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闽中南平—宁化构造带南华纪陆缘弧岩浆活动:对武夷造山带构造演化的新启示

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提要:南平—宁化构造带沿线出露着以万全岩群和楼前组、西溪组等为代表的一系列新元古代火山-沉积岩系。系统的岩石学、年代学和地球化学研究表明,福建明溪和江西瑞金地区的楼前组浅变质英安岩和晶屑凝灰岩分别形成于(729±4)Ma和(735±6.7)Ma(LA-ICP-MS锆石U-Pb法),SiO_2含量变化在65.22%~74.54%,相对富Al_2O_3(11.05%~16.80%)富碱(Na_2O+K_2O=4.88%~10.19%)而贫CaO、MgO和FeO^T,ANK值和A/CNK值分别为1.23~1.78和0.98~1.57,Nb/Ta=12.44~17.28,Nd/Th=2.07~3.51,Ti/Zr=6.08~10.37,Ti/Y=68.51~154.71,属过铝质S型火山岩;明显富集大离子亲石元素(Ba、Rb等)而亏损高场强元素(Nb、Ta、Ti、P等),Zr/Nb=16.65~24.07,Th/Ta=12.94~16.93,δEu呈现明显负异常(0.33~0.62),显示岛弧岩浆岩的地球化学特征。综合区域地质资料及前人研究结果提出,南平—宁化一线在713 Ma前为活动大陆边缘环境,洋壳俯冲引发的岩浆活动形成了沿南平—宁化—瑞金一线展布的陆缘弧中酸性火山岩带,暗示此时南、北武夷之间尚未拼合形成统一的武夷地块,因而华夏地块不存在统一的前南华纪结晶基底。

关 键 词:陆缘弧岩浆活动;南华纪;南平—宁化构造带;武夷地区;华夏地块;地质调查工程

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Neoproterozoic continental margin−arc magmatic activity of the Nanping−Ninghua tectonic belt, South China: Implications for tectonic evolution of the Wuyi orogenic belt

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Abstract: Numerous Neoproterozoic volcanic− sedimentary rocks, e.g., Wanquan Group, Louqian and Xixi Formation, are

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outcropped along the Nanping−Ninghua tectonic belt, South China. This paper presents a systematic petrological, geochronological, and geochemical study of metamorphic rocks from the Louqian Formation in Mingxi County of Fujian and Ruijin County of Jiangxi Province. Zircons from meta−dacite in Mingxi County and meta− crystal tuff in Ruijin County yielded U−Pb weighted mean ages of (729±4)Ma and (735±6.7) Ma (by LA−ICP−MS), respectively. The SiO_2 values of these meta−volcanic rocks range from 65.22% to 74.54%, and they have high Al_2O_3 (11.05%−16.80%) and $Na_2O + K_2O$ content (4.88%−10.19%) but low CaO, MgO, and FeO_T content. Their ANK values and A/CNK ratios are 1.23−1.78 and 0.98−1.57 with Nb/Ta being 12.44−17.28, Nd/Th being 2.07−3.51, Ti /Zr being 6.08−10.37 and Ti /Y being 68.51−154.71, implying the S−type igneous rocks. All samples are enriched in large−ion lithophile elements (LILE; e.g., Ba and Rb) and depleted in high−field−strength elements (HFSE; e.g., Nb, Ta, Ti, and P) with Zr/Nb being 16.65−24.07 and Th/Ta being 12.94−16.93. Marked negative Eu anomalies 0.33−0.62 are similar to those in arc igneous rocks. Based on regional geological data and previous studies, the authors hold that the Nanping−Ninghua tectonic belt had been in an active continental margin setting until 713 Ma. The magmatism was caused by the subduction of oceanic crust and formed an intermediate−acid volcanic belt along the Nanping−Ninghua−Ruijin continental margin, which indicates that the collision between the North and South Wuyi blocks did not form a unified Wuyi Block before 713 Ma, and the Cathaysia Block had not a unified pre−Nanhua crystalline basement.

Key words: continental margin−arc magmatic activity; Nanhua Period; Nanping−Ninghua tectonic belt; Wuyi area; Cathaysia Block; geological survey engineering

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1 引 言

武夷地区尤其是北武夷地区是华夏地块前寒武纪中—深变质岩的主要出露区,主要包括浙北的陈蔡岩群、浙西南的龙泉岩群和八都岩群、闽西北的天井坪岩组、麻源岩群、迪口岩组、马面山岩群、万全岩群等,是研究华夏地块变质基底的理想之地(图1)。

南平—宁化构造带(也称南平—宁化构造-岩浆岩带,图1b),是20世纪90年代以来新厘定的构造-岩浆岩带,呈NEE向展布于福建南平—宁化一线,长约140 km,宽20~30 km,主要分布有北东东或东西向展布的新元古代—寒武纪的火山-沉积岩系及加里东期、印支期、燕山期花岗岩类,另见零星的中生代沉积-火山地层(韦德光等,1997)。通常,以南平—宁化构造带为界将武夷地块划分成南、北武夷两个次级构造单元,福建省内长期将其作为晋宁期的夭折裂谷,响应于华夏和扬子两大地块碰撞拼合后的广泛裂解事件(韦德光等,1997;张庆龙等,2008;李霞等,2013);夭折裂谷发育于新元古代万全岩群变质基底之上,其内充填了以楼前组、西溪组和林田组为代表的南华纪—寒武纪浅变质中酸性火山岩和沉积岩。然前人研究亦表明,南平—宁化构造带可能存在新元古代的岛弧岩浆活动,如福建省地质志(2016a)❶根据省内区域地质调查资料并结合前人研究总结指出,万全岩群中酸性火山岩的地球化学特征与造山带岛弧或活动大陆边缘岩的特征接近;靳松等(2008)认为万全岩群变沉积岩应形成于岛弧-活动陆缘环境;胡宗良等(2002)和Jiang et al.(2018)的研究表明,楼前组中酸性火山岩化学成分同活动大陆边缘或岛弧环境火山岩特征接近。因此,南平—宁化构造带的构造属性是武夷造山带构造演化研究的关键问题,并涉及到华夏地块是否存在统一的前寒武纪变质基底问题。

为此,作者选取了福建明溪楼前和江西瑞金地区的楼前组浅变质中酸性火山岩,开展了详细的岩相学、地球化学以及LA-ICP-MS锆石U-Pb年代学研究,厘定该中酸性火山岩的构造属性,进而探讨南平—宁化构造带新元古代的大地构造背景、华夏陆块的性质和华南前寒武纪的大地构造演化历史。

2 样品及岩相学特征

南平—宁化一带的新元古代浅变质沉积-火山岩系以楼前组和西溪组为代表,与下伏万全岩群多

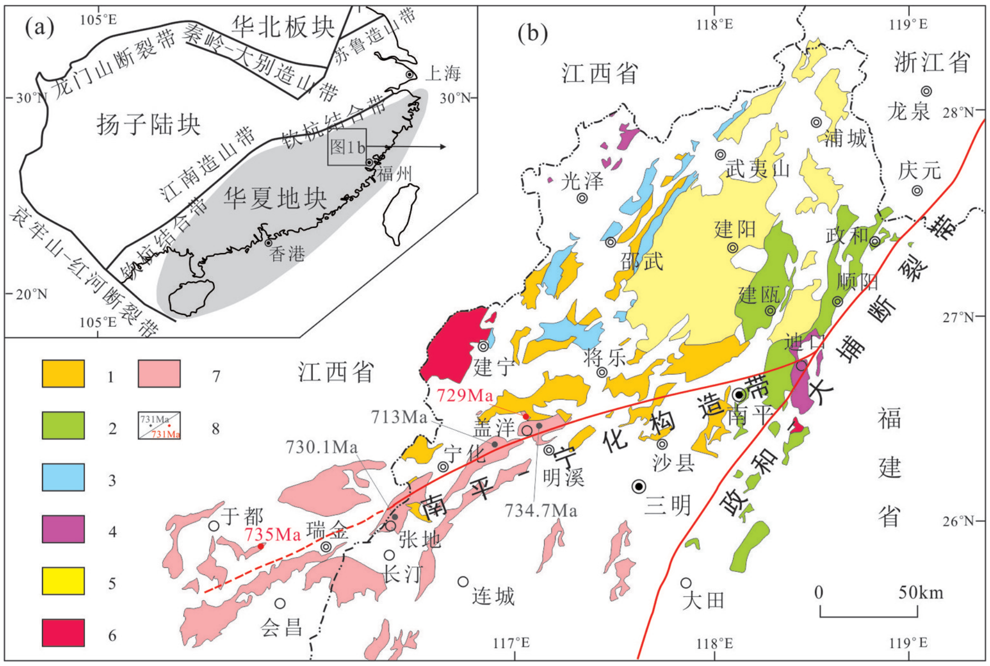

图1 研究区大地构造位置图(a,据Greentree et al., 2006修改)及区域前寒武纪变质岩分布简图(b,据Jiang et al.,2018修改)

