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## 东昆仑祁漫塔格虎头崖铅锌多金属矿区花岗岩 年代学、地球化学及 Hf 同位素特征

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**摘要:** 虎头崖铅锌多金属矿床位于东昆仑祁漫塔格地区, 矿区内中酸性侵入岩体广泛发育, 且与成矿关系密切。LA-ICP-MS 锆石 U-Pb 同位素年龄测试表明, 虎头崖 V 矿带外围花岗闪长岩形成时代为(224.3±0.6) Ma, VIII 号矿带矿体下部正长花岗岩形成时代为(239.7±0.8) Ma, 岩体形成时代为中—晚三叠世。岩石地球化学表明, 花岗闪长岩富钾贫钠(K<sub>2</sub>O/Na<sub>2</sub>O 为 2.02~2.88), 无明显负 Eu 异常(δEu 为 0.68~1.06), 富集 Rb、Th、U、K 等大离子亲石元素, 明显亏损 Nb、P、Ti 等元素, 属 I 型花岗岩; 正长花岗岩具高硅、富碱、低铁镁、贫钙磷钛的特征, 负 Eu 强烈(δEu 为 0.08~0.26), 富集 Rb、Th、U、K, 亏损 P、Ti、Ba、Sr, 属高分异 I 型花岗岩; 二者均形成于后碰撞构造背景; Hf 同位素组成不均一, 指示其经历了壳幔岩浆混合作用, 幔源物质的加入可能带来了丰富的成矿物质。

**关键词:** 花岗岩; 年代学; 地球化学; Hf 同位素; 虎头崖; 东昆仑

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### Geochronology, geochemical characteristics and Hf isotopic compositions of granite in the Hutouya deposit, Qimantag, East Kunlun

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**Abstract:** The Hutouya Pb-Zn polymetallic ore deposit is located in Qimantag, East Kunlun. Intermediate-acid intrusive rocks occur widely in this area, and are closely related to iron polymetallic mineralization. The results of LA-ICP-MS zircon U-Pb isotope dating reveal that the granodiorite in the periphery of No. V ore belt was formed at (224.3±0.6) Ma and the orthoclase granite

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in No. VIII ore belt was formed at (239.7±0.8) Ma. Petrogeochemistry shows that the granodiorite is rich in K and poor in Na, with no strong negative Eu anomalies ( $\delta\text{Eu}=0.68-1.06$ ), and is enriched in Rb, Th, U, K, but depleted in Nb, P, Ti, thus belonging probably to I-type granite series. The orthoclase granite is characterized by high  $\text{SiO}_2$ , high alkali, low TFeO, MgO, CaO,  $\text{P}_2\text{O}_5$  and  $\text{TiO}_2$ , strong negative Eu anomalies ( $\delta\text{Eu} 0.08-0.26$ ), enrichment of Rb, Th, U, K, and depletion of P, Ti, Ba, Sr, belonging probably to highly fractionated I-type granite series. Both of them were formed at the post-collision stage. Variable Hf isotopic compositions of zircon indicate that it experienced magma mixing, which provided large quantities of ore-forming materials for large-scale polymetallic mineralization.

**Key words:** granitoids; geochronology; geochemistry; Hf isotopes; Hutouya; East Kunlun Mountains

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东昆仑造山带是中央造山系的组成部分,其位于青藏高原北部、柴达木盆地西南缘,属古亚洲构造域与特提斯构造域结合部位,经历了复杂的地质构造演化历史,构造-岩浆作用强烈,中酸性侵入岩类广泛发育,构成一条近东西向展布的巨大花岗岩带。早古生代和晚古生代至早中生代是主要的岩浆作用时期,尤其后者是本区最为完整的岩浆构造作用旋回<sup>[1-4]</sup>。巨量花岗岩不仅记录了东昆仑造山带构造演化历史,也与区域铁、铜、金、铅锌、钨锡等多金属成矿密切相关。祁漫塔格位于东昆仑造山带的西段,近些年来,集中发现了一大批与中酸性岩浆侵入活动有关的金属矿床(尕林格、野马泉、它温查汗、四角羊—牛苦头、卡而却卡、虎头崖等),显示了良好地找矿潜力,引起众多学者关注。虎头崖铅锌多金属矿是该区较为典型的矽卡岩型矿床之一,前人对部分岩体开展了年代学研究并探讨了其形成背景<sup>[5-7]</sup>,但矿区各矿带岩体类型不一,无法确定这些岩体是否形成于同一时代,并且已有数据缺乏Hf同位素制约。本文选择虎头崖矿区V矿带、VIII矿带与成矿关系密切的花岗岩为研究对象,对其开展年代学、岩石地球化学及锆石Hf同位素研究,以此来探讨其形成时代、构造背景、源区性质及与成矿的关系,进而为东昆仑构造演化及区域成矿规律提供基础资料。

## 1 地质背景

### 1.1 矿区地质背景

虎头崖铅锌矿床位于青海省祁漫塔格地区,大地构造位置上处于东昆仑西段北昆仑(祁漫塔格)岩浆弧带<sup>[8]</sup>,其南部以黑山—那陵郭勒断裂为界与中昆仑微陆块相邻,北部以昆北断裂带为界与柴达

木陆块相邻(图1-a)。

矿区地层属柴达木地层区的柴达木南缘分区,出露的地层由老到新为:藟县系狼牙山组(Jx1)浅变质岩系碳酸盐岩和碎屑岩,主要呈近东西向分布于矿区南部;奥陶—志留系滩涧山群(O-ST)中浅变质岩系,岩性主要为陆源碎屑岩、中基性火山岩、碳酸盐岩等,主要分布于矿区中部东、西两侧,近东西向展布,地层出露厚度约1600 m;下石炭统大干沟组(C<sub>1</sub>dg)碎屑岩、含生物碎屑碳酸盐岩,呈条带状分布于调查区的中部,与南部狼牙山组(Jx1)及北部滩涧山群(O-ST)均呈断层接触,总体呈近东西向展布,倾向北,倾角50°~70°,出露厚度600~1000 m,岩石普遍发生碎裂现象;上石炭统绉敖苏组(C<sub>2</sub>d)含生物碎屑碳酸盐岩,主要分布于矿区中部及北部,总体走向东西向,南部与滩涧山群(O-ST)地层呈角度不整合或断层接触;中生界上三叠统鄂拉山组(T<sub>3</sub>e)陆相中酸性火山岩,分布于矿区北西侧,岩性主要有晶屑凝灰岩、流纹质含角砾凝灰岩、流纹质玻屑晶屑角砾熔凝灰岩等,地层北倾,倾角47°~62°,南部与上石炭统绉敖苏组(C<sub>2</sub>d)呈断层接触。山麓地带及河床等广泛发育的第四系(Q)松散堆积物。

矿区内褶皱、断裂等构造发育,褶皱构造以轴向近东西向背斜构造为主,断裂以东西向为主,断层破碎带是矿体赋存的有利部位。

矿区侵入岩分布较广,主要出露于矿区中部,呈岩株状产出,以中酸性侵入岩类为主,岩性为钾长花岗岩、二长花岗岩、花岗闪长岩等,其中迎庆沟地区钾长花岗岩中普遍可见暗色微粒包体。岩体侵入于狼牙山组、滩涧山群、大干沟组及绉敖苏组等不同时代地层中,接触带附近围岩蚀变强烈,普遍发育矽卡岩化,伴随强烈地多金属成矿作用。此

