



云南武定左所辉绿岩铂族元素地球化学、 Pb 同位素及其地质意义*

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摘 要 古元古代晚期至中元古代早期, 西南康滇地区发生过一次强烈的构造、岩浆及成矿事件, 即昆阳裂谷, 以广泛出露 1.8~1.5 Ga 基性岩浆岩及铁铜矿床为重要标志。文章报道了滇中武定地区左所辉绿岩的岩石化学、微量元素、Pb 同位素及铂族元素地球化学特征, 通过铂族元素地球化学对昆阳裂谷期的岩石圈演化、壳幔相互作用进行了探讨。左所辉绿岩相对富碱 ($\omega(\text{Na}_2\text{O} + \text{K}_2\text{O})$ 平均为 3.55%)、低 $\omega(\text{SiO}_2)$ 、较高的 $\omega(\text{TiO}_2)$ (均值为 3.30%)、 $\omega(\text{P}_2\text{O}_5)$ (平均值 0.35%)、 CaO/TiO_2 比值 (平均值为 2.4) 及 $\text{Al}_2\text{O}_3/\text{TiO}_2$ 比值 (平均值为 3.4) 低, 具有典型地幔热柱玄武岩的岩石化学特征。左所辉绿岩微量元素中相对富集大离子半径元素, 高场强元素弱亏损, 稀土元素中出现弱的 Eu 负异常, 反映了斜长石的轻度结晶分异。辉绿岩具有较高的铂族元素含量, PPGE 和 IPGE 明显分异, PGE 原始地幔标准化配分曲线呈较明显的左陡倾型。辉绿岩的 Cu/Pd 比值均低于原始地幔值, 表明原始岩浆 S 不饱和, 亦未发生硫化物的熔离过程, 较高的 PGE 含量可能与初始岩浆本身的 S 含量较高有关。高的 Pd/Ir 比值可能与 IPGE 在部分熔融过程中更倾向于残留相以及岩浆演化早期铬铁矿和橄榄石的结晶分异有关。低程度的地幔部分熔融、Pb 同位素特征暗示左所地区辉绿岩的形成过程, 陆内裂谷环境下, 富硫的原始岩浆在上升过程中受到较少下地壳物质的混染, 侵位至浅表并较快冷却, 形成辉绿岩。

关键词 地球化学; 铂族元素; 辉绿岩; 左所; 武定; 昆阳裂谷

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PGE geochemistry and Pb isotopes of Zuosuo Paleoproterozoic diabases in Wuding of Yunnan Province and its geological implications

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Abstract

Late Paleoproterozoic and Early Neoproterozoic Kunyang rift was an intense tectonic, magmatic and metallogenetic event, which was characterized by the formation of plenty of 1.8~1.5 Ga basic rocks and Fe-Cu deposits in Kangdian area, Southwest China. Much research work has been carried out on the petrogeochemistry and geochemistry of mineral deposits for investigating geological background and mineralization of Kunyan rift. In this paper, the characteristics of petrochemistry, trace elements, Pb isotope and platinum group elements

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(PGE) of diabases at Zuosuo in central Kangdian area are reported to discuss the lithospheric evolution and interaction of mantle and crust through PGE geochemistry. The diabases have the typical chemical characteristics of mantle plume basalts, such as rich alkali (the average of $w(\text{Na}_2\text{O} + \text{K}_2\text{O})$ is 3.55%), low $w(\text{SiO}_2)$, high $w(\text{TiO}_2)$ (averagely 3.30%) and $w(\text{P}_2\text{O}_5)$ (averagely 0.35%), and low ratios of CaO/TiO_2 (2.4% on average) and $\text{Al}_2\text{O}_3/\text{TiO}_2$ (3.4 on average). The Zuosuo diabases are relatively enriched in large ion radius elements, with weak depletion of high field strength elements and weak negative Eu anomalies in REEs. The diabases have high content of platinum group elements with obvious differentiation of PPGE (Pt, Pd and Rh) and IPGE (Os, Ir and Ru), and the PGE primitive mantle-normalized patterns exhibit obvious left steep curve. Cu/Pd ratios of diabases are lower than those of primary mantle, indicating that the primary magma was S-unsaturated magma without PGE-enriched sulfide separation. The high Pd/Ir ratio of diabases may be related to that IPGEs are more likely to be hosted in residual phase in partial melting, and crystallization differentiation of chromite and olivine for the primary magma in the early stage. Low partial melting of upper mantle and Pb isotopes indicate the formation process of the basite in Zuosuo: In the environment of inner continental rift, original basic S-rich magma was contaminated by lower crust materials during the rising process, and was then emplaced near the surface of the crust, where it became cool quickly, thus forming the diabases.

Key words: geochemistry, PGE, diabase, Zuosuo, Wuding, Kunyang rift

康滇地区位于中国西南,纵贯川滇两省,区内基底地层广泛出露,元古宙岩浆活动频繁,是研究扬子陆块早期演化的重要窗口,也是最近的研究热点。对于区内重要的昆阳裂谷事件,潘杏南等(1985)认为是 >2.0 Ga 绿岩型裂谷,华仁民(1990)提出 $2.0 \sim 1.9$ Ga 的昆阳拗拉谷,而龚琳等(1996)认为是中元古代至新元古代的裂谷。近年来,随着本区内高精度同位素测年结果的不断涌现,对区内元古代地质构造演化也出现了新的认识(孙志明等,2009;朱华平等,2011;关俊雷等,2011;周家云等,2011;耿元生等,2012;杨红等,2012;王冬兵等,2012,2013;王子正等,2013;郭阳等,2014a,2014b;Zhao X F et al., 2010,2011,2013;Chen W T et al., 2013;Zhu Z M et al., 2013)。根据区内最新的岩浆岩同位素年龄、地球化学特征,郭阳等(2014b)及王生伟等(2016)提出,古元古代晚期至中元古代早期,康滇地区发生了一次由地幔柱引起的陆内裂谷拉张事件,即昆阳地幔柱。

铂族元素(PGE)在研究基性、超基性岩石及岩浆硫化物矿床的成因上具有不可替代的价值(Naldrett et al., 1976; Barnes et al., 1985, 1987; Garuti et al., 1984, 1997; 宋谢炎等, 2009),也成为研究化学地球动力学,特别是涉及到深部地幔过程(包括壳-幔以及核-幔作用)的重要手段,取得了大量的进展(Naldrett et al., 1980; Garuti et al., 1997; Jiang et al., 2003; 张成江, 1998; 孙晓明等, 2006)。对于

康滇地区广泛出露的古-中元古代基性-超基性岩体,除了会理县菜子园及东川铜矿区之外(王生伟等, 2011, 2013b),利用铂族元素地球化学来探讨该期深部地幔演化过程较少,本文较详细的报道了滇中武定地区辉绿岩的岩石地球化学、铂族元素地球化学和 Pb 同位素特征,对该区古-中元古代基性岩浆岩的构造背景、岩石圈演化进行了探讨。

1 地质背景

扬子地台西南缘位于印支地块、青藏地块和扬子板块的交汇部位,区内元古代地层、岩浆岩较为发育,研究显示,区内古元古代晚期至中元古代早期($1.8 \sim 1.6$ Ga)发生了一次强烈的岩浆、沉积及成矿作用。古元古代晚期至中元古代早期的基性岩浆岩以辉绿岩为主,主要分布在东川—通安—河口—武定—大红山一线,其次为出露在武定和会东等地的酸性侵入岩。

研究区在大地构造上属于康滇断隆带中段的武定-元江裂陷槽北段(图 1a)。康滇地轴是扬子地台西缘一个地质构造特殊地带,经历了自元古代陆内裂谷、古中元中代拗拉槽、中元古代弧后盆地、中新元古代大陆边缘陆弧体、新元古代后造山裂谷、古生代块断升降、地裂运动及中生代前陆盆地和山间断陷等漫长的地质演化,构成了本区较为复杂的地质背景,多阶段的地质构造背景造成本区的区域构

造也具多期活动特征(郭阳等, 2014b; 龚琳, 1996)。由西向东, 区域构造线依次为 NNW 向—近 NS 向—NEE 向, 总体呈向南收敛的似放射状排列。

多期多阶段构造-岩浆活动及变质变形作用, 为区内丰富的矿产资源形成提供了有利条件。区内及

邻近地区已发现一大批大、中型铜铁矿床(大红山)、铜矿床(如狮凤山、狮子山、一都厂、峨腊厂、白龙厂、红龙厂)、铁矿床(如迤纳厂、鹅头厂、罗茨)、金矿床(如播卡-拖布卡), 是区域上重要的金属矿产富集区(图1b)。本次研究区内的大美厂铜矿床, 远景预测

