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Thermal Lithospheric Thickness of the Sichuan Basin and its Geological Implications

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Abstract: Thermal lithospheric thickness is an important parameter in studying the tectonic-thermal evolution of basins and plate dynamics. Based on the measured geothermal data and thermophysical properties of the rocks, the thermal lithospheric thickness of the Sichuan Basin was calculated according to the principles of heat conduction in the crust and lithospheric mantle. The calculation results revealed that the thickness of the thermal lithosphere in the Sichuan Basin is 140–190 km and is unevenly distributed. The thickness of the thermal lithosphere in central Sichuan and southwestern Sichuan is less than 160 km, while that in the western Sichuan depression and eastern Sichuan is larger (~180 km). The distribution of the thermal lithospheric thickness in the basin has a good correlation with the geological units and the thickness of the sedimentary layers. The thickness of the thermal lithosphere in the depression area, which has thick sedimentary layers and the fault-fold zone with shallow crustal deformation and thickening, are larger than that in the basement uplifted area, which has thin sedimentary layers. The calculated thermal lithospheric thickness is in good agreement with the geophysical data and reflects the stable conduction temperature field in the Sichuan Basin. The present thermal regime and thermal lithospheric thickness of the Sichuan Basin indicate that flexural thickening of the lithosphere occurred in the eastern Sichuan fault-fold belt and the Longmen Mountain–Western Sichuan depression foreland basin system, while asthenospheric uplift occurred in the central Sichuan region, which were the result of the expansion of the Xuefeng orogeny from the east and the compression of the Tibetan Plateau from the west.

Key words: thermal lithospheric thickness, geothermal field, heat flow, thermal property, Sichuan Basin

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1 Introduction

The thermal structure of the lithosphere, especially the thermal structure and state of the upper mantle, is a basic problem in the field of geodynamics (Xu et al., 1995), which has important significance for understanding deep dynamic mechanisms. The lithosphere has been defined from different perspectives, including the petrological lithosphere, mechanical lithosphere, thermal lithosphere, seismological lithosphere, elastic lithosphere, chemical lithosphere, and seismic-thermal lithosphere. The thermal lithosphere refers to the Earth's outermost heat conduction layer (White, 1988). The thickness of the thermal lithosphere is a direct parameter reflecting the thermal state of the deep lithosphere, which has a good correlation with the effective elastic thickness of the continental lithosphere (Yuan and Zhang, 2005), and it is more reasonable than the lithospheric thickness obtained using other methods (An and Shi, 2006a).

Since the Mesozoic-Cenozoic, the dynamic evolution of the Chinese continent has mainly been characterized by thickening of the lithosphere in the west and thinning of the lithosphere in the east (He et al., 2001). This feature is a response to many geological processes such as the subduction of the Pacific Plate and the collision between the Indian Plate and the Eurasian Plate, and it controls the evolution of the different types of sedimentary basins in eastern and western China. Therefore, studying the thermal lithospheric thickness can not only provide parameters for in-depth studies of the dynamic evolution of the continental lithosphere, but it can also provide a basis for studying the formation and evolution of sedimentary basins, the analysis of the thermal history of petroliferous basins, and the distribution of geothermal resources.

The Sichuan Basin is located in the convergence zone formed by the Qinghai-Tibet Plateau, Qinling, and other large tectonic blocks, and there are many orogenic belt-foreland basin systems around it. Researchers have studied the deep structure of the basin and its periphery using geophysical methods (Gao et al., 2016; Wang et al., 2017; Li J H et al., 2018), as well as the Curie and Moho interfaces (Gao et al., 2014) and the lithospheric thickness (Li M K et al., 2018). A lot of studies (Xu et al., 1995, 2006; He et al., 2001, 2014; Hu et al., 2007; Qiu, et al., 2014,

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2015, 2016a, 2016b; Cui et al., 2020) in the North China Craton have given the detailed evolution of thermal lithosphere thickness from Triassic to present, and the response to the Clatonic destruction process was revealed. However, as an important convergence zone among several huge tectonic blocks, no similar works on the thermal lithosphere of the Sichuan Basin have been done, only few studies had conducted on the thermal lithospheric thickness in the study area based on temperature profiles (Xu et al., 2011a; Huang et al., 2014). The studies on the thermal lithospheric thickness have not been sufficiently systematic in the study area.

