赣东北蛇绿岩带新元古代(~800Ma)高镁安山岩的发现及其意义

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内容提要:在赣东北蛇绿岩带中的樟树墩地区新发现新元古代高镁安山岩,其 LA-ICP-MS 锆石 U-Pb 法年龄为 794.8±6.0 Ma。它们的 SiO_2 介于 54.90%~58.45%,Al_2O_3 介于 15.31%~16.77%(平均小于 16%);CaO 为 2.46%~6.73%,FeO^T/MgO 变化于 0.87~1.20,具有高 MgO(6.39%~8.76%)、高 $Mg^{\#}$(64~71)特点;富集轻稀土元素且具弱负 Eu 异常,明显富集 LILE 而亏损 HFSE,Sr 含量(普遍 $<200\times10^{-6}$)和 Sr/Y 比值(4.11~7.29)均较低,具有典型高镁安山岩的地球化学特征,类似于日本 Setouchi 火山带的 Sanukitoids。锆石 $\varepsilon_{Hf}(t)$ 值介于 10.23~17.79 之间,反映它们起源于亏损地幔。主、微量及同位素特征均表明,本区高镁安山岩是被俯冲板片释放的含水流体交代的地幔楔部分熔融的产物,形成于大洋岛弧(洋内弧)环境,指示赣东北地区在约 800Ma 前时仍存在洋壳俯冲,双溪坞弧尚未增生到扬子东南缘,暗示扬子和华夏两大陆块此时尚未碰撞拼合。

关键词:高镁安山岩;新元古代;樟树墩;赣东北蛇绿岩带;江南造山带

高镁安山岩(high-Mg andesite, HMA)泛指 MgO($Mg^{\#}$)含量高于典型岛弧安山岩的安山岩和部分英安岩类,包括 Boninities、Bajaites、Adakites(汉译名"高锶低钇中酸性岩",亦有人译为"埃达克岩")和 Sanukitoids 等(Kamei et al., 2004)。Tatsumi(2001)指出,高镁安山岩 SiO_2 含量范围通常在 53%~60%,具有高 MgO(>5%)、低 FeO^T/MgO(<1.5)、Al_2O_3(<16%)和 CaO(<10%)等特征。由于其特殊的地球化学特征,高镁安山岩所指示的大地构造背景一直受到关注。一般认为,高镁安山岩大多数形成于汇聚板块边界,与年轻的且热的洋壳(脊)俯冲有关,是交代的岩石圈地幔重融的产物(Tatsumi and Ishizaka, 1981, 1982a, 1982b; Tatsumi, 1982; Kelemen, 1995; Shimoda et al., 1998; Tstsumi and Hanyu, 2003)。因此,高镁安山岩具有明确的构造意义,对高镁安山岩的识别及研究可以有效地限定古俯冲带的位置及演化过程。

华南由扬子和华夏两大陆块组成,在扬子陆块东南缘有一条 NEE 向展布的前寒武纪地质单元称之为江南造山带(郭令智,1980)。赣东北蛇绿岩带位于江南造山带东段,呈 NNE 向展布(图1a)。该蛇绿岩带东侧为新元古代双溪坞火山弧,西侧为新元古代双桥山岩群和溪口岩群分布区,后者一般认为属弧后盆地沉积。对赣东北蛇绿岩的形成时代、构造背景、演化机制从20世纪80年代开始,已有了大量的研究(白文吉等,1986;徐备等,1989;Zhou Guoqing et al., 1991;Chen Jiangfeng et al., 1991;Shu Liangshu et al., 1994;李献华等,1994;赵崇贺等,1995;何科昭等,2000;王博等,2001;吴浩若等,2003;吴新华等,2004;Li Wuxian & Li Xianhua, 2003;Li Wuxian et al., 2008;Gao Jun et al., 2009),已有的研究多数认为该蛇绿岩属于 SSZ 型蛇绿岩,形成于岛弧(邢凤鸣等,1992)或弧后盆地环境(Chen Jiangfeng et al., 1991;赵建新等,1995, Li Xianhua et al., 1997, 2009)。但最近笔者等的研究认为其可能为形成于 1061Ma 的 MOR 型蛇绿岩,后期(约 970Ma)经历了洋内俯冲的 SSZ(俯冲带之上)构造环境(王存智等,2015)。对于扬子与华夏陆块拼合的时代,一直以来众说纷纭。目前较多学者认为,扬子和华夏陆块的最终拼合时间为 880Ma

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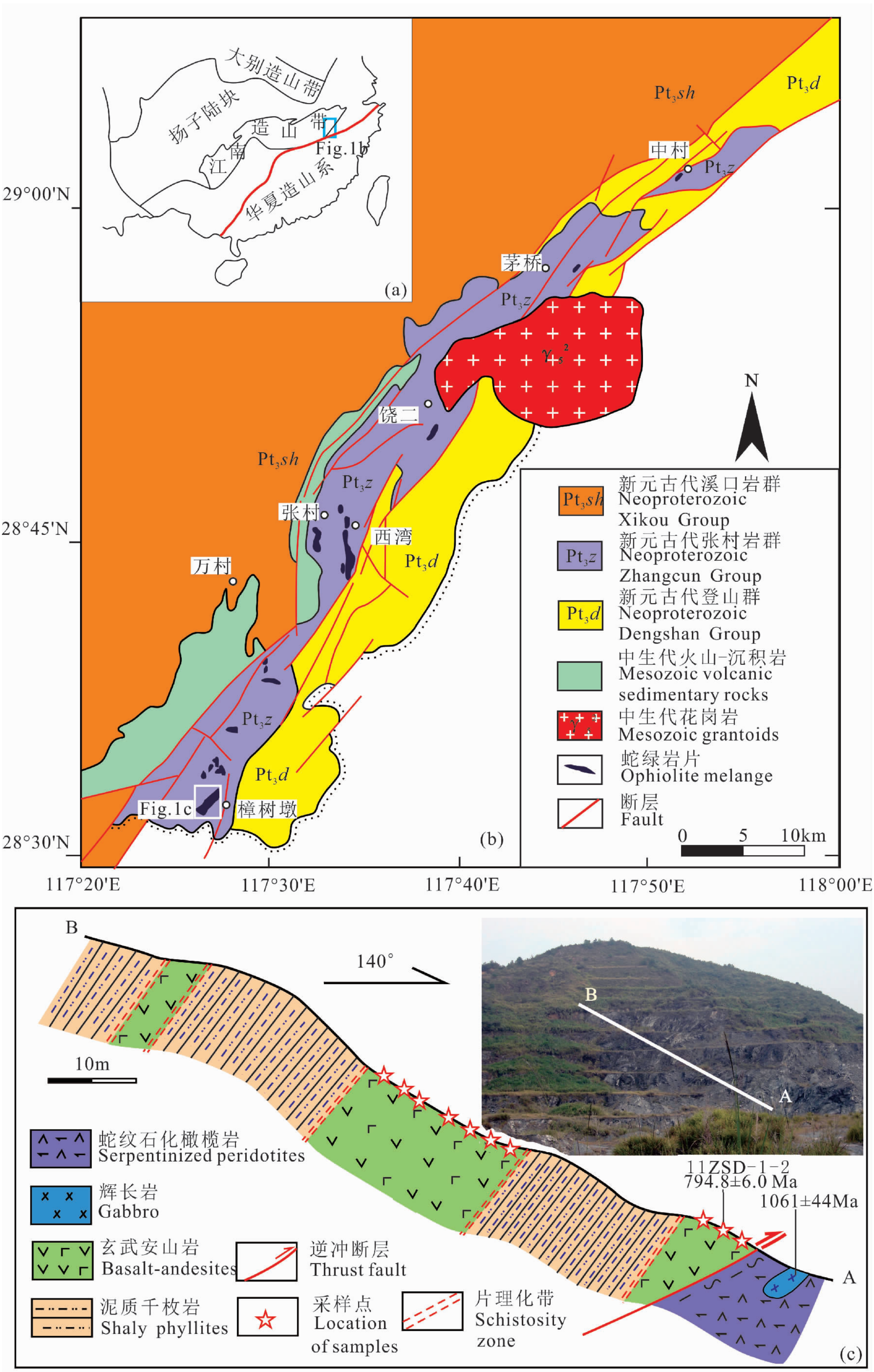