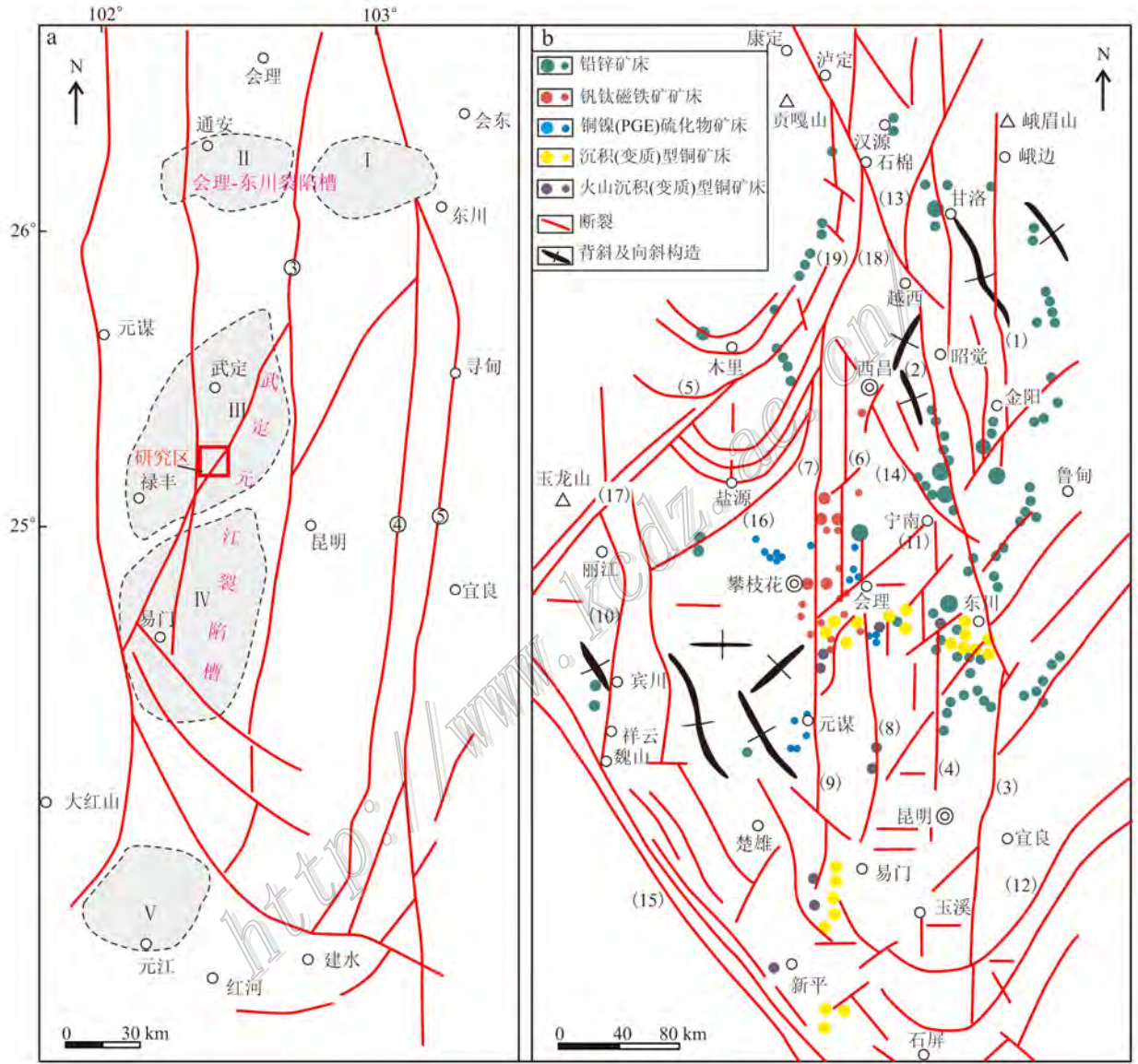


图 1 云南武定地区区域构造(a)及矿床分布图(b)(据廖震文等, 2010 修改)

- a. 区域构造: I—东川断陷盆地; II—笔架山断陷盆地; III—武定断陷盆地; IV—易门断陷盆地; V—元江断陷盆地
区域断裂: ①—元谋-绿汁江断裂; ②—汤郎-易门断裂; ③—普渡河断裂; ④—昆明-滇池断裂; ⑤—小江断裂
- b. 区域控矿断裂: (1)—昭觉断裂; (2)—越西断裂; (3)—小江断裂; (4)—昆明-滇池断裂; (5)—金阳断裂; (6)—安宁河断裂; (7)—雅龙江断裂; (8)—汤朗-易门断裂; (9)—绿汁江断裂; (10)—程海断裂; (11)—宁南—会理断裂; (12)—南盘江断裂; (13)—泸定—越西断裂; (14)—则木河断裂; (15)—红河断裂; (16)—箐河断裂; (17)—裂瓦形断裂; (18)—小金河断裂; (19)—锦屏山断裂
- Fig. 1 Regional tectonics and location of deposits in Wuding area, Yunnan Province(modified after Liao et al., 2010)
- a. Regional structure: I—Dongchuan graben basin; II—Bijashan graben basin; III—Wuding graben basin; IV—Yimen graben basin; V—Yuanjiang graben basin
- Regional fault: ①—Yuanmou-Lvzhijiang fault; ②—Tanglang-Yimen fault; ③—Pudu river fault; ④—Kunming-Dianchi fault; ⑤—Xiaojiang fault
- b. Regional ore-controlling fault: (1)—Zhangjue fault; (2)—Yuexi fault; (3)—Xiaojiang fault; (4)—Kunming-Dianchi fault; (5)—Jinyang fault; (6)—Anninghe fault; (7)—Yalongjiang fault; (8)—Tanglang-Yimen fault; (9)—Lvzhijiang fault; (10)—Chenghai fault; (11)—Ningnan-Huili fault; (12)—Nanpanjiang fault; (13)—Luding-Yuexi fault; (14)—Zenuhe fault; (15)—Honghe fault; (16)—Qinghe fault; (17)—Liewaxing fault; (18)—Xiaojinhe fault; (19)—Jinpingshan fault

