Heat flow and deep temperature of the Kuqa foreland basin, northwestern China

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ABSTRACT

Geothermal regime of sedimentary basins plays a key role in understanding basin (de)formation process and assessing hydrocarbon and geothermal energy resources, and has attracted increasing attention from academia and industry. Here we investigated the geothermal regime of the Kuqa foreland basin, located between the northern Tarim Craton and southern Tianshan Mountain, northwestern China, with the formation temperature data and newly measured thermal properties. The geothermal gradient of the KFB is between 14.8℃/km-29.0℃/km, with a mean of 22.6±3.2℃/km, and the heat flow ranges from 27.4mW/m^2 to 55.6mW/m^2, with an average of 42.2±6.5 mW/m^2. Generally, the present-day geothermal pattern of the Kuqa foreland basin is characterized by high in the north and low in the south, decreasing from the foredeep to the forebulge. We infer that this geothermal pattern of the KFB is affected by the continued Cenozoic convergence between the Tarim Craton and Tianshan Mountain.

1. INTRODUCTION

Geothermal regime of sedimentary basins is controlled by basin tectonic evolution and lithospheric deep processes, and plays an important role in oil and gas generation, migration and accumulation. The determination of heat flow has been a long-lasting topic in the study of petroleum geology since 1980s (Wang and Shi, 1989; Hu and Wang, 1995). Investigating the geothermal regime of sedimentary basins does not only contribute to hydrocarbon resource and geothermal energy assessment, but also could provide constraints on the analysis of the tectonics, thermal processes and formation mechanism of basins (Liu et al., 2016; Qiu et al., 2004; Wang and Shi, 1989).

Tarim Basin, located between the Tibetan Plateau and Tianshan Mountain, is the largest petroliferous sedimentary basin in China, and a number of oil and gas fields have been discovered there during the past decades. It is now the target area for deep and ultra-deep marine hydrocarbon exploration. Owing to the importance of the thermal condition of the basin for hydrocarbon generation and preservation, previous works have been carried out on the geothermal field of the Tarim Basin, and a large quantity of thermal data has been accumulated. The geothermal gradient of this basin is 20-25℃/km, while the heat flow is about 40-45 mW/m^2, indicative of lower in heat flow and cooler in temperature in geothermal regime (Wei, 1992; Zhang and Liu, 1992; Xie, 1993; Wang et al. 1995a, b, 2003, 2005), but the Kuqa Depression, in the northern Tarim Basin, shows a relatively high geothermal background (Wang et al., 2003; Feng et al., 2009). However, the foreland basins worldwide generally show low thermal state owing to their rapid sedimentation and thick sediment filling, the geothermal gradient of typical foreland basins is generally 22-24 °C / km and the average heat flow is about 40 mW/m^2 (Scheck-Wenderoth, 2011； Allen and Allen, 2013; Springer and Förster et al., 1998; Deming and Chapman, 1988; Weides and Majorwicz, 2014; Vigano et al., 2011). So, it naturally raises a question: is the geothermal regime of the Kuqa foreland basin unique? Given the poor heat data coverage and the quality control as well, this apparent heat flow paradox in the Kuqa foreland basin needs further investigation, and the mechanism for this thermal anomaly is still open (Feng et al., 2009, Liu et al., 2015). Thanks to rapid expanding of hydrocarbon exploration in the Kuqa basin, new temperature loggings are increasingly available, enabling an opportunity to revisit the geothermal regime of this basin.

Here we combined the newly acquired geothermal logging with previous data, to investigate the geothermal gradient and heat flow pattern of the Kuqa foreland basin, and then estimated the subsurface temperatures at the depths of 1000-5000 meters for this basin as well. In addition, the major factors that control the geothermal regime of the Kuqa foreland basin are further discussed.

2. GEOLOGICAL SETTING

The Kuqa depression lies on the northern margin of the Tarim Basin, to the north is the Tianshan Mountain (Fig. 1). Given the emplacement between the basin and mountain interactions, the Kuqa depression shows the tectonic characteristics of foreland basins and was affected by the convergence between the Tarim plate and Tianshan Mountain (Jia et al., 1992; He et al., 1996; Lu et al., 1994; Lu et al., 1996; Chen et al., 1996; Graham et al., 1993; Wang et al., 1994). Accordingly, the Kuqa Depression is termed as a foreland basin in literature, and is an important oil and gas production area of the Tarim Basin.

