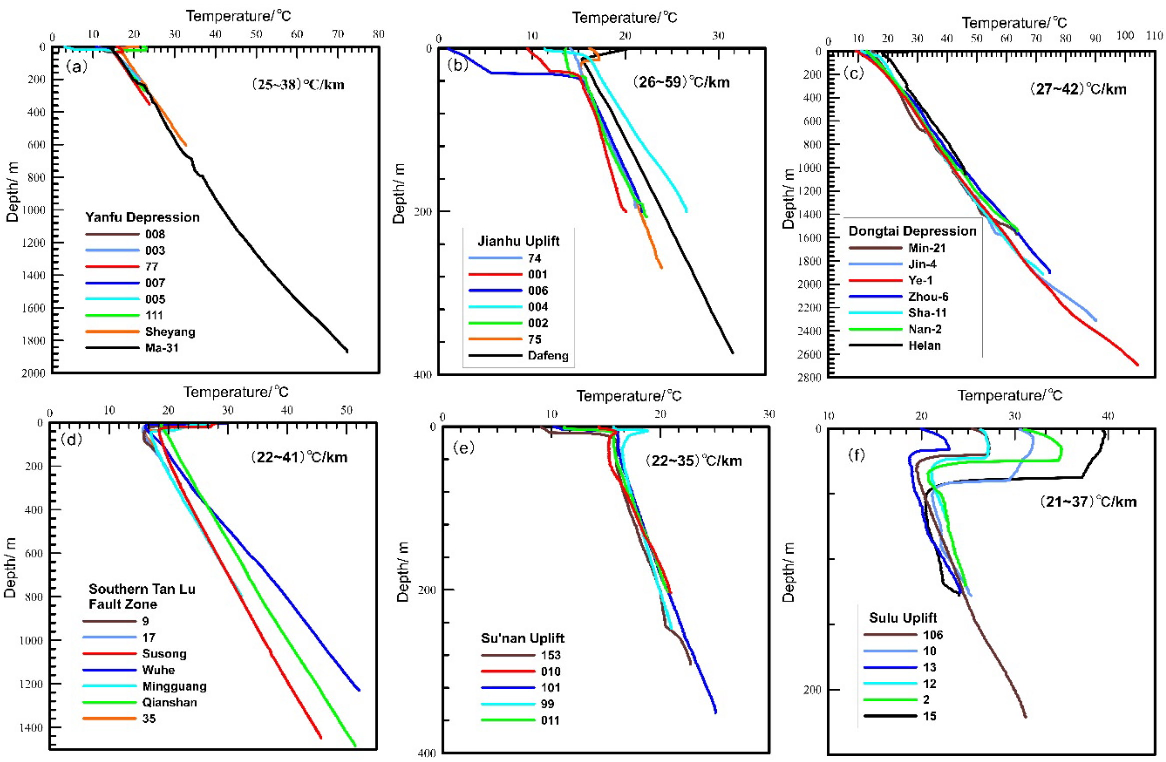

Figure 2. The temperature-depth profiles for the measured boreholes in the North Jiangsu Basin and its adjacent areas

2.2 Thermal physical parameters

For performing regional geothermal field investigations, rock thermal physical characteristics serve as the foundation. Three times between 1986 and 1988, outcrop and core samples have been obtained in the NJB to assess the heat conductivity of certain strata (Wang, 1989; Wang et al., 1995). In the geothermal study of the NJB between 2018 and 2021, the Institute of Geology and Geophysics, Chinese Academy of Sciences, and Geological Survey of Jiangsu Province systematically collected a large number of rock samples and conducted a number of thermal conductivity tests, greatly improving the regional thermal conductivity column. The thermal conductivity values for this compilation were obtained by merging existing research results and producing weighted average values of thermal conductivity for different strata depending on the number of test due to the wide stratigraphic range and uneven distribution. The results of the thermal conductivity test are displayed in Table 1.

