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赣东北枣林碧玄岩地球化学特征及成因

吴美仁[1],陈祺[1],王先广[2],陈国华[1],万浩章[1],严加永[3],欧阳永棚[1]

(1. 江西省地质矿产勘查开发局九一二大队,江西 鹰潭 335001;2. 江西省地质勘查基金管理中心,江西 南昌 330025;3. 中国地质科学院深部探测中心, 北京 100037)

提要:在中国东部赣东北朱溪矿集区枣林地段发现两条新生代碧玄岩岩脉。地球化学研究表明该碧玄岩具有低 SiO_2(41.08%~42.94%),高 $Mg^{\#}$(0.61~0.65),高 TiO_2(2.19%~2.43%),高 Na_2O+K_2O(4.95%~6.30%)的特点。∑REE为 299.16×10^{-6}~375.00×10^{-6},LREE/HREE比值为5.45~6.71,表明轻稀土富集,δEu为0.88~0.94,具微弱Eu负异常。微量元素特征表现出较高Ni、Cr、Sc含量,蛛网图显示明显富集Nb、Ta、Th、Zr等元素,亏损Ba、Ti、K、P等。主量元素相关图解和不相容元素比值显示岩石在演化过程中未遭受地壳混染。综合分析岩石微量元素数据及相关图解,文章认为由于太平洋板块俯冲,导致软流圈地幔携带碳酸盐熔体上涌与岩石圈地幔相互作用,使得0.2%~0.5%石榴石相二辉橄榄岩与0.5%~1%尖晶石相二辉橄榄岩发生部分熔融,生成碧玄岩原始岩浆。

关 键 词:碧玄岩;地球化学特征;岩石成因;朱溪矿集区;枣林地区

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Geochemistry and petrogenesis of the Zaolin basanite in the northeastern Jiangxi Province

WU Meiren[1], CHEN Qi[1], WANG Xianguang[2], CHEN Guohua[1], WAN Haozhang[1], YAN Jiayong[3], OUYANG Yongpeng[1]

(1. *No. 912 Geological Surveying Party, Jiangxi Bureau of Geology and Mineral Exploration and Development, Yingtan* 335001, *Jiangxi, China;* 2. *Administration of Geological Exploration of Jiangxi Province, Nanchang* 330025*, Jiangxi, China;* 3. *China Deep Exploration Center−SinoProbe Center, Chinese Academy of Geological Sciences, Beijing* 100037*, China)*

Abstract: Two Cenozoic basanite dykes were newly discovered in the Zhuxi ore−concentration area, northeastern Jiangxi Province, eastern China. They have high SiO_2 (41.08%−42.94%), Na_2O+K_2O (4.95%−6.30%), TiO_2 (2.19%−2.43%) contents, and high Mg# (0.61 − 0.65). Geochemistry characteristics of these basanite dykes show they are enriched in Nb, Ta, Th, Zr, Ni, Cr, Sc, while depleted in Ba, Ti, K, and P. Their ∑REE values are from 299.16×10^{-6} to 375.00×10^{-6} % with LREE/HREE ratios of 5.45−6.71 and

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作者简介:吴美仁,男,1966年生,高级工程师,从事地质勘查工作;E−mail:1067992037@qq.com。

通讯作者:欧阳永棚,男,1988年生,硕士,工程师,从事地质勘查工作;E−mail:yongpeng0524@163.com。

δEu values of 0.88 to 0.94. According to the geochemical discrimination diagrams and the ratios of incompatible elements, we suggest that the basanite dykes were derived from partial melting of garnet forsterite (0.2%−0.5%) and herzolite (0.5%−1%), which may be caused by upwelling of carbonate melt in the asthenosphere mantle in response of the subduction of the Paleo−Pacific Ocean.

Key words: basanite; geochemistry; petrogenesis; Zhuxi ore−concentration area; Zaolin area

About the first author: WU Meiren, male, born in 1966, senior engineer, mainly engages in geological prospecting and research; E−mail: 1067992037@qq.com.

About the corresponding author: OUYANG Yongpeng, male, born in 1988, master, engineer, mainly engages in geological exploration; E−mail: yongpeng0524@163.com.

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1 引 言

自华北板块与扬子板块拼接以后,由于古太平洋板块与欧亚板块碰撞导致中国东部地区成为活动大陆边缘;随后燕山早期到中期,发生了一系列地壳转换和岩石圈减薄事件;新生代中国东部进入大陆裂谷阶段(Molan et al., 1987; Hsü et al., 1990; Menzies et al., 1993; Charvet et al., 1994; 胡受奚等, 1994; Zhou et al., 2000; 徐夕生等, 2005; 张建芳等, 2017; 蔡逸涛等, 2018; 王帅等, 2018; 刘伟等, 2018)。

在中国东部广泛分布有大量新生代碱性玄武岩,其具有类似OIB型玄武岩微量元素特征(Zhou et., 1982; Tang et al., 2006; Liu et al., 2008; Chen et al., 2009; Zhang et al., 2009; Zeng et al., 2010, 2011; Xu et al., 2012; Zhang et al., 2017)。大陆碱性玄武岩在岩石圈中运移速度快,成分可接近于原始岩浆成分,因而大陆碱性玄武岩是研究大陆岩石圈的主要研究对象(Farmer, 2007)。

