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华夏早古生代俯冲作用(Ⅰ):来自糯垌蛇绿岩的新证据

彭松柏[1,2],刘松峰[1,2],林木森[3],吴长峰[4],韩庆森[1,2]

1.中国地质大学地球科学学院,湖北武汉 430074
2.中国地质大学全球大地构造中心,湖北武汉 430074
3.福州大学紫金矿业学院,福建福州 350108
4.福建闽西地质大队,福建厦门 361000

摘要:早古生代加里东期造山运动(广西运动)的性质是华南大地构造演化长期争议的重大地质问题.桂东南岑溪糯垌一带奥陶纪浅变质地层中出露一套变形变质基性岩系构造岩片,主要由变枕状玄武岩、辉绿岩墙以及少量块状辉长岩和辉石岩组成.变玄武岩、变辉绿岩的 SiO_2 含量为49.20%~52.30%,MgO含量为6.78%~9.11%,$Mg^{\#}$ 为55~63,TiO_2 含量为1.02%~1.34%,属低钾拉斑玄武系列基性岩.稀土元素配分平坦,轻稀土亏损,$(La/Sm)_N$ 为0.72~1.05,$(La/Yb)_N$ 为0.7~1.0,无明显Eu异常,大离子亲石元素Rb、Ba、Th、U、K、Pb相对富集,高场强元素Nb、Ta、Zr、Hf、Ti平坦-略亏损,Ti/V为21.30~25.12,Nb/Th为2.1~4.2,表现出俯冲带之上(SSZ)蛇绿岩的地球化学特征.变辉绿岩LA-ICP-MS锆石U-Pb成岩年龄为437±5 Ma,表明其形成于早志留世.综合研究表明,糯垌变基性岩系应属早古生代形成于俯冲之上(SSZ)弧前构造环境的肢解蛇绿岩残片,这一发现为华南扬子克拉通与华夏地块之间存在早古生代洋盆和俯冲-增生碰撞造山提供了关键证据.

关键词:岑溪地区;蛇绿岩;岩石学;地球化学;早古生代洋盆;大地构造意义.

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Early Paleozoic Subduction in Cathaysia (Ⅰ): New Evidence from Nuodong Ophiolite

Peng Songbai[1,2], Liu Songfeng[1,2], Lin Musen[3], Wu Changfeng[4], Han Qingsen[1,2]

1.*School of Earth Sciences, China University of Geosciences, Wuhan* 430074, *China*
2.*Center for Global Tectonics, China University of Geosciences, Wuhan* 430074, *China*
3.*College of Zijin Minning, Fuzhou University, Fuzhou* 350108, *China*
4.*The Western Geological Party of Fujian, Xiamen* 361000, *China*

Abstract: The nature of Early Paleozoic Caledonian orogeny (Guangxi movement), as one of the key geolocial problems of tectonic evolution in South China, has been controversial for a long time. In this study we report a suite of deformed and metamorphosed basic rocks in tectonic slices that are exposed in epimetamorphic Ordovician strata, located at the Nuodong in the Cenxi area of the Southeast Guangxi, South China. This suite of rock is mainly composed of metamorphic basalt, diabase dike and minor pyroxenite. Petrogeochemical data of the metabasalt and metadiabase dike show the content of SiO_2=49.20%-52.30%, MgO=6.78%-9.11%, $Mg^{\#}$=55-63, TiO_2=1.02%-1.34%, indicating the low potassium tholeiitic series of basic rocks. The chondrite-normalized REE distribution patterns are flat type with light rare earths depleted, no obvious Eu anomaly, $(La/Sm)_N$=0.72-1.05, $(La/Yb)_N$=0.7-1.0, while the N-MORB normalized spider diagrams show slightly enrichment of LILEs (e.g.Rb, Ba, Th, U, K, Pb) and flat-slightly depletion of HFSEs (e.g. Nb, Ta, Zr, Hf, Ti), Ti/V=21.30-25.12, Nb/Th=2.1-4.2. The geological and petrogeochemical features imply that this series of rocks represent a dismembered ophiolites formed in supra-subduction zone (SSZ) tectonic environment. The LA-ICP-MS zircon U-Pb age of the metadiabase is 437±5 Ma, indicating that the ophiolites were formed at the Early Silurian. Based on the above comprehensive study, we propose that the Nuodong metamorphic basic rock series are Early Paleozoic ophiolite fragments formed in a forearc tectonic environ-

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作者简介:彭松柏(1963-),男,教授,博士,主要从事岩石大地构造及蛇绿岩研究.E-mail:psongbai@aliyun.com

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ment in a supra-subduction zone (SSZ). The document of the Early Paleozoic Nuodong ophiolite provides key evidence for the existence of an Early Paleozoic oceanic basin and subduction-accretionary collisional orogenesis between Yangtze craton and Cathaysia blocks in South China.

Key words: Southeast Guangxi; ophiolite; petrology; geochemistry; Early Paleozoic oceanic basin; tectonic significance.

0　引言

云开隆起西北缘岑溪地区位于扬子克拉通与华夏地块(群)或华夏造山系之间钦杭结合带西段南东侧,是研究扬子克拉通与华夏地块早古生代加里东期造山运动(广西运动)的关键地区之一(图 1a).但长期以来对于华南早古生代加里东期造山运动的性质,存在两种截然不同的认识:一种观点是,加里东期造山属板块构造体制下的俯冲—碰撞造山(Guo *et al*.,1989; Hsü *et al*.,1990;李曰俊等,1993;刘宝珺等,1993;殷鸿福等,1999;吴浩若,2000;尹福光等,2001;马瑞士,2006;彭松柏等,2006;刘运黎等,2009;Zhao and Cawood,2012;许效松等,2012;覃小锋等,2013;Zhang *et al*.,2015;陈相艳等,2015);另一种观点是,加里东期造山缺乏洋壳俯冲—碰撞造山的关键性证据,即缺乏早古生代蛇绿岩和岛弧火山岩,故其造山性质应属陆内或板内造山运动(Li,1998;Wang and Li,2003;舒良树,2006,2012;Wang *et al*.,2007;Faure *et al*.,2009;张芳荣等,2009;Charvet *et al*., 2010;Li *et al*.,2010;陈旭等,2012;Cawood *et al*.,2013;Charvet,2013;张国伟等,2013).

本文通过对桂东南岑溪糯垌一带出露于奥陶纪浅变质地层中的一套变基性岩系(简称糯垌变基性岩系)野外地质特征、岩石地球化学、同位素年代学的研究,提出这套变基性岩系为形成于俯冲带之上(SSZ)构造环境的早古生代蛇绿岩残片,其为华南扬子克拉通与华夏地块之间存在早古生代洋盆和加里东期洋壳俯冲—增生碰撞造山提供了关键证据.