1—万全岩群;2—马面山岩群;3—交溪岩群;4—迪口岩组;5—麻源岩群;6—天井坪岩组;7—南华纪—震旦纪火山-沉积岩系;8—前人/本次研究结果

Fig. 1 Tectonic map of the study area (a, after Greentree et al., 2006) and distribution of the Procambrian metamorphic rocks in South China (b, after Jiang et al., 2018)

1-Wanquan Group; 2-Mamianshan Group; 3-Jiaoxi Group; 4-Dikou Formation; 5-Mayuan Group; 6-Tianjingping Formation; 7-Nanhua-Sinian volcanic sedimentary rock series; 8-Previous/this study

呈断层接触,上覆寒武纪林田组浅变质沉积岩。楼前组主体为浅变质中酸性火山岩,主要分布于北武夷隆起区和南武夷晚古生代坳陷区交接地带的明溪盖洋、清流泉上、宁化方田等地,明显受南平—宁化构造带控制,呈近东西向带状展布(图1b)。

本次研究选择的楼前组变火山岩样品分别采自闽西明溪地区和赣南瑞金地区。明溪地区是楼前组的命名地,岩石类型以变流纹岩和变英安-流纹岩为主,在明溪湖上等地近火山喷发中心尚出露有变火山角砾岩、变集块岩等;在瑞金周边则见有楼前组变余晶屑凝灰岩、变凝灰岩等。

岩相学研究表明,浅变质流纹岩样品多呈隐晶质结构和流纹构造,流纹条带细密平直,几乎不见斑晶(图2a、b);浅变质英安岩样品的流动构造不甚发育,可见少量长石和石英斑晶。变余晶屑凝灰岩样品则多呈变余凝灰结构,晶屑主要为石英、钾长石、斜长石和黑云母,多呈棱角状、次棱角状,少量呈次圆状,含量一般不超过10%(图2c、d)。变凝灰岩手感细腻,镜下可见其内几乎不含晶屑。

3 分析方法

LA-ICP-MS锆石U-Pb同位素年代学分析均在中国地质调查局天津地质调查中心同位素实验室完成,采用的仪器为Thermo Fisher公司制造的Neptune多接收器电感耦合等离子体质谱仪(MC-ICP-MS),激光器为美国ESI公司生产的UP193-FX ArF准分子激光器,激光波长193 nm,测试过程中使用的激光剥蚀束斑直径为35 μm。锆石LA-ICP-MS U-Pb同位素年代学测试使用TEMORA作为外部锆石年龄标准,利用中国地质大学刘勇胜博士研发的ICPMSDataCal程序和Kenneth R Ludwig的Isoplot程序进行数据处理,并采用^{208}Pb校正法对普通铅进行校正,选择NIST612玻璃标样作为外标计算锆石样品的Pb、U、Th含量。详细的实验测试过程参见李怀坤等(2009)。

样品的主量元素、微量元素和稀土元素分析在国家地质实验测试中心完成。主量元素使用Phillips 4400X-荧光光谱仪测试,FeO用容量滴定

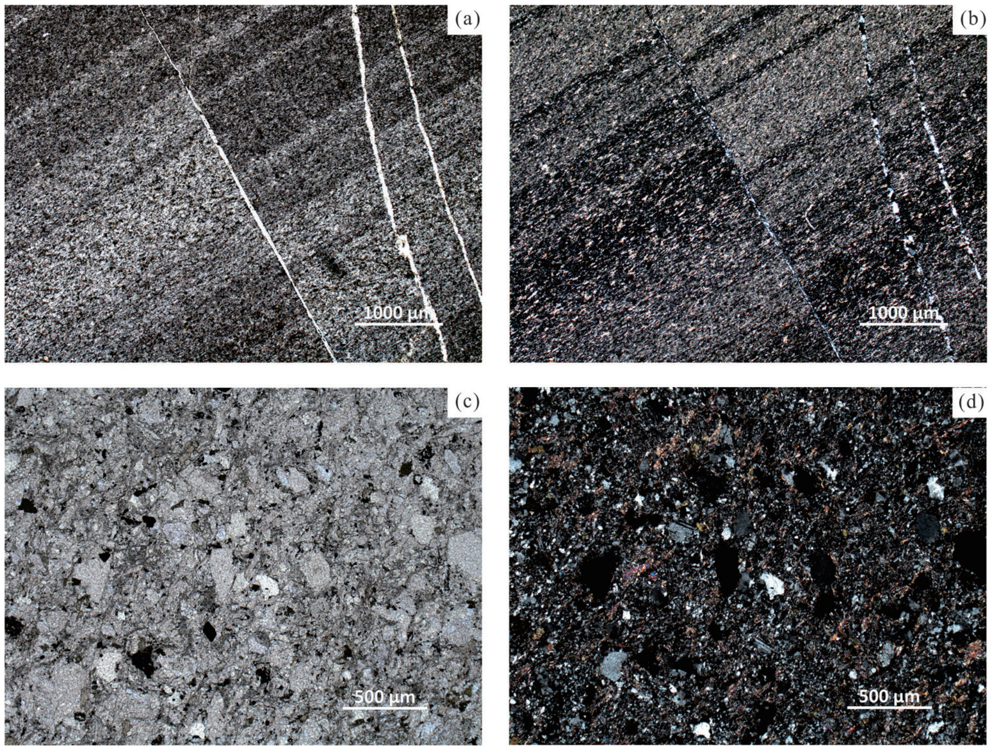

图2 楼前组浅变质流纹岩(a、b)和变余晶屑凝灰岩(c、d)显微照片
Fig. 2 The photomicrographs of Louqian Formation meta-rhyolite and meta-crystal tuff

法测定,烧失量(LOI)通过对样品加热至1000℃后1h称量其重量变化获得,分析误差<5%;微量元素和稀土元素采用等离子体质谱仪(ICP−MS)来测定,标样采用GSR1、GSR2和GSR3,稀土元素采用阳离子交换法分离,含量 $<10\times10^{-6}$ 的分析误差为10%,含量 $>10\times10^{-6}$ 的分析误差<5%。

4　分析结果

4.1　锆石LA−ICP−MS U−Pb年代学

(1)浅变质英安岩

浅变质英安岩(样品:158SM1−3)采自福建明溪县楼前镇,其锆石晶体多呈短柱状自形晶,长轴直径一般100~200μm,锆石阴极发光图像(CL)显示,多数锆石具有明显的震荡环带(图3a)。对20颗锆石进行了U−Th−Pb同位素测定,测得的同位素比值及年龄结果详见表1。

