第42卷第5期　　中　国　地　质　　Vol.42, No.5
2015年10月　　GEOLOGY IN CHINA　　Oct. , 2015

解龙, 顿都, 朱利东, 等. 西藏北冈底斯扎独顶A型花岗岩锆石U-Pb年代学、地球化学及其地质意义[J]. 中国地质, 2015, 42(5): 1214-1227.
Xie Long, Dun Du, Zhu Lidong, et al. Zircon U-Pb geochronology, geochemistry and geological significance of the Zhaduding A - type granites in northern Gangdise, Tibet[J]. Geology in China, 2015, 42(5): 1214-1227(in Chinese with English abstract).

西藏北冈底斯扎独顶A型花岗岩锆石U-Pb年代学、地球化学及其地质意义

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提要：西藏北冈底斯早白垩世花岗岩分布广泛；扎独顶岩体作为其中的一个典型代表，其分布广泛，呈岩基型式产出，在岩性上属二长花岗岩。在岩石化学上扎独顶岩体具有富SiO_2(70.05%~74.97%)和K_2O(4.09%~5.35%)，贫CaO(0.93%~2.19%)、TiO_2(0.22%~0.52%)和Al_2O_3 (12.81%~14.24%)的特征；属于准铝质-弱过铝质(A/CNK=0.99~1.0)高钾钙碱性系列。岩体稀土元素总量偏高($\sum$REE=199.36×10^{-6}~247.91×10^{-6})，相对富集轻稀土元素(LREE/HREE=5.82~6.88)，Eu负异常明显(δEu=0.30~0.45)，球粒陨石标准化分布模式呈向右缓倾的V型。微量元素显示其富集Rb、Th、K、Zr和Hf，亏损Nb、Ta、Sr、Ba、P和Ti，(Zr+Nb+Ce+Y)平均值为427.63。全岩锆石饱和温度(828~838°C)表明岩浆形成温度高。上述岩石地球化学特征表明扎独顶岩体为A型花岗岩。扎独顶岩体LA-ICP-MS锆石U-Pb年龄为（103.8±1.0）Ma，表明其形成于早白垩世晚期；在构造判别图解上位于碰撞后的A_2型花岗岩区，是在碰撞后岩石圈伸展背景下，由于软流圈物质上涌导致岩石圈地幔与壳源熔体部分熔融并经历过一定程度的混合作用而形成的。

关　键　词：西藏；北冈底斯；A型花岗岩；锆石U-Pb年龄；地球化学

中图分类号：P588.12^{+}1；P597^{+}.3；P595　**文献标志码：**A　**文章编号：**1000-3657（2015）05-1214-15

Zircon U-Pb geochronology, geochemistry and geological significance of the Zhaduding A-type granites in northern Gangdise, Tibet

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收稿日期：2015-3-27；**改回日期：**2015-05-05

基金项目：国家自然科学基金(41002055)、高等学校博士学科点专项科研基金(20125122110010)和中国地质调查局项目(1212011121232)联合资助。

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Abstract: Early Cretaceous granites are widely distributed in northern Gangdise, Tibet. The Zhaduding intrusive body, which belongs to monzogranite in lithology, is widely distributed and occurs in the form of batholith, being a typical case of the granites. Petrogeochemically it is characterized by high SiO_2 (70.05%−74.97%) and K_2O (4.09%−5.35%), low CaO (0.93%−2.19%), TiO_2 (0.22%−0.52%) and Al_2O_3 (12.81%−14.24%). Moreover, it belongs to metaluminous or weak peraluminous (A/CNK=0.99−1.06) high−K calc−alkaline series. The rocks are characterized by high REE content ($\sum$REE=$199.36\times10^{-6}-247.91\times10^{-6}$), rich LREE relative to HREE (LREE/HREE=5.82−6.88), and significant negative Eu anomalies (δEu=0.30−0.45). Chondrite−normalized REE patterns exhibit V−type with slight right−oblique feature. Trace elements show that the rocks are enriched in Rb, Th, K, Zr and Hf and depleted in Nb, Ta, Sr, Ba, P and Ti, with average (Zr+Nb+Ce+Y) 427.63. Bulk−rock zircon saturation temperature (828−838°C) shows that the temperature of magma formation was pretty high. The petrogeochemical characteristics show that the Zhaduding rock body is A−type granite. The LA−ICP−MS zircon U−Pb age of 103.8±1.0Ma indicates that Zhaduding rock body was formed in late Early Cretaceous, and is located in the post−collisional A_2−type granite area in discrimination diagrams. It was formed by a certain degree of mixing of the lithosphere mantle and the crustal partial melts, resulting from asthenosphere material upwelling in the post−collision extensional setting.

Key words: Tibet; northern Gangdise; A−type granites; zircon U−Pb dating; geochemistry

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A型花岗岩的概念由Loiselle et al.[1]提出，最初被定义为贫水(anhydrous)、碱性 (alkaline)以及非造山(anorogenic)的花岗岩，由此决定了它与I型和S型花岗岩[2]的区别。在岩石类型上，A型花岗岩几乎囊括了除典型I、S型花岗岩以外的其他花岗岩类[3-4]。在矿物组成上，A型花岗岩主要以石英、长石(碱性长石、斜长石)和镁铁质暗色矿物(角闪石等)等为特征。在化学组成上，A型花岗岩富Si、Na、K、Rb、Th、Zr、Hf、Y等元素，贫Ca、Al、Mg、Sr、Ba、Ti和P等元素，$(Na_2O+K_2O)/Al_2O_3$、FeO^T/MgO和Ga/Al比值高，稀土元素配分曲线大多呈右倾的燕式分布，以明显的负Eu异常为特征[5]。A型花岗岩能反映特定的构造环境，即多数形成于板内伸展阶段(A_1型，大陆裂谷或洋岛)，部分形成于大陆碰撞之后的造山带中(A_2型)[6-7]，因此，在地球动力学背景上其具有某种标型意义。

冈底斯带白垩纪岩浆岩分布广泛。前人对该区的研究也较为深入，但主要集中在冈底斯带中东部地区。如波密岩体(113 Ma)[8]、巴木错岩体(122 Ma)[9]、察隅岩体(130 Ma)[10]、巴尔达岩体(114 Ma)[11]、申扎岩体(113 Ma)[12]、然乌岩体(114 Ma)[13]以及八宿岩体(120 Ma)[14]等，这些岩体均形成于班公湖—怒江洋向南俯冲削减的挤压构造背景，由岩石圈地幔和壳源熔体混合而形成。仅在冈底斯带中部地区有报道形成于碰撞后岩石圈伸展背景下的A型花岗岩(110 Ma)[7]，对于冈底斯西部地区来说，由于研究程度较低，目前尚无有关A型花岗岩的报道。本文以出露于北冈底斯西段扎独顶的A型花岗岩为研究对象，在详细的野外地质调查基础之上，结合岩相学、地球化学、锆石U-Pb年代学数据，探讨扎独顶花岗岩的构造背景和岩石成因。

