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云开池垌志留纪辉长岩体的年代学、地球化学特征及构造意义

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摘要：华南陆块早古生代的构造属性是华南地质研究争论的焦点，主要有洋－陆俯冲/碰撞和陆内构造两种观点之争.而华南陆块早古生代岩浆岩的报道以花岗质岩石为主，对构造指示意义更为明确的同期镁铁质岩浆岩则研究较少，且对已发现的少量早古生代镁铁质岩浆岩的岩石成因也颇具争议.为了更好地限定华南早古生代的构造属性，对云开地区新近识别出的池垌辉长岩体开展了详细的野外地质、年代学和地球化学研究.其SIMS锆石U-Pb年代学测试得到其$^{206}Pb/^{238}U$加权平均年龄为433.9±1.5 Ma，代表其结晶年龄.样品具较低的SiO_2含量（47.81%～48.83%），高的MgO含量（13.02%～14.65%）、Cr含量（278×10^{-6}～356×10^{-6}）和Ni含量（120×10^{-6}～184×10^{-6}），富集大离子亲石元素、亏损高场强元素.$(^{87}Sr/^{86}Sr)_i$＝0.708 5～0.710 7，$\varepsilon_{Nd}(t)$＝－6.0～－8.2，显示EMⅡ型富集地幔的Sr-Nd同位素特征.结合区域Lu-Hf同位素、古生物、古水流等地质资料，云开地区志留纪时期发育一个受古老俯冲交代作用影响的地幔楔，该地幔楔源区在华南广西运动期间才受到热扰动而部分熔融.认为池垌辉长岩是在早古生代华南陆内造山后的伸展背景下由古老俯冲交代地幔楔熔融而成的产物.

关键词：华南陆块；云开地块；早古生代；池垌辉长岩；陆内造山；地球化学.
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Geochronological and Geochemical Constraints of Chidong Silurian Gabbroic Pluton in Yunkai Domain and Its Tectonic Implications

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Abstract: The geodynamic mechanisms of the Early Paleozoic orogeny in the South China block (SCB) remain highly debated, and two major models involving subduction-collision orogeny and intra-continental orogeny have been proposed. The Early Paleozoic granitic rocks are widely developed in the eastern SCB and the synchronous mafic rocks have recently been reported. However, the petrogenesis of these Early Paleozoic mafic rocks are still controversial, thus hindering our understanding for the Early Paleozoic tectonic setting. In this study, it presents new petrographic, geochronological and geochemical data for the Chidong gabbroic pluton in the Yunkai domain. The representative sample for the gabbric pluton yields a SIMS zircon U-Pb age of 433.9±1.5 Ma (MSWD＝0.18). They have SiO_2 of 47.81%－48.83%, MgO of 13.02%－14.65%, Cr of 278×10^{-6}－356×10^{-6} and Ni of 120×10^{-6}－184×10^{-6}. They are enriched in large ion lithophile elements with significantly negative Nb-Ta and Ti anomalies. These samples show EMⅡ-like geochemical affinities with high initial $^{87}Sr/^{86}Sr$ ratios (0.708 5 to 0.710 7) and low $\varepsilon_{Nd}(t)$ values (－6.0 to －8.2), suggestive of derivation from a paleosubduction-modified wedge beneath the Yunkai Do-

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main. The wedge was undisturbed until Silurian and the Kwangsian igneous rocks in the SCB were associated with the intra-continental orogenism rather than the subduction and subsequent collision.

Key words: South China block; Yunkai Domain; Chidong gabbroic pluton; intra-continental orogeny; geochemistry.

0　引言

华南陆块由扬子地块和华夏地块在新元古代沿江南造山带拼合而成(Zhao and Cawood, 1999, 2012; Li *et al.*, 2002, 2008; Wang and Li, 2003; Wang *et al.*, 2005, 2006, 2007a; Zhou *et al.*, 2009; 张玉芝等, 2011; Zhang *et al.*, 2012a; 张国伟等, 2013; Yao *et al.*, 2015; 张玉芝等, 2015). 对于拼合之后华南陆块早古生代的构造属性前人做了部分研究(Guo *et al.*, 1989; 杨树锋等, 1995; 殷鸿福等, 1999; 舒良树等, 2008), 发现华南普遍发育泥盆系与下伏地层的角度不整合、寒武系和奥陶系发生强烈褶皱(徐克勤等, 1960; 任纪舜, 1964, 1990; Zhao *et al.*, 1996; 舒良树等, 2008; Li *et al.*, 2010; 张国伟等, 2013; 夏炎, 2015; Yao *et al.*, 2015), 表明华南拼合之后早古生代存在一次强烈的构造－岩浆事件, 本文沿用"广西运动"名称代表导致华南腹地泥盆纪与前泥盆纪变形地层间角度不整合的构造运动(Ting, 1929; 陈旭等, 2010; Wang *et al.*, 2011).

对于广西运动的构造属性, 目前主要有两种观点. 一些学者认为在新元古代晚期华南陆块发生裂解, 而后在广西运动期发生洋－陆俯冲/碰撞 (Zhang *et al.*, 2015b). 另外一些学者则认为华南陆块自晋宁期碰撞之后, 即进入内硅铝壳发育阶段, 为一个陆内构造属性(Wang *et al.*, 2013b; Zhang *et al.*, 2015a).

