Numerical Modeling of Heat Flow of Kangding Area with New Borehole Data for Purpose of Geothermal Resources Development Evaluation

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Abstract

Terrestrial heat flow is a surface indicator of potential geothermal resources in depth, and its measurement and compilation are important for evaluating the merits of geothermal resources. The Kangding area locates in the western Sichuan Province of China where regional thermal fractures develops showing good potential for geothermal energy development but with barely precise heat flow data. We collect the borehole temperature data from the geological survey report of the Sichuan-Tibet Railway that passes through the Kangding area where geothermal survey data are in lack. In total, 50 sets of high-quality data are compiled. The average heat flow in the study area is calculated as $86.96 \pm 39.73\,\mathrm{mW/m^2}$, which fills the gap of heat flow data in Western Sichuan. With the obtained heat flow data incorporating into the heat flow database, the regional heat flow is numerically studied by the Kriging interpolation method to obtain the map of the geothermal flow in Sichuan Province. A preliminary assessment of the exploitation of geothermal energy resources is finally made in the Kangding area of western Sichuan. The results indicates that Kangding area has the good potential for geothermal exploitation.

Keywords: Terrestrial Heat Flow; Kriging interpolation; geothermal energy in Kangding area; Sichuan-Tibet railway;

I. INTRODUCTION

As a new type of clean energy, geothermal energy resources have environmental and economic advantages over conventional energy sources[1]. China has abundant reserves of geothermal energy resources, of which hydrothermal geothermal resources are equivalent to 1,250 billion tons of standard coal, and the reserves of dry hot rock resources are equivalent to 856 trillion tons of standard coal [2]. According to the evaluation results of geothermal energy resources in mainland China by Guocheng Ren et al. [3], hot dry rock resources at a depth of 3~10km in mainland China total 21×106EJ. If calculated by 2% of the exploitable resources, it is traditional Hydrothermal geothermal energy resources are 16.8 times, approximately equivalent to 4,400 times the total energy consumption of mainland China in 2010.

As an important transportation and tourist route for Sichuan-Tibet Highway and Sichuan-Tibet Railway, Ganzi Prefecture of Sichuan Province has abundant geothermal energy reserves. According to the summary of previous work, there are 264 hot spring spots and 17 geothermal wells in the prefecture [4]. Geothermal energy resources in the form of high-temperature steam and underground hot water can provide a wide range of uses for local tourism, heating, power generation, agricultural planting, etc.

However, the current assessment of the distribution of geothermal energy reserves in Western Sichuan mainly relies on existing hot spring spots and geothermal wells. Spatial distribution characteristics, the resulting evaluation results only have a certain reference value for the surrounding areas of the existing data points, and no research has been conducted to evaluate the regional distribution characteristics of geothermal energy resources in western Sichuan. The main reasons are: sparsely populated areas in western Sichuan, inconvenient transportation, and low local utilization of geothermal energy resources, resulting in a lack of data related to geothermal energy.

This paper supplements the existing heat flow database based on the 50 sets of borehole temperature measurement data screened and calculated based on the borehole temperature measurement data of the Kangding Formation of the Linzhi to Ya'an section of the newly built Sichuan-Tibet Railway, and combined the existing data to draw the Terrestrial Heat Flow map of the Kangding area. An assessment of the regional distribution of geothermal energy and heat storage in Kangding County and surrounding areas in Ganzi Prefecture will lay the foundation for the future development of the geothermal energy industry in this region.

II. OVERVIEW

The Ganzi Prefecture is located in the eastern part of the Qinghai-Tibet Plateau and belongs to the Tethys tectonic domain. Due to the convergence-collision-orogeny of the Indian and Eurasian plates, many lithospheric-scale strike-slip, thrust fault zones and volcanic island arcs have been formed. The average altitude is above 4000m in the plateau area [4]. Frequent geological tectonic movements have made the Ganzi area rich in geothermal resources [5].

There are 264 hot spring spots and 17 geothermal wells in Ganzi Prefecture, including 35 hot springs and 13 geothermal wells in Kangding County (the highest water vapor temperature at the well head reaches 198°C), which has high utilization potential.

