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西大别~2.0 Ga变质花岗岩的发现及其Hf同位素特征

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提要: 扬子陆块广泛存在2.10~1.90 Ga构造热事件的年代学信息,然而在大别地区该时期的岩浆岩体尚未报道,本文在野外地质调查的基础上,对西大别金盘岩体的变质花岗岩开展了锆石年代学和Hf同位素分析。锆石U−Pb测年结果显示变质花岗岩的结晶年龄为(2022±17)Ma(MSWD=2.3),代表了大别造山带古元古代的岩浆活动记录。锆石的$\varepsilon_{Hf}(t)$值(−10.6~ −7.6)及其二阶模式年龄(2.96~3.12 Ga)表明该岩体来源于古老陆壳的再造。综合已有Hf同位素资料,扬子陆块北缘广泛发育2.95~3.18 Ga太古宙地壳,为该类花岗岩的岩浆形成提供了物源。金盘岩体形成于古元古代碰撞造山作用时期(2.03~1.93 Ga),可能指示了Columbia超大陆聚合在大别地区的响应。该~2.0 Ga花岗岩体的识别,为研究大别造山带早前寒武纪构造岩浆事件的演化序列提供了新的资料。

关　键　词: 扬子陆块;大别;古元古代;变质花岗岩; Columbia超大陆;地质调查工程

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The discovery of ~2.0 Ga metamorphosed granite in western Dabie Mountains and its Hf isotopic characteristics

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Abstract: Geochronological data of 2.10−1.90 Ga tectonic thermal events in the Yangtze block are widely documented, but the magmatic rocks of this period in the Dabie area have not been reported. On the basis of field geological survey, the geochronological and zircon Hf isotopes of the metamorphic granite from the Jinpan pluton in western Dabie Mountains were analyzed. U−Pb dating of magmatic zircons from the metamorphic granite yielded age of (2022 ± 17)Ma (MSWD = 2.3), which represents Paleoproterozoic magmatic event in the Dabie orogenic belt. The negative $\varepsilon_{Hf}(t)$ values (−10.6−−7.6) and T_{DM2} ages (2.95−3.12 Ga) of zircons indicate that the Jinpan granite might be derived from the reconstruction of ancient continental crust. The previous Hf isotope results also indicate that the widely−distributed Archean continental crust (2.95−3.18 Ga) in the Yangtze Block provided material source for the

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magmatic evolution of the Jinpan metamorphic granite. The Jinpan pluton was formed in the period of Paleoproterozoic collisional orogeny (2.03−1.93 Ga), and it might be the response to the convergent of Columbia supercontinent. The identification of the ~2.0 Ga granite provides a new evidence for the evolution of Precambrian tectonic−magmatic events in the Dabie orogenic belt.

Key words: Yangtze block; Dabie; Palaeoproterozoic; metamorphic granite; Columbia supercontinent; geological survey engineering

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1 引 言

扬子陆块是中国东部最重要的太古宙克拉通之一,其早期形成与演化对研究中国前寒武纪陆壳的形成、生长、再造过程具有重要意义,同时在全球性元古宙构造热事件响应中扮演着重要的角色。众所周知,华北陆块广泛出露太古宙岩石,记录着大量与Columbia超大陆汇聚和裂解相关的元古宙构造热事件(Zhai and Liu, 2003;Wan et al., 2006;Kusky et al., 2007;Xia et al., 2013;Liu et al., 2017;Wang et al., 2019)。相比而言,由于显生宙盖层影响,元古宙物质在扬子陆块范围出露十分有限。随着近年来的研究和发现,在扬子陆块不同地区的岩石中同样记录着大量2.10~1.90 Ga的年代学信息(Qiu et al., 2000;吴元保等, 2003;夏群科等, 2003;Bryant et al., 2004;Zhang et al., 2006a, b, c;Zheng et al., 2006;Liu et al., 2008a, 2010a; Liu et al., 2008b;Sun et al., 2008;Wu et al., 2008, 2009, 2012;Yin et al., 2013;Li et al., 2014; Guo et al., 2015;Han et al., 2017, 2018;Li et al., 2019;陈超等, 2020),其中大量变质年龄记录所揭示的变质事件已经得到普遍认可,但代表同期岩浆活动的地质实体却少有发现,尤其在大别地区尚未报道,这可能与该区域岩石经历了多期次、强烈的变质和变形改造有关。

大别造山带地处中国中部,是中央造山带的重要组成部分,自太古宙以来经历了多期次、多阶段的碰撞—扩张—聚合的演化过程(Wu and Zheng, 2013;刘晓春等, 2015)。以商麻断裂为界,将大别造山带划为东、西两部分,其中西大别以大悟断裂为界与秦岭—桐柏造山带相接(图1)。该区域广泛发育高压/超高压岩石,根据目前同位素年代学研究结果,其中大部分变质沉积岩中普遍含有古元古代岩浆或变质锆石的年龄信息(Liu et al., 2010a),可能表明古元古代造山作用已由扬子陆块向北延伸至大别地区(Wu et al., 2008),并在扬子陆块早期基底形成与演化过程中起到了至关重要作用。在野外地质调查工作的基础上,本文在湖北省大悟地区大别岩群中识别出一套变质花岗岩体,通过LA−ICP−MS锆石U−Pb测年以及Hf同位素分析,提供了一批新的数据,并结合区域上同期年代学资料来探讨该变质岩体的发现对扬子陆块北缘古元古代构造演化的意义。

2 地质背景及样品采集

金盘岩体出露于西大别地块西南缘大悟地区金盘水库一带,总面积约65 km^2,总体沿北西西向呈带状展布(图2),1∶25万麻城市幅认为其形成于新元古代[1]。岩体周缘被南华系—震旦系所围限,地层岩性主要为白云钠长石英片岩、变粒岩、浅粒岩以及中厚层白云石大理岩、条带状白云石大理岩等[2]。岩体与围岩均呈构造接触关系,大多以片(麻)理化构造接触为主,局部可见断层接触,原始接触界面经强烈改造已难以发现或识别。岩体边部可见绿泥黑云片岩捕虏体,可能为岩体侵位时的围岩捕虏体(图3b、c)。受动力变质作用的改造,岩体、捕虏体以及围岩地层均具有一定程度的变质,在汪家咀、金盘水库水坝一带见有典型的糜棱岩化特征:较为强烈的塑性变形导致长石变晶集合体多呈眼球状、拉长条带状,多发育不对称旋转碎斑、"多米诺骨牌";云母呈暗色条带状集合体,绕长石定向分布,局部发育S−C组构(图3a、c)。

此次研究中用于锆石定年的样品(D3619/1)采于31°19′35.7″N,114°05′18.3″E。岩石具糜棱结构、碎斑状结构,眼球状构造,主要矿物成分为钾长石

