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THEMATIC ISSUE

Thermal conductivity and radioactive heat-producing element content determinations for rocks from Zhangzhou region, SE China, and their constraints on lithospheric thermal regime

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Abstract Radioactive heat-producing element content and rock thermal conductivity together with rock density have been determined for rocks from surface and drilling holes within Zhangzhou region, SE China. The results suggest that the average radiogenic heat production rate of granites is 3.70 μW/m^3, markedly higher than that of middle-acid volcanic rocks, mafic dykes and sedimentary rocks from the same region. Additionally, the main heat production rate is sourced from the decay heat of U and Th with ^{40}K thermal contribution being less than 10 %. The average rock thermal conductivity is 2.83 W/mK, approaching that of the middle-upper crustal rocks. Our new data, in combination with previous geology, geophysics and geothermics data, indicate that mantle contributes more heat flow than crust to the surface heat flow, i.e., Qm/Qc > 1, and that Zhangzhou region has a relatively thinner crustal thickness.

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Keywords Zhangzhou region · Radiogenic heat production · Thermal conductivity · Lithospheric thermal regime

Introduction

It is well known that the Earth's internal thermal energy is an indispensable driving force of plate tectonics and also plays a crucial role in the formation and evolution of the continental crust (Morgan 1984; Rybach 1988). Heat is generated at different ways in the interior of the Earth, of which radioactive heat production accounts for a relatively higher proportion (Arevalo et al. 2009; Pollack and Chapman 1977; Zhao et al. 2015). However, just radioelements like U, Th and ^{40}K with relatively high abundance and long life can release considerable heat. At the same time, the U, Th and K are easily mobile and incompatible during geological processes, so they are not evenly distributed. Therefore, exploring their behaviors and distribution features is beneficial to our understanding on the geochemical and geothermal field. For the solid lithosphere, rock thermal conductivity is another important thermophysical parameter to characterize its heat transmission capacity (Clauser and Huenges 1995). Combined radiogenic heat production rate and rock thermal conductivity data, together with other geophysics data, can provide rigorous constraints on surface and mantle heat flow data, lithosphere thermal thickness and its thermal regime (He 2015; Jaupart et al. 1998; Mareschal et al. 2004).

Zhangzhou geothermal field, located in SE Fujian province along SE China coastal belt, is an important and representative middle-low temperature geothermal field. In the past decades, a large number of studies have been carried out and the results provide strict constraints on its type and genesis (Pang 1987, 2005; Wang 1993). However, we have very little knowledge about the lithosphere thermal regime of Zhangzhou region, which is crucial for understanding on the formation and evolution of the geothermal field.

In the current study, a large number of fresh rock samples from surface and drilling holes in the Zhangzhou region, SE China have been collected and determined involving rock density, radioactive heat-producing element content and thermal conductivity. Our new data, in combination with previous geology, geophysics and geothermics results, shed new light on radiogenic heat production features and the lithospheric thermal regime of the studied area, which is good for geothermal development and utilization.

Regional setting and sample collection

Zhangzhou region located in SE China along the southeastern margin of Eurasian continent is occupied by massive late Mesozoic volcanic and intrusive rocks, belonging to an important part of circum-Pacific magmatic belt (Li et al. 2014; Wang and Zhou 2002). Our target Zhangzhou pluton (or Zhangzhou complex) is a large composite rock body with covering area being larger than 900 km^2, which is bounded by Changle-Nan'ao fault and Zhenghe-Dapu fault in the east and northwest, respectively (Fig. 1). Zhangzhou complex is surrounded/covered by early Jurassic Lishan Formation sedimentary rocks, late Jurassic Nanyuan Formation volcanic rocks, and Neogene Fotan Formation volcanic-clastic sedimentary rocks, which is further developed to form a Quaternary graben basin. According to petrolog-