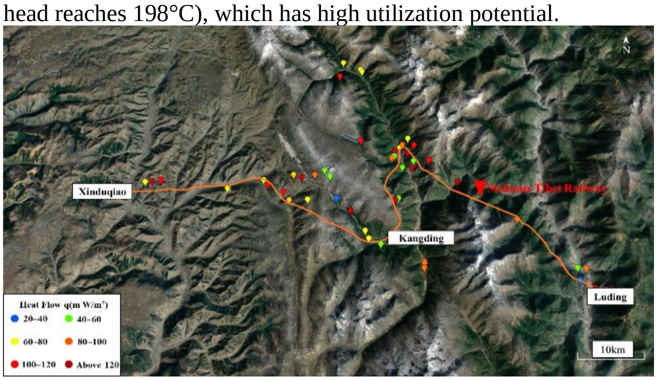

Figure 1 Geographical distribution map of newly increased Terrestrial Heat Flow measurement point

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The new Kangding area of the Nyingchi-Ya'an section of the Sichuan-Tibet Railway is a key control project of the Sichuan-Tibet Railway. During the survey and design stage, a lot of survey work has been done along the line. Therefore, multiple sets of borehole temperature measurement data have been obtained, which is not only for the safety construction of the Sichuan-Tibet Railway, but also provides a data source for understanding the distribution of geothermal energy resources along the line. Figure 1 shows the geographical distribution of new boreholes with temperature measurement.

III. BOREHOLE TEMPERATURE MEASUREMENT AND HEAT FLOW DATA IN KANGDING AREA

The ground heat flow value is defined as the heat flow value through a unit area of the earth's surface per unit time, which is a necessary parameter for evaluating the potential of geothermal energy resources [6]. The study of China’s Terrestrial Heat Flow began in the 1960s when Shanfeng Yi reported three heat flow data in the Northeast Mesozoic basin. In 1979, the Geothermal Group of the Institute of Geology of the Chinese Academy of Sciences officially announced the first batch of 25 Terrestrial Heat Flow data [7]. Wang Jiyang et al. [7-10] successively summarized and updated heat flow data in mainland China, and up to now a total of 1230 sets of heat flow data have been collected.

The China Terrestrial Heat Flow Database ((http://chfdb.xyz/) produced by the Geothermal Resources Research Center of the Institute of Geology and Geophysics, Chinese Academy of Sciences (http://chfdb.xyz/) compiles all currently publicly published data of China’s Terrestrial Heat Flow, and the distribution of existing heat flow data in Sichuan Province (see Figure 2) are mainly distributed in the eastern and southern regions of Sichuan. There are very few data in the northern part and no data in the western part.

