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江南中段慈化地区新元古代高镁安山岩的厘定及其构造意义

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摘要: 江南造山带被普遍认为是扬子与华夏陆块在新元古代的拼合带,其拼合机制及精细时代却一直备受争议.在江南造山带中段湘赣交界慈化地区识别出新元古代火山岩,并对其进行了锆石U-Pb年代学及主微量地球化学研究.该火山岩发育于冷家溪群地层中,其锆石LA-ICP-MS年代学测试得到了832±12 Ma的$^{206}Pb/^{238}U$加权平均年龄(n=16, MSWD=0.12),代表其喷发年龄.主量元素结果显示,SiO_2和MgO含量分别为57.67%~61.33%和3.51%~4.29%,$Mg^{\#}$为52~57,高于正常弧火山岩,属高镁安山岩.微量元素富集轻稀土元素和大离子亲石元素,亏损高场强元素,其Nb-Ta、Ti亏损,具"弧型"地球化学特征,可能来源于受板片熔体/流体或者俯冲再循环沉积物交代的难熔地幔源区.上述资料表明,慈化高镁安山岩是江南造山带中段楔形地幔源区受消减组分交代作用的产物,暗示此时江南造山带中段仍在消减,扬子和华夏陆块尚未完全拼合.结合前人研究成果,江南造山带不同区段的闭合时间可能存在差异.

关键词: 慈化高镁安山岩;锆石U-Pb定年;新元古代俯冲作用;江南中段;地球化学.
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Geochronology and Geochemistry of Cihua Neoproterozoic High-Mg Andesites in Jiangnan Orogen and Their Tectonic Implications

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Abstract: It is generally accepted that the Jiangnan orogenic belt led to the amalgamation of the Yangtze with Cathaysia blocks during the Neoproterozoic period. However, its tectonic evolution and amalgamation timing are still in debate. This paper presents a set of new geochronological and geochemical data for the newly-identified Neoproterozoic high-Mg volcanics from Cihua (Jiangxi). LA-ICP-MS zircon U-Pb dating of the representative sample yields a weighted mean age of 832±12 Ma (n=16, MSWD=0.12), representing the eruption age of the andesite. Geochemical results indicate that they can be classified as high-Mg andesites with SiO_2 ranging from 57.67% to 61.33%, MgO from 3.51% to 4.29% and Mg-number from 52 to 57. Their chondrite-normalized REE patterns exhibit a left-sloping pattern with enriched LREEs relative to HREEs. On the primitive mantle-normalized multi-element patterns, these samples have strong enrichment in LILE and depletion in HFSE with marked negative Nb-Ta, Ti and positive Th anomalies, similar to those of the typical arc volcanics. The generation of the volcanic rocks might have been attributed to an interaction of the subducted melt/fluid or sediment with the overlying refractory mantle, suggesting the central Jiangnan orogen was still on the subduction till ~832 Ma. It is concluded that the Jiangnan orogen consists

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of several branches with distinct amalgamation evolution.

Key words: Cihua high-Mg andesite; zircon U-Pb dating; Neoproterozoic subduction; central Jiangnan orogen; geochemistry.

华南新元古代汇聚作用是国际前寒武纪研究的热点，其中江南造山带被普遍认为是扬子陆块与华夏陆块在新元古代的拼合带，是解析华南前寒武纪汇聚作用的关键地区（Zhao and Cawood, 1999, 2012; Li *et al.*, 2002, 2009; Zhao, 2015），也是恢复华南地区前寒武纪地质演化过程及其与 Rodinia 超大陆关系的理想场所（Wang *et al.*, 2010, 2013）.

不同学者对扬子与华夏陆块拼贴机制及精细年代的理解争议较大，目前代表性观点主要有 4 种：(1)李献华等（1994, 2012）认为扬子与华夏陆块于中－新元古代晋宁早期（约 0.9～1.0 Ga，相当于四堡期或格林威尔期）沿江南一带碰撞拼贴而形成江南（或四堡）造山带，其碰撞结束于约 880 Ma，这一事件被解释为与罗迪尼亚超大陆聚合关系密切，并认为华南大陆介于澳大利亚与劳伦古陆之间，位于罗迪尼亚超大陆中心，扬子周边晋宁晚期（约 0.8 Ga）岩浆作用则被解释为罗迪尼亚超大陆裂解时地幔柱作用的结果（Li *et al.*, 1995, 1999, 2002, 2003a, 2003b, 2004, 2009; Greentree *et al.*, 2006; Wang *et al.*, 2007a; Ye *et al.*, 2007）；(2)周金城等（2003）提出板块俯冲模式，认为其是洋壳俯冲消减于扬子陆块之下的产物（Wang *et al.*, 2004, 2006, 2014a; Zhou *et al.*, 2004; Zhao and Zhou, 2008, 2013; Zhao *et al.*, 2011, 2013）；(3) Zheng *et al.*（2006, 2007, 2008）认为应该用板块－裂谷模式来加以解释，扬子与华夏陆块聚合的终结时间在约 800～830 Ma 的晋宁晚期（Zhou *et al.*, 2004; Wang *et al.*, 2006, 2007b, 2008; Wu *et al.*, 2006; Zhao *et al.*, 2011; Zhang *et al.*, 2012a, 2012b; Zhao, 2015）；(4) Wang *et al.* (2013, 2014b)则提出华南大陆的新元古代造山事件很可能以多陆块北西向幕式拼贴为特征，江南造山带只是拼贴过程中汇聚的一部分. 因此，江南新元古代岩浆作用仍是深入理解华南前寒武纪演化的突破口.

江南造山带的研究更多地集中于分布较广泛的花岗岩浆作用，如皖南许村、歙县和休宁花岗质岩体显示出 815±17 Ma～824±6 Ma 的锆石 U-Pb 年龄范围和以 S 型花岗岩为主、兼有 I 型花岗岩的特征（Wu *et al.*, 2006）. 赣北地区侵入于双桥山群中的九岭花岗质岩石的锆石 U-Pb 年龄为 813±4 Ma～828±2 Ma，兼具 S 型和 I 型花岗岩特征（Li *et al.*, 2003a; 钟玉芳等，2005; 张菲菲等，2011）；侵入于冷家溪群中的叶溪江、长三背、张邦源和西园坑花岗岩体的锆石 U-Pb 定年结果均小于 816±5 Ma，具 S 型花岗岩特征（王孝磊等，2004；马铁球等，2009；柏道远等，2010；张菲菲等，2011）. 桂东北梵净山群与板溪群之间角度不整合，其中花岗质砾石锆石 U-Pb 年龄为 789±11 Ma，$\varepsilon_{Hf}(t)=-2.1\sim-6.0$（Su *et al.*, 2014）. 前人对中基性岩浆作用的研究也多集中于江南造山带东段和西段，尤其是对位于中段的湘赣九岭一线的研究；中基性岩浆作用报道较少使得研究积累相对薄弱. 目前报道的有浏阳－芳溪 N-MORB特征的玄武质岩石及皖南伏川蛇绿岩，测得其锆石 U-Pb 年龄分别为838～860 Ma（Zhang *et al.*, 2013）和 824～848 Ma（丁炳华等，2008; 张彦杰等，2011; Zhang *et al.*, 2012b），均被解释为弧后盆地的产物. 益阳地区出露了一套枕状玄武岩，具有较高的 MgO 含量，Wang *et al.* (2007a)根据其发育的“鬣刺结构”将其定为地幔柱作用产物. 但 Zhao and Zhou(2013)根据其 $\varepsilon_{Nd}(t)<0$ 以及类似于玻安岩的地球化学特征，认为其形成于扬子与华夏陆块聚合过程中与板片俯冲有关的热地幔源区.

以上岩石为江南造山带构造属性的研究提供了基础性资料，但是要更好地解决其多解性争议，需要寻找构造背景指示意义更为明确的岩石. 高镁安山岩泛指 MgO($Mg^{\#}$)含量较高的安山岩和部分英安岩类，主要形成于与消减带相关的构造环境（Rudnick and Fountain, 1995），可作为追溯华南前寒武纪演化的理想岩石探针，指示其形成时的构造环境. 基于上述理解，本文在湘赣交界地区识别出一套高镁安山岩，并对其进行了系统的野外地质、锆石 U-Pb 年代学和主微量地球化学分析工作，以期为江南造山带新元古代构造属性提供有效的岩石学证据.

1　地质背景与样品描述

江南造山带主要是由一套浅变质、强变形的新元古代巨厚沉积－火山岩系及时代相当的侵入体所构成的地质构造单元，其呈 NEE 走向分隔扬子与华夏陆块，绵延逾 1 500 km，宽约 200 km. 江南造山

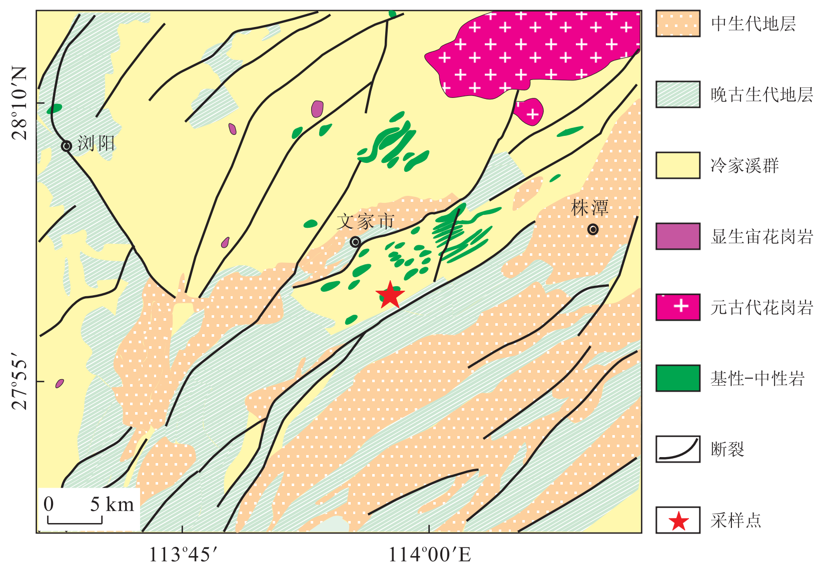

图 1　湘东北—赣西北地区地质概况及采样点位置

Fig. 1　NE Hunan and NW Jiangxi provinces with the sampling location

图 1 改编自 Zhang *et al*., 2013

带的前寒武纪地层主要包括冷家溪群及其相当地层、板溪群及其相当地层以及震旦系(图 1;湖南省地质矿产局,1988;覃永军等,2015).