大别造山带
扬子陆块
江南造山带
华夏造山系
Fig.1b
(a)
29°00'N
28°45'N
28°30'N
117°20'E
117°30'E
117°40'E
117°50'E
118°00'E
Pt3sh
Pt3d
Pt3z
中村
茅桥
饶二
张村
西湾
万村
樟树墩
Fig.1c
N
0 5 10km
(b)
新元古代溪口岩群 Neoproterozoic Xikou Group
新元古代张村岩群 Neoproterozoic Zhangcun Group
新元古代登山群 Neoproterozoic Dengshan Group
中生代火山-沉积岩 Mesozoic volcanic sedimentary rocks
中生代花岗岩 Mesozoic grantoids
蛇绿岩片 Ophiolite melange
断层 Fault
B
140°
10m
A
11ZSD-1-2
794.8±6.0 Ma
1061±44Ma
蛇纹石化橄榄岩 Serpentinized peridotites
辉长岩 Gabbro
玄武安山岩 Basalt-andesites
泥质千枚岩 Shaly phyllites
逆冲断层 Thrust fault
采样点 Location of samples
片理化带 Schistosity zone
(c)

图 1 赣东北地区地质简图:(a) 赣东北地区大地构造位置图;(b) 赣东北蛇绿岩带地质简图(据 Li Wuxian et al. , 2008 修改);(c) 樟树墩蛇绿岩信手剖面图

Fig. 1 Geological sketch map of the northeastern Jiangxi: (a) Schematic tectonic map of South China showing the location of the northeastern Jiangxi; (b) geological map of the NE Jiangxi ophiolite (modified after Li Wuxian et al. , 2008) (c) geological section map of the Zhangshudun ophiolites

前后,最重要的依据是 Shu Liangshu 等(1994)所报道西湾蓝闪石片岩 K-Ar 年龄(866 ± 14Ma),以及西湾 880 ± 19Ma 的仰冲型淡色花岗岩(Li Wuxian et al. , 2008)。不同的是,许靖华等将华南同北美阿巴拉契亚地区进行对比,提出江南造山带可能为印支期造山带(Hsü et al. , 1988, 1990)。有学者曾报导了赣东北存在晚古生代放射虫硅质岩等,支持印支期碰撞观点(赵崇贺等, 1995)。另外,Wong 等(2011)通过对江山—绍兴(江绍)断裂带两侧中生代酸性岩的研究认为这两个陆块在新元古代时期可能并未完全拼合。可见,对于两者之间的碰撞拼合时间仍存在较大争议。鉴于赣东北蛇绿岩带特殊的构造位置,对其时代与构造属性的研究,可为探讨扬子与华夏两大陆块的碰撞拼合时间提供证据。

最近,笔者等在赣东北蛇绿岩中发现了新元古代 ~800Ma 与俯冲作用相关的高镁安山岩,指示该时期仍存在洋壳俯冲,两大陆块可能仍尚未拼贴。这对深入认识江南造山带的形成演化,以及华夏和扬子陆块的拼合时限等具有重要意义。

1　地质概况及岩石学特征

赣东北蛇绿岩带南起弋阳樟树墩,北至德兴中村,全长约 100km,呈 NNE 方向展布(图 1b),主要出露于樟树墩、西湾、饶二和茅桥等地,构造侵位在双桥山群浅变质火山—沉积岩中(徐备等, 1989; Chen Jiangfeng et al. , 1991; Li Xianhua et al. , 1997)。组成赣东北蛇绿岩的主要岩石类型为变质橄榄岩、堆晶辉长岩、辉绿岩、闪长岩、斜长花岗岩、玄武岩、安山岩和硅质岩等,普遍经历了低绿片岩相变质和强烈的构造变形(Zhou Guoqing,1989)。

樟树墩地区的蛇绿岩岩石类型最为齐全和典型,出露面积约 0. 162km^2,沿 NE 方向延伸(白文吉等,1986)。在樟树墩蛇纹石矿采场,蛇绿岩出露较好,其东南侧主要由强烈蛇纹石化的方辉橄榄岩组成,构造变形强烈,包裹球状异剥钙榴岩,局部见直闪石矿物集合体,其中还发育多处辉长辉绿岩脉;西北侧上覆深灰色浅变质泥质千枚岩,其中夹有多层火山岩。千枚岩与火山岩接触面均发生强烈的片理

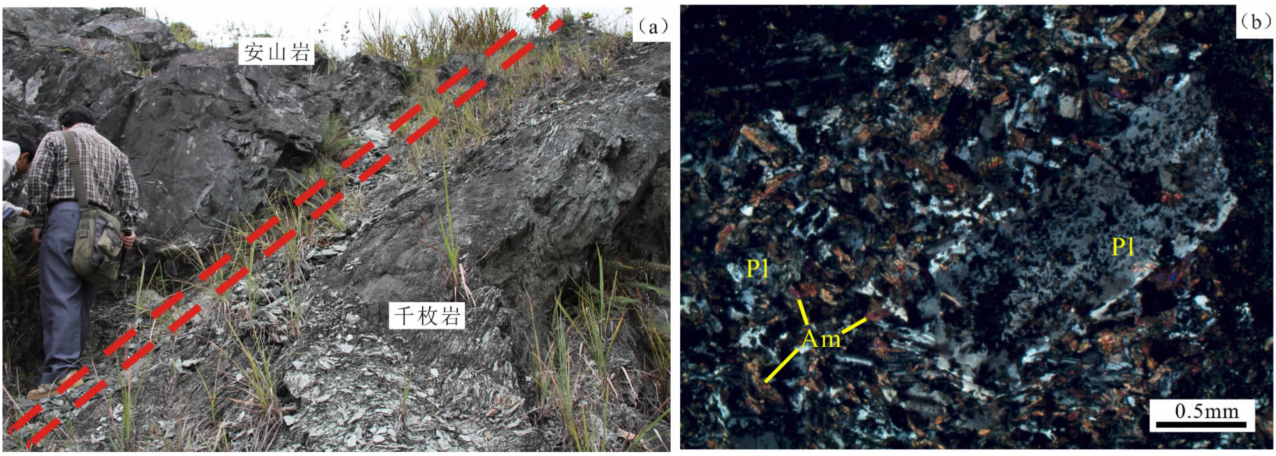

图 2 赣东北樟树墩高镁安山岩野外特征及显微照片:(a)安山岩与千枚岩界线,接触处强烈片理化;(b)安山岩正交偏光显微照片,岩石具斑状结构,基质玻晶交织结构,斑晶为斜长石

Fig. 2 Field outcrop and microstructure of high-Mg andesites at Zhangshudun, NE Jiangxi: (a) contact boundary between high-Mg andesites and phyllites, showing as an intense schistosity zone; (b) the microscope photograph of high-Mg andesite shows porphyritic texture and hyalopilitic texture of the matrix, and its phenocryst is plagioclase

Pl—斜长石;Am—角闪石

Pl— plagioclase; Am—amphibole

化和韧性变形(图 2a),总体构成向南东逆冲的叠瓦构造(图 1c)。

本次研究的样品分别取自于采场北西侧千枚岩中不同的火山岩夹层,采样位置(GPS 坐标为:N28°32′45″,E117°26′44″)见剖面(图 1c)。所采样品均为安山岩,整体较为新鲜,新鲜面呈灰黑色,斑状结构,斑晶含量小于 10%,几乎全为斜长石;基质为玻晶交织结构,斜长石微晶具半定向排列,在斜长石间隙中充填有角闪石微晶和玻璃质(图 2b),角闪石均有不同程度的绿帘石化和碳酸盐化。

2 分析方法

在薄片鉴定基础上,选择其中最新鲜样品用于地球化学分析。全岩主量元素分析在中国地质大学(武汉)生物地质与环境地质国家重点实验室完成,主量元素分析采用 XRF-1800 型荧光光谱仪分析,分析精度优于 1% ~5%;微量元素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,微量元素分析采用 Perkin-Elmer Sciex ELAN 6000 型电感耦合等离子体质谱仪(ICP-MS),分析精度优于 2% ~5%,详细实验方法见刘颖等(1996)。