可达小-中型铜矿床规模。

武定左所地区夹持于发窝-中干河断裂和德古老断裂之间,中元古代昆阳群因民组-绿汁江组碎屑

岩-碳酸盐岩系是本区出露的主要岩系(图2)。左所地区出露大量的基性岩,主体为辉绿岩,其次为少量辉绿辉长岩等,主要呈岩株、岩墙等侵位于东川

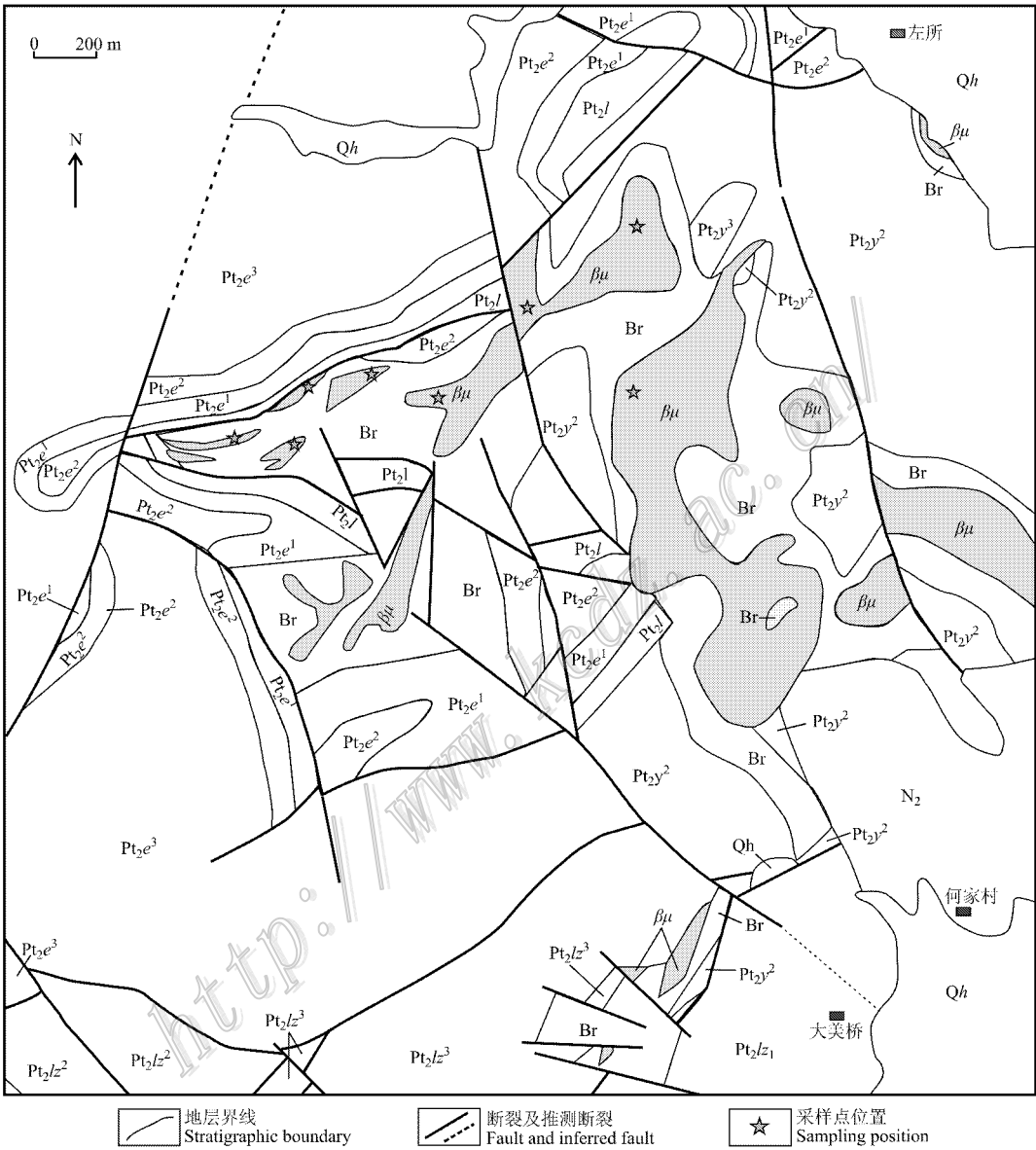


图 2 云南武定左所地区地质图

Qh—渐新系;N—新近系;Pt₂l₃³—绿汁江组三段白质云灰岩;Pt₂l₃²—绿汁江组二段条带状粉晶白云岩;Pt₂l₃¹—绿汁江组一段细晶白云岩;Pt₂e₃³—鹤头厂组三段砖红色粉砂质板岩;Pt₂e₃²—鹤头厂组二段变质石英细砂岩、杂砂岩;Pt₂e₃¹—鹤头厂组一段炭质板岩、粉砂质板岩夹白云岩;Pt₂l₃¹—落雪组白云岩、硅质白云岩;Pt₂y₃³—因民组三段灰黄色变质砂岩、绢云母板岩;Pt₂y₃²—因民组二段灰紫色绢云板岩、角砾岩;β_μ—辉绿岩;Br—与岩体及气液有关的角砾岩

Fig. 2 Regional geological map of the Zuosuo area, Wuding, Yunnan Province
Qh—Oligocene; N—Neogene; Pt₂l₃³—Dolomite limestone of third member of Lvzhijiang Formation; Pt₂l₃²—Banded crystal powder dolomite of second member of Lvzhijiang Formation; Pt₂l₃¹—Fine grained dolomite of first member of Lvzhijiang Formation; Pt₂e₃³—Brick-red sil-slate of third member of Etouchang Formation; Pt₂e₃²—Metamorphic fine sandstone and greywacke of second member of Etouchang Formation; Pt₂e₃¹—Carbonaceous and silty slate with dolomite of first member of Etouchang Formation; Pt₂l₃¹—Dolomite and siliceous dolomite of Luoxue Formation; Pt₂y₃³—Grayish yellow metamorphic sandstone and sericite slate of third member of Yinmin Formation; Pt₂y₃²—Gray purple sericite slate and breccia of second member of Yinmin Formation; β_μ—Diabase; Br—Breccia related to magmatic rocks and gas-fluid

群鹅头厂组-绿汁江组中,有些顺层发育,有些穿插地层,且无固定产状,侵入时代应稍晚于所侵入地层的时代,辉绿岩单颗粒斜锆石 TIMS U-Pb 年龄为 (1688 ± 48) Ma (郭阳,待刊数据),辉绿岩整体走向近南北向,出露面积约 1.5 km^2 。

研究区内的主要矿床为大美厂小型铜矿床,矿体赋存于落雪组第二段下部的白云岩及第一段的白云岩夹层或白云岩透镜体中,与东川地区典型的“落雪式”铜矿(即主要赋存于东川群落雪组、因民组白云岩中的层控型铜矿床,如落雪大型铜矿床、汤丹大型铜矿床)相似,空间上大美厂铜矿床与辉绿岩关系亦较紧密。

2 样品描述与分析方法

2.1 样品采集及样品描述

本文所涉及的主量元素、微量元素、稀土元素、铂族元素及 Pb 同位素样品全部来自左所地区的辉绿岩体,采样过程中注意避开岩石变质程度较高的地带,尽量采集新鲜的样品。采样位置位于左所村南西方向,8件辉绿辉长岩样品分别采自于6个不同的岩体,其中有3件样品采集于最大岩体的不同位置,采集位置的公里网坐标范围为:2809500~2810500;18218600~18220400。

岩石手标本观察岩石呈暗绿色、淡绿色,镜下观察可见(变余)辉长辉绿结构。矿物成分:斜长石(中-拉长石)55%,辉石及角闪石(普通角闪石)20%~40%、黑云母5%~10%、碳酸盐、铁质5%、磁铁矿-钛铁矿3%~5%、榍石1%。

斜长石:呈半自形柱状、柱粒状组成辉长辉绿结构格架,部分绿帘石化,少量绢云母化,纳长石双晶和卡纳双晶发育,属中-拉长石系列。辉石:呈长柱状、不规则状碎裂(粒)状,有的微带浅绿色,有的含斜长石嵌晶,即含长嵌晶结构, $C\lambda Ng$ $17^\circ \sim 20^\circ$,角闪石:主要为普通角闪石,已部分绿帘-绿泥石化呈浅绿色,具多色性,柱状,常为破碎粒状,部分绿泥石化、碳酸盐化等。黑云母:细小叶片状,填隙状集合体,为浅棕色、浅绿色,具特征的黑云母式多色性和吸收性。碳酸盐、铁质:呈他形粒状。磁铁矿-钛铁矿:主要与填隙暗色矿物角闪石、黑云母共生,伴生少量榍石。辉绿岩中存在原生角闪石,指示原始岩浆富水,与洋中脊环境下形成的无水岩浆不同。

2.2 分析方法

取辉长岩样品的新鲜部分在玛瑙研钵中磨至200目以下。主量元素分析由XRF法测试,分析精度好于5%,微量元素仪器为电感耦合等离子体质谱仪(Peikhe-EherELAN DRC-e型 ICP-MS),分析精度优于 $\pm 10\%$,详细分析方法见 Qi 等(2000)。铂族元素采用镍硫火试金结合 ICP-MS 分析,采用同位素稀释法。所有分析均在国家地质测试中心完成。

铂族元素采用镍硫火试金法结合 ICP-MS 测定,具体操作如下:称取15 g全岩粉末样品(< 200 目),与20 g硼酸锂、10 g碳酸钠、2 g羰基镍粉、2 g硫粉和一定量的二氧化硅充分混合均匀,在试金炉内高温(1150°C)熔融2 h后取出镍扣,用6 mol/L盐酸将其溶解完全,加入1 mg/mL的碲溶液2 mL和1 mol/L的 SnCl_2 溶液4 mL进行共沉淀,抽滤,将沉淀用2.5 mL的王水溶解,加入内标铟和铱并稀释到50 mL待测。选用的同位素为: ^{193}Ir 、 ^{101}Ru 、 ^{103}Rh 、 ^{195}Pt 和 ^{105}Pd 。实验方法的检测限是通过在TJA ProExcell型 ICP-MS 上连续测定所选用的同位素11次,由空白溶液的3倍标准偏差计算得到。

Pb同位素分析流程:试样加入硝酸、盐酸和氢氟酸,微波消解,然后用扇形磁场等离子体质谱(HR-ICP-SFMS)测定Pb的含量。若Pb含量低,需要分离,即将消解好的溶液蒸干,加入3 mol硝酸,通过Eichrom的离子交换树脂把Pb分离出来。把待测样品溶液中的Pb调整到适当的浓度,加入内标(Tl)以便需要校正铅的质量分馏。用扇形磁场等离子体质谱(HR-ICP-SFMS)测定Pb同位素,数据经内标(Tl同位素比率)和外部校准(自然铅物质标样)标准化。每个消解好的样品测试2次,以获得其标准差SD(检测结果一起报告出来)。若样品中的Pb含量足够,相对偏差RSD一般小于0.1%~0.2%。实验室控制的允许相对偏差 $\text{RSD} < 0.2\%$ 。