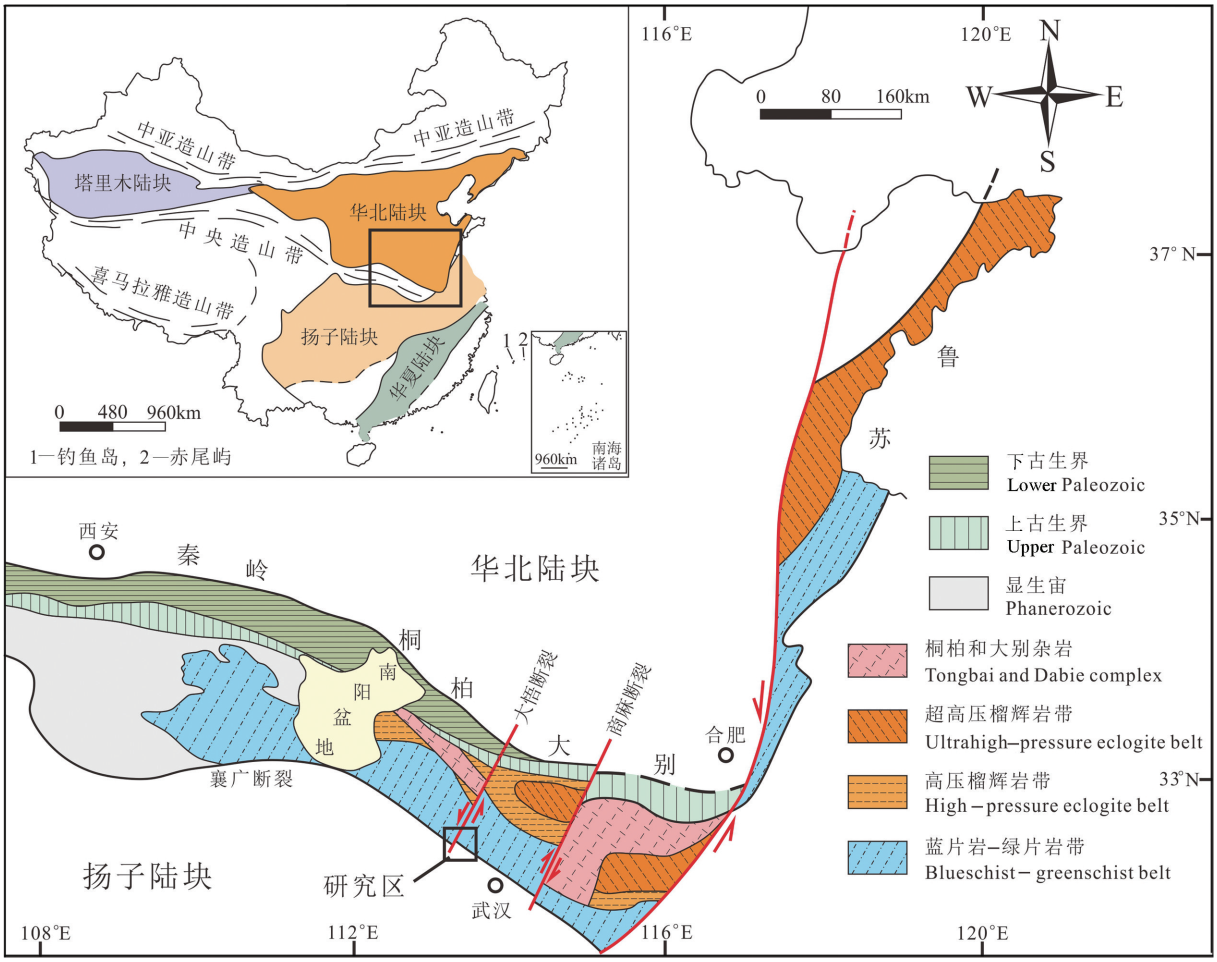

图1 秦岭—桐柏—大别—苏鲁造山带区域构造图及研究区位置
(据Liu et al., 2010a；Zhao and Cawood, 2012修改)
Fig.1 Regional tectonic map of the Qinling–Tongbai–Dabie–Sulu orogenic belt and location of the study area
(modified from Liu et al., 2010a; Zhao and Cawood, 2012)

(27%~37%)、斜长石(15%~25%)、石英(20%~30%)、黑云母(15%~20%),含少量绿帘石、磁铁矿以及榍石。其中钾长石以条纹长石为主,多见条纹状双晶,可见格子双晶,呈棱角状、次棱角状外形,碎裂特征明显;斜长石以更长石或钠更长石为主,见紧密聚片双晶。岩石受到韧性动力变质作用,在定向应力作用下原岩碎裂的矿物呈定向排列,较多的长石碎块外形呈碎斑状、眼球状,石英呈丝带状重结晶,片状矿物黑云母集中成层,以网脉状形式分布于长英质矿物之间(图3d、e)。

3　样品加工及测试方法

锆石分选、制靶和反射光、透射光以及阴极发光照相均在南京宏创地质勘查技术服务有限公司完成,将样品粉碎至80~100目,利用常规的浮选和电磁法分离出锆石,在双目镜下挑选出晶型较好的锆石制靶,阴极发光(CL)采用TESCAN MIRA3场发射扫描电镜和TESCAN公司阴极发光探头进行锆石内部结构分析研究。

锆石原位微区U-Pb同位素和微量元素组成分析在湖北省地质试验测试中心利用LA-ICP-MS完成,测试仪器采用美国Coherent Inc公司生产的GeoLasPro全自动版193 nm ArF准分子激光剥蚀系统(LA)和美国Agilent公司生产的7700X型电感耦合等离子质谱仪(ICP-MS)。分析采用的激光剥蚀孔径为32 μm,实验中用He作为剥蚀物质的载气。标准锆石91500作为外标,测试值为(1064±10)Ma;GJ-1为监控标样,测试值为(600±10)Ma。具体操作详见(周亮亮等, 2017)。

锆石Lu-Hf同位素分析在中国地质大学(武汉)