在江西省,除了在抚州广昌、萍乡安源等地发现了少量新生代基性岩脉外,新生代玄武岩鲜有报道。此次,在朱溪矿集区枣林地段发现了两条基性岩脉。前人在塔前幅1:5万地质图说明书中将其定名为苦橄玢岩;江西省地质矿产勘查开发局九一二大队在2017年所编写的《朱溪铜钨矿成矿模式与成矿预测示范研究成果报告》中将其定名为碱性玄武玢岩❶;Pan et al.(2019)对其重新开展矿物学研究,发现基质中有霞石的存在,将其重新定名为碧玄岩,且对其进行Ar−Ar测年,获得其成岩年龄为(44.05±0.52)Ma。因此,本文认为在朱溪矿集区枣林地段发现的两条基性岩脉为新生代碧玄岩脉。目前,前人对江西省新生代岩浆活动的研究相对欠缺。本文拟通过研究枣林碧玄岩岩石地球化学特征,探讨江西省新生代地幔源区特征及碧玄岩成因。

2 区域地质背景

枣林位于江西省景德镇市南部,该区主要出露有新元古代浅变质岩,部分地区出露呈NE向展布的晚古生代—中生代海陆交互相−浅海碳酸盐台地相碳酸盐岩和含煤碎屑岩;断裂构造主要呈NE向展布;晚侏罗世—早白垩世花岗岩侵入于二叠纪灰岩、白云岩中(图1)。枣林地区见有2条碧玄岩岩脉,一条呈NE 45°展布,倾向315°,倾角46°;另一条受构造控制明显,在两组断裂交汇处,脉体明显膨大,宽达20~30 m,与围岩接触界线清晰,脉壁平直,未见明显围岩蚀变。野外可见后期褶皱变形将其错断发生位移(图2a),在岩脉中还见有较多围岩捕掳体。碧玄岩岩脉侵位于石炭—二叠纪含炭灰岩,且与围岩接触部位发育构造角砾岩,局部烘烤现象明显。

3 岩相学特征与测试方法

枣林碧玄岩呈铁灰色,风化后为灰黑色,斑状结构,块状构造。岩石主要由斑晶橄榄石(15%)、辉石(5%)和基质(80%)组成。橄榄石斑晶呈短柱状,自形,粒径0.2~0.8 mm,裂纹发育,沿裂纹可见有蛇纹石化;辉石斑晶呈柱状,自形,粒径0.2~0.8 mm,具辉石式解理;基质具显微粒状、显微柱状结构,由大量微晶斜长石、辉石、橄榄石及基质等组成(图3)。副矿物有磁铁矿、白钨矿和黄铜矿等。

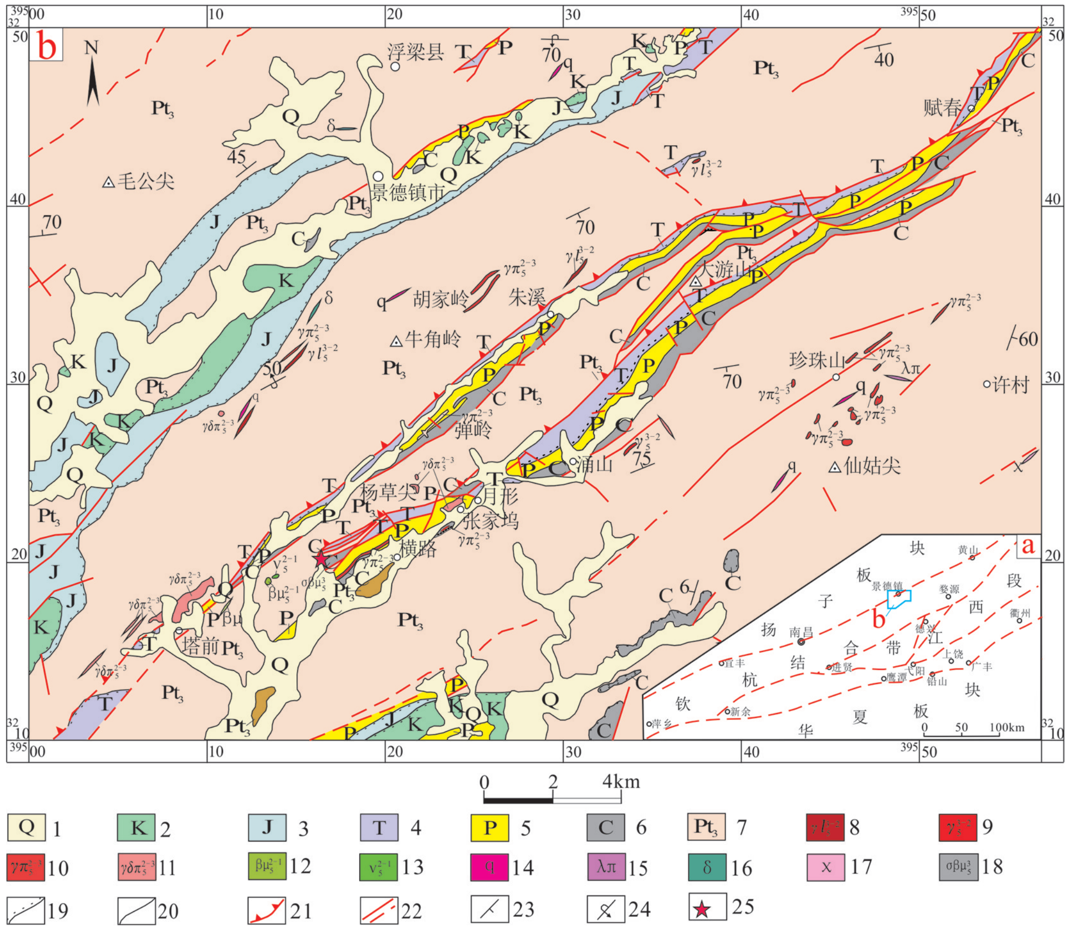

图1 枣林地区区域地质简图

1—第四系;2—白垩系;3—侏罗系;4—三叠系;5—二叠系;6—石炭系;7—新元古界;8—白垩纪花岗细晶岩;9—白垩纪细粒花岗岩;10—白垩纪花岗斑岩;11—白垩纪花岗闪长斑岩;12—白垩纪辉绿岩;13—白垩纪辉长岩;14—石英脉;15—流纹斑岩;16—闪长(玢)岩二长岩;17—煌斑岩;18—碧玄岩;19—不整合接触界线;20—地质界线;21—逆冲推覆断层;22—实(推)测断层;23—岩层产状;24—倒转岩层产状;25—采样点