1　地质背景及岩石学特征

云开隆起西北缘岑溪糯垌地区,在大地构造上位于华南扬子克拉通与华夏地块之间钦杭结合带西南段博白—岑溪—罗定—广宁断裂带南东侧(图 1a).该区主要发育一套早古生代奥陶纪—志留纪绿片岩—低角闪岩相浅变质变形地层,少量晚古生代泥盆纪地层.奥陶系—志留系主要为经历强烈变形的千枚岩、云母石英片岩、云母片岩、石英岩、变质粉砂岩等深海—半深海相复理石建造,并夹有少量规模不等的透镜状、似层状变基性岩.泥盆系主要为弱/未变形变质含砾砂岩、砂岩等滨海—浅海相沉积,其与志留系呈平行不整合和构造接触(陆济璞和康云骥,1999).之后,奥陶系—泥盆系又遭受了中生代印支期、燕山期花岗岩岩浆活动的侵入(图 1b).在岑溪糯垌油茶林场一带,中—晚奥陶世浅变质变形地层中出露有一套呈北东向带状展布、规模较大的似层状变形变质基性岩系(构造岩片),其与上覆构造变形变质分异或"混合岩化"奥陶系和下伏弱变形浅变质奥陶系均呈构造接触关系.变基性岩系主要由变形变质的玄武岩(含杏仁、气孔玄武岩、枕状玄武岩)、辉绿岩脉(岩墙)群,少量呈透镜状的块状辉石岩、辉长岩组成,韧性—脆性构造片理、韧性变形构造透镜体普遍发育,片理、糜棱面理总体呈北东走向,倾向南东,倾角一般>50°,并与变基性岩系空间展布方向基本一致(图 1c).

本文重点对岑溪糯垌油茶林场一带新开水泥公路地质剖面中出露的变基性岩片进行了详细研究,现对这套变基性岩系主要岩石类型作简要描述.

变玄武岩(杏仁状、枕状玄武岩):浅灰绿色到灰黑色,多呈似层状、透镜状产出,片理普遍发育,沿片理、裂隙充填微细石英脉,细粒—隐晶质结构、变余斑状结构,变余气孔、杏仁构造,局部弱变形域可见较典型的气孔、杏仁、枕状构造(图 2a,2b).变玄武岩中通常斑晶、杏仁体含量占 10%~20%,主要为基性斜长石、角闪石以及斜长石与石英杏仁状集合体(图 2e),其中斜长石多呈他形、透镜体状、聚斑状,边缘不规则,聚片双晶发育.角闪石多退变为阳起石和绿泥石.基质矿物主要为微晶角闪石(40%~45%)、微晶斜长石(40%~45%)和少量磁铁矿(2%).此外,局部弱变形域片理不发育气孔、杏仁状玄武岩中杏仁体多呈圆形或椭圆形,直径为 0.5~2.0 mm,充填物为石英、斜长石、方解石等矿物集合体,基质矿物主要为微晶—隐晶角闪石、斜长石(图 2b).

变辉绿岩:浅灰绿色到灰黑色,岩脉(岩墙)群与玄武岩多呈构造互层相间产出,片理普遍发育,沿片理充填石英细脉(图 2c,2d),矿物常见定向排列,细粒变余辉绿、变余辉绿—辉长结构,块状构造、片状

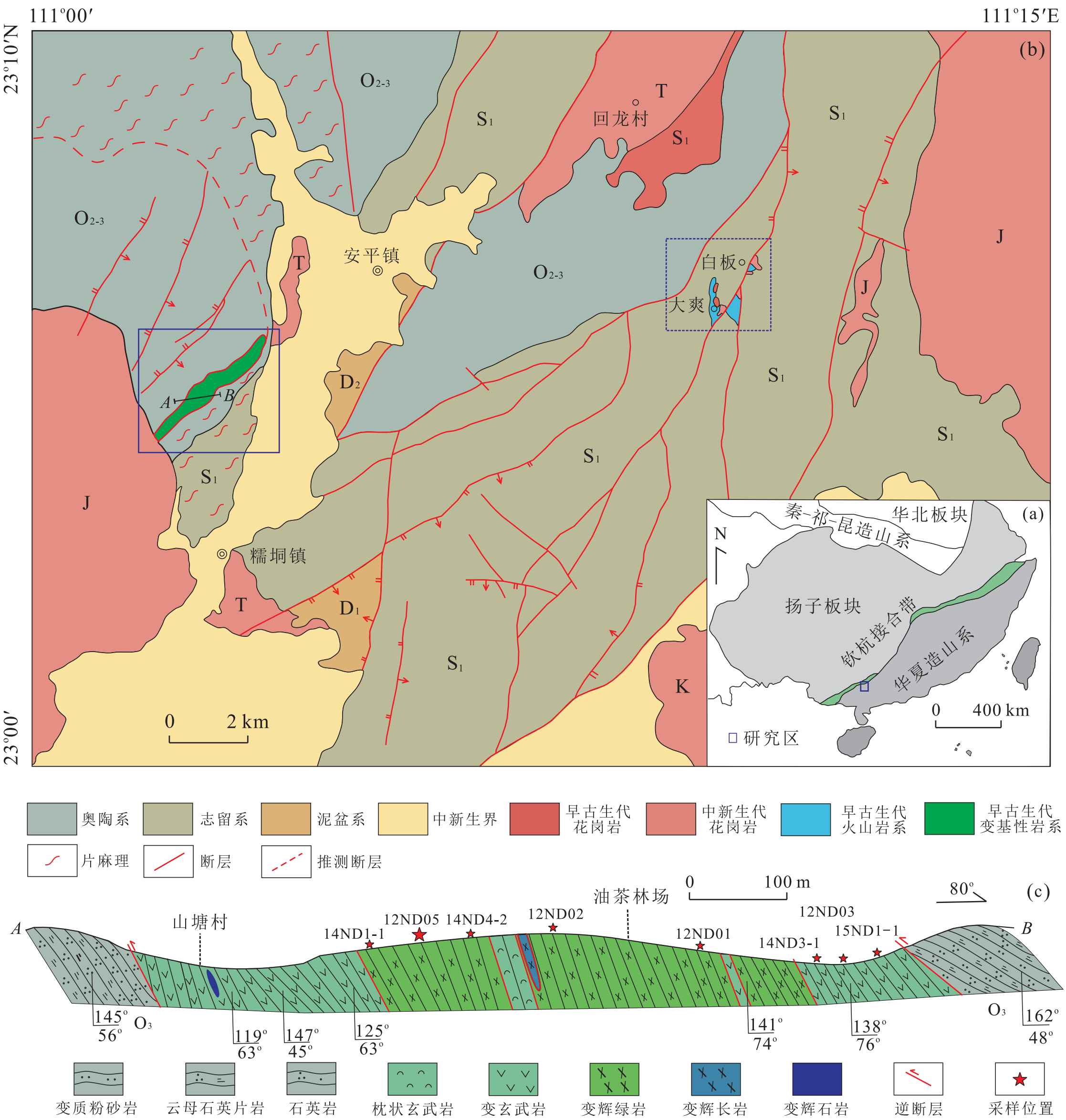

图 1　华南大地构造基本单元(a)、糯垌地区地质简图(b)和糯垌变基性岩系地质剖面(c)

Fig.1　The tectonic framework of the South China (a), the geological sketch of Nuodong area (b) and geological section of the Nuodong metamorphic basic rock series (c)

图 b 据广西壮族自治区区域地质调查队 1∶5 万地质图修编

构造.岩石主要矿物组成为基性斜长石(40%～45%)、角闪石(40%～50%)和磁铁矿(3%～5%).角闪石呈柱状、似眼球状，两组节理发育，局部残留有较大斑晶，粒径为 0.3～0.5 mm，多蚀变为阳起石、绿帘石、绿泥石.基性斜长石呈板柱状，半自形，聚片双晶发育，粒径为 0.1～0.3 mm(图 2f,2g).

