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Li Hongwei, Qu Shangxia, Lin Xiaoming, Xiao Guangming, Huang Jianhua, Liao Bingbing. 2021. Petrogeochemistry, zircon U−Pb age and Hf isotope of Xinping granodiorite(104 Ma) in Xinfeng area, Guangdong Province[J]. Geology in China, 48(5): 1524−1539(in Chinese with English abstract).

广东新丰新坪花岗闪长岩(104 Ma)地球化学、锆石U−Pb年龄和Hf同位素研究

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提要:新坪铜钼矿化花岗闪长岩体位于佛冈复式岩体中北部,LA−ICP−MS锆石U−Pb年龄为(104.6±1.8)Ma (MSWD=1.2),侵位时间为早白垩世晚期。岩石呈中酸性(SiO_2=63.43%~65.27%)、准铝质(ACNK=0.76~0.92)、中等碱含量(ALK=6.09%~7.63%)和富钾钙碱性特征,富集轻稀土,LREE/HREE=8.26~13.20,$(La/Yb)_N$=8.17~16.64,轻微的铕亏损(δEu=0.73~0.87),富集Rb、U、Th和La,亏损Nb、Ta、Ti和P、Ba、Sr。锆石$\varepsilon_{Hf}(t)$值为−3.0~0.2,Hf二阶段模式年龄t_{DM2}=1.16~1.36Ga,镁指数($Mg^{\#}$)=42.64~46.95,表明源岩主要为中元古代地壳物质,并有亏损地幔组分的参与。Nb/U和Nb/La比值分别为0.20~0.38和1.7~2.2,显示源区受古太平洋板块俯冲流体交代作用的影响。研究表明,新坪岩体成岩过程主要受部分熔融作用控制,形成于燕山晚期古太平洋板片俯冲消减作用下的伸展拉张环境,与玄武质岩浆底垫诱发中元古代结晶基底的部分熔融有关。早白垩世晚期为中国东南部晚中生代重要的Cu−Au−Mo成矿期,位于南岭中东段的新坪花岗闪长岩体与邻区闽西南紫金山铜多金属岩(矿)体形成时代一致、岩石地球化学特征较为相似,且野外能观察到明显的铜钼矿化,因此具有较好的铜钼找矿前景。

关 键 词:花岗闪长岩;铜钼矿化;U−Pb年龄;地球化学;Hf同位素;矿产资源调查工程;新丰;广东

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Petrogeochemistry, zircon U−Pb age and Hf isotope of Xinping granodiorite (104Ma) in Xinfeng area, Guangdong Province

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Abstract: Located in the north-central part of the Fogang complex pluton, the Xinping Cu-Mo mineralization granodiorite pluton formed in late Early Cretaceous, and its LA-ICP-MS zircon U-Pb age is (104.6±1.8)Ma(MSWD=1.2). The granodiorite is characterized by medium acidity (SiO_2=63.43%-65.27%), quasi-aluminium(ACNK=0.76-0.92), medium alkali(ALK=6.09%-7.63%) and high-K Calc-alkaline. It shows enrichment in light rare earth elements Rb, U, Th and La, and the ratio of LREE/HREE is 8.26-13.20 while $(La/Yb)_N$ is 8.17-16.64. Otherwise, it shows depletion in Nb, Ta, Ti, P, Ba and Sr, with minor loss of Eu (δEu=0.73-0.87). The $\varepsilon_{Hf}(t)$ range from -3.0 to +0.2, and the two-stage model age of Hf(t_{DM2}) is 1.16-1.36Ga, and the index of Mg($Mg^{\#}$) is 42.64-46.95. All of these indicate that the source rocks are mainly crustal materials formed in Mesoproterozoic, with the participation of deficient mantle components. The ratio of Nb/U and Nb/La is respectively 0.20-0.38 and1.7-2.2, which indicates that the source area is affected by the fluid metasomatism in subduction of Paleo-Pacific Plate. This study shows that the Xinping granodiorite is dominated by partial melting in process of diageneesis. The Xinping pluton formed in the extensional setting under the subduction of the Paleo-Pacific plate in late Yanshanian period, which is related to the partial melting of the Mesoproterozoic crystalline basement induced by the basaltic magma. In late Early Cretaceous, it was an important Cu-Au-Mo mineralization period in late Mesozoic in southeastern China, while the Xinping granodiorite, located in the middle east of Nanling mountains, coincide with the diagenetic age of the Zijinshan copper polymetallic rocks or ores in the southwestern Fujian Province, with similar petrochemical characteristics. Also, the obvious copper-molybdenum mineralization can be observed in the field, so it will have a good prospecting prospect for copper-molybdenum deposits.

Key words: granodiorite; Cu-Mo mineralization; U-Pb age; geochemistry; Hf isotope; mineral survey engineering; Xinfeng; Guangdong

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1 引　言

南岭主要由3条近EW向花岗岩山岭组成，区域地质演化历史复杂，受古太平洋和特提斯两大构造域联合制约，以多幕式构造-岩浆活动及多期“成矿大爆发”为主要特色，历来为地质学界所重视。广东佛冈复式岩体是南岭花岗岩南带(佛冈—新丰江花岗岩带)的重要组成部分，出露面积为5000~6000 km^2，呈近东西走向(陈小明等，2002；徐夕生等，2007)，主体岩性为晚侏罗世早期中粗粒斑状黑云母花岗岩、中粗粒黑云母二长花岗岩，其次为晚侏罗世晚期铝质碱长花岗岩、早白垩世早期方钠石正长岩和晚白垩世早期花岗斑岩、细粒二长花岗岩，局部出露含角闪石的花岗闪长岩、闪长岩和辉长岩(包志伟等，2003)(图1)。此外，在佛冈岩体内部或与地层接触带附近，产出有大量的W、Sn、Cu、Pb、Zn等金属矿床(点)及花岗岩型“三稀”矿床和铀矿床(赵正等，2014；王登红等，2014)。

目前，有关佛冈岩体的岩石类型判别存在较多分歧(庄文明等，2000；包志伟等，2003；徐夕生等，2007；陈璟元等，2015)。但可以确定的是，它源自地壳的部分熔融，并经历了不同程度的地幔物质参与(Zhou et al., 2006)。佛冈复式岩体成岩演化晚期岩性主要为壳幔混源A型花岗岩(南昆山岩体)和幔源碱性岩(石岭杂岩体)(苏扣林等，2015)，表明区域地壳自中侏罗世以来不断伸展拉张，幔源岩浆作用逐渐增强，经历了早期的板内岩浆活动阶段和晚期陆缘弧岩浆活动阶段(Zhou et al., 2006)。

本文报道的新坪铜钼矿化花岗闪长岩体，LA-ICP-MS锆石U-Pb年龄为(104.6±1.8)Ma，成岩时代属早白垩世晚期。这一时期的花岗闪长岩主要见于粤东及浙闽沿海一带(图1a)，研究程度较高，而在南岭地区较为稀少，整个中国东南内陆地区仅零星出露，因此新坪花岗闪长岩包含有重要的成岩成矿信息。文章结合区域地质及岩石学特征，重点开展了岩石地球化学、锆石年代学以及Hf同位素研究，旨在探讨岩石成因及其形成构造背景，进一步理解佛冈复式岩体演化至早白垩世晚期阶段的成

