阿尔金造山带南缘岩浆混合作用:玉苏普阿勒克塔格岩体岩石学和地球化学证据*

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Abstract The calc-alkaline granites of the Yusupuleke Tagh batholiths are associated with abundant mafic magmatic enclaves (MME) and aplite dikes. The granitc complex exhibits excellent evidence for magma mixing and mingling, such as the K-feldspar megacrysts in MME, long prisms of apatite, rapakivi feldspars (plagioclase-mantled K-feldspars), oikocrysts of quarts and feldspar-sphene ocelli. These suggest that mixing process of granitic and more mafic magmas induce the formation of the rapakivi texture. Textural evidence of the rapakivi magmas is better preserved in aplite than in the more deep-seated rapakivi granites formed by slow cooling, that indicate the decompression during crystallization of the magmas may promote the production of the mantled alkali feldspar megacrysts. Geochemical, there are linear arrays in binary diagrams. MME and host granitoids are considered cogenetic, and are hybrid rocks that were produced by the mixing of two components in different proportions. The granites are characterized by high Ga/Al, K_2O/Na_2O, Fe/Mg and low CaO, and showing A-type granite signatures but the aplites are peraluminous, high Na_2O, CaO, similar to more felsic, fractionated A-type granites. Chemical data suggest that the MME originated from the enriched mantle melts, whereas the felsic component was produced by partial melting of preexisting crustal materials. Deep-seated interactions between felsic and mafic magmas were responsible for the common characteristics of both magma suites. The chemical evolution of post-orogenic plutnism indicates mantle-crust interactions at decreasing depths in an actively extending orogen. The distinct composition and rapakivi-texture of the granitoids reflects two stages of hybridization and emplacement at the end of an orogenic cycle.

Key words Rapakivi texture; Disequilibrium texture; Mafic microgranular enclaves; Magma mixing; Yusupuleke Tagh granite complex; Altyn

摘 要 阿尔金造山带南缘玉苏普阿勒克塔格岩体中的似斑状中粗粒黑云钾长花岗岩发育有岩浆成因的暗色包体,并且该花岗岩被花岗细晶岩呈脉状侵入。该岩体含有丰富的岩浆混合作用特征:如暗色包体中的碱性长石斑晶、针状磷灰石、长石的环斑结构、石英/斜长石主晶和榍石眼斑等。暗色包体、寄主花岗岩和花岗细晶岩代表了岩浆混合演化过程中不同端元比例混合的产物。地球化学特征上,钾长花岗岩和暗色包体的主要氧化物含量在 Harker 图解中多呈线性变化。暗色包体主要为闪长质,MgO、K_2O 含量高,为钾玄岩系列,总体上高场强元素不亏损,显示了岩浆混合中的基性端元信息,可能为慢源熔体结晶分异或壳幔物质的混合产物。寄主花岗岩均为准铝质,富碱,为高钾钙碱性系列,亏损 Nb、Ta、Sr、P、Ti 等高场强元素,

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高 K_2O/Na_2O,富集高不相容元素,Ga 含量高,显示了 A 型花岗岩的特征,Th/U 和 Nb/Ta 比值分别介于为 6.67~10.96、8.99~11.94,代表了下地壳源区。花岗细晶岩均为钠质、过铝质,TiO_2、MgO 含量低,Na_2O 和 CaO 含量高,具有混合岩浆侵位后分异的特征。岩相学和地球化学特征说明岩浆混合作用对于环斑结构花岗岩的形成起到重要作用。花岗细晶岩中环斑长石的斜长石外环与钾长石内核的厚度比大于钾长花岗岩中的环斑长石,指示混合岩浆在一定的减压条件下更有利于环斑结构的形成。玉苏普阿勒克塔格岩体中的钾玄质暗色包体、高钾钙碱性花岗岩和中钾钙碱性花岗细晶岩代表了岩浆演化不同阶段的产物,反映了一个幔源岩浆和下地壳不断相互作用,引起地壳连续伸展减薄的过程,指示阿尔金南缘在早古生代末期存在造山后伸展背景下的幔源岩浆底侵作用。同一岩体中两种不同时代岩性的环斑结构显示了该岩体形成历史中的一定时空演化关系,代表了伸展过程中不同阶段的产物。

关键词 环斑结构;不平衡结构;暗色包体;岩浆混合作用;玉苏普阿勒克塔格岩体;阿尔金

中图法分类号 P588.121;P597.3

岩浆混合作用研究对于讨论大陆地壳物质演化、壳-幔相互作用和岩浆动力学等问题具有重要的科学意义(Wilcox, 1999; Wiebe *et al.*, 1997; 王涛, 2000; 李昌年, 2002; 莫宣学等, 2002; Sklyarov and Fedorovskii, 2006)。花岗质岩石中的镁铁质暗色包体(Vernon, 1991; Barbarin and Didier, 1992; Barbarin, 2005)和特殊的岩相学混合结构(Didier and Barbarin, 1991; Wilcox, 1999; Baxter and Feely, 2002; Hibbard, 1991; Andersson and Eklund, 1994; Müller *et al.*, 2000; Zhu, 1994; Zhu *et al.*, 2002; Zhu and Ogasawara, 2004)为认识岩浆混合作用过程和壳幔演化过程中花岗岩的成因提供了有效途径。

阿尔金造山带位于青藏高原北缘。早古生代花岗岩是阿尔金造山带主要演化事件的岩浆响应。然而由于受到阿尔金山恶劣的自然条件的限制,目前对阿尔金造山带的岩浆作用过程研究较为薄弱。本文以阿尔金南缘断裂带南侧玉苏普阿勒克塔格岩体中具有环斑结构的花岗岩、暗色包体和花岗细晶岩为对象,通过岩石学、地球化学研究,来讨论其成因和阿尔金造山带古生代岩浆作用过程,为深入认识阿尔金造山带的地质演化提供有力支持。

1 区域地质背景

阿尔金造山带地处青藏高原的北部边缘,介于塔里木板块、柴达木微板块以及祁连—昆仑造山带之间。阿尔金造山带是主体由早古生代古板块(或地块)之间相互俯冲-碰撞形成的复杂构造带。依据区内地质特征、岩石学以及地球化学和同位素年代学研究,该造山带由北向南依次可划分为阿北变质地体、北阿尔金红柳沟—拉配泉俯冲碰撞混杂岩带、阿中(米兰河—金雁山)地块、南阿尔金茫崖俯冲碰撞混杂岩带等四个构造单元(刘良等, 1999)(图 1)。