湘东北—赣西北地区位于江南造山带中部湘赣交界地区,桥接江南造山带东段(赣东北—浙北)和西段(湘西—桂北).该地区主要出露新元古代冷家溪和双桥山群地层,并且发育 823~804 Ma 的花岗质岩石(Li *et al*., 2003a; 张菲菲等, 2011).湘北一带的冷家溪群最大可靠厚度逾 25 000 m,属绿片岩相,以板岩为主,杂砂岩中仅见杂基部分轻微变质,无重结晶现象.由于经历了多期构造叠加事件,构造变形强烈,发育板劈理、紧闭褶皱和等斜倒转褶皱(湖南地质矿产局,1988).冷家溪群及其相当地层长期以来一直被划属中元古代(郭令智等, 1980; 江西省地质矿产局, 1984; 广西壮族自治区地质矿产局, 1985; 湖南省地质矿产局, 1988; 唐晓珊等, 1997),近年的研究结果表明其碎屑岩中锆石 U-Pb 年龄的最小峰值为 850~870 Ma (Wang *et al*., 2007b; Zhao *et al*., 2011; Zhang *et al*., 2015),代表了其最大沉积年龄,因此其沉积时代应为新元古代.

本文研究样品取自湘赣交界的慈化地区(图 1).冷家溪地层内呈 NEE 向顺层产出中基性岩,包括辉长岩、辉绿岩、细碧岩、粒玄岩、粗粒安山岩和凝灰岩(江西地质矿产局, 1984; 湖南地质矿产局, 1988; 王孝磊等, 2003; Wang *et al*., 2008; Zhou *et al*., 2009; Zhang *et al*., 2013).以往的报道主要为基性岩,而对安山岩研究较少,笔者的工作在区内识别出了安山岩和英安岩,二者在野外共存,厚度为 2~4 m.安山岩呈灰绿色、灰黑色,具斑状结构、气孔状构造.斑晶占 5%~15%,主要为斜长石和角闪石,含少量碱性长石、黑云母,斜长石多呈自形—半自形,部分具环带结构;基质主要由微晶斜长石和玻璃质组成,副矿物有磷灰石、磁铁矿等.

2　分析方法

本文用于 U-Pb 定年的锆石采自新鲜的全岩样品,通过人工重砂法分选出锆石,然后在双目显微镜下挑选出晶形好、无裂隙、透明干净的自形锆石颗粒,在玻璃板上用环氧树脂固定,并抛光至锆石中心,然后进行反射光和透射光照相.本次锆石阴极发光图像研究在中国科学院广州地球化学研究所 JXA-8100 电子探针仪上完成.锆石 U-Pb 同位素分析在香港大学地球科学系用 LA-MC-ICP-MS 仪器以标准测定程序进行,详细的实验原理、分析流程及有关参数见 Xia *et al*. (2011).数据的离线处理(包括对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及 U-Th-Pb 同位素比值和年龄计算)采用软件 ICP-MS DataCal(Liu *et al*., 2008)完成,谐和图的绘制利用 Isoplot 3.0 (Ludwig, 2001)完成.

全岩主微量元素的分析测试均在中国科学院广州地球化学研究所同位素地球化学国家重点实验室完成.主量元素用 Rigaku RIX 2000 型荧光光谱仪

分析，其详细步骤与 Li *et al*.（2005）所述相同. 样品的含量由 36 种涵盖硅酸盐样品范围的参考标准物质双变量拟合的工作曲线确定，基体校正根据经验的 Traill-Lachance 程序进行，分析精度优于 1%. 微量元素的分析则采用 Perkin-Elmer Sciex ELAN 6000 型电感耦合等离子体质谱仪，具体的流程见 Li(1997). 使用 USGS 标准 W-2 和 G-2 及国内标准 GSR-1、GSR-2 和 GSR-3 来校正所测样品的元素含量，分析精度一般为 2%～5%.

3 分析结果

3.1 LA-ICP-MS 锆石 U-Pb 定年

本文对来自慈化的代表性安山岩样品(12WS-79A)的 30 颗锆石进行了 ICP-MS 激光 U-Pb 定年，分析数据列于表 1. 用于定年分析的锆石呈半透明到透明状，颜色为浅棕到无色，以浅棕色为主. 锆石多呈短柱状，长度一般为 80～150 μm，发育较为规律的振荡环带结构(图 2b)，结合其较高的 Th/U 比值(0.12～1.18)，指示其为岩浆锆石成因. 其中 16 个较年轻的分析点的年龄为 827±24 Ma～837±24 Ma，给出的 $^{206}Pb/^{238}U$ 均值年龄为 832±12 Ma(MSWD=0.12)(图 2a)，代表了慈化高镁安山岩的形成年龄. 8 个点(12WS-79A-02、12WS-79A-07、12WS-79A-16、12WS-79A-22、12WS-79A-24、12WS-79A-27、12WS-79A-28 和 12WS-79A-30)的年龄为 1 722±56 Ma～1 910±54 Ma，给出了 1 841±38 Ma(MSWD=0.94)的 $^{207}Pb/^{206}Pb$ 均值年龄. 其余 12WS-79A-04、12WS-79A-06、12WS-79A-12、12WS-79A-25 和 12WS-79A-29 给出的 $^{207}Pb/^{206}Pb$ 表观年龄分别为 2 450±51 Ma、1 189±60 Ma、1 587±56 Ma、2 015±53 Ma 和 2 394±50 Ma，与前述 1 841±38 Ma 均代表了捕虏锆石的年龄.

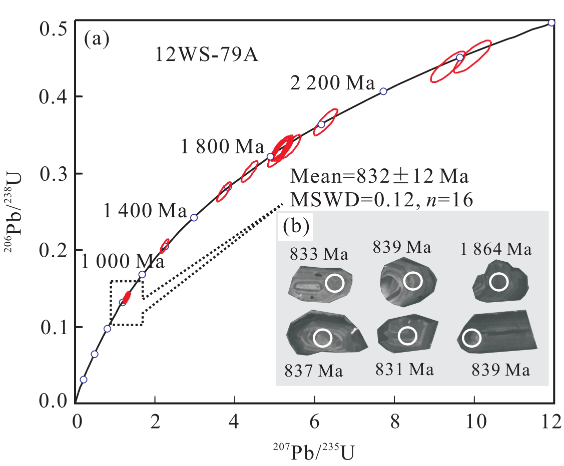

图 2 慈化高镁安山岩样品 LA-ICP-MS 锆石 U-Pb 年龄谐和图和阴极发光图像(CL)

Fig. 2 Concordia diagrams of zircon U-Pb data for the Cihua high-Mg andesitic sample

3.2 元素地球化学特征

本次测试的 5 个火山岩样品主微量元素分析数据见表 2. 它们的 SiO_2 含量为 57.67%～61.33%，Al_2O_3 为 17.25%～20.59 %，FeO^t 为 7.10%～7.80%，在 TAS 图上均显示为亚碱性，落在安山岩范围内(图 3a). 其 MgO 含量为 3.82%～4.29%，$Mg^{\#}(Mg^{\#}=Mg^{2+}/Mg^{2+}+Fe^{2+})$ 为 52.2～57.1，Ni 为 34×10^{-6}～40×10^{-6}，Cr 为 55×10^{-6}～109×10^{-6}，明显高于正常弧火山岩，与正常玻安岩(富硅，SiO_2>52%；富镁，MgO>8%；贫钛，TiO_2<0.5%；le Bas, 2000；Zhao and Asimow, 2014)相比，样品 SiO_2>52.00%，但 MgO<8.00%，TiO_2>0.5%. 因此归类为高镁安山岩(图 3b).

在稀土元素球粒陨石标准化图解上，样品都表现出一致的 LREE 富集的"右倾型"配分模式(图 4a)，$(La/Yb)_{CN}$=7.78～12.29(CN 代表球粒陨石标准化)，$(Gd/Yb)_{CN}$=1.52～1.62，具轻微 Eu 负异常(Eu^*=0.49～0.80). 在微量元素原始地幔标准化配分图解中，样品呈现明显的"峰－谷"结构，富集大离子亲石元素(LILE)，亏损高场强元素(HFSE)(图 4b)，具显著的 Nb-Ta、P 和 Ti 负异常，$(Nb/La)_N$(N 代表原始地幔标准化)=0.29～0.39，$(Th/La)_N$=3.05～3.68，而无明显 Zr-Hf 负异常(Hf/Sm=1.00～1.36)，这种模式类似于弧火山岩.

4 讨论

4.1 慈化高镁安山岩的岩石成因

自从 20 世纪 80 年代以来，高镁安山岩得到了广泛研究，它已成为汇聚板块边缘区岩石圈地幔演化研究的一个重要指针(Kamei, 2004). 其成分往往很复杂：可能包含俯冲大洋板片(玄武质洋壳或洋壳沉积物)或俯冲陆壳沉积物熔体或流体组分，或者地幔源区组分，有时也可能包含拆沉下地壳熔体组分. 目前的研究表明，高镁安山岩主要有 3 种成因模式：(1)由榴辉岩地壳的部分熔融而成；(2)由年轻的热的板片部分熔融而成；(3)由消减带板片部分熔融的熔体/流体交代地幔而成(BakerandStolper, 1994；

