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安徽省岩浆岩放射性生热率特征研究

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摘 要: 安徽省位于中国东南部,岩浆活动频繁,燕山期岩浆活动最为发育,岩浆岩出露面积超过 13 000 km^2,不同类型、不同成因的岩石均有发育,并以大别山、长江中下游和皖南地区较为集中。本研究在安徽省不同岩浆岩带共采集 159 块样品开展岩石密度和放射性生热元素含量测试,结合前人对安徽省岩浆岩放射性生热元素的测试结果,首次对安徽省岩浆岩开展了系统的放射性生热元素统计研究。结果表明:安徽省岩浆岩总体上 U、Th、K 平均含量相差较大,花岗质岩石及中酸性火山岩的 U、Th、K 含量较高,基性岩浆岩的 U、Th、K 含量较低;不同类型的岩浆岩放射性生热率相差较大,花岗质岩石和中酸性火山岩生热率相对较高且变化范围较宽,基性岩浆岩生热率较低且变化范围较窄;金寨和长江中下游地区部分花岗岩生热率超过 5 μW/m^3,为高产热花岗岩;岩浆岩的热贡献主要来自于 U 和 Th 的放射性衰变热,K 的衰变热贡献相对较低,一般不超过 10%。通过本文研究,结合前人对安徽省地质地热等方面的研究成果,发现岩浆岩放射性生热对安徽省温泉分布、干热岩勘探和 U 矿床勘探等具有重要的意义,可为安徽省后续地热资源勘查开发研究提供支撑。

关键词: 放射性生热率; 热贡献; 岩浆岩体; 地热; 安徽省
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Characteristics of radioactive heat generation rates of magmatic rocks in Anhui Province

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Abstract: Anhui Province is located in the southeastern China, where magmatism is frequent, and the Yanshanian magmatism is the most developed. The exposed area of magmatic rocks is more than 13 000 km^2, and rocks of different types and origins are all developed, and they are concentrated in the Dabie Mountains, the middle and lower reaches of the Yangtze River, and southern Anhui. In this study, we collected 159 samples from different magmatic rock belts in Anhui Province and carried out rock density and radioactive heat-generating element content determinations. Combined with the previous test results of radioactive heat-generating elements of magmatic rocks in Anhui Province, we have carried out a systematic study on radioactive heat-generating elements of magmatic rocks in Anhui Province for the first time. The results suggest that the average contents of U, Th, and K of magmatic rocks in

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Anhui Province is quite different. Granitic rocks and intermediate-acid volcanic rocks have higher U, Th, and K contents, and basic magmatic rocks have relatively lower U, Th, and K contents. The radioactive heat generation rate of different types of magmatic rocks is quite different. The heat generation rates of granitic rocks and intermediate-acid volcanic rocks are relatively higher and the variation range is wide, while basic magmatic rocks are relatively lower and the variation range is narrow. The heat generation rates of some granites in Jinzhai and the middle and lower reaches of the Yangtze River exceed 5 μW/m^3, which are high heat production granites. The main thermal contribution of magmatic rocks comes from the radioactive decay heat of U and Th, while that of K is relatively lower, generally no more than 10%. Through this study, combined with previous research results on geology and geothermal in Anhui Province, it is found that the radioactive heat generation of magmatic rocks is of great significance to the distribution of hot springs, dry hot rock exploration and U deposits exploration in Anhui Province, which can provide further support for the subsequent exploration and development of geothermal resources in Anhui Province.

Key words: radioactive heat generation rates; thermal contribution; magmatic rocks; geothermal; Anhui Province

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地球内热主要由其自身余热和放射性元素衰变所产生的热量(约占80%)组成(Pollack *et al.*, 1993; Turcotte *et al.*, 2001)。同时,地球内热也是推动整个地球形成、发展和演化的原动力,与地球内热有关的两个重要参数分别是大地热流和岩石放射性生热率(汪集旸等, 2015)。地壳岩石中含有多种放射性元素,这些放射性元素衰变所释放出的热量是地球内热的主要来源之一(汪集旸等, 2001)。并不是所有的放射性元素都有地热研究意义,只有同时满足半衰期较长、衰变热量较高以及具有足够丰度3个条件的放射性元素才具有研究意义,U、Th、K 3种放射性元素具备上述条件,且对地球内热有足够明显的热贡献,属于放射性生热元素(赵平等, 1995; 吴耀等, 2005; Wang *et al.*, 2016)。大陆地区的地表热流主要由地幔热流和地壳内放射性生热元素U、Th、K的同位素衰变所产生的地壳热流两部分组成(胡圣标等, 1994; 汪集旸等, 2012; Erbek and Dolmaz, 2019),研究地壳中不同地区生热元素的赋存状态及其分布规律特征,对于限定大地热流的壳/幔分配、解释地温场的分布特征、寻找隐伏的增强型地热系统及研究岩石圈热结构等方面具有非常重要的意义(Kremenetsky *et al.*, 1989)。

