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东昆中构造混杂岩带清泉沟弧前玄武岩地质、地球化学特征及构造环境

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摘要:东昆中构造混杂岩带东段清泉沟玄武岩岩石源区及构造环境研究具有重要意义.通过对清泉沟玄武岩进行详细的地质、地球化学和构造环境研究,结果表明,该套玄武岩属于亚碱性拉斑玄武岩系列,球粒陨石标准化稀土元素配分图呈现轻稀土元素弱亏损－弱富集的特征,与正常大洋中脊玄武岩(NMORB)和西太平洋IBM弧前玄武岩(FAB)配分特征相似.岩石成因研究表明其源区具亏损地幔特征,且地幔熔融程度比NMORB源区熔融程度较高.构造环境研究表明该套玄武岩形成于大洋初始俯冲阶段的弧前环境.综合区域地质资料,认为东昆中古洋盆至少于中寒武世(510 Ma)之前开始向北俯冲,在俯冲初期形成了清泉沟弧前玄武岩,构成了俯冲带初始弧壳或不成熟洋内岛弧.

关键词:东昆仑;蛇绿岩;清泉沟;弧前玄武岩;地球化学.

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Geochemistry and Tectonic Setting of Qingquangou Forearc Basalts in Central Tectonic Mélange of East Kunlun Orogen

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Abstract: The research on magmatic source and tectonic setting of Qingquangou basalts in eastern section of East Kunlun is important for discussion of the tectonic evolution of East Kunlun ocean. This paper presents a systematic field geology, geochemistry, and tectonic setting research. The results show that the SiO_2 contents of Qingquangou basalts range from 48.60% to 49.28%, MgO contents range from 7.72%－8.00%, TiO_2 contents range from 1.07%－1.10% (average values, 1.09%), which are similar to the values of Izu-Bonin-Mariana forearc basalt, West Pacific. The basalts are classified into the tholeiitic basalt of subalkaline series based on the major elements feature. Qingquangou basalts are characterized by the $\sum$LREEs range from $22.64\times10^{-6}-33.31\times10^{-6}$, $\sum$HREEs range from $13.13\times10^{-6}-18.37\times10^{-6}$, $\sum$REEs range from $36.02\times10^{-6}-51.68\times10^{-6}$, and $(La/Yb)_N$ range from 0.88－1.10. The chondrite normalized REE patterns show the widely enriched-depleted feature of LREE, resembling the feature of NMORB basalts and IBM forearc basalts, West Pacific. Moreover, the samples have low ratios of Ti/Y (312) and Ti/V (<20), also indicative of the

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forearc basalt feature. The primitive mantle normalized trace element spider diagram shows enriched LILEs and undifferentiated HFSEs (e.g., Nb, Ta, Zr, Hf, etc.) features. Petrogenesis research shows that its source was derived from the depleted mantle, and further proves that its partial melting degree is higher than that of NMORB-type basalts. Additionally, the tectonic discrimination diagram suggests that the basalts formed in forearc tectonic setting. Combined with the previous data, it is concluded that East Kunlun ocean began to subduct northward at Middle Cambrian (ca.510 Ma), and that Qingquangou forearc basalts were generated meanwhile, forming the nascent island arc crust.

Key words: East Kunlun; ophiolite; Qingquangou; forearc basalt; geochemistry.

0 引言

蛇绿岩作为古洋壳和上地幔的残余碎片(Coleman,1971),为恢复古大洋或古大陆边缘盆地演化历史提供了物质组成、构造、地球化学等较多的证据.蛇绿岩通常保存在碰撞型和增生型造山带缝合带中,标志着汇聚板块或增生地体间的重要构造边界(张旗,1995,2014; Dilek,2003; Dilek *et al*., 2005; Dilek and Thy,2009).近年来研究表明,造山带中的蛇绿岩绝大多数形成于洋壳俯冲带构造环境(SSZ型蛇绿岩),少数蛇绿岩形成于大洋扩张脊环境(MORB型蛇绿岩)(Dilek,2003;Shervais *et al*., 2004; Pearce, 2008; Whattam and Stern, 2011; Dilek and Furne, 2014).现代西太平洋Izu-Bonin-Mariana弧沟系统是研究程度最高的现代SSZ型蛇绿岩带之一(Reagan, 2010; Dilek and Furnes, 2011;Ishizuka *et al*., 2014).