Based on the geothermal field and thermophysical properties of the Sichuan Basin and a stratigraphic model of the sedimentary layers and crust, in this study, the thickness of the thermal lithosphere was calculated, the heterogeneity of the thermal lithospheric thickness of the sub-tectonic units in the basin was analysed, and its geothermal significance was explained. The results of this study provide geothermal support for understanding the dynamic mechanism of the evolution of the surrounding basin-mountain systems and the exploration of petroleum and geothermal resources in the basin.

2 Geological Setting

The Sichuan Basin is located in the western margin of the Upper Yangtze Plate. It has an obvious rhomboid border, extends slightly to the northeast and is shorter to the northwest. The northwest and southeast boundary faults are relatively straight, while the northeast and southwest boundaries are serrated, indicating that the deep NE trending faults in the basin experienced significant compressional shearing in the late stage, while the deep NW trending faults in were faulted and reformed by the deep NE trending faults (Fig. 1a). Around the basin, the Longmen Mountain fault-fold belt is located to the northwest, the Daba Mountain fault-fold belt is located to the northeast and is bounded by the Chengkou fault, and the Yunnan–Guizhou–Sichuan–Hubei inner platform fault -fold belt is located to the southeast–southwest (Meng et al., 2005). The strata of these surrounding tectonic units are similar to the sedimentary facies in the basin, so they should belong to the same sub-tectonic units formed through the evolution of deep faults in the Yangtze paraplatform, and they structurally and topographically constitute the peripheral mountains of the Sichuan Basin (Guo et al., 1996).

The Sichuan Basin has deposits of sedimentary rocks that are up to 10,000 m thick and can be dated to early as Sinian (Guo et al., 1996; Liu et al., 2006), with diverse rock types and depositional systems. The Sinian–Middle Triassic strata are marine facies, which are dominated by carbonate rocks such as limestone and dolomite but also contain mudstone and sandstone. From the Middle–Late Triassic onward, a thick set of foreland basin deposits formed, including sandstone, mudstone, and other terrestrial clastic deposits (Fig. 1b).