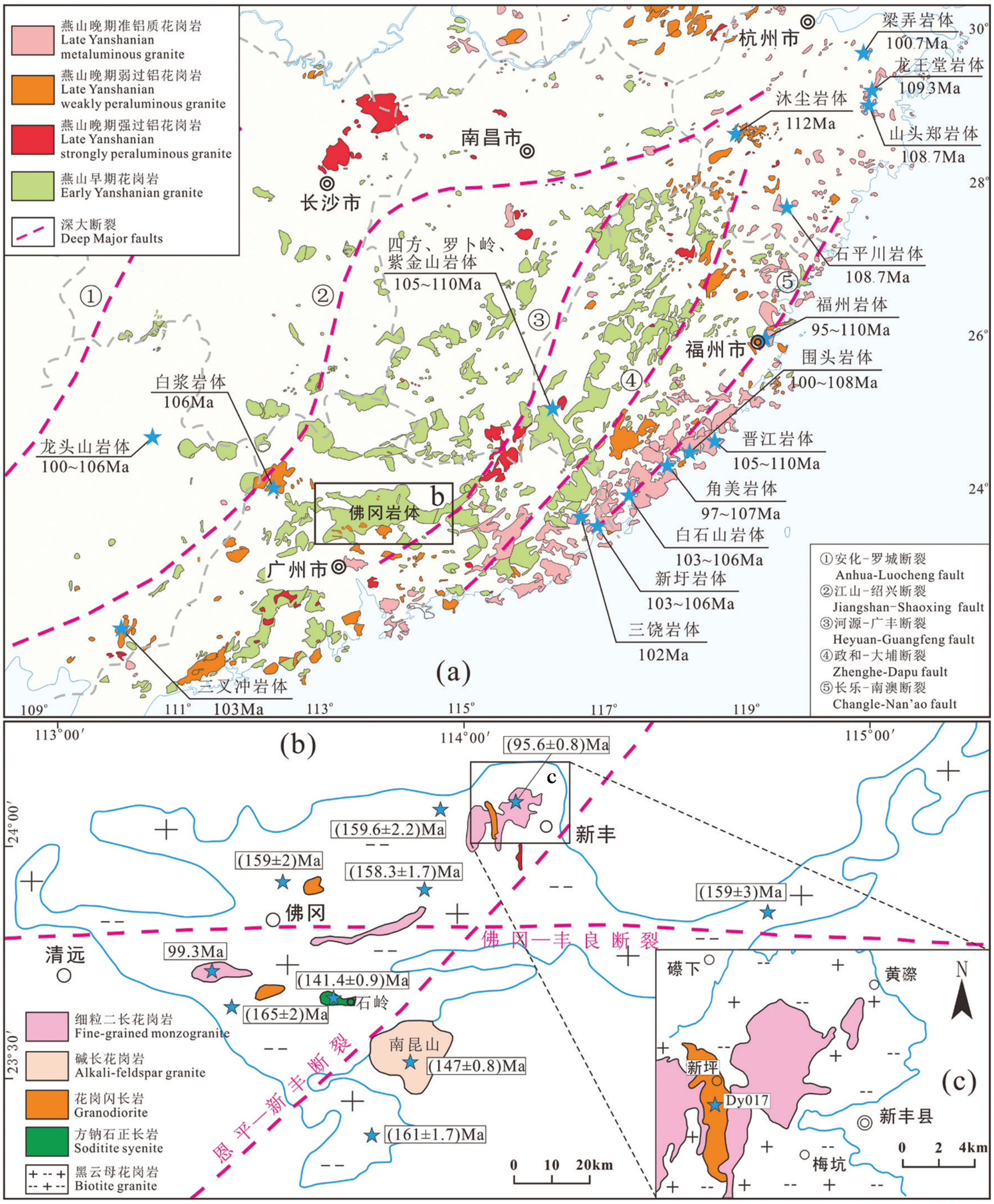


图1 佛冈复式岩体及新坪岩体地质简图(底图据孙涛, 2006; 徐夕生等, 2007修改; 岩体U−Pb年龄数据来源引自陈江峰等, 1991; 邱检生等, 1999; 高剑锋等, 2005; 刘昌实等, 2005; Li et al., 2007; 陈富文等, 2008; 李艳军等, 2009; 林清茶等, 2011; 邱检生等, 2012; Chen et al., 2013; 杨金豹等, 2013;郭海浩等, 2014; 杨振等, 2014; 苏扣林等, 2015; Duan et al., 2017; 贾丽辉, 2018)

a—华南燕山期花岗岩及早白垩世晚期(100~110 Ma)岩体分布图;b—佛冈复式岩体花岗岩分布图;c—新坪岩体地质简图

Fig.1 Sketch geological map of the Fogang composite pluton and Xinping granodiorite pluton (modified from Sun Tao, 2006, Xu Xisheng et al., 2007; Age data of pluton from Chen Jiangfeng et al., 1991; Qiu Jiansheng et al., 1999; Gao Jianfeng et al., 2005; Liu Changshi et al., 2005; Li et al., 2007; Chen Fuwen et al., 2008; Li Yanjun et al., 2009; Lin Qingcha et al., 2011; Qiu Jiansheng et al., 2012; Chen et al., 2013; Yang Jinbao et al., 2013; Guo Haihao et al., 2014; Yang Zhen et al., 2014; Su Koulin et al., 2015; Duan et al., 2017; Jia Lihui, 2018)

a−Distribution map of Yanshanian granites and Late period of Early Cretaceous (100−110Ma) plutons in South China; b− Distribution map of Granites in Fogang composite pluton; c− Sketch geological map of Xinping pluton

岩成矿过程。

2　岩体地质与岩石学

新坪岩体位于佛冈复式岩体中北部(图1b),距新丰县城约20 km,呈南北带状展布,出露面积约24.2 km^2,岩性为中细粒黑云母花岗闪长岩,局部为石英闪长岩,整体呈青灰、灰白、灰黑色。该侵入体与佛冈岩体主体岩性——晚侏罗世(~160 Ma)粗中粒黑云母二长花岗岩呈侵入接触,并被晚白垩世(~95 Ma)细粒二长花岗岩侵入。岩石碎裂断口呈参差状,易风化,常造成路基破坏或局部半风化岩土质高边坡崩塌。在双门顿一带,花岗闪长岩中发育硅化、黄铁矿化网脉,并见浸染状辉钼矿化,化探异常揭示具有较好的铜钼矿找矿前景。本次研究对象为主体岩性花岗闪长岩,用于锆石U-Pb定年的样品(Dy017)地理坐标:N24°5′30″,E114°3′20″。

样品具半自形粒状结构、块状构造,主要矿物组合为斜长石(~50%)+钾长石(~10%)+石英(~22%)+黑云母(~13%),次要矿物含量约5%,见少量角闪石(图2)。长石类矿物为半自形板状,粒径0.5~5 mm,钠长石见聚片双晶及卡钠复合双晶,钾长石见卡式双晶,斜长石见聚片双晶和环带构造,弱绢云母化;石英呈它形粒状,粒径0.35~2.5 mm,常见波状消光;黑云母片径0.3~2 mm,呈褐色—浅黄褐色,弱绿泥石化;角闪石呈半自形—他形柱状、粒状,粒径0.35~1.2 mm,浅绿—深绿色。副矿物组合类型为绿帘石-锆石-褐帘石型,磁铁矿远多于钛铁矿。

3　测试方法

锆石挑选由河北省区域地质矿产调查研究所实验室完成,锆石制靶和阴极发光(CL)照相在北京锆年领航科技有限公司完成。锆石U-Pb同位素测试由合肥工业大学资源与环境工程学院激光剥蚀电感耦合等离子体质谱仪(LA-ICP-MS)完成,剥蚀直径采用32 μm。数据处理采用ICPMS Data Cal (Liu et al.,2008;Liu et al., 2010a;Liu et al., 2010b)和Isoplot/Ex_ver3 (Andersen, 2002)软件。普通Pb采用ComPbCorr#3.18程序(Ludwig, 2003)校正。标准锆石91500的U-Th-Pb同位素比值采用Wiedenbeck et al.(1995)推荐值,监控样标准锆石$^{206}Pb/^{238}U$年龄采用Plesovice (Sláma et al., 2008)推荐值: (337.13 ±0.37)Ma (2σ)。样品LA-ICP-MS锆石U-Pb同位素测试结果见表1。

锆石Hf同位素测试是在北京科荟测试技术有限公司Neptune plus多接收等离子质谱及配套的ESI NWR193紫外激光剥蚀系统(LA-MC-ICP-MS)上进行的,采用He作为剥蚀物质载气,剥蚀直径采用40 μm。仪器运行条件及详细流程见文献(Wu et al., 2006;侯可军等,2007)。分析过程中锆石标准GJ1的$^{176}Hf/^{177}Hf$测试加权平均值分别为0.282007 ± 0.000007 (2σ, n=36),与文献报道值(Morel et al., 2008)在误差范围内完全一致。锆石Hf同位素分析结果见表2。

