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三江地区俯冲增生-碰撞造山过程中含矿斑岩的地球化学特征对比: 对成矿物质源区差异的指示

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摘 要: 青藏高原东南部三江地区在中-新生代时期的大洋俯冲增生和陆-陆碰撞造山过程中, 为不同时期的成矿过程提供了有利的构造环境, 其中最为典型的是与洋壳俯冲相关的晚三叠世中甸弧斑岩成矿区和与陆内汇聚作用相关的新生代玉龙-马厂箐斑岩成矿带。虽然上述含矿斑岩均为具有高 Sr/Y 比值的埃达克质岩组成特征; 但两者在其他地球化学组成上还是存在一定的差异。同玉龙-马厂箐成矿带相比, 中甸弧成矿区含矿斑岩有着相对较高的 TiO_2 含量、MgO 含量、$Mg^{\#}$值以及高的 CaO/Na_2O 比值、低的 Al_2O_3/TiO_2 和 La/Yb 比值。上述地球化学组成的差异, 结合研究区晚三叠世和新生代早期的构造演化, 指示中甸弧成矿区含矿斑岩的母岩浆很可能为俯冲的大洋板片熔体与其上覆的地幔楔相互作用的结果, 同时这些含矿熔体在随后的上升过程中并没有经历广泛的 MASH (即熔融作用、同化作用、存储和均一化)过程; 而玉龙-马厂箐成矿带含矿斑岩母岩浆很可能是含石榴子石角闪岩相的加厚下地壳与少量的源于富集地幔的钾质熔体相互作用并在地壳深部经历了一定程度分异的结果。

关键词: 含矿斑岩; 中甸弧; 岩石地球化学; 源区组成; 玉龙-马厂箐; 三江地区

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Geochemical comparison of the Mesozoic and Cenozoic ore-bearing porphyries related to subduction accretion and collision orogenesis in the Sanjiang region: Implication for source variety

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Abstract: Since the Mesozoic, the Sanjiang region in SE Tibet has transitioned from an oceanic subduction accretion to intra-continental collision orogeny, which has formed numerous porphyry Cu deposits, such as the Late Triassic Zhongdian arc and the Cenozoic Yulong-Machangqing porphyry Cu belts. Although these ore-bearing porphyries have some adakitic affinities (high Sr/Y ratios), there still are some differences between them in other geochemical compositions. Compared with ore-bearing porphyries developed in the Yulong-Machangqing belt, those in the Zhongdian arc have high TiO_2, MgO, $Mg^{\#}$, CaO/Na_2O, and low Al_2O_3/TiO_2 and

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La/Yb values. These differences, when combined with tectonic evolution during the Meso-Cenozoic in the study region, indicate that the ore-bearing parent magmas of the Zhongdian arc were probably produced by the interaction between melts derived from subducted oceanic slab and overlying mantle wedges. Furthermore, these ore-bearing melts did not experience extensive melting-assimilation-storage-homogenization processes during ascent. The Yulong-Machangqing ore-bearing porphyries probably resulted from the mixing of melts originating from a thickened lower crust and the enriched mantle (potassic melts), which subsequently experienced some differentiation in the deep crust (≥ 30 km).

Key words: ore-bearing porphyiers; Zhongdian arc; petrogeochemistry; source composition; Yulong-Machangqing; Sanjiang region

0 引 言

斑岩型矿床作为一种重要的铜、钼和金矿床类型, 主要产于岛弧及陆缘环境[1]。基于大量弧环境斑岩型矿床的研究而建立的经典斑岩铜成矿模型[2], 在后来环太平洋成矿带斑岩型矿床的勘查中取得了重大突破[3–7]。然而近年来中国矿床学家研究发现, 斑岩型矿床不仅可以产于岛弧及陆缘环境之中, 还可以形成于碰撞造山带中[8–13]。这些形成于不同构造环境中的含矿斑岩, 其地球化学特征及物质源区是否存在一定的差异, 对认识斑岩矿床的成矿作用具有重要意义。青藏高原东南部三江地区(金沙江、澜沧江和怒江)经历了印支期大规模大洋俯冲增生造山作用、燕山期碰撞造山和喜马拉雅期陆内汇聚过程[14], 记录了不同构造演化阶段的成矿作用, 如晚三叠世与甘孜-理塘洋西向俯冲相联系的中甸弧斑岩成矿区和新生代与陆-陆碰撞相联系的玉龙-马厂箐斑岩成矿带, 从而成为研究大洋俯冲增生和陆-陆碰撞造山及其与之有关成矿作用的理想场所[12–15]。为了从整体上了解三江地区中-新生代含矿斑岩物质源区组成和深部动力学机制, 本文拟总结和对比近年来前人发表的有关三江地区典型斑岩型矿床的含矿斑岩地球化学数据(主要为中甸弧斑岩铜矿区和玉龙-马厂箐斑岩铜矿带), 据此来探讨三江地区中-新生代的成矿作用特征, 进而加深对俯冲增生和碰撞造山过程斑岩铜矿床成矿理论的认识。

1 区域地质概况

青藏高原主要由一系列近东西向的地块(体)组成, 从北向南依次为松潘-甘孜地块、羌塘地块、拉萨地块和喜马拉雅带。它们分别被金沙江、班公湖-怒江和雅鲁藏布江缝合带所分隔[16]。三江地区位于青藏高原东南部, 沿着金沙江-哀牢山-红河断裂带将其分为东、西两部分。东部以扬子板块西缘为主, 主要由太古宙变质岩基底和古-中元古代沉积岩及显生界的碎屑岩和碳酸盐岩组成; 西部目前认为是青藏高原的东延部分, 主要由前寒武纪变质基底、晚古生代碎屑岩和碳酸盐岩、中-新生代花岗岩、基性侵入岩和火山岩组成[17–18] (图 1)。

