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南祁连化隆地区鲁满山花岗岩的岩石成因: 地球化学、锆石 U-Pb 年代学及 Hf 同位素约束

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摘要: 位于南祁连化隆地区的鲁满山花岗岩体, 岩石类型主体为黑云二长花岗岩。LA-ICP-MS 锆石 U-Pb 定年测得其成岩年龄为(452.9±1.8) Ma, 属于加里东期岩浆活动的产物。化学组成上, 岩体具有高硅、富碱的特征, 属于弱过铝质高钾钙碱性系列。微量和稀土元素组成上, 岩体富集大离子亲石元素 Rb、U、Th、K 和 Pb, 亏损 Ba、Sr、Ta、Nb、P、Ti, 具明显轻稀土富集, 重稀土亏损特征, 显示较强烈的负 Eu 异常($\delta\text{Eu}=0.06\sim 0.55$, 平均 0.31), 综合地质地球化学资料指示该岩体应属于高分异的 I 型花岗岩。锆石 Hf 同位素分析结果显示, 岩体的 $\epsilon\text{Hf}(t)$ 为 -7.4~0.1, 二阶段模式年龄介于 1425~1930 Ma, 指示成岩过程中应有亏损地幔组分参与, 其壳源源区很可能包括化隆岩群。结合区域构造演化, 认为鲁满山花岗岩体形成于柴北缘洋壳与中南祁连陆壳俯冲碰撞的地球动力学背景下, 由幔源岩浆与其诱发的地壳物质熔融产生的长英质岩浆在地壳深部混合后再经历分异演化形成。

关键词: 锆石 U-Pb 年龄; 地球化学; Hf 同位素; 鲁满山花岗岩; 南祁连化隆地区

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Petrogenesis of Lumanshan granites in Hualong area of southern Qilian Mountain: Constraints from geochemistry, zircon U-Pb geochronology and Hf isotope

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Abstract: The pluton in Lumanshan of Hualong area, located in southern Qilian Mountain, is mainly composed of biotitic monzogranites. Zircon LA-ICP-MS dating yielded a concordant age of 452.9±1.8 Ma, indicating that the pluton was formed in Caledonian. Geochemical data show that the Lumanshan pluton is silica enriched in alkali. It is a weakly peraluminous granite and

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belongs to the high-K calc-alkaline series. In trace and REE aspects, the granites are enriched in Rb, Th, U, K, Pb and LREE and depleted in Ba, Sr, Ti, P with strong negative anomaly of Eu ($\delta\text{Eu}=0.06\text{--}0.55$ with a mean value of 0.31). Integrated geological and geochemical data suggest that the Lumanshan pluton should be genetically ascribed to highly fractionated I-type granites. The Hf isotope shows that the $\varepsilon\text{Hf}(t)$ values of the pluton range from -7.4 to 0.1 , with t_{DM2} ages between 1425Ma and 1930Ma, indicating that depleted mantle materials had been involved in magma formation and the source region of granite probably included the Hualong Group. In combination with comprehensive analysis of the tectonic evolution, the authors hold that the Lumanshan pluton was formed in a subduction-collision environment between the Qaidam and South Qilian terrane and most likely generated by mixing of a depleted mantle-derived magma and an induced crustal-melted felsic magma in the deep crust; later, it suffered further differentiation during magma ascent.

Key words: zircon U-Pb geochronology; geochemistry; Hf isotope; Lumanshan pluton; Hualong area of southern Qilian Mountain

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化隆地块位于祁连造山带南部,是祁连造山带的重要组成部分,由于发育有与Cu-Ni(-PGE)矿密切相关的基性-超基性岩体而倍受关注。对于化隆地块的研究,主要集中于前寒武系化隆杂岩的年代研究^[1-8]和与Cu-Ni(-PGE)矿有关的基性-超基性岩体的研究^[8-11]。但对其中的中酸性侵入岩浆作用研究相对薄弱,化隆地块内岩浆活动较频繁,花岗岩质侵入体较发育,前人对该区岩浆岩的形成时代进行了一些研究,如徐旺春等^[4]对侵入于化隆杂岩的弱片麻状花岗岩的锆石U-Pb年代学进行了研究,认为该花岗岩形成年龄为(875±8) Ma;万渝生等^[3]利用TIMS法获得侵入于化隆杂岩中的钾质花岗岩锆石U-Pb年龄为(750±30) Ma;青海地矿局^①对侵入于化隆杂岩内的尕吾山黑云母花岗闪长岩体进行Rb-Sr等时线定年,获得其形成时代为443 Ma,但总体研究仍较薄弱。另外,岩石成因、形成的构造背景及与构造演化的对应关系研究相对较少。位于化隆地块的鲁满山花岗岩体,是化隆地块中出露最大的花岗岩体,对该花岗岩体的研究,可为揭示南祁连化隆地区花岗岩体的形成机制提供重要资料。本文在详细野外工作的基础上,选择鲁满山花岗岩体进行岩石学、岩石地球化学、LA-ICP-MS锆石U-Pb年代学及Hf同位素研究,对其成岩时代、岩石成因以及动力学背景等进行初步探讨。

1 地质背景

化隆地块位于南祁连造山带东段,其前寒武系

基底出露于化隆盆地南部的关藏沟—尕吾山一带,呈北西-北北西向展布,北以拉脊山南缘断裂为界,南为青海湖—天水断裂(图1-a),主体以元古宇为主(图1-b),称为化隆杂岩,是一套以石英岩、黑云母石英片岩、黑云

斜长片麻岩、混合岩化片麻岩和混合岩为主体,变质程度较深的中-中深变质岩系。从下到上划分为智尕昂组、关藏沟组和鲁满山组,其与上覆古近一新近系呈角度不整合接触,局部为断层接触。

鲁满山花岗岩体是化隆地区出露面积最大的花岗岩体,沿尕吾南山—鲁满山一带分布,岩体侵入于化隆杂岩中(图1-c, 2-a),露头面积大约43 km²,总体呈圆形,受区内近东西向断层影响,该岩体被分割为南北两部分(图1-c),北侧花岗岩主要分布于尕儿郎寺一带,南侧花岗岩主要出露于鲁满山南坡,岩体呈不规则的长轴状,平均宽度5 km,长约12 km,岩体边界东侧较规则,大致顺围岩走向延伸,西侧边界不规则,呈港湾状。整个地区花岗岩体岩性为花岗闪长岩、黑云母二长花岗岩、斑状黑云母二长花岗岩,不同岩性之间呈渐变过渡关系,为同一期次不同岩相带分布的结果,岩体由内向外岩性分别为似斑状黑云母花岗岩和中细粒黑云母花岗岩(图1-c),局部可见暗色包体(图2-b)。

2 样品特征和分析方法

2.1 样品特征

本文研究样品采集于鲁满山花岗岩体的边缘

①青海省地质矿产局. 1:5万上加合一化隆回族自治区幅区域地质调查报告[R]. 1987.