3 分析结果

3.1 主量元素

左所地区辉绿岩的主量元素、微量元素数据见表1,辉绿岩 SiO_2 含量很稳定, $w(\text{SiO}_2)$ 为47.07%~47.83%,均值为47.34%, $w(\text{Na}_2\text{O} + \text{K}_2\text{O})$ 平均值为3.55%,在TAS分类图解均落入辉长岩范围,位于亚碱性低钾区(图3); $w(\text{TiO}_2)$ 和 $w(\text{P}_2\text{O}_5)$ 均较高,均值分别为3.30%和0.35%, CaO/TiO_2 比值及 $\text{Al}_2\text{O}_3/\text{TiO}_2$ 比值较低,前者为2.3~2.6,平均值为

表 1 左所辉绿岩主量元素及微量元素组成

Table 1 Compositions of major and trace elements for Zuosuo diabases

组分	ZS-1	ZS-2	ZS-3	ZS5-4	ZS-5	ZS-6	ZS5-7	ZS-8	平均值
$\omega(B)\%$									
SiO ₂	47.26	47.16	47.07	47.83	47.44	47.37	47.14	47.44	47.34
TiO ₂	3.30	3.32	3.18	3.28	3.34	3.40	3.36	3.23	3.30
Al ₂ O ₃	10.99	11.01	11.42	11.31	11.17	11.13	11.43	11.38	11.23
Fe ₂ O ₃	9.59	9.59	9.75	10.35	9.75	9.34	9.54	8.67	9.57
FeO	8.68	8.6	7.74	7.99	8.62	9.08	8.28	8.89	8.49
MnO	0.23	0.23	0.23	0.23	0.23	0.22	0.23	0.23	0.23
MgO	4.32	4.35	4.66	4.2	4.2	4.24	4.62	4.54	4.39
CaO	7.89	7.88	8.27	7.61	7.56	7.79	8.3	8.24	7.94
Na ₂ O	2.88	2.85	2.84	2.94	2.82	2.82	2.77	2.81	2.84
K ₂ O	0.76	0.76	0.64	0.7	0.73	0.74	0.69	0.68	0.71
P ₂ O ₅	0.35	0.35	0.33	0.36	0.36	0.35	0.33	0.35	0.35
LOI	2.24	2.39	2.31	2.13	2.28	1.96	2.35	2.15	2.23
总和	98.49	98.49	98.44	98.93	98.5	98.44	99.04	98.61	98.62
$\omega(B)(\mu\text{g/g})$									
Cu	62.21	61.02	64.84	89.64	98.43	91.39	76.42	63.51	75.93
Co	39.1	41.5	39	40	42.4	38.4	37.9	37.7	39.50
Ni	37.3	39.1	41.8	35.2	38.5	38.9	42.7	41.3	39.35
Rb	39.7	39.6	22.6	31.8	40.5	44	26.2	28.9	34.16
Sr	219	209	228	205	186	185	225	225	210.25
Ba	293	310	339	232	253	341	225	278	283.88
Ga	22.4	22.8	22.3	22.5	23.1	23.9	23.1	23	22.89
Nb	23.8	24	22.1	23.8	24.8	25.6	23	22.8	23.74
Ta	1.77	1.76	1.64	1.78	1.81	1.8	1.67	1.67	1.74
Zr	246	221	193	239	269	217	234	232	231.38
Hf	6.29	5.95	5.82	6.52	6.73	6.15	6.25	6.47	6.27
Th	3.96	3.6	3.2	3.89	4.11	3.65	3.61	3.68	3.71
Pb	3.5	10.1	3.71	3.82	3.31	3.12	2.02	1.47	3.475
V	536	546	523	506	535	544	557	522	533.63
Cr	28.2	28	51.8	15.8	15.9	17.3	49.6	44.4	31.38
Sc	44.4	45.1	5.6	42.1	44	44.5	47.5	45.3	44.81
U	0.75	0.72	0.59	0.8	0.86	0.7	0.77	0.73	0.74
La	27.9	26.5	22.8	22.1	22.2	26	23.3	26.7	24.69
Ce	48	46.2	45	41.1	38.7	40.9	39.8	41.4	42.64
Pr	8.85	8.58	7.23	7.68	7.73	9.22	7.55	8.4	8.16
Nd	39.2	7.6	31.2	34.3	34.4	40.9	33.9	37.3	36.10
Sm	10	9.73	8.07	8.92	8.9	10.8	8.79	9.75	9.37
Eu	2.97	2.83	2.45	2.67	2.78	3.17	2.62	2.85	2.79
Gd	11.4	11.5	9.37	10.4	10.8	12	10.4	10.9	10.85
Tb	1.73	1.72	1.43	1.65	1.67	1.78	1.56	1.62	1.65
Dy	10.4	10.3	8.73	10	10.4	11.2	9.6	9.94	10.07
Ho	2.08	2.06	1.76	1.97	2.04	2.21	1.95	2.01	2.01
Er	5.52	5.39	4.76	5.35	5.39	5.69	5.17	5.32	5.32
Tm	0.79	0.76	0.67	0.76	0.81	0.83	0.74	0.77	0.77
Yb	5.22	5.05	4.49	5.18	5.32	5.4	4.94	5.1	5.09
Lu	0.78	0.76	0.65	0.77	0.8	0.84	0.73	0.75	0.76
ΣREE	174.84	168.98	148.61	152.85	151.94	170.94	151.05	162.81	160.25
LREE/HREE	3.61	3.50	3.66	3.24	3.08	3.28	3.30	3.47	3.39
δEu	0.85	0.82	0.86	0.85	0.87	0.85	0.84	0.84	0.85
δCe	0.74	0.75	0.85	0.77	0.72	0.65	0.73	0.67	0.74

注：比值单位为 1。

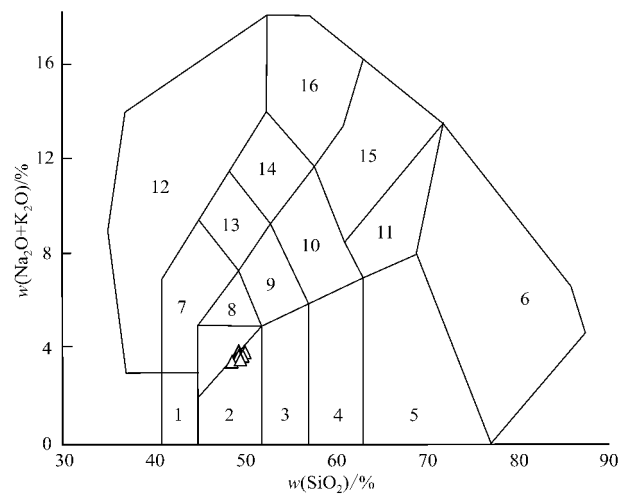


图 3 左所辉绿岩的 TAS 图解(据 Middlemost ,1994)
1—橄榄辉长岩 ;2—辉长岩 ;3—辉长闪长岩 ;4—闪长岩 ;5—花
岗闪长岩 ;6—花岗岩 ;7—似长石辉长岩 ;8—二长辉长岩 ;
9—二长闪长岩 ;10—二长岩 ;11—石英二长岩 ;12—似长石岩 ;
13—似长石二长闪长岩 ;14—似长石二长正长岩 ;15—正长岩 ;
16—似长石正长岩

Fig. 3 TAS diagram of the Zuosuo diabases
(after Middlemost ,1994)

- 1—Olivine-gabbro ;2—Gabbro ;3—Gabbro-diorite ;4—Diorite ;
5—Granodiorite ;6—Granite ;7—Foid gabbro ;8—Monzogabbro ;
9—Monzodiorite ;10—Monzonite ;11—Quartz monzonite ;
12—Foidite ;13—Feldspar-like monzodiorite ;14—Feldspar-like
monzosyenite ;15—Syenite ;16—Feldspar-like syenite

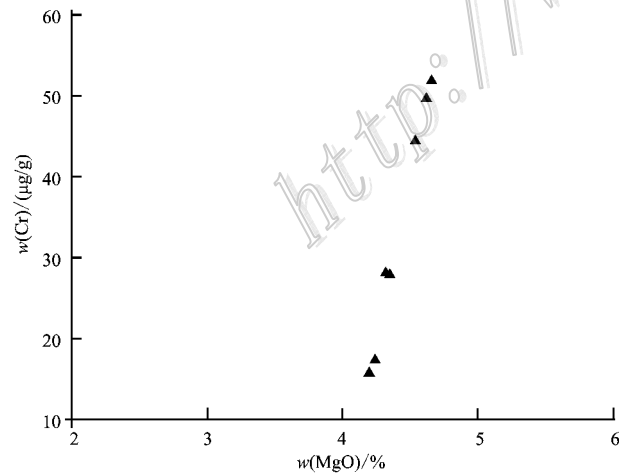


图 4 左所辉绿岩的 Cr-MgO 图

Fig. 4 Cr-MgO diagram of the Zuosuo diabases

2.4 后者为 3.3~3.5 均值为 3.4 ,与西南地区晚二
叠世峨眉山高 Ti 玄武岩及典型地幔柱玄武岩特征
相似(Stein et al. , 1992 ;1995 ; Lee et al. , 1994 ;