Fig.2 Regional geological and mineral resources map of the Zaolin area

1–Quaternary; 2–Cretaceous; 3–Jurassic; 4–Triassic; 5–Permian; 6–Carboniferous; 7–Neoproterozoic Wannian Group; 8–Cretaceous fine-grained rock; 9–Cretaceous fine-grained granite; 10–Cretaceous granite porphyry; 11–Cretaceous granite diorite porphyry; 12–Cretaceous diabase; 13–Cretaceous gabbro; 14–Quartz vein; 15–Rhyolitic porphyry; 16–Porphyrite monzonite; 17–Lamprophyre; 18–Basanite; 19–Unconformity boundary; 20–Geological boundary; 21–Thrust nappe fracture; 22–Measured/inferred fracture; 23–Stratigraphic attitude; 24–Attitude of overturned strata; 25–Sampling point

样品较为新鲜,测试工作在江西省地质矿产开发局九一二大队实验室完成,主量、微量元素分别在美国PerKinELmer电感耦合等离子体发射光谱仪(ICP−OES)和美国赛默飞电感耦合等离子体质谱仪(ICP−MS)上进行分析,分析精度优于2%~5%。分析方法和过程详见刘颖等(1996)论述。

4 岩石学地球化学特征

本次研究共采集了10个碧玄岩样品,主量元素和微量元素测试结果详见表1。岩石中SiO_2含量为41.08%~42.94%(平均为42.07%);MgO含量为9.77%~11.46%(平均10.94%);Na_2O含量为3.27%~4.45%(平均4.06%),K_2O含量为1.00%~1.90%(平均1.44%),Na_2O+K_2O含量为4.95%~6.30%(平均5.50%);Al_2O_3含量为11.44%~12.28%(平均11.81%);TiO_2含量相对较均匀为2.19%~2.43%(平均2.30%);P_2O_5含量为0.36%~0.80%(平均0.62%);A/CNK值为0.688~0.797,A/NK值为1.92~2.36,$Mg^{\#}$为0.61~0.65。$SiO_2-(Na_2O+K_2O)$分类图解上岩石主要落入碧玄岩区(图4)。岩石总体上呈现出高碱、高铝、高钛、高磷的特点。随着MgO含量增加,CaO、P_2O_5含量逐渐升高,Al_2O_3含量呈现升高趋势,K_2O+Na_2O含

