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藏南亚东地区花岗质片麻岩 LA-ICP-MS 锆石 U-Pb 定年及其地球化学特征

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摘要: 亚东地区出露高喜马拉雅结晶岩系, 是研究喜马拉雅造山带地质演化的理想地区。为探讨该区花岗质片麻岩的成因类型、岩浆源区、形成时代以及大地构造意义, 对其进行了 LA-ICP-MS 锆石定年和地球化学特征研究。结果显示, 该区的花岗质片麻岩具有高 SiO_2 、 Al_2O_3 、 Na_2O 、 K_2O 含量和低 Fe_2O_3 、 MgO 、 MnO 含量, 轻、重稀土明显分馏, 相对富集 LREE 和 LILE 元素 (Rb、Th、U、K), 亏损 HFSE 元素 (Ba、Nb、Ta、Sr、P、Ti), 锆石表面年龄介于 $498.5 \pm 14.7 \text{ Ma} \sim 480.0 \pm 11.7 \text{ Ma}$ 。总体显示未分异的钙碱性铝质 S 型花岗岩类的特征, 可能是后碰撞造山阶段陆源杂砂岩经历高温深熔作用的产物。

关键词: 花岗质片麻岩; 锆石定年; 亚东; 藏南; 地球化学。

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LA-ICP-MS Zircon U-Pb Dating of Granitic Gneiss from Yadong Area in South Tibet and Its Geochemical Characteristics

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Abstract: The high Himalaya crystalline rock series occurred in Yadong area, which is an ideal area for studying the tectonic evolution of the Himalayan orogenic belt. In order to discuss the genetic type, magmatic source, formation age and tectonic significance of granitic gneiss in the Yadong area, the LA-ICP-MS zircon dating and geochemical characteristics of these granitic gneisses were studied. The results show that the granite gneisses have high SiO_2 , Al_2O_3 , Na_2O and K_2O contents, while they are low in Fe_2O_3 , MgO and MnO contents. The granitic gneisses have experienced obvious REE fractionation, which are relatively enriched in LREE and LILE (Rb, Th, U and K elements) but are depleted in HFSE (Ba, Nb, Ta, Sr, P and Ti elements), and their zircon $^{206}\text{Pb}/^{238}\text{U}$ ages vary from $498.5 \pm 14.7 \text{ Ma}$ to $480.0 \pm 11.7 \text{ Ma}$. Thus, the granitic gneisses generally show the geochemical characteristics of undifferentiated S-type granites with calcium-alkaline and strong peraluminous properties, which might be formed by the high-temperature anatexis of terrigenous greywacke during the post-collision orogeny stage.

Key words: granitic gneiss; zircon dating; Yadong; South Tibet; geochemistry.

喜马拉雅造山带是世界上最年轻的山系, 是印度板块与欧亚板块新生代碰撞作用的产物, 可作为

研究大陆碰撞造山和板块构造的天然实验室 (Burg *et al.*, 1984; Hodges *et al.*, 1992; Beaumont *et al.*,

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2001;李旺超等,2015;唐磊,2016).喜马拉雅造山带核部的高喜马拉雅结晶岩系,经历了印度板块俯冲到欧亚板块之下的高级变质作用和部分熔融作用,是揭示和研究喜马拉雅造山带形成与构造演化的重要地区(李旺超等,2015;唐磊,2016).

前人先后在变质作用类型与温压条件、部分熔融过程与机制、变质作用时间范围、变质条件和熔融程度的空间变化等方面对高喜马拉雅结晶岩系进行了研究(Jamieson *et al.*, 2004; Kohn, 2008; Groppo *et al.*, 2012; Imayama *et al.*, 2012; Rubatto *et al.*, 2012; 李旺超等, 2015; 唐磊, 2016), 提出楔形挤出模式(Burchfiel and Royden, 1985; Grujic *et al.*, 1996)、隧道流模式(Beaumont *et al.*, 2001; Hodges *et al.*, 2001; Godin *et al.*, 2006)、构造楔模式(Yin, 2006; Webb *et al.*, 2007)等多种不同的造山模型.

然而,对高喜马拉雅结晶岩系早古生代造山作用机制的认识还存在较多争议,目前主要存在两种观点.一种观点认为高喜马拉雅结晶岩系是泛非造山作用的产物,与东西冈瓦纳大陆聚合引起的碰撞

造山作用密切相关(Sahni, 1982; Klootwijk *et al.*, 1985; 许志琴等, 2005; Liu *et al.*, 2006; 时超等, 2010);另一种观点认为,在东西冈瓦纳大陆拼合之后,原特提斯洋向冈瓦纳大陆北缘俯冲及亚洲陆块增生作用导致了东冈瓦纳北缘的安底斯造山作用,形成了高喜马拉雅结晶岩系(Meert, 2003; Cawood and Buchan, 2007; 张泽明等, 2008; 董昕等, 2009; 王晓先等, 2011; 蔡志慧等, 2013; 唐磊, 2016).

亚东地区出露高喜马拉雅结晶岩系,是研究喜马拉雅造山带构造演化的理想地区(李旺超等, 2015).因此,本文对亚东地区花岗质片麻岩进行详细的地球化学和 LA-ICP-MS 锆石年代学研究,探讨岩石成因类型、岩浆源区、形成时代以及大地构造意义,以期对喜马拉雅造山带形成与演化过程提供重要信息.