1　地质背景及岩石学特征

冈底斯带是指近东西向展布于青藏高原南部的[15]、南北界分别为雅鲁藏布缝合带和班公湖—怒江缝合带的狭长区域，长约2500 km，南北宽150~300 km，面积达450000 km^{2}的巨型构造-岩浆带[16-18]；以沙莫勒—麦拉—洛巴堆—米拉山断裂(SMLMF)、噶尔—隆格尔—扎日南木错—措麦断裂带(GLZCF)和狮泉河—拉果错—永珠—纳木错—嘉黎蛇绿混杂岩带(SNMZ)为界，由南向北将冈底斯带划分为南冈底斯(即传统的冈底斯)、冈底斯弧背断隆带、中冈底斯和北冈底斯[10, 19](图1-a)。

本文涉及的扎独顶地区位于北冈底斯西段狮泉河以北(图1-b)，区内主要由侏罗系—白垩系火山沉积地层和相关侵入岩组成。区内出露有大面积花岗岩类，包括斜长花岗岩、钾长花岗岩、花岗闪长岩、二长花岗岩等。扎独顶岩体属于该花岗岩类中

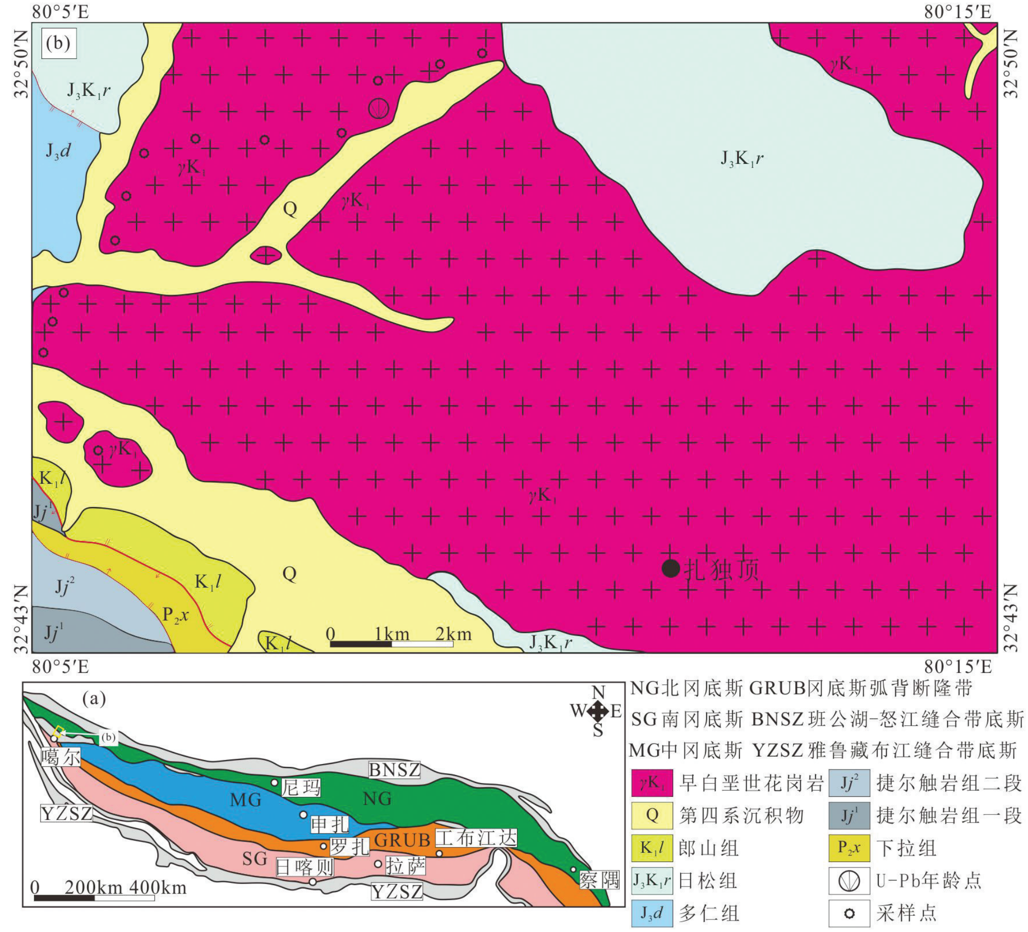

图1 研究区地质简图 (a)—冈底斯构造单元划分地质简图(据文献[10]);(b)—扎独顶地区地质简图
Fig.1 Geological sketch map of the study area (a)−Geological sketch map of tectonic units of Gangdise (after reference [10]); (b)−Geological sketch map of the Zhaduding area

的一个侵入体,岩体规模较大,呈岩基形式产出,侵入于日松组、多仁组和去申拉组等地层中,外接触带热接触变质蚀变较发育,与围岩接触界线清楚,局部见有地层捕虏体,形态不规则大小一般为10~20 m,常具角岩化、硅化等接触变质现象。岩体中可见到数量不少的暗色闪长质包体,其与寄主岩之间接触较清楚,呈不规则圆状、椭圆状分布,大小一般为7~15 cm不等,含有钾长石和石英斑晶,表明为岩浆混合成因。扎独顶岩体的岩性主要为二长花岗岩,二长花岗岩岩石呈浅灰—灰白色,全晶质半自形粒状结构,块状构造,主要矿物为斜长石(25%~30%)、钾长石(30%~38%)、石英(28%~30%),暗色矿物主要为黑云母(5%~10%),角闪石(2%~5%),副矿物有锆石、磷灰石,磁铁矿等。长石为自形板状,解理发育,且有蚀变(绢云母化),石英呈他形粒状,黑云母多色性强,发育极完全解理,局部可见包晶结构或文象结构。

