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Radiogenic Heat Production of Granites and Potential for Hot Dry Rock Geothermal Resource in Guangdong Province, Southern China

Zhanxue Sun[1], Andong Wang[1,2], Jinhui Liu[1], Baoqun Hu[1,2] and Gongxin Chen[1]

[1]State Key Laboratory Breeding Base of Nuclear Resources and Environment, East China Institute of Technology, Nanchang 330013, China

[2] College of Earth Sciences, East China Institute of Technology, Nanchang 330013, China

E-mail address:zhxsun@ecit.cn

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ABSTRACT

Enhanced or Engineered Geothermal Systems (EGS) have been recognized by geothermal energy experts as being the necessary technology for substantially increasing the contribution of geothermal energy to the world's production of electricity. As one of the largest energy consumption countries, China has started a China Geological Survey sponsored project-Hot Dry Rock Investigation and EGS Pilot Project of China in 2013. As one of the project tasks, radiogenic heat production of granites in southeastern China is being systematically investigated. This paper presents the study of radiogenic heat generation caused by the decay of the unstable isotopes ^{238}U, ^{232}Th and ^{40}K of granites in Guangdong, an important industrial province in southeastern coastal area of China. The concentrations of uranium, thorium and potassium as well as density of 207 samples taken from five big granite bodies in the province are analyzed. The weighted mean radiogenic heat generation rates of five granite bodies have a range of 5.28-7.11μW/m^3. Based on heat flow, radiogenic heat generation rate, cap rock properties and some other factors, the potential for Hot Dry Rock geothermal resource in the Province is preliminarily evaluated. Evidences show that the province has great potential to develop HDR geothermal resource.

1. INTRODUCTION

The concept of Hot Dry Rock (HDR), which is originally defined as the deep hot crystalline rocks with temperatures generally being higher than 150ºC, has firstly been proposed by American scientists at early 1970s during the time of first global oil crisis (Robinson et al., 1971). Subsequently, the Los Alamos National Laboratory together with Department of Energy has conducted HDR drilling experiments at Fenton Hill of New Mexico. Up to now, several other countries including England, Germany, France (European), Sweden, Japan, Switzerland and Australia have also carried out HDR drilling experiments (Rybach et al., 1978; Tenzer, 2001; Chopra and Wyborn, 2003; Ledésert and Hébert, 2012; Wang et al., 2014). Available data strongly suggest that electricity power generation from HDR is feasible, and HDR geothermal resource is regarded to be a kind of local, renewable and clean energy source. However, voluminous studies also show that the so-called HDRs are not impermeable and dry as previously thought. Some micro-paths in the form of joints and micro-faults and fluids were detected in the deep continental crust. Accordingly, some authors call the deep crystalline rock with natural fractures and water as Hot Wet Rock (HWR) with the aim to distinguish it from traditional HDR (Baria et al., 1999). In contrast to conventional geothermal resources, the energy abstraction for both HDR and HWR must be through artificial fractures, external fluid injection and retrieve, which is totally known as Enhanced or Engineered Geothermal Systems (EGS).

Due to the serious social and environmental problems caused by fossil energy resources, more and more countries especially developing ones plan to develop geothermal resources especially HDR geothermal energy. As one of the largest energy consumption countries, China has stated a large-scale HDR Investigation and EGS Pilot Project, which are sponsored by China Geological Survey (CGS) (Wang et al., 2014). Guangdong Province located in the Southeastern China is an important province with relatively high industrialized and economic level, and it is also a province with giant energy demand but limited fossil energy resources. In the present investigation, we explore the HDR development potential of Guangdong province on the basis of multidisciplinary points.

2. GEOLOGICAL SETTING AND GRANITE DISTRIBUTION

Guangdong is an important southern province belonging to Pearl River Delta of China. Geologically, Guangdong Province is located in the hinterland of Catyaysia Block along the SE margin of the South China Block. Different from most early Precambrian blocks, the Catyaysia Block is relatively young only with minor Paleoproterozoic rocks, although some Archean zircons have been reported. With the exception of minor Paleoproterozoic rocks (2.1-1.8Ga), several discrete episodes of granitic magmatism including Caledonian, Indosinian, early and late Yanshanian were widely distributed in this province, where the S-type or crustally-remelting type granite is an important rock type. In addition, these granite bodies are closely associated with several deep faults and various types of sedimentary basins (Zhou, 2006; Wang et al., 2013). In the following, we firstly introduce the potential advantage for developing HDR geothermal resources of Guangdong Province and then present the features of granite bodies.

2.1 Potential advantage for developing HDR geothermal resource for Guangdong Province

Rybach et al. (1978) firstly divided a HDR site into deep basement rocks (i.e., the deep crystallization rocks, "basement" in short in the next) and their overlying sediments or sedimentary rocks ("cover" in short in the next). In order to reduce cost and skill risks, or to minimize the depth of drilling roles, we should select basement rocks with relatively high radioactive U, Th and K concentrations giving high heat productivity, and cover rocks with low conductivity blocking the thermal loss of underlying basement rocks.