The Kuqa foreland basin has experienced a long and complex geological history of tectonic evolution. In the Precambrian, the northern margin of the Tarim plate underwent extension to form a passive continental margin. In the Silurian, the Southern Tien Shan region spread to form an oceanic crust and the Ili Block separated from the Tarim plate. At the end of the period, the Southern Tien Shan Ocean subducted towards the Middle Tien Shan (Che et al., 1994; Guo et al., 1993; Lu et al., 1994). In the Late Devonian, the Tarim plate subducted northwards. From the Carboniferous to the Early Permian, the remnant ocean basin to the north of the Tarim Plate closed and the Tarim Plate collaged with the Ili Block. In the Late Permian, the Tarim plate subducted towards the Ili Block, forming the Kuqa foreland basin on the southern edge of the Southern Tianshan Mountains (Lu et al., 1996). Along with the continuous orogenic process, the wedge moved towards the foreland and the sedimentation continued, and the northern Tarim basin evolved into a foreland basin in the early Jurassic (He et al., 1994).

At the end of the Eocene, the Indian plate collided with the Eurasian plate, led to a far-field stress effect (Monlar and Tapponnier, 1975; Guo et al., 1992). By the late Oligocene, the collisional stress had been transferred to the northern margin of the Tarim Basin, resulting in the rejuvenation of the Paleozoic collisional orogenic belt in the northern part of the Tarim Basin, and the Kuqa area and its adjacent areas had entered the evolutionary stage of the rejuvenated foreland basin (Liu et al., 2000).

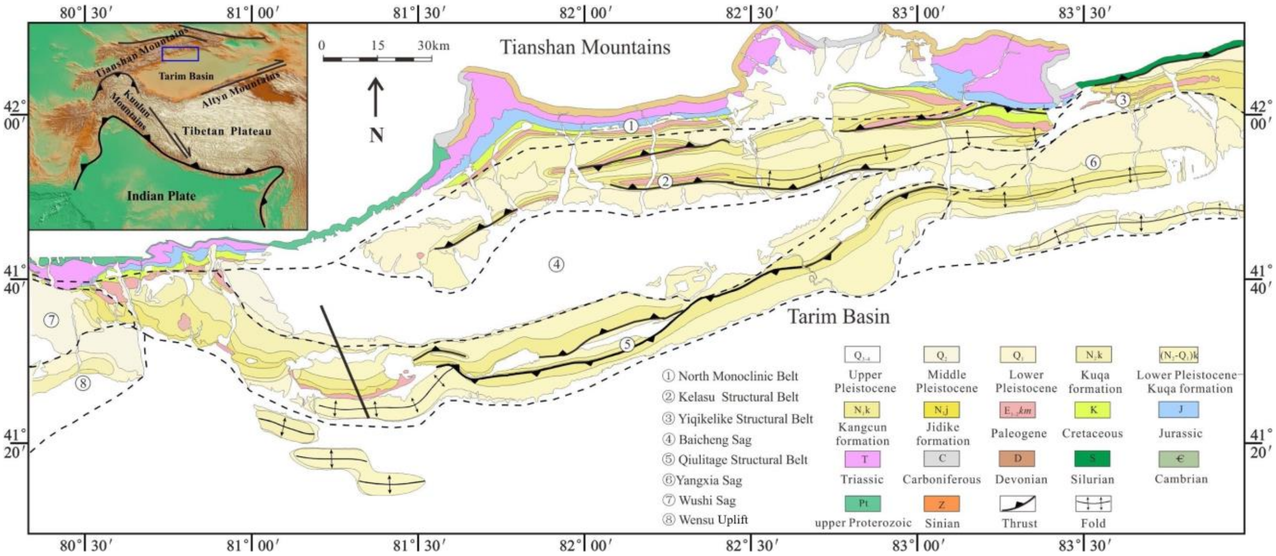


Figure 1: Sketch showing the tectonic subdivision of the Kuqa foreland basin (Modified by Neng et al., 2018)

3. METHOD AND DATA

3.1 Thermal properties

In the study, a number of core samples were collected from the wells of the Kuqa foreland basin and its adjacent areas for thermal conductivity measurements. In addition, we also compiled previous thermal conductivity data for better coverage (Wang et al., 1995a; Wang et al., 2005). A total of 215 thermal conductivity data were used in this study, covering different rock types such as sandstone, mudstone, granite, dolomite, coal, shale, limestone, conglomerate and claystone.