表 1　慈化高镁安山岩样品 LA- ICP-MS 锆石 U-Pb 分析结果

Table 1　LA-ICP-MS zircon U-Pb dating results for the Cihua high-Mg andesite

分析点	Th/U	$^{207}Pb/^{206}U$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}U$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$	
		比值	±1σ	比值	±1σ	比值	±1σ	年龄(Ma)	±1σ	年龄(Ma)	±1σ	年龄(Ma)	±1σ
12WS-79A-01	0.13	0.067 7	0.002 0	1.289 1	0.039 6	0.138 2	0.004 2	859	63	834	24	841	18
12WS-79A-02	0.47	0.112 3	0.003 4	5.156 5	0.156 9	0.332 9	0.010 1	1 839	54	1 852	49	1 845	26
12WS-79A-03	0.59	0.067 9	0.002 0	1.285 7	0.039 7	0.137 2	0.004 2	878	36	829	24	839	18
12WS-79A-04	1.18	0.159 5	0.004 8	9.952 4	0.308 7	0.452 5	0.014 0	2 450	51	2 406	62	2 430	29
12WS-79A-05	0.33	0.067 0	0.002 0	1.273 2	0.042 9	0.137 3	0.004 6	839	63	829	26	834	19
12WS-79A-06	0.98	0.079 3	0.002 4	2.240 3	0.069 4	0.204 9	0.006 3	1 189	60	1 202	34	1 194	22
12WS-79A-07	0.24	0.116 9	0.003 5	5.402 9	0.165 2	0.335 2	0.010 3	1 910	54	1 864	49	1 885	26
12WS-79A-08	0.28	0.067 7	0.002 0	1.278 0	0.039 4	0.136 9	0.004 2	861	63	827	24	836	18
12WS-79A-09	0.33	0.069 2	0.002 1	1.314 7	0.040 5	0.137 8	0.004 2	906	61	832	24	852	18
12WS-79A-10	0.27	0.068 2	0.002 1	1.293 8	0.040 1	0.137 4	0.004 2	876	62	830	24	843	18
12WS-79A-11	0.36	0.068 6	0.002 1	1.303 7	0.040 0	0.137 8	0.004 2	887	56	832	24	847	18
12WS-79A-12	0.57	0.098 0	0.002 9	3.734 6	0.114 5	0.276 2	0.008 5	1 587	56	1 572	43	1 579	25
12WS-79A-13	0.12	0.067 0	0.002 0	1.270 7	0.039 0	0.137 6	0.004 2	839	63	831	24	833	17
12WS-79A-14	0.38	0.067 3	0.002 0	1.282 3	0.039 2	0.138 1	0.004 2	856	63	834	24	838	17
12WS-79A-15	0.44	0.067 4	0.002 0	1.281 4	0.039 4	0.137 8	0.004 2	850	68	832	24	837	18
12WS-79A-16	0.60	0.112 8	0.003 4	5.166 7	0.159 0	0.332 2	0.010 2	1 844	54	1 849	49	1 847	26
12WS-79A-17	0.27	0.066 8	0.002 0	1.276 6	0.039 6	0.138 5	0.004 3	831	63	836	24	835	18
12WS-79A-18	0.18	0.066 6	0.002 0	1.260 5	0.038 5	0.137 2	0.004 2	833	63	829	24	828	17
12WS-79A-19	0.35	0.067 1	0.002 0	1.276 9	0.039 2	0.137 9	0.004 2	843	62	833	24	835	17
12WS-79A-20	0.61	0.067 0	0.002 0	1.276 7	0.039 3	0.138 2	0.004 2	839	63	834	24	835	18
12WS-79A-21	0.23	0.067 8	0.002 0	1.295 2	0.039 8	0.138 6	0.004 2	861	63	837	24	844	18
12WS-79A-22	0.55	0.111 8	0.003 4	5.126 7	0.156 5	0.332 6	0.010 1	1 829	55	1 851	49	1 841	26
12WS-79A-23	0.26	0.067 0	0.002 0	1.272 5	0.039 2	0.137 8	0.004 2	837	63	832	24	833	18
12WS-79A-24	0.51	0.114 0	0.003 4	5.214 4	0.159 4	0.331 5	0.010 1	1 865	54	1 846	49	1 855	26
12WS-79A-25	0.12	0.124 0	0.003 7	6.275 6	0.192 6	0.367 1	0.011 3	2 015	53	2 016	53	2 015	27
12WS-79A-26	0.35	0.067 7	0.002 0	1.285 0	0.039 4	0.137 7	0.004 2	857	63	831	24	839	18
12WS-79A-27	1.05	0.104 8	0.003 2	4.369 4	0.133 9	0.302 2	0.009 2	1 722	56	1 702	46	1 707	25
12WS-79A-28	0.52	0.113 8	0.003 6	5.120 1	0.188 5	0.325 9	0.011 4	1 861	57	1 819	55	1 839	31
12WS-79A-29	0.59	0.154 2	0.004 6	9.340 4	0.286 5	0.439 1	0.013 5	2 394	50	2 347	60	2 372	28
12WS-79A-30	0.48	0.113 3	0.003 4	5.219 6	0.160 4	0.333 9	0.010 2	1 853	54	1 857	50	1 856	26

表2 慈化高镁安山岩主量(%)和微量元素(10^{-6})分析结果

Table 2 Major (%) and trace element (10^{-6}) analytical results for the Cihua high-Mg andesite

样品号	12WS-79A	12WS-79B	12WS-79C	12WS-79D	12WS-79E
SiO_2	57.03	59.67	55.89	56.71	59.78
Al_2O_3	19.46	16.78	19.96	18.76	18.10
CaO	2.76	3.25	3.02	4.63	3.10
FeO^t	6.19	6.59	6.47	6.83	6.93
MgO	4.05	3.61	3.78	3.48	3.35
MnO	3.92	3.72	4.16	3.51	3.43
K_2O	0.07	0.10	0.08	0.11	0.09
Na_2O	1.76	1.41	1.63	1.72	1.47
P_2O_5	0.14	0.15	0.12	0.13	0.14
TiO_2	0.91	1.02	0.96	1.09	0.86
Loi	2.49	2.24	2.48	2.03	1.86
Total	99.47	99.54	99.40	99.37	99.49
$Mg^{\#}$	57.1	53.3	57.0	53.2	52.2
Sc	22.8	23.0	24.3	14.2	16.1
V	163	176	214	110	140
Cr	109.0	91.6	102	54.9	75.1
Co	18.2	18.2	19.5	17.3	19.8
Ni	39.3	39.8	40.4	34.1	36.3
Rb	189	201	180	182	173
Sr	107.0	149.0	136.0	62.0	73.7
Y	35.7	38.4	39.2	26.7	28.9
Zr	196	262	265	194	212
Nb	15.4	17.7	18.0	13.1	14.4
Ba	1 123	402	371	355	354
La	42.5	59.0	59.7	35.8	36.0
Ce	89.3	118.0	121.0	73.8	71.7
Pr	11.10	14.90	14.80	9.25	8.80
Nd	39.4	53.1	55.2	32.8	33.5
Sm	8.13	10.20	10.00	6.40	6.25
Eu	1.97	2.37	2.28	1.04	0.98
Gd	7.22	8.06	8.34	5.61	5.89
Tb	1.14	1.30	1.30	0.90	0.91
Dy	6.62	7.24	7.48	5.27	5.52
Ho	1.40	1.55	1.56	1.14	1.16
Er	3.79	4.19	4.37	3.03	3.11
Tm	0.58	0.62	0.65	0.46	0.48
Yb	3.92	4.12	4.40	2.99	3.18
Lu	0.59	0.62	0.69	0.44	0.49
Hf	5.97	7.82	6.98	6.07	5.56
Ta	1.33	1.57	1.64	1.15	1.21
Pb	26.1	30.0	29.6	15.9	15.4
Th	19.4	23.7	22.5	14.4	13.8
U	3.85	4.74	4.79	3.04	3.05

Kelemen, 1995; Yogodzinski *et al.*, 1995; Hirose, 1997; Shimoda *et al.*, 1998; Kawabata and Shuto, 2005; Hoang *et al.*, 2009; Wang *et al.*, 2009).

研究显示,拆沉榴辉岩质下地壳发生熔融产生的熔体会与地幔橄榄岩发生相互作用(Kelemen *et al.*, 1998)而形成高镁安山岩. 榴辉岩熔融产生的熔体具有特定微量元素组成:熔体中HREE的含量远低于原岩,并具有Sr和Eu正异常(Stern and Hanson, 1991),与本文慈化安山岩样品特征不相符. 并且慈化安山岩样品相对于华南陆块下地壳和全球平均地壳(Zhang *et al.*, 1994; Rudnick and Fountain, 1995; Gao *et al.*, 1998)具更高的LILE和LREE含量及低的$(Nb/La)_N$比值. 慈化样品在Cr-Ni图解中位于板片派生熔体－橄榄岩相互作用混合线的下方(图5). 所以,慈化安山岩不可能由来源于华南陆块的榴辉岩质下地壳拆沉形成. 慈化样品Eu负异常较为明显,无Sr和Ba正异常,表明源区缺失斜长石成分. 且Sr和Ce未表现出异常,排除此岩石形成过程中俯冲洋壳部分熔融的可能性(Kelemen, 1995). 且尚无地质证据表明在江南造山带存在约830 Ma的俯冲洋壳. 因此,新元古代慈化安山岩的形成也不是洋壳熔融的结果.

这些高镁安山岩的高Cr、Ni含量和高$Mg^{\#}$表明其来自于一个经历过早期玄武质熔体抽离的难熔地幔源区,且与母岩浆熔体保持平衡(Yogodzinski *et al.*, 1995). 高压熔融实验证明含水的难熔橄榄岩的低程度部分熔融可以产生高镁熔体(Tatsumi, 1981; Falloon *et al.*, 1988; Kushiro, 1990; Baker *et al.*, 1995; Hirose, 1997). 一般认为,受碳酸盐岩熔体/流体交代的橄榄岩会使原始的斜方辉石变成次生辉石,导致源区中富含斜辉石/斜方辉石(Yaxley *et al.*, 1998; Kogarko *et al.*, 2001),来源于这种源区的岩石一般富集K_2O和CaO,亏损Al_2O_3和SiO_2,且具有非常高的Zr/Hf比值(高达100)和LREE含量(100×10^{-6})(Woodhead, 1996; Chauvel *et al.*, 1997; Gasparik and Litvin, 2002; Hammouda, 2003),与慈化高镁安山岩特征相异. 相对正常高镁安山岩来说,慈化样品具有相对较高的SiO_2含量,有可能是源区在异常低压条件下发生熔体抽离,也有可能是板片派生流体或者沉积物相关的交代作用,使得斜方辉石含量升高,从而导致SiO_2含量相对较高(van der Laan *et al.*, 1989; Kushiro, 1990; Gallagher and Hawkesworth, 1992; Chalot-Prat and Boullier, 1997). 因此,这些"弧组分"元素特征(例如高LREE和LILE含量,高的La/Nb、Ba/Th和Ba/La比值以及Nb-Ta、Ti的负异常)表明其可能来源于受俯冲板片熔体/流体或者再循环沉积物交代的难熔地幔源区(Evans and Hanson, 1997; Rapp *et al.*, 1999; Sajona *et al.*,