锆石分选在廊坊市宇能岩石矿物分选技术服务有限公司完成,锆石制靶及阴极发光(CL)照相在北京锆年领航科技有限公司完成。

锆石测年在合肥工业大学资源与环境工程学院质谱实验室采用 LA-ICP-MS U-Pb 法完成,采用仪器型号为 Agilent 7500a,激光剥蚀系统为 Geo Las 2005。样品经剥蚀后,由 He 气作为载气,再与 Ar 气混合后进入 ICP-MS 进行分析。激光束斑直径为 32μm,频率为 6Hz。使用美国国家标准技术研究院的人工合成硅酸盐玻璃质标准矿物 NIST SRM610 进行仪器最佳化。U-Pb 分馏利用哈佛大学国际标准锆石 91500 来校正,锆石标样 Mud Tank(交点年龄为 732 ±5Ma)(Black and Gulson, 1978)作为参考标样。每轮测试的开头和结尾分别测 2 个 91500 标样和 2 个 Mud Tank 标样,中间每分析 5 个样品点,分析 2 次 91500,控制分析精度。数据处理采用中国地质大学(武汉)开发的 ICPMSDataCal 8.0 软件完成,选取谐和度 >90% 的样品点数据进行分析,采用 Isoplot/Ex_ver3 软件绘制谐和图并计算加权平均年龄。详细的分析方法和流程见严峻等(2012)和 Jackson 等(2004)。

锆石 Lu-Hf 同位素分析在中国地质调查局天津地质调查中心同位素实验室的多接收器电感耦合等离子体质谱仪(NEP TUNE)和氟化氩准分子激光器(NEW WAVE 193nm EX)上进行,详细的实验分析过程见文献(耿建珍等,2011)。对已进行过 U-Pb 同位素分析的锆石进行 Lu-Hf 同位素分析,激光剥蚀的斑束直径为 50μm,能量密度为 10 ~11 J/cm^2,频率为 8 ~10Hz。在实验过程中,标准锆石 GJ-1 和 MUD 的 $n(^{176}Hf)/n(^{177}Hf)$ 加权平均值均与已报道值(Elhlou et al., 2006;侯可军等,2007)相一致。

3 结果

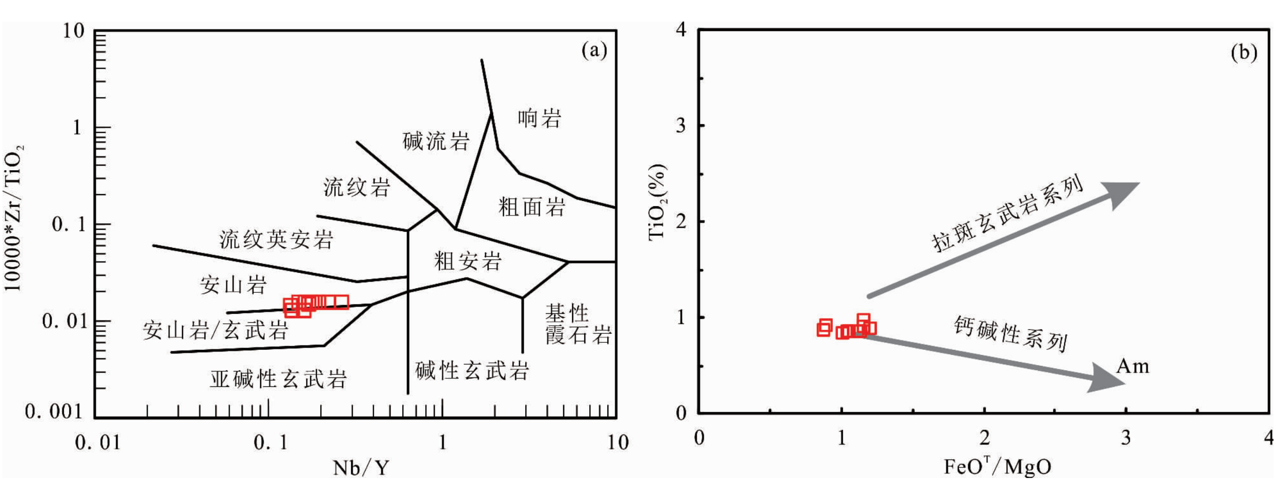

图 3 赣东北樟树墩高镁安山岩 Nb/Y—Zr/TiO_2 分类图(Winchester and Floyd, 1977)(a)和 FeO^T/MgO—TiO_2 图解(Miyashiro,1974)(b)

Fig. 3 Nb/Y vs. Zr/TiO_2 classification diagram (after Winchester and Floyd, 1977) (a) and FeO^T/MgO vs. TiO_2 diagram (after Miyashiro, 1974) (b) of the high-Mg andesites from Zhangshudun, NE Jiangxi

3.1　地球化学特征

火山岩样品的全岩主量元素、稀土和微量元素分析结果列于表 1。通过烧失量校正后,它们的 SiO_2 为 54.90% ~58.45%,全部介于典型高镁安山岩的 SiO_2 变化范围内(53% ~60%),具有较高的 MgO(6.39% ~8.76%,均大于 5%),FeO^T/MgO 变

表 1 赣东北樟树墩高镁安山岩全岩主量元素(%)、稀土元素和微量元素含量(μg/g)

Table 1 Major element(%), REE and trace element(μg/g) contents of high-Mg andesites from Zhangshudun, NE Jiangxi

Sample	11ZSD-1-2	11ZSD-1-3	11ZSD-1-5	11ZSD-1-6	1210ZSD-2-3C	1210ZSD-2-4B	1210ZSD-2-5C	1210ZSD-2-3A	1210ZSD-2-5A	1210ZSD-2-5B
SiO_2	54.22	54.45	54.89	55.16	53.06	54.57	54.02	55.95	53.22	54.37
TiO_2	0.85	0.89	0.88	0.84	0.91	0.97	0.83	0.86	0.85	0.85
Al_2O_3	15.33	15.45	14.79	15.49	15.19	15.55	15.41	16.05	14.75	15.41
Fe_2O_3	7.96	8.19	8.62	7.85	8.54	8.31	7.94	6.93	7.59	7.66
MnO	0.13	0.13	0.14	0.13	0.11	0.12	0.11	0.14	0.12	0.11
MgO	6.44	6.35	6.49	6.22	8.47	6.33	6.94	7.16	6.47	6.60
CaO	6.43	6.29	4.79	5.49	4.31	5.14	5.57	2.35	6.45	4.80
Na_2O	3.37	3.22	4.54	4.21	3.14	4.82	3.24	3.29	3.44	2.85
K_2O	2.16	2.14	1.36	1.90	2.80	1.19	2.93	2.88	2.82	3.47
烧失	3.34	3.16	3.30	3.00	3.63	2.42	3.21	4.48	4.45	4.02
总量	100.33	100.37	99.91	100.40	100.28	99.53	100.31	100.20	100.26	100.23
Na_2O/K_2O	1.56	1.50	3.34	2.22	1.12	4.05	1.11	1.14	1.22	0.82
$Mg^{\#}$	65	64	64	65	70	64	67	71	67	67
FeO^T	7.16	7.37	7.76	7.06	7.68	7.48	7.14	6.24	6.83	6.89
FeO^T/MgO	1.11	1.16	1.20	1.14	0.91	1.18	1.03	0.87	1.06	1.04
La	10	12.3	10.7	9.31	7.816	10.64	10.42	11.9	13.4	12.7
Ce	24.4	27.6	25.9	21.9	19.47	25.09	24.59	30.7	33.8	33.1
Pr	3.16	3.56	3.26	2.96	2.708	3.425	3.363	3.11	3.67	3.56
Nd	13.7	16	14.7	13.3	12.41	15.67	15.48	12.5	15.3	14.5
Sm	3.85	4.3	3.98	3.61	3.072	3.927	3.847	3.04	3.98	3.8
Eu	1.13	1.19	0.96	0.99	0.773	0.997	0.933	0.88	1.06	0.98
Gd	4.94	5.24	4.7	4.13	3.55	4.487	4.431	3.4	4.79	4.66
Tb	0.88	0.9	0.8	0.74	0.622	0.787	0.766	0.61	0.85	0.8
Dy	5.58	5.8	5.34	4.66	3.905	4.879	4.832	3.98	5.29	5.05
Ho	1.13	1.17	1.1	0.95	0.842	1.054	1.032	0.76	1.13	1.11
Er	3.31	3.57	3.23	2.84	2.469	3.007	2.989	2.37	3.28	3.09
Tm	0.51	0.51	0.47	0.4	0.372	0.453	0.436	0.33	0.46	0.44
Yb	3.21	3.46	3.09	2.69	2.489	2.903	2.903	2.16	3.21	2.95
Lu	0.48	0.51	0.45	0.39	0.372	0.43	0.433	0.33	0.44	0.43
Sc	28.6	27.8	30.3	28.6	24.43	23.42	23.76	27.5	28.2	30.9
Rb	52.9	57.4	31.9	44.8	80.51	47.87	87.62	78.4	79.2	92.9
Cs	1.95	2.12	1.43	1.56	3.693	1.688	2.85	2.87	2.64	3.63
Ba	388	312	275	429	432	373.6	353.8	367	314	375
Sr	189	207	130	168	93.41	154.5	139	78.8	191	135
Zr	133	139	133	125	114.6	121.7	117.9	131	132	131
Nb	4.69	4.71	4.68	4.06	3.639	3.96	3.871	5.35	6.7	5.3
Hf	3.14	3.6	3.21	2.76	3.327	3.558	3.485	3.2	3	3.2
Ta	0.39	0.32	0.37	0.31	0.29	0.311	0.31	0.5	0.57	0.51
Pb	9.31	12.7	13.5	6.18	4.321	3.394	8.551	22.3	6.55	6.34
Th	2.04	2.52	2.44	2.06	2.132	2.477	2.433	2.53	2.6	2.56
U	0.62	0.7	0.67	0.61	0.59	0.667	0.627	0.67	0.63	0.58
V	209	203	216	202	167.1	158	148.4	186	188	192
Cr	154	147	169	151	178.9	170.6	200.6	194	179	183
Co	34.8	33.8	38.1	33.8	34.19	28.81	29.1	29.4	30.5	32.1
Ni	86.6	83.9	89.9	85.3	113.9	93.2	102.9	115	101	104
Y	31.3	28.4	25.8	23.6	22.74	28.9	28.46	20.3	30.2	27
Ga	18.2	18.6	16.1	16.8	14.71	14.06	15.41	17.3	16.7	17.4