Numerical simulation results indicate that cover rocks are vital for developing HDR geothermal resources. As a matter of fact, some HDR drilling holes are deepened from abandoned oil or gas wells, which greatly reduce the cost of HDR experiments.

As for basement rocks, previous studies confirm that granites especially young S-type or crustally-remelting granites are most suitable for HDR geothermal development (Rybach et al., 1978; Wang et al., 2014). Our statistical results based on more than 1000 samples from Guangdong Province and their adjoining provinces display that the granites have far more U, Th and K contents than those of basalts, gneisses, quartzites and migmatites and the granites have a weighted mean radiogenic heat production rate of 4.11μW/m^3. What is more, the radiogenic heat production rates of granites linearly increase from Jinningian, through Caledonian and Indosinian, to early and late Yanshanian granites (Zhou, 2006). More than 20% of the Guangdong Province is occupied by granitic rocks with different formation ages, which supply a superior condition for developing HDR geothermal resources.

As for the cover rocks, previous data display that approximately 19% of the continental area of Guangdong Province are covered by Mesozoic to Cenozoic basins, which include para-foreland basins, rift basins and faulted or graben basins (Zhou, 2006). These basins especially faulted or graben basins are vital for blocking thermal loss of underlying basement rocks. In addition, these basement and cover rocks are closely associated with deep faults like Sihui-Wuchuan and Wuzhou-Sihui faults, which guarantee the thermal and work fluid can pass through between basement and cover rocks.

In addition to radiogenic heat production rates of basement rocks, another important parameter is surface heat flow value, which is a function of radioactive element contents below the continents, the latest thermal event, and the intensity of tectonic activities. Available results suggest that Guangdong Province has relatively high heat flow values with many regions being larger than 80 mW/m^2 (Hu et al., 2000; Wang et al., 2012). Many hot springs distributed around the granite bodies also confirm that the province is a thermal anomaly area with great geothermal development potential.

Guangdong Province is rich in water resources, which also supply an important base for abstracting HDR geothermal resources because water is essential as work fluid.

2.2 Distribution of Granite bodies

More than two hundred granitic bodies with a total area of 135000 km^2 are distributed in the Nanling Range, South China. Totally, these granites can be grouped into three nearly parallel E-W granitoid belts, i.e., Southern granite belt with length of ca. 260 km and width of ca. 50 km, Middle granite belt with width and length of ca. 35 km and ca. 400 km, and Northern granite belt of ca. 35 km width and ca. 300 km length. In the present study, we select five representative large granite bodies from different granite belts and focus on their radiogenic U, Th and K content determination, which is the major target of EGS Investigation Project of China in 2003. Here, five representative granite bodies in question are briefly introduced as follow (Figures 1 and 2).

Fogang granite body of Southern granite belt cover a total area of 6000 km^2, it is a compound granite body with main magma emplacement timing at ca. 162 Ma (Figure 2). More than 90% Fogang rock body is hornblende-bearing granite with minor A-type granite. Elemental and isotopic data indicate that most of the granites are sourced from remelting of pre-existing crustal materials with minor mantle material involvement (Zhao, 1993; Zhou et al., 2000; Wang et al., 2013).

