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Dao Yan, Li Feng, Wang Rong, et al. Petrogenesis of the granite porphyry related to the Jiudingshan Cu-Mo deposit in western Yunnan: Constraints from LA-ICP-MS zircon U-Pb chronology, Sr-Nd-Hf isotopes and petrogeochemistry[J]. Geology in China, 2015, 42(1): 134-148(in Chinese with English abstract).

滇西九顶山铜钼矿花岗斑岩成因: LA-ICP-MS锆石U-Pb年龄、岩石地球化学和Sr-Nd-Hf同位素制约

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提要: 对滇西九顶山铜钼矿床主要的含矿花岗斑岩开展了系统的年代学、岩石地球化学以及全岩Sr-Nd-Hf同位素的分析工作。LA-ICP-MS锆石U-Pb定年结果表明, 九顶山花岗斑岩成岩年龄为34.5~34.9 Ma, 与已有的成矿年龄(33.9~35.3 Ma)一致或略早于成矿年龄, 处在滇西新生代富碱岩浆活动高峰期内(45~30 Ma), 属于青藏高原碰撞造山带的晚碰撞转换成矿作用(40~26 Ma)的产物。详细的岩石地球化学研究表明, 研究区花岗斑岩有高硅(SiO_2=62.86%~71.57%)、高钾(K_2O/Na_2O=1.64~2.78)和富碱(K_2O+Na_2O=8.98%~11.28%)的特点, 属于钾玄岩系列岩石。岩体轻稀土元素富集(LREE/ HREE=4.84~7.64), 具有轻微的负铕异常(δEu=0.82~0.93), 富集大离子亲石元素(Rb、Ba、Th、U)和亏损高场强元素(Nb、Ta、Zr、Hf)。Sr-Nd-Hf同位素的研究分析显示岩浆源区起源于"EMII型"富集地幔, "EMII型"富集地幔岩浆在上涌的过程中受到地壳物质的混染, 形成壳幔混合源富钾含矿岩浆。

关　键　词: 九顶山铜钼矿; 过铝质花岗岩; 锆石U-Pb定年; Sr-Nd-Hf同位素
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Petrogenesis of the granite porphyry related to the Jiudingshan Cu-Mo deposit in western Yunnan: Constraints from LA-ICP-MS zircon U-Pb chronology, Sr-Nd-Hf isotopes and petrogeochemistry

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Abstract: In this study, the authors carried out a comprehensive research including zircon U-Pb dating, petrogeochemical investigation and Sr-Nd-Hf isotope analysis of the granite porphyry related to the Jiudingshan Cu-Mo deposit in western Yunnan. LA-ICP-MS zircon U-Pb chronology indicates that the porphyry was emplaced at 34.5-34.9 Ma, consistent with or slightly earlier than the formation of the Cu-Mo deposit (33.9-35.3 Ma) and similar in time to the peak of Cenozoic alkali-rich magmatic activity

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(45−30 Ma) in western Yunnan, indicating that they were formed by the ore−forming process in the period of late−collisional transformation (40−26 Ma). The granite porphyry is silica−rich (SiO_2=62.86%−71.57%), potassium−rich (K_2O/Na_2O=1.64−2.78) and alkali−rich (K_2O+Na_2O = 8.98%−11.28%), belonging to shoshonitic series peraluminous granite, with the characteristics of LREE enrichment, HREE depletion, and weak negative Eu anomaly (δEu=0.82−0.93). The porphyry is enriched in LILEs such as Rb, Ba, Th and U, and depleted in HFSEs such as Nb, Ta, Zr and U. Sr−Nd−Hf isotopes imply that the magma originated from the EMII which was contaminated by crustal materials in the process of magmatic upwelling to form a potassium−rich ore−bearing magma with mixed sources of the crust and the mantle.

Key words: Jiudingshan Cu−Mo deposit; peraluminous granite; zircon U−Pb dating; Sr−Nd−Hf isotopes

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九顶山斑岩型铜钼金多金属矿床是西南“三江”金沙江—红河新生代碱性斑岩成矿带中的重要矿床之一。该矿区发育复式小杂岩体群,是金沙江—哀牢山富碱侵入岩带的重要组成部分。由于独特的大地构造背景以及构造−成岩−成矿的多期多阶段性,众多业界学者研究了矿区内铜钼矿床和相关岩体的动力学背景及机制[1−16]。研究表明,九顶山复式岩体具有多期多阶段侵入的特征,出露正长斑岩、石英正长斑岩、花岗斑岩、斑状花岗岩、碱长花岗斑岩和早晚两期的煌斑岩等岩浆岩,年龄在23.18~64.8 Ma,其中花岗斑岩K−Ar年龄和Rb−Sr年龄分别为48.0 Ma和36.6 Ma[17],具有滇西富碱侵入岩源区显著的EMII富集地幔端元的特点,形成于印度—欧亚大陆碰撞后的剪切和拉张构造环境[18]。岩浆岩呈4个阶段侵入:正长斑岩(石英正长斑岩)→斑状花岗岩+煌斑岩(早)→花岗斑岩+煌斑岩(晚)→碱长花岗斑岩,其中花岗斑岩为第Ⅲ阶段侵入岩,是矿区主要的含矿岩体。前人对九顶山各斑岩体形成年龄有争议,缺少同位素方面的研究,尤其是与主成矿期有关的花岗斑岩的研究还不全面。因此,本文通过系统的锆石LA−ICP−MS U−Pb年代学、岩石地球化学和Sr−Nd−Hf同位素研究,确定矿区花岗斑岩具体的成岩年龄及其与金沙江—红河(哀牢山)成矿带含矿斑岩体的关系,为九顶山地区的岩浆源区性质及岩浆演化提供一定的依据,同时可以完善花岗斑岩与成矿的关系,有助于今后进一步找矿工作。

1 地质背景和岩石学特征

九顶山斑岩型铜钼金多金属矿区大地构造位置处于扬子准地台西缘金沙江—红河断裂与程海断裂交汇部位(图1),是西南三江地区重要的多金属矿床之一,矿区新生代构造运动频繁,岩浆活动和成矿作用强烈。

矿区岩浆活动受控于区域性NW向金沙江—红河深大断裂、SN向程海断裂、NE向次级断裂及近EW向隐伏断裂构造。其中,金沙江—红河断裂是扬子地台西缘喜马拉雅期斑岩带的区域性控岩构造;程海断裂(与金沙江—红河断裂交汇处)是控制九顶山斑岩群分布的关键控岩构造;NE向及EW向次级(隐伏)断层是不同阶段小岩体的储岩构造。矿区褶皱也较发育,主要包括区域性向阳复背斜的南端、金厂箐—人头箐背斜、宝兴厂(铜厂)—乱硐山向斜和双马槽向斜,它们对岩体及矿体的就位也起到明显的控制作用。

矿区出露的地层主要有下奥陶统向阳组(O_1x^4)长石石英砂岩、粉砂岩、炭泥质细砂岩夹条带状灰岩、泥质白云岩透镜体以及下泥盆统康廊组(D_1k)灰岩地层以及第四系(Q)。九顶山铜钼矿区岩浆岩具有多期多阶段侵入的特征,主要由斑状花岗岩、正长斑岩、花岗斑岩和碱长花岗斑岩等构成九顶山复式杂岩体。其中,岩体中以大面积出露的斑状花岗岩为主,而花岗斑岩与铜钼金成矿有着密切关系。