岩石地球化学分析在河北省区域地质矿产调

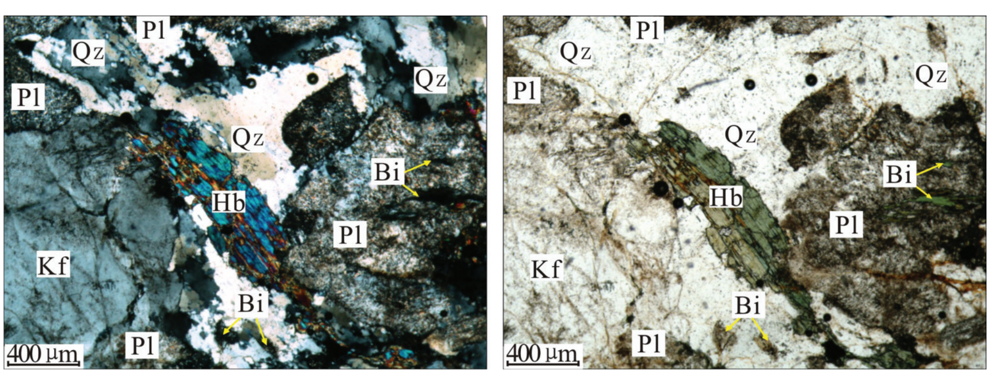


图2 新坪花岗闪长岩的岩相学显微照片(左:正交偏光;右:单偏光)
Hb—角闪石;Kf—钾长石;Pl—斜长石;Qz—石英;Bi—黑云母
Fig.2 Microphotographs of the Xinping granodiorite(Left: crossed polarizer; Right: single polarizer)
Hb-Hornblende; Kf-Potassium feldspar; Pl-Plagioclase; Qz-Quartz; Bi-Biotite

表1 新坪花岗闪长岩LA−ICP−MS锆石U−Pb测试结果

Table 1 LA−ICP−MS zircon U−Pb dating results of the Xinping granodiorite

分析点	$Th/10^{-6}$	$U/10^{-6}$	Th/U	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{208}Pb/^{232}Th$	1σ	$^{207}Pb/^{235}U$ t/Ma	1σ	$^{206}Pb/^{238}U$ t/Ma	1σ	$^{207}Pb/^{206}Pb$ t/Ma	1σ	谐和度
Dy017-01	326.95	439.17	0.74	0.15	0.01	0.02	0.0005	0.01	0.0002	139.46	10.77	108.14	3.39	738.90	164	0.74
Dy017-02	212.34	418.78	0.51	0.10	0.01	0.02	0.0005	0.01	0.0002	98.19	5.16	104.42	3.02	13.10	133	0.93
Dy017-03	228.48	386.03	0.59	0.11	0.01	0.02	0.0005	0.01	0.0002	108.49	5.27	102.73	2.98	300.05	125	0.94
Dy017-04	268.10	453.43	0.59	0.11	0.01	0.02	0.0005	0.01	0.0002	109.74	5.89	104.40	3.10	255.60	144	0.95
Dy017-05	416.18	592.00	0.70	0.11	0.01	0.02	0.0005	0.00	0.0002	105.13	5.79	100.72	2.95	176.01	142	0.95
Dy017-06	518.52	764.85	0.68	0.11	0.01	0.02	0.0005	0.01	0.0002	107.80	5.10	103.44	3.04	188.97	130	0.95
Dy017-07	223.72	391.47	0.57	0.16	0.01	0.02	0.0005	0.01	0.0003	151.03	7.60	103.60	3.02	961.11	123	0.62
Dy017-08	379.26	551.27	0.69	0.10	0.01	0.02	0.0004	0.00	0.0002	94.86	4.65	99.23	2.81	13.06	126	0.95
Dy017-09	291.39	426.59	0.68	0.12	0.01	0.02	0.0005	0.01	0.0002	115.13	5.59	104.67	2.99	331.54	122	0.90
Dy017-10	734.89	749.34	0.98	0.10	0.00	0.02	0.0005	0.01	0.0002	97.84	4.50	103.84	3.00			0.94
Dy017-11	308.98	453.17	0.68	0.10	0.01	0.02	0.0005	0.01	0.0002	100.89	5.33	104.36	3.00	20.47	146	0.96
Dy017-12	305.72	430.82	0.71	0.09	0.01	0.02	0.0005	0.01	0.0002	91.47	4.89	100.98	2.91			0.90
Dy017-13	187.02	349.93	0.53	0.12	0.01	0.02	0.0005	0.01	0.0002	118.93	6.66	107.87	3.19	450.05	139	0.90
Dy017-14	354.22	505.20	0.70	0.11	0.01	0.02	0.0005	0.01	0.0002	108.30	5.41	104.64	2.99	272.28	99	0.96
Dy017-15	235.46	370.15	0.64	0.11	0.01	0.02	0.0005	0.00	0.0002	104.30	5.66	104.89	3.18	333.00	144	0.99
Dy017-16	301.76	445.65	0.68	0.13	0.01	0.02	0.0005	0.01	0.0002	124.67	6.68	106.49	3.11	635.20	130	0.84
Dy017-17	288.68	446.75	0.65	0.11	0.01	0.02	0.0005	0.01	0.0002	108.81	5.61	111.41	3.17	190.82	133	0.97
Dy017-18	227.74	394.95	0.58	0.10	0.01	0.02	0.0005	0.01	0.0002	96.65	4.98	111.29	3.16			0.85
Dy017-19	237.80	378.23	0.63	0.11	0.01	0.02	0.0005	0.01	0.0002	102.86	5.09	111.29	3.19	27.88	126	0.92
Dy017-20	278.06	419.61	0.66	0.11	0.01	0.02	0.0005	0.01	0.0002	106.33	5.02	107.62	3.04	120.46	118	0.98

查研究所实验室完成。主量元素检测仪器为Axios^{max}X射线荧光光谱仪，烧失量、H_2O^-等采用电子分析天平称重法，微量元素采用X Serise 2等离子体质谱仪检测。样品地球化学分析数据及相关参数见表3。

4 测试结果

4.1 锆石U−Pb定年与Hf同位素

锆石U−Pb定年样品中锆石呈黄色、透明—半透明，自形—半自形双锥柱状，长宽比为1∶1至5∶1，

表2 新坪花岗闪长岩体锆石Hf同位素分析结果

Table 2 Zircon Hf isotopic compositions of the Xinping granodiorite pluton

序号	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$(^{176}Hf/^{177}Hf)_i$	$\varepsilon_{Hf}(0)$	$\varepsilon_{Hf}(t)$	t_{DM}/Ma	t_{DM2}/Ma	$f_{Lu/Hf}$	U−Pb分析点
1	0.032176	0.000897	0.282642	0.000016	0.282642	-4.5	-2.3	858	1313	-0.97	Dy017-03
2	0.027425	0.000773	0.282642	0.000015	0.282642	-4.5	-2.3	856	1314	-0.98	Dy017-04
3	0.048489	0.001327	0.282676	0.000019	0.282676	-3.3	-1.1	819	1237	-0.96	Dy017-05
4	0.038758	0.001094	0.282694	0.000017	0.282694	-2.7	-0.5	789	1197	-0.97	Dy017-06
5	0.022922	0.000643	0.282646	0.000016	0.282646	-4.4	-2.2	849	1306	-0.98	Dy017-07
6	0.027559	0.000785	0.282675	0.000017	0.282675	-3.4	-1.1	810	1239	-0.98	Dy017-08
7	0.053720	0.001416	0.282697	0.000017	0.282697	-2.5	-0.4	791	1189	-0.96	Dy017-11
8	0.045514	0.001213	0.282712	0.000017	0.282712	-2.0	0.2	766	1156	-0.96	Dy017-12
9	0.029384	0.000796	0.282624	0.000016	0.282624	-5.2	-3.0	882	1355	-0.98	Dy017-13
10	0.032186	0.000885	0.282634	0.000017	0.282634	-4.8	-2.6	870	1332	-0.97	Dy017-14
11	0.025813	0.000724	0.282658	0.000017	0.282658	-4.0	-1.8	834	1279	-0.98	Dy017-15
12	0.033022	0.000888	0.282612	0.000019	0.282612	-5.6	-3.4	901	1382	-0.97	Dy017-16
13	0.036325	0.000995	0.282653	0.000017	0.282653	-4.1	-1.9	845	1288	-0.97	Dy017-17
14	0.023348	0.000664	0.282674	0.000015	0.282674	-3.4	-1.2	810	1243	-0.98	Dy017-18
15	0.022164	0.000645	0.282650	0.000015	0.282650	-4.3	-2.0	843	1296	-0.98	Dy017-19