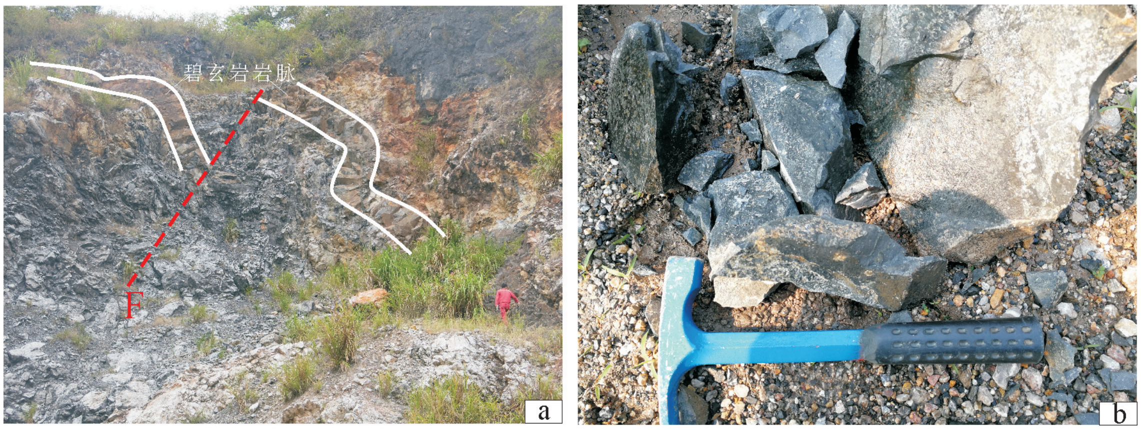

图2 枣林碧玄岩的野外特征

Fig.2 Outcrop characteristics of Zaolin basanite

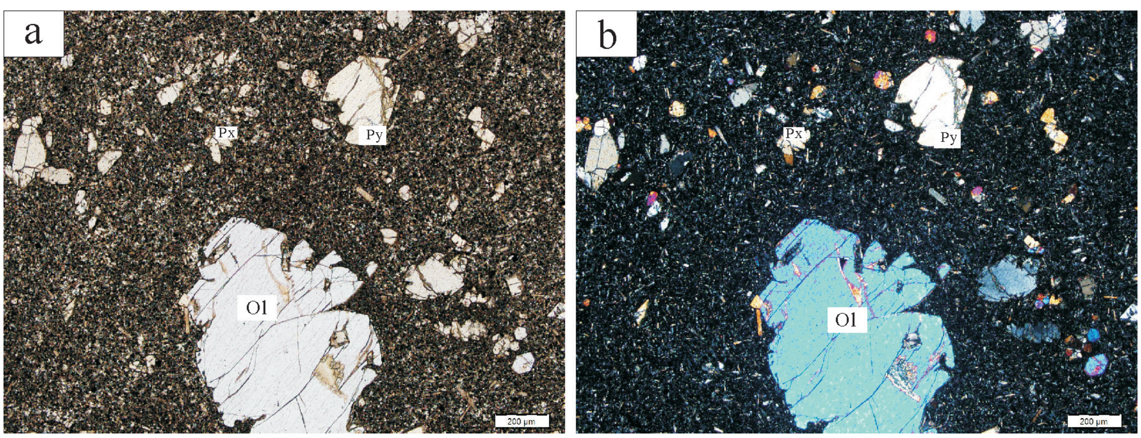

图3 枣林碧玄岩显微照片

a—正交偏光;b—单偏光;Ol—橄榄石;Px—辉石;Py—黄铁矿

Fig.3 Microphotograph of Zaolin basanite

a−Crossed nicols; b−Plainlight; Ol−Olivine; Px−Pyroxene; Py−Pyrite

量逐渐降低,TiO_2含量变化不明显(图5)。

样品稀土总量∑REE为299.16×10^{-6}~375.00×10^{-6}(平均为346.08×10^{-6}),$(La/Yb)_N$比值为25.42~37.01(平均为32.08),LREE/HREE比值为5.45~6.71(平均为6.10),属于轻稀土富集。δEu为0.88~0.94,具微弱Eu负异常(图6a)。微量元素特征表明该类岩石中具有较高的Ni(309.8×10^{-6}~378.7×10^{-6})、Cr(285×10^{-6}~467×10^{-6})、Sc(16.33×10^{-6}~19.41×10^{-6});微量元素原始地幔分布蛛网图(图6b)显示岩石明显富集Nb、Ta、Th、Zr等元素,亏损Ba、Ti、K、P等元素。

5 讨　论

5.1 地壳混染

枣林碧玄岩元素具有如下特征:低SiO_2(41.08%~42.94%),高$Mg^{\#}$(0.61~0.65)、Ni(309.8×10^{-6}~378.7×10^{-6})、Cr(285×10^{-6}~467×10^{-6})、Co(59.63×10^{-6}~67.86×10^{-6})、Sc(16.33×10^{-6}~19.41×10^{-6}),表明碧玄岩岩浆具有原生幔源岩浆性质。显微镜下观察,可发现岩石样品中具有大量火山玻璃。因此,本文认为枣林碧玄岩是原始岩浆固结的产物。

原始岩浆在源区产生后,向上运移过程中,不可避免地会与地壳岩石发生接触,导致玄武岩岩浆的成分变化,这种经历混染作用的岩石并不能够反映原始岩浆的成分。样品中Nb/U值为26.73~33.31(平均为30.67),接近于原始地幔(Nb/U值为30),明显高于陆壳(Nb/U值为10);Zr元素(736×10^{-6}~1075×10^{-6})和Nb元素(90.51×10^{-6}~123.3×10^{-6})明显高于地壳值(Gao et al., 2002);在Ba/Th−Nb/U和Nb/La−

表1 枣林碧玄岩全岩主量(%)、微量元素含量(10^{-6})分析结果

Table 1 Whole rock analyses of major (%) and trace (10^{-6}) elements of Zaolin basanite

样品编号	ZL-YQ1	ZL-YQ2	ZL-YQ3	ZL-YQ4	ZL-YQ5	ZL-YQ6	ZL-YQ7	ZL-YQ8	ZL-YQ9	ZL-YQ10
SiO_2	41.74	42.94	42.24	42.36	41.58	42.28	42.08	42.80	41.60	41.08
Al_2O_3	11.70	11.51	11.97	11.86	11.89	11.79	12.08	12.28	11.64	11.44
Fe_2O_3	1.95	2.45	2.46	3.99	4.72	3.70	2.98	4.73	4.39	3.79
TiO_2	2.35	2.20	2.32	2.33	2.36	2.19	2.36	2.43	2.26	2.24
FeO	9.26	8.81	8.88	7.33	7.33	8.49	8.23	6.95	7.27	7.53
MnO	0.18	0.19	0.18	0.18	0.18	0.19	0.18	0.17	0.18	0.17
CaO	9.37	9.06	9.86	10.28	10.72	9.47	9.89	10.06	10.32	11.67
MgO	11.45	11.39	11.11	10.58	10.63	11.46	11.35	10.60	11.02	9.77
K_2O	1.50	1.90	1.15	1.00	1.12	1.88	1.85	1.01	1.32	1.68
Na_2O	4.28	3.68	4.28	4.03	4.12	4.22	4.45	4.34	3.94	3.27
P_2O_5	0.44	0.36	0.50	0.70	0.70	0.50	0.70	0.80	0.70	0.80
$Mg^{\#}$	0.65	0.65	0.64	0.63	0.62	0.63	0.65	0.63	0.64	0.61
K_2O+Na_2O	5.78	5.58	5.43	5.03	5.24	6.10	6.30	5.35	5.26	4.95
A/CNK	0.772	0.786	0.783	0.774	0.745	0.757	0.746	0.797	0.747	0.688
A/NK	2.02	2.06	2.20	2.36	2.27	1.93	1.92	2.29	2.22	2.31
La	75.80	73.67	76.07	64.35	79.33	74.42	71.42	81.11	70.19	69.86
Ce	143.93	135.19	141.53	116.59	141.13	136.72	129.87	145.28	129.87	126.09
Pr	15.69	14.72	15.51	12.86	15.99	14.90	14.23	16.30	14.03	14.03
Nd	63.47	59.23	63.27	50.68	62.37	60.70	57.22	65.92	58.00	56.32
Sm	11.63	11.14	11.35	9.61	11.70	11.64	10.65	12.14	10.63	10.62
Eu	3.55	3.25	3.51	2.85	3.49	3.40	3.19	3.65	3.17	3.12
Gb	11.37	10.81	11.19	9.46	11.84	11.53	10.95	12.23	10.53	10.86
Tb	1.30	1.27	1.32	1.11	1.39	1.42	1.30	1.39	1.22	1.29
Dy	5.75	5.83	5.86	5.23	6.52	6.68	6.17	6.39	5.56	6.15
Ho	0.94	0.95	0.95	0.86	1.12	1.15	1.05	1.02	0.93	1.00
Er	2.11	2.21	2.21	2.00	2.62	2.80	2.47	2.38	2.13	2.30
Tm	0.24	0.27	0.26	0.23	0.30	0.33	0.29	0.26	0.25	0.27
Yb	1.47	1.64	1.60	1.39	1.88	2.10	1.75	1.62	1.52	1.65
Lu	0.19	0.22	0.21	0.19	0.25	0.27	0.23	0.22	0.20	0.22
Y	23.43	24.00	23.55	21.73	28.54	29.08	26.48	25.09	22.80	25.25
∑REE	360.87	344.41	358.39	299.16	368.47	357.14	337.28	375.00	331.04	329.02
LREE	314.06	297.20	311.24	256.94	314.00	301.78	286.59	324.40	285.90	280.05
HREE	46.81	47.20	47.15	42.22	54.46	55.36	50.69	50.60	45.14	48.97
LREE/HREE	6.71	6.30	6.60	6.09	5.77	5.45	5.65	6.41	6.33	5.72
δEu	0.93	0.89	0.94	0.90	0.90	0.89	0.90	0.91	0.91	0.88
Li	13.08	24.30	14.75	13.52	11.10	17.23	14.98	11.30	12.93	12.91
Be	4.94	6.50	4.88	5.61	5.15	5.98	6.09	4.68	4.19	5.24
Sc	17.81	18.32	19.41	18.74	17.97	16.99	18.25	18.24	18.10	16.33
Ti	14076	13210	13904	13950	14135	13156	14134	14565	13554	13416
V	199	201	207	203	200	188	198	199	198	181
Cr	285	467	426	409	339	326	359	367	354	385
Co	61.32	63.77	63.46	64.70	62.16	65.34	62.55	59.63	67.86	62.33
Ni	309.8	339.1	326.3	341.2	318.6	342.9	332.0	315.8	378.7	349.8
Cu	51.14	64.06	57.14	59.01	57.27	70.42	60.05	54.78	57.65	51.38