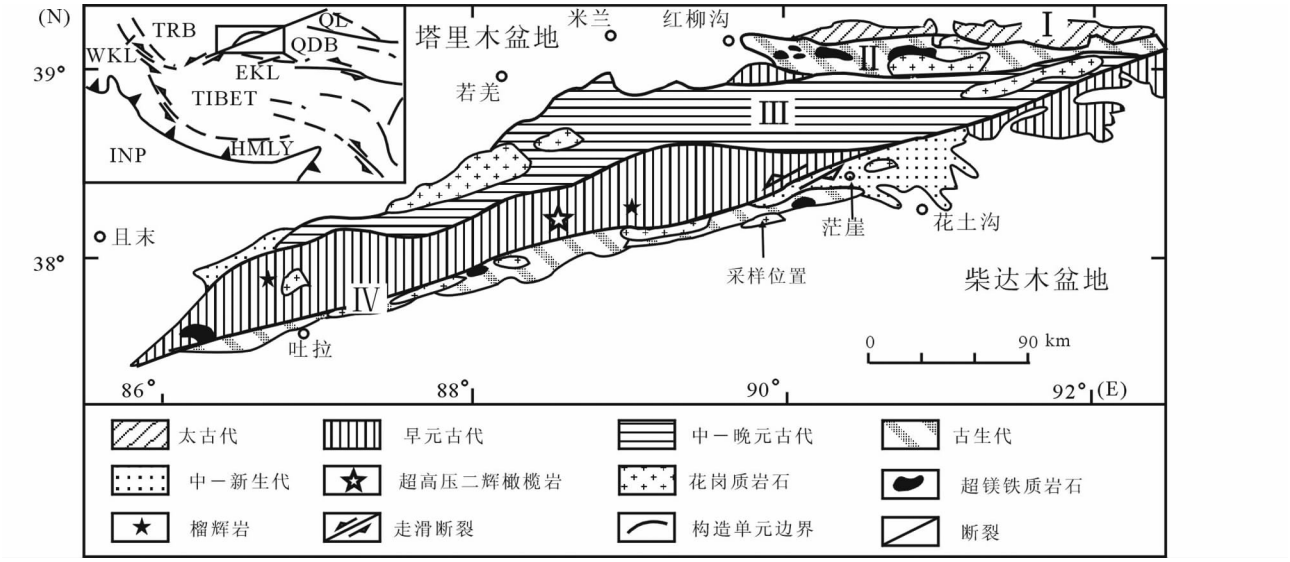


图 1 阿尔金及邻区构造地质略图(据刘良等,1996 等修改)

TRB-塔里木盆地; QL-祁连山; QDB-柴达木盆地; HMLY-喜马拉雅山; INP-印度板块; WKL-西昆仑山; EKL-东昆仑山. Ⅰ-阿北变质地体; Ⅱ-红柳沟-拉配泉混杂岩带; Ⅲ-米兰河-金雁山地块; Ⅳ-南阿尔金俯冲碰撞混杂岩带

Fig. 1 Geological sketch map of Altyn Tagh and its adjacent areas (after Liu *et al.*, 1996)

TRB-Tarim Basin; QL-Qilian Mountains; QDB-Qaidam Basin; HMLY-Himalaya Mountains; INP-Indian Plate; WKL-Western Kunlun Mountains; EKL-Eastern Kunlun Mountains. Ⅰ-North Altyn Tagh Archean complex; Ⅱ-Hongliugou-Lapeiquan melange; Ⅲ-Milanhe-Jinyanshan block; Ⅳ-South Altyn Tagh subduction - collision complex

南阿尔金俯冲碰撞混杂岩带主体由分布在阿尔金西部从米兰河以西直到且末县南部的中高级变质岩系和呈透镜体状产出于其中的榴辉岩等高压-超高压变质岩、蛇绿岩、花岗岩和少量碎屑岩所组成。其中,高压-超高压变质岩石的变质时代集中在约500Ma左右,正变质高压-超高压岩石原岩的形成时代多为1000~750Ma(Liu *et al.*, 2007)。蛇绿岩以茫崖石棉矿一带出露比较典型,其主要由蛇纹石化纯橄岩、方辉橄榄岩、基性火山岩、少量辉长岩组成。基性火山岩具有MORB的特征,其全岩Sm-Nd等时线年龄为492.7~481.3Ma(刘良, 1999)。依据这些资料分析,南阿尔金俯冲碰撞杂岩带应形成于早生代。该带西端的吐拉花岗岩体锆石SHRIMP U-Pb年龄为385.2Ma±8.1Ma,形成于中泥盆世末期造山后的伸展环境(吴锁平等, 2007)。但该带中的其它花岗质岩体尚未见有研究报道。

2 岩体野外地质和岩相学特征

本文研究的玉苏普阿勒克塔格岩体发育于阿尔金南缘主断裂之南,呈北东东向带状分布,北侧为茫崖蛇绿混杂岩,南侧被侏罗系河湖相碎屑岩不整合覆盖,时代被定为(O-D)①。由于该岩体地处阿尔金主断裂附近,岩体节理发育,与相邻地质体多呈规模较大的断层接触。通过野外工作,我们发现该岩体中似斑状中粗粒黑云钾长花岗岩具有环斑结构,并且其中还发育有岩浆成因的暗色包体,并且该花岗岩被灰白色具有环斑结构长石的花岗细晶岩呈脉状侵入。这些新发现均为本文的主要研究对象。

似斑状中粗粒黑云角闪钾长花岗岩

为暗色包体的寄主岩石,岩石呈浅肉红色,具似斑状结构,块状构造(图2a,b)。斑晶为微斜条纹长石(约45%)、更长石(An约10~30)(约25%)、石英(约25%)和黑云母(5%)等,其中微斜长石直径约为2cm~3 cm。副矿物为榍石、黄铁矿、磷灰石、锆石等。一些浑圆状钾长石斑晶边部被斜长石或斜长石集合体环绕,呈环斑结构(图2b)。斜长石环带厚度远小于钾长石。内核钾长石斑晶内包含有黑云母、角闪石、榍石、斜长石和石英,石英呈细脉枝状或环绕其中的斜长石分布(图2d),见部分石英包体被钾长石溶蚀。内核钾长石斑晶周围被角闪石、黑云母等暗色矿物环绕。

暗色包体

暗色包体的形态和成分存在变化,主要为闪长质,呈浑圆状,或细小斑杂状分布于钾长花岗岩之中(图2a)。包体为细粒半自形粒状结构,块状构造。主要组成矿物有角闪石(15%~25%)、黑云母(10%~25%)、斜长石(30%~50%)和石英(5%~10%),副矿物有榍石、磷灰石、锆石、金红石和钛铁矿等。黑云母为褐色,多发生绿泥石化。