3 Methods

The necessary condition for mantle melting is the

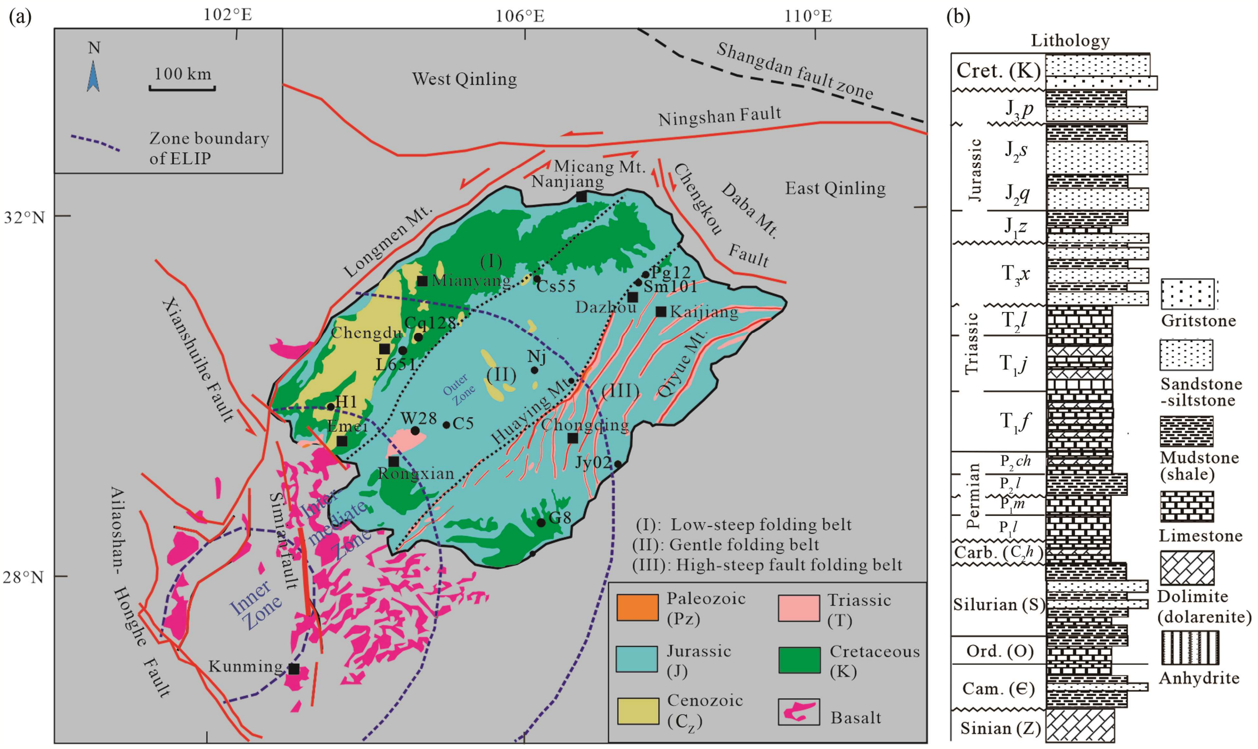

Fig. 1. (a) Geologic setting and well locations in the Sichuan Basin; (b) stratigraphic column for the study area.
The geologic map is based on Zhu et al. (2018a, b) and Meng et al. (2005), the distribution and zoning of the Emeishan Large Igneous Province (ELIP) is based on He et al. (2003, 2007), and the stratigraphic column was modified from Rao et al. (2011).

intersection of geothermal line and mantle solidus (Xu et al., 2006). There are three methods of determining the position of the bottom of the thermal lithosphere (He et al., 2014).

(1) A certain adiabatic isotherm can be taken as the bottom boundary temperature of the lithosphere, such as 1200°C (Petitjean et al., 2006), 1250°C (Lewis et al., 2003), or 1350°C (Wang and Cheng, 2011). (2) The depth of the intersection of the heat conduction geothermal line and the dry basalt solidus (DBS) can be defined as the bottom interface of the lithosphere (Pollack and Chapman, 1977; Lachenbruch, 1978; Hu et al., 2007). (3) The depth of the intersection of the heat conduction geothermal line and the adiabatic mantle solidus can be defined as the bottom interface of the lithosphere (Liu et al., 2005). Although the methods are different, in general, the bottom boundary of the thermal lithosphere is closer to the upper boundary of the rheological boundary layer (He, 2014).

The second method was adopted to calculate the thickness of the thermal lithosphere in the Sichuan Basin, and two adiabats (Rudnick et al., 1998) were used to constrain the upper and lower bounds of the thickness of the thermal lithosphere.

$$\text{Upper limit: } T_1 = 1200°\text{C} + 0.5Z \quad (1)$$

$$\text{Lower limit: } T_2 = 1300°\text{C} + 0.3Z \quad (2)$$

In Equations (1) and (2), T is the temperature on the DBS at a certain depth (°C), and Z is the certain depth (km).

The temperatures in the depth can be determined by temperature logging (T-logging), while the temperatures of undrilled strata can be constrained by the equation of heat conduction:

$$T_z = T_{i0} + q_{i0} \times \frac{Z}{K_i} - A_i \times Z^2 / (2K_i) \quad (3)$$

where T_{i0} is the temperature for the top surface of a sedimentary layer (°C or K), q_{i0} is the heat flow for the top surface of the layer (mW/m^2), K_i is the thermal conductivity of the layer (W/(m·K)), A_i is the heat generation rate of the layer (μW/m^3), and Z is the stratum thickness from the top of the layer to a certain depth in it (km). If the heat generation rate of the stratum decreases exponentially with the depth, this results in the following equation:

$$Tz = T_0 + \frac{q_0 Z}{K} - A' \times D^2 (1 - e^{-\frac{Z}{D}}) / K \quad (4)$$

where q_0 is the heat flow of the top surface of the stratum (mW/m^2), K is the rock thermal conductivity of the stratum (W/(m·K)), A' is the heat generation rate in the top of the stratum (μW/m^3), and D is the thickness of a certain part of crust that radioactive elements mainly enriched in (km), normally 8–14 km depends on the nature of the lithosphere (Hu et al., 2007).

Equation (3) is mostly used to calculate deep temperatures in sedimentary strata, and equation (4) is mostly used to calculate temperatures below the basement. Figure 2 presented the principles to determine the temperature profiles (Fig. 2a) and to constrain the thermal lithosphere thickness using the temperature profile and the 'Dry Basalt Solidus' (DBS) (Fig. 2b).

In the calculation process, the factors affecting the results mainly include the thermal conductivity, heat generation rate (A), stratigraphy of the crust, and terrestrial heat flow (q). The thermal conductivity (K), heat generation rate of the sedimentary layers and some basement rocks, and the terrestrial heat flow are mainly based on measurement results, which have been systematically summarized in previous studies (Xu et al., 2011b; Jiang et al., 2016; Zhu et al., 2018b; Tang et al., 2019; Qiu et al., 2022; Zhu et al., 2022). In addition to the measured heat flows (Table 1), interpolation values were also taken into the calculation (Fig. 3). The crustal heat generation rate is obtained from the model of the crustal structure and the seismic wave velocity (Wang et al., 2019). The initial thermal conductivities of the lower crust and upper mantle were set to 2.6 W/(m·K) and 4 W/(m·K), respectively, and the temperature correction method of