续表1

样品编号	ZL-YQ1	ZL-YQ2	ZL-YQ3	ZL-YQ4	ZL-YQ5	ZL-YQ6	ZL-YQ7	ZL-YQ8	ZL-YQ9	ZL-YQ10
Zn	163.2	232.2	169.4	171.0	217.0	242.0	174.7	143.7	152.5	130.3
Ga	25.38	25.46	26.00	25.90	25.88	24.76	25.79	24.44	24.74	23.35
Ge	3.21	2.91	2.84	2.97	2.81	2.79	2.85	2.80	2.77	2.59
Rb	41.60	46.60	42.11	48.01	37.03	38.84	35.98	44.43	46.84	45.93
Sr	1194	1162	1188	1176	1165	1135	1232	1144	1166	1097
Zr	736	1009	1071	1057	1075	979	1068	1056	1064	970
Nb	100.6	107.9	123.3	120.3	113.8	106.5	112.1	111.6	112.5	96.51
Mo	8.36	17.57	12.92	11.28	16.82	11.80	10.79	9.81	10.99	10.24
Sb	0.35	0.75	0.88	0.92	0.74	0.56	0.85	0.79	1.15	2.18
Cs	2.61	6.61	2.66	6.05	2.67	5.93	3.37	7.31	14.24	34.55
Ba	384	484	377	379	394	421	424	467	446	438
Hf	14.21	17.72	18.85	18.71	19.09	17.20	18.59	18.68	19.09	16.80
Ta	7.23	7.21	7.19	7.53	7.51	7.05	8.16	8.60	9.33	7.00
W	1.34	25.10	7.83	5.15	8.21	9.68	5.40	5.25	5.50	4.58
Pb	9.81	17.63	11.73	15.25	14.53	19.16	15.72	11.87	15.65	12.11
Bi	0.43	5.12	1.81	1.16	0.95	2.18	1.34	0.79	1.50	0.80
Th	9.36	10.80	11.11	10.89	10.90	10.82	10.75	10.47	10.64	9.85
U	3.04	4.04	3.71	3.61	3.78	3.72	3.65	3.53	3.70	3.32
As	19.02	12.63	5.19	5.34	6.41	7.46	8.67	4.59	7.61	9.55
Ag	0.17	0.28	0.18	0.18	0.23	0.24	0.15	0.15	0.27	0.21
Sn	2.81	17.63	3.39	3.04	4.70	8.29	3.10	3.38	5.39	3.76
La/Sm	6.52	6.62	6.70	6.70	6.78	6.39	6.70	6.68	6.60	6.58
La/Ta	10.48	10.22	10.58	8.55	10.56	10.56	8.75	9.44	7.52	9.97
Th/U	3.08	2.67	3.00	3.02	2.88	2.91	2.94	2.97	2.87	2.97
Nb/U	33.05	26.73	33.28	33.31	30.08	28.67	30.67	31.65	30.38	29.10
Th/Ta	1.29	1.50	1.55	1.45	1.45	1.53	1.32	1.22	1.14	1.41
Rb/Sr	0.035	0.040	0.035	0.041	0.032	0.034	0.029	0.039	0.040	0.042
Ba/Rb	9.23	10.39	8.96	7.89	10.64	10.83	11.78	10.51	9.52	9.53

