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广东河源白石岗岩体：一个高分异的 I 型花岗岩

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内容提要:广东河源白石岗岩体位于近东西向展布的佛冈花岗岩带的东端, 主体岩性为中粗粒黑云母花岗岩, 主要组成矿物为石英(25%~35%)、微纹长石(45%~50%)、斜长石($An=20\sim30$, 15%~20%)和黑云母(5%~10%)。锆石 U-Pb 定年结果表明其形成年龄为 148.5 ± 1.6 Ma, 属晚侏罗世岩浆活动的产物。化学成分上, 该岩体铝弱过饱和, A/NKC 值主要变化于 1.0~1.1 之间; 富硅, 富钾 ($K_2O/Na_2O = 1.31\sim1.70$), 全碱含量中等偏低 ($K_2O+Na_2O = 7.44\%\sim8.48\%$), 碱铝指数(AKI 值)为 0.75~0.88, 可归为高钾钙碱性岩系。微量和稀土元素组成上, 岩体富 Rb、Th、U、Pb 和轻稀土, 贫 Ba、Sr、P、Ti, Rb/Sr 比值高, K/Rb 比值低, 铕负异常显著 ($\delta Eu = 0.05\sim0.28$), Nb、Ta、Zr、Hf 等高场强元素含量及 $10^4\times Ga/Al$ 比值(2.43~3.26)较之典型 A 型花岗岩均偏低。岩体的 $\epsilon_{Nd}(t)$ 值为 $-5.99\sim-7.51$, T_{DM} 值偏低(1.42~1.54 Ga), 综合地球化学资料指示其应属高分异的 I 型花岗岩。结合对区域动力地质背景的全面分析, 表明白石岗岩体形成于后造山的伸展引张环境, 是由底侵的幔源基性岩浆及其诱发的长英质岩浆在深部岩浆房混合, 并经高程度分离结晶的产物。

关键词: 高分异 I 型花岗岩; 壳幔相互作用; 地球化学; 岩石成因; 广东白石岗岩体

南岭花岗岩类分布十分广泛, 约占全区总面积的 1/5(袁忠信等, 1992)。花岗岩的成因及其产出构造背景是该区地质研究的核心问题, 长期以来倍受关注。近年来的研究表明, 南岭自早中生代开始即处于岩石圈伸展—减薄的引张构造背景(赵振华等, 1998; Chen et al., 2002; Li et al., 2003; Wang et al., 2003; 范蔚茗等, 2003), 一些具低 T_{DM} 值和高 $\epsilon_{Nd}(t)$ 值花岗岩带的发现指示它们的形成受到了岩石圈上地幔过程的制约, 是壳幔相互作用的结果(Gilder et al., 1996; Chen et al., 1998; Hong et al., 1998; Sewell et al., 2000; Shen et al., 2000), 这些新认识极大地推动了南岭花岗岩研究的进展。白石岗岩体位于广义的规模巨大的佛冈花岗岩带的东端, 处于近东西向的佛冈—丰良深断裂与北东向邵武—河源深断裂的交汇部位(图 1), 是区内壳幔相互作用形成的花岗质岩石的典型代表。本文拟报道该岩体的锆石 U-Pb 年龄, 并结合元素—同位素地球化学资料, 探讨其成因和形成的构造背景, 这一研究对于进一步揭示南岭地区的构造演化和壳幔相互作用过程均具有重要意义。

1 岩体地质与岩相学特征

白石岗岩体侵入的最新地层为下侏罗统蓝塘群砂页岩(图 1), 与围岩呈突变接触, 接触面倾向围岩, 出露面积约 440 km²。结合与区域范围内相关岩石的对比, 广东省地质矿产局(1988)将其归为燕山第三期($155\pm5\sim137\pm5$ Ma)岩浆活动的产物。岩体岩性较均一, 相带分异不明显, 主体岩性为中粗粒黑云母花岗岩, 仅在局部与围岩接触处粒度有变细的现象, 同时围岩也不同程度的热变质, 岩体中缺乏或很少含岩石包体。

组成岩石的矿物主要为石英(25%~35%)、微纹长石(45%~50%)、斜长石($An=20\sim30$, 15%~20%)和黑云母(5%~10%), 副矿物有锆石、磷灰石、萤石和钛铁氧化物等。微纹长石多不同程度泥化, 条纹主要呈细脉状和树枝状, 部分薄片微纹长石具发育的格子双晶, 偶尔可见石英与微纹长石呈文象交生, 指示岩体定位深度较浅。岩体中有时还出现少量白云母, 根据显微镜下白云母粒度较细, 形态多为半自形—他形, 主要呈细小鳞片状分布在长石表面, 或与黑云母呈反应关系等特征, 表明它们应属

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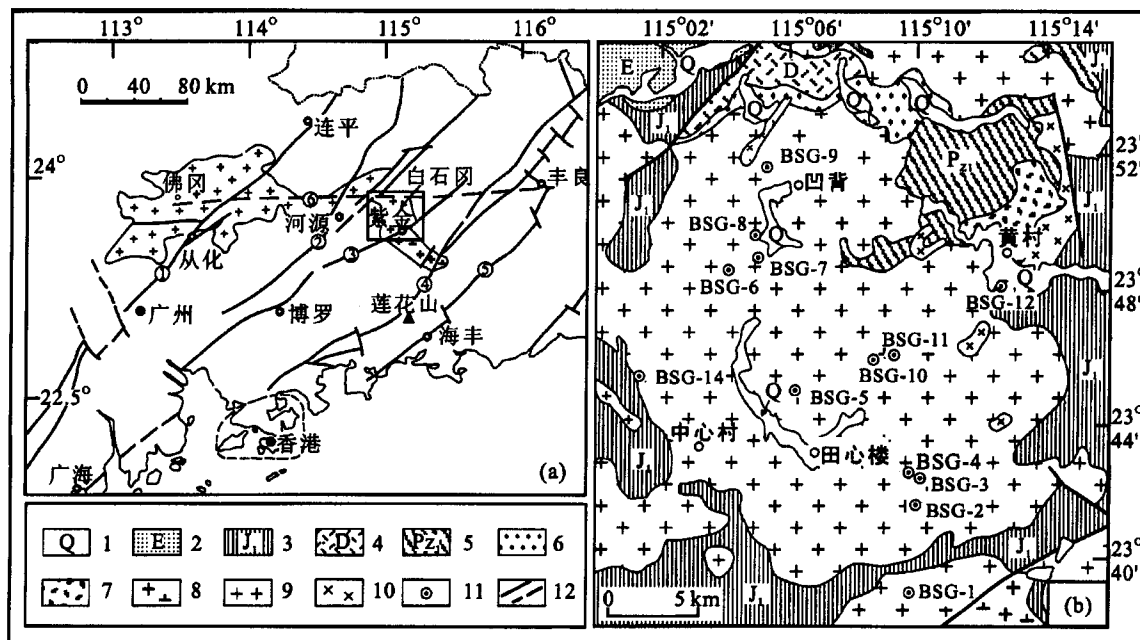