Table 1. Thermal conductivity and heat production of different rock types in the North Jiangsu Basin

Stratum	Formation	Abbreviation	Thermal conductivity		Heat production	
			Mean (W/m/K)	Number	Mean (μW/m³)	Number
Q	Dongtai	Q	1.56	87	1.40	10
N	Yancheng	N	1.68	16	1.25	5
E	Sanduo	E_3s	1.40	6	1.20	3
	Dai'nan	E_2d	2.38	3	1.01	2
	Fu'ning	E_4f	--	--	2.65	2
		E_3f	2.61	4	2.05	2
		E_2f	2.44	5	1.62	2
		E_1f	2.45	2	2.68	1
K	Taizhou	K_2t	2.99	1	2.21	2
	Chishan	K_2c	--	--	1.67	1
	Pukou	K_2p	2.28	8	2.08	1
		K_1	--	--	--	--
J		J	4.38	4	1.25	1
T		T	2.84	2	2.64	2
P	Dalong	P_2d	--	--	--	--
	Longtan	P_2l	2.78	10	2.71	1
	Qixia	P_1q	3.32	3	--	--
C	Chuanshan	C_3c	3.26	3	--	--
	Huanglong	C_2h	2.80	2	--	--
	Hezhou	C_1h	3.18	2	2.67	1
	Laohudong	C_1l	--	--	--	--
	Gaolishan	C_1g	3.98	3		
D	Wutong	D_3w	3.70	5	1.12	1

		D_{1+2}	--	--	--	--
S	Maoshan	$S_2\ m^1$	7.99	1	--	--
	Fentou	S_2f	3.91	8	2.3	1
	Gaojiabian	S_1g	3.34	17		
O		O	3.85	1	2.55	2
Є	Guanyintai	$Є_3g$	3.31	2		
	Paotaishan	$Є_3p$	--	--	2.82	1
	Mufushan	$Є_3\ m$	4.57	2	--	--
Z	Dengying	Z_2d	6.11	6	--	--
	Huangxu	Z_2h	2.59	4	2.07	1
	Liantuo	Z_1l	--	--	--	--
Pt	Picheng	Pt_2p	3.39	18	1.05	5

The test findings demonstrate that the average rock thermal conductivity of each stratum in the area varies greatly; the Quaternary clay and sand has a thermal conductivity of 0.6 W/m/K, while the S_2m^1 has a thermal conductivity of 7.99 W/m/K. In general, as it moves from old to fresh strata, the thermal conductivity gradually drops.

In this work, 47 samples' U, Th, and K radioactive element compositions were examined and assembled, and the stratigraphic heat production was computed using the approach suggested by (Rybach, 1976). The findings demonstrate that the average heat production of all rock types in the NJB ranges from 1.1 to 2.7 mW/m^3, with the Middle Proterozoic Pt_2p having the lowest heat production and the E_4f having the greatest. Rocks with higher silt and mud content often produce more heat, and lithological variations are strongly connected to the difference in heat production.

2.3 Heat flow

The heat flow map is a crucial tool for evaluating regional geothermal resources, determining target areas for mining, and understanding the thermal background of tectonic units. All over the world, the NJB has one of the highest densities of heat flow measuring point. We eventually mapped the heat flow distribution in the NJB, as shown in Figure 1, by combining the 237 heat flow data in and around the basin.

The NJB's average heat flow value is 68 mW/m^2, which is a little higher than the average for East China. The eastern margin of the Dongtai Depression, the northern portion of the Jinhu sag, and the middle-eastern portion of the Jianhu uplift are relatively high heat flow areas within the basin, with mean geothermal heat flow values exceeding 70 mW/m^2. The heat flow in the uplift area is higher than that in the depression area, according to statistical calculations of heat flow values of sub-tectonic units in the basin, but some of the highs in the depression area have heat flows that are higher still, some of which even surpass those in the uplift area, suggesting that the highs in the depression may also be good places for deep geothermal convergence.