Weis et al. , 1993 ; Hauri , 1996 ; 侯增谦等 , 1996a ;
1996b ;1996c ;肖龙等 , 2003a ,2003b ,2003c) ,也与邻
近同时代的海孜辉绿岩岩石化学接近(郭阳等 ,
2014b ;王生伟等 ,2016) 。同时 ,Cr 与 MgO 含量均
呈正相关关系(图 4) 暗示其原始岩浆发生了铬铁矿
和橄榄石的结晶分异。

3.2 微量、稀土元素

稀土元素含量较为稳定 , Σ REE 为(148.61 ~
174.84) $\times 10^{-6}$,8 件样平均值为 160.25×10^{-6} ,轻
稀土元素比重稀土元素略富集 ,LREE/HREE 比值
为 3.08~3.66 ,平均值为 3.39 ,球粒陨石标准化配
分曲线为向右倾的平缓曲线(图 5) ,不同于以 LREE
亏损为特征的洋底玄武岩。上地壳及中等部分熔融
的下地壳富集轻稀土元素(Weaver et al. , 1984) ,本
区辉绿岩富集 LREE 可能暗示岩浆中有陆壳物质的
混入(赵振华 ,1997) 。

微量元素蛛网图(图 6)中 ,大离子半径元素 ,如
Rb、Ba 相对富集 ,而高场强元素如 Nb、Ta、Zr、Hf 等
亏损不明显 ,这些特征与洋岛玄武岩及峨眉山高 Ti
玄武岩(肖龙等 ,2003b)及邻近同时代的武定海孜辉
绿岩相似(郭阳等 ,2014b) ,可能暗示地幔柱成因(王
生伟等 ,2016) 。

3.3 铂族元素

左所的 PGE 成分分析结果见表 2 ,铂族元素总
量 Σ PGE 变化于 $25.24 \times 10^{-9} \sim 35.66 \times 10^{-9}$ 之间 ,
含量较高 ,较国内一些研究程度较高的基性岩的
PGE 含量 ,如峨眉山玄武岩(张成江等 ,1998) 大别
造山带祝家铺辉长岩(刘庆等 ,2005) 高出一个数量

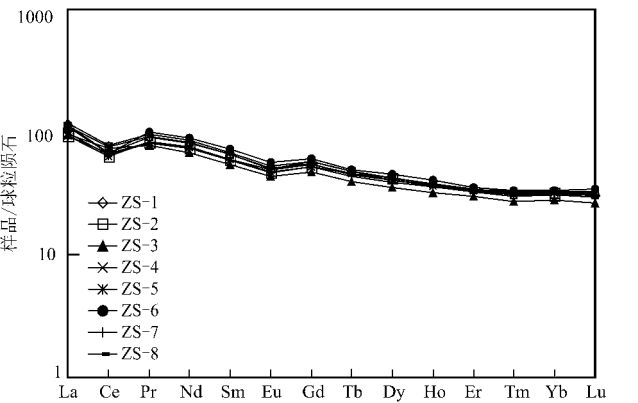


图 5 左所辉绿岩稀土元素配分型式
(球粒陨石标准化值引自 Sun et al. ,1989)

Fig. 5 REE patterns of the Zuosuo diabases
(normalization values are from Sun et al. , 1989)

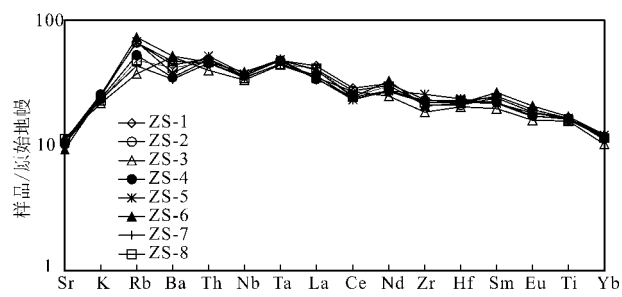


图 6 左所辉绿岩的微量元素蛛网图
(原始地幔标准化值引自 Sun et al. ,1989)

Fig. 6 Trace element spidergrams of the Zuosuo diabbases (normalization values are from Sun et al. ,1989)

级,但明显低于西南地区白马寨、金宝山等岩浆硫化物矿床中的 PGE 含量(王生伟等,2006;2007)。铂族元素含量分别为 $w(\text{Os}) 0.04 \times 10^{-9} \sim 0.07 \times 10^{-9}$ 、 $w(\text{Ir}) 0.10 \times 10^{-9} \sim 0.14 \times 10^{-9}$ 、 $w(\text{Ru}) 0.06 \times 10^{-9} \sim 0.16 \times 10^{-9}$ 、 $w(\text{Rh}) 0.48 \sim 0.66 \times 10^{-9}$ 、 $w(\text{Pt}) 10.70 \times 10^{-9} \sim 15.40 \times 10^{-9}$ 、 $w(\text{Pd}) 13.70 \times 10^{-9} \sim 19.30 \times 10^{-9}$ 。铂族元素中,Pt 和 Pd 相对于 Os、Ir、Ru 含量更高。PPGE(Pt、Pd、Rh)和 IPGE(Os、Ir、Ru)明显分异,Pd/Ir 平均值为 133 (Pd + Pt)/(Or + Ir + Ru)比值平均为 100。Ir 与 Rh、Ir

与 Pd 以及 Pd 与 Pt、Pd 与 Rh 之间显示明显的正相关关系(图 7),Ir 与 MgO、Ni 均呈负相关(图 8),可能反映区内辉绿岩的铂族元素体系受到后期蚀变作用的影响较小。

左所地区辉绿岩的 PGE 原始地幔标准化配分曲线总体呈显著左倾型(图 9),从 Os 到 Ru 相对平坦,从 Ru 到 Pd 明显变陡。相对原始地幔而言(Barnes et al. ,1999),Os、Ir、Ru 强烈亏损,Rh 为弱亏损,Pt、Pd 显著富集。在 Ni/Cu-Pd/Ir 及 Cu/Ir-Ni/Pd 图解(图 10a、b)中,本区样品均落入或者接近溢流玄武岩区。

3.4 Pb 同位素特征

Pb 同位素是示踪物质来源的重要手段,左所地区辉绿岩 Pb 同位素分析结果见表 3。

铅同位素组成较为均一,但放射性成因铅含量较高,其中²⁰⁶Pb/²⁰⁴Pb、²⁰⁷Pb/²⁰⁴Pb 和²⁰⁸Pb/²⁰⁴Pb 的变化范围分别为 19.454~19.975、15.766~15.890 和 40.330~41.546。通过校正后²⁰⁶Pb/²⁰⁴Pb、²⁰⁷Pb/²⁰⁴Pb 和²⁰⁸Pb/²⁰⁴Pb 的变化范围分别为 16.652~17.657、15.520~15.663、37.570~38.781、在²⁰⁷Pb/²⁰⁴Pb-²⁰⁶Pb/²⁰⁴Pb 和²⁰⁸Pb/²⁰⁴Pb-²⁰⁶Pb/²⁰⁴Pb 图解中,数据点集中于下地壳区域而靠近造山带区域(图

表 2 左所辉绿岩铂族元素含量及主要参数表
Table 2 PGE content and main parameters for Zuosuo diabbases

组分	$w(\text{B}) \times 10^{-9}$								平均值
	ZS-1	ZS-2	ZS-3	ZS-4	ZS-5	ZS-6	ZS-7	ZS-8	
Os	0.06	0.07	0.06	0.04	0.05	0.07	0.05	0.05	0.06
Ir	0.13	0.12	0.10	0.14	0.13	0.13	0.13	0.12	0.13
Ru	0.11	0.14	0.15	0.12	0.16	0.11	0.06	0.10	0.12
Rh	0.62	0.63	0.49	0.66	0.65	0.66	0.54	0.48	0.59
Pt	14.00	13.90	10.70	15.40	14.40	15.40	12.10	11.00	13.36
Pd	17.50	17.90	14.00	19.30	17.90	18.60	14.00	13.70	16.61
ΣPGE	32.42	2.76	5.50	35.66	33.29	34.97	26.88	25.45	30.87
Pt + Pd	31.50	31.80	24.70	34.70	32.30	34.00	26.10	24.70	29.98
IPGE	0.30	0.33	0.31	0.30	0.34	0.31	0.24	0.27	0.30
(Pd + Pt)/(Os + Ir + Ru)	105	96	80	116	95	110	109	91	100
Cu/Pd	3555	3409	4632	4645	5499	4913	5459	4636	4593
Pd/Os	292	256	233	483	358	266	280	274	305
Pd/Ru	159	128	93	161	112	169	233	137	149
Pd/Ir	135	149	140	138	138	143	108	114	133
Ni/Pd	2131	2184	2986	1824	2151	2091	3050	3015	2429
Pd/Pt	1.25	1.29	1.31	1.25	1.24	1.21	1.16	1.25	1.25
Cu/Ir	478523	508492	648440	640286	757154	703000	587846	529250	606624
Ni/Pd	2131	2184	2986	1824	2151	2091	3050	3015	2429