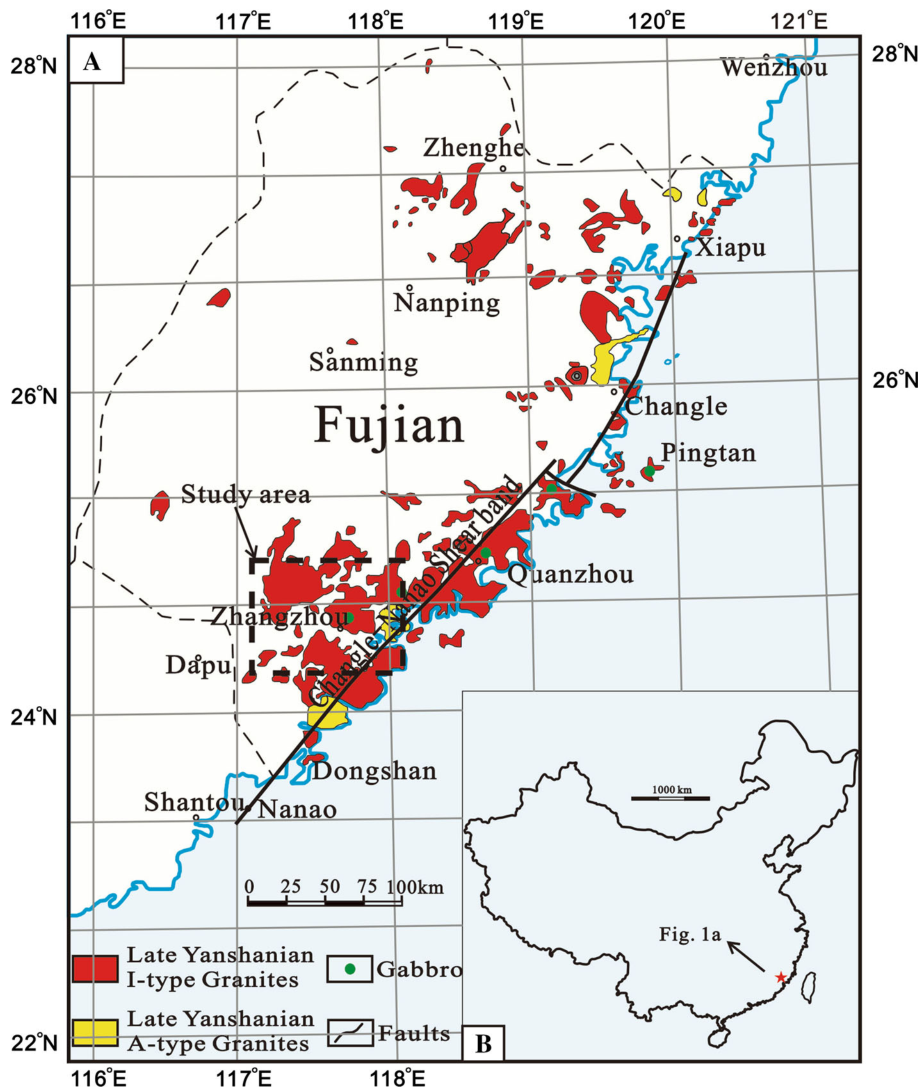

Fig. 1 Simplified geological map showing late Mesozoic igneous rock distribution in the coastal region of Fujian (modified from Li et al. 2014). *Rectangle with dotted lines* in **a** represents studied area of Zhangzhou Pluton (Complex), and **b** showing the geographical position of studied area in China

ical, geochemical and isotopic data, Wang and Zhou (2002) suggested that the late Mesozoic volcanic and intrusive rocks are closely associated in time, space and source, i.e., both volcanic and intrusive rocks were formed contemporaneously from the same source materials but with different occurrences and subsequent evolution processes. It is a consensus that the Fujian coastal magmatic belt including Zhangzhou complex is related to the subduction of the Palaeo-Pacific Plate beneath Eurasian continent (Li et al. 2014; Wang and Zhou 2002; Zhou and Li 2000).