图 1 白石岗岩体地质略图

Fig. 1 Sketch geological map of the Baishigang pluton

图 a 据赵子杰等(1987)修改;图 b 据 1:200000 紫金幅区调报告①;1—第四系;2—第三系;3—下侏罗统蓝塘群;4—泥盆系;5—下古生界;6—加里东期花岗岩;7—印支期花岗岩;8—燕山第二期花岗岩;9—燕山第三期花岗岩;10—燕山第四期花岗岩;11—采样点;12—实测及推测断裂:①—广州—从化断裂,②—邵武—河源断裂,③—紫金—博罗断裂,④—莲花山断裂,⑤—丽水—海丰断裂,⑥—佛冈—丰良断裂

Figure (a) is modified after Zhao Zijie et al. (1987) and Figure (b) is after regional survey report of Zijin area (1:200000)①;1—Quaternary System; 2—Tertiary System; 3—Lantang Group of Lower Jurassic; 4—Devonian System; 5—Lower Palaeozoic Group; 6—Caledonian granite; 7—Indosinian granite; 8—the second stage granite of Yanshanian; 9—the third stage granite of Yanshanian; 10—the forth stage granite of Yanshanian; 11—sample localities; 12—measured or inferred faults: ①—Guangzhou—Conghua fault, ②—Shaowu—Heyuan fault, ③—Zijin—Boluo fault, ④—Lianhuashan fault, ⑤—Lishui—Haifeng fault, ⑥—Fogang—Fengliang fault

次生白云母(孙涛等,2002)。

2 分析方法

锆石 U-Pb 同位素定年在国土资源部天津地质矿产研究所用 VG-354 质谱仪测定,详细的分析过程见陆松年等(1991),全流程本底 Pb 为 $5 \times 10^{-11} \text{g}$, U 为 $2 \times 10^{-12} \text{g}$ 。主量元素在南京大学现代分析中心用 XRF 方法测定,相对标准样品的偏差,高含量氧化物小于 2%,低含量氧化物小于 10%。微量元素(包括稀土元素)在南京大学成矿作用国家重点实验室用 ICP-MS 方法分析,精度优于 10%。Nd 同位素组成在南京大学现代分析中心用 VG354 质谱测定,详细的分析方法见王银喜等(1988),在本文样品分析过程中,该仪器测定的 La Jolla 标样的 $^{143}\text{Nd}/^{144}\text{Nd} = 0.511854 \pm 6(2\sigma)$,Nd 同位素比值采用 $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ 进行质量分馏校正,Sm、Nd 实验室全流程本底为 $5 \times 10^{-11} \sim 7 \times 10^{-11} \text{g}$ 。

3 年代学

前人对白石岗岩体进行过 K-Ar 年龄测定,所报道的 2 个年龄值分别为 139 Ma 和 142 Ma(广东省地质矿产局,1988)。由于 K-Ar 体系的抗扰动性差,加之封闭温度低(约 $200 \pm 50^\circ\text{C}$,郑永飞等,1997),使得定年结果常低于岩体的实际年龄。而锆石 U-Pb 计时体系的封闭温度($700 \pm 50^\circ\text{C}$,Dodson et al., 1985)与花岗质岩石的结晶温度相近,被认为是花岗质岩石定年最为可靠的方法。由表 1 所列的白石岗岩体锆石 U-Pb 定年结果可以看出,除 4 号锆石点的 $^{207}\text{Pb}/^{206}\text{Pb}$ 表面年龄偏高外,其余的表面年龄在测试误差范围内基本一致。在 $^{207}\text{Pb}/^{235}\text{U}$ - $^{206}\text{Pb}/^{238}\text{U}$ 图解中,4 颗锆石点均投影在 U-Pb 谐和线上(图 2),说明样品中放射成因铅基本没有扩散丢失。由于半衰期差异,锆石中放射成因 ^{207}Pb 的丰度比放射成因 ^{206}Pb 的丰度约低一个数量级,因而对年轻锆石来说, $^{206}\text{Pb}/^{238}\text{U}$ 年龄值精度较高

表 1 白石岗岩体锆石 U-Pb 同位素定年结果

Table 1 U-Pb dating results for zircons from the Baishigang pluton

点号	样品情况		浓度($\mu\text{g/g}$)		样品普通 铅含量 (ng)	同位素原子比率					表面年龄(Ma)		
	锆石特征	重量 (μg)	U	Pb		$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{208}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$
1	浅紫红色透明 长柱状自形晶	30	2419	58	0.097	1139	0.07566	0.02355 (21)	0.1593 (26)	0.04906 (64)	150.1	150.1	150.5
2	浅紫红色透明 长柱状自形晶	40	3144	73	0.150	1283	0.06110	0.02325 (19)	0.1573 (17)	0.04909 (31)	148.1	148.4	151.9
3	紫红色透明短 柱状自形晶	40	6397	146	0.200	1925	0.05527	0.02320 (6)	0.1570 (8)	0.04907 (20)	147.9	148.1	151.0
4	浅紫红色透明 细长柱自形晶	30	1300	32	0.054	1077	0.1223	0.02327 (40)	0.1581 (45)	0.04928 (105)	148.3	149.1	161.3

注:1~4 号点 $^{206}\text{Pb}/^{238}\text{U}$ 表面年龄加权平均值: $148.5 \pm 1.6 \text{ Ma}$; 括号内的数字为 2σ 绝对误差,例如: $0.02355(21)$ 表示 $0.02355 \pm 0.00021(2\sigma)$ 。

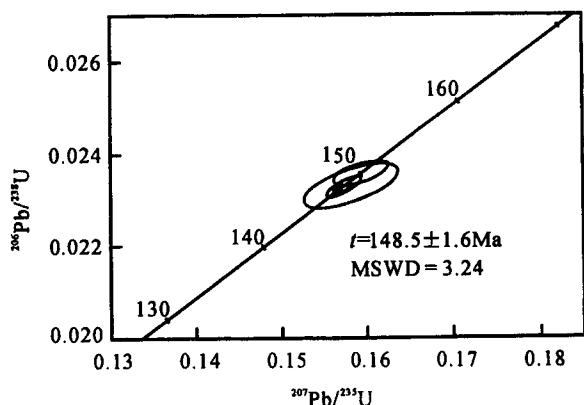


图 2 白石岗岩体锆石 U-Pb 年龄谐和图

Fig. 2 U-Pb concordia diagram for zircons of the Baishigang pluton

(Compston et al., 1992; Shen et al., 2000)。由 4 个锆石颗粒计算出白石岗岩体的 $^{206}\text{Pb}/^{238}\text{U}$ 表面年龄统计权重平均值为 $148.5 \pm 1.6 \text{ Ma}$, 这一年龄代表了该岩体的侵位年龄,因此,白石岗岩体应属晚侏罗世岩浆活动的产物。