1 地质概况

研究区位于中国西藏自治区的最南端,大地构

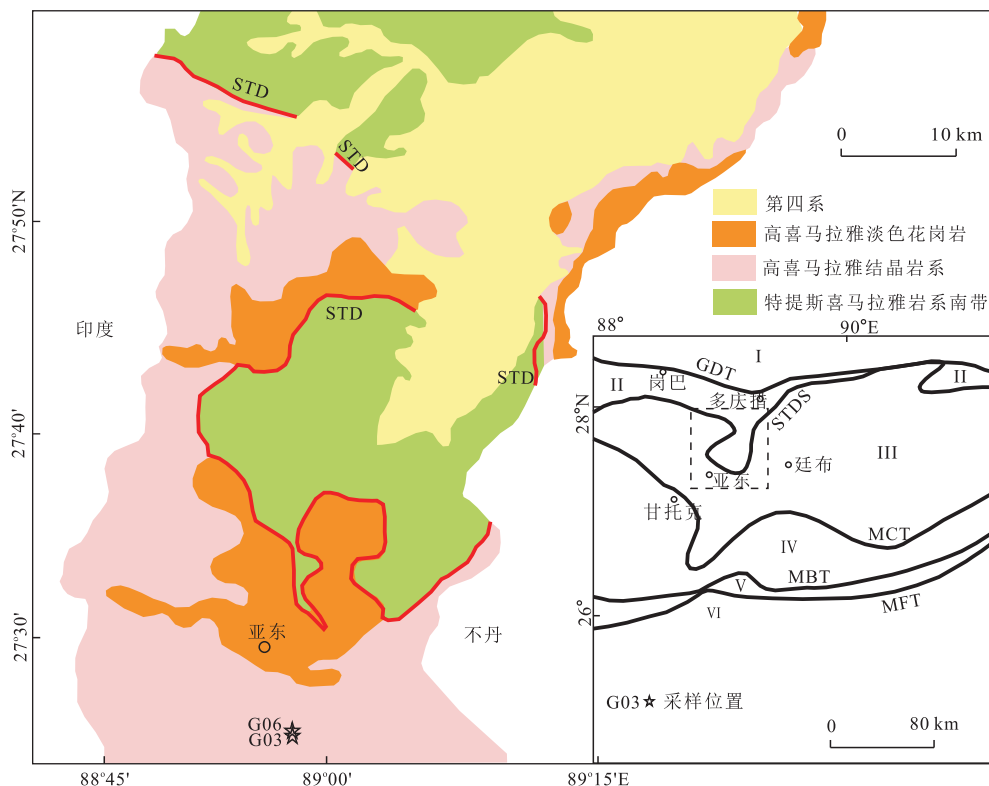


图 1 亚东地区地质简图

Fig.1 Geological sketch of Yadong area in South Tibet

I.喜马拉雅特提斯岩系北带;II.喜马拉雅特提斯岩系南带;III.高喜马拉雅结晶岩系;IV.低喜马拉雅岩系;V.次喜马拉雅岩系;VI.印度地块;MCT.主中央逆冲断裂;STDS.藏南拆离系;MBT.主边界逆冲断裂;MFT.主前缘逆冲断裂.底图据张祥信等(2005)和唐磊(2016)修改

造位置位于喜马拉雅造山带中段的高喜马拉雅结晶岩系中(图 1),其北侧以藏南拆离系(STDS)为界,与喜马拉雅特提斯岩系南带为邻,南侧以主中央逆冲断裂(MCT)为界,与低喜马拉雅岩系相邻(周志广等,2003;张祥信等,2005;唐磊,2016)。

亚东地区主要出露高喜马拉雅结晶岩系、喜马拉雅特提斯岩系,且被大量的淡色花岗岩侵入(唐磊,2016;图 1)。高喜马拉雅结晶岩系是印度大陆北缘结晶基底的重要组成部分,经历了角闪岩相到麻粒岩相的变质作用,主要由正片麻岩、副片麻岩、泥质麻粒岩以及少量石英岩、大理岩、钙硅酸盐岩组成,发育大面积的淡色花岗岩(Yin and Harrison,2000;张祥信等,2005;苟正彬等,2015)。喜马拉雅特提斯岩系主要由晚寒武纪至早古生代的低级变质沉积岩和变质碎屑岩组成,发育一系列的片麻岩穹窿和淡色花岗岩(Zhang *et al.*,2012)。

前人根据岩石组合、变质程度及变形特征等方面的差异,将亚东地区的结晶岩系划分为亚东岩群(An CY)和聂拉木岩群(An CN)(张祥信等,2005)。其中,亚东岩群主要由多种片麻岩、多种混合岩和少量变粒岩组成,变质程度为角闪岩相—高角闪岩相,岩石以发育深融柔流褶皱、无根勾状褶皱和韧性变形为主要特征。聂拉木岩群主要由变粒岩、大理岩、多种片麻岩及少量石英岩、片岩和钙硅酸盐岩组成,变质相为绿片岩相—角闪岩相,变形特征以顺层掩卧褶皱和无根勾状褶皱为主。

2 样品特征及分析方法

2.1 样品特征

本文用于锆石 U-Pb 定年的样品 G06 和用于岩石地球化学分析的样品 G03 均采自西藏亚东县高

喜马拉雅结晶岩系(图 1),其地理坐标分别为:88°58′17″N,27°21′27″E, $H=2\,883\text{ m}$ 和 88°58′14.3″N,27°21′30.8″E, $H=2\,871\text{ m}$,样品重约 1 kg。样品岩性为糜棱岩化花岗质片麻岩,呈灰色—灰白色,主要由斜长石、钾长石、石英、黑云母组成(图 2a),岩石经历了强烈的糜棱岩化改造(图 2b),矿物定向明显,呈糜棱片状构造,变斑状—糜棱结构。显微镜下见碎斑和基质,碎斑含量约为 15%,由石英、斜长石、钾长石组成,碎斑呈透镜状定性分布,石英碎斑见波状消光,变形带发育;基质主要由石英和黑云母组成,有少量斜长石和绢云母,鳞片粒状变晶结构,黑云母片状定向明显。

2.2 分析方法

主量、微量、稀土元素分析均在中国地质调查局西安地质调查中心自然资源部岩浆作用成矿与找矿重点实验室进行,采用 X 荧光光谱分析(XRF)和离子质谱仪(ICP-MS)测定,主量元素的分析测试误差小于 1%,微量元素和稀土元素的分析测试误差小于 5%。

锆石样品是经过人工重砂、电磁选,在双目镜下挑选后,从花岗质片麻岩(G06)中将结晶好、透明度高、无裂隙、无包体的颗粒,用环氧树脂固定并抛光至锆石颗粒完全暴露,然后进行阴极发光(CL)内部结构和 LA-ICP-MS 同位素分析测试。锆石的分选工作是在河北廊坊诚信地质服务有限公司完成,锆石制靶和 CL 照相工作是在北京地时科技有限公司完成,LA-ICP-MS 锆石定年是在中国地质调查局西安地质调查中心自然资源部岩浆作用成矿与找矿重点实验室完成。

激光剥蚀系统为 GeoLas Pro,ICP-MS 为 Agilent 7700x。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,二者在进入 ICP 之前通过一个 T 型接头混合。每个时间分辨分析数据包括大

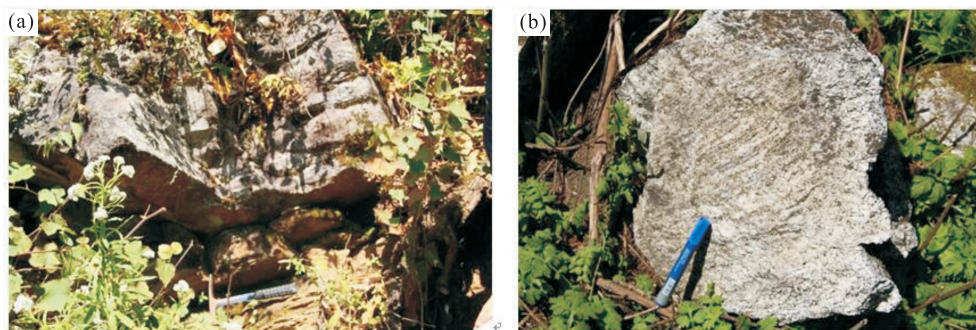


图 2 糜棱岩化花岗质片麻岩(a)和强糜棱岩化花岗质片麻岩(b)

Fig.2 Mylonitized granitic gneiss (a) and granitic gneiss with strong mylonitization (b)

约 10 s 的空白信号和 40 s 的样品信号. 对分析数据的离线处理(包括对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及 U-Th-Pb 同位素比值和年龄计算)采用软件 Glitter 4.4(van Achterbergh *et al.*, 2001)完成, 详细仪器参数和测试过程可参考李艳广等(2015).