位于金沙江缝合带东侧的义敦弧是印支期甘孜-理塘特提斯洋西向俯冲形成的增生岛弧[22]。中甸弧是义敦弧的南段部分, 经历了印支期洋壳俯冲、燕山期陆-陆碰撞和喜马拉雅期陆内汇聚三大造山阶段, 是三江地区东部典型的中生代斑岩成矿区[23–25]; 其东部和南部均以甘孜-理塘洋结合带为界, 西部以格咱-乡城断裂为界(图 1b)。区内主要出露三叠系地层-火山系统, 火山岩主要为晚三叠世以安山岩为主的钙碱性玄武岩和安山岩, 侵入岩主要为与俯冲作用相关的晚三叠世(218~215 Ma)中酸性浅成斑岩[26–32], 相应发育了一系列与岩浆同期的斑岩型矿床(图 2), 如印支期雪鸡坪、春都、普朗、松诺、烂泥塘、高赤坪、浪都等斑岩型矿床。

印度与欧亚大陆在新生代早期的陆-陆碰撞诱发了金沙江-哀牢山大规模的走滑断裂系统[11], 玉龙-马厂箐富碱斑岩含矿带沿着金沙江-哀牢山以西的这些走滑断裂分布(图 1c), 是三江地区西部典型的新生代斑岩成矿带。该成矿带由西北往东南主要有玉龙、北衙和马厂箐等[11]一系列浅成-超浅成中酸性岩株构成[38–46], 其主成矿期为 43~34 Ma[47–51]。前人研究结果显示, 它们的形成时代与整个三江地区广泛发育的始新世富钾火山岩形成时代(41~31 Ma)[52–57]一致, 属于金沙江-哀牢山新生代富碱斑岩带的一部分[58]。

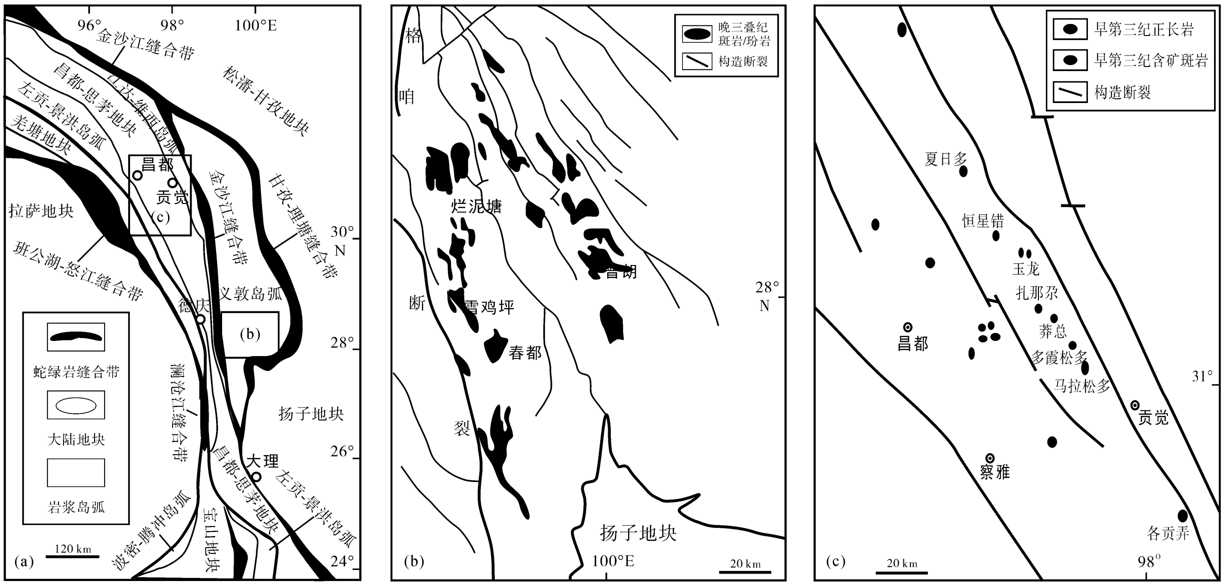

图 1　三江地区区域构造图(a，据文献[19–20])；中甸弧晚三叠世斑岩分布图(b，据文献[21])；玉龙成矿带简单的构造特征和斑岩以及富钾火山岩的分布图(c，据文献[11])

Fig.1　Distribution of typical porphyry deposits in Tibet (a, after references [19–20]); structural features and porphyry distribution in the Xujiping-Pulang porphyry copper area, Zhongdian arc, Sanjiang region (b, after reference [21]); structural features and porphyry distribution in the Yulong porphyry copper belt (c, after reference [11])

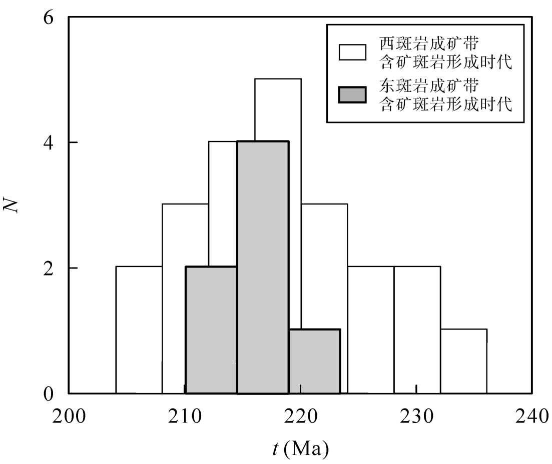

图 2　三江地区中甸弧含矿斑岩时代统计图(数据引自文献[21–24,26,28,33–37])

Fig.2　Age distribution of ore-bearing porphyry in Zhongdian arc, Sanjiang region (after [21–24,26,28,33–37])

2　含矿斑岩地球化学特征

本文数据搜集及对比的对象主要为晚三叠世与大洋俯冲增生过程相关的中甸弧成矿区的普朗和雪鸡坪含矿斑岩，以及与陆-陆碰撞相关的新生代早期玉龙-马厂箐成矿带的含矿斑岩；部分对比矿床的相关信息见表 1。

