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西藏玛日埃错地区花岗斑岩岩石成因及其对班公湖—怒江缝合带中段演化的制约

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摘要:为进一步了解班公湖—怒江缝合带中段闭合时限及构造演化模式, 对西藏双湖县玛日埃错地区花岗斑岩进行了锆石U-Pb定年、岩石地球化学和Sr-Nd-Pb同位素方面的研究。结果显示, 玛日埃错地区花岗斑岩形成于晚白垩世晚期(78.3 ± 0.4 Ma); 具有高硅(72.41%~74.06%)、富碱($\text{Na}_2\text{O} + \text{K}_2\text{O} = 6.66\% \sim 7.14\%$)的特点, 属钙碱性系列, A/CNK值介于1.01~1.07, 具弱过铝质特征; 稀土配分模式为轻稀土富集、重稀土亏损的右倾型, 并且富集大离子亲石元素(如Rb、Ba、U、K、Th等), 亏损高场强元素(如Nb、Ta、P、Ti), 显示其源区残留相为石榴石一角闪岩相。岩石具有相对较低的 $^{87}\text{Sr}/^{86}\text{Sr}$ 初始比值(0.7052~0.7060)和较低的正 $\epsilon_{\text{Nd}}(t)$ 值(1.5~2.3), 及相对年轻的二阶段模式年龄($t_{\text{DM2}} = 692 \sim 758$ Ma); Pb同位素组成相对均一, 具造山带演化特征。综合分析研究表明, 玛日埃错地区花岗斑岩可能起源于伸展背景下的新生地壳部分熔融, 源区富含流体, 残留相以石榴石一角闪岩为主, 不含斜长石。玛日埃错花岗斑岩形成于班怒洋盆闭合、两侧地体碰撞后的伸展背景下, 表明班公湖—怒江缝合带中段地区在晚白垩世晚期已经进入后碰撞伸展阶段。

关键词:岩石成因; 后碰撞伸展环境; 花岗斑岩; 玛日埃错地区; 班公湖—怒江缝合带中段; 岩石学。

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Petrogenesis of Granite Porphyry in Mariaicuo Area, Shuanghu County, Tibet, and Constraints on the Evolution in the Middle Section of Bangonghu-Nujiang Suture Zone

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Abstract: LA-ICP-MS zircon U-Pb dating, geochemical and Sr-Nd-Pb isotopic data analysis were conducted on the granite porphyry in Mariaicuo area in order to determine its formation time, petrogenesis, structural setting and geological significance. LA-ICP-MS zircon U-Pb dating of the granite porphyry in Mariaicuo yields a crystallization age of 78.3 ± 0.4 Ma, indicating that the rock formed in the late of Late Cretaceous. Petrogeochemically, the samples of the rocks are high in SiO_2 (72.41%~74.06%) and rich in $\text{Na}_2\text{O} + \text{K}_2\text{O}$ of 6.66%~7.14%, which belong to calc-alkaline series. Its A/CNK ratios of

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1.01–1.07 are of characteristics of weakly peraluminous granites. They are enriched in the large-ion lithophile elements of Rb, Ba, U, K and Th, and strongly depleted in high field strength elements Nb, Ta, P, and Ti. The REE distribution mode is obvious right-leaning, indicating that it remains garnet-amphibolite facies in source area. Their isotopic compositions are characterized by low initial ($^{87}\text{Sr}/^{86}\text{Sr}$)_i of 0.7052–0.7060 and low positive $\epsilon_{\text{Nd}}(t)$ (1.5–2.3) values and relatively young second-stage model age ($t_{\text{DM2}} = 692–758$ Ma) of crust. It has relatively homogeneous Pb isotope composition with the evolution of orogenic characteristics. Comprehensive analysis shows that the granite porphyry in Mariaicuo area may originate from the new partial melting of crust within extensional background, and its source region is enriched in fluid and remains garnet-amphibolite facies, excluding plagioclase. It formed in the post-collision extensional environment, which occurred after the closure of Bangonghu-Nujiang Tethys Ocean (BTO) and collision between terranes on both sides, when the middle section of Bangonghu-Nujiang suture zone has entered the extension phase in Late Cretaceous.

Key words: petrogenesis; post-collision; granite porphyry; Mariaicuo area; middle section of Bangonghu-Nujiang suture zone; petrology.

板块缝合带通常经历了古洋壳的俯冲和闭合,以及随后洋壳两侧古老地体的碰撞过程,而上述地质过程中发育的大量花岗岩体则较好地记录了缝合带的构造演化历史,同时花岗岩又是大陆地壳的重要组成部分,是了解板块缝合以及造山带演化的重要窗口(de Paolo *et al.*, 1991; Rudnick, 1995).班公湖—怒江缝合带(以下简称班怒带)横贯青藏高原中部,东西跨度达2 000 km以上,被认为是南羌塘地体与北拉萨地体之间的古板块缝合线,班公湖—怒江缝合带两侧大量中生代岩浆作用研究为还原这一地区构造演化和矿床的形成提供了更多的依据(Zhang *et al.*, 2012; Zhu *et al.*, 2013),并因带内发育的多金属矿产而成为地质研究工作的热点(芮宗瑶等,2004;李光明等,2007;李德威,2008;张璋等,2011;丁帅等,2017;郑有业等,2017).

玛日埃错地区位于班怒带中段,研究程度较低,部分学者对区内出露的塔仁本洋岛玄武岩进行了地球化学、年代学研究(朱弟成等,2006),区内少量分布的蛇绿混杂岩、去申拉火山岩、燕山晚期—喜山晚期酸性侵入岩等未做详细研究。玛日埃错南部多巴地区的雄巴岩体和班戈地区的雪如岩体成岩年龄在晚白垩世晚期(约80 Ma),前人认为该地区班怒特提斯洋盆在中侏罗世之前已开始向南俯冲消减,一直持续至早白垩世中期最终闭合(130~125 Ma),拉萨地体与羌塘地体开始发生碰撞作用,这种碰撞作用大约持续了20~30 Ma,在晚白垩世早期进入后碰撞伸展阶段(100~80 Ma,高顺宝等,2011a,2011b),定立等(2012)对班戈附近的雄巴岩体研究后亦支持上述观点。而部分学者对班戈地区雪如岩体研究认为其在80 Ma时仍处于同碰撞阶段(王江朋等,2012;李小赛等,2013)。班怒带中段A型花岗岩的发现显示,班怒特提斯洋盆应该在早白垩世闭

合,并在约110 Ma时已经进入后碰撞伸展阶段(曲晓明等,2012; Qu *et al.*, 2012)。因此关于班怒带中段班怒特提斯洋盆的闭合、南羌塘与北拉萨地体的碰撞时限存在明显争议。

前人对于班怒带中段中酸性花岗岩的研究大部分基于年代学、地球化学等,而缺乏放射性同位素方面的探讨分析,本文拟对位于班怒带内中段的玛日埃错花岗斑岩进行年代学、岩石地球化学和Sr-Nd-Pb同位素的研究,旨在探明其岩石成因和构造环境,并进一步限定班怒带中段的演化时限。

1 区域地质背景及岩相学特征

作为青藏高原多条重要缝合带之一,班公湖—怒江缝合带位于青藏高原中部,西起班公湖,自西向东经改则、东巧、丁青和嘉玉桥至八宿县,是新特提斯洋盆闭合、北拉萨地体与南羌塘地体碰撞拼合的产物。缝合带中主要发育的岩体有晚二叠世至早三叠世MORB型蛇绿岩(黄启帅等,2012)、中侏罗世SSZ型蛇绿岩(Shi, 2007b)、早白垩世OIB型玄武岩(朱弟成等,2006)、早白垩世去申拉组(K_{1q})火山岩(安山岩、玄武岩)(李伟,2012)、以及贯穿整个白垩世的中酸性花岗质侵入岩,发育的地层主要有中一下侏罗统木嘎岗日群复理石建造、上侏罗统沙木罗组灰岩和上白垩统竟柱山组磨拉石建造等。

玛日埃错地区位于青藏高原羌塘地体南缘,班公湖—怒江缝合带内中段(图1a),该区酸性侵入岩分布较少,出露面积仅约2 km²,多呈NNE向带状分布,与区内主要构造线展布方向基本一致,主要岩石组合为花岗斑岩—花岗闪长斑岩。研究样品为灰白色花岗斑岩(图2a,2b),主要侵位于上侏罗统沙木罗组(J_{3s})生物碎屑灰岩地层和早白垩世去申拉

