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西藏吉塘花岗岩地球化学特征及成因*

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Abstract The Lancang River tectonic zone in southwestern Yunnan and eastern Tibet is important for the study of the evolution of the Paleotethys. The most important component of the Lancang River tectonic zone is the Triassic granitoids which occur over 1000km from Leiwuqi, Tibet in the north to Yunnan in the south. The Jitang granitoid intrusion is a representative body in the northern part of this granite belt. It consists of granodiorite and monzonitic biotite granite. The outcrop of this intrusion is 70km long and 2 ~ 10km wide. The overall straking of the intrusion is NNW. It occur in the west side of Lancang River, ~3km west of Jitang Town, Changdu City. Whole-rock Rb-Sr isochron age is ~220Ma according to a previous study. This paper reports whole-rock major and trace element compositions, and Sr, Nd isotopes for the Jitang granitoid intrusion. These data are used to evaluate source characteristics and tectonic setting for the intrusion. The Jitang granitoid samples contain 63.5% ~ 70.9% SiO_2, 2.8% ~ 4.2% Na_2O and 1.7% ~ 3.4% K_2O. The alumina-saturation index (A/CNK molar) of the samples vary from 1.1 to 1.5. These characteristics, together with the presence of CIPW-norm corundum in the samples (1.5% ~ 5.6%) indicate that these samples belong to the peraluminous and calc-alkaline series. According to the classification of Chappel and White (1992), the Jitang granitoids belong to S-type granite. The granodiorite samples from the Jitang intruson have initial $^{87}Sr/^{86}Sr$ ratios of 0.7280 ~ 0.7395 and $\varepsilon_{Nd}(i)$ values of -14.1 ~ -16.2. These data suggest that the parental magma was not produced by subduction zone magmatism, but by anatexis of ancient crustal materials. The depleted mantle Nd model ages (t_{DM}) of the Jitang granitoids are close to 2.0Ga, similar to the age of gneisses of the Jitang Group which formed by metamorphism of dacite or dacitic pyroclastic protoliths. The Sr-Nd isotopic compositions of the Jitang granitoids are similar to that of the Jitang gneisses. Strong depletion of Eu and Sr in whole rocks suggests residual plagioclase in the source region; depletion of Ba in whole rocks suggests that K-fieldspar was also a residual phase. These features, together with high whole-rock CaO/Na_2O ratios of ~0.8 support an interpretation that the parental magma was derived by biotite-dehydration melting from a source with composition similar to greywacke, not pelite. We proposed that the melting took place at about 25km in the middle crust due to extension of the thickened crust after the closure of the paleo-Lancang ocean. Our results support the hypothesis that the Lancang River tectonic zone represents a remnant Paleo-Tethyan main ocean preserved in the collision suture between a Gondwana-derived microcontinent and the continental margin of the Yangtze craton. The Paleo-Tethyan ocean in the Lancang River area should have been closed before the formation of the Jitang granitoid pluton at 220Ma. The closure is more likely to have taken place at ~280Ma (Early Permian) based on other geological data.

Key words Jitang granitoid intrusion; Lancang River; Anatexis; Changdu; Sanjiang Tethys

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摘 要 沿澜沧江结合带发育一条长达1000余千米的印支期澜沧花岗岩带，吉塘岩体位于该带北段，产出在吉塘以西约3km，轴向NNW，侵位于古元古代吉塘群变质岩系中，长70km，宽2~10km、出露面积341km^2。主要由花岗闪长岩和二长花岗岩组成，Rb-Sr等时线年龄值为220Ma。本文对吉塘岩体开展了系统的岩石地球化学特征分析。研究结果表明吉塘岩体为过铝质钙碱性S型花岗岩，吉塘岩体在岩石化学组成上，SiO_2含量63%~71%，平均66.5%，Na_2O含量2.8%~4.2%，K_2O含量1.7%~3.4%，铝饱和指数A/CNK=1.09~1.48，CIPW标准矿物中刚玉1.5%~5.6%，微量元素组成类似于片麻岩质的中地壳。$(^{87}Sr/^{86}Sr)_i$值为0.7280~0.7395，$\varepsilon_{Nd}(i)$为-14.1~-16.2，指示岩浆源区为地壳物质，成因上与俯冲作用无关，Nd同位素亏损地幔模式年龄(t_{DM})在2.0Ga左右，与昌都陆块变质基底古元古代吉塘群的原始形成年代相当，岩体Sr、Nd同位素组成也与变质基底吉塘群片麻岩一致，综合分析认为，岩浆源岩为变质杂砂岩成分的古元古代吉塘群片麻岩，其原岩建造主要是火山弧成因的英安岩或英安质火山碎屑岩，微量元素组成指示为黑云母脱水熔融。分析认为岩浆形成于地壳加厚增温环境下的地壳深熔作用，构造上与板块碰撞后的环境相联系。支持澜沧江构造带为冈瓦纳与扬子大陆边缘多岛弧系统的边界即古特提斯主洋盆的观点。澜沧江洋的闭合时间早于澜沧花岗岩带的形成年龄220Ma，根据构造带上相关研究成果，倾向于认同碰撞时间在280Ma左右。

关键词 吉塘花岗岩; 澜沧江; 深熔作用; 昌都; 三江特提斯

中图法分类号 P588.121

1 引言

澜沧江构造带被认为可能是冈瓦纳与扬子大陆边缘多岛弧系统的边界(莫宣学等, 1993; 刘本培等, 1993; 钟大赉, 1998; 莫宣学和潘桂棠, 2006)，在三江古特提斯构造演化研究中具有突出意义，对界定古特提斯时期扬子板块西缘大陆边缘及微陆块系统地质构造演化过程具有至关重要的作用。但长期以来，关于是否存在澜沧江缝合带？澜沧江构造带的性质？缝合带的闭合时限等尚未取得一致意见(从柏林等, 1993; 钟大赉, 1998; 张旗等, 1985; Heppe *et al.*, 2007; 范蔚茗等, 2009; Hennig *et al.*, 2009; 邓军等, 2010)。沿澜沧江结合带发育一条长达1000余千米的印支期澜沧花岗岩带(陈福忠等, 1994)，包括吉塘、东达山、白马雪山、鲁甸岩体及临沧花岗岩基等(图1)，澜沧花岗岩带提供了认识澜沧江结合带性质的重要地质窗口。目前，对该岩带的研究以临沧花