3. CHARACTERISTICS OF THE DEEP TEMPERATURE FIELD

Deep temperature field characteristics are both an important basis for the study of the thermal structure of the lithosphere and also for the study of deep geothermal resources. The simulation study of the 2-D temperature field takes into account the lateral heat transfer and reveals more about the real situation of the depth temperature field than the calculation of the one-dimensional temperature. Taking into account the pattern of NEE-SWW spreading, we choose the perpendicular profile for simulating. We ran the simulations at a depth of 20 km to minimize the effects of shallow heat refraction and the configuration of the bottom boundary heat flow on the outcomes. Finally, we got the large-scale 2D temperature field simulation (Figure 3).

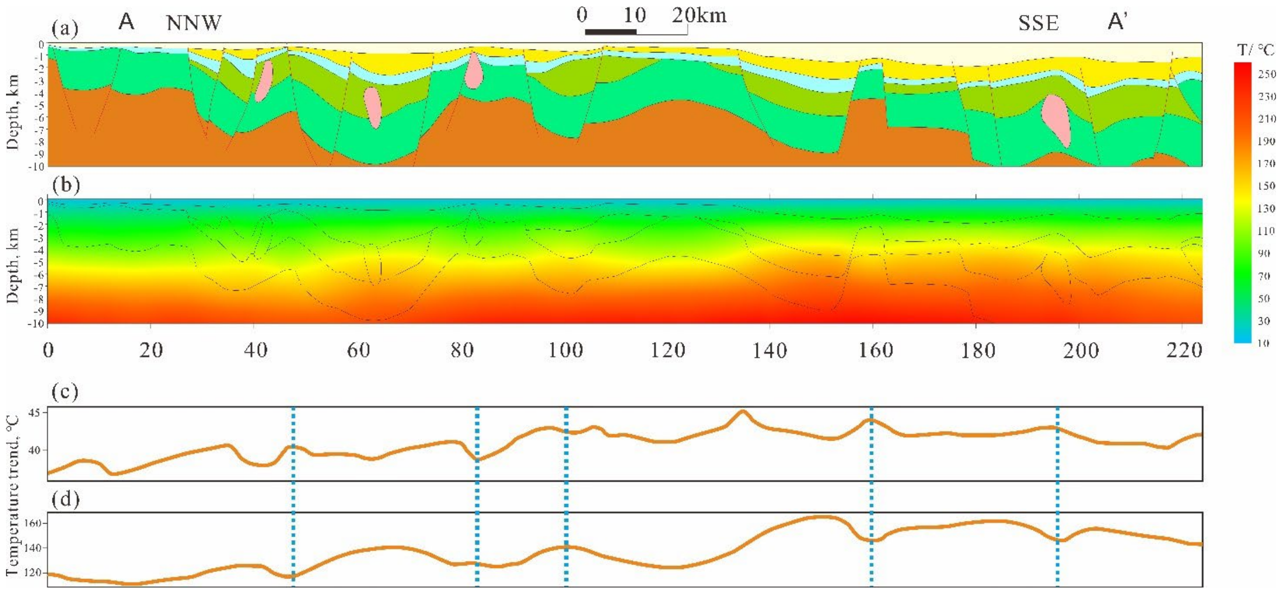

Figure 3. The temperature-depth profiles for the measured boreholes in the North Jiangsu Basin and its adjacent areas

From the heat flow map of the NJB (Figure 6), it can be seen that the uplifts or highs have a strong convergence of heat flow, i.e., a significant thermal refraction effect occurs, and have higher heat flow values relative to the depressions and sags. 2D temperature field simulations of the b profile (Figure 1) show that the area where the uplift of the isothermal surface occurs is concentrated in the southern depression area, which does not correspond

According to the NJB's heat flow map, the uplifts or highs exhibit strong heat flow convergence, having greater heat flow values than the depressions and sags. The isothermal surface uplift is focused in the Dongtai depression in the south and the Yanfu depression in the north, rather than concentrated in the Jianhu uplift (Figure 3). Besides, using profile AA' as an example, we displayed the temperature fluctuation at 0.5 km and 4.5 km depths, as shown in Figure 3 (c) and (d). Indicating the variability of the lateral heat transfer of thermal conductivity at various depths, the two lateral trends exhibit a very clear mirror image phenomenon.