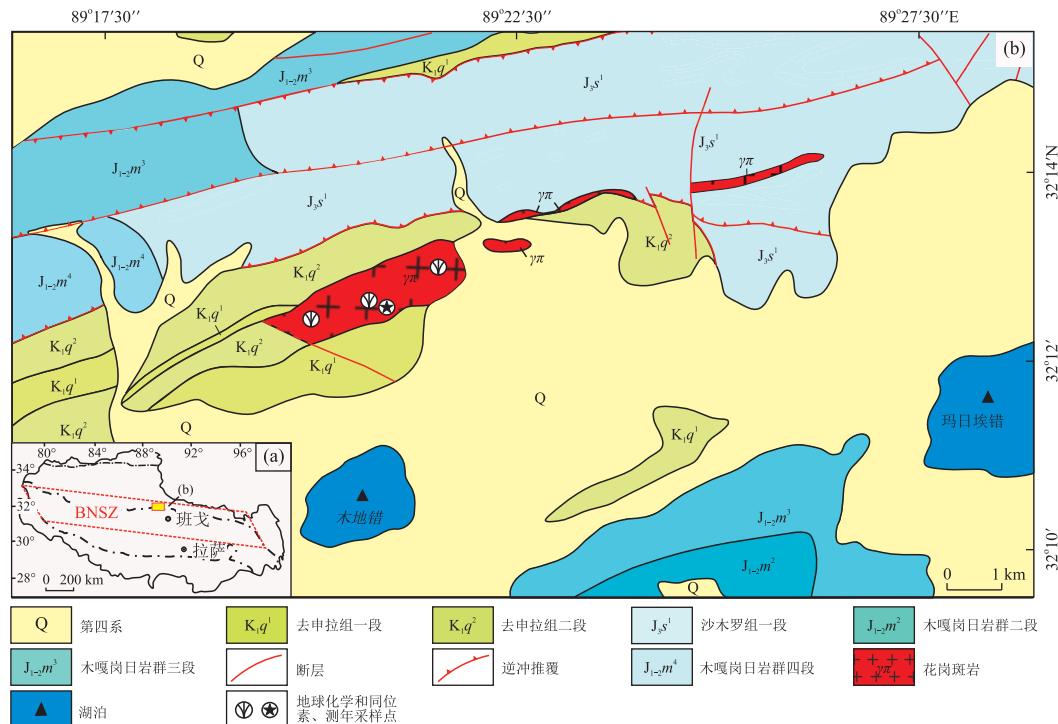


图1 西藏双湖县玛日埃错地区地质简图

Fig.1 Geological sketch map of Mariaicuo area, Shuanghu County, Tibet

图a据宋扬等(2014)修改;图b据西藏双湖县赞宗错地区1/5万四幅区域地质调查成果报告修改(内部资料未刊发)

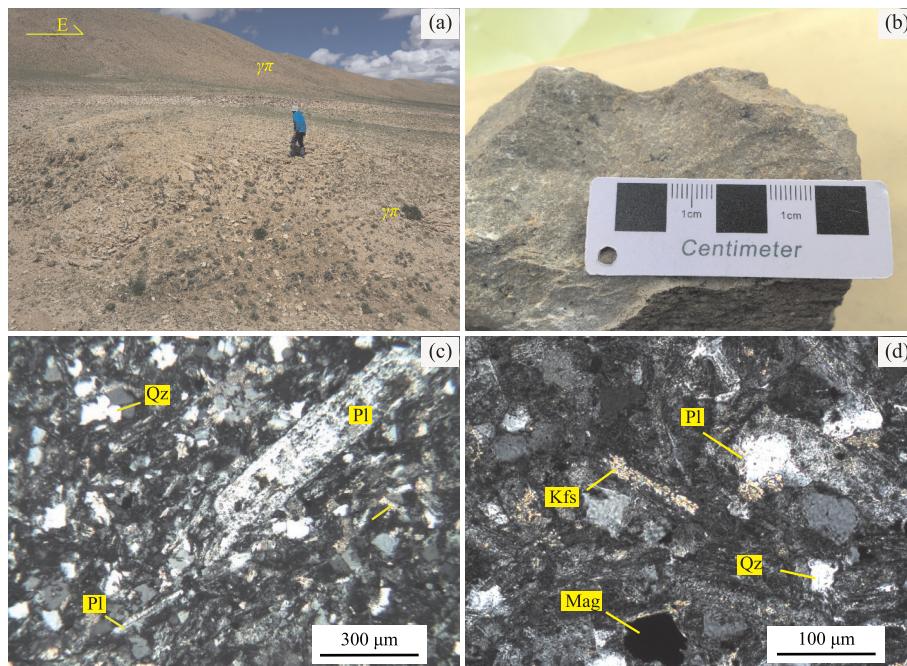


图2 西藏双湖县玛日埃错地区花岗斑岩野外及镜下正交偏光照片

Fig.2 Field image orthonormal polarizing microphotograph of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

a.花岗斑岩岩体野外宏观照片;b.岩石手标本照片;c,d.镜下正交偏光照片;Qz.石英;Pl.斜长石;Kfs.钾长石;γπ.花岗斑岩;Mag.磁铁矿

组火山岩(K_1q)中(图1b),野外观察岩体呈岩株和岩瘤状产出,中等风化,蚀变主要为高岭土化,未见脉岩及暗色包体,岩性较为均一,无明显分带现象;

岩相学显示岩石为斑状结构,斑晶为斜长石,多呈自形一半自形板状,大小1~2 mm,含量5%左右,星散状分布,略显筛状熔蚀,绢云母化严重,但保留原

始晶型;基质为斜长石、钾长石、石英,大小多为0.01~0.05 mm,部分0.05~0.10 mm;斜长石呈半自形板状,被绢云母交代,含量占45%~50%,钾长石呈半自形—他形粒状,被高岭土交代,含量为25%~35%,石英呈半自形—他形粒状,星散状分布,表面新鲜干净,含量在20%~25%(图2b);副矿物包括磁铁矿、锆石、磷灰石等。

2 分析方法

2.1 LA-ICP-MS 锆石 U-Pb

本文选取发育面积较大($\sim 2 \text{ km}^2$)的花岗斑岩岩体作为采样对象,沿其展布方向(NNE)两个样品为一组,由西向东依次采取3组新鲜地球化学和同位素测试样品,分别为HX1和HX2、HX3和HX4、HX5和HX6,地球化学样品命名为 γ -HX,同位素样品命名为g-HX;在岩体中部(北纬: $32^{\circ}12'49.46''$,东经: $89^{\circ}20'17.71''$)选取新鲜花岗斑岩作为锆石U-Pb定年样品,命名为R-GS。岩石样品破碎和锆石挑选工作由河北省欣航测绘院完成,样品破碎至80~120目后经淘洗除去比重轻的矿物,采用浮选和磁选分选出锆石,在双目镜下挑选晶形、色泽较好,透明度高的锆石颗粒用环氧树脂进行制靶(宋彪等,2002),利用阴极发光(CL)显微照相观察锆石的内部结构,避开包裹体、裂隙及残留核进行圈点。锆石U-Pb分析在中国地质科学院地质研究所实验室完成。所用的LA-MC-ICP-MS为美国ThermoFisher公司最新一代NeptunePlus型多接收等离子体质谱仪。采用的激光剥蚀系统为美国Coherent公司生产的GeoLasPro193 nm。激光剥蚀所用束斑直径为 $32 \mu\text{m}$,频率为10 Hz,能量密度约为 2.5 J/cm^2 ,以He为载气,最后按照所圈点进行测试分析。锆石年龄计算以国际标准锆石91500和GJ-1为外标,实验室测定值分别为 $^{206}\text{Pb}/^{238}\text{U}=1\ 065.6 \pm 3.5 \text{ Ma}$ 和 $^{206}\text{Pb}/^{238}\text{U}=607 \pm 2.8 \text{ Ma}$,与前人报道的结果在误差范围内一致(侯可军等,2009)。测试结果用ICPMsDataCal程序计算(Liu et al., 2010),未进行铅校正,之后用Isoplot(Ludwig, 2003)程序完成年龄计算及谐和图绘制。具体分析步骤和数据处理过程参照文献(Gao et al., 2002; 柳小明等, 2002; 侯可军等, 2009)。

2.2 全岩地球化学分析

选取的6个样品的主量、微量元素分析在中国地质大学(北京)科学研究院完成,主量元素分析在飞利浦PW2404X射线荧光光谱仪上进行,按照

GB/T14506.28-93硅酸盐岩石化学分析方法X射线荧光光谱法测定。微量元素和稀土元素在Finnigan MAT ELEMENT型高分辨率等离子体质谱仪(ICP-MS)上测定,采用DZ/T0223-2001电感耦合等离子体质谱方法,大致过程为:准确称取50 mg样品粉末放于PTFE溶样器(bomb)中,每个样品中加入1 mL的HF(38%)和0.5 mL的HNO₃(68%),蒸干溶液以除掉大部分的硅。加入1 mL的HF和0.5 mL的HNO₃,置于190 °C烘箱中加热12 h。冷却后加入1 mL浓度为0.5 μg/mL的Rh内标溶液,加热至约150 °C蒸干溶液,加入1 mL的HNO₃蒸干,再加一次HNO₃蒸干。用8 mL 40%的HNO₃提取最终的残留物,重新密封溶样器,将其放入110 °C烘箱中加热3 h,冷却之后,加入去离子水将溶液稀释至100 mL。

2.3 Sr-Nd-Pb分析

Sr-Nd-Pb同位素分析在中国科学院广州地球化学研究所同位素地球化学实验室完成,Sr和Nd同位素比值利用MC-ICP-MS测定。样品采用小于180目的粉末,用HF+HNO₃(1:1)在Teflon容器中低温溶解,采用AG 50W×8(H⁺)阳离子交换柱和P507萃淋树脂分离出纯净的Rb、Sr、Sm和Nd。 $^{87}\text{Sr}/^{86}\text{Sr}$ 和 $^{143}\text{Nd}/^{144}\text{Nd}$ 测定比值分别用 $^{87}\text{Sr}/^{86}\text{Sr}=0.119\ 4$ 和 $^{146}\text{Nd}/^{144}\text{Nd}=0.721\ 9$ 进行标准化,分析误差用 2σ 给出。BCR1标准样品 $^{143}\text{Nd}/^{144}\text{Nd}=0.512\ 626 \pm 9(n=12)$,NBS987多次测定 $^{87}\text{Sr}/^{86}\text{Sr}$ 平均值为 $0.710\ 265 \pm 12(n=9)$ 。整个实验流程本底Sr为 $2 \times 10^{-10} \sim 5 \times 10^{-10} \text{ g}$,Nd小于 $5 \times 10^{-11} \text{ g}$ 。