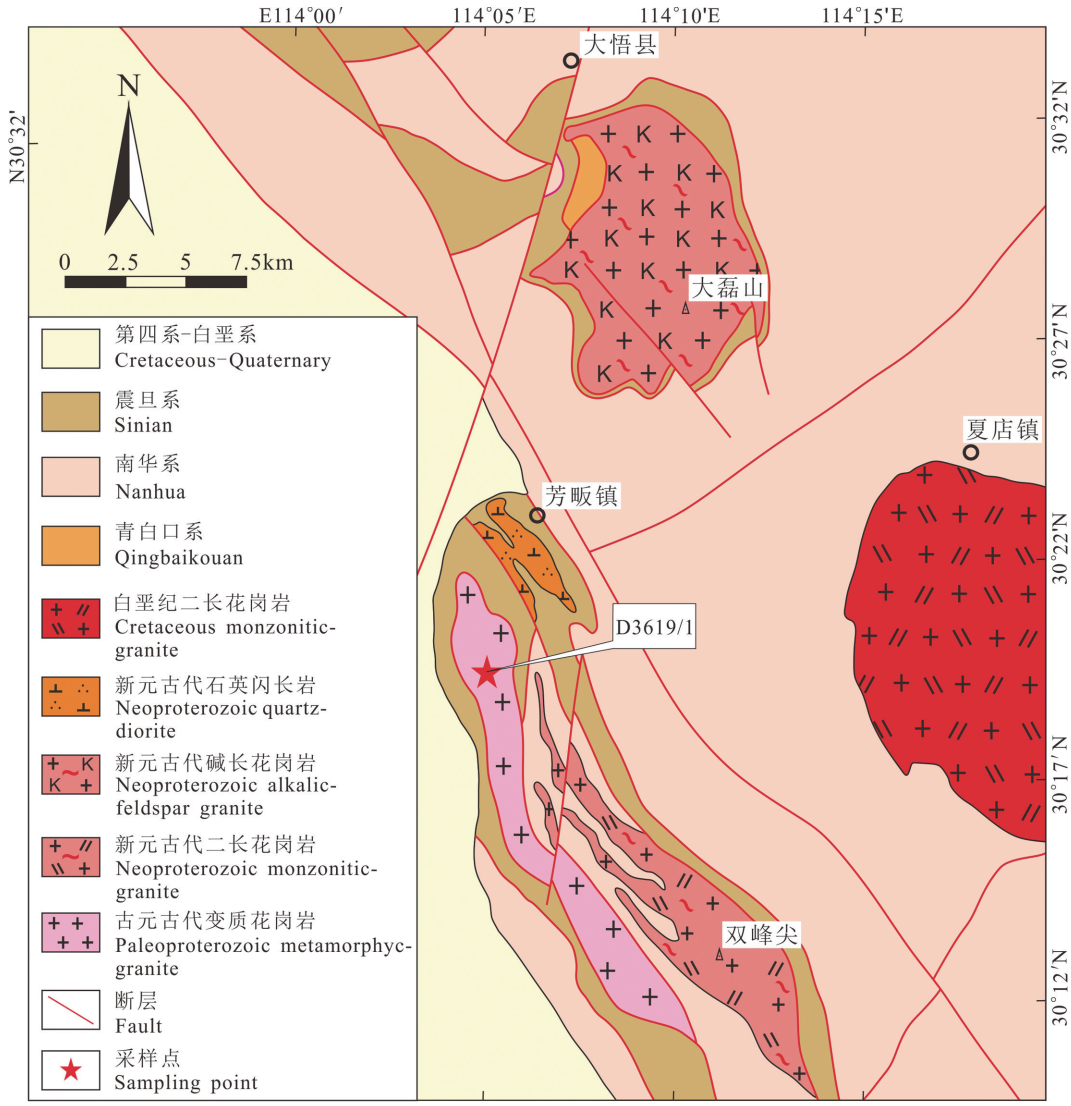

图2 金盘岩体地质简图及采样位置

Fig.2 Simplified geological map of the Jinpan pluton showing sampling location

地质过程与矿产资源国家重点实验室完成，实验室采用德国MicroLas公司生产的GeoLasPro2005激光剥蚀系统作为进样的采集系统，测试仪器为Neptune Plus型MC-ICP-MS。分析斑束为44 μm，频率为10 Hz。实验过程通过分析标准锆石91500，TEMORA以及GJ-1进行数据质量监控，分析结果分别为0.282290±0.000023(n=4, 1σ)、0.282662±0.000040(n=4, 1σ)以及0.282023±0.000021(n=4, 1σ)，与推荐值(0.282307±0.000031, 2σ;0.282680±31, 2σ;0.282015±0.000019, 2σ)(Wu et al., 2006)在误差范围内一致。Lu-Hf同位素体系计算时所用参数分别为(^{176}Lu/^{177}Hf)$_{CHUR}$=0.0332、(^{176}Hf/^{177}Hf)$_{CHUR}$=0.282772(Blichert-Toft and Albarède, 1997)；(^{176}Lu/^{177}Hf)$_{DM}$=0.0384、(^{176}Hf/^{177}Hf)$_{DM}$=0.28325 (Vervoort and Blichert-Toft, 1999)；(^{176}Lu/^{177}Hf)$_{CC}$=0.015(Griffin et al., 2002)；λ=1.867×10^{-11} a^{-1}(Albarède et al., 2006)。

采用ICPMSDataCal(V8.6)对锆石U-Pb及Lu-Hf同位素测试数据进行处理(Liu et al., 2010b, c)，结果见表1和表2，其中U-Pb同位素数据利用Isoplot 3.6程序进行谐和图绘制和加权平均年龄计算(Ludwig, 2008)。