Zhangzhou region is also rich in geothermal resources, belonging to an indispensible part of the “southeastern coastal geothermal zone” in China (Pang 1987; Wang 1993). A substantial number of hot springs are widely distributed in the whole area with the record of the highest temperature ever measured in southeast of China (114 °C at the well-head and 122 °C at a depth of 90 m from surface) (Pang 2005). On the basis of SiO_2 geothermometer (mixing model) and other geochemical data, Pang (1987) and Wang (1993) thought that the reservoir temperature is about 140 °C with circulating depth at about 4 km, and they further suggested that the Zhangzhou geothermal system is a medium–low temperature convective type geothermal field, which is developed within a granitic batholith through the deep-circulating of meteoric water. However, Xiong et al. (1991) speculated that there is probably a partial melting magma body at the depth of Zhangzhou region in terms of seismic refraction profile observation.

There are many types of granitic rocks occurring in the Zhangzhou Complex, including coarse- to medium-grained granites, fine-grained granites, monzonitic granites, K-feldspar granites, biotite granites, granodiorite, granite porphyries, miarolitic granites, spherical weathered granites and hornblende-bearing granites. The field contact relationship between different types of granites (Fig. 2a), MMEs (mafic microgranular enclaves) occurring in the granitic rocks (Fig. 2b), and mafic dykes cutting the granitic rocks (Fig. 2c) has been observed in the field trip. Additionally, the direct contact relationship between nearly coeval intrusive and volcanic rocks has also been found (Fig. 2d). In the current study, 188 fresh surface granitic rocks, 11 and 27 granitic samples from drilling holes at depth range of 10–120 and 30–120 m within Liren School and Zhishan Park, and 99 surface non-granitic rocks including middle-acid volcanic rocks, basalts, mafic dykes, argillites and conglomerates have been collected.

Analytical methods

With the aim to calculate radiogenic heat production rates, 325 rock samples including 188 surface granites, 11 drilling hole granites from Liren School, 27 drilling hole granites from Zhishan Park, 51 middle-acid volcanic rocks and other 48 rock samples including basalts, mafic dykes, argillites and conglomerates have been carried out for rock density and radioactive heat-producing element content

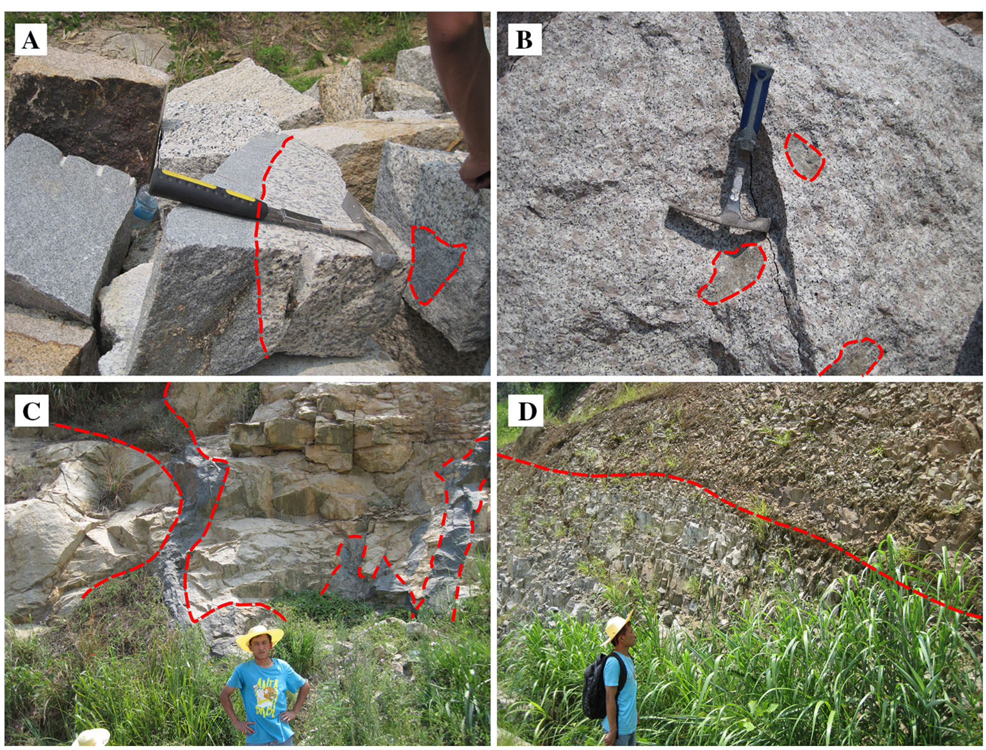

Fig. 2 Field photographs showing the features of Zhangzhou Complex

Table 1 The statistical rock density and radiogenic geochemistry features of the rocks from Zhangzhou region