自20世纪60年代以来,人们开始对岩石放射性生热率进行相关研究。Birch等(1968)根据美国部分地区岩体热流和生热率的联合测量,首次提出了热流和生热率之间存在着线性关系,并提出了大地热流省的概念;随后,大量研究者对不同地区不同类型生热率开展了广泛研究,如Ahmed等(2006)利用伽玛射线光谱仪对埃及中东部沙漠岩石进行放射性元素分析,探讨了放射性元素生热率与岩石的类型有很大关系;Hasterok等(2017)详细综述了世界范围内不同类型火成岩的放射性生热元素和生热率特征,并提出了相关理论解释。国内,沈显杰等(1989)对西藏地区岩石放射性生热率开展了研究,研究结果对西藏地热的开发利用产生了重要影响;赵平等(1995, 1996)研究了中国东南地区岩石生热率分布特征以及热流和岩石生热率的关系;21世纪以来,国内越来越多专家学者开展了岩石放射性生热率的相关研究工作,如西北地区油气沉积盆地、青海共和盆地、福建、广东、浙江、江西等,取得了丰硕的成果(邱楠生, 2002; 王安东等, 2015; 刘道荣等, 2019; 张超等, 2020; 旷健等, 2020; 宋炉生等, 2020)。

安徽省是一个内陆省份,位于中国东南部华东地区,地热资源丰富,开发利用潜力巨大,自20世纪50年代末以来在地质地热方面开展了大量工作,主要集中于一些浅层地热能等地热资源,然而有关安徽岩浆岩放射性生热率的研究甚少。前人对两淮煤田煤系地层岩石生热率特征进行了研究(彭涛等, 2016); Wang等(2019)对郯庐断裂带南段的热流、生热率、热结构等进行研究表明:庐枞盆地热流值最高且上地壳岩石放射性生热率极高,为15~20

μW/m³，可能与局部 U 矿化作用有关。但整体上安徽省岩体放射性生热率研究程度较低。本研究在安徽省不同地区共采集 159 块样品，并对其开展岩石密度和放射性生热元素 U、Th、K 含量测试，并系统收集前人发表的安徽省 1 240 块岩浆岩的 U、Th、K 生热元素数据，结合安徽不同岩性岩浆岩平均密度，从而计算岩石放射性生热率，探讨安徽省岩浆岩放射性生热率特征、放射性生热元素的热贡献率以及岩石放射性生热率对安徽省温泉和干热岩勘探等地热资源的意义，为安徽省后续地热资源勘查研究提供参考。

1　区域地质背景

安徽省跨华北与华南两大区域，自太古宙以来各时代地层均有发育。安徽省地层整体上可划分为华北地层区、扬子地层区和秦岭-大别地层区等 3 个地层区：华北地层区位于安徽省西北部(六安-肥西-定远-明光西北部分的地区)，整个华北地层区大都被第四系所覆盖，除部分地层缺失外，整个地层及其岩性较为发育；扬子地层区位于安徽省东南部(宿松-庐江-滁州东南部分的地区)，地层缺失较少，发育较好；秦岭-大别地层区则位于华北地层区和扬子地层区之间(安徽省地质矿产局，1987)。

安徽省岩浆活动较为频繁，主要发生在蚌埠期、晋宁期、燕山期和喜马拉雅期等。岩浆岩出露面积超过 13 000 km²，其中侵入岩占一半以上，并以大别山、长江中下游和皖南地区较为集中。自晚古生代至新生代，安徽省大地构造经历了蚌埠旋回、凤阳旋回、喜马拉雅旋回等 8 个构造旋回的演化过程，形成了一系列的断裂和坳陷，主要有东西向断裂、北北东向断裂、北东向断裂、北西向断裂、南北向断裂、逆掩断层及推覆构造等。结合安徽省岩浆岩空间分布特征与区域构造演化阶段，安徽省岩浆岩带自北向南可划分为 6 个岩浆岩带(图 1)，分别为：华北南缘岩浆岩带、北淮阳岩浆岩带、大别岩浆岩带、下扬子岩浆岩带、皖南岩浆岩带和浙西岩浆岩带(安徽省地质矿产局，1987)。