2.1　主元素和微量元素特征

中甸弧成矿区和玉龙-马厂箐成矿带含矿斑岩主要为钙碱性系列(图 3a)；其中中甸弧成矿区含矿斑岩主要为安山质岩和英安质岩，而玉龙-马厂箐成矿带以英安质岩为主，同时包括少量的流纹质岩。同以高钾和钾玄岩系列为主的玉龙-马厂箐成矿带含矿斑岩相比(图 3b)，中甸弧成矿区含矿斑岩组成从钙碱性系列到钾玄岩系列均存在。两个成矿区的含矿斑岩主量元素组成均有着一定的变化特征，如随着 SiO_2 含量的增加，Al_2O_3、TiO_2、MgO、TFe_2O_3 和 P_2O_5 的含量降低(图 4)。同时，中甸弧成矿区含矿斑岩同玉龙-马厂箐成矿带含矿斑岩相比，有着相对较高的 TiO_2、MgO、TFe_2O_3 含量和 $Mg^{\#}$值(图 4，表 2)。

在球粒陨石标准化稀土元素(REE)分布模式(图 5a)中，中甸弧成矿区和玉龙-马厂箐成矿带含矿斑岩均表现为轻稀土元素(LREE)富集型，Eu 表现出从无异常到轻微的负异常。在原始地幔标准化微量元素蛛网图(图 5b)中，中甸弧成矿区和玉龙-马厂箐成矿带含矿斑岩有着的相似的分布特征，如具有富集强不相容性元素 Rb、Th、U 和相对亏损 Nb、Ta、Ti 的特点，并且 Sr 无明显负异常。

另外，三江地区含矿斑岩具有一定的类似于埃达克岩的地球化学特征(表 2)，如高的 SiO_2(> 56%)、Al_2O_3 (> 14%)、Sr 含量，低的重稀土元素(HREE)和 Y 含量，以及相对较高的 Sr/Y 和 La/Yb 比值(图 4a，图 6a~6b)。

表 1　三江地区相关中-新生代斑岩矿床地质信息概述

Table 1　Summary of geological features for the Mesozoic-Cenozoic porphyry deposit in the Sanjiang region

矿 区	位 置	金属类型	赋矿主岩	蚀 变	矿石矿物	矿床类型	*t* (Ma)	数据来源
中甸弧成矿区								
普朗	云南中甸	Cu	石英闪长斑岩、石英二长斑岩和花岗闪长岩	从中心向外依次为硅化带→钾化带→绢英岩化带→青磐岩化带	黄铜矿、斑铜矿、辉钼矿、铜蓝、磁黄铁矿、 黄铁矿、方铅矿和闪锌矿	斑岩铜矿	锆石 U-Pb (226±3)~(228±3); 辉钼矿 Re-Os 213.0±3.8	曾普胜等[24]; 王守旭等[33]; 曹殿华等[59]; 庞振山等[60]; Li *et al.*[27]; 任江波[21]; Cao *et al.*[34]
雪鸡坪	云南中甸	Cu	闪长斑岩和二长斑岩	硅化、绿泥石化和石英-绢云母化	黄铜矿、黄铁矿和磁铁矿	斑岩铜矿	锆石 U-Pb (215.3±2.3)~(218.4±1.7); 辉钼矿 Re-Os 221.4±2.3	林清茶等[35]; 曹殿华等[36]; Leng *et al.* [61]
松诺	云南中甸	Cu	石英闪长斑岩、黑云母石英二长岩斑岩, 闪长斑岩和石英二长斑岩	硅化、绿泥石化和碳酸盐化	黄铜矿、斑铜矿、黄铁矿、磁铁矿和方铅矿	斑岩铜矿	锆石 U-Pb 220.9±3.5	冷成彪等[37]
玉龙-马厂箐成矿带								
玉龙	西藏江达	Cu-Mo	二长岩、花岗斑岩和石英二长岩,	从中心向外依次为钾化带→石英-绢云母化带→泥化带→青磐岩化带	黄铜矿、辉钼矿、黄铁矿、斑铜矿、黝铜矿、方黄铜矿、闪锌矿、方铅矿、自然金和自然银	斑岩铜-钼矿	主成矿期锆石 U-Pb 37~45	张玉泉等[38]; Jiang *et al.*[43]; 杨志明等[41]; 梁华英等[44,48]; Xu *et al.*[47]
北衙	云南鹤庆	Au	石英钠长斑岩	钾化、硅化、黄铁绢英岩钠长石化和碳酸盐化	黄铁矿、方铅矿、闪锌矿、菱铁矿和黄铜矿	斑岩铜-金矿	锆石 U-Pb 34~37	徐兴旺等[62]; 薛传东等[42]; 肖晓牛等[55]; Lu *et al.*[49];
马厂箐	云南祥云	Cu-Mo	正长斑岩、石英二长斑岩、花岗斑岩和斑状花岗岩	从中心向外依次为强硅化核→石英钾长石化带→石英绢云母化带	黄铜矿、黄铁矿、辉钼矿、斑铜矿、辉铜矿和磁铁矿	斑岩铜-钼矿	锆石 U-Pb 34~37	郭晓东等[45]; 和文言等[51]; 王治华等[50]; Xu *et al.*[47]

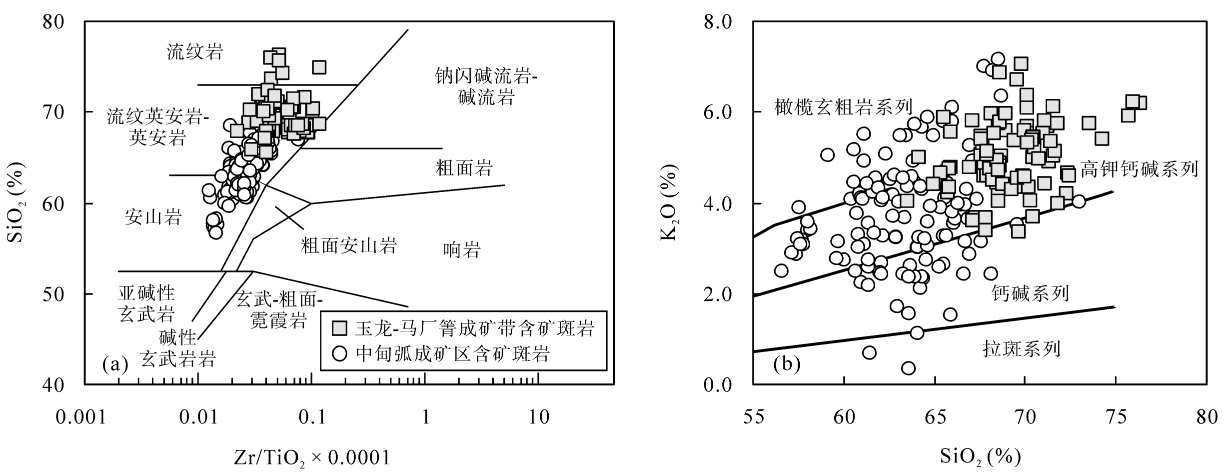

图 3　三江地区晚三叠世中甸弧成矿区含矿斑岩和始新世玉龙-马厂箐成矿带含矿斑岩 SiO_2-Zr/TiO_2 (a) 和 TAS (b)图(据文献[63])