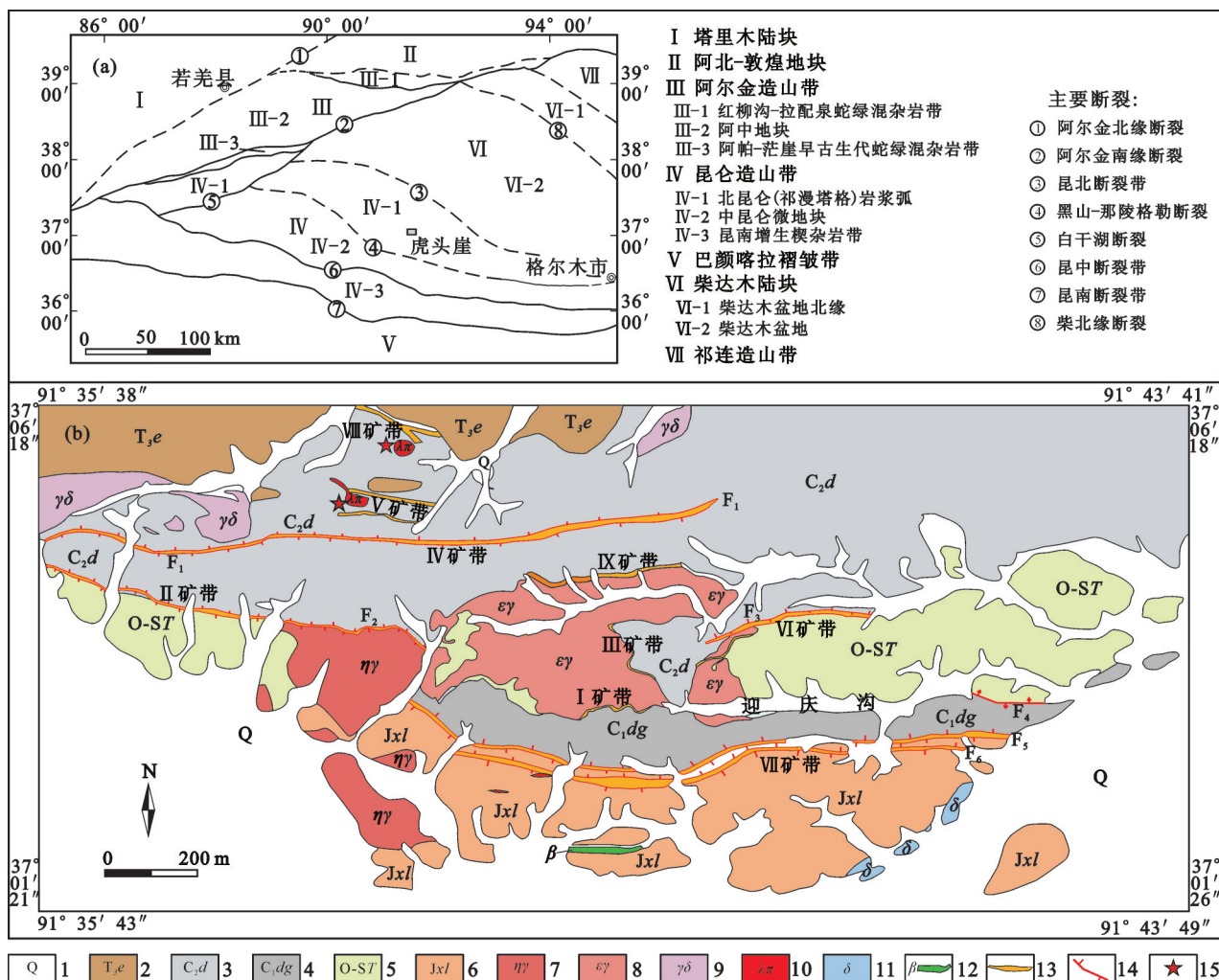


图1 区域构造简图(a)及虎头崖矿区地质矿产图(b)(a图据文献[8]修改;b图据文献[6]修改)

1—第四系;2—上三叠统鄂拉山组;3—上石炭统蒂敦苏组;4—下石炭统大干沟组;5—奥陶—志留系滩间山群;6—蓟县系狼牙山组;  
 7—二长花岗岩;8—钾长花岗岩;9—花岗闪长岩;10—闪长岩;11—花岗斑岩脉;12—辉绿岩脉;13—砂卡岩化带;14—断层;15—采样位置

Fig.1 Regional tectonic sketch map (a) and geological map of the Hutouya Pb-Zn polymetallic ore deposit (b)

1—Quaternary; 2—Upper Triassic Elashan Formation; 3—Upper Carboniferous Di'ao'sou Formation; 4—Lower Carboniferous Dagangou Formation;  
 5—Ordovician-Silurian Tanjianshan Group; 6—Langyashan Formation of Jixian System; 7—Mozonitic granite; 8—Moyite; 9—Granodiorite;  
 10—Diorite; 11—Granite-porphry; 12—Diabase vein; 13—Skarn ore belt; 14—Fault; 15—Sampling location

外,矿区南部有闪长岩小面积出露,主要侵入于狼牙山组中,同时见少量辉绿岩脉(图1-b)。

## 1.2 矿床地质

矿区矿化规模较大,矿体数量众多,目前共划分为9条多金属矿带(图1-b),50余条矿体。矿体主要产于中酸性侵入岩体与碳酸盐岩地层接触之内接触带及断层破碎带中,呈层状、似层状、透镜状产出,矿石金属元素组合复杂,随距离岩体距离不同矿石矿物组合有所差异。岩体与奥陶—志留系滩间山群、下石炭统大干沟组、上石炭统蒂敦苏组的接触带形成砂卡岩型铁多金属矿体,矿石矿物

主要为磁铁矿、锡石、方铅矿、闪锌矿及黄铁矿等(I、II、III、VIII、IX矿带),而在断层破碎带中矿化类型以方铅矿化、闪锌矿化、黄铜矿化、辉钼矿化等为主(IV、V、VI、VII矿带)。脉石矿物主要为透辉石、阳起石、透闪石、石榴子石、方解石、石英等。围岩蚀变发育,主要有硅化、绿泥石化、绿帘石化等,具有较典型砂卡岩化特征。

## 2 采样位置及岩石学特征

花岗闪长岩样品取自V号矿带北侧,侵入于上石炭统蒂敦苏组浅灰色大理岩、白云质灰岩中,接



矿带发育矽卡岩型铜铅锌多金属矿体。矿体地表主要为网脉状斑铜矿、浸染状方铅矿、闪锌矿及孔雀石等。取样位置:37°05'16"N,91°36'00"E。岩石呈浅肉红色,块状构造,似斑状结构。斑晶主要由斜长石、碱性长石、石英等组成,斜长石含量(约15%)略高于碱性长石(约10%),石英含量约5%;斜长石斑晶多产生不同程度的次生蚀变,被绢云母、帘石和少量方解石交代,蚀变轻者可见斜长石斑晶或环带结构;碱性长石斑晶种属为正长石,呈板状或粒状,晶体有轻微次生蚀变,多为泥化。基质中石英含量增高至20%,斜长石与碱性长石含量约50%。基质中石英常呈显晶包含有碱性长石小晶体,形成显微包含结构,斜长石常为细小的粒状晶体与石英、碱性长石相间分布。

正长花岗岩样品来自Ⅷ号矿带ZK1501中矿体底部,侵入于晚石炭世蒂敦苏组(C<sub>2</sub>d)中,与成矿关系密切。岩石呈肉红色、块状构造,不等粒结构。矿物成分:斜长石25%,钾长石44%,石英26%,黑云母2%,金属矿物2%,褐帘石<1%,楣石少量。钾长石多为条纹长石,晶体形态不规则,粒径大小不等,可从0.8~7 mm。斜长石呈粒状,粒径小于钾长石。长石晶体中有泥化现象。

### 3 分析方法

主量元素、稀土元素、微量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-MC-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MC-ICP-MS实验室完成,定年分析仪器为Finnigan Neptune型MC-ICP-MS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。对锆石标准的定年精度和准确度在1%(2s)左右,锆石U-Pb定年以锆石GJ-1为外标,U、Th含量以锆石M127(U:  $923 \times 10^{-6}$ ; Th:  $439 \times 10^{-6}$ ; Th/U: 0.475)<sup>[9]</sup>为外标进行校正。测试过程中在每测定5~7个样品前后重复测定2个锆石GJ-1对样品进行校

正,并测量一个锆石Plesovice,观察仪器的状态以保证测试的精确度。数据处理采用ICPMSDataCal程序<sup>[10]</sup>,锆石年龄谱和图用Isoplot 3.0程序获得。详细实验测试过程可参见侯可军等<sup>[11]</sup>。样品分析过程中,Plesovice标样作为未知样品的分析结果为(337.2±2.0)Ma(n=12, 2σ),对应的年龄推荐值为(337.13±0.37)Ma(2σ)<sup>[9]</sup>,两者在误差范围内完全一致。

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国土资源部成矿作用与资源评价重点实验室Neptune多接收等离子质谱和Newwave UP213紫外激光剥蚀系统(LA-MC-ICP-MS)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,测定时使用锆石国际标样GJ-1作为参考物质,分析点与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<sup>[12]</sup>。分析过程中锆石标准GJ-1的<sup>176</sup>Hf/<sup>177</sup>Hf测试加权平均值为(0.281993 ± 15)(2SD,n=21),与文献报道值<sup>[12-13]</sup>在误差范围内完全一致。

