doi: 10.12029/gc20190615

康丛轩, 杨献忠, 蔡逸涛, 黄先觉, 孔广林, 李朝维. 2019. 华北克拉通南缘蚌埠隆起古元古代侵入体地质地球化学特征[J]. 中国地质, 46(6): 1481−1495.

Kang Congxuan, Yang Xianzhong, Cai Yitao, Huang Xianjue, Kong Guanglin, Li Chaowei. 2019. Geological and geochemical characteristics of the Paleoproterozoic intrusions in Bengbu uplift, southeast North China Craton[J]. Geology in China, 46(6): 1481−1495(in Chinese with English abstract).

华北克拉通南缘蚌埠隆起古元古代侵入体地质地球化学特征

康丛轩[1,2],杨献忠[1],蔡逸涛[1],黄先觉[3],孔广林[3],李朝维[3]

(1.中国地质调查局南京地质调查中心,江苏 南京 21006;2.河海大学地球科学与工程学院,江苏 南京 211100;
3.安徽省地质矿产勘查局312地质队,安徽 蚌埠 233040)

提要:华北陆块是世界上最古老、最大的克拉通地块之一。蚌埠隆起作为华北陆块的组成部分,其初始陆壳的形成时限为中太古代晚期,随着扬子陆块与华北陆块碰撞、拼接,经历了较为复杂的演化过程。为了深入探讨蚌埠隆起带古元古代岩浆活动,更新补充年代学及岩石地球化学分析数据,本次通过对区内古元古代侵入体的野外观察、年代学和岩石地球化学研究,在庄子里岩体和磨盘山岩体中分别获得锆石U-Pb年龄为(2089±44)Ma、(2133±27)Ma。地球化学研究显示两岩体明显富钠贫钾,总体铝碱比偏高,钙碱比偏低,属准铝—铝过饱和类型;轻稀土相对富集,具明显的铕负异常,铈异常不明显或无异常;K、Nb、Sr、P和Ti有较明显的亏损,Rb、Th、U、Nd、Zr和Sm相对富集,成因类型具备造山后A型花岗岩特征。$\varepsilon_{Nd}(t)$值介于−3.87~+3.20,暗示侵入体可能来源于同一源区,Nd两阶段模式年龄(2.37~2.84 Ga)与华北克拉通主体形成于太古宙,并以2.40~2.50 Ga为主体相一致。$\varepsilon_{Hf}(t)$值介于−9.77~+9.59,且差别较大,说明其具物质起源的复杂性,古老的两阶段Hf模式年龄(2.27~2.96 Ga)说明其物质起源主要为新太古宙,与蚌埠隆起拉张背景时间上具有一致性。构造环境判别属板内花岗岩范畴,表现为非造山构造环境,暗示其伸展构造背景。

关 键 词:华北克拉通;蚌埠隆起带;古元古代侵入体;地球化学;年代学;安徽省;地质调查工程

中图分类号:P581 **文献标志码**:A 文章编号:1000−3657(2019)06−1481−15

Geological and geochemical characteristics of the Paleoproterozoic intrusions in Bengbu uplift, southeast North China Craton

KANG Congxuan[1,2], YANG Xianzhong[1], CAI Yitao[1], HUANG Xianjue[3], KONG Guanglin[3], LI Chaowei[3]

(1.*Nanjing Center of Geological Survey, CGS, Nanjing* 210016*, Jiangsu, China;* 2. *School of Earth Sciences and Engineering, Hohai University, Nanjing* 210016*, Jiangsu, China;*3. *No. 312 Geological Party, Bureau of Geology and Mineral Resources Exploration of Anhui Province, Bengbu* 233040*, Anhui, China*)

收稿日期:2018−04−26;**改回日期**:2019−04−04

基金项目:安徽省公益性地质调查基金项目(2014−K−5)资助。

作者简介:康丛轩,男,1985年生,博士生,助理研究员,主要从事矿物、岩石、矿床学及工程地质研究;E−mail:kangcongxuan@sina.com。

Abstract: North China landmass is the oldest landmass and one of the largest craton massifs in the world. Bengbu uplift is a part of the North China landmass, and its initial formation of continental crust is late Archean in the time limit. With the collisions and stitching of the Yangtze platform and North China continental block, the Bengbu uplift experienced complex evolution processes. In order to further explore the Paleoproterozoic magmatic activity in the Bengbu uplift, the authors updated the data of geochronologic and geochemical analysis. Based on field observation, geochronology and geochemistry of Paleoproterozoic intrusions in this area, the authors obtained zircon U−Pb ages of (2089±44)Ma and (2133±27)Ma for Zhuangzili and Muopanshan granites. The geochemical data show that granites have high−Na and low−K significantly, and belong to the quasi−aluminum supersaturated type. They are characterized by relative enrichment of LREE with a strong Eu negative anomaly and insignificant Ce anomaly. The elements of K, Nb, Sr, P and Ti are characterized by measurable depletion, and there exists relative enrichment of Rb, Th, U, Nd, Zr and Sm. Intrusion projection points are distributed in A type granite area in the discrimination diagram of genetic type. Nd two−phase age (2.37−2.84 Ga) is consistent with the age of North China Craton formed in Archean, with 2.40−2.50 Ga being the main stage. $\varepsilon_{Hf}(t)$ values vary between −9.77 and +9.59, with obvious differences, suggesting the complexity of the origin of the material, and the old two−phase Hf model age (2.27−2.96 Ga) suggests that the main material was derived during Neoarchean. The tectonic environment belongs to the granite category within the plate and non−orogenic tectonic environment, which implies its extensional tectonic setting.

Key words: North China Craton; Bengbu uplift; Paleoproterozoic intrusions; geochemistry; chronology; Anhui Province; geological survey engineering

About the first author: KANG Congxuan, male, born in 1985, doctor candidate, mainly engages in the study of minerals, rocks, deposit geology and engineering geology; E−mail：kangcongxuan@sina.com.

Fund support: Supported by Anhui Public Welfare Geological Survey Fund (No. 2014−K−5).

1 引　言

蚌埠隆起带位于华北克拉通东南缘,区内花岗质岩石出露广泛,前人研究积累了大量的年代学和同位素地球化学数据(邱瑞龙等,1999;靳克等,2003;许文良等,2004;徐祥等,2005;杨德彬等,2005,2006,2007,2009;郭素淑等,2009;Liu et al., 2009, 2013, 2017;李印等,2010;王娟等,2014、2016;刘贻灿等,2015;宋利宏等,2016;Wang et al., 2017;Kang et al., 2017;赵越等,2017;康丛轩等,2018a,b;刘书生等,2018)。花岗岩是研究深部作用的“探针”,通过对花岗岩岩石学、地球化学的研究可以获得深部地壳结构和物理化学过程,分析其物质来源、构造背景等信息。近年来华北克拉通的研究取得了较多的成果,华北克拉通基底岩石的高精度定年结果显示,其主要经历了2500 Ma和1800 Ma左右两次重大的地质事件(Zhao, 2001)。郭素淑等(2009)通过对蚌埠隆起区五河群大理岩层所夹的榴闪岩透镜体变质年龄和蚌埠隆起东端石门山变形花岗岩的岩浆结晶年龄的研究指出,华北陆块东南缘也存在古元古代活动带,它的变质和岩浆事件发生时代与华北克拉通其他3个古元古代活动带一致。区域内五河岩群变质地层中包含大量的古深成侵入体,成分上大体相当于英云闪长质、奥长花岗质、花岗闪长质、二长花岗质和钾长花岗质。这些岩石在空间上紧密共生,成因上紧密联系(童劲松等,2014)。杨德彬等(2009)通过庄子里和磨盘山钾长花岗岩中锆石的LA−ICP−MS U−Pb定年结果和岩石地球化学以及锆石的Hf同位素特征讨论了岩石成因。这些成果对进一步理解华北克拉通的演化提供了精细的研究数据和成熟的理论依据。

为了进一步探讨本区古元古代侵入体的特征及其对区域岩浆作用的制约,加深对本期变质侵入体成因的理解,本文结合笔者的实际工作,通过对蚌埠隆起带东部边缘,出露于郯庐断裂带内的目标岩体进行系统岩石学、年代学、地质地球化学分析,对比前人研究成果及对前人成果的再认识,对该期侵入体进行成因分析,总结归纳其动力学背景,更新和补充了蚌埠隆起带古元古代侵入体年代学及岩石地球化学分析成果,希望在前人基础上进一步深入理解华北克拉通东南部古元古代时限内的岩浆作用及动力学演化,对蚌埠隆起带构造演化的进一步理解有一定的科学意义。

2　地质背景及岩体地质

蚌埠隆起带东接郯庐断裂，南邻大别造山带后陆盆地，总体呈东西向带状展布。区内岩浆作用以中生代和新生代最为强烈，侵入岩以中酸性花岗岩类为主。区内出露的古元古代侵入体主要为庄子里岩体和磨盘山岩体，分布于石门山断裂西侧的庄子里、磨盘山一带，磨盘山岩体在凤阳县的大王府和乔涧子也有出露，围岩为五河杂岩，二者侵入接触关系明显（图1）。

庄子里岩体（样品采于五河县庄子里南侧玉皇山东坡）位于五河县庄子里南侧约1 km，岩石呈土黄-浅肉红色，具似斑状结构。矿物组合主要为石英（38%~43%）、斜长石(37%~42%)及钾长石（10%~15%）（图2）；磨盘山岩体（样品采于凤阳县磨盘山西坡）出露于蚌埠市东约52 km处的石门山镇北部，岩石呈肉红色，具似斑状结构。矿物组合主要为石英（36%~41%）、斜长石(26%~31%)及钾长石（23%~28%）。两岩体岩石镜下特征相似，石英多呈他形粒状，粒径较小；斑晶主要为斜长石，基质中少见，聚片双晶发育，多具有强烈的绢云母化（图3）。

3　样品分析方法

本次研究所用样品全岩主、微量元素的测试分析在国土资源部华东矿产资源监督检测中心（南京地质调查中心）完成。主量分析仪器为帕纳科公司的Axios 4.0型波长色散X射线荧光光谱仪，微量及稀土元素分析仪器为电感耦合等离子体质谱仪，型号为美国Thermo Fisher公司的ICAP Q。

单矿物挑选在河北省廊坊市诚信地质服务有限公司完成。将挑选出的锆石颗粒置于环氧树脂制靶，固化之后抛光，用于阴极发光（CL）照相、锆石U-Pb定年及Lu-Hf同位素分析。锆石制靶及阴极发光照相在北京锆年领航科技有限公司完成。

锆石U-Pb定年及Lu-Hf同位素测试在中国地质调查局天津地质调查中心完成。定年所用仪器为多接收等离子体质谱仪，束斑直径为40 μm。采样方式为单点剥蚀、跳峰采集。普通铅校正采用Anderson(2002)提出的ComPbCorr#3.17校正程序，U-Pb谐和图、年龄分布频率图绘制和年龄权重平均计算采用Isoplot/Exver 3(Ludwig, 2008)程序完成；Lu-Hf同位素测试所用仪器为Neptune II MC-