4 地球化学

4.1 主量元素

表 2 列出白石岗岩体代表性岩石样品的化学成份、CIPW 标准矿物及主要岩石化学参数。其主要元素特征可归结为:① 富硅, $\text{SiO}_2 = 73.37\% \sim 76.05\%$, $D.I. = 87.9 \sim 94.1$, 反映岩体经历了高程度分异演化作用。② 铝弱过饱和, $\text{Al}_2\text{O}_3 = 12.00\% \sim 13.16\%$, A/NKC 值主要变化于 $1.0 \sim 1.1$ 之间, 绝大多数样品的 CIPW 标准矿物中均出现刚玉分子,但含量多在 1% 以下,与典型的强过铝 S 型花岗岩($A/NKC > 1.1$, CIPW 标准矿物中刚玉分子

表 2 白石岗岩体岩石化学成分(%),CIPW 标准矿物及主要岩石化学参数

Table 2 Petrochemical compositions (%), CIPW-normative minerals and predominant petrochemical parameters of the Baishigang pluton

样号	BSG -1	BSG -2	BSG -3	BSG -5	BSG -7	BSG -8	BSG -9	BSG -10	BSG -14
SiO_2	73.37	76.05	74.37	73.66	74.61	76.05	74.3	74.81	75.34
TiO_2	0.24	0.07	0.12	0.23	0.21	0.15	0.10	0.18	0.10
Al_2O_3	13.16	12.47	13.02	13.06	12.41	12.00	13.11	12.81	12.68
TFe_2O_3	2.37	1.18	1.69	2.42	2.26	1.78	1.30	1.99	1.39
MnO	0.05	0.03	0.04	0.04	0.04	0.03	0.04	0.04	0.05
MgO	0.38	0.08	0.14	0.26	0.19	0.13	0.20	0.16	0.11
CaO	1.32	0.91	0.87	1.31	1.16	1.10	1.06	1.27	0.85
Na_2O	2.92	3.33	3.39	3.11	2.86	3.22	3.19	3.09	3.36
K_2O	4.71	5.02	5.03	4.77	4.86	4.22	5.29	4.60	4.86
P_2O_5	0.07	0.01	0.03	0.05	0.03	0.02	0.02	0.03	0.01
SO_3	0.02	0.04	0.02	0.04	0.03	0.04	0.05	/	0.04
烧失	0.69	0.90	0.65	0.92	0.44	0.61	0.49	0.66	0.43
总量	99.30	100.09	99.40	99.80	99.10	99.30	99.10	99.60	99.10
Q	34.51	35.79	33.86	34.64	37.21	39.20	33.46	36.74	35.70
Or	28.31	29.95	30.14	28.52	29.15	25.29	31.73	27.49	29.11
Ab	25.08	28.39	29.03	26.57	24.51	27.57	27.34	26.38	28.76
An	6.24	4.25	4.20	6.28	5.66	5.41	5.22	6.19	4.21
C	1.01	/	0.47	0.49	0.39	0.17	0.24	0.49	0.36
ALK	7.63	8.35	8.42	7.88	7.72	7.44	8.48	7.69	8.22
A.R.	2.35	2.98	2.91	2.53	2.46	2.93	2.64	2.56	2.97
K/N	1.61	1.51	1.48	1.53	1.70	1.31	1.66	1.49	1.45
AKI	0.75	0.88	0.85	0.79	0.80	0.82	0.84	0.79	0.85
A/NKC	1.07	0.99	1.03	1.03	1.03	1.01	1.02	1.04	1.03
D.I.	87.9	94.1	93.0	89.7	90.9	92.1	92.5	90.6	93.6

注:Q—石英; Or—钾长石; Ab—钠长石; An—钙长石; C—刚玉; ALK = $\text{K}_2\text{O} + \text{Na}_2\text{O}$; A.R.—碱度率; K/N = $\text{K}_2\text{O}/\text{Na}_2\text{O}$; AKI = $(\text{Na}_2\text{O} + \text{K}_2\text{O}) / \text{Al}_2\text{O}_3$ (分子比); A/NKC = $\text{Al}_2\text{O}_3 / (\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})$ (分子比); D.I.—分异指数。

含量 $> 1\%$, Chappell et al., 2001) 有一定差别, 也不同于华南陆壳改造系列花岗岩(刘昌实等, 1990)。在 ACF 三角图解中, 样品点均投影在 I 型与 S 型花岗岩交界区(图 3)。③ 碱含量中等偏低, $\text{K}_2\text{O} + \text{Na}_2\text{O}$

$= 7.44\% \sim 8.48\%$, $A.R.$ 值变化于 $2.35 \sim 2.98$, AKI 值介于 $0.75 \sim 0.88$ 之间, 与区内时代相近的花山和佛冈主体花岗岩相似(花山: $0.83 \sim 0.84$, 朱金初等, 1989; 佛冈: $0.72 \sim 0.88$, 陈小明等, 2002), 但较之 A 型花岗岩的平均值 (0.95 , Whalen et al., 1987) 明显偏低。按洪大卫等 (1987) 提出的碱性、偏碱性和钙碱性花岗岩 AKI 值分界线 (≥ 1.0 , $0.9 \sim 1.0$ 和 < 0.9), 则岩体属钙碱性花岗岩。④ 富钾, $K_2O = 4.22\% \sim 5.29\%$, $K_2O/Na_2O = 1.31 \sim 1.70$, 其总体特征与 Barbarin (1999) 划分的富钾钙碱性花岗岩类 (KCG) 相似。⑤ 铁、镁、钙、钛含量低, 贫磷, P_2O_5 含量均在 0.10% 以下, 且 P_2O_5 与 SiO_2 含量之间有较显著的负消长演化关系 (图 4), 这点也明显不同于典型的 S 型花岗岩, 后者常具有较高的 P_2O_5 含量, 且随分异作用的进行 P_2O_5 有递增的演化趋势 (Chappell, 1999)。其 P_2O_5 及 CIPW 标准矿物中刚玉分子含量均与澳大利亚 Lachlan 褶皱带的 I 型花岗岩 (Chappell, 1999) 相似, 结合岩石分异演化程度高的特点, 表明白石冈岩体应属分异的 I 型花岗岩。

4.2 稀土及微量元素

白石冈岩体代表性岩石样品的稀土及微量元素测定结果列于表 3。由表中数据可看出, 岩体的稀土总量偏高, $\Sigma REE = 114.19 \times 10^{-6} \sim 398.78 \times 10^{-6}$; 富轻稀土, $LREE/HREE = 3.12 \sim 14.77$, $(La/Yb)_N = 2.79 \sim 21.21$, 其中轻稀土的分馏较之重稀土明显, $(La/Sm)_N$ 及 $(Gd/Yb)_N$ 比值分别为 $1.69 \sim 5.47$ 和 $1.04 \sim 2.50$; 铈亏损强烈, $\delta Eu = 0.05 \sim 0.28$ 。随