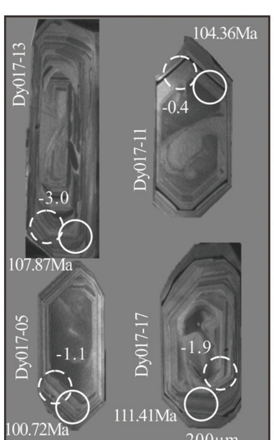
颗粒大小为100~370 μm，锆石U和Th分别为349.93×10^{-6}~764.85×10^{-6}和187.02×10^{-6}~734.89×10^{-6}，Th/U值(0.51~0.74)大于0.5，CL图像显示锆石发育典型的震荡环带，表明为岩浆成因锆石(Hoskin et al., 2000；吴元保等，2004)。参考透射光和反射光成像，避开锆石包裹体、核部及裂纹，在震荡环带部位进行激光剥蚀定年和Hf同位素测定。由于普通Pb的校正，年轻锆石采用$^{206}Pb/^{238}U$年龄(Griffin et al., 2004)。分析点01、07、16、18年龄谐和度小于90%需舍弃，其余16个分析点数据位于谐和曲线附近，且较为集中，锆石$^{206}Pb/^{238}U$年龄为99.23~111.4 Ma，加权平均年龄值为(104.6±1.8) Ma (MSWD=1.2)，解释为新坪花岗闪长岩体的侵位年龄(图3)。

对新坪花岗闪长岩(Dy017)12粒锆石进行了12次Lu-Hf同位素分析，分析点均位于新生岩浆锆石的震荡环带内，部分锆石Hf同位素测试点位置见图3。被测锆石的$^{176}Yb/^{177}Hf$= 0.020164~0.053720，$^{176}Lu/^{177}Hf$=0.000645~0.001416，$^{176}Hf/^{177}Hf$=0.282624~0.282712，锆石$^{176}Lu/^{177}Hf$值很小(<0.002)，表明锆石形成之后很少有放射性Hf的积累，因而可以用初始$^{176}Hf/^{177}Hf$比值代表锆石形成时的$^{176}Hf/^{177}Hf$。以t=104 Ma计算的$\varepsilon_{Hf}(t)$值为-3.0~0.2，绝大多数为负值。在$t-\varepsilon_{Hf}(t)$关系图(图4)上，样品点均落在南岭地区前寒武纪地壳演化域之上，且位于球粒陨石均一储库(CHUR)附近。

4.2 岩石地球化学特征

新坪花岗闪长岩主量元素具有以下特征：(1)偏酸性，SiO_2变化范围较小，含量为63.43%~65.27%；(2)碱含量中等，ALK=6.09%~7.63%，在$SiO_2-(K_2O+Na_2O)$关系图(图5a)上，样品投点在亚碱性系列的花岗闪长岩区，与岩石矿物定名结果相一致。碱度率指数(A.R.)=1.89~2.28，在SiO_2-碱度率(A.R)关系图(图5b)上，样品落在钙碱性区。里特曼指数(σ)为1.67~2.85，均值2.13，属钙碱性岩；(3)相对富钾，K_2O=3.55% ~4.34% ，Na_2O=2.53% ~3.29% ，K_2O/Na_2O=1.32~1.65，在SiO_2-K_2O关系图上，样品主要落在高钾钙碱性系列范围(图5c)；(4)具准铝质特征，Al_2O_3=15.11%~15.97%，铝饱和指数(A/CNK)和碱铝指数(A/NK)值分别为0.76~0.92和1.56~1.88，在A/CNK-A/NK关系图上，样品均落在亚碱准铝质区域(图5d)；(5)FeO^T、MgO、CaO氧化物含量相对较高，分别为4.32%~4.84%、1.81%~2.3%和3.43%~4.61%，镁指数$Mg^{\#}$为42.64~46.95。

岩石稀土元素总量中等，ΣREE=150.73×10^{-6}~212.99×10^{-6}；富集轻稀土，LREE/HREE=8.26~13.20，$(La/Yb)_N$=8.17~16.64，轻稀土分馏程度大于重稀土，$(La/Sm)_N$=3.87~6.49，$(Gd/Yb)_N$=1.45~1.81；岩石稀土



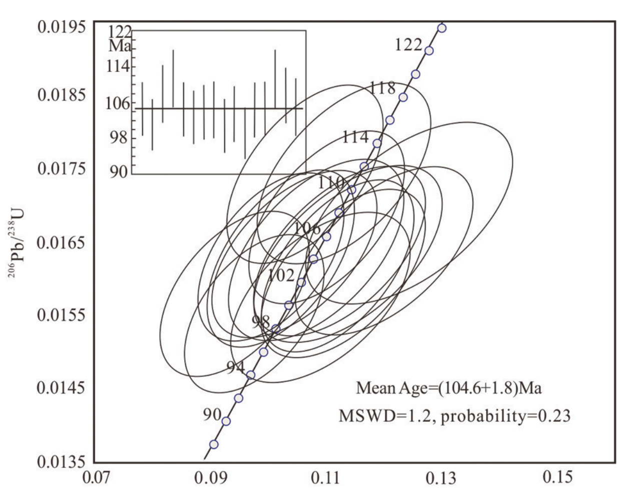


图3 新坪岩体花岗闪长岩样品(Dy017)锆石代表性阴极发光(CL)图像和锆石U-Pb年龄谐和图
阴极发光(CL)图像中：实线圆圈代表U-Pb分析点，虚线圆圈代表相应的Hf同位素分析点
Fig.3 Cathodoluminescence (CL) images of representative zircons in sample (Dy017) and concordia diagrams of LA-ICP-MS zircon U-Pb data from the Xinping granodiorite pluton
The solid circles represent the analysis spots of U-Pb and dotted circles represent the analysis spots of corresponding Hf isotope in the cathodoluminescence (CL) images

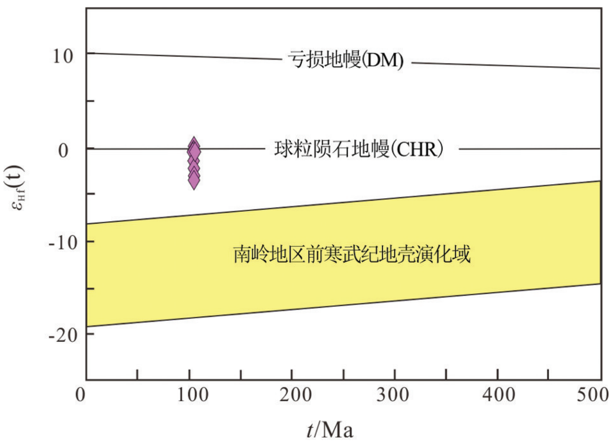


图4 新坪花岗闪长岩 $t-\varepsilon_{Hf}(t)$ 关系图

Fig.4 $t-\varepsilon_{Hf}(t)$ diagram of the Xinping granodiorite

元素球粒陨石标准化配分曲线呈明显的右倾斜型(图6a),轻微的铕负异常(δEu=0.73~0.87),与典型的S型花岗岩"海鸥型"稀土配分形式(徐克勤等, 1989)有较明显差别。Sr含量中等,变化范围为288×10^{-6}~542.88×10^{-6}(1个样品Sr<400×10^{-6}),Y和Yb含量中等偏低,Y=17.84×10^{-6}~21.82×10^{-6}(均值19.64×10^{-6}),Yb=1.87×10^{-6}~2.7×10^{-6}(均值2.27×10^{-6});具较低的相容元素含量,Cr=18.4×10^{-6}~29.2×10^{-6},Ni=5.34×10^{-6}~9.86×10^{-6},V=84×10^{-6}~123.8×10^{-6}。微量元素原始地幔标准化蛛丝图显示,高场强元素Nb、Ta、Zr、Ti相对亏损,Rb、U、Th和La、Hf相对富集,Ba相对于Rb和Th亏损(图6b)。富集大离子亲石元素和轻稀土、亏损高场强元素,指示新坪花岗闪长岩应属于地壳来源。