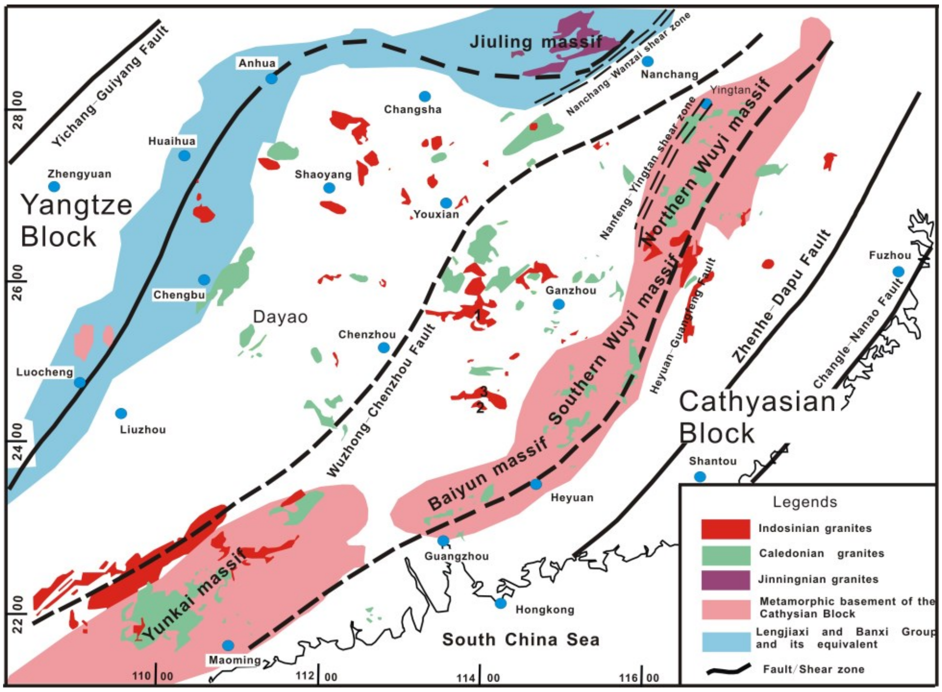

Figure 1: The figure showing the major granite bodies in Guangdong province and its adjoining provinces (modified from Wang et al., 2013). Three Indosinian granites are investigated in this study. 1=Zhuguang rock body, 2= Reshui rock body, 3=Guidong rock body.

Guidong, Reshui and Xiazhuang granite bodies belong to the Middle granite belt, which cover areas of 60 km^2, 185 km^2 and 300 km^2, respectively. Zircon U-Pb dating results suggest that they are formed at ca. 239 Ma, 228 Ma and 164 Ma, respectively (Figures 1 and 2). Although they have different formation ages, their rock types are of biotite granites. Integrated petrological, elemental and isotopic data show that they are of S-type granites, which originate from partial melting of meta-sedimentary rocks with no involvement of mantle-derived materials (Zhao, 1993; Zhou et al., 2000; Wang et al., 2013). It is noted here that these three granite bodies could be a big compound body in the depth.

Zhuguang granite body with a total area of ca. 5000 km^2 belongs to the Northern granite belt. It is a compound rock body with different granite emplacement ages, of which Indosinian granite are predominant (Figure 1). Geochemical data exhibit that these Indosinian granites are mainly sourced from remelting of Paleoproterozoic metamorphic basement rocks (Zhao, 1993; Zhou et al., 2000; Wang et al., 2013).

3. SAMPLING AND ANALYSIS

For present study, 207 samples have been collected from above-mentioned five granite bodies. Specially, 37 samples were collected from various locations of Fogang granite body, 4, 12 and 26 samples were taken from Guidong, Reshui and Xiazhuang rock bodies, respectively, and 128 samples were collected from Zhuguang granite body.

The Th, U and K_2O concentrations of all the granite samples are determined by ICP-MS and XRF, respectively. Analytical uncertainties range from ± 1% to ± 5% for K_2O, from ± 5% to ± 10% for Th and U, respectively. Densities of all the samples are measured by means of Archimedes' principle (buoyancy method).

The radiogenic heat production rates of granites are calculated using the following equation (Rybach, 1988);

$$A[\mu W/m^3]=10^{-5} \times \rho[kg*m^{-3}] \times (2.56\times C_{Th} [ppm] +9.52 \times C_U [ppm] + 3.48\times C_K [\%])$$

The results will be discussed in Section 4.