注:$FeO^T = Fe_2O_3 * 1.1113$;$Mg^{\#} = 100\, n(Mg^{2+})/[n(Mg^{2+}) + n(Fe^{2+})]$,$Fe^{2+}$ 为全铁。

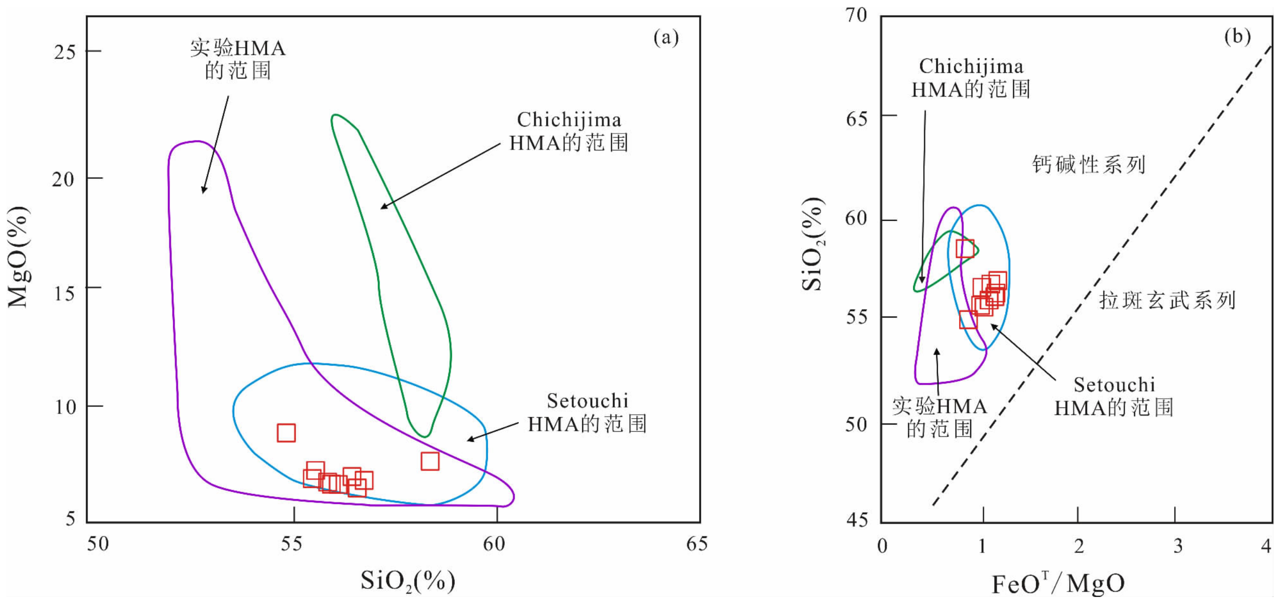

图 4 赣东北樟树墩高镁安山岩的 SiO_2—MgO 图(a)和 SiO_2—FeO^T/MgO 图(b)(底图据邓晋福等,2010,2015a)

Fig. 4 Plots of SiO_2 vs. MgO (a) and SiO_2 vs. FeO^T/MgO (b) for high-Mg andesites from Zhangshudun, NE Jiangxi (modified after Deng Jinfu et al., 2010&, 2015a&)

化于 0.87 ~ 1.20(均小于 1.5),Al_2O_3 介于 15.31% ~ 16.77%(平均为 15.87%),CaO 为 2.46% ~ 6.73%(均小于 10%),与 Tatsumi 等(2001)定义的高镁安山岩主量元素地球化学特征完全相符。此外,火山岩样品还具有比较稳定的 TiO_2(0.83% ~ 0.97%)、MnO(0.11% ~ 0.14%)、P_2O_5(0.09% ~ 0.12%)和 Fe_2O_3T(6.93% ~ 8.62%),Na_2O 介于 2.85% ~ 4.82%,Na_2O/K_2O 普遍 > 1(最高达 4.05),表现为相对富 Na 低 K 的特点。在 Nb/Y—Zr/TiO_2 岩石分类命名图解中(Winchester and Floyd, 1977),样品均位于安山岩区域内(图 3a)。在 FeO^T/MgO 对 TiO_2 图解中,所有样品均显示钙碱性系列(图 3b)。在 SiO_2—MgO 和 SiO_2—FeO^T/MgO 图解中,样品位于日本 Setouchi 火山带的 Sanukitoids(高镁安山岩/HMA)范围和实验的高镁安山岩/HMA 范围内(图 4)。

所分析样品的稀土元素含量较低,∑REE 介于 83.61 ~ 120.86μg/g 之间,轻稀土略富集(LREE/

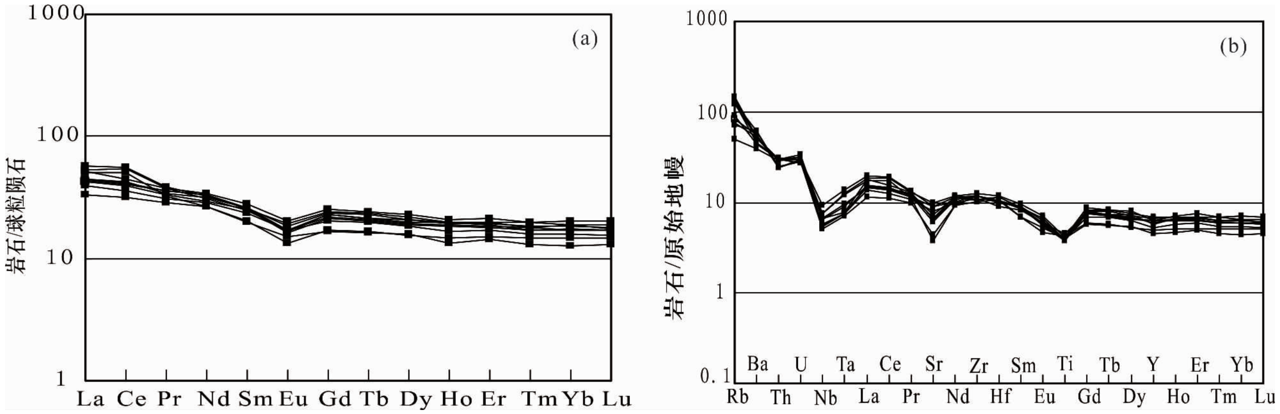

图 5 赣东北樟树墩高镁安山岩球粒陨石标准化稀土元素配分图(a)和原始地幔标准化微量元素蛛网图(b)(球粒陨石和原始地幔的标准值据 McDonough and Sun, 1995)

Fig. 5 Chondrite-normalized REE diagrams (a) and primitive mantle-normalized trace element spidergrams (b) for high-Mg andesites from Zhangshudun, NE Jiangxi (normalization values after McDonough and Sun, 1995)

HREE) =1.10 ~1.81),轻重稀土分异不明显[$(La/Yb)_N$ =2.24 ~3.95],在球粒陨石标准化的稀土元素配分图上表现为不明显的右倾配分曲线,并具有弱的 Eu 负异常(δEu =0.68 ~0.83)(图 5a)。在原始地幔标准化的微量元素蛛网图上,明显亏损高场强元素(HFSE)如 Nb、Ta、Ti、P 等,而富集大离子亲石元素(LILE)如 Rb、Ba 等元素(图 5b),显示岛弧岩浆岩特征。