## 4 测试结果

### 4.1 主量元素

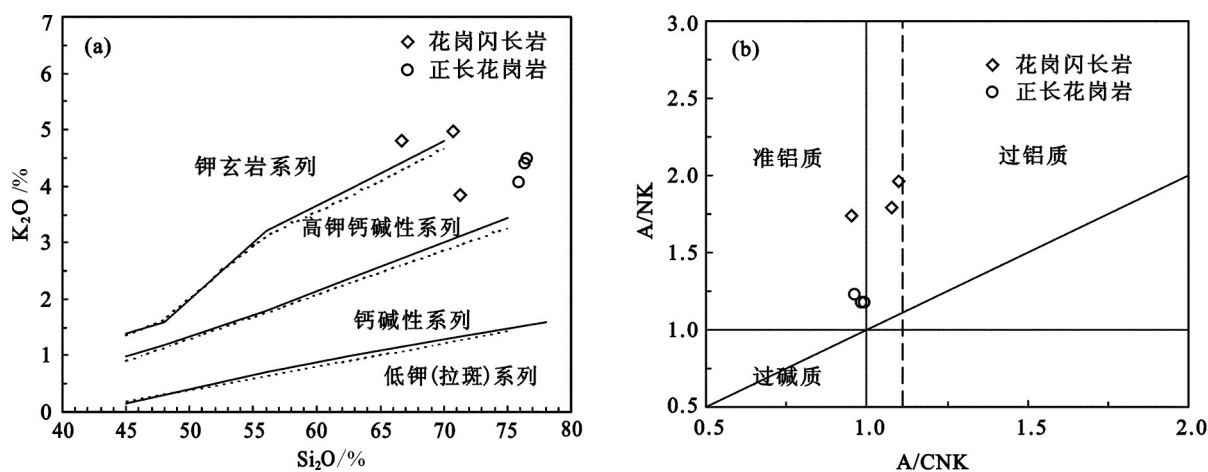
样品的主、微量元素分析结果见表1。花岗闪长岩SiO<sub>2</sub>含量为66.72%~71.30%,全碱(Na<sub>2</sub>O+K<sub>2</sub>O)含量5.70%~6.71%,岩石富钾贫钠,K<sub>2</sub>O/Na<sub>2</sub>O为2.02~2.88,在SiO<sub>2</sub>-K<sub>2</sub>O图解中投入高钾钙碱性-钾玄岩系列中(图2-a);TiO<sub>2</sub>较低,含量为0.27%~0.29%,A/CNK值为0.95~1.10,为准铝质-弱过铝质(图2-b);里特曼指数为1.15~1.79。正长花岗岩SiO<sub>2</sub>含量较高(75.84%~76.48%),全碱(Na<sub>2</sub>O+K<sub>2</sub>O)含量高(5.70%~6.71%),Na<sub>2</sub>O/Na<sub>2</sub>O为1.09~1.32,在SiO<sub>2</sub>-K<sub>2</sub>O图解中投入高钾钙碱性系列中(图2-a);含有较低的MgO(0.09%~0.12%),CaO(1.13%~1.58%),P<sub>2</sub>O<sub>5</sub>(0.01%)及TiO<sub>2</sub>(0.07%~0.08%);A/CNK值为0.96~0.99,属准铝质(图2-b);里特曼指数为1.80~1.90。

### 4.2 稀土及微量元素

虎头崖铅锌多金属矿区花岗闪长岩及正长花岗岩稀土及微量元素分析结果见表2。花岗闪长岩稀土元素总量不高,ΣREE为127.59×10<sup>-6</sup>~152.46×10<sup>-6</sup>,LREE/HREE为9.32~10.01,La<sub>N</sub>/Yb<sub>N</sub>为10.14~

表1 虎头崖花岗闪长岩、正长花岗岩主量元素分析结果(%)

Table 1 Compositions of main elements of the granodiorite/orthoclase granite in Hutouya (%)									
岩性	样号	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO
花岗闪长岩	HTN-01	66.72	0.28	13.93	0.46	3.01	0.27	0.99	3.64
	HT11-23	71.30	0.27	14.18	0.81	1.68	0.12	0.78	3.13
正长花岗岩	HT11-24	70.72	0.29	14.74	0.04	1.63	0.05	0.93	2.98
	HT11-26	75.84	0.07	12.53	1.11	0.45	0.12	0.11	1.17
	HT11-29	76.48	0.08	12.73	0.42	0.40	0.02	0.09	1.13
	HT11-30	76.35	0.08	12.62	0.15	0.34	0.01	0.12	1.58
岩性	样号	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	LOI	Total	K <sub>2</sub> O/Na <sub>2</sub> O	FeO*	A/CNK
花岗闪长岩	HTN-01	1.70	4.81	0.08	2.18	98.07	2.83	3.42	0.95
	HT11-23	1.86	3.84	0.08	2.09	100.14	2.06	2.41	1.10
	HT11-24	1.73	4.98	0.07	1.77	99.93	2.88	1.67	1.08
正长花岗岩	HT11-26	3.76	4.08	0.01	0.75	100.00	1.09	1.45	0.98
	HT11-29	3.61	4.49	0.01	0.54	100.00	1.24	0.78	0.99
	HT11-30	3.34	4.40	0.01	0.99	99.99	1.32	0.47	0.96

图2 花岗闪长岩、正长花岗岩K<sub>2</sub>O-SiO<sub>2</sub>图解(a)及A/NK-A/CNK图解(b)

(a)底图据文献[14]; (b)底图据文献[15]

Fig. 2 Diagram of K<sub>2</sub>O-SiO<sub>2</sub> and A/NK-A/CNK of the granodiorite/orthoclase granite (base map (a) after reference [14]; (b) after reference [15])

11.56, 轻稀土较重稀土明显富集。配分曲线呈轻稀土明显右倾、重稀土平坦的特征(图3-a), 具较弱的负Eu异常,  $\delta\text{Eu}$ 为0.68~1.06。花岗闪长岩稀土总量比花岗闪长岩稍高,  $\Sigma\text{REE}$ 为 $112.54 \times 10^{-6}$ ~ $230.91 \times 10^{-6}$ , LREE/HREE为3.83~5.45,  $\text{La}_N/\text{Yb}_N$ 为2.78~4.75, 轻稀土较重稀土富集, 配分曲线同样显示轻稀土明显右倾、重稀土平坦的特征, 但负Eu明显(图3-a),  $\delta\text{Eu}$ 为0.08~0.26, 可能指示了岩浆经历了较强地斜长石分离结晶作用。

微量元素组成上(图3-b), 花岗闪长岩富集Rb、Th、U、K等大离子亲石元素, 明显亏损Nb、P、Ti等元素; 正长花岗岩微量元素同样富集Rb、Th、U、K等大离子亲石元素, P、Ti等高场强元素亏损更加明显, 与花岗闪长岩不同的是其明显亏损Ba、Sr元素, 可能与斜长石分离结晶作用有关。

#### 4.3 锆石年代学

根据锆石阴极发光图像和镜下特征, 选择晶形完整、颗粒较大的锆石颗粒进行锆石U-Pb同位素

表2 虎头崖花岗闪长岩、正长花岗岩微量元素分析结果(10<sup>-6</sup>)

**Table 2 Compositions of rare elements of the granodiorite/ adamellite granite in Hutouya (10<sup>-6</sup>)**

岩性	样号	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
花岗闪长岩	HTN-01	28.60	53.10	5.67	19.30	3.47	0.73	2.98	0.47	2.91	0.61	1.71	0.30	1.92	0.32	18.20
	HT11-23	24.60	47.60	5.07	18.20	3.30	1.10	2.95	0.46	2.70	0.60	1.72	0.26	1.74	0.29	17.00
	HT11-24	31.60	57.40	6.02	21.50	3.81	0.83	3.32	0.52	3.08	0.68	1.94	0.29	1.96	0.31	19.20
正长花岗岩	HT11-26	28.10	62.50	7.75	26.70	6.05	0.17	6.55	1.00	7.06	1.38	3.67	0.61	4.28	0.66	41.70
	HT11-29	33.90	73.00	9.10	32.00	7.26	0.24	7.10	1.06	8.04	1.61	4.12	0.70	5.12	0.76	46.90
	HT11-30	13.70	29.40	3.65	13.20	3.24	0.29	3.44	0.59	4.43	0.91	2.59	0.48	3.53	0.59	32.50

岩性	样号	ΣREE	$\frac{LREE}{HREE}$	$\frac{La_N}{Yb_N}$	δEu	δCe	Rb	Ba	Tu	U	Ta	Nb	Sr	Zr	Hf	Ga
花岗闪长岩	HTN-01	140.29	9.88	10.68	0.68	0.96	243	794	20.8	8.09	1.54	9.12	242	146	4.22	15.1
	HT11-23	127.59	9.32	10.14	1.06	0.99	168	2420	17.6	7.38	1.46	9.18	199	112	3.8	16
	HT11-24	152.46	10.01	11.56	0.70	0.95	291	1150	22.4	9.33	1.49	8.73	309	94.3	3.35	16.5
正长花岗岩	HT11-26	198.18	5.21	4.71	0.08	1.02	251	119	32.2	10.6	2.08	20.3	115	81.5	3.24	19.1
	HT11-29	230.91	5.45	4.75	0.10	1.00	286	161	39.3	13.6	3.31	27	133	104	4.63	20.3
	HT11-30	112.54	3.83	2.78	0.26	1.00	275	293	21.2	8.71	3.46	21.9	173	66.1	3.06	16.8