4 测试结果

样品D3619/1中的锆石颜色单一，以淡黄色为

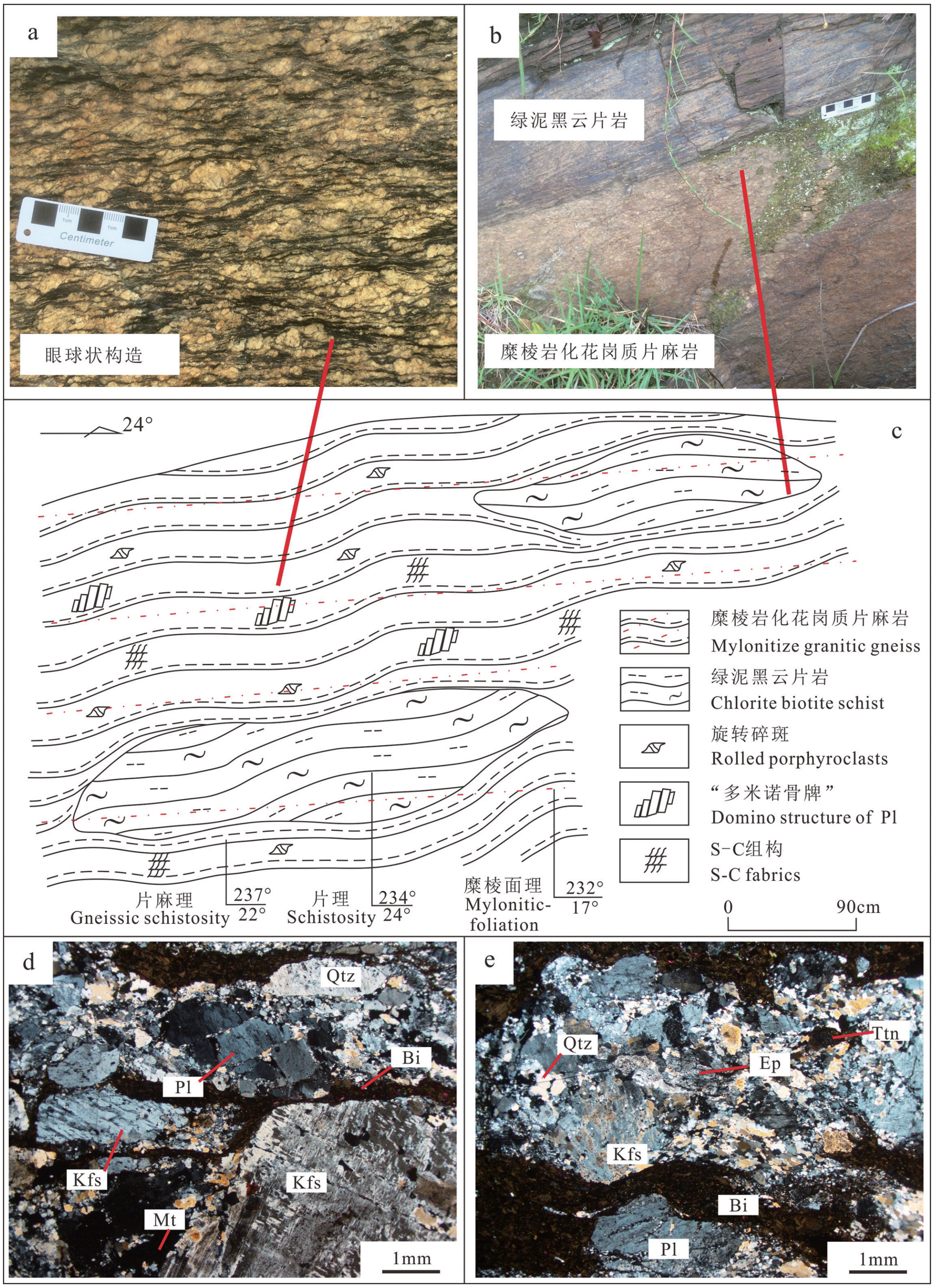

图3 金盘岩体野外产状和显微照片

a—糜棱岩化花岗质片麻岩眼球状构造特征；b—岩体与捕虏体接触关系；c—糜棱岩化花岗质片麻岩与绿泥黑云片岩捕虏体接触关系素描图；d、e—花岗质糜棱岩矿物共生关系；Kfs—钾长石；Pl—斜长石；Qtz—石英；Bi—黑云母；Mt—磁铁矿；Ep—绿帘石；Ttn—榍石

Fig.3 Field photographs and microphotographs of the Jinpan pluton

a−Photograph of augen structure of mylonitize granitic gneiss; b−Photograph of the contact relationship between pluton and xenolith; c−Sketch of the contact relationship between mylonitize granitic gneiss and chlorite biotite schist xenoliths; d, e−Paragenesis of mylonitize granitic gneiss; Kfs−K−feldspar; Pl−Plagioclase; Qtz−Quartz; Bi−Biotite; Mt−Magnetite; Ep−Epidote; Ttn−Titanite

表1 金盘岩体样品D3619/1 LA−ICP−MS锆石U−Pb同位素测年结果

Table 1 LA−ICP−MS zircon U−Pb isotope date of the sample D3619/1 from the Jinpan pluton

分析点号	元素含量/10^{-6}		Th/U	同位素比值						年龄/Ma						谐和度/%
	^{232}Th	^{238}U		^{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	
D3619/1-01	59	77	0.77	0.12321	0.00197	5.85248	0.12237	0.34413	0.00655	2003	28	1954	18	1907	31	97
D3619/1-02	104	130	0.79	0.12304	0.00143	6.20042	0.08681	0.36497	0.00413	2067	21	2005	12	2006	20	99
D3619/1-03	34	39	0.86	0.12593	0.00198	6.23764	0.12420	0.35956	0.00582	2043	28	2010	17	1980	28	98
D3619/1-04	72	83	0.86	0.12555	0.00154	6.28250	0.09651	0.36254	0.00457	2037	22	2016	14	1994	22	98
D3619/1-05	45	51	0.89	0.12206	0.00177	6.14653	0.11048	0.36511	0.00522	1987	26	1997	16	2006	25	99
D3619/1-06	42	63	0.66	0.12351	0.00166	6.21549	0.10772	0.36484	0.00534	2009	24	2007	15	2005	25	99
D3619/1-07	35	46	0.76	0.12454	0.00182	6.20262	0.11024	0.36132	0.00519	2033	26	2005	16	1988	25	99
D3619/1-08	75	93	0.81	0.12210	0.00165	6.06553	0.09457	0.36033	0.00465	1987	24	1985	14	1984	22	99
D3619/1-09	49	55	0.90	0.12324	0.00182	6.22638	0.11578	0.36657	0.00572	2003	26	2008	16	2013	27	99
D3619/1-10	45	58	0.77	0.12240	0.00183	6.40581	0.12225	0.37934	0.00556	1992	27	2033	17	2073	26	98
D3619/1-11	35	45	0.78	0.12379	0.00160	6.26408	0.10877	0.36733	0.00581	2013	23	2013	15	2017	27	99
D3619/1-12	70	84	0.83	0.12307	0.00134	6.42203	0.10672	0.37743	0.00476	2067	19	2035	15	2064	22	98
D3619/1-13	43	53	0.81	0.12279	0.00161	6.50489	0.10934	0.38442	0.00532	1998	23	2047	15	2097	25	97
D3619/1-14	41	50	0.82	0.11965	0.00185	6.38883	0.10937	0.38837	0.00564	1951	32	2031	15	2115	26	95
D3619/1-15	79	104	0.76	0.12345	0.00153	6.56810	0.10806	0.38566	0.00521	2006	22	2055	15	2103	24	97
D3619/1-16	60	75	0.80	0.11974	0.00164	6.39458	0.11582	0.38728	0.00577	1954	24	2032	16	2110	27	96
D3619/1-17	33	43	0.78	0.12357	0.00187	6.26898	0.12756	0.36744	0.00546	2009	27	2014	18	2017	26	99
D3619/1-18	92	120	0.76	0.12363	0.00143	6.26943	0.09462	0.36762	0.00467	2010	21	2014	13	2018	22	99
D3619/1-19	84	104	0.81	0.12113	0.00127	6.26818	0.09651	0.37460	0.00472	1973	19	2014	14	2051	22	98
D3619/1-20	67	76	0.88	0.12269	0.00145	6.48811	0.09086	0.38352	0.00476	1995	20	2044	12	2093	22	97
D3619/1-21	129	202	0.64	0.12112	0.00115	6.35160	0.08130	0.37939	0.00385	1973	12	2026	11	2073	18	97
D3619/1-22	71	112	0.64	0.12189	0.00147	6.58163	0.11200	0.39055	0.00514	1984	21	2057	15	2125	24	96
D3619/1-23	93	112	0.83	0.12302	0.00146	6.31355	0.09559	0.37135	0.00449	2067	21	2020	13	2036	21	99
D3619/1-24	39	56	0.69	0.12445	0.00185	6.40345	0.11708	0.37364	0.00618	2021	27	2033	16	2047	29	99