变辉石岩：浅灰绿到深灰绿色，呈透镜状、块状夹于变辉绿岩、变玄武岩中，变形变质较弱.灰绿色，中细粒变晶结构，块状构造.岩石主要矿物组成为透辉石(40%～50%)、角闪石(35%～40%)、基性斜长石(5%～10%)和磁铁矿(2%～3%).透辉石无色或浅灰绿色，弱多色性，两组解理近垂直，半自形—自形柱状，简单双晶常见，斜消光，粒径为 2～5 mm.角闪石以直闪石和透闪石为主，浅灰绿色，柱状，具多色性，两组解理斜交，粒径为 1～3 mm.基性斜长石呈板柱状，半自形，大部分已蚀变，完整晶型少见(图 2h).

2　分析方法

2.1　主量元素和微量元素分析方法

选取比较新鲜、均一的变玄武岩、变辉绿岩分析样品，去除风化表皮将样品粉碎至 3～5 mm，用碳

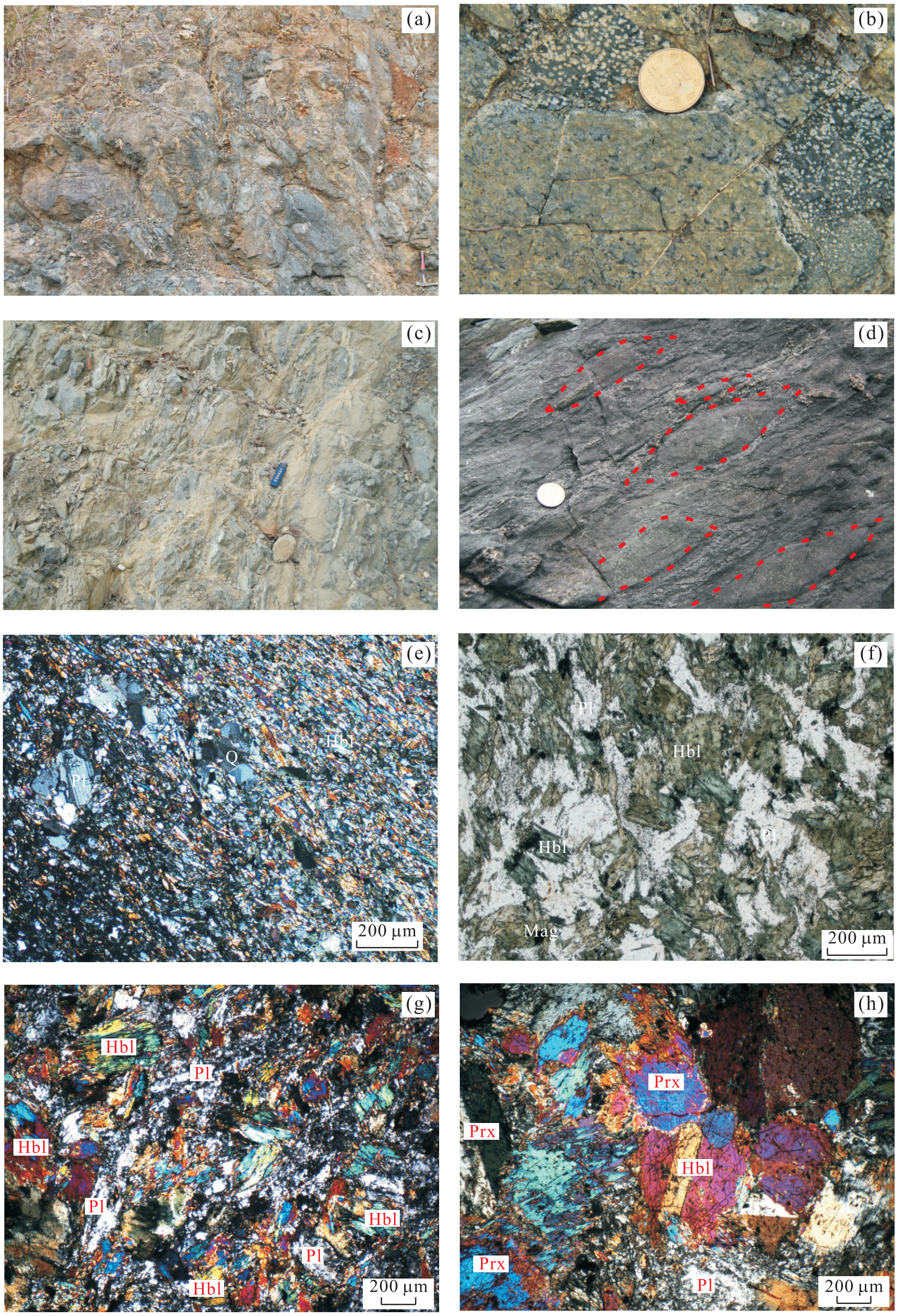

图 2 变玄武岩、辉绿岩及变辉石岩野外宏观和显微照片

Fig.2 Representative field and thin section photomicrographs of the metabasalt and metadiabase

a.枕状玄武岩野外露头;b.杏仁状玄武岩野外露头;c.变辉绿岩岩脉(岩墙)群野外露头;d.强烈韧性剪切变形形成的玄武岩与辉绿岩岩脉(岩墙)似层状构造;e.变玄武岩中变余杏仁结构(正交镜);f.变辉绿岩中变余辉绿－辉长结构(单偏镜);g.变辉绿岩中变余辉绿结构(正交镜);h.变辉石岩中变余粒状结构(正交镜).矿物缩写:Prx.辉石;Hbl.角闪石;Pl.斜长石;Mag.磁铁矿;Q.石英

化钨研钵研磨至 200 目进行化学分析测试.部分样品主量元素测试在武汉综合岩矿测试中心完成,微量元素测试由中国地质大学(武汉)地质过程与矿产资源国家重点实验室 LA-ICP-MS 分析实验室完成,分析精度优于 1%～3%.部分样品主量元素、微量元素分析测试在广州澳实矿物实验室中心完成.

主量元素用 X 射线荧光光谱法(XRF)测定,样品粉末加入包含硝酸锂在内的助熔剂,充分混合后高温熔融成玻璃,在 XRF 上用外标法测定其氧化物含量,氧化亚铁含量用重铬酸钾溶液滴定法获得,氧

化物总量分析误差为5%.微量元素测定采用等离子质谱(ICP-MS)法测定，酸溶制成溶液，然后在ICP-MS上用内标法进行测定，分析精度优于10%.笔者采用地球化学工具软件包 GeoKit 程序(路远发，2004)对常量元素、微量元素分析测试数据进行岩石地球化学数据处理.样品分析测试结果见表1.