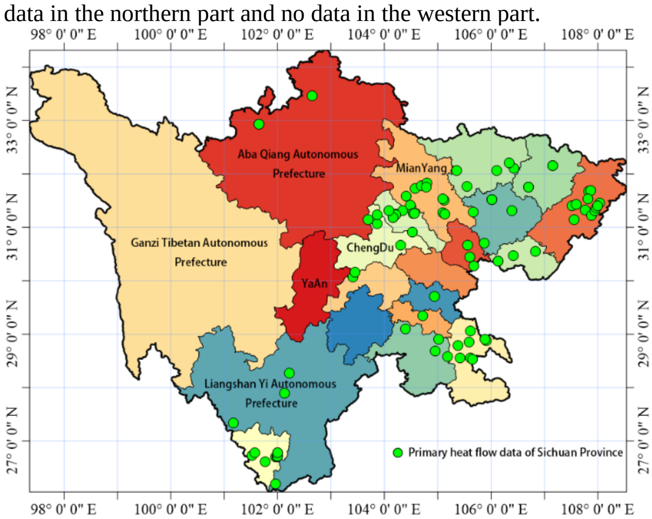

Figure 2. Distribution of existing heat flow data in Sichuan Province

The existing 89 sets of heat flow data in Sichuan Province (see Figure 3) meet the characteristics of normal distribution. The minimum, the maximum, and the average heat heat flow values are respectively $27.4\ \mathrm{mW/m^2}$, $94.7\ \mathrm{mW/m^2}$, and $53.75 \pm 12.24\ \mathrm{mW/m^2}$. Compared with the 4th edition of the statistical results of heat flow in mainland China [7] with average of $61.5 \pm 13.9\ \mathrm{mW/m^2}$, the average of this area is smaller, indicating that the existing heat flow data belong to the middle and low heat flow areas. The high-temperature hot water activity in western Sichuan is rich in geothermal resources, but the utilization rate is less than 8% [11].

On one hand, it is because of inconvenient transportation and sparsely populated people. On the other hand, it is mainly due to the lack of geothermal drilling information. The present research data is mainly derived from the central, eastern, and southern regions of Sichuan province. As consequence, it is impossible to accurately quantify the Terrestrial Heat Flow in the western Sichuan region so as to evaluate the geothermal energy storage.

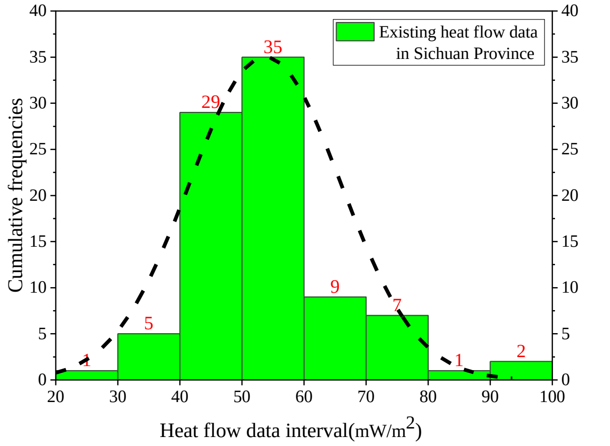

Figure 3. Bar statistics of existing heat flow data in Sichuan Province

The values of the borehole geothermal gradient and rock thermal conductivity are based on the field test results. For a single formation, the relationship between the Terrestrial Heat Flow value and the geothermal gradient and rock thermal conductivity is:

$$q = k\frac{dT}{dx} \tag{0.1}$$

where q is the earth heat flow value, k is the thermal conductivity of the rock, and ${}^{dT}\!/_{dx}$ is the geothermal gradient;

Considering the complexity and diversity of actual engineering geology, the stratum in the borehole cannot be single. The rock thermal conductivity can be calculated according to the weighted average of the thickness of different rock layers in the borehole.

$$k = \sum_i k_i \frac{H_i}{H} \tag{0.2}$$

For a set of borehole temperature measurement data, k_i is the thermal conductivity of the rock, H_i is the stratum thickness, and H is the borehole depth.

The value of rock thermal conductivity refers to the empirical values provided in the "Code for Geological Survey of Geothermal Resources" (GB/T 11615-2010) [12], as shown in Table 1.

Table 1 Rock thermal conductivity

Rock name	Thermal conductivity(W/m℃)
granite	2.721
Limestone	2.010
sandstone	2.596
Sandy clay	0.921

Using the above formula, filtering and calculating on-site data can get 50 sets of heat flow data as shown in Table 2.