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. 对于与分析时间有关的 U-Th-Pb 同位素比值漂移, 利用 91500 的变化采用线性内插的方式进行了校正. 锆石样品的 U-Pb 年龄谐和图绘制和年龄权重平均计算均采用 Isoplot/Ex_ver 3 (Ludwig, 2003)完成. 锆石微量元素含量利用参考标样 NIST610 玻璃作为外标、Si 作内标的方法进行定量计算. NIST610 玻璃中元素含量的推荐值据 GeoReM 数据库 (<http://georem.mpch-mainz.gwdg.de/>).

3 花岗质片麻岩年代学特征

本文对亚东地区花岗质片麻岩(G06)进行了锆石内部结构阴极发光(CL)观察(图 3)和 LA-ICP-MS 锆石 U-Pb 定年测试, 测点选择韵律环带结构清晰的部分, 代表性有效分析点位置及分析结果如图 3 和表 1 所示. 双目镜下显示, 所测锆石基本上透明、无色, 晶形相对较好, 具有密集振荡型环带, 显示典型的岩浆锆石特征; 锆石 Th/U 比值介于 0.18~

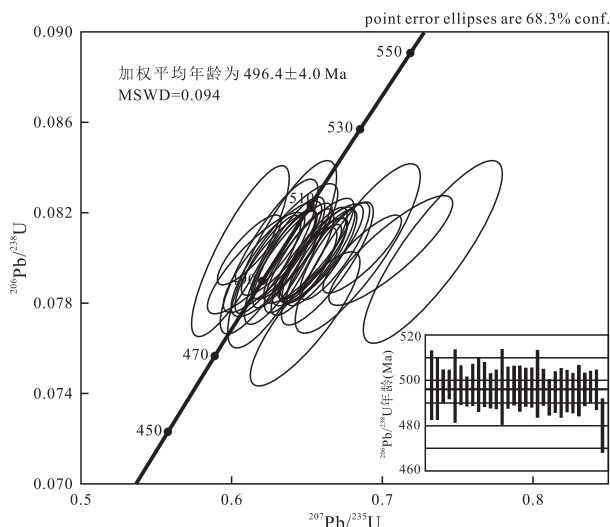


图 4 亚东地区花岗质片麻岩锆石 U-Pb 年龄谐和图
Fig.4 Concordia plot of zircon U-Pb ages about the granitic gneiss from Yadong area

1.21(表 1), 不同于一般变质和热液成因锆石的 Th/U 比值(<0.1), 与典型的岩浆锆石特征相符合(>0.1 ; Hoskin and Black, 2002; 赵振华, 2010).

亚东地区花岗质片麻岩(G06)的锆石 U-Pb 分析结果经校正后的有效数据点共有 30 个(表 1), 所测点数据在谐和图中围绕谐和线成群集中分布(图 4), 锆石 $^{206}\text{Pb}/^{238}\text{U}$ 表面年龄为 $480.0 \pm 11.7 \text{ Ma} \sim 498.5 \pm 14.7 \text{ Ma}$, 其加权平均值为 $496.4 \pm 4.0 \text{ Ma}$ (MSWD=0.094)(图 3), 代表了花岗质片麻岩的形成年龄.

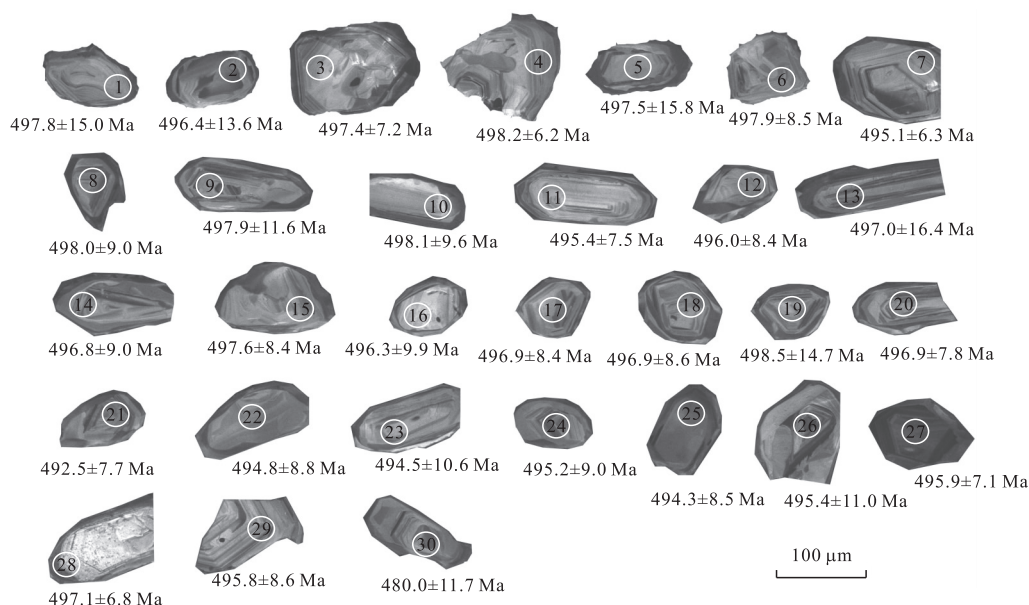
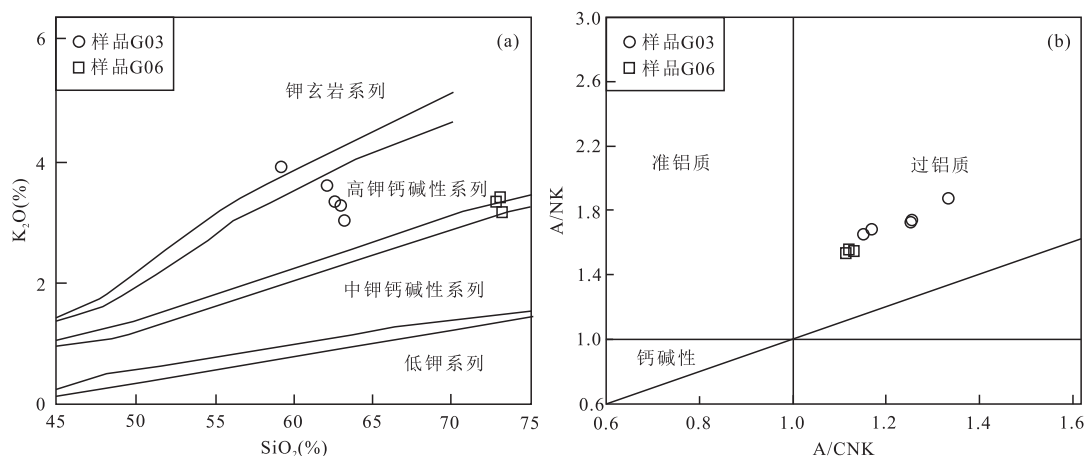