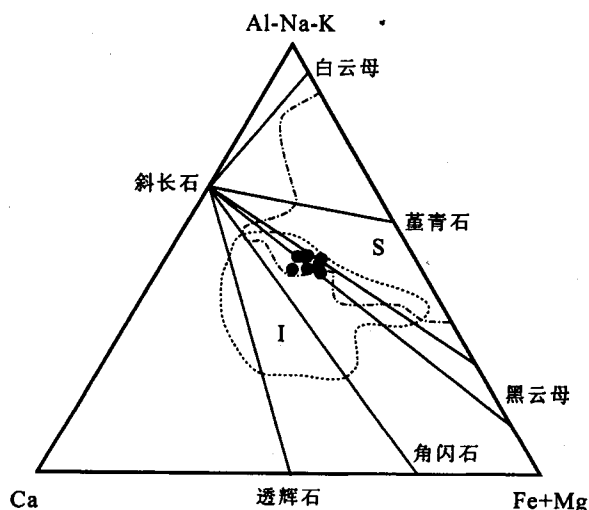


图 3 白石冈岩体 ACF 图
Fig. 3 ACF diagram of the Baishigang pluton

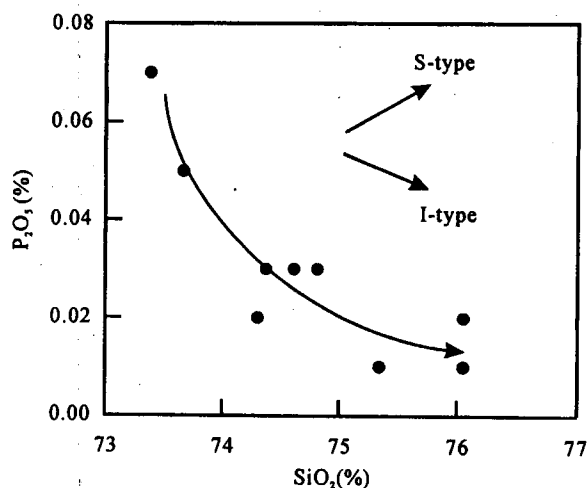


图 4 白石冈岩体 SiO_2 - P_2O_5 关系图
Fig. 4 SiO_2 vs. P_2O_5 diagram of the Baishigang pluton
图中 I 型和 S 型花岗岩 P_2O_5 随 SiO_2 递增的变异趋势据 Chappell (1999)
The variation trends of P_2O_5 with increasing SiO_2 for I- and S-type granites are after Chappell (1999)

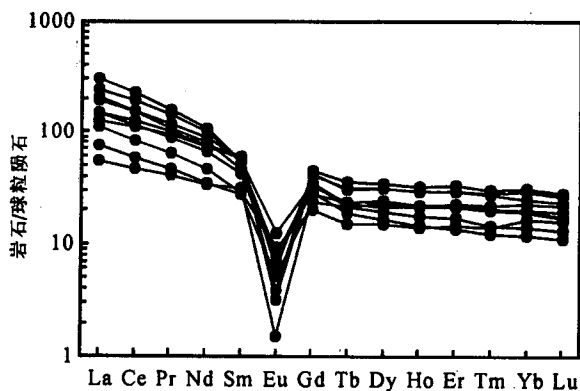


图 5 白石冈岩体稀土元素球粒陨石标准化配分型式
Fig. 5 Chondrite-normalized REE distribution patterns of the Baishigang pluton
球粒陨石值据 Boynton (1984)
The chondrite values are after Boynton (1984)

着分异指数的增大, 轻、重稀土比值及 δEu 值具有明显降低的演变趋势, 指示成岩过程中存在富轻稀土矿物(如磷灰石、褐帘石、独居石等)和斜长石的分离结晶作用。岩石的稀土元素球粒陨石标准化配分型式呈明显的右倾斜形 (图 5), 与佛冈主体黑云母花岗岩相似 (陈小明等, 2002), 但明显不同于典型 S 型花岗岩常表现出的“海鸥型”稀土配分型式。

微量元素组成上, 白石冈岩体富 Rb、Th、U、Pb, 贫 Ba、Sr、P、Ti (图 6), Rb/Sr 比值高 ($2.36 \sim$

表 3 白石岗岩体稀土及微量元素含量($\times 10^{-6}$)Table 3 REE and trace element abundances of the Baishigang pluton ($\times 10^{-6}$)

样号	BSG-1	BSG-2	BSG-3	BSG-5	BSG-7	BSG-8	BSG-9	BSG-10	BSG-14
La	63.47	16.82	45.84	93.09	75.13	58.93	23.54	45.59	39.81
Ce	125.10	37.80	101.55	183.52	155.84	124.12	47.80	93.89	90.84
Pr	13.24	5.02	12.22	19.66	17.62	14.60	5.71	11.00	11.40
Nd	47.65	20.47	45.73	65.60	59.93	52.49	21.03	39.78	43.69
Sm	9.13	6.25	11.63	10.70	10.38	10.91	5.51	8.25	11.31
Eu	0.62	0.11	0.28	0.91	0.59	0.44	0.38	0.51	0.23
Gd	7.35	7.14	11.85	9.17	9.10	10.89	6.18	8.52	10.71
Tb	0.90	1.12	1.68	1.03	1.08	1.45	1.01	1.11	1.48
Dy	5.32	7.86	11.25	6.31	6.83	10.25	7.36	7.65	10.33
Ho	1.03	1.62	2.33	1.26	1.53	2.16	1.54	1.56	2.13
Er	2.90	4.71	7.12	3.64	4.68	6.31	4.77	4.58	6.26
Tm	0.40	0.66	0.99	0.48	0.68	0.91	0.73	0.65	0.92
Yb	2.49	4.06	6.52	2.96	4.07	5.33	4.79	4.15	6.27
Lu	0.37	0.56	0.93	0.43	0.58	0.77	0.71	0.63	0.87
Σ REE	279.98	114.19	259.92	398.78	348.03	299.55	131.06	227.87	236.25
LREE/HREE	12.48	3.12	5.09	14.77	11.20	6.87	3.84	6.90	5.06
(La/Yb) _N	17.16	2.79	4.74	21.21	12.43	7.46	3.31	7.40	4.28
(La/Sm) _N	4.37	1.69	2.48	5.47	4.55	3.40	2.69	3.48	2.21
(Gd/Yb) _N	2.38	1.42	1.47	2.50	1.80	1.65	1.04	1.66	1.38
δ Eu	0.22	0.05	0.07	0.28	0.18	0.12	0.20	0.19	0.06
Cs	20.66	11.97	15.70	5.58	10.57	10.50	20.63	8.98	11.34
Rb	275.10	384.86	464.76	217.69	279.99	288.68	450.35	308.46	441.62
Sr	116.44	18.48	40.15	104.64	55.85	45.97	51.86	62.10	29.30
Ba	457.25	39.93	162.02	781.91	250.11	193.88	131.49	293.18	30.82
U	8.94	11.29	16.74	7.34	9.82	10.24	26.59	15.16	20.13
Th	45.23	34.25	46.38	35.63	49.30	57.21	43.52	38.81	59.24
Pb	35.69	32.38	43.08	29.27	30.75	98.87	43.70	39.22	40.57
Ga	19.13	17.44	22.45	18.33	18.35	18.88	16.89	19.28	18.95
Sc	5.46	2.99	4.54	5.27	3.25	4.18	2.55	4.05	3.66
Y	28.96	43.33	68.01	32.28	50.65	58.26	44.91	41.39	60.20
Nb	17.01	24.49	23.83	14.38	17.17	21.32	18.58	18.35	22.65
Ta	2.76	3.70	4.56	1.44	1.76	2.49	3.66	2.92	5.93
Zr	144.01	73.16	122.72	204.95	226.07	123.34	102.58	169.33	101.96
Hf	4.52	3.62	5.17	5.91	7.19	4.33	3.48	6.14	3.97
Rb/Sr	2.36	20.82	11.58	2.08	5.01	6.28	8.68	4.97	15.07
K/Rb	142.07	108.23	89.81	181.82	144.03	121.30	97.47	123.74	91.32
Nb/Ta	6.15	6.61	5.22	9.99	9.74	8.57	5.08	6.28	3.82
$10^4 \times \text{Ga/Al}$	2.75	2.64	3.26	2.65	2.79	2.97	2.43	2.84	2.82

