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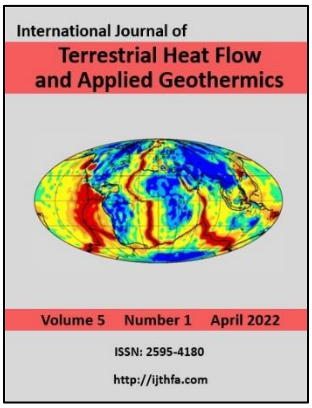

Heat Flow in the Asian Continent and Surrounding Areas

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Abstract

Heat flow is a key parameter to describe the interior heat of the Earth and provides constraints on understanding the thermal structure of lithosphere and assessment of the geothermal resource potential. Based on the latest heat flow database, here we present the heat flow pattern of the Asian continent and its surrounding areas and discuss the correlation between heat flow and tectonics. The mean heat flow of Asian continent and its surrounding areas is 71 ± 34 mW/m^2, slightly higher than the global continental mean value, and the overall heat flow pattern in Asia exhibits remarkable heterogeneity, characterized by higher values in the eastern marginal seas, the Red Sea, the Gulf of Aden and the Qinghai-Tibet Plateau, while lower in large areas of North Asia and Central Asia. Cratons show a lower mean heat flow and smaller standard deviation, indicating the tectonic stability. The Cenozoic rifts, marginal seas and the Neo-Tethyan Tectonic Domain all exhibit higher heat flow. The geothermal pattern in Asia is controlled by the geodynamic processes of the subduction of Pacific Plate, the Indo-Asia continental collision and the break-up between Arabia and Africa.

1. Introduction

Heat flow, indicative of the energy flux through the surface of the Earth, is a critical parameter to explore the interior heat of the earth. The inner heat of the Earth drives plate motion, and the Earth is kind of a thermal engine. Understanding Earth's heat flow is fundamental for studies about planetary energy balance and the thermodynamic conditions within the interior (Fuchs et al., 2021). It also plays an important role in constraining the lithospheric thermal structure and geodynamic process, as well as evaluating the potential of geothermal resources (Balling, 1995; Furlong and Chapman, 2013). Besides, geothermal energy is a competitive renewable energy source that is stable and environmentally friendly (Guan et al., 2018). High energy utilization coefficient makes it effective on reducing carbon emissions and easing energy shortage, which meets the urgent needs of contemporary energy utilization. Accordingly investigating the regional heat flow pattern is the precondition for exploration, development and utilization of geothermal energy.

According to previous compilations of heat flow data of Asian continent, several local studies have been conducted and provided the fundamental database for further investigation. The representative works include: Hu et al. (2000) analyzed 862 observations and pointed out that mean heat flow of the continental area of China is 61 ± 15.5 mW/m^2 with a range of 30 to 140 mW/m^2. In addition, the overall heat flow pattern appears to be characterized by high values in the east and southwest while low values prevail in the center and northwest. Recently Jiang et al. (2019) further updated the heat flow data in continental China, extending to 1230 observations. Under the new data frame, the background heat flow values range from 30 to 140 mW/m^2 with a mean of 60.4 ± 12.3 mW/m^2, excluding local anomalies. In addition, Kim and Lee (2007) integrated the heat flow data in Korea and suggested that mean heat flow of the Republic of Korea is 60 ± 11 mW/m^2, with high heat flow values in the southeastern, the central western, and the northeastern part of the Republic of Korea. Based on newly published thermal data, Tanaka (2004a, 2004b) compared heat flow and geothermal gradient with the lower limit of crustal earthquake focal distributions beneath the Japanese Islands. The results showed that the lower limit of seismicity is inversely related to heat flow and geothermal gradient. However, few studies have taken Asia as a whole to outline the regional heat flow pattern, therefore calling for an integrative reconnaissance with the updated data.