图 3 亚东地区花岗质片麻岩锆石 CL 图像

Fig.3 Zircon CL images of granitic gneiss from Yadong area in South Tibet

表 1 亚东地区花岗质片麻岩锆石 LA-ICP-MS U-Pb 分析结果

点号	同位素比值						年龄(Ma)						元素含量(10^{-6})						
	$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{208}\text{Pb}/^{232}\text{Th}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{208}\text{Pb}/^{232}\text{Th}$		Th	U	Th/U				
	比值	1 σ	比值	1 σ	比值	1 σ	年龄	1 σ	年龄	1 σ	年龄	1 σ							
G06A01	0.0553	0.0021	0.6061	0.0216	0.0803	0.0025	0.0225	0.0019	433.4	85.2	481.1	13.7	497.8	15.0	450.6	37.6	194.7	366.5	0.53
G06A02	0.0560	0.0013	0.6251	0.0219	0.0801	0.0023	0.0252	0.0013	453.8	17.6	493.0	13.7	496.4	13.6	503.5	24.8	1839.6	1645.2	1.12
G06A03	0.0567	0.0014	0.6313	0.0162	0.0802	0.0012	0.0233	0.0011	479.7	83.3	496.9	10.1	497.4	7.2	466.2	21.5	242.9	388.3	0.63
G06A04	0.0549	0.0013	0.6119	0.0143	0.0803	0.0010	0.0256	0.0013	409.3	53.7	484.7	9.0	498.2	6.2	510.2	24.9	190.6	442.2	0.43
G06A05	0.0650	0.0015	0.7332	0.0308	0.0802	0.0027	0.0243	0.0015	775.9	52.8	558.4	18.1	497.5	15.8	486.0	29.5	183.4	1012.7	0.18
G06A06	0.0571	0.0014	0.6403	0.0178	0.0803	0.0014	0.0254	0.0013	494.5	53.7	502.5	11.0	497.9	8.5	507.0	26.2	222.8	556.8	0.40
G06A07	0.0590	0.0013	0.6524	0.0136	0.0798	0.0011	0.0256	0.0012	568.6	48.1	510.0	8.3	495.1	6.3	510.9	23.2	174.6	501.1	0.35
G06A08	0.0580	0.0015	0.6509	0.0197	0.0803	0.0015	0.0271	0.0015	531.5	57.4	509.1	12.2	498.0	9.0	541.3	30.3	286.9	609.4	0.47
G06A09	0.0568	0.0020	0.6347	0.0233	0.0803	0.0019	0.0251	0.0016	483.4	47.2	499.0	14.5	497.9	11.6	500.2	32.5	344.0	456.9	0.75
G06A10	0.0634	0.0026	0.7055	0.0277	0.0803	0.0016	0.0264	0.0015	724.1	88.9	542.1	16.5	498.1	9.6	527.6	29.2	223.4	184.2	1.21
G06A11	0.0588	0.0013	0.6543	0.0149	0.0799	0.0012	0.0255	0.0013	561.1	50.0	511.1	9.2	495.4	7.5	509.9	25.5	276.3	656.8	0.42
G06A12	0.0592	0.0013	0.6559	0.0154	0.0800	0.0014	0.0257	0.0013	576.0	46.3	514.3	9.4	496.0	8.4	513.2	26.0	211.6	745.8	0.28
G06A13	0.0572	0.0015	0.6338	0.0239	0.0802	0.0028	0.0268	0.0013	498.2	63.9	498.4	14.8	497.0	16.4	533.7	24.8	400.8	982.0	0.41
G06A14	0.0589	0.0017	0.6574	0.0201	0.0801	0.0015	0.0271	0.0015	561.1	67.6	513.0	12.3	496.8	9.0	540.0	29.5	288.0	571.1	0.50
G06A15	0.0602	0.0015	0.6682	0.0153	0.0803	0.0014	0.0274	0.0013	609.3	55.5	519.6	9.3	497.6	8.4	546.1	26.2	247.5	394.3	0.63
G06A16	0.0566	0.0020	0.6273	0.0218	0.0800	0.0017	0.0268	0.0018	476.0	75.9	494.4	13.6	496.3	9.9	533.7	34.9	87.8	188.7	0.47
G06A17	0.0588	0.0014	0.6544	0.0152	0.0801	0.0014	0.0268	0.0012	566.7	50.0	511.2	9.3	496.9	8.4	534.9	22.9	624.7	814.2	0.77
G06A18	0.0592	0.0014	0.6576	0.0160	0.0801	0.0014	0.0270	0.0012	572.3	56.5	513.2	9.8	496.9	8.6	537.7	23.1	293.6	534.2	0.55
G06A19	0.0612	0.0021	0.6840	0.0270	0.0804	0.0025	0.0278	0.0016	655.6	74.1	529.2	16.3	498.5	14.7	554.4	31.9	258.5	341.5	0.76
G06A20	0.0570	0.0013	0.6351	0.0147	0.0801	0.0013	0.0280	0.0014	500.0	51.8	499.2	9.1	496.9	7.8	557.3	26.9	374.4	814.3	0.46
G06A21	0.0587	0.0013	0.6482	0.0144	0.0794	0.0013	0.0281	0.0014	566.7	50.0	507.4	8.9	492.5	7.7	559.2	26.6	241.0	746.1	0.32
G06A22	0.0558	0.0022	0.6162	0.0213	0.0798	0.0015	0.0287	0.0018	455.6	80.5	487.5	13.4	494.8	8.8	571.5	34.7	233.3	333.2	0.70
G06A23	0.0595	0.0014	0.6633	0.0199	0.0797	0.0018	0.0294	0.0015	587.1	18.4	516.6	12.1	494.5	10.6	585.9	29.1	228.4	717.7	0.32
G06A24	0.0580	0.0012	0.6447	0.0150	0.0798	0.0015	0.0303	0.0012	531.5	44.4	505.2	9.3	495.2	9.0	602.6	23.0	628.1	1211.1	0.52
G06A25	0.0564	0.0012	0.6242	0.0142	0.0797	0.0014	0.0273	0.0011	477.8	50.9	492.4	8.9	494.3	8.5	543.9	21.0	397.5	869.2	0.46
G06A26	0.0568	0.0011	0.6357	0.0176	0.079	0.0018	0.0299	0.0012	483.4	42.6	499.6	10.9	495.4	11.0	595.0	23.2	479.0	1470.0	0.33
G06A27	0.0585	0.0014	0.6539	0.0153	0.0800	0.0012	0.0304	0.0024	546.3	51.8	510.9	9.4	495.9	7.1	604.5	46.1	164.9	806.3	0.20
G06A28	0.0611	0.0015	0.6866	0.0172	0.0802	0.0011	0.0317	0.0017	642.6	52.6	530.8	10.3	497.1	6.8	629.9	33.4	113.3	456.3	0.25
G06A29	0.0573	0.0014	0.6348	0.0136	0.0800	0.0014	0.0278	0.0013	505.6	58.3	499.1	8.5	495.8	8.6	553.6	25.9	346.6	591.4	0.59
G06A30	0.0594	0.0020	0.6488	0.0240	0.0773	0.0020	0.0276	0.0017	583.4	72.2	507.7	14.8	480.0	11.7	550.4	33.0	229.4	485.8	0.47