此外,这些火山岩均具有高的 Cr(147 ~200μg/g)、Ni(85 ~115μg/g)、∑HREE(13.94 ~21.16μg/g)含量,其低的 Sr 含量(78.8 ~ 207μg/g)、Sr/Y(3.9 ~ 7.3)及 La/Yb 比值 < 5.5,远低于一般 Adakite 的 Sr 含量(>300μg/g)和 Sr/Y 比值(>20)(Castillo, 2006),而更接近于日本 Setouchi 火山岩带的中新世高镁安山岩(Tatsumi, 1982, 2006; Tatsumi and Ishizaka, 1982a; Shimoda et al., 1998; Tatsumi and Hanyu, 2003)。

3.2　锆石年代学

选择樟树墩高镁安山岩(样品号 11ZSD-1-2)进行了 LA-ICP-MS 锆石 U-Pb 法测年。所分选出来的锆石均为透明无色,大多数为短柱状,只有少部分为长柱状、不规则状,一般长轴在 80 ~120μm 之间,长宽之比在 1 ~2 之间。在 CL 图像中,大部分锆石常常表现出宽的、模糊的环带结构(图 6)。对分选出来的 24 颗锆石进行了分析,结果列于表 2。它们的 Th 含量为 64.4 ~782μg/g,U 含量为 105 ~794 μg/g,除 11 号点外,所有颗粒的 Th/U 值均变化于 0.66 ~1.41 之间,为典型的岩浆锆石(Wu Yuanbao and Zheng Yongfei, 2004)。其中 11 号测点具有较老的 $^{207}Pb/^{206}Pb$ 年龄,为 1798 ±8Ma,应为捕获锆石;其它 23 个测点在误差范围内具有谐和的年龄,获得的 $^{206}Pb/^{238}U$ 加权平均年龄为 794.8 ±6.0 Ma(n =23, MSWD =3.7)(图 7),代表了樟树墩高镁安山岩的喷发年龄。

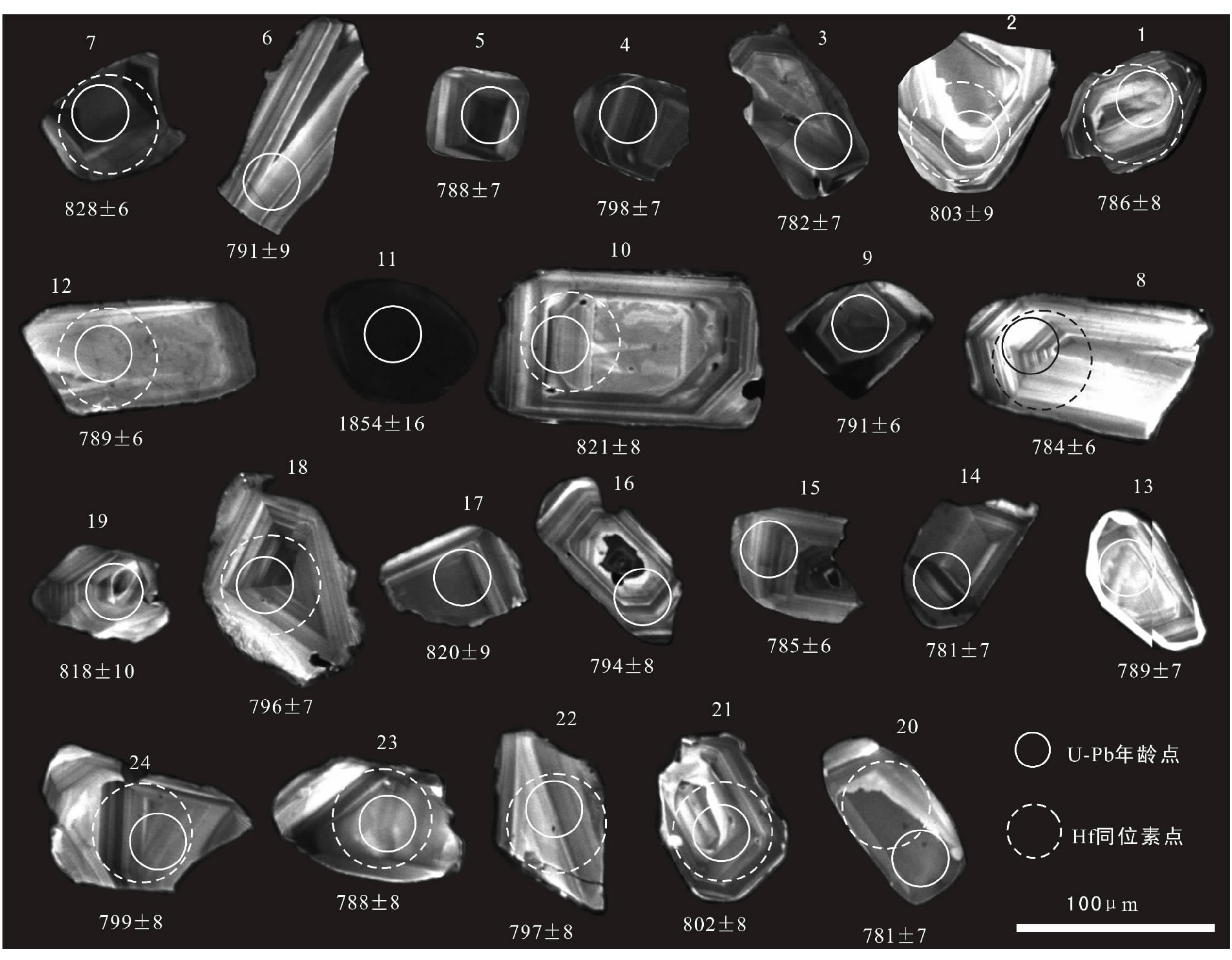

图 6 赣东北樟树墩高镁安山岩(11ZSD-1-2)锆石阴极发光(CL)图像

Fig. 6 CL images of zircons from Zhangshudun high-Mg andesite, NE Jiangxi (Sample 11ZSD-1-2)

3.3 锆石 Hf 同位素

对高镁安山岩样品 11ZSD-1-2 进行了 12 个点的锆石 Hf 同位素测定，点位同 U-Pb 测年点相对应，分析结果列于表 3。测得锆石颗粒的 $n(^{176}Lu)/n(^{177}Hf)$ 和 $n(^{176}Hf)/n(^{177}Hf)$ 比值范围较大，分别变化于 0.001779 ~ 0.002959 和 0.282591 ~ 0.282842，根据锆石的 LA-ICP-MS 年龄计算求得 Hf 同位素初始比值 $\varepsilon_{Hf}(t)$ 值在 +10.23 ~ +17.79 之间（计算方法参考王彦斌等，2010）。

4 讨论

4.1 岩石成因

对于高镁安山岩的形成机制，通常认为可能有三种：

（1）俯冲板片产生的熔体与地幔楔相互作用（Stern & Hanson，1991；Beakhouse et al.，1999）。

（2）伸展环境下的拆沉下地壳形成的熔体与上覆地幔岩反应的产物（Smithies & Champion，1999；Gao Shan et al.，2004）。

（3）含水地幔部分熔融的产物（Kushiro，1974；Tatsumi，1981；Defant & Drummond，1990；张旗等，2004，2005）。

现根据樟树墩高镁安山岩的地球化学特征，对其可能的成因分析如下：

（1）由于俯冲板片在部分熔融过程中，石榴子石往往作为残留相，而长石则会进入熔体，所产生的岩浆往往具有异常高的 Sr、极低的 Y 和 Yb 含量，相应地具有高的 Sr/Y、La/Yb 值（Defant and Drummoud，1990；Defant et al.，2002），在 Sr/Y—Y 以及球粒陨石标准化的 $(La/Yb)_N$—Yb_N 图解中（图 8）应位于"Adakite"区域。如前所述，樟树墩高镁安山岩具极低的 $(La/Yb)_N$、Sr/Y 和 Sr 含量，与俯冲板

表 2 樟树墩高镁安山岩（11ZSD-1-2）LA-ICP-MS 锆石 U—Th—Pb 同位素分析结果

Table 2 LA-ICP-MS zircon U—Th—Pb data of high-Mg andesite (Sample11ZSD-1-2) from Zhangshudun