2 样品描述及实验方法

2.1 样品描述

本文实验样品均取自野外新鲜的无蚀变的花岗斑岩,样品号分别为JDS162、JDS025、JDS164和JDS129。据大量的野外岩石样品及镜下观察,九顶

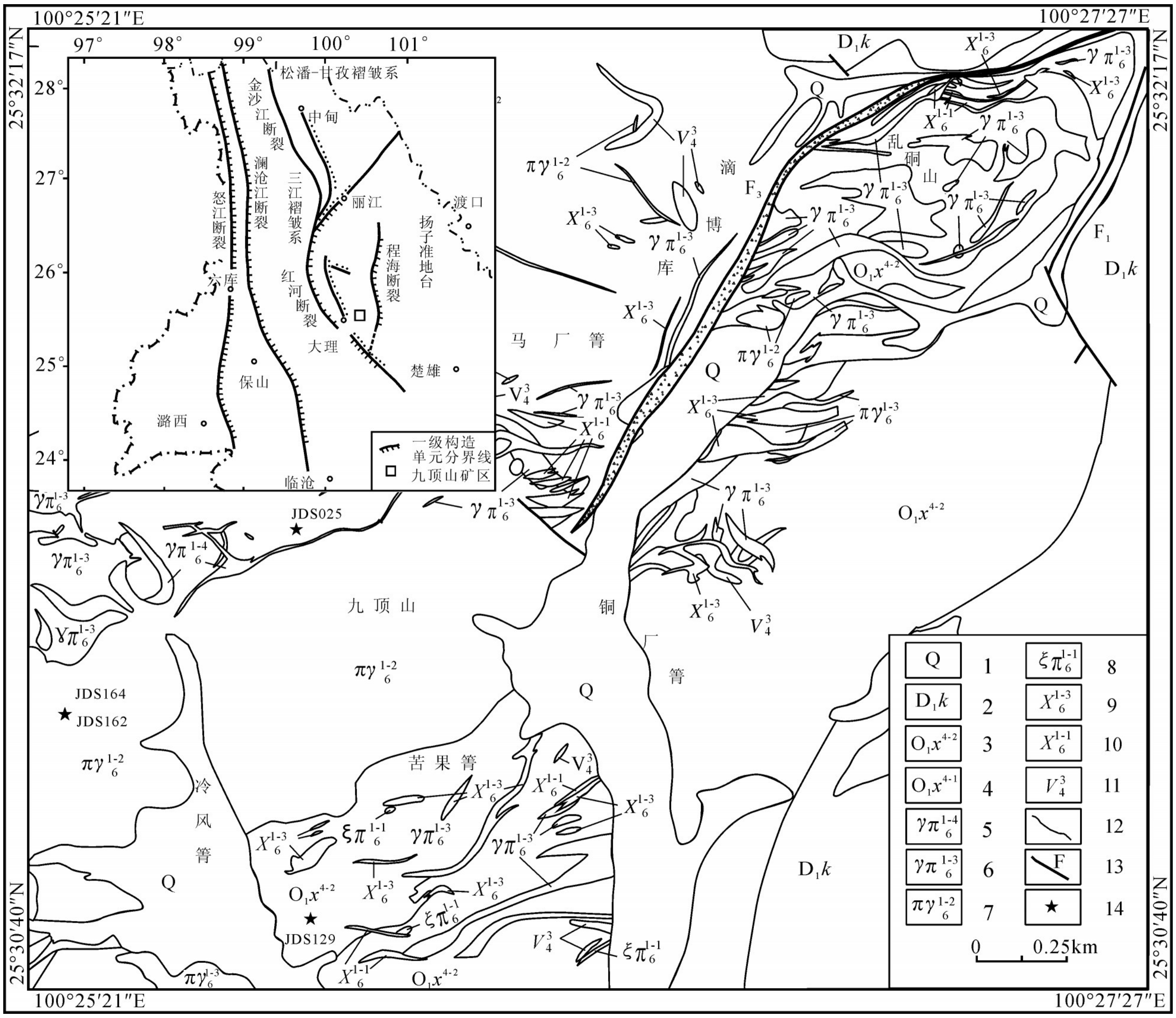

图1 研究区地质简图(据资料❶修改)

1—第四系; 2—下泥盆统康廊组灰岩; 3—下奥陶统向阳组四段二亚段紫灰泥质粉砂岩夹泥灰岩透镜体; 4—下奥陶统向阳组三段黑色局部紫色夹灰绿色石英砂岩; 5—碱长花岗斑岩; 6—花岗斑岩; 7—斑状花岗岩; 8—正长斑岩; 9—晚期煌斑岩; 10—早期煌斑岩; 11—辉长岩; 12—岩体界线; 13—断层(F_1为响水断裂; F_3为乱硐山断裂); 14—取样位置

Fig.1 Regional geological map of Jiudingshan, western Yunnan (modified after reference❶)

1−Quaternary; 2−Limestone of Lower Devonian Kanglang Formation; 3−Gray argillaceous siltstone intercalated with marl lens at the bottom of the second submember of the fourth member in Lower Ordovician Xiangyang Formation; 4−Pale red coarse feldspathic quartz sandstone intercalated with conglomerate of the first submember of the fourth member in Lower Ordovician Xiangyang Formation; 5− Alkali feldspar granite porphyry; 6− Granite porphyry; 7−Porphyritic granite; 8−Syenite porphyry; 9−Late lamprophyre; 10−Early lamprophyre; 11−Gabbro; 12−Rock boundaries; 13−Fault; 14−Sample location

山花岗斑岩总体呈浅灰、灰白色致密块状, 斑状结构。斑晶主要由正长石、斜长石、石英和黑云母组成, 基质为微粒石英、斜长石和黑云母, 正长石斑晶多呈灰白色−肉红色, 厚板状, 具有卡氏双晶, 粒径为5~15 mm; 斜长石斑晶呈无色−白色, 斑状, 部分已绢云母化, 粒径0.3~3.2 mm, 斜长石中见少量钠长石律聚片双晶; 石英斑晶呈浅灰色−无色, 粒径为0.2~1.9 mm; 暗色矿物主要为黑云母, 呈黑色细小鳞

❶西南冶金地质勘探公司310 地质队. 祥云马厂箐铜钼矿床成矿规律图1∶5000. 1981.

片状、星点状分布于岩石中,粒径为1 mm左右。基质有强绢云母化、钾化、硅化。斑岩体中发育浸染状、细脉浸染状铜钼矿化,岩石中副矿物主要有磷灰石、磁铁矿、锆石,偶见白钨矿等。

2.2 实验方法

(1)元素地球化学分析

主量元素测试在中国科学院地球化学研究所矿床地球化学国家重点实验室完成。主元 素测试采用Axios PW4400型X荧光光谱仪,分析精度优于3%,分析结果列于表1;微量元素分析采用ELAN 6000 ICP-MS完成,分析精度优于5%,分析结果列于表2。

(2)锆石U-Pb定年

用于定年的4个花岗斑岩锆石挑选在河北廊坊地质调查研究院完成,手工挑出晶形完好、透明度和色泽度好的锆石用环氧树脂固定于样品靶上。样品靶表面经研磨抛光,直至锆石新鲜截面露出。对靶上锆石进行镜下透射光、反射光照相,锆石阴极发光(CL)显微照相在中国地质大学(武汉)地质过程与矿产资源国家重点实验室电子探针室进行。

锆石U-Pb同位素定年和元素含量在中国地质大学(武汉)地质过程与矿产资源国家重点实验室利用LA-ICP-MS分析完成。U-Pb同位素定年和元素含量采用了同时分析和独立分析2种测试方法。激光剥蚀系统为GeoLas 2005, ICP-MS为Ag-ilent 7500a,激光斑束为32 μm,激光剥蚀过程中采用氦气作载气、氩气为补偿气以调节灵敏度。每个时间分辨分析数据包括20~30 s的空白信号和50 s的样品信号。U-Pb同位素定年中采用锆石标准91500作外标进行同位素分馏校正,每分析5个样品点,分析2次91500,锆石标准91500的U-Pb同位素比值推荐值据Wiedenbeck等[19]。详细的分析方法及仪器参数可参考Chipley等[20]。普通铅校正采用Andersen[21]的方法进行,样品的U-Pb年龄谐和图绘制和年龄权重平均计算均采用Isoplot / Ex-ver3[22]完成,分析结果列于表3。

(3)Sr-Nd-Hf同位素组成测定

全岩Sr-Nd-Hf同位素测定均在南京大学内生金属矿床成矿机制研究国家重点实验室运用德国赛默飞世尔科技Neptune-Plus多接收等离子体质谱仪(MC-ICPMS)分析测试。Sr、Nd、Hf同位素比值分别采用 $^{86}Sr/^{88}Sr=0.1194$、$^{146}Nd/^{144}Nd=0.7219$、$^{179}Hf/^{177}Hf=0.7325$进行质量分馏校正,采用指数法。实验过程测定的标样NIST SRM987的 $^{87}Sr/^{88}Sr$ = (0.710261 ± 17) (2σ, n=18),标样JNDi-1的 $^{143}Nd/^{144}Nd$=(0.512101±5)(2σ, n=18), Hf同位素标准样品Alfa Hf 14374的测定结果为(0.282154±7)(2σ, n=18)。4件代表性样品的测试数据及计算结果列于表4。