Table 2 Newly added Sichuan heat flow data in this article

Numbering	longitude	latitude	Heat flow value（mW / m²）
1	102°12'25.20"	29°55'50.88"	37.80
2	101°56'02.40"	30°05'59.28"	40.50
3	101°55'31.44"	29°59'22.92"	72.90
4	101°38'39.84"	30°03'49.32"	62.10
5	101°55'15.24"	30°07'03.72"	48.60
6	101°51'52.92"	30°08'28.68"	62.10
7	101°48'13.32"	30°05'25.08"	43.20
8	101°47'15.72"	30°05'03.48"	81.00
9	101°45'57.96"	30°04'50.16"	162.00
10	101°45'09.36"	30°05'04.56"	81.00
11	101°42'36.72"	30°04'12.00"	110.00
12	101°49'22.80"	30°02'52.44"	34.56
13	102°13'18.48"	29°56'44.16"	86.50
14	102°12'26.64"	29°56'48.48"	42.39
15	102°06'56.88"	30°00'59.76"	86.40
16	102°01'30.00"	30°04'39.36"	180.90
17	101°58'40.44"	30°06'32.04"	116.30
18	101°56'38.76"	30°07'21.36"	133.00
19	101°57'16.92"	30°08'04.56"	115.00
20	101°56'43.44"	30°08'49.20"	64.80
21	101°56'08.88"	30°08'13.56"	83.70
22	101°57'12.24"	30°06'39.24"	32.40
23	101°57'03.24"	30°06'02.88"	170.10
24	101°55'53.40"	30°08'00.60"	67.50
25	101°55'21.72"	30°07'50.88"	197.10
26	101°54'59.40"	30°06'49.32"	97.20
27	101°55'09.12"	30°02'42.00"	175.50
28	101°55'27.48"	30°02'53.88"	51.30
29	101°46'34.32"	30°02'40.92"	62.10
30	101°44'09.60"	30°03'32.40"	110.70
31	101°52'06.96"	29°59'58.92"	74.25
32	101°52'26.76"	29°59'18.24"	67.50
33	101°44'44.88"	30°02'42.72"	91.80

34	101°42'10.44''	30°04'40.08''	74.25
35	101°48'45.00''	30°04'51.96''	45.90
36	101°50'43.80''	30°01'44.04''	145.00
37	101°33'05.76''	30°04'44.76''	54.00
38	101°32'00.60''	30°04'43.68''	108.75
39	101°31'04.80''	30°04'37.92''	132.30
40	101°30'25.20''	30°04'32.52''	75.60
41	101°53'33.72''	29°58'44.40''	56.70
42	101°57' 50.04''	29°57' 14.76''	79.89
43	101°57' 50.04''	29°57' 14.76''	82.12
44	101°57' 37.80''	29°56' 43.08''	73.85
45	101°57' 50.04''	29°57' 06.84''	82.22
46	101°52' 04.80''	30°16' 13.80''	77.36
47	101°50' 15.36''	30°16' 56.64''	78.50
48	101°50' 15.36''	30°16' 58.08''	77.56
49	101°52' 13.80''	30°15' 58.32''	74.94
50	101°13' 15.24''	30°51' 10.44''	87.16

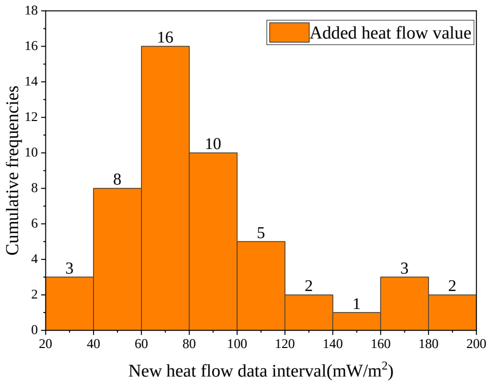

Figure 4 Newly added bar graph of heat flow data

IV. HEAT FLOW MODELING

In recent years, with the rapid development of Geographic Information System (GIS), spatial interpolation methods have been widely used. Among them, Kriging Interpolation is the most widely used.

Kriging interpolation (Kriging), also known as spatial local interpolation [15], is a method of unbiased optimal estimation of regionalized variables in a limited area based on the theory of variogram and structural analysis. One of the main contents of statistics, which is widely used in rainfall distribution, petroleum engineering, hydrology, meteorology, geology and other fields.

Based on the newly added 50 sets of heat flow data in this paper and the existing heat flow data in Sichuan Province and surrounding areas, Surfer commercial software is used to complete the drawing of heat flow maps in this paper.

A. Heat flow data collection

In order to avoid the influence of the interpolation boundary error on the heat flow inversion, we collected 400 sets of heat flow data in Sichuan and surrounding areas(see Figure 5). In Sichuan Province, there are 89 sets of existing heat flow data and 50 sets of new data, for a total of 139 sets of data.