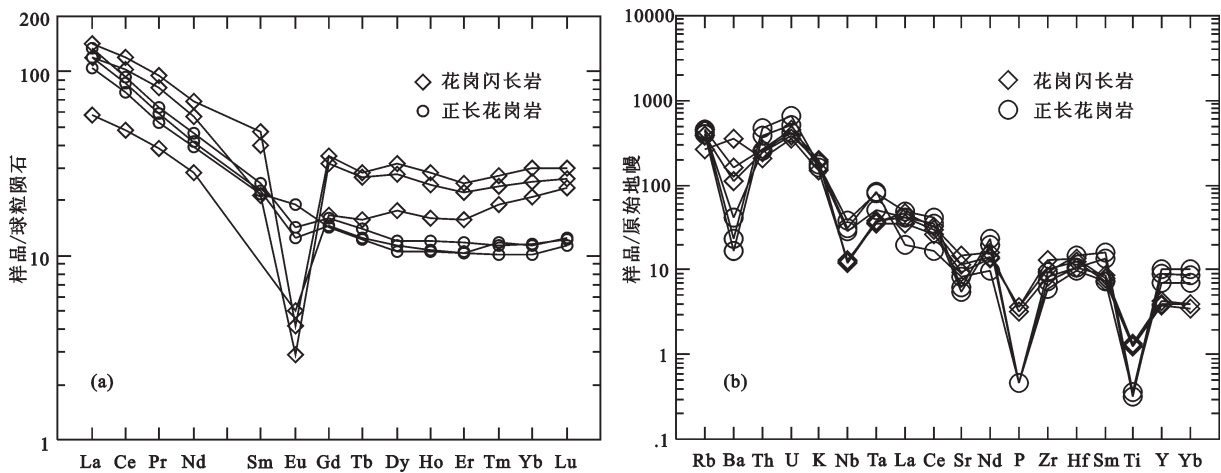


图3 花岗闪长岩、正长花岗岩稀土配分图(a)及微量元素蛛网图(b)(标准化值据文献[16])

Fig.3 Chondrite-normalized REE patterns (a) and primitive mantle-normalized trace element spidergrams (b) of the granodiorite/ orthoclase granite (normalization values after reference [16])

组成分析。

花岗闪长岩(HTN-01)锆石晶体粗大,晶型以长柱及短柱状为主,自形程度高,具明显的震荡环带结构(图4)。Th/U比值为0.33~0.73,平均0.50,具有岩浆结晶锆石的特征。测试共获取有效数据26个(表3),集中于谐和线附近(图5-a),表明这些锆石几乎没有U或Pb的丢失和加入,年龄可信度高。样品<sup>206</sup>Pb/<sup>238</sup>U表观年龄为(222.0±1.3)Ma~

(227.5±1.2)Ma,加权平均年龄为(224.3±0.6)Ma(MSWD=1.9)(图5-b),代表了花岗闪长岩的形成年龄。正长花岗岩(HT11-28)锆石以短柱状为主,Th/U比值为0.15~1.18,平均0.56,具震荡环带结构,属岩浆结晶锆石。测试获取有效数据17个(表3),集中于谐和线附近(图5-c),<sup>206</sup>Pb/<sup>238</sup>U表观年龄为(238.0±2.0)Ma~(242.9±2.0)Ma,加权平均年龄为(239.7±0.8)Ma(MSWD=1.2)(图5-d),代表了正长



图4 花岗闪长岩及正长花岗岩锆石阴极发光图像和 $^{206}\text{Pb}/^{238}\text{U}$ 年龄(Ma)

Fig.4 CL images and age of  $^{206}\text{Pb}/^{238}\text{U}$  of zircons of the granodiorite/adamellite granite (circles are the positions of laser spots)

花岗岩的形成年龄。

#### 4.4 Hf同位素

在紧邻年龄分析点的部位又进行了锆石原位Hf同位素测试,分析结果见表4。

花岗闪长岩共获得有效测试点24个,锆石 $^{176}\text{Hf}/^{177}\text{Hf}$ 为0.282542~0.282664,平均0.282598;  $\epsilon_{\text{Hf}}(0)$ 为-8.1~-3.8,平均为-6.2;按照加权平均年龄计算,  $\epsilon_{\text{Hf}}(t)$ 为-3.33~0.80,平均为-1.49;二阶段模式年龄 $T_{2\text{DM}}$ 为1207~1470 Ma,平均为1352 Ma。正长花岗岩的共获得有效测试点16个,锆石 $^{176}\text{Hf}/^{177}\text{Hf}$ 为0.282574~0.282688,平均0.282619;  $\epsilon_{\text{Hf}}(0)$ 为-7.0~-3.0,平均为-5.4;按照加权平均年龄计算,  $\epsilon_{\text{Hf}}(t)$ 为-1.87~-1.83,平均为-0.46,  $T_{2\text{DM}}$ 为1153~1388 Ma,平均为1299 Ma。

## 5 讨论

### 5.1 岩体年龄

由于与成矿作用关系密切,前人对虎头崖矿床不同矿带花岗岩已经开展过一些测年工作,积累了一批岩体年龄数据。刘云华等<sup>[5]</sup>获得矿区西段景忍

地区正长花岗岩SHRIMP锆石U-Pb年龄为(204±2.6)Ma;丰成友等<sup>[6]</sup>获得矿区中部I矿带和II矿带中间花岗闪长岩LA-ICP-MS锆石U-Pb年龄为(235.4±1.8)Ma,II矿区南侧正长花岗岩SHRIMP锆石U-Pb年龄为(219.2±1.4)Ma;张爱奎等<sup>[7]</sup>获得VI矿带钻孔中正长花岗岩LA-ICP-MS锆石U-Pb年龄为(217.5±1.1)Ma。本文选择虎头崖矿区V矿带外围花岗闪长岩和VIII号矿带矿体下部正长花岗岩进行LA-ICP-MS锆石U-Pb测试,得到花岗闪长岩加权平均年龄为(224.3±0.6)Ma, VIII号矿带矿体下部正长花岗岩加权平均年龄为(239.7±0.8)Ma,分别代表了岩体形成年龄,二者属于中一晚三叠世,与前人所获花岗岩年龄基本一致,证明印支期是矿区主要的中酸性岩浆活动期。

### 5.2 花岗岩成因分类

花岗闪长岩样品中无碱性暗色矿物及强过铝矿物,岩石地球化学上 $\text{SiO}_2$ 含量不高(66.72%~71.30%),全碱( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ )含量中等,  $A/\text{CNK} \leq 1$ (平均1.04),稀土总量较低( $127.59 \times 10^{-6}$ ~ $152.46 \times 10^{-6}$ )且无明显负Eu异常,过渡元素Sr、Ba相对含量较



表3 虎头崖花岗岩锆石 LA-ICP-MS U-Pb 测试数据和结果  
Table 3 LA-ICP-MS U-Pb data and analyses of the granitic rocks in the Hutouya deposit