20个测点均位于锆石核部,测得的 $^{206}Pb/^{238}U$ 年龄明显可分为两组:第一组包括4~5、9~11和15~16等7颗锆石,其 ^{232}Th 和 ^{238}U 含量略低,分别为 65×10^{-6}~374×10^{-6} 和 47×10^{-6}~234×10^{-6},$^{232}Th/^{238}U$ 比值为0.34~1.76,除11号和15号测得的 $^{206}Pb/^{238}U$ 年龄为777 Ma和836 Ma外,其余测点的 $^{207}Pb/^{206}U$ 年龄均介于1807~2564 Ma,应该为捕获锆石;第二组包括1~3、6~8、12~14和17~20等13颗锆石,^{232}Th 和 ^{238}U 含量分别为 77×10^{-6}~765×10^{-6} 和 58×10^{-6}~243×10^{-6},$^{232}Th/^{238}U$ 比值为0.58~3.40,获得的 $^{206}Pb/^{238}U$ 年龄较为一致,加权平均值为(729±4)Ma(MSWD=0.31,*n*=13),应该代表了浅变质英安岩的成岩年龄(图3b)。

(2)变余晶屑凝灰岩

该变余晶屑凝灰岩(样品:16CT9−1)采自江西瑞金市黄麟乡,其锆石晶体多呈短柱状自形晶,长轴直径一般100~200 μm,锆石阴极发光图像(CL)显示,多数锆石亦具有明显的震荡环带(图3c)。对46颗锆石进行了U−Th−Pb同位素测定,测得的同位素比值及年龄结果详见表1。

46个测点均位于锆石核部,测得的 $^{206}Pb/^{238}U$ 年龄明显可分为3组:第一组包括3、5~6、8~10、13、15~16、18、20、25、27~31、35~36、38、44和46号等22颗锆石,其 ^{232}Th 和 ^{238}U 含量分别为 54×10^{-6}~475×10^{-6} 和 45×10^{-6}~679×10^{-6},$^{232}Th/^{238}U$ 比值为0.35~1.66,获得的 $^{207}Pb/^{206}U$ 年龄明显偏老,介于1765~2864 Ma,应

表1 楼前组浅变质火山岩LA−ICP−MS锆石U−Th−Pb同位素分析结果

Table 1 LA−ICP−MS U−Th−Pb zircon geochronologic results for Louqian Formation meta−volcanic rocks

点号	Pb/10^{-6}	Th/10^{-6}	U/10^{-6}	Th/U	^{207}Pb/^{206}Pb	1σ	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ	年龄/Ma					
											^{207}Pb/^{206}Pb	1σ	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ
明溪楼前浅变质英安岩(样品:158SM1-3)																
1	19	248	101	2.46	0.0643	0.0017	1.0553	0.0286	0.1189	0.0012	752	56	731	20	724	7
2	11	111	58	1.92	0.0744	0.0028	1.2223	0.0476	0.1189	0.0012	1053	77	811	32	724	8
3	10	81	64	1.27	0.0757	0.0022	1.2522	0.0375	0.1200	0.0012	1086	59	824	25	731	7
4	20	65	47	1.39	0.1105	0.0020	4.6122	0.0907	0.3026	0.0031	1807	33	1751	34	1704	17
5	87	68	200	0.34	0.1513	0.0021	8.2778	0.1268	0.3968	0.0039	2360	24	2262	35	2155	21
6	44	408	243	1.68	0.0653	0.0011	1.0780	0.0200	0.1197	0.0012	785	37	743	14	729	7
7	34	174	225	0.77	0.0728	0.0013	1.2156	0.0222	0.1210	0.0012	1009	35	808	15	736	7
8	16	169	71	2.37	0.0745	0.0021	1.2308	0.0351	0.1198	0.0012	1055	56	815	23	730	7
9	75	74	137	0.54	0.1707	0.0024	10.7922	0.1640	0.4587	0.0044	2564	24	2505	38	2434	24
10	67	75	186	0.40	0.1462	0.0021	6.2719	0.0982	0.3113	0.0033	2302	24	2015	32	1747	18
11	44	374	234	1.59	0.0700	0.0011	1.2349	0.0213	0.1280	0.0013	928	33	817	14	777	8
12	54	765	225	3.40	0.0726	0.0012	1.1887	0.0208	0.1188	0.0012	1003	34	795	14	724	7
13	27	243	160	1.52	0.0764	0.0014	1.2562	0.0239	0.1193	0.0012	1105	36	826	16	726	7
14	20	86	148	0.58	0.0761	0.0015	1.2589	0.0259	0.1199	0.0012	1098	39	827	17	730	7
15	10	87	49	1.76	0.0742	0.0025	1.4228	0.0512	0.1385	0.0016	1046	69	899	32	836	10
16	48	112	103	1.08	0.1227	0.0018	5.9683	0.0923	0.3527	0.0034	1996	26	1971	30	1948	19
17	18	159	94	1.70	0.0647	0.0017	1.0741	0.0292	0.1204	0.0012	765	56	741	20	733	8
18	19	115	109	1.06	0.0773	0.0016	1.2828	0.0280	0.1206	0.0012	1128	42	838	18	734	8
19	12	77	73	1.05	0.0753	0.0020	1.2383	0.0340	0.1193	0.0012	1076	54	818	22	726	7
20	12	79	62	1.27	0.0714	0.0024	1.1752	0.0410	0.1194	0.0012	968	69	789	28	727	8
瑞金黄麟乡变余晶屑凝灰岩(样品:16CT9-1)																
1	28	184	159	1.16	0.0619	0.0013	1.0963	0.0369	0.1288	0.0045	672	44	752	18	781	26
2	25	148	155	0.95	0.0644	0.0015	1.0478	0.0299	0.1181	0.0028	754	247	728	15	720	16
3	86	198	191	1.04	0.1119	0.0016	4.9764	0.0855	0.3220	0.0050	1831	25	1815	15	1800	25
4	28	192	148	1.30	0.0646	0.0013	1.1529	0.0293	0.1293	0.0025	761	43	779	14	784	14
5	183	170	368	0.46	0.1393	0.0017	7.5541	0.2058	0.3925	0.0105	2220	21	2179	24	2135	48
6	85	168	202	0.83	0.1087	0.0016	4.7043	0.0986	0.3137	0.0065	1789	27	1768	18	1759	32
7	33	136	221	0.62	0.0678	0.0017	1.1622	0.0438	0.1233	0.0025	861	56	783	21	750	15
8	31	58	75	0.77	0.1094	0.0021	4.5677	0.1071	0.3025	0.0053	1791	40	1743	20	1703	26
9	56	116	128	0.91	0.1135	0.0020	4.9989	0.1237	0.3196	0.0071	1857	31	1819	21	1788	35
10	22	70	45	1.55	0.1079	0.0021	4.5820	0.1033	0.3081	0.0052	1765	36	1746	19	1731	26
11	42	299	238	1.26	0.0649	0.0013	1.0756	0.0249	0.1202	0.0019	772	43	742	12	732	11
12	37	287	205	1.40	0.0645	0.0016	1.0750	0.0359	0.1205	0.0027	761	51	741	18	733	16
13	307	164	474	0.35	0.1743	0.0022	12.2901	0.2478	0.5103	0.0083	2600	16	2627	19	2658	35
14	88	350	573	0.61	0.0640	0.0011	1.0701	0.0251	0.1216	0.0028	743	42	739	12	740	16
15	21	54	46	1.17	0.1112	0.0024	4.8216	0.1256	0.3157	0.0073	1820	34	1789	22	1769	36
16	323	475	679	0.70	0.1266	0.0017	6.2962	0.1218	0.3610	0.0071	2051	23	2018	17	1987	34
17	47	346	236	1.47	0.0656	0.0015	1.1639	0.0326	0.1285	0.0022	792	49	784	15	779	13
18	129	374	268	1.40	0.1097	0.0017	4.8805	0.1009	0.3231	0.0066	1794	27	1799	17	1805	32
19	61	366	367	1.00	0.0632	0.0012	1.0716	0.0246	0.1232	0.0027	717	46	740	12	749	15
20	61	161	131	1.23	0.1125	0.0020	4.8822	0.1245	0.3149	0.0072	1840	33	1799	22	1765	35
21	92	763	487	1.57	0.0664	0.0011	1.1083	0.0237	0.1215	0.0029	820	34	757	11	739	17
22	49	326	245	1.33	0.0667	0.0013	1.2497	0.0288	0.1357	0.0025	828	45	823	13	821	14
23	81	338	526	0.64	0.0638	0.0014	1.0819	0.0313	0.1230	0.0028	744	51	745	15	748	16
24	39	259	232	1.12	0.0662	0.0014	1.0819	0.0279	0.1185	0.0024	813	44	745	14	722	14
25	56	182	110	1.66	0.1127	0.0021	4.9577	0.1158	0.3199	0.0074	1843	33	1812	20	1789	36
26	57	276	345	0.80	0.0663	0.0012	1.1627	0.0396	0.1270	0.0039	815	37	783	19	771	22
27	76	229	153	1.49	0.1149	0.0022	5.0770	0.1555	0.3198	0.0083	1880	39	1832	26	1789	41
28	194	183	392	0.47	0.1319	0.0021	6.9357	0.1567	0.3812	0.0080	2124	28	2103	20	2082	37
29	262	264	521	0.51	0.1417	0.0019	7.2971	0.1168	0.3729	0.0062	2248	24	2148	14	2043	29
30	46	119	98	1.21	0.1114	0.0017	4.7670	0.1161	0.3093	0.0065	1833	27	1779	20	1737	32