3 结　果

3.1 LA-ICP-MS 锆石U-Pb定年

实验所分选的锆石呈无色透明,颗粒大,晶形完好,一般为长柱状,长宽比多为1∶1~3∶1,长70~210 μm,宽为30~95 μm。锆石阴极发光图像(图2)显示,大部分锆石内部发育良好的振荡环带结构,所测试的锆石具有较高的U和Th含量,分别变化于(163~2388)×10^{-6}和(71.1~2130)×10^{-6}, Th /U比值在0.20~1.24(>0.1)变化,具有岩浆锆石的特征[48]。由表1和图3可见,测试花岗斑岩(JDS129)的4颗岩浆锆石,获得$^{206}Pb/^{238}U$年龄变化于34.9~35.8 Ma,加权平均年龄为(34.9±2.0) Ma(n=4, MSWD=3.0),另外1、3、4、5和6测点锆石的年龄变化于555~795 Ma,这5颗锆石不仅呈明显的振荡环带结构,还具有核幔构造,这些锆石具有继承或捕获锆石的特征;测试花岗斑岩(JDS025)的10颗锆石,$^{206}Pb/^{238}U$年龄变化于

表1 九顶山花岗斑岩主量元素化学分析测试数据(%)

Table 1 Analyses of major elements of granite porphyries in Jiudingshan intrusion, Yunnan (%)

样号	SiO_2	Al_2O_3	FeOt	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	LOI	Total	A/CNK	FeO*
JDS149	66.73	14.37	1.71	1.24	1.82	3.40	5.58	0.02	0.13	0.30	4.70	100	0.96	1.54
JDS025	62.86	14.66	1.91	0.66	1.52	2.98	8.30	0.03	0.11	0.34	6.63	100	0.88	1.72
JDS033	71.57	13.07	1.11	0.93	0.83	3.53	7.57	0.02	0.09	0.22	1.00	99.95	0.84	1.00
JDS164	62.89	15.91	2.49	0.81	2.15	3.91	6.76	0.04	0.11	0.36	4.59	100.02	0.90	2.24

表2 九顶山花岗斑岩微量元素和稀土元素分析数据(10^{-6})

Table 2 Analyses of trace elements and rare earth elements of granite porphyries in Jiudingshan, west Yunnan (10^{-6})

样号	Li	Be	Sc	Ni	Cu	Ga	Rb	Sr	Nb	Cs	Ba	Hf	Ta	W	Pb	Th	U	Cr	La	Ce	Pr	Nd	Sm	Eu	Gd
JDS149	30.18	5.10	7.63	21.20	116.28	17.40	195.65	648.51	9.75	4.51	1 273.82	4.56	0.62	5.00	26.28	17.63	6.81	41.41	39.63	73.94	7.64	26.42	4.59	1.28	4.03
JDS025	10.28	3.79	11.16	16.58	3257.49	17.60	247.39	726.02	11.08	2.92	2 244.48	5.23	0.51	14.01	16.74	10.95	3.78	13.84	37.07	71.07	7.75	28.13	4.78	1.36	4.65
JDS033	10.03	1.95	3.42	5.69	318.17	8.96	131.82	243.27	4.90	2.28	518.18	1.72	0.31	43.81	6.62	10.13	3.22	5.97	17.43	32.56	3.35	11.65	1.79	0.48	1.74
JDS164	12.65	5.73	10.45	2.88	67.85	18.72	224.75	1 256.96	11.45	4.38	2 262.74	5.51	0.53	2.92	32.56	11.91	4.79	9.38	43.06	80.09	8.54	31.17	5.76	1.71	5.35

样号	Tb	Dy	Ho	Er	Tm	Yb	Lu	V	Co	Zn	Y	Zr	Cd	In	Bi	∑REE	LREE	HREE	LR/HR	δ Eu	δ Ce	$(La/Yb)_N$	$(Sm/Eu)_N$
JDS149	0.47	2.25	0.42	1.13	0.15	0.91	0.13	39.21	4.77	22.86	11.50	166.68	0.16	0.02	0.56	174.51	153.50	21.00	7.31	0.89	0.98	43.44	3.59
JDS025	0.59	3.00	0.65	1.77	0.25	1.64	0.26	48.29	12.04	65.23	17.51	202.93	1.31	0.14	3.50	180.47	150.15	30.31	4.95	0.87	0.98	22.57	3.52
JDS033	0.18	0.85	0.16	0.47	0.06	0.40	0.06	17.43	1.54	9.11	4.87	59.38	0.50	0.03	1.11	76.07	67.26	8.80	7.64	0.82	0.98	43.06	3.73
JDS164	0.72	3.52	0.76	1.96	0.28	1.83	0.26	40.26	2.49	31.89	20.53	222.43	0.20	0.03	0.38	205.54	170.32	35.21	4.84	0.93	0.96	23.54	3.37

表3 九顶山花岗斑岩的LA-ICP-MS锆石U-Pb年龄测定结果

Table 3 LA-ICP-MS zircon U-Pb dating results of granite porphyries in Jiudingshan area

测点编号	ωB/10^{-6}			Th/U	同位素比值								同位素年龄/Ma							
	Pb	^{232}Th	^{238}U		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{208}Pb/^{232}Th$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{208}Pb/^{232}Th$	
					比值	1σ	比值	1σ	比值	1σ	比值	1σ	年龄	1σ	年龄	1σ	年龄	1σ	年龄	1σ
花岗斑岩（JDS162），样品点坐标：N25°31.15′，E100°25.167′																				
12JDS162_01	6.65	517	1063	0.49	0.0669	0.0071	0.0482	0.0040	0.00555	0.0001	0.00215	0.0001	835	225	47.8	3.9	35.7	0.9	43.4	2.7
12JDS162_03	7.20	651	1091	0.60	0.0637	0.0043	0.0490	0.0036	0.00570	0.0001	0.00195	0.0001	733	144	48.5	3.5	36.6	0.8	39.4	2.3
12JDS162_05	5.76	569	962	0.59	0.0503	0.0041	0.0341	0.0024	0.00516	0.0001	0.00153	0.0001	209	191	34.1	2.4	33.2	0.6	30.9	1.3
12JDS162_06	7.88	802	1234	0.65	0.0477	0.0026	0.0353	0.0018	0.00546	0.0001	0.00150	0.0001	87	122	35.2	1.8	35.1	0.6	30.4	1.2
12JDS162_07	6.98	649	1110	0.58	0.0467	0.0028	0.0348	0.0021	0.00540	0.0001	0.00161	0.0001	35.3	137	34.7	2.0	34.7	0.6	32.6	1.4
12JDS162_08	4.72	410	761	0.54	0.0596	0.0043	0.0439	0.0031	0.00541	0.0001	0.00145	0.0001	591	153	43.6	3.0	34.8	0.6	29.3	1.6
12JDS162_09	6.38	620	1013	0.61	0.0522	0.0038	0.0381	0.0026	0.00536	0.0001	0.00158	0.0001	295	165	37.9	2.6	34.5	0.5	31.8	1.4
12JDS162_10	5.85	558	936	0.60	0.0505	0.0030	0.0369	0.0021	0.00531	0.0001	0.00153	0.0001	217	139	36.8	2.0	34.2	0.5	31.0	1.4
花岗斑岩（JDS025），样品点位置: 2640中段SZ11-61测点岔口，样品点坐标: N25°31.426′，E100°25.825′																				
11JDS025_01	4.26	272	633	0.43	0.0616	0.0035	0.0466	0.0025	0.00559	0.0001	0.00227	0.0001	661	123	46.2	2.4	35.9	0.7	45.8	2.3
11JDS025_02	7.10	409	1162	0.35	0.0504	0.0030	0.0366	0.0021	0.00530	0.0001	0.00179	0.0001	213	141	36.5	2.1	34.1	0.5	36.2	1.8
11JDS025_03	16.83	2130	2388	0.89	0.0501	0.0026	0.0373	0.0019	0.00535	0.0001	0.00181	0.0001	198	123	37.2	1.9	34.4	0.5	36.5	1.2
11JDS025_04	4.71	211	783	0.27	0.0600	0.0038	0.0437	0.0024	0.00537	0.0001	0.00194	0.0001	606	140	43.5	2.3	34.5	0.6	39.2	2.4
11JDS025_05	3.17	190	523	0.36	0.0565	0.0037	0.0415	0.0025	0.00546	0.0001	0.00218	0.0002	472	144	41.3	2.5	35.1	0.8	44.0	3.2
11JDS025_06	4.52	255	646	0.39	0.0577	0.0035	0.0456	0.0027	0.00572	0.0001	0.00298	0.0003	517	133	45.2	2.7	36.8	0.9	60.1	5.6
11JDS025_07	7.85	698	1225	0.57	0.0679	0.0053	0.0519	0.0040	0.00541	0.0001	0.00210	0.0001	866	161	51.4	3.9	34.8	0.7	42.4	2.3
11JDS025_08	7.09	506	1128	0.45	0.0483	0.0031	0.0363	0.0022	0.00541	0.0001	0.00179	0.0001	117	144	36.2	2.2	34.8	0.5	36.2	1.6
11JDS025_09	6.93	443	1129	0.39	0.0483	0.0027	0.0365	0.0021	0.00549	0.0001	0.00177	0.0001	117	126	36.4	2.0	35.3	0.6	35.8	1.8
11JDS025_10	8.38	630	1281	0.49	0.0491	0.0036	0.0362	0.0024	0.00554	0.0001	0.00171	0.0001	150	172	36.1	2.4	35.6	0.6	34.5	1.4