Fig.3　SiO_2-Zr/TiO_2 (a) and TAS (b) diagrams for Late Triassic and Paleogene ore-bearing porphyry of Zhongdian arc and Yulong-Machangqing deposit belt, respectively, in the Sanjiang region (after reference [63])

中甸弧含矿斑岩数据引自文献[21,24,26–28,33,34,37,59,60,64–66]; 玉龙-马厂箐成矿带含矿斑岩数据引自文献[38–43,62,67]

Data source of Late Triassic ore-bearing porphyry in Zhongdian arc from references [21,24,26–28,33,34,37,59,60,64–66]; mafic enclaves in porphyry of Yulong-Machangqing from references [38–43,62,67]

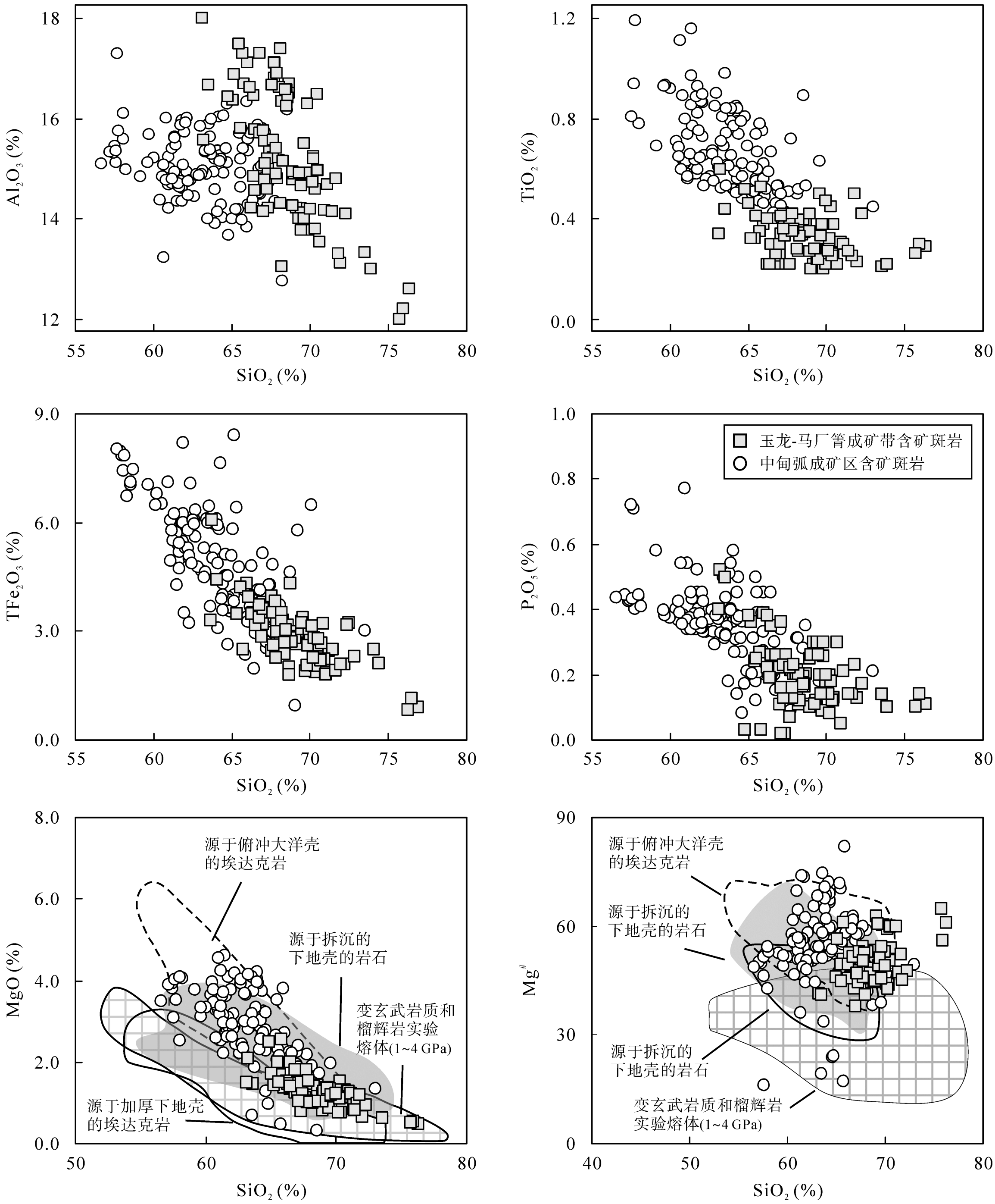

图 4 三江地区晚三叠世中甸弧含矿斑岩和始新世玉龙-马厂箐含矿斑岩 Harker 图(据文献[68]) (数据来源同图 3)

Fig.4 Harker diagrams for Late Triassic and Paleogene ore-bearing porphyry in Zhongdian arc and Yulong-Machangqing areas, respectively (MgO *vs*. SiO_2 and $Mg^{\#}$ *vs*. SiO_2 based on reference [68]) (data sources as in Fig.3)

表 2 三江地区相关中-新生代含矿斑岩与典型埃达克岩地球化学组成对比

Tabel 2 Comparison of geochemical compositions for the typical adakite and the Mesozoic-Cenozoic ore-bearing of porphyry in the Sanjiang region