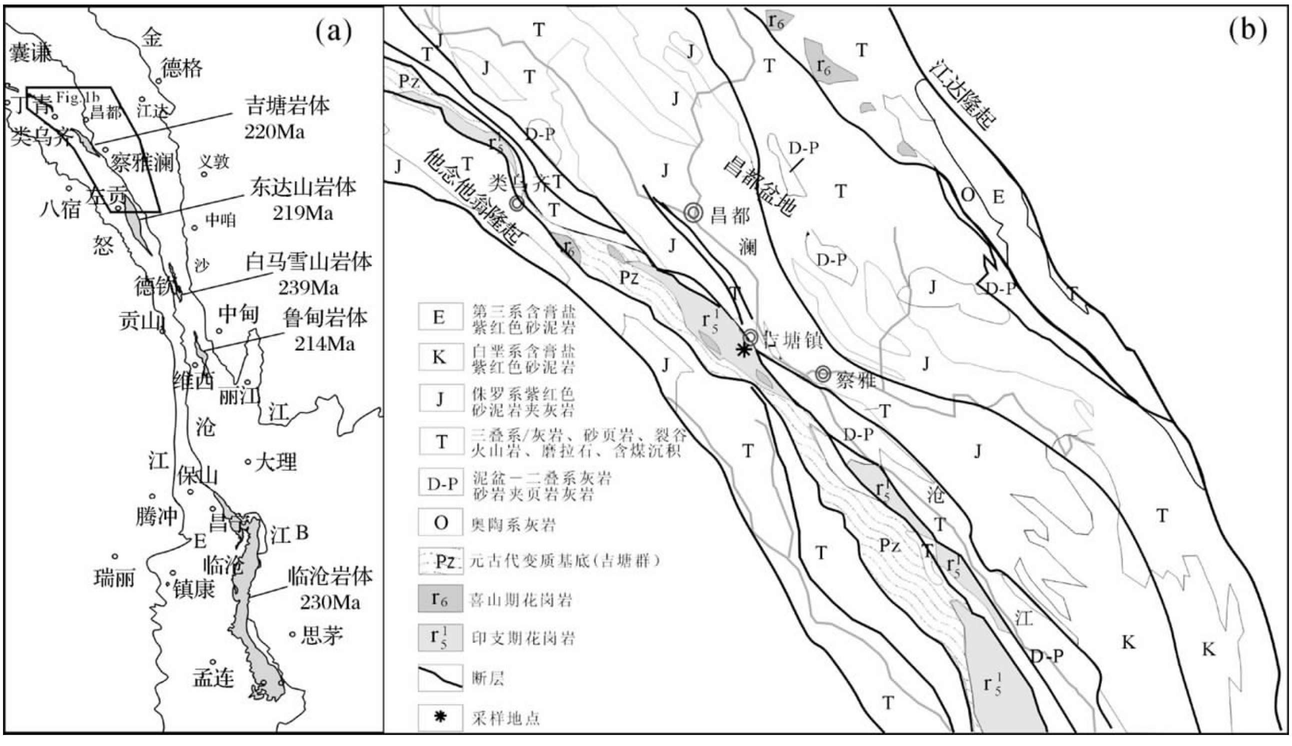

图1 澜沧花岗岩带分布(a)和吉塘岩体所在区域地质略图(b)(据潘桂棠等, 2004修改)

Fig. 1 Simplified map showing the distribution of the Triassic Lancangjiang granite belt alone Lancang River (a) and geological sketch map of the Jitang granitoid intrusion and surrounding areas (b) (modified after Pan *et al.*, 2004)

岗岩为重点(刘昌实等,1989; 彭头平等,2006),对其他岩体的研究相对较少,对整个岩带的属性及成因的认识还不充分,其形成的构造背景存在碰撞晚期-碰撞后构造环境(彭头平等,2006),同碰撞花岗岩(Hennig *et al.*, 2009)、裂谷盆地花岗岩(Heppe *et al.*, 2007)、陆缘弧环境(俞赛赢等,2003)等多种认识。因此对澜沧江结合带性质及演化过程也存在认识上的分歧。本文以澜沧花岗岩带北段的吉塘岩体为研究对象,根据岩石地球化学特征分析,揭示岩体成因,为进一步认识澜沧江结合带的性质及构造演化提供新的事实依据。

2 地质背景

2.1 澜沧花岗岩带

澜沧花岗岩带沿澜沧江结合带两侧分布,主要有吉塘、东达山、白马雪山、鲁甸岩体及三江地区规模最大的临沧花岗岩基(图1a),长达1000余千米(陈福忠等,1994)。该岩带向南进入泰国中部、甚至延伸到马来西亚,总长超过4000余千米(彭头平等,2006; Hennig *et al.*, 2009),同位素年龄显示为印支期(215~240Ma)。岩石类型上主要为二长花岗岩、花岗闪长岩,属过铝质钙碱性花岗岩。澜沧花岗岩带主要岩体的形成年龄在近年的研究中得到了精确界定,临沧花岗岩基锆石SHRIMP U-Pb年龄229.4±3.0Ma和230.4±3.6Ma(Peng *et al.*, 2006)、239±1Ma(Hennig *et al.*, 2009);白马雪山岩体锆石SHRIMP U-Pb年龄为239±6Ma、鲁甸黑云母二长花岗岩为214±6Ma(Jian *et al.*, 2003),东达山岩体Rb-Sr等时线年龄为219.6Ma(陈福忠等,1994),研究表明,它们共同组成了印支期的巨大的相同成因、时代和岩类的花岗岩带(陈福忠等,1994)。

2.2 区域地质概况

岩带西侧有不连续的具有冈瓦纳基底的小陆块(如同卡、腾冲、保山地块)(Chen *et al.*, 2007; 李才等,2008; Liu *et al.*, 2009; 陶琰等,2010),岩带与冈瓦纳基底的小陆块之间,认为存在古特提斯洋盆闭合带,在德钦南发现有蛇绿岩(彭兴阶和罗万林,1982),岩带南部临沧花岗岩西侧的昌宁-孟连混杂带被认为是洋盆闭合带。作为古特提斯分支洋盆,东部有金沙江-哀牢山洋闭合带。一般认为古特提斯洋盆在晚二叠世闭合,局部残余的古特提斯洋盆可一直持续到早中三叠世。

在古特提斯洋和特提斯洋的演化过程中,昌都属于多岛弧系统中的一个陆块(莫宣学等,1993; 莫宣学和潘桂棠,2006)。西侧的特提斯洋(班公-怒江洋),为早二叠世开始形成,从中晚侏罗世(约159Ma)至早白垩世末(约99Ma)逐渐关闭(莫宣学和潘桂棠,2006)。其后,作为陆缘边缘海的昌都地区结束海相沉积,形成有一些陆相湖盆沉积(李金高等,2001)。

昌都陆块基底为吉塘群变质岩(李璞,1955),沿他念他翁-紫曲-吉塘一线分布,由黑云斜长片麻岩、黑云角闪斜长片麻岩、斜长角闪岩、黑云斜长二辉片麻岩、二辉暗色麻粒岩组成。原岩建造形成的时代有争议(雍永源等,1990; 李才等,2009),一般认为是古、中元古代或前寒武纪(雍永源等,1990; 谢尧武等,2008①),也有研究人员将其归为早古生代(陈炳蔚等,1987; 艾长兴和陈炳蔚,1986; 张峰根,1987)。原岩以凝灰质长石石英砂岩为主,夹中酸性-基性火山岩、泥质岩和碳酸盐岩(王建平,2003),有研究人员据其原岩建造和地球化学特征判定为1700~1900Ma的岛弧型火山岩及火山碎屑岩、是扬子大陆西部活动大陆边缘火山活动产物(蒋光武等,2009)。