续表3

测点编号	ωB/10⁻⁶			Th/U	同位素比值								同位素年龄/Ma							
	Pb	^{232}Th	^{238}U		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{208}Pb/^{232}Th$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{208}Pb/^{232}Th$	
					比值	1σ	比值	1σ	比值	1σ	比值	1σ	年龄	1σ	年龄	1σ	年龄	1σ	年龄	1σ
花岗斑岩（JDS164），样品点经纬度坐标: N25°31.15′，E100°25.167′																				
12JDS164_03	6.37	528	967	0.55	0.0493	0.0025	0.0366	0.0017	0.00544	0.0001	0.00183	0.0001	161	120	36.5	1.7	35	1	37.0	1.6
12JDS164_05	5.98	596	898	0.66	0.0524	0.0036	0.0378	0.0023	0.00540	0.0001	0.00167	0.0001	302	156	37.7	2.2	35	1	33.8	1.5
12JDS164_06	9.02	860	1452	0.59	0.0439	0.0029	0.0310	0.0019	0.00518	0.0001	0.00158	0.0001	error		31.0	1.9	33	1	32.0	1.2
12JDS164_09	7.61	412	1270	0.32	0.0476	0.0028	0.0346	0.0020	0.00537	0.0001	0.00169	0.0001	79	133	34.6	2.0	35	1	34.2	1.9
12JDS164_10	2.42	83	409	0.20	0.0756	0.0060	0.0522	0.0038	0.00561	0.0002	0.00316	0.0002	1083	161	51.6	3.7	36	1	63.7	4.5
12JDS164_11	3.47	254	568	0.45	0.0567	0.0033	0.0404	0.0022	0.00537	0.0001	0.00199	0.0001	480	132	40.2	2.1	34	1	40.1	2.5
12JDS164_01	23.03	71	225	0.32	0.0627	0.0019	0.8612	0.0345	0.09911	0.0028	0.03335	0.0014	698	64.8	631	18.8	609	16	663	26.6
12JDS164_02	48.30	823	662	1.24	0.0633	0.0018	0.4374	0.0124	0.05001	0.0008	0.01828	0.0004	717	59.3	368	8.7	315	5	366	8.4
12JDS164_04	25.76	147	163	0.90	0.0617	0.0022	1.0502	0.0385	0.12219	0.0017	0.03595	0.0009	665	78.7	729	19.1	743	10	714	17.7
12JDS164_07	7.70	171	406	0.42	0.0708	0.0050	0.1548	0.0110	0.01606	0.0003	0.00635	0.0004	950	151	146	9.7	103	2	128	7.3
12JDS164_08	19.97	215	482	0.45	0.0785	0.0032	0.3587	0.0141	0.03332	0.0005	0.01577	0.0005	1161	81.9	311	10.6	211	3	316	10.1
花岗斑岩（JDS129），样品点经纬度坐标: N25°29.95′，E100°25.367′																				
11JDS129_02	4.50	345	724	0.48	0.0547	0.0035	0.0395	0.0022	0.00543	0.0001	0.00208	0.0001	398	142	39.4	2.2	34.9	0.7	42.0	2.5
11JDS129_07	9.51	289	1657	0.17	0.0472	0.0024	0.0354	0.0018	0.00546	0.0001	0.00186	0.0001	61	115	35.4	1.8	35.1	0.4	37.5	2.1
11JDS129_08	4.93	277	800	0.35	0.0454	0.0025	0.0347	0.0017	0.00557	0.0001	0.00189	0.0001	error		34.6	1.7	35.8	0.6	38.2	2.0
11JDS129_10	7.43	759	1196	0.63	0.0476	0.0036	0.0337	0.0025	0.00522	0.0001	0.00166	0.0001	80	170	33.7	2.4	33.5	0.6	33.5	1.5
11JDS129_01	8.46	39.5	54.0	0.73	0.0629	0.0036	1.0913	0.0578	0.13039	0.0022	0.04072	0.0016	706	116	749	28.1	790	12.4	807	30.2
11JDS129_03	23.97	122	152	0.80	0.0662	0.0023	1.1425	0.0405	0.12478	0.0013	0.04106	0.0010	813	74.1	774	19.2	758	7.2	813	20.1
11JDS129_04	29.84	110	192	0.57	0.0640	0.0022	1.1568	0.0381	0.13117	0.0014	0.04183	0.0011	743	39.8	780	18.0	795	7.8	828	21.0
11JDS129_05	19.78	113	174	0.65	0.0634	0.0028	0.7918	0.0361	0.08993	0.0015	0.03366	0.0010	720	92.6	592	20.5	555	9.2	669	19.1
11JDS129_06	43.47	148	354	0.42	0.0651	0.0022	0.9591	0.0315	0.10650	0.0011	0.03518	0.0010	777	75.0	683	16.3	652	6.3	699	18.9

表4 九顶山花岗斑岩Sr, Nd和Hf同位素组成

Table 4 Sr, Nd and Hf isotope compositions of granite porphyries in Jiudingshan area

样品号	t/Ma	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ	I_{Sr}	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	$f_{Sm/Nd}$	$\varepsilon_{Nd}(t)$	I_{Nd}	t_{2DM}/Ga	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ
JDS149	35.30	0.8667	0.707001	8	0.70657	0.1012	0.512337	5	−0.49	−5.44	0.512313624	1.290286324	0.0039	0.282791	15
JDS025	34.80	0.9859	0.708944	8	0.70846	0.1027	0.512390	5	−0.48	−4.42	0.512366635	1.206801131	0.0068	0.282788	7
JDS033	34.40	1.5675	0.706995	11	0.70623	0.0930	0.512421	7	−0.53	−3.78	0.512400085	1.154200519	0.0047	0.282815	4
JDS164	34.70	0.5172	0.707512	9	0.70726	0.1117	0.512424	8	−0.43	−3.80	0.512398655	1.156104078	0.0067	0.282821	8