花岗细晶岩

呈浅色脉体侵入钾长花岗岩之中。手标本呈灰色,似斑状结构(图2c)。斑晶含量占40%,主要为斜长石(约67%)、黑云母(约30%)和石英(约3%);基质含量占60%,主要为石英、斜长石和黑云母。斜长石多为中长石,具有环带结构;黑云母常见绿泥石化。副矿物为锆石、磷灰石和不透明矿物等。部分肉红色钾长石存在灰白色斜长石外环,大多数斑晶直径约1cm,呈环斑结构。斜长石环带厚度等于或大于钾长石。花岗细晶岩中环斑长石的斜长石外环与钾长石内核的厚度比大于钾长花岗岩中的环斑长石。

3 分析方法

全岩的主量和微量元素分析在西北大学大陆动力学国家重点实验室完成。主量元素分析在日本理学RIX2100 XRF仪上测定;微量和稀土元素是在美国Perkin Elmer公司Elan 6100DRC型电感耦合等离子质谱(ICP-MS)仪上进行的,样品测试经AVG-1和BHVO-1国际标样监控。

4 地球化学特征

寄主花岗岩、暗色包体和细晶岩的主量和微量元素分析结果见表1。

寄主花岗岩SiO_2含量介于63%~69%之间,高Ti(0.57%~0.89%),主体为准铝质(图3),富K_2O、Na_2O,$\sigma<3.3$,在TAS(Na_2O+K_2O-SiO_2)图解中(图略)落入钙碱系列,$K_2O/Na_2O>1$,在SiO_2-K_2O图解上(图3)均落于高钾钙碱性区域。$Mg^{\#}$($Mg^{\#}=Mg/(Mg+Fe^{2+}$(全铁))均高于0.42,表明它们可能受过幔源物质的混染(Rapp, 1997)。在稀土元素球粒陨石标准化配分图上(图4a),轻重稀土分异明显,富集轻稀土,$(La/Yb)_N=8.67\sim14.69$,具有中等的负铕异常($\delta_{Eu}=0.43\sim0.53$)。微量元素组成上,寄主花岗岩样品均显示富集Cs、Rb、Ba、Th、K等大离子亲石元素,亏损Nb、Ta、Sr、P、Ti等高场强元素。

暗色包体的地球化学有较大变化范围,SiO_2含量介于50%~57%之间,总体上MgO、K_2O含量高,ACNK<1,均为准铝质。大多数样品$K_2O/Na_2O>1$,在TAS图解中落入碱性系列,$\sigma=5.43\sim6.69>3.3$,在K_2O-SiO_2图中,所有样品均落入钾玄岩区域。不同暗色包体的稀土元素分馏不甚一致,总体上轻重稀土分异较寄主花岗岩弱(图4c);重稀土含量变化大,可能主要是由暗色包体中的暗色矿物和副矿物含量控制的。在微量元素原始地幔标准化蛛网图上,富集Cs、Rb、Ba、Th、K等大离子亲石元素,但总体上高场强元素不亏损。