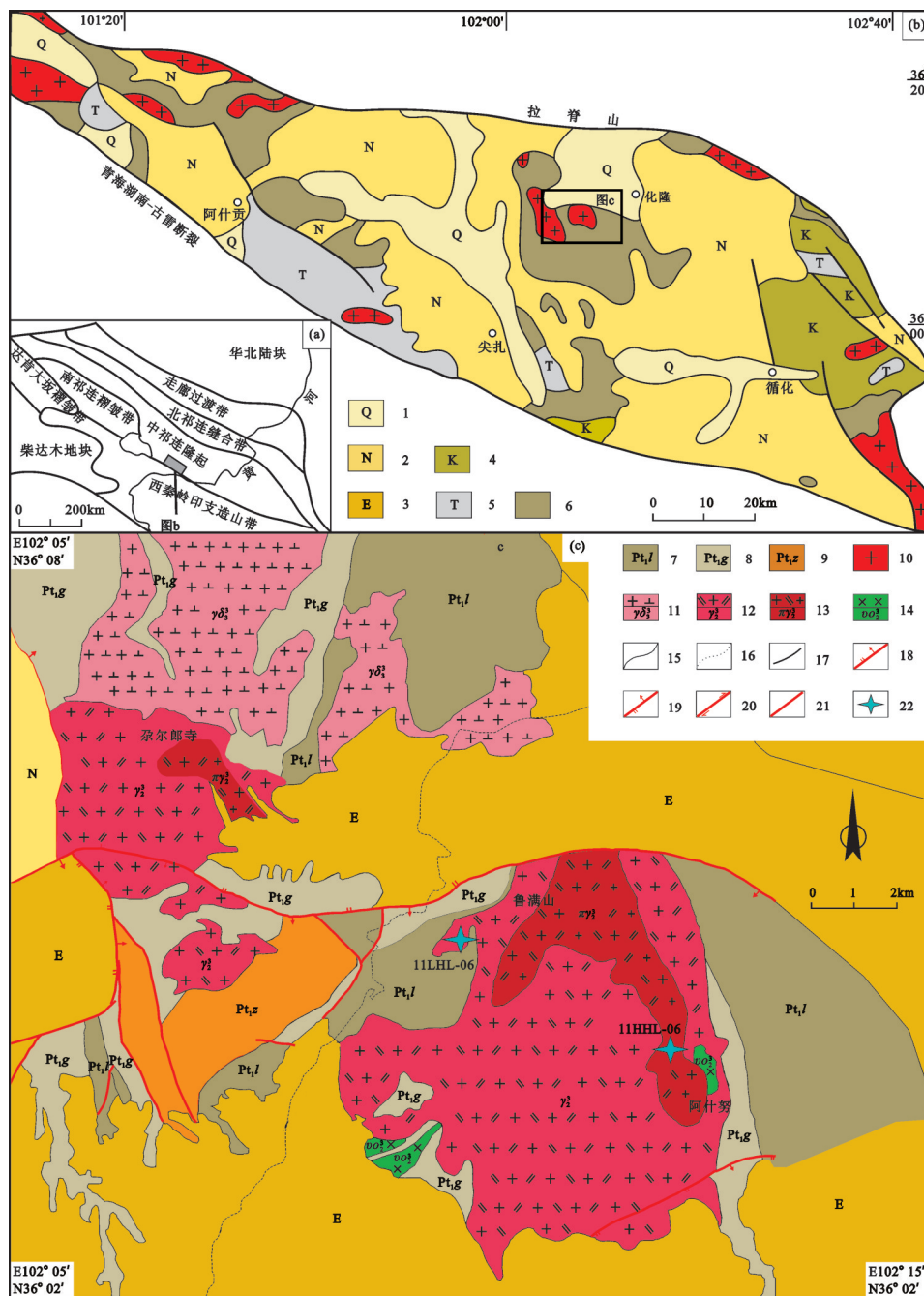


图1 化隆地区地质简图(据青海省地质矿产局,1987^①;徐旺春,2007^[4],有修改)

1—第四系;2—新近系;3—古近系;4—白垩系;5—三叠系;6—化隆杂岩;7—元古宇化隆群鲁满山组;8—元古宇化隆岩群关藏沟组;9—元古宇化隆岩群智昂组;10—花岗岩;11—花岗闪长岩;12—中细粒黑云二长花岗岩;13—似斑状黑云二长花岗岩;14—辉长岩;15—地质界线;16—推测界线;17—断层;18—逆断层;19—正断层;20—走滑断层;21—性质不明断层;22—采样位置及编号

Fig.1 Simplified geological map of Hualong (modified after ①[4])

1—Quaternary; 2—Neogene; 3—Paleogene; 4—Cretaceous; 5—Triassic; 6—Hualong complex; 7— Lumanshan Formation of Proterozoic Hualong Group; 8— Guanzangou Formation of Proterozoic Hualong Group; 9— Zhigang Formation of Proterozoic Hualong Group; 10—Granite; 11— Granodiorite; 12—Fine-medium grained biotite adamellite; 13—Porphyritic biotite adamellite; 14—Gabbro; 15—Geological boundary; 16—Inferred boundary; 17—Fault; 18—Thrust fault; 19—Normal fault; 20—Strike-slip fault; 21—Unknown fault; 22—Sampling position and its serial number

①青海省地质矿产局. 1:5万上加合一化隆回族自治区幅区域地质调查报告[R]. 1987.

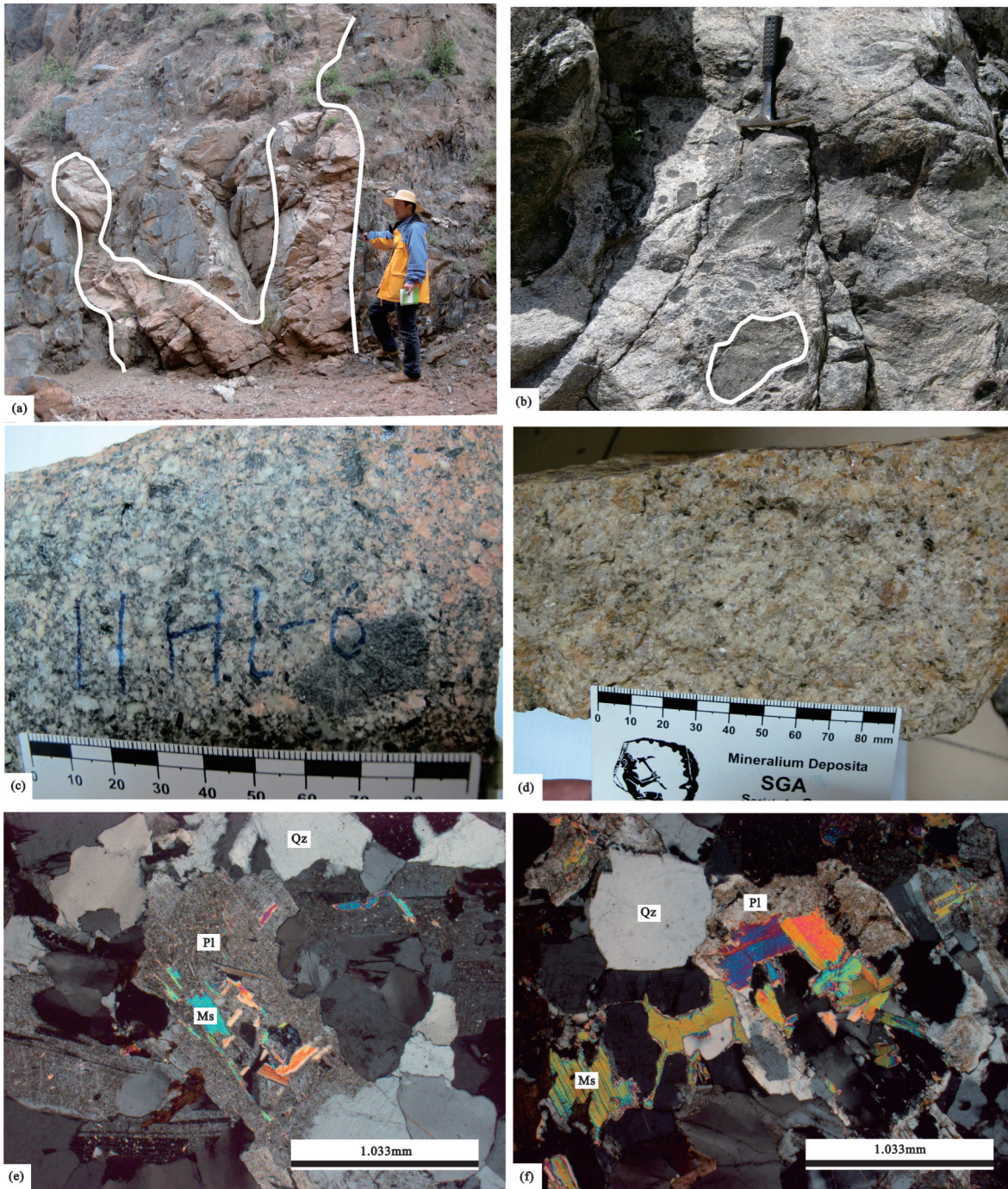


图2 鲁满山花岗岩的野外标本照片及镜下特征(正交偏光)

a—黑云二长花岗岩侵入于化隆群地层中; b—黑云二长花岗岩中的暗色包体; c—斑状黑云二长花岗岩(含有暗色包体); d—中细粒黑云二长花岗岩; e—中细粒黑云二长花岗岩的矿物成分和结构; f—斑状黑云二长花岗岩的矿物成分和结构; Pl—斜长石, Qz—石英, Ms—白云母

Fig. 2 Outcrop photograph and micrographs of Lumanshan pluton (crossed nicols)

a—Biotite adamellite that intruded into Hualong Group; b—Dark enclaves in biotite adamellite; c—Porphyritic biotite adamellite (with dark enclaves); d—Fine-medium grained biotite adamellite; e—Microphotograph of fine-medium grained biotite adamellite; f— Microphotograph of porphyritic biotite adamellite; Pl—Plagioclase; Qz—Quartz; Ms—Muscovite