续表1

点号	Pb/10^{-6}	Th/10^{-6}	U/10^{-6}	Th/U	^{207}Pb/^{206}Pb	1σ	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ	年龄/Ma					
											^{207}Pb/^{206}Pb	1σ	^{207}Pb/^{235}U	1σ	^{206}Pb/^{238}U	1σ
31	171	214	311	0.69	0.1445	0.0026	8.1304	0.2099	0.4092	0.0111	2283	36	2246	23	2211	51
32	30	189	181	1.04	0.0671	0.0013	1.0841	0.0295	0.1171	0.0025	840	41	746	14	714	15
33	27	246	138	1.78	0.0657	0.0012	1.0911	0.0257	0.1203	0.0023	794	33	749	13	733	13
34	122	647	780	0.83	0.0678	0.0010	1.0941	0.0254	0.1172	0.0028	861	33	751	12	714	16
35	102	182	246	0.74	0.1126	0.0018	4.8716	0.0959	0.3149	0.0069	1843	28	1797	17	1765	34
36	62	187	127	1.48	0.1142	0.0021	4.9456	0.1195	0.3156	0.0081	1933	32	1810	20	1768	40
37	41	201	260	0.77	0.0662	0.0016	1.1230	0.0295	0.1238	0.0032	813	50	764	14	752	18
38	63	151	137	1.10	0.1193	0.0023	5.4799	0.1265	0.3343	0.0076	1946	29	1897	20	1859	37
39	46	278	290	0.96	0.0659	0.0011	1.0939	0.0314	0.1202	0.0029	1200	35	750	15	732	17
40	82	377	539	0.70	0.0652	0.0010	1.1397	0.0295	0.1267	0.0031	783	31	772	14	769	18
41	47	256	300	0.85	0.0652	0.0012	1.1014	0.0321	0.1222	0.0029	781	38	754	16	743	16
42	28	134	181	0.74	0.0651	0.0015	1.0790	0.0322	0.1200	0.0021	776	53	743	16	731	12
43	54	204	355	0.58	0.0658	0.0013	1.1309	0.0279	0.1246	0.0022	798	36	768	13	757	13
44	65	58	134	0.43	0.1457	0.0027	7.6904	0.1702	0.3831	0.0073	2296	31	2195	20	2091	34
45	72	623	382	1.63	0.0650	0.0010	1.1061	0.0220	0.1234	0.0022	776	31	756	11	750	13
46	393	437	554	0.79	0.2047	0.0031	14.3095	0.3678	0.5075	0.0131	2864	24	2770	24	2646	56

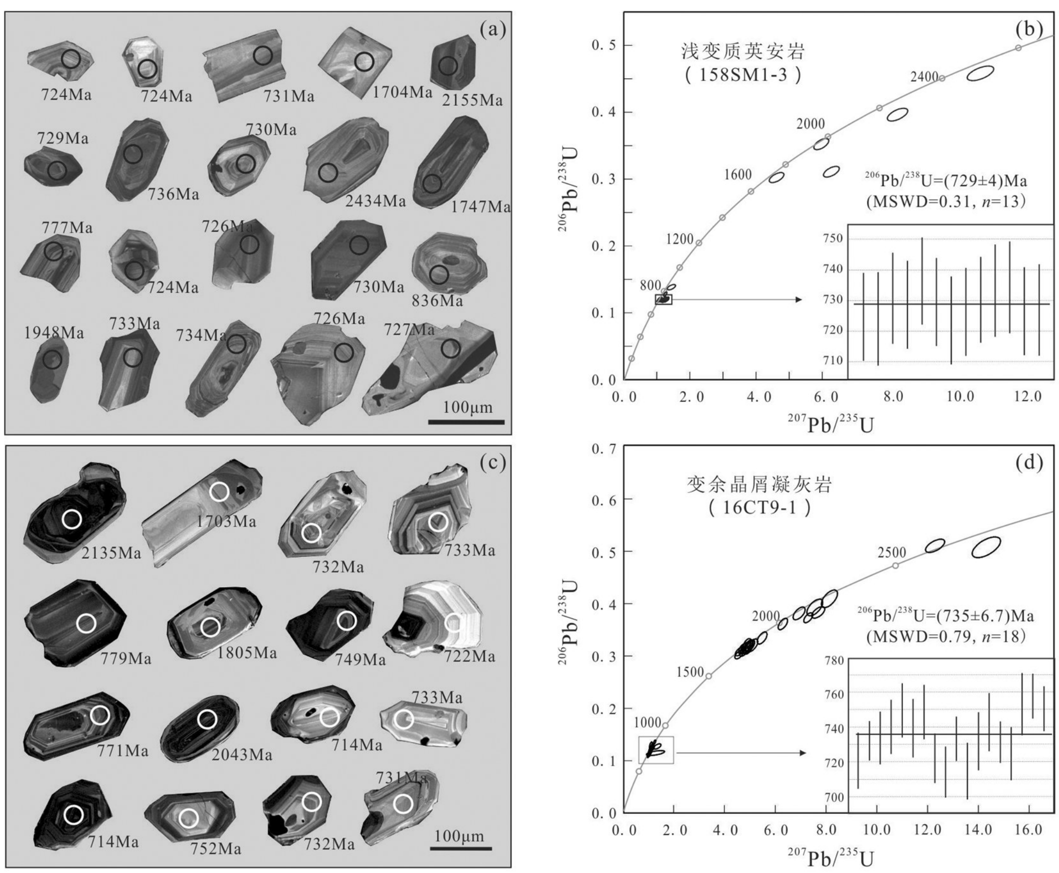

图3 楼前组浅变质英安岩(样品:158SM1−3)和变余晶屑凝灰岩(样品:16CT9−1)典型锆石的阴极发光(CL)图像(a,c)和LA−ICP−MS U−Pb年龄谐和图(b,d)

Fig. 3 Zircon CL images (a,c) and LA−ICP−MS zircon U−Pb concordia diagrams (b,d) of Louqian Formation meta−dacite (sample: 158SM1−3) and meta−crystal tuff (sample: 16CT9−1)