2　样品采集及分析测试方法

2.1　样品采集与收集

安徽省岩浆岩岩石类型多样，有花岗岩、二长花岗岩、钾长花岗岩、花岗斑岩、花岗闪长岩、石英闪长岩、正长岩、安山岩、粗面(安)岩、流纹岩、英安岩、玄武岩、辉绿岩、辉石岩、辉长岩等。本研究在安徽省 6 个地区共采集了 113 块地表出露的新鲜的各种类型岩浆岩样品、在金寨地区的两个钻孔 ZK52 和 ZK101 分别采集了 27 个和 19 个岩浆岩样品(岩性主要为花岗岩、二长花岗岩、花岗斑岩及石英正长岩)，每个地区确保主要岩浆岩类型样品均有采集，且所有采集样品均为新鲜样品，未见明显蚀变现象(采样位置范围见图 1)。

另外本研究在实地采集样品基础之上，系统收集前人发表的安徽省 1 240 块岩浆岩的 U、Th、K 生热元素数据，收集数据在安徽省 6 个岩浆岩带中均有分布，主要包括：华北南缘岩浆岩带的蚌埠地区、栏杆地区、徐淮地区(杨德彬等，2006，2009；童劲松，2008；李印等，2010；Yang *et al.*，2010；徐丽娟，2013；张洁等，2015；蔡逸涛等，2018；霍腾飞等，2018；陈洁等，2018；康丛轩等，2018；陈杨等，2019；周虎等，2019；Li *et al.*，2020；王伟等，2020；杨阳等，2021)；北淮阳岩浆岩带的金寨地区、舒城地区(赵新福等，2007；黄皓，2012；王萍，2013；何韬，2016；陈芳等，2016；代富强，2017；鹿献章等，2017；何俊，2018；刘晓强，2018；刘晓强等，2018；彭智等，2018；杨义忠等，2018；张晋喆等，2018；万秋等，2020；赵丹蕾，2020)；大别岩浆岩带的肥东、潜山、太湖、桐城、岳西以及张八岭地区(周承福等，2001；马昌前等，2003；赵子福等，2003；徐小军等，2005；Zhao *et al.*，2005，2007；李全忠等，2008；童劲松，2008；资锋等，2008；周力等，2014；张媛媛，2017；刘晓强，2018；尚德锋等，2018；钱辉等，2020；谭东波，2020)；下扬子岩浆岩带的安庆-贵池地区、枞阳、铜陵地区、怀宁盆地、庐枞盆地、宣城、芜湖-马鞍山及滁州地区(刘洪等，2002；黄顺生等，2004；闫峻等，2005，2012；杨小男等，2007；范裕等，2008；谢成龙等，2008；袁峰等，2008；吴才来等，2010，2016；Li *et al.*，2011；孟祥金等，2011；张智宇等，2011；刘园园等，2012；彭戈等，2012；刘春等，2012；王斌等，2012；薛怀民等，2013，2015；邱宏，2014；段留安等，2015；胡子龙，2015；苏阳，2015；杨一增，2015；褚庚，2016；江峰，2017；夏冬梅，2017；杜欣，2018；梁胜男，2018；王世伟等，2018；张继开，2018；张赞赞等，2018；李现锁，2019；刘光贤，2019；