注: 同位素校正公式: $(^{87}Sr/^{86}Sr)_i = (^{87}Sr/^{86}Sr)_s + {}^{87}Rb/^{86}Sr\,(e^{\lambda t}-1)$, $\lambda=1.42\times10^{-11}\,a^{-1}$; $(^{143}Nd/^{144}Nd)_i = (^{143}Nd/^{144}Nd)_s + {}^{147}Sm/^{144}Nd\times(e^{\lambda t}-1)$, $\varepsilon_{Nd}(t) = [(^{143}Nd/^{144}Nd)_s/(^{143}Nd/^{144}Nd)_{CHUR}(t)-1]\times10^4$, $(^{143}Nd/^{144}Nd)_{CHUR}(t)=0.512638-0.1967\times(e^{\lambda t}-1)$, $f_{Sm/Nd} = [(^{147}Sm/^{144}Sm)_s/(^{147}Sm/^{144}Nd)_{CHUR}]-1$; $\varepsilon_{Hf}(t)=\{[(^{176}Hf/^{177}Hf)_s-(^{176}Lu/^{177}Hf)_s\times(e^{\lambda t}-1)]/[(^{176}Hf/^{177}Hf)_{CHUR,0}-(^{176}Lu/^{177}Hf)_{CHUR}\times(e^{\lambda t}-1)]-1\}\times10000$, $(^{176}Lu/^{177}Hf)_{CHUR}=0.0332$; $(^{143}Nd/^{144}Nd)_{CHUR}=0.512638$, $(^{147}Sm/^{144}Nd)_{CHUR}=0.1967$, $(^{176}Hf/^{177}Hf)_{CHUR,0}=0.282772$ [26]; $\lambda=1.867\times10^{-11}\,a^{-1}$ [27]; s为测量值, t为锆石结晶年龄。

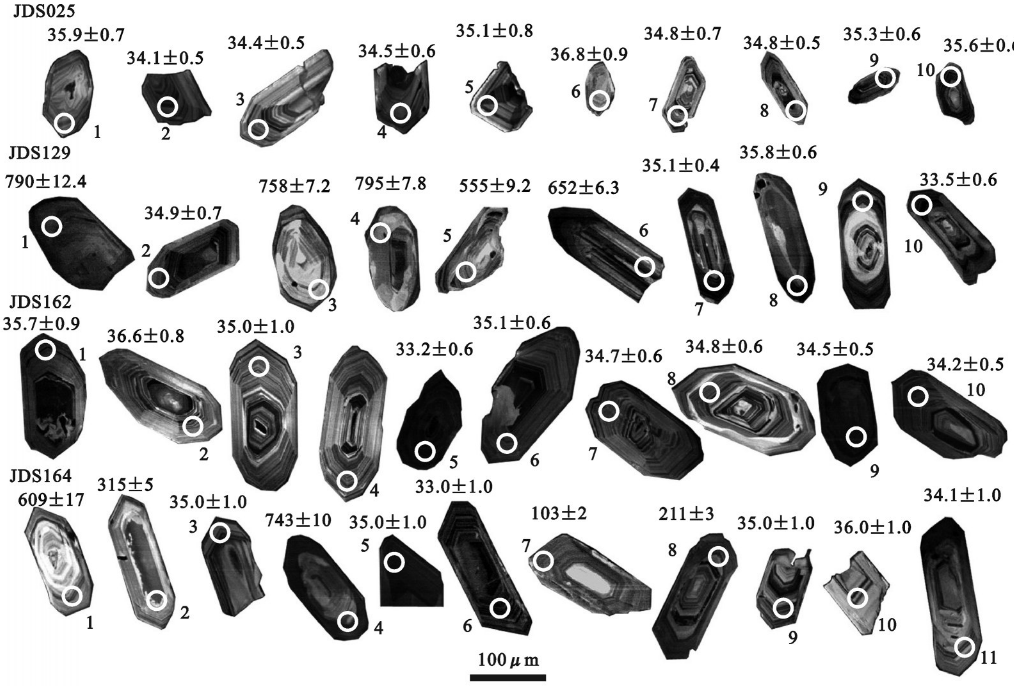

图2 锆石阴极发光图像、测点位置及年龄测试结果（Ma）
Fig.2 Cathodoluminescence images of the zircon, spot site and the dating results（Ma）

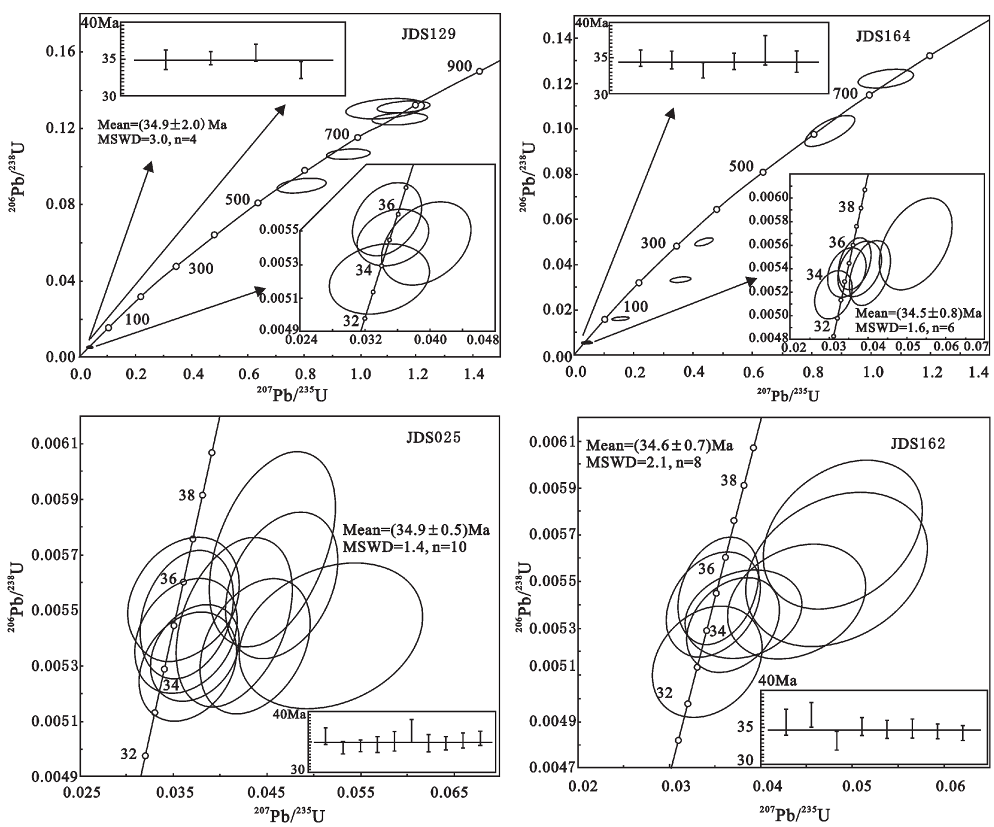

图3 九顶山花岗斑岩LA-ICP-MS 锆石U-Pb年龄谐和图解
Fig.3 LA-ICP-MS zircon U-Pb concordia diagrams of granite porphyries in Jiudingshan

34.1~36.8 Ma，加权平均年龄为(34.9±0.5) Ma(n=10, MSWD=1.4)；测试钾化花岗斑岩(JDS162)的10颗锆石，其中，第2颗和第4颗锆石的测定值偏离平均值过大，舍弃不用，其余8颗锆石的$^{206}Pb/^{238}U$年龄变化于33.2~36.6 Ma，加权平均年龄为(34.6±0.7) Ma (n=8, MSWD=2.1)；测试钾化花岗斑岩(JDS164)的6颗岩浆锆石，获得$^{206}Pb/^{238}U$年龄变化于34.0~36.0 Ma，加权平均年龄为(34.5±0.8) Ma(n=6, MSWD=1.6)，测点01、02、04、07和08锆石的$^{206}Pb/^{238}U$年龄变化于103~743 Ma，具有继承或捕获锆石的特征。

3.2 地球化学特征

主量元素分析结果(表1)显示九顶山花岗斑岩具有高的SiO_2(62.86%~71.57%)、Al_2O_3(13.07%~15.91%)和K_2O(5.58%~8.30%)，全碱(K_2O+Na_2O)含量为8.98%~11.28%，K_2O/Na_2O比值为1.64~2.78。在SiO_2-K_2O相关图解(图4-b)中，所有样品均落在钾玄岩系列；MgO=0.66%~1.24%，图4-a中所有样品均落在过铝质花岗岩中。