20.82), K/Rb 比值低(绝大多数样品均小于 150, 表 3), 上述微量元素组成特征同样指示岩体经历了高分化的分异演化, 其 Ba、Sr、P、Ti 亏损应是成岩过程中斜长石、磷灰石和钛铁矿等的分离结晶所致。岩体的 Nb、Ta、Zr、Hf 等高场强元素含量及 Ga/Al 比值均较之典型 A 型花岗岩(Whalen et al., 1987)偏低, 在 $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}) - 10^4 \times \text{Ga/Al}$ 关系图上, 样品点主要落在分异的 I 型花岗岩区(Eby, 1990, 图 7), 其 Nb/Ta 比值(3.82~9.99)与分异花岗岩的相应值(2.3~9.9, Dostal et al., 2000)十分接近, 这

一特征也说明白石岗岩体应属分异的 I 型花岗岩。

4.3 Nd 同位素

由于白石岗岩体具高的 Rb/Sr 比值, 使得年龄对 I_{Sr} 值的校正十分敏感, 在这种情况下, 岩石的 Sr 同位素组成往往不具有明确的成岩意义, 而 Nd 同位素由于其强的抗扰动性则能有效地示踪岩浆源区性质, 为此, 本文仅报道其 Nd 同位素组成的测定结果。

由表 4 所列数据可看出, 白石岗岩体的 Nd 同位素组成相对均一, $\epsilon_{\text{Nd}}(t) = -5.99 \sim -7.51$, 与

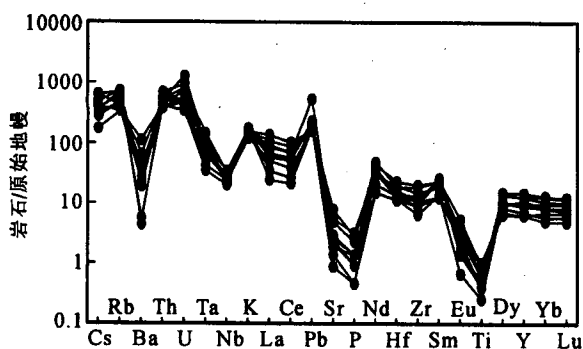


图 6 白石冈岩体微量元素相对于原始地幔标准化蛛网图

Fig. 6 Primitive mantle-normalized spidergrams for trace elements of the Baishigang pluton
原始地幔值据 Sun & McDonough (1989)

The primitive mantle values are from Sun & McDonough (1989)

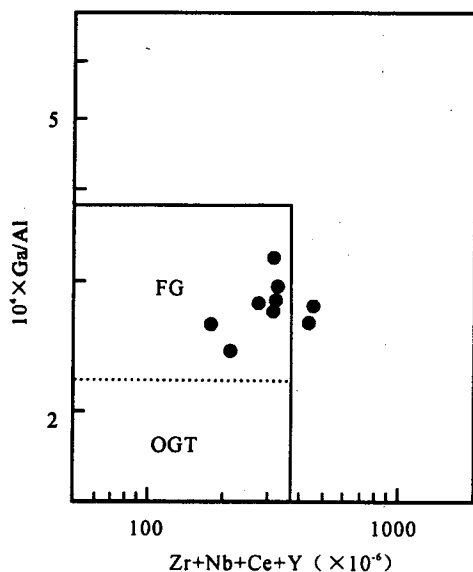


图 7 白石冈岩体 $(Zr+Nb+Ce+Y)-10^4 \times Ga/Al$ 关系图

Fig. 7 $(Zr+Nb+Ce+Y)$ vs. $10^4 \times Ga/Al$ diagram of the Baishigang pluton

OGT—I、S 和 M 型花岗岩区; FG—分异的 I 型花岗岩区;
底图据 Eby (1990)

OGT—Field for I-, S- and M-type granitoids; FG—field for fractionated I-type granitoids; the base map is after Eby (1990)

区内时代相近的佛冈主体黑云母花岗岩 ($t=167$ Ma, $\epsilon_{Nd}(t) = -6.20 \sim -8.93$, 陈小明等, 2002; 包志伟等, 2003) 及龙窝花岗闪长岩 ($t=169.1$ Ma, $\epsilon_{Nd}(t) = -6.53 \sim -8.89$, 邱检生等, 2004a) 相似, 也可与千里山第一阶段斑状黑云母花岗岩 ($t=152$ Ma, $\epsilon_{Nd}(t) = -6.39 \sim -7.59$, 毛景文等, 1995) 相对比。在 $t-\epsilon_{Nd}(t)$ 关系图上, 样品点投影于华南元古宙地壳演化域上方 (图 8), 说明它们并非单纯起

源于基底变质岩的部分熔融, 成岩过程中应有幔源组份的参与。

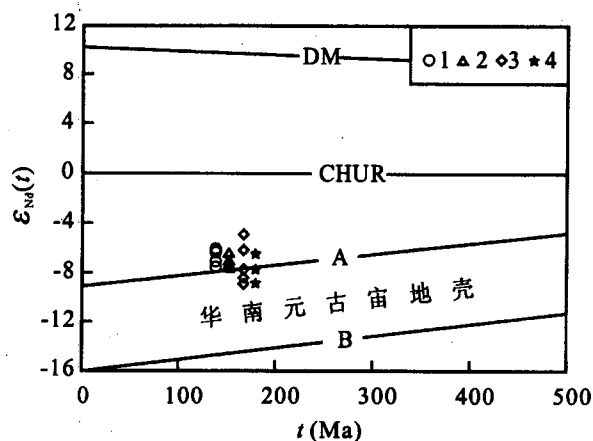


图 8 白石冈岩体 $\epsilon_{Nd}(t)-t$ 关系图

Fig. 8 $\epsilon_{Nd}(t)-t$ diagram of the Baishigang pluton

A—华南成熟度较低的元古宙地壳; B—华南成熟度较高的元古宙地壳; DM—亏损地幔; CHUR—球粒陨石均一储库; 底图据沈渭洲等 (1993); 1—白石冈 (本文资料); 2—千里山 (毛景文等, 1995); 3—佛冈 (陈小明等, 2002; 包志伟等, 2003); 4—龙窝 (邱检生等, 2004a), 为了清晰地对比 Nd 同位素组成, 图中将各岩体的数据点作了适当分开, 因此, 样品点对应的横坐标并不代表各岩体的精确形成年龄