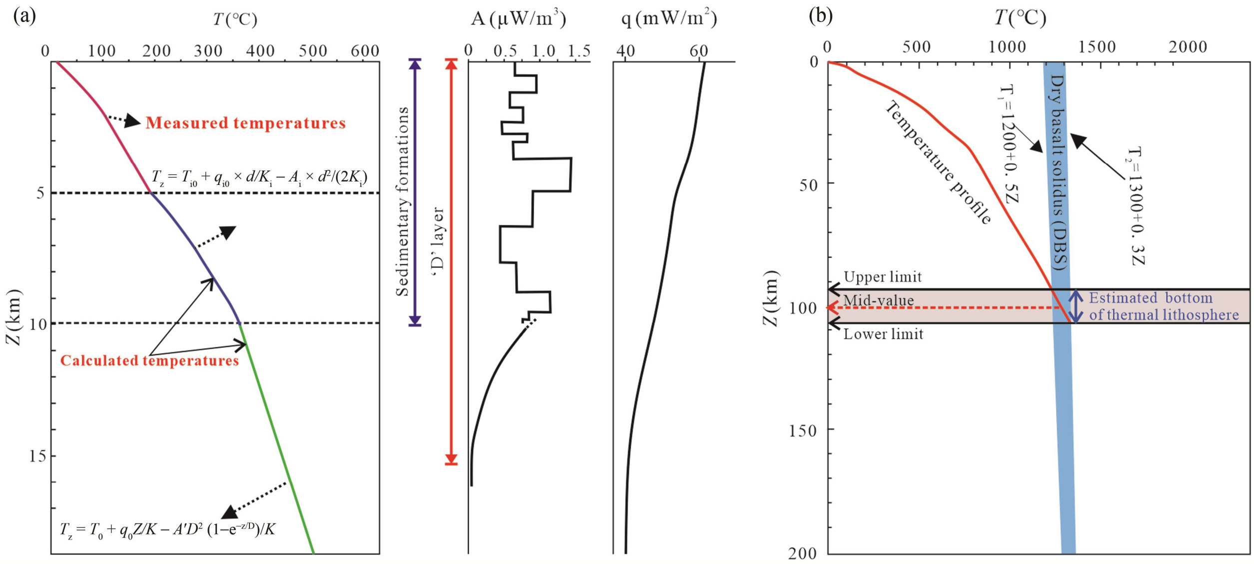

Fig. 2. (a) The principles to determine the temperature profiles and (b) calculation of the thermal lithospheric thickness (modified after Rudnick et al., 1998 and Cui et al., 2020).

The 'D' layer is the part of crust that radioactive elements mainly enriched in. The bottom boundary of the thermal lithosphere is defined as the intersection of the geothermal line and the DBS.

Table 1 The measured heat flow and the calculated thermal lithosphere thickness of boreholes in the Sichuan Basin

Bore hole	Logging depth (m)	G (°C/km)	q (mW/m^2)	Depth of the thermal lithosphere bottom (km)		
				Upper limit	Lower limit	Mid-value
TB1	0–1340	20.56	54.5	163	182	172
SM101	0–2252	23.25	55.5	162	178	171
DS1	0–3340	16.65	60.3	167	184	176
CQ128	0–3280	22.37	58.3	174	192	183
CS55	0–3020	22.01	57.0	173	192	183
LS1	0–4810	22.44	63.9	174	192	184
Ch5	0–1540	22.63	64.2	147	163	155
L651	0–3301	24.01	55.3	165	184	175

Note: The T-logging data sourced from Xu et al. (2011b).

Seipold (1998) was adopted.

4 Results

In this study, typical well calculations and grid data iterative calculations were used to calculate the deep geothermal distribution and to determine the thickness of the thermal lithosphere. A lithospheric temperature profile at typical well locations (Fig. 4 and Table 1) and a map of the planar distribution of the thermal lithospheric thickness (Fig. 5) were obtained. Eqs. (1) and (2) were used to calculate the thermal lithospheric thickness, and the mean values of the two were used as the reference for the thickness of the thermal lithosphere in the Sichuan Basin.

The temperature distribution characteristics and thermal lithospheric thickness at typical well locations are shown in Fig. 4, and these factors vary to some extent. Well W28 in the central Sichuan Basin has a high temperature gradient and a thin thermal lithospheric thickness of 135–150 km (mid-value: 142.5 km). Well Cm39 in the western Sichuan depression and well G8 in the eastern Sichuan fault-fold belt have thick thermal lithospheric thicknesses of 170–185 km (mid-value: 177.5 km).