5 讨论

5.1 岩石成因与源区性质

新坪花岗闪长岩A/CNK<1(=0.76~0.92),具准

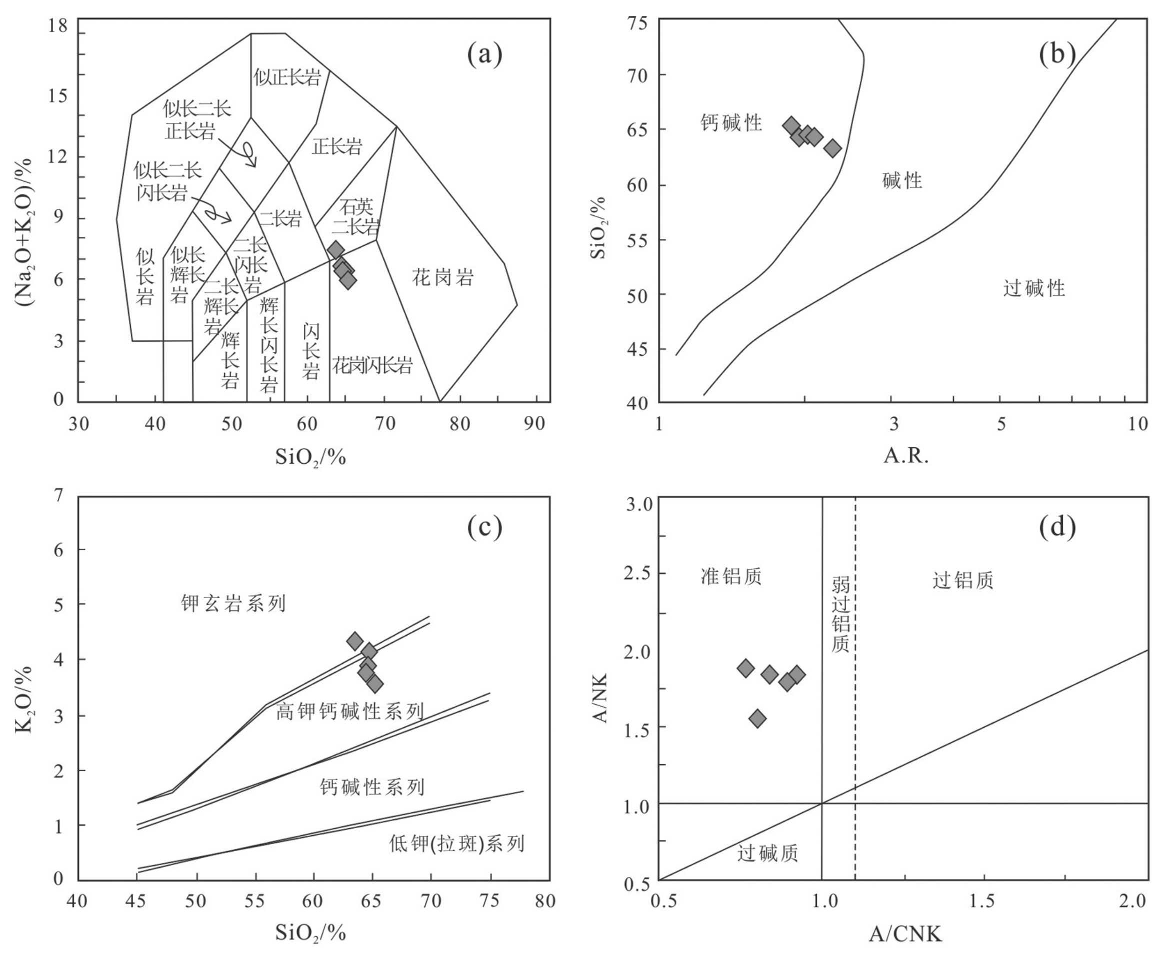


图5 新坪花岗闪长岩主量元素判别图

a—TAS分类图解(底图据Middlemost, 1994); b—SiO_2−A.R.图解; c—K_2O-SiO_2图解(底图据Peccerillo et al., 1976); d—A/NK−A/CNK图解

Fig.5 Plots of major element compositions of Xinping granodiorite

a−Total alkalis vs. silica(after Middlemost, 1994); b−Silica vs. A.R.; c−Potassium vs. silica(after Peccerillo et al., 1976); d− A/NK vs. A/CNK

表3 新坪花岗闪长岩主量元素(%)及微量、稀土元素(10^{-6})分析结果

Table 3 Major element(%), trace and rare earth element (10^{-6}) analyses of the Xinping granodiorite

样品号	Dy017-1	Dy017-2	Dy017-3	Dy017-4	Dy017-5
SiO_2	64.43	63.43	65.27	64.52	64.4
TiO_2	0.51	0.48	0.46	0.52	0.51
Al_2O_3	15.97	15.74	15.11	15.69	15.88
Fe_2O_3	2.22	2.15	2.53	2.51	2.28
FeO	2.57	2.49	1.79	2.33	2.35
MnO	0.089	0.094	0.11	0.087	0.089
MgO	2.06	2.3	1.81	2.02	2.07
CaO	3.43	3.8	4.61	3.45	4.06
Na_2O	2.68	3.29	2.54	2.53	2.71
K_2O	3.94	4.34	3.55	4.16	3.83
P_2O_5	0.262	0.28	0.25	0.259	0.27
LOT	1.66	1.44	1.8	1.69	1.39
TOTAL	99.82	99.83	99.85	99.78	99.84
FeO^T	4.8	4.63	4.32	4.84	4.63
ALK	6.62	7.63	6.09	6.69	6.54
A/CNK	0.92	0.8	0.76	0.9	0.84
A/NK	1.84	1.56	1.88	1.81	1.84
$Mg^\#$	43.38	46.95	42.8	42.64	44.39
Rb	182.3	170.21	170.21	163.4	167.38
Ba	748.57	1083.94	878.28	811.1	768.38
Th	29.79	33.2	37.22	28.68	30.45
U	6.77	6.68	8.27	6.9	6.8
Ta	1.09	1.03	1.13	1.49	1.88
Nb	14.93	12.43	14.54	12.92	11.23
Sr	288	542.88	513.59	420.1	492.21
Zr	124.68	127.69	141.02	162.86	111.78
Hf	5.23	8.84	5.92	7.54	3.39
Y	18.73	21.82	20.21	17.84	19.59
Sc	12.48	15.3	13.4	10.99	12
Cu	12.10	9.25	6.42	15.50	16.60
V	123.80	121.00	112.00	84.00	104.00
Ni	7.90	9.86	8.02	5.90	5.34
Cr	21.80	19.80	18.40	22.00	29.20
Nb/U	2.20	1.86	1.76	1.87	1.65
Nb/Ta	13.75	12.12	12.86	8.68	5.97
Zr/Hf	23.85	14.44	23.81	21.59	32.99
Dy/Yb	1.69	1.46	1.63	1.65	1.57
Sc/Th	0.42	0.46	0.36	0.38	0.39
La	43.91	33.13	40.02	39.31	55.6
Ce	77.82	58.26	62.7	68.96	92.28
Pr	8.45	7.75	8.12	7.71	9.87
Nd	30	28.58	28.92	26.3	33.45
Sm	5.2	5.38	5.27	4.68	5.39
Eu	1.23	1.35	1.27	1.05	1.39
Gd	4.35	4.9	4.76	3.96	5.05
Tb	0.67	0.73	0.71	0.59	0.69
Dy	3.61	4.01	3.84	3.08	3.55
Ho	0.7	0.8	0.74	0.61	0.69
Er	2.09	2.34	2.13	1.79	2.06
Tm	0.35	0.41	0.38	0.31	0.35
Yb	2.13	2.74	2.35	1.87	2.26
Lu	0.3	0.34	0.3	0.26	0.35
ΣREE	180.81	150.73	161.49	160.47	212.99
LREE	166.61	134.46	146.3	148.01	197.99
HREE	14.2	16.27	15.2	12.46	15
LREE/HREE	11.73	8.26	9.63	11.87	13.2
La_N/Yb_N	13.95	8.17	11.49	14.18	16.64
δEu	0.77	0.79	0.76	0.73	0.8
t_{Zr}(℃)	779	781	790	802	755

注：$ALK=K_2O+Na_2O$；$FeO^T=FeO+0.8998\times Fe_2O_3$；$Mg^\#=100\times(MgO/40.3044)/(MgO/40.3044+FeO^T/71.844)$