喜山期随着新特提斯洋的俯冲关闭以及印度板块向欧亚大陆俯冲,昌都地区所在的青藏高原东缘晚碰撞构造转换带承接了来自印度板块巨大的北东向应力,发生强烈构造变形,包括剪切和强烈的逆冲推覆,形成一系列叠瓦岩片(Hou *et al.*, 2007; Hou and Cook, 2009),并伴有新生代岩浆活动(毕献武等,2005; 梁华英等,2009)。

3 岩相学特征及样品分析

3.1 吉塘岩体

吉塘岩体位于吉塘以西约3km。岩体为一轴向NW的岩株,侵位于古元古代吉塘群变质岩系中,长70km,宽2~10km、出露面积340km^2,(图1b)主要由花岗闪长岩和二长花岗岩组成(四川省地质局第三区域地质测量大队,1974②; 陈福忠等,1994)。

据资料介绍(陈福忠等,1994),吉塘花岗闪长岩全岩Rb-Sr等时线年龄值为220Ma,锶同位素初始值($^{87}Sr/^{86}Sr$)=0.725,其生成时代相当于中三叠世末期。

花岗闪长岩:具似花岗结构,主要由斜长石(35%~45%)、条纹长石(10%~20%)、石英(20%)、黑云母(8%~15%)、以及副矿物磷灰石、锆石、钛铁矿、褐帘石等组成。斜长石为更-中长石。条纹长石出溶密集而狭窄的纳长石条带。黑云母含较多副矿物包裹体。

二长花岗岩:具花岗结构,由条纹长石(30%~40%)、斜长石(25%~30%)、石英(25%~30%)以及黑云母、绿泥石、磁铁矿、榍石、磷灰石、锆石、褐帘石组成。斜长石呈半自形板状,粒径0.5~3mm,弱绢云母化。条纹长石呈半自形-他形板状,粒径约0.5mm。石英呈半自形-他形粒状,粒径0.5~1.5mm,也见呈自形-半自形浑园状者嵌于条纹长石中,波状消光。磷灰石、锆石、褐帘石均呈自形柱状。

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① 谢尧武,彭兴阶,陈应明. 2008. 1:250000囊谦县幅、昌都县幅、江达县幅区域地质调查报告

② 四川省地质局第三区域地质测量大队. 1974. 1:100万昌都幅区域地质调查报告(地质部分)

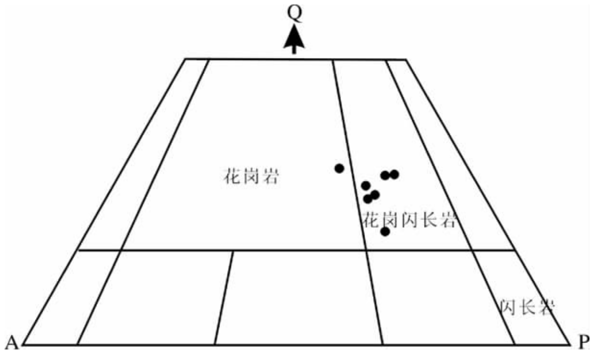

图2 吉塘花岗岩 CIPW 标准矿物组成

Q-石英; A-碱性长石; P-斜长石

Fig. 2 CIPW compositions of the Jitang granitoids

Q-quartz; A-alkali feldspar; P-plagioclase. Nomenclature taken from Streckeisen (1976)

3.2 样品分析

岩石主化学组成、微量元素含量及 Sr、Nd 同位素组成分析在中科院地球化学研究所矿床地球化学国家重点实验室完成，岩石主化学组成采用 Axios PW4400 型 X 荧光仪测定；微量元素采用 ICP-MS 分析，分析方法见 Qi *et al.* (2000)；Rb-Sr、Sm-Nd 同位素组成采用热电离质谱(TIMS) 分析，所用仪器是 Thermo Fisher 公司生产的 Triton 型热电离质谱仪，分析方法参见李晓彪(2009)。

3.3 分析结果

吉塘岩体岩石主化学组成、微量元素含量及 Sr、Nd 同位素组成分析结果如表 1。

吉塘岩体 CIPW 标准矿物组成属于花岗闪长岩(图2)。SiO_2 含量为 63% ~71%，平均 66.5%，碱含量较低(K_2O + Na_2O = 4.3% ~6.2%)，CaO 含量为 0.8% ~2.6%，平均 2.25%，属于钙碱性系列(图3a)。Al_2O_3 含量约为 14.2% ~16.8%，CIPW 刚玉 1.5% ~5.6%，平均 3.2%(>1%)，铝饱和指数 A/CNK = 1.09 ~1.48 (>1.05)、表现为过铝质性质(图3b)。

吉塘花岗岩微量元素组成上强烈富集大离子亲石元素 Rb、Th，高场强元素和 Nb、Ta、Ti 明显的负异常，Eu、Sr、Ba、P 强烈的负异常；稀土总量(∑REE) 为 200×10^{-6} ~ 307×10^{-6}，$(La/Sm)_N$ 为 3.37 ~4.18、略高于片麻岩质的中地壳(3.3)；$(La/Yb)_N$ 为 8.21 ~21.41，高于片麻岩质的中地壳(4.1)，Eu 异常 δEu = 0.27 ~0.56，与一般壳型花岗岩的 δEu 值(0.46) 相当，远低于壳幔型花岗岩的 δEu 值(0.84)。吉塘花岗岩原始地幔标准化的微量元素蛛网图、球粒陨石标准化后的稀土配分型式(图4)，与片麻岩质的中地壳相似，但 Rb、Th 富集更显著，Ba、Sr、Eu、P 的亏损也更强烈。吉塘花岗岩微量元素组成与硅镁质的下地壳差异更显著。

按岩体年龄 220Ma 计算样品初始 Sr、Nd 同位素组成，

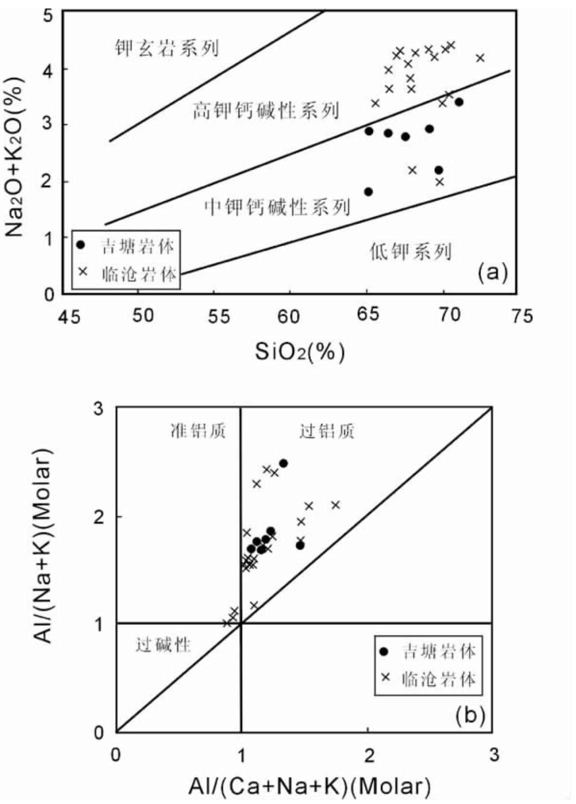

图3 吉塘花岗岩性质判别图解

(a) -SiO_2-K_2O 图解(岩石系列分界线据 Winchester and Floyd, 1977)；(b) -A/NK-A/CNK 图解. 临沧花岗岩数据来源于钟大赉(1998)，俞赛赢等(2003)