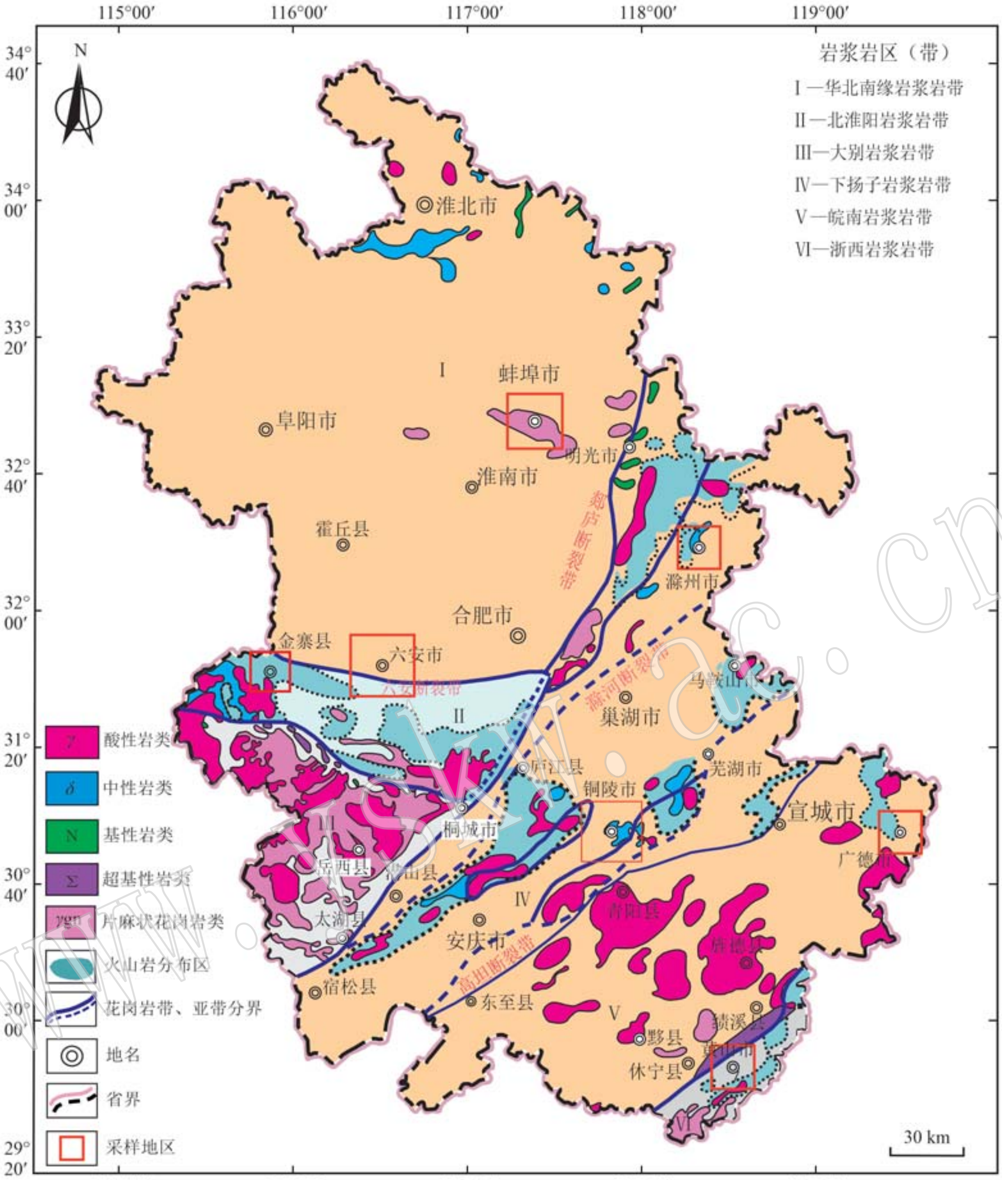

图 1 安徽省岩浆岩带分布简图(据安徽省地质矿产局, 1987)

Fig. 1 Geological sketch of magmatic rock belts in Anhui Province (revised from Bureau of Geology and Mineral Exploration of Anhui Province, 1987)

罗贤文, 2019; Wang *et al.*, 2019; 杨彪等, 2020; 汪海, 2020; 吴迪, 2020; 徐晓春等, 2020; 岳娜等, 2020); 皖南岩浆岩带的池州、宣城、旌德、祁门、青阳-九华山及歙县地区(李献华等, 2002; Wu *et al.*, 2006; 吴荣新等, 2007; Zheng *et al.*, 2008; 王文俊, 2009; 王德恩等, 2011; 李双等, 2012, 2014; 王斌等, 2012; 周翔等, 2012; 张俊杰等, 2012; 陈雪霏等, 2013; 何苗, 2013; 周洁等, 2013; 陈芳等, 2014, 2015; 陈思, 2014; 范羽等, 2016; 汪雅菲, 2015; 雷丁尔, 2016; 周术召等, 2016; 陈雪锋等, 2017; 蔡杨等, 2018; 胡青, 2018; 孔志岗等, 2018; 刘秀等, 2019; 付翔等, 2020; 柯宏飙等, 2020; 汪子莘, 2020; 岳倩, 2020; 王存智等, 2021; 薛怀民, 2021; 张建芳等, 2021); 浙西岩浆岩带的长陔、青山、大岭脚及古祝岩体(樊佳星, 2015)。

考虑到二长花岗岩、花岗斑岩、花岗闪长岩和正长岩等岩石的放射性生热元素含量和生热率值相近, 把它们归为花岗质岩石大类; 流纹岩、英安岩和安山岩等岩石的放射性生热元素含量和生热率值相近, 把它们归为中酸性火山岩大类; 辉长岩、辉绿