总结前人研究, 华南早古生代的岩浆岩主要为花岗岩类, 出露于安化－罗城断裂以东, 且以 440～390 Ma 的黑云母花岗岩等过铝质花岗岩为主(徐克勤等, 1960; 任纪舜, 1990; Zhao and Cawood, 1999, 2012; Li *et al.*, 2002, 2009; Wang *et al.*, 2007b, 2013b; 舒良树等, 2008; Shu *et al.*, 2008; 张爱梅等, 2010; Zhang *et al.*, 2012b; Charvet, 2013; 夏炎, 2015; Zhao, 2015; 徐文景, 2017). 基性岩是研究中下地壳和岩石圈地幔岩浆作用的理想样品, 研究基性岩成因可对其构造背景提供明确的指示意义. 云开地区志留纪辉长岩的研究对厘定华南广西运动构造属性具有重要意义. 此外, 对华南陆块早古生代基性岩浆作用同样认识不足且争议犹在(舒良树等, 2008; 舒良树, 2012; 覃小锋等, 2013; 易立文等, 2014; Yao *et al.*, 2015; 周岱等, 2017a), 如 Wang *et al.*(2013b)和 Zhang *et al.*(2015a)认为华南早古生代基性岩是古老俯冲交代的岩石圈地幔在早古生代部分熔融的产物; 彭松柏等(2006a)则认为华南早古生代基性岩是华南新元古代－早古生代洋盆闭合过程中蛇绿混杂岩体的一部分; Zhang *et al.*(2015b)认为华南早古生代基性岩是陆－陆碰撞造山过程的产物. 本文对云开地区最近识别出的池垌辉长岩体开展了详细的年代学和地球化学分析, 讨论了池垌辉长岩的成因和大地构造背景, 为进一步理解云开地区早古生代构造背景提供了重要启示.

1　地质背景与样品描述

华南陆块是中国重要的地质单元, 北部以秦岭－大别－苏鲁造山带为界, 西部以龙门山断裂为界, 西南部以哀牢山－红河－松马缝合带为界. 华南陆块由西北部的扬子地块和东南部的华夏地块沿江南造山带拼合而成. 拼合后的华南陆块的岩浆作用主要以中酸性岩浆为主. 华夏地块新元古代岩浆岩主要出露一系列的蛇绿岩、镁铁质－超镁铁质岩、花岗岩类以及裂谷相关的双峰式火山岩(夏炎, 2015). 华夏地块早古生代的岩浆作用以过铝质花岗岩为主, 集中在武夷－云开地区(Shu *et al.*, 2008; Charvet, 2013). 近年来, 云开地区陆续有少量早古生代辉长质岩体的报道(彭松柏等, 2006a; Wang *et al.*, 2013b; Yao *et al.*, 2014; 夏炎, 2015; 徐文景, 2017; 周岱等, 2017b). 华夏地块中生代岩浆作用较为强烈, 以过铝质的花岗质岩浆大范围侵入或喷出为主. 岩性主要为花岗岩、流纹岩、英安岩等, 伴生有少量的安山岩和玄武岩(Lapierre *et al.*, 1997; 俞云文和徐步台, 1999).

云开地区位于华夏地块西部的两广交界处, 大致包括广东郁南、罗定、信宜地区和广西梧州、容县、北流、陆川等地区. 区域主要构造格架由吴川－四会断裂、分界断裂、信宜－廉江断裂、黎村－文地断裂、陆川－岑溪断裂和博白－梧州断裂等多条 NE-SW 向的断裂控制(Wang *et al.*, 2013b; 周岱等, 2017a, 2017b). 研究区出露有寒武系、奥陶系、泥盆系、石炭系、白垩系和新生界地层(图 1), 覆盖于前寒武纪变质基底之上. 出露的火成岩主要为广西期、印支期和