Fig. 3 Classification diagram of the Jitang granitoid

(a) -SiO_2-K_2O diagram (after Winchester and Floyd, 1977), All of the major element data have been recalculated to 100% on a LOI-free basis; (b) -molar Al/(K + Na) vs. Al/(Ca + Na + K) diagram. The data for the Lincang granite is from Zhong (1998) and Yu *et al.* (2003)

$^{87}Sr/^{86}Sr(i)$ 值为 0.728049 ~0.739452，$\varepsilon_{Nd}(i)$ 值在 -10 ~ -14.5，其 Sr、Nd 同位素组成与临沧花岗岩基本一致，并与昌都陆块变质基底古中元古代吉塘群黑云母二长石英片麻岩相当(图5a)，高的放射性 Sr 同位素组成反映岩浆源于地壳物质的熔融、基本上没有地幔物质的贡献，并与俯冲作用无关。

样品 $\varepsilon_{Nd}(i)$ 和 Nd 的含量无关(图5b)，反映岩浆来源于统一的源区，没有显著的混染作用影响，样品 Nd 含量的差异与结晶分异作用有关。

根据全岩主微量元素分析结果，采用锆石饱和温度计(Watson and Harrison, 1983) 计算吉塘岩体花岗闪长岩锆石饱和温度为 T(zircon) = 738 ~847℃(表1)，平均 786℃，大致反映岩体结晶温度范围。

4 讨论

4.1 岩体成因类型及岩浆源区

在岩石地球化学特征上，吉塘岩体铝饱和指数 A/CNK

表 1 吉塘岩体岩石主化学组成(wt%)、微量元素含量($\times 10^{-6}$)及 Sr、Nd 同位素组成分析结果

Table 1 Major elements composition (wt%), trace elements abundances ($\times 10^{-6}$) and Sr, Nd isotopic composition of the Jitang granitoids

样品号	JR2	JR3	JR4	JR5	JR6	JR7	JR8
SiO_2	68.73	70.87	66.74	65.66	62.80	67.61	63.45
TiO_2	0.65	0.57	0.75	0.74	0.58	0.62	0.67
Al_2O_3	14.78	14.20	15.09	15.27	14.57	15.87	15.16
Fe_2O_3	4.35	3.95	5.22	6.02	6.25	3.56	7.00
MnO	0.06	0.06	0.07	0.08	0.11	0.03	0.10
MgO	1.97	1.68	2.48	2.83	3.14	1.97	3.83
CaO	2.59	2.17	2.31	2.27	2.65	0.83	2.90
Na_2O	3.19	2.85	3.32	3.16	3.41	4.22	2.56
K_2O	2.88	3.39	2.76	2.82	2.76	2.12	1.75
P_2O_5	0.14	0.13	0.07	0.08	0.13	0.16	0.07
LOI	1.54	0.98	2.00	1.53	1.09	2.20	2.16
Total	100.89	100.84	100.81	100.47	97.49	99.19	99.64
CIPW 刚玉(%)	2.0	2.2	2.6	3.1	1.5	5.7	4.1
Li	15.4	19.4	24.2	31.5	21.8	9.88	22.1
Be	3.02	2.47	1.86	1.49	1.36	4.87	4.73
Sc	11.7	11.6	13.2	19.1	17.1	13.7	18
V	71	64.5	82	93.7	79.5	70	113
Cr	42	38.6	74.3	78.8	86	41.7	122
Co	136	135	109	123	105	86.1	103
Ni	19	19.6	35.8	34.9	34.2	19.1	52.9
Cu	13.85	14.82	7.60	14.03	13.05	14.74	14.91
Zn	93.1	105	121	162	122	55.9	141
Ga	18.4	18.4	21.6	22.3	20.5	18.9	23.3
Ge	1.30	1.31	1.52	1.60	1.70	1.41	1.48
As	10.96	11.94	12.04	12.30	11.52	11.52	11.42
Rb	147	162	166	180	143	116	96.3
Sr	134	97.3	90	112	131	152	136
Y	27.1	30	66.1	48.9	35.4	30.3	16.1
Zr	139	105	171	153	99	229	153
Nb	16.5	11.8	15.6	16.1	9.85	12.4	8.66
Mo	0.48	1.30	0.35	0.42	0.37	0.25	0.49
Ag	0.496	0.425	0.479	0.59	0.342	0.389	0.309
Cd	0.309	0.257	0.351	0.327	0.264	0.172	0.22
In	0.076	0.075	0.096	0.101	0.154	0.060	0.090
Sn	5.38	4.91	5.05	3.73	5.35	3.83	3.31
Sb	1.70	1.19	1.22	1.38	0.96	1.03	13.06
Cs	4.46	4.64	4.25	5.3	3.69	1.36	2.72
Ba	458	469	249	333	538	697	540
La	45.1	47.5	62.9	54.5	68.3	54.1	43.2
Ce	86.5	94.1	124	110	145	105	86.2
Pr	9.84	11	14.6	13	16.9	12.1	10.1
Nd	35.1	40.5	52.9	47.3	62.5	43.7	36.9
Sm	7.15	8.29	11.6	9.8	12.7	8.12	7.22
Eu	1.00	0.85	1.05	1.08	1.24	1.11	1.27
Gd	6.18	7.95	11.64	10.29	12.09	7.12	6.64
Tb	1.07	1.16	1.88	1.57	1.73	1.13	0.868
Dy	5.51	5.93	10.9	8.52	7.9	5.6	3.49
Ho	1.07	1.16	2.36	1.78	1.42	1.12	0.614
Er	2.85	2.92	6.56	4.47	3.35	3.12	1.57
Tm	0.368	0.365	0.869	0.566	0.382	0.408	0.197
Yb	2.42	2.39	5.39	3.09	2.37	2.61	1.42