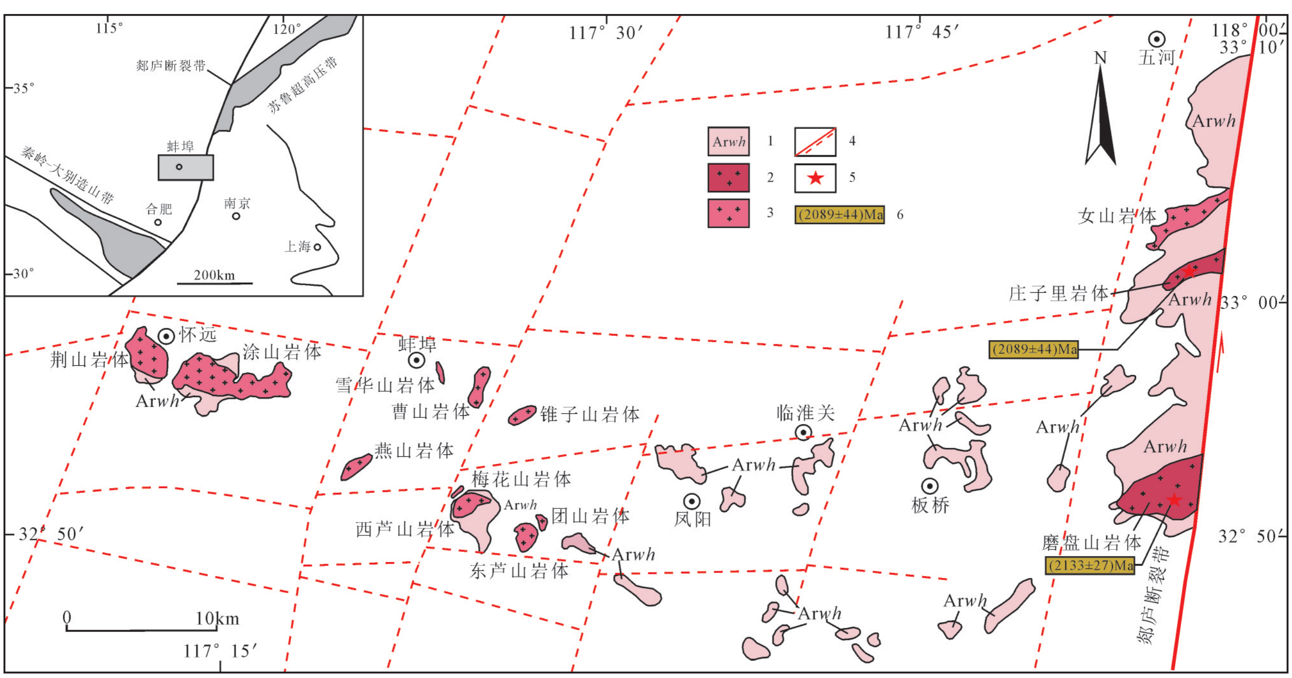


图1 蚌埠隆起地质简图（据安徽省东部1∶20万地质图；宋利宏等，2016修编）

1—五河群；2—古元古代侵入体；3—其他侵入体；4—断裂构造；5—采样位置；6—本文定年结果

Fig.1 Geology sketch of Bengbu uplift (after 1∶200000 geological map of eastern Anhui province and Song Lihong et al., 2016)

1-Wuhe group; 2-Paleoproterozoic intrusions; 3-Other intrusions; 4-Fracturing structure; 5-Sampling locations; 6-Dating results of this article

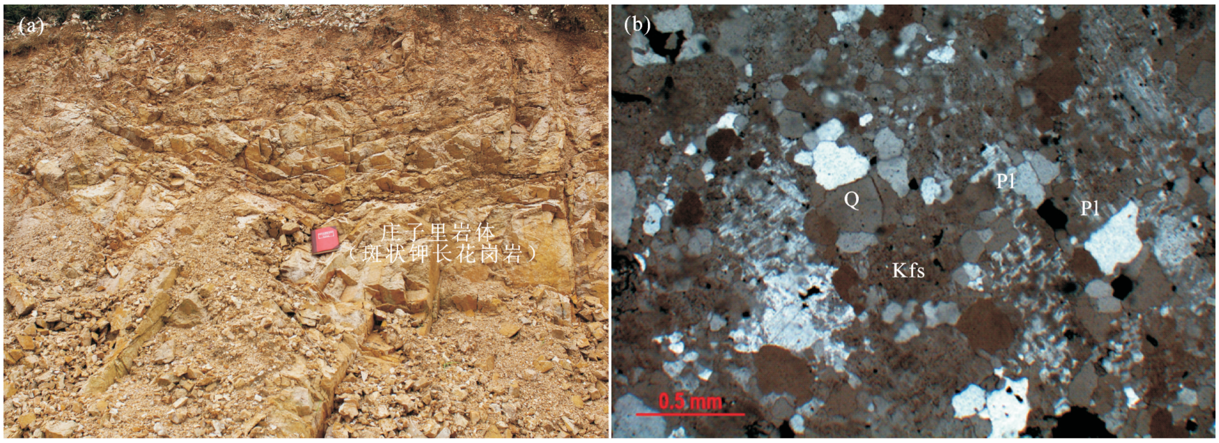


图2 庄子里岩体野外露头(a)及镜下显微照片(b)
Q—石英；Pl—斜长石；Kfs—钾长石（斜长石交代钾长石，斜长石可见聚片双晶）
Fig.2 Field outcrops (a) and microscopic microphotograph (b) of Zhuangzili granites
Q−Quartz; Pl−Plagioclase; Kfs−Potash feldspar

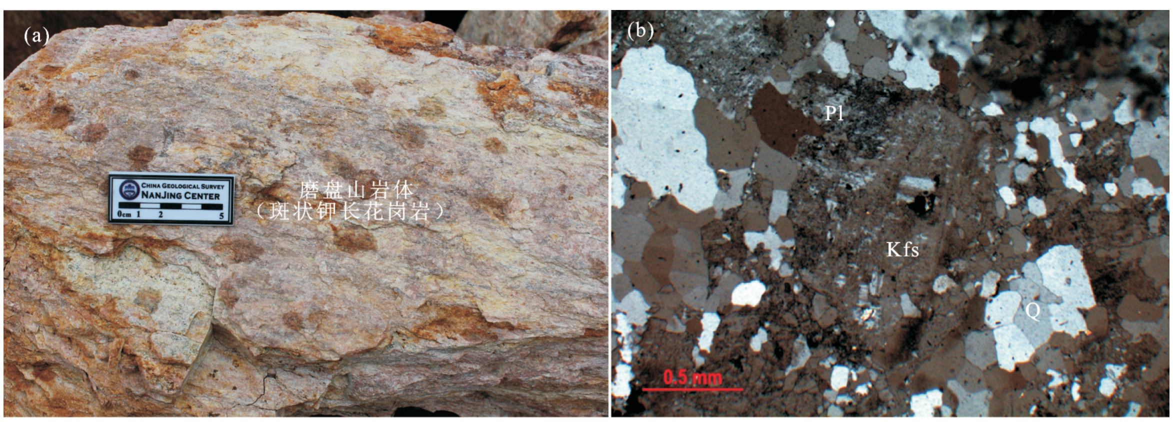


图3 磨盘山岩体野外露头(a)及镜下显微照片(b)
Q—石英；Pl—斜长石；Kfs—钾长石（似斑状结构，斜长石交代钾长石）
Fig.3 Field outcrops (a) and microscopic microphotograph (b) of Muopanshan granites
Q−Quartz; Pl−Plagioclase; Kfs−Potash feldspar

ICP−MS，对锆石测试点进行原位分析。测定时使用锆石国际标样GJ1作为参考物质。全岩Sm−Nd同位素测定在核工业北京地质研究院完成，所用仪器为IsoProbe热电离质谱仪，仪器型号为ISOPROBE−T。

4 分析结果

4.1 岩石地球化学

蚌埠隆起带古元古代侵入体全岩主量元素分析结果列于表1。庄子里岩体SiO_2含量变化于70.31%~73.18%，平均71.35%，磨盘山岩体SiO_2含量变化于77.05%~78.85%，平均78.18%；庄子里岩体分异指数*DI*=88.92%~92.74%，磨盘山岩体*DI*=90.69%~97.90%，反映了岩体经过高程度的分异演化作用；庄子里岩体(K_2O+Na_2O)=8.34%~9.09%，平均8.71%，磨盘山岩体(K_2O+Na_2O)=5.42%~7.71%，平均6.60%，表明岩浆碱硅质分异演化较为彻底，TAS图解上投影点落入亚碱性花岗岩范围（图4）；两岩体Al_2O_3含量平均分别为12.85%和11.85%；庄子里岩体钠钾比变化于1.24~1.76，磨盘山岩体为0.51~50.23；两岩体铝饱和指数（A/CNK）为0.85~1.19和0.97~1.96，庄子里岩体更接近于1；铝碱比为

表1 蚌埠隆起带古元古代侵入体主量元素组成(%)

Table 1 Major compositions of Paleoproterozoic intrusions in Bengbu uplift (%)

样品	DZZL-1	DZZL-2	DZZL-3	DMPS-1	DMPS-2	DMPS-3
SiO_2	73.18	70.31	70.55	78.85	78.64	77.05
TiO_2	0.58	0.67	0.62	0.15	0.12	0.20
Al_2O_3	12.90	12.61	12.24	11.12	12.19	12.23
Fe_2O_3	2.60	3.60	3.34	0.58	0.86	0.83
FeO	0.43	0.56	0.47	0.14	0.36	0.71
MnO	0.01	0.02	0.02	0.00	0.02	0.02
MgO	0.35	0.71	0.56	0.19	0.26	0.21
CaO	0.08	1.51	1.51	0.12	0.14	0.14
Na_2O	3.02	4.06	3.61	5.11	0.17	0.13
K_2O	5.32	5.03	5.10	2.60	5.25	6.53
P_2O_5	0.12	0.14	0.13	0.02	0.02	0.02
L.O.I	0.93	0.89	1.90	0.66	2.10	1.76
Total	99.52	100.17	100.10	99.54	98.04	98.07
Na_2O+K_2O	8.34	9.09	8.71	7.71	5.42	6.66
K_2O/Na_2O	1.76	1.24	1.41	0.51	30.88	50.23
σ	2.30	3.03	2.75	1.66	0.82	1.30
A/CNK	1.19	0.89	0.85	0.97	1.96	1.62
A/NK	1.20	1.04	1.07	0.99	2.04	1.68

注:DMPS-2~3样品数据来源1∶25万蚌埠市幅区域地质调查报告,DZZL-2~3数据来自杨德彬等,2009;其余数据为本文实测,测试单位为国土资源部华东矿产资源监督检测中心。