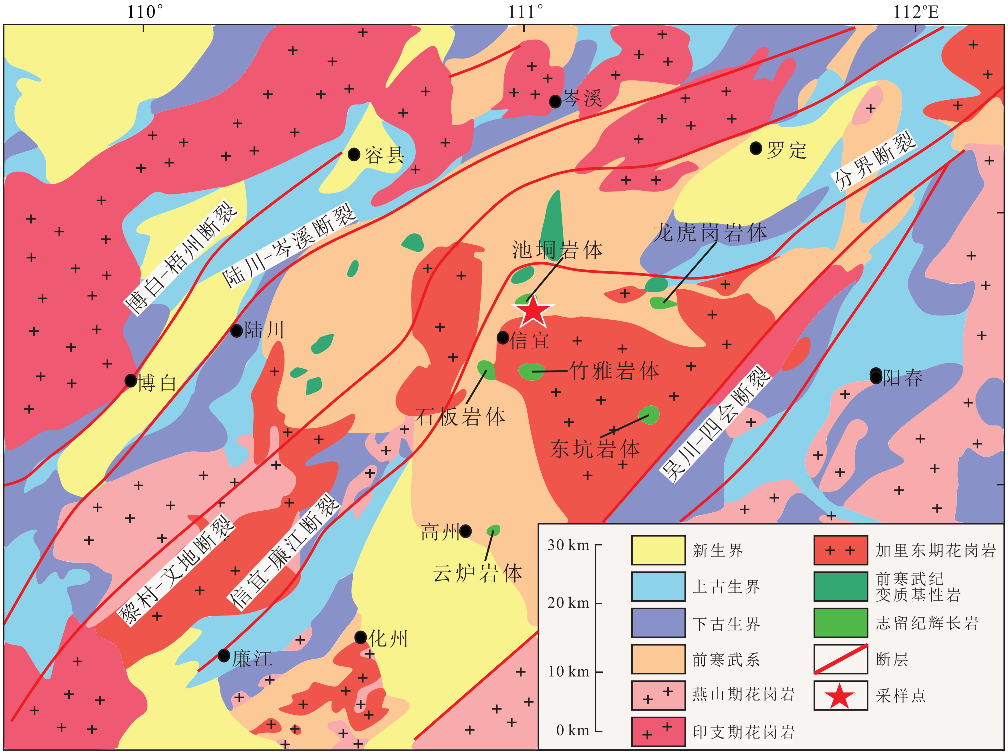

图 1　信宜—罗定地区地质概况及采样点位置

Fig.1　Geological sketch of Xinyi-Luoding with the sampling location

燕山期花岗岩，以及零星出露的广西期基性岩.其中目前报道的云开地区广西期基性岩主要有龙虎岗岩体(432±8 Ma)、竹雅岩体 (448±6 Ma)、石板岩体(445±7 Ma)、东坑岩体和云炉岩体等(彭松柏等，2006a；Wang *et al.*，2013b；Yao *et al.*，2014；周岱等，2017b).最近对云开地区的野外调研在广东省信宜市池垌地区识别出了池垌辉长岩体，除竹雅岩体、东坑岩体侵入早古生代岩浆岩中外，池垌等同时代的辉长岩体均呈小岩株状侵入前寒武纪变质地层中.池垌岩体以中—细粒辉长岩为特征，呈不等粒结构、辉长辉绿结构、填间结构和块状构造.其中斜长石呈半自形粒状结构，粒度较大，约占 57%，可见斜长石聚片双晶与卡—钠复合双晶；普通辉石呈半自形—他形粒状充填于斜长石晶体之间，约占 30%；普通角闪石中可见包含有辉石颗粒，约占 30%；副矿物主要为磷灰石和锆石等，含量较低.

2　分析测试方法

锆石挑选采用传统的人工重砂法，在双目镜下挑选出无裂隙、无包体、透明的自形锆石颗粒用环氧树脂固定并抛光至锆石核部，通过透反光图像和阴极发光图像(CL)选取合适的位置进行锆石 U-Pb 同位素测年.锆石 CL 图像的拍摄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(广州地球化学研究所同位素实验室)利用 JXA-8100 电子探针完成，锆石 U-Pb 同位素分析在广州地化所同位素实验室利用 Cameca IMS 1280HR 二次离子质谱仪(SIMS)完成.详细的实验流程及数据处理方法见李玲等(2016).锆石谐和图和加权平均年龄的计算利用 Isoplot ver.4.15(Ludwig，2003)完成.

全岩主微量元素分析测试在广州地球化学研究所同位素实验室进行.主量元素测试采用熔片法，利用 Rigaku RIX 2000 X 射线荧光光谱(XRF)进行.将样品加热至 950 ℃与硼酸锂混合熔剂在铂金坩埚中共熔，再加入碘化铵(NH_4I)脱模剂制成熔片，分析精度优于 1%.详细的实验流程及数据处理方法见 Li *et al.*(2005).微量元素分析采用 Perkin-Elmer Sciex Elan 6000 电感耦合等离子质谱仪(ICP-MS)进行，将样品溶解在溶样器中，加入高浓度氢氟酸(HF)和硝酸(HNO_3)蒸干溶液，再加入 HF 和 HNO_3 密封加热.再次蒸干后加入 HNO_3 并保持恒温，之后将溶液转移到聚乙烯瓶中，稀释后进行仪器测试.使用美国地质调查局标准 W-2 和 G-2 以及国内标准 GSR-1、GSR-2 和 GSR-3 校正样品的含量，

分析精度优于 5%，详细的实验流程及数据处理方法见 Li(1997).

全岩 Sr-Nd 同位素在广州地球化学研究所同位素实验室测定. Sr 和 Nd 的化学分离分别使用 HF+浓盐酸(HCL)和 HNO_3 溶解样品，再分别使用阳离子树脂和二-(2-乙基己基)磷酸(HDEHP)进行化学分离，采用 VG-354 固体质谱仪进行测试. 使用标准值 $^{87}Sr/^{86}Sr=0.1194$ 和 $^{143}Nd/^{144}Nd=0.7219$ 进行标准化. VG-354 测定的 NBS987 标样的 $^{87}Sr/^{86}Sr=0.7103$，$^{143}Nd/^{144}Nd=0.5119$.详细的实验流程及数据处理方法见李献华等(2002).

3　测试结果

3.1　SIMS 锆石 U-Pb 年龄

从池垌辉长岩样品(CD-1)中选择了 15 颗无裂隙的干净锆石进行 SIMS 锆石 U-Pb 定年，详细的测试结果见附表 1. CD-1 样品中的锆石呈无色或浅黄色，透明至半透明，内部结构清晰，长约 100～120 μm，锆石长宽比约为 2∶1. CL 图像中表现有典型岩浆振荡环带(图 2)，锆石 Th/U 比值变化于 0.60～1.62 之间，为典型岩浆成因锆石. 15 个分析点给出的 $^{206}Pb/^{238}U$ 加权平均年龄为 433.9±1.5 Ma (MSWD=0.18)，代表了辉长岩的结晶年龄(图 2).

3.2　全岩地球化学特征

本文选择池垌辉长岩体的 6 件代表性样品进行了主微量元素测试，其结果见表 1. 样品的 SiO_2 含量变化介于 47.81%～48.83%，相对富 MgO (13.02%～14.65%)，Al_2O_3=11.40%～14.28%，全碱(Na_2O+K_2O)含量在 1.60%～2.25%之间，全铁(FeO^T)为 9.38%～10.30%，K_2O/Na_2O 比值在 0.63～1.63 之间. 样品具有高的 Cr($278\times10^{-6}\sim356\times10^{-6}$)和 Ni 含量($120\times10^{-6}\sim184\times10^{-6}$). 在 TAS 图解(图 3a)中，样品落在亚碱性辉长岩区域. 在 SiO_2-K_2O 图解(图 3b)中落在中钾钙碱性系列区域. 稀土元素球粒陨石标准化图解中(图 4a)，池垌辉长岩样品表现为轻稀土元素(LREE)略富集的平缓右倾型稀土元素配分模式(图 4a)，$(La/Yb)_{cn}$=2.43～3.10，$(Gd/Yb)_{cn}$=1.12～1.23，Eu 负异常不明显(δEu=0.80～0.94). 在微量元素原始地幔标准化配分图解中(图 4b)，样品富集大离子亲石元素(LILE)，亏损高场强元素(HFSE)，具明显 Nb-Ta 和 Ti 负异常，其$(Nb/La)_{PM}$变化于 0.27～0.36，显示岛弧型地球化学特征.