花岗细晶岩的SiO_2含量介于70.18%~70.65%之间,MgO含量低(平均为0.9%),Al_2O_3含量高(>15%),低钛($TiO_2=$

① 西安地质矿产研究所. 2003. 1∶25万苏吾什杰幅区域地质调查报告

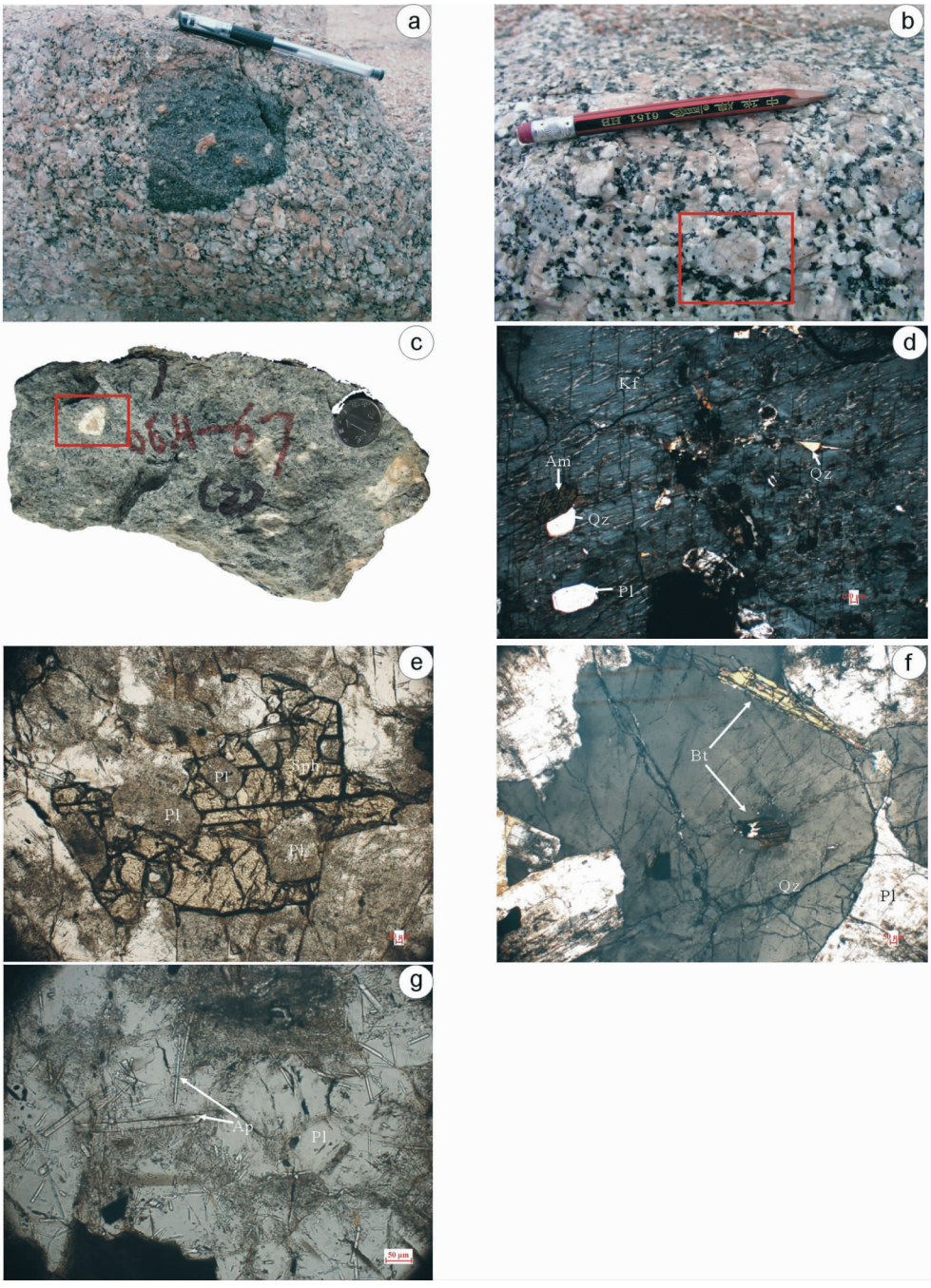


图 2 含暗色包体的钾长花岗岩和花岗细晶岩及各种岩石的镜下照片

a-似斑状钾长花岗岩中的暗色包体,包体中具有碱性长石斑晶;b-似斑状钾长花岗岩中的环斑长石,见红色方框;c-具有环斑长石的花岗细晶岩,红色方框内为环斑长石;d-环斑长石中钾长石内核含有石英、斜长石等包晶,部分石英呈脉枝状;e-榍石-斜长石眼斑;f-石英和斜长石主晶,花岗岩细晶岩中的石英内部包裹有早期形成的斜长石、角闪石和黑云母,斜长石内部浑圆状石英,在钾长花岗岩中也有类似现象;g-暗色包体中的针状磷灰石. 图 2d、f 为正交偏光,e、g 为单偏光照片;矿物代号:Kf-钾长石, Pl-斜长石, Am-角闪石, Bt-黑云母, Qz-石英, Sph-榍石, Ap-磷灰石

Fig. 2 Photographs showing the granite, aplite and the rock textures related to magma mixing

a-Mafic enclave (MME) hosted in Yusupuleke Tagh granite, and showing K-feldspar megacrysts in MME; b-Rapakivi feldspars in the moyite (indicated with red rectangle); c-Rapakivi feldspars in the aplite (indicated with red rectangle); d-Hornblende, quartz and plagioclase as xenocrysts in the cores of megacrystic alkali feldspar. Transimitted light image, cross-polarized light; e-feldspar-sphene ocelli. Transimitted light image, plane-polarized light; f-biotite xenocrysts in the oikocrysts of quarts. Transimitted light image, cross-polarized light; g-long prisms of apatite in the MME. Transimitted light image, plane-polarized light. Kf-K-feldspars, Pl-plagioclase, Am-Hornblende, Bt-biotite, Qz-quarts, Sph-sphene, Ap-apatite

表 1 玉苏普阿勒克塔格岩体中的暗色包体、钾长花岗岩和花岗细晶岩主量(wt%)、微量元素($\times10^{-6}$)分析结果

Table 1 Major (wt%) and trace elements ($\times10^{-6}$) composition of granite, MME and aplite from Yusupuleke Tagh

样品号	06A-60	06A-61	06A-63	06A-64	06A-69	06A-70	06A-66	06A-67(1)	06A-67(2)	06A-67(3)
岩性	钾长花岗岩				暗色包体			花岗细晶岩		
SiO_2	67.82	67.78	68.89	63.48	50.52	57.32	53.36	70.18	70.30	70.65
TiO_2	0.63	0.65	0.57	0.89	1.18	0.81	1.26	0.24	0.26	0.26
Al_2O_3	14.74	14.46	14.64	15.48	16.71	14.8	17.40	15.35	15.70	15.19
$Fe_2O_3^T$	3.93	3.82	3.38	5.34	12.38	9.15	9.37	2.59	2.53	2.61
MnO	0.06	0.05	0.05	0.07	0.21	0.17	0.15	0.04	0.04	0.04
MgO	1.45	1.39	1.28	2.02	4.03	3.23	3.97	0.91	0.90	0.89
CaO	2.78	2.79	2.3	3.73	5.30	3.04	5.43	3.01	3.02	2.96
Na_2O	3.01	3.60	3.01	3.18	4.17	2.00	3.61	3.61	3.84	3.89
K_2O	4.74	4.39	5.01	4.08	2.57	7.79	3.89	2.58	2.65	2.64
P_2O_5	0.15	0.15	0.13	0.22	0.35	0.20	0.30	0.11	0.11	0.11
LOI	1.00	0.91	0.73	1.15	2.85	1.01	1.47	0.90	0.82	0.67
TOTAL	100.31	99.99	99.99	99.64	100.27	99.52	100.21	99.52	99.54	98.91
K_2O/Na_2O	1.57	1.22	1.66	1.28	0.62	3.90	1.08	0.71	0.69	0.68
K_2O+Na_2O	7.75	7.99	8.02	7.26	6.74	9.79	7.50	6.19	6.49	6.53
K/Rb	203.00	196.84	204.03	193.13	135.33	151.05	127.57	68.79	139.44	126.27
σ(里特曼指数)	2.42	2.58	2.48	2.57	6.04	6.69	5.43	1.41	1.54	1.54
Be	3.18	3.30	3.29	3.44	2.46	6.29	6.07	1.47	2.72	2.91
Sc	8.43	8.41	7.92	11.85	5.23	22.23	21.12	3.71	5.50	5.51
V	48.81	48.70	42.26	73.67	31.26	91.73	138.41	14.20	27.87	28.03
Cr	23.13	18.02	15.77	26.63	8.05	60.47	28.24	6.97	5.99	5.67
Co	90.66	103.83	90.95	85.46	139.11	53.55	42.86	126.76	3.35	3.57
Ni	12.18	11.50	9.95	16.39	4.67	20.16	26.31	3.83	1.60	1.57
Cu	5.27	6.28	5.63	10.58	2.43	11.57	13.45	4.08	35.87	37.56
Zn	48.54	47.48	43.64	62.54	38.59	125.37	110.48	36.54	18.40	18.61
Ga	20.89	21.45	20.19	24.05	18.54	24.52	25.83	20.29	1.46	1.49
Rb	193.8	185.1	203.8	175.3	157.6	427.9	253.0	311.2	157.7	173.5
Sr	182.8	178.1	176.5	236.2	314.0	82.1	181.4	71.4	315.2	305.3
Y	43.13	44.51	51.19	40.33	17.34	88.64	35.26	42.41	17.46	18.94
Zr	212.0	288.3	272.2	355.9	148.9	280.9	304.1	115.6	155.1	143.7
Nb	19.54	20.11	20.14	22.33	15.10	35.72	26.04	7.32	15.08	15.49
Cs	6.27	6.60	6.69	5.17	11.82	20.12	13.87	4.92	11.98	14.23
Ba	682.2	521.0	568.3	696.3	448.1	506.3	335.2	601.3	451.8	426.7
La	58.25	69.55	53.70	74.21	31.19	14.89	28.61	34.88	31.38	23.46
Ce	117.49	137.74	113.20	144.28	57.46	49.79	58.88	73.64	58.16	42.35
Pr	12.42	14.21	12.29	14.70	5.86	8.34	6.86	8.00	5.94	4.33
Nd	47.02	52.92	48.05	54.73	20.99	42.60	27.50	30.82	21.25	15.67
Sm	8.88	9.61	9.78	9.59	3.75	12.88	5.87	6.84	3.79	2.97
Eu	1.39	1.32	1.34	1.61	0.75	0.89	0.90	0.99	0.78	0.73
Gd	8.40	8.94	9.31	9.01	3.54	13.12	5.91	6.74	3.40	2.84
Tb	1.28	1.34	1.47	1.28	0.52	2.33	0.93	1.14	0.51	0.46
Dy	7.54	7.81	8.81	7.38	2.89	14.64	5.59	7.07	2.91	2.83
Ho	1.46	1.52	1.72	1.41	0.56	3.00	1.14	1.45	0.59	0.60
Er	4.16	4.33	4.90	3.90	1.57	8.72	3.39	4.31	1.61	1.74
Tm	0.64	0.66	0.76	0.59	0.25	1.38	0.55	0.68	0.25	0.28
Yb	3.74	3.92	4.44	3.60	1.59	8.70	3.59	3.97	1.65	1.88
Lu	0.55	0.57	0.62	0.54	0.24	1.40	0.60	0.56	0.24	0.29
Hf	5.37	7.11	6.69	8.66	3.75	7.55	7.14	3.28	3.93	3.68
Ta	2.17	2.20	2.73	1.87	1.86	2.00	1.40	0.96	1.50	1.73
Pb	22.26	21.93	23.00	19.25	15.92	35.29	24.32	37.86	16.89	16.14
Th	25.86	32.82	36.31	24.77	12.50	7.62	10.03	23.68	14.17	13.53
U	3.14	3.71	3.31	3.71	2.67	2.09	3.41	2.34	3.02	3.24
Nb/Ta	8.99	9.15	7.38	11.94	8.11	17.86	18.62	7.66	10.04	8.96
Zr+Nb+Ce+Y	392.2	490.7	456.8	562.8	238.8	455.0	424.2	239.0	245.8	220.4
10000Ga/Al	2.68	2.80	2.60	2.94	2.10	3.13	2.80	2.50	0.18	0.19
$Mg^{\#}$	0.42	0.42	0.43	0.43	0.39	0.41	0.46	0.41	0.41	0.40
ACNK	0.97	0.92	1.01	0.94	0.87	0.86	0.87	1.08	1.07	1.04
δEu	0.49	0.43	0.43	0.53	0.63	0.21	0.47	0.45	0.66	0.77
$(La/Yb)_N$	11.16	12.74	8.67	14.79	14.07	1.23	5.71	6.31	13.62	8.93