图 5 亚东地区花岗质片麻岩 SiO_2 — K_2O (a)和 A/CNK — A/NK (b)图解Fig.5 SiO_2 — K_2O (a) and A/CNK — A/NK (b) diagrams of the granitic gneiss from Yadong area

底图 a 据 Grunsky and Massey(1995);底图 b 据 Maniar and Piccoli(1989)

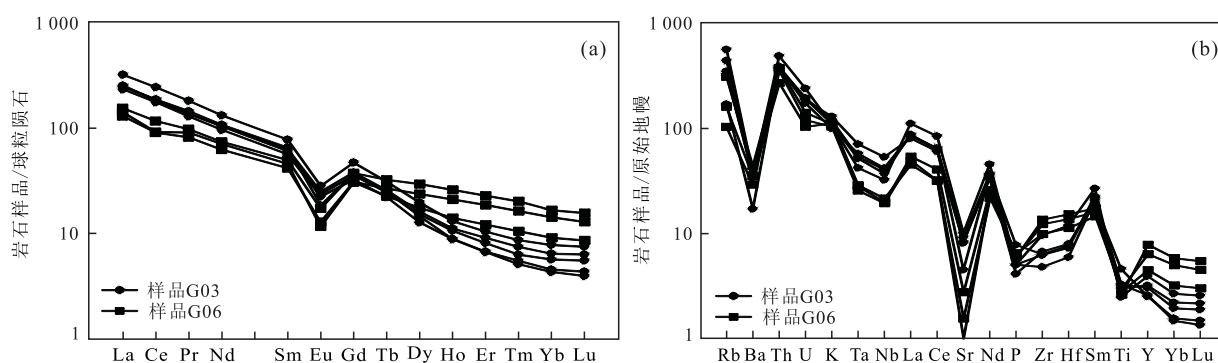


图 6 亚东地区花岗质片麻岩稀土元素配分图(a)与微量元素蛛网图(b)

Fig.6 Chondrite-normalized REE patterns (a) and primitive mantle-normalized trace element patterns (b) of the granitic gneiss from Yadong area

标准化数值据 Sun and McDonough(1989)

4.2 稀土和微量元素地球化学特征

亚东地区花岗质片麻岩稀土元素分配型式总体相似(图 6a), ΣREE 含量介于 $152.95 \times 10^{-6} \sim 339.16 \times 10^{-6}$, 稀土总量偏高; 轻重稀土比值(LREE/HREE)介于 $6.28 \sim 17.30$, $(\text{La}/\text{Yb})_N$ 比值介于 $9.17 \sim 58.46$, $(\text{La}/\text{Sm})_N$ 比值介于 $3.11 \sim 4.15$, 反映轻、重稀土元素分异程度很高。 δEu 和 δCe 值分别介于 $0.30 \sim 0.50$ 和 $0.79 \sim 0.97$ (表 3), 具有明显的负 Eu 异常和微弱的负 Ce 异常。

在稀土标准化配分模式图中(图 6a), 正片麻岩稀土元素表现为较缓右倾斜型, 总体具有轻稀土(LREE)富集、重稀土(HREE)亏损、较强 Eu 异常和微弱 Ce 异常的特征。这些特征表明该矿床斑岩体轻、重稀土强烈分异, Eu 异常暗示岩浆演化过程中结晶分异不占主导作用, 或源区缺少含 Eu 的矿物(马鸿文, 1990)。轻稀土强烈富集、重稀土亏损表明

岩浆区残留相中存在角闪石或石榴石(马鸿文, 1990; Shafiei *et al.*, 2008)。

亚东地区花岗质片麻岩微量元素经过原始地幔标准化后, 大离子亲石元素(LILE)与高场强元素(HFSE)具有明显的分异(图 6b), 显示 S 型花岗岩的特征(Pearce *et al.*, 1984; 雍拥等, 2008; 辜平阳等, 2013)。Rb、Th、U、K 等大离子亲石元素相对富集, Ba、Nb、Ta、Sr、P、Ti 等高场强元素明显亏损, 说明含水条件导致富含 Nb、Ta、Ti 的金红石等矿物稳定残留(Tatsumi *et al.*, 1986)。

5 讨论

5.1 岩石成因类型

亚东地区花岗质片麻岩地球化学特征显示, 该

表 3 亚东地区花岗质片麻岩稀土、微量元素含量及参数值

Table 3 REE and trace element contents and their parameter values of the granitic gneiss from Yadong area

样号	G03-1	G03-2	G03-3	G03-4	G03-5	G06-1	G06-2	G06-4
稀土元素(10^{-6})								
La	60.20	55.40	58.40	59.50	76.50	37.10	31.20	34.10
Ce	112.00	108.00	114.00	115.00	150.00	72.20	56.20	56.80
Pr	13.00	12.30	13.00	13.80	17.30	9.38	7.86	8.74
Nd	49.40	45.00	48.60	50.30	61.80	35.00	29.50	33.30
Sm	9.69	8.64	9.26	10.00	11.90	7.69	6.44	7.07
Eu	1.44	1.30	1.36	1.07	1.64	1.01	0.75	0.68
Gd	7.77	6.64	7.33	7.66	9.68	7.74	6.41	6.34
Tb	0.96	0.83	0.92	0.94	1.16	1.22	1.01	0.85
Dy	4.10	3.23	3.84	3.70	4.99	7.56	6.08	4.48
Ho	0.63	0.50	0.60	0.50	0.74	1.48	1.20	0.80
Er	1.50	1.11	1.34	1.10	1.72	3.81	3.11	2.02
Tm	0.19	0.14	0.16	0.13	0.22	0.52	0.42	0.27
Yb	1.09	0.77	0.96	0.73	1.32	2.85	2.44	1.56
Lu	0.16	0.11	0.14	0.10	0.19	0.40	0.33	0.22
Y	14.60	11.50	13.90	11.80	17.90	35.30	28.70	20.20
ΣREE	262.13	243.97	259.91	264.53	339.16	187.96	152.95	157.23
LREE	245.73	230.64	244.62	249.67	319.14	162.38	131.95	140.69
HREE	16.40	13.33	15.29	14.86	20.02	25.58	21.00	16.54
LREE/HREE	14.98	17.30	16.00	16.80	15.94	6.35	6.28	8.51
(La/Yb) _N	39.62	51.61	43.64	58.46	41.57	9.34	9.17	15.68
(La/Sm) _N	4.01	4.14	4.07	3.84	4.15	3.11	3.13	3.11
δEu	0.49	0.50	0.49	0.36	0.45	0.40	0.35	0.30
δCe	0.94	0.97	0.97	0.95	0.97	0.92	0.86	0.79
La/Sm	6.21	6.41	6.31	5.95	6.43	4.82	4.84	4.82
Eu/Sm	0.15	0.15	0.15	0.11	0.14	0.13	0.12	0.10
微量元素(10^{-6})								
Cr	64.0	112.0	71.7	61.8	41.3	19.2	20.1	21.9
Ni	16.20	30.60	19.10	17.00	12.30	6.95	8.34	8.94
Co	10.40	15.50	10.30	9.20	8.40	6.28	6.99	6.80
Li	152.0	245.0	172.0	126.0	126.0	53.4	65.6	56.7
Rb	222.0	358.0	281.0	108.0	206.0	199.0	103.0	66.1
Cs	19.00	32.60	31.80	21.80	17.00	13.70	10.20	8.71
Mo	0.07	0.11	0.09	0.13	0.13	0.15	0.09	0.27
Sr	194.0	175.0	172.0	95.3	214.0	57.5	32.2	20.8
Ba	245	261	254	120	260	306	245	204
V	78.3	113.0	78.6	79.3	66.0	50.5	57.3	53.5
Sc	11.40	20.00	13.20	10.50	11.40	11.00	7.45	5.44
Nb	26.6	38.2	29.0	29.9	23.1	14.1	15.3	13.8
Ta	2.13	2.91	2.21	2.36	1.73	1.15	1.18	1.05
Zr	70.0	75.4	53.9	71.0	108.0	151.0	110.0	137.0
Hf	2.26	2.46	1.84	2.37	3.68	4.70	3.47	4.22
Be	6.96	4.75	7.49	6.64	5.46	3.86	3.31	3.20
Ga	26.8	33.3	28.5	28.3	26.2	19.0	17.0	16.7
U	4.04	3.93	4.11	3.66	5.06	2.98	2.19	2.53
Th	33.0	30.8	32.1	32.7	41.7	32.2	23.2	30.5
La/Ta	28.26	19.04	26.43	25.21	44.22	32.26	26.44	32.48
Nb/Ta	12.49	13.13	13.12	12.67	13.35	12.26	12.97	13.14
Rb/Sr	1.14	2.05	1.63	1.13	0.96	3.46	3.20	3.18