As shown in Figure 2 and Table 1, dolomite has the largest average thermal conductivity of 4.10 ± 0.16 W/m·k, while the granite has an average thermal conductivity of 2.13 ± 0.19 W/m·k. For the limestone, the average thermal conductivity is 2.87 ± 0.69 W/m·k, and that for the conglomerate is 2.78 ± 0.75 W/m·k, 2.11 ± 0.04 W/m·k for the mudstone, 2.22 ± 0.61 W/m·k for the sandstone, and 2.17 ± 0.80 W/m·k for the claystone. Coal has the lowest mean thermal conductivity of 0.32 ± 0.04 W/m·k, and that of the shale is also relatively low and 1.57 ± 0.44 W/m·k.

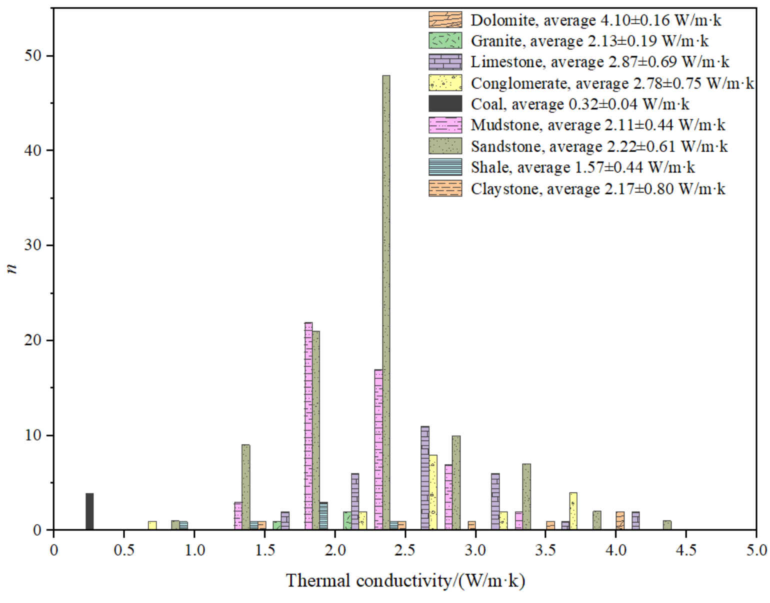


Figure 2: Histogram of thermal conductivities in the Kuqa foreland basin

Table 1: Thermal conductivities for different rocks in the Kuqa foreland basin

Lithology	Well	Numbers	Thermal conductivity(W/m·k)
Dolomite	TC1	3	4.10 ± 0.16
Granite	TC1	3	2.13 ± 0.19
Limestone	TC1、LN5、LN46	29	2.87 ± 0.69
Conglomerate	TC1、LN5、LN46、KL2	17	2.78 ± 0.75
Coal		4	0.32 ± 0.04
Mudstone		51	2.11 ± 0.44
Sandstone	TC1、LN5、LN46、KL2、H1	99	2.22 ± 0.61
Shale		6	1.57 ± 0.44
Claystone		3	2.17 ± 0.80

3.2 Temperature data and geothermal calculation

Geothermal gradient (dT/dZ) refers to the growth rate of formation temperature with depth, in the unit of ℃/km. A total of 416 temperature data at different depths from 64 drilling wells in the Kuqa foreland basin were used (Fig. 3). The vertically average geothermal gradient (G in °C/km) within the depth of Z (km) with a temperature of T (°C) is calculated as follows:

$$G = \frac{T - T_0}{Z} \tag{1}$$

T_0 here refers to the annual average air temperature of Xinjiang area and is taken as 12℃ here (Wang et al., 2003).

For boreholes with abundant temperature measurements, the geothermal gradient can be obtained by linear fitting of the least square method. With the application of the inverse distance interpolation in the ArcGIS software, the distribution pattern of the geothermal gradient in the Kuqa foreland basin is given in the Fig. 3.