前人已对东昆仑造山带古生代—中生代构造岩浆事件进行了大量研究(王国灿等,1999;朱云海等,1999;刘成东等,2004;李瑞保,2012;李瑞保等,2012;Meng *et al*.,2013a;刘金龙等,2015;马昌前等,2015;裴先治等,2015;丰成友等,2016;祁晓鹏等,2016;赵菲菲等,2017),取得了较多成果.然而,前人对东昆中蛇绿构造混杂岩带的研究相对较少,并在形成时代、构造环境及岩浆源区属性等方面仍存在争议.早期研究认为东昆中构造混杂岩中的蛇绿岩形成于中元古代,其中橄辉岩全岩Sm-Nd同位素年龄介于1 297~1 372 Ma(王国灿等,1999;朱云海等,1999);近些年东昆中蛇绿岩中辉长岩锆石U-Pb测年成果表明其形成于寒武纪,锆石U-Pb同位素年龄介于518~512 Ma(Yang *et al*.,1996;Li *et al*.,2017),基本证实了早古生代蛇绿岩的存在.最近,Dong *et al*.(2017)认为东昆中蛇绿混杂岩带是一个包含寒武纪—三叠纪的增生型蛇绿构造混杂岩带,并将其与布青山蛇绿混杂岩共同作为古特提斯洋最终关闭的物质记录.此外,前人对东昆中蛇绿岩的形成环境及岩浆源区属性未达成共识,王国灿等(1999)和朱云海等(1999)研究表明,东昆中蛇绿混杂岩带清水泉蛇绿岩的玄武岩为轻稀土富集型,轻重稀土分馏强,代表弧后盆地或陆壳基底上拉张的小洋盆构造环境.然而,龙晓平等(2004)基于东昆中清水泉地区岩石组合及岩石地球化学分析结果则认为其很可能代表变薄的陆壳下底辟侵位的上地幔.因此,东昆中蛇绿岩究竟形成于洋中脊(MORB型)或者弧后盆地,还是俯冲带(SSZ型)上盘弧(洋)壳的产物,尚待进一步研究.

最近,我们在东昆中构造混杂岩带的都兰县巴隆乡清泉沟地区识别出一套弧前基性火山岩.本文对清泉沟基性火山岩进行了详细的岩石学及岩石地球化学研究,以期对其形成环境及源区属性进行限定,从而为东昆中蛇绿岩的进一步研究提供新的依据.

1 区域地质背景

东昆仑造山带位于中央造山系西段(图1a,1b),东西长约1 000 km,南北宽约50 km,西隔阿尔金断裂与西昆仑造山带为邻,东隔秦祁昆岔口(共和盆地)与西秦岭造山带相接,北侧为柴达木地块,南侧为布青山—阿尼玛卿构造混杂带(图1b).以东昆中断裂带和东昆南断裂带为界,可将东昆仑造山带自北而南划分为东昆北构造带、东昆南构造带和布青山—阿尼玛卿构造混杂带(图1b).研究区中北部以大面积出露古老变质岩系为特征,主要由高角闪岩相变质的古元古界白沙河岩组(Pt_1b)、以变质石英质岩石为主的中元古界小庙岩组(Pt_2x)和早古生代绿片岩相变质的纳赤台岩群(Pz_1N)组成,区域上被晚泥盆世牦牛山组伸展型磨拉石建造不整合覆盖.其中,白沙河岩组与小庙岩组构成东昆仑地区的变质基底.东昆仑造山带还出露一套呈带状近东西向延伸的晚二叠世—早三叠世花岗岩体,其形成与古特提斯洋北向俯冲密切相关(刘成东等,2004;熊富浩等,2011;李碧乐等,2012;李瑞保等,2012,