2 岩石地球化学

2.1 主量元素

岩石化学成分结果表明(表1),扎独顶A型花岗岩富 SiO_2(70.05%~74.97%,平均72.29%)、K_2O(4.09%~5.35%)和Na_2O(3.07%~3.60%),K_2O/Na_2O比值为1.17~1.74,全碱(Na_2O+K_2O)含量偏高(7.44%~8.48%)。在TAS图解(图2)中,7件样品全部落入花岗岩区域,且均为位于Irvine分界线下的亚碱性系列区域;钙和钛含量较低,分别为0.93%~2.19%、0.22%~0.52%,全铁(FeO^T)含量(1.35%~3.31%)比镁含量(0.26%~1.11%)高;在SiO_2-K_2O图解(图3-a)中,所有样品均投在高钾钙碱性系列区域;Al_2O_3含

表1 扎独顶A型花岗岩主量元素(%)、微量元素(10^{-6})及稀土元素(10^{-6})分析结果

Table 1 Major elements (%), trace elements (10^{-6}) and REE (10^{-6}) analyses of the Zhaduding A-type granites

样品编号	D2770-YQ1	D4332-YQ1	D4333-YQ1	D1514-YQ1	D4318-YQ1	D4330-YQ1	D4331-YQ1
岩性	二长花岗岩	二长花岗岩	二长花岗岩	二长花岗岩	二长花岗岩	二长花岗岩	二长花岗岩
SiO_2	71.68	73.41	72.85	70.37	74.97	70.05	72.7
TiO_2	0.32	0.28	0.3	0.47	0.22	0.52	0.31
Al_2O_3	13.31	13.35	13.49	14.12	12.81	14.24	13.42
Fe_2O_3	0.66	0.48	0.41	0.58	0.18	0.49	0.43
FeO	2.19	1.64	1.93	2.68	1.19	2.87	1.95
MnO	0.05	0.03	0.04	0.06	0.03	0.06	0.03
MgO	1.11	0.39	0.44	0.82	0.26	0.88	0.47
CaO	1.13	0.93	1.3	1.93	1.13	2.19	1.32
Na_2O	3.6	3.55	3.36	3.38	3.07	3.35	3.49
K_2O	4.22	4.93	4.87	4.42	5.35	4.09	4.8
P_2O_5	0.05	0.04	0.04	0.09	0.02	0.09	0.04
烧失量	1.44	0.79	0.77	0.88	0.58	0.98	0.85
总量	99.76	99.82	99.80	99.80	99.81	99.81	99.80
FeO^T	2.78	3.11	2.07	3.2	0.85	1.42	3.46
Rb	198	228	218	227	156	193	248
Ba	452	388	434	404	428	307	374
Th	19.5	17.2	18.2	17.4	21.2	17.8	19.6
U	1.44	1.76	1.82	1.8	1.88	1.85	3.01
K	35031.5	40925.4	40427.3	36691.7	44412	33952.3	39846.2
Ta	1.24	1.24	1.21	1.3	1.37	1.39	1.44
Nb	14.3	13.7	13.4	14.5	14.4	14.8	15.2
Sr	102	66.6	80.6	106	76.4	110	71
P	227	174.6	174.6	392.8	87.29	392.81	174.58
Zr	259	251	254	262	279	266	275
Hf	8.08	8.29	8.58	8.48	8.62	8.12	8.92
Ti	1900	1700	1800	2800	1300	3100	1900
La	45.6	45.2	42.6	38.6	46.6	35.8	45.9
Ce	96	104	98.2	90.2	108	86.5	106
Pr	10.4	11.2	10.5	9.85	11.5	9.27	11.4
Nd	37.1	37	36.3	33.8	38.7	32	38
Sm	7.07	7.66	7.2	7.34	7.87	6.8	7.86
Eu	0.93	0.85	0.9	0.99	0.79	0.99	0.87
Gd	7.19	7.35	7.16	7.29	8.17	6.6	7.82
Tb	1.37	1.46	1.42	1.51	1.64	1.34	1.54
Dy	8.17	8.3	7.99	8.6	9.41	7.59	9.04
Ho	1.68	1.65	1.59	1.75	1.9	1.53	1.81
Er	4.97	4.82	4.72	5.14	5.64	4.6	5.37
Tm	0.76	0.78	0.76	0.85	0.95	0.75	0.9
Yb	5.09	4.9	4.92	5.17	5.88	4.92	5.58
Lu	0.73	0.69	0.7	0.75	0.86	0.67	0.81
Y	44.2	49.1	48.2	54	59.2	46.3	57.2
ΣREE	227.06	235.86	224.96	211.84	247.91	199.36	242.9
LREE	197.1	205.91	195.7	180.78	213.46	171.36	210.03
HREE	29.96	29.95	29.26	31.06	34.45	28	32.87
LREE/HREE	6.58	6.88	6.69	5.82	6.20	6.12	6.39
$(La/Yb)_N$	6.43	6.62	6.21	5.36	5.68	5.22	5.90
δEu	0.39	0.34	0.38	0.41	0.30	0.45	0.34
石英(Q)	29.68	30.65	30.28	27.18	33.31	27.53	29.58
钙长石(An)	5.49	4.49	6.36	9.2	5.41	10.49	6.45
钠长石(Ab)	30.98	30.33	28.71	28.91	26.18	28.68	29.84
正长石(Or)	25.36	29.42	29.06	26.4	31.86	24.45	28.66
透辉石(Di)	0	0	0	0	0.18	0	0
刚玉(C)	0.85	0.55	0.39	0.44	0	0.51	0.14
紫苏辉石(Hy)	5.9	3.21	3.92	5.88	2.3	6.38	3.98
钛铁矿(Il)	0.62	0.54	0.58	0.9	0.42	1	0.59
磁铁矿(Mt)	0.97	0.7	0.6	0.85	0.26	0.72	0.63
磷灰石(Ap)	0.12	0.09	0.09	0.21	0.05	0.21	0.09
锆石(Zr)	0.05	0.05	0.05	0.05	0.06	0.05	0.06
合计	100.02	100.04	100.04	100.02	100.03	100.02	100.02

注: A /CNK = $Al_2O_3/(CaO+Na_2O+K_2O)$摩尔比，$FeO^T=0.9\times Fe_2O_3^T$。

量(12.81%~14.24%)偏低，A/CNK=0.99~1.06；在A/CNK-A/NK图解(图3-b)中，样品投入准铝质-弱过铝质系列区域。

2.2 稀土及微量元素

扎独顶A型花岗岩稀土元素总量偏高(ΣREE=199.36×10^{-6}~247.91×10^{-6}，平均227.13×10^{-6})，轻重稀土元素比值(LREE/HREE=5.82~6.88)较高，$(La/Yb)_N$=5.22~6.62，表明轻稀土富集而重稀土相对亏损，在稀土元素球粒陨石标准化分布型式图解(图4-a)中，各个样品变化趋势一致，负Eu异常(δEu=0.30~0.45，平均0.37)明显，具有向右缓倾的V型特征。在微量元素原始地幔标准化蛛网图解(图4-b)中，所有