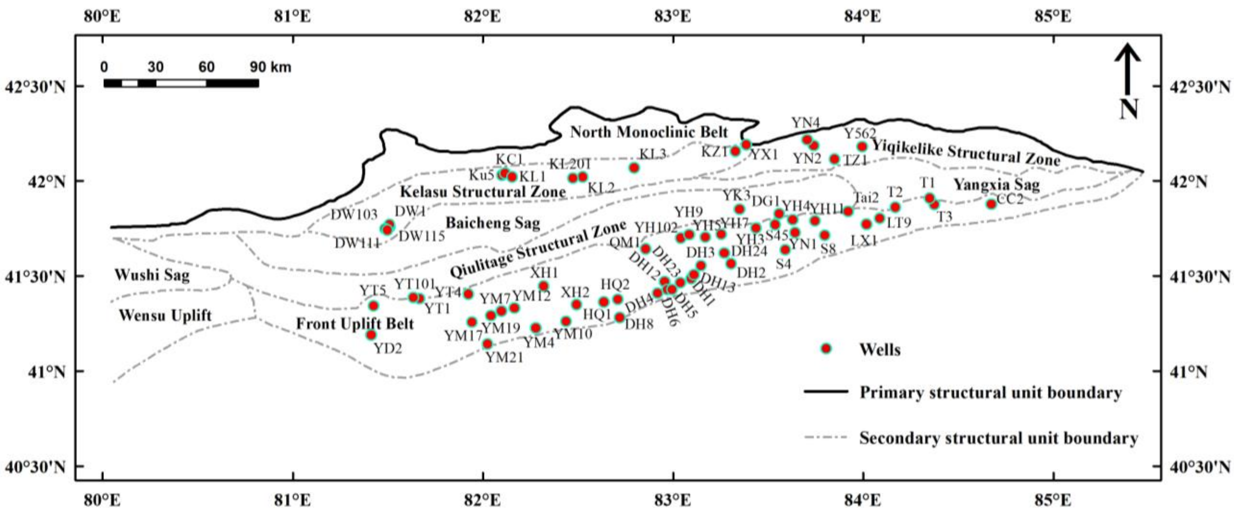


Figure 3: Boreholes with temperature data of the Kuqa foreland basin

Based on the geothermal gradient in the Kuqa foreland basin, we can estimate the temperatures of the deep formation within the basin to characterize the geothermal field of this area. The subsurface formation temperature (T_g in °C) at a given depth of Z_g (km) can be predicted:

$$T_g = \mathrm{G} \times Z_g + T_0 \tag{2}$$

Where T_0 is taken as 12 ℃, and the average geothermal gradient is mentioned above.

4. GEOTHERMAL PATTERN

4.1 Geothermal gradient distribution

Generally, the present-day geothermal gradient in the Kuqa foreland basin region is between14.8 and 29 ℃/km (Fig. 4). Among them, the wells XH1 and XH3 in the southern Kuqa foreland basin have the lowest geothermal gradient of 14.8 and 15.5 ℃/km respectively, while the DW1, KL3, DW111, TZ1 in the northern basin have the highest geothermal gradient, about 28.3-29.0 ℃/km. Generally, the geothermal gradient of the southern part of the basin (including the Qiulitage Structure Zone and Front Uplift Belt) is between 14.8 and 25.8 ℃/km, averaging 21.5 ℃/km, while the geothermal gradient of the northern part of the basin (including the North Monoclinic Belt, Kelasu Structure Zone, Yiqikelike Structure Zone and Baicheng Sag) reaches 21.9-29.0 ℃/km, averaging 25.9 ℃/km. As shown in the figure 4, the geothermal gradient in the Kuqa foreland basin is characterized by lower in the south and higher in the north, suggesting that the geothermal gradient decreases gradually from north to south.