The upper and lower limits of the bottom boundary of the thermal lithosphere were calculated in the grid data calculations (Fig. 5a, b; the calculations did not consider the northern and southwestern Sichuan regions, which lack measured heat flow values), and the median values of the two were used as the reference thermal lithospheric thickness (Fig. 5c). As is shown in Fig. 5, the thickness of the thermal lithosphere in the Sichuan Basin ranges from 140 to 190 km. The thermal lithosphere in central Sichuan and southwest Sichuan is relatively thin, with a thickness of less than 160 km. The thickness of the thermal lithosphere in the western Sichuan depression and eastern Sichuan is relatively large. For instance, in the western Sichuan depression, it reaches 180 km. The distribution of the thermal lithospheric thickness in the basin has a good correlation with the thickness of the sedimentary layers and the burial depth of the basement (Fig. 5d) (Zhang et al., 2012). That is, the thermal lithosphere is thicker in the areas with thick sedimentary layers, while it is relatively thin in the area where the basement has been uplifted and the sedimentary layers are thin.

5 Discussions

5.1 Reliability evaluation

Since the asthenosphere under the lithosphere has come

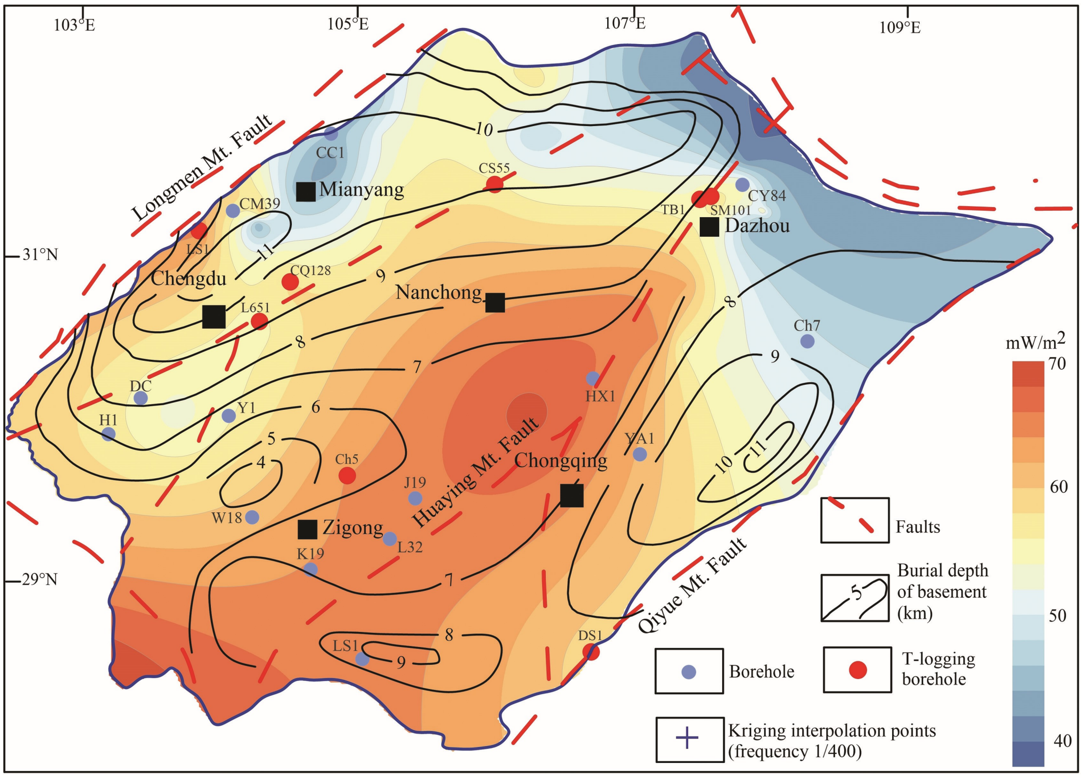

Fig. 3. The heat flow distribution (edited after Xu et al., 2011a; Zhu et al., 2018b) and the burial depth of the folded basement (edited after Luo et al., 1998) of the Sichuan Basin.