1.04~1.20和0.99~2.04,总体上铝碱比偏高,钙碱比偏低;SiO_2−K_2O图解中(图5a),投影点基本落于高钾钙碱性−钾玄岩区域,庄子里岩体的一个样品落入钙碱性系列,可能与后期的分异演化有关。A/CNK−A/NK图解中显示属准铝−铝过饱和类型(图5b)。

全岩微量、稀土元素分析结果见表2,庄子里岩体稀土总量为176.05×10^{-6}~313.98×10^{-6},磨盘山岩体为138.97×10^{-6}~384.38×10^{-6};轻稀土总量分别为159.05×10^{-6}~276.82×10^{-6}、98.89×10^{-6}~359.10×10^{-6};重稀土总量为17.00×10^{-6}~37.16×10^{-6}、25.28×10^{-6}~40.08×10^{-6};轻重稀土比值(LREE/HREE)为7.31~9.36、2.47~14.20,轻稀土相对富集;$(La/Yb)_N$=5.93~7.96、1.60~33.91;δEu=0.53~0.57、0.25~0.41,表现为明显的铕负异常,稀土配分图显示为右斜"V"字型曲线;δCe=1.02~1.68、0.70~1.20,显示铈异常不明显或无异常。原始地幔标准化微量元素蛛网图上显示K、Nb、Sr、P和Ti元素有较明显的亏损,Rb、Th、U、Nd、Zr和Sm元素相对富集(图6a、b)。

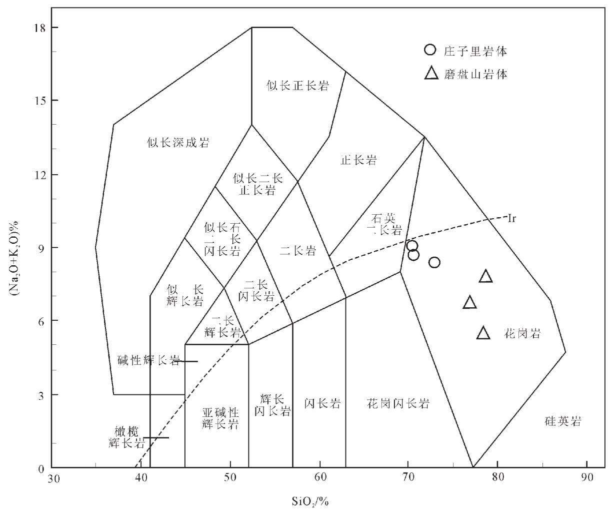


图4 蚌埠隆起带古元古代侵入体全碱−硅(TAS)分类(据Middlemost,1994)

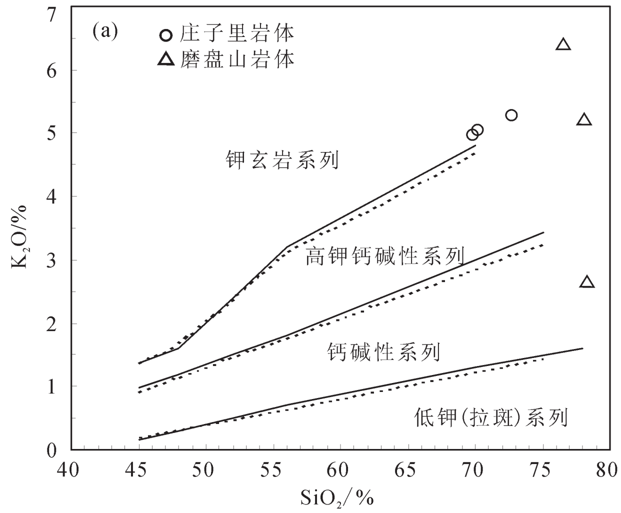
Ir−Irvine分界线,上方为碱性,下方为亚碱性

Fig.4 Diagrams of total alkali silica (TAS) classification of Paleoproterozoic intrusions in Bengbu uplift(after Middlemost, 1994) Ir−Boundary of Ir−Irvine, Upper: alkaline, Lower: Subalkaline

4.2 锆石U−Pb年龄

蚌埠隆起带古元古代侵入体样品中的锆石颗粒CL图像显示的振荡环带结构不是很明显,庄子里岩体锆石多为半自形,结构简单,发育有溶蚀结构,绝大多数碎裂,粒径50~150 μm,部分锆石内部见小晶核,可能为捕获或继承锆石或原锆石经历了重结晶等后期改造(Li et al., 2009;Liu et al., 2014);磨盘山岩体锆石,破碎程度较高,粒径30~120μm,两岩体微弱的振荡环带和高Th/U暗示了侵入体锆石岩浆成因的特点(Koschek,1993)。

本次研究测年样品中庄子里岩体选取17个测点进行微区定年,获得$^{206}Pb/^{238}U$年龄值变化于(644±8)Ma~(2176±27)Ma,$^{207}Pb/^{206}Pb$年龄变化于(1612±25)Ma~(2296±22)Ma,测试结果大都位于谐和线及其附近,其构成的不一致曲线上交点年龄为(2102±24)Ma,下交点年龄为(385±20)Ma,相对谐和的数据加权平均年龄为(2089±44)Ma,MSWD=4.4。磨盘山岩体中锆石碎裂及受后期变质作用改造较严重,本次选取8个测点,结合前人测年数据,所得年龄误差较小(表3),其$^{206}Pb/^{238}U$年龄介于(1624±16)Ma~(2153±21)Ma,$^{207}Pb/^{206}Pb$年龄变化于(2106±32)Ma~(2174±31)Ma,其上交点年龄为(2178±22)Ma,下交



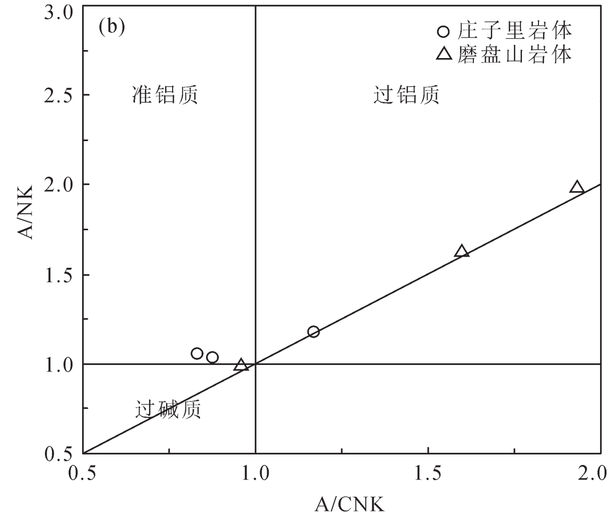


图5 蚌埠隆起带古元古代侵入体SiO_2–K_2O图解(a)(实线据 Peccerillo and Taylor, 1976;虚线据 Middlemost, 1985)及A/CNK–A/NK图解(b)(底图据Middlemost,1994)

Fig.5 SiO_2–K_2O diagram (a) (the solid line after Peccerillo and Taylor, 1976; the dotted line after Middlemost, 1985) and A/CNK–A/NK diagram (b) (after Middlemost,1994) of Paleoproterozoic intrusions in Bengbu uplift

点年龄为(321±21)Ma,相对谐和的数据加权平均年龄为(2133±27)Ma,MSWD=1.1。岩浆成因锆石,上交点年龄通常为锆石形成,即岩浆结晶或岩石形成的年龄,两岩体锆石均具有岩浆锆石特征,其相对谐和的加权平均年龄(2089±44)Ma、(2133±27)Ma分别代表了庄子里岩体及磨盘山岩体的形成年龄(图7)。

4.3 全岩Sm–Nd同位素

全岩Sm–Nd同位素数据见表4。庄子里岩体$\varepsilon_{Nd}(t)$值变化为−2.60~−3.87,$^{147}Sm/^{144}Nd$变化为0.11130~0.11831,$^{143}Nd/^{144}Nd$变化为0.51127~0.51142,两组数据均较前人获得的结果小;两阶段模式年龄(T_{DM2})变化为2.74~2.84 Ga;磨盘山岩体$\varepsilon_{Nd}(t)$值变化为−3.02~3.20,$^{147}Sm/^{144}Nd$变化为0.11570~0.14639,$^{143}Nd/^{144}Nd$变化为0.51135~0.51186,也小于前人结果,两阶段模式年龄(T_{DM2})变化为2.07~2.81 Ga。

4.4 Lu–Hf同位素

蚌埠隆起带古元古代变形变质侵入体的同位素研究前人做过一定的系统工作,本次Lu–Hf同位素测试选择了磨盘山岩体锆石(表5),结合前人研究数据(Yang et al., 2009)显示研究区磨盘山岩体$^{176}Hf/^{177}Hf$比值为0.281415~0.281731,平均值为0.281479;计算所得$\varepsilon_{Hf}(t)$的值介于−1.86~7.08,平均值为−0.45,大多数集中于−0.86~1.31;二阶段模式年龄T_{DM2}变化范围为2.27~2.82 Ga,平均为2.69 Ga。庄子里岩体$^{176}Hf/^{177}Hf$比值为0.281318~0.281569,平均值为0.281488;计算所得$\varepsilon_{Hf}(t)$的值介于−9.77~9.59,平均值为−1.66;二阶段模式年龄变化范围为2.40~2.96 Ga,平均为2.76 Ga。Hf同位素相关计算公式,采用平均陆壳的$^{176}Lu/^{177}Hf$比值0.015(Griffin et al., 2002)。

5 讨 论

5.1 岩体成因及岩浆源区

蚌埠隆起带古元古代侵入体出露于研究区东北部,野外地质调查显示其总体侵入于五河群之中,二者界线清楚。该侵入体锆石发育震荡生长环带,结合高的Th/U比值,暗示了它们的岩浆结晶成因。侵入体锆石大多自形程度较差,碎裂较严重,部分有重结晶和溶蚀现象,CL图像显示具细微震荡生长环带的存在,反映了锆石结晶时为中低温环境(吴元保等,2004)。庄子里岩体锆石Th/U比介于0.27~1.40,磨盘山岩体锆石Th/U为0.46~1.08,均反映了岩浆锆石特征。局部露头所见该侵入体侵入于变质地层中的事实显示这套古深成侵入岩形成时间应略晚于五河岩群。涂荫玖(1994)等对钻孔中新鲜、未蚀变的岩石进行了同位素年代学研究,

表2 蚌埠隆起古元古代侵入体微量、稀土元素组成(10^{-6})
Table 2 Trace element composition of Paleoproterozoic intrusions in Bengbu uplift(10^{-6})