项 目	埃达克岩(1)	中甸弧含矿斑岩	玉龙-马厂箐含矿斑岩
SiO_2 (%)	≥56	56.6~73.0 (*n* = 128(2); 平均 63.3)	63.5~74.3 (*n* = 67; 平均 68.2)
Al_2O_3 (%)	≥15	11.8~17.3 (*n* = 128; 平均 15.0)	13.4~18.3 (*n* = 67; 平均 15.8)
MgO (%)	< 3	0.31~4.60 (*n* = 128; 平均 2.81)	0.60~2.51 (*n* = 67; 平均 1.33)
Na_2O (%)	3.0~7.4	1.24~5.98 (*n* = 128; 平均 3.40)	2.09~4.84 (*n* = 67; 平均 3.60)
Sr (μg/g)	≥400	206~1980 (*n* = 126; 平均 881)	276~1220 (*n* = 36; 平均 743)

(续表 2)

项 目	埃达克岩(1)	中甸弧含矿斑岩	玉龙-马厂箐含矿斑岩
Y (μg/g)	≤18	8.29~21.6 (n = 127; 平均 16.1)	2.10~20.8 (n = 36; 平均 12.9)
Yb (μg/g)	≤1.9	0.83~2.86 (n = 127; 平均 1.49)	0.53~1.52 (n = 36; 平均 1.18)
Sr/Y	≥20	14.6~103 (n = 122; 平均 54.8)	19.5~81.2 (n = 35; 平均 58.0)
La/Yb	≥8	6.16~55.6 (n = 127; 平均 26.5)	28.0~73.7 (n = 36; 平均 51.3)
$^{87}Sr/^{86}Sr$	< 0.7040	0.7044~0.7080 (n = 29; 平均 0.7063)	0.7060~0.7070 (n = 14; 平均 0.7066)

注: (1) 数据源于文献[69]; (2) 数据来源同图 3

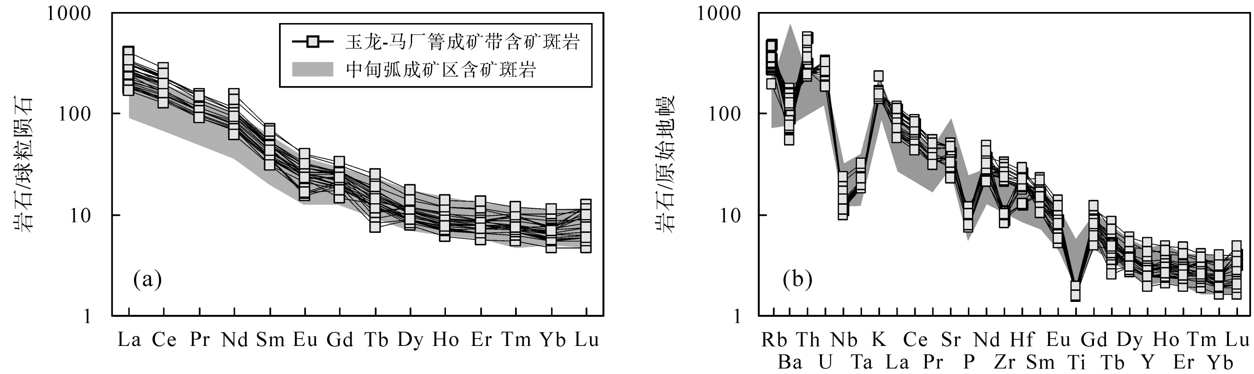

图 5 球粒陨石标准化 REE 分布模式(a)和原始地幔标准化微量元素蛛网图(b)

Fig.5 Chondrite-normalized REE distribution patterns (a) and primitive mantle-normalized trace element spider diagram (b)

标准化数据引自文献[70], 数据来源同图 3

Normalizing values are from reference [70]. Data sources as in Fig.3

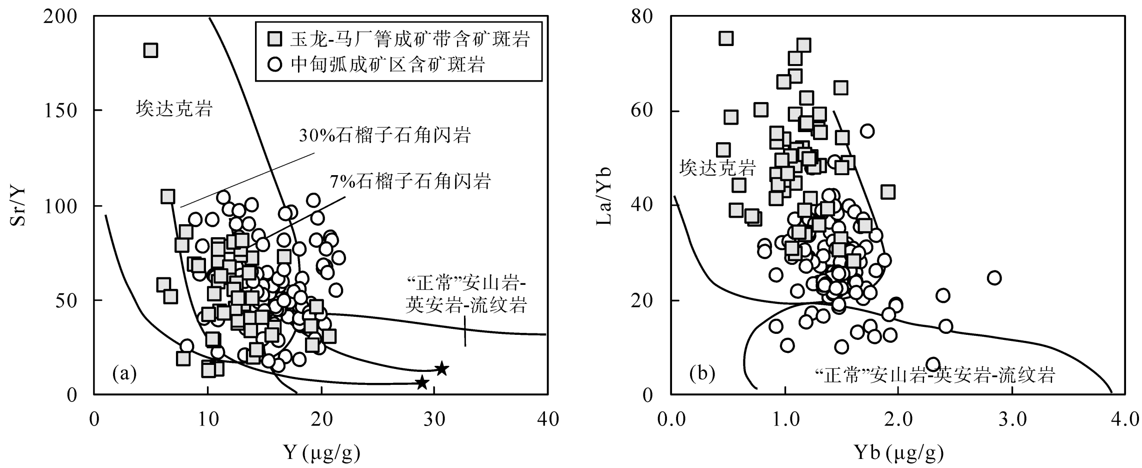

图 6 三江地区晚三叠世中甸弧含矿斑岩和始新世玉龙-马厂箐含矿斑岩 Sr/Y-Y (a, 据文献[71])和 La/Yb-Yb (b, 据文献[72])图(数据来源同图 3)

Fig.6 Sr/Y *vs*. Y (a, after reference [71]) and La/Yb *vs*. Yb (b, after reference [72]) diagrams for Late Triassic and Paleogene ore-bearing porphyry in Zhongdian are and Yulong-Machangqing, respectively (data sources as in Fig.3)