相和中间相,其中边缘相采集化学样品6件(11LHL01、11LHL02、11LHL03、11LHL04、11LHL05、11LHL06),均位于化隆县鲁满山西侧地区,地理坐标为:36°4'44"N,102°9'33"E;中间相采集化学样6件(11HHL01、11HHL02、11HHL03、11HHL04、11HHL05、11HHL06),其中11LHL06号样品同时取测年样品,样品位于化隆县鲁满山南坡阿什努乡西北,地理坐标为:36°3'51"N,102°11'50"E。采样过程中注意避开岩石包体及蚀变严重地带,选择较为新鲜岩石采样,样品位置及编号如图1-c。

鲁满山中细粒黑云二长花岗岩,中细粒花岗岩结构,块状构造(11LHL06,图2-d),主要矿物组成为:斜长石(约30%)、钾长石(25%~30%)、石英(约30%)、黑云母(5%~10%)(图2-e)。斜长石矿物晶体形态多呈半自形板状,少数为粒状,粒径大小0.5~2 mm,晶体常有不同程度的绢云母化,少量具有钾化和绿泥石化。钾长石为条纹长石和微斜长石,晶体形态呈粒状,粒径大小一般0.5~2 mm。石英晶体呈粒状,粒径大小不等,介于0.5~3 mm,常呈波状消光。黑云母呈片状,粒径大小一般<1.2 mm。另见交代斜长石、黑云母形成的次生白云母,常呈细鳞片状产出。

鲁满山斑状黑云二长花岗岩(11HHL06,图2-c),似斑状结构,块状构造,主要矿物组成差异不大,斑晶约占30%,斑晶矿物有斜长石、钾长石、石英,主要矿物特征:斜长石(约占30%)形态多呈板状或粒状,粒径大小0.5~2 mm,晶体常有程度不同的绢云母化,少量长石具有钾化和绿泥石化,个别晶体局部被微斜长石交代,偶见交代蠕虫结构。钾长石(占25%~30%)为条纹长石和微斜长石,晶体形态呈粒状,粒径大小0.5~2 mm,见条纹长石与石英形成文象交生结构。石英(约占30%)晶体呈粒状,粒径大小不等,介于0.5~3 mm,常呈波状消光。黑云母(占5%~10%)呈片状,粒径大小一般<1.2 mm。多见呈片状、细鳞片状,可见交代斜长石、黑云母产出的次生白云母(图2-f)。

2.2 分析方法

花岗岩体的主量元素、微量元素、稀土元素分析在西安地质矿产研究所实验测试中心完成,其中主量元素采用X荧光光谱(XRF)进行分析,分析精度优于1%;稀土和微量元素利用SX-2型电感耦合等离子质谱仪(ICP-MS)进行测定,分析精度优于5%~10%。

锆石分选在河北区域地质调查研究所采用浮选和电磁选方法完成,锆石的CL图像在西北大学大陆动力学国家重点实验室电子探针仪加载的阴极发光仪上完成,LA-ICP-MS锆石U-Pb定年测试分析在中国地质科学院矿产资源研究所国家重点实验室完成。定年分析仪器为Finnigan Neptune型及与之配套的Newwave UP 213激光剥蚀系统,激光剥蚀所用斑束直径为25 μm ,以He为载气。详细实验测试过程可参见侯可军等文献^[12-14]。

锆石Hf同位素测试也是在中国地质科学院矿产资源研究所重点实验室Neptune多接收等离子质谱和Newwave UP 213紫外激光剥蚀系统上进行的,实验过程中采用He作为剥蚀物质载气,剥蚀直径采用55 μm ,分析点选择典型锆石与U-Pb定年分析点为同一位置。相关仪器运行条件及详细分析流程见侯可军等^[15-16]。

3 分析结果

3.1 锆石LA-ICP-MS定年

本次工作在化隆地区鲁满山采集了中细粒黑云二长花岗岩样品(11HH06),进行了LA-ICP-MS锆石U-Pb同位素分析,其结果见表1。

中细粒黑云二长花岗岩的锆石多为无色,近等轴状或柱状-长柱状晶型(长100~250 μm),长宽比为1:1~1:3,显微镜下及阴极发光照片显示,大部分锆石具有清晰的岩浆韵律环带(图3),环带一般比较窄,并见扇形分带(图3中的16测试点),为典型的岩浆成因锆石。锆石中并见继承锆石的残留核(图3中的3、20测试点)。

样品年龄较为复杂,其中2、5、6、7、8、12、15、17、20测试点分别给出了822 Ma、1330 Ma、884 Ma、1222 Ma、921 Ma、1443 Ma、911 Ma、877 Ma、1451 Ma的年龄值,为锆石的继承核年龄(图3),变化于822~1451 Ma。其余12个测点年龄介于451~457 Ma,在谐和线上位于一个范围较小的集中区,其加权平均年龄为(452.9 \pm 1.8) Ma (MSWD=0.38)(图4),代表了中细粒黑云二长花岗岩的结晶年龄。

3.2 主量元素特征

鲁满山花岗岩边缘相和中间相样品(11HHL和11LHL)具有相似的主量元素地球化学特征,除样品11HHL05、11LHL03和11LHL06的SiO₂含量略低

表1 鲁满山花岗岩LA-ICPMS锆石U-Pb定年分析结果
Table 1 LA-ICPMS U-Pb analyzed results of the zircons from the Lumanshan pluton

点号	含量/ 10^{-6}		Th/U	同位素比值										年龄/Ma						
	Pb	Th		U	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{208}\text{Pb}/^{232}\text{Th}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{208}\text{Pb}/^{232}\text{Th}$	1σ
11HHL06-1	74	35	23	1.52	0.05853	0.00089	0.58457	0.01062	0.07239	0.00060	0.00896	0.00090	550	33	467	7	451	4	180	18
11HHL06-2	45	14	13	1.14	0.07668	0.00145	1.43431	0.02948	0.13600	0.00191	0.02004	0.00314	1122	37	903	12	822	11	401	62
11HHL06-3	298	129	489	0.26	0.06101	0.00017	0.60964	0.00339	0.07248	0.00034	0.00808	0.00040	639	10	483	2	451	2	163	8
11HHL06-4	280	157	512	0.31	0.05733	0.00014	0.57894	0.00345	0.07326	0.00040	0.00624	0.00032	506	6	464	2	456	2	126	7
11HHL06-5	319	63	188	0.34	0.09337	0.00022	2.94762	0.01731	0.22915	0.00143	0.01735	0.00083	1495	4	1394	4	1330	8	348	17
11HHL06-6	103	33	65	0.50	0.07025	0.00026	1.42319	0.00954	0.14698	0.00086	0.01231	0.00086	1000	7	899	4	884	5	247	17
11HHL06-7	228	52	163	0.32	0.08241	0.00020	2.37253	0.01563	0.20878	0.00124	0.01556	0.00103	1255	6	1234	5	1222	7	312	20
11HHL06-8	145	22	220	0.10	0.07481	0.00020	1.58422	0.01102	0.15362	0.00105	0.02292	0.00171	1065	38	964	4	921	6	458	34
11HHL06-9	542	300	710	0.42	0.06242	0.00038	0.62813	0.00740	0.07300	0.00080	0.00650	0.00034	687	13	495	5	454	5	131	7
11HHL06-10	140	95	307	0.31	0.05608	0.00027	0.56853	0.00853	0.07346	0.00094	0.00574	0.00046	457	5	457	6	457	6	116	9
11HHL06-11	107	83	154	0.54	0.05625	0.00050	0.56299	0.00482	0.07261	0.00032	0.00519	0.00059	461	20	453	3	452	2	105	12
11HHL06-12	329	69	76	0.91	0.09660	0.00022	3.34120	0.01396	0.25086	0.00094	0.01796	0.00079	1561	5	1491	3	1443	5	360	16
11HHL06-13	155	82	328	0.25	0.05607	0.00032	0.56029	0.00576	0.07250	0.00071	0.00719	0.00076	454	18	452	4	451	4	145	15
11HHL06-14	80	48	374	0.13	0.05603	0.00019	0.56256	0.00446	0.07282	0.00052	0.00773	0.00065	454	3	453	3	453	3	156	13
11HHL06-15	366	116	172	0.68	0.07196	0.00023	1.50555	0.01131	0.15182	0.00111	0.01230	0.00091	985	1	933	5	911	6	247	18
11HHL06-16	254	139	475	0.29	0.05677	0.00015	0.56887	0.00539	0.07269	0.00066	0.00693	0.00074	483	6	457	3	452	4	140	15
11HHL06-17	165	48	136	0.35	0.06955	0.00020	1.39654	0.01271	0.14566	0.00128	0.01324	0.00158	917	6	887	5	877	7	266	31
11HHL06-18	175	78	222	0.35	0.06074	0.00057	0.61218	0.01890	0.07313	0.00219	0.00985	0.00167	632	20	485	12	455	13	198	33
11HHL06-19	378	199	602	0.33	0.06075	0.00022	0.61161	0.00737	0.07303	0.00086	0.00783	0.00069	632	3	485	5	454	5	158	14
11HHL06-20	800	174	132	1.32	0.09991	0.00023	3.48142	0.03209	0.25252	0.00210	0.02051	0.00135	1633	5	1523	7	1451	11	410	27
11HHL06-21	184	123	782	0.16	0.05847	0.00022	0.58868	0.00407	0.07301	0.00040	0.00596	0.00047	546	14	470	3	454	2	120	10