岩体具有高的 SiO_2 、 Al_2O_3 、 Na_2O 、 K_2O ，低 Fe_2O_3 、 MgO 、 MnO 的特征。 P_2O_5 含量与大多数 S 型花岗岩的 P_2O_5 含量特征一致(王梁等,2015)。里特曼指数 σ 显示钙碱性的特征。在 $\text{SiO}_2 - \text{K}_2\text{O}$ 图解中,大多数样

品落入了高钾钙碱性系列区域(图 5a), DI 指数说明岩石分异程度不高, 在岩石成因类型判别图中(图 7a, 7b), 所有样品点均落入了未分异的 I、S、M 型花岗岩的区域内, 为一套分异程度比较低的花岗岩。

铝饱和指数 A/CNK 显示强过铝质 S 型花岗岩的特征。在 $A/CNK-A/NK$ 图解中, 所有样品均落入过铝质的区域(图 5b)。标准矿物分子中出现刚玉

而未出现透辉石, 具有典型强过铝质 S 型花岗岩的特征, 暗示是沉积岩同熔的结果(表 2; 刘洪等, 2016)。在 $Rb-Th$ 和 $Rb-Y$ 图解中(图 7c, 7d), 亚东地区花岗质片麻岩样品明显拟合在 S 型花岗岩演化曲线上, 明显不同于 I 型花岗岩; 在岩石成因类型判别图中(图 7e, 7f), 所有样品点均落入 S 型花岗岩的区域内。以上证据均表明, 亚东地区花岗质片麻岩

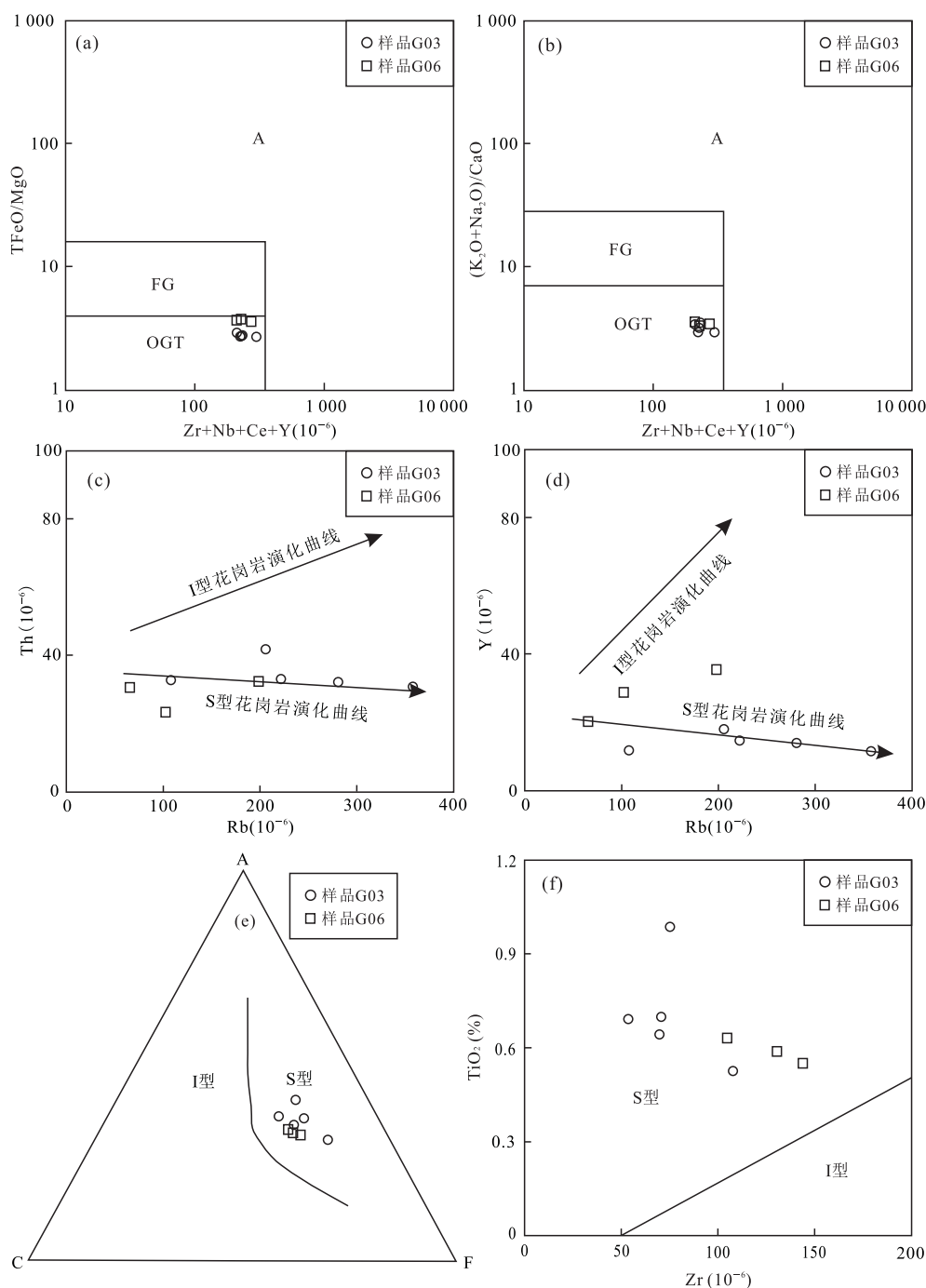


图 7 亚东地区花岗质片麻岩石成因判别图解

Fig.7 Discrimination diagrams for the genesis types of the granitic gneiss from Yadong area