铝质特征。K_2O/Na_2O平均值为1.45，低于华南S型花岗岩平均值1.61(高剑锋等, 2005)。在岩石类型判别K_2O-Na_2O图解(图7a)中，样品落在I型花岗岩区域；并且样品P_2O_5与SiO_2呈负线性关系(图7b)，岩石中常见角闪石等暗色矿物，表明其岩石类型为I型花岗岩(Chappell et al., 1992; Wolf et al., 1994)。

I型花岗岩通常具有相对较低的FeO^T/MgO、Rb/Sr比值和(Zr+Nb+Ce+Y)含量，以及相对中等的成岩温度。新坪花岗闪长岩FeO^T/MgO=1.92~2.27，Rb/Sr=0.31~0.63，Zr+Nb+Ce+Y=220×10^{-6}~263×10^{-6}，均低于A型花岗岩平均值(相应值分别为13.4，350×10^{-6}和3.52, Whalen et al., 1987)；锆石饱和温度计(Watson et al., 1983)计算出的新坪闪长岩体成岩温度(t_{Zr})为755~802℃，平均值为781℃(n=5)，显著低于A型花岗岩(=883℃，刘昌实等，2003)，略高于S型花岗岩(=764℃，King et al.,1997)，与前人统计的I型花岗岩(=781℃，King et al.,1997)相一致。

前人研究表明，I型花岗岩类主要有3种可能成因：地壳岩石的部分熔融(Chung et al., 2003)、交代岩石圈地幔低程度部分熔融(Jiang et al., 2006)以及长英质－玄武质混浆作用(Streck et al., 2007; Danyushevsky et al., 2008)。笔者认为新坪岩体I型花岗闪长岩主要源于地壳岩石的部分熔融，这是因为：(1)交代岩石圈地幔经部分熔融一般形成钾玄质成分的岩浆(徐克勤等, 1989)，而新坪岩体的高钾钙碱性特征，暗示其成因与交代岩石圈地幔无关。另外，岩石Sr含量中等，Ba相对于原始地幔亏损，与俯冲流体交代造成富集地幔起源的岩浆富集Ba、Sr等特征恰恰相反；(2)新坪花岗闪长岩中未见镁铁质暗色微粒包体(MME)，且Hf同位素$\varepsilon_{Hf}(t)$变化范围较小，表明不可能由岩浆混合作用形成。

新坪花岗闪长岩富硅、富钾，属于高钾钙碱性系列，亏损高场强元素Nb、Ta，富集大离子亲石元素和轻稀土元素，指示与大陆地壳物质具有明显的亲缘性。岩石Nb/Ta=5.97~13.75，平均值为10.67，接近大陆地壳Nb/Ta比值(=10~14)。而$MgO-SiO_2$(图8a)和$Ni-Mg^\#$图(图8b)显示新坪岩体源于下地壳物质的熔融作用，这与岩石副矿物特征所反映的结果相一致。新坪花岗闪长岩中副矿物含量较高(4735×

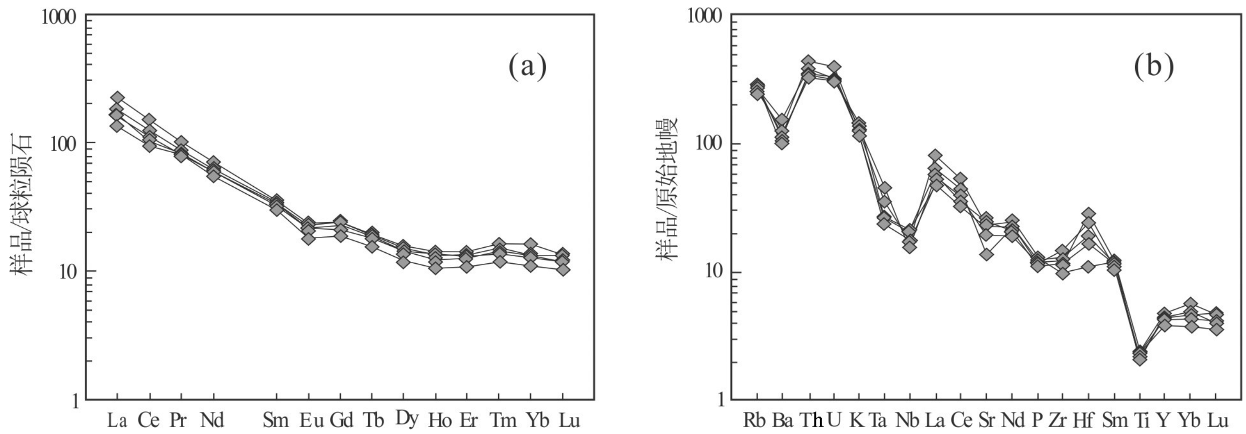


图6 新坪花岗闪长岩稀土元素球粒陨石标准化配分曲线(a, 标准化值据 Taylor et al., 1985)和微量元素原始地幔标准化蛛丝图(b, 标准化值据 Sun et al., 1989)

Fig.6 Diagrams of chondrite−normalized rare earth elements (a, the normalized values after Taylor et al., 1985)and Primitive mantle−normalized trace elements spidergrams(b, the normalized values after Sun et al., 1989) of the Xinping granodiorite pluton

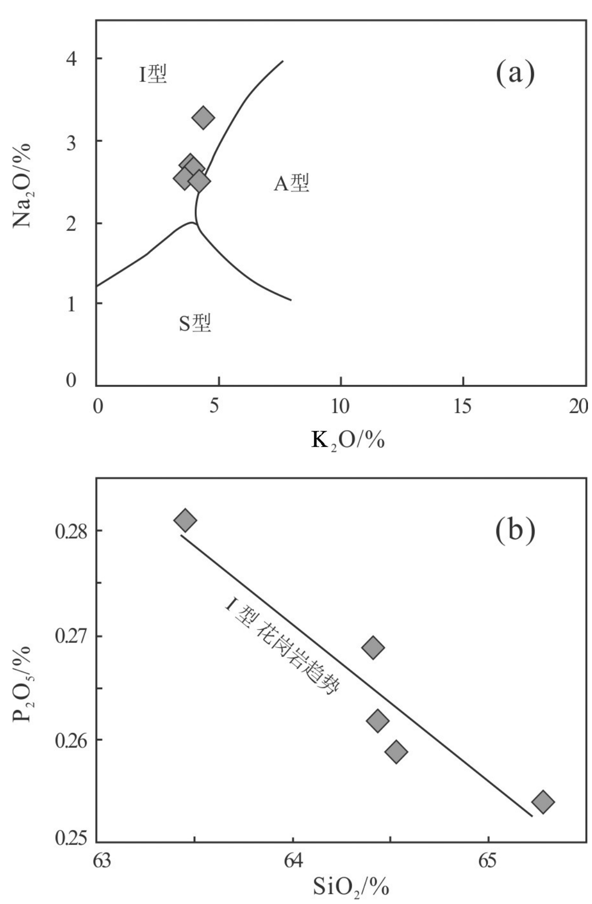


图7 新坪花岗闪长岩 K_2O-Na_2O(a)和 $SiO_2-P_2O_5$(b)图

Fig.7 Discrimination diagrams of K_2O-Na_2O(a) and $SiO_2-P_2O_5$(b) for the Xinping granodiorite pluton

10^{-6}~6580×10^{-6}),且种类较少,以磁铁矿(4658×10^{-6}~6164×10^{-6})、榍石为主,少见钛铁矿,相当于华南花岗岩以下地壳为主要物质来源的成岩系列(张绍立等, 1983)。岩石 δEu=0.73~0.87,指示在成岩过程中发生了斜长石的分离结晶或岩浆源区有斜长石残留;Y/Yb=7.96~9.53(均值8.65),$(Ho/Yb)_N$=0.85~0.95(均值0.91),重稀土(Ho−Lu)曲线相对平坦,表明岩浆源区残留相主要为角闪石(葛小月等, 2002);亏损Nb、Ta、P和Ti,可能与磷灰石、榍石和Fe−Ti氧化物等残留在源区有关。