该为捕获锆石;第二组包括1、4、17、22、26和40号等6颗锆石,^{232}Th和^{238}U含量介于184×10^{-6}~377×10^{-6}和148×10^{-6}~539×10^{-6},$^{232}Th/^{238}U$比值为0.70~1.47,获得的$^{206}Pb/^{238}U$年龄稍稍偏老,介于769~821 Ma,可能亦为捕获锆石;第三组锆石包括剩余的18颗锆石,^{232}Th和^{238}U含量介于134×10^{-6}~763×10^{-6}和138×10^{-6}~780×10^{-6},$^{232}Th/^{238}U$比值为0.58~1.78,其$^{206}Pb/^{238}U$年龄较为一致,加权平均值为(735 ± 6.7) Ma (MSWD=0.79,n=18)(图3d),代表了变余晶屑凝灰岩的成岩年龄。

4.2 岩石地球化学特征

楼前组浅变质火山岩13件样品的分析结果(表2)表明,它们的SiO_2含量介于65.22%~74.54%,富碱(Na_2O+K_2O=4.88%~10.19%,平均为7.78%),Al_2O_3含量亦相对较高(11.05 %~16.80%,平均为14.35%),ANK值和A/CNK值分别为1.23~1.78和0.98~1.57,总体显示过铝质的特征,在ANK−ACNK判别图解上,除样品158SM1−8外,其余12个样品均落入强过铝质花岗岩区域(图略);贫CaO、MgO和FeO^T(分别为0.30%~2.27%、0.48%~1.72%和1.63%~4.59%)。在TAS图解上,13件样品基本落入粗面(英安)岩−流纹岩区域(图4a),其中3件样品落入粗面(英安)岩区域,另有10件样品落入流纹岩区域,反映岩浆是往高硅低碱的方向演化。在SiO_2-K_2O图解上基本位于高钾钙碱性系列区域(图4b)。

所有样品具有较一致的微量元素地球化学行为,均相对富集大离子亲石元素(Ba、Rb等)而亏损高场强元素(Nb、Ta、Ti、P等),在原始地幔标准化的微量元素蛛网图上表现出强烈的Nb−Ta、Ti和P的负异常(图5a),显示岛弧岩浆岩的地球化学特征。它们的稀土总量∑REE介于122.82×10^{-6}~296.26×10^{-6},LREE/HREE比值介于8.42~14.56;$(La/Sm)_N$为3.90~5.31,$(Gd/Lu)_N$为0.86~1.65,$(La/Yb)_N$=7.89~19.67,说明其轻稀土分异较强、重稀土分异弱、轻重稀土元素分异明显,在球粒陨石标准化的稀土元素配分图上显示为右倾的轻稀土富集型(图5b)。各样品Eu均呈现明显的负异常(δEu=0.33~0.62)。

5 讨 论

5.1 岩石成因与构造环境

楼前组浅变质火山岩富Al_2O_3(平均为14.35%)、富K_2O(平均为4.07%)和Na_2O(平均为3.71%)而低FeO^T(平均为2.75%)、MgO(平均为0.98%),FeO^T/MgO(2.15~3.59)和$Mg^\#$(36.9~48.5)值低;ANK值和A/CNK值均较高,属过铝质岩浆岩,与典型的A型或I型花岗岩差异较大。微量元素方面,岩石的Nb/Ta和Nd/Th值分别为12.44~17.28和1.52~3.51,接近壳源岩石(Nb/Ta=12,Nd/Th=3)而与幔源岩石(Nb/Ta=22,Nd/Th>15)有较大差别(Bea et al.,2001);Ti /Zr和Ti /Y值分别为6.08~10.37和68.51~154.71,全部落在壳源岩石Ti /Zr和Ti /Y值范围内(Ti /Zr<30,Ti /Y< 200);在Rb−Th和Rb−Y判别图解上,样品沿S型花岗岩演化趋势展布(图6),意味着楼前组英安质−流纹质火山岩应该为S型火山岩。

楼前组浅变质火山岩具有弧岩浆岩的地球化学特征,如富集大离子亲石元素而亏损高场强元素;其Zr/Nb值在16.65~23.33,落在弧火山岩的Zr/Nb值范围内(Zr/Nb=0~60),在(Y+Nb)−Rb和Y−Nb构造环境判别图解中,亦基本落入火山弧花岗岩区域(图7a、b)。楼前组浅变质火山岩的Th/Ta值为12.94~16.93,与活动大陆边缘火山岩特征一致(Th/Ta=6~20)。在Ta/Yb−Th/Yb和Yb−Th/Ta构造环境判别图解上,均落入活动大陆边缘区域内(图7c、d)。结合楼前组的大地构造位置推断,其应该形成在与俯冲作用有关的活动大陆边缘。

5.2 南华纪中酸性陆缘弧岩浆活动带

本次测得的江西瑞金黄麟乡和福建明溪楼前两地楼前组浅变质火山岩的时代与前人报道的长汀张地((730.1±7)Ma)、明溪盖洋((734.7±3.3)Ma)等地的楼前组浅变质火山岩时代在误差范围内基本一致(表3),意味着南平—宁化构造带南华纪~730 Ma的火山活动自福建明溪地区延伸至了江西省境内,这对于研究南平—宁化构造带在江西省境内的延伸提供了重要依据。

本次研究也表明,福建明溪楼前和江西瑞金黄麟乡两地的楼前组浅变质火山岩为典型的活动大陆边缘弧岩浆岩,这亦与Jiang et al.(2018)报道的明溪盖洋地区的楼前组浅变质火山岩的构造环境一致。另据福建省地质调查研究院(2016a)❶总结,楼前组之上浅变质沉积岩系形成于快速且动荡的沉积环境,地球化学特征与大陆岛弧或活动大陆边缘

表2 楼前组浅变质火山岩主量元素(%)、稀土元素和微量元素丰度(10^{-6})

Table 2 Major (%) and trace element (10^{-6}) data of Louqian Formation metamorphic volcanic rocks