Sample Type and number	Average/range of density (g/cm^3)	Average/range of Th contents (ppm)	Average/range of U contents (ppm)	Average/range of K_2O contents (wt%)
Surface granites/188	2.60 (2.22–2.84)	23.6 (4–59)	6.6 (4–17)	4.28 (0.27–6.64)
Granites from Liren School drilling hole/11	2.62 (2.52–2.77)	24.7 (13–38)	9.1 (5–13)	1.70 (0.48–3.10)
Granites from Zhishan Park drilling hole/27	2.58 (2.18–2.79)	35.2 (29–38)	6.8 (4–11)	5.25 (5.09–5.52)
Middle-acid volcanic rocks/51	2.57 (2.29–2.77)	21.9 (4–41)	5.6 (4–11)	4.26 (1.34–6.73)
Other non-granites[a]/48	2.56 (2.24–2.81)	8.7 (4–36)	4.3 (4–7)	1.74 (0.17–5.60)

[a] Other non-granites refer to the basic volcanic rocks, basic dykes, sandstones and siltstones

determination (Table 1). The rock density has been measured in the State Key Laboratory Breeding Base of Nuclear Resources and Environment, East China University of Technology by means of Archimedes' principle (buoyancy method) with error margin being smaller than ±2 %. The radioactive Th, U and K concentrations are determined in the Guangzhou ALS Laboratory Group by ICP-MS and XRF, respectively. Analytical uncertainties range from ±1 to ±2 % for K, from ±1 to ±10 % for Th and U. The radiogenic heat production rates of the determined rocks are calculated according to Rybach (1988).

One hundred and thirty representative rock samples including 59 granitic rocks and 71 non-granitic rocks have been conducted for thermal conductivity determination in the State Key Laboratory Breeding Base of Nuclear Resources and Environment, East China University of Technology by TCi thermal conductivity analyzer with error margin smaller than ±5 %.

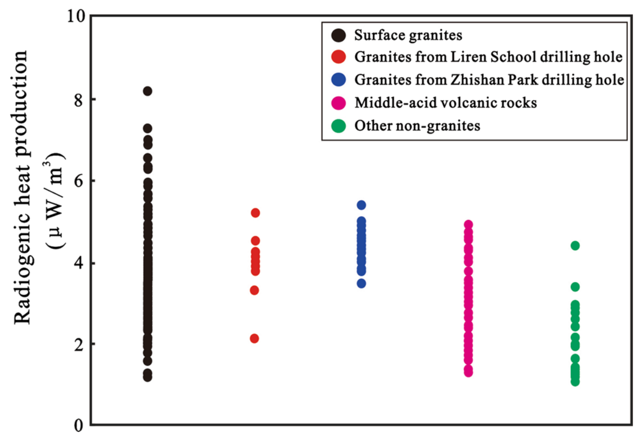

Fig. 3 Radiogenic heat production rates of different types rocks. It is noted that other non-granites represent basalts, mafic dykes, argillites and conglomerates