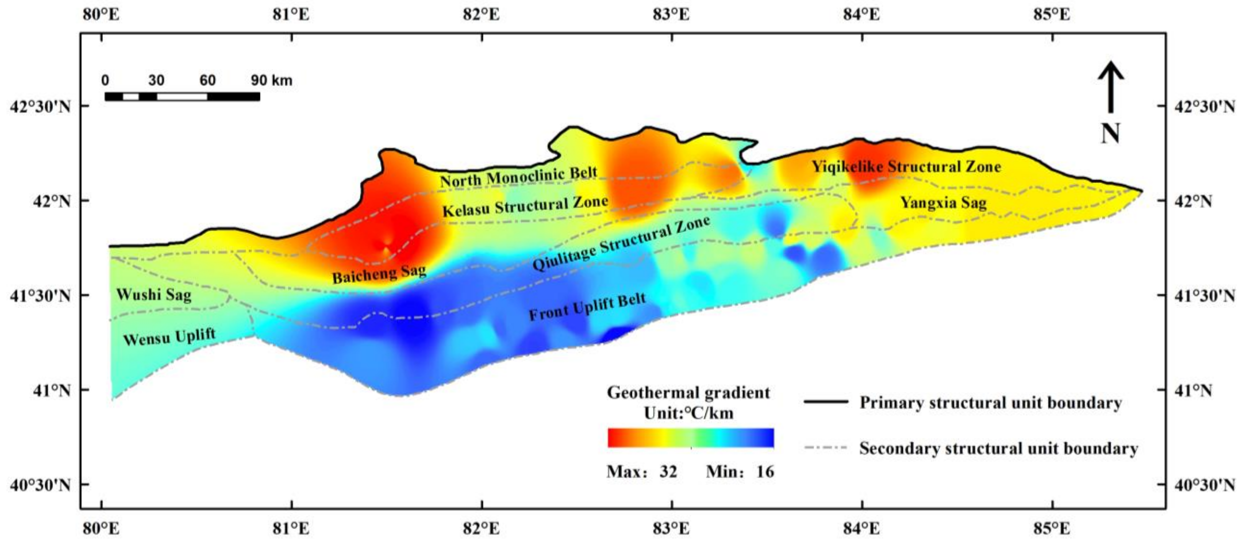


Figure 4: Present-day geothermal gradient pattern in the Kuqa foreland basin

4.2 Heat flow distribution

We compiled heat flow data from a total of 43 wells in the Kuqa foreland basin available (Feng et al., 2009; Liu et al., 2015; Wang et al., 1995a; Wang et al., 1995b; Wang et al., 2005) and some new data (Wu et al., 2022), to outline the spatial pattern in this basin (Fig.5). The heat flow in the Kuqa foreland basin ranges from 27.4 to 56.1 mW/m^2, with an average of 42.8 mW/m^2. Among them, the XH1 and XH3 in the southern part of the Kuqa foreland basin show the lowest heat flow of 27.4 and 27.6 mW/m^2 respectively, while the Ku5 in the northern part of the basin have the highest heat flow of 55.6 mW/m^2.

Interestingly, the spatial distribution of heat flow also shows a similar trend with the geothermal gradient. The heat flow of the southern part of the basin is between 27.4 and 52.4 mW/m^2, averaging 41.1 mW/m^2, while the heat flow of the northern part of the basin ranges from 40.9 to 55.6 mW/m^2, with a mean of 47.6 mW/m^2. As shown in the figure 5, relatively high heat flow areas mainly occur in the North Monoclinic Belt, Kelasu Structure Zone, Yiqikelike Structure Zone and Baicheng Sag. Similar to the above, the heat flow in the northern part of the Kuqa foreland basin is high as a whole, while that in the southern part is generally low (Fig. 5). The heat flow of the Kuqa foreland basin also decreases from north to south gradually.