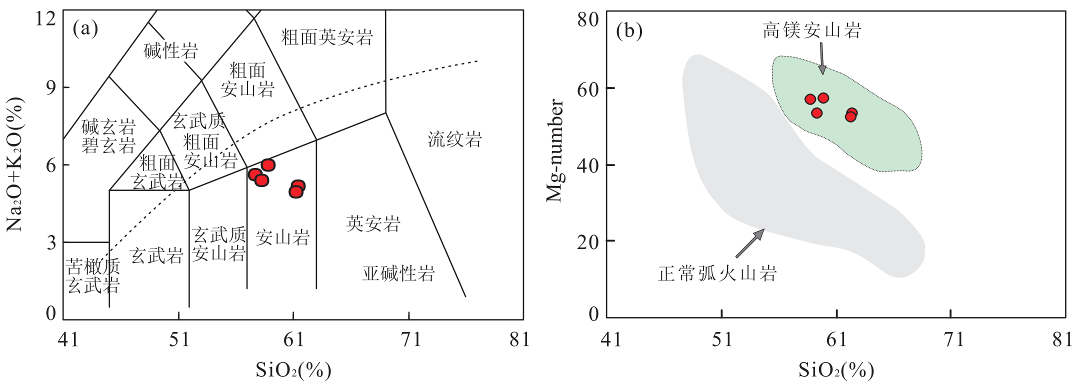

图 3　慈化高镁安山岩样品 SiO_2-K_2O+Na_2O (a)和 SiO_2-Mg-number (b)关系

Fig. 3　Relation of SiO_2-K_2O+Na_2O (a) and SiO_2-Mg-number (b) for the Cihua high-Mg andesite in NW Jiangxi Province

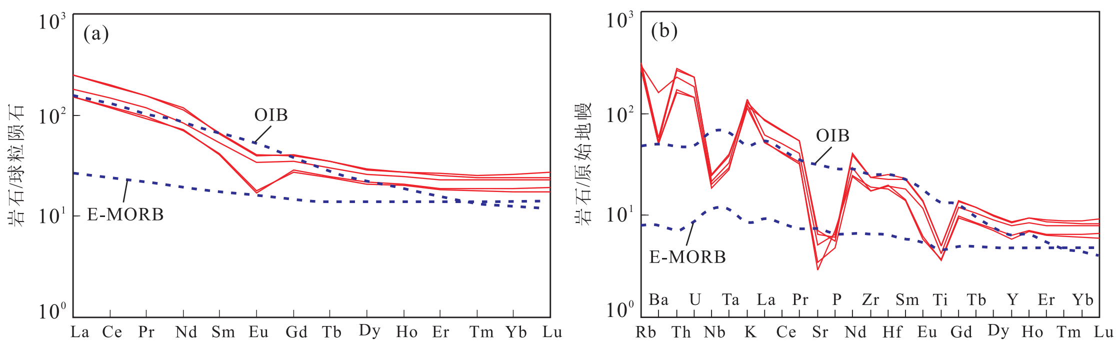

图 4　慈化高镁安山岩球粒陨石标准化稀土元素配分图(a)和原始地幔标准化微量元素蛛网图(b)

Fig. 4　The patterns of the chondrite-normalized rare-earth elements (a) and primitive mantle-normalized spidergram (b) for the Cihua high-Mg andesite in NW Jiangxi Province

球粒陨石和原始地幔标准化数据分别引自文献 Taylor and McLennan(1985)和 Sun and McDonough(1989)

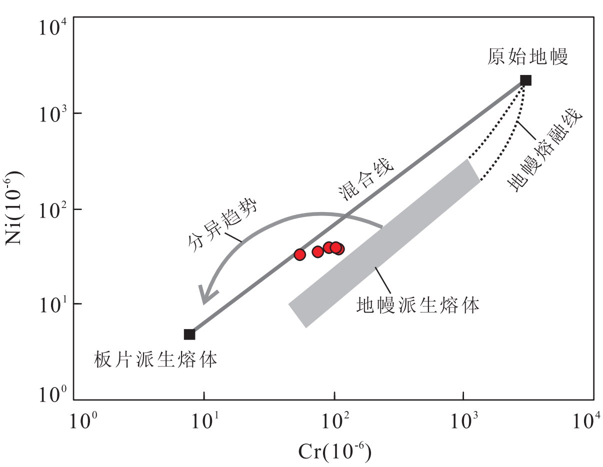

图 5　慈化高镁安山岩样品 Cr-Ni 关系

Fig. 5　Plot of Cr vs. Ni for the Cihua high-Mg andesite in NW Jiangxi Province

2000; Smithies and Champion, 2000; Prouteau *et al*., 2001; Moyen *et al*., 2003; Kamei, 2004; Oliveira *et al*., 2009). 其$(Ta/La)_N=0.18\sim0.60$, $(Hf/Sm)_N=1.07\sim2.16$,与俯冲相关的流体/熔体交代源区类似的特征进一步证明了这一点(LaFlèche *et al*., 1998; Wang *et al*., 2007c).

因此,慈化高镁安山岩应该是楔形地幔源区因消减组分加入而发生交代作用反应形成.本文慈化地区的高镁安山岩为“弧型”特征,文家市—芳溪地区 MORB 岩石特征显示其来自于比 N-MORB 更难熔的地幔源区,后经历了与俯冲相关的富集过程,受到了板片流体和一定比例的再循环沉积物组分的联合影响(Zhang *et al*., 2013).笔者对高镁安山岩和 MORB 岩石的微量元素和稀土元素进行了对比,推断 MORB 岩石来源于地幔源区,而高镁安山岩是楔形地幔源区因消减组分加入而发生交代作用反应形成(图 6).且 MORB 岩石的年龄(838～860 Ma)大于高镁安山岩,所以高镁安山岩应该产出于 MORB 岩石之后.

4.2　构造启示

江南造山带在 830 Ma 时的构造演化地球动力学模式尚存争议,主要有 3 种争议:(1)“地幔柱”模式(Li *et al*., 1995, 1999, 2003a, 2003b, 2004; Ge

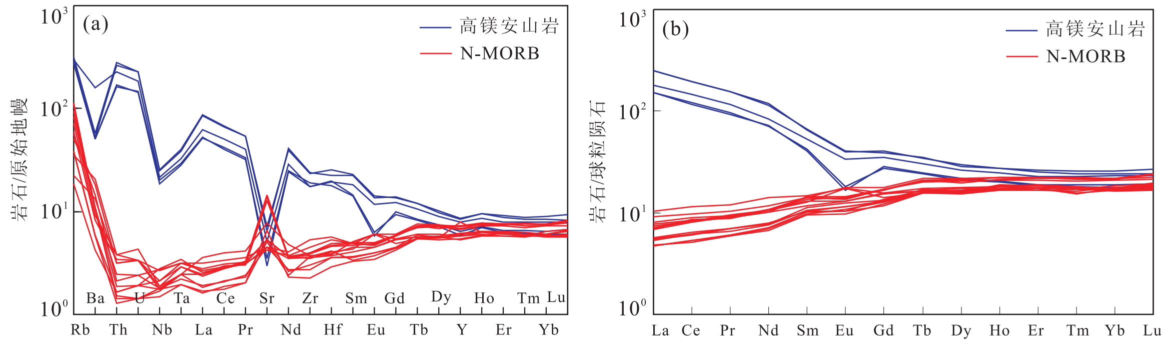

图 6 慈化高镁安山岩与文家市—芳溪 N-MORB 岩石球粒陨石标准化稀土元素配分图(a)和原始地幔标准化微量元素蛛网图(b)

Fig. 6 The chondrite-normalized rare-earth elements (a) and primitive mantle-normalized spidergram (b) of the Cihua high-Mg andesite and Wenjiashi-Fangxi N-MORB

b. 数据来自 Zhang *et al.*, 2013

et al., 2001; Wang *et al.*, 2007a);(2)"俯冲—碰撞"模式(周金城等, 2003; Wang *et al.*, 2004, 2006, 2007b, 2014a; Zhou *et al.*, 2004, 2009; Zhao and Zhou, 2008, 2013; Zhao *et al.*, 2011, 2013);(3)"板片—裂谷"模式(Zheng *et al.*, 2006, 2007, 2008).

识别古老地幔柱主要手段是寻找其标志性的地质记录.例如大规模火山作用及火山作用前地壳抬升而成的穹状隆起(Campbell, 2002).如图 1 所示,江南造山带的新元古代岩浆作用主要呈带状零星出露. Wang *et al.* (2007a)认为益阳 825 Ma"科马提岩"为华南新元古代地幔柱活动提供了直接的高温证据(李献华等, 2012),其面积仅有17 km^2.但其定年样品(05YY-2)为高镁安山质岩石(SiO_2 = 61.1%, MgO = 5.90%, $Mg^{\#}$ = 71). Zhao and Zhou (2013)的研究表明该套岩石 $\varepsilon_{Nd}(t)<0$,微量元素蛛网图显示"弧型"特征,其地幔源区温度可能只有 1 440～1 500 ℃,有别于地幔柱岩浆作用特征.因此,有学者更趋向于认为其为扬子与华夏地块拼贴过程中的俯冲板片与地幔相互作用的结果(Zhang *et al.*, 2012a; Zhao and Zhou, 2013).另外,也没有典型地幔柱作用伴生岩石的相关报道(例如大陆溢流玄武岩和碱性玄武岩; Wang *et al.*, 2004; Zheng *et al.*, 2007, 2008)."科马提岩"的围岩为冷家溪群砂岩,冷家溪群及其相当地层(包括赣东北双桥山群、黔东南梵净山群和桂北四堡群等)发育鲍马序列层序,被认为发育于弧后盆地背景(顾雪祥等, 2003;孙海清等,2009).另外,与地幔柱伴随的地质特征是,常常出现放射状的岩墙群或断裂,而江南地区并无席状岩墙群或断裂的报道.