2.2　锆石 U-Pb 定年分析方法

锆石分选采用常规方法粉碎，用摇床淘洗、磁选

表1　变玄武岩、辉绿岩主量元素(%)和微量元素(10^{-6})组成

Table 1　Major elements (%) and trace elements (10^{-6}) composition of the metabasalt and metadiabase

岩性	变玄武岩			变辉绿岩				
	12ND03	14ND3-1	15ND1-1	12ND01	12ND02	12ND05	14ND1-1	14ND4-2
SiO_2	51.00	49.20	50.60	51.78	51.45	52.30	50.10	50.00
TiO_2	1.07	1.04	1.27	1.34	1.15	1.02	1.20	1.07
Al_2O_3	15.04	15.10	15.00	14.87	14.43	15.63	14.50	15.20
Fe_2O_3	2.41	2.24	2.57	2.61	2.75	1.98	2.49	1.84
FeO	7.25	7.63	7.89	8.20	7.55	6.65	8.34	7.68
MnO	0.18	0.19	0.17	0.16	0.17	0.13	0.18	0.18
MgO	7.59	9.11	7.22	7.09	7.54	6.78	7.46	7.75
CaO	10.63	11.70	9.48	8.07	10.21	11.30	10.15	12.10
Na_2O	3.01	2.20	3.19	4.15	2.53	2.17	2.80	2.48
K_2O	0.08	0.09	0.14	0.13	0.12	0.15	0.19	0.16
P_2O_5	0.08	0.08	0.11	0.11	0.09	0.08	0.10	0.08
LOI	0.88	0.69	0.61	0.90	1.21	1.00	0.52	0.63
Total	99.22	99.27	98.25	99.33	99.20	99.19	98.03	99.17
$Mg^{\#}$	59	63	56	55	58	59	56	60
Ba	13.8	15.3	20.0	54.6	26.4	68.2	30.5	26.0
Rb	1.3	0.7	1.7	0.9	2.7	3.4	2.7	1.9
Th	0.54	0.61	0.82	0.74	0.96	0.90	0.80	0.59
Pb	0.60	2.00	1.10	0.94	0.71	0.81	1.20	1.90
Nb	2.11	2.10	3.10	2.57	2.67	1.93	3.30	2.30
Sr	83.8	92.1	80.9	64.1	85.3	122.0	104.0	91.2
Zr	57.4	60.0	69.0	74.7	69.1	62.8	72.0	60.0
Y	28.0	26.4	34.5	36.0	33.3	28.4	34.4	26.7
Cr	216	211	116	143	205	136	98	216
V	301	282	303	370	303	273	303	283
Ni	80.4	81.0	47.0	40.8	71.7	59.4	46.0	86.0
Co	46.1	52.0	51.0	48.4	44.4	47.8	45.0	54.0
Cs	0.08	0.06	0.18	0.08	0.16	0.24	0.20	0.02
Ta	0.16	0.10	0.17	0.18	0.19	0.17	0.20	0.20
Hf	1.70	1.90	2.10	2.28	2.05	1.84	2.20	1.90
U	0.23	0.19	0.31	0.23	0.17	0.16	0.19	0.23
La	2.73	3.00	4.30	3.81	4.11	3.28	4.40	3.20
Ce	7.64	7.90	10.60	9.98	9.36	8.62	10.50	8.20
Pr	1.24	1.31	1.68	1.65	1.69	1.38	1.70	1.33
Nd	6.73	6.40	7.90	8.85	8.53	7.48	8.30	6.40
Sm	2.46	2.29	2.92	3.05	2.82	2.55	2.70	2.21
Eu	0.81	0.92	1.05	1.03	0.99	0.90	1.04	0.91
Gd	3.42	3.46	4.71	4.40	4.00	3.41	4.11	3.45
Tb	0.67	0.67	0.83	0.85	0.79	0.69	0.80	0.67
Dy	4.62	4.54	5.41	5.93	5.44	4.66	5.48	4.26
Ho	0.99	0.94	1.26	1.29	1.17	0.96	1.15	0.93
Er	2.95	3.01	3.73	3.85	3.56	3.00	3.66	2.92
Tm	0.41	0.44	0.62	0.57	0.51	0.43	0.50	0.41
Yb	2.89	2.84	3.57	3.77	3.41	2.95	3.31	2.64
Lu	0.44	0.40	0.55	0.57	0.53	0.45	0.48	0.40

表2 变辉绿岩LA-ICP-MS锆石U-Pb测年结果

Table 2 Analyses results of LA-ICP-MS zircon U-Pb dating for the metadiabase

测点	Th(10^{-6})	U(10^{-6})	Th/U	同位素比值(±1σ)			年龄Ma(±1σ)		
				$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$
1	1 129	963	1.17	0.054 5±0.001 3	0.538 6±0.012 9	0.071 2±0.000 7	391±49.1	437±8.5	443±4.1
2	127	167	0.76	0.069 1±0.002 4	1.141 8±0.040 5	0.119 1±0.001 5	902±72.2	773±19.2	725±8.4
3	1 245	1 879	0.66	0.056 1±0.001 3	0.541 4±0.012 1	0.069 4±0.000 6	457±50.0	439±8.0	433±3.9
4	466	550	0.85	0.056 2±0.001 9	0.566 0±0.018 6	0.072 5±0.000 8	461±106	455±12.1	451±4.5
5	214	386	0.55	0.054 5±0.002 0	0.545 2±0.019 9	0.072 0±0.000 8	391±81.5	442±13.1	448±5.0
6	186	294	0.63	0.056 6±0.002 5	0.535 6±0.023 6	0.068 3±0.000 9	476±98.1	435±15.6	426±5.4
7	395	778	0.51	0.056 4±0.001 7	0.563 2±0.015 8	0.072 0±0.000 6	478±32.4	454±10.3	448±3.8
8	426	465	0.92	0.055 7±0.001 7	0.544 1±0.017 4	0.069 9±0.000 7	443±68.5	441±11.4	435±4.1
9	742	1178	0.63	0.055 1±0.001 4	0.524 5±0.013 4	0.068 3±0.000 6	417±54.6	428±8.9	426±3.8
10	535	672	0.80	0.055 2±0.001 8	0.535 3±0.016 8	0.069 7±0.000 8	420±76.8	435±11.1	434±4.5
11	116	666	0.17	0.121 0±0.003 0	5.825 3±0.137 6	0.345 4±0.003 1	1 972±43.8	1 950±20.5	1 912±14.9
12	333	711	0.47	0.054 9±0.001 6	0.535 7±0.015 7	0.070 1±0.000 7	409±66.7	436±10.4	437±4.2
13	497	523	0.95	0.055 8±0.002 0	0.529 8±0.018 1	0.068 4±0.000 8	443±79.6	432±12.0	427±4.6
14	351	467	0.75	0.064 3±0.002 1	0.996 7±0.043 4	0.109 1±0.002 9	750±69.3	702±22.1	668±16.8
15	299	618	0.48	0.053 6±0.002 1	0.532 2±0.021 7	0.071 4±0.000 9	354±90.7	433±14.4	445±5.5
16	828	838	0.99	0.053 9±0.001 9	0.532 6±0.017 7	0.071 4±0.000 8	369±84.3	434±11.7	444±4.8
17	315	469	0.67	0.052 7±0.001 8	0.580 9±0.019 4	0.079 3±0.001 0	317±75.9	465±12.4	492±5.8
18	285	461	0.62	0.106 5±0.002 6	4.444 6±0.107 5	0.299 8±0.002 9	1 740±44.8	1 721±20.1	1 690±14.5
19	1 167	1 016	1.15	0.055 6±0.001 5	0.538 0±0.014 0	0.069 6±0.000 7	435±59.3	437±9.3	434±4.2
20	371	647	0.57	0.056 0±0.001 8	0.533 9±0.016 8	0.068 9±0.000 6	454±67.6	434±11.1	429±3.8