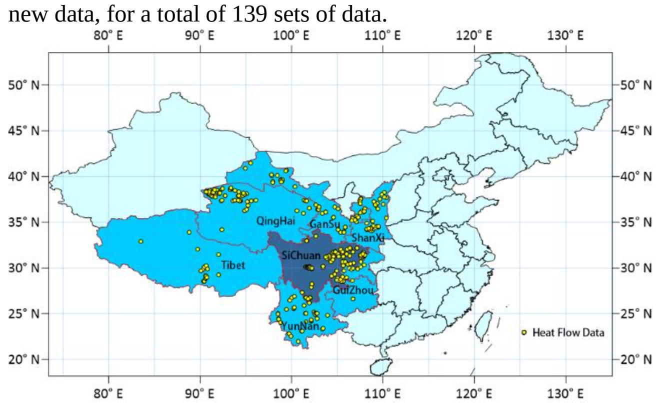

Figure 5 Heat flow data distribution map

B. Verification of the correctness of the interpolation method

In order to verify the accuracy of the Kriging interpolation method, we firstly draw the heat flow map of the China area and compare it with previous work.

The data for drawing China's Terrestrial Heat Flow map comes from the official website of the International Heat Flow Commission (IHFC). The latest database shows that China has 1621 sets of heat flow data. Figure 6 shows the use of Surfer to map the terrestrial heat flow in China and the Terrestrial Heat Flow map drawn by surfer can be seen in Figure 6.

By comparing with the heat flow map drawn by Jiang et al. [16, 17], the overall distribution characteristics and the heat flow distribution characteristics in the structural geological zone in this paper are basically the same as the previous work. Such as Qinghai The Republic Basin, the Guangdong-Hong Kong-Macao Greater Bay Area, the Asia-Europe plate-Pacific plate, and the Asia-Europe plate-Indian Ocean plate junctions have obvious high heat flow area characteristics, which also verifies the accuracy of the heat flow mapping method in this paper.

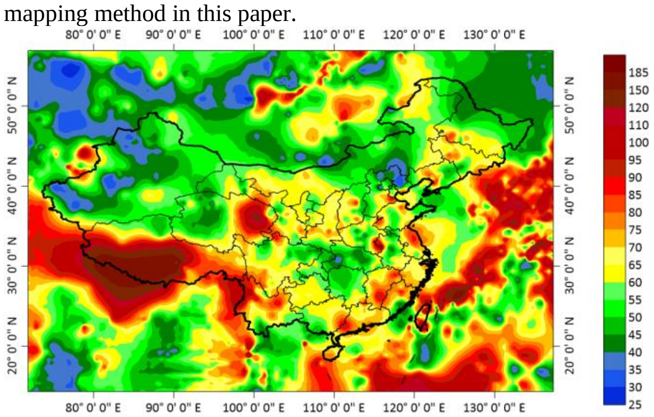

Figure 6 Terrestrial Heat Flow map in China mainland

C. Heat flow data plotting

The land-continent collision of the India-Eurasian plate is the main cause of the intense crustal activity and abnormal regional heat flow on the Qinghai-Tibet Plateau. The Western Sichuan Plateau is affected by the global geological structure and the accompanying regional fault structures, giving the Western Sichuan Plateau a tectonic background and geothermal conditions that give birth to intense hydrothermal activity. Figure 7 shows the distribution of hot springs along the fault zone in the Western Sichuan region.