岩、辉石岩和玄武岩等放射性生热元素含量和生热率值相近, 把它们归为基性岩大类。

2.2　分析测试方法

样品的密度测试工作由东华理工大学核资源与环境国家重点实验室完成。将采集的 159 块新鲜岩石样品经室内处理后, 采用电子天平浮称法结合蜡封法处理测得所有岩石样品的密度, 密度测试过程中克服了机械天平所存在的缺陷, 进一步提高测试精度, 误差范围为 5%。放射性生热元素含量由安徽省地质实验研究所和安徽省核工业勘查技术总院测定完成。在地球化学分类上, U 和 Th 属于微量元素, 而 K 则属于主量元素, 所以一般用氧化物 K_2O 来表示。其中, 微量元素 U 采用激光荧光法, 微量元素 Th 采用 ICP-AES 法, 误差均在 5% 范围以内; 主要元素 K 则采用火焰原子吸收法, 误差在 2% 范围以内。

3　分析结果及讨论

3.1　岩石放射性生热率计算

岩石放射性生热率是指单位体积的岩石在单位时间内由其所含的放射性元素衰变所产生的热量。对于岩体放射性生热率计算问题的研究, 不同学者提出了不同的计算公式(Rybach, 1976; Wollenberg and Smith, 1987)。本文采取 Rybach 等(1978)提出的岩石放射性生热率计算经验公式 $A = 10^{-5}\rho(9.52\ C_U+2.56\ C_{Th}+3.48\ C_K)$ 对安徽省岩浆岩进行生热率计算。其中, A 为岩石放射性生热率, 单位为 $\mu W/m^3$; ρ 为岩石密度, 单位为 kg/m^3; C_U、C_{Th} 分别为岩石中放射性元素 U、Th 的含量, 单位为 10^{-6}; C_K 为岩石中 K 的质量分数, 单位为%。由该公式也可以看出, 岩石放射性生热率的大小与岩石密度及岩石中放射性生热元素 U、Th、K 的含量密切相关。

本文采集到的岩浆岩样品按照其实测的密度及 U、Th、K 含量进行计算; 收集到的各岩浆岩放射性生热率计算采用安徽省不同岩性岩浆岩平均密度及收集到的岩浆岩 U、Th、K 含量进行计算; 岩性略有差异时, 采用其近似岩类的平均密度值进行计算。安徽省不同岩性岩浆岩平均密度见表 1。将本文采集的 159 块样品的密度和 U、Th、K 含量以及收集的岩浆岩 U、Th、K 含量和各岩类的平均密度分别代入放射性生热率经验计算公式可计算出岩石放射性生热率, 计算结果见表 2。图 2 对比了安徽省不同岩性岩浆岩的放射性生热元素含量。

表 1　安徽不同岩性岩浆岩平均密度

Table 1　Average density of magmatic rocks of different lithology in Anhui Province

岩性	$\rho/(kg\cdot m^{-3})$
花岗岩	2 620.00
花岗斑岩	2 540.00
流纹岩	2 330.00
安山岩	2 500.00
(石英)闪长岩	2 670.00
玄武岩	2 720.00
辉绿岩	2 740.00
辉长岩	2 920.00

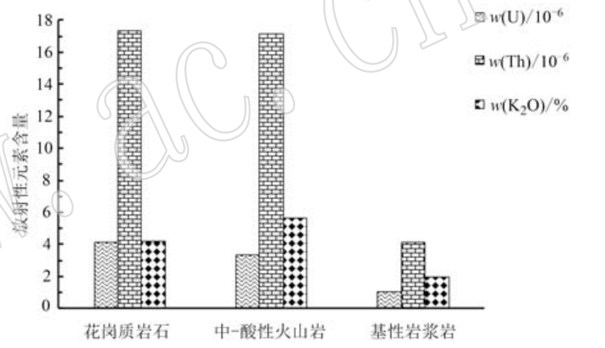

图 2　安徽不同类型岩浆岩放射性元素平均含量对比

Fig. 2　Comparison of average contents of radioactive elements in different types of magmatic rocks in Anhui Province

由表 2 和图 2 可知, 安徽省岩浆岩总体上 U、Th、K 平均含量相差较大, 花岗质岩石及中酸性火山岩的 U、Th、K 含量较高, 基性岩浆岩的 U、Th、K 含量较低; 金寨地区采集的钻孔岩芯样品, 整体上 U、Th、K 的含量以及生热率都相对较高。这与前人研究总结出岩石圈中的酸性岩富集 U 和 Th, 基性岩亏损 U 和 Th 这一结论是一致的。