续表 1

Continued Table 1

样品号	JR2	JR3	JR4	JR5	JR6	JR7	JR8
Lu	0.35	0.347	0.751	0.383	0.321	0.353	0.205
Hf	4.10	3.04	4.91	4.36	2.82	6.30	4.24
Ta	1.5	1.18	1.47	1.46	0.773	1.2	0.562
W	871	819	634	671	549	428	503
Tl	0.786	0.771	0.775	0.855	0.686	0.416	0.434
Pb	27.54	33.56	22.10	57.63	24.42	4.76	18.86
Bi	0.46	0.39	0.416	0.233	0.189	0.166	0.152
Th	25.5	28.3	43	35.3	47.4	28.4	23.8
U	2.3	2.73	2.99	2.38	1.8	2.3	1.8
$(La/Sm)_N$	3.95	3.59	3.40	3.49	3.37	4.18	3.75
$(La/Yb)_N$	13.12	13.99	8.21	12.41	20.28	14.59	21.41
δEu	0.46	0.32	0.27	0.33	0.31	0.44	0.56
T_{Zr}(℃)	777	758	797	789	738	847	795
$^{87}Sr/^{86}Sr$	0.738668	0.748054	0.743193	0.741306	0.741628		0.745266
σ(Sr)	5	5	7	7	7		8
$^{87}Sr/^{86}Sr(i)$	0.729661	0.734383	0.728049	0.728110	0.732665		0.739452
$^{143}Nd/^{144}Nd$	0.511949	0.511965	0.511917	0.511917	0.511954		0.511849
σ(Nd)	2	2	3	2	2		2
$^{143}Nd/^{144}Nd(i)$	0.511788	0.511803	0.511743	0.511753	0.511793		0.511694
$\varepsilon_{Nd}(i)$	−14.08	−13.79	−14.95	−14.76	−13.98		−15.91
t_{DM}(Ma)	2066	2055	2360	2166	2052		2105

注: T_{Zr}为锆石饱和温度(据 Watson and Harrison, 1983); Sr 同位素初始值及 $\varepsilon_{Nd}(i)$ 按 220Ma 计算,采用衰变常数 $\lambda(^{87}Rb) = 1.42\times10^{-11}$ year^{-1}, $\lambda_{Sm}^{147} = 6.54\times10^{-12}$ year^{-1},现代球粒陨石储集库采用: $(^{147}Sm/^{144}Nd)^{CHUR}$ now = 0.1967, $(^{143}Nd/^{144}Nd)^{CHUR}$ now = 0.512638(据 Jacobsen and Wasserburg, 1980);亏损地幔 Nd 同位素模式年龄 t_{DM} 据李献华等(1991)推荐公式计算

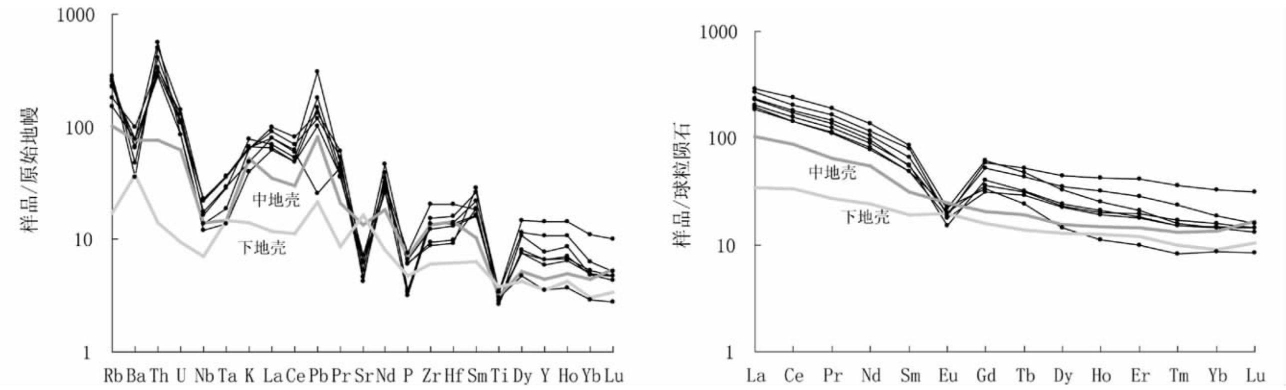

图 4 吉塘花岗岩微量元素原始地幔标准化蛛网图及球粒陨石标准化稀土配分曲线

原始地幔值据 Sun and McDonough (1989); **球粒陨石值据** Anders and Grevesse (1989); **中地壳及下地壳数据据** Rudnick and Gao (2003)

Fig. 4 Primitive mantle-normalized trace element patterns and chondrite-normalized rare-earth element patterns for the Jitang granitoids

The primitive mantle value is after Sun and McDonough (1989), chondrite is after Anders and Grevesse (1989), and the middle crust and lower crust (after Rudnick and Gao, 2003) are show for comparison

= 1.09 ~ 1.48($>$1.05), Na_2O 含量 2.8% ~ 4.2%,平均 3.25%, SiO_2 含量较低(63% ~ 71%,平均 66.5%),CIPW 标准矿物含刚玉 1.5% ~ 5.6%、平均 3.2%($>$1%),CaO 含量较低为 0.8% ~ 2.6%,平均 2.25%($<$3.7%),岩体高初始 $^{87}Sr/^{86}Sr$ 在 0.728049 ~ 0.739452,具有较低的 $\varepsilon_{Nd}(i)$ 值在 −10 ~ −14.5。这些特征均表明为吉塘岩体为过铝质 S 型花岗岩的特点。在 A-C-F 判别图解中也落入 S 型花岗岩区(图 6),因此判定吉塘岩体为过铝质钙碱性 S 型花岗岩。吉

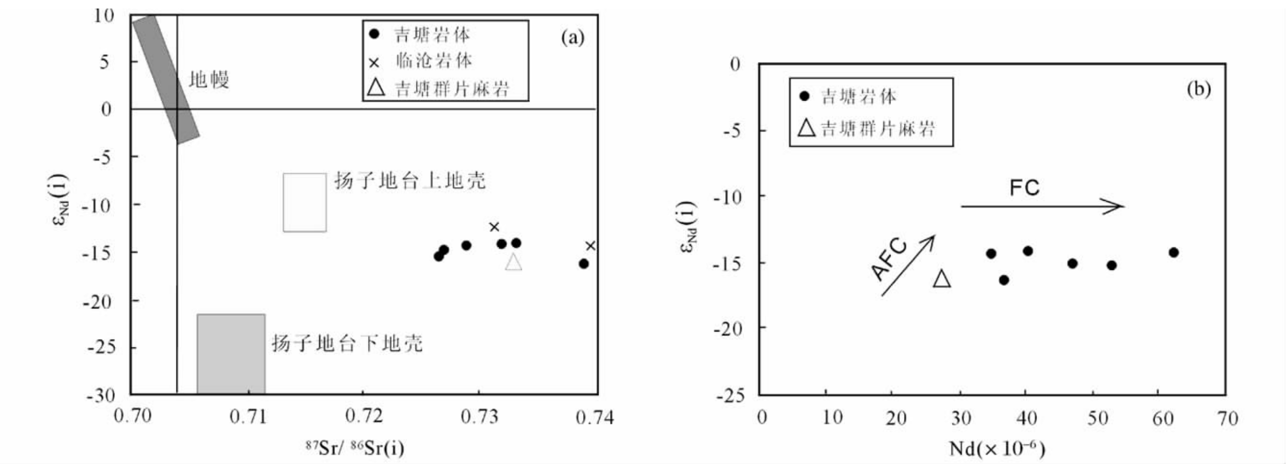

图5 吉塘花岗岩 ε_{Nd}(i)-($^{87}Sr/^{86}Sr$)$_i$ 图(a)和 ε_{Nd}(i)-Nd 图(b)