样品	DZZL-1	DZZL-2	DZZL-3	DMPS-1	DMPS-2	DMPS-3
Pb	7.00	7.11	4.88	11.70	—	9.40
Cr	12.60	9.38	9.98	8.00	—	—
Ni	27.10	4.98	21.30	30.10	—	—
Co	545.00	3.51	2.88	496.00	—	—
Rb	79.00	91.80	115.00	152.00	286.60	217.90
Sr	36.40	41.60	51.50	34.60	36.00	23.00
Ba	554.00	634.00	786.00	1090.00	161.00	835.00
V	36.30	35.50	32.70	5.30	—	35.80
Sc	7.70	9.51	8.75	4.30	—	—
Nb	21.20	25.40	23.70	11.80	36.50	25.30
Ta	2.80	2.09	2.11	1.60	2.74	1.63
Zr	280.00	404.00	397.00	140.00	194.00	195.00
Hf	9.60	10.30	9.94	4.30	7.57	5.46
U	3.90	4.03	3.72	4.70	4.20	5.60
Th	21.90	18.10	17.00	16.30	25.60	19.20
La	28.10	60.20	56.50	104.00	17.90	43.00
Ce	97.60	131.00	117.00	142.00	60.20	108.00
Pr	6.80	14.60	12.90	21.50	3.71	10.61
Nd	21.80	57.90	50.70	75.60	14.10	41.80
Sm	4.00	11.20	9.90	14.20	2.67	8.82
Eu	0.75	1.92	1.82	1.80	0.31	1.03
Gd	4.00	10.40	9.45	11.90	5.22	7.86
Tb	0.66	1.69	1.55	1.50	1.17	1.52
Dy	4.10	10.10	9.12	5.80	11.46	11.42
Ho	0.92	1.96	1.81	0.90	2.80	2.53
Er	2.90	5.82	5.43	2.30	8.80	7.48
Tm	0.52	0.87	0.83	0.33	1.36	1.15
Yb	3.40	5.52	5.09	2.20	8.02	7.08
Lu	0.50	0.80	0.74	0.35	1.25	0.99
Y	25.20	57.4	53.20	24.80	78.64	67.06
ΣREE	176.05	313.98	282.84	384.38	138.97	253.29
LREE	159.05	276.82	248.82	359.1	98.89	213.26
HREE	17.00	37.16	34.02	25.28	40.08	40.03
LREE/HREE	9.36	7.45	7.31	14.20	2.47	5.33
La_N/Yb_N	5.93	7.82	7.96	33.91	1.60	4.36
δEu	0.57	0.53	0.57	0.41	0.25	0.37
δCe	1.68	1.05	1.02	0.70	1.72	1.20

注:DMPS-2~3样品数据来源1:25万蚌埠市幅区域地质调查报告,DZZL-2~3数据来自杨德彬等,2009;其余数据为本文实测,测试单位为国土资源部华东矿产资源监督检测中心;"—"表示未测。

也获得了单颗粒锆石的年龄(2408±13)Ma~(2458±10)Ma,这些表明该套岩石主要形成于古元古代早期。本次MC-ICP-MS锆石U-Pb定年结果显示:庄子里岩体锆石年龄为(2089±44)Ma,磨盘山岩体为(2133±27) Ma,表明两岩体形成时代为古元古代,这与华北克拉通古元古代变质和岩浆事件发生的时间一致。

从岩石学、岩石地球化学分析表明,侵入体既包括了早期以高铝、富钠为特征的花岗岩演化趋势,又叠加了后期的相对低铝、富钾的钙碱性趋势,总体反映了从过渡性陆壳向成熟陆壳转化的趋势。岩石总体富硅,富碱。岩体分异指数DI=88.92%~97.90%,显示岩浆碱硅质分异演化较为彻底,反应了岩体经过高程度的分异演化作用。岩体明显富钠贫钾,铝碱比偏高,钙碱比偏低,属准铝-铝过饱和类型。稀土元素配分模式相似,轻稀土相对富集,具明显的铕负异常,铈异常不明显或无异常,具右斜"V"字型稀土配分曲线。K、Nb、Sr、P和Ti元素有较明显的亏损,Rb、Th、U、Nd、Zr和Sm元素相对富集,暗示其可能是表壳岩系部分熔融的产物,或是岩浆强烈分异的结果。钾质花岗岩一般是硅铝质地壳局部熔融的产物,由较高的Rb/Sr、$\omega(K_2O)$和K_2O/Na_2O比值表明其源于陆壳硅铝质岩石,在Y+Nb-Rb和Yb+Ta-Rb构造环境判别图中,投影点落于板内花岗岩区域。研究区古元古代侵入体P_2O_5平均为0.08%,低于高分异S型花岗岩;Na_2O平均含量2.68%,高于高分异S型花岗岩(King et al.,1997),Na_2O/K_2O平均为14.34,A/CNK平均为1.25,全铁含量(TFeO)为2.22%。结合岩石地球化学数据,在成因类型判别图上,蚌埠隆起带古元古代侵入体投影点分布情况显示其具备造山后A型花岗岩的特征(Whalen et al., 1987; Eby,1990, 1992; King et al., 1997)(图8a、b)。

花岗岩主要都是地壳来源的(Wu et al., 2007)。杨进辉等通过锆石Hf同位素的研究解决了花岗岩的形成过程是否发生了混合作用的问题(Yang et al.,2007),而Nd同位素组成被广泛用于高分异演化花岗岩的源区判别。蚌埠隆起带古元古代侵入体$\varepsilon_{Nd}(t)$的值介于-3.87~+3.20,变化不大。DMPS-3样品$^{147}Sm/^{144}Nd$的值大于0.13,说明成岩时Sm/Nd有明显的分馏,以上特征暗示侵入体可能来源于同一源区。Nd单阶段模式年龄2.35~2.79 Ga,Nd两阶段模式年龄2.37~2.84 Ga,古老的模式年龄代表了样品从地幔分离的时间,相近的模式年龄暗示物质分离时间较短,这与华北克拉通主体形成于太古宙,并以2.40~2.50 Ga为主,部分地区经历

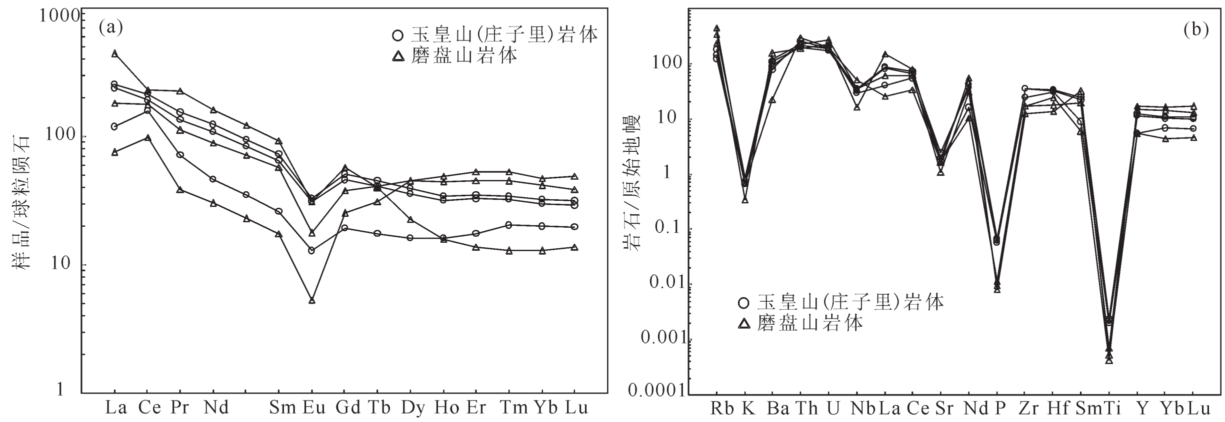


图6 蚌埠隆起带古元古代侵入体球粒陨石标准化稀土元素配分图(a)及原始地幔标准化微量元素蛛网图(b)
(标准化数值据Sun and McDonough,1989)
Fig.6 Chondrite-normalized REE patterns (a) and primitive mantle-normalized spider diagram (b) of Paleoproterozoic intrusions in Bengbu uplift (normalization values after Sun and McDonough,1989)

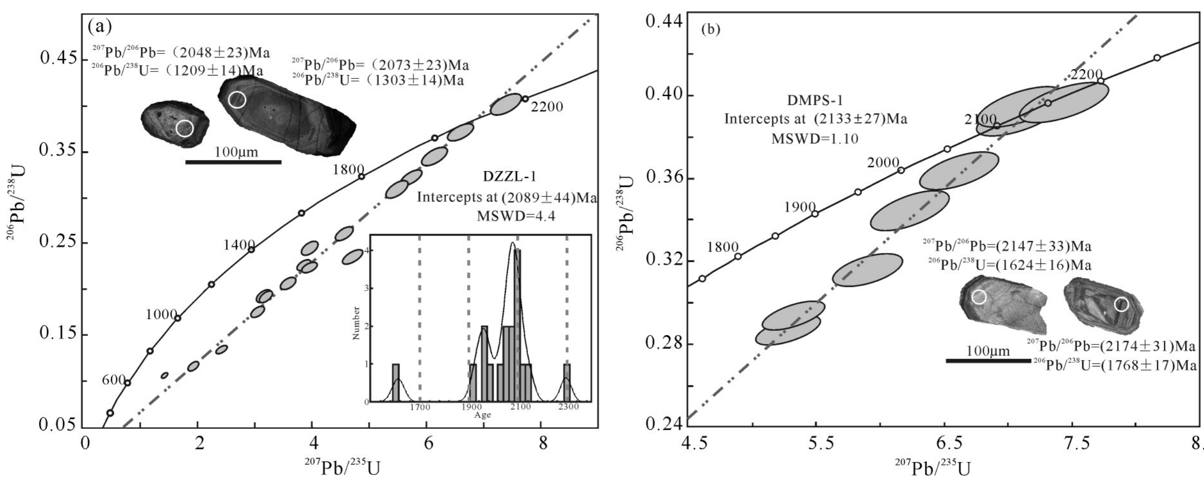


图7 蚌埠隆起带古元古代侵入体锆石LA-ICP-MS U-Pb年龄谐和图(a—庄子里岩体,b—磨盘山岩体)
Fig.7 Zircon LA-ICP-MS U-Pb ages concordia diagram of Paleoproterozoic intrusions in Bengbu uplift (a-Zhuangzili granites, b-Muopanshan granites)

了古元古代的高级变质作用相一致(Ma et al.,1998; Zhao et al.,2001)。

$\varepsilon_{Hf}(t)$值介于-9.77~+9.59,且差别较大,说明其具物质起源的复杂性,古老的两阶段Hf模式年龄(2.27~2.96 Ga),说明其物质起源主要为新太古宙,结合Nd同位素特征及相近的锆石U-Pb年龄暗示其源区物质可能主要为亏损地幔中分离出的新生下地壳物质(图9),并有古老地壳物质的部分熔融,后期可能有少量地幔物质参与改造和再循环。