Pb同位素测定时,先称重100 mg岩石粉末放到Teflon容器中,并在140 °C下溶解于HNO₃+HF混合物达72 h。将溶液蒸发至干,然后加入2 mL浓HNO₃,并在140 °C的热板上加热24 h。再次蒸发至干,随后加入2 mL HCl,并在140 °C的热板上再次加热24 h。最后溶解在HBr溶液中至Pb纯化。通过常规的阴离子交换技术(AG1X8)将稀释的HBr作为洗脱剂分离和纯化Pb。详细的分析程序请参考Baker and Waight(2002)。分析期间,标准值参考为 $^{206}\text{Pb}/^{204}\text{Pb}=16.936\ 8 \pm 4(2\sigma)$, $^{207}\text{Pb}/^{204}\text{Pb}=15.488\ 1 \pm 5(2\sigma)$,以及 $^{208}\text{Pb}/^{204}\text{Pb}=36.678\ 8 \pm 11(2\sigma)$ 。

3 分析测试结果

3.1 锆石 LA-ICP-MS 定年

玛日埃错地区花岗斑岩的锆石U-Pb定年结果显示(表1),锆石内部Th含量为 $189.1 \times 10^{-6} \sim$

表1 西藏双湖县玛日埃错地区花岗斑岩锆石 LA-ICP-MS U-Pb 定年结果

Table 1 Dating results of LA-ICP-MS zircon U-Pb of granite porphyry for the samples in Mariaicuo area, Shuanghu County, Tibet

样品号	含量(10^{-6})				同位素比值						年龄(Ma)						备注
	Pb	Th	U	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	
R-GS-01	5.1	189.1	334.2	0.57	0.050 1	0.001 9	0.084 0	0.003 4	0.012 2	0.000 2	198.2	88.9	81.9	3.2	78.3	1.3	
R-GS-02	5.7	209.1	345.8	0.61	0.050 4	0.002 1	0.085 5	0.003 6	0.012 5	0.000 2	213.0	91.7	83.3	3.3	79.8	1.0	
R-GS-03	9.1	392.9	584.2	0.67	0.050 1	0.003 1	0.081 7	0.005 4	0.012 0	0.000 1	198.2	144.4	79.7	5.1	76.9	0.8	
R-GS-04	7.9	326.9	500.8	0.65	0.050 0	0.001 6	0.082 8	0.002 6	0.012 2	0.000 1	194.5	108.3	80.8	2.4	78.3	0.9	
R-GS-05	6.4	240.9	403.1	0.60	0.047 2	0.001 9	0.079 4	0.003 0	0.012 6	0.000 2	57.5	92.6	77.6	2.9	80.6	1.3	
R-GS-06	8.8	364.7	547.3	0.67	0.049 9	0.001 6	0.084 5	0.002 6	0.012 5	0.000 2	190.8	71.3	82.3	2.5	79.8	1.0	
R-GS-07	4.8	255.2	282.4	0.90	0.078 9	0.005 6	0.125 9	0.008 2	0.012 3	0.000 3	1168.5	142.6	120.4	7.4	78.9	1.8	排除
R-GS-08	10.7	408.6	666.0	0.61	0.049 2	0.001 5	0.0833	0.002 6	0.012 3	0.000 1	166.8	74.1	81.2	2.4	79.1	0.8	
R-GS-09	14.9	626.0	944.8	0.66	0.071 3	0.002 4	0.114 8	0.004 0	0.011 6	0.000 1	966.4	66.7	110.3	3.7	74.7	0.8	排除
R-GS-10	8.7	327.4	563.2	0.58	0.046 6	0.001 8	0.076 6	0.002 8	0.012 1	0.000 1	27.9	92.6	75.0	2.7	77.2	0.9	
R-GS-11	7.1	290.9	441.5	0.66	0.049 6	0.002 1	0.082 2	0.003 1	0.012 4	0.000 2	176.0	128.7	80.2	2.9	79.1	1.0	
R-GS-12	10.2	452.6	635.8	0.71	0.048 5	0.001 6	0.081 2	0.002 7	0.012 2	0.000 1	124.2	77.8	79.3	2.5	78.2	0.8	
R-GS-13	7.7	297.9	497.5	0.60	0.049 3	0.001 9	0.081 8	0.002 9	0.012 3	0.000 1	161.2	88.9	79.8	2.7	78.8	0.9	
R-GS-14	7.3	260.1	463.8	0.56	0.054 9	0.001 9	0.092 2	0.003 1	0.012 3	0.000 1	405.6	77.8	89.6	2.9	79.0	1.0	排除
R-GS-15	6.7	275.6	424.9	0.65	0.049 4	0.002 0	0.082 4	0.003 3	0.012 3	0.000 1	164.9	96.3	80.4	3.1	78.8	0.9	
R-GS-16	11.2	572.5	688.8	0.83	0.049 1	0.001 5	0.080 6	0.002 3	0.012 1	0.000 1	150.1	78.7	78.7	2.2	77.3	0.7	
R-GS-17	12.1	550.9	767.0	0.72	0.048 4	0.001 4	0.080 6	0.002 4	0.012 1	0.000 1	120.5	68.5	78.7	2.2	77.6	0.8	
R-GS-18	7.6	243.0	511.2	0.46	0.048 0	0.001 6	0.079 5	0.002 6	0.012 2	0.000 1	101.9	71.3	77.7	2.4	77.9	0.9	
R-GS-19	11.7	595.3	706.1	0.83	0.047 9	0.001 4	0.079 7	0.002 2	0.012 2	0.000 1	100.1	70.4	77.8	2.1	78.3	0.8	
R-GS-20	10.6	415.6	663.1	0.63	0.055 2	0.001 7	0.091 8	0.002 6	0.012 3	0.000 1	420.4	68.5	89.2	2.4	78.8	0.9	排除
R-GS-21	10.9	518.2	663.3	0.78	0.047 6	0.001 4	0.079 2	0.002 4	0.012 1	0.000 1	79.7	70.4	77.4	2.2	77.6	0.9	
R-GS-22	8.8	367.0	551.0	0.67	0.048 2	0.001 6	0.080 5	0.002 6	0.012 2	0.000 1	109.4	78.7	78.6	2.4	78.5	0.8	
R-GS-23	11.5	631.2	707.7	0.89	0.048 1	0.001 6	0.077 8	0.002 5	0.011 9	0.000 1	105.6	75.0	76.1	2.4	76.1	0.7	
R-GS-24	9.9	332.2	649.5	0.51	0.047 9	0.001 6	0.079 2	0.002 5	0.012 1	0.000 1	100.1	77.8	77.4	2.3	77.8	0.8	
R-GS-25	10.2	445.7	642.2	0.69	0.048 1	0.001 4	0.081 0	0.002 4	0.012 3	0.000 1	101.9	70.4	79.1	2.3	78.9	0.9	

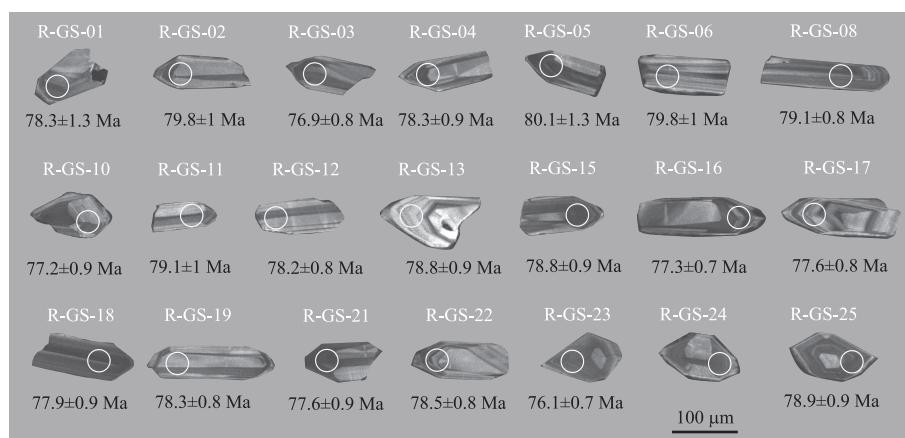


图3 西藏双湖县玛日埃错地区花岗斑岩样品 R-GS 锆石阴极发光图像及锆石 U-Pb 定年结果

Fig.3 Cathodoluminescence images and result of zircon U-Pb isotopic analyses of granite porphyry from sample R-GS in Mariaicuo area in Shuanghu County, Tibet

631.2×10^{-6} , U 含量介于 $334.2 \times 10^{-6} \sim 707.7 \times 10^{-6}$, Th/U 的平均比值为 0.67, 表明锆石可能为岩浆成因(吴元保和郑永飞, 2004). 一般认为, 锆石中某一区域的 U、Th 和 REE 等微量元素含量越高, 对应的 CL 图像越暗(Hanchar and Miller, 1993; Ru-

batto and Gebauer, 2000; Crofus *et al.*, 2003; 王楠等, 2016). 阴极发光 CL 图像显示(图 3), 锆石多呈灰黑色, 晶形较好, 主要呈长柱状, 部分呈短柱状和板状, 长轴介于 $80 \sim 160 \mu\text{m}$, 短轴长度介于 $40 \sim 60 \mu\text{m}$, 大部分具典型环带结构, 少数具核幔结构. 本