本文具有弧型特征的高镁安山岩的形成时代在 832±12 Ma,表明江南造山带中段在约 832 Ma 时仍处于消减阶段,扬子陆块与华夏陆块尚未闭合.笔者在浏阳—芳溪地区发现具亏损 N-MORB 特征的变玄武岩,顺层产出于冷家溪群地层,其锆石定年结果在 838～860 Ma,皖南伏川蛇绿岩中的锆石给出的 U-Pb 年龄为 824～848 Ma,均被解释为弧后盆地产物(丁炳华等, 2008; Zhang *et al.*, 2013).益阳具"鬣刺结构"的枕状玄武岩形成于 823±6 Ma (Wang *et al.*, 2007a),也可能是扬子与华夏地块拼贴过程中俯冲板片与地幔相互作用产物(Zhao and Zhou, 2013).介于冷家溪群与板溪群之间的区域性角度不整合可被认为是扬子与华夏陆块沿江南隆起带造山结束的直接记录,其中不整合面之下的银珠坝组高镁火山岩显示出 822～824 Ma 的锆石 U-Pb 年龄,被解释为碰撞后产物(Zhang *et al.*, 2012b).因此,这些资料表明江南造山带中段扬子与华夏陆块的最终聚合碰撞时间约为 825 Ma.

江南东段浙北地区的新元古代岩浆作用主要沿樟树墩至双溪坞一带发育,其岩性包括有约 880～970 Ma 的辉长岩、富铌玄武岩、含蓝闪石变质花岗岩、含角闪石石英闪长岩、花岗闪长岩、高镁闪长岩、斜长花岗岩和埃达克岩等,代表了俯冲环境产物(李献华等, 1994; Li and Li, 2003; Ye *et al.*, 2007;陈志洪等, 2009a, 2009b; Gao *et al.*, 2009).例如江山—绍兴拼合带平水地区的高镁闪长岩、富 Nb 玄武玢岩、斜长花岗岩锆石 U-Pb 年龄分别为 932±7 Ma、916±6 Ma、902±5 Ma,均显示出活动陆缘特征(陈志洪等,2009a);平水群角斑岩据 Nd-Hf 同位素推测为年轻岛弧地壳再造的产物,定年在 904±

8 Ma～906±10 Ma(陈志洪等，2009b)；侵入于平水群的西裘岩体和桃红岩体锆石 U-Pb 定年结果分别为913±15 Ma和 905±14 Ma，为同期幔源岩浆分异形成的典型Ⅰ型花岗岩，亦形成于活动大陆边缘环境(Ye *et al*.，2007)；浙北双溪坞群中段出露的北坞流纹岩和上段出露的章村流纹岩锆石定年分别为926±15 Ma 和 891±12 Ma，其地球化学特征也显示为活动大陆边缘环境(Li *et al*.，2009)．赣东北西湾蛇绿岩中的埃达克质花岗岩在约 970 Ma(李献华等，1994；Li and Li，2003；Gao *et al*.，2009)，西湾仰冲型浅色花岗岩 U-Pb 年龄为 880±19 Ma(Li *et al*.，2008a)．蓝闪石片岩给出的变质 K-Ar 年龄为 866±10 Ma(舒良树等，1993；Charvet *et al*.，1996)．其后到约 850 Ma 为非造山环境(Li *et al*.，2008b，2010a，2010b)，在浙北显示非造山特征的辉绿岩脉锆石 U-Pb 年龄为 849±7 Ma，赣东北珍珠山双峰式火山岩显示为裂谷环境，SIMS 定年结果为 849±6 Ma(Li *et al*.，2010a)．赣东北横峰的港边地区出露的碱性杂岩中，正长岩 SIMS 定年结果为 848±4 Ma，其地球化学特征显示其也为非造山环境(Li *et al*.，2010b)．江南造山带东段最终聚合的时间为 880～910 Ma，而在约 850 Ma 时已进入非造山阶段，远早于江南造山带中段．因此，江南造山带不同区段可能有着差异的碰撞时间，或者沿樟树墩至双溪坞一带分布的新元古代岩浆作用可能并不属于江南造山带的一部分，而是双溪坞弧拼贴到华夏陆块的结果(Wang *et al*.，2013，2014b；Yin *et al*.，2013)．

5　结论

(1)江南造山带中段湘赣交界慈化地区发育高镁安山岩，锆石 LA-ICP-MS 年代学测试得到 832±12 Ma 的 $^{206}Pb/^{238}U$ 加权平均年龄，代表了该安山岩的喷发年龄．慈化高镁安山岩微量元素富集轻稀土元素和大离子亲石元素，亏损 Nb-Ta、Ti，具“弧型”地球化学特征．

(2)慈化高镁安山岩是江南造山带中段受消减组分交代作用楔形地幔源区的产物，暗示此时江南造山带中段此时仍在消减，扬子陆块和华夏陆块尚未完全拼合．

(3)结合前人研究成果，笔者认为江南造山带不同区段可能有着差异的闭合时间．

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References

Bai, D. Y., Jia, B. H., Liu, W., et al., 2010. Zircon SHRIMP U-Pb Dating of the Igneous Rocks from Chengbu, Hunan: Constraint on the Neoproterozoic Tectonic Evolution of the Jiangnan Orogenic Belt. *Acta Geologica Sinica*, 84(12): 1715－1726 (in Chinese with English abstract).

Baker, M. B., Hirschmann, M. M., Ghiorso, M. S., et al., 1995. Compositions of Nearsolidus Peridotite Melts from Experiments and Thermodynamic Calculations. *Nature*, 375(129): 308－311. doi: 10.1038/375308a0

Baker, M. B., Stolper, E. M., 1994. Determining the Composition of High-Pressure Mantle Melts Using Diamond Aggregates. *Geochim. Cosmochi. Acta*, 58(6529): 2811－2827.

Bureau of Geology and Mineral Resources of Guangxi, 1985. Regional Geology of Guangxi Autonomous Region. Geological Publishing House, Beijing (in Chinese).

Bureau of Geology and Mineral Resources of Hunan Province, 1988. Regional Geology of Hunan Province. Geological Publishing House, Beijing (in Chinese).

Bureau of Geology and Mineral Resources of Jiangxi Province, 1984. Regional Geology of Jiangxi Province. Geological Publishing House, Beijing (in Chinese).

Campbell, I. H., 2002. Identification of Ancient Mantle Plumes. Mantle Plumes: Their Identification through Time. *GSA Special Paper*, 352: 5－22.

Chalot-Prat, F., Boullier, A. M., 1997. Metasomatism in the Subcontinental Mantle beneath the Eastern Carpathians (Romania): New Evidence from Trace Element Geochemistry. *Contrib. Mineral. Petrol.*, 129(4): 284－307.

Charvet, J., Shu, L. S., Shi, Y. S., et al., 1996. The Building of South China, Collision of Yangzi and Cathaysia Blocks, Problems and Tentative Answers. *J. Southeast Asian Earth Sci.*, 13(3－5): 223－235. doi: 10.1016/0743－9547(96)00029－3

Chauvel, C., McDonough, W., Guille, G., et al., 1997. Contrasting Old and Young Volcanism in Rurutu Island, Austral Chain. *Chem. Geol.*, 139(1－4): 125－143. doi: 1016/S0009－2541(97)00029－6

Chen, Z. H., Guo, K. Y., Dong, Y. G., et al., 2009a. Possible Early Neoproterozoic Magmatism Associated with Slab Window in the Pingshui Segment of the Jiangshan-Shaoxing Suture Zone: Evidence from Zircon LA-ICP-

MS U-Pb Geochronology and Geochemistry. *Science in China* (*Series D*),39(7):994—1008 (in Chinese).

Chen,Z. H.,Xing,G. F.,Guo,K. Y.,et al.,2009b. Petrogenesis of Keratophyes in the Pingshui Group,Zhejiang:Constraints from Zircon U-Pb Ages and Hf Isotopes. *Chinese Science Bulletin*,54(5):610—617 (in Chinese).

Ding,B. H.,Shi,R. D.,Zhi,X. C.,et al.,2008. Neoproterozoic (~850 Ma) Subduction in the Jiangnan Orogen:Evidence from the SHRIMP U-Pb Dating of the SSZ-Type Ophiolite in Southern Anhui Province. *Acta Petrologica et Mineralogica*,27(5):375—388 (in Chinese with English abstract).

Evans,O. C.,Hanson,G. N.,1997. Late- to Post-Kinematic Archean Boninitoids of the S. W. Superior Province:Derivation through Direct Mantle Melting,Greenstone Belts. Oxford University Press,Oxford,280—295.

Falloon,T. J.,Green,D. H.,Hatton,C. J.,et al.,1988. Anhydrous Partial Melting of a Fertile and Depleted Peridotite from 2 to 30 kbar and Applications to Basalt Petrogenesis. *J. Petrol.*,29:1257—1282. doi:10.1093/petrology/29.6.1257

Gallagher,K.,Hawkesworth,C. J.,1992. Dehydration Melting and the Generation of Continental Flood Basalts. *Nature*,358:57—59. doi:10.1038/358057a0

Gao,J.,Klemd,R.,Long,L. L.,et al.,2009. Adakitic Signature Formed by Fractional Ophiolitic Mélange Belt,South China. *Lithos*,110(1—4):277—293.

Gao,S.,Luo,T. C.,Zhang,B. R.,et al.,1998. Chemical Composition of the Continental Crust as Revealed by Studies in East China. *Geochi. Cosmochimi. Acta*,62(11):1959—1975. doi:10.1016/j.lithos.2009.01.009

Gasparik,T.,Litvin,Y. A.,2002. Experimental Investigation of the Effect of Metasomatism by Carbonatic Melt on the Composition and Structure of the Deep Mantle. *Lithos*,60(3—4):129—143. doi:10.1016/S0024—4937(01)00078—0

Ge,W. C.,Li,X. H.,Li,Z. X.,et al.,2001. Geochemical Studies on Two Types of Neoproterozoic Peraluminous Granitoids in Northern Guangxi. *Geochimica*,30(1):24—34 (in Chinese with English abstract).

Greentree,M. R.,Li,Z. X.,Li,X. H.,et al.,2006. Late Mesoproterozoic to Earliest Neoproterozoic Basin Record of the Sibao Orogenesis in Western South China and Relationship to the Assembly of Rodinia. *Precambrian Res.*,151(1—2):79—100. doi:10.1016/j.precamres.2006.08.02

Gu,X. X.,Liu,J. M.,Schulz,O.,et al.,2003. Geochemical Constraints on the Tectonic Setting of the Proterozoic Turbidites in the Xuefeng Uplift Region of the Jiangnan Orogenic Belt. *Geochimica*,32(5):406—426 (in Chinese with English abstract).

Guo,L. Z.,Shi,Y. S.,Ma,R. S.,1980. The Geotectonic Framework and Crustal Evolution of South China. In:Scientific Paper on Geology for International Exchange. Geological Publishing House,Beijing,109—116 (in Chinese).