Thanks to the application of new measurement techniques and the expansion of the hydrocarbon exploration, global heat flow data has increased rapidly in recent years, along with better coverage of heat flow sites. The International Heat Flow Commission (IHFC; www.ihfc-iugg.org) has been working on providing objective, unique and unambiguous heat-flow data since 1963 (Fuchs et al., 2021). In 2020, an updated version came out with a new parent-child system for each heat flow data, consisting of four parameters that affect heat flow calculation and interpretation. The new database now comprises 74,548 heat flow measurements, 40,870 of which are located in continental areas and 33,678 in marine areas. Given the updated data and improved coverage in Asian continent, it is now available to refine the heat flow pattern and discuss the relationship between heat flow and tectonics.

Asia consists of numerous continental and oceanic fragments collaged together by plate convergences (Sengör, 1985; Yin, 2010), and shows mosaic structure and complex geological evolution, influenced by the Neo-Tethyan Tectonic Domain, the Pacific Tectonic Domain and the Paleo-Asian Ocean Tectonic Domain, respectively (Ren et al., 2013; Dai et al., 2013) (Fig. 1).

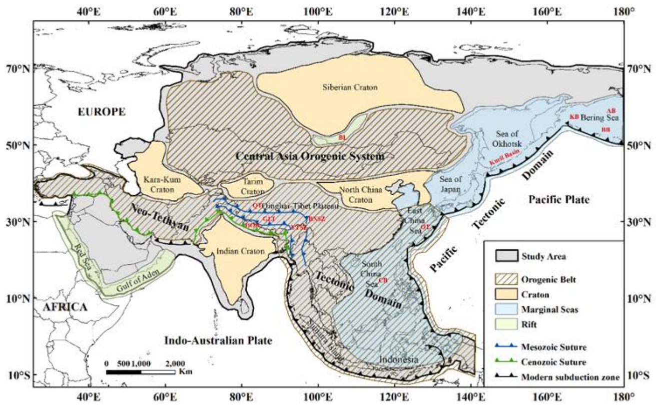

Figure 1 - Sketch showing the major tectonic units in Asian continent and its surrounding areas (modified from Zuza and Yin (2017), Sengör et al. (2018), Wu et al. (2020) and Zhu et al. (2021)). BL – Baikal Lake, AB - Aleutian Basin, BB - Bowers Basin, KB - Kamchatka Basin, OT - Okinawa Trough, CB – Central Basin, QT - Qiangtang Terrane, GLT - Gangdise-Lhasa Terrane, HOB - Himalayan Orogenic Belt, BNSZ - Bangonghu-Nujiang Suture Zone, YTSZ - Yarlung Tsangpo Suture Zone.

The major tectonic units in Asia include the Precambrian cratons, Phanerozoic orogenic belts and Cenozoic rifts. The Neo-Tethyan Tectonic Domain is a giant latitudinal orogenic belt spreading across Eurasia, covering all the Meso-Cenozoic orogenic belts from the Alps through the Middle East, Qinghai-Tibet Plateau, to the Indo-Malay Peninsula and Indonesia (Ren et al., 2016). The evolution of the Paleo-Tethys Ocean and Neo-Tethys Ocean for a prolonged period and the eventual closure has led to the geological complexity of this region (Sengör, 1987; Wu et al., 2020; Zhu et al., 2021). The Central Asia Orogenic System, also referred as the Central Asia Orogenic Belt, is the largest continental orogenic belt in the world (Xiao et al., 2019). It was formed as a result of long-term subduction and accretion of the Paleo-Asian Ocean, hence the name Paleo-Asian Tectonic Domain (Dobretsov et al., 1995; Khain et al., 2003; Windley et al., 2007). The unique tectonic setting makes Asian continent an ideal place to decipher the Cenozoic intracontinental deformation and lithospheric dynamics (Molnar and Tapponnier, 1975; Sengör, 1985; Yin, 2010). Thermal state and rheology of the Asian continental lithosphere plays an important role in modulating stress and strain partition associated the Indo-Asia collision. This has allowed a better understanding of heat flow pattern in Asia. This article aims at revealing the heat flow pattern of the whole Asia and exploring the relationship between heat flow and tectonics on regional scale, based on the updated heat flow database in Asia.