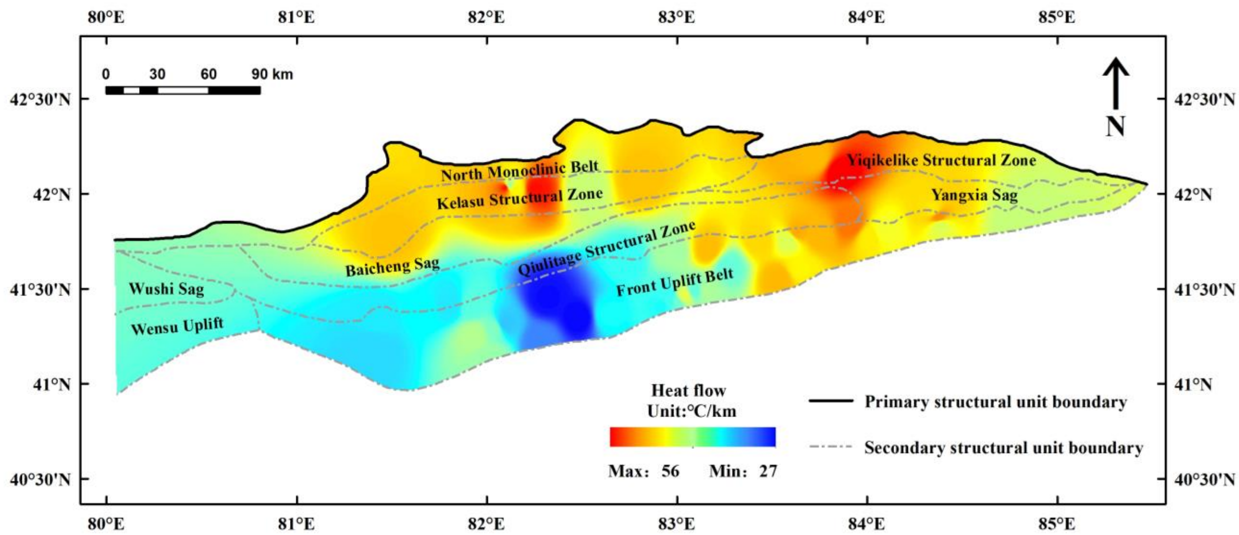
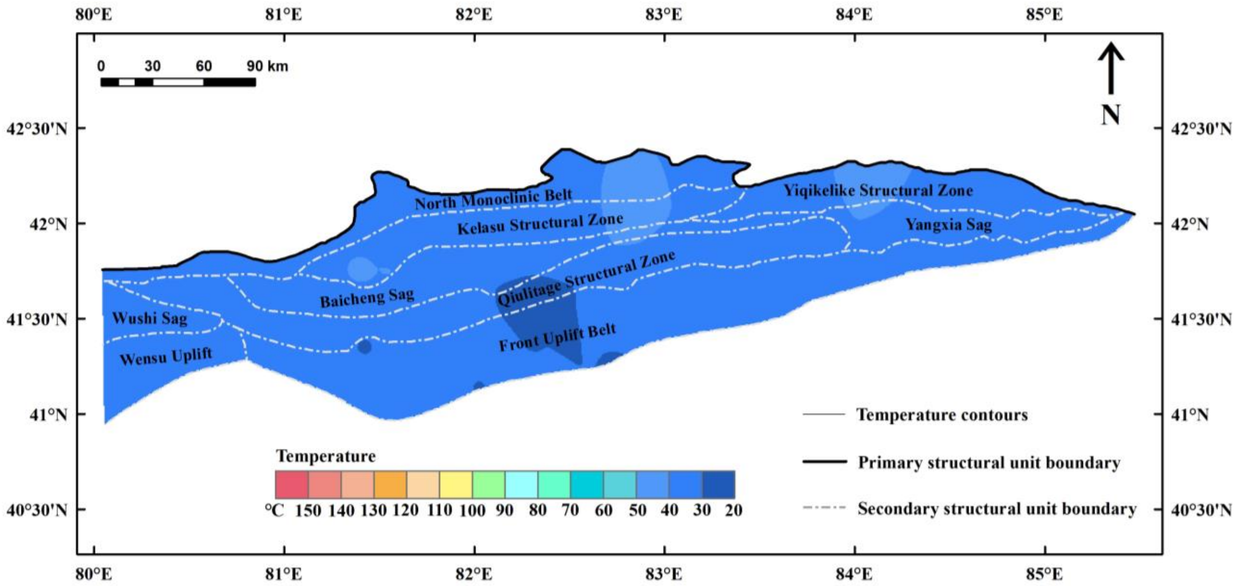


Figure 5: Spatial pattern of the present-day heat flow in the Kuqa foreland basin