5.2 构造背景

华北陆块是世界上最古老,最大的克拉通地块之一,保存有>3.6 Ga的古老地壳物质(Liu et al., 1992; Zheng et al., 2004; Wu et al., 2008; Zhang et al., 2012)。蚌埠隆起作为华北陆块的组成部分其初始陆壳的形成时限为中太古代晚期(2886±28)Ma,是目前该地区基底岩石记录最老年龄。基底岩石可能经历较为复杂的演化过程(Nie et al., 2015)。自三叠纪末期扬子陆块与华北陆块碰撞、拼接以来,以发育大型逆冲、推覆构造和郯庐断裂带大规模走滑平移为标志, 该区经历了复杂的构造变形, 并产生了一系列的岩浆作用(Tong et al., 2008),同时也经历了多次的伸展与裂解。对于A型花岗岩目前比

表3 蚌埠隆起带古元古代侵入体锆石U−Pb年龄数据

Table 3 Zircon U−Pb age data of Paleoproterozoic intrusions in Bengbu uplift

样品号	Th	U	Th/U	同位素比值						年龄/Ma					
	/10^{-6}			$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
DZZL-1															
1	148	226	0.65	0.1274	0.0017	4.5748	0.0706	0.2603	0.0029	2063	23	1745	27	1492	16
2	150	154	0.97	0.1335	0.0018	7.3912	0.1196	0.4015	0.0049	2145	23	2160	35	2176	27
3	404	499	0.81	0.1264	0.0016	3.5964	0.0563	0.2064	0.0024	2048	23	1549	24	1209	14
4	183	198	0.92	0.1294	0.0017	6.1487	0.094	0.3446	0.0039	2090	23	1997	31	1909	22
5	1220	1907	0.64	0.1271	0.0016	3.0681	0.0535	0.1751	0.0024	2058	23	1425	25	1040	14
6	559	610	0.92	0.1457	0.0019	4.7237	0.0774	0.2352	0.0031	2296	22	1771	29	1362	18
7	554	549	1.01	0.1282	0.0017	3.9596	0.0574	0.2241	0.0023	2073	23	1626	24	1303	14
8	129	471	0.27	0.1181	0.0016	3.9752	0.0625	0.2442	0.003	1927	24	1629	26	1409	17
10	1501	2706	0.55	0.1207	0.0016	3.198	0.0482	0.1922	0.0021	1966	23	1457	22	1133	12
11	255	373	0.68	0.1244	0.0016	3.8728	0.056	0.2257	0.0024	2021	23	1608	23	1312	14
12	523	373	1.4	0.1196	0.0016	3.1598	0.0552	0.1915	0.0028	1951	23	1447	25	1130	17
13	365	383	0.95	0.1295	0.0017	5.7364	0.0832	0.3213	0.0034	2091	23	1937	28	1796	19
14	202	373	0.54	0.1313	0.0017	2.4229	0.0429	0.1338	0.002	2116	23	1249	22	809	12
15	553	782	0.71	0.1212	0.0016	1.9338	0.0425	0.1157	0.0021	1974	23	1093	24	706	13
16	75	83	0.91	0.1293	0.0018	5.4995	0.0896	0.3085	0.0038	2088	25	1901	31	1733	21
17	181	269	0.67	0.1292	0.0017	6.6143	0.098	0.3713	0.004	2087	23	2061	31	2036	22
DMPS-1															
1	114	248	0.46	0.1314	0.0024	6.2341	0.1281	0.344	0.0039	2117	32	2009	41	1906	22
2	204	350	0.58	0.1318	0.0024	7.0852	0.1373	0.3898	0.004	2122	31	2122	41	2122	22
3	66	119	0.55	0.136	0.0025	7.4374	0.1447	0.3965	0.0039	2177	32	2165	42	2153	21
4	577	535	1.08	0.1315	0.0023	5.3264	0.1014	0.2938	0.0029	2118	31	1873	36	1661	16
5	68	100	0.68	0.1337	0.0025	5.2833	0.1053	0.2865	0.0029	2147	33	1866	37	1624	16
6	137	166	0.83	0.1358	0.0025	5.9049	0.1141	0.3155	0.0031	2174	31	1962	38	1768	17
7	70	123	0.57	0.1306	0.0024	7.1009	0.1397	0.3944	0.004	2106	32	2124	42	2143	22
8	109	182	0.6	0.1323	0.0024	6.6233	0.1293	0.3631	0.0036	2129	32	2062	40	1997	20

注：年龄数据为本文实测，测试单位为中国地质调查局天津地质调查中心。

表4 蚌埠隆起带古元古代侵入体Sm−Nd同位素组成

Table 4 Sm−Nd isotopic compositions of Paleoproterozoic intrusions in Bengbu uplift

样号	Sm/10^{-6}	Nd/10^{-6}	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$(^{143}Nd/^{144}Nd)_i$	T_{DM}/Ma	T_{DM2}/Ma	$\varepsilon_{Nd}(0)$	$\varepsilon_{Nd}(t)$	$f_{Sm/Nd}$
DYHS-1	3.85	20.9	0.11130	0.51127	0.509739	2792	2841	-26.76	-3.87	-0.43
DZZL-2	11.20	57.90	0.11693	0.51140	0.509780	2735	2765	-24.10	-2.60	-0.41
DZZL-3	9.90	50.70	0.11831	0.51142	0.509781	2747	2739	-23.80	-2.60	-0.40
DMPS-1	13.9	72.6	0.11570	0.51135	0.509725	2794	2810	-25.2	-3.02	-0.41
DMPS-2	15.80	81.10	0.11752	0.51166	0.509960	2354	2366	-19.10	3.20	-0.40
DMPS-3	13.20	54.70	0.14639	0.51186	0.509743	2897	2066	-15.10	-1.90	-0.26

注：DZZL−2~3；DMPS−2~3数据来自杨德彬等，2009；其余数据为本文实测，测试单位为核工业北京地质研究院。

表5 蚌埠隆起带古元古代侵入体Lu−Hf同位素分析结果

Table 5 Zircon Lu−Hf isotopic compositions of Paleoproterozoic intrusions in Bengbu uplift

样号	t/Ma	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	T_{DM}/Ma	T_{DM2}/Ma	$f_{Lu\text{-}Hf}$
庄子里										
DZZL-1.1	1921	0.038117	0.001385	0.281518	0.000018	-44.35	-3.29	2449	2756	-0.96
DZZL-1.2	2028	0.053728	0.001889	0.281508	0.000021	-44.70	-1.98	2496	2758	-0.94
DZZL-1.3	2485	0.029959	0.001119	0.281518	0.000023	-44.35	9.59	2432	2401	-0.97
DZZL-1.4	2087	0.078832	0.002743	0.281569	0.000021	-42.54	0.25	2467	2666	-0.92
DZZL-1.5	1944	0.028776	0.001099	0.281474	0.000022	-45.90	-3.97	2491	2816	-0.97
DZZL-1.6	2076	0.049417	0.001609	0.281465	0.000024	-46.22	-2.09	2538	2802	-0.95
DZZL-1.7	1633	0.033350	0.001231	0.281507	0.000020	-44.74	-9.77	2455	2939	-0.96
DZZL-1.8	2075	0.038195	0.001489	0.281512	0.000018	-44.56	-0.27	2464	2689	-0.96
DZZL-1.9	2086	0.097248	0.003291	0.281475	0.000023	-45.87	-3.89	2642	2920	-0.90
DZZL-1.10	2045	0.054165	0.001741	0.281407	0.000022	-48.27	-5.01	2627	2957	-0.95
DZZL-1.11	2094	0.019648	0.000766	0.281488	0.000023	-45.41	0.34	2451	2668	-0.98
DZZL-1.12	1904	0.079063	0.002724	0.281554	0.000027	-43.07	-4.11	2488	2794	-0.92
DZZL-1.13	2083	0.025574	0.000996	0.281478	0.000022	-45.76	-0.58	2479	2716	-0.97
DZZL-1.14	1985	0.038655	0.001400	0.281460	0.000020	-46.40	-3.96	2531	2848	-0.96
DZZL-1.15	2116	0.016898	0.000679	0.281485	0.000018	-45.51	0.85	2449	2653	-0.98
DZZL-1.16	2025	0.026963	0.001040	0.281484	0.000022	-45.55	-1.73	2474	2742	-0.97
DZZL-1.17	2080	0.033705	0.001282	0.281526	0.000044	-44.06	0.63	2432	2638	-0.96
DZZL-1.18	2165	0.009859	0.000418	0.281318	0.000018	-51.42	-3.61	2657	2964	-0.99
DZZL-1.19	2113	0.048201	0.001532	0.281487	0.000028	-45.44	-0.39	2502	2726	-0.95
DZZL-1.20	2105	0.059130	0.002175	0.281523	0.000027	-44.17	-0.19	2495	2709	-0.93
磨盘山										
DMPS-1.1	2117	0.035656	0.001010	0.281433	0.000021	-47.37	-1.48	2542	2796	-0.97
DMPS-1.2	2122	0.048291	0.001377	0.281434	0.000017	-47.32	-1.86	2565	2823	-0.96
DMPS-1.3	2177	0.024123	0.000743	0.281415	0.000017	-47.98	-0.38	2548	2774	-0.98
DMPS-1.4	2118	0.093131	0.002467	0.281731	0.000024	-36.81	7.08	2218	2272	-0.93
DMPS-1.5	2147	0.024959	0.000719	0.281481	0.000025	-45.67	1.31	2458	2648	-0.98
DMPS-1.6	2174	0.039518	0.001109	0.281474	0.000023	-45.90	1.11	2492	2681	-0.97
DMPS-1.7	2106	0.025614	0.000759	0.281429	0.000025	-47.51	-1.51	2531	2790	-0.98
DMPS-1.8	2129	0.025675	0.000755	0.281438	0.000023	-47.18	-0.67	2518	2755	-0.98

注:庄子里岩体数据来自杨德彬等,2009;磨盘山岩体数据为本文实测,测试单位为天津地质调查中心。

较统一的认识是其形成于伸展构造背景(Pitcher, 1993),在A型花岗岩分类中,侵入体投影点分布于A2(造山后A型花岗岩)区域,并在(Y+Nb)−Rb和(Yb+Ta)−Rb构造环境判别图中(Pearce et al.,1984),投影点落于板内花岗岩区域,表现为非造山构造环境,显示其伸展构造背景(图10)。

根据华北陆块内部和北部的麻粒岩包体和变质地体岩石研究表明,华北陆块在前寒武纪发生过幕式地壳生长(Rudnick,1995;Liu et al., 2015),主要峰期集中在2.7 Ga和2.5 Ga(Jahn et al., 2008; Zheng et al., 2009; Jiang et al., 2010,2013; Diwu et al., 2011; Wan et al., 2011, 2013; Liu et al., 2012a; 2012a; Zhang, 2012; Liu et al., 2013a;Zhao et al., 2013),白瑾等(1996)在总结华北克拉通古元古代构造格架时大致以2 .1 Ga为界划分2.4~2.1 Ga时期近东西向的拉张背景。本文对蚌埠隆起带古元古代侵入体锆石原位测试结果获得的较古老的两阶段Hf模式年龄(2.27~2.96 Ga)、Nd模式年龄(2.37~2.84 Ga)和相近的结晶年龄也证明了其物质起源与蚌埠隆起拉张背景时间上的一致性。