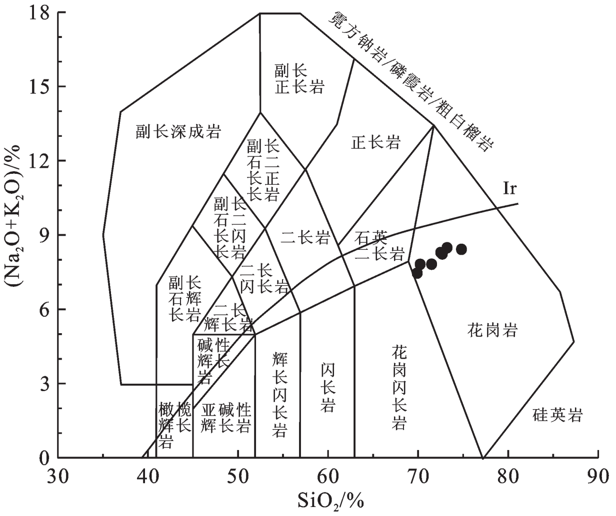

图2　扎独顶A型花岗岩TAS图解(据文献[20])
Fig.2　TAS diagrams of the Zhaduding A−type granites (after reference [20])

样品均富集Rb、Th、K等大离子亲石元素(LILE)，相对亏损Nb、Ta、Sr、P、Ti等高场强元素(HFSE)。该岩石负Eu异常明显，亏损Sr、Ba、Ti、P，相对富集Rb、Th、K、Zr、Hf，显示出A型花岗岩特征。

2.3　锆石饱和温度

由于在岩浆冷却过程中矿物和熔浆会达到热平衡以及缺乏对温度足够敏感的矿物温度计，从而造成岩浆的初始温度难以计算[26]。但Watson et al. (1983)[27]通过实验研究发现，锆石中的Zr的分配系数对温度极其敏感，而其他因素对其影响甚微。因此，锆石的饱和温度可以近似地代表花岗质岩石的液相线温度，其计算公式为：

$$\ln D_{Zr}(496000/Zr_{melt}) = [-3.80-0.85(M-1)] + 12900/T \qquad (1)$$

这里的T为绝对温度，D为分配系数，将(1)式整理并换算成摄氏温度(°C)后为：

$$t_{Zr}(°C) = \{12900/[\ln D_{Zr}(496000/Zr_{melt}) + 0.85M + 2.95]\} - 273.15 \qquad (2)$$

令Si+Al+Fe+Mg+Ca+Na+K+P=1(原子分数)，则全岩岩石化学参数M=(2Ca+K+Na)/(Si×Al)，若不作锆石中Zr、Hf的校正，纯锆石中的Zr含量为$496000×10^{-6}$，由于锆石在花岗质岩浆中是较早结晶的副矿物，并且其晶体能长时间保持稳定，因此，可用全岩的Zr含量近似代表熔体中的Zr含量，由(2)式和全岩M和Zr值可计算熔体锆石饱和温度。计算结果表明(表2)，扎独顶花岗岩的锆石饱和温度为828~838°C，平均832°C，与班公湖—怒江缝合带中段A型花岗岩平均值833°C一致[7]。

扎独顶A型花岗岩富SiO_2和K_2O，全碱含量高，$(Na_2O+K_2O)/Al_2O_3$和FeO^T/MgO比值高，富集Rb、Th、Zr、Hf和Y等高场强元素，贫Ca、Mg和Al，亏损Nb、Ta、Sr、Ba、Ti和P，稀土元素配分曲线大多呈右倾的燕式分布，Eu负异常明显；在(Zr+Nb+Ce+Y)−$(Na_2O+K_2O)/CaO$图解(图5−a)及(Zr+Nb+Ce+Y)−FeO^T/MgO图解(图5−b)中，所有样品全部落入A型花岗岩区域；锆石饱和温度计算表明，花岗岩岩浆形成温度较高，平均832°C。前述所有特征均表明

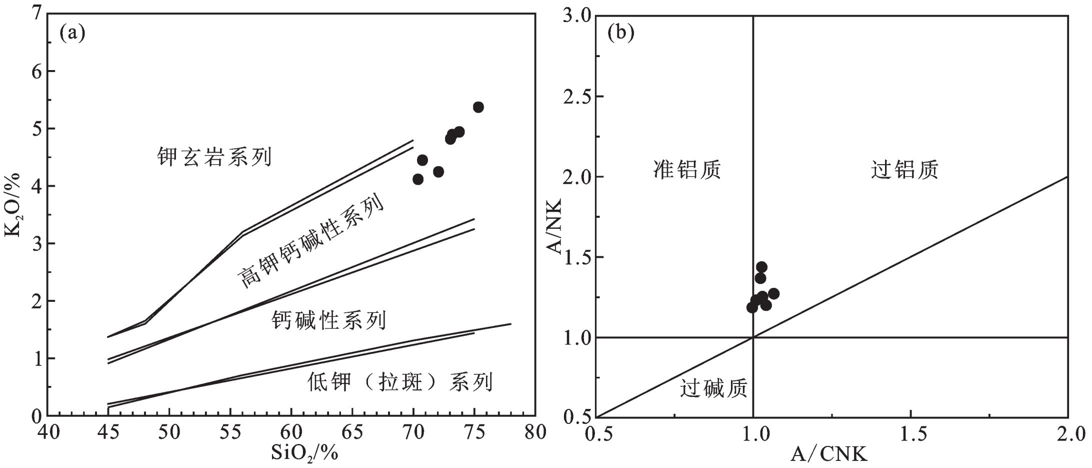

图3　扎独顶A型花岗岩SiO_2−K_2O图解(a, 据文献[21−22])和A/CNK−A/NK图解(b, 据文献[23])
Fig.3　SiO_2−K_2O (a, after reference [21−22]) and A/CNK−A/NK (b, after reference [23]) diagrams of the Zhaduding A−type granites