2.2 Sr-Nd-Hf-O 同位素特征

在 $\varepsilon_{Nd}(t)$-($^{87}Sr/^{86}Sr$)$_i$ 同位素相关图(图 7)中, 三江地区含矿斑岩有着较低的 $\varepsilon_{Nd}(t)$值(−5.4~0.7)和较高的($^{87}Sr/^{86}Sr$)$_i$ 值(0.7044~0.7080), 暗示其物质源区并非直接源于亏损地幔的初始岩浆, 并且成矿物质源区有着一定的壳源物质存在。除部分纳日贡玛斑岩外, 玉龙-马厂箐成矿带中的其他含矿斑岩与三江地区始新世富钾的火山岩有着相似的 Sr-Nd 同位素分布范围。

最近的研究表明中甸弧成矿区含矿斑岩具有相对较高且均一的氧同位素组成(5.83‰~6.89‰), 这些锆石氧同位素具有地幔亲和性的特征表明, 它们源于均一的地幔源区或者地幔衍生的岩浆源区[76]; 结合这些含矿斑岩的锆石具有较大变化范围的 $\varepsilon_{Hf}(t)$值(−3.9~7.0[34,36,77]), 指示其物质源区有着一定的壳源的加入。而玉龙-马厂箐成矿带含矿斑岩体的锆石具有更加宽泛变化范围的 $\varepsilon_{Hf}(t)$值(−4.2~10.6), 显示其物质源区也为壳幔物质混合的产物[43,46,49,58]。

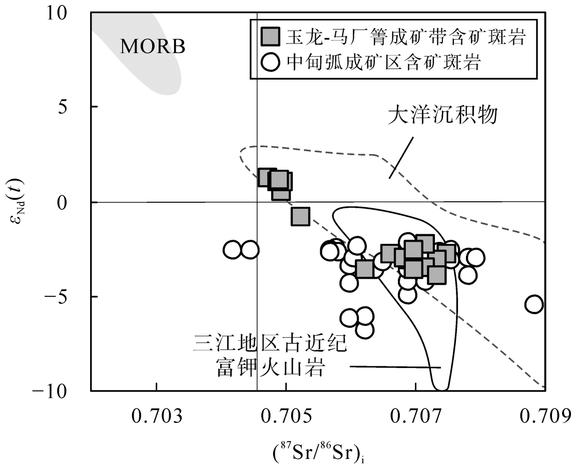

图 7 $\varepsilon_{Nd}(t)$-$(^{87}Sr/^{86}Sr)_i$图(据文献[73])

Fig.7 $\varepsilon_{Nd}(t)$ *vs*. $(^{87}Sr/^{86}Sr)_i$ diagram (after reference [73])

三江地区始新世富钾火山岩引自文献[53,73–75], 其他数据来源同图 3

Paleogene K-rich volcanic rocks of Sangjiang from references [53,73–75], and other data as in Fig.3

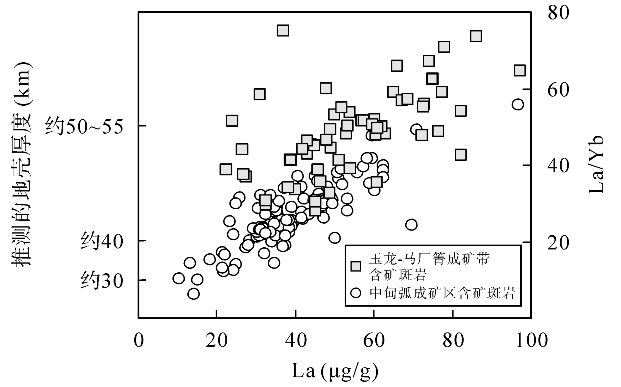

图 8 三江地区晚三叠世中甸弧含矿斑岩和始新世玉龙-马厂箐含矿斑岩 La/Yb-La 图(据文献[82]; 数据来源同图 3)

Fig.8 La/Yb *vs*. La diagram for Late Triassic and Paleogene ore-bearing porphyry in Zhongdian are and Yulong-Machangqing, respectively (after reference [82]; data sources as in Fig.3)

3 讨 论

3.1 含矿斑岩物质源区讨论

有上面的论述可知, 三江地区晚三叠世中甸弧成矿区和玉龙-马厂箐成矿带的含矿斑岩均有着一定的埃达克质岩的地球化学组成特征, 而目前有关埃达克质岩成因的主要观点有: 俯冲年轻洋壳的部分熔融[74]、底侵或加厚的下地壳的部分熔融[78]、幔源玄武质岩浆的结晶分异[75–79]、拆沉的下地壳的部分熔融[80]和俯冲流体交代改造的富集岩石圈地幔的部分熔融。

3.1.1 中甸弧成矿区含矿斑岩的岩石成因

甘孜-理塘洋形成于晚石炭世末或早二叠世初[15], 而中甸弧成矿区含矿斑岩主要形成于晚三叠世(218~215 Ma)[15,25–32]; 并且, 同典型的俯冲洋壳发生部分熔融形成的埃达克岩相比, 中甸弧成矿区含矿斑岩有着明显低的 $\varepsilon_{Nd}(t)$和高的$(^{87}Sr/^{86}Sr)_i$ 值, 指示研究区的含矿斑岩并非是年轻洋壳俯冲作用的产物(表 2)。实验研究结果显示[58], 加厚下地壳或底侵的玄武岩发生部分熔融形成的熔体一般 $Mg^{\#}$值小于 40, 而中甸弧成矿区含矿斑岩有着相对较高的 MgO 含量和 $Mg^{\#}$值(多数大于 40) (图 4), 表明它们可能并非是底侵或加厚的下地壳镁铁质物质部分熔融的产物。同时, 这些含矿斑岩缺乏明显的 Sr、Eu 负异常特征和 La/Yb 与 La(图 8)的正相关关系等, 表明它们也并非是幔源玄武质岩浆结晶分异的产物。虽然拆沉的下地壳发生部分熔融可以产生高 $Mg^{\#}$埃达克质岩[77], 但考虑到甘孜-理塘洋的俯冲时期主要为中晚三叠世[14]、研究区北部的金沙江洋闭合在晚三叠世以及成矿斑岩主要形成于晚三叠世, 中甸弧成矿区含矿斑岩岩浆可能并非是加厚下地壳拆离并发生部分熔融的产物。