2. Heat Flow Data

We selected 10,404 measurements from the newest IHFC database, including 6,574 in the continental domain and 3,830 in the marine domain (Fig. 2). Each measurement contains the following information: site name, geographical latitude, geographical longitude, heat flow value, primary reference, geographical elevation, domain (continental or marine), country, and tectonic plate. As can be seen in figure 2, heat flow sites generally show a better geographic coverage, compared with previous compilations. However, more observations are located at the northwest and east part of Asia, partly owing to the extending hydrocarbon exploration, while fewer at the northeast and southwest. In the meanwhile, certain countries even have no data site, such as Pakistan, Iraq, Nepal, Bangladesh and Bhutan.

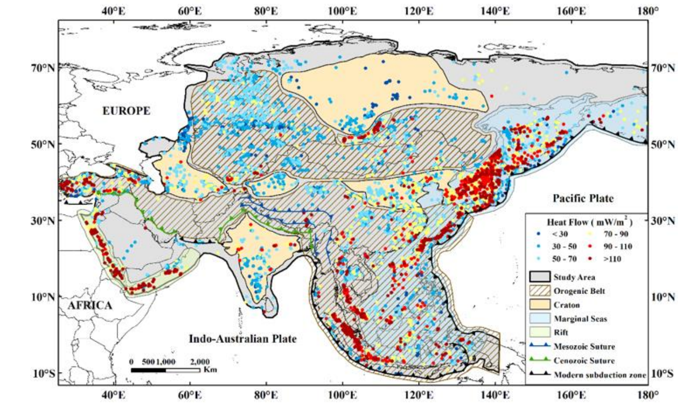

Figure 2 - Heat flow sites of Asian continent and its surrounding areas.

Heat flow values in Asian continent and its surrounding areas reveal considerable scatter, and most of them vary from 20-100 mW/m^2. Several anomalous values that are higher than 200 mW/m^2 or lower than 20 mW/m^2 also exist. The extremely high values (of >1000 mW/m^2) are located in the Cenozoic rifts of the Okinawa Trough and the Red Sea. Such anomalous heat flow values were excluded from the current analysis as these small amounts of data would not affect the overall pattern of the heat flow distribution. Besides, in order to break the limitation of data numbers, we used ArcGIS software to construct the heat flow distribution map and rendered it by the inverse distance weight interpolation method to compensate for those areas of low data density.

3. Heat Flow pattern of Asian Continent

As mentioned above, most of the heat flow in Asian continent is vary from 20-100 mW/m^2, and the mean heat flow is 71 ± 34 mW/m^2 except anomalous values. The overall heat flow pattern exhibits higher values in the marginal seas, the Red Sea, the Gulf of Aden and the Qinghai-Tibet Plateau, while lower in large areas of North Asia and Central Asia (Fig. 3).

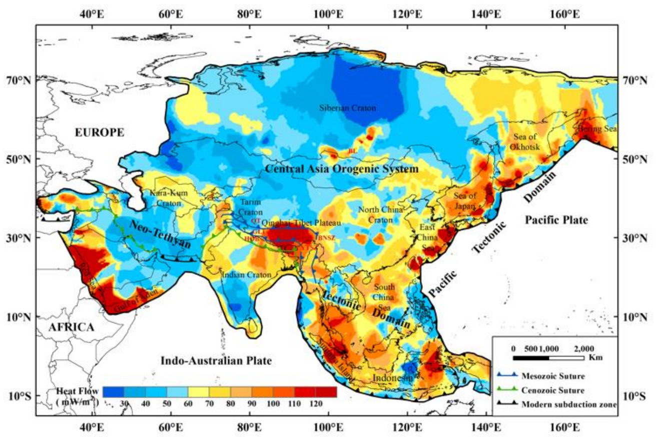

Figure 3 - Heat flow interpolation diagram of Asian continent and its surrounding areas. BL – Baikal Lake, QT - Qiangtang Terrane, GLT - Gangdise-Lhasa Terrane, HOB - Himalayan Orogenic Belt, BNSZ - Bangonghu-Nujiang Suture Zone, YTSZ - Yarlung Tsangpo Suture Zone.

In terms of the tectonic units of Asian continent, their heat flow values are significantly different and are summarized in the Table 1.