4. GEOTHERMAL GENESIS MECHANISM

The mechanism of geothermal characteristics in the Lower Yangtze Craton/East China can be summarized as "two times, two sources", "two times", that is, the huge lithospheric thickness thinning caused by the late Mesozoic craton destruction in East China, and the Cenozoic lithospheric extension; the deep anomalous mantle-source heat is determined by these two tectono-thermal processes together, and thermal refraction mostly controls the upper crustal-scale heat.

4.1 Thermal concentration—"Two times"

Since the Mesozoic, the Izanagi plate's subduction has resulted in the dehydration and decarbonization of the underlying plate, which has led to the disruption of cratons in East China, peaking at the end of the Early Cretaceous (He, 2014; Zhang, 2005), while the upper crust has undergone extensive extensional tectonic deformation (Lin and Li, 2021; Lin and Wei, 2018), and the Lower Yangtze Craton's lithosphere thickness significantly decreased as a result of the craton destruction of East China.

The Pacific plate has gradually replaced the Izanagi plate since around 60 Ma, which has had an impact on the tectonic development of East Asia (Zhu et al., 2017). The old Izanagi plate eventually subducted into the mantle as a result of the Pacific plate subducting in a NW or W direction. A tectono-thermal event (45-60 Ma) of this period was recorded in the Lower Yangtze Craton under the influence of the subduction of the oceanic ridge due to the presence of Mid-Ocean Ridge connecting two oceanic plates (Izanagi plate and Pacific plate), which may have caused regional extension of the lithosphere overlying the plate window (Zhu et al., 2017) (Figure 4). High-angle subduction caused trench retreat and slab rollback as the age of the subducted oceanic crust grew older. During the Oligocene and Miocene, regional extensional tectonics got more vigorous, and significant volumes of basaltic rocks produced in the back-arc area (Niu, 2005; Xu, 2001). Additionally, there are some hypotheses that the back-arc extension brought on by the subduction of the western Pacific plate may be the primary source of the Cenozoic volcanism and high heat flow in the basins of East China (He, 2015; Liu et al., 2016; Qiu et al., 2016). It is determined that Cenozoic basalts originate from a barren mantle, indicating weakening of the atmosphere (Xu, 2001; Xu et al., 2009). In the Eocene and Oligocene, the NJB basin's surface heat flow reached 78~86 mW/m^2, as shown by the apatite fission track and Ro data (Zeng, 2005).