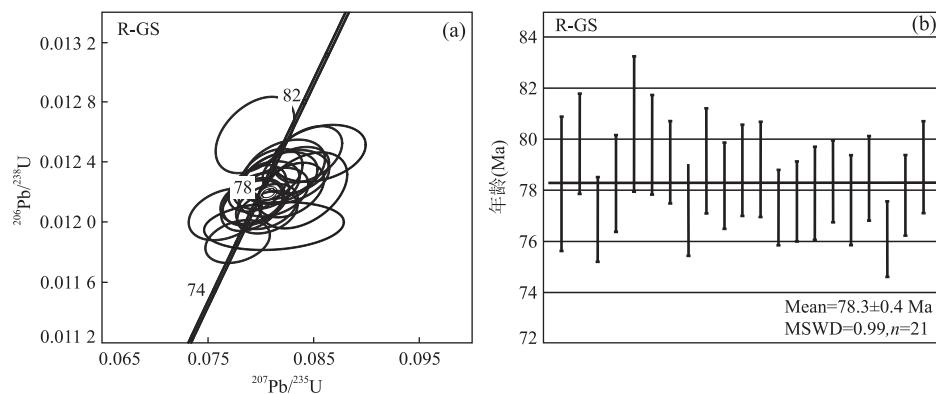


图 4 西藏双湖县玛日埃错地区花岗斑岩样品 R-GS 的 U-Pb 年龄谱和图(a)和加权平均年龄(b)

Fig.4 Zircon U-Pb data concordia diagram (a) and weighted average ages diagram (b) of granite porphyry from the sample R-GS in Mariaicuo area, Shuanghu County, Tibet

表 2 西藏双湖县玛日埃错地区花岗斑岩主量元素(%)、稀土元素(10^{-6})和微量元素(10^{-6})测试结果及有关参数

Table 2 Compositions of major elements (%), REE (10^{-6}) and trace elements (10^{-6}) of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

Sample	γ -HX1	γ -HX2	γ -HX3	γ -HX4	γ -HX5	γ -HX6	Sample	γ -HX1	γ -HX2	γ -HX3	γ -HX4	γ -HX5	γ -HX6
SiO_2	70.27	70.83	69.73	70.36	69.52	71.68	Lu	0.10	0.11	0.08	0.10	0.11	0.10
TiO_2	0.27	0.27	0.27	0.28	0.27	0.28	ΣREE	88.77	90.63	86.56	84.53	90.23	87.18
Al_2O_3	14.68	14.40	14.67	14.46	14.55	14.81	LREE	83.21	84.78	81.35	79.17	84.50	81.71
$\text{Fe}_{2\text{O}}_3^{\text{T}}$	0.99	1.74	1.43	1.18	1.96	1.12	HREE	5.57	5.84	5.21	5.36	5.73	5.47
MnO	0.01	0.02	0.02	0.01	0.03	0.01	LREE/HREE	14.94	14.51	15.60	14.77	14.75	14.95
MgO	0.28	0.27	0.46	0.25	0.29	0.29	La_N/Yb_N	22.73	21.67	26.79	22.06	22.34	22.94
CaO	2.64	2.09	2.74	2.84	2.77	1.72	δEu	1.03	1.03	0.94	1.02	1.04	1.02
Na_2O	3.66	3.54	3.85	3.50	3.71	3.92	δCe	1.00	1.00	1.00	0.99	0.99	0.99
K_2O	3.03	2.86	3.02	2.97	2.84	2.85	Li	65.598	76.771	56.196	70.974	64.854	85.086
P_2O_5	0.09	0.11	0.08	0.08	0.07	0.11	P	402.508	447.332	394.570	392.020	386.750	435.540
LOI	3.31	3.34	3.30	3.75	3.61	2.59	Sc	4.170	4.299	3.888	3.812	4.100	4.185
Total	99.23	99.47	99.57	99.68	99.62	99.38	Ti	1 596.27	1 663.10	1 573.56	1 494.00	1 509.48	1 598.58
N/K	1.21	1.24	1.27	1.18	1.31	1.38	V	31.13	32.68	29.90	28.57	29.45	29.56
A/CNK	1.04	1.13	1.01	1.02	1.02	1.17	Cr	20.06	24.56	18.86	16.13	22.03	24.30
DI	83.81	84.58	82.8	82.84	82.02	86.88	Mn	100.05	231.56	165.95	102.85	235.98	75.16
$\text{Mg}^{\#}$	35.91	23.51	38.92	29.56	22.67	33.90	Co	2.53	0.98	0.41	2.50	0.44	2.10
σ_{43}	1.64	1.47	1.77	1.53	1.62	1.60	Ni	10.10	17.47	13.06	12.40	12.09	11.93
R_1	2 753	2 852	2 626	2 827	2 701	2 770	Cu	16.71	15.58	17.28	15.22	15.57	14.60
R_2	609	541	627	625	621	505	Zn	24.47	35.67	35.50	18.24	38.12	23.46
La	21.50	21.82	20.99	20.60	21.92	21.32	Ga	16.12	16.18	15.78	15.19	15.34	16.02
Ce	40.94	41.78	40.11	38.83	41.48	40.13	Rb	112.68	106.48	108.34	102.87	101.68	105.95
Pr	4.13	4.21	4.04	3.95	4.19	4.03	Sr	198.04	194.96	180.54	196.92	207.18	203.76
Nd	13.59	13.80	13.26	12.89	13.77	13.22	Zr	137.69	151.96	50.84	137.90	140.06	141.22
Sm	2.31	2.41	2.29	2.21	2.38	2.29	Y	8.91	9.43	8.29	8.62	9.24	8.77
Eu	0.74	0.77	0.66	0.70	0.77	0.72	Nb	6.12	6.33	6.06	5.79	5.85	6.08
Gd	1.98	2.07	1.93	1.89	2.02	1.94	Cs	4.93	4.15	4.63	4.18	4.32	4.46
Tb	0.26	0.27	0.25	0.25	0.27	0.26	Ba	718.87	391.24	649.80	802.80	534.20	1 483.40
Dy	1.43	1.49	1.38	1.38	1.47	1.41	Hf	3.34	3.66	1.50	3.30	3.38	3.39
Ho	0.27	0.29	0.25	0.26	0.28	0.26	Ta	0.39	0.39	0.39	0.41	0.37	0.39
Er	0.74	0.77	0.66	0.70	0.77	0.72	Pb	15.09	14.74	14.48	13.74	13.92	13.62
Tm	0.10	0.11	0.09	0.10	0.11	0.10	Th	11.51	11.75	11.17	11.20	11.71	11.90
Yb	0.68	0.72	0.56	0.67	0.70	0.67	U	2.27	2.45	2.26	2.20	2.38	2.02

注: A/CNK = $\text{Al}_2\text{O}_3 / (\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ 摩尔比; $\text{Mg}^{\#} = 100 \times (\text{MgO} / 40.31) / (\text{MgO} / 40.31 + \text{Fe}_{2\text{O}}_3^{\text{T}} \times 2 / 159.7)$; $\sigma = (\text{Na}_2\text{O} + \text{K}_2\text{O})^2 / (\text{SiO}_2 - 43)$; DI = Qz + Or + Ab + Ne + Lc + Kp。

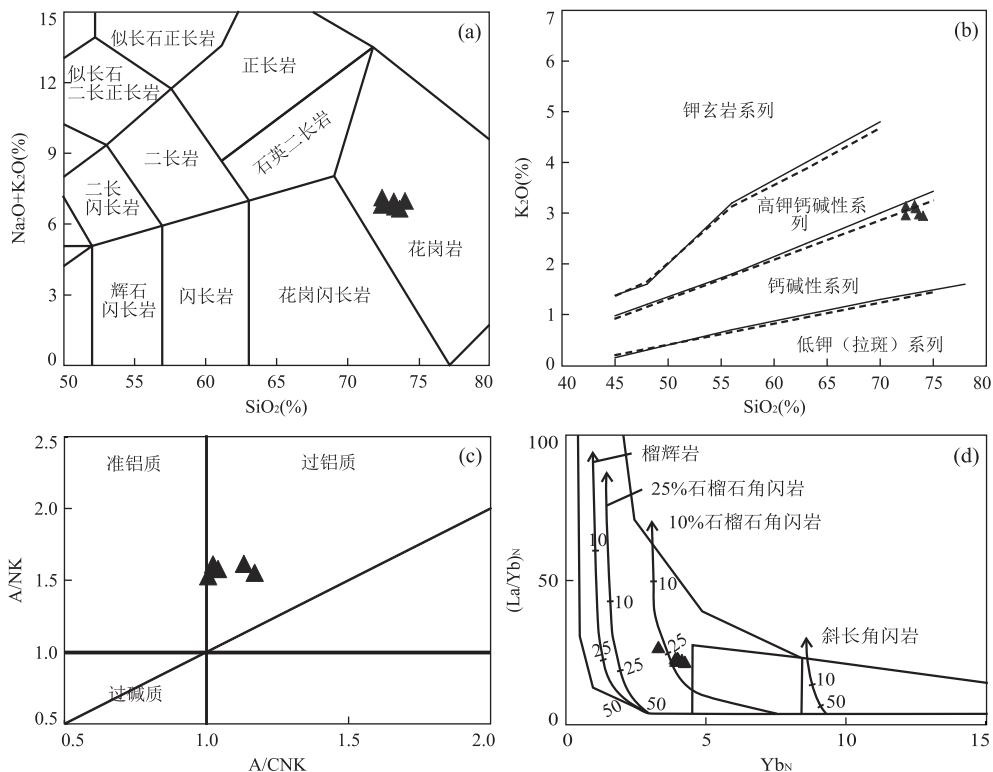
图5 西藏双湖县玛日埃错地区花岗斑岩TAS图解(a)、 K_2O - SiO_2 图解(b)、A/NK-A/NCK图解(c)、 $(La/Yb)_n$ - Yb_N 图解(d)