Table 1 - Heat flow in several tectonic units of Asian continent and its surrounding areas.
(Abbreviations: STD – Standard deviation; N – Number of data)

Type	Tectonic unit	Mean (mW/m^2)	STD (mW/m^2)	N
Craton	Siberian	37	12	148
	Kara-Kum	52	17	265
	Tarim	44	9	102
	North China	64	16	690
	Indian	58	22	309
Rift	Gulf of Aden	116	56	44
	Red Sea	172	68	267
Marginal Sea and Continental shelf	Bering	73	23	54
	Okhotsk	81	34	345
	Japan	94	25	534
	East China (shelf)	68	8	43
	Okinawa Trough	210	215	373
	South China	76	20	394
Orogenic belt	Central Asia	53	17	194
	Indonesia	95	39	867
	Qinghai-Tibet Plateau	72	42	129

Generally, cratons in Asia usually have lower mean heat flow, accompanied by smaller standard deviation; while the rift belts and marginal seas all exhibit higher values. As for orogenic belts, the heat flow in Central Asia Orogenic Belt is not quite high, since numerous Precambrian ancient microcontinents are embedded. The Neo-Tethyan Tectonic Domain, however, are characterized by high heat flow values, in spite of the uneven distribution of data. The sections below provide descriptions in detail separately.

3.1. Cratons

Cratons are major components of the Asian continent. The heat flow pattern in cratons vary significantly, but most exhibit relatively low values (Fig. 4). The spatial distribution of heat flow measurements in the Siberian Craton is extremely heterogeneous, with higher data density in the southeast and fewer in the northwest. Values range between 15-83 mW/m^2 with a mean of 37 ± 12 mW/m^2 (N=148). Most of such heat flows lower than 30 mW/m^2 are located in the central part. The Kara-Kum Craton displays a mean heat flow of 52 ± 17 mW/m^2 (N=265), and high values are mainly found in the southern and central regions. The mean heat flow value of the Tarim Basin is 44 ± 9 mW/m^2 (N=102), with only four values in the southeast higher than 60 mW/m^2. Compared to other cratons, relatively high values occur in the North China Craton. Its mean heat flow value is 64 ± 16 mW/m^2 (N=690), with the majority within 40-100 mW/m^2. East area has higher heat flow than the west area. Low heat flow is also observed in the Indian Craton, with an average value of 58 ± 22 mW/m^2 (N=309). Generally, more measurements are located in the southern area, most of which are lower than 65 mW/m^2. Limited data in the north, near the Himalayan orogenic belt, reveal 'hotter' thermal state.

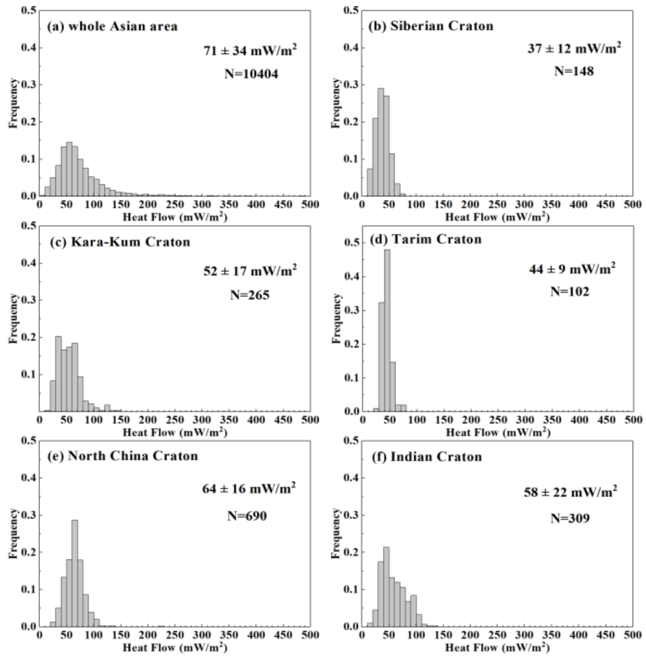

Figure 4 - Frequency histograms of heat flow values in (a) Whole Asian area, (b) Siberian Craton, (c) Kara-Kum Craton, (d) Tarim Craton, (e) North China Craton, (f) Indian Craton. Mean heat flow value, standard deviation and total data volume are marked on the top right corner of each graph.