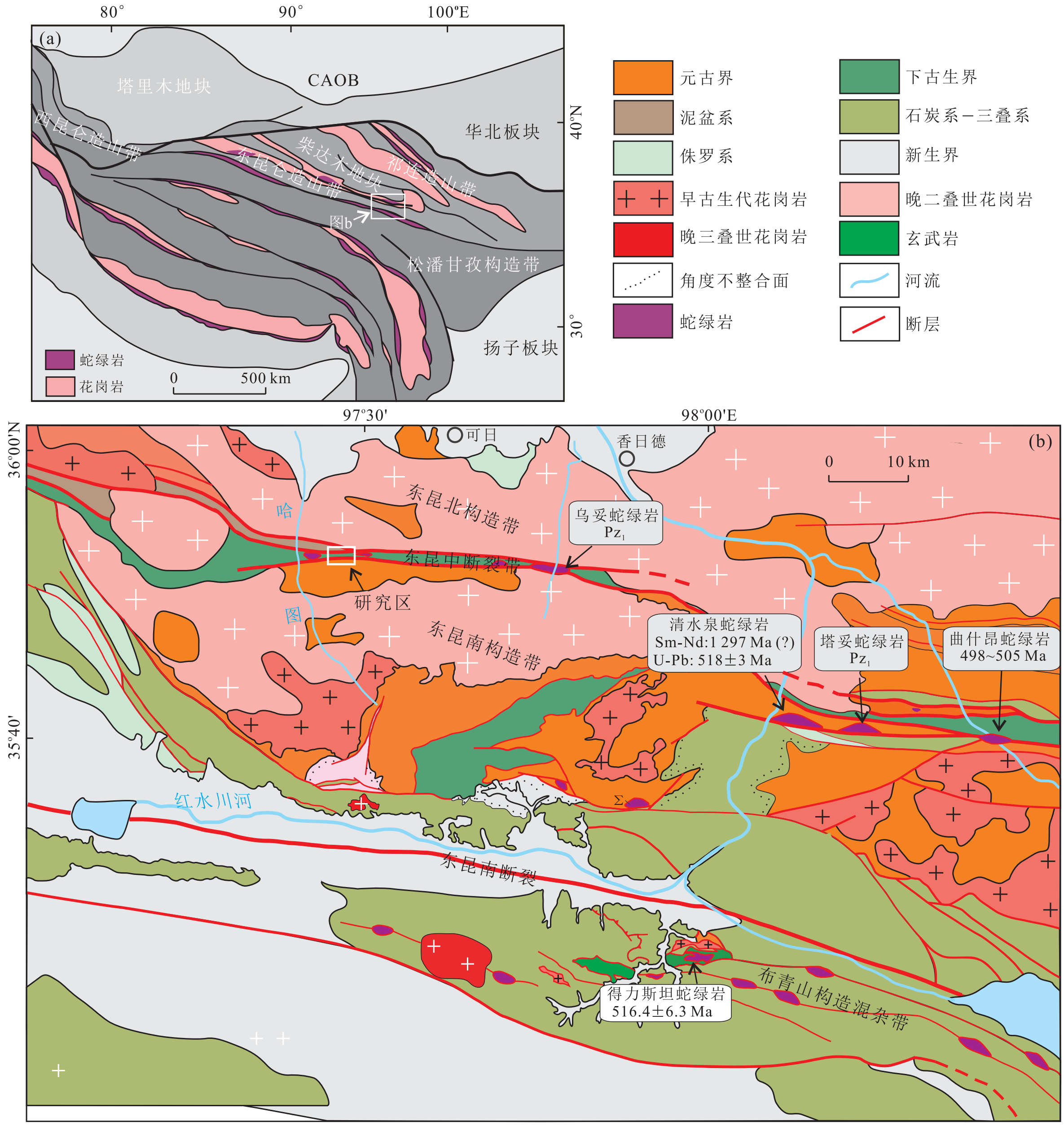

图 1　东昆仑造山带及邻区构造简图(a)和研究区及邻区地质简图(b)

Fig.1　Simplified tectonic map of East Kunlun orogen and neighboring area (a) and geological map of studying area and neighboring area (b)

2015；马昌前等，2015)．此外，在研究区南侧的布青山—希里可特地区还出露有少量具面状展布特征的晚三叠世碰撞型花岗岩(陈国超等，2013；李佐臣等，2013；刘金龙等，2015)．