注:比值单位为 1。

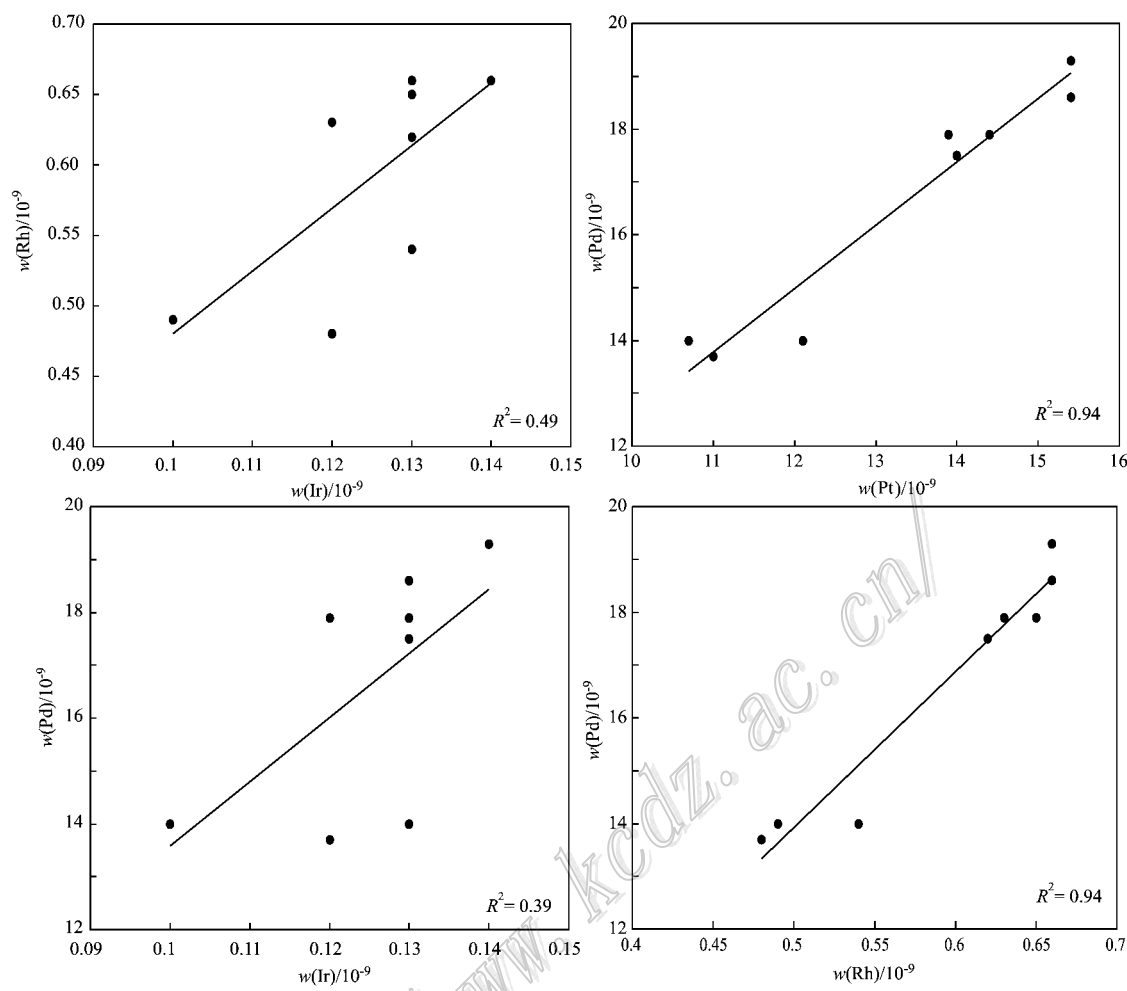


图 7 左所辉绿岩主要铂族元素含量相关性图解

Fig. 7 Relationship of main PGE content for Zuosuo diabases

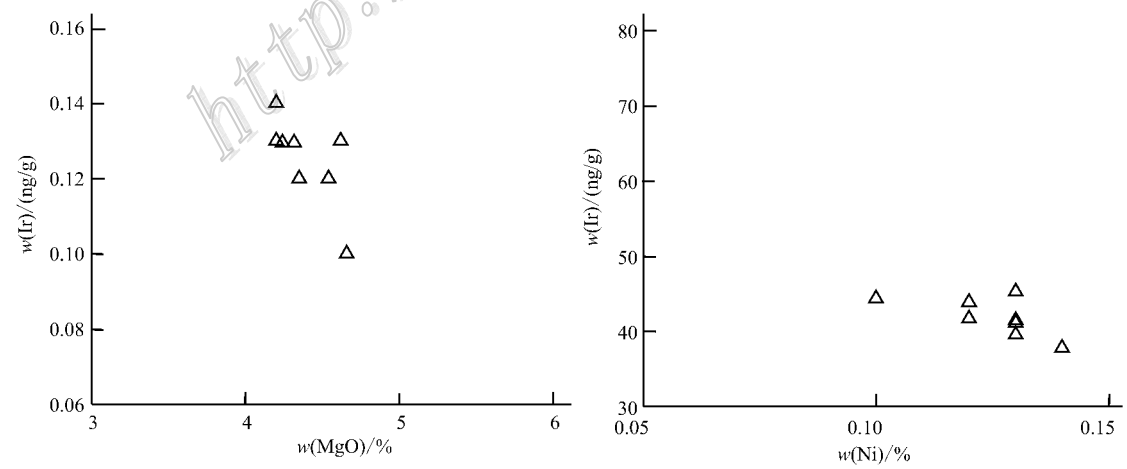


图 8 左所辉绿岩中 Ir 与 MgO 及 Ir 与 Ni 相关性图解

Fig. 8 Relationships of iridium versus magnesia and iridium versus nickel for the Zuosuo diabases

表 3 左所地区辉绿岩铅同位素比值
Table 3 Pb and Sr isotopic ratios of Zuosuo diabbases

样号	(²⁰⁶ Pb/ ²⁰⁴ Pb) _i	(²⁰⁷ Pb/ ²⁰⁴ Pb) _i	(²⁰⁸ Pb/ ²⁰⁴ Pb) _i	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
ZS-1	19.880	15.880	41.285	17.657	15.663	37.729
ZS-3	19.975	15.820	41.546	16.652	15.495	38.781
ZS-5	19.454	15.766	40.330	16.933	15.520	37.777
ZS-7	19.856	15.890	41.246	16.815	15.593	37.570

注：原始 Pb 校正的计算基于 Steiger 等(1977) $\lambda^{238}\text{U} = 1.55125 \times 10^{-10} \text{ a}^{-1}$, $\lambda^{235}\text{U} = 9.8485 \times 10^{-10} \text{ a}^{-1}$, $\lambda^{232}\text{Th} = 4.9475 \times 10^{-11} \text{ a}^{-1}$ (现代 $^{238}\text{U}/^{235}\text{U} = 137.88$)

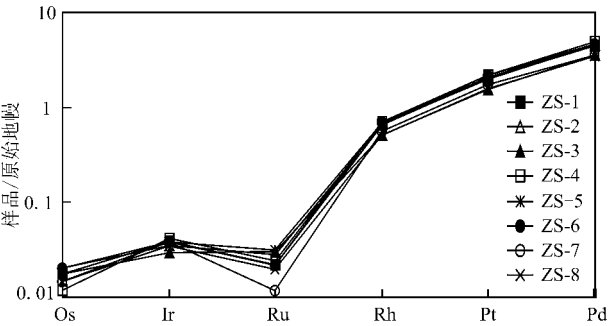


图 9 左所辉绿岩 PGE 原始地幔标准化分布模式
(原始地幔值据 Barnes et al. ,1999)

Fig. 9 Mantle-normalized platinum-group element patterns (PGE) of the Zuosuo diabbases (data of primitive mantle after Barnes et al. ,1999)