测点	元素含量（μg/g）			Th/U	同位素比值						年龄（Ma）				谐和度（%）
	Pb	Th	U		$n(^{207}Pb^*)/n(^{206}Pb^*)$		$n(^{207}Pb^*)/n(^{235}U)$		$n(^{206}Pb^*)/n(^{238}U)$		$n(^{206}Pb)/n(^{238}U)$		$n(^{207}Pb)/n(^{206}Pb)$		
					测值	±1σ	测值	±1σ	测值	±1σ	测值	±1σ	测值	±1σ	
01	33.5	125	174	0.72	0.0667	0.0012	1.1949	0.0236	0.1296	0.0015	828	39	786	8	98
02	26.1	103	130	0.79	0.0673	0.0012	1.2320	0.0232	0.1327	0.0016	856	37	803	9	98
03	92.9	373	521	0.72	0.0695	0.0009	1.2432	0.0205	0.1290	0.0012	922	26	782	7	95
04	102.1	453	485	0.93	0.0681	0.0009	1.2424	0.0193	0.1318	0.0012	872	28	798	7	97
05	83.0	411	375	1.10	0.0668	0.0009	1.2008	0.0175	0.1299	0.0012	831	-171	788	7	98
06	57.7	297	252	1.18	0.0668	0.0011	1.2133	0.0262	0.1305	0.0016	833	33	791	9	98
07	140	698	535	1.30	0.0662	0.0007	1.2541	0.0145	0.1371	0.0010	813	21	828	6	99
08	43.0	241	171	1.41	0.0676	0.0010	1.2080	0.0196	0.1294	0.0011	857	27	784	6	97
09	74.8	326	361	0.90	0.0664	0.0008	1.1993	0.0165	0.1306	0.0010	820	31	791	6	98
10	41.6	171	187	0.92	0.0664	0.0010	1.2477	0.0219	0.1359	0.0014	820	33	821	8	99
11	243.6	203	553	0.37	0.1133	0.0010	5.4192	0.0517	0.3459	0.0021	1854	16	1915	10	98
12	36.3	141	187	0.76	0.0664	0.0010	1.1910	0.0194	0.1301	0.0011	820	31	789	6	99
13	18.8	60.9	92.0	0.66	0.0666	0.0013	1.1980	0.0248	0.1302	0.0012	833	41	789	7	98
14	62.4	277	298	0.93	0.0682	0.0011	1.2162	0.0213	0.1288	0.0012	876	33	781	7	96
15	88.4	439	411	1.07	0.0657	0.0008	1.1774	0.0156	0.1295	0.0010	798	24	785	6	99
16	48.9	202	252	0.80	0.0652	0.0009	1.1786	0.0187	0.1310	0.0014	789	30	794	8	99
17	36.7	134	188	0.72	0.0689	0.0023	1.2865	0.0392	0.1356	0.0017	894	64	820	9	97
18	45.1	207	215	0.96	0.0666	0.0010	1.2078	0.0193	0.1315	0.0013	833	30	796	7	99
19	40.3	202	166	1.21	0.0702	0.0014	1.3149	0.0299	0.1353	0.0018	933	38	818	10	95
20	46.7	208	230	0.91	0.0652	0.0011	1.1577	0.0196	0.1287	0.0013	789	33	781	7	99
21	27.9	98.9	147	0.67	0.0647	0.0011	1.1818	0.0195	0.1325	0.0014	765	234	802	8	98
22	36.1	161	167	0.96	0.0654	0.0011	1.1913	0.0231	0.1316	0.0014	787	42	797	8	99
23	45.1	214	203	1.05	0.0660	0.0009	1.1890	0.0198	0.1300	0.0014	807	30.4	788	8	99
24	38.7	163	187	0.87	0.0652	0.0010	1.1922	0.0213	0.1320	0.0013	789	33.3	799	8	99

注：表中测点编号前省略了"10ZSD-1-2-"。

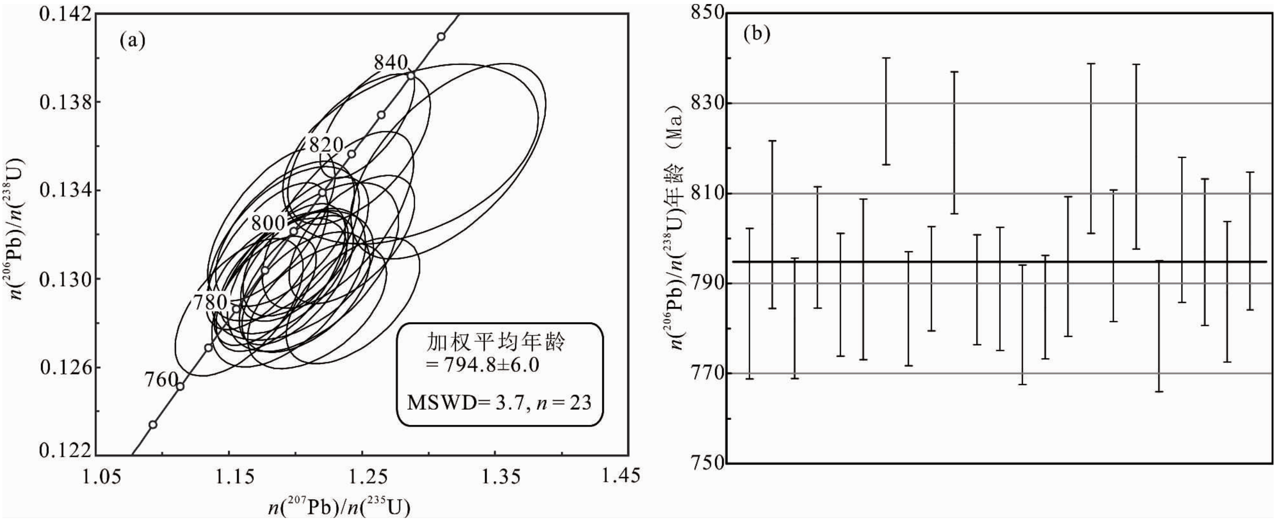

图 7 赣东北樟树墩高镁安山岩(11ZSD-1-2)LA-ICP-MS 锆石 U-Pb 年龄谐和图(a)和加权平均值(b)

Fig. 7 Zircon U-Pb concordia diagram (a) and $^{206}Pb/^{238}U$ age plot (b) for high-Mg andesite (Sample 11ZSD-1-2) from Zhangshudun, NE Jiangxi

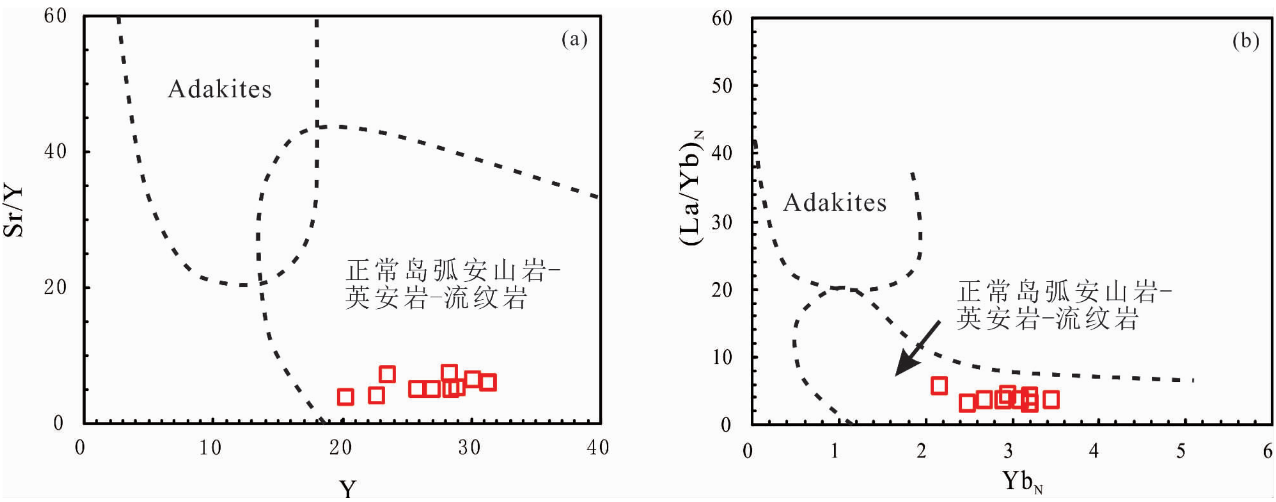

图 8 赣东北樟树墩高镁安山岩 Sr/Y—Y 图解(a)和球粒陨石标准化的$(La/Yb)_N$— Yb_N图解(b)
(底图据 Defant and Drummond, 1990)