因沿东昆中断裂带断续出露有多个蛇绿岩块，学者们习惯地将其称之为东昆中蛇绿构造混杂岩带或东昆中缝合带．东昆中蛇绿混杂岩带自东向西出露的典型地区有吉日迈、曲什昂、清水泉、塔妥、乌妥、可日、阿此特、清泉沟、哈图沟、宗加南清水河等地．详细的地质调查表明，清水泉蛇绿岩主要发育蛇纹岩、变辉长岩和变玄武岩等，不同单元间呈断层接触关系，构造环境研究表明其形成于岛弧环境(姜春发等，2000)．塔妥地区蛇绿混杂岩主要包括蛇纹岩、块状辉长岩、变玄武岩及深水相硅泥质板岩等．乌妥和可日蛇绿混杂岩岩石组合相对单一，主要包括墨绿色块状蛇纹岩及变基性火山岩．变基性火山岩发育有同构造分泌石英细脉，脉体变形较强，多呈不对称碎斑状，显示自北向南的高角度韧性逆冲运动学特征．阿此特蛇绿岩主要包括蛇纹岩、弧前玄武岩、玻安质辉长岩等，地质地球化学特征表明其形成于

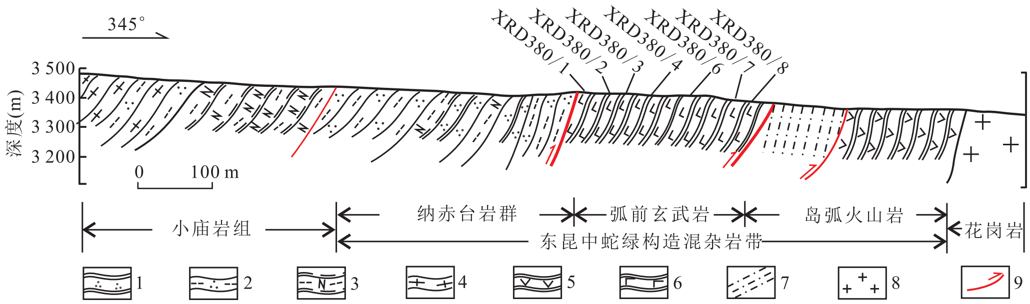

图 2　清泉沟玄武岩实测地质剖面

Fig.2　Measured geological section of Qingquangou basalts

1.石英岩;2.黑云石英片岩;3.黑云斜长片麻岩;4.花岗质片麻岩;5.变安山岩;6.变玄武岩;7.长英质糜棱岩;8.印支期花岗岩;9.断裂构造

弧前环境(Li *et al*.,2017).本次工作在青海省都兰县香日德镇南西 10 km 处的清泉沟地区厘定出一套弧前玄武岩与岛弧火山岩组合(forearc basalts,FABs)(图 2).该弧前玄武岩南侧出露有新元古代花岗质片麻岩、中元古界小庙岩组和早古生代纳赤台岩群(Pz_1N)(图 3a,3b),它们之间呈断层接触.清泉沟玄武岩出露于东昆中断裂带内,伴随着东昆中断裂带的多期变质变形作用(李小兵等,2014),形成一组透入性片理构造(图 3c,3d),片理南倾,产状介于 190°∠60°～210°∠72°.弧前玄武岩北侧发育有长英质糜棱岩以及岛弧型火山岩和印支期花岗闪长岩.

2　岩相学特征

清泉沟玄武岩风化面为深灰色,新鲜面为灰绿色,发育有一组透入性片理构造,具条纹－条带状构造.显微镜下,具有显微鳞片粒状变晶构造(图 3e).岩石主要组成矿物为斜长石(55%～60%)和角闪石(35%～40%)及少量副矿物.其中,角闪石多为辉石退变产物,部分仍具有辉石晶体形态.部分角闪石晶体呈眼球状及旋转碎斑(图 3e,3f),显示左行韧性剪切变形特征.斜长石平行片理分布,多已碎裂岩化及糜棱岩化.岩石发生一定程度蚀变,角闪石部分绿泥石化,斜长石发生绿帘石化.

3　测试方法

用于岩石地球化学研究的玄武岩样品采自清泉沟(图 1b,图 2).样品分别进行主量元素和微量元素分析测试.全岩主量元素测试采用 XRF 法,测试在长安大学西部矿产资源与地质工程教育部重点实验室完成,测定流程包括烧失量的计算和玻璃熔融制