测试点	Pb	$^{232}\text{Th}$		$^{238}\text{U}$		$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{208}\text{Pb}/^{232}\text{Th}$		$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{208}\text{Pb}/^{232}\text{Th}$				
		$10^6$		比值	$1\delta$	比值	$1\delta$	比值	$1\delta$	比值	$1\delta$	比值	$1\delta$	比值	$1\delta$	年龄/Ma	$1\delta$	年龄/Ma	$1\delta$	年龄/Ma	$1\delta$	年龄/Ma	$1\delta$	
花岗岩长岩 (HTN-01)																								
HTN-01-1	13.02755	62.63803	190.81200	0.05212	0.00066	0.25300	0.00347	0.03521	0.00015	0.00514	0.00085	0.00015	0.00514	0.00085	300.1	29.6	229.0	2.8	223.1	0.9	103.7	17.0		
HTN-01-2	34.39040	193.61868	370.14016	0.05330	0.00061	0.25770	0.00310	0.03510	0.00015	0.00385	0.00052	0.00015	0.00385	0.00052	342.7	23.1	232.8	2.5	222.4	0.9	77.6	10.5		
HTN-01-3	37.56047	155.97385	336.71127	0.05352	0.00050	0.26440	0.00253	0.03586	0.00016	0.00410	0.00052	0.00016	0.00410	0.00052	350.1	20.4	238.2	2.0	227.1	1.0	82.7	10.4		
HTN-01-4	16.30980	141.90497	326.96988	0.05308	0.00037	0.25920	0.00198	0.03543	0.00014	0.00357	0.00043	0.00014	0.00357	0.00043	331.5	14.8	234.0	1.6	224.4	0.9	72.1	8.6		
HTN-01-5	22.93703	121.14495	245.77836	0.05309	0.00064	0.26131	0.00356	0.03572	0.00020	0.00437	0.00048	0.00020	0.00437	0.00048	331.5	30.6	235.7	2.9	226.3	1.3	88.1	9.7		
HTN-01-6	23.72276	233.81498	321.11327	0.05161	0.00034	0.25066	0.00176	0.03524	0.00013	0.00344	0.00032	0.00013	0.00344	0.00032	333.4	14.8	227.1	1.4	223.3	0.8	69.5	6.4		
HTN-01-7	26.06965	233.32989	383.64335	0.05206	0.00032	0.25212	0.00147	0.03517	0.00013	0.00341	0.00028	0.00013	0.00341	0.00028	287.1	14.8	228.3	1.2	222.8	0.8	68.7	5.6		
HTN-01-8	20.83045	75.37033	189.93806	0.05269	0.00077	0.25825	0.00387	0.03558	0.00015	0.00467	0.00050	0.00015	0.00467	0.00050	316.7	33.3	233.3	3.1	225.4	0.9	94.2	10.1		
HTN-01-9	32.58839	258.52137	600.53908	0.05177	0.00023	0.25159	0.00127	0.03527	0.00014	0.00364	0.00025	0.00014	0.00364	0.00025	276.0	11.1	227.9	1.0	223.5	0.9	73.5	5.0		
HTN-01-10	34.28859	361.30413	565.86664	0.05257	0.00027	0.25729	0.00128	0.03556	0.00016	0.00359	0.00021	0.00016	0.00359	0.00021	309.3	11.1	232.5	1.0	225.2	1.0	72.4	4.3		
HTN-01-11	33.26008	350.16289	554.60847	0.05208	0.00028	0.25217	0.00183	0.03513	0.00018	0.00342	0.00017	0.00018	0.00342	0.00017	287.1	13.0	228.3	1.5	222.6	1.1	69.0	3.5		
HTN-01-12	55.75806	524.69586	1031.24539	0.05333	0.00016	0.26189	0.00212	0.03562	0.00027	0.00309	0.00016	0.00027	0.00309	0.00016	342.7	2.8	236.2	1.7	225.6	1.7	62.3	3.1		
HTN-01-13	43.81151	345.81222	669.93553	0.05364	0.00024	0.26535	0.00143	0.03593	0.00019	0.00384	0.00018	0.00019	0.00384	0.00018	366.7	9.3	239.0	1.1	227.5	1.2	77.5	3.7		
HTN-01-14	21.64954	310.51480	523.52811	0.05159	0.00028	0.25138	0.00257	0.03535	0.00032	0.00127	0.00014	0.00032	0.00127	0.00014	333.4	13.0	227.7	2.1	223.9	2.0	25.7	2.9		
HTN-01-15	37.97553	536.94088	1085.57711	0.05226	0.00021	0.25485	0.00151	0.03541	0.00021	0.00129	0.00015	0.00021	0.00129	0.00015	298.2	9.3	230.5	1.2	224.3	1.3	26.1	3.1		
HTN-01-16	20.80708	167.06568	496.37380	0.05360	0.00045	0.26408	0.00193	0.03584	0.00019	0.00149	0.00021	0.00019	0.00149	0.00021	353.8	13.9	238.0	1.5	227.0	1.2	30.0	4.3		
HTN-01-17	17.91077	179.90872	432.81868	0.05336	0.00045	0.26106	0.00208	0.03559	0.00020	0.00144	0.00024	0.00020	0.00144	0.00024	342.7	20.4	235.5	1.7	225.4	1.2	29.1	4.7		
HTN-01-18	17.22262	209.01256	569.33232	0.05135	0.00025	0.24986	0.00150	0.03530	0.00017	0.00132	0.00024	0.00017	0.00132	0.00024	257.5	38.9	226.5	1.2	223.7	1.1	26.7	4.8		
HTN-01-19	19.26045	268.26106	423.25613	0.05278	0.00043	0.25805	0.00220	0.03555	0.00025	0.00112	0.00023	0.00025	0.00112	0.00023	320.4	18.5	233.1	1.8	225.2	1.5	22.6	4.7		
HTN-01-20	15.83623	169.25089	508.78704	0.05279	0.00047	0.25810	0.00275	0.03555	0.00030	0.00140	0.00024	0.00030	0.00140	0.00024	320.4	20.4	233.1	2.2	225.2	1.9	28.2	4.9		
HTN-01-21	22.98295	312.14126	514.29301	0.05271	0.00034	0.25614	0.00214	0.03530	0.00025	0.00121	0.00019	0.00025	0.00121	0.00019	316.7	14.8	231.6	1.7	223.6	1.6	24.4	3.8		



续表3

测试点	Pb	$^{232}\text{Th}$ $10^6$	$^{238}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{208}\text{Pb}/^{232}\text{Th}$		$^{207}\text{Pb}/^{206}\text{Pb}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{208}\text{Pb}/^{232}\text{Th}$			
				比值	1 $\delta$	比值	1 $\delta$	比值	1 $\delta$	比值	1 $\delta$	年龄/Ma	1 $\delta$	年龄/Ma	1 $\delta$	年龄/Ma	1 $\delta$		
花岗岩长岩 (HTN-01)																			
HTN-01-22	16.30257	182.90401	392.82609	0.05140	0.00047	0.24922	0.00203	0.03537	0.00030	0.00144	0.00022	257.5	20.4	225.9	1.6	224.1	1.8	29.1	4.4
HTN-01-23	18.31425	187.87861	415.83823	0.05292	0.00046	0.25714	0.00232	0.03536	0.00026	0.00157	0.00022	324.1	20.4	232.4	1.9	224.0	1.6	31.7	4.4
HTN-01-24	18.15265	206.90642	481.34429	0.05097	0.00114	0.24420	0.00493	0.03504	0.00020	0.00161	0.00022	239.0	56.5	221.9	4.0	222.0	1.3	32.5	4.4
HTN-01-25	7.10536	141.63140	247.20493	0.05074	0.00044	0.24721	0.00298	0.03539	0.00035	0.00169	0.00028	227.8	23.1	224.3	2.4	224.2	2.2	34.1	5.6
HTN-01-26	29.64577	357.74798	713.51327	0.05101	0.00081	0.24731	0.00389	0.03526	0.00018	0.00141	0.00019	242.7	32.4	224.4	3.2	223.4	1.1	28.5	3.9
正长花岗岩 (HT11-28)																			
HT11-28-1	255.7607038	335.7220537	1353.9055569	0.05601	0.00018	0.29459	0.00292	0.03815	0.00035	0.00439	0.00021	453.8	2.8	262.2	2.3	241.3	2.2	88.5	4.3
HT11-28-2	139.660469	239.1117536	228.5643829	0.05297	0.00030	0.27731	0.00276	0.03796	0.00029	0.00326	0.00017	327.8	8.3	248.5	2.2	240.2	1.8	65.8	3.5
HT11-28-3	594.9901831	911.9809995	1407.049932	0.05308	0.00018	0.28104	0.00257	0.03840	0.00032	0.00333	0.00014	331.5	7.4	251.5	2.0	242.9	2.0	67.2	2.8
HT11-28-4	248.3817286	397.0257608	335.3590823	0.05571	0.00051	0.29427	0.00673	0.03831	0.00079	0.00306	0.00021	442.6	20.4	261.9	5.3	242.3	4.9	61.8	4.2
HT11-28-5	235.3892489	332.9640912	402.6345652	0.05112	0.00028	0.26908	0.00198	0.03818	0.00020	0.00318	0.00020	255.6	11.1	242.0	1.6	241.6	1.2	64.3	4.1
HT11-28-6	116.7602772	173.1647414	248.5408041	0.05203	0.00040	0.27140	0.00279	0.03781	0.00019	0.00336	0.00034	287.1	-13.9	243.8	2.2	239.3	1.2	67.7	6.8
HT11-28-7	263.2780691	417.7625251	467.1030536	0.05426	0.00020	0.28291	0.00137	0.03782	0.00013	0.00295	0.00015	383.4	9.3	253.0	1.1	239.3	0.8	59.4	3.0
HT11-28-8	103.3472254	171.9511201	242.4449292	0.05092	0.00029	0.26401	0.00173	0.03761	0.00011	0.00307	0.00023	235.3	8.3	237.9	1.4	238.0	0.7	62.0	4.6
HT11-28-9	125.4858459	192.0035237	323.1347629	0.05438	0.00032	0.28609	0.00216	0.03817	0.00022	0.00357	0.00021	387.1	13.0	255.5	1.7	241.5	1.4	72.1	4.3
HT11-28-10	117.342596	208.8724531	931.0794186	0.05408	0.00029	0.28562	0.00330	0.03830	0.00038	0.00273	0.00022	376.0	13.0	255.1	2.6	242.3	2.4	55.2	4.5
HT11-28-11	140.5787702	289.8271823	1107.261886	0.05398	0.00030	0.28050	0.00333	0.03766	0.00036	0.00242	0.00017	368.6	8.3	251.1	2.6	238.3	2.2	48.8	3.4
HT11-28-12	33.57807878	74.27521072	498.24496	0.05214	0.00071	0.27336	0.00500	0.03792	0.00035	0.00360	0.00034	300.1	31.5	245.4	4.0	239.9	2.2	72.6	6.9
HT11-28-13	102.1700582	221.5649004	861.2444763	0.05427	0.00025	0.28247	0.00299	0.03772	0.00034	0.00244	0.00017	383.4	11.1	252.6	2.4	238.7	2.1	49.3	3.5
HT11-28-14	68.24108791	140.7632601	248.7304303	0.05389	0.00043	0.28421	0.00279	0.03827	0.00025	0.00232	0.00025	364.9	16.7	254.0	2.2	242.1	1.6	46.8	5.0
HT11-28-15	274.3068693	607.0866573	2282.726524	0.05324	0.00022	0.27633	0.00281	0.03760	0.00032	0.00126	0.00012	338.9	11.1	247.7	2.2	238.0	2.0	25.5	2.5
HT11-28-16	52.23963681	119.5106308	269.0312509	0.05173	0.00046	0.26853	0.00312	0.03765	0.00029	0.00153	0.00033	272.3	20.4	241.5	2.5	238.2	1.8	31.0	6.6
HT11-28-17	206.9125926	445.5631647	765.2566249	0.05309	0.00032	0.27834	0.00267	0.03801	0.00027	0.00073	0.00019	331.5	13.0	249.3	2.1	240.5	1.7	14.7	3.8