$\sigma=(K_2O+Na_2O)^2/(SiO_2-43)$; $\delta Eu=Eu_N/(Sm_N+Gd_N)^{1/2}$; $Mg^{\#}=Mg^{2+}/(Mg^{2+}+Fe^{2+}(total))$, 其中 $Fe^{2+}(total)=wt\%\ (Fe_2O_3^T)/80$

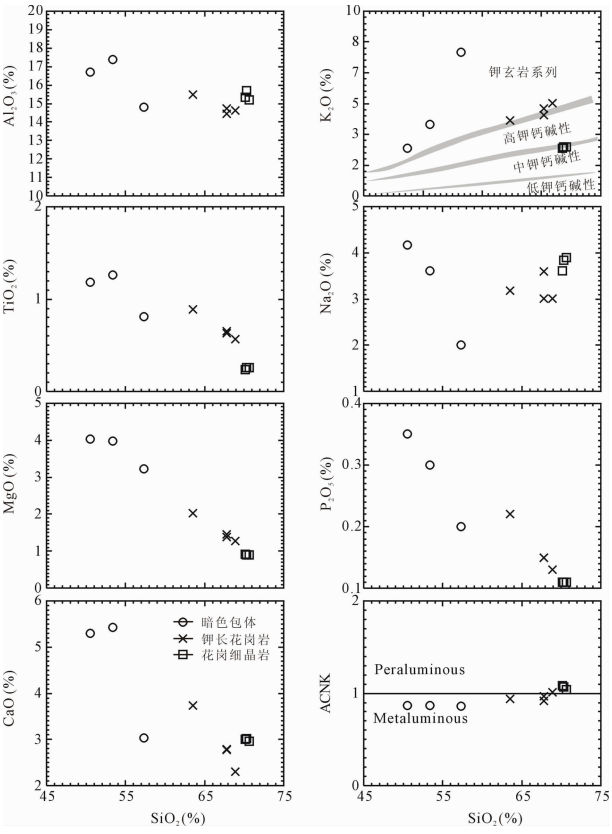


图 3 SiO_2 与主要元素协变图

Fig. 3 SiO_2 vs. other elements of granite, MME and aplite from Yusupuleke Tagh

0.24% ~ 0.26%)。K_2O、Na_2O 含量低 ($K_2O + Na_2O$ = 6.19% ~6.53%),K_2O/Na_2O <1,σ<3.3,为过铝质(ACNK =1.04 ~1.08);在 TAS 图解中落入钙碱系列,为中钾钙碱系列(图 3)。轻重稀土分异程度介于前两类岩石之间,$(La/Yb)_N$ =6.31 ~13.62,具弱的负铕异常(δ_{Eu} =0.45 ~0.77)。富集 Cs、Rb、Ba、Th、K 等大离子亲石元素, Nb、Ta 和 Ti 负异常明显(图 4f),总体上 Sr 异常不明显。

5 岩石成因

5.1 岩浆混合的岩相学证据

(1) 寄主岩石发育岩浆暗色包体(图 2a)。一些包体和寄主岩石呈截然关系,也常见过渡关系。这些花岗质岩石中的包体常具有岩浆岩结构,由于混合程度不均一,包体组分有差异。暗色岩浆包体的发育是岩浆混合的最直接证据。

(2) 暗色包体含碱性长石斑晶。碱性长石斑晶或环斑长石不仅发育于寄主岩石中,而且还发育于暗色包体及其边界之中(图 2a)。这代表了岩浆混合过程中酸性岩浆早期结晶的长石呈固态运移到基性岩浆(包体)中及边缘的结果(Vernon, 1991)。详细的微量地球化学和同位素特征也表明长石斑晶能够在长英质和镁铁质岩浆共存的条件下运移(Vernon and Paterson, 2008)。