池垌辉长岩体代表性样品的 Sr-Nd 同位素测试结果见表 2. 样品 $^{87}Sr/^{86}Sr$ 比值介于 0.717 185～0.721 194，$^{143}Nd/^{144}Nd$ 比值为 0.512 153～0.512 221. 对应的 Sr 同位素初始比值为 0.708 477～0.710 660 和 $\varepsilon_{Nd}(t)$值变化于 -6.0～-8.2.

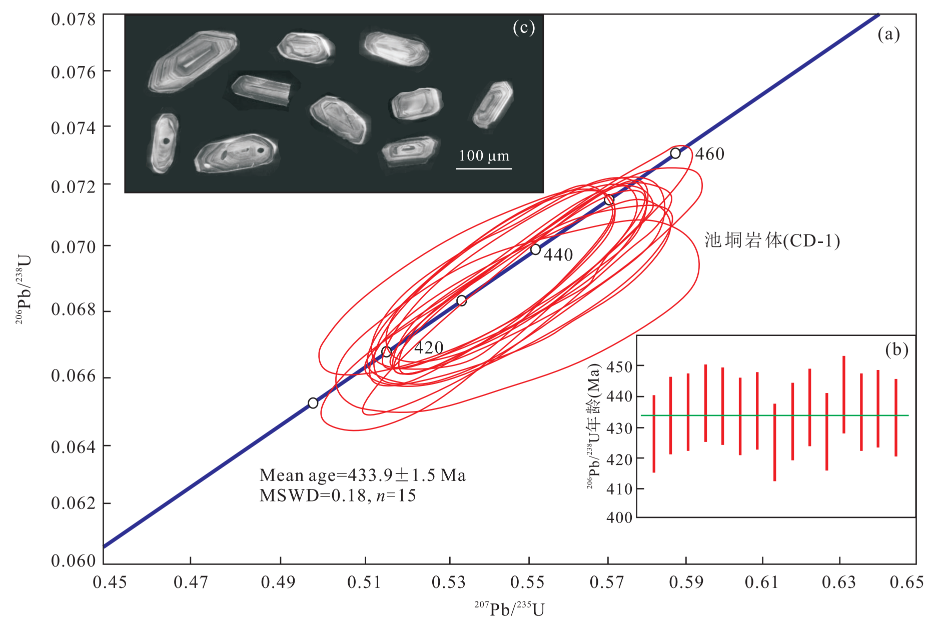

图 2　池垌辉长岩样品(CD-1)的 SIMS 锆石 U-Pb 定年谐和图(a)、年龄加权平均图(b)和 CL 图像(c)

Fig.2　Concordia diagram of SIMS zircon U-Pb data for the Chidong gabbroic sample (CD-1) (a), inserts note the recalculated weighted mean $^{206}Pb/^{238}U$ ages (b) and the respective cathodoluminescenece images for zircons (c)

表1 池垌辉长岩样品主量元素(%)、微量元素(10^{-6})分析结果

Table 1 Major (%) and trace (10^{-6}) element analytical results for the Chidong gabbroic samples

样号	CD-4	CD-5	CD-8	CD-10	CD-12	CD-15
SiO_2	48.38	48.53	48.83	47.81	47.94	48.05
TiO_2	0.38	0.37	0.34	0.29	0.28	0.43
Al_2O_3	12.98	11.40	12.10	14.28	13.12	11.79
FeO^T	9.52	10.30	9.66	9.38	10.07	10.13
MgO	13.80	14.65	14.13	13.02	13.97	14.32
MnO	0.18	0.20	0.18	0.17	0.19	0.19
CaO	7.63	8.21	7.96	8.99	8.51	8.90
K_2O	1.34	0.96	1.19	1.17	0.90	0.62
Na_2O	0.82	0.72	1.06	1.08	0.97	0.98
P_2O_5	0.02	0.03	0.02	0.01	0.01	0.02
L.O.I	3.35	2.92	2.94	2.21	2.35	2.91
Total	99.45	99.44	99.49	99.47	99.43	99.46
$Mg^{\#}$	72.3	71.9	72.5	71.4	71.4	71.8
Sc	39.6	43.1	41.3	38.3	38.5	42.5
V	188	203	185	175	173	209
Cr	278	291	292	327	356	278
Co	57.5	63.8	61.7	64.4	64.1	62.5
Ni	135	133	134	175	184	120
Rb	66.1	46.3	62.7	55.8	43.9	30.9
Sr	93.0	85.6	107	153	111	96.5
Y	9.79	9.31	9.32	7.76	7.10	9.65
Zr	24.8	23.9	28.4	18.4	18.9	32.5
Nb	1.22	1.39	1.26	0.97	0.79	1.30
Ba	120	102	104	120	97.4	63.6
La	3.25	4.24	4.09	3.17	2.79	3.52
Ce	6.89	8.42	8.08	5.62	5.12	7.25
Pr	1.00	1.08	1.06	0.81	0.71	0.96
Nd	3.95	4.72	4.59	3.40	3.10	3.97
Sm	1.14	1.15	1.17	0.89	0.81	1.16
Eu	0.34	0.35	0.33	0.31	0.28	0.36
Gd	1.42	1.38	1.41	1.14	1.04	1.39
Tb	0.25	0.24	0.25	0.20	0.18	0.26
Dy	1.55	1.51	1.50	1.23	1.11	1.59
Ho	0.33	0.33	0.33	0.27	0.25	0.34
Er	0.99	0.98	0.97	0.81	0.77	1.02
Tm	0.15	0.15	0.15	0.12	0.11	0.15
Yb	0.96	0.98	0.98	0.81	0.77	1.00
Lu	0.14	0.15	0.15	0.12	0.12	0.15
Hf	0.70	0.77	0.75	0.53	0.53	0.84
Ta	0.10	0.12	0.10	0.11	0.06	0.09
Pb	3.56	14.5	9.23	3.28	2.85	4.19
Th	0.98	1.01	1.14	0.71	0.76	1.05
U	0.23	0.26	0.36	0.21	0.17	0.28