主，基本呈半自形—自形长柱状，少数等轴粒状，大部分锆石晶形完整，少数呈破裂残缺状，长轴大小集中在100~210 μm，长宽比一般为1∶1~2.3∶1。锆石阴极发光图像(图4)显示其绝大多数具有较好的振荡环带结构，其中一些具有继承锆石残留核；少量出现扇形分带结构，可能由于外部条件变化导致锆石结晶时各晶面生长速率不一致(Vavra G et al., 1996)。本次定年选择24颗锆石共测试24个分析点，所有分析点均选择同心振荡环带区域。由表1可知，它们的Th含量为33×10^{-6}~129×10^{-6}，U含量为39×10^{-6}~202×10^{-6}，Th/U比值为0.64~0.90(平均值0.79)均大于0.4，表现出岩浆锆石的特点(吴元保等, 2004)。另外，由锆石稀土元素球粒陨石标准化分布型式图(图5b)可看出，岩体锆石LREE含量低，HREE富集，Ce正异常明显，同样显示岩浆成因(Hoskin, 2005；Pelleter et al., 2007)。部分锆石环带模糊，可能受后期变质重结晶的影响，但从谐和曲线图可知(图5a)，大多分析点获得谐和年龄且位于谐和曲线之上及其附近，表明大多数锆石U−Pb体系仍保持封闭系统，仅个别发生了轻微的放射成因铅丢失。所有分析点构成不一致线与谐和曲线的上交点年龄为(2007±8)Ma(MSWD=0.86)，取其中16个谐和分析点(谐和度为98%~99%)的^{207}Pb/^{206}Pb加权平均年龄值为(2022±17)Ma(MSWD=2.0)，代表了岩体结晶年龄。另外，锆石中没有发现中生代年龄值，可能是早中生代板块俯冲变质作用以及燕山期岩浆作用对该岩体影响较小，锆石没有明显的增生，因此没有足够区域进行准确的定年。

Lu−Hf同位素方面，选择8颗锆石共测试8个分析点，数据结果见表2。它们^{176}Hf/^{177}Hf比值为0.28121~0.281299，且具有负的$\varepsilon_{Hf}(t)$值特征，其范围为−10.6~ −7.6(加权平均值为−8.99±0.66，MSWD=0.91)，一阶亏损地幔模式年龄(T_{DM1})为2.69~2.80 Ga(平均值为2.74 Ga)，二阶地壳模式年龄(T_{DM2})为2.96~3.12 Ga(平均值为3.04 Ga)。

5 讨 论

5.1 大别地区古元古代中期岩浆事件

尽管桐柏—大别造山带受多期变质改造较为强烈，古元古代年龄信息已在该地区不同类型的高压—超高压变质岩(如麻粒岩、榴辉岩、角闪岩、石英岩、变泥质岩以及长英质片麻岩等)中识别出来，

表2 金盘岩体样品D3619/1的锆石Lu−Hf同位素测定结果

Table 2 Lu−Hf isotope date of zircons from the sample D3619/1 from the Jinpan pluton

分析点号	$^{176}Hf/^{177}Hf$	1σ	$^{176}Lu/^{177}Hf$	1σ	$^{176}Yb/^{177}Hf$	1σ	t/Ma	$ε_{Hf}(0)$	1σ	$ε_{Hf}(t)$	1σ	T_{DM1}/Ma	T_{DM2}/Ma	$f_{Lu/Hf}$
D3619/1-01	0.281250	0.000019	0.000418	0.000004	0.013479	0.000146	2022	-53.8	0.8	-9.3	0.9	2749	3051	-0.99
D3619/1-06	0.281254	0.000022	0.000446	0.000012	0.015295	0.000260	2022	-53.7	0.9	-9.2	1.0	2746	3046	-0.99
D3619/1-11	0.281277	0.000020	0.000445	0.000008	0.014039	0.000342	2022	-52.9	0.9	-8.3	1.0	2714	3001	-0.99
D3619/1-13	0.281299	0.000018	0.000499	0.000005	0.016440	0.000224	2022	-52.1	0.8	-7.6	0.9	2688	2964	-0.98
D3619/1-15	0.281260	0.000018	0.000466	0.000002	0.014908	0.000162	2022	-53.5	0.8	-9.0	0.9	2738	3035	-0.99
D3619/1-17	0.281274	0.000021	0.000512	0.000005	0.016099	0.000148	2022	-53.0	0.9	-8.6	1.0	2723	3013	-0.98
D3619/1-18	0.281215	0.000017	0.000459	0.000002	0.015164	0.000118	2022	-55.1	0.8	-10.6	0.9	2799	3121	-0.99
D3619/1-20	0.281263	0.000026	0.000850	0.000007	0.027640	0.000267	2022	-53.4	1.1	-9.4	1.2	2762	3059	-0.97

其中大部分为变质年龄，主要集中在2.03~1.94 Ga（夏科群等, 2003；Wu et al., 2008；Sun et al., 2008；Liu et al., 2008a, 2010a；胡娟等, 2012）。部分岩浆锆石年龄信息则主要来自榴辉岩、石英岩以及长英质片麻岩的原岩，年龄范围在1.98~1.96 Ga（Wu et al., 2008；Liu et al., 2008a, 2010a；胡娟等, 2012）。同时，扬子陆块中部新元古代沉积岩中出现了大量2.1~2.0 Ga的碎屑锆石，它们均显示出岩浆成因（佘振兵, 2007；Liu et al., 2008b）。另外，在扬子陆块各地出露的钾镁煌斑岩中同样发现有~2.0 Ga的锆石捕虏晶（Zheng et al., 2006），甚至在中生代花岗岩中也有（1929±25）Ma、（2023±41）Ma以及2091~2025 Ma的继承锆石年龄信息（Bryant et al., 2004；王彦斌等, 2004）。以上证据表明桐柏—大别造山带可能存在2.09~1.93 Ga的岩浆事件。本文获得的金盘岩体侵位年龄为（2022±17）Ma，表明其形成于古元古代中期，进一步证明大别地区存在~2.0 Ga的岩浆活动，为扬子陆块北缘广泛发育约2.08~1.93 Ga的重要岩浆事件提供了新的年代学证据。