九顶山花岗斑岩的稀土元素特征显示，稀土元素总量∑REE=76.07×10^{-6}~205.54×10^{-6}，ω(∑LREE)/ω(∑HREE)比值4.84~7.64，在球粒陨石标准化图解为平滑的右倾曲线(图5-a)，显示轻稀土元素富集而重稀土元素亏损的特征，具有轻微的负铕异常(δEu=0.82~0.93)，无铈异常(δCe=0.96~0.98)。微量元素特征显示研究区花岗斑岩具有显著的Nb、Ta异常，并且富集大离子亲石元素(Rb、Ba、Th、U)，亏损高场强元素(Nb、Ta、Zr、Hf)的特征。

3.3 Sr-Nd-Hf同位素

九顶山花岗斑岩的Sr-Nd-Hf同位素组成(表4)显示，各岩体岩石$^{87}Rb/^{86}Sr$比值变化范围相对较大，变化于0.5172~1.5675，$^{87}Sr/^{86}Sr$比值变化范围介于0.706995~0.708944，I_{Sr}值为0.70623~0.70846；岩体的$^{147}Sm/^{144}Nd$比值变化于0.0930~0.1117，$^{143}Nd/^{144}Nd$变化于0.512337~0.512424，$\varepsilon_{Nd}(t)$变化范围介于−3.78~−5.44，有一定的变化范围，暗示了可能发生过岩浆的混合，物质来自于地壳或富集地幔源，$^{143}Nd/^{144}Nd$初始比值I_{Nd}均介于0.512313624~0.512400085，样品的Sm/Nd富集因子$f_{Sm/Nd}$变化于−0.43~−0.53，暗示其具有典型的大陆岩石圈特征。$^{176}Lu/^{177}Hf$范围为0.0039~0.0068，$^{176}Hf/^{177}Hf$变化于0.282788~0.282821，$\varepsilon_{Hf}(t)$=0.57~1.73。

4 讨 论

4.1 花岗斑岩成岩年龄

从同位素年龄数据可以看出，九顶山矿区花岗斑岩锆石U-Pb年龄为34.5~34.9 Ma，彭建堂等[10]获得花岗斑岩K-Ar年龄为29.88~33.7 Ma，胡祥昭等[17]使用K-Ar和Rb-Sr法获得年龄在36~48 Ma，

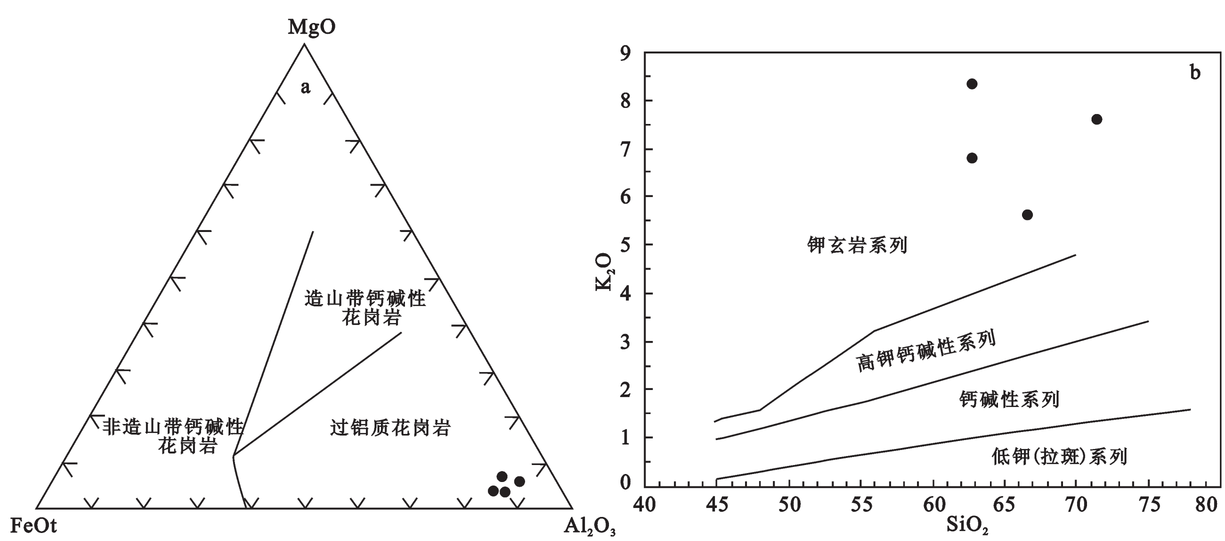

图4　九顶山花岗斑岩岩石化学系列分类图解(a引自[23]，b底图据[24])

Fig.4 Petrochemical series classification diagrams of the Jiudiangshan composite intrusion (a after reference [23]; b after reference [24])

罗君烈等[28]通过对滇西特提斯演化也对该研究区花岗斑岩进行全岩Rb−Sr法测定得到36.3 Ma, 梁华英等[29]对研究区富钾碱性岩体研究, 获得花岗斑岩全岩Rb−Sr等时线年龄为36 Ma, 吕伯西等[30]在对三江地区花岗岩类进行探讨时, 对该研究区花岗斑岩体进行锆石U−Th−Pb定年, 为35.0 Ma。因此, 本文应用LA−ICP−MS锆石U−Pb测年方法所获得的年龄与前人获得的年龄存在误差, 而本次用的测年方法是目前应用广泛, 精确度较高的方法, 更具有可靠性, 因此, 本文获得的34.5~34.9 Ma即为研究区花岗斑岩的岩浆结晶年龄。此外, 用于测年的锆石中存在继承锆石, 年龄在103~795 Ma, 表明该区可能存在远古结晶基底, 继承锆石的年龄数据也为该区岩浆来源提供了一个深源证据。

野外观察以及结合前人研究, 花岗斑岩为研究区含矿岩体, 铜钼矿矿化年龄33.9~35.3 Ma[31, 32]与花岗斑岩相吻合或稍晚于花岗斑岩成岩年龄。此外, 九顶山岩体属于复式岩体, 正长斑岩、斑状花岗岩、煌斑岩和碱长花岗斑岩等属于喜马拉雅运动早期岩浆活动的产物, 本文研究的花岗斑岩与区内大规模岩浆作用的同时性和地球化学特征相似, 反映它们在构造背景、物质来源和成岩机制上的联系。喻学惠等[33]得出滇西新生代富碱岩浆活动高峰期为45~30 Ma, 九顶山富碱岩体属于滇西富碱斑岩一部分, 获得的年龄与其岩浆活动高峰期相吻合, 在大地构造位置上处于金沙江—红河剪切带内, 这条深大断裂受到青藏高原碰撞造山带的晚碰撞造山作用(40~26 Ma)的影响[34], 印度与亚洲大陆的持续汇聚和SN向挤压, NW向金沙江—红河断裂带左旋走滑(35~17 Ma)[35, 36]断裂及北东向断裂形成构造的多期活动, 穿透性较好, 为多期岩浆活动及成矿提供有利的构造条件。

4.2 源区性质

九顶山花岗斑岩的元素线性相关关系(图6)显示, 样品 SiO_2 组分与主量元素之间良好的线性关系, 与不相容元素Zr、Nb、La和Yb具有一定的负相关性, 稀土元素与微量元素蛛网图上曲线分布型式几乎一致(图5), 这些特征表明区内花岗斑岩岩浆来源于同一源区。从全岩Sr−Nd同位素来看, 各样品中$(^{87}Sr/^{86}Sr)_i$值相近, 且$\varepsilon_{Nd}(t)$值<0, 指示岩浆可能来源于古老地壳物质的深熔或重熔[37], 而部分样品中含有代表古老结晶基底的继承锆石。九顶山花岗斑岩是矿区含矿岩体, 李峰等[38]认为正常的古老地壳的重熔, 难以形成含矿的岩浆, 只有幔源物质注入地壳岩浆源区, 引起上地壳底部重熔, 才易形成富金属富S的含矿岩浆, 因此含矿岩浆来源排除单一的地壳深熔或重熔, 可能有地幔物质的参与。在$\varepsilon_{Hf}(t)-\varepsilon_{Nd}(t)$图解(图7−a)中, 所有样品指示"EMⅡ"型地幔源, $\varepsilon_{Hf}(t)$与$\varepsilon_{Nd}(t)$ 相关图(图7−b)也显示岩浆来源具有地幔趋势的特点。因此, 可以推断区域内岩浆来源于地幔和地壳两个端元, 岩浆具有壳−幔混合的特点。成矿作用受制于富碱岩浆同源、但以