Fig.5 TAS diagram (a), K_2O vs. SiO_2 diagram (b), A/NK vs. A/NCK diagram (c) and $(La/Yb)_n$ vs. Yb_N diagram (d) of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

图a据Middlemost(1994);图b据Irvine and Baragar(1971);图c据Shand(1927);图d据Drummond and Defant(1990)

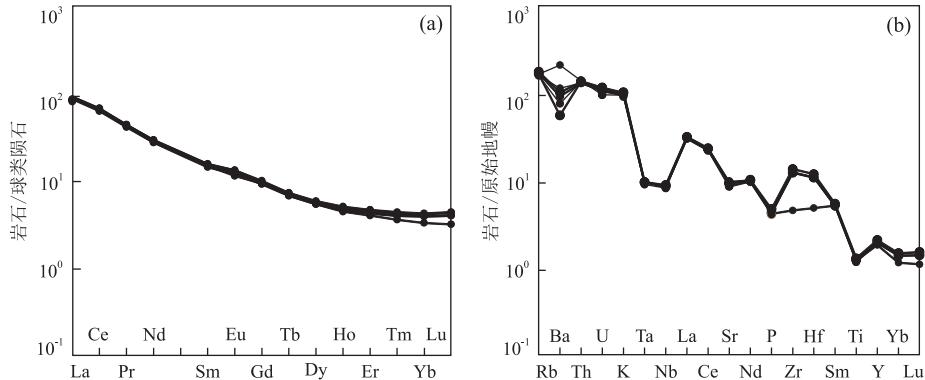


图6 西藏双湖县玛日埃错地区花岗斑岩岩石稀土元素球粒陨石标准化配分图解(a)和微量元素原始地幔标准化蛛网图(b)

Fig.6 Chondrite-normalized REE distribution patterns (a) and primitive mantle-normalized trace elements spider diagram (b) of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

标准化值据Sun and McDonough(1989)

次选择25个具有代表性的锆石进行U-Pb年龄测试,测点位置均圈定在环带结构中;测试结果显示(表1),测点07、09、14、20谐和度较差,在谐和年龄图中明显偏离谐和线,因此拟合谐和年龄时排除以上4点(表1),有效测点21个,获得的 $^{206}Pb/^{238}U$ 加权平均年龄为 78.3 ± 0.4 Ma(MSWD=0.99)(图4),时代为晚白垩世晚期,可代表该岩体的结晶年龄。

3.2 全岩地球化学

3.2.1 主量元素 花岗斑岩全岩地球化学分析结果显示(表2), SiO_2 含量为 $72.41\% \sim 74.06\%$,平均为 73.2% ; Na_2O 和 K_2O 含量分别介于 $3.68\% \sim 4.05\%$ 和 $2.94\% \sim 3.16\%$;全碱($Na_2O + K_2O$)含量介于 $6.66\% \sim 7.14\%$,平均为 6.89% ; $Na_2O/K_2O = 1.18 \sim 1.38$ 。TAS图解中,所有样品均落在花岗岩范

表 3 西藏双湖县玛日埃错地区花岗斑岩 Sr-Nd 同位素分析结果

Table 3 Results of Sr-Nd isotope analyses of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

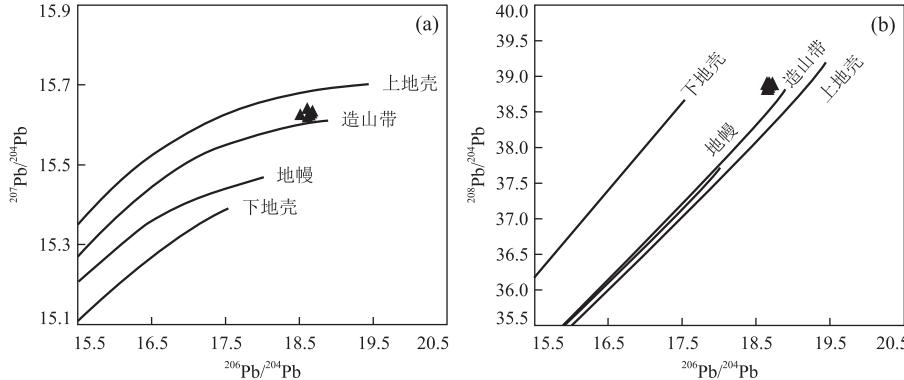
样品	<i>t</i> (Ma)	Rb (10^{-6})	Sr (10^{-6})	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ (10^{-6})	2σ $(^{87}\text{Sr}/^{86}\text{Sr})_i$	Sm (10^{-6})	Nd (10^{-6})	$^{143}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$ (10^{-6})	2σ $(^{143}\text{Nd}/^{144}\text{Nd})_i$	$(^{143}\text{Nd}/^{144}\text{Nd})_{\text{DM}}$	ϵ_{Nd}	t_{DM1} (<i>t</i>)	t_{DM2} (Ma)	$f_{\text{Sm/Nd}}$	
g-HX1	78.3	112.68	198.04	1.641 998	0.707 89	16	0.706 07	2.31	13.59	0.102 88	0.512 685	9	0.512 632	1.9	640	729	-0.48
g-HX2	78.3	106.48	194.96	1.576 324	0.707 01	11	0.705 25	2.41	13.80	0.105 44	0.512 668	8	0.512 614	1.5	679	758	-0.46
g-HX3	78.3	108.34	180.54	1.731 888	0.707 36	11	0.705 43	2.29	13.26	0.104 35	0.512 672	6	0.512 619	1.6	667	751	-0.47
g-HX4	78.3	102.87	196.92	1.507 632	0.707 11	13	0.705 44	2.21	12.89	0.103 58	0.512 670	6	0.512 617	1.6	665	754	-0.47
g-HX5	78.3	101.68	207.18	1.416 422	0.707 04	16	0.705 46	2.38	13.77	0.104 57	0.512 709	8	0.512 655	2.3	617	692	-0.47
g-HX6	78.3	105.95	203.76	1.500 618	0.707 43	11	0.705 76	2.29	13.22	0.104 63	0.512 687	7	0.512 633	1.9	648	727	-0.47

注: Sm、Nd 含量及 $^{147}\text{Sm}/^{144}\text{Nd}$ 比值均是依据微量元素的 ICPMS 分析结果及公式换算得到的。参数 $^{87}\text{Sr}/^{86}\text{Sr}$ 初始比值 = 0.705 4, $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{DM/CHUR}} = 0.512 638$; $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{DM}} = 0.213 7$, $\lambda = 6.54 \times 10^{-12} \text{ a}^{-1}$ (Lugmair and Marti, 1978)。

表 4 西藏双湖县玛日埃错地区花岗斑岩 Pb 同位素分析结果

Table 4 Results of Pb isotope analyses of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

样品	<i>t</i> (Ma)	U (10^{-6})	Th (10^{-6})	Pb (10^{-6})	$^{206}\text{Pb}/^{204}\text{Pb}$	2σ	$^{207}\text{Pb}/^{204}\text{Pb}$	2σ	$^{208}\text{Pb}/^{204}\text{Pb}$	2σ	$(^{206}\text{Pb}/^{204}\text{Pb})_t$	$(^{207}\text{Pb}/^{204}\text{Pb})_t$	$(^{208}\text{Pb}/^{204}\text{Pb})_t$
g-HX1	78.3	2.27	11.51	15.09	18.653	0.000 6	15.627	0.000 6	38.864	0.001 9	18.522	15.621	38.652
g-HX2	78.3	2.45	11.75	14.74	18.666	0.000 7	15.630	0.000 7	38.898	0.002 2	18.522	15.623	38.677
g-HX3	78.3	2.26	11.17	14.48	18.660	0.000 7	15.627	0.000 8	38.875	0.002 2	18.525	15.621	38.661
g-HX4	78.3	2.20	11.20	13.74	18.663	0.000 7	15.630	0.000 7	38.882	0.002 1	18.524	15.623	38.656
g-HX5	78.3	2.38	11.71	13.92	18.672	0.000 7	15.631	0.000 6	38.892	0.001 9	18.523	15.624	38.659
g-HX6	78.3	2.02	11.90	13.62	18.644	0.000 7	15.628	0.000 7	38.899	0.001 9	18.516	15.622	38.657

图 7 玛日埃错地区花岗斑岩 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ (a) 和 $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 增长曲线图 (b)Fig. 7 $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (a) and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ growth curve (b) of granite porphyry in Mariaicuo area
底图据 Zartman and Doe(1981)

围内(图 5a);里特曼指数 $\sigma = 1.47 \sim 1.77$, 在 $\text{SiO}_2-\text{K}_2\text{O}$ 图解中, 岩石样品均落在钙碱性系列区域(图 5b);铝饱和指数 $A/\text{CNK} = 1.02 \sim 1.17$, 根据 $A/\text{NK-A/CNK}$ 图解(图 5c), 属弱过铝质花岗岩。

3.2.2 微量元素 花岗斑岩稀土总量 $\Sigma \text{REE} = 84.53 \times 10^{-6} \sim 90.63 \times 10^{-6}$, 平均为 87.98×10^{-6} , 稀土配分模式图上表现为富集 LREE, 亏损 HREE 的明显右倾型, 曲线显示具有较好的一致性(图 6a), $\text{LREE/HREE} = 14.51 \sim 15.60$, $\text{La}_{\text{N}}/\text{Yb}_{\text{N}} = 22.06 \sim 22.79$, 轻重稀土元素分馏明显。 Eu 无异常 ($\delta \text{Eu} = 0.94 \sim 1.04$), 暗示源区岩浆演化过程中未经斜长石的分离结晶作用或源区未残留斜长石. 微

量元素分析结果(表 2)和原始地幔标准化微量元素蛛网图(图 6b)显示, 微量元素的配分模式近似一致, 相对于原始地幔, 表现出了富集大离子亲石元素 Rb、Ba、Th、U、K, 以及相对亏损高场强元素 Nb、Ta、P、Ti 的特点, 其中样品 γ -HX3 具有相对较高的 Ba 和较低的 Zr、Hf 含量, 本文猜测样品 γ -HX3 在制备或测试过程中可能受到外界混染的影响.