5.2 大别地区太古宙地壳生长

源自下地壳新生玄武质岩石再造所形成的锆石通常具有$ε_{Hf}(t)$正值特征（吴福元等, 2007）。金盘岩体变质花岗岩的岩浆锆石具有明显的负$ε_{Hf}(t)$值特征，其范围在−10.9±0.9~−8.0±0.9，表明该花岗质岩浆产自于古老地壳物质的重熔，没有幔源新生地壳物质的加入。因此金盘岩体源区更可能来自于上地壳的火成岩或变沉积岩石。此外，岩体的$ε_{Hf}(t)$值相对均一，且野外地质调查中未发现其含有暗色微粒包体，因此可排除岩浆混合源区。锆石二阶模式年龄T_{DM2}为2964~3121 Ma（平均3036 Ma），表明其岩浆源区物质在~3.0 Ga由亏损地幔分异而来。在扬子陆块内部，崆岭杂岩出露有最为典型的太古

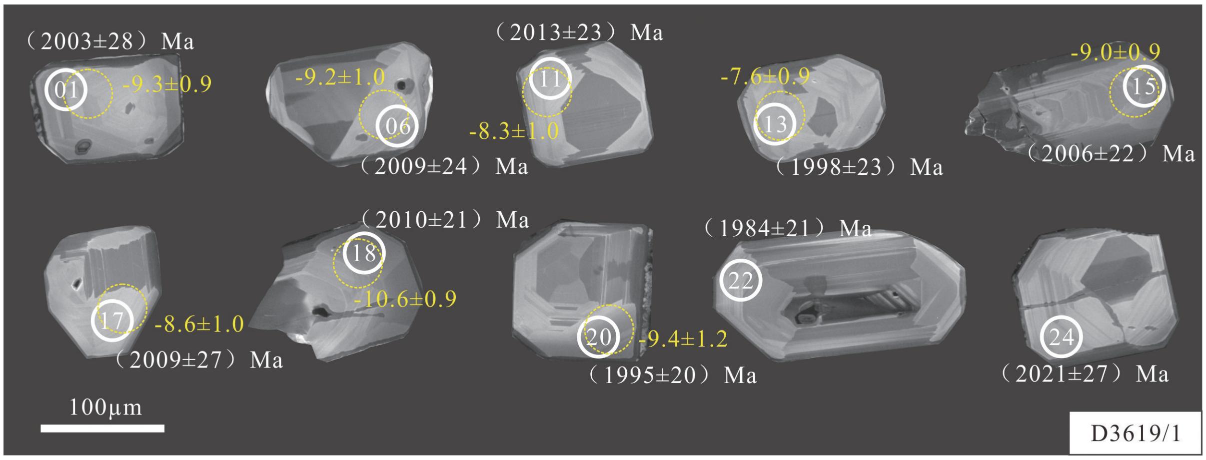

图4 金盘岩体代表性锆石阴极发光图

(白色实线圈和黄色虚线圈分别代表U−Pb和Lu−Hf同位素分析点，白色和黄色数字分别表示锆石$^{207}Pb/^{206}Pb$年龄值以及$ε_{Hf}(t)$值)

Fig.4 Cathodoluminescence (CL) images of representative zircons from the Jinpan pluton

(Solid white circles and dashed yellow circles represent the points for U−Pb and Lu−Hf isotope analysis, respectively. The numbers in white color refer to the zircon $^{207}Pb/^{206}Pb$ ages, and $ε_{Hf}(t)$ values are indicated in yellow color)

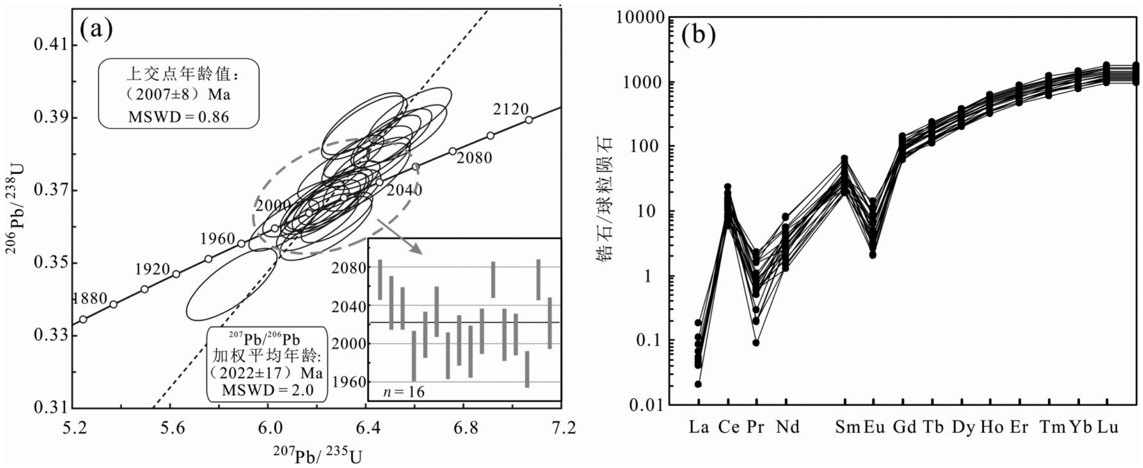

图5 金盘岩体锆石U-Pb年龄谐和图(a)和锆石REE球粒陨石标准化分布型式图(b,球粒陨石标准化数据引自Sun and McDonough,1989)

Fig.5 U-Pb isotopic concordia diagram (a) and chondrite-normalized REE distribution patterns of zircons from the Jinpan pluton (b,the chondrite-normalized data are all from Sun and McDonough,1989)

宙基底物质,它记录着扬子克拉通早期地壳形成与演化的重要过程(Gao et al., 1999, 2011; Qiu et al., 2000; Zhang et al., 2006a,b,c)。前人对基底物质的碎屑锆石研究表明,3.8~3.2 Ga、3.00~2.95 Ga、2.70~2.60 Ga和2.7~2.6 Ga的年龄峰值记录了太古宙地壳4次重要的增生与再造事件(Zhang et al., 2006a; Liu et al., 2008b; Gao et al., 2011; Chen et al,. 2013)。其中最古老的锆石年龄~3.8 Ga以及~4.0 Ga的Hf模式年龄指示了扬子陆块最早的生长与再造时间可能达4.0 Ga和3.8 Ga(张少兵和郑永飞, 2007)。因此,与3.00~2.95 Ga峰值相对应,金盘岩体~3.0 Ga的Hf模式年龄可能代表了大别地区中太