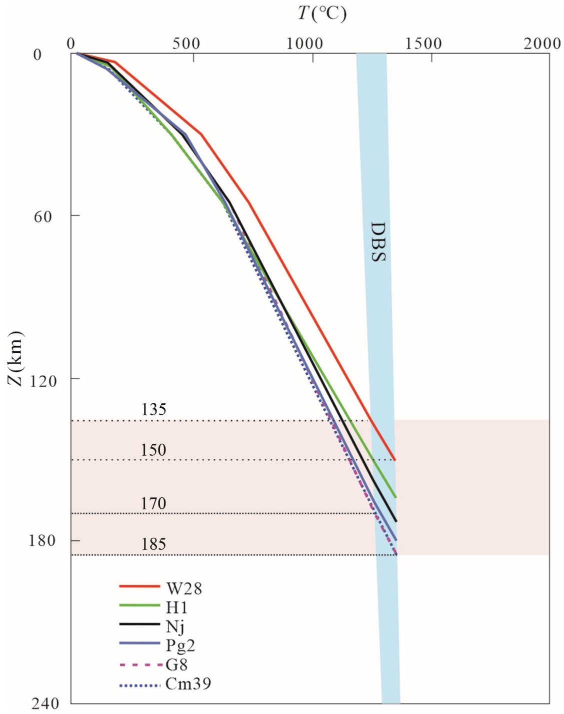

Fig. 4. Geothermal profiles of the lithosphere in different wells and their relationship with the dry basalt solidus (DBS).

close to or reached a certain level of (partial) melting, it has a higher deformation ability than the lithosphere, from this perspective, the thermal lithospheric estimation method is compatible with the concept of lithospheric plate tectonics, so the estimate is more reasonable than that of the effective elastic thickness (An and Shi, 2006a). The results of this study can be compared with those obtained using other methods to some extent. Based on the S-wave velocity, the thickness of the lithosphere in the Sichuan Basin is 180–200 km (Li M K et al., 2018), which is generally consistent with the calculation results obtained in this study, but the thickness of the lithosphere at the basin-mountain junction is significantly lower, which is speculated to be caused by lithospheric delamination and asthenospheric flow. The lithosphere in southwestern Sichuan is also relatively thin, which is consistent with the results of this study. Gao et al. (2014) studied the Curie interface in the eastern margin of the Qinghai-Tibet Plateau and determined that the depth of the Curie interface in southwestern and central Sichuan is shallow (20–26 km), while it is deep (≥ 30 km) in the northern and western Sichuan depression. This is consistent with the distribution of the thickness of the sedimentary layers (Fig. 5d).

Nevertheless, there are some shortcomings and uncertainties in estimating the lithospheric thickness using