4 讨论

4.1 岩浆作用与岩石成因

池垌辉长岩样品的烧失量较低(2.21%～3.35%),表明样品未经过明显的低温蚀变作用.池垌辉长岩样品的 $Mg^{\#}=71～72$,具较高的 Cr($278\times10^{-6}～356\times10^{-6}$)、Co($58\times10^{-6}～64\times10^{-6}$)和 Ni 含量($120\times10^{-6}～184\times10^{-6}$),暗示其经历了橄榄石和辉石的结晶分异作用.池垌辉长岩样品的 REE 配分模式呈 LREE 略富集的平缓右倾型(图 4a),且样品具高的 $Mg^{\#}$(71～72)、Cr 含量($278\times10^{-6}～356\times10^{-6}$)、Ni 含量($120\times10^{-6}～184\times10^{-6}$)和低的 Al_2O_3 含量(11.40%～14.28%).样品 Sr-Nd 同位素显示其 EMⅡ型富集地幔源区(图 5a),表明岩浆源区可能受到了地壳组分的交代(Ajaji *et al*.,1998;夏炎,2015).池垌辉长岩样品的关键性地球化学指标(如 LILE 的富集、Nb-Ta 和 Ti 的亏损、低 Nb/La 比值(0.31～0.38)和高 Zr/Nb 比值(17.19～23.92)等)都类似于岛弧岩浆作用特征(李曙光,1993;王岳军等,2001;Wang *et al*.,2013b),La/Nb-Nb/Th 图解也显示出弧火山岩特征(图 5b).基性岩的岛弧地球化学特征往往暗示其源区受到了俯冲相关的熔体/流体交代作用.池垌辉长岩样品具低的 Nb/U 比值(3.50～5.35)、Ta/U 比值(0.28～0.52)和 Nb/Th 比值(1.04～1.38),表明样品以源区交代为主,而非岩浆上升过程中围岩的交代作用(Kepezhinskas *et al*.,1997;王亚磊等,2016).池垌及其邻近岩体的 Nb/Zr-Th/Zr 图解显示了与俯冲相关的岩浆作用趋势,样品投在了造山型岩浆作用范围(图 5c).推测池垌岩体俯冲组分主要来自于俯冲过程中板片沉积物脱水部分熔融(图 5d),并交代上部岩石圈地幔的过程.上述特征表明,池垌辉长岩可能是俯冲沉积物交代岩石圈地幔的产物.

一般认为新生板片俯冲改造幔源组分的 $\varepsilon_{Nd}(t)$ 值为正,池垌辉长岩样品给出的 $\varepsilon_{Nd}(t)$ 值为负(−6.0～−8.2),龙虎岗岩体给出的 $\varepsilon_{Nd}(t)$ 值介于 −1.9～−3.5(Wang *et al*.,2013b),这可能是地幔物质被壳源物质混染的结果.据前人研究提出的早古生代华南大陆地壳和富集地幔源区的 Nd/Pb−$\varepsilon_{Nd}(t)$ 比值模型计算(柏道远等,2007;Wang *et al*.,2013b)发现,池垌辉长岩的 $\varepsilon_{Nd}(t)$ 值需要 55%～60%地壳组分混入.如此高比例的地壳组分加入后,SiO_2 含量将高于 55%,与池垌辉长岩样品的主量元素特征相矛盾.此外,按上述比例混合后的岩浆中,Cr、Ni、Mg 等元素含量也将显著低于池垌岩体.此外,池垌辉长岩体低的 Zr 含量($18.4\times10^{-6}～32.5\times10^{-6}$)和 Zr/Y 比值(2.37～3.37)与岛弧玄武岩类似,而显著低于板内玄武岩(徐学义等,2009),与地壳混染特征不符.样品较高的 Ba/La 比值(18.07～37.85)也暗示了俯冲改造的过程(Wang *et al*.,2004;Basta *et al*.,2011;何慧莹等,2016).一