和电磁选等方法进行分选，然后在双目镜下挑出锆石颗粒，将锆石颗粒粘在双面胶上用无色透明环氧树脂固定，待环氧树脂充分固化后，表面进行抛光至近锆石核部.锆石阴极发光(CL)图像在中国地质大学(武汉)地质过程与矿产资源国家重点实验室(GPMR)利用扫描电子显微镜完成，分析电压15 kV.锆石U-Pb年龄分析数据在GPMR利用激光剥蚀电感耦合等离子质谱仪(LA-ICP-MS)完成，激光剥蚀系统为GeoLas 2005，激光器为193 nm ArF准分子激光器，电感耦合等离子质谱仪为Agilent 7500a，激光剥蚀束斑直径为24 μm，载气为He.

锆石测年计算采用国际标准锆石91500作为外标，元素含量采用多个USGS参考玻璃(BCR-2G和BIR-1G)作为外标、Si作为内标的方法进行定量计算(Liu *et al*.，2010).锆石测年分析数据处理(包括对样品和空白信号选择、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ICPMSDataCal完成(Liu *et al*.，2008).锆石U-Pb年龄谐和图绘制和年龄权重平均值计算采用Isoplot/Ex_ver3(Ludwing，2003)完成.分析测试结果见表2.

3 岩石地球化学特征

糯垌变玄武岩、辉绿岩由于后期遭受绿片岩—角闪岩相变质变形，对相对活动元素具有一定影响(Ludden *et al*.，1982；Murphy and Hynes，1986；Polat and Hofmann，2003).因此，本研究主要采用变形变质过程中不易活动迁移的高场强元素(HFSE)Ti、Zr、Nb、Ta、Hf、Th、REE和过渡金属元素(Sc、V、Cr、Ni)进行岩石地球化学分类、成因和形成构造环境分析.

3.1 主量元素

糯垌变玄武岩、辉绿岩，在不活动元素Nb/Y-Zr/Ti岩石化学分类图中(Floyd and Winchester，1975；Pearce，1996)，均落于玄武岩区(图3a).在不活动元素Zr-Y岩浆岩系列判别图中(Polat *et al*.，2009)，均落于拉斑玄武系列基性岩区(图3b).因此，变玄武岩、辉绿岩属低钾拉斑玄武系列的基性岩.变玄武岩主量元素SiO_2含量为49.20%～51.00%，MgO含量为7.22%～9.11%，$Mg^{\#}$为56～63，TFeO/MgO为1.06～1.41，TiO_2含量为1.04%～1.27%，Na_2O/K_2O为22.79～37.63.变辉绿岩主量元素SiO_2含量为50.00%～52.30%，MgO含量为6.78%～7.75%，$Mg^{\#}$为55～60，TFeO/MgO为1.21～1.49，TiO_2含量为1.02%～1.34%，Na_2O/K_2O为14.47～31.92.上述特征表明，变玄武岩、辉绿岩均为低钾拉斑玄武岩系列的基性岩，其主量元素地球化学特征基本一致，介于典型大洋中脊

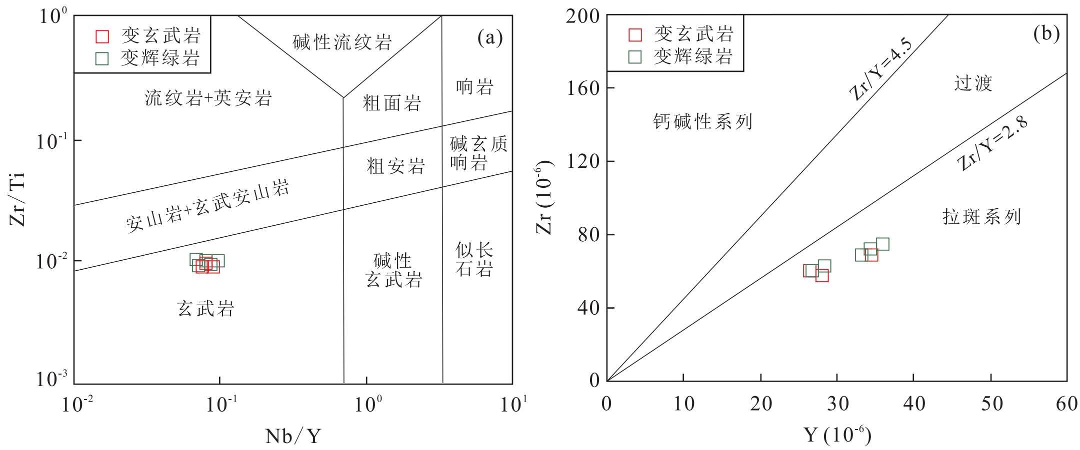

图 3　变玄武岩、辉绿岩岩石化学分类和岩浆岩系列判别

Fig.3　Geochemical classification and magmatic series discriminant diagrams of the metabasalt and metadiabase

a.Zr/Ti-Nb/Y 岩石化学分类图(Floyd and Winchester,1975;Pearce,1996);b.Y-Zr 岩浆系列判别图(Polat *et al*.,2009)

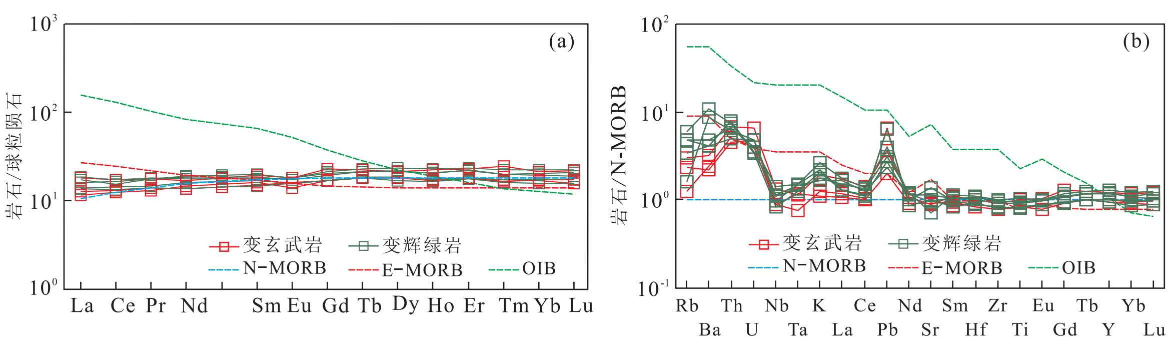

图 4　变玄武岩、辉绿岩稀土元素球粒陨石标准化配分型式(a)和微量元素 N-MORB 标准化蛛网图(b)

Fig.4　Chondrite-normalized REE diagram (a) and N-MORB-normalized trace elements spider-diagram of the metabasalt and metadiabase (b)

玄武岩(N-MORB)与过渡性洋中脊玄武岩(T-MORB)之间.