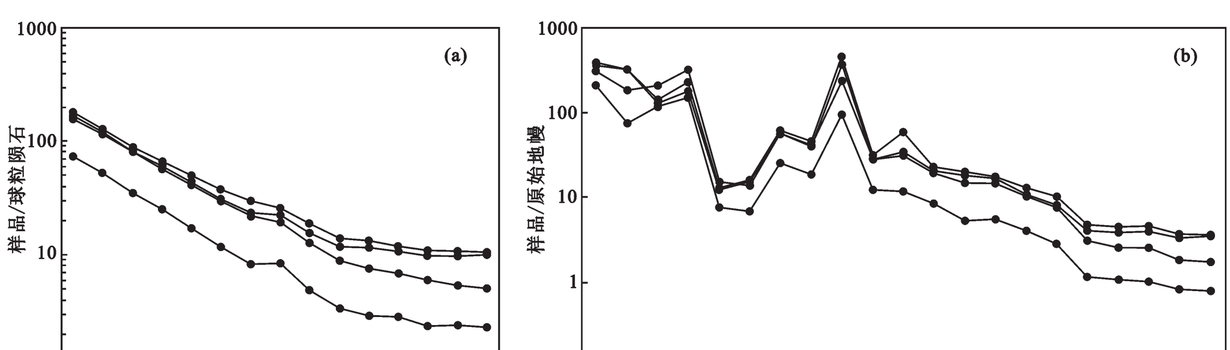

图5 九顶山花岗斑岩稀土元素球粒陨石标准化分配图解(a)和微量元素原始地幔标准化图解(b)
(球粒陨石和原始地幔标准化数据均引自文献[25])
Fig. 5 Chondrite-normalized (a)REE patterns and primitive mantle normalized spidergrams (b) of granite porphyries from the Jiudingshan area, western Yunnan
(normalizing values of chondrite and primitive mantle after reference [25])

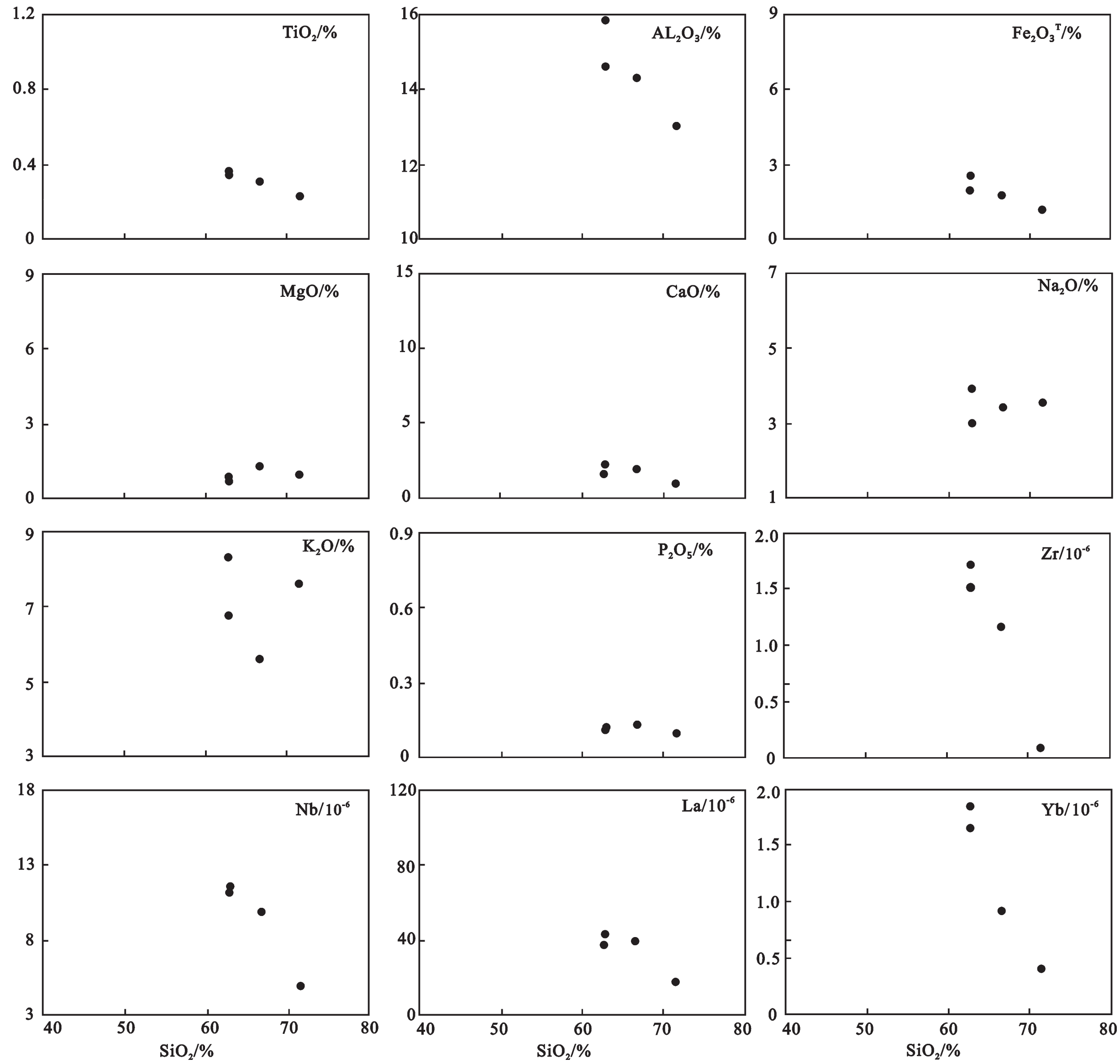

图6 九顶山喜山期花岗斑岩SiO_2协变图解(Hark图解)与不相容元素La-Nd-Zr-Yb相关图
Fig.6 Plots of SiO_2 versus incompatible elements and Harker diagrams of granite porphyries in Jiudingshan

互不混溶方式与其同步运移,岩浆流体发生壳幔混染,岩浆缓慢冷凝过程中,在热驱动下移动到物理化学边界层或混沌边缘聚集成矿[50]。

4.3 岩浆形成与演化

花岗质岩浆在演化过程中,会伴随不同矿物的分离结晶,表现为元素的富集和亏损[51]。九顶山花岗斑岩样品具有高的SiO_2含量(62.86%~71.57%)、全碱$w(K_2O+Na_2O)$=8.98%~11.28%和FeO*/MgO比值(1.07~2.77),岩浆经历了一定程度结晶分异,该岩体为过铝质花岗岩,属于钾玄岩系列。九顶山花岗斑岩样品的比值Al_2O_3/TiO_2较低,为43.12~59.41,与Sylvester[42]通过对后碰撞强过铝质花岗岩研究得到的Al_2O_3/TiO_2的比值相近,表明岩体形成于较高的温度(≥875 ℃)。九顶山花岗斑岩的元素线性相关关系(图6)说明地壳部分熔融形成的岩浆可能发生了分离结晶作用,图中SiO_2与Al_2O_3和CaO的负相关关系可用斜长石的分离结晶来解释[43],而稀土配分图解中没有明显的Eu负异常,这两者显然互相矛盾,因此排除斜长石分离结晶的可能。岩浆过程判别图解(图8)中表现出该岩浆具有地壳部分熔融或