Result and discussion

The features of radiogenic heat production rates

The main statistical results of rock density, radiogenic heat-producing element contents are listed in Table 1. As shown in Table 1, the average densities of granite samples from surface and drilling holes (2.58–2.62 g/cm^3) are slightly higher than those of middle-acid volcanic rocks and other non-granitic rocks (2.56–2.57 g/cm^3). With the exception of K contents of drilling hole granites from Liren School, the radioelement U, Th and K contents of granitic rocks irrespective of surface or drilling holes are remarkably higher than those of middle-acid volcanic rocks and other non-granitic rocks. Our new data are in good agreement with previous results, which were determined by different analytical methods (Pang 1987; Zhao et al. 1995). Consequently, the radiogenic heat production rates of granitic rocks both from surface and drilling holes with average values of 3.52, 4.05 and 4.39 $\mu W/m^3$ are systematically higher than those of middle-acid volcanic rocks and other non-granitic rocks with average values of 2.82 and 1.62 $\mu W/m^3$ (Fig. 3). One explanation for the relatively higher radiogenic heat production rates of drilling hole granites may be the fact that circulating fluid bring some heat-producing elements. Although the radiogenic heat production rates of drilling hole granites are slightly higher than those of surface granites, yet the average value 3.70 $\mu W/m^3$ of all granites is considered to be the radiogenic heat production rate of Zhangzhou Complex. Our new data confirm that the radiogenic heat production rates of granites from southeastern coastal region is markedly lower than those of granites from Nanling Region of South China (Sun et al. 2015; Wang et al. 2014; Zhao et al. 1995), but 1.5 times that of global average granite (McLaren et al. 2003).

Another important aspect is to explore the U, Th and K contributions to the radiogenic heat production rates of granites. The ^{40}K contribution to the radiogenic heat production rates is generally less than 10 %, which is consistent with the analytical results from Southeastern Nigeria (Joshua et al. 2008). The radiogenic heat production rates are mainly from the decay heat of radioelements U and Th. In most samples, the U contribution is nearly equal to that of Th (Fig. 4).

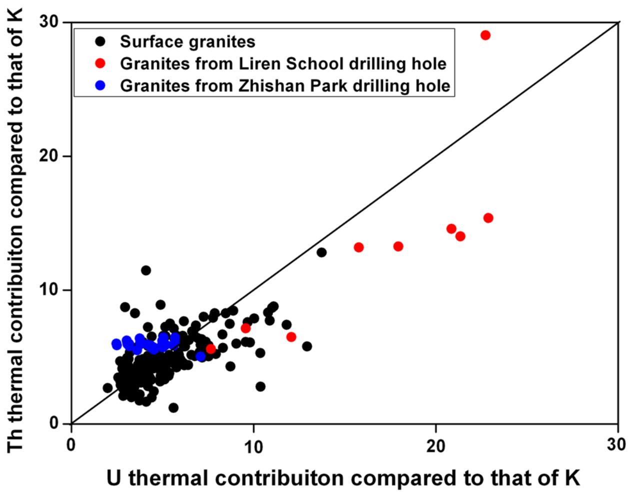

Fig. 4 U thermal contribution to radiogenic heat production rates normalized to that of K versus Th thermal contribution to radiogenic heat production rates normalized to that of K

The features of rock thermal conductivities

One hundred and thirty representative rock samples including 59 granite samples and 71 non-granite samples have been carried out for thermal conductivity determination. The granites and non-granites exhibit average values of 3.19 and 2.52 W/mK, respectively, indicating that the thermal conductivity of granites is higher than that of non-granites in the studied area. The average value for all 130 rock samples is 2.83 W/mK, which is slightly higher than the recommended value 2.70 W/mK of middle-upper crust (Smithson and Decker 1974), and the previously determined value 2.47 W/mK from the same region by different analytical method (Pang 1987).

Lithospheric thermal regime of Zhangzhou region

The lithospheric thermal regime is crucial for our understanding on the lithospheric thermal evolution, heat flow and continental geochemical composition (Arevalo et al. 2009; He 2015; McLennan and Taylor 1996; Morgan 1984). Our new data, in combination with previous geology, geochemistry, geophysics and geothermics data, can provide strong constraints on lithospheric thermal regime.