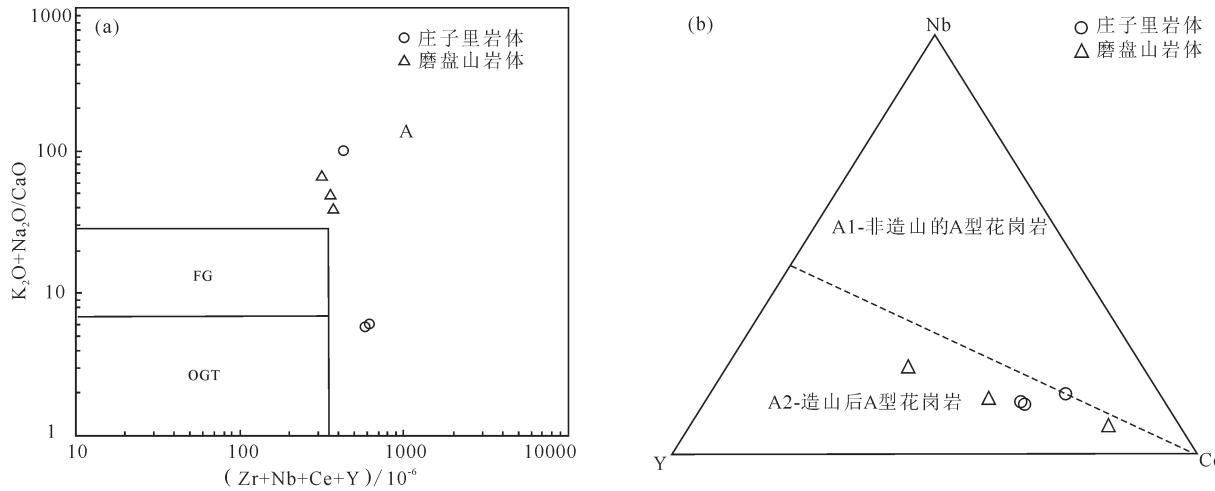


图8 蚌埠隆起带古元古代侵入体成因类型判别图(a)及A型花岗岩分类图(b)
（a据Whalen et al., 1987;b据Eby,1990,1992）
FG—分异的I、S型花岗岩;OGT—未分异的I、S、M型花岗岩;A—A型花岗岩
Fig.8 Genetic type discrimination diagrams of Paleoproterozoic intrusions in Bengbu uplift
(after Whalen et al., 1987; b after Eby, 1990, 1992)
FG−Differentiated I, S−type granites; OGT−Undifferentiated I, S and M−type granites; A−A−type granite

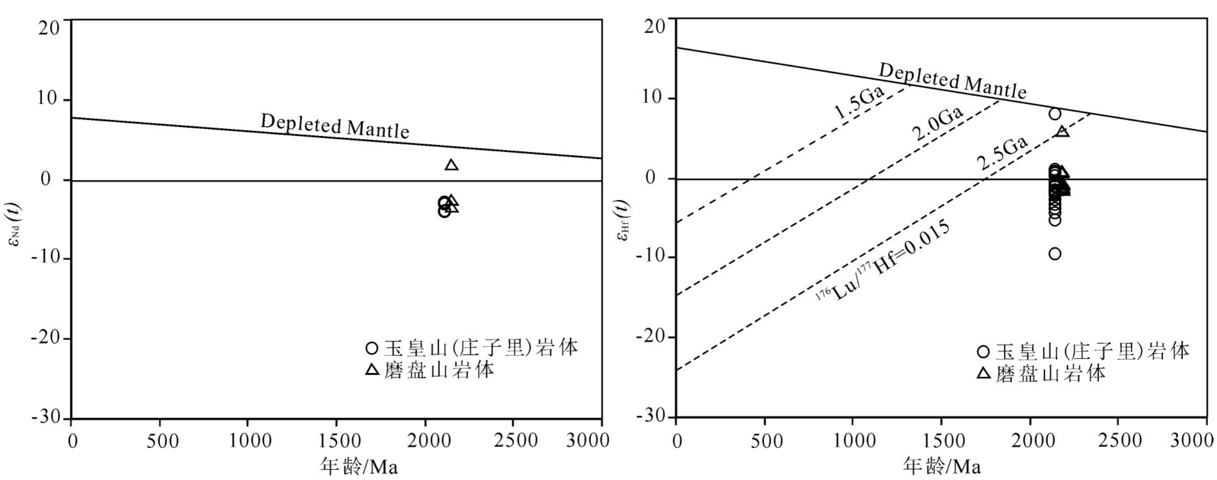


图9 蚌埠隆起带古元古代侵入体锆石U−Pb年龄与$\varepsilon_{Nd}(t)$及$\varepsilon_{Hf}(t)$关系图解
Fig.9 Zircon U−Pb ages and $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ relationship of Paleoproterozoic intrusions in Bengbu uplift

6 结　论

（1）庄子里岩体和磨盘山岩体斑状钾长花岗岩U−Pb的定年结果分别为(2089±44)Ma和(2133±27)Ma,代表了其古元古代形成年龄。

（2）庄子里岩体和磨盘山岩体斑状钾长花岗岩明显富钠贫钾,属准铝−铝过饱和类型,具有明显的铕负异常,铈异常不明显或无异常。K、Nb、Sr、P和Ti有较明显的亏损,Rb、Th、U、Nd、Zr和Sm相对富集,$\varepsilon_{Nd}(t)$值（−3.87~+3.20）和$\varepsilon_{Hf}(t)$值（−9.77~+9.59）暗示两侵入体可能来自物源较复杂的同一源区,古老的Nd两阶段年龄（2.37~2.84 Ga）与Hf模式年龄（2.27~2.96 Ga）说明其物质起源主要为新太古宙。

（3）庄子里岩体和磨盘山岩体为造山后伸展背景下的A型花岗岩,结合岩体年龄也证明了其与蚌埠隆起拉张背景时间上的一致性。

致谢:感谢中国地质调查局南京地质调查中心

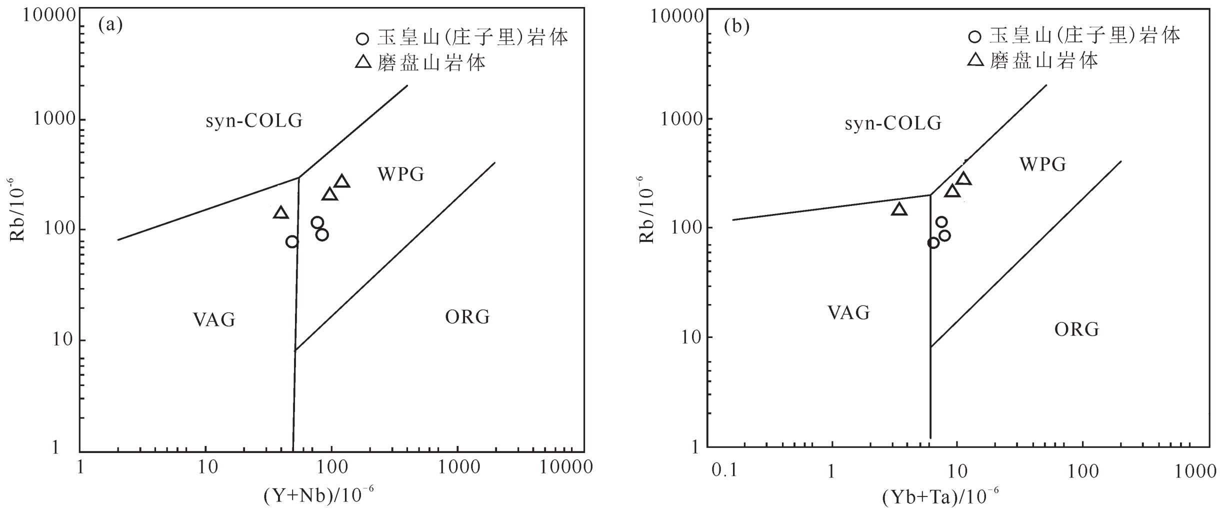


图10 蚌埠隆起带古元古代侵入体(Y+Nb)−Rb及(Yb+Ta)−Rb构造环境判别图解(据Pearce et al.,1984)

WPG—板内花岗岩; ORG—大洋脊花岗岩; VAG—火山弧花岗岩; syn−COLG—同碰撞花岗岩; Post−COLG—后碰撞花岗岩

Fig.10 (Y+Nb)−Rb and (Yb+Ta)−Rb structural environment discrimination diagram of Paleoproterozoic intrusions in Bengbu uplift (after Pearce et al.,1984)

WPG−Intraplate granite; ORG−Ocean−ridge granite; VAG−Volcanic−arc granite; syn−COLG−Syn−collision granite; post−COLG−Post−collision granite

黄光召研究员在岩石薄片鉴定上给予的帮助,感谢审稿专家为本文提出的宝贵修改意见和建议。

References

Chappell B W, White A J R. 1974. Two contrasting granite types[J]. Pacific Geology, 8: 173−174.

Collins W J, Beams S D, White A J R, Chappell B W. 1982. Nature and origin A− type granites with particular reference to southeastern Australia[J]. Contributions to Mineral Petrol, 80(2): 189−200.

Diwu C R, Sun Y, Guo A L, Wang H L, Liu X M. 2011. Crustal growth in the North China Craton at ~2.5Ga: Evidence from in situ zircon U− Pb ages, Hf isotopes and whole− rock geochemistry of the Dengfeng complex[J]. Gondwana Research, 20(1):149−170.

Eby G N. 1990. The A− type granitoids: A review of their occurrenceand chemical characteristics and speculations on their petrogenesis[J].Lithos,26:115−134.

Eby G N. 1992. Chemical subdivision of the A− type granitoids: Petrogenetic and tectonic implications[J]. Geology, 20:641−644

Griffin W L, Wang X, Jackson S E, Pearson N J, O' Reilly S Y, Xu X S, Zhou X M. 2002. Zircon chemistry and magma mixing SE China: In−situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes[J]. Lithos, 61: 237−269.

Guo Sushu, Li Shuguang. 2009. SHRIMP zircon U− Pb ages for the Paleoproterozoic metamorphic− magmatic events in the southeast margin of the North China Craton[J]. Science China− Earth Sciences, 39(6):694−699(in Chinese with English abstract).

Jahn B M, Liu D Y, Wan Y S, Song B , Wu J S. 2008. Archean crustal evolution of the Jiaodong Peninsula, China, as revealed by zircon SHRIMP geochronology, elemental and Nd− isotope geochemistry[J]. American Journal of Science, 308(3): 232−269.

Jiang N, Guo J H, Zhai M G , Zhang S Q. 2010. ~2.7Ga crust growth in the North China craton[J]. Precambrian Research, 179(1/4) : 37−49.