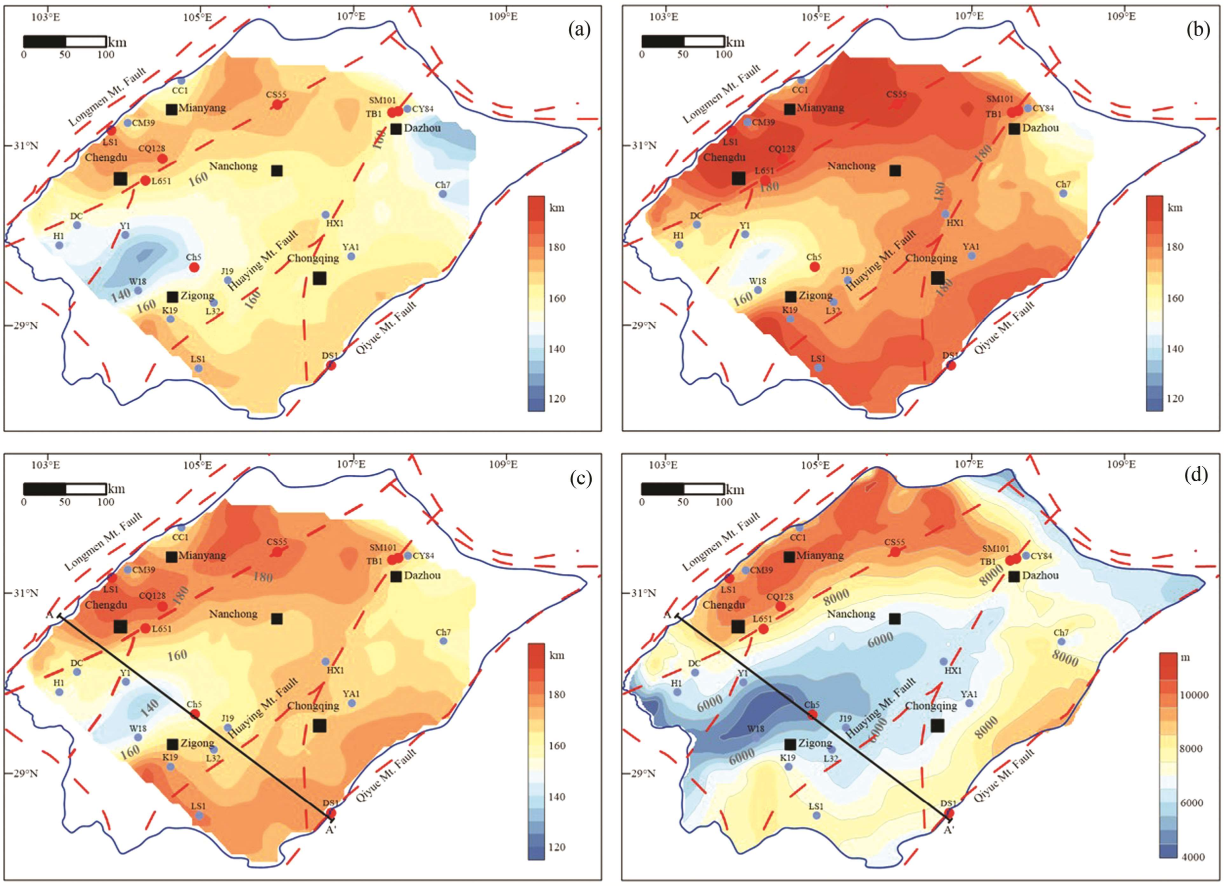

Fig. 5. The (a) upper limit, (b) lower limit, and (c) mid-value of the bottom of the thermal lithosphere; (d) the thickness of the sedimentary layers.

The areas with few measured heat flow data (northern Sichuan Basin-northeastern edge of the basin, southwestern Sichuan Basin) (Xu et al., 2011b; Jiang et al., 2016) were not calculated.

thermal methods. Primarily, only the lithospheric temperature field derived from steady-state heat conduction is reliable (An and Shi, 2006a). The Emeishan mantle plume activity in the Middle–Late Permian was the most significant thermal event in the Sichuan Basin. After that, the magmatism was not extensive, and thus the present geothermal field in the basin is controlled by a steady conductive geothermal regime, which has suitable conditions for this method. However, other uncertainties are inevitable, such as errors in the heat flow data and the thermal parameters of the rocks, which may lead to large uncertainty in the calculation of the deep temperature and thermal lithospheric thickness (An and Shi, 2006a; Hu et al., 2007).

Additionally, the results may be affected by many other factors, such as the approximation of the upper mantle solidus as the dry basalt solidus (Hu et al., 2007), crustal partial melting, and the rheological boundary layer between the solid lithosphere and asthenosphere (He et al., 2014). Researchers (Pasquale et al., 1990; Hu et al., 2007) have concluded that an uncertainty of 15% for the estimated lithospheric thickness can be expected. However, the uncertainty may depend on the specific geological nature of the study area.

5.2 Geological implications of thermal lithospheric thickness in the Sichuan Basin

An and Shi (2006a, b; 2007) studied the lithospheric thickness of the Chinese continent using a combination of seismic and thermal methods and concluded that the thickness of the lithosphere in the interior of the Yangtze Plate is up to 170 km, which is close to the results of this study. The thickness of the thermal lithosphere in the Sichuan Basin is larger than that in eastern China (e.g., 60 –120 km in the Bohai Bay Basin) (He, 2001; Liu et al., 2005), but it is relatively thin compared with that of the Tibetan Plateau (160–220 km) (An and Shi, 2006a, b) and most global cratons (Artemieva, 2006).

The thinning of the lithosphere and the corresponding changes in the lithosphere's thermal structure should have affected the near surface temperature field in the parts of the basins away from the magmatic zones (Hu et al., 2007). The geothermal line of the upper mantle is higher in eastern China than in the old shield and ocean areas, but it is similar to the temperature profiles in the southern part of eastern Australia. This is consistent with the high surface heat flow, asthenospheric uplifting, and magmatic activity in the area, and it also corresponds to the extensional environment of the entirety of eastern China during the Cenozoic (Xu et al., 1995). Similarly, the good consistency between the thickness of the thermal lithosphere, the sedimentary thickness (Zhang et al., 2012), the surface heat flow (Xu et al., 2011b; Jiang et al., 2016; Zhu et al., 2018b), and the mantle heat flow (Fig. 6) (Qiu et al., 2022; Zhu et al., 2022) reflects the conductive lithospheric thermal structure in the Sichuan Basin, and indicates that flexural thickening of the lithosphere occurred in the eastern Sichuan fault-fold belt and the Longmenshan–Western Sichuan depression foreland basin system, while asthenospheric uplift occurred in the central Sichuan.