样品号	16CT7-1	16CT9-1	16CT10-2	16CT10-3	16CT10-4	158SM-1-1	158SM-1-2	158SM-1-3	158SM-1-4	158SM-1-5	158SM-1-7	158SM-1-8	158SM-1-10
采样点	江西瑞金黄麟乡					福建明溪楼前							
SiO_2	72.25	71.63	65.58	70.25	71.52	70.62	65.22	69.94	70.38	74.54	72.55	71.15	67.74
TiO_2	0.42	0.40	0.42	0.47	0.36	0.35	0.59	0.28	0.39	0.29	0.31	0.31	0.48
Al_2O_3	13.45	14.26	16.80	14.02	14.89	15.01	15.35	15.89	15.12	11.05	13.29	13.29	14.19
Fe_2O_3	1.18	2.26	2.42	1.72	2.19	1.4	2.97	0.98	1.41	1.48	1.08	1.29	0.57
FeO	2.34	0.83	1.29	1.8	0.54	0.86	1.92	0.75	0.97	1.29	0.75	0.93	2.62
MnO	0.05	0.05	0.05	0.09	0.04	0.06	0.11	0.05	0.07	0.1	0.05	0.09	0.1
MgO	1.04	1.03	1.22	1.06	0.85	0.95	1.72	0.76	0.96	1.09	0.48	0.68	0.88
CaO	0.40	0.50	0.30	1.12	0.33	0.91	1.64	1.09	1.51	2.27	1.57	1.95	1.42
Na_2O	1.56	4.30	1.92	4.18	4.24	4.23	3.67	5.56	4.93	1.61	3.65	3.79	4.56
K_2O	4.87	3.89	8.27	3.45	4.22	3.98	4.3	3.51	2.62	3.27	3.73	3.53	3.31
P_2O_5	0.06	0.09	0.1	0.11	0.06	0.07	0.11	0.06	0.09	0.09	0.08	0.07	0.12
LOI	2.35	1.1	1.78	2.04	1.37	1.33	1.74	1.04	1.26	2.41	2.34	3.01	3.07
ALK	6.43	8.19	10.19	7.63	8.46	8.21	7.97	9.07	7.55	4.88	7.38	7.32	7.87
FeO^T	3.40	2.86	3.47	3.35	2.51	2.12	4.59	1.63	2.24	2.62	1.72	2.09	3.13
FeO^T/MgO	3.27	2.78	2.84	3.16	2.95	2.23	2.67	2.15	2.33	2.40	3.59	3.07	3.56
$Mg^{\#}$	39.1	43.0	42.5	39.9	41.5	48.5	44.0	49.4	47.4	46.6	36.9	40.6	37.1
ANK	1.71	1.26	1.38	1.32	1.29	1.33	1.43	1.23	1.38	1.78	1.32	1.32	1.28
ACNK	1.57	1.17	1.33	1.11	1.22	1.16	1.12	1.06	1.10	1.07	1.03	0.98	1.04
Li	71.9	22.7	28.6	39.2	19.4	23.2	45.9	18.8	70.5	27.2	17.6	13.7	76.5
Be	3.61	2.52	3.27	2.38	2.65	2.5	2.23	2.49	1.67	1.84	1.86	1.95	2.12
Cr	28.2	11.9	8.38	11.1	9.73	5.16	23.5	6.26	6.26	8.7	6.34	6.45	14.2
Co	7.95	5.32	5.14	7.04	3.2	3.83	11.3	3.15	4.53	4.79	1.67	2.59	6.76
Ni	15.9	4.84	5.37	4.6	3.3	5.09	11.6	4.96	6.06	8.14	3.52	4.39	8.45
Cs	14.3	3.04	7.06	6.22	4.28	4.29	5.16	2.55	2.57	6.78	6.7	8.28	6.04
V	36.9	41.5	25	41.3	30	17.5	68.7	14	24.5	24.7	21	21.6	36.3
Rb	163	116	252	110	125	116	125	95.2	74.6	111	116	116	91.1
Ba	843	1043	1289	874	1094	741	956	660	813	963	655	709	963
Th	15.6	13.5	22.9	13.2	13.9	15.4	16.8	17.5	12.7	8.49	11.2	12.4	12
U	2.67	2.21	2.78	2.63	2.49	1.71	2.67	2	2.21	0.9	1.35	1.7	1.82
Pb	21.2	22.1	6.9	26.8	15.4	23.8	31.2	20.4	20.4	15.4	11.2	16.3	12.9
Nb	15.8	13.1	19.4	12.9	12.3	14.4	16.2	14.9	12.6	8.67	12.7	12.5	14
Ta	1.14	0.91	1.56	1.02	0.98	0.96	1.1	1.06	0.75	0.54	0.8	0.82	0.81
Sr	135	143	101	200	132	155	100	189	186	172	72.3	96.6	133
Zr	263	282	344	256	296	282	336	276	294	173	283	257	284
Hf	7.36	7.24	10.7	7.34	8.46	8.23	8.54	8.2	7.96	4.89	7.64	7.22	7.3
Ti	2562	2420	2326	2654	1995	2098	3537	1679	2338	1739	1858	1858	2878
Sc	7.73	7.09	8.97	8.27	6.79	5.86	9.39	5.83	6.2	5.73	5.83	6.16	6.7
Y	28.4	22.3	26.7	19.9	16.7	24.4	24.9	24.5	22.3	21.2	18.3	23.1	18.6
P	262	393	437	480	262	306	480	262	393	393	349	306	524
K	40472	32328	68728	28671	35070	33076	35735	29170	21774	27175	30998	29336	27508
La	52.9	48.5	69	56.8	27.5	66.5	61.6	64.5	56.9	38.4	43.6	46.9	56.5
Ce	102	116	132	102	50.8	115	110	112	105	72.6	76.2	85	102

续表2

样品号	16CT7-1	16CT9-1	16CT10-2	16CT10-3	16CT10-4	158SM-1-1	158SM-1-2	158SM-1-3	158SM-1-4	158SM-1-5	158SM-1-7	158SM-1-8	158SM-1-10
采样点	江西瑞金黄麟乡					福建明溪楼前							
Pr	11.3	10	14.4	11.4	5.92	12.9	12	12.2	11.6	8.25	8.56	9.26	10.8
Nd	38.4	31.9	47.4	37.2	21.1	47.4	41.4	44.1	44.6	29.6	29.6	32.3	39.1
Sm	7.09	6.04	9.4	6.91	3.95	8.63	7.84	8.14	7.59	6.35	5.89	6.68	6.96
Eu	0.92	0.94	1.13	1.24	0.51	1	1.21	0.79	1.14	0.94	0.8	0.97	1.2
Gd	6.11	4.74	6.59	5.08	2.98	6.25	5.73	6.11	5.41	4.4	4.54	5.49	4.46
Tb	0.93	0.75	1.04	0.79	0.53	0.93	0.92	0.92	0.81	0.7	0.69	0.85	0.68
Dy	5.5	4.45	6.01	4.38	3.39	5.33	5.2	5.22	4.61	4.13	3.91	4.56	3.91
Ho	1.14	0.95	1.12	0.8	0.66	1	1.01	0.98	0.88	0.84	0.73	0.94	0.75
Er	3.1	2.64	3.57	2.43	2.22	3.02	3.16	3.05	2.81	2.62	2.36	3.01	2.35
Tm	0.52	0.42	0.49	0.32	0.33	0.41	0.45	0.44	0.4	0.37	0.33	0.42	0.32
Yb	3.04	2.46	3.48	2.31	2.5	2.63	2.86	2.95	2.68	2.31	2.3	2.77	2.06
Lu	0.51	0.4	0.58	0.38	0.43	0.48	0.47	0.53	0.46	0.39	0.39	0.48	0.34
LREE	212.61	213.38	273.33	215.55	109.78	251.43	234.05	241.73	226.83	156.14	164.65	181.11	216.56
HREE	20.85	16.81	22.88	16.49	13.04	20.05	19.80	20.20	18.06	15.76	15.25	18.52	14.87
∑REE	233.46	230.19	296.21	232.04	122.82	271.48	253.85	261.93	244.89	171.90	179.90	199.63	231.43
LREE/HREE	10.20	12.69	11.95	13.07	8.42	12.54	11.82	11.97	12.56	9.91	10.80	9.78	14.56
δEu	0.42	0.52	0.42	0.61	0.44	0.40	0.53	0.33	0.52	0.52	0.46	0.48	0.62
$(Gd/Yb)_N$	1.66	1.59	1.57	1.82	0.99	1.97	1.66	1.71	1.67	1.58	1.63	1.64	1.79
$(La/Sm)_N$	4.82	5.18	4.74	5.31	4.49	4.97	5.07	5.12	4.84	3.90	4.78	4.53	5.24
$(Gd/Lu)_N$	1.48	1.46	1.40	1.65	0.86	1.61	1.51	1.42	1.45	1.39	1.44	1.41	1.62
$(La/Yb)_N$	12.48	14.14	14.22	17.64	7.89	18.14	15.45	15.68	15.23	11.92	13.60	12.14	19.67
Nb/Ta	13.86	14.40	12.44	12.65	12.55	15.00	14.73	14.06	16.80	16.06	15.88	15.24	17.28
Nd/Th	2.46	2.36	2.07	2.82	1.52	3.08	2.46	2.52	3.51	3.49	2.64	2.60	3.26
Ti /Zr	9.74	8.58	6.76	10.37	6.74	7.44	10.53	6.08	7.95	10.05	6.57	7.23	10.13
Ti /Y	90.21	108.52	87.12	133.37	119.46	85.99	142.05	68.51	104.85	82.01	101.55	80.45	154.71
Zr/Nb	16.65	21.53	17.73	19.84	24.07	19.58	20.74	18.52	23.33	19.95	22.28	20.56	20.29
Th/Ta	13.68	14.84	14.68	12.94	14.18	16.04	15.27	16.51	16.93	15.72	14.00	15.12	14.81