11) 表明左所地区辉绿岩原始岩浆可能受到下地壳物质的混染,铅同位素组成可能还受到康滇地区中元古早-中期的局部造山作用的影响。

4 讨论

4.1 原始岩浆的硫饱和度

岩浆演化过程中,硫化物的饱和程度是控制残

留地幔和玄武质岩浆中 PGE 含量的首要因素 (Keays ,1995)。铂族元素如 Pt、Pd 在硫化物中的分配系数远大于 Cu (Crocket et al. ,1977 ; Fleet et al. ,1996),因此,Cu/Pd 比值对指示硫化物的存在状态具有重要意义,也是判断岩浆硫饱和度的有效工具 (Brugmann et al. ,1993)。相应的 Cu/Pd 比值、Cu/Pt 比值也是评价岩体铂族元素富集程度及岩浆演化的重要参数 (Barnes ,1990 ;1993 ;Maier et al. ,1996)。

左所辉绿岩中 Cu/Pd 比值为 3408.88 ~ 5498.88 (表 2),均明显低于地幔值 6300 (Barnes et al. ,1988),在 Pd-Cu/Pd 图解 (图 12) 中,样品均落入正常地幔值区域,由于 PGE 在硫化物/硅酸盐中的分配系数高出 Cu 一个数量级,如果岩浆演化早期过程出现硅酸盐 S 饱和,硫化物熔体 (密度较硅酸盐大) 从硅酸盐熔体中熔离出来,PGE 较 Cu 更多地进入硫化物熔体,则剩余硅酸盐中 Cu/Pd 比值会高于地幔值,如白马寨铜镍硫化物矿床的 Cu/Pd 比值达 $10^4 \sim 10^5$ 级,反映其初始岩浆经历过明显的硫化物熔离过程 (王生伟等,2006)。左所辉绿岩 Cu/Pd 比值低于原始地幔值,表明其初始岩浆 S 未达到饱和,亦未发生过硫化物的熔离,其 Cu/Pd 比值更接近西南地区著名的金宝山铂钯矿床的 Cu/Pd 比值 (王

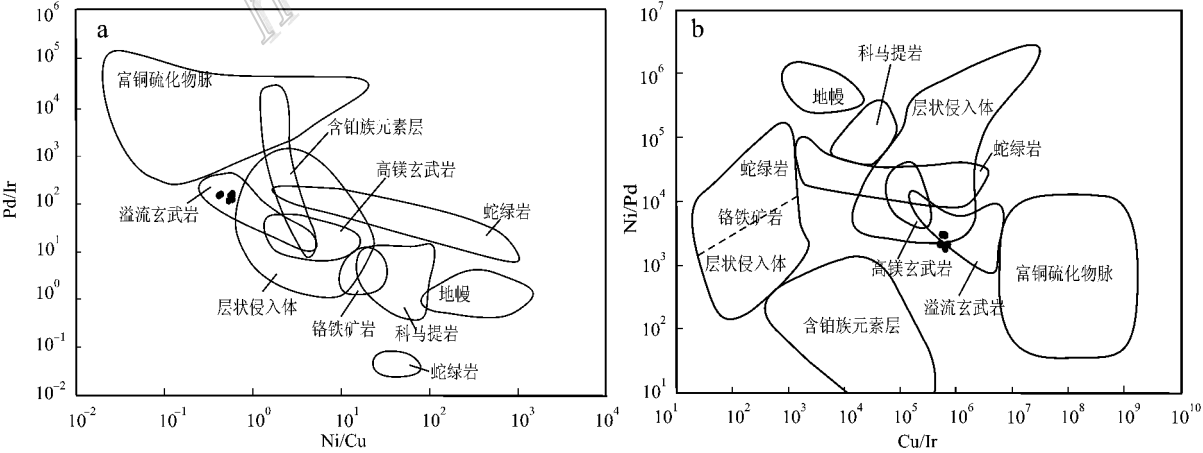


图 10 左所辉绿岩 Ni/Cu-Pd/Ir (a) 及 Cu/Ir-Ni/Pd (b) 图 (据 Barnes et al. ,1985)

Fig. 10 Ni/Cu-Pd/Ir (a) and Cu/Ir-Ni/Pd (b) diagram of the Zuosuo diabbases (after Barnes et al. ,1985)

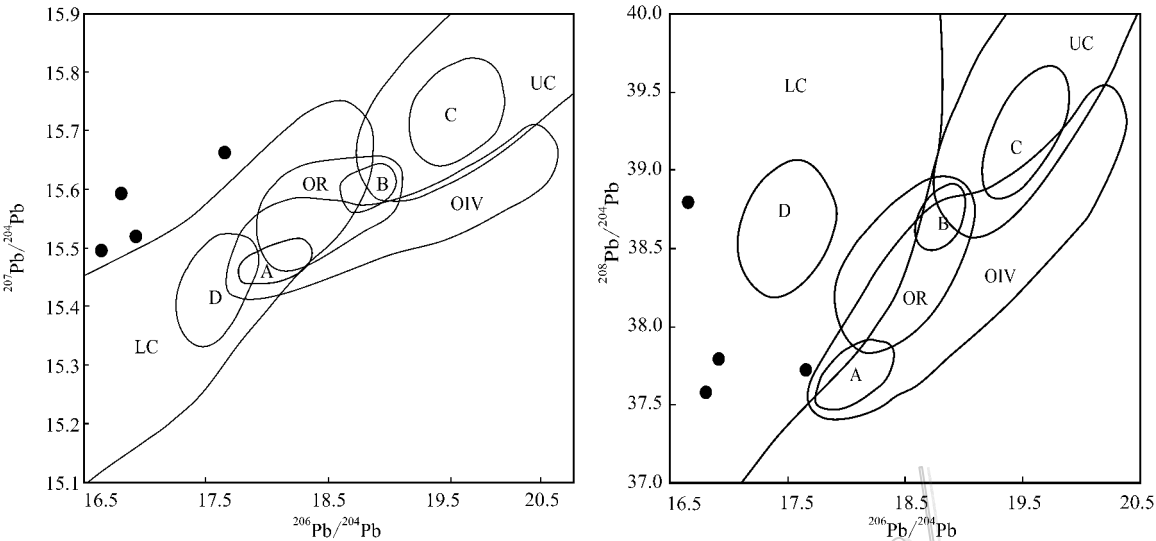


图 11 左所辉绿岩的 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 和 $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ 图解(底图据 Zartman et al. ,1981)

LC—下地壳; UC—上地壳; OIB—洋岛火山岩; OR—造山带; A, B, C, D 分别为各区域中样品相对集中区

Fig. 12 $^{207}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams for Zhusuo diabases (base map after Zartman et al. ,1981)

LC—Lower crust ; UC—Upper crust ; OIB—Ocean island basalt ; OR—Orogenic belt ; A , B , C and D show the areas of sample concentration

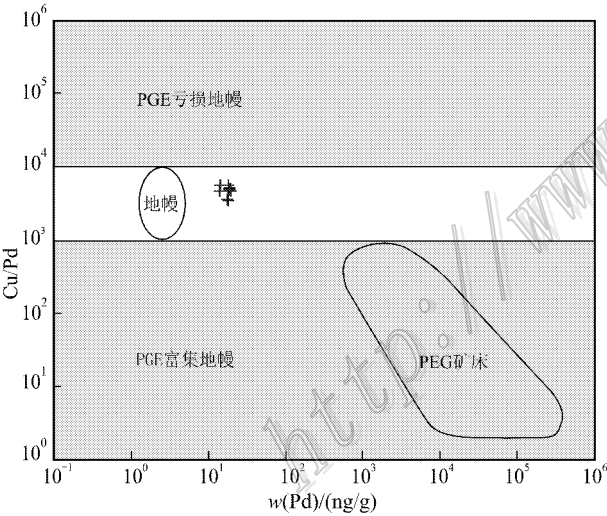


图 12 左所辉绿岩 Cu/Pd-Pd 图(底图据 Barnes et al. , 1993)

Fig. 12 Cu/Pd versus Pd diagram of the Zhusuo diabases (base map after Barnes et al. , 1993)

生伟等 2007)。包括左所辉绿岩在内的康滇地区古-中元古代基性岩浆岩 PGE 总量较高,如东川铜矿区内辉绿岩 $\omega(\text{Pt} + \text{Pd})$ 平均值接近 50×10^{-6} (王生伟等 2011),这类高 PGE 含量及低 Cu/Pd 比值的基性岩浆岩在中国少见。已有的研究结果认为正常情况下,地幔中的硫化物只在部分熔融程度偏高的条件下 ($>25\%$),才能完全溶解进入熔体 (Maier et al. ,

2003),而本区辉绿岩的部分熔融程度较低,高温状态下,硫化物与硅酸盐形成混熔体,在物理化学条件发生改变,尤其长英质的加入和温度降低时,硫在硅酸盐熔体中的溶解度降低,硫化物/硅酸盐二元体系分离,且硫化物的密度更大,从硅酸盐熔体中熔离出,从前面讨论可知,本区辉绿岩高场强元素亏损不明显,表明中上地壳长英质物质的加入可以忽略不计,因此导致其富 PGE,且 Cu/Pd 比值低于地幔值的原因,可能与其初始岩浆 S 含量较高但又未及饱和和有关。