安徽省不同类型的岩石放射性生热率相差较大(图 3), 花岗质岩石(0.51~15.84 $\mu W/m^3$)和中酸性火山岩(0.72~6.56 $\mu W/m^3$)生热率变化范围较宽, 均值分别为 2.51 $\mu W/m^3$ 和 2.27 $\mu W/m^3$; 基性岩浆岩平均生热率变化范围较窄(0.16~2.57 $\mu W/m^3$)且较低, 均值为 0.73 $\mu W/m^3$。通过本研究计算:安徽省花岗岩平均生热率为 2.51 $\mu W/m^3$, 接近世界范围内花岗岩放射性生热率的平均值 2.5 $\mu W/m^3$(McLaren *et al.*, 2003; Wang *et al.*, 2016), 低于福建漳州花岗岩放射性生热率平均值 4.22 $\mu W/m^3$(杨立中等, 2016; Wang *et al.*, 2016); 金寨地区钻

表 2 安徽不同类型岩浆岩 U、Th、K 含量,生热率及放射性生热元素热贡献

Table 2 U, Th, K contents, heat generation rate and thermal contribution of radioactive heat-producing elements of different types of magmatic rocks in Anhui Province

岩浆岩带/地区	岩石类型实测数(收集数)	U 含量范围(均值)/10^{-6}	Th 含量范围(均值)/10^{-6}	K_2O 含量范围(均值)/%	生热率范围(均值)/μW/m^3	A_U/A_K 范围(平均值)	A_{Th}/A_K 范围(平均值)	Th/U 范围(平均值)
华北南缘岩浆岩带	花岗质岩石 4(127)	0.45~12.91(2.77)	0.68~29.60(6.94)	1.74~5.76(3.86)	0.51~4.23(1.45)	0.37~8.11(2.30)	0.11~5.51(1.51)	0.05~17.83(2.69)
	基性岩浆岩(29)	0.15~1.26(0.74)	0.75~5.06(3.12)	0.26~2.75(1.49)	0.16~0.89(0.54)	0.47~2.66(1.60)	0.63~4.19(1.91)	3.44~6.14(4.52)
北淮阳岩浆岩带	中酸性火山岩 6(53)	0.48~9.94(2.44)	5.51~58.20(17.08)	0.73~10.62(4.39)	0.72~6.56(1.99)	0.60~11.38(2.10)	1.27~21.19(3.74)	4.10~21.90(7.43)
	花岗质岩石 51(150)	0.32~20.80(3.98)	3.04~79.3(20.70)	0.46~7.90(4.40)	0.72~9.06(2.70)	0.11~15.58(2.89)	0.57~13.35(4.10)	0.54~31.29(6.69)
	基性岩浆岩(10)	0.27~0.84(0.47)	1.52~6.41(3.05)	0.62~2.77(1.55)	0.24~0.84(0.46)	0.48~2.13(1.22)	0.80~3.45(2.05)	5.17~7.63(6.26)
大别岩浆岩带	花岗质岩石(95)	0.58~9.45(2.93)	4.19~51.54(16.31)	2.06~5.76(4.29)	0.71~6.18(2.15)	0.55~6.41(2.23)	1.03~9.40(3.29)	3.04~12.72(5.84)
	基性岩浆岩(36)	0.08~4.62(1.03)	0.90~9.79(3.09)	0.45~3.90(1.72)	0.28~2.19(0.65)	0.10~10.26(2.65)	0.43~4.09(1.79)	0.77~23.93(4.17)
下扬子岩浆岩带	中酸性火山岩(97)	0.79~16.25(3.89)	4.51~49.20(17.42)	1.89~15.69(6.61)	0.80~3.14(2.46)	0.29~8.69(2.37)	0.36~7.82(2.80)	0.84~12.26(5.02)
	花岗质岩类 11(317)	0.71~19.60(3.44)	2.84~86.90(16.14)	0.52~33.21(4.14)	0.72~10.28(2.26)	0.16~13.95(2.89)	0.11~14.84(3.40)	0.96~25.58(4.66)
	基性岩浆岩 6(29)	0.37~5.26(1.60)	2.04~13.10(6.56)	0.55~6.16(2.83)	0.28~2.57(1.09)	0.41~8.41(2.79)	0.91~6.29(2.77)	0.90~11.41(5.19)
皖南岩浆岩带	中酸性火山岩 8	1.36~4.55(3.34)	8.56~19.77(14.19)	1.15~5.06(3.1)	1.04~2.68(2.06)	2.33~5.98(3.79)	2.19~7.19(4.53)	1.88~6.86(4.55)
	花岗质岩石 17(279)	1.00~20.10(4.88)	3.78~67.60(19.22)	0.59~9.44(4.16)	0.88~8.70(2.81)	0.91~13.69(3.84)	0.69~16.37(4.10)	0.33~13.25(4.34)
	基性岩浆岩 10	0.58~1.21(0.82)	2.48~4.89(3.51)	0.94~1.64(1.22)	0.46~0.83(0.59)	1.92~2.79(2.22)	2.00~3.21(2.56)	3.71~5.22(4.29)
浙西岩浆岩带	花岗质岩石(18)	3.20~17.75(6.87)	9.39~27.50(16.88)	3.63~5.47(4.55)	1.76~5.97(3.19)	2.85~11.87(4.95)	2.09~6.08(3.28)	0.98~4.97(2.91)
金寨地区钻孔	花岗质岩石 46	1.85~29.46(10.41)	4.20~123.90(30.89)	2.56~6.45(4.79)	1.16~15.84(5.01)	1.29~25.11(7.03)	0.87~28.83(5.52)	1.14~8.91(3.26)