Jiang N, Guo J H , Chang G H. 2013. Nature and evolution of the Lower crust in the eastern North China craton: A review[J]. Earth−Science Reviews, 122(122): 1−9.

Jin Ke, Xu Wenliang, Wang Qinghai, Gao Shan , Liu Xiaochun. 2003. Formation time and sources of the Huaiguang "Migmatitic Granodiorite" in Bengbu, Anhui Province: Evidence from SHRIMP zircon U−Pb geochronology[J]. Acta Geoscientia Sinica, 24(4):331−335(in Chinese with English abstract).

Kang Congxuan,Yang Xianzhong, Cai Yitao, Zong Wen, Zhu Xiaoting. 2017. Geological and geochemical characteristics of Middle Jurassic granites in Bengbu uplift, Southeast of North China craton[J]. Acta Geologica Sinica, 91(supp.1): 83−85.

Kang Congxuan, Yang Xianzhong, Cai Yitao, Zong Wen, Huang Xianjue, Kong Guanglin, Li Chaowei. 2018a. Causes and dynamics background of Late Early Cretaceous adamellite in Bengbu uplift, southeast of North China Craton[J].Acta Geologica Sinica,92(4):687−703.

Kang Congxuan, Yang Xianzhong, Cai Yitao, Zong Wen, Huang Xianjue, Kong Guanglin, Li Chaowei. 2018b. Re− understanding geochemical characteristics of Jingshan− Tushan granites in Bengbu uplift, southeast of North China Craton[J]. Geoscience, 32(6): 1242−1253.

Koschek, G. 1993. Origin and significance of the SEM cathodoluminescence from zircon[J]. Journal of Microscopy, 171 (3): 223−232.

King P L, White A J R, Chappell B W, Allen C M. 1997. Characterization and origin of aluminous A− type granites from the Lachlan fold belt, southeastern Australia[J]. Journal of Petrology, 38 (3):371−391.

Li Yin, Han Feng, Ling Mingxing, Liu Jian, Li Xianhua, Li Qiuli. 2010. Geochronology, geochemical characteristics and geodynamic significance of the Jingshan and Tushan granites in the Bengbu Uplift[J]. Geotectonica et Metallogenia, 34(1):114−124(in Chinese with English abstract).

Li Ruibao, Pei Xianzhi, Ding Saping, Li Zuochen, Feng Jianyun, SunYu, Zhang Yafeng, Liu Zhanqing. 2009. LA−ICP−MS zircon U−Pb dating of the Pipasi basic volcanic rocks within the Mian−Lue Tectonic Zone in the southern margin of West Qinlin and its geological Implication[J]. Acta Geoscientia Sinica, 83(11):1612−1623(in Chinese with English abstract).

Liu D Y, Nutman A P, Compston W, Wu J S, Shen Q H. 1992. Remnants of 3800 Ma crust in the Chinese part of the Sino−Korean craton[J]. Geology, 20(4): 339−342.

Liu F, Guo J H, Peng P, Qian Q. 2012a. Zircon U− Pb ages and geochemistry of the Huai'an TTG gneisses terrane: Petrogenesis and implications for ~2.5Ga crustal growth in the North China Craton[J]. Precambrian Research, 212−213: 225−244.

Liu J H, Liu F L, Ding Z J, Liu C H, Yang H, Liu P H, Wang F, Meng E. 2013a. The growth, reworking and metamorphism of Early Precambrian crust in the Jiaobei terrane, the North China Craton: Constraints from U− Th− Pb and Lu− Hf isotopic systematic, and REE concentrations of zircon from Archean granitoid gneisses[J]. Precambrian Research, 224: 287−303.

Liu Yue, Deng Jun, Wang Zhongliang, Zhang Liang, Zhang Chao, Liu Xiangdong, Zheng Xiaoli, Wang Xudong. 2014. Zircon U−Pb age, Lu−Hf isotopes and petrogeochemistry of the monzogranites from Xincheng gold deposit, northwestern Jiaodong Peninsula, China[J]. Acta Petrologica Sinica, 30(9): 2559− 2573(in Chinese with English abstract).

Liu Yican, Wang Chengcheng, Zhang Pingang, Nie Jiazhen. 2015. Growth and metamorphic evolution of the Precambrian lower crust at the southeastern margin of the North China Block[J]. Acta Petrologica Sinica, 31(10): 2847− 2862(in Chinese with English abstract).

Liu Y C, Wang C C, Zhang P G, Groppo C, Rolfo F , Wang A D.2015. Granulite facies metamorphism, partial melting and metasomatism in the Wuhe Complex at the southeastern margin of the North China Block[J]. Journal of Earth Sciences and Environment, 37(1): 1−11(in Chinese with English abstract)

Liu Y C, Wang A D, Rolfo F. 2009. Geochronological and petrological constraints on Palaeoproterozoic granulite facies metamorphism in southeastern margin of the North China Craton[J]. Journal of Metamorphic Geology, 27(2): 125−138.

Liu Y C, Wang A D, Li S G. 2013. Composition and geochronology of the deep− seated xenoliths from the southeastern margin of the North China Craton[J]. Gondwana Research, 23(3): 1021−1039.

Liu Y C, Zhang P G, WangC C. 2017. Petrology, geochemistry and zirconology of impure calcite marbles from the Precambrian metamorphic basement at the southeastern margin of the North China Craton[J]. Lithos, 290−291: 189−209.

Liu Shusheng, Yang Yongfei, Guo Linnan, Nie Fei, Peng Zhiming, Pan Guitang. 2018. Tectonic characteristics and metallogeny in Southeast Asia[J]. Geology in China, 45(5): 863− 889(in Chinese with English abstract)

Ludwing K R.2003. ISOPLOT 3.0: A Geochronological Toolkit for Microsoft Excel[M]. Berkeley Geochronology Center Special Publication.

Middlemost E A K. 1985. Magmas and Magmatic Rocks: An Introduction to Igneous Petrology[M]. London: Longman.

Middlemost E A K. 1994. Naming materials in the magma/igneous rock system[J]. Earth−Science Reviews, 37(3/4):215−224.

Nie Feng, Shi Yonghong, Zhang Zhongbao, Wang Juan. 2015. The initial time of the Tan− Lu wrench fault: In the view of geochronological data of the basement rocks, northern Anhui Province[J]. Chinese Science Bulletin, 60(24):2315− 2326(in Chinese with English abstract).

Pearce J A, Harris N B W, Tindle A G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks[J].Journal of Petrology, 25(4):956−983.

Peccerillo A, Taylor S R. 1976. Geochemistry of Eocene calc−alkaline volcanic rocks from the Kastamonu area, norther Turkey[J]. Contributions to Mineralogy and Petrology, 58:63−81.

Pitcher W S.1993.The Nature and Origin of Granite[M]. Blackie Academic and Professional, London, 321.

Qiu Ruilong, Xu Xiang, Huang Dezhi. 1999. Theisotopicageof the Jingshan intrusive in the Bengbu region of the southeastern edge of the North China block and its geological implications[J]. Geology in Anhui, 9(3):161−164(in Chinese with English abstract).

Rudnick R L. 1995. Making continental crust[J]. Nature, 378(6557): 571−578.

Song Lihong, Zhu Guang, Zhao Tian, Lin Shaoze. 2016. Deformation records in Late Mesozoic plutons in the Bengbu Uplift in the Southeastern North China Craton and their tectonic implications[J]. Geological Review, 62(2):400− 418(in Chinese with English abstract).

Tong Jinsong, Lu Yulin, Guan Yuncai, Chu Dongru, Geng Xiaoguang. 2008. Geochemical characteristics of Yanshanian high−Mg intermediate−acid intrusive rocks in eastern Anhui and their dynamic significance[J]. Geology in China, 35(1):18− 31(in Chinese with English abstract).

Tong Jinsong, Chu Dongru, Lou Qing, Guan Yuancai, Qiu Junqiang, Geng Xiaoguang. 2014. Magmatism and Dynamic Evolution in Yanshan Period of Bengbu Uplift Belt[C]//Nanjing Center of Geological Survey, CGS(eds.). The Collection of Geological Survey Projects in East China. Wuhan: China University of Geosciences Press, 3−17(in Chinese with English abstract).

Wan Y S, Liu D Y, Wang S J, Yang E X, Wang W, Dong C Y, Zhou H Y, Du L L, Yang Y H , Diwu C R. 2011.~2. 7Ga juvenile crust formation in the North China Craton (Taishan−Xintai area, western Shandong Province): Further evidence of an understated event from U− Pb dating and Hf isotopic composition of zircon[J]. Precambrian Research, 186(1/4) : 169−180.

Wan Y S, Xu Z Y, Dong C Y, Nutman A P, Ma M Z, Xie H Q, Liu S J, Liu D Y, Wang H C , Cu H. 2013. Episodic Paleoproterozoic (~2.45, ~1.95 and~1.85 Ga) mafic magmatism and associated high temperature metamorphism in the Daqingshan area, North China Craton: SHRIMP zircon U− Pb dating and whole− rock geochemistry[J]. Precambrian Research, 224: 71−93

Wang C C, Liu Y C, Zhang P G. 2017. Zircon U−Pb geochronology and geochemistry of two types of Paleoproterozoic granitoids from the southeastern margin of the North China Craton: Constraints on petrogenesis and tectonic significance[J]. Precambrian Research, 303: 268−290.

Whalen J B, Currie K L, Chappell B W.1987. A− type granites: geochemical characteristics, discriminations and petrogenesis[J]. Contributions to Mineralogy and Petrology, 95(4):407−419.

Wang Juan, Sheng Yong, Pu Xiangping, Kang Tao, Shi Yonghong. 2014. The investigation on metamorphic petrology and P− T conditions of Wuhe complex rocks: Evidences from drill ZK02 in the south of Mengcheng area[J]. Chinese Journal of Geology, 49 (2): 556−575(in Chinese with English abstract).

Wang Juan, Song Chuanzhong. 2016. Analysis of metamorphic P−T conditions and zircon U−Pb age for garnet−pyroxenite in Bengbu uplift tectonic[J]. Chinese Journal of Geology, 51(4): 1223− 1245 (in Chinese with English abstract).

Whalen J B, Currie K L, Chappell B W. 1987. A− type granites: geochemical characteristics,discriminatuon and petrogenesis[J]. Contributions to Mineralogy and Petrology, 95(4): 407−419.

Wu Fuyuan, Jiang Boming, Lin Qiang. 1997. Isotopic characteristics of granitoids in the orogenic belt of northern China and their implications for crustal growth[J]. Chinese Science Bulletin, 42 (20):2188−2192(in Chinese).

Wu Fuyuan, Li Xianghua, Yang Jinghui, Zheng Yongfei. 2007. Discussions on the petrogenesis of granites[J]. Acta Petrologica Sinica, 23 (6):1217−1238(in Chinese with English abstract).