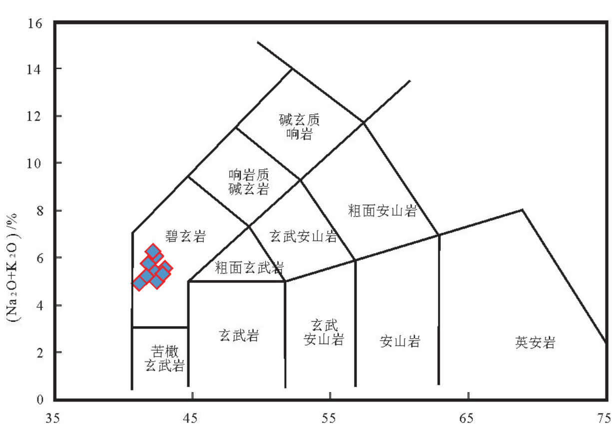

图4 枣林碧玄岩 SiO_2−K_2O+Na_2O 图解
Fig.4 SiO_2−(K_2O+Na_2O) plots of Zaolin basanite

Nb/U图解中,可以看出样品远离大陆地壳(图7);同时,在显微镜下观察,并未发现任何地壳捕虏晶。以上特征均表明枣林地区碧玄岩并没有受到地壳混染。

5.2 源区特征

实验岩石学研究表明,贫硅辉石岩或榴辉岩、碳酸盐化橄榄岩、角闪岩部分熔融可以形成碱性玄武岩 (Hirschmann et al., 2003; Kogiso et al., 2006; Dasgupta et al., 2007)。对于中国东部大陆新生代碱性玄武岩的源区,目前主要有两种观点:一是低硅玄武岩的地幔源区为贫硅辉石岩与富含角闪石的岩石部分熔融,高硅玄武岩形成于富硅辉石岩和橄榄岩部分熔融(钱生平等,2015);二是源区为碳酸盐化橄