注:表中实测数据为本文数据,收集数据来源文献见正文 2.1 节。

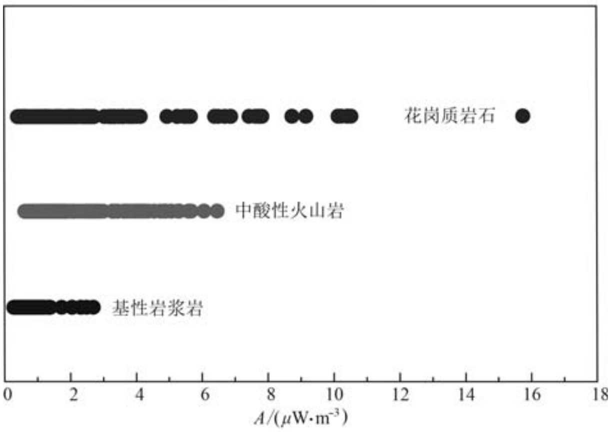

图 3 安徽不同类型岩浆岩放射性生热率对比

Fig. 3 Comparison of radioactive heat generation rates of different types of magmatic rocks in Anhui Province

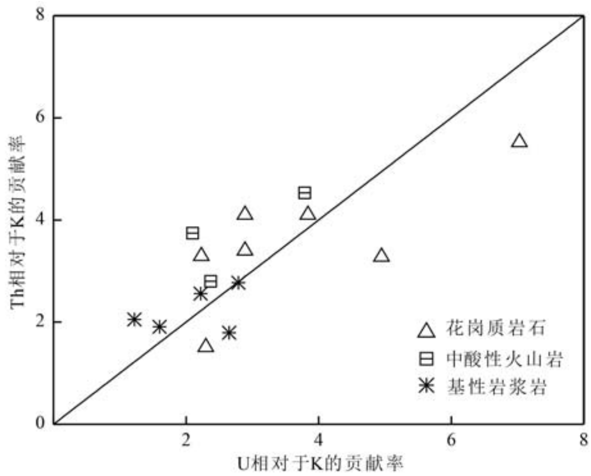

图 4 安徽不同类型岩浆岩 U、Th 相对 K 的热贡献率关系图

Fig. 4 Thermal contribution ratio of U and Th to K in different types of magmatic rocks in Anhui Province

孔花岗质岩石平均生热率为 5.01 μW/m^3，均值超过 5 μW/m^3，属于高产热花岗岩(Kamonporn, 2010)。

3.2 岩体放射性生热元素热贡献及 Th/U 特征分析

放射性生热元素的热贡献率是放射性生热率特征的重要体现。岩石放射性生热率 A 由 $A_U = 10^{-5}\rho \cdot 9.52\ C_U$，$A_{Th} = 10^{-5}\rho \cdot 2.56\ C_{Th}$ 和 $A_K = 10^{-5}\rho \cdot 3.48\ C_K$ 三部分构成，而放射性生热元素 U、Th、K 随着地球演化而不断衰变，丰度值逐渐降低，放射性生热量也随之不断减少。根据岩石放射性生热率计算公式可以进一步计算出 U 和 Th 相对于 K 的贡献率：A_U/A_K 和 A_{Th}/A_K。计算结果见表 2。

为进一步表征 U 和 Th 的相对贡献率，对安徽境内不同类型的岩浆岩分别作 U 相对 K 的贡献率与 Th 相对 K 贡献率的关系图(图 4)，结果显示(表 2 和图 4)：安徽省整体上，只有小部分的花岗质岩石和基性岩浆岩 $A_U/A_K>A_{Th}/A_K$；其他花岗质岩石、中-酸性火山岩和基性岩浆岩 $A_U/A_K<A_{Th}/A_K$。这可能是因为 Th 的半衰期较长，热贡献的相对比例逐渐增大，而 U 的半衰期较短，热贡献的相对比例逐渐减小，与前人研究结果一致(Arevalo *et al*., 2009)。热贡献特征上，安徽省岩浆岩尤其是花岗质岩石明显不同于南岭地区花岗质岩石，后者 U 的贡献率一般高于 Th 的贡献率，这也与整个南岭地区花岗岩整体上富 U 这一事实相一致。