Many pervious works on the tectonic-structural nature of the Sichuan Basin and its surrounding mountain systems pointed out that the lithosphere deformation of the basin boundaries were the results of collisions (Liu et al., 2005, 2015; Zhang et al, 2013; Zhu et al., 2019). Li and Li (2007) gave the eastern margin of the basin as the western limit of the far-field effect of the Paleo-Pacific subduction, and many researchers considered the progressive deformation in Western Hunan–Hubei–Eastern Sichuan was result from the Jiangnan–Xuefeng Mesozoic intracontinental orogenesis (Mei et al., 2010; Wang et al., 2012), associated with clockwise rotation of the Yangtze plate relative to the North China plate (Liu et al., 2005).

6 Conclusions

(1) The thickness of the thermal lithosphere in the Sichuan Basin ranges 140–190 km and is unevenly

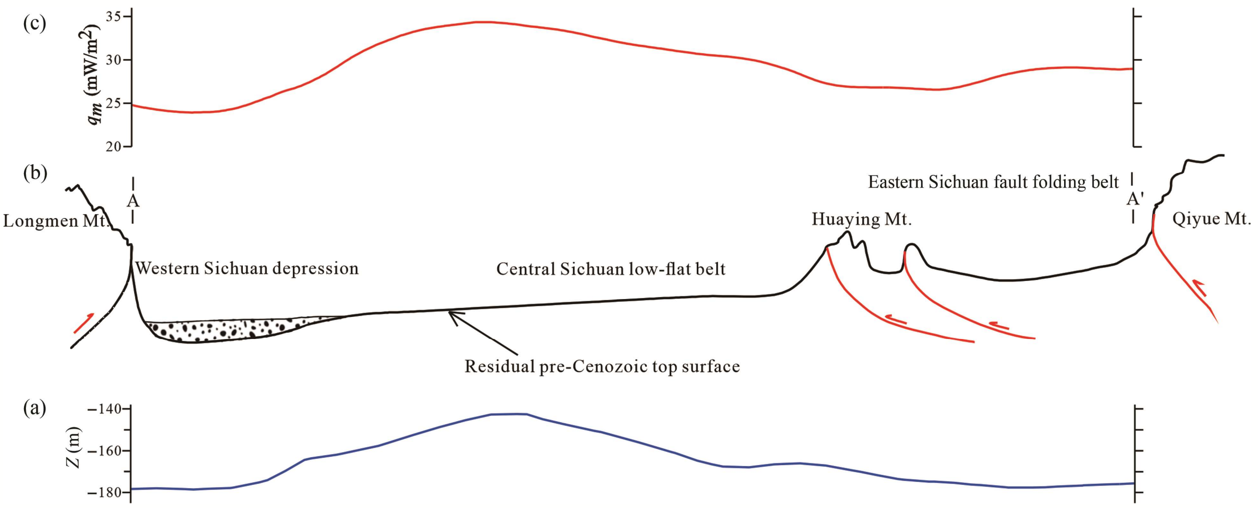

Fig. 6. Consistency of (a) the thermal lithosphere with (b) the tectonic units and (c) the mantle heat flow.
Note that the burial depth, not the elevation depth was used to characterize the thermal lithosphere.

distributed. The thickness of the thermal lithosphere in central Sichuan and southwestern Sichuan is less than 160 km, while the thickness of the thermal lithosphere in the western Sichuan depression and eastern Sichuan is larger (~180 km). The distribution of the thermal lithospheric thickness in the basin has a good correlation with the geological units and the thickness of the sedimentary layers. The thickness of the thermal lithosphere in the depression area, which has thick sedimentary layers and a fault fold zone with shallow crustal deformation and thickening, is larger than that in the basement uplifted area, which has thin sedimentary layers.

(2) The present thermal regime and thermal lithospheric thickness of the Sichuan Basin indicate that flexural thickening of the lithosphere occurred in the eastern Sichuan fault-fold belt and the Longmen Mountain–Western Sichuan depression foreland basin system, while asthenospheric uplift occurred in the central Sichuan area.

(3) Limited by the accuracy of the heat flow data and the thermal physical parameters, as well as the complexity of the internal structure and physical properties of the Earth, there are some uncertainties or errors in the calculation of the thermal lithospheric thickness. The results in this study are in good agreement with other observations and calculations and reflect the stable conduction temperature field in the Sichuan Basin and the reliability of the results of the thermal lithospheric thickness.

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