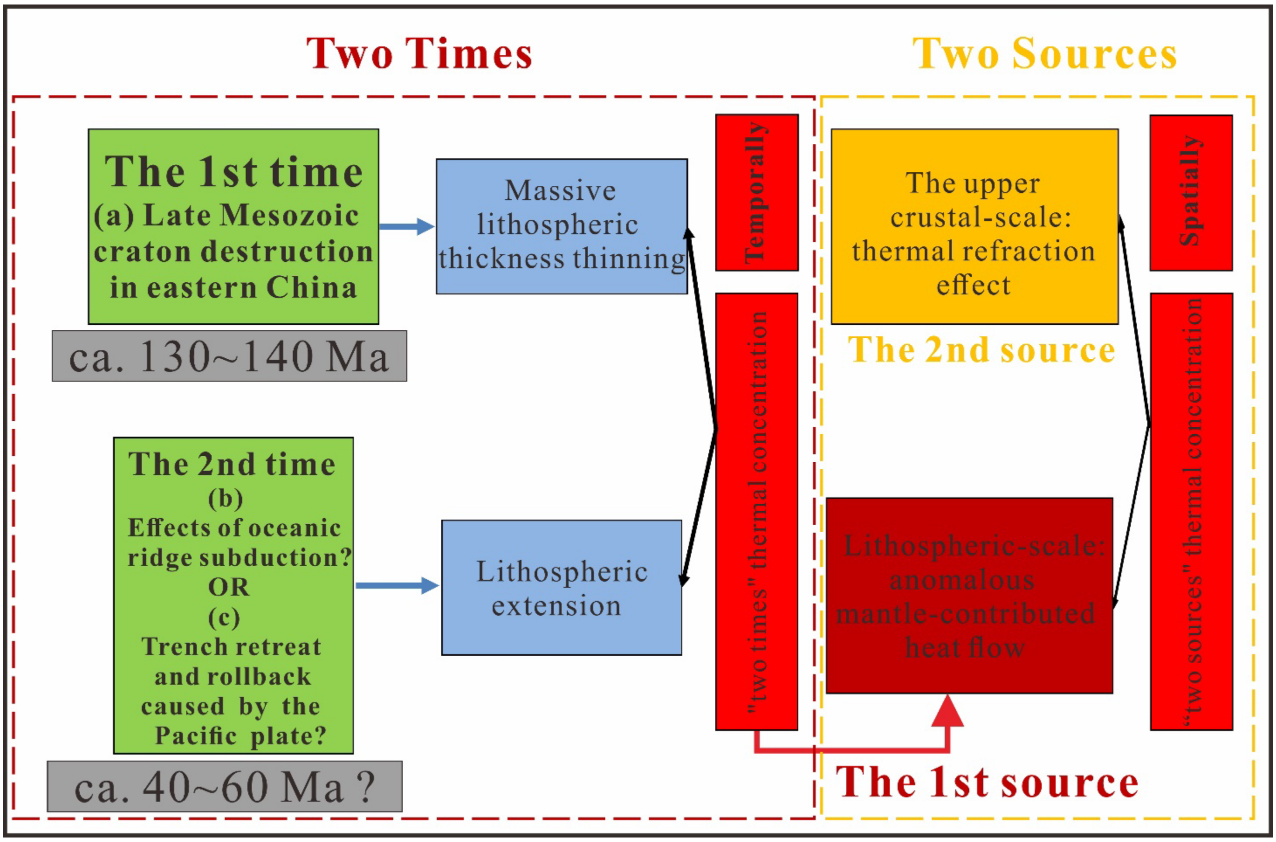

Figure 4. The kinetic mechanism and model of "two times, two sources" thermal concentration in the Lower Yangtze Craton/East China

4.2 Thermal concentration—"Two sources"

The deep anomalous mantle-source heat is determined by the two tectono-thermal events as a whole, as previously explained. Similar to how water always preferentially transfers in the direction of lower resistance, the influence of stratigraphic relief on the superficial temperature field is primarily reflected in the variation of rock thermal conductivity. This causes the redistribution of heat in the lateral direction or the thermal refraction effect. In the NJB, Paleozoic and Ediacaran strata have thermal conductivity that are significantly higher than those since Mesozoic (Table 1). The control element is more significant as the size of the Paleozoic and Ediacaran strata with high thermal conductivity layers increases. As a result, the Dongtai depression on the south side of Jianhu uplift has the strongest controlling influence on the local geothermal field at the upper crustal scale.

Specifically, the simulation results in Figure 3 are used as an example. In the shallow (<ca. 3 km), heat converges from the depression to the uplift; in the deep section (> ca. 3 km), it is nearly the opposite. It may be broken down further into three sections for the favorable area of geothermal resources: an uplift area (< ca. 1 km) with a high temperature; a depression area (ca. 2-3 km) with a high temperature; and a relative shallow depression area (ca. 3.5–5 km) with a much higher temperature. Based on the aforementioned data and simulations, it is simple to identify the "sweet spots" of geothermal resources at various scales in the sedimentary basin.

5. CONCLUSION

Using the most recent, top-notch data on heat flow, thermal conductivity, and heat production of the rocks, we ascertained the thermal conditions of the NJB. The average heat flow in the NJB was about 68 mW/m^2.

A detailed discussion of the geothermal characteristics of basin and causal mechanisms of the Lower Yangtze Craton/East China were thoroughly discussed. The "sweet spots" of geothermal resources in the sedimentary basin are different at different research scales. The genesis mechanism of geothermal characteristics in East China can be summarized as "two times, two sources".

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