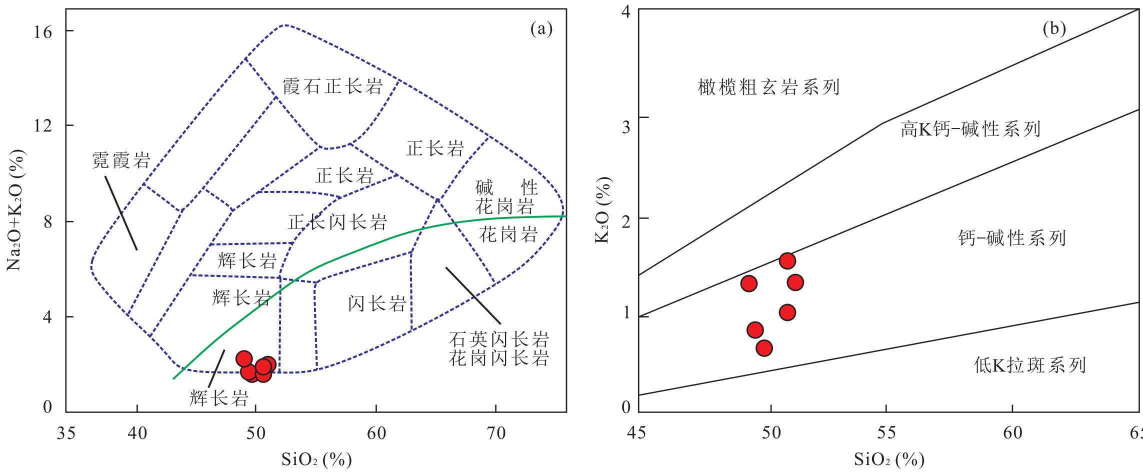

图 3　池垌辉长岩样品 TAS 图解(a)和 SiO_2-K_2O 图解(b)

Fig.3　TAS diagram (a) and SiO_2-K_2O diagram (b) for the Chidong gabbroic samples

图 a 据 Wilson(1989),图 b 据 Morrison(1980)修改

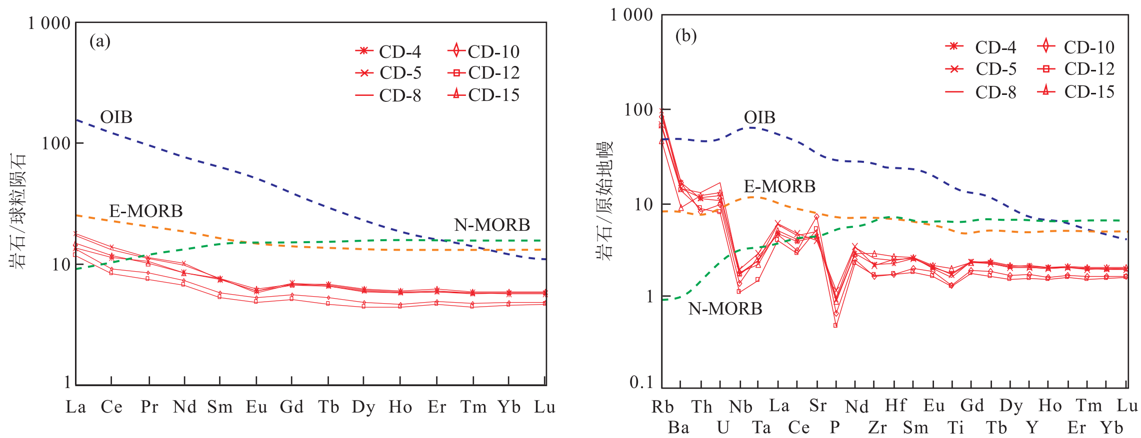

图 4　池垌辉长岩样品稀土元素球粒陨石标准化图解(a)和微量元素原始地幔标准化配分图(b)

Fig.4　Chondrite-normalized REE patterns diagram (a) and primitive mantle-normalized spidergram (b) for the Chidong gabbroic samples

球粒陨石、原始地幔、OIB 及 MORB 数据引自 Sun and McDonough(1989)

表 2　池垌辉长岩样品 Sr-Nd 同位素分析结果

Table 2　Sr-Nd isotopic results for the Chidong gabbroic samples

样号	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$\pm 2\sigma$	$(^{87}Sr/^{86}Sr)_i$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\pm 2\sigma$	$(^{143}Nd/^{144}Nd)_t$	$\varepsilon_{Nd}(t)$
CD-10	1.056	0.717 185	14	0.710 660	0.158	0.512 221	18	0.511 772	−6.0
CD-4	2.058	0.721 194	14	0.708 477	0.174	0.512 153	17	0.511 658	−8.2

注:采用加权平均年龄 434 Ma 求得样品 Sr、Nd 同位素的初始比值.参数采用 $\lambda(^{87}Rb)=1.42\times10^{-11}(a^{-1})$,$\lambda(^{147}Sm)=6.54\times10^{-12}(a^{-1})$(Lugmair and Marti,1978),$(^{143}Nd/^{144}Nd)_{CHUR,现在}=0.512\ 638$(Goldstein *et al*.,1984),$(^{147}Sm/^{144}Nd)_{CHUR,现在}=0.196\ 7$(Peucat *et al*.,1988).

般认为,高的 La/Sm 比值(>4.5)指示地壳混染过程(王键等,2016),池垌辉长岩样品的 La/Sm 比值介于 2.85~3.69,也与地壳混染特征不同.显然,池垌辉长岩不可能是地幔与地壳物质混染的结果.相反地壳物质早期加入其源区并参与熔融的源区混染过程更可能是池垌辉长岩形成的成因基础.池垌辉长岩体的地球化学特征与云开地区新元古代富集地幔相似:具高的 Sr 同位素初始比值(0.708 5~0.710 7),负的 $\varepsilon_{Nd}(t)$值(−6.0~−8.2),高的 Th/Ce 比值(0.12~0.15)和 Nd/U 比值(3.50~5.35),以及低的 Nb/Ta 比值(8.82~14.44,球粒陨石为 17),并具有岛弧属性的稀土元素配分模式和微量元