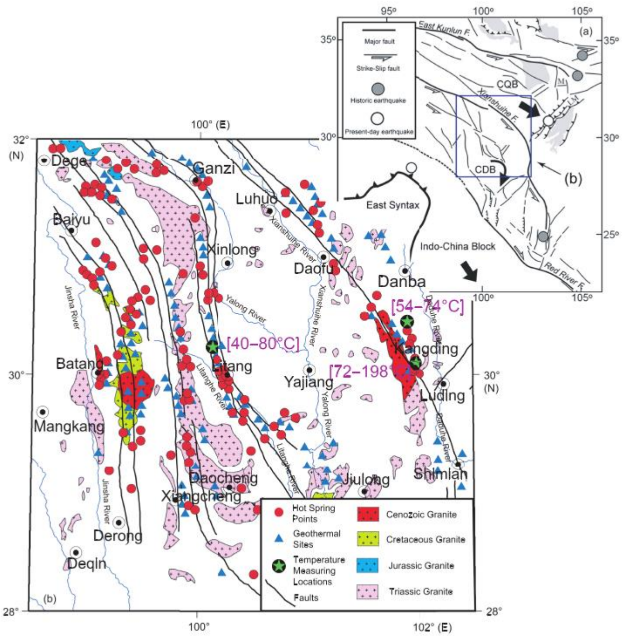

Figure 7 Geothermal geological map of western Sichuan [11]

Using the Kriging interpolation method, in order to improve the accuracy of the interpolation results, the raster data spacing is set to $0.1^{\circ} \times 0.1^{\circ}$, and the Terrestrial Heat Flow map of Sichuan Province and Kangding area is drawn as shown in Figure 8 and Figure 9.

From the inversion results of the Terrestrial Heat Flow in Sichuan Province, Fig. 8 shows that the Terrestrial Heat Flow in Sichuan Province is decreasingly distributed from west to east, and is obviously higher in the west and lower in the east. The areas of high heat flow are mainly distributed in Derong, Xiangcheng, Daocheng in the southwest and along the northwest. It is spread near the deep fault zone area.

Due to the land-continent collision of the Cenozoic India-Eurasian plate along the Yarlung Zangbo suture zone and the magmatism of the Mediterranean-Himalayan geothermal activity zone, resulting in a high heat flow distribution in the southwest of Sichuan Province. And there is a long-range diminishing effect of heat transfer from the east structural junction along the north-east direction. But it does not continue to decrease, because the Xianshuihe, Ganzi-Litang, Dege-Xiangcheng, Jinshajiang, and Batang fault zones are still affected in western Sichuan. It shows that the deep fault zone is the main controlling factor of the geothermal anomaly area in western Sichuan [11].