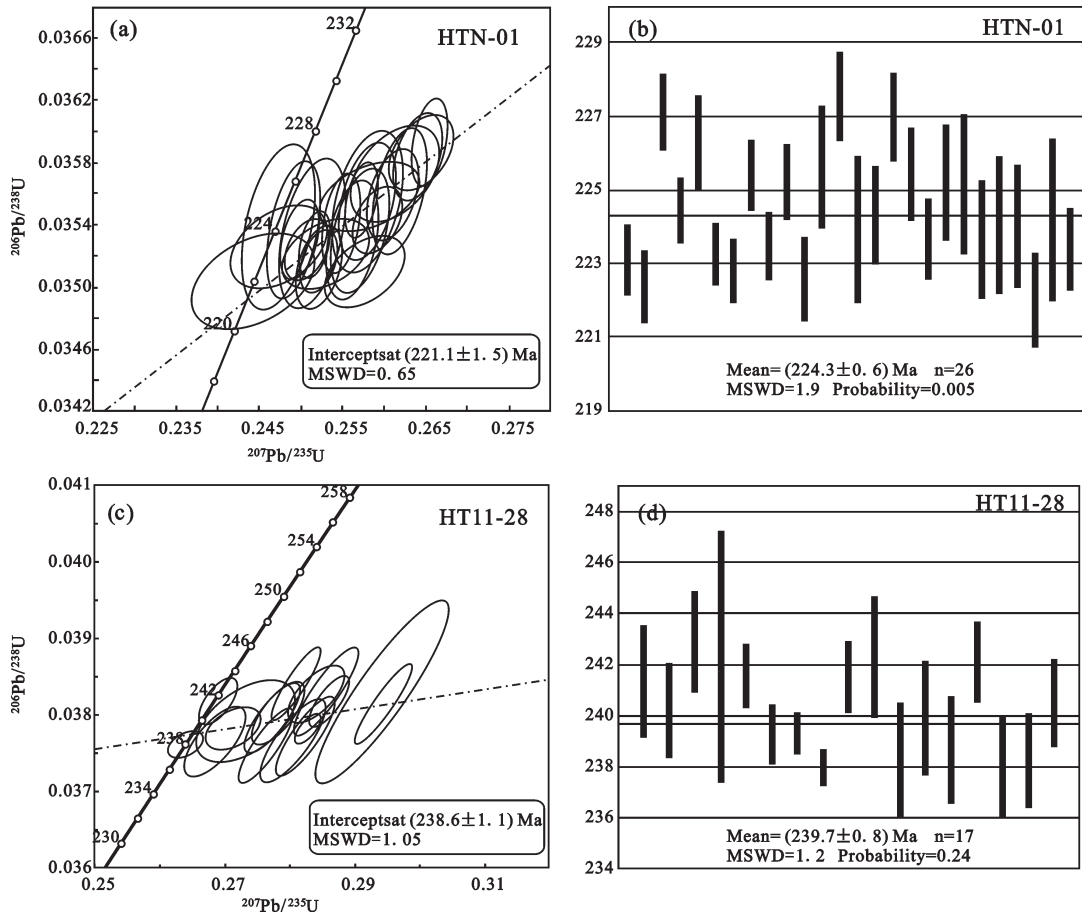


图5 锆石U-Pb谐和图(a,c)及加权平均年龄(b,d)  
Fig.5 Zircon U-Pb concordia diagrams and weighted average of  $^{206}\text{Pb}/^{238}\text{U}$  age

高,显示出I型花岗岩的特点<sup>[20]</sup>。

正长花岗岩具高硅、富碱、低铁镁、贫钙磷钽的特征,  $\text{FeO}^*/\text{MgO}$  值高(3.96~13.17), 样品中无角闪石, 岩石分异指数(DI)达91.2~93.3, 表明岩石经历了较高分异演化。样品中无堇青石、石榴子石及白云母等强过铝矿物;  $\text{A}/\text{CNK} < 1$ , CIPW标准矿物计算中并不出现刚玉分子; 具很低的  $\text{P}_2\text{O}_5$  含量, 而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  $\text{SiO}_2$  的增加而降低<sup>[21]</sup>, 这些特征与S型花岗岩有显著区别。而样品中无碱性暗色矿物出现,  $\text{FeO}^* < 1.00\%$  (平均0.90%), Rb含量  $> 270 \times 10^{-6}$  (平均  $271 \times 10^{-6}$ ),  $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y} < 350 \times 10^{-6}$  (平均  $202 \times 10^{-6}$ ), Ba、Sr、Ga含量均相对较低与A型花岗岩相区别, 而符合高分异型I型花岗岩的特征<sup>[22]</sup>。其富集Th、U等大离子亲石元素, 明显亏损Nb、P、Ti等元素, 较强的负Eu异常等特点, 均可与

冈底斯东部察隅<sup>[23]</sup>及华南佛冈<sup>[24]</sup>高分异I型花岗岩对比。综上认为正长花岗岩属高分异I型花岗岩。

### 5.3 构造背景

在Pearce花岗岩构造环境判别图解<sup>[25]</sup>上, 花岗闪长岩落入火山弧和同碰撞花岗岩区(图6-a), 正长花岗岩则落入板内花岗岩区(图6-b)。对于高分异I型花岗岩而言, 由于其与A型花岗岩在地球化学特征的相似性, 造成常用构造环境判别图解失效<sup>[26]</sup>, 在Pearce花岗岩构造判别图中通常落于板内花岗岩区域<sup>[27]</sup>。花岗闪长岩与正长花岗岩在Rb/30-Hf-3×Ta图解<sup>[28]</sup>中均落入同碰撞-碰撞后花岗岩区(图6-c), 同时落入Pearce于Rb-(Y+Nb)图解中划出的后碰撞构造环境区域<sup>[29]</sup>(图6-d)。

东昆仑造山带是一个多期叠加的多旋回造山带<sup>[30-31]</sup>, 前人根据沉积构造、火成岩构造组合等方面证据, 认为东昆仑造山带华力西-印支造山期为一

表4 虎头崖地区锆石原位 Hf 同位素测试结果  
Table 4 Zircon in situ Hf isotopic data of the granitic rocks in the Hutouya deposit