Hammouda,T.,2003. High-Pressure Melting of Carbonated Eclogite and Experimental Constraints on Carbon Recycling and Storage in the Mantle. *Earth Planet. Sci. Lett.*,214(1—2):357—368. doi:10.1016/S0012—821X(03)00361—3

Hirose,K.,1997. Melting Experiments on Lherzolite KLB-1 under Hydrous Conditions and Generation of High-Mg Andesitic Melts. *Geology*,25(1):42—44. doi:10.1130/0091—7613(1997)0252.3.CO;2

Hoang,N.,Yamamoto,T.,Itoh,J.,et al.,2009. Anomalous Intra-Plate High-Mg Andesites in the Choshi Area (Chiba,Central Japan) Produced during Early Stages of Japan Sea Opening? *Lithos*,112(3—4):545—555. doi:10.1016/j.lithos.2008.11.012

Kamei,A.,2004. An Adakitic Pluton on Kyushu Island,Southwest Japan Arc. *J. Asian Earth Sci.*,24(1):43—58. doi:10.1016/j.jseaes.2003.07.001

Kawabata,H.,Shuto,K.,2005. Magma Mixing Recorded in Intermediate Rocks Associated with High-Mg Andesites from the Setouchi Volcanic Belt,Japan:Implications for Archean TTG Formation. *J. Volcanol. Geotherm. Res.*,140(4):241—271. doi:10.1016/j.jvolgeores.2004.08.013

Kelemen,P. B.,1995. Genesis of High-Mg Andesites and the Continental Crust. *Contrib. Mineral. Petrol.*,120(1):1—19.

Kelemen,P. B.,Hart,S. R.,Bernstein,S.,1998. Silica Enrichment in the Continental Upper Mantle via Melt/Rock Reaction. *Earth Planet. Sci. Lett.*,164(1—2):387—406. doi:10.1016/S0012—821X(98)00233—7

Kogarko,L. N.,Kurat,G.,Ntaflos,T.,2001. Carbonatite Metasomatism of the Oceanic Mantle beneath Fermando de Noronha Island,Brazil. *Contrib. Mineral. Petrol.*,140(5):577—587.

Kushiro,I.,1990. Partial Melting of Mantle Wedge and Evolution of Island Arc Crust. *J. Geophys. Res.*,95(B10):15929—15939. doi:10.1029/JB095iB10p15929

LaFlèche,M. R.,Camire,G.,Jenner,G. A.,1998. Geochemistry of Post-Acadian,Carboniferous Continental Intra-plate Basalts from the Maritimes Basin, Magdalen Islands, Quebec. *Canada Chemi. Geol.*, 148(3－4): 115－136. doi:10.1016/S0009－2541(98)00002－3

Le Bas, M. J., 2000. IUGS Reclassification of the High-Mg and Picritic Volcanic Rocks. *J. Petrol.*, 41(10): 1467－1470.

Li, W. X., Li, X. H., 2003. Adakitic Granites within the NE Jiangxi Ophiolite, South China: Geochemical and Nd Isotopic Evidence. *Precambrian Res.*, 122(1－4): 29－44. doi:10.1016/S0301－9268(02)00206－1

Li, W. X., Li, X. H., Li, Z. X., 2008a. Middle Neoproterozoic Syn-Rifting Volcanic Rocks in Guangfeng, South China: Petrogenesis and Tectonic Significance. *Geol. Mag.*, 145(4): 475－489. doi: 10.1017/S0016756808004561

Li, W. X., Li, X. H., Li, Z. X., et al., 2008b. Obduction-Type Granites within the NE Jiangxi Ophiolite, Implications for the Final Amalgamation between the Yangtze and Cathaysia Blocks. *Gondwana Res.*, 13(3): 288－301. doi:10.1016/j.gr.2007.12.010

Li, W. X., Li, X. H., Li, Z. X., 2010a. ca. 850 Ma Bimodal Volcanic Rocks in Northeastern Jiangxi, South China: Initial Extension during the Breakup of Rodinia. *American J. Sci.*, 310: 951－980.

Li, X. H., 1997. Geochemistry of the Longsheng Ophiolite from the Southern Margin of Yangtze Craton, SE China. *Geochem. J.*, 31: 323－337.

Li, X. H., Li, W. X., He, B., 2012. Building of the South China Block and Its Relevance to Assembly and Breakup of Rodinia Supercontinent: Observations, Interpretations and Tests. *Bulletin of Mineralogy, Petrology and Geochemistry*, 31(6): 543－559 (in Chinese with English abstract).

Li, X. H., Li, W. X., Li, Q. L., et al., 2010b. Petrogenesis and Tectonic Significance of the ～850 Ma Gangbian Alkaline Complex in South China, Evidence from in Situ Zircon U-Pb Dating, Hf-O Isotopes and Whole-Rock Geochemistry. *Precambrian Res.*, 114: 1－15. doi: 10.1016/j.lithos.2009.07.011

Li, X. H., Li, W. X., Li, Z. X., et al., 2009. Amalgamation between the Yangtze and Cathaysia Blocks in South China, Constraints from SHRIMP U-Pb Zircon Ages, Geochemistry and Nd-Hf Isotopes of the Shuangxiwu Volcanic Rocks. *Precambrian Res.*, 174(1－2): 117－128. doi: 10.1016/j.precamres.2009.07.004

Li, X. H., Li, Z. X., Ge, W. C., et al., 2003a. Neoproterozoic Granitoids in South China, Crustal Melting above a Mantle Plume at ca. 825 Ma? *Precambrian Res.*, 122(1－4): 45－83. doi: 10.1016/S0301－9268(02)00207－3

Li, X. H., Li, Z. X., Ge, W. C., et al., 2004. Reply to the Comment, Mantle Plume, but not Arcrelated Neoproterozoic Magmatism in South China. *Precambrian Res.*, 132(4): 405－407. doi: 10.1016/j.precamres.2004.03.008

Li, X. H., Su, L., Chung, S. L., et al., 2005. Formation of the Jinchuan Ultramafic Intrusion and the World's Third Largest Ni-Cu Sulfide Deposit, Associated with the ～825 Ma South China Mantle Plume? *Geochem., Geophys., Geosyst.*, 6: Q11004. doi: 10.1029/2005GC001006

Li, X. H., Zhou, G. Q., Zhao, J. X., et al., 1994. SHRIMP Ion Microprobe Zircon U-Pb Age of the NE Jiangxi Ophiolite and Its Tectonic Implications. *Geochimica*, 23(2): 125－131 (in Chinese with English abstract).

Li, Z. X., Li, X. H., Kinny, P. D., et al., 1999. The Breakup of Rodinia, Did It Start with a Mantle Plume beneath South China? *Earth Planet. Sci. Lett.*, 173(3): 171－181. doi: 10.1016/S0012－821X(99)00240－X

Li, Z. X., Li, X. H., Kinny, P. D., et al., 2003b. Geochronology of Neoproterozoic Syn-Rift Magmatism in the Yangtze Craton, South China and Correlations with Other Continents, Evidence for a Mantle Superplume that Broke up Rodinia. *Precambrian Res.*, 122(1－4): 85－109. doi: 10.1016/S0301－9268(02)00208－5

Li, Z. X., Li, X. H., Zhou, H., et al., 2002. Grenvillian Continental Collision in South China, New SHRIMP U-Pb Zircon Results and Implications for the Configuration of Rodinia. *Geology*, 30(2): 163－166. doi: 10.1130/0091－7613(2002)030<0163:gccisc>2.0.CO

Li, Z. X., Zhang, L. H., Powell, C. M. A., 1995. South China in Rodinia, Part of the Missing Link between Australia-East Antarctica and Laurentia? *Geology*, 23(5): 407－410.

Liu, Y. S., Hu, Z. C., Gao, S., et al., 2008. In-Situ Analysis of Major and Trace Elements of Anhydrous Minerals by LA-ICP-MS without Applying an Internal Standard. *Chem. Geol.*, 257(1－2): 34－43. doi:10.1016/j.chemgeo.2008.08.004

Ludwig, K. R., 2001. Users Manual for Isoplot/Ex Rev. 2.49, A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center, Berkeley, 53－55.

Ma, T. Q., Chen, L. X., Bai, D. Y., et al., 2009. Zircon SHRIMP Dating and Geochemical Characteristics of Neoproterozoic Granites in Southeast Hunan. *Geology in China*, 36(1): 65－73 (in Chinese with English abstract).

Moyen, J. F., Martin, H., Jayananda, M., et al., 2003. Late Archaean Granites: A Typology Based on the Dharwar

Craton (India). *Precambrian Res.*, 127(1－3): 103－123. doi: 10.1016/S0301－9268(03)00183－9

Oliveira, M. A., Agnol, R. D., Althoff, F. J., et al., 2009. Mesoarchean Sanukitoid Rocks of the Rio Maria Granite-Greenstone Terrane, Amazonian Craton, Brazil. *J. South America Earth Sci.*, 27(2－3): 146－160. doi: 10.1016/j.jsames.2008.07.003

Prouteau, G., Scaillet, B., Pichavant, M., et al., 2001. Evidence for Mantle Metasomatism by Hydrous Silicic Melts Derived from Subducted Oceanic Crust. *Nature*, 410: 197－200. doi: 10.1038/35065583

Qin, Y. J., Du, Y. S., Mou, J., et al., 2015. Geochronology of Neoproterozoic Xiajiang Group in Southeast Guizhou, South China, and Its geological Implications. *Earth Science—Journal of China University of Geosciences*, 40(7): 1107－1120 (in Chinese with English abstract).

Rapp, R. P., Shimizu, N., Norman, M. D., 1999. Reaction between Slab-Derived Melts and Peridotite in the Mantle Wedge: Experimental Constraints at 3.8 GPa. *Chem. Geol.*, 160(4): 335－356.