3.3 Sr-Nd-Pb 同位素

玛日埃错地区花岗斑岩样品 Sr-Nd 同位素和 Pb 同位素结果分别见表 3 和表 4. 花岗斑岩 $^{87}\text{Sr}/^{86}\text{Sr}$ 比值为 $0.707 01 \sim 0.707 89$, $^{143}\text{Nd}/^{144}\text{Nd}$ 比值为 $0.512 668 \sim 0.512 709$, 初始 Sr、Nd 参数采用锆石

U-Pb 加权平均年龄 78.3 Ma 进行计算, 获得的初始 Sr、Nd 同位素初始比值分别介于 0.705 25~0.706 07 和 0.512 614~0.512 655, $f_{\text{Sm}/\text{Nd}}$ 值介于 -0.48~-0.46, Nd 同位素模式年龄 (t_{DM}) 具有地质意义(吴福元等, 1997), Nd 二阶段模式年龄 $t_{\text{DM}2}$ 集中于 692~758 Ma, 明显大于岩体结晶年龄。花岗斑岩 $^{206}\text{Pb}/^{204}\text{Pb}$ 比值为 18.644~18.672, $^{207}\text{Pb}/^{204}\text{Pb}$ 比值为 15.627~15.631, $^{208}\text{Pb}/^{204}\text{Pb}$ 比值为 38.864~38.899, Pb 同位素比值时间校正计算($t=78.3$)后的 $(^{206}\text{Pb}/^{204}\text{Pb})_t$ 、 $(^{207}\text{Pb}/^{204}\text{Pb})_t$ 和 $(^{208}\text{Pb}/^{204}\text{Pb})_t$ 分别为 18.516~18.525、15.621~15.624 和 38.652~38.677, 在 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 增长曲线和 $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 增长曲线(图 7)上均处于造山带增长区域。

4 讨论

4.1 岩石成因及源区性质

1:25 万昂达尔错幅区域地质调查对该区花岗闪长斑岩进行了 K-Ar 定年, 结果表明其结晶年龄为 68.9 Ma(曲永贵等, 2006, 中华人民共和国 1:25 万昂达尔错幅地质调查报告)。而本文通过 LA-ICPMS U-Pb 定年所得该区侵入岩结晶年龄为 78.30 Ma, 并定名为花岗斑岩。结合其地球化学图解(图 8)分析认为, 该花岗斑岩 SiO_2 与 FeO^T 、 Al_2O_3 、 CaO 、 MgO 未呈现出明显的线性关系, 因此判断玛日埃错花岗斑岩的形成与岩浆熔体的分离结晶作用无太大关联。前人研究发现, $\text{Mg}^\#$ 值是判断是否存在

地幔作用的一个重要指标, 实验岩石学证明, 玄武岩的部分熔融产生的熔体 $\text{Mg}^\# < 45$ (Rapp, 1997), $\text{Mg}^\#$ 值大于 50 通常表明源区受到了更为基性物质的混染(吴福元等, 2002), 玛日埃错地区花岗斑岩 $\text{Mg}^\#$ 值为 22.67~38.92(平均 30.75), 小于玄武岩质下地壳部分熔融成因花岗岩的 $\text{Mg}^\#$ 值, 未受到更为基性物质的混染。岩石微量元素比值显示(表 2), Th/U 值介于 4.79~5.85(平均 5.11), 低于下地壳的 Th/U 比值(6.00, Rudnick and Gao, 2003), 接近中地壳值(4.9, Rudnick and Gao, 2003), Nb/Ta 比值为 14.24~16.08(平均 15.46), 同样接近中地壳(16.5, Rudnick and Gao, 2003)。以上特征共同表明花岗斑岩可能来源于壳源物质。

长英质岩浆演化过程中的斜长石分离结晶作用或源区部分熔融过程中发生斜长石的残留都可能引起熔体中 Eu 元素的负异常(Rollison et al., 2000), 玛日埃错花岗斑岩 δEu 值为 0.94~1.04, 显示无异常, 因此可能表明源区物质部分熔融过程中未发生斜长石等富 Eu 矿物的残留。研究表明, Nb、Ta 亏损而 Y 不亏损, 可能表明岩浆源区存在较多的石榴石或角闪石残留(Pearce and Norry, 1979; 侯增谦等, 2003)。根据不同 HREE 元素在石榴石和角闪石中分配系数的不同, 可对岩浆源区特征进行限定: 当石榴石为源区主要残留相时, 形成的熔体具有倾斜的 HREE 配分模式, Y/Yb 比值一般明显大于 10; 而当角闪石为源区主要残留相时, 形成的熔体具有较为平坦的 HREE 配分模式, Y/Yb 比值也接近于 10(高永丰等, 2003)。玛日埃错地区花岗斑岩 Y/Yb 值

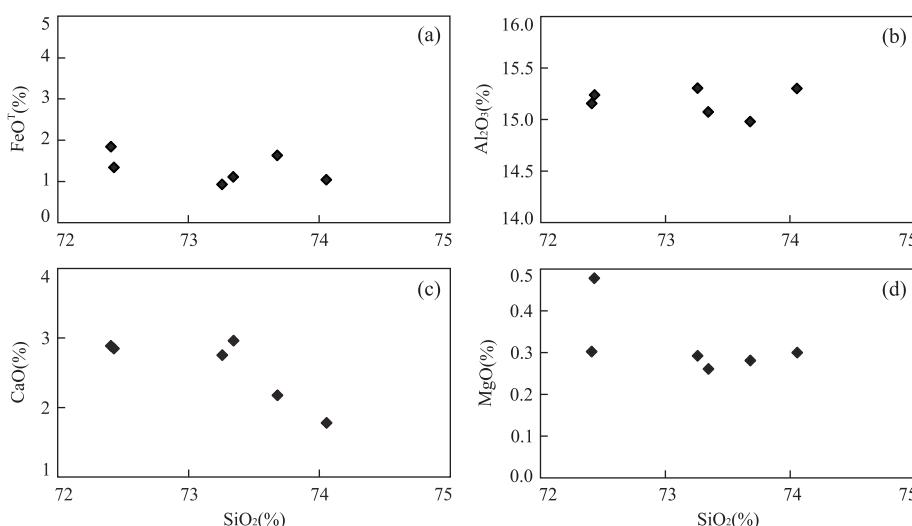


图 8 西藏双湖县玛日埃错地区花岗斑岩地球化学图解

Fig.8 Diagrams of geochemistry of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

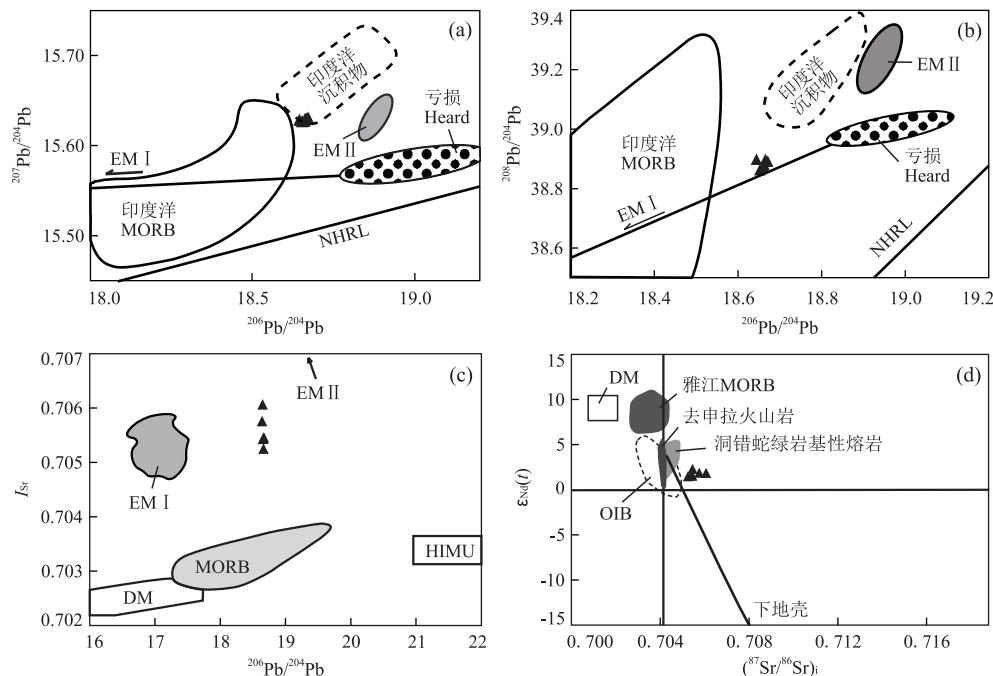


图 9 西藏双湖县玛日埃错地区花岗斑岩 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 图解(a)、 $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 图解(b)、 I_{Sr} - $^{206}\text{Pb}/^{204}\text{Pb}$ 图解(c)和 $\epsilon_{\text{Nd}}(t)$ - $(^{87}\text{Sr}/^{86}\text{Sr})_i$ 图解(d)

Fig.9 $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (a), $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (b), I_{Sr} vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (c) and $\epsilon_{\text{Nd}}(t)$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram (d) of granite porphyry in Mariaicuo, Shuanghu County, Tibet
图 b 修改自 Edwards et al.(1994); 图 d 修改自 Miller et al.(1999), Zhang et al.(2008); 康志强等(2010)

介于 12.9~14.8, 稀土元素球粒陨石标准化配分图解显示(图 6a), HREE 具有基本无分馏或轻微分馏的特征,且具有较为平坦的 HREE 配分模式,表明岩浆源区残留相以角闪石相为主,可能含有少量的石榴石(Defant and Drummond, 1990).正如实验熔融曲线(La/Yb)_N- Yb_N 图解显示,源区可能主要残留角闪石而少石榴石(少于 10%)(图 5d),微量元素原始地幔标准化蛛网图(图 6d)显示 Ti 元素亏损,指示岩浆可能形成于富流体的源区条件下,指示早期俯冲到深部的洋壳板片释放的流体对该区花岗斑岩的形成起到了重要作用(曲晓明等, 2001).综上,玛日埃错地区花岗斑岩源区富含流体,残留相可能为石榴石一角闪岩相,无斜长石.