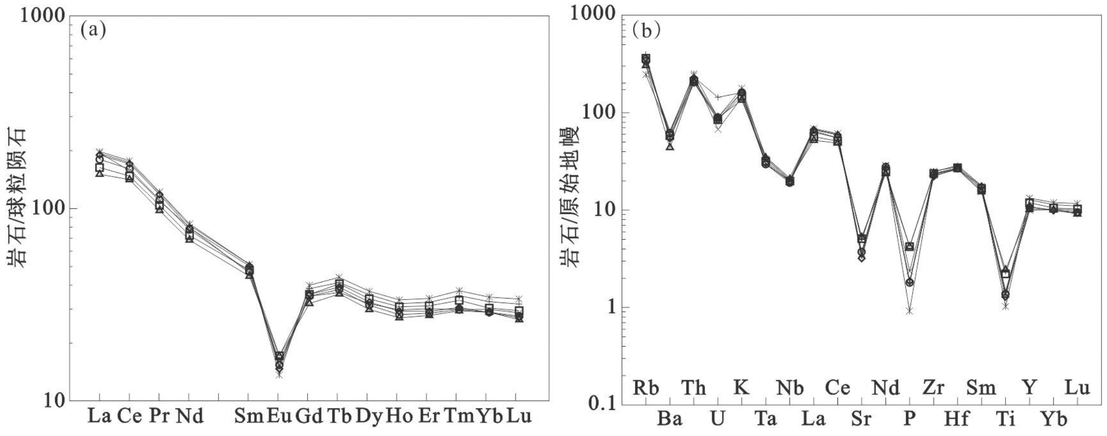

图4 扎独顶A型花岗岩稀土元素球粒陨石标准化分布型式图(a, 标准化值据文献[24])和微量元素原始地幔标准化蛛网图(b, 标准化值据文献[25])

Fig.4 Chondrite-normalized REE patterns (a, normalized data after reference [24]) and primitive mantle-normalized trace element patterns (b, normalized data after reference [25]) for the Zhaduding A-type granites

表2 扎独顶A型花岗岩全岩主量元素(%)组成及Zr温度计算结果

Table 2 Major element (%) compositions and the calculated zircon saturation temperatures of the Zhaduding A-type granites

样品编号	D2770-YQ1	D9011-YQ1	D4332-YQ1	D1514-YQ1	D1516-YQ1	D1517-YQ1	D2691-YQ1
岩性	二长花岗岩						
SiO_2	71.68	73.41	72.85	70.37	74.97	70.05	72.7
TiO_2	0.32	0.28	0.3	0.47	0.22	0.52	0.31
Al_2O_3	13.31	13.35	13.49	14.12	12.81	14.24	13.42
Fe_2O_3	0.66	0.48	0.41	0.58	0.18	0.49	0.43
FeO	2.19	1.64	1.93	2.68	1.19	2.87	1.95
MnO	0.05	0.03	0.04	0.06	0.03	0.06	0.03
MgO	1.11	0.39	0.44	0.82	0.26	0.88	0.47
CaO	1.13	0.93	1.3	1.93	1.13	2.19	1.32
Na_2O	3.6	3.55	3.36	3.38	3.07	3.35	3.49
K_2O	4.22	4.93	4.87	4.42	5.35	4.09	4.8
P_2O_5	0.05	0.04	0.04	0.09	0.02	0.09	0.04
Zr(10^{-6})	259	251	254	262	279	266	275
D_{Zr}	1915.06	1976.10	1952.76	1893.13	1777.78	1864.66	1803.64
ln D_{Zr}	7.56	7.59	7.58	7.55	7.48	7.53	7.50
M	1.36	1.36	1.38	1.44	1.39	1.44	1.41
t_{Zr}(°C)	833	830	829	828	838	829	834

扎独顶花岗岩为A型花岗岩。

3 锆石U—Pb年代学

本文对1件A型花岗岩样品(D3455)进行了LA-ICP-MS锆石U-Pb定年(表3)。测试工作在中国地质大学(武汉)地质过程与矿产资源国家重点实验室完成。锆石阴极发光(CL)图像和年龄谐和图见图6，A型花岗岩样品(D3455)中锆石晶形多为长柱状或短柱状，长度介于100~150 μm，长宽比为2:1~4:1，形态较为完整，晶体棱角分明；阴极发光(CL)图像显示它们具有清晰且均一的震荡环带(图6-a)，Th/U比值为0.34~0.63，为典型岩浆成因锆石[29-31]。18个测点得出的$^{206}Pb/^{238}U$年龄较为均一，介于100~108 Ma，在置信度为95%时加权平均年龄为(103.8±1.0) Ma(MSWD=1.2)(图6-b)，该年龄代表了A型花岗岩的形成年龄，表明该岩体形成于早白垩世晚期。

4 讨　论

4.1 构造背景

A型花岗岩最早被定义为碱性(alkaline)、贫水

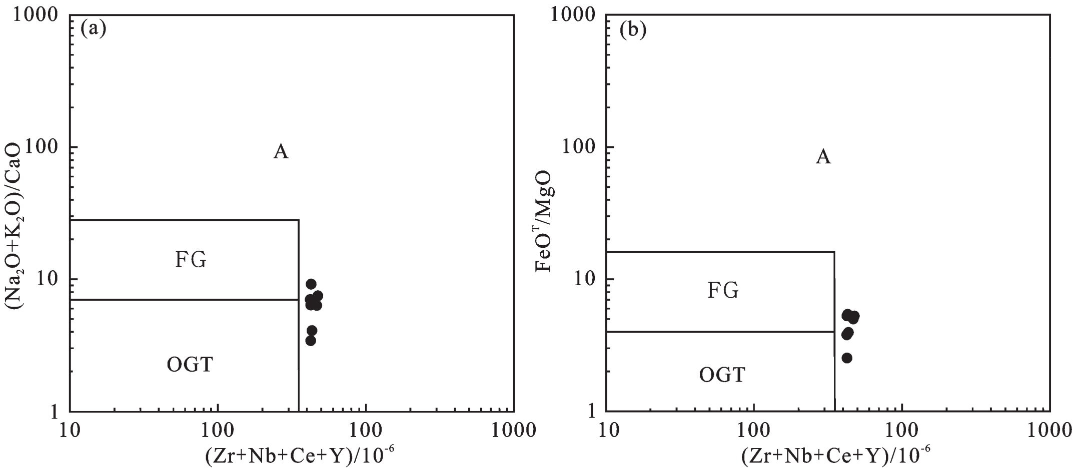

图5 扎独顶A型花岗岩(Zr+Nb+Ce+Y)−(Na$_2$O+K$_2$O)/CaO图解(a, 据文献[28])和(Zr+Nb+Ce+Y)−FeO^T/MgO图解(b)
Fig.5 (Zr+Nb+Ce+Y)−(Na$_2$O+K$_2$O)/CaO (a, after reference [28]) and (Zr+Nb+Ce+Y)−FeO^T/MgO (b) diagrams from the Zhaduding A−type granites