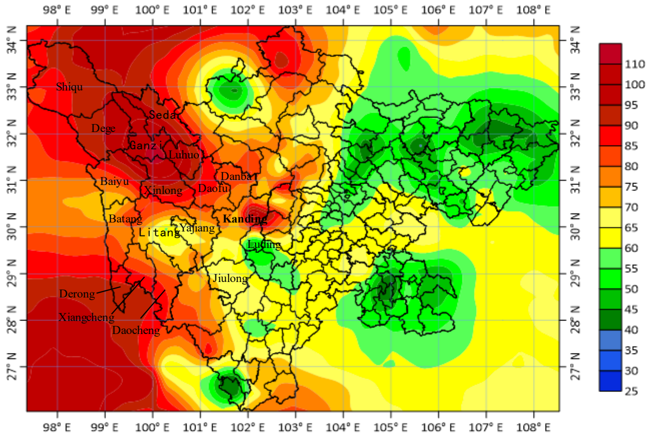

Figure 8 Terrestrial Heat Flow map of Sichuan Province

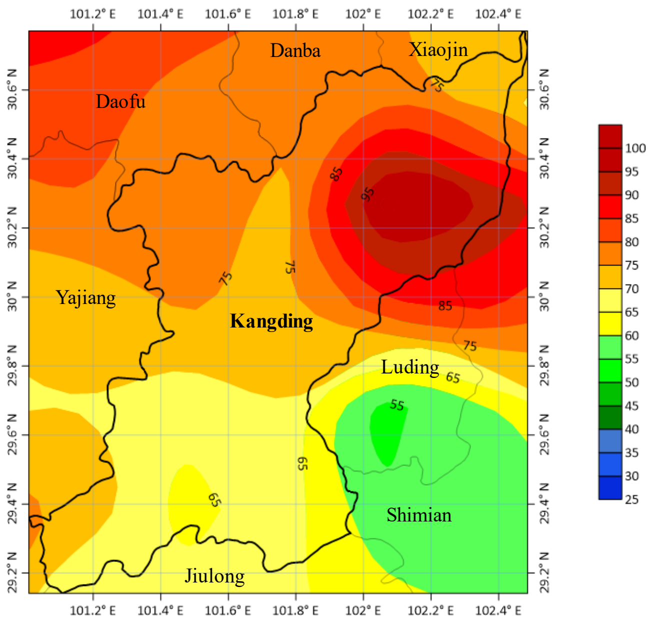

Figure 9 Terrestrial Heat Flow map in Kangding area

V. EVALUATION OF GEOTHERMAL POTENTIAL IN KANGDING AREAS

Analyzing the heat flow map of Kangding County, we can find that the Terrestrial Heat Flow values of Kangding County vary from 64 to 101, which are higher than the original average heat flow data of Sichuan Province ($53.75 \pm 12.24\ mW/m^2$), the average heat flow value of mainland China ($61 \pm 15.5\ mW/m^2$) and the global average heat flow value. ($65 \pm 1.6\ mW/m^2$) [13]. The overall heat flow value is high, and it has the potential for geothermal exploitation. The heat flow value in the north is higher than that in the south, and reaches the highest value of $101\ mW/m^2$ in the northeast of Kangding. The Kangding County is affected by the Xianshuihe fault zone, which is a deep and large high-temperature shear zone and characterized by intense hydrothermal activity, high geothermal gradient and high heat flow, inducing high heat flow value of this area.

Daofu County, Danba County and the northeastern part of Kangding County are all located nearby the Xianshuihe fault zone. The heat flow value is high and distributed along the northwest. The heat flow value ranges from 75~101 mW/m^2, and the heat flow value reaches the highest value of 101 in the northeast of Kangding County. The heat flow value of Xiaojin County, which borders the northern part of Kangding County, ranges from 72~ 77 mW/m^2. The heat flow value of Yajiang County, which borders the eastern part of Kangding County, ranges from 70~80 mW/m^2. The Jiulong County, which borders the southern region of Kangding County, the Luding County, which borders the central region, and the Shimian County presents the phenomenon of long-distance decline in heat transfer from east to east, with heat flow values ranging from 54~64 mW/m^2. In the southern part of Luding, the lowest heat flow is 54 mW/m^2. The result shows that the heat flow distribution in Kangding area is significantly affected by regional tectonic effects and high heat flow areas. The formation of the zone is the result of the combined effect of the East structure and the Xianshuihe fault zone.

The heat flow in the Xianshuihe fault zone is significantly higher, indicating that the Xianshuihe fault zone is the main reason for the formation of the high heat flow zone according to the above earth heat flow values. The distribution characteristics provide the evidence that it has good potential to exploit and utilize the geothermal resources in Kangding area.

VI. CONCLUSION

In this paper, by processing the borehole data in the geological survey report of the Kangding area of the Sichuan-Tibet Railway, 50 sets of high-quality data are initially obtained. Based on the newly added heat flow data, a heat flow map of Sichuan Province and Kangding area was drawn. The following conclusions can be drawn from the work done:

1) The average heat flow value in the Kangding area is 86.96 ± 39.73 mW/m^2 obtained from the borehole temperature data of Sichuan-Tibet Raiway geological survey.

2) The high heat flux zone is distributed along the northwest of Kangding area. The terrestrial heat flow value of Kangding County ranges from 64~101 mW/m^2 with the highest value of 101 mW/m^2 in the northeast Kangding County.

3) The formation of the high heat flux zone in Kangding area is the result of the joint action of the Xianshuihe fault zone and the eastern structure junction. Due to the diminishing effect of the heat transfer of the east structure junction, the high heat flow zones are mainly distributed along the northwest, and the active Xianshuihe fault zone is the main reason for the formation of the high heat flow zones in Kangding County and its surrounding areas.

The above opinions on the exploitation and utilization of geothermal energy resources in different areas of Sichuan Province need to be specifically investigated in conjunction with the specific local engineering geological conditions, which is also the work to be done in future.

VII. ACKNOWLEDGEMENTS

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