Sr-Nd-Pb 同位素是探讨岩石物质来源的有效示踪剂(蔡剑辉等, 2004), 玛日埃错花岗斑岩的 $^{87}\text{Sr}/^{86}\text{Sr}$ 初始比值 = 0.705 2~0.706 0, $\epsilon_{\text{Nd}}(t) = 1.5 \sim 2.3$, 二阶段模式年龄 $t_{\text{DM2}} = 692 \sim 758 \text{ Ma}$. 区内发育的去申拉组火山岩为一套典型的岛弧型岩石,是俯冲沉积物流体交代的地幔楔部分熔融的产物(康志强等, 2010), 图 9d 显示花岗斑岩均落在去申拉组火山岩范围之外,说明其与去申拉组火山岩具有不同的岩浆源区,表明玛日埃错花岗斑岩并非早

期结晶的去申拉组火山岩二次演化形成.结合岩石微量元素比值,较低的 $^{87}\text{Sr}/^{86}\text{Sr}$ 初始比值,较低的 $\epsilon_{\text{Nd}}(t)$ 正值,以及图 9 中显示的由亏损地幔向弱富集的下地壳演化的特征,显示玛日埃错地区花岗斑岩起源于新生地壳的部分熔融(沈渭洲等, 2000; 杨志明等, 2011; Li et al., 2014), 综上推测玛日埃错地区花岗斑岩起源于新生下地壳部分熔融.

4.2 构造环境判别

班公湖—怒江特提斯洋的开启、俯冲极性、闭合以及碰撞时限等问题一直以来都是国内外地质学者争论的焦点.缝合带中 MOR 型蛇绿岩的发现及其年龄(254~217 Ma)的获得,表明主洋盆可能裂解于晚二叠世至早三叠世(黄启帅等, 2012), 史仁灯(2007)对班公湖 SSZ 型蛇绿岩的年代学和地球化学研究指示,班怒洋盆至少在中侏罗世(177~162 Ma)开始由扩张转换为俯冲消减, Larelaxin 岛弧型花岗岩的发现证明 168 Ma 左右开始进入洋壳俯冲阶段,进一步限定了其俯冲初始时间(Liu et al., 2013). 关于班怒带俯冲极性,存在北向俯冲(Kapp et al., 2003; 曲晓明等 2009)、南向俯冲(潘桂棠等, 2004; 高顺宝等, 2011a; 定立等, 2012)和双向俯冲(刘庆宏等, 2004; 廖六根等, 2005; 莫宣学和

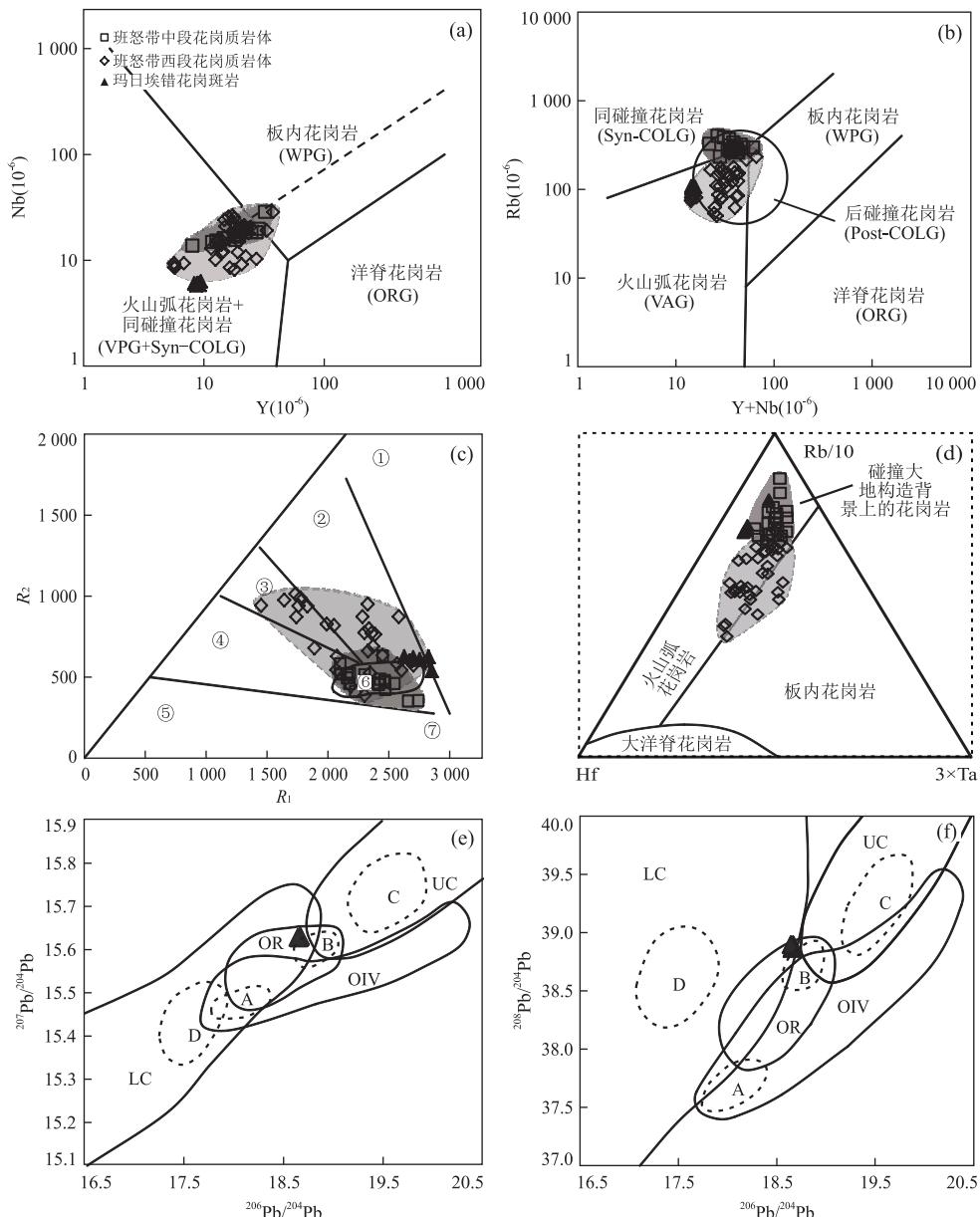


图 10 西藏双湖县玛日埃错地区花岗斑岩 Y-Nb (a)、Rb-(Y+Nb) (b)、 R_1 - R_2 图解 (c)、Rb/10-Hf-3×Ta 图解 (d)、 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ (e) 和 $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ (f) 图解

Fig.10 Diagrams of Y vs. Nb (a), Rb vs. (Y+Nb) (b), R_1 vs. R_2 (c), Rb/10 vs. Hf vs. 3×Ta (d), $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (e) and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (f) of granite porphyry in Mariaicuo area, Shuanghu County, Tibet

底图据 Zartman and Doe(1981); Pearce *et al.*(1984); Batchelor and Bowden(1985); Harris(1986); Pearce(1996).①地幔斜长花岗岩;②板块碰撞前花岗岩;③板块隆起期花岗岩;④晚造山期花岗岩;⑤非造山区 A型花岗岩;⑥同碰撞花岗岩;⑦造山期后 A型花岗岩.LC.下地壳;UC.上地壳;OIV.洋岛火山岩;OR.造山带;图 e,f 中的 A,B,C,D 分别为各区域中样品相对集中区域;图 a,b,c,d 中班怒带中段数据来自高顺宝等(2011b);定立等(2012);王江朋等(2012);李小赛等(2013);班怒带西段数据来自江军华等(2011);张志等(2013, 2017);李华亮等(2014);张硕等(2014);关俊雷等(2014);秦雅东等(2015)

潘桂堂, 2006)3 种认识, 推断班公湖—怒江特提斯洋可能存在双向俯冲演化过程, 且南向俯冲约在 160 Ma 开始(Wang *et al.*, 2016)。关于洋盆的闭合时间, Kapp *et al.*(2003)、陈国荣等(2004)、曲晓明和辛洪波(2006)、曲晓明等(2012)以及 Qu *et al.*

(2012)认为洋盆闭合时间在侏罗世末—白垩世初(约 145 Ma), 而赵元艺等(2011)对班怒带中段舍索矿区的成矿岩体的研究发现, 成岩于 116 Ma 的花岗闪长岩属俯冲碰撞闭合之前的岛弧型花岗岩类, 将洋盆闭合时间约束在 116 Ma 之后, 以陆相磨拉石