A—Immature Proterozoic crust in south China; B—mature Proterozoic crust in south China; DM—depleted mantle; CHUR—chondritic uniform reservoir; the base map is after Shen Weizhou et al. (1993); 1—Baishigang (this paper); 2—Qianlishan (Mao Jingwen et al., 1995); 3—Fogang (Chen Xiaoming et al., 2002; Bao Zhiwei et al., 2003); 4—Longwo (Qiu Jiansheng et al., 2004a); Data points of each plutons are properly separated for clarity and thus no accurate age differences are implied

白石冈岩体的二阶段 Nd 模式年龄变化于 1.42 ~ 1.54 Ga (表 4), 较之华夏地块基底变质岩的 Nd 模式年龄 (主要为 1.8 ~ 2.2 Ga, 陈江峰等, 1999) 显著偏低。近年来, 在华南相继识别出多条具低 T_{DM} 值的花岗岩带, 这些具低 T_{DM} 值的花岗岩理论上可通过二种方式形成, 其一为起源于年轻地壳物质的部分熔融, 其二是成岩过程中有不同比例地幔物质的加入。由于本区基底岩石的 T_{DM} 值主要为古、中元古代 (沈渭洲等, 1993; 陈江峰等, 1999), 不支持年轻地壳的存在, 因此, 目前普遍认为这些具低 T_{DM} 值的花岗岩是地幔物质参与成岩过程的重要表现 (Gilder et al., 1996; Chen et al., 1998; Hong et al., 1998; Shen et al., 2000)。白石冈岩体空间上大致位于陈江峰等 (1999) 划分的 S_3 低 T_{DM} 值花岗岩带上, 无疑指示地幔物质参与了成岩过程。

5 讨论

表4 白石岗岩体 Sm-Nd 同位素组成

Table 4 Sm-Nd isotopic compositions of the Baishigang pluton

样号	Sm($\times 10^{-6}$)	Nd($\times 10^{-6}$)	Sm/Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}(\pm 2\sigma)$	I_{Nd}	$\epsilon_{\text{Nd}}(t)$	$T_{2\text{DM}}(\text{Ga})$	$f(\%)$
BSG-2	6.62	21.05	0.314	0.1847	0.512264 ± 4	0.512085	-7.07	1.49	42.6
BSG-3	12.08	46.17	0.262	0.1539	0.512270 ± 18	0.512120	-6.37	1.45	46.3
BSG-5	10.24	64.87	0.158	0.09868	0.512232 ± 6	0.512136	-6.06	1.43	47.8
BSG-9	5.85	22.04	0.265	0.1585	0.512216 ± 7	0.512062	-7.51	1.54	40.2
BSG-10	9.29	40.11	0.232	0.1255	0.512246 ± 10	0.512124	-6.30	1.45	46.6
BSG-14	10.94	42.79	0.256	0.1566	0.512292 ± 6	0.512140	-5.99	1.42	48.2

注:为减少 $^{147}\text{Sm}/^{144}\text{Nd}$ 变化对Nd模式年龄计算产生的影响,表中所列 $T_{2\text{DM}}$ 年龄统一采用二阶段模式计算, f 为根据刘昌实等(1990)方法计算的岩浆源区中地幔物质的混入比例。

5.1 成岩过程

Nd同位素示踪指示白石岗岩体成岩过程中有地幔组份的参与,即岩体属壳幔混源型花岗岩。壳幔物质的混合既可以发生在岩浆源区,也可以发生在幔源岩浆上侵途经地壳的过程中。由于岩体的Nd同位素组成相对均一, $\epsilon_{\text{Nd}}(t)$ 值与相应样品的 SiO_2 及Nd含量之间缺乏明显的线性演化关系,加之岩体岩性较均匀,各类岩石包体均不发育,说明成岩过程中壳幔物质的混合应发生在岩浆源区,因为深部岩浆房中的对流混合有利于岩浆均一化(Martin et al., 1994)。

选择华南陆壳和亏损地幔作为混合端元,利用刘昌实等(1990)和Faure(1986)提供的二端元参数,将其Sr、Nd同位素组成校正到岩石形成时($t=148.5\text{ Ma}$)的初始值,则有华南陆壳: $\text{Nd}=28 \times 10^{-6}$, $\epsilon_{\text{Nd}}(t)=-13.28$; 亏损地幔: $\text{Nd}=14 \times 10^{-6}$, $\epsilon_{\text{Nd}}(t)=9.69$ 。再按简单的二元混合模拟计算,可以得出白石岗岩体成岩过程中地幔物质的卷入比例变化于40.2%~48.2%之间(表4)。如果这一比例地幔与地壳物质混合形成的岩浆直接结晶,显然难以形成目前所观测到的主量和微量元素地球化学特征。岩体富硅,Rb/Sr比值高,K/Rb比值低,Sr、Ba、P、Ti、Nb、Eu等元素显著亏损,这些特征充分说明岩浆经历了高分异的分离结晶作用。根据造岩矿物中上述元素分配系数的大小(Arth, 1976; Hanson, 1978; Green et al., 1986), Sr、Ba、Eu的亏损指示成岩过程中发生了斜长石和钾长石的分离结晶,而P和Ti、Nb的亏损则分别与磷灰石及含钛矿物(如钛铁矿、榍石等)的分离结晶有关(Raith, 1995; Wu et al., 2003)。岩石的轻稀土含量及轻、重稀土比值随分异演化程度增高而明显降低的演变趋势,应是成岩过程中富轻稀土矿物(如磷灰石、褐帘石、独居石等)的分离结晶所致。按Rayleigh分离结晶方程,经计算得到由矿物分离结晶作用形成的

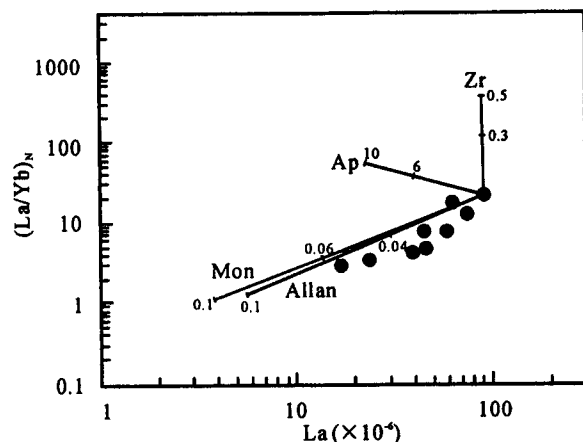


图9 白石岗岩体副矿物分离结晶作用过程判别图解
Fig. 9 Discrimination diagram showing the fractional crystallization process by separation of accessory minerals for the Baishigang pluton