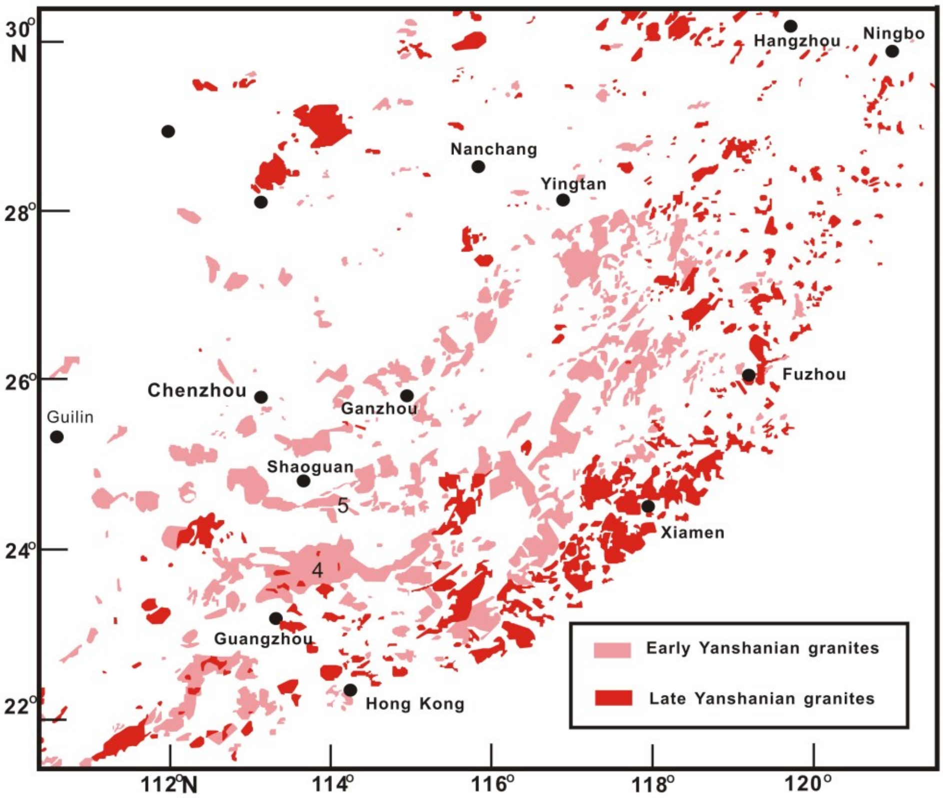

Figure 2: The figure showing the major granite bodies in Guangdong province and its adjoining provinces (modified from Wang et al., 2013). Two early Yanshanian granites are investigated in this study. 4=Fogang rock body, 5= Xiazhuang rock body.

4. RESULTS AND DISCUSSION

The Whole 207 granite samples from Guangdong Province are carried out for density, U, Th and K content determination, respectively. The 207 granite samples display a limited range from 2.42 to 2.72 g/cm^3, and Zhuguang, Guidong, Xiazhuang, Reshui and Fogang rock bodies have weighted rock densities of 2.60, 2.61, 2.60, 2.59 and 2.57g/cm^3, respectively (Table 1). Totally, they have a relatively wide range of Th, U and K contents fitting the features of normal distribution, which are in good agreement with the previous results. Weighted mean U, Th and K_2O contents and the radiogenic heat production rates (A) are listed in Table 1. The weighted mean Th contents are 40, 41, 31, 46, 51 ppm, U contents are 11, 9, 18, 14, 11 ppm, K_2O contents are 5.43, 4.02, 5.34, 4.95 and 5.12 %, respectively. U, Th and K_2O contents are systematically higher than those of continental crust. Volumetric heat production rates of the five granite bodies are 5.98, 5.28, 6.92, 7.11, 6.77 μW/m^3, respectively (Table 1), which are equal to or higher than those of Switzerland HDR sites (Rybach et al., 1978). In addition, the radiogenic heat production rates decrease from Reshui, through Fogang and Xiazhuang, to Zhuguang and Guidong rock bodies. Different from the other granite rock bodies, the Xiazhuang rock body has much lower Th/U ratio of 2.14, which is even lower than that of continental crust, implying that the Xiazhuang rock body is rich in U but poor in Th. In fact, some big uranium deposits are found in Xiazhuang rock body.

Our new data, in combination with previous petrology, geochronology, geochemistry, geothermics, together suggest that Guangdong Province is an important thermal anomaly region, which is only next to Southwest China (Wang et al., 2014). Thus, Guangdong Province has great potential to develop HDR geothermal resources.

Developing HDR geothermal resources in Guangdong Province also have some special implications. Firstly, Guangdong is an important industrialized province with great energy consumption but with limited fossil energy exposure, which seriously constrain its economical and social development. If we can massively develop local HDR geothermal resources in this province, it will rapidly prompt its development level. Secondly, the whole Guangdong Province is largely occupied by granite bodies, a small portion of which are ore-bearing granites. For a long time, the ore-barren granites are mostly used as dimension stones, which resulted in serious pollution but with economic value. Lastly, southern provinces of China like Guangdong Province are frequently subjected to freezing rain in winter, which cause serious social damages. Some Japanese authors thought that the heat work fluid form HDR production well can be used to melt the frozen pavement.

For the Province EGS technology are still in the initial stage. More research like siting and tracing will be done in the future. However, there is no doubt that Guangdong Province is very promising as a target area to explore HDR geothermal resources.

Table 1 Weighted mean Th, U, K_2O contents for five granite bodies and their Radiogenic heat production rates

Rock body	Sample No.	Th	U	Th/U	K_2O	Average Density	A
		ppm	ppm		%		μW/m^3
ZG	128	40	11	4.83	5.43	2.60	5.98
GD	4	41	9	4.08	4.02	2.61	5.28
XZ	26	31	18	2.14	5.34	2.60	6.92
RS	12	46	14	4.01	4.95	2.59	7.11
FG	37	51	11	4.96	5.12	2.57	6.77
Total	207	41	12	4.45	5.31		6.29
Continental Crust(CC)		3.5	0.91	3.85	1.1		

Note: ZG=Zhuguang, GD=Guidong, XZ=Xiazhuang, RS=Reshui, FG=Fogang. Continental crust values are from Taylor and McLennan (1985).

4. CONCLUSION

Our new radioactive U, Th and K content determination, in combination with previous petrology, geochronology, geochemistry and geothermics data together suggest that Guangdong Province from Southeastern China has great potential for developing HDR geothermal resources.

5. ACKNOWLEDGEMENT

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