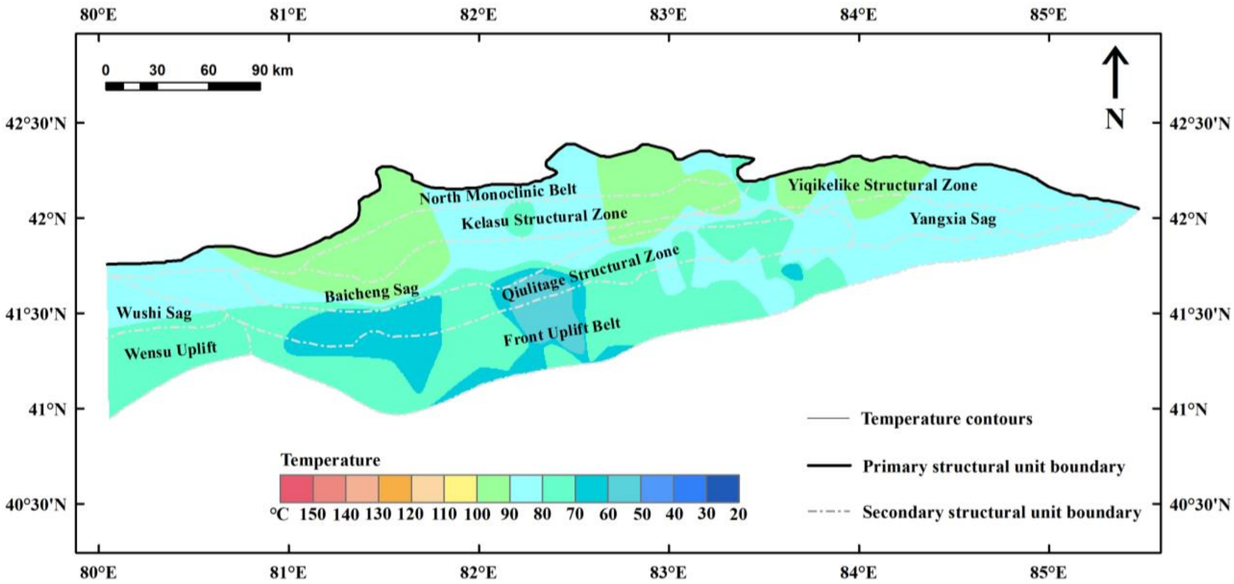
4.3 Estimated temperatures-at-depth

The temperatures at the depth of 1000, 3000 and 5000 m in the Kuqa area with inverse distance interpolation are presented in the Fig. 6. Among them, the temperatures at 1000 m depth are between 27 and 41 ℃, and 56 to 99 ℃ at 3000 m, 86 to 157 ℃ at 5000 m. In a word, the formation temperature increases with the depth, which reflects the influence of burial depth on temperature field. While the lateral variation in deep temperature pattern reflects the control of the difference of the geothermal gradient.

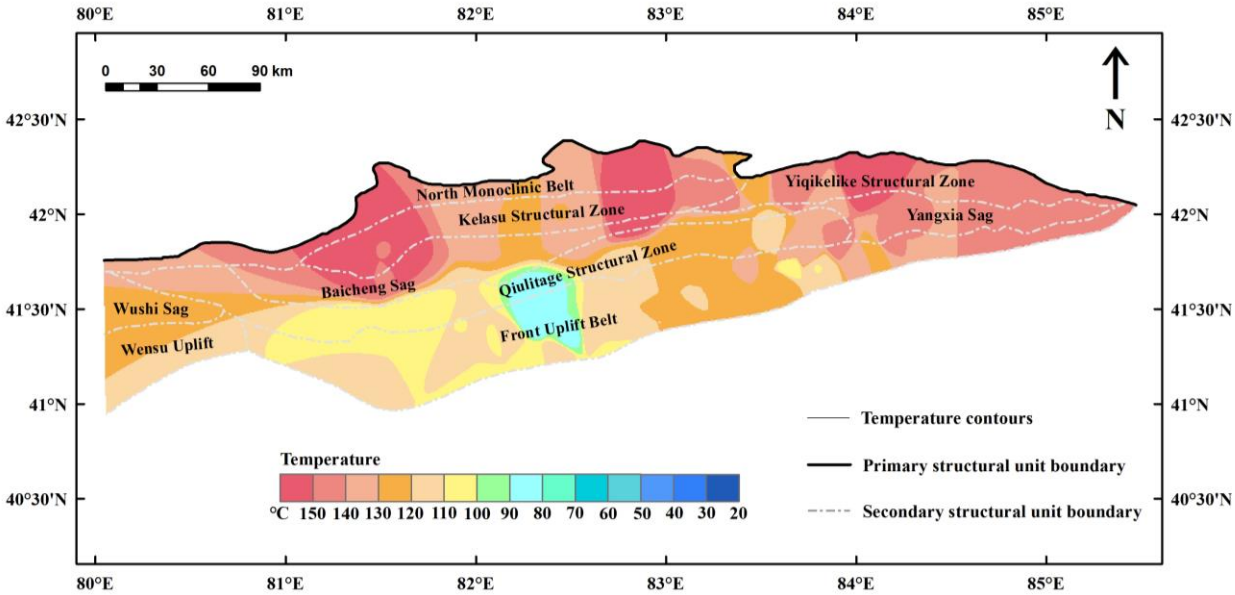
It is found that the high temperature areas are mainly concentrated in the northern part of the basin, while the southern areas are relatively cold (Fig. 6). The average estimated temperatures in the northern basin at the depth of 1000, 3000 and 5000 meters are 38, 90 and 142 °C respectively, while those of the southern region are 34, 76, 119 ℃, with a temperature difference of about 4-22 °C at the same depth.