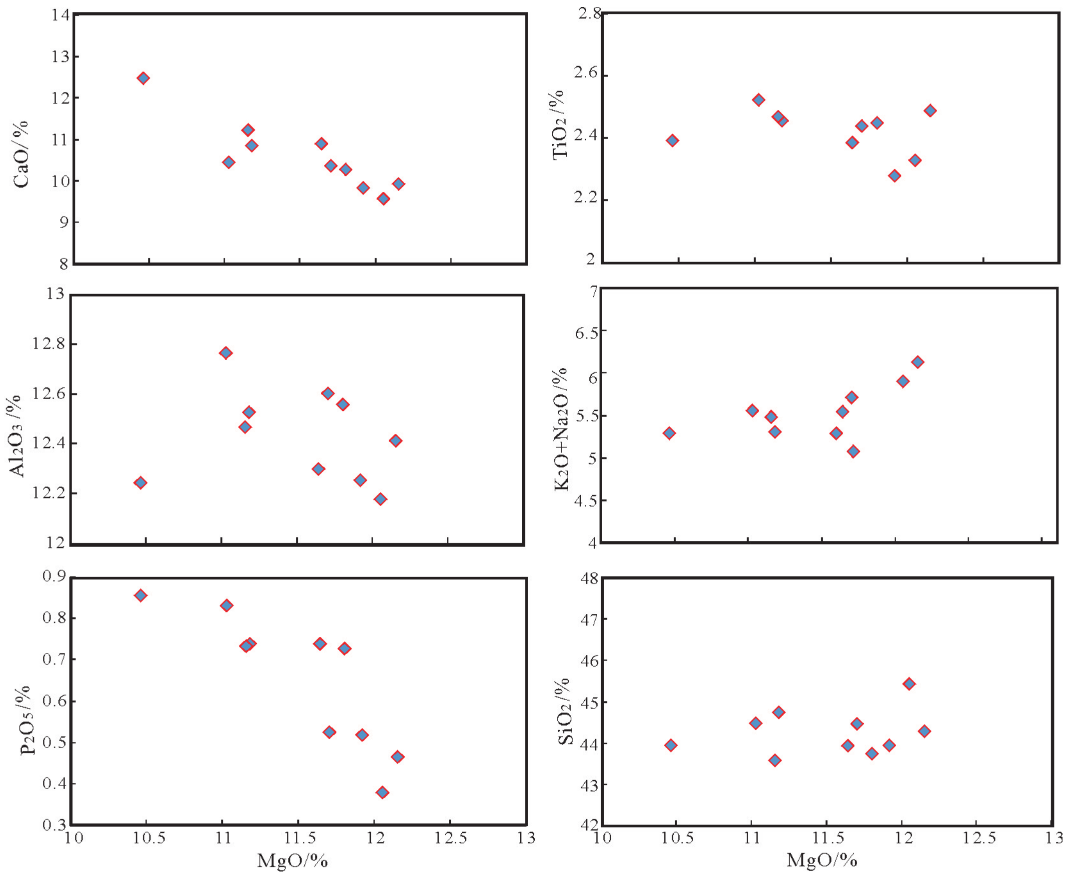

图5 枣林碧玄岩的哈克图解
Fig.5 Harker diagrams of Zaolin basanite

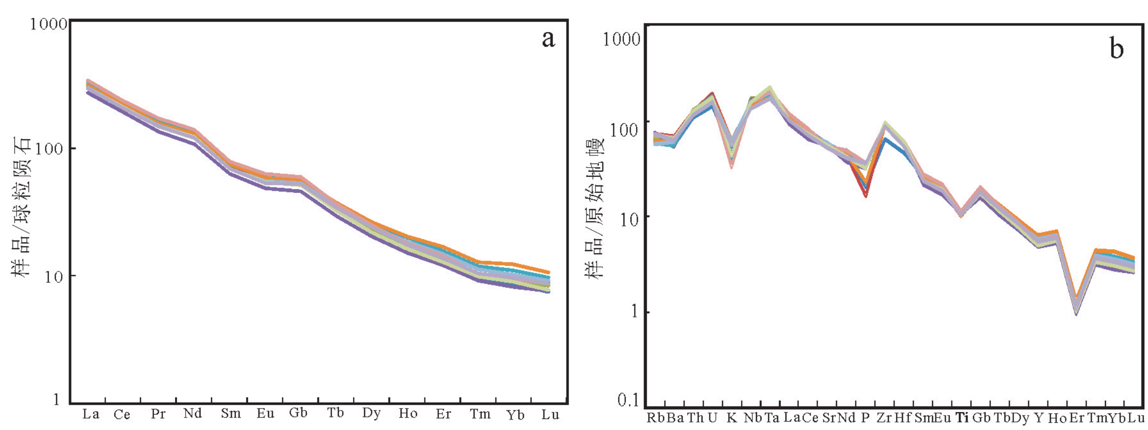

图6 枣林碧玄岩的球粒陨石标准化稀土配分曲线(a)和微量元素原始地幔标准化图解(b)
(标准化数据来源Sun et al., 1989)
Fig.6 Chondrite−normalized REE patterns (a) and primitive mantle−normalized trace element patterns (b) of Zaolin basanite
(normalized data from Sun et al., 1989)

榄岩部分熔融(Zeng, 2010;陈立辉等,2012)。

枣林地区碧玄岩样品具有较高的CaO含量(9.06%~11.67%),显示源区为橄榄岩,而不是辉石岩。样品富集LREE,原始地幔标准化图上具有Rb、Ba、K、P、Ti负异常,Nb、Ta、Th、Zr正异常,显示源区富集地幔特征。样品中高Sm/Yb比值表明原岩具

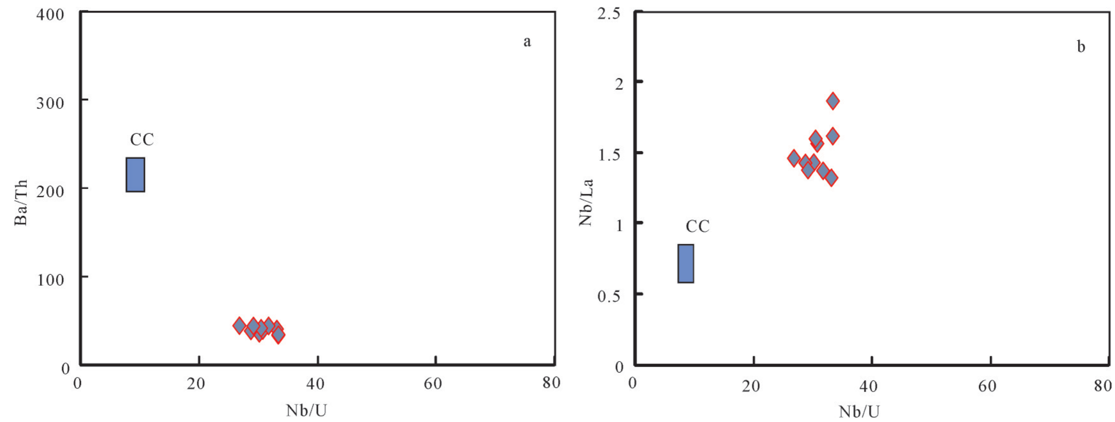

图7 枣林碧玄岩Ba/Th−Nb/U(a)和Nb/La−Nb/U(b)图解(CC−大陆地壳，数据来源Rudnick et al., 1995)
Fig.7 Diagram of Ba/Th−Nb/U (a) and Nb/La−Nb/U(b) for Zaolin basanite (CC−Continental Crust, data from Rudnick et al., 1995)

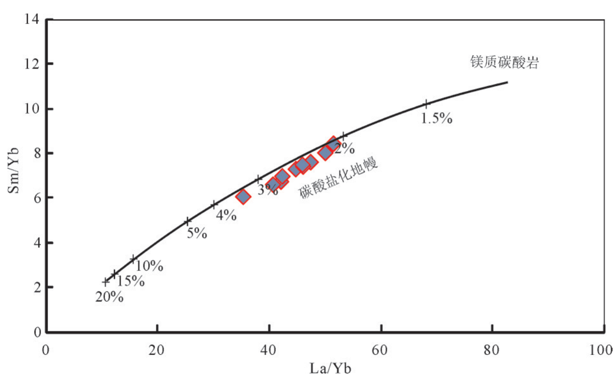

图8 枣林碧玄岩在La/Yb−Sm/Yb相关图解上的熔融曲线(部分熔融曲线计算方法见Zeng et al., 2010)
Fig.8 Melting curve for the Zaolin basanite in the plot of La/Yb versus Sm/Yb (the calculations for the partial melting curve from Zeng et al., 2010)

有残余石榴子石，橄榄岩无法部分熔融出低SiO_2、高FeO，但是在Sm/Yb−La/Yb相关图解上(图8)样品拟和出的熔融曲线，支持了源区碳酸盐化的观点。微量元素原始地幔分布蛛网图显示具有明显K、Ti负异常，表明了源区碳酸盐化(Nelson et al., 1988; Zeng et al., 2010)。在岩浆演化过程中，Zr/Hf比值保持不变，本文较高的Zr/Hf比值表明源区受到了小体积碳酸盐的交代富集作用(Dupuy et al., 1992; Rudnick et al., 1995; Furman et al., 1999)。Pan et al. (2019)对枣林碧玄岩矿物学研究表明基质中存在大量碳酸盐岩矿物，也支持了源区为碳酸盐化橄榄岩部分熔融的观点。$(La/Yb)_N-(Dy/Yb)_N$图解(图9)表明枣林地区碧玄岩原始岩浆是在地幔0.2%~0.5%石榴石相二辉橄榄岩与0.5%~1%尖晶石相二辉橄榄岩按不同比例混合而形成的产物。因此，本文认为枣林玄武岩的源区为富集地幔碳酸盐化橄榄岩的部分熔融。