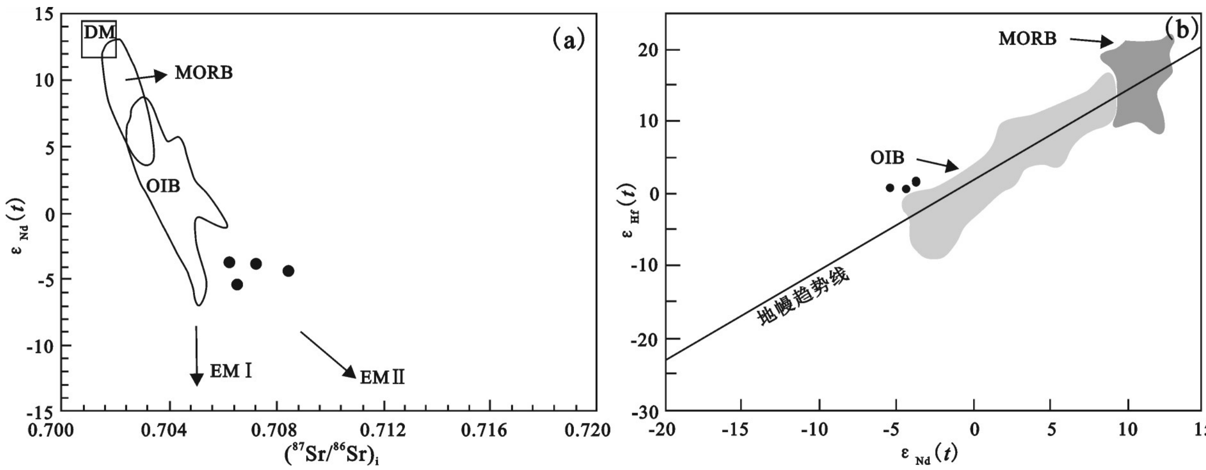

图7 九顶山花岗斑岩$\varepsilon_{Nd}(t)$ − $(^{87}Sr/^{86}Sr)_i$相关图解(a)与$\varepsilon_{Hf}(t)$−$\varepsilon_{Nd}(t)$相关图解(b)(a底图据[40]; b底图据[39])
b图中MORB和OIB及地幔趋势线数据引自[41]
Fig. 7 ε_{Nd}(t) versus initial $^{87}Sr/^{86}Sr$ diagram (a) and $\varepsilon_{Hf}(t)$ versus $\varepsilon_{Nd}(t)$ plots (b) of granite porphyries in Jiudingshan

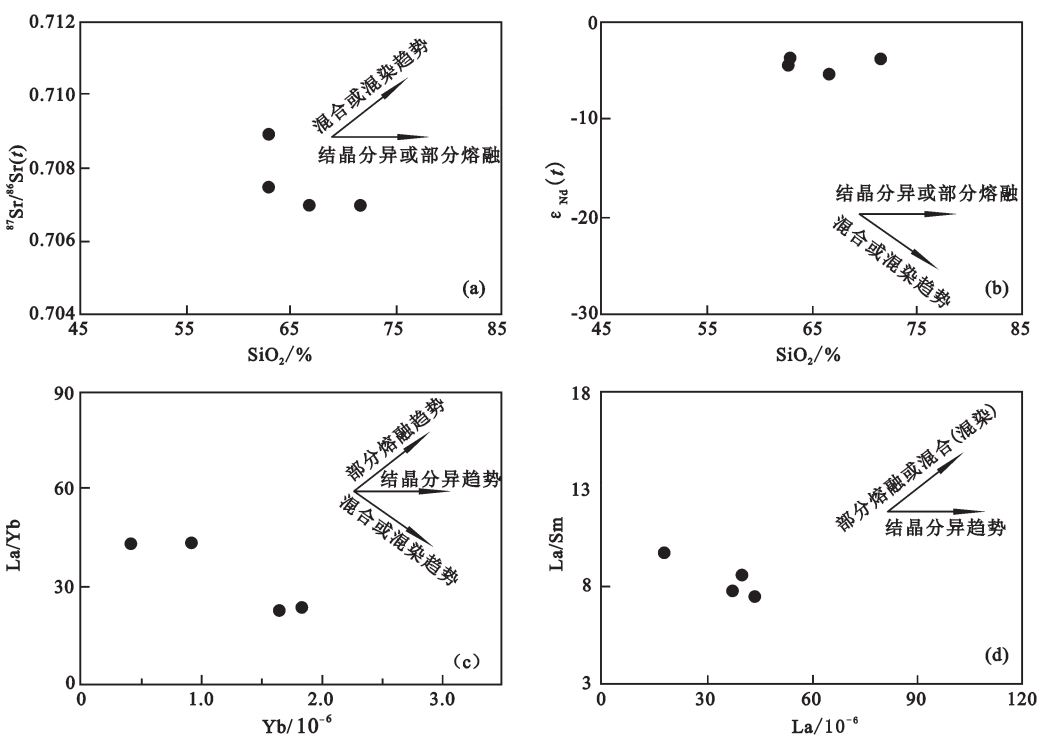

图8 九顶山喜山期花岗斑岩岩浆过程判别图解(底图据文献[44])
Fig. 8 Magma process discrimination diagrams of the Himalayan granite porphyries from the Jiudingshan area (after reference [44])

结晶分异的趋势, 再次确定岩浆有部分熔融的特征。笔者认为九顶山酸性岩具有相对富集大离子亲石元素(Rb、Sr) 和亏损高场强元素(Nb、Ta、Zr 和 Ti) 的特征, 与源区存在流体的交代作用有关[45], 俯冲板块脱水作用所释放的流体较大程度地影响地幔楔中亲石岩浆元素(Rb、K、Sr、Ba、U、Pb) 的含量[46, 47], 而高场强元素在水中的溶解度较小而相对亏损。九顶山矿区花岗斑岩岩浆来源于"EMⅡ"型地幔和地壳部分熔融, 而"EMⅡ"地幔端元与俯冲和再循环的地壳物质密切相关[49], 由于受到板块碰撞和陆块

对挤,激发深部地幔,俯冲板片上方的"EMⅡ"型地幔楔发生部分熔融形成具有富集LILE和LREE、亏损HFSE和富集Sr-Nd同位素组成的酸性岩浆,地幔物质涌入,向下地壳注入新生物质,并诱发下地壳物质熔融,从而形成壳幔混合源富钾含矿岩浆。

5 结 论

(1)九顶山地区含矿花岗斑岩体的LA-ICP-MS锆石U-Pb年龄为34.5~34.9 Ma,属于喜马拉雅运动早期始新世(E_2)岩浆活动,处于滇西新生代富碱岩浆活动高峰期(45~30 Ma)范围内,是青藏高原碰撞造山带的晚碰撞造山作用(40~26 Ma)的产物。区内成矿作用紧随成岩之后,成岩-成矿地质作用过程的连续性与斑岩热液成矿系统的持续时间相当。

(2)主、微量元素研究表明,研究区花岗斑岩均为过铝质花岗岩,属于钾玄岩系列岩石,轻稀土元素富集(LREE/ HREE=4.84~7.64),岩体具有轻微的负铕异常(δEu=0.82~0.93)和显著的Nb、Ta异常,并且富集大离子亲石元素Rb、Ba、Th、U,亏损高场强元素Nb、Ta、Zr、Hf。

(3)九顶山地区碰撞造山环境下形成的酸性含矿岩浆具有高铝、富钾的特点。微量元素及Sr-Nd-Hf同位素的研究分析表明,九顶山岩浆岩具有与金沙江—哀牢山富碱斑岩带相似的高I_{Sr}值、低$\varepsilon_{Nd}(t)$值和不均一的$\varepsilon_{Hf}(t)$同位素特征。揭示了岩浆源区是壳幔物质混合的一种"EMII型"富集地幔岩浆,其母岩浆很可能是幔源岩浆诱发古老地壳物质重熔并与壳源熔体混合形成。

(4)印度大陆板块和亚洲大陆板块后碰撞期,陆内板块持续汇聚和陆块对挤,被激发的深部地幔发生局部熔融,并沿穿透性好的断裂带上涌,地幔物质涌入,向下地壳注入新生物质,诱发下地壳物质熔融,形成壳幔混合源富钾含矿岩浆。

致谢: 中国地质大学地质过程与矿产资源国家重点实验室宗克清博士和叶晓峰同学在锆石U-Pb同位素测试分析中提供了帮助,评审专家及责任编辑杨艳老师对本文提出宝贵的修改意见,在此一并表示衷心的感谢!

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