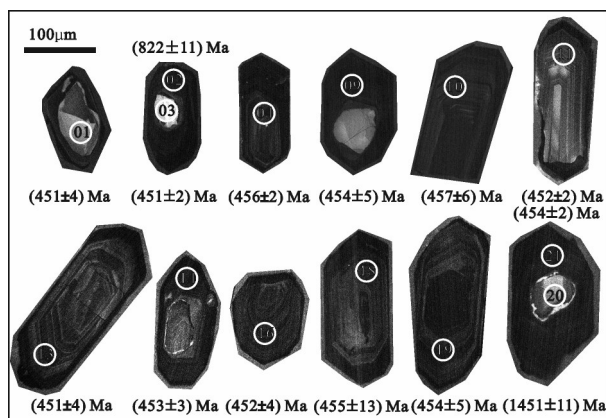


图3 鲁满山花岗岩代表性锆石的阴极发光图像
Fig. 3 Cathodoluminescence (CL) images of representative zircons from the Lumanshan pluton

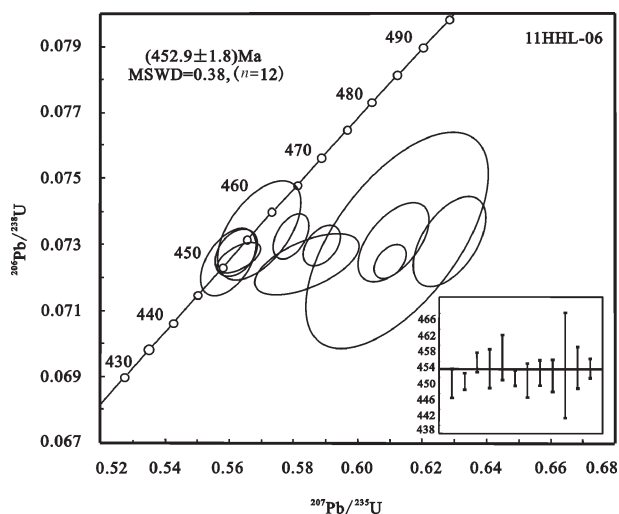


图4 鲁满山花岗岩锆石 U-Pb 年龄谱和图
Fig. 4 U-Pb zircon concordia diagram for the Lumanshan pluton

外,其他样品的 SiO_2 含量均在70%以上。主量元素含量: SiO_2 为63.89%~75.73%,平均71.83%, Al_2O_3 为12.90%~19.14%, P_2O_5 为0.04%~0.13%, CaO 为0.32%~2.26%, MgO 为0.15%~0.92%, $(\text{K}_2\text{O}+\text{Na}_2\text{O})$ 为7.12%~12.89%,平均8.48%, $\text{K}_2\text{O}/\text{Na}_2\text{O}$ 为0.89~2.39,平均1.60,铝饱和指数(A/CNK)介于1.04~1.17,大多集中在1~1.1,分异指数 $DI=81.23\sim 94.15$,平均为89.13。在 SiO_2 - K_2O 图解上(图5-a)大多落在高钾钙碱性系列区域,在A/CNK-A/NK图解上(图5-b),绝大多数落在过铝质和强过铝质分界线附近。总体上,鲁满山花岗岩具有高硅富碱特点,

属于弱过铝质高钾钙碱性系列。

3.3 微量和稀土元素特征

鲁满山花岗岩中间相和边缘相样品(11HHL和11LHL)具有相似的微量元素和稀土元素地球化学特征(图6)。微量元素蛛网图(图6-a)显示,鲁满山花岗岩富集大离子亲石元素Rb、U、Th、K和Pb元素,亏损Ba、Sr、Ta、Nb、P、Ti元素。稀土元素总量为 $198.22\times 10^{-6}\sim 359.16\times 10^{-6}$,平均为 252.47×10^{-6} ,LREE/HREE为2.24~15.68,平均8.96, $(\text{La}/\text{Yb})_N$ 为2.30~30.38,平均14.14,表明具有较明显的轻稀土富集,重稀土亏损特征。在稀土元素球粒陨石标准化图解(图6-b)上,显示较强烈的负Eu异常(δEu 为0.06~0.55,平均0.31),反映了形成它的花岗质熔体经历了高度的分离结晶作用,属于高演化岩浆体系^[19]。

3.4 锆石 Hf 同位素组成

在锆石U-Pb年龄测试之后进行了Hf同位素测试,分析结果见表3。锆石的 $^{176}\text{Yb}/^{177}\text{Hf}$ 比值范围为0.013279~0.061857, $^{176}\text{Lu}/^{177}\text{Hf}$ 比值范围为0.000353~0.001493, $^{176}\text{Lu}/^{177}\text{Hf}$ 比值均小于0.002,表明这些锆石在形成后,仅有较少的放射成因的Hf的积累,因而可以用初始 $^{176}\text{Hf}/^{177}\text{Hf}$ 比值代表锆石形成时的 $^{176}\text{Hf}/^{177}\text{Hf}$ 比值^[21]。样品的 $f_{\text{Lw/Hf}}$ 的平均值在-0.96~-0.99,明显小于镁铁质地壳的 $f_{\text{Lw/Hf}}$ 值(-0.34)^[22]和硅铝质地壳的 $f_{\text{Lw/Hf}}$ 值(-0.72)^[23],故二阶段模式年龄更能反映其源区物质从亏损地幔被抽取的时间(或其源区物质在地壳的平均存留年龄)。鲁满山花岗岩的初始 $^{176}\text{Hf}/^{177}\text{Hf}$ 比值介于0.282082~0.282502, $\varepsilon_{\text{Hf}}(t)$ 变化范围为-7.4~0.1,地壳模式年龄 t_{DM}^{C} 变化范围在1425~1901 Ma。

4 讨 论

4.1 岩石成因类型

花岗岩成因类型的判定是花岗岩研究最重要的基础问题,不同学者曾从不同角度提出过多种判别方法^[24-28]。从矿物组成上,角闪石、堇青石和碱性铁镁矿物被认为是判断I型、S型和A型花岗岩最有效的矿物学标志^[21,29],而鲁满山花岗岩体缺乏标志性矿物,从矿物学上难以划分成因类型。鲁满山花岗岩体具高的 SiO_2 含量(最高达75.37%)、全碱含量($\text{K}_2\text{O}+\text{Na}_2\text{O}=7.29\%\sim 12.89\%$)、较高的分异指数($DI=81.23\sim 94.15$,平均为89.13)以及明显的Eu负异常,

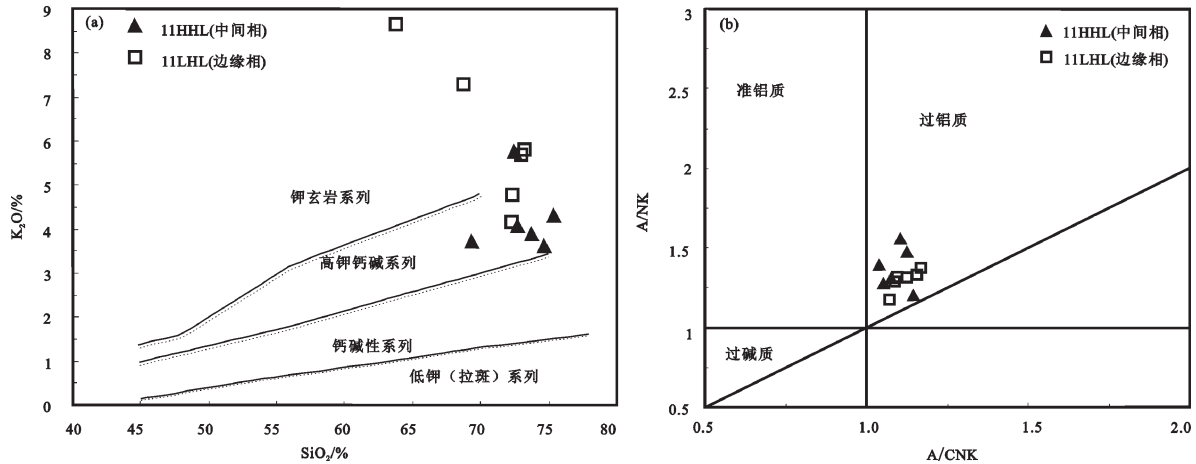


图5 鲁满山花岗岩的SiO₂-K₂O图解(a, 据Rickwood, 1989^[17])及A/CNK-A/NK图解(b, 据Peccerillo and Taylor, 1976^[18])
Fig. 5 SiO₂-K₂O (a, after Rickwood, 1989^[17]) and A/CNK-A/NK (b, after Peccerillo and Taylor, 1976^[18]) plots for the Lumanshan pluton