3.2　微量元素

变玄武岩稀土元素∑REE 为 $38.00\times10^{-6}\sim49.13\times10^{-6}$,$(La/Sm)_N$ 为 0.72～0.95,$(La/Yb)_N$ 为 0.68～0.86,$(Gd/Yb)_N$ 为 0.98～1.09,δEu 为 0.85～1.00.变辉绿岩稀土∑REE 为 $37.93\times10^{-6}\sim49.63\times10^{-6}$,$(La/Sm)_N$ 为 0.81～1.05,$(La/Yb)_N$ 为 0.72～0.95,$(Gd/Yb)_N$ 为 0.96～1.08,δEu 为 0.86～1.01.变玄武岩、辉绿岩在稀土元素球粒陨石标准化图中(Sun and Mcdonough,1989),表现为稀土元素配分平坦,轻稀土略亏损,无明显 Eu 异常,轻重稀土无明显分异的基本特征,这与典型洋中脊玄武岩(N-MORB)特征基本一致(图 4a).

变玄武岩微量元素 Zr/Nb 为 22.26～28.57,Zr/Y 为 2.00～2.27,Ti/Y 为 220.63～236.10,Ti/V 为 21.30～25.12,Nb/Th 为 3.4～3.9,Th/Yb 为 0.19～0.23.变辉绿岩微量元素 Zr/Nb 为 21.82～32.49,Zr/Y 为 2.07～2.25,Ti/Y=207.28～240.19,Ti/V 为 21.68～23.74,Nb/Th 为 2.1～4.1,Th/Yb 为 0.20～0.31.变玄武岩、辉绿岩在微量元素 N-MORB标准化蛛网图上(Sun and Mcdonough,1989),具有大离子亲石元素 Rb、Ba、Th、U、K、Pb 相对富集,Sr 无明显富集,高场强元素 Nb、Ta、Zr、Hf、Ti 平坦—略亏损的特征(图 4b).上述特征表明,其与形成于俯冲带之上(SSZ)构造环境具有大离子亲石元素富集、高场强元素平坦—略亏损蛇绿岩(T-MORB)中玄武岩、辉绿岩脉(岩墙)地球化学特征是一致的(Pearce,1982,2008,2014;Pearce *et al*.,1984;Dilek and Fures,2011,2014).

4　锆石 U-Pb 年代学特征

本次研究选取糯垌油茶林场场部西侧变基性岩

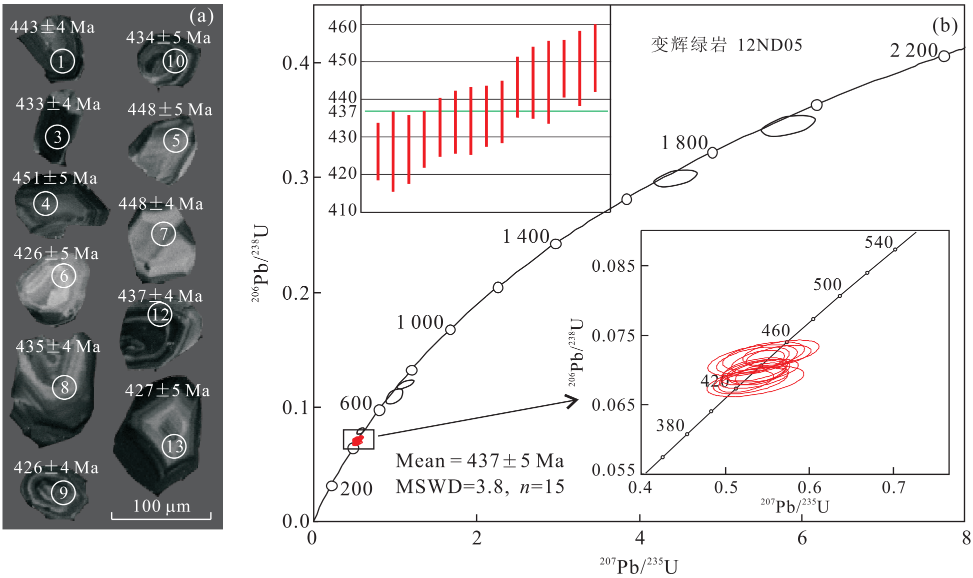

图5　变辉绿岩代表性锆石CL图像(a)及锆石年龄协和图(b)

Fig.5　Representative CL images (a) and U-Pb concordia diagram for zircons of the metadiabase (b)

系中变辉绿岩岩脉(岩墙)进行LA-ICP-MS锆石U-Pb年代学分析,测年样品(编号12ND05)采样位置坐标:23°04′53″N,111°02′46″E,在地质剖面中采样位置见图1c.变辉绿岩样品较新鲜,弱片理化变形,块状—片状构造,变余辉绿—辉长结构,主要矿物为角闪石(40%～50%)、基性斜长石(40%～45%)、磁铁矿(3%～5%)和石英(1%～2%).

变辉绿岩中锆石主要为短柱状,自形—半自形,粒度一般长为50～200 μm,宽为50～100 μm.CL图像显示大部分锆石具有清晰的岩浆韵律环带,无明显核—边结构,Th/U比为0.17～1.17,显示岩浆锆石特征(图5a).变辉绿岩20颗锆石分析测试结果见表1,其中有5颗岩浆锆石谐和年龄分别为:1 972±44 Ma、1 740±45 Ma、725±8 Ma、668±17 Ma、492±6 Ma,属捕获的继承性岩浆锆石,其余15颗锆石Th/U比为0.47～1.17,均显示典型岩浆锆石特征,锆石$^{206}Pb/^{238}U$加权平均年龄为437±5 Ma(±2σ,MSWD=3.8,n=15),置信度为95%,代表变辉绿岩成岩年龄(图5b),这一测年结果与覃小锋等(2014,会议摘要)报道的这套变基性岩系成岩年龄(444±3 Ma)基本一致.因此,糯垌变基性岩系形成时代介于早古生代晚奥陶世—早志留世(437～444 Ma)之间.