底图 a, b 据 Whalen *et al.* (1987); 底图 c, d 据 Chappell and White (1992) 和 Chappell (1999); 底图 f 据 Jung and Pfänder (2007)

为未分异的钙碱性过铝质 S 型花岗岩类。

5.2 岩浆源区

亚东地区花岗质片麻岩轻、重稀土明显分异,相对富集 LREE 和 LILE 元素 (Rb、Th、U、K), 亏损 HFSE 元素 (Ba、Nb、Ta、Sr、P、Ti), 不相容元素 Ba、Sr、Nb、Ta、Ti 具有明显的负异常 (图 6), 表明岩体源区有陆壳组分参与。由于不相容元素具有相似的分配系数, 其比值不受分离结晶作用的影响, 因此常被用来指示源区特征 (朱弟成等, 2006)。亚东地区花岗质片麻岩 La/Ta、La/Sm 比值分别介于 19.04~44.22、4.82~6.43 (表 3), 不同于地幔源岩浆, 接近于地壳混染的岩浆 (Lassiter and DePaolo, 1997; 张招崇等, 2004); Nb/Ta、Eu/Sm 比值分别为 12.26~13.35、0.10~0.15, 接近平均地壳值 (分别为 11~13、0.16~0.20) (Hofmann, 1988; Green, 1995; Barth *et al.*, 2000); Rb/Sr 比值介于 0.96~3.46, 远远大于上地壳 Rb/Sr 比值 (大约为 0.32) 和大陆地壳平均 Rb/Sr 比值 (0.24), 不同于亏损 K、Rb 元素的上地幔 (Taylor and McLeannan, 1985)。以上稀土、微量元素特征均表明亚东地区花岗质片麻岩的源岩来自上部地壳 (表 3)。

前人研究发现, 酸性岩的成分与其源区密切相关, 源于泥质岩和砂质岩的富片麻岩均可作为 S 型花岗岩的母岩 (Brown and Pressley, 1999; 刘洪等, 2016)。亚东地区花岗质片麻岩具有较低的 SiO_2 含量、较高的 $\text{TFeO} + \text{MgO} + \text{TiO}_2$ 含量, 显示杂砂岩源岩的特征 (钟长汀等, 2007)。该区花岗质片麻岩的

$\text{CaO}/\text{Na}_2\text{O}$ 比值说明其源岩可能为富含斜长石、贫黏土的杂砂岩, 源区成熟度相对不高 (Sylvester, 1998; 肖庆辉等, 2002; 邓晋福等, 2004; 辜平等, 2013)。该区花岗质片麻岩强烈的负 Eu 异常, 可能是由于岩浆在部分熔融或分离结晶过程中大量斜长石晶出, 使原始流体强烈亏损 Eu, 也说明岩浆源区存在斜长石。Sr、Ba 是斜长石的相容元素, Rb 为不相容元素, 导致杂砂岩源岩具有较低的 Rb/Sr 和 Rb/Ba 比值 (Sylvester, 1998; 肖庆辉等, 2002; 邓晋福等, 2004), 在源岩判别图解中 (图 8), 亚东地区花岗质片麻岩样品主要落入杂砂岩源岩的范围, 也证实了杂砂岩来源的观点。

温度升高促使黑云母、钛铁矿等含钛矿物分解, 导致更多的 TiO_2 进入熔浆中, 因此 $\text{Al}_2\text{O}_3/\text{TiO}_2$ 比值是用作判别源区岩浆形成温度的标志 (Sylvester, 1998)。亚东地区花岗质片麻岩的 $\text{Al}_2\text{O}_3/\text{TiO}_2$ 比值介于 18.46~34.98, 均小于 100, 表明其部分熔融温度为高温 ($>875^\circ\text{C}$), 与杂砂岩熔融所需的高温条件一致 (辜平等, 2013), 可能是壳源杂砂岩在相对高温的条件下发生深熔作用的产物 (钟长汀等, 2007)。

5.3 大地构造意义

自从 Gansser (1964) 提出喜马拉雅造山带形成于早古生代的观点以来, 喜马拉雅造山带与泛非造山作用之间的关系一直成为该区域研究的热点问题之一 (辜平等, 2013)。中外地质学家在喜马拉雅地区先后做了大量定年工作, 认为喜马拉雅造山带是

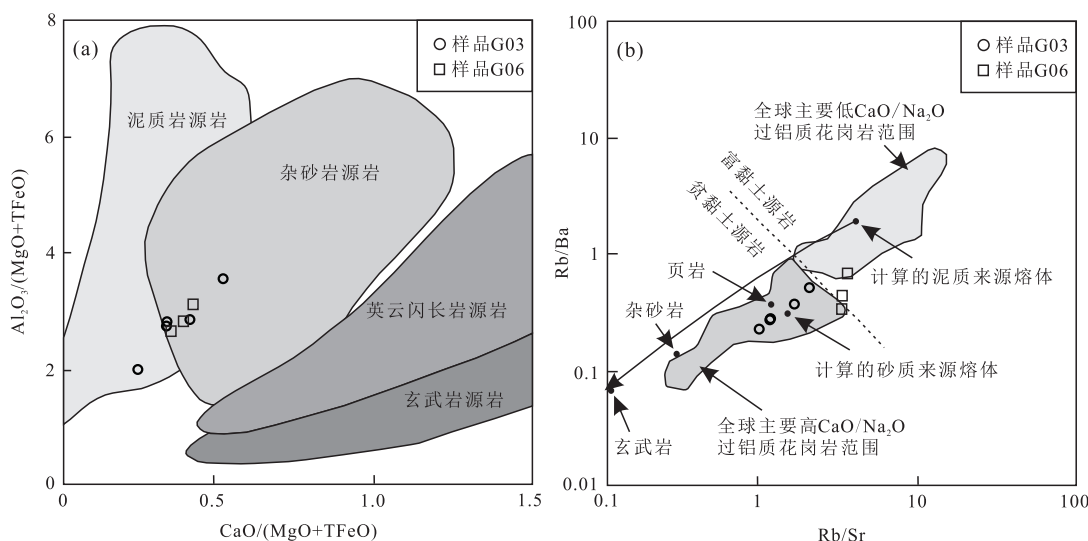


图 8 亚东地区花岗质片麻岩源岩判别图解

Fig.8 Discrimination diagrams for the source rocks of the granitic gneiss from Yadong area