(3) 发育环斑长石(图 2b,c)。钾长石斑晶外部被斜长石环绕形成的环斑结构与特定条件下岩浆的物理化学条件(温度和压力)变化相关。实验和岩石学研究资料表明形成环斑结构最有可能的机制有两种:① 两种不同组分和温度的岩浆混合作用 (Hibbard, 1991; Wark and Stimac, 1992; Müller *et al.*, 2005; 王晓霞等, 2005; Wang *et al.*, 2008); ② 岩浆上升过程中压力降低导致花岗质熔体结晶的产物(Nekvasil, 1991; Eklund and Shebanov, 1999)。在一定部位和时间内,基性岩浆注入到酸性岩浆的混合导致主岩浆温度异常升高和成分变化, 改变已晶出碱性长石斑晶平衡的结晶条件,当压力降低时,钾长石进入不稳定状态发生熔蚀,形成卵球状形态,斜长石呈新的晶体或以钾长石为内核开始成核结晶。在这一结晶过程中,斜长石在已有的碱性长石结晶中心上开始生长,形成斜长石外壳,即构成环斑结构长石。

(4) 常见楣石—斜长石眼斑(图 2e)。楣石通常与板状斜长石构成"辉绿结构"(Baxter and Feely, 2002),这种结构被斜长石 ± 石英 ± 钾长石组成的环带包围,周围没有黑云母和角闪石。这种结构发育于玉苏普阿勒克塔格岩体的暗色包体中。Hibbard (1991)认为这种结构是岩浆两阶段混合形成的。在初次混合时,镁铁质岩浆冷却导致斜长石和楣石结晶,在镁铁质岩浆中构成辉绿结构;再次混合使楣石-斜长石单元被斜长石、钾长石和石英环绕,和镁铁质岩浆的第二次混合引起部分结晶单元的分解,导致眼斑内部黑云母结晶。

(5) 含早期形成矿物包体的石英和斜长石主晶(图 2f)。花岗岩和花岗岩细晶岩中的石英内部包裹有早期形成的斜长石、角闪石和黑云母。斜长石内部包裹有黑云母和浑圆状石英等构成筛状结构。这种主晶通常被认为岩浆混合后,酸性和基性岩浆体系达到热平衡后的结晶产物(Vernon, 1991; Castro *et al.*, 1991; Hibbard, 1991; Andersson and Eklund, 1994)。

(6) 暗色包体中发育针状磷灰石(图 2g)。实验资料说明长柱状-针状磷灰石为岩浆快速冷却的产物(Wyllie *et al.*, 1962),通常被认为是岩浆混合过程中基性岩浆注入到温度较低酸性岩浆房中导致基性岩浆温度迅速下降的结果(Hibbard, 1991)。

上述岩浆混合成因花岗岩中的常见结构现象,表明该岩体的形成过程中曾发生过明显的岩浆混合作用。

5.2 岩浆源区性质及成因

岩浆混合的岩相学特征说明暗色包体、寄主花岗岩和细晶岩可看作为基性岩浆和酸性岩浆不同比例混合的产物,它们继承了部分相应端元的岩浆源区信息。由 Harker 图解可以看出,玉苏普阿勒克塔格岩体中 Na_2O 与 Al_2O_3 随着 SiO_2 含量的变化不呈明显的线性关系,而 MgO、MgO、P_2O_5 与 TiO_2 随着 SiO_2 含量的增加而减少,K_2O 随着 SiO_2 含量的增加而增加;另外,一些特征元素的比值不同,指示寄主花岗岩和暗

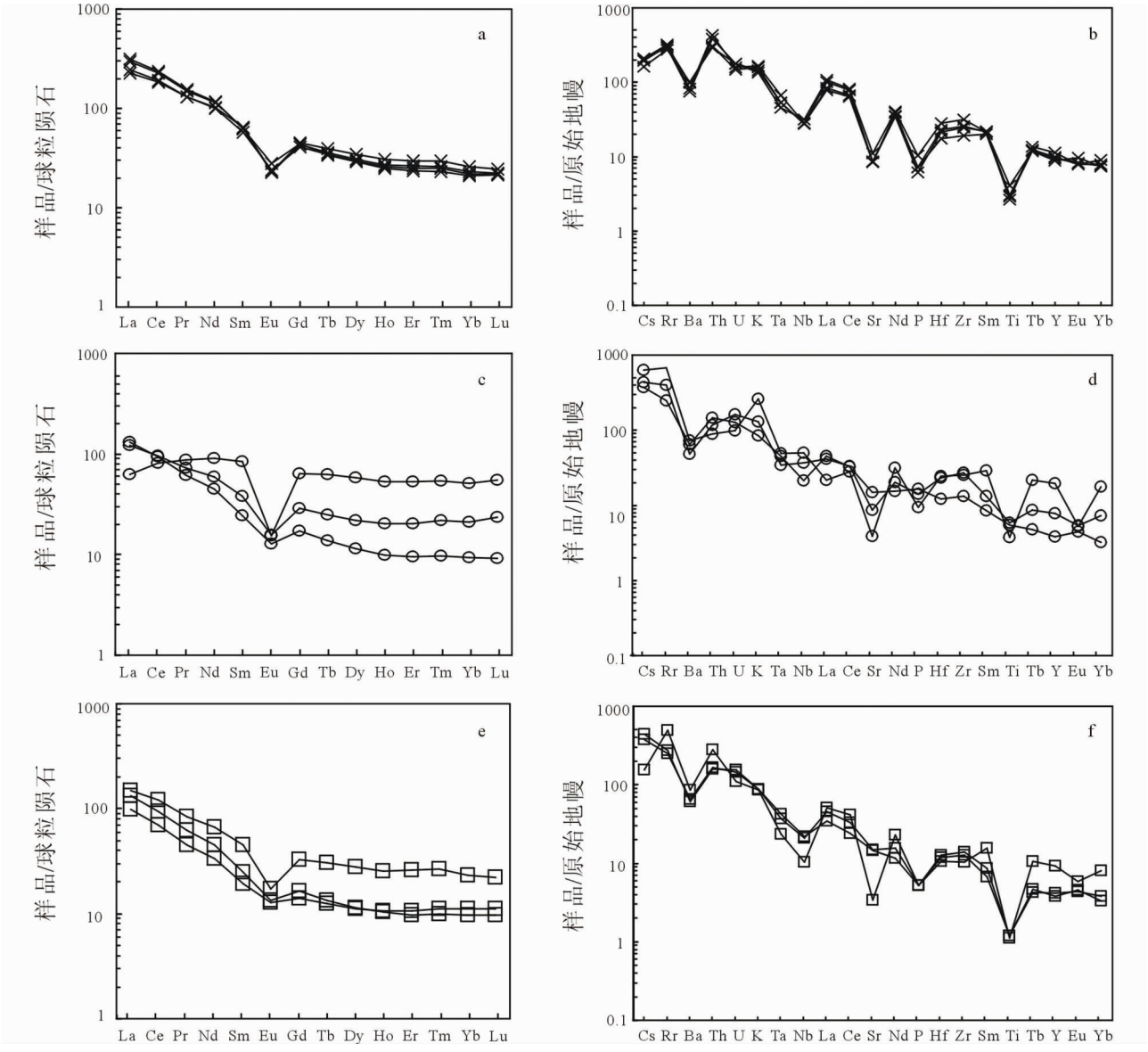


图 4 寄主花岗岩(a、b)、暗色包体(c、d)和花岗细晶岩(e、f)的球粒陨石标准化稀土配分图和微量元素原始地幔标准化蛛网图

球粒陨石标准化值和原始地幔标准化值均引自 Sun and McDonough, 1989。图例同图 3

Fig. 4 Chondrite-normalized REE-patterns and Primaitive-Mantle-normalized trace element patterns for the granite, MME and aplite from Yusupuleke Tagh