5　讨论

5.1　成因及形成构造环境

华夏地块(群)云开隆起西北缘桂东南岑溪地区出露的总体呈北东走向的糯垌变基性岩系(岩片),主要为一套经历了绿片岩—角闪岩相变形变质的玄武岩(杏仁状、枕状玄武岩)、辉绿岩岩脉(岩墙)群,由少量块状辉长岩和辉石岩组成.岩石地球化学研究显示典型钠质拉斑玄武质系列的基性岩,明显不同于俯冲带岛弧低Ti钙碱性基性岩浆岩,更有别于大陆裂谷或地幔柱作用形成的以高Ti、K为特征的碱性玄武质岩浆岩.变玄武岩、辉绿岩的稀土元素配分平坦,轻稀土亏损,$(La/Sm)_N$为0.72～1.05,$(La/Yb)_N$为0.7～1.0,无明显Eu异常,轻重稀土无明显分异,并具有大离子亲石元素Rb、Ba、Th、U、K、Pb相对富集,高场强元素Nb、Ta、Zr、Hf、Ti平坦—略亏损,Ti/V为21.30～25.12,Ce/Nb为3.2～4.5,Nb/Th为2.1～4.2的地球化学特征.上述特征表明,糯垌变玄武岩、辉绿岩具有典型亏损洋中脊玄武岩(N-MORB)与过渡性洋中脊玄武岩(T-MORB)之间的地球化学特征,这与有少量壳源物质或流体加入形成于俯冲带之上(SSZ)构造环境蛇绿岩中玄武岩、辉绿岩的地球化学特征是完全一致的(Pearce,1982,2008,2014;Pearce *et al*.,1984;张旗和周国庆,2001;史仁灯,2005;Dilek and Furnes,2011,2014;张进等,2012).

在图6a中,糯垌变玄武岩、辉绿岩均落入洋中脊玄武岩和火山弧玄武岩(MORB+VAB)区,这表明其不可能形成于陆内或板内构造环境;而在图6b中,其均落入大洋中脊(MORB)环境蛇绿岩区;在图6c中,其则落入与俯冲带之上(SSZ)构造环境蛇绿

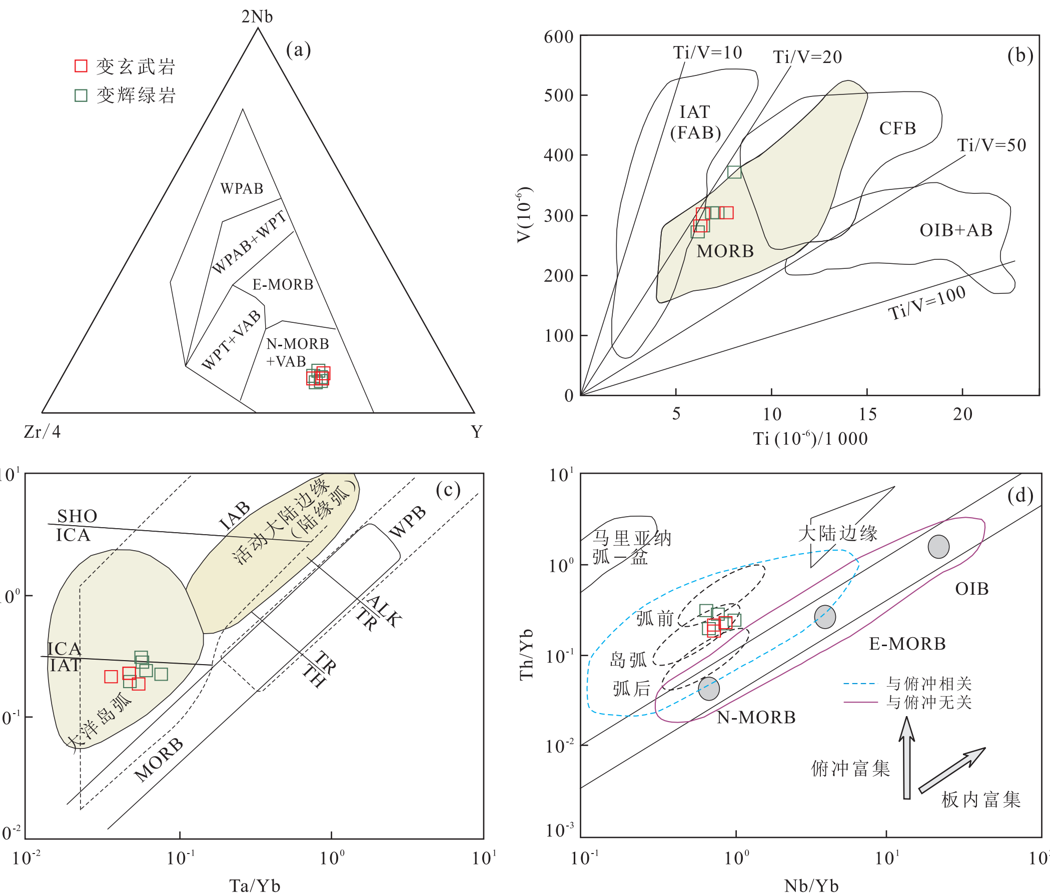

图 6　变玄武岩、辉绿岩构造环境判别图

Fig.6　Tectonic discriminant diagrams of the metabasalt and diabase

a.2Nb-Zr/4-Y 判别图解(Meschede，1986)；b.V-Ti 判别图解(Shervais，1982)；c.Th/Yb-Ta/Yb 判别图解(Pearce，1982)；d.Th/Yb-Nb/Yb 判别图解(Pearce，2008，2014；Dilek and Furnes，2011；Angerer *et al*.，2013).N-MORB.正常洋脊玄武岩；E-MORB.富集洋脊玄武岩；IAB.岛弧玄武岩；IAT.岛弧拉斑玄武岩；ICA.岛弧钙碱性玄武岩；CAB.钙碱性玄武岩；WPB.板内玄武岩；WPT.板内拉斑玄武岩；WPAB.板内碱性玄武岩；OIB.洋岛玄武岩；AB.弧玄武岩；SHO.钾玄岩；CFB.大陆溢流玄武岩；FAB.弧前玄武岩

岩区；在图 6d 中，其均落入俯冲带之上(SSZ)构造环境蛇绿岩区，并在弧前(FAB)、岛弧(AB)和弧后(BAB)蛇绿岩判别图上(Angerer *et al*.，2013)，落入俯冲带之上构造环境的弧间—弧前蛇绿岩区.上述成因构造环境判别结果表明，糯垌变基性岩系属早古生代晚奥陶世—早志留世(437～444 Ma)，形成于俯冲带之上(SSZ)构造环境的弧前蛇绿岩，其可能是在俯冲板片后撤弧前扩张构造环境下形成的具少量俯冲板片壳源物质或流体加入影响的弧前洋壳(图 7)，后期又遭受挤压逆冲剪切构造肢解的洋壳残片.如果结合笔者最新在早古生代糯垌蛇绿岩东侧十几千米处的大爽、白板一带(图 1b)发现和识别的一套早古生代早志留世形成于俯冲岛弧弧前构造环境的高镁—镁质玄武安山岩—安山岩(赞岐岩)—英安岩系(430～441 Ma，另文发表)，则更进一步表明早古生代糯垌蛇绿岩应形成于弧前构造环境.