新坪花岗闪长岩锆石Hf二阶段模式年龄(t_{DM2})集中1.16~1.36 Ga,$\varepsilon_{Hf}(t)$大部分为负值(−3.0~0.2),表明其可能主要来源于中元古代结晶基底的熔融。Gilder et al.(1996)对华南中生代花岗岩进行了Sr−Nd同位素分析,证实了华南地区存在广泛的中元古代地壳。在扬子地块南部和华夏地块的武夷山、南岭和云开等地区的新元古代沉积岩中也发现相当数量的1.3~1.4 Ga的碎屑锆石,且为正 $\varepsilon_{Hf}(t)$值和较年轻二阶段模式年龄,说明在华南板块东南部存在增生的中元古代地壳(Yu et al.,2008; Yu et al., 2010; Wang et al.,2010),这些中元古代地壳为燕山晚期岩浆岩提供了重要的物质来源。李献华等(1991)统计前人数据,发现华南地壳主要有大于2.5 Ga、1.8 Ga和1.2~1.4 Ga三期幕式增长,而新坪岩体源区对应

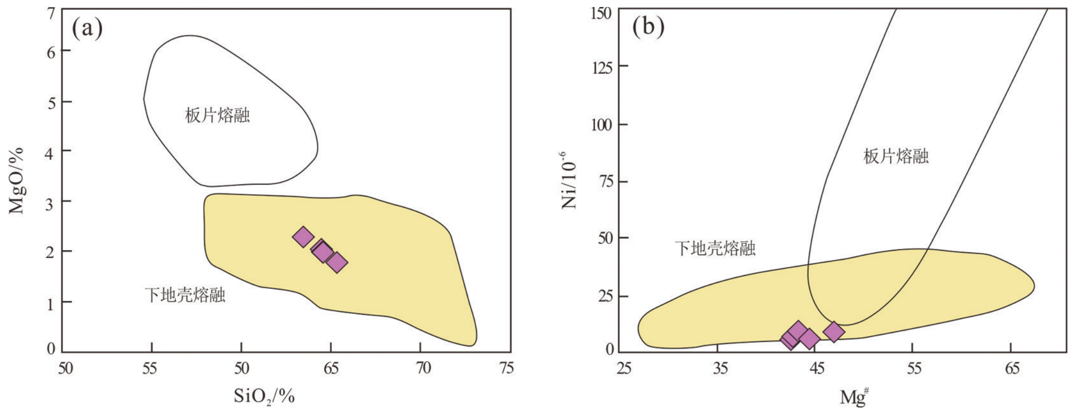


图8 新坪花岗闪长岩MgO−SiO_2图(a)和Ni−$Mg^{\#}$图(b)
（底图数据来源：a, 据Hou et al., 2004; Zhu et al.,2009;b, 据Guo et al., 2012）
Fig.8 Discrimination diagrams of MgO−SiO_2(a) and Ni−$Mg^{\#}$(b) for the Xinping granodiorite
（Date sources: a, after Hou et al., 2004; Zhu et al., 2009; b, after Guo et al., 2012）

于最后一期华南地壳的幕式生长。

实验岩石学研究表明，玄武质下地壳发生部分熔融产生的熔体，不管熔融程度如何，均具有低$Mg^{\#}$值(＜40)特征，然而在地幔组分参与时，才能导致熔体的$Mg^{\#}$值大于40(Rapp et al.,1995)。新坪花岗闪长岩具较高的MgO含量，$Mg^{\#}$=42.64~46.95，表明必须有幔源组分参与成岩过程。锆石Hf同位素特征同样支持这一观点，新坪花岗闪长岩样品投点位于南岭前寒武纪地壳演化域之上，靠近球粒陨石均一储库(CHUR)附近(图4)，且一颗锆石$\varepsilon_{Hf}(t)$为正值，暗示其成岩过程必须有亏损地幔物质的加入。

Nb/U比值能够反映源区是否发生过俯冲流体交代作用。在俯冲板块脱水熔融过程中，大离子亲石元素首先运移到俯冲流体中，而高场强元素(如Nb、Ta)则赋存在金红石或钛铁矿残留相中，导致俯冲板片脱水熔融的流体具有较低的Nb/U比值(0.22，Ayers，1998)。新坪花岗闪长岩Nb/U比值(1.7~2.2)明显低于下地壳的估算值(25)和上地壳的平均值(4.5，Rudnick et al., 2003)，暗示纯陆壳物质部分熔融产生的岩浆不可能有如此低的Nb/U比值。此外，新坪花岗闪长岩亏损Nb−Ta和低的Nb/La值(0.20~0.38)，亦表明源区受到了俯冲流体的交代作用。Yb−La/Yb(图9a)和La−La/Sm(图9b)反映了新坪岩体源区的不均一特征(地壳物质+地幔物质+俯冲流体)以及主要受部分熔融作用控制。

综上所述，新坪花岗闪长岩的源区主要为中元古代地壳物质，并经历了幔源组分的加入和板片俯冲流体的交代作用，岩浆主要受部分熔融作用控制。新坪岩体侵位时间为晚白垩世早期，这一时期中国东南部整体处于伸展拉张构造背景，古太平洋

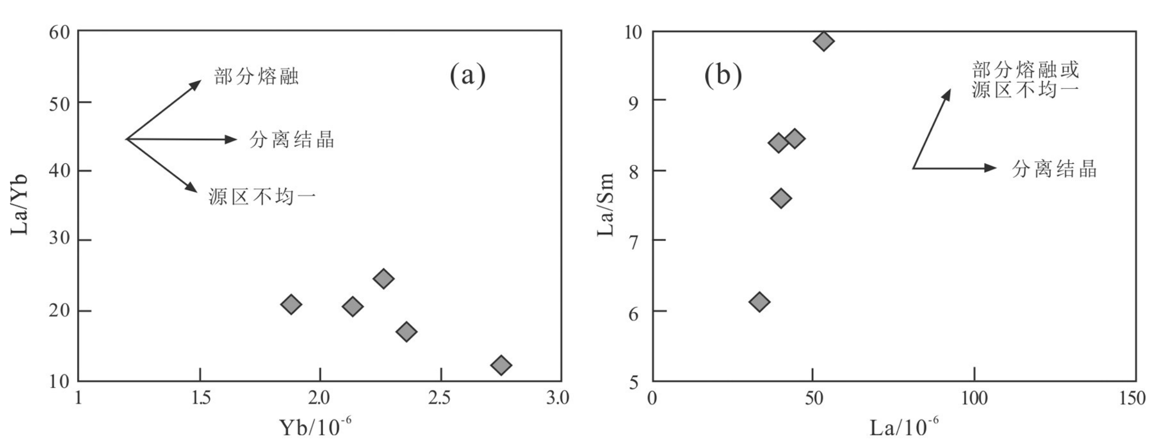


图9 新坪花岗闪长岩La−Yb (a)和La/Sm−La (b)图
Fig.9 Major and trace element variation diagrams of Xinping granodiorite

板片的俯冲消减导致玄武质岩浆底垫诱发区域元古代结晶基底发生部分熔融，因此新坪花岗闪长岩具有明显的陆缘弧岩浆活动特征(Zhou et al.,2006)(图10)。

5.2 早白垩世晚期岩浆活动与Cu-Au-Mo成矿

早白垩世晚期(110~100 Ma)是中国东南部重要的构造-岩浆活动期，这一时期形成了大量的中酸性侵入岩以及少量火山岩和中基性脉岩，具有陆内双峰式岩浆活动特征。侵入岩以粤闽浙沿海地区最为发育，集中分布在长乐—南澳断裂带附近，岩性为花岗闪长岩、石英闪长岩、石英二长岩以及少量二长花岗岩，呈小岩体或岩株状，属高钾钙碱性偏铝质花岗岩类，如粤东三饶岩体(102±1)Ma和新圩岩体(103~106 Ma)(LA-ICP-MS锆石U-Pb)(贾丽辉, 2018)，福建的福州杂岩体(100~107Ma)(LA-ICP-MS锆石U-Pb)(林清茶等，2011)、漳州岩体(100~107 Ma) (LA-ICP-MS锆石U-Pb)(Chen et al., 2013)、漳州角美岩体((106.4±1.8)Ma) (LA-ICP-MS锆石U-Pb)(杨金豹等, 2013)、漳浦复式岩体中的程溪花岗闪长岩((101.3±3.2)Ma) (LA-ICP-MS锆石U-Pb)(邱检生等，2012)，闽西南四方岩体((109.5±0.8)Ma)、罗卜岭岩体(105.4~107 Ma)、紫金山岩体(104.5~107.5 Ma) (LA-ICP-MS锆石U-Pb)(Duan et al.,2017)，浙江沿海普陀山岩体((110.2±1.1) Ma)(TIMS锆石U-Pb)(邱检生等，1999)、龙王堂岩体((109.8±0.4)Ma)(黑云母Ar-Ar)(陈江峰等, 1991)以及石平川岩体((103±1)Ma)(LA-ICP-MS锆石U-Pb)(李艳军等，2009)。该期岩体多被后期(100~90 Ma)碱长(晶洞)花岗岩或二长花岗岩侵入，新编的广东省区域地质志(2017)[1]将粤东地区早白垩世晚期(102~109 Ma)和晚白垩世早期(~95 Ma)岩浆岩分别厘定为早白垩世第四阶段和第五阶段侵入岩，研究区新坪花岗闪长岩同样被较晚期((95.6±0.8) Ma)花岗斑岩侵入，反映了二者之间呈脉动接触关系，为同期岩浆活动的不同阶段产物，这与东南沿海燕山晚期I-A型复合岩体的形成相一致(邱检生等, 1999)。