Wu F Y, Zhang Y B, Yang J H, Xie L W , Yang Y H. 2008. Zircon U− Pb and Hf isotopic constraints on the Early Archean crustal evolution in Anshan of the North China Craton[J]. Precambrian Research, 167 (3): 339−362.

Wu Yuanbao, Zheng Yongfei. 2004. Geogenic mineralogy of zircon and its restriction on U−Pb age interpretation[J]. Chinese Science Bulletin, 49(16): 1589−1604(in Chinese with English abstract).

Xu Wenliang, Wang Qinghai, Wang Dongyan, Pei Fuping, Gao Shan. 2004. Processes and mechanism of Mesozoic lithospheric thinning in eastern North China Craton: Evidence from Mesozoic igneous rocks and deep−seated xenoliths[J]. Earth Science Frontiers, 11(3): 309−317(in Chinese with English abstract).

Xu Wenliang, Wang Dongyan, Wang Qinghai, Pei Fuping, Lin Jingqian. 2004. ^{40}Ar/^{39}Ar dating of hornblende and biotite in Mesozoic intrusive complex from the North China Block: Constraints on the time of lithospheric thinning[J]. Geochimica, 33 (3):221−231(in Chinese with English abstract).

Xu Xiang, Hou Mingjin, Qiu Ruilong, Wu Libin, Li Jianshe. 2005. ^{40}Ar−^{39}Ar dating of granites and related dikes in the Bengbu area on the southeastern margin of the North China block[J]. Geology in China, 32(4):588− 595(in Chinese with English abstract).

Yang Debin, Xu Wenliang, Pei Fuping, Wang Qinghai, Liu Xiaoming. 2005. Formation time and magma source of granites in Bengbu uplift: Evidence from LA− ICPMS zircon U− Pb dating and tracing[J]. Geochimica, 24(5):443− 454(in Chinese with English abstract).

Yang Debin, Xu Wenliang, Wang Qinghai, Pei Fuping, Ji Weiqiang. 2006. Petrogenesis of Late Jurassic Jingshan granite in Bengbu uplift, Anhui Province: Constraints from geochemistry and Hf isotopic of zircons[J]. Acta Petrologica Sinica, 22(12):2923−2932 (in Chinese with English abstract).

Yang Debin, Xu Wenliang, Wang Qinghai, Pei Fuping, Ji Weiqiang. 2007. Petrogenesis of the Mesozoic granite in Bengbu uplift: Constraints from zircon Hf isotopic[J]. Acta Petrologica Sinica, 23 (2):381−392(in Chinese with English abstract).

Yang Debin, Xu Wenliang, Pei Fuping, Wang Qinghai. 2009. Petrogenesis of the Paleoproterozoic K− Feldspar granites in Bengbu Uplift: Constraints from petro− geochemistry, Zircon U− Pb dating and Hf isotope[J]. Earth Science− Journal of China University of Geosciences, 34(1):148−164(in Chinese with English abstract).

Yang Debin. 2009. Chronology and Geochemistry of Granitoids in Bengbu Uplift, Central China: Constraints on Tectonic Evolution in the Eastern North China Craton[D]. Changchun: Jilin University(in Chinese).

Yang J H, Wu F Y, Wilde S A, Xie L W, Yang Y H, Liu X M.2007. Tracing magma mixing in granite genesis:in situ U−Pb dating and Hf−isotope analysis of zircons[J]. Mineralogy and Petrology,153: 177−190.

Zhang H F. 2012. Destruction of ancient lower crust through magma underplating beneath Jiaodong Peninsula, North China Craton: U-Pb and Hf isotopic evidence from granulite xenoliths[J]. Gondwana Research, 21(1) : 281-292

Zhao G C, Zhai M G. 2013. Lithotectonic elements of Precambrian basement in the North China Craton: Review and tectonic implications[J]. Gondwana Research, 23(4) : 1207-1240.

Zhao G C. 2001. Palaeoproterozoic assembly of the North China craton[J]. Geological Magazine,138:87-91.

Zhao Yue, Zhai Mingguo, Chen Hong, Zhang Shuanhong. 2017. Paleozoic-early Jurassic tectonic evolution of North China Craton and its adjacent orogenic belts[J]. Geology in China, 44(1): 44-60 (in Chinese with English abstract).

Zheng J P, Griffin W L, O'Reilly S Y, Lu F X, Yu C M, Zhang M , Li H M. 2004a. U-Pb and Hf-Isotope analysis of zircons in mafic xenoliths from Fuxian kimberlites: Evolution of the Lower crust beneath the North China craton[J]. Contributions to Mineralogy and Petrology, 148(1) : 79-103.

Zheng J P, Griffin W L, O'Reilly S Y, Zhao J H, Wu Y B, Liu G L, Pearson N, Zhang M, Ma C Q, Zhang C Q, Yu C M, Su Y P , Tang H Y. 2009. Neoarchean (2.7~2.8 Ga) accretion beneath the North China Craton: U-Pb age, trace elements and Hf isotopes of zircons in diamondiferous kimberlites[J]. Lithos, 112(3/4) : 188-202.

附中文参考文献

郭素淑,李曙光.2009.华北克拉通东南缘古元古代变质和岩浆事件的锆石 SHRIMP U-Pb 年龄[J].中国科学 D辑:地球科学,39(6): 694-699.

靳克,许文良,王清海,高山,刘晓春.2003.蚌埠淮光"混合花岗闪长岩"的形成时代及源区:锆石SHRIMP U-Pb地质年代学证据[J].地球学报,24(4): 331-335.

康丛轩,杨献忠,蔡逸涛,宗雯,黄先觉,孔广林,李朝维.2018a.华北克拉通东南缘蚌埠隆起带早白垩世晚期二长花岗岩成因及动力学背景[J].地质学报,92(4):687-703

康丛轩,杨献忠,蔡逸涛,宗雯,黄先觉,孔广林,李朝维.2018b.华北克拉通东南缘蚌埠隆起带荆山—涂山岩体地质地球化学特征再认识[J].现代地质,32(6): 1242-1253.

李印,韩峰,凌明星,刘健,李献华,李秋立,孙卫东.2010.蚌埠荆山和涂山岩体的年代学、地球化学特征及其动力学意义[J].大地构造与成矿学, 34(1):114-124.

李瑞保,裴先治,丁仨平,李佐臣,冯建赟,孙雨,张亚峰,刘战庆. 2009. 西秦岭南缘勉略带琵琶寺基性火山岩LA-ICP-MS锆石U-Pb年龄及其构造意义[J].地质学报, 83(11):1612-1623.

刘书生,杨永飞,郭林楠,聂飞,彭智敏,潘桂堂.2018.东南亚大地构造特征与成矿作用[J].中国地质, 45(5): 863-889.

刘跃,邓军,王中亮,张良,张潮,刘向东,郑小礼,王旭东.2014.胶西北新城金矿床二长花岗岩岩石地球化学、锆石U-Pb年龄及Lu-Hf同位素组成[J].岩石学报, 30(9):2559-2573.

刘贻灿,王程程,张品刚,聂佳珍.2015.华北东南缘前寒武纪下地壳的生长和变质演化[J].岩石学报, 31(10): 2847-2862.

聂峰,石永红,张忠宝,王娟,曹晟.2015.安徽北部郯庐断裂两侧基底岩石年龄及对郯庐断裂初始开启时间的限定[J].科学通报,60 (24):2315-2326.

邱瑞龙,徐祥,黄得志.1999,华北陆块东南缘蚌埠地区荆山岩体同位素年龄及其地质意义[J].安徽地质,9(3):161-164.

宋利宏,朱光,赵田,林少泽.2016.华北克拉通东南部蚌埠隆起晚中生代花岗岩类岩体内变形记录与构造意义[J].地质论评,62(2):400-418.

童劲松,路玉林,管运才,储东如,耿小光.2008.皖东地区燕山期高镁中酸性侵入岩地球化学特征及动力学意义[J].中国地质,35(1):18-31.

童劲松,储东如,娄清,管远才,邱军强,耿小光. 2014. 蚌埠隆起带燕山期岩浆作用与动力学演化[C]//中国地质调查局南京地质调查中心(eds.).华东地区地质调查项目成果集.武汉:中国地质大学出版社, 3-17.

王娟,盛勇,卜香萍,康涛,石永红 2014.五河杂岩的变质岩石学及P-T条件分析——来自蒙城南ZK02钻孔的研究[J].地质科学, 49(2): 556-575.

王娟,宋传中.2016.蚌埠隆起区石榴辉石岩变质PT轨迹及年代学研究[J].地质科学, 51(4): 1223-1245.

吴福元,江博明,林强.1997.中国北方造山带造山后花岗岩的同位素特点与地壳生长意义[J].科学通报,42(20):2188-2192.

吴福元,李献华,杨进辉,郑永飞.2007.花岗岩成因研究的若干问题[J].岩石学报, 23 (6):1217-1238.

吴福元,郑永飞.2004.锆石成因矿物学研究及其对U-Pb年龄解释的制约[J].科学通报, 49(16): 1589-1604.

许文良,王清海,王冬艳,裴福萍,高山.2004.华北克拉通东部中生代岩石圈减薄的过程与机制:中生代火成岩和深源捕虏体证据[J].地学前缘, 11(3):309-317.

许文良,王冬艳,王清海,裴福萍,林景仟.2004.华北克拉通中东部中生代侵入杂岩中角闪石和黑云母的^{40}Ar-^{39}Ar定年:对岩石圈减薄时间的制约[J].地球化学, 33(3):221-231.

徐祥,侯明金,邱瑞龙,吴礼彬,李建设.2005.华北陆块东南缘蚌埠地区花岗岩与相关脉岩^{40}Ar-^{39}Ar定年[J].中国地质,32(4):588-595.

杨德彬,许文良,裴福萍,王清海,柳小明.2005.蚌埠隆起区花岗岩形成时代及岩浆源区性质:锆石LA-ICP-MS U-Pb定年与示踪[J].地球化学,24(5):443-454.

杨德彬,许文良,王清海,裴福萍,纪伟强.2006.安徽蚌埠荆山晚侏罗世花岗岩岩体成因——来自地球化学和锆石Hf同位素的制约[J].岩石学报,22(12):2923-2932.

杨德彬,许文良,王清海,裴福萍,纪伟强.2007.蚌埠隆起区中生代花岗岩的岩石成因:锆石Hf同位素的证据[J].岩石学报,23(2):381-392.

杨德彬,许文良,裴福萍,王清海.2009.蚌埠隆起区古元古代钾长花岗岩的成因:岩石地球化学、锆石U-Pb年代学与Hf同位素的制约[J].地球科学:中国地质大学学报,34(1):148-164.

杨德彬.2009.蚌埠隆起区花岗岩的年代学和地球化学:对华北克拉通东部构造演化的制约[D].长春:吉林大学博士学位论文.

赵越,翟明国,陈虹,张拴宏.2017.华北克拉通及相邻造山带古生代—侏罗纪早期大地构造演化[J].中国地质, 44(1): 44-60.