Allan—褐帘石; Mon—独居石; Ap—磷灰石; Zr—锆石; 褐帘石和锆石分配系数数据 Mahood 等(1983); 独居石分配系数数据 Yurimoto 等(1990); 磷灰石的分配系数数据 Arth (1976) 和 Fujimaki (1986); 图中黑点代表白石岗黑云母花岗岩样品的投影点, 分异趋势线上的数字代表分离结晶作用的程度, 计算过程中假定分异程度最低的样品为初始熔体

Allan—Allanite; Mon—monazite; Ap—apatite; Zr—zircon; partition coefficients are from Mahood et al. (1983) for allanite and zircon; Yurimoto et al. (1990) for monazite, Arth (1976) and Fujimaki (1986) for apatite. The solid circles in this figure are sample plot points of the Baishigang pluton, and the data shown on the differentiation tendency lines represent the fractionation degree of the accessory minerals. During the calculation, the least fractionated sample is supposed to be the parent melt

La-(La/Yb)_N 变异图解(图9),从白石岗岩体样品点在图中的分布来看,独居石和褐帘石的分离结晶是控制成岩过程中稀土元素变异的主要因素。

5.2 构造意义

对中国东南部中生代岩浆作用构造背景的认识是正确理解区内花岗岩成因的关键。自上世纪70年代以来,随着板块构造学说的兴起,许多学者认为华南中生代属于安第斯型活动大陆边缘,岩浆活动与

古太平洋板块向欧亚大陆的俯冲有关(郭令智等, 1983; 王鸿祯等, 1983; 任纪舜等, 1990)。Zhou 等(2000)提出自中侏罗世开始, 古太平洋板向中国东南大陆俯冲消减, 由此诱发玄武质岩浆的底侵, 并促使中下地壳部分熔融, 这一机制是产生区内各类花岗质岩浆的主要原因。近年来, 越来越多的学者主张南岭地区自早中生代开始(175 Ma±)即处于软流圈上隆的陆内岩石圈伸展引张构造背景(Li et al., 2003; Wang et al., 2003; 范蔚茗等, 2003)。可见对华南中生代岩浆作用动力地质背景的认识尚存在分歧。

南岭中生代花岗岩基本均呈 EW 向展布, 大致可分为 3 条岩浆活动带, 自北向南依次为诸广山—青障山带、大东山—贵东带及佛冈—新丰江带(Shu et al., 2004)。已有资料表明, 自燕山早期开始, 古太平洋板块沿 NW 向朝欧亚大陆俯冲(Maruyama et al., 1986), 随后俯冲方向逐渐向 NNW 向过渡(Engelbreton et al., 1985), 按此俯冲方向, 则南岭内陆不太可能形成一系列呈东西向展布的岩浆活动带, 说明南岭中生代岩浆活动并非完全受控于古太平洋构造域。近年来, 在南岭地区相继厘定了一系列印支期花岗岩(Xu et al., 2003; 邱检生等, 2004b; 张文兰等, 2004), 表明该区中生代岩浆作用受到过特提斯构造域的制约, 南岭地区深部表现出的 EW 向粤北幔拗—佛冈幔坡—广州幔隆和近 EW 向均匀单一完整的重力梯度带(舒良树等, 2002)应是特提斯构造动力体系影响的印记。

白石冈岩体形成于燕山早期, 化学成分上富钾, 属高钾钙碱性岩石。Liegeois 等(1998)认为高钾钙碱性岩石的岩浆源区通常与先期的俯冲作用有关, 它们主要形成于同碰撞岩石圈加厚之后的伸展垮塌向非造山板内的过渡阶段。大量研究资料表明, 华南印支期以挤压逆冲推覆和地壳叠置加厚为主要特征

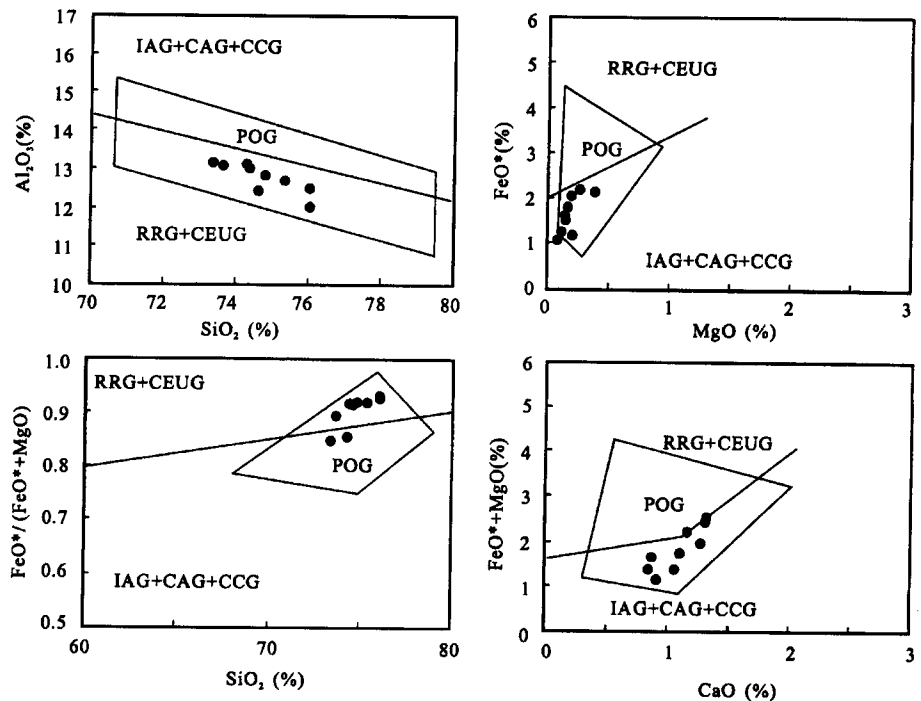


图 10 白石冈岩体主量元素构造环境判别图解

Fig. 10 Tectonic discrimination diagram using major elements for the Baishigang pluton
IAG—岛弧花岗岩类; CAG—大陆弧花岗岩类; CCG—大陆碰撞花岗岩类; POG—后碰撞花岗岩类;
RRG—与裂谷有关的花岗岩类; CEUG—与大陆造陆抬升有关花岗岩类; 底图据 Maniar 等(1989)
IAG—Island arc granitoids; CAG—continental arc granitoids; CCG—continental collision granitoids;
POG—post-collisional granitoids; RRG—rift-related granitoids; CEUG—continental epeirogenic uplift granitoids. The base map is after Maniar et al. (1989)