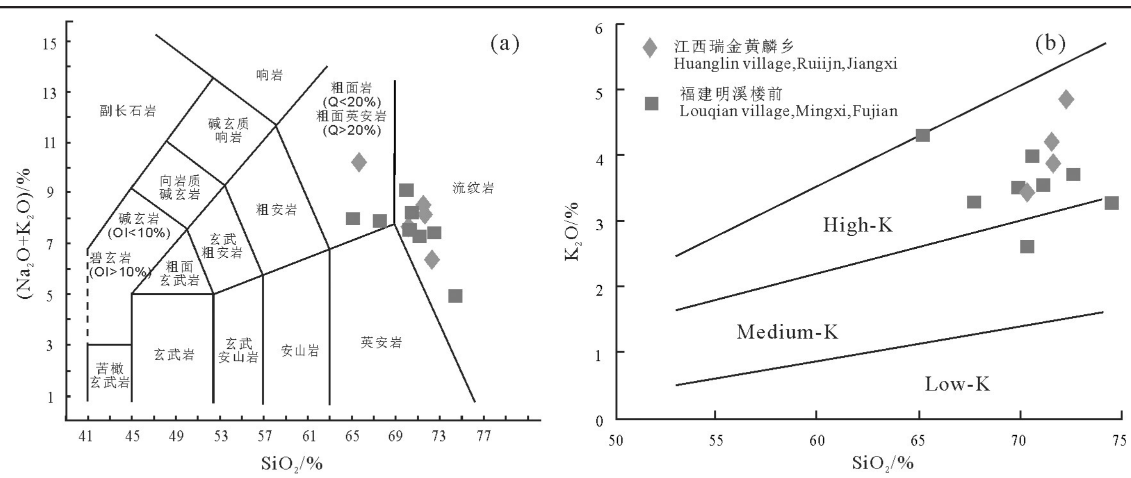

图4 楼前组浅变质火山岩的TAS图解（a，底图据Middlemost, 1994）和SiO_2−K_2O判别图解（b，底图据Peccerillo and Taylor,1976）
Fig.4 TAS diagram (a, after Middlemost, 1994) and SiO_2− K_2O diagram (b, after Peccerillo and Taylor,1976) of the Louqian Formation meta-volcanic rocks

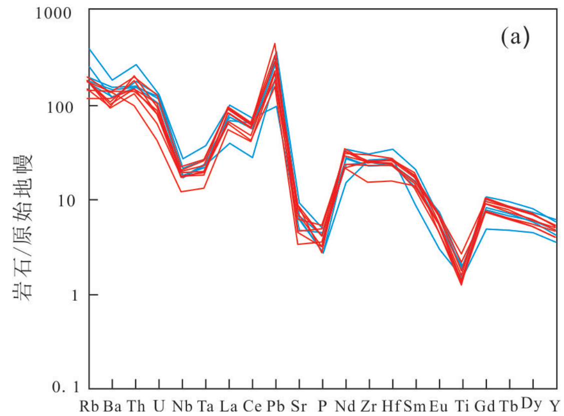

图5 楼前组浅变质火山岩微量元素蛛网图(a)和稀土元素配分模式图(b)
(球粒陨石和原始地幔的值引自Sun and McDonough, 1989)
Fig.5 Primitive-mantle-normalized trace element spider diagrams (a) and chondrite-normalized rare earth element (REE) patterns (b) for meta-volcanic rocks from the Louqian Formation (normalization factors after Sun and McDonough,1989)

的杂砂岩特征相近。故此推断,区域~730 Ma的火山活动为陆缘弧岩浆活动,形成了沿南平—宁化构造带展布、自福建省明溪地区南南西向延伸至江西省境内的南华纪中酸性陆缘弧火山岩带。

另外,根据胡宗良等(2002)报道的明溪林地(图1,表3)楼前组浅变质流纹岩成岩时代((713±7) Ma)推测,该期陆缘弧岩浆活动可能持续到713 Ma左右甚至更晚。这也意味着,730~713 Ma,南平—宁化—瑞金一线并非前人认为的南华纪裂谷环境而是南华纪活动大陆边缘。

5.3 南、北武夷碰撞拼合时限

南、北武夷碰撞拼合时代与过程,是研究武夷造山带构造演化的关键问题。目前主要有两种观点:一种观点认为南、北武夷之间在新元古代时碰撞拼合形成统一的武夷地块,随后发生裂解并沿南平—宁化一线形成裂谷,响应于全球Rodinia超大陆的聚合与之后广泛的裂解(韦德光等,1997;黄家龙,2001;张庆龙等,2008;李霞,2013);另一种观点认为二者的碰撞拼合时间可能在加里东期(王培宗等,1993;边效曾等,1993;Jiang et al.,2018),且由于南平—宁化构造-岩浆带的存在与活动,使得闽西北和闽西南地区从新元古代至早中生代,无论是沉积建造、岩浆活动、变质作用或是区域构造特征等方面都有明显差别。

本次研究查明,735~713 Ma时沿南平—宁化—瑞金一线仍存在强烈的陆缘弧岩浆活动,意味着南、北武夷迟至南华纪时尚未碰撞拼合形成统一的武夷地块,进一步支持了南、北武夷并非在新元古

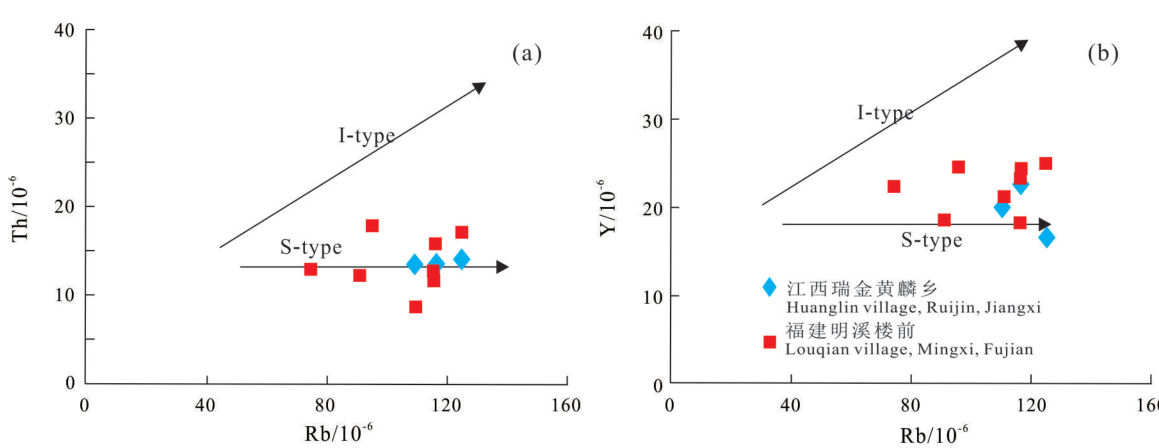

图6楼前组浅变质火山岩Rb-Th和Rb-Y判别图解(底图据Allegre and Minster, 1978)
Fig.6 Rb versus Th(a) and Rb versus Y(b) plots for meta- volcanic rocks from the Louqian Formation (after Allegre and Minster, 1978)