5.3 岩石成因

前已述及，枣林碧玄岩原始岩浆来源于富集地幔源区。引起岩石圈地幔发生交代富集作用主要有三种情况：(1)软流圈上升的熔体或流体使岩石圈地幔发生富集(Meen et al., 1989)；(2)地幔小比例的部分熔融造成地幔成分的变化(Roden et al., 1985; Arai et al., 1989)；(3)俯冲过程中富含碱、轻稀土元素及不相容元素的洋壳进入地幔发生脱水作用与深部地幔发生交代(Holm et al., 1982)。

样品中Rb/Sr值为0.029~0.042，接近于原始地幔0.03(Thompson, 1982)；Ba/Rb值为7.89~11.78，接近于原始地幔约11(Thompson, 1982)，说明源区的富集与流体相矿物金云母和角闪石无关。前人在对中国东部碱性玄武岩大量地幔捕虏体研究表明，中国东部地区由于软流圈上涌交代岩石圈地幔而导致岩石圈地幔富集(吴福元等, 1999; Xu et al., 2000; 支霞臣等, 2004; Zheng et al., 2004; 马振东等, 2013)。发生熔体有关的交代富集作用Th/Zr比值相对比较稳定，而发生流体有关的Nb/Zr比值相对比较稳定，因此熔体和流体的交代富集作用可以用Th/Zr− Nb/Zr比值判别图进行区分(Ma et al., 2014)。根据图10可以看出枣林地区碧玄岩地幔源区的交代富集与软流圈上涌的熔体有关。

Li et al.(2017)近些年发现中国东部新生代碱性

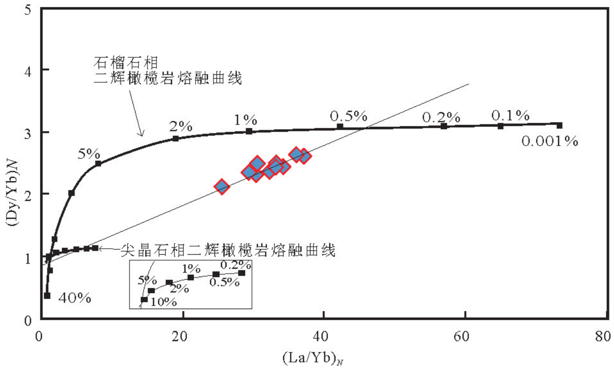

图9 枣林碧玄岩$(Dy/Yb)_N$−$(La/Yb)_N$图解(标准化数据来源Sun et al., 1989)

Fig.9 Diagram of $(Dy/Yb)_N$−$(La/Yb)_N$ for Zaolin basanite (normalized data from Sun et al., 1989)

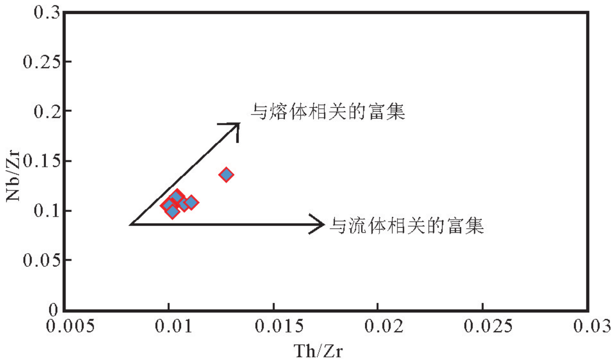

图10 枣林碧玄岩Th/Zr−Nb/Zr图解

Fig.10 Diagram of Th/Zr−Nb/Zr for Zaolin basanite

玄武岩具有轻Mg同位素组成,表明中国东部新生代碱性玄武岩是地幔过渡带滞留的西太平洋俯冲板片携带碳酸盐熔体交代对流上地幔的产物。出露于中国东部的江西省枣林碧玄岩,与其他中国东部新生代碱性玄武岩具有类似的OIB型玄武岩特征。结合前一章节论证的枣林碧玄岩源区为石榴石相橄榄岩与尖晶石相橄榄岩的部分熔融,这意味着原始岩浆熔融深度在逐渐变浅,而软流圈与地幔柱的相互作用可以导致岩石圈减薄,岩浆熔融深度变浅。因此,笔者认为枣林碧玄岩原始岩浆是在新生代,由于太平洋板块俯冲,导致软流圈地幔携带碳酸盐熔体上涌,与岩石圈地幔相互作用下产生的。

6 结 论

(1)岩石地球化学特征表明,枣林碧玄岩总体具有低硅、高镁、高钛、高碱等特点;稀土元素数据显示轻稀土富集,微弱负Eu异常;微量元素显示其具有较高Ni、Cr、Sc含量,明显富集Nb、Ta、Th、Zr等元素,亏损Ba、Ti、K、P等特点。

(2)在太平洋板块俯冲作用下,软流圈携带碳酸盐熔体上涌,与岩石圈地幔相互作用,在碳酸盐化地幔中0.2%~0.5%石榴石相二辉橄榄岩与0.5%~1%尖晶石相二辉橄榄岩按不同比例经过部分熔融而形成枣林碧玄岩原始岩浆。

注释

❶江西省地质矿产勘查开发局九一二大队. 2017. 朱溪铜钨矿成矿模式与成矿预测示范研究成果报告[R].

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