(a) estimated temperature at the depth of 1000m



(b) estimated temperature at the depth of 3000m



(c) estimated temperature at the depth of 5000m

Figure 6: estimated temperatures-at-depths in the Kuqa foreland basin

5. DISCUSSION

5.1 Geothermal characterization of the basin

The Kuqa foreland basin is a cool basin with low temperature in geothermal regime. As shown in the former section, the geothermal gradient of the Kuqa foreland basin is between 15~29℃/km, with a mean of 23℃/km, while the heat flow ranges from 27mW/m^2 to 56mW/m^2, and the mean is 43 mW/m^2. Comparing with other sedimentary basins in China, the geothermal regime of the Kuqa foreland basin is relatively low, it is a cool basin with low temperature (Table 2). However, the geothermal regime of the Kuqa foreland basin is slightly higher than other sub-units of the Tarim Basin, and the heat flow of the basin decreases from the north (foredeep) to the south (forebulge).

It should be mentioned that the data coverage and the quality control are much improved in this study, and the updated geothermal regime of the Kuqa foreland basin represent the best one till now. However, it seems belong to the geothermal regime of the typical foreland basins in the world, with the geothermal gradient of 22-24 °C / km and the average heat flow about 40 mW/m^2 (Scheck-Wenderoth, 2011； Allen and Allen, 2013). In addition, the Kuqa foreland basin also shares similar thermal states of other foreland basins in China (Lu et al., 2005a; Xu et al., 2011; Wang et al., 2000; Rao et al., 2013;). Accordingly, the heat flow of the Kuqa foreland basin is not larger than that of other basins as expected in previous studies. We still need more data to confirm the geothermal regime of this basin, given limited data coverage in the northern area.

Table2 Compilation of geothermal data for the major sedimentary basins in China

Depth/m	**Formation temperature/℃**					
	Kuqa Basin	Tarim Basin	Songliao Basin	North China Basin	Ordos Basin	Sichuan Basin
1000	27~41	29~41	40~50	40~45	35~40	35~45
2000	42~70	46~71	70~80	70~80	60~70	60~70
3000	56~99	63~100	90~110	90~100	90~100	90~100
Thermal gradient /(℃/km)	15~29	15~30	35~40	34~35	28~30	24~25
Heat flow/(mW/m^2)	27~56	26~66	51~90	30~90	43~70	50~80
References	This study	Liu et al., 2016	Wang et al., 1994; Jiang et al., 2016	Wang et al., 1994; Zhang et al., 2007	Wang et al., 1994; Ren et al., 2007	Wang et al., 1994; Sun et al., 2022

5.2 Mechanism for the geothermal characterization of the basin

The decline in heat flow from the north of the Kuqa foreland basin to the south, that is from the piedmont to the interior of the basin, is probably related to the Cenozoic convergence between the Tarim Basin and the Tianshan Mountains. Seismic observations show that the lithosphere of the Tarim Basin underthrusts northward the South Tianshan Mountain (Gao et al., 2013; He et al., 2017; Lu et al., 2000; Lu et al., 2005b; Mi et al., 2005), and the GPS observation and seismic profile interpretation also demonstrate that a rapid convergence between them (Li et al., 2019). This is the result of the far-field effects of the Cenozoic India-Eurasian continental collision (Molnar and Tapponnier, 1975; Guo et al., 1992), and associated uplift of the southern Tianshan leads to strong deformation in the basin and range interactive zone. The friction heating during the underthrust process contributes to the observed high heat flow in the piedmont zone, and the exhumation of the basement also could regulate the heat flow pattern within the basin.

In addition, the Tarim Basin is thermally cold and rheologically rigid, given the low heat flow condition (Wang et al., 1996; Wang et al., 2000), which indicates that it could keep tectonically stable during the far-field collisional process. So, the Cenozoic basin and mountain interaction only limits to the edge of the basin, and the deformation gradually weakens from the piedmont zone to the interior, coincident with the variation in heat flow of the Kuqa foreland basin.

6. CONCLUSIONS

The Kuqa foreland basin has a mean geothermal gradient of 23 ℃/km and a mean heat flow of 42 mW/m^2, the estimated temperature at the depth of 1000 meters is 27-41 ℃, 56-99 ℃ at 3000 meters, 86-157 ℃ at 5000 meters. Comparing with other sedimentary basins in China and foreland basin worldwide, the Kuqa foreland basin is a cool basin with low temperature.

Geothermal regime of the Kuqa foreland basin show obvious contrast between the north and south, and a gradual decline in heat flow from the piedmont zone (north) to the interior (south) is observed. This variation is the result of the basin-mountain interaction process associated with the far field effects of the Cenozoic Indian-Eurasian continental collision.

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