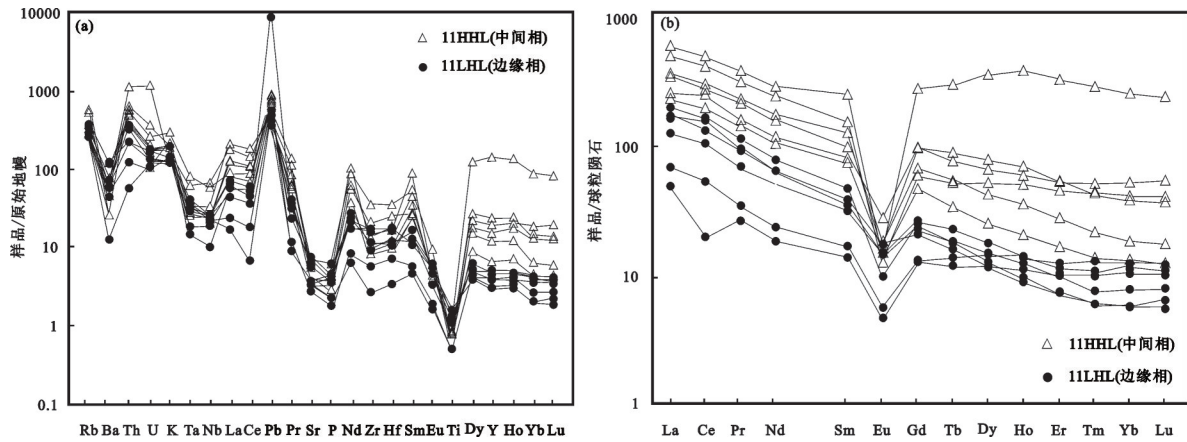


图6 鲁满山花岗岩的微量元素原始地幔标准化蛛网图(a)及稀土元素球粒隕石标准化配分曲线图(b)
(标准化数值据Sun和McDonough, 1989^[20])

Fig. 6 Chondrite-normalized REE patterns (a) and primitive mantle-normalized trace element patterns (b) for the Lumanshan pluton (normalized data after Sun and McDonough, 1989)

表明其经历了较高程度的结晶分异,但其FeO*/MgO比值集中在2.44~5.70,又区别于A型花岗岩显著富铁的特征(FeO*/MgO>10)^[26]。实验研究表明,在准铝质到弱过铝质岩浆中,磷灰石的溶解度很低,并在岩浆分异过程中随SiO₂的增高而降低;而在强过铝质岩浆中,磷灰石溶解度变化趋势与此相反,随SiO₂的增加而增高或基本保持不变^[30],磷灰石在I型和S型花岗岩浆中这种不同行为已被成功地用于区分I型和S型花岗岩类^[27,31-32]。本文数据表明,鲁满山花岗岩体的P₂O₅含量较低(0.04%~0.13%),明显不同于S型花岗岩常具较高P₂O₅含量(>0.20%)^[27]

的特征,在SiO₂-P₂O₅图解上(图7-a),P₂O₅随着SiO₂的增加而降低,在Rb-Th图解上(图7-b),Rb、Th之间呈正消长演化趋势,均与I型花岗岩演化趋势一致^[30,33]。另外,鲁满山花岗岩体的A/CNK值主要介于1~1.1,也不同于典型S型花岗岩A/CNK>1.1的特征^[24,33]。因此,笔者认为鲁满山花岗岩体应属高分异的I型花岗岩。

4.2 源区特征

研究表明,不同的源岩可以熔出不同的花岗质岩浆^[34]。早期研究一般认为,I型花岗岩的源岩是地壳深部中基性变火成岩^[24,35]。然而,近年基于锆石

表2 鲁满山花岗岩的主量元素(%）、微量元素(10^{-6})分析结果
 Table 2 Analyzed results of major elements (%) and trace elements (10^{-6}) of the Lumanshan pluton

样号	11HHL01	11HHL02	11HHL03	11HHL04	11HHL05	11HHL06	11LHL01	11LHL02	11LHL03	11LHL04	11LHL05	11LHL06
SiO ₂	75.37	73.76	72.45	74.67	69.36	72.65	72.36	73.24	63.89	72.35	73.04	68.83
Al ₂ O ₃	13.62	13.86	14.10	13.54	15.47	14.08	12.90	13.59	19.14	14.73	13.85	16.63
Fe ₂ O ₃	0.13	0.45	0.51	0.14	0.98	0.47	1.06	0.89	0.46	1.01	0.68	0.25
FeO	0.97	1.16	0.88	0.77	1.61	1.48	2.34	1.17	1.12	0.43	0.61	0.26
CaO	0.32	1.86	1.27	1.25	2.26	1.63	0.91	0.82	0.83	0.99	1.14	1.31
MgO	0.22	0.47	0.43	0.18	0.92	0.67	0.52	0.32	0.53	0.15	0.20	0.15
K ₂ O	4.33	3.87	5.73	3.63	3.72	4.07	4.76	5.77	8.63	4.13	5.67	7.29
Na ₂ O	4.01	3.49	2.77	4.06	3.57	3.11	2.83	2.43	4.26	3.83	2.69	3.05
TiO ₂	0.11	0.16	0.17	0.11	0.35	0.26	0.34	0.24	0.17	0.21	0.20	0.16
P ₂ O ₅	0.04	0.08	0.08	0.05	0.13	0.10	0.08	0.05	0.05	0.12	0.07	0.06
MnO	0.05	0.04	0.03	0.02	0.05	0.04	0.07	0.03	0.02	0.02	0.05	0.02
灼失量	0.82	0.81	1.57	1.59	1.59	1.44	1.78	1.46	0.89	2.05	1.81	2.00
总量	99.99	100.01	99.99	100.01	100.01	100.00	99.95	100.01	99.99	100.02	100.01	100.01
K ₂ O+Na ₂ O	8.34	7.36	8.50	7.69	7.29	7.18	7.59	8.20	12.89	7.96	8.36	10.34
K ₂ O/Na ₂ O	1.08	1.11	2.07	0.89	1.04	1.31	1.68	2.37	2.03	1.08	2.11	2.39
FeO*/MgO	4.45	3.00	2.80	4.48	2.44	2.56	5.70	5.54	2.60	8.03	5.50	2.91
DI	94.15	86.56	89.55	91.08	81.23	85.47	87.49	90.41	90.86	90.84	90.91	91.01
A/CNK	1.15	1.04	1.08	1.05	1.10	1.13	1.13	1.16	1.07	1.17	1.10	1.09
Cu	3.41	12	5.27	4.56	7.15	4.69	10	3.57	2.68	2.88	2.13	2.91
Pb	29.1	26.6	37.3	31.1	36.4	658	38.4	49.2	61.7	51.9	53.9	58
Cr	5.45	6.1	8.28	4.42	12.4	8.38	4.94	1.92	1.4	0.98	1.78	3.24
Ni	3.54	3.28	4.43	23.8	6.36	5.58	2.9	1.31	0.87	0.88	0.65	1.27
Co	1.33	2.72	2.67	1.7	4.55	3.88	1.84	1.27	0.92	1.63	1.03	0.56
Rb	226	179	230	161	202	175	186	233	346	205	233	327
Cs	4.33	4.42	4.14	2.94	10.2	4.43	2.71	3.89	3.11	3.39	2.39	3.52
Mo	0.53	0.34	1.14	0.37	0.28	0.46	0.9	0.63	0.26	0.73	0.56	0.5
Sr	56.5	117	156	75.4	148	158	87	70.4	66	65.2	63.6	93.8
Ba	322	293	818	87.3	426	467	580	533	332	182	325	500
Nb	15	18.1	7.3	16.5	18.3	13.5	47	23.4	41.6	23.1	18.4	16.3
Ta	1.46	1.67	0.59	1.11	1.23	0.76	2.54	1.19	3.25	1.41	1.03	1.08
Zr	62.9	102	124	29.5	192	172	390	226	212	107	155	91.9
Hf	2.17	3.2	3.6	1.05	5.41	5.04	10.9	7.57	7.61	4.04	5.58	2.97
Ga	14.9	17.8	14.5	14.7	18.3	16.2	29.2	22.8	26.5	23.2	21.2	19.7
U	2.06	2.62	3.43	2.5	2.85	3.64	4.18	3.62	5.33	24.2	7.38	2.2
Th	10.4	27.8	18.6	4.75	18.7	30.5	34.4	34.6	46.6	94.8	51.8	40
La	16.4	48	41.5	11.7	30.2	39.7	120	83.4	61.2	142	88.3	53.6
Ce	32.8	104	82.2	12.2	64.2	94.8	256	173	153	309	185	121
Pr	3.26	11	8.84	2.52	6.62	9.03	30.4	20.6	15.3	37	22.4	13.7
Nd	11.1	36.5	29.4	8.56	23.6	29.8	114	74.4	54.5	137	82.1	49.5
Sm	2.53	7.27	5.33	2.1	4.83	5.9	23.8	15.2	12.3	38.5	19.6	11.4
Eu	0.32	0.56	1.02	0.27	0.84	0.79	1.6	1.09	0.72	0.99	0.84	0.9
Gd	2.61	5.36	4.23	2.55	4.48	4.87	20.2	13.8	12.2	58.1	20	9.6
Tb	0.44	0.84	0.59	0.5	0.67	0.66	2.82	2.04	1.93	11.4	3.29	1.26
Dy	2.94	4.41	2.92	3.64	3.65	3.12	16.4	10.8	13.2	92	20	6.36
Ho	0.62	0.78	0.5	0.79	0.68	0.53	3.35	2.03	2.87	21.8	3.93	1.15
Er	1.64	1.88	1.22	2.01	1.58	1.19	8.91	4.57	7.42	55.2	8.83	2.7
Tm	0.25	0.27	0.15	0.33	0.19	0.15	1.29	0.54	1.1	7.58	1.11	0.34
Yb	1.78	1.97	0.98	2.14	1.31	0.95	8.88	3.12	7.09	44.3	6.56	2.17
Lu	0.26	0.27	0.14	0.3	0.2	0.16	1.38	0.44	1.02	6.06	0.93	0.31
Y	17.7	20.7	13.2	23.3	17.7	14	86.5	54.2	68.8	63.9	106	29.8
ΣREE	76.95	223.11	179.02	49.61	143.05	191.65	609.03	405.03	343.85	960.93	462.89	273.99
LREE	66.41	207.33	168.29	37.35	130.29	180.02	545.80	367.69	297.02	664.49	398.24	250.10
HREE	10.54	15.78	10.73	12.26	12.76	11.63	63.23	37.34	46.83	296.44	64.65	23.89
LREE/HREE	6.30	13.14	15.68	3.05	10.21	15.48	8.63	9.85	6.34	2.24	6.16	10.47
La _N /Yb _N	6.61	17.48	30.38	3.92	16.54	29.98	9.69	19.17	6.19	2.30	9.66	17.72
δEu	0.38	0.27	0.66	0.36	0.55	0.45	0.22	0.23	0.18	0.06	0.13	0.26
δCe	1.10	1.11	1.05	0.55	1.11	1.23	1.04	1.02	1.23	1.05	1.02	1.09
Rb/Sr	4.00	1.53	1.47	2.14	1.36	1.11	2.14	3.31	5.24	3.14	3.66	3.49
Rb/Nb	15.07	9.89	31.51	9.76	11.04	12.96	3.96	9.96	8.32	8.87	12.66	20.06
Nb/Ta	10.27	10.84	12.37	14.86	14.88	17.76	18.50	19.66	12.80	16.38	17.86	15.09
Zr/Hf	28.99	31.88	34.44	28.10	35.49	34.13	35.78	29.85	27.86	26.49	27.78	30.94