4.2 地幔部分熔融程度

高程度部分熔融的岩浆如科马提岩浆富集 IPGE 元素 (Os, Ir 等) (Maier et al. , 2003), PGE 标准化曲线呈平缓或略右倾的配分模式,而低程度部分熔融的样品出现则富集 PPGE 元素 (Rh, Pt, Pd 等),标准化曲线呈现明显的左倾形式。左所地区的辉绿岩铂族元素分析结果显示其具有较高的 Pt 和 Pd, PPGE 元素含量总体明显高于 IPGE 元素。Pd/Ir 比值为 $107.69 \sim 149.17$,远远大于原始地幔值 ($\text{Pd/Ir} \approx 1$, Barnes et al. , 1988),其原始地幔的 PGE 标准化曲线呈明显的左倾配分型式 (图 9)。较低程度的部分熔融通常会导致 PPGE 比 IPGE 更富集,引起 Pd/Ir 比值的增高 (Crocket et al. , 1977 ; Aland et al. , 2000 ; 孙赫等 , 2008)。此外,前人研究表明, Ir

在地幔部分熔融过程更倾向于非硫化物残留相中富集,亦可导致 Pd/Ir 比值较高(Barnes, 1985);其次,岩浆早期演化过程中,JPGE 较 PPGE 更容易寄主于橄榄石、尖晶石、铬铁矿及难熔合金,亦可产生二者分异(Agiorgitis et al., 1978; Mitchell et al., 1981; Oshin et al., 1982; Brugmann et al., 1987; Zhou et al., 1994; Capohianco et al., 1994; Balhaus et al., 1995),导致 Pd/Ir 比值明显增大,与前述常量元素得出的初步结论,即本区岩浆演化过程发生过铬铁矿、橄榄石等的结晶分异相吻合。

4.3 构造背景及岩石成因

康滇地区古元古代晚期至中元古代早期发生一次重要的岩浆成矿事件,近年来,不少学者开展了大量的研究工作,大多数学者均倾向于以陆内裂谷为主(Greentree et al., 2008; 王生伟等, 2012; 孙志明等, 2009),且与昆阳地幔柱活动紧密相关(王生伟等, 2016),只有 Zhu 等(2013)认为是岛弧环境。在 Ta/Hf-Th/Hf 图解(图 13)中,左所辉绿岩样品投点位于陆内裂谷、陆源裂谷玄武岩和陆内裂谷碱性玄武岩范围,表明本区辉绿岩形成于陆内裂谷构造背景,与武定海孜辉绿岩、东川铜矿区辉绿岩以及会理河口地区辉绿辉长岩具有相似的构造背景(Chen et

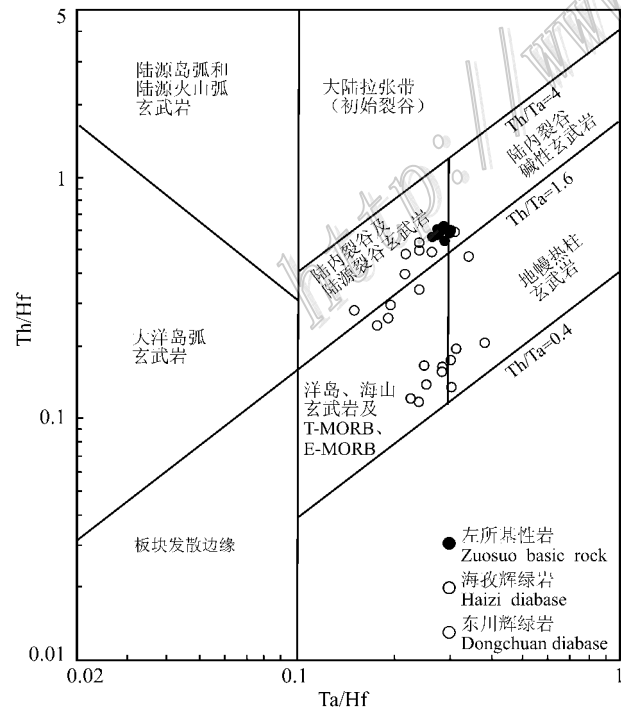


图 13 左所辉绿岩 Ta/Hf-Th/Hf 图解(据汪云亮等, 2001)

Fig. 13 Ta/Hf-Th/Hf diagram for Zuosuo diabases
(after Wang et al., 2001)

al., 2013; 王生伟等, 2013a; 郭阳等, 2014b)左所微量元素的配分模式中, Nb 和 Zr 等高场强元素出现弱的负异常,指示岩浆中有陆壳物质的混入,反映了原始岩浆可能受到轻度的壳源物质混染(Green et al., 2000),从 Ti/Yb-Nb/Th 图解(图 14)中可以判断,少量的混染主要源于下地壳;从其 Cu/Pd 比值也可以反映出来,但混染的量不大,如果大量壳源物质混染,尤其是硅铝质或长英质的中上地壳物质大量加入岩浆,则会出现硫化物从硅酸盐岩浆中融离出来,进而导致侵位后的基性岩浆岩 Cu/Pd 比值大于原始地幔值,在 Pd-Cu/Pd 图上进入 PGE 亏损范围。

综合以上分析,可以大致勾勒出本区辉绿岩浆岩的形成、演化过程:在地幔柱引起的陆内裂谷的拉张环境下,地幔较低程度部分熔融形成富 S 的原始基性岩浆上涌,在上升过程中受到较少下地壳物质的混染,侵位至浅表,较快冷却形成本区辉绿岩。

5 结 论

(1) 左所地区辉绿岩相对富碱($w(\text{Na}_2\text{O} + \text{K}_2\text{O})$ 平均为 3.55%),较低 $w(\text{SiO}_2)$ 以及较高的 $w(\text{TiO}_2)$ (均值为 3.30%), $w(\text{P}_2\text{O}_5)$ (平均值 0.35%),高 CaO/TiO_2 (平均值为 2.4) 及 $\text{Al}_2\text{O}_3/\text{TiO}_2$ (平均值为 3.4) 比值,辉绿岩富集大离子半径元素,高场强元素亏损不明显,具有典型地幔热柱玄武

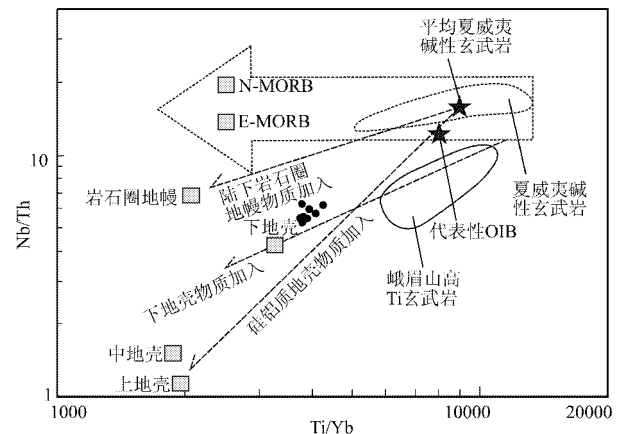


图 14 左所辉绿岩 Ti/Yb-Nb/Th 图解(据朱弟成等, 2006)

N-MORB—正常大洋中脊玄武岩; E-MORB—富集型大洋中脊玄武岩; OIB—洋岛玄武岩

Fig. 14 Ti/Yb-Nb/Th for Zuosuo diabases

(after Zhu et al., 2006)

N-MORB—Normal mid-ocean ridge basalt; E-MORB—Enriched mid-ocean ridge basalt; OIB—Ocean island basalt

岩的岩石化学特征。

(2) 左所辉绿岩 PGE 含量较高, Cu/Pd 比值均低于原始地幔值, 表明原始岩浆未达到 S 饱和, 亦未发生少量硫化物的熔离过程, 由于 PGE 强烈亲 S, 较高的 PGE 含量可能与初始岩浆本身富 S 有关。

(3) 左所辉绿岩 PPGE 和 IPGE 发生强烈的分异, Pd/Ir 比值平均高达 133, PGE 原始地幔标准化配分曲线呈较明显的向左陡倾型曲线, IPGE 相对于 PPGE 强烈亏损可能与其在部分熔融中更倾向于残留相以及岩浆早期演化过程中铬铁矿和橄榄石的结晶分异有关。

(4) Pb 同位素特征表明, 原始岩浆在上升过程中主要受到下地壳物质的混染, 但混染的量不大。推测左所辉绿岩形成于由地幔柱上涌形成的陆内裂谷拉张环境, 地幔较低程度部分熔融形成富 S 原始基性岩浆, 上升过程中受到较少下地壳物质的混染, 侵位至浅表并较快冷却后形成辉绿岩。

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