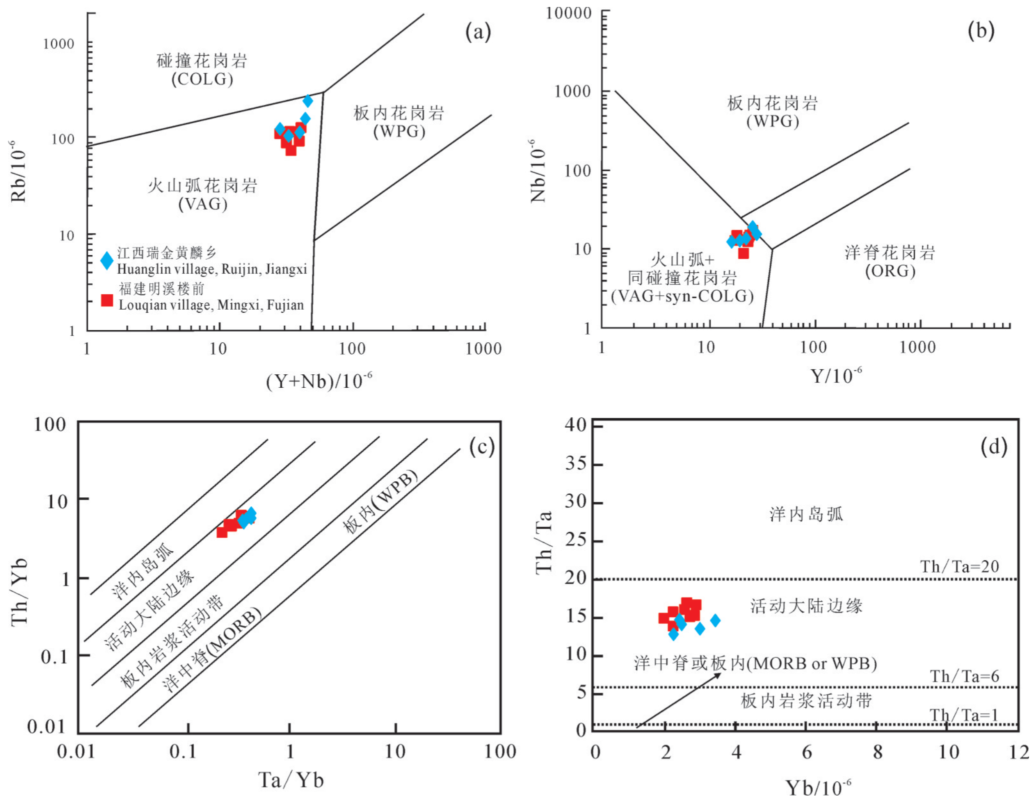

图7 楼前组浅变质火山岩(Y+Nb)−Rb(a, 据Pearce et al., 1984)、Y−Nb(b, 据Pearce et al., 1984)、Ta/Yb−Th/Yb(c, 底图据Pearce, 1983)和Yb−Th/Ta(d, 底图据Gorton and Schandl, 2000)判别图解

Fig. 7 (Y+Nb)−Rb (a, after Pearce et al., 1984), Y versus Nb(b, after Pearce et al., 1984), Ta/Yb−Th/Yb (c, after Pearce, 1983) and Yb−Th/Ta (d, after Gorton and Schandl, 2000) tectonic discrimination diagrams for meta−volcanic rocks from the Louqian Formation

代碰撞拼合的认识。此外,前人研究表明,南、北武夷地区均广泛存在泛非期的碎屑/捕获/继承锆石(Yu et al.,2008; Wang et al.,2010; Li et al.,2014)记录,近期Li et al.(2017)又在福建省政和县发现了泛非期变质的角闪石岩(变洋岛玄武岩),均表明武夷地区可能经历了泛非期造山事件,可能暗示南、北武夷的碰撞拼合即是在泛非期。

5.4 “华夏古陆”的性质

1924年,美国人葛利普(Grabau)在《Stratigraphy of China》一书中,首次提出了“华夏古陆”的概念,认为中国东南部在早古生代(包括震旦纪)为一古陆区,主要分布于现今粤闽中东部和浙南东部、经东海延达日本东北部海域(Grabau,1924)。水涛、徐步台等(1987,1988)通过对浙闽变质岩的研究,提出了华夏古陆基底的双层结构模式,在以后的研究中不断得到证实和发展(李曙光等,1996;李献华等,1998;许德如等,2001;胡宗良等,2003;周新民,2003;Li et al.,2005;覃小锋等,2006;沈渭洲,2006 ;Wan et al., 2007)。近10余年来,全球掀起Rodinia超大陆研究的热潮,也再次引发了对“华夏古陆”的

表3 楼前组浅变质火山岩年代学数据统计

Table 3 Geochronological data for Louqian Formation metamorphic volcanic rocks

岩性	采样地点	测试方法	测试结果/Ma	文 献
变质流纹岩	明溪林地	单颗粒锆石U−Pb稀释法	713±7	胡宗良等,2002
变质流纹岩	长汀张地	锆石LA−ICP−MS U−Pb法	730.1±7	福建省地质调查研究院,2016b(未发表资料)❷
变流纹岩	明溪盖洋	锆石LA−ICP−MS U−Pb法	734.7±3.3	Jiang et al., 2018
浅变质英安岩	明溪楼前	锆石LA−ICP−MS U−Pb法	729±4	本次研究
变晶屑凝灰岩	瑞金黄麟	锆石LA−ICP−MS U−Pb法	735±6.7	本次研究

研究,越来越多的人认为华南存在一个主要由古元古代和中元古代地壳组成的变质基底,称“华夏陆块”或“华夏地块”等,只是在与扬子克拉通碰撞后又裂解了(陈毓川等,1995;Li et al.,1996,1999,2002;张业明等,1997;陈旭和戎嘉余,1999;李献华等,1999;王剑,2000;马振东等,2000;葛文春等,2001;王德滋等,2003;丘元禧等,2006;沈渭洲,2006;章邦桐等,2006;舒良树,2006;覃小锋等,2006;于津海等,2006,2007)。

然而,“华夏古陆”自提出以来,其性质及其演化长期以来仍存在较大争议。随着高精度锆石测年技术的发展,许多被认为是古、中元古代的地层,如万全岩群、马面山岩群、龙泉岩群等的时代,都上提至新元古代甚至寒武纪(张祥信,2006;Wan et al.,2007;Li et al.,2010;徐先兵等,2010;任纪舜等,2016;Yang et al.,2019),陈蔡岩群被认定为加里东期的俯冲增生杂岩(赵希林等,2018;Zhao et al.,2019),意味着所谓的“华夏古陆”可能并不存在古、中元古代或者更古老的陆核。不少研究者认为“华夏古陆”应为加里东期或者中生代的造山带(孙云铸,1954;许靖华等,1987;任纪舜等,2016),如任纪舜等(2016)将武夷地区作为加里东造山带的核心地带;亦有部分研究者提出包括华夏在内的华南长期处于多岛洋(陈海泓和肖文交,1998;殷鸿福等,1999)或一系列沟弧盆(郭令智等,1980;潘桂堂等,2016)的构造格局,强调华南存在多个微板块或块体并经历多块体拼合形成了统一的华南大陆。本次厘定南华纪晚期时华夏地块内部仍存在强烈的弧岩浆活动,说明此时区域存在南、北武夷两个块体,因而并不存在统一的前南华纪结晶基底。

6 结 论

(1)福建明溪楼前和江西瑞金黄麟乡两地楼前组浅变质火山岩的LA-ICP-MS锆石U-Pb年龄分别为(729±4)Ma和(735±6.7)Ma,形成于活动陆缘环境,显示弧岩浆岩的地球化学特征。

(2)南平—宁化—瑞金一线发育北东东向展布的735~713 Ma陆缘弧岩浆岩,说明其为南华纪活动大陆边缘,暗示此时的南、北武夷之间尚未发生碰撞拼合形成统一的武夷地块,而华夏地块不存在统一的前南华纪结晶基底。

致谢:中国地质调查局天津地质调查中心郝爽工程师在锆石U-Pb同位素测试中提供了帮助,在此表示衷心的感谢。

致谢:

❶福建省地质调查研究院.2016. 福建省地质志[R].

❷福建省地质调查研究院. 2016. 1∶5万长汀县、南岩、策田、濯田幅区域地质调查报告[R].

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