中甸弧成矿区含矿斑岩具有较低的 $\varepsilon_{Nd}(t)$和较高的$(^{87}Sr/^{86}Sr)_i$ 值(图 7), 同时部分含矿斑岩样品有着高的 K_2O 含量(图 3)以及低的 Sr/Y 比值(小于 40) (图 6a), 指示有壳源物质成分的加入[83]。这与最近对中甸弧成矿区的锆石原位氧同位素研究结果相一致[76]。同时, 这些锆石氧同位素的地幔亲和性表明它们来自于均一的地幔源区或者地幔衍生的岩浆源区, 而非在锆石生长过程中经受了强烈的同化混染作用[76], 且中甸弧成矿区内也很少发现有地壳成因的捕虏体。上述中甸弧含矿斑岩地球化学及其 Sr-Nd-O-Hf 等同位素的组成, 结合研究区晚三叠世的构造演化, 指示中甸弧含矿斑岩的母岩浆很可能是源于俯冲的大洋板片的融体与上覆因俯冲物质的加入而导致富集的地幔楔相互作用的结果。

3.1.2 玉龙-马厂箐成矿带含矿斑岩的岩石成因

玉龙-马厂箐成矿带含矿斑岩形成于始新世的羌塘地块东部和金沙江-哀牢山走滑带的西部(图 1), 位于羌塘地块北部金沙江-哀牢山缝合带和其南侧的班公湖-怒江缝合带分别形成于晚三叠世-早侏罗世时期[84]和中-晚侏罗世[85]时期, 因此它们不可能是俯冲洋壳发生部分熔融的产物。而研究区并没有发现同时期的大量的镁铁质岩浆作用, 指示玉龙-马厂箐成矿带含矿斑岩可能并非是幔源玄武质岩浆结晶分异的产物。玉龙-马厂箐含矿斑岩具有低的 $\varepsilon_{Nd}(t)$

和高的($^{87}Sr/^{86}Sr)_i$值(图 7)、变化范围较宽的 Hf 同位素组成、高的 K_2O (图 3)和 SiO_2 含量(63.5%~74.3%; 平均 68.2%; 表 2)、远低于幔源熔体但却明显高于壳源熔体的 Mg#值(绝大部分含矿斑岩 Mg#值大于 40) (图 4)以及物质源区形成的深度远大于正常的地壳厚度(≥40 km) (图 8), 表明它们很可能是与加厚下地壳相关的并有一定幔源物质参与的结果。另外, 由前面的论述可知, 玉龙-马厂箐成矿带的主成矿期(43~34 Ma)[47–51]与整个三江地区体积小但广泛发育的始新世超钾质-钾质火山岩形成时代(41~31 Ma)[52–57]一致的时代特征, 同时考虑到研究区这些始新世超钾质-钾质火山岩富含与成矿有关的大量挥发分和流体, 以及研究区含矿斑岩具有上述同期的碱性岩变化一致的 Ba/Rb 和 Rb/Sr 比值(图 9), 暗示玉龙-马厂箐成矿带含矿斑岩很可能是源于富集地幔的超钾质-钾质岩浆与加厚下地壳相互作用的产物。

3.2　俯冲增生-碰撞造山过程中含矿斑岩成矿物质源区对比

近年来, 人们逐渐认识到具有高 Sr/Y 比值的埃达克(质)岩与斑岩型 Cu(-Au-Mo)矿床有着十分密切的关系[86–89]。然而从前面的论述可知, 这些埃达克(质)岩有着不同的物质源区和形成机制; 另外, 斑岩型矿床不仅可以形成于俯冲环境, 而且也可以形成于陆-陆碰撞环境之中[90]。这样使得埃达克(质)岩与斑岩型 Cu(-Au-Mo)矿床之间的关系变得复杂化。

Richards *et al*.[79]认为含矿斑岩的母岩浆为俯冲板片释放流体交代楔形地幔而发生部分熔融并经历 MASH(即熔融作用、同化作用、存储、均一化)过程的产物, 即并非直接源于洋壳的部分熔融。这些经过演化的钙碱性中酸性弧岩浆不仅具有高的氧逸度, 同时具有富含流体的矿物如角闪石。Loucks[91]通过对全球含 Cu 矿斑岩地球化学组成统计研究后认为, 经过演化的钙碱性中酸性富矿融体不仅具有高 Sr/Y 比值(≥40), 同时也具有高的 Al_2O_3/TiO_2 比值(≥40)。另外, Stern *et al*.[92]认为源于俯冲大洋板片的融体与上覆地幔楔相互作用的程度可以通过 CaO/Na_2O 比值推测。虽然中甸弧成矿区域和玉龙-马厂箐成矿带含矿斑岩均有着高的 Sr/Y 比值, 但前者却有着比后者明显低的 Al_2O_3/TiO_2 和较高的 CaO/Na_2O 比值(图 10 和图 11), 指示前者含矿斑岩的母岩浆很可能并未经历传统认为广泛的 MASH 过程, 而其成矿物质来源很可能与俯冲的甘孜-理塘大洋板片发生部分熔融有关[93], 即这些含矿融体很可能是角闪岩相的俯冲板片熔体与富集的地幔楔相互作用的结果。同中甸弧与大洋俯冲相联系的含矿斑岩相比, 玉龙-马厂箐含矿斑岩虽然具有高的 La/Yb、Al_2O_3/TiO_2 比值, 但其同时具有较低的 CaO/Na_2O 比值, 结合其 Sr 和 Eu 并没有明显的负异常, 指示这些含矿岩浆很可能主要源于含有石榴子石角闪岩相下的加厚地壳