U、Th、K 元素尤其是 U、Th 元素在地球内热演化中的特殊意义，不少研究者探讨了 U、Th 元素之间的内在变化关系，并基于已有的大量岩石地球化学数据开展统计分析，从而为重新认识放射性生热元素的分布特征和变化规律提供了新的研究视角。由于 Th、U、K 均为不相容元素，在岩浆活动过程中易进入熔体相，因此大部分情况下在自然界岩石中它们之间具有一定的关联性。Taylor 等(1985)、Van Schmus(1995)和 Rudnick 等(2004)基于大量数据统计给出全球上地壳的 Th/U 值在 3.8 到 4.3 之间；许保良等(1995)按岩体的 Th/U 值大小将岩体划分为富铀花岗岩(Th/U<3)，正常花岗岩(3<Th/U<6)，低铀花岗岩(Th/U>6)。由表 2 可知，华北南缘、浙西岩浆岩带和金寨地区花岗质岩石 Th/U 值相对较低，华北南缘低 Th/U 值可能与其为高分异的淡色花岗岩有关(郭素淑等，2009)；浙西岩浆岩带的低 Th/U 值可能与其地处十杭带、壳-幔混合成因有关(Zhou *et al*., 2020)；上述两地花岗岩 Th/U 值较低且生热元素含量和生热率均不太高，可能是岩浆源区和演化过程造成的低 Th/U 值，并不是真正意义上的富铀花岗岩。金寨地区花岗岩不仅 Th/U 值较低且生热率相对较高，与 Wang 等(2019)报道的长江中下游地区部分花岗岩的特征类似，它们可以代表真正意义上的富铀高产热花岗岩，且这两地在野外均见有铀矿化点。

3.3 安徽岩体放射性生热与地热资源

地热资源作为一种可再生清洁能源在供暖、发电、洗浴、种养殖等方面得到广泛利用，利用率较高且开发前景较好。地热资源一般分为 3 类，分别为浅层地热能、水热型地热资源和干热岩资源。

安徽省温泉在地理分布上多数位于隆起的大别山区、长江沿岸的巢湖-和县一带以及皖南山区，皖东及淮北较少(李肖雪等，2020)。根据前人研究，复杂的构造体系可以为温泉提供冷热水富集通道，花岗岩类岩体可提供比较可靠的热来源，大多数温泉都发育在花岗岩类岩体中。大量的花岗岩类岩体通过放射性元素产生的热量，为温泉提供良好的热来源(李文庆，2015)。本研究显示北淮阳-大别岩浆岩带、下扬子岩浆岩带和皖南岩浆岩带具有相对高的岩石生热率，而安徽省目前发现的地热资源也主要集中在上述3个区域，表明岩石生热率与温泉出露关系密切，对地热分布主要良好的控制作用。此外，北淮阳金寨地区和长江中下游部分地区岩体生热率较高，超过5 $\mu W/m^3$，属于高产热花岗岩，对于寻找干热岩也具有十分重要的意义。由于安徽省干热岩研究基础资料相对较少，如大地热流、盖层及岩体地温梯度、隐伏岩体的分布等研究程度较低，金寨地区和长江中下游地区是否具有干热岩资源潜力尚需要进一步工作验证。

4 结论

(1) 安徽省不同类型的岩浆岩放射性生热率相差较大。花岗质岩石及中酸性火山岩生热率相对较高且变化范围较宽，分别为0.51~15.84 $\mu W/m^3$ 和0.72~6.56 $\mu W/m^3$，均值分别为2.51 $\mu W/m^3$ 和2.27 $\mu W/m^3$；基性岩浆岩生热率相对较低且变化范围较窄，范围为0.16~2.57 $\mu W/m^3$，均值为0.73 $\mu W/m^3$。

(2) 安徽省不同类型岩浆岩整体上Th热贡献率大于U。华北南缘、浙西岩浆岩带花岗质岩石Th/U值相对较低，且生热元素含量和生热率均不太高；金寨地区花岗岩Th/U值较低且生热率相对较高(5.01 $\mu W/m^3$)，属于富铀高产热花岗岩，可为U矿床勘探提供依据。

(3) 北淮阳金寨地区和长江中下游部分地区岩体生热率较高，超过5 $\mu W/m^3$，属于高产热花岗岩。结合有效资料分析，金寨地区和长江中下游地区可能适合进一步开展高放射性产热型干热岩勘查。

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