测试点	$^{176}\text{Lu}/^{177}\text{Hf}$		$^{176}\text{Hf}/^{177}\text{Hf}$		年龄/Ma	$f_s$	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	$T_{2\text{DM}}/\text{Ma}$
	比值	$2\sigma$	比值	$2\sigma$					
花岗岩长岩 (HTN-01)									
HTN-01-1	0.000786	0.000004	0.282587	0.000018	224.3	-0.98	-6.5	-1.73	1368
HTN-01-2	0.001387	0.000015	0.282560	0.000020	224.3	-0.96	-7.5	-2.78	1434
HTN-01-3	0.001866	0.000033	0.282550	0.000024	224.3	-0.94	-7.9	-3.20	1461
HTN-01-4	0.000825	0.000009	0.282542	0.000020	224.3	-0.98	-8.1	-3.33	1470
HTN-01-5	0.001493	0.000080	0.282586	0.000022	224.3	-0.96	-6.6	-1.87	1377
HTN-01-6	0.002640	0.000088	0.282583	0.000030	224.3	-0.92	-6.7	-2.15	1394
HTN-01-7	0.001525	0.000009	0.282569	0.000024	224.3	-0.95	-7.2	-2.48	1415
HTN-01-9	0.002759	0.000022	0.282578	0.000031	224.3	-0.92	-6.9	-2.34	1407
HTN-01-10	0.001904	0.000013	0.282584	0.000017	224.3	-0.94	-6.6	-2.00	1385
HTN-01-11	0.001543	0.000021	0.282615	0.000018	224.3	-0.95	-5.6	-0.85	1312
HTN-01-12	0.001654	0.000030	0.282594	0.000016	224.3	-0.95	-6.3	-1.61	1360
HTN-01-13	0.001717	0.000042	0.282597	0.000017	224.3	-0.95	-6.2	-1.52	1354
HTN-01-14	0.001061	0.000011	0.282548	0.000023	224.3	-0.97	-7.9	-3.15	1458
HTN-01-15	0.002516	0.000034	0.282656	0.000023	224.3	-0.92	-4.1	0.45	1229
HTN-01-16	0.001764	0.000007	0.282618	0.000021	224.3	-0.95	-5.4	-0.78	1307
HTN-01-17	0.001602	0.000022	0.282640	0.000021	224.3	-0.95	-4.7	0.02	1256
HTN-01-18	0.001723	0.000010	0.282575	0.000019	224.3	-0.95	-7.0	-2.30	1404
HTN-01-19	0.001778	0.000017	0.282597	0.000020	224.3	-0.95	-6.2	-1.53	1355
HTN-01-20	0.001655	0.000025	0.282650	0.000017	224.3	-0.95	-4.3	0.37	1234
HTN-01-21	0.002082	0.000028	0.282664	0.000022	224.3	-0.94	-3.8	0.80	1207
HTN-01-23	0.000660	0.000007	0.282593	0.000018	224.3	-0.98	-6.3	-1.50	1353
HTN-01-24	0.001971	0.000056	0.282604	0.000017	224.3	-0.95	-5.6	-0.91	1316
HTN-01-25	0.000975	0.000016	0.282638	0.000019	224.3	-0.94	-5.9	-1.31	1341
HTN-01-26	0.001784	0.000024	0.282640	0.000015	224.3	-0.97	-4.7	0.04	1255
正长花岗岩 (HT11-28)									
HT11-28-1	0.002401	0.000025	0.282584	0.000021	239.7	-0.93	-6.7	-1.77	1382
HT11-28-2	0.001568	0.000018	0.282615	0.000023	239.7	-0.95	-5.6	-0.54	1304
HT11-28-3	0.001787	0.000015	0.282611	0.000019	239.7	-0.95	-5.7	-0.72	1315
HT11-28-4	0.000730	0.000019	0.282597	0.000019	239.7	-0.98	-6.2	-1.04	1335
HT11-28-5	0.001257	0.000007	0.282604	0.000019	239.7	-0.96	-6.0	-0.89	1326
HT11-28-6	0.001503	0.000029	0.282625	0.000020	239.7	-0.95	-5.2	-0.18	1281
HT11-28-7	0.002011	0.000029	0.282587	0.000022	239.7	-0.94	-6.5	-1.58	1370
HT11-28-8	0.001377	0.000010	0.282676	0.000019	239.7	-0.96	-3.4	1.64	1165
HT11-28-9	0.001679	0.000026	0.282595	0.000023	239.7	-0.95	-6.3	-1.26	1350
HT11-28-10	0.003963	0.000047	0.282657	0.000015	239.7	-0.88	-4.1	0.56	1233
HT11-28-12	0.001716	0.000024	0.282598	0.000014	239.7	-0.95	-6.2	-1.16	1343
HT11-28-13	0.003006	0.000015	0.282688	0.000019	239.7	-0.91	-3.0	1.83	1153
HT11-28-14	0.001610	0.000017	0.282612	0.000020	239.7	-0.95	-5.7	-0.66	1312
HT11-28-15	0.004446	0.000040	0.282679	0.000021	239.7	-0.87	-3.3	1.27	1188
HT11-28-16	0.000888	0.000015	0.282574	0.000021	239.7	-0.97	-7.0	-1.87	1388
HT11-28-17	0.001311	0.000022	0.282601	0.000018	239.7	-0.96	-6.1	-0.99	1333

注:  $\varepsilon_{\text{Hf}}(t) = 10000 \times \{ [(^{176}\text{Hf}/^{177}\text{Hf})_s - (^{176}\text{Lu}/^{177}\text{Hf})_s \times (e^{\lambda t} - 1)] / [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} \times (e^{\lambda t} - 1)] - 1 \}$ ;  
 $T_{\text{DM}} = 1/\lambda \ln \{ 1 + [(^{176}\text{Hf}/^{177}\text{Hf})_s - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}] / [(^{176}\text{Hf}/^{177}\text{Hf})_s - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}] \}$ ;  $T_{2\text{DM}} = T_{\text{DM}} - (T_{\text{DM}} - t) \times [(f_s - f_{\text{DM}})]$ ,  
 $f_{\text{LuHf}} = (^{176}\text{Lu}/^{177}\text{Hf})_s / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} - 1$ ; 其中:  $\lambda = 1.867 \times 10^{-11}/\text{a}$  (据文献[17]);  $(^{176}\text{Lu}/^{177}\text{Hf})_s$  和  $(^{176}\text{Hf}/^{177}\text{Hf})_s$  为样品测量值,  $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} = 0.0332$ ,  $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} = 0.282772$  (据文献[18]);  $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$ ,  $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}} = 0.28325$  (据文献[19]);  $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{平均地壳}} = 0.015$ ;  
 $f_s = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{平均地壳}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}] - 1$ ,  $f_{\text{DM}} = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}] - 1$ 。

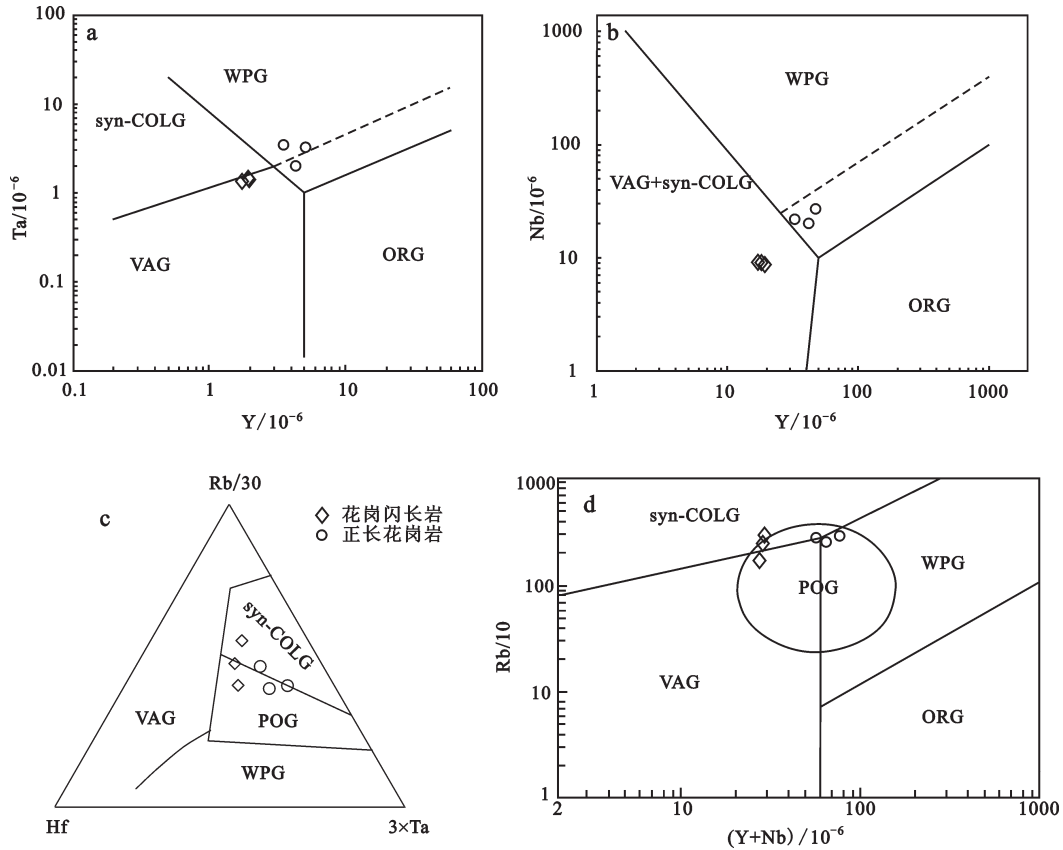


图6 虎头崖矿床花岗岩构造环境判别图  
Fig.6 Granite tectonic discrimination diagrams of the Hutouya deposit