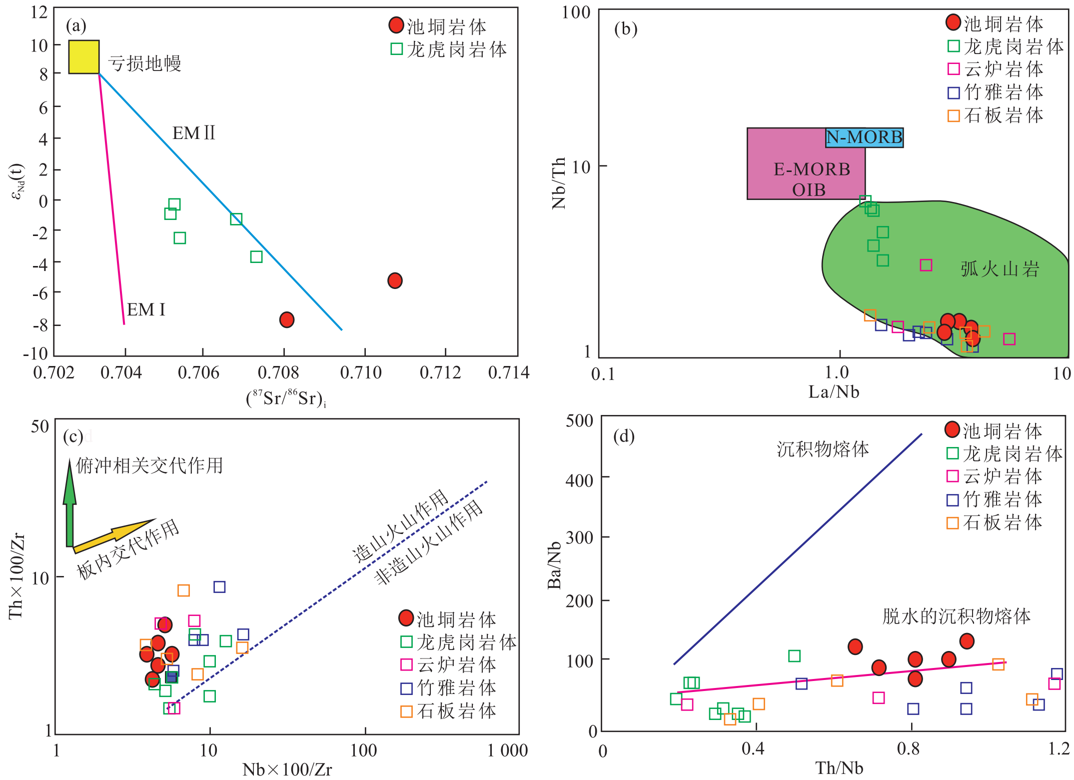

图 5　池垌辉长岩体的 $(^{87}Sr/^{86}Sr)_i-\varepsilon_{Nd}(t)$ 图解(a)、La/Nb－Nb/Th 图解(b)、Nb×100/Zr－Th×100/Zr 图解(c)和 Th/Nb－Ba/Nb 图解(d)

Fig.5　$(^{87}Sr/^{86}Sr)_i-\varepsilon_{Nd}(t)$ diagram (a), La/Nb－Nb/Th diagram (b), Nb×100/Zr－Th×100/Zr diagram (c) and Th/Nb－Ba/Nb diagram (d) for the Chidong gabbroic samples

龙虎岗岩体数据据 Wang *et al*.(2013b),云炉岩体数据据彭松柏等(2006a),竹雅岩体和石板岩体数据据彭松柏等(2006a)和周岱等(2017b)

素特征(彭松柏等,2006b;Wang *et al*.,2013b;张爱梅,2013).此外,华夏地块从新元古代晚期到早中生代基本为远离俯冲带的滨海－大陆坡环境,缺失大规模火山活动、大规模幔源岩浆侵入作用或洋壳的出现(Liu *et al*.,2001;舒良树等,2006, 2012;舒良树等, 2008;Shu *et al*.,2011;Wang *et al*.,2013b;张国伟等,2013).华南东部广泛发育有早古生代浅海相沉积岩,未见早古生代的蛇绿岩套,下古生界砂岩沉积给出了单一方向、而非双向的古水流特征(Chen and Jahn,1998;曾勇和廖群安,2000;舒良树等,2006,2012;Rong *et al*.,2007;舒良树等,2008;Zeng *et al*.,2008;Li *et al*.,2010;张爱梅等,2010;Zhang *et al*.,2012b;李聪等,2010;Wang *et al*.,2011;张国伟等,2013).寒武纪－奥陶纪的沉积地层具有较为连续的古生物序列和过渡相沉积建造(Rong *et al*.,2007;戎嘉余等,2010;陈旭等,2010,2012)以及相似的碎屑锆石谱系(Wang *et al*.,2010,2013a).以上资料表明,早古生代时期华南东部处于陆内构造背景,不存在志留纪洋－陆俯冲事件.由此推断池垌辉长岩体的岛弧型地球化学特征及其富集的同位素组成并非新近俯冲沉积物改造的结果,而是古老俯冲改造地幔楔于志留纪部分熔融而成.池垌岩体的地球化学特征与云开新元古代富集地幔具有相似性,且前人研究表明,武夷－云开地区存在着一个 1 000～900 Ma 的俯冲事件(Zhang *et al*.,2012a;Wang *et al*.,2013b).因此可以推断,池垌辉长岩体可能是新元古代俯冲改造的地幔楔部分熔融的产物.