The chondrite and Primaitive-Mantle values from Sun and McDonough, 1989. Symboles as in Fig. 3

色包体可能来自于不同的岩浆源区,但线性关系也指示了二者存在岩浆混合的特征。

在 Rb-Y+Nb 图解上(图略),寄主花岗岩均落入板内花岗岩区域,富碱(高 K_2O+Na_2O),高 K_2O/Na_2O,富集高不相容元素($Zr+Nb+Ce+Y>350\times10^{-6}$; Whalen *et al.*, 1987),高 Ga(Ga/Al × 10,000 > 2.6; Whalen *et al.*, 1987),显示了 A 型花岗岩的特征。这些特征与大量环斑结构花岗岩的特征一致(Haapala and Ramö, 1999)。典型的环斑花岗岩常与铁镁质的岩石在时间和空间上密切共生,构成双峰式(长英质-铁镁质)组合特征。它们是同一构造-岩浆作用的结果,但起源于不同的源区(Haapala and Ramö, 1999)。

A 型花岗岩的源区可以来自于玄武质岩浆的分异或部分熔融,在成因上直接(如原始岩浆)或间接(提供熔融的热源)的存在地幔的贡献(Frost *et al.*, 2001; Turner *et al.*, 1992);也可以来自于地壳石英闪长岩或花岗闪长岩组分的部分熔融,并且由于熔融深度和氧逸度不同可以造成 A 型花岗岩组分的多样性(Patiño Douce, 1997; Dall'Agnol and Oliveira, 2007; Klimm *et al.*, 2008)。Frost and Frost (1997)

提出高 K_2O 和 $FeO^T/(FeO^T + MgO)$ 比值的还原型环斑结构花岗岩来自于幔源拉斑玄武岩的分异或底侵玄武岩的部分熔融。本文具有环斑长石的 A 型寄主花岗岩的 Th/U 比值为 6.67 ~ 10.96,与下地壳的 Th/U 比值(6.00, Rudnick and Gao, 2003)相近,Nb/Ta 比值 8.99 ~ 11.94,平均为 9.3,略高于下地壳的比值(8.3, Rudnick and Gao, 2003),与有角闪石和金红石残留的壳源花岗岩(≈9.00, Dostal and Chatterjee, 2000)几乎一致,指示该花岗岩为下地壳熔融的产物。

暗色包体则表现为钾玄岩的地球化学特征。钾玄岩可能形成于富集地幔的部分熔融(Bacon, 1990; Janoušek *et al.*, 2000)和玄武质岩浆的结晶分离作用(Meen, 1987)。阿尔金玉苏普阿勒克塔格岩体中的暗色包体富集大离子亲石元素和轻稀土元素。偏基性的暗色包体(样品 06A-69)的 MgO、FeO 含量高,Nb/Ta (=8) 比值低,Eu、Sr 和 Ti 的负异常很弱,说明源区可能不存在斜长石的残留。而其余暗色包体样品 MgO、FeO 含量稍低,K_2O 含量高,但其 Nb/Ta 比值约为 18,接近于原始地幔值(Nb/Ta = 17.5 ± 2.0),蛛网图(图 4d)中的 Ba、Ti 的负异常分别代表了黑云母和金红石的分异,Eu 和 Sr 的负异常说明存在斜长石分异。所以暗色包体并非纯的地幔熔体,可能为幔源熔体结晶分异或壳幔物质的混合。岩浆混合程度的不均一造成包体岩石组分会有差异,从而导致暗色包体的稀土配分模式不一致。

花岗细晶岩高 SiO_2,均为钠质,微量元素配分模式与花岗岩相近。Nb/Ta 比值 7.66 ~ 10.04,平均为 8.9,接近于下地壳的比值(8.3, Rudnick and Gao, 2003),与有角闪石和金红石残留的壳源花岗岩(≈ 9.00, Dostal and Chatterjee, 2000)一致,也指示了下地壳源区特征。但是 Nb、Ta 和 Ti 负异常更为明显,K/Rb 为 68.79 ~ 139.44 < 150,表明岩浆分异或水热作用明显(Dostal and Chatterjee, 2000),并且其形成时代比花岗岩晚 18Ma 左右(待发表数据),可能为分异的 A 型花岗岩(King *et al.*, 2001)。

A 型花岗岩代表了一个造山旋回末期(后造山或后碰撞)的伸展环境(Frost and Frost, 1997)。结合区域资料与上述岩石学和地球化学资料,玉苏普阿勒克塔格含暗色包体的环斑结构花岗岩体可被认为是热的幔源镁铁质岩浆底侵,使下地壳熔融,为基性和酸性岩浆发生混合作用不同阶段的产物。这一认识,为我们深入讨论 A 型花岗岩的成因和壳幔演化过程提供了良好的载体。岩浆的 K_2O 含量通常与来源深度存在正相关关系。熔融实验也表明压力控制着花岗质岩浆的 K_2O 含量(Skjerlie and Johnston, 1996),这在俯冲带环境(Ellam, 1992)、陆缘弧(Defant and Drummond, 1990)和后碰撞岩浆作用(王超等, 2007)中均有发现。玉苏普阿勒克塔格岩体中钾玄质暗色包体、具有 A 型花岗岩特征的的高钾钙碱性准铝质花岗岩和中钾钙碱性过铝质花岗细晶岩代表了来源于不同深度的岩浆演化不同阶段产物,反映了一个幔源岩浆和下地壳不断相互作用,引起地壳连续伸展减薄的过程。