3.2 Rifts

In contrast to cratons, the rifts in Asia are characterized by high heat flow (Fig. 5). At the border between Africa and Asia, the Gulf of Aden has a mean heat flow of 116 ± 56 mW/m^2 (N=44), with data ranging from 16 mW/m^2 to 348 mW/m^2. Much higher and more discrete heat flow values are observed in the Red Sea, with several higher than 1000 mW/m^2. Even if the observed values higher than 400 mW/m^2 are not considered, its average can reach 172 ± 68 mW/m^2 (N=267). As for the Baikal Lake, the average value is 89 ± 60 mW/m^2 (N=651), with most of the values ranging from 20 to 300 mW/m^2. Moreover, high heat flow occurs in the middle, while the values on the two sides are relatively low.

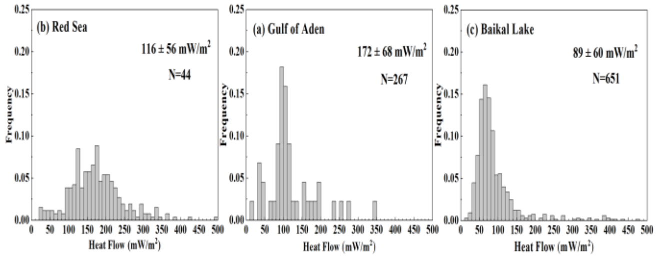

Figure 5 - Frequency histograms of heat flow values in (a) the Red Sea (b) Gulf of Aden and (c) Baikal Lake. Mean heat flow value, standard deviation and total data volume are marked on the top right corner of each graph.

3.3. Marginal seas

Another high heat flow region is the series of marginal seas in the eastern part of Asia (Fig. 1). These manifest high heat flow of different extent (Fig. 6).

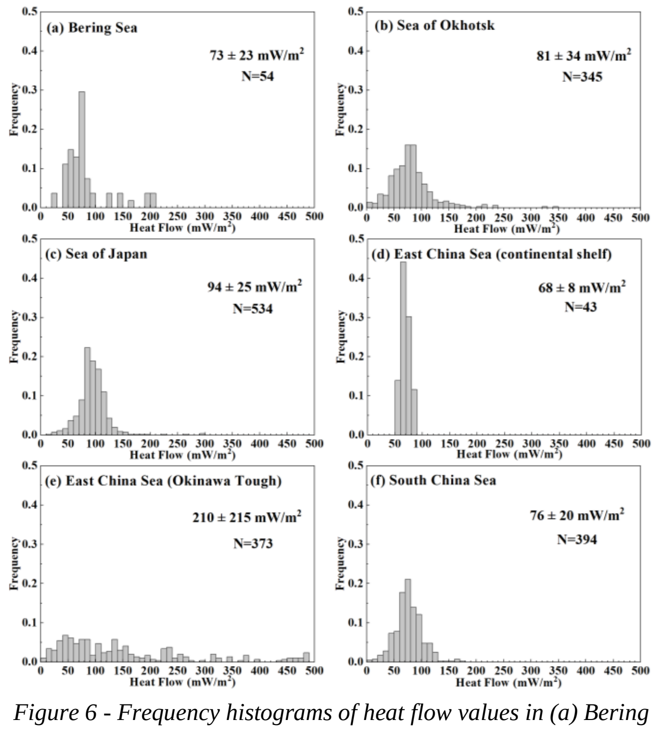

Figure 6 - Frequency histograms of heat flow values in (a) Bering Sea, (b) Sea of Okhotsk, (c) Sea of Japan, (d) East China Sea (continental shelf), (e) East China Sea (Okinawa Trough) and (f) South China Sea. Values of mean heat flow, standard deviation and total data are marked on the top right corner of each graph.