表3 鲁满山花岗岩锆石 Hf 同位素数据
Table 3 Zircon Hf isotopic compositions of the Lumanshan pluton

编号	年龄/Ma	¹⁷⁶ Hf/ ¹⁷⁷ Hf	2s	¹⁷⁶ Yb/ ¹⁷⁷ Hf	2s	¹⁷⁶ Lu/ ¹⁷⁷ Hf	2s	(¹⁷⁶ Hf/ ¹⁷⁷ Hf) _t	ε _{Hf} (t)	T _{DM} /Ma	T _{DM} ^C /Ma	f _{Lw/Hf}
11HHL06-1	451	0.282479	0.000036	0.035422	0.000167	0.001360	0.000005	0.282467	-0.9	1104	1484	-0.96
11HHL06-6	454	0.282502	0.000026	0.027393	0.000233	0.001048	0.000011	0.282493	0.1	1062	1425	-0.97
11HHL06-7	457	0.282397	0.000027	0.053241	0.000722	0.001469	0.000013	0.282384	-3.6	1223	1666	-0.96
11HHL06-8	452	0.282404	0.000026	0.049525	0.000411	0.001369	0.000013	0.282393	-3.5	1210	1651	-0.96
11HHL06-10	451	0.282331	0.000026	0.061857	0.001025	0.001493	0.000031	0.282319	-6.1	1317	1816	-0.96
11HHL06-11	453	0.282294	0.000020	0.013279	0.000342	0.000353	0.000012	0.282291	-7.0	1329	1877	-0.99
11HHL06-12	452	0.282418	0.000020	0.032468	0.000115	0.000803	0.000003	0.282411	-2.8	1173	1610	-0.98
11HHL06-14	455	0.282448	0.000020	0.037894	0.000613	0.000930	0.000015	0.282440	-1.7	1134	1542	-0.97
11HHL06-15	454	0.282284	0.000020	0.020073	0.000574	0.000457	0.000015	0.282280	-7.4	1346	1901	-0.99
11HHL06-16	454	0.282436	0.000019	0.040223	0.000715	0.000992	0.000017	0.282427	-2.2	1153	1572	-0.97

注: ε_{Hf}(t)=10000×{[(¹⁷⁶Hf/¹⁷⁷Hf)_s-(eλ^t-1)]/[(¹⁷⁶Hf/¹⁷⁷Hf)_{CHUR,0}-(¹⁷⁶Lu/¹⁷⁷Hf)_{CHUR}×(eλ^t-1)]-1}; t_{DM}=1/λln{1+[(¹⁷⁶Hf/¹⁷⁷Hf)_s-(¹⁷⁶Hf/¹⁷⁷Hf)_{DM}]/[(¹⁷⁶Hf/¹⁷⁷Hf)_s-(¹⁷⁶Lu/¹⁷⁷Hf)_{DM}]}; t_{DM}^C=t_{DM}-(t_{DM}-t)×[(f_s-f_{DM})]/f_{Lw/Hf}; f_{Lw/Hf}=(¹⁷⁶Lu/¹⁷⁷Hf)_s/[(¹⁷⁶Lu/¹⁷⁷Hf)_{CHUR}-1]; 其中: λ=1.867×10⁻¹¹/a; (¹⁷⁶Lu/¹⁷⁷Hf)_s和(¹⁷⁶Hf/¹⁷⁷Hf)_s为样品测量值, (¹⁷⁶Lu/¹⁷⁷Hf)_{CHUR}=0.0332, (¹⁷⁶Hf/¹⁷⁷Hf)_{CHUR,0}=0.282772; (¹⁷⁶Lu/¹⁷⁷Hf)_{DM}=0.0384, (¹⁷⁶Hf/¹⁷⁷Hf)_{DM}=0.28325; (¹⁷⁶Lu/¹⁷⁷Hf)_{平均地壳}=0.015; f_s=[(¹⁷⁶Lu/¹⁷⁷Hf)_{平均地壳}/(¹⁷⁶Lu/¹⁷⁷Hf)_{CHUR}]-1, f_s=f_{Lw/Hf}; f_{DM}=[(¹⁷⁶Lu/¹⁷⁷Hf)_{DM}/(¹⁷⁶Lu/¹⁷⁷Hf)_{CHUR}]-1。