5.3 结晶历史、混合机制和动力学

岩体中暗色包体显示了塑性特征,并且内部包含长石巨晶,表明岩浆混合开始时,酸性岩浆已经结晶出碱性长石斑晶,两种岩浆基本处于近液态-晶粥状态,两种岩浆基本为同时代的。寄主花岗岩中环斑长石中的钾长石斑晶内包含有黑云母、角闪石、榍石等暗色矿物说明基性岩浆侵位于高位酸性岩浆房之前已发生了结晶作用(图 2d)。斑晶内的的石英呈细脉枝状或环绕斜长石分布,另有部分石英包体被钾长石溶蚀,说明花岗质熔体在结晶早期迅速达到了低共熔状态。钾长石斑晶外围被角闪石、黑云母等暗色矿物环绕,说明这些镁铁质矿物在钾长石、斜长石和石英结晶后开始结晶,代表了镁铁质岩浆的侵入,而大量针状磷灰石的结晶又指示该基性岩浆的快速冷却。随着组分调整和压力条件变化,形成环斑结构长石。环斑长石斑晶外部的部分石英颗粒内部包含有早期形成的小颗粒石英和黑云母,这通常为酸性组分和基性组分达到热平衡的岩浆混合后的结晶现象(Vernon, 1991; Castro *et al.*, 1991)。

上述特征表明混合作用不是简单的单一过程,可能是个复杂的多期次作用过程。热的基性岩浆导致岩浆房中热量不稳定从而产生对流混合作用(Couch *et al.*, 2001)或母岩浆的再次补充(Klimm *et al.*, 2008)。这种运动导致两个端元体系间的晶体和化学组分发生多次交换,岩浆房中基性和酸性组分混合时间和空间的差异,可以引起两个端元混合时的相对比例和物理性质不同,从而产生不同结构和组分的暗色包体或基性物质团块(Janoušek *et al.*, 2004; Barbarin, 2005)。

花岗细晶岩中斜长石多为中长石,具有环带结构。中长石富 An 的内核可能代表了镁铁质岩石的残余斑晶,由于后期与更加酸性的岩浆发生混合和热的再调整,内部的富 An 斜长石会被溶蚀同时外部形成富 Ab 的斜长石外环。花岗细晶岩富 SiO_2,均为钠质、过铝质,具有高的 Na_2O 和 CaO 含量,表明酸性组分所占比例较大,其地质产状和地球化学特征又显示了岩浆混合后分异的特征(见上节)。

岩石基质的结构特征由水的含量控制 (Almashoor, 1980)。似斑状钾长花岗岩的粗粒基质表明了缓慢结晶过程,黑云母远比角闪石富集指示水含量较多。随着矿物结晶,岩浆中的水达到饱和,最后水压大于围岩压力,围岩发生破裂,岩浆侵入地壳的较高部位。这个过程反复持续直到岩浆达到次火山岩相,迅速结晶,从而产生细晶岩。花岗细晶岩和寄主花岗岩的形成时代分别为 406Ma 和 424Ma(待刊数据),花岗细晶岩的形成比花岗岩晚 18Ma 左右,花岗细晶岩的形成可能反映了一个岩浆上升减压过程花岗质熔体结晶的过程。

上述特征说明岩浆混合作用对于环斑结构花岗岩的形成起到重要作用。同一岩体中两种不同时代岩性的环斑结构代表了混合岩浆不同演化阶段的产物,显示了该岩体形成

历史中的一定时空演化关系。本文花岗细晶岩中环斑长石的斜长石外环与钾长石内核的厚度比大于钾长花岗岩中的环斑长石(图2b,c),表明混合岩浆在一定的减压条件下更有利于环斑结构的形成,环斑结构在快速冷却的次火山岩或接触带部位的花岗岩比深部就位缓慢冷却的花岗岩更容易形成,这与岩浆混合的产物通常保存在快速冷却的火山岩中一致(Anderson, 1976; Davidson *et al.*, 1998; Tepley *et al.*, 1999)。

6 结论

丰富的暗色岩浆包体、不平衡结构(环斑长石、被溶蚀的石英包体、针状磷灰石和石英眼斑等)和岩石地球化学等证据表明阿尔金南缘玉苏普阿勒克塔格花岗质岩体具有岩浆混合作用的信息。暗色包体、寄主花岗岩和花岗细晶岩代表了岩浆混合演化过程中不同阶段的产物。暗色包体主要提供了基性端元的信息,可能为幔源熔体结晶分异或壳幔物质的混合,而寄主花岗岩代表了下地壳源区。幔源岩浆的底侵导致下地壳的熔融从而形成不同比例端元(基性和酸性)混合的岩浆房。

花岗细晶岩富 SiO_2,均为钠质、过铝质, Na_2O 和 CaO 含量较高,表明酸性组分所占比例较大,其地质产状和地球化学特征又显示了混合岩浆侵入高位后分异的特征。细晶岩和花岗岩不同程度的环斑结构指示了混合岩浆不同阶段或不同深度的演化特征。似斑状钾长花岗岩的粗粒基质表明了缓慢结晶过程。随着矿物结晶,岩浆中的水达到饱和,最后水压大于围岩压力,围岩发生破裂,岩浆侵入到地壳的较高部位,产生细晶岩。花岗细晶岩中环斑长石的斜长石外环与钾长石内核的厚度比大于钾长花岗岩中的环斑长石,说明环斑结构在快速冷却的次火山岩或接触带部位的花岗岩比深部就位缓慢冷却的花岗岩更容易形成,指示混合岩浆在一定的减压条件下更有利于形成环斑结构。

玉苏普阿勒克塔格岩体中钾玄质暗色包体、具有A型花岗岩特征的高钾钙碱性花岗岩和中钾钙碱性花岗细晶岩代表了岩浆演化不同阶段的产物,反映了一个幔源岩浆和下地壳不断相互作用,引起地壳连续伸展减薄的过程,指示阿尔金南缘在早古生代末期存在造山后伸展背景下的幔源岩浆底侵作用。同一岩体中两种不同时代岩性的环斑结构显示了该岩体形成历史中的一定时空演化关系,代表了伸展过程中不同阶段的产物。

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赣东北前寒武纪港边火成杂岩体广泛发育不同类型的矿物间不平衡结构,指示该杂岩体曾发生过广泛的岩浆混合作用.对该杂岩体进行详细的薄片岩石学研究,总结了岩浆混合结构类型,包括斜长石环边、角闪石环带、文象钾长石的环斑结构与斜长石反环斑结构、石英-角闪石眼球状、钾长石巨斑的角闪石环和蜂窝状的斜长石等混合结构类型;镁铁质包体中指示岩浆混合作用的结构类型:石英/钾长石嵌晶结构、榍石-长石眼球结构、叶片状黑云母、针状磷灰石结构、斜长石的细条状结构、斜长石的蜂窝状环和斜长石的海绵式蜂窝状熔融结构,对这些结构类型进行了成因机理讨论.

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