Morgan (1984) proposed that the surface heat flow is mainly composed of crust heat flow (Qc) and mantle heat flow (Qm). The Qc is a first-order function of radiogenic heat-producing element contents, and the Qm mainly depends on the lithospheric thickness. Previous data show that the thickness of radioelement-rich crustal layer in Zhangzhou region is 10–12 km (Ma et al. 2015; Pang 1987), the geothermal gradient is 30–40 °C/km (Ma et al. 2015 and references therein). Additionally, the radiogenic heat production rate and thermal conductivity obtained in this study is 3.70 $\mu W/m^3$ and 2.83 W/mK, respectively. Therefore, the calculated surface heat flow is in the range of 85–113 mW/m^2, in good agreement with previously determined value of 90–115 mW/m^2 (Hu et al. 2000, 2001; Wang and Huang 1988, 1990). The crust heat flow can be approximatively considered to be the product of thickness of radioelement-rich crustal layer (10–12 km) and the radiogenic heat production rate (3.70 $\mu W/m^3$), whose value is 37–45 mW/m^2. Thus, the calculated Qm is 40–75 mW/m^2, which is larger than Qc with Qm/Qc ratio being more than 1. The Qm contribution to surface heat flow is 55–65 %. Previous Sr–Nd isotopic geochemistry data also indicate that ca. 60 % mantle-derived materials are involved in the granite magma resource (Zhou et al. 1988). The high Qm value implies that the lithospheric thickness in Zhangzhou region is relatively thin. Geophysical data confirm that the crustal thickness is about 29 km (Xiong et al. 1991), which is smaller than the normal crust thickness. Briefly, relatively thinner lithosphere in Zhangzhou region triggers mantle upwelling, which contributes largely to the surface heat flow.

Conclusions

Some important conclusions can be addressed in the following:

1. The average radiogenic heat production rate for more than 200 granite samples from surface and drilling holes in Zhangzhou region, SE China, is 3.70 $\mu W/m^3$, 1.5 times higher than that of global average granites.
2. Thermal conductivity of middle-upper crust rocks from Zhangzhou region is 2.83 W/mK, in consistent with the recommended value of global middle-upper crust.
3. The Qm/Qc ratio in the region is larger than 1, implying that the mantle heat flow contribution is larger than that of crust heat flow and the crust thickness is relatively thinner.

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References

Arevalo R, McDonough WF, Luong M (2009) The K/U ratio of the silicate Earth: insights into mantle composition, structure and thermal evolution. Earth Planet Sci Lett 278(3):361–369. doi:10.1016/j.epsl.2008.12.023

Clauser C, Huenges E (1995) Thermal conductivity of rocks and minerals. In: Ahrens TJ (ed) Rock physics & phase relations: a handbook of physical constants, vol 3. AGU Publisher, Washington, pp 105–126. doi:10.1029/RF003p0105

He LJ (2015) Thermal regime of the North China Craton: implications for carton destruction. Earth Sci Rev 140:14–26. doi:10.1016/j.earscirev.2014.10.011

Hu SB, He LJ, Wang JY (2000) Heat flow in the continental area of China: a new data set. Earth Planet Sci Lett 179(2):407–419. doi:10.1016/S0012-821X(00)00126-6

Hu SB, He LJ, Wang JY (2001) Compilation of heat flow data in the China continental area (3rd edition). Chin J Geophys 44(5):611–626 **(in Chinese with English abstract)**

Jaupart C, Mareschal JC, Guillou-Frottier L, Davaille A (1998) Heat flow and thickness of the lithosphere in the Canadian Shield. J Geophys Res Solid Earth 103(B7):15269–15286. doi:10.1029/98JB01395

Joshua E, Ehinola O, Akpanowo M, Oyebanjo O (2008) Radiogenic heat production in crustal rock samples of Southeastern Nigeria. Eur J Sci Res 23(2):305–316

Li Z, Qiu JS, Yang X (2014) A review of the geochronology and geochemistry of Late Yanshanian (Cretaceous) plutons along the Fujian costal area of southeastern China: implications for magma evolution related to slab break-off and rollback in the Cretaceous. Earth Sci Rev 128:232–248. doi:10.1016/j.earscirev.2013.09.007

Ma F, Sun HL, Lin WJ, Gan HN, Wang GL (2015) Target site selection and indexes matrix evaluation of EGS demonstration in China. Sci Technol Rev 33(8):41–47. doi:10.3981/j.issn.1000-7857.2015.08.006

Mareschal JC, Nyblade A, Perry HKC, Jaupart C, Bienfait G (2004) Heat flow and deep lithospheric thermal structure at Lac de Gras, Slave Province, Canada. Geophys Res Lett. doi:10.1029/2004GL020133