个完整的造山旋回<sup>[32-34]</sup>。晚泥盆世陆相磨拉石的发育及区域性不整合的存在,标志着早古生代造山旋回的结束及华力西—印支造山旋回的开始<sup>[34]</sup>;泥盆纪—二叠纪东昆仑总体处于拉张的大陆动力学背景下,形成了裂陷海盆和有限洋盆<sup>[35]</sup>,发育浅海相碎屑岩—碳酸盐岩建造(大干沟组、迪奥苏组、打柴沟组);板块俯冲自中—晚石炭世开始,中—晚二叠世到早三叠世为主要的俯冲造山期,广泛发育与安底斯活动大陆边缘弧火成岩类相似的弧火山岩类和弧花岗岩类<sup>[34]</sup>;中—晚三叠世为碰撞—后碰撞阶段。据已有研究表明,后碰撞岩浆作用高钾钙碱性岩浆最为发育<sup>[36]</sup>,多数造山带的后碰撞花岗岩类以中—高钾钙碱性I型花岗岩为主,有些花岗岩类具有更高的钾含量,属于钾玄岩系列<sup>[37]</sup>。虎头崖V矿带花岗闪长岩为高钾钙碱性—钾玄岩系列,Ⅷ矿带正长花岗岩为高钾钙碱性系列,综合其时代信息,应该形成于碰撞造山背景下的后碰撞阶段。

#### 5.4 源区性质

锆石具有较高的Hf含量,而Lu的含量又极低,

因此,锆石在形成后基本没有明显的放射性成因Hf的积累,所测定的<sup>176</sup>Hf/<sup>177</sup>Hf比值基本代表了其形成时体系的Hf同位素组成。同时锆石较高的结晶温度、极强的稳定性使其较少受后期变质事件及风化作用的影响,因此锆石成为目前探讨地壳演化和示踪岩石源区的重要工具<sup>[38-41]</sup>。本次测试锆石分析点的<sup>176</sup>Hf/<sup>177</sup>Hf比值较小(大多数小于0.002),表明锆石形成后放射性成因Hf积累十分有限。花岗闪长岩锆石二阶段模式年龄 $T_{2DM}$ 为1207~1470 Ma,平均1352 Ma;正长花岗岩 $T_{2DM}$ 为1153~1388 Ma,平均1299 Ma,均远大于其结晶年龄,表明其主要由古老地壳物质重熔形成; $T_{2DM}$ 较为接近(图7-a),暗示其具有共同的物质来源。花岗闪长岩与正长花岗岩锆石 $\epsilon_{Hf}(t)$ 变化范围均较大(图7-b),Hf同位素的不均一性可能指示了更具放射成因Hf的幔源和有较少放射成因Hf的壳源这两种端元之间的相互作用<sup>[42]</sup>。东昆仑造山带存在地幔源岩浆底侵活动<sup>[43-50]</sup>,碰撞—后碰撞背景下幔源岩浆底侵诱发古老陆壳重熔,岩体二阶段模式年龄可能是幔源物质的加



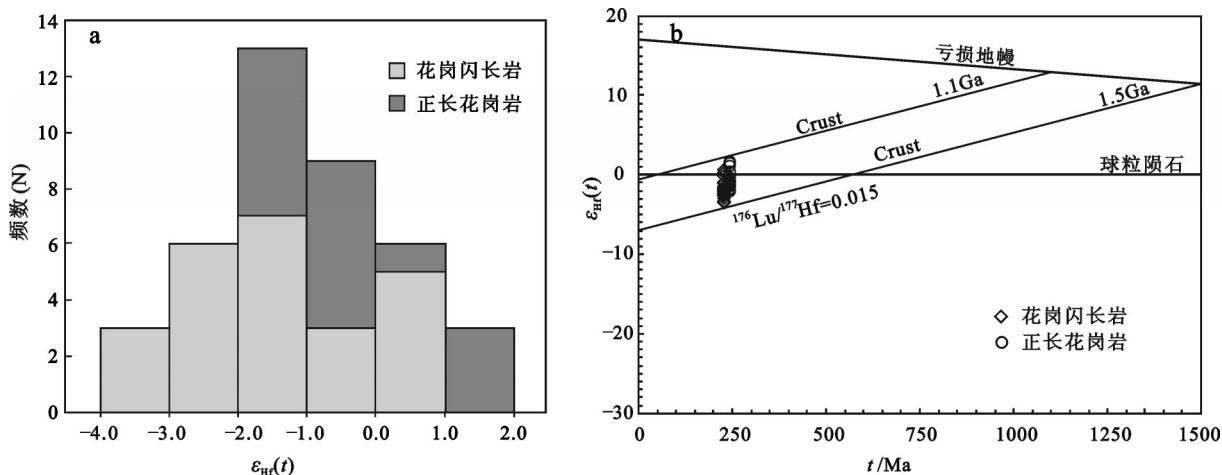


图7 虎头崖矿区岩体锆石 $\epsilon_{Hf}(t)$ 分布直方图(a)和 $\epsilon_{Hf}(t)$ -锆石年龄相关图(b)

Fig.7 Histogram of  $\epsilon_{Hf}(t)$  for zircon (a) and  $\epsilon_{Hf}(t)$  versus U-Pb age diagram for zircon (b) of granitic rock in the Hutouya deposit

入并与中酸性岩浆混合的结果。

### 5.5 岩浆作用与成矿

祁漫塔格地区中一晚三叠世中酸性侵入岩体广泛发育,与成矿作用有关的有约格鲁花岗闪长岩<sup>[45]</sup>(242 Ma),乌兰乌珠儿花岗斑岩<sup>[51]</sup>(215.1 Ma),鸭子沟钾长花岗斑岩<sup>[52]</sup>(224.0 Ma),玛兴大坂二长花岗岩<sup>[53]</sup>(218 Ma),尕林格石英二长闪长岩和石英二长岩<sup>[48]</sup>(228.3 Ma, 234.4 Ma),野马泉南带石英二长闪长岩、正长花岗岩<sup>[49]</sup>(219 Ma, 213 Ma)、它温查汉花岗岩<sup>[50]</sup>(227.7 Ma),长山钾长花岗岩<sup>[50]</sup>(219.9 Ma)等,说明该区在印支期中一晚三叠世不仅曾发生大量地花岗质岩浆侵入活动,而且还产生强烈的多金属成矿作用。

虎头崖矿床V矿带西民采铜内矽卡岩型铜钼多金属矿石Re-Os等时线年龄(225±4.0)Ma, VII矿带西段矽卡岩型铜钼矿石Re-Os等时线年龄(230.1±4.7)Ma<sup>[6]</sup>,与岩体形成时代基本相同,成岩成矿作用均发生在中一晚三叠世。矿体主要产于中酸性侵入岩体与地层接触部位及断层破碎带中,电子探针数据显示闪锌矿中Zn/Cd<300(135~198),方铅矿中Ag含量为 $33 \times 10^{-6} \sim 302 \times 10^{-6}$ ,具有岩浆热液成因特征;流体包裹体测试表明成矿流体以岩浆水为主,并有少量大气降水的混入<sup>[54]</sup>;矿石组合、脉石矿物及围岩蚀变等均显示矽卡岩型矿床的特点。矿石S、Pb同位素数据显示虎头崖矿区成矿物质主要来源于深源岩浆区,Pb为上地壳和地幔混合来源<sup>[54-55]</sup>;碰撞-后碰撞背景下幔源岩浆底侵并发生

壳-幔岩浆混合作用可能带来了丰富的成矿物质,对矿床形成有巨大贡献。

## 6 结 论

(1)通过LA-ICP-MS锆石U-Pb同位素年龄测定,虎头崖V矿带外围花岗闪长岩加权平均年龄为(224.3±0.6)Ma, VIII号矿带矿体下部正长花岗岩加权平均年龄为(239.7±0.8)Ma,岩体形成时代为中一晚三叠世。

(2)花岗闪长岩为I型花岗岩,正长花岗岩具高分异I型花岗岩特征,二者均形成于东昆仑造山带晚古生代一早中生代构造旋回构造旋回的碰撞-后碰撞造山阶段。Hf同位素数据显示岩浆可能经历了壳幔岩浆混合作用。

(3)矿床成因类型为矽卡岩型矿床,成矿物质主要来源于中酸性岩浆活动。东昆仑广泛分布的中酸性岩体说明本区有巨大的找矿潜力。

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