The Bering Sea has a small number of heat flow observations and displays a mean value of 73 ± 23 mW/m^2 (N=54). The Kamchatka Basin has higher values than the Aleutian Basin and Bowers Basin. Mean heat flow of 81 ± 34 mW/m^2 (N=345) is observed in the Sea of Okhotsk. The Kuril Basin in the south is characterized by higher values, while the continental shelf has lower values. The Sea of Japan reveals a much higher mean heat flow of 94 ± 25 mW/m^2 (N=534) and the heat flow sites are located much more evenly. Values in the East China Sea are the most discrete. On the continental shelf, the heat flow values have a smaller range and the average value is relatively lower, 68 ± 8 mW/m^2 (N=43). In the Okinawa Trough, the lowest value is 8 mW/m^2, while more than 20 values exhibit higher than 2000 mW/m^2. Given this large variation, the average value is 210 ± 215 mW/m^2 (N=373). Mean heat flow in the South China Sea is 76 ± 20 mW/m^2 (N=394). The whole Central Oceanic Basin is a high heat flow region. As for the continental margins, the western and the southwest portions are characterized by relatively high heat flow values when compared with those of the southeast portion.

3.4. Orogenic Belts

The spatial coverage of heat flow observations within the Central Asian Orogenic System is highly uneven, with more values in the west and less in the east (Fig. 2). Very little data can be found in Mongolia and data in northern China is mainly concentrated in oil-bearing sedimentary basins (Jiang et al., 2019). The mean heat flow value of the whole Central Asia Orogenic System is 53 ± 17 mW/m^2 (N=1294). This is not high (Fig. 7a) relative to values found in the Tien Shan Mountain in the southwest and the sedimentary basins of northern China. It should be noted that, the average heat flow of Central Asia Orogenic System might be underestimated since the relatively dense distribution of low values in the western part.

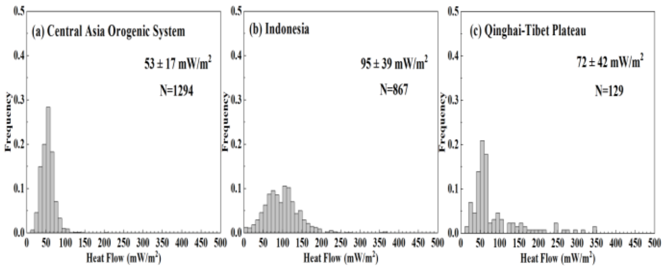

Figure 7 - Frequency histograms of heat flow values in (a) Central Asia Orogenic System, (b) Indonesia and (c) Qinghai-Tibet Plateau. Mean heat flow value, standard deviation and total data volume are marked on the top right corner of each graph.

In terms of the Neo-Tethyan Tectonic Domain that extends from west to east throughout Asia, the sites of heat flow measurements are distributed highly unevenly. The majority are concentrated in Turkey, southern China, Thailand and Indonesia. Particularly, several countries in West and South Asia, such as Pakistan, Iraq, Nepal, Bangladesh and Bhutan, have low data density. High heat flow values are mainly located in Turkey, Qinghai-Tibet Plateau, Gulf of Thailand and Indonesia, while southern China appears to have a 'cooler' thermal state due to the presence of the South China Craton. Given the overly heterogeneous spatial distribution of heat flow data in the Neo-Tethyan Tectonic Domain, only Indonesia and the Qinghai-Tibet Plateau are used here as examples for relative evaluations. The majority of heat flow values in Indonesia lie within the range of 30-160 mW/m^2 and the mean value is 95 ± 39 mW/m^2 (N=867) (Fig. 7b). Most high values occur in the Sumatra Island, where the average reaches 124 mW/m^2. A total of 129 heat flow observations are located in the Qinghai-Tibet Plateau, mostly in the north and only a few in the south. The data coverage is poor in the central region. The Qinghai-Tibet Plateau exhibits a heat flow pattern of higher values in the south and lower ones in the north. The average heat flow value of the whole plateau is 72 ± 42 mW/m^2 (Fig. 7c). Particularly, the mean value of the southern Tibetan part reaches 121 mW/m^2 (N=46), indicating a remarkably anomalous thermal state.