Rudnick, R. L., Fountain, D. M., 1995. Nature and Composition of the Continental Crust, a Lower Crustal Perspective. *Rev. Geophys.*, 33(3): 267－309. doi: 10.1029/95RG01302

Sajona, F. G., Maury, R. C., Pubellier, M., et al., 2000. Magmatic Source Enrichment by Slab-Derived Melts in a Young Post-Collision Setting, Central Mindanao (Philippines). *Lithos*, 54(3－4): 173－206. doi: 10.1016/S0024－4937(00)00019－0

Shimoda, G., Tatsumi, Y., Nohda, S., et al., 1998. Setouchi High-Mg Andesite Revisited; Geochemical Evidence for Melting of Subducting Sediments. *Earth Planet. Sci. Lett.*, 160(3－4): 479－492. doi: 10.1016/S0012－821X(98)00105－8

Shu, L. S., Zhou, G. Q., Shi, Y. S., et al., 1993. Study on the High Pressure Blueschist of Eastern Segment of Jiangnan Erogenic Belt and Its Geological Age. *Chinese Science Bulletin*, 38(20): 1879－1882 (in Chinese).

Smithies, R. H., Champion, D. C., 2000. The Archean High-Mg Diorite Suite: Links to Tonalite-Trondhjemite-Granodiorite Magmatism and Implications for Early Archean Crustal Growth. *J. Petrol.*, 41: 1653－1671. doi: 10.1093/petrology/41.12.1653

Stern, R. A., Hanson, G. N., 1991. Archean High-Mg Granodiorite: A Derivative of Light Rare Earth Element-Enriched Monzodiorite of Mantle Origin. *J. Petrol.*, 32(1): 201－238. doi: 10.1093/petrology/32.1.201

Su, J. B., Zhang, Y. Q., Dong, S. W., et al., 2014. Geochronology and Hf Isotopes of Granite Gravel from Fanjingshan, South China: Implication for the Precambrian Tectonic Evolution of Western Jiangnan Orogen. *J. Earth Sci.*, 25(4): 619－629.

Sun, H. Q., Chen, J., Meng, D. B., et al., 2009. The Dayaogu Formation of Northeast Hunan Province. *Geology and Mineral Resources of South China*, (4): 54－58 (in Chinese with English abstract).

Sun, S. S., McDonough, W. F., 1989. Geochemical and Isotopic Systematics of Oceanic Basalts: Implication for Mantle Composition and Processes. In: Saunders, A. D., Norry, M. J., eds., Magmatism in the Ocean Basins, 42. *Geol. Soc. London Spec. Pub.*, 42(1): 313－345.

Tang, X. S., Huang, J. Z., Guo, L. Q., 1997. Hunan Banxi Group and Its Tectonic Environment. *Hunan Geology*, 16(4): 219－226 (in Chinese with English abstract).

Tatsumi, Y., 1981. Melting Experiments on a High Magnesian Andesite. *Earth Planet. Sci. Lett.*, 54: 357－365.

Taylor, S. R., McLennan, S. M., 1985. The Continental Crust: Its Composition and Evolution. Oxford Press Blackwell, Oxford, 1－312.

van der Laan, S. R., Flower, M. F. J., van Groos, A. F. K., 1989. Experimental Evidence for the Origin of Boninites: Near-Liquidus Phase Relations to 7.5 kbar. In: Crawford, A. J., ed., Boninite and Relate Rocks. Unwin Hyman, London, 112－147.

Wang, X. C., Li, X. H., Li, W. X., et al., 2007a. ca. 825 Ma Komatiitic Basalts in South China, First Evidence for >1 500 ℃ Mantle Melts by a Rodinia Mantle Plume. *Geology*, 35(12): 1103－1106. doi: 10.1130/G23878a.1

Wang, X. L., Zhao, G. C., Zhou, J. C., et al., 2008. Geochronology and Hf Isotopes of Zircon from Volcanic Rocks of the Shuangqiaoshan Group, South China, Implications for the Neoproterozoic Tectonic Evolution of the Eastern Jiangnan Orogen. *Gondwana Res.*, 14(3): 355－367. doi: 10.1016/j.gr.2008.03.001

Wang, X. L., Zhou, J. C., Griffin, W. L., et al., 2007b. Detrital Zircon Geochronology of Precambrian Basement Sequences in the Jiangnan Orogen, Dating the Assembly of the Yangtze and Cathaysia Blocks. *Precambrian Res.*, 159(1－2): 117－131. doi: 10.1016/j.precamres.2007.06.005

Wang, X. L., Zhou, J. C., Griffin, W. L., et al., 2014a. Geochemical Zonation across a Neoproterozoic Orogenic Belt: Isotopic Evidence from Granitoids and Metasedimentary Rocks of the Jiangnan Orogen, China. *Precambrian Res.*, 242: 154－171. doi: 10.1016/j.precamres.

2013.12.023

Wang,X. L.,Zhou,J. C.,Qiu,J. S.,et al.,2003. Geochemistry of the Meso-Neoproterozoic Volcanic-Intrusive Rocks from Hunan Province and Its Petrogenic Significances. *Acta Petrologica Sinica*,19(1):49—60 (in Chinese with English abstract).

Wang,X. L.,Zhou,J. C.,Qiu,J. S.,et al.,2004. Geochemistry of the Meso- to Neoproterozoic Basic-Acid Rocks from Hunan Province,South China,Implications for the Evolution of the Western Jiangnan Orogen. *Precambrian Res.*,135(1—2):79—103. doi:10.1016/j.precamres.2004.07.006

Wang,X. L.,Zhou,J. C.,Qiu,J. S.,et al.,2004. Petrogenesis of Neoproterozoic Peraluminous Granites from Northeastern Hunan Province:Chronological and Geochemical Constraints. *Geological Review*,50(1):65—76 (in Chinese with English abstract).

Wang,X. L.,Zhou,J. C.,Qiu,J. S.,et al.,2006. LA-ICP-MS U-Pb Zircon Geochronology of the Neoproterozoic Igneous Rocks from Northern Guangxi,South China,Implications for Petrogenesis and Tectonic Evolution. *Precambrian Res.*,145(1—2):111—130. doi:10.1016/j.precamres.2005.11.014

Wang,Y. J.,Zhang,A. M.,Cawood,P. A.,et al.,2013. Geochronological,Geochemical and Nd-Hf-Os Isotopic Fingerprinting of an Early Neoproterozoic Arc-Back-Arc System in South China and Its Accretionary Assembly Accretionary Assembly along the Margin of Rodinia. *Precambrian Res.*,231:343—371. doi:10.1016/j.precamres.2013.03.020

Wang,Y. J.,Zhang,F. F.,Fan,W. M.,et al.,2010. Tectonic Setting of the South China Block in the Early Paleozoic,Resolving Intracontinental and Ocean Closure Models from Detrital Zircon U-Pb Geochronology. *Tectonics*,29(6):TC6020. doi:10.1029/2010TC002750

Wang,Y. J.,Zhang,Y. Z.,Fan,W. M.,et al.,2014b. Early Neoproterozoic Accretionary Assemblage in the Cathaysia Block:Geochronological,Lu-Hf Isotopic and Geochemical Evidence from Granitoid Gneisses. *Precambrian Res.*,249:144—161. doi:10.1016/j.precamres.2014.05.003

Wang,Y. J.,Zhang,Y. Z.,Zhao,G. C.,et al.,2009. Zircon U-Pb Geochronological and Geochemical Constraints on the Petrogenesis of the Taishan Sanukitoids (Shandong):Implications for Neoarchean Subduction in the Eastern Block,North China Craton. *Precambrian Res.*,174(3—4):273—286. doi:10.1016/j.precamres.2009.08.005

Wang,Y. J.,Zhao,G. C.,Fan,W. M.,et al.,2007c. LA-ICP-MS U-Pb Zircon Geochronology and Geochemistry of Paleoproterozoic Mafic Dykes from Western Shandong Province:Implications for Back-Arc Basin Magmatism in the Eastern Block,North China Craton. *Precambrian Res.*,154(1—2):107—124. doi:10.1016/j.precamres.2006.12.010

Woodhead,J. D.,1996. Extreme HIMU in an Oceanic Setting:the Geochemistry of Mangaia Island (Polynesia),and Temporal Evolution of the Cook-Austral Hotspot. *J. Volcanol. Geotherm. Res.*,72(1—2):1—19. doi:10.1016/0377—0273(96)00002—9

Wu,R. X.,Zheng,Y. F.,Wu,Y. B.,et al.,2006. Reworking of Juvenile Crust,Element and Isotope Evidence from Neoproterozoic Granodiorite in South China. *Precambrian Res.*,146(3—4):179—212. doi:10.1016/j.precamres.2006.01.012

Xia,X. P.,Sun,M.,Geng,H. Y.,et al.,2011. Quasi-Simultaneous Determination of U-Pb and Hf Isotope Compositions of Zircon by Excimer Laser-Ablation Multiple-Collector ICP-MS. *J. Anal. At. Spectrom.*,26:1868—1871. doi:10.1039/CIJA10116A

Yaxley,G. M.,Green,D. H.,Kamenetsky,V.,1998. Carbonatite Metasomatism in the Southeastern Australian Lithosphere. *J. Petrol.*,39(11—12):1917—1930. doi:10.1093/petroj/39.11—12.1917

Ye,M. F.,Li,X. H.,Li. W. X.,et al.,2007. SHRIMP Zircon U-Pb Geochronological and Whole-Rock Geochemical Evidence for an Early Neoproterozoic Sibaoan Magmatic Arc along the Southeastern Margin of the Yangtze Block. *Gondwana Res.*,12(1—2):144—156. doi:10.1016/j.gr.2006.09.001

Yin,C. Q.,Lin,S. F.,Davis,D. W.,et al.,2013. Tectonic Evolution of the Southeastern Margin of the Yangtze Block:Constraints from SHRIMP U-Pb and LA-ICP-MS Hf Isotopic Studies of Zircon from the Eastern Jiangnan Orogenic Belt and Implications for the Tectonic Interpretation of South China. *Precambrian Res.*,236:145—156. doi:10.1016/j.precamres.2013.07.022

Yogodzinski,G. M.,Kay,R. W.,Volynets,O. N.,et al.,1995. Magnesian Andesite in the Western Aleutian Komandorsky Region,Implications for Slab Melting and Processes in the Mantle Wedge. *Geol. Soc. Am. Bull.*,107(5):505—519. doi:10.1130/0016—7606(1995)1072.3.CO;2

Zhang,B. R.,Luo,T. C.,Gao,S.,et al.,1994. Geochemical Study of the Lithosphere,Tectonism and Metallogenesis in the Qinling-Dabashan Region. China University of

Geosciences Press, Wuhan, 1−446.

Zhang, F. F., Wang, Y. J., Fan, W. M., et al., 2011. Zircon U-Pb Geochronology and Hf Isotopes of the Neoproterozoic Granites in the Central of Jiangnan Uplift. *Geotectonica et Metallogenia*, 35(1): 73−84 (in Chinese with English abstract).