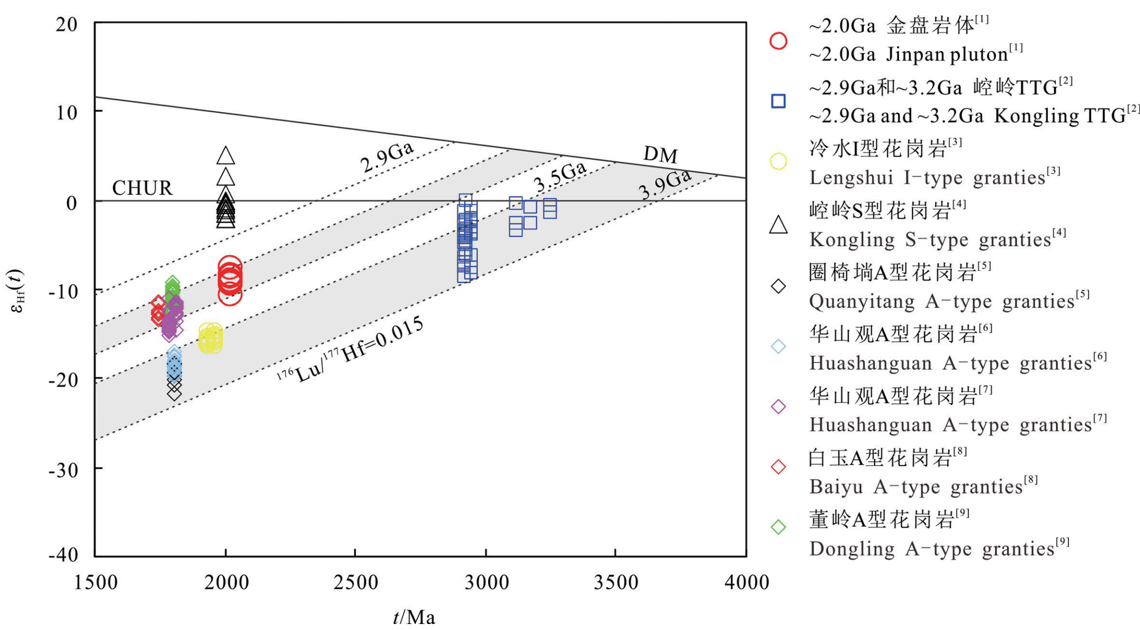

图6 $\varepsilon_{Hf}(t)-t$同位素演化图解

(数据引自: [1] 本文数据; [2] Zhang et al., 2006c; [3] Wang et al., 2015; [4] Yin et al., 2013; [5] Peng et al., 2012; [6] Zhou et al., 2017; [7] 黄明达等, 2019; [8] 邓奇等, 2017; [9] Chen and Xing, 2016)

Fig.6 Hf isotope evolution diagram

(Data from : [1] This study; [2] Zhang et al., 2006c; [3] Wang et al., 2015; [4] Yin et al., 2013; [5] Peng et al., 2012; [6] Zhou et al., 2017; [7] Huang et al., 2019; [8] Deng et al., 2017; [9] Chen and Xing, 2016)

古代时期的一次地壳生长事件，进一步佐证了扬子陆块北缘太古宙基底物质的分布更加广泛，向北已延伸至大别造山带（Wu et al., 2008）。

另外，沿扬子陆块北缘广泛存在2.0~1.8 Ga的岩浆作用事件，如崆岭杂岩中识别出的2.00~1.98 Ga同碰撞S型花岗岩（Yin et al., 2013；Li et al., 2014），冷水杂岩中1.96 Ga同碰撞I型花岗岩（Wang et al., 2015）以及1.85~1.79 Ga后造山伸展环境形成的A型花岗岩（张丽娟等, 2011；Peng et al., 2012；Chen and Xing, 2016；Zhou et al., 2017；邓奇等, 2017；黄明达等, 2019）。结合已有$\varepsilon_{Hf}(t)$资料（图6），金盘岩体变质花岗岩与碑坝白玉、董岭以及华山观（黄明达等, 2019）A型花岗岩锆石具有类似的$\varepsilon_{Hf}(t)$演化模式，并表现出一致的二阶模式年龄（2945~3183 Ma）。而冷水I型花岗岩则与圈椅埫和华山观（Zhou et al., 2017）A型花岗岩表现出相似的Hf同位素演化趋势，且样品点均落入3.2~2.9 Ga崆岭TTG的演化区域，说明这些花岗岩类岩石可能源于其部分熔融（Wang et al., 2015），3527~3637 Ma的二阶模式年龄则表明它们可能源自＞3.5 Ga时期相同的先存陆壳物质。由此可见，扬子陆块可能存在两套具有不同演化历史的太古宙陆壳物质，对比两类来源的岩体目前的分布范围，其中形成于2945~3183 Ma的太古宙陆壳物质可能分布更加广泛。