4. Discussion

4.1. General thermal characterization of Asian continent

With the latest data compilation, the mean heat flow value of the Asian continent is 71 ± 34 mW/m^2. This estimate, which excludes anomalous values, is slightly higher than global continental mean value of 65 - 67 mW/m^2 (Pollack et al., 1993; Lucazeau, 2019), indicating a relatively anomalous thermal state. Actually, the high heat flow regions that include the marginal seas along the eastern Asia, the Gulf of Aden as well as the Red Sea are all integrated in this study, which could result in the larger average heat flow of Asia.

Given the updated data set in this study, the mean heat flow value of Asia could be slightly different, compared with previous compilations (Pollack et a., 1993; Hu et al., 2000). In addition, Asia exhibits higher heat flow in contrast with most other continents. To be specific, Africa has a lower average heat flow value (55 ± 20 mW/m^2) than Asia (Gomes et al., 2021), as well as Australia (67 ± 16 mW/m^2), Europe (66 ± 21 mW/m^2) and North America (63 ± 20 mW/m^2) (Lucazeau, 2019). Only South America displays higher heat flow as 76 ± 35 mW/m^2 (Vieira and Hamza, 2019; Lucazeau, 2019). So, the observed value of relatively high heat flow of Asia should be related to Meso-Cenozoic tectonic deformation since its formation.

4.2 Heat flow and tectonics in Asia

The heat flow pattern is controlled by plate tectonics and Meso-Cenozoic dynamic processes of lithosphere (Mareschal and Jaupart, 2013; Jiang et al., 2019). Occurrence of high heat flow is accompanied with intensive magmatism and or tectonics, while the low heat flow occurs in tectonically stable areas. This correlation is also valid for Asian continent and its surrounding areas.

In the eastern margin of Asia, where subduction of the Pacific Plate occurs relative to Eurasian Plate, a series of Cenozoic marginal seas have formed over western Pacific area. These are characterized by relatively high heat flow. Actually studies have revealed that most of the back-arc regions manifest high heat flow state, no matter whether there has been significant recent tension (e.g. Okinawa Trough of East China Sea) or not (e.g. Aleutian Basin of Bering Sea). This appear to be the reason for high mean value and large scatter in younger regions (Barazangi et al., 1975; Watanabe et al., 1977; Flanagan and Wiens, 1994; Wiens and Smith, 2003; Currie et al., 2004; Currie and Hyndman, 2006). As for regional heat sources, in addition to heat release from metamorphism, radiation and friction on the surface of subducting plate, the shallow thermal convection in the upper mantle is also proposed for the observed high heat flow (Hyndman, 2010). Such vigorous thermal convection can efficiently carry heat from deep mantle up into the subduction region, leading to observed high temperature areas of back-arc areas. Therefore, the observed high heat flow values in marginal seas are mainly contributed by the mantle.

While for Indonesia, the subduction of the Indo-Australian Plate towards the Eurasian Plate accounts for regional high heat flow. For example, the Sumatra Island mainly consists of the Barisan Mountains in the southwest and the plains in the northeast, with NW-SE striking. Subduction around Sumatra dates back at least to Cretaceous and formed a large number of volcanoes (Da Silva Carvalho et al., 1980). Although the compression of subduction by the Asian plate prevented the opening of a back-arc basin (Da Silva Carvalho et al., 1980), the eastern plains still exhibit high heat flow, similarly to that in the marginal seas.

The Gulf of Aden and the Red Sea reveal another situation, where the heat flow pattern is related to their tectonic nature of being modern examples of young rifted margins. Both of them were formed by the Cenozoic break-up of Arabia and Africa (Manighetti et al., 1997; Stockli and Bosworth, 2019; Saada et al., 2021). The Gulf of Aden opened earlier and experienced two stages of extension, diffuse extension in a rift valley environment without an organized spreading center and then concentrated extension along a single axis (true seafloor spreading) (Cochran, 1981), Thus the main trough is underlain by oceanic crust (Fairhead, 1973). During the extension, continuous magmatic activities shaped the high heat flow pattern in the Gulf of Aden. As for the Red Sea, it is suggested that the southern Red Sea Rift is located where the seafloor spreading occurs and forms oceanic crust. The central part is thus a transition zone mainly consisting of disconnected oceanic crust, while the northern portion is within the last stage of the rift-related magmatic intrusion or the first stage of seafloor spreading (Saada et al., 2021). Although different parts of the spreading rift are within different evolution stages, there is no doubt that the region of Red Sea rift is undergoing vigorous magmatism. The thinning of crust and the upwelling of mantle has contributed to the abnormal high heat flow in the Red Sea.