Fig. 8 Plots of Sr/Y vs. Y (a) and Zr/$(La/Yb)_N$ vs. Yb_N(b) of high-Mg andesites from Zhangshudun, NE Jiangxi (after Defant and Drummond, 1990)

片来源的 Adakite 截然不同,在 Sr/Y—Y 以及$(La/Yb)_N$—Yb_N 图解中均落于正常岛弧火山岩范围内(图 8),因此可排除其属于上述俯冲板片熔体与地幔楔相互作用的第一种可能成因。

(2)研究表明,在伸展环境下,拆沉下地壳榴辉岩部分熔融产生的熔体与地幔相互作用可形成具高 Sr/Y 的 adakite 特征岩石(Defant et al., 2002),这同样与樟树墩高镁安山岩的低 Sr/Y 特征不符;另外,拆沉下地壳熔体的锆石 Hf 同位素应较为富集,而樟树墩高镁安山岩的锆石 Hf 同位素异常亏损。因此,也可排除其属于拆沉下地壳来源的第二种可能成因。

(3)樟树墩高镁安山岩具有较高的 MgO (6.39% ~8.76%)、Cr(147 ~200μg/g)、Ni(85 ~115μg/g)含量,暗示其成因与地幔熔融或含有较多地幔组分有关。实验岩石学研究表明,高镁安山岩不可能来自于干的地幔橄榄岩的熔融,只可能来自于地幔岩—H_2O 体系的熔融(Tatsumi, 1981;邓晋福

等,2010,2015b)。因此,推断它们应属于上述第三种成因,是来自俯冲板片释放的流体交代地幔楔形成的含水地幔源区。

世界上最为经典的高镁安山岩是日本西南 Setouchi 中新世火山岩带的 Sanukitoids,以高 $Mg^{\#}$值(>60)、较高 Cr、Ni 含量为特征,富集 LILE 和 LREE,通常具弱的负 Eu 异常,亏损 HFSE,具地幔熔融的初始岩浆性质,是由含水富集地幔部分熔融形成的,产于弧前环境(Tatsumi, 1982, 2006; Tatsumi and Ishizaka, 1982a; Shimoda et al., 1998; Tatsumi and Hanyu, 2003)。樟树墩高镁安山岩具有与 Setouchi 火山带中的 Sanukitoids 极为相似的 MgO、Cr、Ni 含量及地球化学特征,暗示两者具有较为一致的成因。此外,樟树墩高镁安山岩具有异常亏损的锆石 $\varepsilon_{Hf}(t)$(+10.23 ~ +17.79),类似于洋岛玄武岩(OIB)或洋中脊玄武岩(MORB)的特征,并接近于亏损地幔演化线(图 9),说明不仅其地幔楔源区是极度亏损的 MORB 型地幔,而且俯冲板片也是较新鲜的热的洋壳,因而其释放的俯冲流体也相对亏损,暗示其形成环境为大洋岛弧(洋内弧);且可能由于俯冲流体对地幔楔的不均匀交代作用,导致高镁安山岩的锆石 $\varepsilon_{Hf}(t)$具有一定的变化范围。

综上所述,樟树墩高镁安山岩最为可能是亏损地幔楔在受到俯冲板片来源的含 H_2O 流体交代后,发生部分熔融的产物,形成于大洋岛弧(洋内弧)环境。

4.2 大地构造意义

华南前寒武纪大地构造格局的演化,特别是江南造山带的形成演化、华夏与扬子两大陆块碰撞拼合时间和过程等,长期以来是学术界关注的热点。根据造山带内新元古代褶皱基底与上覆盖层之间的区域不整合面、赣东北和皖南蛇绿岩、浙北双溪坞岛弧火山岩、赣东北蓝闪石片岩、新元古代花岗岩等的研究(Zhou Guoqing, 1989; 程海等, 1993; Shu Liangshu et al., 1994; Wu Rongxin et al., 2006; Zheng Yongfei et al., 2008; 丁炳华等, 2008; Li Xianhua et al., 2003, 2009; 薛怀民等, 2010; Zhang Shaobing et al., 2012),一般认为扬子与华夏陆块拼合于新元古代早中期,包括了约 970 ~ 880 Ma 的岛

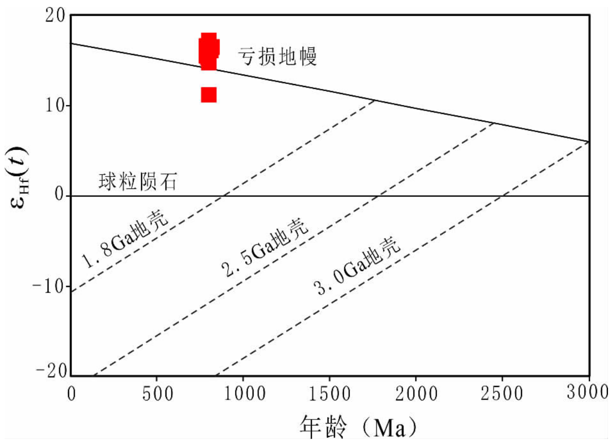

图 9 赣东北樟树墩高镁安山岩(11ZSD-1-2)锆石 U-Pb 年龄和 Hf 同位素相关图

Fig. 9 Plot of $\varepsilon_{Hf}(t)$ vs. $^{206}Pb/^{238}U$ age of zircons from high-Mg andesites in Zhangshudun, NE Jiangxi (Sample 11ZSD-1-2)

表 3 赣东北樟树墩高镁安山岩(11ZSD-1-2)锆石 Hf 同位素组成

Table 3 Zircon Hf isotopic compositions of high-Mg andesite (sample 11ZSD-1-2) from Zhangshudun, NE Jiangxi

测点号	年龄(Ma)	$n(^{176}Yb)/n(^{177}Hf)$	$n(^{176}Lu)/n(^{177}Hf)$	$n(^{176}Hf)/n(^{177}Hf)$ 测值	$n(^{176}Hf)/n(^{177}Hf)$ 1σ	$[n(^{176}Lu)/n(^{177}Hf)]_i$	$\varepsilon_{Hf}(t)$ 测值	$\varepsilon_{Hf}(t)$ 1σ	T_{DM} (Ga)	T_{DM}^{C} (Ga)	$f_{Lu/Hf}$
11ZSD-1-2-1	786	0.08273	0.002542	0.282752	0.000013	0.282715	15.33	0.45	0.74	0.72	-0.92
11ZSD-1-2-2	803	0.06468	0.002157	0.282766	0.000013	0.282733	16.37	0.46	0.71	0.66	-0.94
11ZSD-1-2-7	828	0.29149	0.007152	0.282842	0.000013	0.282730	16.83	0.45	0.70	0.65	-0.78
11ZSD-1-2-8	784	0.11992	0.002848	0.282807	0.000016	0.282765	17.10	0.57	0.66	0.60	-0.91
11ZSD-1-2-10	821	0.11992	0.002848	0.282766	0.000013	0.282722	16.36	0.45	0.73	0.68	-0.91
11ZSD-1-2-12	789	0.06883	0.001779	0.282752	0.000013	0.282725	15.77	0.45	0.72	0.69	-0.95
11ZSD-1-2-18	796	0.10877	0.002806	0.282819	0.000014	0.282778	17.79	0.49	0.64	0.56	-0.92
11ZSD-1-2-20	781	0.07556	0.002265	0.282758	0.000010	0.282725	15.58	0.35	0.72	0.70	-0.93
11ZSD-1-2-21	802	0.06720	0.001997	0.282591	0.000015	0.282560	10.23	0.51	0.96	1.06	-0.94
11ZSD-1-2-22	797	0.07646	0.002102	0.282733	0.000009	0.282701	15.11	0.32	0.76	0.74	-0.94
11ZSD-1-2-23	788	0.10681	0.002959	0.282766	0.000014	0.282722	15.64	0.47	0.73	0.70	-0.91
11ZSD-1-2-24	799	0.08816	0.002375	0.282725	0.000011	0.282689	14.73	0.39	0.78	0.77	-0.93

注:表中各参数的计算公式及有关常数值见王彦斌等,2010。

弧岩浆活动、~870 ~850 Ma 的陆—陆拼接及 ~850 ~760Ma 的后造山伸展(Wang Xiaolei et al., 2006, 2012)或者地幔柱活动(Li et al., 1999, 2003; Li Xianhua et al., 2003, 2010)等过程。尽管对于造山阶段及其时限的认识各有不同,但是多数学者认为华夏与扬子陆块于约 830 ~820Ma 完成碰撞拼接。