扬子地台上、下地壳据 Chen and Jahn (1998); **吉塘片麻岩据陶琰待刊资料; 临沧花岗岩据** Hennig *et al*. (2009)

Fig. 5 ε_{Nd}(i) vs. ($^{87}Sr/^{86}Sr$)$_i$ diagram (a) and ε_{Nd}(i) vs. Nd diagram (b) for the the Jitang granitoids

The data for the middle crust and the lower crust are from Chen and Jahn (1998); The data for the Jitang gnessis are from Tao unpublished data; The data for the Lincang granite is from Hennig *et al*. (2009)

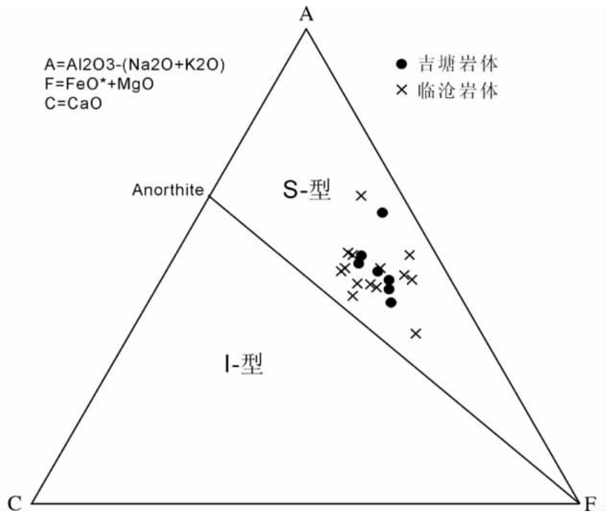

图6 吉塘花岗闪长岩 ACF 成因类型判别图(据 Chappell and White, 1992)

临沧花岗岩数据来源于钟大赉(1998),俞赛赢等(2003)

Fig. 6 Plots of the Jitang granitoids in ACF diagram for division of I-and S-type granites (after Chappell and White, 1992)

The data for the Lincang granite is from Zhong (1998) and Yu *et al*. (2003)

塘花岗岩以很高的放射性 Sr 同位素组成，与 A 型和 I 型花岗岩有明显差异(Zhang *et al*., 2007; Xiao *et al*., 2007; Zhong *et al*., 2007, 2009)。

一般认为，以泥质岩和杂砂岩为源岩的副片麻岩是 S 型花岗岩的源岩，花岗闪长岩熔体来源于变质杂砂岩成分的黑云母脱水熔融(Brown and Pressley, 1999)。实验结果表明，在脱水熔融实验中，花岗岩熔体中的 CaO/Na_2O 比值与温度压力无关，主要受源岩成分的控制(Jung and Pfander, 2007)。由于泥质岩贫斜长石，如果斜长石完全消失，Na_2O 会逐渐富集到熔体中，而 CaO 则会较多的集中在残余相如角闪石、单斜辉石中，因此，以泥质岩为源岩的熔体 CaO/Na_2O 比值会很低(<0.5)。相反，富含斜长石的变质杂砂岩的熔融将导致熔体 CaO/Na_2O 比值与残余相相当或仅仅略低一点，斜长石在残余相中保持稳定(Skjerlie and Johnston, 1996)，因此，变质杂砂岩熔融形成的熔体有较高的 CaO/Na_2O 比值 >0.3。吉塘岩体 CaO/Na_2O 比值在 0.8 左右，远高于实验泥质岩熔融、而在变质杂砂岩熔融的范畴内(图7a)。

吉塘岩体 Rb/Sr 和 Rb/Ba 比值也指示源岩为变质杂砂岩成分，Sr、Ba、Eu 主要富集在长石中，D_{Sr}(pl/melt) = 13; D_{Sr}(kf/melt) = 13, D_{Ba}(pl/melt) = 1.5; D_{Ba}(kf/melt) = 18,(据 Icenhower and London, 1995, 1996; Nash and Crecraft, 1985; Nabelek and Bartlett, 1998)，吉塘岩体 Eu、Sr 的强烈亏损反映源区斜长石为熔融残留相矿物，而 Ba 的亏损则指示钾长石也存在于残留相矿物中，显示熔融源区为杂砂岩成分。一般，泥质岩为源岩的熔体 Rb/Ba >> 0.25, Rb/Sr > 2.6 (Miller, 1985; Harris and Inger, 1992)，吉塘岩体 Rb/Sr、Rb/Ba 比值分布在 1 左右和 0.3~0.6 之间，指示源区为富斜长石的变质杂砂岩成分(图7b)。

吉塘岩体花岗岩($^{87}Sr/^{86}Sr$)i 值为 0.7265~0.7388, ε_{Nd}(i) -14.1~-16.2，反映岩浆来源于地壳物质的熔融(图5a)。亏损地幔 Nd 同位素模式年龄(t_{DM})分布在 2.0Ga 左右(图8)，指示岩浆源区为古元古代地壳物质。这一年龄与昌都陆块变质基底古元古代吉塘群的原始形成年代相当，岩体 Sr、Nd 同位素组成也与变质基底吉塘群片麻岩相当(图5a)，吉塘群片麻岩化学成分上相当于英安岩，有研究人员据

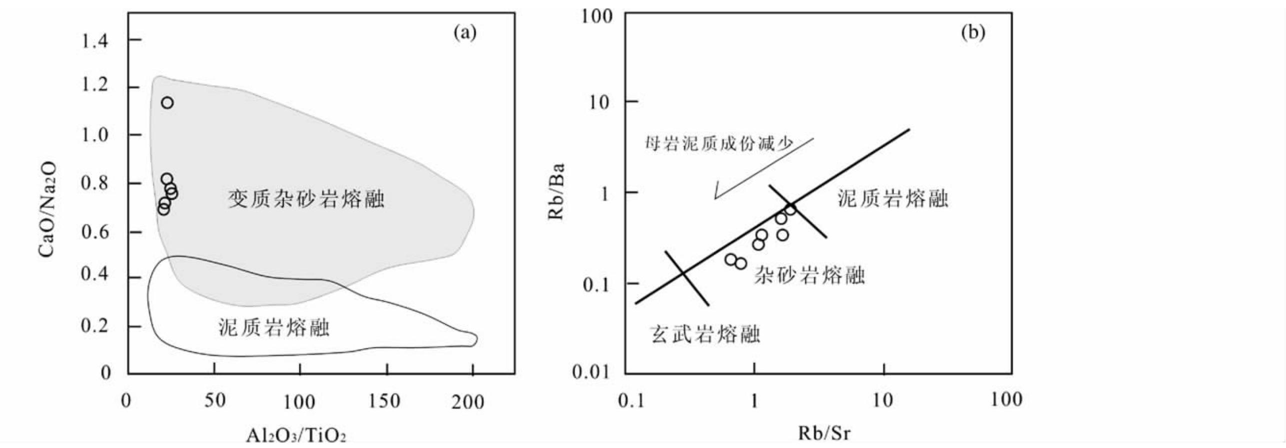

图7 吉塘岩体化学组成(%)与变质泥岩、变质杂砂岩实验熔体成份对比(a,据 Jung and Pfander, 2007; 泥岩实验熔体成份据 Patiño Douce and Johnston, 1991)和吉塘花岗岩 Rb/Sr-Rb/Ba 图解(b,据 Sylvester, 1998)