底图 a 据 Gerdes *et al.* (2000); 底图 b 据 Sylvester (1998)

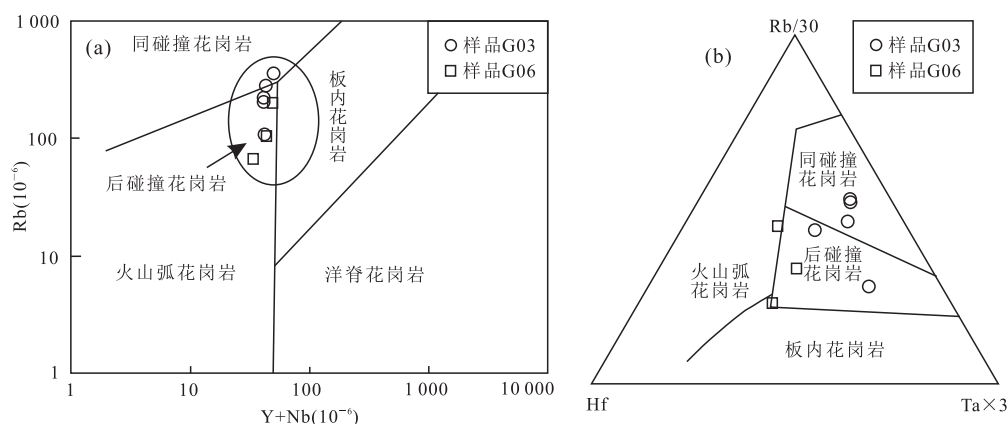


图 9 亚东地区花岗质片麻岩构造环境图解

Fig.9 Discrimination diagrams for the tectonic environment of the granitic gneiss from Yadong area

底图据 Pearce *et al.* (1984)

泛非—早古生代构造—热事件的产物 (Foster, 2000; Gehrels *et al.*, 2003; 许志琴等, 2005; 夏斌等, 2008; 张泽明等, 2008; 董昕等, 2009; 辜平阳等, 2013; 王晓先等, 2016)。

许志琴等 (2005) 研究发现, 亚东地区的含砂线石黑云斜长片麻岩形成年龄为 512 Ma, 是早古生代花岗岩变质作用的产物。Liu *et al.* (2006) 在亚东地区结晶岩中获得了大约 500 Ma 的岩浆事件年龄, 认为亚东地区属于泛非造山带的延伸部分之一。时超等 (2010) 对亚东地区片麻状含石榴石黑云母花岗岩闪长岩进行锆石 U-Pb 定年, 获得其结晶时代为 499.2 ± 3.9 Ma。唐磊 (2016) 对亚东地区的片麻岩进行定年研究, 获得了 496 ± 15 Ma ~ 507 ± 40 Ma 的岩浆事件年龄。同样, 在亚东西侧的吉隆地区发现了年龄为 474 ~ 514 Ma 的二云二长片麻岩 (王晓先等, 2011; Wang *et al.*, 2012; 蔡志慧等, 2013); 在尼泊尔境内的高喜马拉雅结晶岩系中也发现了约 486 Ma 的片麻岩 (Hodges *et al.*, 1996; Godin *et al.*, 2001; Gehrels *et al.*, 2003; Cawood and Buchan, 2007; 王晓先等, 2016)、455 Ma 的花岗质片麻岩 (王晓先等, 2016); 在印度北部的高喜马拉雅结晶岩系中获得了约 500 Ma 的片麻岩 (Bhanot *et al.*, 1979; Miller *et al.*, 2001; Spencer *et al.*, 2012)。

本文通过 LA-ICP-MS 锆石 U-Pb 方法对亚东地区花岗质片麻岩进行高精度测年, 获得的岩浆结晶年龄为 496.4 ± 4.0 Ma, 与前人研究成果吻合, 是泛非构造—热事件在亚东地区高喜马拉雅结晶岩系的地质记录, 说明亚东地区的结晶岩系在古生代早期卷入了泛非造山过程中。

前人研究发现过铝质花岗岩既可产生于同碰撞

早期挤压环境中 (Pitcher, 1983; Harris *et al.*, 1986), 也可产生于后碰撞伸展环境中 (Sylvester, 1998; Kalsbeek, 2001)。Sylvester (1998) 认为杂砂岩来源的强过铝质花岗岩通常产于未成熟的板块边缘 (岛弧、大陆弧) 等俯冲环境。亚东地区花岗质片麻岩具有高的 K_2O 含量、低的 σ 比值, 属于高钾钙碱性系列, 显示后碰撞岩浆活动的重要特征之一 (Zhao *et al.*, 1996; Liégeois *et al.*, 1998)。在构造环境判别图解中 (图 9), 花岗质片麻岩样品大多落入同碰撞花岗岩、后碰撞花岗岩和火山弧花岗岩叠加的位置, 说明亚东地区花岗质片麻岩形成于构造环境转换的地球动力学背景下, 由同碰撞的挤压环境向后碰撞的伸展环境转变, 这一过程中的降压和升温导致壳源杂砂岩发生熔融作用 (吴福元等, 2007; 辜平阳等, 2013)。

研究显示冈瓦纳大陆北缘喜马拉雅和冈底斯带是全球泛非运动持续时间最长、结束最晚的大陆边缘地区 (490 ~ 485 Ma) (周志广等, 2004; Song *et al.*, 2007), 本文获得的亚东地区花岗质片麻岩年龄介于 498.5 ± 14.7 Ma ~ 480.0 ± 11.7 Ma, 明显小于泛非造山作用所处的年代 (750 ~ 510 Ma), 说明泛非碰撞造山在亚东地区可能已经结束, 进入了后碰撞造山的构造演化阶段 (Meert, 2003; Cawood and Buchan, 2007)。泛非时期冈瓦纳大陆拼合之后, 冈瓦纳大陆北缘的亚东地区高喜马拉雅结晶岩系进入了后碰撞造山阶段, 导致壳源杂砂岩发生熔融作用形成具有强过铝质 S 型花岗岩特性的花岗质片麻岩。

6 结论

(1) 亚东地区花岗质片麻岩具有高 SiO_2 、

Al_2O_3 、 Na_2O 、 K_2O 含量,低 Fe_2O_3 、 MgO 、 MnO 含量,总体显示未分异的钙碱性过铝质 S 型花岗岩类的特征。

(2) 亚东地区花岗质片麻岩轻、重稀土明显分异,相对富集 LREE 和 LILE 元素(Rb、Th、U、K),亏损 HFSE 元素(Ba、Nb、Ta、Sr、P、Ti),不相容元素 Ba、Sr、Nb、Ta、Ti 具有明显的负异常。地球化学特征表明亚东地区花岗质片麻岩来源于上部地壳,可能是壳源杂砂岩在相对高温的条件下发生深熔作用的产物。

(3) 亚东地区花岗质片麻岩的岩浆结晶年龄为 496.4 ± 4.0 Ma,明显小于泛非造山作用所处的年代(750~510 Ma),说明该地区的花岗质片麻岩可能是在后碰撞造山阶段形成的。

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