(anhydrou)和非造山(anorogenic)的花岗岩[1]，即3A花岗岩，和物质来源无关，并以此区别I型和S型花岗岩[2]，此后，又被扩展为5A花岗岩[6]，即碱性(alkaline)、贫水(anhydrou)、非造山(anorogenic)、铝质(aluminous)和模棱两可(ambiguous)的花岗岩。Whalen et al.(1987)[27]指出A型花岗岩的形成与伸展构造背景相关。Eby(1992)[32]系统总结了A型花岗岩的岩石学和地球化学特征，并根据物质来源和构造背景的差异，将A型花岗岩分为A_1和A_2两个亚类，其中A_1产于非造山环境(大陆裂谷或板内环境)，A_2产于碰撞后环境，并且A_1和A_2之间没有截然的界线，两者之间为过渡类型；洪大卫等(1995)[33]根据地质学、岩石学、地球化学及构造背景等特征，将A型花岗岩分为AA型(非造山)花岗岩和PA型(后造山)花岗岩，并且两者之间存在若干过渡类型，其中AA型和PA型分别对应A_1型和A_2型。可见，A型花岗岩产于陆−陆碰撞后的伸展构造背景已得到普遍认可[30, 32-38]。

扎独顶A型花岗岩富钾，体现出碰撞后的A型花岗岩特征[39]。在Y−Nb图解(图7−a)和Yb−Ta图解(图7−b)中，扎独顶A型花岗岩所有样品均投入板内环境区域，反映了碰撞后的岩浆生成环境；在Nb−Y−Ce图解(图8−a)上，样品全部投入A_2型花岗岩区域，同样体现出了碰撞后的构造背景。此外，部分学者根据地层与蛇绿岩的不整合关系等，认为班公湖—怒江洋闭合于晚侏罗世末期—早白垩世早期[41-43]；大量年代学研究也表明[7, 38, 44-48]，班公湖—怒江洋闭合时间不晚于早白垩世晚期，且在110 Ma已经处于岩石圈伸展背景下的碰撞后阶段[7, 38]。综合上述分析，笔者认为扎独顶A型花岗岩(103.8±1.0 Ma)是碰撞后岩石圈伸展背景下的产物。

4.2 岩石成因

关于A型花岗岩的成因众说纷纭，包括：(1)下地壳岩石的部分熔融和再熔融[30, 49-51]；(2)幔源岩浆的分离结晶或部分熔融[40, 52-53]；(3)壳幔物质的混合作用[54-60]；(4)幔源拉斑质岩浆高度分异或玄武质岩石部分熔融[61-63]；(5)上地壳钙碱性岩石低压熔融[64-65]。可见，A型花岗岩形成过程比较复杂，岩浆源区具有多样性；因此，笔者认为研究A型花岗岩的成因，应结合具体的岩体以及岩体的大地构造背景、岩石学和地球化学等多种特征综合分析。

假如扎独顶A型花岗岩为幔源基性岩浆直接分异的产物，那么扎独顶A型花岗岩周围应该有大量基性岩的产出，而事实是扎独顶A型花岗岩周围没有与之密切相关的基性岩；岩体中大量的闪长质包体也不支持这一假设；同时，扎独顶A型花岗岩亏损Nb，从而基本排除了其由地幔基性岩浆结晶分异形成的可能性[66]。此外，已有研究表明，冈底斯带在早白垩世发生了岩浆大爆发，且在早白垩世早期，北冈底斯发生了以桑日群、多尼组火山岩和相

表3 扎独顶A型花岗岩LA−ICP−MS锆石U−Pb定年分析结果

Table 3 LA−ICP−MS zircon U−Pb dating results of the Zhaduding A−type granites

测点号	含量/10^{-6}		Th/U	同位素比值						表面年龄/Ma					
	Th	U		$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
D3455															
D3455-01	391	704	0.56	0.05079	0.00342	0.10887	0.00709	0.01562	0.00027	231	145	105	6	100	2
D3455-02	353	637	0.55	0.04906	0.00265	0.10758	0.00567	0.01597	0.00024	151	115	104	5	102	2
D3455-03	164	413	0.40	0.05495	0.00332	0.12260	0.00739	0.01637	0.00028	410	133	117	7	105	2
D3455-04	352	630	0.56	0.05666	0.00394	0.12585	0.00915	0.01613	0.00025	478	162	120	8	103	2
D3455-05	324	626	0.52	0.05436	0.00297	0.12455	0.00681	0.01659	0.00024	386	122	119	6	106	2
D3455-06	339	650	0.52	0.05160	0.00264	0.11520	0.00612	0.01623	0.00026	268	119	111	6	104	2
D3455-07	269	563	0.48	0.04605	0.00205	0.10223	0.00424	0.01610	0.00026		95	99	4	103	2
D3455-08	262	416	0.63	0.07295	0.01355	0.15592	0.02683	0.01608	0.00028	1013	376	147	24	103	2
D3455-09	147	256	0.57	0.06109	0.00713	0.13296	0.01524	0.01579	0.00034	642	262	127	14	101	2
D3455-10	253	533	0.47	0.05268	0.00403	0.11906	0.00893	0.01639	0.00025	315	176	114	8	105	2
D3455-11	388	951	0.41	0.05709	0.00339	0.13088	0.00753	0.01663	0.00025	495	135	125	7	106	2
D3455-12	427	798	0.54	0.05387	0.00297	0.12247	0.00691	0.01641	0.00025	366	126	117	6	105	2
D3455-13	280	549	0.51	0.06000	0.00368	0.13577	0.00815	0.01643	0.00030	603	127	129	7	105	2
D3455-14	362	695	0.52	0.06285	0.00537	0.13850	0.01206	0.01583	0.00024	703	189	132	11	101	2
D3455-15	304	885	0.34	0.05221	0.00334	0.12243	0.00739	0.01695	0.00026	295	136	117	7	108	2
D3455-16	287	615	0.47	0.05954	0.00500	0.13885	0.01075	0.01678	0.00034	587	167	132	10	107	2
D3455-17	333	690	0.48	0.05321	0.00426	0.11923	0.00856	0.01610	0.00023	338	162	114	8	103	1
D3455-18	271	555	0.49	0.06734	0.00625	0.15036	0.01222	0.01660	0.00049	848	162	142	11	106	3