Fig. 7 Composition of the Jitang granitoids in comparison to compositional fields of experimentally derived partial melts of metapelites and metagreywackes (a, after Jung and Pfander, 2007; Data for experimentally pelite derived liquids from Patiño Douce and Johnston, 1991) and Rb/Sr-Rb/Ba diagram for the Jitang granitoids (b, after Sylvester, 1998)

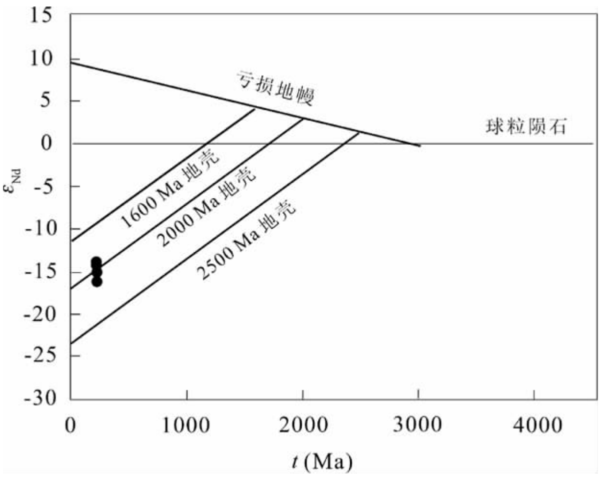

图8 吉塘花岗岩 Nd 同位素组成的两阶段演化模式

地壳源区 $^{147}Sm/^{144}Nd = 0.12$,亏损地幔演化线据 Faure(1986)

Fig. 8 Nd isotopic evolution diagram of the Jitang granitoids

Chondritic uniformreservoir: $(^{147}Sm/^{144}Nd)^{CHUR}$ now = 0.1967, $(^{143}Nd/^{144}Nd)^{CHUR}$ now = 0.512638 (Jacobsen and Wasserburg, 1980). Depleted mantle evolution is calculated by using $^{143}Nd/^{144}Nd = 0.513114$ and $^{147}Sm/^{144}Nd = 0.222$ for MORB at present (Faure, 1986). The corresponding lines of crustal extraction are calculated by using the $^{147}Sm/^{144}Nd$ ratio of 0.12 for the average continental crust

其原岩建造和地球化学特征判定为古元古代的岛弧型火山岩及火山碎屑岩(蒋光武等,2009)。因此,综合分析认为,吉塘岩体岩浆源岩为变质杂砂岩成分的吉塘群片麻岩,推测其原岩建造主要是火山弧成因的英安岩或英安质火山碎屑岩,大致与澜沧江南段澜沧群相类似(翟明国等,1990)。

吉塘岩体 Nd 同位素亏损地幔模式年龄与扬子地块的基底模式年龄(1.8~2.1Ga)相一致(Li *et al.*, 1992; Chen and Jahn, 1998; Zhang *et al.*, 2006),支持岩浆源区为古元古代地壳,并暗示昌都地块与扬子板块的亲缘关系,昌都地块可能是扬子板块大陆边缘一个支离的板片。

4.2 岩石成因

对花岗质岩浆主要矿物相微量元素分配系数的研究已积累了大量资料,以 Rb、Sr、Ba 在斜长石、钾长石、黑云母中的分配系数,可以估算熔融固相矿物(残留相)对熔体成分的影响,或岩浆结晶分异过程。如以片麻岩质的中地壳组成(Rudnick and Gao, 2003)为吉塘岩体岩浆源岩成分,作为残留相残余单矿物斜长石、钾长石、黑云母对熔体成分的影响如图所示(图9),岩石的总体成分显示出斜长石为残留相,估计有20%~30%残留斜长石固相,在残留固相中可能有少量钾长石,黑云母必定完全熔出。

吉塘花岗闪长岩岩浆为杂砂岩成分的黑云母脱水熔融,Rb、Sr、Ba 含量特征表现为黑云母的耗尽,则熔融温度压力超过黑云母的稳定范围(Thompson, 1996),研究表明杂砂岩成分的黑云母脱水熔融温度需要超过830℃(Johannes and Holtz, 1996; Thompson, 1996; Vielzeuf and Montel, 1994),由杂砂岩成分的黑云母脱水熔融产生的花岗闪长岩岩浆一般形成于地壳25~30km深度,熔融作用是地壳加厚增温造成的(Brown and Pressley, 1999)。上述有关杂砂岩成分的黑云母脱水熔融温度与吉塘岩体花岗闪长岩锆石饱和温度738~847℃(表1)的上限基本一致,分析认为吉塘岩体花岗闪长岩岩浆熔融温度大致在850℃作用。

一般情况下(静态地温曲线),25km 左右深度的地壳温度只有400℃左右,而且在推覆作用下地壳加厚均衡后的极限温度也只能达到750℃左右(England and Thompson, 1984),因此,熔融所需的温度还需要来自深部异常热流的部

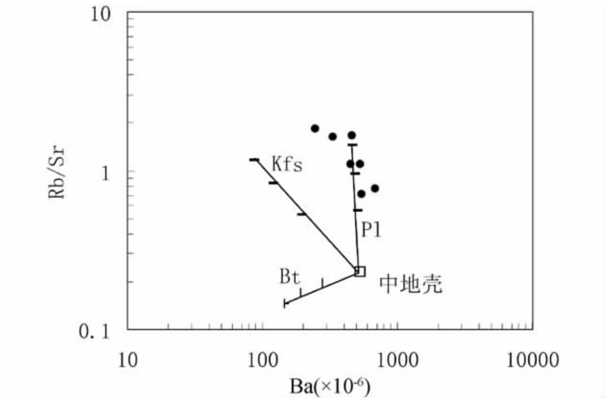

图 9 吉塘花岗岩 Rb/Sr-Ba 图解

以片麻岩质的中地壳组成(据 Rudnick and Gao, 2003)为熔融源岩成分，作为残留相的单矿物斜长石(Pl)、钾长石(Kfs)、黑云母(Bt)对熔体成分的影响，矢量线及标记指示熔体成分随残余矿物相百分数的变化，间隔为 10%. 计算采用的元素分配系数据 Icenhower and London (1995, 1996) 及 Nash and Crecraft (1985)