Zhang, S. B., Wu, R. X., Zheng, Y. F., 2012a. Neoproterozoic Continental Accretion in South China, Geochemical Evidence from the Fuchuan Ophiolite in the Jiangnan Orogen. *Precambrian Res.*, 220−221: 45−64. doi: 10.1016/j.precamres.2012.07.010

Zhang, Y. J., Zhou, X. H., Liao, S. B., et al., 2011. Geological and Geochemical Characteristics and Petrogenesis of the Mafic Rocks from Zhangyuan, Northern Jiangnan Orogen. *Geological Journal of China Universities*, 17(3): 393−405 (in Chinese with English abstract).

Zhang, Y. Z., Wang, Y. J., Fan, W. M., et al., 2012b. Geochronological and Geochemical Constraints on the Metasomatised Source for the Neoproterozoic (~825 Ma) High-Mg Volcanic Rocks from the Cangshuipu Area (Hunan Province) along the Jiangnan Domain and Their Tectonic Implications. *Precambrian Res.*, 220−221: 139−157. doi: 10.1016/j.precamres.2012.07.003

Zhang, Y. Z., Wang, Y. J., Geng, H. Y., et al., 2013. Early Neoproterozoic (~850 Ma) Back-Arc Basin in the Central Jiangnan Orogen (Eastern South China): Geochronological and Petrogenetic Constraints from Meta-Basalts. *Precambrian Res.*, 231: 325−342. doi: 10.1016/j.precamres.2013.03.016

Zhang, Y. Z., Wang, Y. J., Zhang, Y. H., et al., 2015. Neoproterozoic Assembly of the Yangtze and Cathaysia Blocks: Evidence from the Cangshuipu Group and Associated Rocks along the Central Jiangnan Orogen, South China. *Precambrian Res.*, 269: 18−30.

Zhao, G. C., 2015. Jiangnan Orogen in South China: Developing from Divergent Double Subduction. *Gondwana Res.*, 27: 1173−1180. doi: 10.1016/j.gr.2014.09.004

Zhao, G. C., Cawood, P. A., 1999. Tectonothermal Evolution of the Mayuan Assemblage in the Cathaysia Block, New Evidence for Neoproterozoic Collision-Related Assembly of the South China Craton. *Am. J. Sci.*, 299: 309−339. doi: 10.2475/ajs.299.4.309

Zhao, G. C., Cawood, P. A., 2012. Precambrian Geology of China. *Precambrian Res.*, 222−223: 13−54. doi: 10.1016/j.precamres.2012.09.017

Zhao, J. H., Asimow, P. D., 2014. Neoproterozoic Boninite-Series Rocks in South China: A Depleted Mantle Source Modified by Sediment-Derived Melt. *Chem. Geol.*, 388: 98−111. doi: 10.1016/j.chemgeo.2014.09.004

Zhao, J. H., Zhou, M. F., 2008. Neoproterozoic Adakitic Suite at the Northwestern Margin of the Yangtze Block, China, Evidence for Partial Melting of Thickened Lower Crust and Secular Crustal Evolution. *Lithos*, 104(1−4): 231−248. doi: 10.1016/j.lithos.2007.12.009

Zhao, J. H., Zhou, M. F., 2013. Neoproterozoic High-Mg Basalts Formed by Melting of Ambient Mantle in South China. *Precambrian Res.*, 233: 193−205. doi: 10.1016/j.precamres.2013.04.017

Zhao, J. H., Zhou, M. F., Yan, D. P., et al., 2011. Reappraisal of the Ages of Neoproterozoic Strata in South China, no Connection with the Grenvillian Orogeny. *Geology*, 39(4): 299−302. doi: 10.1130/G31701.1

Zhao, J. H., Zhou, M. F., Zheng, J. P., 2013. Constraints from Zircon U-Pb Ages, O and Hf Isotopic Compositions on the Origin of Neoproterozoic Peraluminous Granitoids from the Jiangnan Fold Belt, South China. *Contrib. Mineral. Petrol.*, 166: 1505−1519. doi: 10.1007/S00410−013−0940−z

Zheng, Y. F., Wu, R. X., Wu, Y. B., et al., 2008. Rift Melting of Juvenile Arc-Derived Crust, Geochemical Evidence from Neoproterozoic Volcanic and Granitic Rocks in the Jiangnan Orogen, South China. *Precambrian Res.*, 163(3−4): 351−383. doi: 10.1016/j.chemgeo.2008.01.004

Zheng, Y. F., Zhang, S. B., Zhao, Z. F., et al., 2007. Contrasting Zircon Hf and O Isotopes in the Two Episodes of Neoproterozoic Granitoids in South China, Implications for Growth and Reworking of Continental Crust. *Lithos*, 96(1−2): 127−150. doi: 10.1016/j.lithos.2006.01.003

Zheng, Y. F., Zhao, Z. F., Wu, Y. B., et al., 2006. Zircon U-Pb Age, Hf and O Isotope Constraints on Protolith Origin of Ultrahigh-Pressure Eclogite and Gneiss in the Dabie Orogen. *Chem. Geol.*, 231(1−2): 135−138. doi: 10.1016/j.chemgeo.2006.01.005

Zhong, Y. F., Ma, C. Q., She, Z. B., et al., 2005. SHRIMP U-Pb Zircon Geochronology of the Jiuling Granitic Complex Batholith in Jiangxi Province. *Earth Science—Journal of China University of Geosciences*, 30(6): 685−691 (in Chinese with English abstract).

Zhou, J. C., Wang, X. L., Qiu, J. S., 2009. Geochronology of Neoproterozoic Mafic Rocks and Sandstones from Northeastern Guizhou, South China, Coeval Arc Magmatism and Sedimentation. *Precambrian Res.*, 170(1−2): 27−42. doi: 10.1016/j.chemgeo.2008.11.002

Zhou, J. C., Wang, X. L., Qiu, J. S., et al., 2003. Lithogeochemistry of Meso- and Neoproteozoic Mafic-Ultramafic Rocks from Northern Guangxi. *Acta Petrologica Sinica*，19(1)：9－18 (in Chinese with English abstract).

Zhou，J. C.，Wang，X. L.，Qiu，J. S.，et al.，2004. Geochemistry of Meso- and Neoproterozoic Mafic-Ultramafic Rocks from Northern Guangxi，China，Arc or Plume Magmatism? *Geochem. J.*，38：139－152.

附中文参考文献

柏道远，贾宝华，刘伟，等，2010. 湖南城步火成岩锆石 SHRIMP U-Pb 年龄及其对江南造山带新元古代构造演化的约束. 地质学报，84(12)：1715－1726.

广西壮族自治区地质矿产局，1985. 广西壮族自治区区域地质志. 北京：地质出版社.

湖南地质矿产局，1988. 湖南省区域地质志. 北京：地质出版社.

江西地质矿产局，1984. 江西省区域地质志. 北京：地质出版社.

陈志洪，郭坤一，董永观，等，2009a. 江山－绍兴拼合带平水段可能存在新元古代早期板片窗岩浆活动，来自锆石 LA-ICP-MS 年代学和地球化学的证据. 中国科学(D 辑)，39(7)：994－1008.

陈志洪，邢光福，郭坤一，等，2009b. 浙江平水群角斑岩的成因－锆石 U-Pb 年龄和 Hf 同位素制约. 科学通报，54(5)：610－617.

丁炳华，史仁灯，支霞臣，等，2008. 江南造山带存在新元古代～850 Ma 俯冲作用，来自皖南 SSZ 型蛇绿岩锆石 SHRIMP U-Pb 年龄证据. 岩石矿物学杂志，27(5)：375－388.

顾雪祥，刘建明，Schulz，O.，等，2003. 江南造山带雪峰隆起区元古宙浊积岩沉积构造背景的地球化学制约. 地球化学，32(5)：406－426.

郭令智，施央申，马瑞士，1980. 华南大地构造格架和地壳演化. 见：第 26 届国际地质大会国际交流学术论文集. 北京：地质出版社，109－116.

李献华，李武显，何斌，2012. 华南陆块的形成与 Rodinia 超大陆聚合－裂解——观察、解释与检验. 矿物岩石地球化学通报，31(6)：543－559.

李献华，周国庆，赵建新，等，1994. 赣东北蛇绿岩的离子探针锆石 U-Pb 年龄及其构造意义. 地球化学，23(2)：125－131.

马铁球，陈立新，柏道远，等，2009. 湘东北新元古代花岗岩体锆石 SHRIMP U-Pb 年龄及地球化学特征. 中国地质，36(1)：65－73.

舒良树，周国庆，施央申，等，1993. 江南造山带东段高压变质蓝片岩及其地质时代研究. 科学通报，38(20)：1879－1882.

覃永军，杜远生，牟军，等，2015. 黔东南地区新元古代下江群的地层年代及其地质意义. 地球科学——中国地质大学学报，40(7)：1107－1120.

孙海清，陈俊，孟德饱，等，2009. 湘东北地区冷家溪群大药菇组. 华南地质与矿产，(4)：54－58.

唐晓珊，黄健中，郭乐群，1997. 再论湖南板溪群及其大地构造环境. 湖南地质，16(4)：219－226.

王孝磊，周金城，邱检生，等，2003. 湖南中－新元古代火山－侵入岩地球化学及成因意义. 岩石学报，19(1)：49－60.

王孝磊，周金城，邱检生，等，2004. 湘东北新元古代强过铝花岗岩的成因：年代学和地球化学证据. 地质论评，50(1)：65－76.

张菲菲，王岳军，范蔚茗，等，2011. 江南隆起带中段新元古代花岗岩锆石 U-Pb 年代学和 Hf 同位素组成研究. 大地构造与成矿学，35(1)：73－84.

张彦杰，周效华，廖圣兵，等，2011. 江南造山带北缘鄣源基性岩地质－地球化学特征及成因机制. 高校地质学报，17(3)：393－405.

钟玉芳，马昌前，佘振兵，等，2005. 江西九岭花岗岩类复式岩基锆石 SHRIMP U-Pb 年代学. 地球科学——中国地质大学学报，30(6)：685－691.

周金城，王孝磊，邱检生，等，2003. 桂北中－新元古代镁铁质－超镁铁质岩的岩石地球化学. 岩石学报，19(1)：9－18.