5.3 大别地区与Columbia超大陆聚合有关的岩浆事件

古元古代Columbia超大陆的存在已经得到较为普遍的认可，随着近年来对扬子陆块前寒武纪构

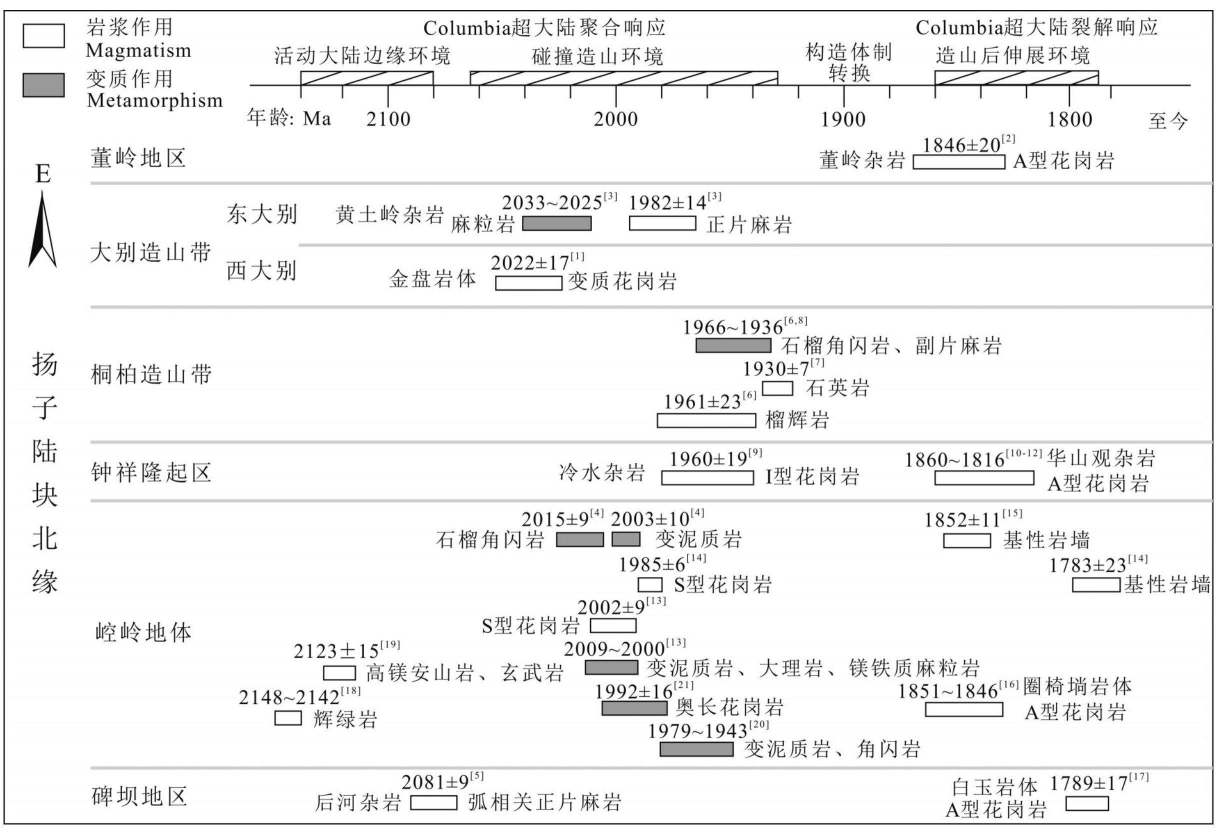

图7 扬子陆块北缘古元古代岩石的时空分布格局（单位：Ma）

（锆石U−Pb年龄数据引自：[1] 本文数据；[2] Chen and Xing, 2016；[3] Wu et al., 2008；[4] Wu et al., 2009；[5] Wu et al., 2012；[6] 胡娟等, 2012；[7] Liu et al., 2008a；[8] Liu et al., 2010a；[9] Wang et al., 2015；[10] Zhou et al., 2017；[11] 黄明达等, 2019；[12] 张丽娟等, 2011；[13] Yin et al., 2013；[14] Li et al., 2014；[15] 彭敏等, 2009；[16] Peng et al., 2012；[17] 邓奇等, 2017；[18] Han et al., 2017；[19] Han et al., 2018；[20] Zhang et al., 2006b；[21] Qiu et al., 2000）

Fig.7 Temporal and spatial distribution of Paleoproterozoic rocks in the northern Yangtze Block

(Data of zircon U−Pb isotope ages from: [1] This study；[2] Chen and Xing, 2016；[3] Wu et al., 2008；[4] Wu et al., 2009；[5] Wu et al., 2012；[6] Hu et al., 2012；[7] Liu et al., 2008a；[8] Liu et al., 2010a；[9] Wang et al., 2015；[10] Zhou et al., 2017；[11] Huang et al., 2019；[12] Zhang et al., 2011；[13] Yin et al., 2013；[14] Li et al., 2014；[15] Peng et al., 2009；[16] Peng et al., 2012；[17] Deng et al., 2017；[18] Han et al., 2017；[19] Han et al., 2018；[20] Zhang et al., 2006b；[21] Qiu et al., 2000)

造演化的研究工作不断深入，大量古元古代变质-岩浆事件逐渐被发现。与华北陆块类似，扬子陆块同样广泛存在2.1~1.9 Ga构造热事件的年代学记录（图7）。

Han et al.（2017）首次在北黄陵厘定出一套蛇绿混杂岩，识别出~2.15 Ga与俯冲相关的铁镁质-超铁镁质岩石，随后发现的~2.1 Ga高镁玄武岩和安山岩指示了古元古代存在安第斯山型大陆边缘环境（Han et al., 2018）。Wu et al.（2012）也报道了碑坝地区后河杂岩体中形成于（2081±9）Ma的花岗岩，指示了与弧相关的活动大陆边缘环境。同时，崆岭杂岩中出露的古元古代孔兹岩反映出先存的稳定大陆边缘环境（Zhang et al., 2006b；Wu et al., 2009；邱啸飞等, 2017）。前人对扬子北缘的崆岭群太古宙变质基底和桐柏—大别造山带中包括（镁铁质）麻粒岩、变泥质岩、大理岩、角闪岩等高级变质岩以及新元古代沉积岩的年代学研究显示，它们的变质年龄集中在2.03~1.93 Ga（Zhang et al., 2006a, b, c；Sun et al., 2008；Liu et al., 2008a, b,2010a；Wu et al., 2009；赵国春, 2009；2012；胡娟等, 2012；魏君奇和景明明, 2013；Li et al., 2014），表明扬子陆块存在一条古元古代的高级变质带。这些变质岩石记录了顺时针的$P-T$演化轨迹，指示了一次陆-陆碰撞的大地构造背景（Wu et al., 2008, 2009；Yin et al., 2013）。同时，来自崆岭杂岩的S型花岗岩以及钟祥隆起区冷水杂岩的I型花岗岩侵位于2.00~1.96 Ga，代表了该时期重要的岩浆活动，它们均形成于碰撞环境，指示了扬子北缘古元古代发生的弧-陆或陆-陆碰撞造山事件（Yin et al., 2013；Li et al., 2014；Wang et al., 2015）。之后，在扬子陆块北缘发现的一系列A型花岗质岩石和伸展相关的基性岩脉（彭敏等, 2009；张丽娟等, 2011；Peng et al., 2012；Chen and Xing, 2016；Zhou et al., 2017；邓奇等, 2017；黄明达等, 2019），被认为是在~1.9 Ga后扬子陆块北缘发生了构造体制转换的有力证据，即由碰撞造山环境转变为造山后伸展的构造背景。

综上所述，扬子陆块北缘与Columbia超大陆汇聚有关的碰撞造山事件主要发生于2.12~1.93 Ga，本文研究发现的2.0 Ga变质花岗岩同样形成于该时期，揭露了古元古代重要的岩浆事件，这可能代表了Columbia超大陆聚合在大别地区的响应。

6 结 论

（1）锆石LA-ICP-MS U-Pb测年结果表明，金盘岩体侵位年龄为（2022±17）Ma，证明大别地区存在~2.0 Ga的岩浆活动。

（2）$\varepsilon_{Hf}(t)$值（-10.6~-7.6）及其二阶模式年龄（2.96~3.12 Ga）表明金盘岩体的变质花岗岩来源于古老陆壳物质的再造，结合已有$\varepsilon_{Hf}(t)$值资料，扬子陆块北缘发育更为广泛的2.95~3.18 Ga太古宙陆壳物质。

（3）金盘岩体形成于古元古代碰撞造山作用时期（2.03~1.93 Ga），其代表的岩浆活动事件可能是Columbia超大陆聚合在大别地区的响应。

致谢：感谢刘彬副教授的技术指导、审稿专家提出的建设性意见及所有为本文提供帮助的同仁们！

注释

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