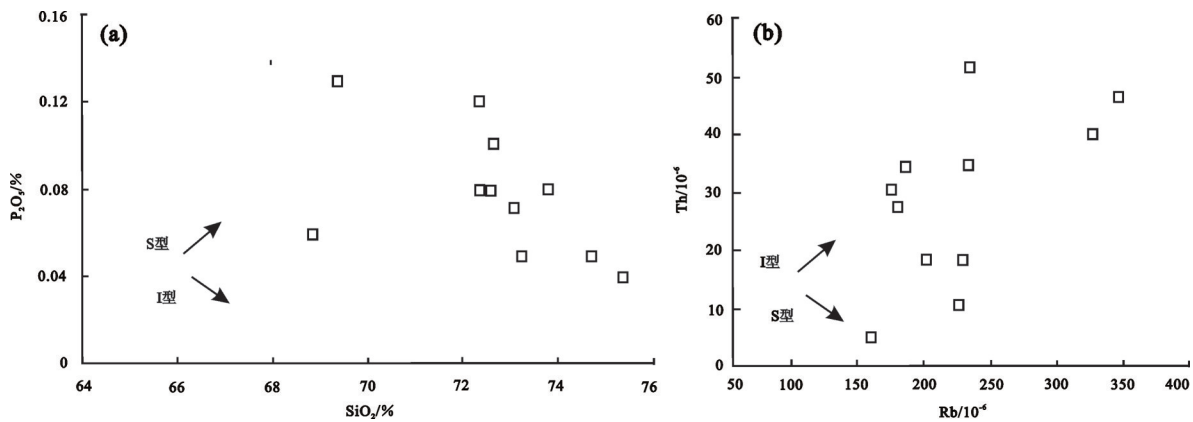


图7 鲁满山花岗岩体的 SiO₂-P₂O₅(a)和 Rb-Th (b)图解(据 Chappell and White, 1992^[33])

Fig.7 SiO₂-P₂O₅(a) and Rb-Th (b) diagrams of the granites from Lumanshan pluton (after Chappell and White, 1992^[33])

U-Pb 年龄、锆石 Hf-O 同位素的研究发现, 受幔源岩浆改造的沉积物重熔同样也可以形成 I 型花岗岩^[36], 此外, 在地壳重熔过程中沉积物贡献的减少和火成岩等成分的增多同样可以使岩浆成分由 S 型向 I 型转变, 形成 I 型或者 I-S 过渡类型岩浆^[37]。鲁满山花岗岩体相对富集大离子亲石元素和轻稀土, 亏损高场强元素, 不相容元素 Nb、Ta、Ti 具有明显的负异常, Rb/Sr 比值(1.11~5.24)和 Rb/Nb 比值(3.96 ~ 31.51)明显高于全球上地壳的平均值(分别为 0.32 和 4.5)^[38], 偏古老的地壳模式年龄 t_{DM}^C (1425~1901 Ma), 类似于地壳物质的特征。花岗岩的 CaO/Na₂O 比值主要受源区中斜长石/粘土比例的控制, 过铝质花岗

岩的 CaO/Na₂O 比值对于源区的成分有很好的指示意义, CaO/Na₂O >0.3 指示源区为砂岩、正变质岩, CaO/Na₂O <0.3, 表明源区为泥质岩^[39], 鲁满山花岗岩的 CaO/Na₂O 比值为 0.08~0.63, 变化范围较大, 指示鲁满山花岗岩体的源岩可能属于砂岩和泥质岩的混合物。然而, 鲁满山花岗岩体的 Nb/Ta 比值(10.27~19.66), 多数明显高于壳源岩石的 Nb/Ta 比值(约为 11)^[38,40], 而接近或高于幔源岩石的 Nb/Ta 比值(约为 17.5)^[40-41], 并且岩体的 Zr/Hf 比值(26.49~35.78)接近幔源岩石的 Zr/Hf 值(约为 36.3)^[40-41], 而部分高于地壳岩石的 Zr/Hf 值(约为 33)^[38,41]。另外, 鲁满山花岗岩体的 ε_{Hf}(t) 值相对较高(-7.4~0.1), 在 t-ε_{Hf}(t)

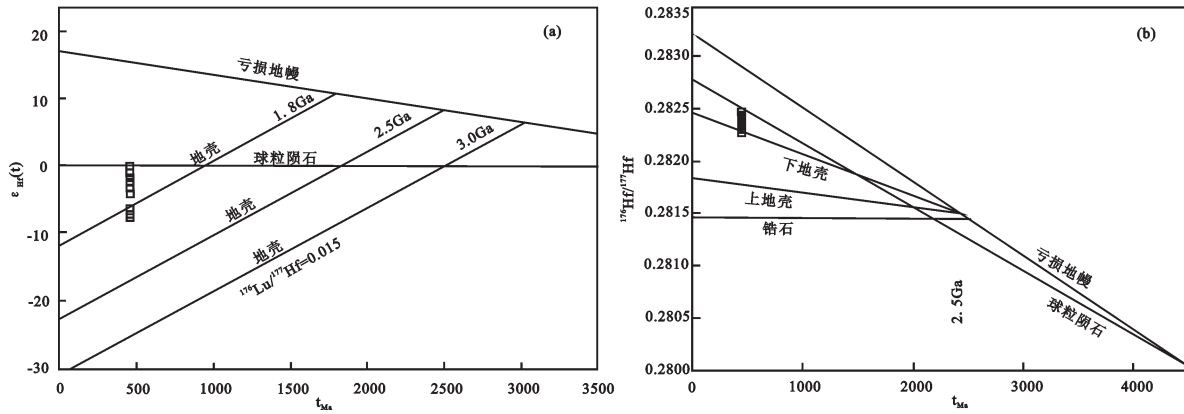


图8 鲁满山花岗岩体的 $t-\epsilon_{Hf}(t)$ (a)和 $t-^{176}\text{Hf}/^{177}\text{Hf}$ (b)图解
 Fig.8 $t-\epsilon_{Hf}(t)$ (a) and $t-^{176}\text{Hf}/^{177}\text{Hf}$ (b) diagrams of the granites from Lumanshan pluton

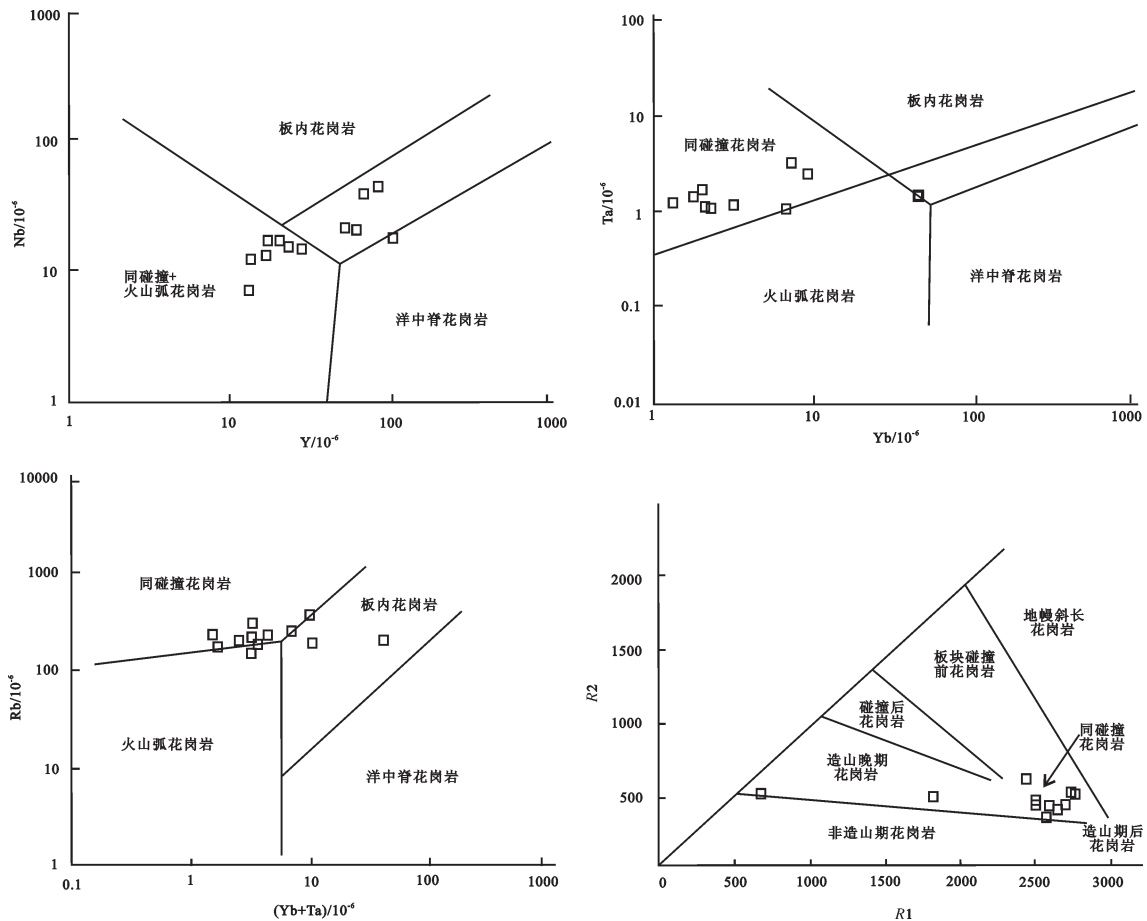


图9 鲁满山花岗岩体的构造判别图解
 Fig.9 Tectonic discrimination diagrams of the granites from Lumanshan Pluton