表 5 班公湖—怒江成矿带 80 Ma 左右花岗质侵入岩体特征对比

Table 5 Comparison of the granitic pluton in Bangonghu-Nujiang suture zone at about 80 Ma

序号	地区	岩性	年龄(Ma)	源区性质及岩石成因	构造环境	来源
1	班戈县雪如岩体	似斑状二长花岗岩	79.7	下地壳石榴石角闪岩相—斜长角闪岩相镁铁质岩石部分熔融形成	后碰撞	高顺宝等, 2011b
2	班戈县雪如、查朗拉、更乃矿床	似斑状二长花岗岩、斜长花岗岩	79.7~76.1	下地壳石榴石角闪岩相—斜长角闪岩相镁铁质岩石部分熔融形成	同碰撞	王江朋等, 2012; 李小赛等, 2013
3	雄巴岩体	花岗闪长岩	77.4、79.8	/	后碰撞	定立等, 2012
4	冈底斯西北缘	石英二长岩	85.6	地幔软流圈底辟作用造成先存的构造薄弱带发生地壳线性热隆伸展和部分熔融	洋陆转换、热隆伸展	李华亮等, 2014
5	杂尔穷、嘎拉勒	石英闪长玢岩、花岗闪长岩	87.1、88	成矿物质来源具有地幔与壳源混源特征	伸展构造环境	唐菊兴等, 2013; 张志等, 2013, 2017; 姚晓峰等, 2013
6	日松岩体、甲维岩脉	花岗闪长岩、英云闪长岩、花岗闪长玢岩	82、90.7	可能与加厚下地壳熔融以及幔源玄武质岩浆底侵作用有关	板内伸展环境	张硕等, 2014
7	日土南拉梅拉山口	花岗岩体(钾长花岗岩、二长花岗岩、花岗闪长岩)	79.4、81、81.3	富角闪石的下地壳, 既有新生地壳, 又有古老基底地壳构成的混合地壳发生部分熔融而形成	南向俯冲碰撞的产物	关俊雷等, 2014
8	班公湖地区日土县一带	闪长玢岩或石英闪长玢岩、花岗斑岩	76.9、79.6	花岗斑岩岩浆源区较浅, 斜长石和角闪石残留; 闪长玢岩岩浆形成于更大的深度, 源区以榴辉岩或石榴石角闪岩相	伸展环境	江军华等, 2011
9	班公湖地区蛇绿混杂岩带内	斜长花岗斑岩和花岗闪长岩、辉石闪长岩脉	97.4、91.9、80~76	斜长花岗斑岩和花岗闪长岩推测为玄武质岩浆底侵加厚下地壳部分熔融形成, 辉石闪长岩脉源区为经过熔体交代的上地幔	在 97~92 Ma 为同碰撞环境; 92 Ma 后, 挤压转变为伸展; 80~76 Ma, 伸展加剧	秦雅东等, 2015

注: “/”表示原文出处无此项内容。

建造为特征的上白垩统竟柱山组角度不整合在蛇绿混杂岩上以及其年龄的确定, 进一步将班怒特提斯洋盆的闭合时间限定在 96 Ma 之前 (Liu *et al.*, 2013; 李华亮等, 2016)。

前人认为, 岛弧岩浆作用会造成 Nb、Ta、Ti 等元素的强烈亏损和 Rb、K、Sr、Pb 等元素的明显富集 (Wilson, 1989)。但近年研究认为碰撞—后碰撞等非俯冲构造环境同样可以形成具有此特征的岩浆岩 (Tunér *et al.*, 1996; Miller *et al.*, 1999; 莫宣学等, 2003)。Nb-Y 图解 (图 10a) 显示, 玛日埃错花岗斑岩均落在火山弧和同碰撞区域, Rb/10-Hf-Ta×3 图解 (图 10d) 显示为同碰撞环境。²⁰⁷Pb/²⁰⁴Pb-²⁰⁶Pb/²⁰⁴Pb 和 ²⁰⁸Pb/²⁰⁴Pb-²⁰⁶Pb/²⁰⁴Pb 图解中样品落在了造山带集中区域 (图 10e, 10f), 上述判别图解均暗示 78.3 Ma 时玛日埃错地区可能处于同碰撞构造环境中, 但 Rb-(Y+Nb) 图解 (图 10b) 显示其落在火山弧花岗岩范围并靠近后碰撞花岗岩区域, R₁-R₂ 图解 (图 10c) 中显示其位于火山弧花岗岩一侧并接近同碰撞花岗岩区域。其构造环境还需进一步讨论。

构造判别图解存在一定的局限性和多解性

(Pearce, 1996; Förster *et al.*, 1997), 花岗岩类的许多构造环境判别图解思路都是来自于玄武岩的研究成果, 能否用来判别花岗岩的构造环境一直备受争议 (吴福元等, 2007; 张旗等, 2007), 因此岩体形成的构造背景不能单一地运用构造环境图解来解释, 必须结合其时空分布特征及整个区域的构造演化历程来研究 (韩宝福, 2007)。研究表明, 班怒带中段班戈地区的雪如岩体和雄巴岩体的构造环境判别显示, 晚白垩世晚期该地区地壳已经进入后碰撞伸展阶段 (高顺宝等, 2011b; 定立等, 2012)。结合班怒带内多个 80 Ma 左右的花岗质岩体进行地质年代、岩石成因和形成环境类型统计 (表 5), 并将位置投影到地质简图 (图 11) 上发现, 班怒带西段和中段均存在约 80 Ma 的岩浆活动, 侵位时代为 97.4~76.1 Ma。但其构造环境大同小异, 前人研究分析认为班怒带西段班公湖地区 ~80 Ma 基本已进入后碰撞伸展阶段 (Zhao *et al.*, 2008; 江军华等, 2011; 宋扬等, 2013; 李华亮等, 2014; 张硕等, 2014; 秦雅东等, 2015), 而部分学者认为班怒带中段晚白垩世晚期亦进入后碰撞伸展阶段 (高顺宝等, 2011a, 2011b; 定立等, 2012)。本文将大量统计数据投图发现 (图 10), 班怒带西段和中段

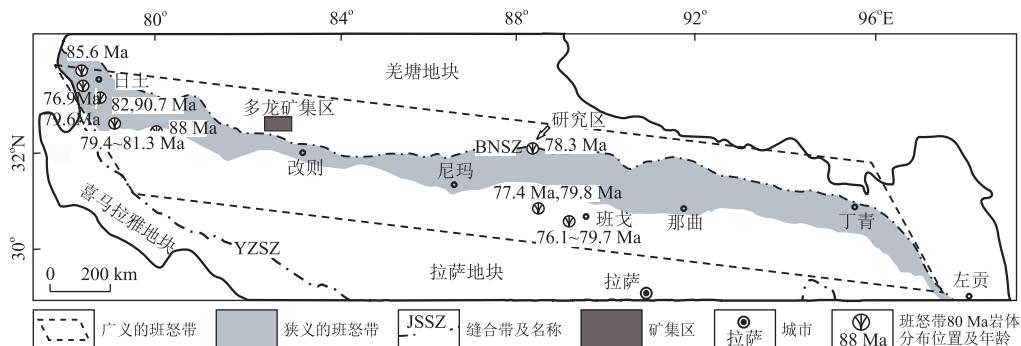


图 11 班公湖—怒江缝合带 80 Ma 左右花岗质岩体分布简图

Fig.11 Distribution of the granitic pluton in BNSZ at about 80 Ma

据宋扬等(2014)修改.BNSZ.班公湖—怒江缝合带;YZSZ.雅鲁藏布江缝合带

地区在晚白垩世晚期的构造环境特点大同小异,玛日埃错地区花岗斑岩大部分落入班怒带西段构造环境分布范围内,因此判断玛日埃错花岗斑岩可能形成于后碰撞伸展环境。其南部约 10 km 处的花岗斑岩(114 Ma)属于俯冲阶段的岛弧型花岗岩(据高轲等,未发表),可进一步将闭合时间限定在 114 Ma 之后、78.3 Ma 之前。结合前人研究结果可总结出整个班怒带的演化历史:晚二叠世至早三叠世(254~217 Ma)班怒洋开始裂解→中侏罗世(168 Ma 之后)班怒洋盆由扩张转换为洋壳俯冲(北向俯冲)→晚侏罗世(160 Ma 之后)班怒洋盆双向俯冲→早白垩世晚期至晚白垩世晚期(114~78.3 Ma)洋盆闭合、两侧地体持续碰撞并进入后碰撞伸展阶段。

5 结论

(1) 西藏双湖县玛日埃错地区花岗斑岩岩体锆石 LA-ICP-MS U-Pb 加权平均年龄为 78.3 ± 0.4 Ma, 形成于晚白垩世晚期。花岗斑岩具高硅高碱特点, 属钙碱性系列, 具弱过铝质特征; 富集大离子亲石元素 Rb、Ba、Th、U、K, 相对亏损高场强元素 Nb、Ta、P、Ti; 轻重稀土元素分馏明显, 无 Eu 异常, 稀土配分模式为富集 LREE, 亏损 HREE 的明显右倾型。

(2) 玛日埃错地区花岗斑岩可能起源于伸展背景下的新生下地壳部分熔融, 源区富含流体, 残留相以石榴石一角闪岩为主, 不含斜长石。

(3) 玛日埃错地区花岗斑岩形成于后碰撞伸展环境, 表明晚白垩世晚期(78.3 Ma)班怒带中段地区已经进入后碰撞伸展阶段。

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