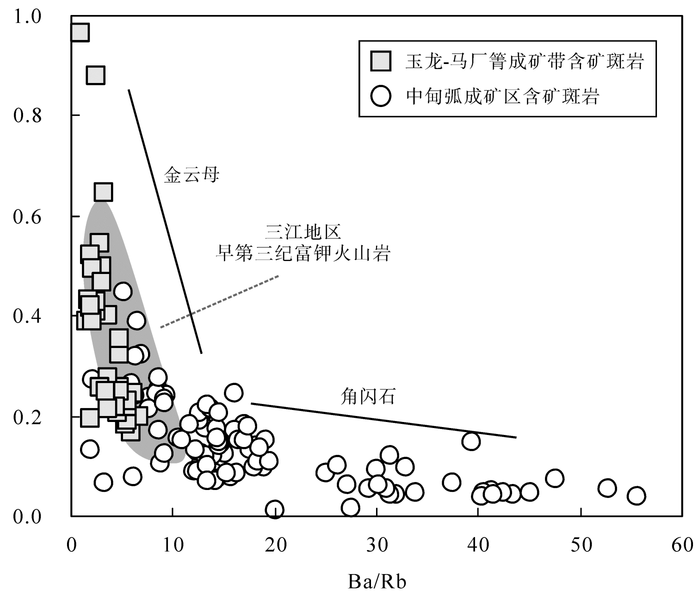

图 9　三江地区晚三叠世中甸弧含矿斑岩和始新世玉龙-马厂箐含矿斑岩 Rb/Sr-Ba/Rb 图

(据文献[72]; 数据来源和图例同图 3)

Fig.9　Rb/Sr *vs*. Ba/Rb diagram for Late Triassic and Paleogene ore-bearing porphyry in Zhongdian are and Yulong-Machangqing, respectively (after reference [72]; data sources as in Fig.3)

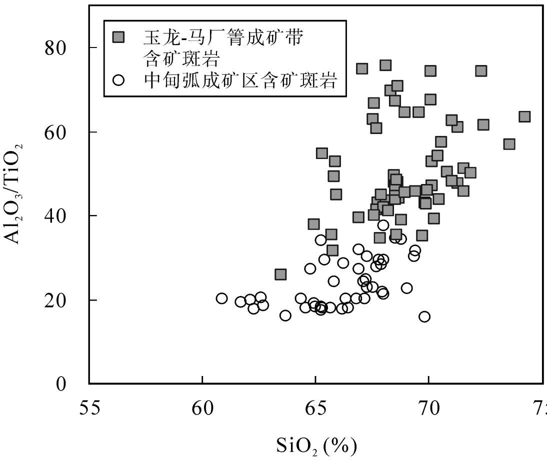

图 10 三江地区晚三叠世中甸弧含矿斑岩和始新世玉龙-马厂箐含矿斑岩 Al_2O_3/TiO_2-SiO_2 图(数据来源和图例同图 3)

Fig.10 Al_2O_3/TiO_2 *vs*. SiO_2 diagram for Late Triassic and Paleogene ore-bearing porphyry in Zhongdian are and Yulong-Machangqing, respectively (data sources as in Fig.3)

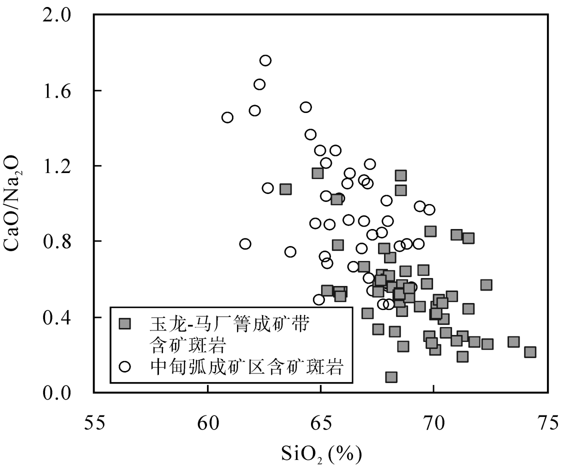

图 11 三江地区晚三叠世中甸弧含矿斑岩和始新世玉龙-马厂箐含矿斑岩 CaO/Na_2O-SiO_2 图(数据来源和图例同图 3)

Fig.11 CaO/Na_2O *vs*. SiO_2 diagram for Late Triassic and Paleogene ore-bearing porphyry in Zhongdian are and Yulong-Machangqing, respectively (data sources as in Fig.3)

与少量的幔源物质相互作用的结果，并且上述含矿熔体在地壳深部(≥30 km)经历了一定的分异作用；而其高的 Rb/Sr 和低的 Ba/Rb 比值很可能为同期的源于富集地幔的钾质熔体与其相互作用所致(图 9)。因此中甸弧含矿斑岩熔体很可能是源于富含角闪石的大洋板片在俯冲过程中发生部分熔融，这些具有高 Sr/Y 的熔体与富集的地幔楔发生反应形成中甸弧含矿斑岩的母岩浆，同时这些含矿融体在随后的上升和演化过程中并没有经历广泛的 MASH 过程；而玉龙-马厂箐含矿斑岩熔体则很可能是源于富含石榴子石角闪岩的加厚下地壳熔体与少量的源于富集地幔的钾质熔体相互作用并在地壳深部经历了一定分异的结果。

4 结 论

(1) 三江地区分别形成于晚三叠世和始新世时期的中甸弧成矿区和玉龙-马厂箐成矿带的含矿斑岩虽然均具有高 Sr/Y 比值等埃达克质岩的组成特征，但两者在地球化学组成上还是存在一定的差异，如前者具有明显低的 Al_2O_3/TiO_2、La/Yb、高的 CaO/Na_2O 比值。

(2) 结合研究区晚三叠世和始新世时期的构造特征，我们初步认为晚三叠世中甸弧含矿斑岩熔体很可能是俯冲的角闪岩相的大洋板片融体与上覆富集地幔楔相互作用的结果，且含矿融体在随后的上升过程中并没有经历广泛的 MASH 过程；而在始新世时期形成的玉龙-马厂箐成矿带含矿斑岩熔体则很可能是源于富含石榴子石角闪岩相的加厚下地壳熔体与源于富集地幔的钾质熔体相互作用并在地壳深部经历了一定演化的结果。

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