图解(图8-a)和 $t-^{176}\text{Hf}/^{177}\text{Hf}$ 图解(图8-b)中, 样品均落在球粒陨石演化线附近及以下的下地壳区域, 表明其岩浆可能来源于古老地壳的重熔, 成岩过程可

能有年轻组分的参与。上述特征均表明, 鲁满山花岗岩体并非由单纯的古老地壳物质重熔形成, 其形成过程可能有年轻组分的参与。年轻组分参与花

岗岩成岩过程的方式可能两种情形,其一为幔源岩浆与其诱发的地壳物质部分熔融形成的长英质岩浆在地壳深部混合形成壳幔混源岩浆^[16,42-43];另一种是幔源岩浆首先侵入到地壳基底岩石中形成初生地壳,然后在后期热事件的影响下,这种既有初生地壳又有古老基底地壳构成的混合地壳原岩发生部分熔融^[44-47]。鲁满山花岗岩体的 $\varepsilon_{\text{Hf}}(t)$ 值相对较高(-7.4~0.1),且变化范围均较大,这就需要有一个开放系统来引起熔体中 $^{176}\text{Hf}/^{177}\text{Hf}$ 比值的明显变化^[36]。由于锆石Hf同位素比值不会随部分熔融或分离结晶而变化,因此源区的这种Hf同位素不均一性可以理解为幔源和壳源这两种端元之间相互作用的结果^[48],即可能是幔源物质(大的正 $\varepsilon_{\text{Hf}}(t)$ 值)和古老地壳物质(大的负 $\varepsilon_{\text{Hf}}(t)$ 值)混合后的产物。另外,从该岩体中发育有暗色包体来看,也说明其很可能由岩浆混合作用形成。鲁满山花岗岩体的Hf同位素分析结果显示其地壳模式年龄 t_{DM}^c 介于1425~1930 Ma,由于锆石Hf同位素地壳模式年龄是从锆石 $\varepsilon_{\text{Hf}}(t)$ 值计算得来,而经历壳幔相互作用后获得的锆石 $\varepsilon_{\text{Hf}}(t)$ 值实际上代表了幔源物质和古老地壳物质混合后的产物,因此获得的古老地壳物质的 $\varepsilon_{\text{Hf}}(t)$ 值应该更负,其对应的地壳模式年龄应该更老,因此推测其壳源源区很可能为古元古代-中元古代的古老地壳岩石。作为南祁连造山带基底残块的化隆岩群,随着近年来精细锆石同位素年代学数据的获得,其形成于太古宙-古元古代的传统认识发生了动摇,陆松年等^[9]利用锆石SHRIMP和LA-MC-ICPMS共测定了60个锆石微区同位素年龄数据,二者重复后显示出1782 Ma、1562 Ma两个重要年龄值的高频区,认为化隆岩群最可能是中元古代晚期的产物。前人对祁连造山带及邻区深变质基底研究认为化隆岩群变质岩系以变泥砂质岩石为主,变泥质砂岩稀土元素总量为 120.4×10^{-6} ~ 320.8×10^{-6} , δEu 为0.47~0.71, $(\text{La}/\text{Yb})_N$ 为8.15~15.5,除元素Nb、P、Ti亏损外,亏损Ba^[3],鲁满山花岗岩的微量、稀土元素地球化学特征与其具有相似性。因此,鲁满山花岗岩体的壳源源区很可能包括化隆岩群变泥砂质岩石。

4.3 岩体形成时代及地球动力学背景

南祁连地区岩浆活动十分强烈,分布也广泛,不仅保留了洋盆演化、大陆裂解过程中形成的镁铁

质-超镁铁质蛇绿岩,也分布了与洋-陆俯冲、碰撞、造山晚期大陆伸展阶段过程有关的中酸性岩浆岩岩石组合,其中加里东期花岗质岩浆活动最为强烈^[1],本次研究获得鲁满山花岗岩体的形成时代为 (452.9 ± 1.8) Ma,正是加里东期岩浆作用的产物,与相邻的侵入于湟源群的董家庄花岗岩体 (446.9 ± 1) Ma及新店岩体 (454 ± 5) Ma^[49]相近。锆石年龄中822~921 Ma的数据可能记录了化隆地块受Rodinia超大陆聚合裂解事件的影响^[3-4,50-51],而1.2~1.5 Ga的继承锆石的残核可能指示其来自于中元古代的古老陆壳基底。在构造判别图解上(图9),多数样品点落入火山弧花岗岩和碰撞花岗岩分界线附近及碰撞花岗岩区域内。

南祁连造山带位于秦祁昆中央造山带的中部,夹持于北祁连造山带与柴达木地块之间,其北部的北祁连是中国最早研究的俯冲带之一,其早古生代的蛇绿岩、火山岩、高压变质岩及大地构造演化研究,取得了许多重要进展^[52-63]。而南部的柴北缘也是研究热点,在其中识别出一条早古生代的超高压变质带^[64-68]。近年来,众多学者对南祁连造山带的演化也进行了研究,主要有华北板块不同程度裂解的“开-合构造”演化和始特提斯洋域微板块碰撞拼贴演化两种模式,出现分歧可能主要在于祁连地块的属性和来源存在不同看法。以往大多认为祁连造山带的陆块基底是华北陆块裂解的产物,但近几年通过对祁连地块前寒武纪基底锆石SHRIMP U-Pb年代学研究使这一问题有了新的进展,董国安等^[69]认为祁连地块前寒武纪基底岩石的碎屑锆石年代峰值主要集中在中新元古代,反映其新元古代期间发生过聚合、裂解和区域变质作用改造,这与华北地块在新、中元古代时为一稳定地台有所不同,而与扬子地块前寒武纪基底岩石的年龄频谱相似。陆松年等^[6]通过对塔里木、祁连、扬子板块构造热事件的研究提出,秦-祁-昆造山带中的祁连、柴达木及北秦岭等地块,其前寒武纪演化特点与塔里木及扬子克拉通有较大相似性,而与华北克拉通有明显区别。研究表明,北祁连洋盆在早古生代发生了俯冲消减作用^[54,57,70-72],但对俯冲极向存在较大争议,许多学者认为板块向北俯冲^[56,58,62-63,73],但也有不少学者认为向南俯冲^[52,60-61,74-76],还有部分学者认为向南北双向俯冲^[54-55,77-78]。而南部的柴北缘是典

型的早古生代大陆碰撞过程^[64-66,68,79],其发育的柴北缘超高压变质带,证明陆壳岩石发生了深俯冲作用^[66],超高压变质作用发生在500~440 Ma^[66-67,80]。早奥陶世开始,柴北缘地区存在大洋板块的俯冲作用,即柴北缘洋壳俯冲于中南祁连陆壳之下,于460 Ma左右形成I型花岗质岩浆,并对应于超高压变质作用^[81-82],奥陶纪晚期,整个祁连地区正处于由俯冲造山向碰撞造山的转换时期^[83]。鲁满山花岗岩体可能就是由这种俯冲碰撞的地球动力学背景下诱导产生的幔源岩浆引起古老地壳物质重熔并与重熔产物混合再经历较程度分异演化作用形成的。

5 结 论

(1) LA-ICP-MS 锆石 U-Pb 测年结果表明,鲁满山花岗岩体的形成时代为(452.9±1.8) Ma,属于加里东期岩浆活动的产物。

(2) 鲁满山花岗岩体具有高硅、富碱的特征,属于弱过铝质高钾钙碱性系列。微量和稀土元素组成上,岩体富集大离子亲石元素 Rb、U、Th、K 和 Pb 元素,亏损 Ba、Sr、Ta、Nb、P、Ti,具明显轻稀土富集,重稀土亏损特征,显示较强烈的负 Eu 异常($\delta Eu = 0.06 \sim 0.55$, 平均 0.31),属于高分异的I型花岗岩。

(3) 锆石 Hf 同位素分析结果显示,岩体的 $\epsilon_{Hf}(t)$ 为 -7.4~0.1,二阶段模式年龄介于 1425~1930 Ma,其成岩过程中应有亏损地幔组分参与,其壳源源区很可能包括化隆岩群变泥砂质岩石。

(4) 结合区域构造演化,认为鲁满山花岗岩体形成于柴北缘洋壳与中南祁连陆壳俯冲碰撞的地球动力学背景下,由幔源岩浆与其诱发的地壳物质熔融产生的长英质岩浆在地壳深部混合后再经历分异演化形成。

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