关的花岗岩类为代表的岛弧岩浆作用[19]，因此，扎独顶A型花岗岩((103.8±1.0)Ma)的岩浆源区很可能与这些岛弧岩浆岩的源区接近；扎独顶A型花岗岩属于高钾钙碱性系列，富集大离子亲石元素(Rb、Th、K)，相对亏损高场强元素(Nb、Ta、Sr、Ti)，亏损Ba、P和Eu负异常明显的地球化学特征与这些岛弧岩浆岩的地球化学特征相似；并且在Nb−Nb/Th图解(图8−b)上，所有样品均投入火山弧附近，从Y/Nb−Ce/Nb图解(图8−c) 和Y/Nb−Yb/Ta图解(图8−d)中也可以看出，虽然扎独顶A型花岗岩样品落入A_2型花岗岩区域，但是其紧邻岛弧玄武岩(IAB)区，表明其源区物质与岩石圈地幔有关。至于此时为什么形成的是A型花岗岩而不是岛弧型花岗岩，原因在于岛弧型花岗岩形成于俯冲削减的构造背景[67-69]，而A型花岗岩形成于碰撞后的伸展构造背景[7, 33, 38]。

Nb/Ta为强不相容元素，在侵蚀和变质作用过程中比较稳定，因此，可以示踪原始岩浆源区的特征[70-71]。本文扎独顶A型花岗岩Nb/Ta比值(10.51~11.53)低于幔源岩浆值17±1[72]，而接近地壳平均值12~13[70]，暗示岩浆可能主要源于地壳。

扎独顶A型花岗岩中大量的闪长质包体是岩浆混合作用最直接和最显著的证据[73-74]；同时，也反映了幔源玄武质岩浆和壳源花岗质岩浆在混合程度上存在显著的差异[75]，即扎独顶A型花岗岩中闪长质包体的源岩是进入花岗质岩浆中的小体积玄武质岩浆，而不是进入玄武质岩浆中的小体积花岗质岩浆[75-76]。闪长质包体形成后，玄武质岩浆消失，而花岗质岩浆的成分几乎没有改变。这和扎独顶A型花岗岩的岩浆源区与岩石圈地幔相关以及Nb/Ta比值接近地壳平均值反映的结果相吻合，即闪长质包体进一步暗示了岩浆主要来源于地壳，并与幔源玄武质岩浆的底侵作用有关。

如前文所述，扎独顶A型花岗岩亏损Sr、Ba、P、Ti以及Eu负异常，表明部分熔融过程中源区存在斜长石、钾长石、磷灰石和钛铁矿的残留体，而不是分离结晶造成的；这是因为花岗质岩浆粘度大，表现为晶粥体[77-79]，很难发生分离结晶作用[78-80]。此外，扎独顶A型花岗岩全岩锆石饱和温度高(平均832°C)，与班公湖—怒江缝合带中段A型花岗岩平均值833°C一致[7]，表明初始岩浆温度高，同时，也暗示软流圈在其形成过程中发挥了重要作用。结合扎独顶A型花岗岩构造背景可知，岩石圈伸展可促使软流圈物质上涌，导致岩石圈地幔部分熔融，从而形成幔源玄武质岩浆；同时幔源玄武质岩浆底侵导致

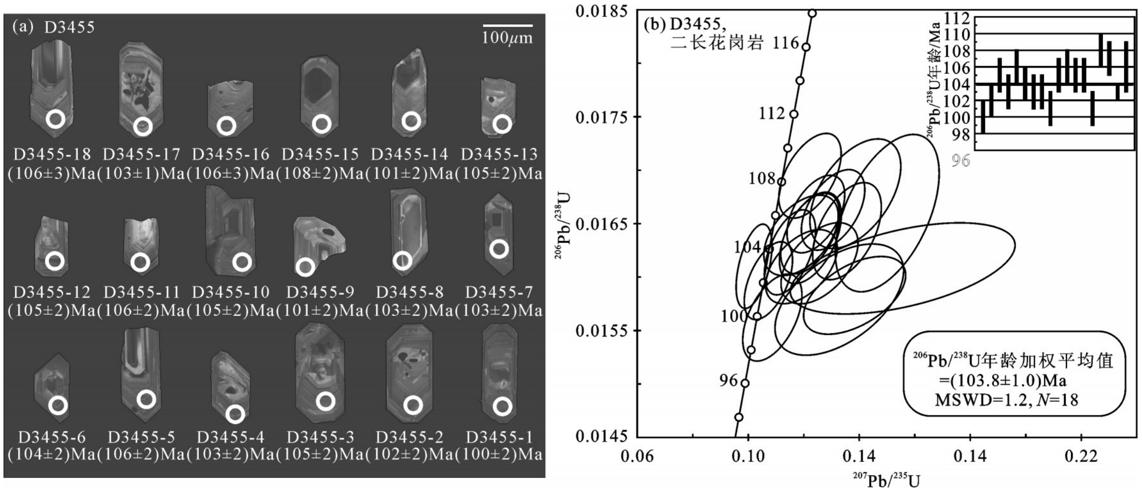

图6 扎独顶A型花岗岩锆石阴极发光图(a)和U-Pb年龄谐和图(b)

Fig.6 Cathodoluminescence images of zircon grains (a) and U-Pb age concordia plots (b)of the Zhaduding A-type granites

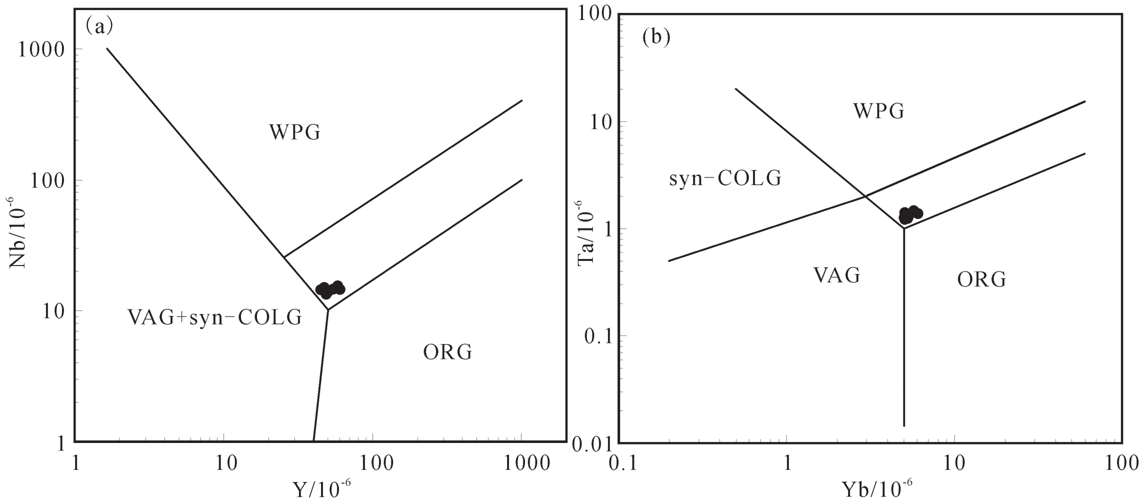

图7 扎独顶A型花岗岩Y-Nb图解(a, 据文献[40])和Yb-Ta图解(b)