McLaren S, Sandiford M, Hand M, Neumann N, Wyborn L, Bastrakova I (2003) The hot southern continent: heat flow and heat production in Australian Proterozoic terranes. Geol Soc Am Spec Papers 372:157–167. doi:10.1130/0-8137-2372-8.157

McLennan S, Taylor S (1996) Heat flow and the chemical composition of continental crust. J Geol 104(4):369–377. doi:10.1086/629834

Morgan P (1984) The thermal structure and thermal evolution of the continental lithosphere. Phys Chem Earth 15(107–193):1946. doi:10.1016/0079-(84)90006-5

Pang ZH (1987) Zhangzhou basin geothermal system. Dissertation. Institute of Geology, Academia Sinica (in Chinese with English abstract)

Pang ZH (2005) Origin of sulphur compounds and application of isotope geothermometry in selected geothermal systems of China. In: IAEA (Ed.) Use of isotopes to trace the origin of acidic fluid in geothermal systems

Pollack H, Chapman D (1977) On the regional variation of heat flow, geotherms, and lithospheric thickness. Tectonophysics 38(3):279–296. doi:10.1016/0040-1951(77)90215-3

Rybach L (1988) Determination of heat production rate. In: Hanel R et al (eds) Handbook of terrestrial heat flow density determination. Kluwer, Dordrecht, pp 125–142

Smithson S, Decker E (1974) A continental crustal model and its geothermal implications. Earth Planet Sci Lett 22(3):215–225. doi:10.1016/0012-821X(74)90084-3

Sun ZX, Wang AD, Liu JH, Hu BQ, Chen GX (2015) Radiogenic heat production of granites and potential for hot dry rock geothermal resource in Guangdong Province, Southern China. In: Proceedings world geothermal congress 2015, Melbourne, Australia, 19–25 April 2015

Wang JY (1993) Low-medium temperature geothermal system of convective type. Science press, Beijing **(in Chinese with English abstract)**

Wang JY, Huang SP (1988) Compilation of heat flow data in the China continental area. Sci Geol Sin 2:196–204 **(in Chinese with English abstract)**

Wang JY, Huang SP (1990) Compilation of heat flow data in the China continental area (2nd edition). Seismol Geol 12(4):351–366 **(in Chinese with English abstract)**

Wang DZ, Zhou XM (2002) The genesis of Late Mesozoic granitic volcanic-intrusive complex from SE China and its crustal evolution. Science Press, Beijing **(in Chinese)**

Wang AD, Sun ZX, Hu BQ, Liu JH, Liu CD (2014) Guangdong, a potential province for developing Hot Dry Rock geothermal resource. Appl Mech Mater 492:583–585. doi:10.4028/www.scientific.net/AMM.492.583

Xiong SB, Jin DM, Sun KQ, Zou YS, Fan XB, Du XG (1991) Some characteristics of deep structure of the Zhangzhou geothermal field and it's neighbourhood in the Fujian province. Acta Geophys Sin 34(1):55–63 **(in Chinese with English abstract)**

Zhao P, Wang JY, Wang JA, Luo DG (1995) Characteristics of heat production distribution in SE China. Acta Petrol Sin 11(3):292–305 **(in Chinese with English abstract)**

Zhao P, He LJ, Liu SW, Sun ZX (2015) Thermal structure of the lithosphere. In: Wang AD et al (eds) Geothemics and its applications. Science Press, Beijing (in Chinese with English abstract)

Zhou XM, Li WX (2000) Origin of Late Mesozoic igneous rocks in Southeastern China: implications for lithosphere subduction and underplating of mafic magmas. Tectonophysics 326(3):269–287. doi:10.1016/S0040-1951(00)00120-7

Zhou XR, Chen AG, Song XH, Wu KL, Yan BQ, Wu ZT (1988) Rb-Sr isotope ages and prelimary studies of genesis on Zhangzhou granitoid intrusive body, Fujian Province. Bull Nanjing Inst Geol Min Resour 9(2):55–67 **(in Chinese with English abstract)**