Another typical rift valley is the Baikal Lake, but it is far away from plate boundaries, unlike the Gulf of Aden and Red Sea. The Baikal rift system formed as the combined effects of mantle upwelling and the Indo-Asian continental collision (Mats, 1993; Yang et al., 2003). The largest, deepest and earliest faults developed in the center of this rift system (Yang et al, 1995; Yang et al., 2003), corresponding to higher heat flow at the axis and lower on the sides.

The control of tectonic activities on heat flow pattern is particularly evident in the southern Qinghai-Tibet Plateau. As illustrated in Fig. 1, the southern Qinghai-Tibetan Plateau consists of several blocks from south to north with different properties, corresponding to the N-S strips of thermal state (Ma and Kong, 2001). Specifically, high heat flow values are found in the Himalayan orogenic belt and the Gangdise-Lhasa terrane, with average heat flow values of 145 mW/m^2 and 195 mW/m^2, respectively. While the heat flow in the Qiangtang terrane decreases to about 45-75 mW/m^2. Since Late Cretaceous, the Tethys Oceanic Plate rapidly subducted towards the Eurasia continent along the Yarlung Tsangpo River. This led to the Gangdise-Lhasa terrane which gradually folded and uplifted to form the Gangdise Mountains (Bai et al., 2006). During the mid to Late Cenozoic, the Himalayan orogenic belt and the Gangdise-Lhasa terrane underwent strong tectonic deformation again due to the Indo-Asian collision (Deng et al., 2017). Thickening of the crust in the southern region associated with plate convergence, lead to significant contribution of radioactive heat production to the surface heat flow. Large-scale plate movements also induced multiple phases of regional magmatic intrusion and multiple volcanic eruption events in the southern plateau, especially in the Gangdise-Lhasa terrane (Bai et al., 2006). Studies reveal that the Himalayan orogenic belt has 'hot' crust and 'cold' mantle. On the other hand, the Gongdise-Lhasa terrane is of 'hot' crust as well as 'hot' mantle, and the low velocity and high conductivity body detected within the middle crust in the Lhasa-Gongdise terrane is regarded as due to rise of partially molten magma (Shen et al., 1990; Wu et al., 1996; Bai et al., 2006). In contrast, the Qiangtang terrane is stable. After long term uplift and erosion, the crust lacks heat generating elements and thus has limited crustal heat flow, and the mantle heat flow is not that high in the meantime (Shen et al., 1990). Generally, the geothermal distribution of the southern Qinghai-Tibet Plateau is consistent with the tectonic propagation direction, abrupt changes in heat flow and differences in thermal structure among different tectonic units that exist there.

5. Conclusions

The mean heat flow of Asian continent and its surrounding areas is 71 ± 34 mW/m^2 (N=10,404), with the exception of extremely anomalous values. The overall heat flow pattern exhibits higher values in the eastern Asian marginal seas, in the Red Sea, and in the Gulf of Aden. Similar trends also occur in the Qinghai-Tibet Plateau, while lower values occur in large areas of North Asia and Central Asia.

Heat flow pattern in different geological units of Asia vary remarkably. Cratons usually have relatively low mean heat flow (<50 mW/m^2) and smaller standard deviation. The heat flow of the Central Asia Orogenic Belt is moderate. On the other hand, rifts, marginal seas and the Neo-Tethyan Tectonic Domain all exhibit higher values. The heat flow pattern of Asian continent and its surrounding areas is consistent with the current understanding of plate tectonics and Meso-Cenozoic lithospheric processes.

5. Acknowledgments

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