Fig. 9 Plot of Rb/Sr vs. Ba for the Jitang granitoids

Vectors for plagioclase (Pl), K-feldspar (Kf) and biotite (Bt) as residual in restite of melting are calculated using partition coefficients of Icenhower and London (1995, 1996) and Nash and Crecraft (1985), Nabelek and Bartlett (1998). The composition of the middle crust after Rudnick and Gao (2003) is assumed to represent the source of melting. Tick marks indicate percentage of mineral phase exist in restite, in 10% intervals

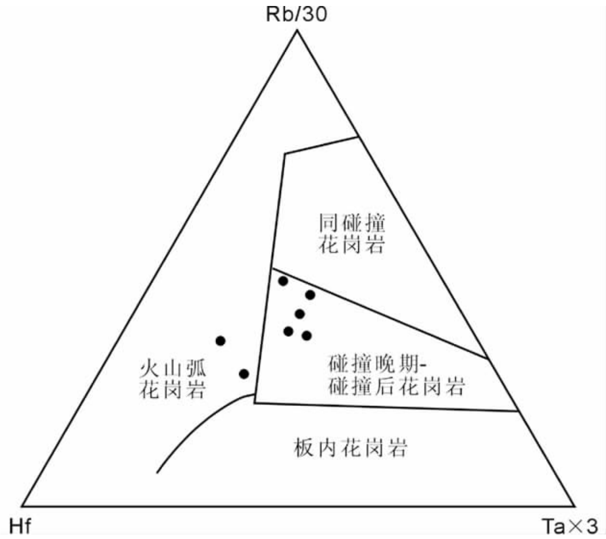

图 10 吉塘花岗岩 Rb/30-Hf-Ta×3 判别图解(据 Pearce *et al.*, 1984)

Fig. 10 Plot of Rb/30-Hf-Ta×3 for the Jitang granitoids (after Pearce *et al.*, 1984)

分贡献，可能与岩石圈的剪切、伸展有关，即岩浆形成于碰撞造山作用导致地壳加厚之后的伸展期，可以认为吉塘花岗岩是地壳加厚增温后及与岩石圈剪切、伸展期有关的深熔作用形成的。

4.3 构造环境

岩石地球化学特征表明吉塘岩体在成因上与俯冲作用无关，岩浆成因与地壳加厚增温环境下伸展期的地壳深熔作用有关，应属于板块碰撞后的构造环境。

在花岗岩形成的构造环境判别图解(Rb/30-Hf-Ta×3)中，吉塘岩体投影到后碰撞或板内环境，部分投影点落入火山弧环境(图 10)可能与源岩为变质基底古元古代片麻岩有关，这些片麻岩的原岩建造主要为古元古代的岛弧型火山岩及火山碎屑岩(蒋光武等，2009)。

吉塘花岗岩的地球化学特征表明岩浆成因与俯冲作用无关，形成板块碰撞加厚地壳的深熔。已有研究表明从地壳碰撞加厚到岩浆形成需要有一个较长的时长，可以从几十到上百个百万年(England and Thompson, 1984)，因此，澜沧江洋的闭合时间远早于花岗岩带的形成年龄 215 ~ 240Ma，结合澜沧江构造带上局部出露的镁铁超镁铁岩的年代学等成果(彭兴阶和罗万林，1982; 莫宣学等，1998; 钟大赉，1998; 王立全等，2000; 简平等，2003, 2004; 吴根耀，2006; Jian *et al.*, 2009; 曾庆高等，2010)，我们认为大洋闭合时间在 280Ma 左右，在澜沧江南段可能更早一些。

本次工作表明吉塘花岗岩与临沧花岗岩及白马雪山花岗岩的形成时代基本相同，岩石地球化学性质及成因基本一致，这就进一步证明吉塘岩体为澜沧花岗岩带的组成部分(陈福忠等，1994)，且澜沧花岗岩带具有统一的构造岩浆活动模式。

长期以来对是否存在大洋性质的古澜沧江洋一直存在争议(钟大赉，1998; 张旗等，1985; Heppe *et al.*, 2007; 范蔚茗等，2009; Hennig *et al.*, 2009)。一般认为，沿澜沧江一带被认为是介于冈瓦纳的一个微板块与扬子大陆板块之间的古特提斯缝合带(范蔚茗等，2009)，吉塘花岗岩 Nd 同位素亏损地幔模式年龄与临沧花岗岩继承锆石年龄反映出澜沧江构造带变质基底具有与扬子地台的亲合性，根据岩带西侧有不连续的具有冈瓦纳基底的小陆块(如同卡、腾冲、保山地块)(Chen *et al.*, 2007; 李才等，2008; Liu *et al.*, 2009; 陶琰等，2010)，支持澜沧江构造带为冈瓦纳与扬子大陆边缘多岛弧系统的边界即古特提斯主洋盆的观点。

吉塘岩体侵入在相当于岩浆源岩的吉塘群片麻岩中，分析认为岩浆侵位于较大深度，岩体目前出露地表可能主要是由于新生代喜马拉雅碰撞造山期强烈的剪切逆冲推覆造成的。昌都地块西缘所在的澜沧江构造带位于板块构造边界，并经历了中生代特提斯和新生代喜马拉雅碰撞造山期强烈的剪切和逆冲推覆，结合岩浆形成深度及临沧花岗岩侵位深度的有关研究(李兴林，1996; 刘海龄等，2004)，认为吉塘岩体是从深部地壳抬升至浅表的，并认为强烈的剪切和逆冲推覆作用造成了原地系统的巨大破坏，古特提斯澜沧江洋演化期的构造岩浆系统已大部分被支离和剥蚀。

5 结论

吉塘花岗岩与临沧花岗岩及白马雪山花岗岩岩石地球化学性质及成因一致、形成时代基本相同,为澜沧花岗岩带的组成部分,支持澜沧花岗岩带具有统一的构造岩浆活动成因模式。

吉塘岩体为过铝质钙碱性 S 型花岗岩,岩浆源岩为由杂砂岩成分的古元古代吉塘群副片麻岩,其原岩建造中包含火山弧成因的英安岩或英安质火山碎屑岩。

吉塘岩体在成因上与俯冲作用无关,岩浆形成于地壳加厚增温环境下伸展期的地壳深熔作用,构造上属板块碰撞后的环境。澜沧江洋的闭合时间要早于岩体形成年龄 220Ma,可能在 280Ma 左右。昌都地块变质基底具有与扬子地台的亲合性,从而支持了澜沧江构造带为冈瓦纳与扬子大陆边缘多岛弧系统的边界即古特提斯主洋盆的观点。

致谢 野外地质调查得到昌都地区国土局及西藏地矿局地热地质大队的大力支持,中国科学院地球化学研究所彭建堂研究员对本文研究工作提出了宝贵建议;薛伟、阳杰华、杨晨同志一同参加了野外地质调查;匿名审稿人对文稿进行了细致的审阅并提出大量建设性修改意见,使本文得以改进;在此谨致谢忱!

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