这一时期的岩浆岩在东南内陆地区呈零星出露，除文中报道的新坪花岗闪长岩(104.6±1.8 Ma)外，尚有粤西连阳复式岩体中的白浆黑云母花岗岩((106±0.7)Ma) (LA-ICP-MS锆石U-Pb)(高剑锋等，2005)、赣南会昌埃达克质粗面岩((110.7±1.0) Ma) (SHRIMP锆石U-Pb)(钟志菲等，2015)和会昌橄榄玄粗岩((107.3±2.3)Ma)(全岩Rb-Sr)(章邦桐等, 2008)，云开地区广西陆川三叉冲黑云母花岗岩(103±1 Ma) (LA-MC-ICP-MS锆石U-Pb)(杨振等, 2014)以及广西龙头山流纹斑岩((103.7±2.4)Ma)和花岗斑岩((100.3±1.4)Ma) (SHRIMP锆石U-Pb)(陈富文等, 2008)，等等。

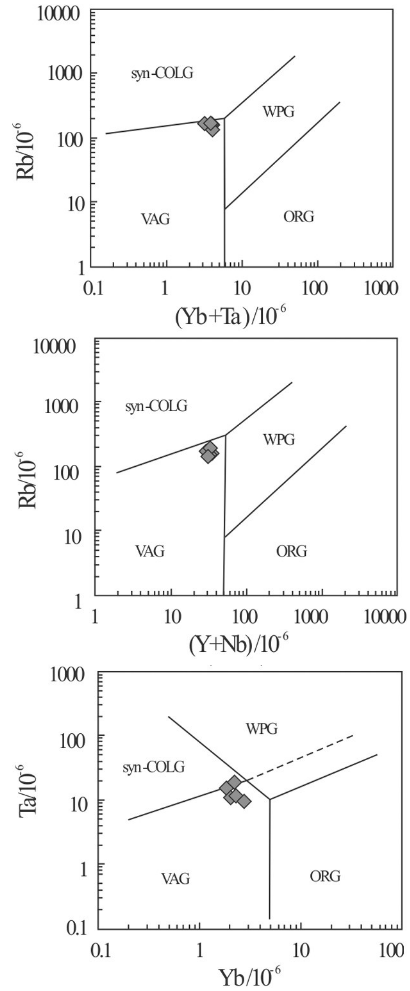


图10 新坪花岗闪长岩的构造背景判别图(据Pearce et al., 1984)
WPG—板内花岗岩；ORG—洋中脊花岗岩；VAG—火山弧花岗岩；syn—COLG-同碰撞花岗岩
Fig.10 Diagrams of tectonic environment for Xinping granodiorite by trace elements(after Pearce et al.,1984)
WPG-within plate granite; ORG-oceanic ridge granite; VAG-volcanic arc granite; syn-COLG-syn-collision granite on

有关早白垩世晚期花岗质岩浆的成因，目前普遍认为与古太平洋板块消减背景下幔源岩浆的底

侵作用有着重要关系(Zhou et al.,2006；Wang et al., 2012；杨金豹等，2013；Chen et al.,2014；Duan et al., 2017；张永谦等，2019)。广东麒麟新生代玄武质角砾岩筒中的辉长质麻粒岩捕虏体获得其Sm-Nd等时线年龄为(112.3±17.8)Ma(徐夕生等，1999)，表明中国大陆边缘存在这一时期玄武质岩浆的底侵作用。粤浙闽沿海中酸性侵入岩中普遍存在着铁镁质暗色包体(MME)，锆石 $\varepsilon_{Hf}(t)$ 值相对集中且为正值，表明成岩过程中有地幔物质的参与，并发生大规模的基性-酸性岩浆混合作用(Chen et al., 2013；Zhang et al., 2019)。然而，粤西北白浆黑云母花岗岩为过铝质S型花岗岩(高剑锋等，2005)，粤北—赣南地区产出同时期的花岗闪长岩、橄榄玄武岩等，暗示了早白垩世晚期的岩浆活动从内陆向东南沿海幔源岩浆参与程度的不断增加，内陆不同地区壳幔作用程度差异可能与古太平洋板块消减作用下局部软流圈地幔上涌有关。

早白垩世晚期同样也是中国东南沿海铜、金、钼的重要成矿期（宋传中等，2019），矿床主要见于浙闽一带，如浙东的余坑、半岭斑岩型Cu-Au矿床、浙东南的怀溪Cu-Au矿床(101~102 Ma)(李艳军等, 2010)，以及闽西南紫金山斑岩型Cu-Au-Mo矿床(Li et al., 2015)。紫金山矿区罗卜岭花岗闪长斑岩(105.4~107 Ma)是典型的铜(钼)矿体，四方岩体((109.5±0.8)Ma)也具有铜多金属成矿亲缘性，获得的矿区辉钼矿Re-Os年龄为110~105 Ma(Duan et al., 2017)，黄铜矿等时线年龄为103 Ma(Jiang et al., 2017)，表明Cu多金属成矿与成岩作用同期。毛景文等(2014)研究表明，斑岩铜钼矿或斑岩铜金钼矿多产于板块消减边界的大陆边缘，成因上主要与中酸性的钙碱性弧岩浆有关。新坪岩体岩性为花岗闪长岩，属高钾钙碱性岩浆岩，形成于燕山晚期的陆缘弧岩浆活动阶段，岩体侵位时代和岩石地球化学特征均与邻区紫金山含矿岩体基本一致，并且野外能观察到明显的辉钼矿化，因此具有较好的铜钼矿找矿前景。

6　结　论

(1)佛冈复式岩体新坪花岗闪长岩具有中酸性(SiO_2=63.43%~65.27%)、准铝质(ACNK=0.76~0.92)、中等碱含量(ALK=6.09%~7.63%)和高钾钙碱性特征。富集轻稀土，LREE/HREE=8.26~13.20，$(La/Yb)_N$=8.17~16.64，轻稀土分馏较重稀土明显，$(La/Sm)_N$=3.87~6.49，$(Gd/Yb)_N$=1.45~1.81，轻微的铕亏损，δEu=0.73~0.87。富集大离子亲石元素Rb、U、Th和La，亏损高场强元素Nb、Ta、Ti和P、Ba、Sr。

(2)新坪花岗闪长岩 $\varepsilon_{Hf}(t)$ 值为−3.0~＋0.2，Hf二阶段模式年龄 t_{DM2}=1.16~1.36 Ga，镁指数($Mg^{\#}$)＝42.64~46.95(＞40)，表明其源区主要为中元古代地壳物质，并有一定程度的亏损地幔组分参与。岩石Nb/U=1.7~2.2，Nb/La值=0.20~0.38，显示了岩浆源区受到俯冲流体的交代作用。岩石地球化学特征显示在岩体成岩过程中，主要受部分熔融作用控制。

(3)新坪花岗闪长岩体侵位时间为104 Ma，为早白垩世晚期岩浆活动的产物，具有陆缘弧岩浆活动特征。岩体形成于燕山晚期古太平洋板片俯冲消减作用下的伸展拉张构造环境，与玄武质岩浆底垫诱发中元古代结晶基底发生部分熔融有关。早白垩世晚期为中国东南部晚中生代重要的Cu-Au-Mo成矿期，位于南岭中东段的新坪花岗闪长岩与邻区闽西南紫金山铜多金属岩(矿)体形成时代相同，岩石地球化学特征相似，且野外能观察到明显的铜钼矿化，因此具有较好的铜钼矿找矿前景。

注释

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