在江南造山带东段研究中,扬子陆块东南缘的双溪坞弧和以双桥山群和溪口群沉积岩系为代表的新元古代弧后盆地被赋予了特别重要的意义,赣东北蛇绿岩带也被认为是弧后洋盆关闭的产物(Chen Jiangfeng et al., 1991; Li Xianhua et al., 2009)。一般认为,新元古代期间,华南洋向扬子陆块北西向俯冲,导致双溪坞弧和华夏陆块与扬子陆块碰撞,赣东北—皖南地区以双桥山群和溪口群为代表的弧后盆地关闭,在东乡—德兴一带形成赣东北蛇绿岩带(Shu Liangshu et al., 1994; 舒良树等,2012;Charvet et al., 1996; Ye Meifang et al., 2007; Li et al., 2007; Li Wuxian et al., 2008)。因此,赣东北蛇绿岩带的形成时限,是认识江南造山带构造演化、乃至扬子与华夏陆块碰撞过程的关键所在。

需要指出的是,双溪坞弧与西北侧的双桥山群和溪口群是否构成配套的弧盆体系?这仍是值得进一步探讨的问题。一方面,双溪坞弧与双桥山群和溪口群在时代上存在明显差异。双溪坞群属典型的活动大陆边缘钙碱性系列火山弧,形成时代为 ~970 ~890Ma(Li Xianhua et al.,2009),明显早于双桥山群和溪口群(850 ~800Ma)(王剑,2000;Wang Jian & Li Zhengxiang,2003;Yao Jinlong et al., 2013;李双应等,2014);另一方面,双桥山群和溪口群硅质碎屑岩的化学成分显示其沉积于活动陆缘(黄修保等,2003),它们的火山岩均有明显的岛弧岩浆岩属性,推断应属岩浆弧(Wang Xiaolei et al.,2013)。这说明,双桥山群和溪口群可能不是与双溪坞弧相配套的弧后盆地沉积。此外,浙西北地区双溪坞群曾被认为层位相当于双桥山群和溪口群,其上覆骆家门组则为沉积盖层,它们之间的“神功运动”面则是与四堡运动面、晋宁运动面可对比的区域性不整合面,骆家门组底部的砾岩属底砾岩(马瑞士和张健康,1977;Li Xianhua et al.,2009);而最近的研究认为骆家门组底部砾岩可能为水下扇的主沟道沉积,缺乏底砾岩的特征,其底面也主要为侵蚀冲刷面或断层面,并非不整合面;且骆家门组底部凝灰岩锆石年龄为 855 ~860Ma,时代早于双桥山群和溪口群;同时双溪坞群与双桥山群、溪口岩群沉积地层的碎屑锆石年龄谱也截然不同,指示它们具有不同构造热演化史(周效华等,2014)。因此,双溪坞弧并非对应于赣东北—皖南弧后盆地的“弧”,而可能为外来增生弧(Yin Changqing et al., 2013),这意味着赣东北蛇绿岩可能并非弧后洋盆关闭的标志。

前人研究表明,在赣东北蛇绿岩带中,存在多期代表蛇绿岩构造就位的年龄信息。如:Li Wuxian et al.(2008)获得西湾仰冲花岗岩的 SHRIMP 锆石 U-Pb 法年龄为 880 ± 19Ma;Shu Liangshu 等(1994)报道了西湾蓝闪石片岩 K-Ar 年龄为 866 ±14Ma;胡世玲等(1992)报道了西湾糜棱岩化钠长花岗岩中青铝闪石的^{40}Ar-^{39}Ar 高温阶段年龄为 799Ma。这些年龄是否暗示了赣东北蛇绿岩并非由单个洋盆关闭形成,而是多个小洋盆陆续关闭形成的?此外,笔者报道了赣东北蛇绿岩带的形成时代为 1061Ma(王存智等,2015),结合本次樟树墩 ~800Ma 高镁安山岩的发现,推断赣东北地区可能自中元古代末即存在洋盆,并一直持续到青白口纪末期,如此持续存在长达 200Ma 的洋盆,我们推断可能为古南华洋的分支洋,包括了一系列先后关闭的小洋盆,并迟至 ~800Ma 之后才最终关闭,形成赣东北蛇绿岩带。

值得一提的是,在江南造山带西段和中段,也有 ~830Ma 高镁闪长岩(Chen Xin et al., 2014)和 ~825Ma 的高镁安山岩(Zhang Yuzhi et al., 2013)的报道,樟树墩高镁安山岩与它们之间的关系如何,也是值得进一步研究的。此外,前人研究表明,扬子陆块周缘在新元古代广泛发育岩浆活动,它们的年龄呈现两个峰值,分别为 830 ~ 800Ma 和 780 ~740Ma,其中早期岩浆事件(830 ~ 800Ma)对应大洋俯冲至弧—陆碰撞阶段(Zhang Shaobing et al., 2013a),指示这一俯冲过程可能持续至 ~800Ma(Yan Zhen et al., 2010;Dong Yupeng et al., 2012;敖文昊等, 2014)、甚至可能到 740Ma(Zhao Junhong& Zhou Meifu, 2008;Sun Weihua, et al., 2008)。因此,樟树墩 ~800Ma 高镁安山岩的发现,意味着当时赣东北地区属于扬子陆块周缘俯冲带的组成部分。最近,在扬子陆块东南缘的浙江绍兴—诸暨—金华一线,还新厘定出一套新元古代(930 ~790Ma)陆缘弧型 TTG 组合,指示直到 ~790Ma 扬子陆块东南缘仍受到强烈的洋壳俯冲(姜杨等,2014),其最晚时代与本文报道的樟树墩高镁安山岩时代基本一致,表明 ~800Ma 时双溪坞弧两侧均可能同时存在大洋,并未增生到扬子陆块之上,这也暗示扬子与华夏两大陆块尚未发生碰撞。

综上所述,赣东北樟树墩 ~800Ma 高镁安山岩的发现,对于重新认识江南造山带的构造格局及其演化、扬子与华夏两大陆块碰撞拼贴时限等,均具有重要的科学意义。

5 结论

(1)樟树墩安山岩属于典型的高镁安山岩,其 LA-ICP-MS 锆石 U-Pb 年龄为 794.8 ±6.0 Ma,代表了高镁安山岩的喷发时代。

(2)岩石地球化学及锆石 Hf 同位素研究表明,樟树墩高镁安山岩为受俯冲洋壳释放的含 H2O 流体交代的地幔楔后,发生部分熔融的产物,形成于大洋岛弧(洋内弧)构造环境。

(3)赣东北蛇绿岩带新元古代高镁安山岩的发现,指示 ~800Ma 时双溪坞弧尚未增生到扬子东南缘,暗示扬子和华夏两大陆块此时尚未碰撞拼合。

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Recognition and Significance of Neoproterozoic (ca. 800 Ma) High-Mg Andesites in the NE Jiangxi Ophiolite Belt

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Abstract: The newly discovered Neoproterozoic high-Mg andesites are located at Zhangshudun of the NE Jiangxi ophiolite belt and are dated at a zircon U-Pb age of 794.8 ± 6.0 Ma. They have variable SiO_2 (54.90% ~ 58.45%), CaO (2.46% ~ 6.73%), relatively consistent Al_2O_3 (15.31% ~ 16.77%, mostly less than 16%) and FeO^T/MgO values (0.87 ~ 1.20), and show relatively high MgO contents (6.22 ~ 8.47%), high $Mg^\#$ (64 ~ 71), which clearly exhibits the diagnostic features of typical high-Mg andesites. The study samples are enriched in LREE and have slightly negative Eu anomalies. In spider diagram, they show enrichment of LILE (eg. Rb, Ba) while depleted in Nb and Sr elements. These andesites have relatively low Sr abundance and Sr/Y ratios (4.11 ~ 7.29), similar to Sanukitoids of the Setouchi volcanic belt in Japan. The zircon Hf isotopes show positive initial epsilon Hf values ranging from +10.3 to +17.8. These geochemical data indicate Zhangshudun high-Mg andesites should derived from the deplted mantle wedge metasomatized by fluids released from the subducted slab, within an oceanic arc setting. Therefore, it is inferred that the Shuangxiwu arc was away from the southeastern margin of the Yangtze Block, and the Yangtze and Cathaysia blocks had not collided at least at ca. 800Ma.

Keywords: High-Mg andesite; Neoproterozoic; Zhangshudun; the NE Jiangxi ophiolite belt; Jiangnan orogen

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