(Chen, 2001; Wang et al., 2002), 主体变形作用的时间发生在 258~192 Ma(范蔚茗等, 2003)。至燕山早期, 则发育有 A 型花岗岩类(176~178 Ma)和双峰式火山岩(158~179 Ma)组合(Chen et al., 2002), 并在燕山早期发现有具 OIB 特征的板内拉斑或碱性玄武岩(175~178 Ma, 赵振华等, 1998; 陈培荣等, 1999), 上述岩石组合的出现是软流圈上涌和岩石圈伸展减薄的最直接证据, 因此, 南岭地区燕山早期的火成岩组合应形成于板内环境, 主要受控于印支造山运动之后的后造山大陆裂解的地球动力学背景(Chen et al., 2002)。

采用相关的构造环境判别图投影也表明, 白石冈岩体的投影点均落在后碰撞(post-collisional)或后碰撞伸展(post-collision extension)花岗岩区(图 10, 图 11)。尽管高场强元素(Nb、Ta、Zr、Hf、Ti 等)的强烈亏损是与俯冲有关岩浆岩的典型特征(Kelemen et al., 1990; Stolz et al., 1996), 但白石冈岩体形成于板内环境, 其 Nb、Ta、Ti 等高场强元素亏损的

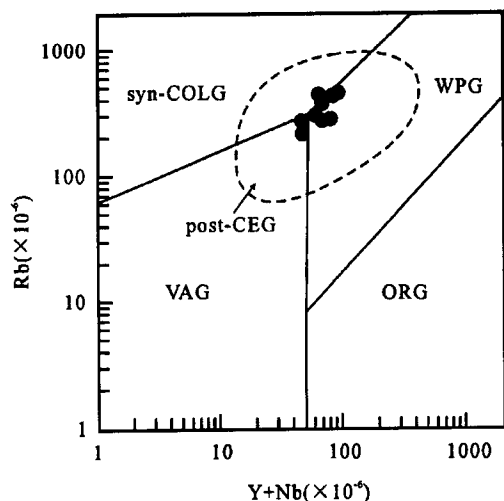


图 11 白石岗岩体(Y+Nb)-Rb 关系图

Fig. 11 (Y+Nb)-Rb diagram of the Baishigang pluton
底图据 Pearce 等(1984); 图中 post-CEG 区域据 Forster 等(1997)资料圈定; VAG—火山弧花岗岩; ORG—洋脊花岗岩; WPG—板内花岗岩; syn—COLG—同碰撞花岗岩; post-CEG—后碰撞伸展花岗岩

The base map is after Pearce et al. (1984), and the range of the post-CEG is after Forster et al. (1997); VAG—volcanic arc granites; ORG—ocean ridge granites; WPG—within plate granites; syn-COLG—syn-collision granites; post-CEG—post-collision extension granites

特征应是从源岩中继承而来的,而不应被视为产于俯冲环境的标志,因为典型地壳熔体高场强元素含量很低(Ryerson et al., 1987)。基于以上的讨论可以设想,自燕山早期以来,南岭地区由于后造山拉张裂解作用,导致软流圈上涌和岩石圈伸展减薄,由此诱发幔源基性岩浆底侵于地壳下部。在断裂引起的减压作用和幔源基性岩浆底侵带来足够热量的影响下,促使了地壳物质的部分熔融形成长英质岩浆。幔源基性岩浆与长英质岩浆在深部岩浆房混合产生混染的母岩浆,后者再经高分异的演化,即形成本文所讨论的白石岗岩体,这一模式较好地解释了目前所观测到的岩体的地质地球化学特征。

6 结论

(1) 白石岗岩体锆石 U-Pb 年龄为 148.5 ± 1.6 Ma, 属晚侏罗世岩浆活动的产物。

(2) 白石岗岩体铝弱过饱和,富硅,富钾,富 Rb、Th、U、Pb 和轻稀土,贫 Ba、Sr、P、Ti、Rb/Sr 比值高,K/Rb 比值低,铕负异常显著。其 Nb、Ta、Zr、Hf 等高场强元素含量及 Ga/Al 比值均较之典型 A 型花岗岩偏低,并具偏高的 $\epsilon_{\text{Nd}}(t)$ 值($-5.99 \sim$

-7.51)和偏低的 T_{DM} 值($1.42 \sim 1.54$ Ga),综合地球化学资料指示岩体应属高分异的 I 型花岗岩。

(3) 白石岗岩体形成于后造山的伸展引张环境,是由底侵的幔源基性岩浆及其诱发的长英质岩浆在深部岩浆房混合,并经高程度分离结晶的产物。

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注 释

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The Baishigang Pluton in Heyuan, Guangdong Province: A Highly Fractionated I-type Granite

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Abstract

The Baishigang Pluton is located at the eastern end of the E-W-trending Fogang granite belt, and has an outcrop area of about 440 km². It intruded into the Lower Jurassic Lantang Group and is made up mainly of medium- to coarse-grained biotite granites. The major mineral phases of the granites are quartz (25%~35%), microperthite (45%~50%), plagioclase ($An=20\sim30$, 15%~20%) and biotite (5%~10%). Zircon U-Pb isotopic dating yields an age of 148.5 ± 1.6 Ma, indicating that it was formed in the Late Jurassic. Chemical analyses show that the granites have high SiO₂ (= 73.37%~76.05%) and moderate Al₂O₃ (12.00%~13.16%). They are slightly peraluminous with A/NKC values ranging mainly from 1.0 to 1.1 and normative corundum <1%. The rocks also have moderate to low alkaline contents ($K_2O+Na_2O=7.44\sim8.48\%$, NK/A [molecular $(K_2O+Na_2O)/Al_2O_3$] = 0.75~0.88) and high potassium contents ($K_2O=4.22\sim5.29\%$, $K_2O/Na_2O=1.31\sim1.70$), thus can be ascribed to the rocks of the high-K calc-alkaline series. Trace and rare earth elements of the granites are characterized by rich Rb, Th, U, Pb and LREE, and poor Ba, Sr, P, Ti, and have high Rb/Sr (2.36~20.82) and low K/Rb ratios (<150 for most of the samples). Chondrite-normalized REE patterns are right-inclined and display significant negative europium anomalies ($\delta Eu=0.05\sim0.28$). Their HFSE (e. g., Nb, Ta, Zr, Hf) concentrations and Ga/Al ratios are lower than that of the respective values of A-type granites. The granites have a more enriched Nd isotopic composition with initial ϵ_{Nd} values from -5.99 to -7.51, and show younger depleted-mantle model ages ($T_{DM}=1.42\sim1.54$ Ga). Integrated geochemical data suggest that the rocks are highly fractionated I-type granites. By combining with comprehensively analyses of the tectonic settings, we suggest that the Baishigang pluton was formed in a post-collisional tensile environment, and the granites were generated by a two-stage process including mixing of underplating basaltic magma with the induced felsic melts in the source region and subsequent high-degree fractional crystallization.

Key words: highly fractionated I-type granite; crust-mantle interaction; geochemistry; petrogenesis; Baishigang pluton; Guangdong Province