Fig.7 Y-Nb (a, after reference [40]) and Yb-Ta (b) diagrams of the Zhaduding A-type granites

地壳物质重熔并形成壳源花岗质岩浆，并且部分幔源玄武质岩浆与壳源花岗质岩浆混合形成了闪长质包体；最后，闪长质包体随花岗质岩浆一起侵位，从而形成了含有闪长质包体的扎独顶A型花岗岩。

5 结 论

通过对扎独顶A型花岗岩野外地质调查、岩相学、岩石地球化学和锆石U-Pb测年等的研究，可得出如下结论。

(1)扎独顶A型花岗岩分布面积广泛，呈岩基形式产出，在岩性上属二长花岗岩。

(2) 扎独顶A型花岗岩在岩石化学上富 SiO_2 (70.05%~74.97%)和K_2O(4.09%~5.35%)，钙(0.93%~2.19%)和钛(0.22%~0.52%)含量较低，(Na_2O+K_2O)/Al_2O_3 和 FeO^T/MgO 比值高，分别为 0.52~0.66 和 2.50~5.31，Al_2O_3 含量(12.81%~14.24%)偏低，A/CNK=0.99~1.06，显示准铝质-弱过铝质特征；在地球化学上富集Rb、Th、K、Zr和Hf，亏损Nb、Ta、Sr、Ba、P和Ti，Eu负异常明显(δEu =0.30~0.45，平均0.37)，在球粒陨石标准化分布型式图上具有向右缓

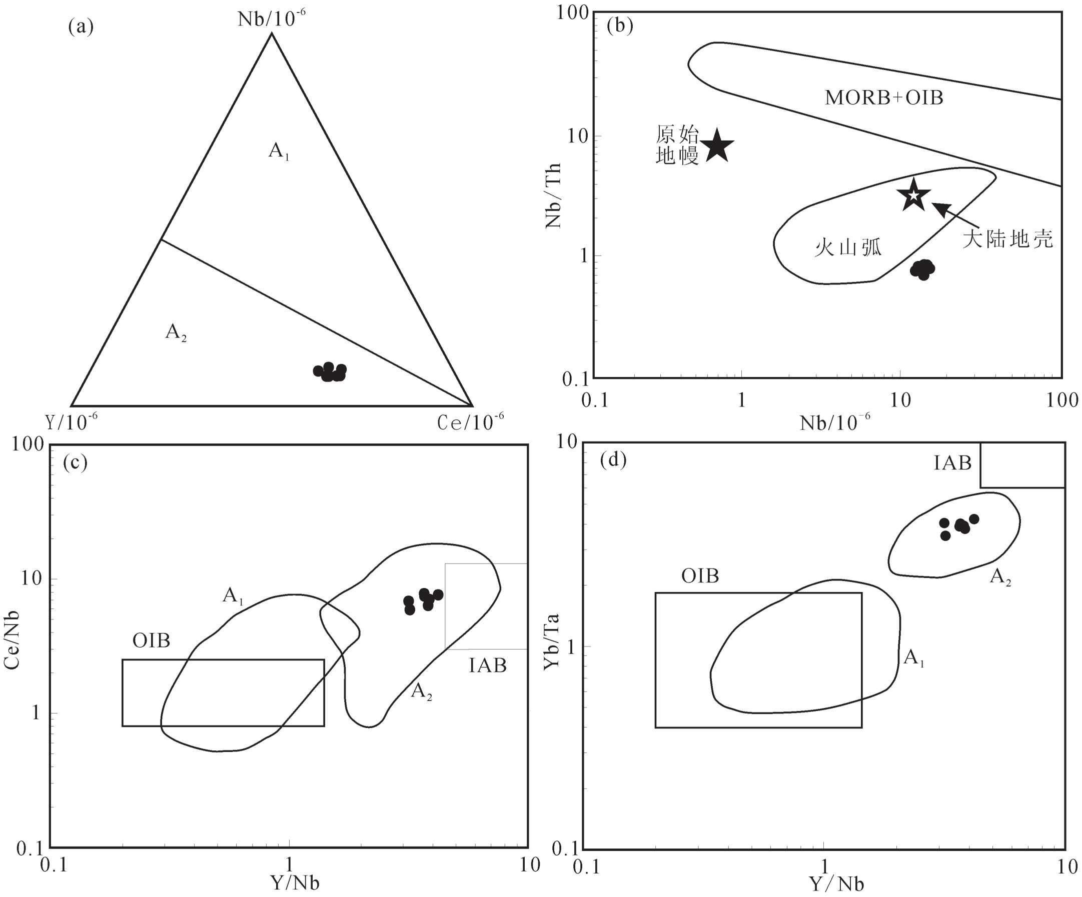

图8 扎独顶A型花岗岩Nb-Y-Ce图解(a, 据文献[32])、Nb-Nb/Th图解(b, 据文献[7])、Y/Nb-Ce/Nb图解(c)和Y/Nb-Yb/Ta图解(d)

Fig.8 Nb-Y-Ce (a, after reference [32]), Nb-Nb/Th (b, after reference [7]), Y/Nb-Ce/Nb (c) and Y/Nb-Yb/Ta (d) diagrams of the Zhaduding A-type granites

倾的V型特征;属于碰撞后岩石圈伸展背景下的A_2型花岗岩。

(3) 扎独顶A型花岗岩LA-ICP-MS锆石U-Pb年龄为(103.8±1.0)Ma,表明其形成于早白垩世晚期。

(4) 扎独顶A型花岗岩是在碰撞后岩石圈伸展背景下由于软流圈物质上涌导致岩石圈地幔和地壳物质部分熔融并经历过一定程度的混合作用而形成的。

致谢: 褚永彬和曾璐博士,研究生秦川、李超、李杜文和刘和等在野外和室内工作中给予了帮助,评审专家提出了建设性的修改意见,在此一并表示衷心的感谢。

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