桂东南岑溪地区糯垌一带变基性岩系及围岩野外地质构造的研究表明，变形变质杏仁状、枕状玄武岩、辉绿岩岩脉(岩墙)群，以及少量辉长岩、辉石岩呈构造接触产出，并与上覆和下伏变形变质奥陶纪云母石英片岩、石英岩、变质粉砂岩等深海—半深海复理石建造呈构造接触关系，普遍发育产状近于一致向南东高角度倾斜的挤压剪切构造片理、构造透镜体，显示它们与围岩共同经历了一期由南东向北西的强烈挤压剪切逆冲推覆构造变形变质事件，而且其上覆强构造变形变质分异或“混合岩化”的奥陶系(云母片岩、云母石英片岩、石英片岩等)与下伏弱变形变质的奥陶系(变质泥岩、粉砂岩、变质砂岩等)，两者在岩石组合、变形变质特征等方面呈现出明显差异，显然不是一套正常连续沉积地层系统，而可能是由南东向北西挤压逆冲推覆形成的构造岩片叠置地层系统.此外，侵入强变形奥陶纪—志留纪浅

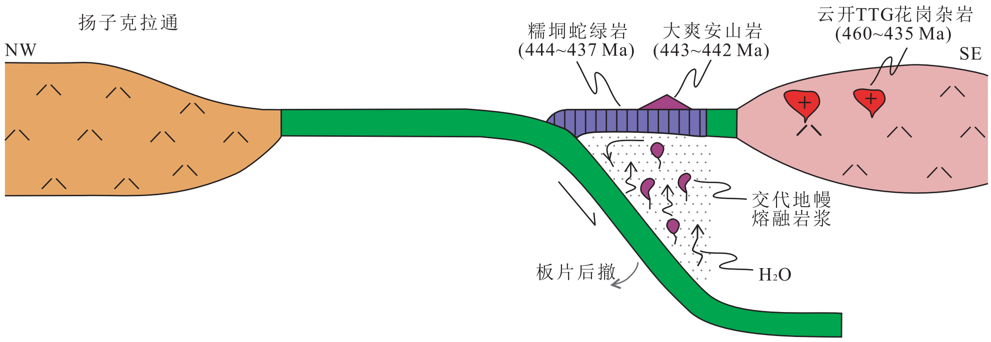

图 7 桂东南早古生代蛇绿岩和高镁－镁质玄武岩－安山岩成因示意

Fig.7 Genetic sketch of Early Paleozoic ophiolite and high magnesian-magnesian basalt-andesite in the southeastern Guangxi

变质地层以及弱/未变形变质泥盆纪地层的中生代印支期、燕山期花岗岩均未发生透入性构造变形.因此,笔者推断这期由南东向北西挤压剪切逆冲推覆变形变质事件对应于早古生代志留纪末的加里东期构造运动(即广西运动).

上述特征表明,岑溪地区糯垌变基性岩系(岩片)应属早古生代晚奥陶世－早志留世形成于俯冲带之上(SSZ)弧前构造环境的蛇绿岩,并遭受加里东期由南东向北西挤压逆冲推覆构造作用的强烈改造和肢解.

5.2 大地构造意义

华南地区扬子克拉通与华夏地块(群)之间早古生代加里东期造山运动(广西运动)性质是陆内或板内造山,还是俯冲－碰撞造山,近年来成为许多华南大地构造研究者关注和争论的一个焦点和热点问题.而解决这一重大地质问题的两个判决性证据是:早古生代蛇绿岩和岛弧火山岩是否存在.虽然许多研究者已从沉积地层、岩浆岩、变质岩、构造等方面提供了大量华南加里东期造山属板块构造体制下俯冲－碰撞造山的地质证据,但一直未发现早古生代的蛇绿岩.因此,桂东南地区岑溪早古生代糯垌蛇绿岩的发现,无疑为华夏存在早古生代洋盆和洋壳俯冲－碰撞造山作用提供了关键性的证据.最近,易立文等(2014)在广东粤北韶关地区河口、上洞一带发现的早古生代晚奥陶世(449 Ma)英安岩;覃小锋等(2015)在广西桂东鹰扬关地区发现识别的早古生代志留世(415 Ma)与俯冲－消减作用有关的细碧岩、石英角斑岩及相关火山碎屑岩,也都为华夏地区存在与加里东期洋壳俯冲有关的岛弧火山岩浆活动提供了新的重要证据.而于津海等(2014)在赣东北弋阳县南发现的经历早古生代中－高压高温麻粒岩相变质(436 Ma)的麻粒岩;陈相艳等(2015)、Zhang *et al*.(2015)在浙江龙游发现的经历早古生代高压榴辉岩相变质(440 Ma)的石榴石角闪岩(退变榴辉岩),则为扬子与华夏之间存在加里东期俯冲－碰撞有关的高压麻粒岩－榴辉岩相变质事件提供了新的重要证据.云开隆起西北缘桂东南地区岑溪早古生代糯垌蛇绿岩的发现暗示,华夏地块(群)可能属东冈瓦纳大陆的一部分,在古特提斯洋打开之前,东冈瓦纳大陆和劳亚大陆之间应存在一个原特提斯洋,或新元古华南残留洋盆,新元古晋宁造山运动扬子与华夏之间并未完全闭合(Lin *et al*.,2015).

实际上,从两广交界云开隆起区大规模出露形成于早古生代晚奥陶世－早志留世俯冲－碰撞构造环境具 TTG 特征的深熔花岗杂岩带(彭松柏等,2006;覃小锋等,2013),到云开隆起区西北缘桂东南岑溪大爽早古生代早志留世弧前高镁－镁质玄武安山岩－安山岩(赞岐岩)－英安岩系,再到大爽西侧的糯垌早古生代晚奥陶世－早志留世弧前蛇绿岩(图 1b),在空间上恰好构成华夏造山系南部早古生代加里东期洋盆由北西向南东俯冲－增生碰撞造山形成的一套弧前增生构造蛇绿岩混杂岩浆岩组合(李继亮,2004,2009;潘桂棠等,2008).这与华南扬子与华夏之间早古生代前陆或弧前盆地沉积地层由南东向北西逐次迁移推进演化的特征(李曰俊等,1993;刘宝珺等,1993;尹福光等,2001;陈洪德等,2006;Su *et al*.,2009;杜远生和徐亚军,2012;何卫红等,2015)、早古生代地层不整合界面时代由南东向北西逐步迁移变新的特征(吴浩若,2005;许效松等,2012;陈旭等,2012)、加里东期－印支期构造变形由南东向北西韧性剪切逆冲推覆的基本特征都是完全一致的(丘元禧和梁新权,2006;林伟等,2011).因此,华南扬子克拉通与华夏地块之间大致沿钦杭构造带一线早古生代加里东期造山运动属板块构造

体制下的俯冲—增生碰撞造山.

6 结论

(1)桂东南岑溪糯垌变基性岩系构造岩片是一套早古生代(437～444 Ma)形成于俯冲带之上(SSZ)弧前构造环境被肢解的蛇绿岩残片.

(2)桂东南岑溪糯垌早古生代蛇绿岩的发现识别表明,华南扬子克拉通与华夏地块群之间存在早古生代洋盆和俯冲—增生碰撞造山运动.

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