4.2　构造启示

华夏地块在新元古代裂解为多个古陆残块,其间的陆间海槽在志留纪闭合形成华南广西期陆内造山带(舒良树,2006,2012;Wang *et al*.,2011,2013b;张国伟等,2013),致使泥盆系与下伏地层之间广泛发育角度不整合(徐克勤等,1960;任纪舜,1964,1990;陈旭和米切尔,1996;Zhao *et al*.,1996;舒良树等,2008;Li *et al*.,2010;夏炎,2015;Yao *et al*.,2015).武夷－云开地区的变质岩给出了468～426 Ma 期间的顺时针 *P*-*T* 轨迹 (Zhao and Cawood,1999;Charvet *et al*.,2010;

Wan *et al*.，2010；Li *et al*.，2011；Wang *et al*.，2012，2013a)，其峰期压力达 1.0～1.1 GPa (Yu *et al*.，2005；于津海等，2007；Li *et al*.，2010)，对应地壳厚度约30～40 km.华南东部早古生代岩浆岩以花岗质岩石为主，主体形成于 440～390 Ma (徐克勤等，1963；舒良树等，2008；Faure *et al*.，2009；Wang *et al*.，2011，2012，2013b；Zhang *et al*.，2012b)，其时序上大致对应于峰期变质之后.以往的研究也认为云开地区广西期造山作用峰期约在 460～435 Ma (Wang *et al*.，2013b)，在 440 Ma 左右进入造山垮塌伸展阶段 (于津海等，2006，2007；Li *et al*.，2010；Yao *et al*.，2012；Wang *et al*.，2013b)，对应于云开地区 440～390 Ma 过铝质花岗岩的产出 (徐克勤等，1963；舒良树等，2008；Faure *et al*.，2009；Wang *et al*.，2011，2012；Zhang *et al*.，2012b).而现有的资料表明华南东部峰期变质作用之后的过铝质花岗岩形成于<0.5 GPa 的深熔条件，对应深熔地壳厚度<18 km (夏炎，2015)，这表明自峰期变质之后、过铝质花岗岩形成之前在武夷－云开地区经历了一个地壳快速减薄过程，很可能指示一个后造山环境.

尽管现有的资料表明华南东部早古生代岩浆岩以 440～390 Ma 的花岗质岩石为主 (徐克勤等，1963；舒良树等，2008；Faure *et al*.，2009；Wang *et al*.，2011，2012；Zhang *et al*.，2012b)，但最近的一些研究也证明了云开地区志留纪基性岩的存在.如本文的池垌辉长岩给出了 433.9±1.5 Ma 的锆石 $^{206}Pb/^{238}U$ 年龄，龙虎岗、石板和竹雅辉长岩也给出了 432±8 Ma、445±7 Ma 和 448±6 Ma 的锆石 U-Pb 年龄 (彭松柏等，2006a；Wang *et al*.，2013b；周岱等，2017b).这些基性岩的年龄基本上与华南东部的花岗质岩石的形成年龄一致，这暗示他们之间的内在动力学联系，同样形成于后碰撞的垮塌伸展阶段.现有研究表明，华南大面积志留纪花岗岩的形成反映陆内背景下的地壳深熔作用，我们的资料表明云开地区志留纪辉长岩源于古老俯冲交代的地幔楔，这表明在后碰撞的垮塌伸展阶段的应力释放可能促进了岩石圈热界面上升，使古老富集岩石圈地幔发生热扰动作用继而导致富集地幔的部分熔融.池垌辉长岩体就是在此伸展背景下由古老俯冲交代的地幔楔于志留纪熔融而来.

5　结论

(1) 粤西池垌辉长岩体形成于 433.9±1.5 Ma，属于志留纪产物.

(2) 粤西池垌辉长岩体是在志留纪陆内伸展背景下由古老俯冲交代的地幔楔熔融而成.

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附表 1 见本刊官网 (http://www.earth-science.net).

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附表 1 池垌辉长岩样品(CD-1)的 SIMS 锆石 U-Pb 同位素分析结果

Appendix table 1 SIMS zircon U-Pb isotopic results for the Chidong gabbroic sample (CD-1)

分析点	Th/U	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$	
		比值	1σ	比值	1σ	比值	1σ	年龄(Ma)	1σ	年龄(Ma)	1σ	年龄(Ma)	1σ
CD-1-01	0.72	0.056 1	0.544 8	0.530 0	1.645 6	0.068 5	1.552 8	455	12	432	6	427	6
CD-1-02	1.19	0.055 9	0.726 8	0.536 5	1.668 3	0.069 6	1.501 6	448	16	436	6	434	6
CD-1-04	1.62	0.055 3	0.436 2	0.532 5	1.562 3	0.069 8	1.500 2	426	10	433	6	435	6
CD-1-05	1.55	0.055 5	0.519 5	0.537 6	1.602 2	0.070 3	1.515 6	432	12	437	6	438	6
CD-1-06	0.73	0.055 9	0.902 0	0.540 6	1.752 1	0.070 1	1.502 1	448	20	439	6	437	6
CD-1-07	0.82	0.054 8	1.087 6	0.526 2	1.852 8	0.069 6	1.500 0	406	24	429	7	434	6
CD-1-08	1.29	0.055 6	0.620 4	0.535 6	1.624 3	0.069 8	1.501 2	438	14	436	6	435	6
CD-1-09	1.17	0.055 9	0.949 3	0.525 7	1.789 4	0.068 2	1.516 9	449	21	429	6	425	6
CD-1-10	1.18	0.056 0	1.082 4	0.534 5	1.851 8	0.069 3	1.502 6	451	24	435	7	432	6
CD-1-11	0.60	0.055 1	0.724 3	0.531 9	1.667 6	0.070 0	1.502 1	416	16	433	6	436	6
CD-1-12	0.89	0.056 4	1.665 9	0.533 8	2.244 3	0.068 7	1.503 9	466	36	434	8	428	6
CD-1-15	0.60	0.055 5	0.376 6	0.542 0	1.548 2	0.070 8	1.501 7	434	8	440	6	441	6
CD-1-16	0.83	0.055 4	0.959 8	0.532 9	1.782 0	0.069 8	1.501 5	427	21	434	6	435	6
CD-1-17	1.07	0.055 3	0.488 8	0.533 7	1.579 8	0.070 0	1.502 2	424	11	434	6	436	6
CD-1-18	0.62	0.055 9	0.547 8	0.535 1	1.596 9	0.069 5	1.500 0	448	12	435	6	433	6