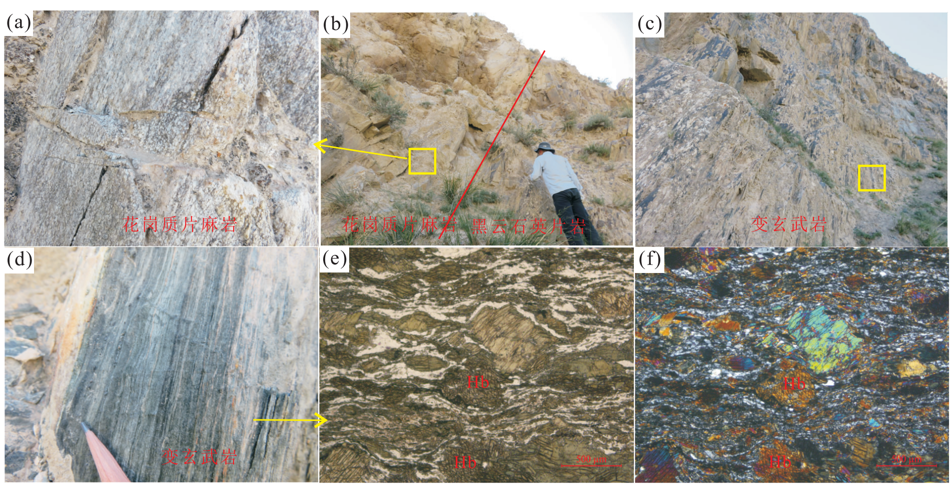

图 3　清泉沟玄武岩及其围岩野外及镜下特征

Fig.3　Field photos and micrograph features of Qingquangou basalts and wall rocks

a.花岗质片麻岩;b.花岗质片麻岩与纳赤台岩群黑云石英片岩呈断层接触;c,d.强片理化变玄武岩;e.变玄武岩镜下特征(单偏光);f.变玄武岩镜下特征(正交偏光);Hb.角闪石

表 1 清泉沟玄武岩主量元素(%)和微量元素(10^{-6})分析结果

Table 1 Results of major elements(%) and trace elements (10^{-6}) from Qingquangou basalts

样品	XRD380-1	XRD380-2	XRD380-3	XRD380-4	XRD380-6	XRD380-7	XRD380-8
SiO_2	48.78	49.05	49.23	49.28	48.94	48.60	48.94
TiO_2	1.10	1.08	1.07	1.07	1.09	1.10	1.09
Al_2O_3	14.14	13.97	13.69	13.85	13.57	13.97	13.86
$Fe_2O_3{}^T$	13.45	12.80	12.83	12.77	13.01	12.23	12.31
MnO	0.20	0.18	0.19	0.19	0.20	0.19	0.21
MgO	7.65	7.75	7.63	7.62	7.81	8.00	7.92
CaO	10.67	11.16	11.10	11.35	11.42	11.40	11.14
Na_2O	2.30	2.24	2.46	2.05	2.34	2.32	2.56
K_2O	0.26	0.14	0.12	0.16	0.23	0.17	0.15
P_2O_5	0.08	0.09	0.08	0.09	0.09	0.09	0.08
LOI	0.69	1.07	0.82	0.84	0.69	0.90	0.68
Total	99.32	99.53	99.22	99.27	99.39	98.97	98.94
La	2.86	4.78	2.95	3.16	3.13	3.74	3.26
Ce	8.04	11.83	8.03	9.45	8.59	9.26	8.32
Pr	1.24	1.95	1.27	1.33	1.31	1.56	1.41
Nd	7.34	10.53	7.23	7.55	7.60	7.82	7.21
Sm	2.34	3.26	2.30	2.42	2.43	2.48	2.38
Eu	0.88	0.97	0.85	0.91	0.89	0.90	0.84
Gd	3.14	4.18	3.12	3.20	3.20	3.15	2.99
Tb	0.56	0.75	0.55	0.56	0.56	0.56	0.54
Dy	3.72	5.10	3.69	3.74	3.74	3.79	3.70
Ho	0.80	1.11	0.80	0.81	0.82	0.80	0.80
Er	2.38	3.34	2.36	2.37	2.39	2.26	2.32
Tm	0.35	0.50	0.34	0.35	0.35	0.36	0.37
Yb	2.03	2.92	1.95	1.99	2.00	2.38	2.49
Lu	0.33	0.47	0.33	0.33	0.33	0.37	0.37
ΣREE	36.02	51.68	35.77	38.16	37.35	39.43	37.00
ΣLREE	22.70	33.31	22.64	24.82	23.95	25.76	23.42
ΣHREE	13.32	18.37	13.13	13.34	13.40	13.67	13.58
ΣLREE/ΣHREE	1.70	1.81	1.72	1.86	1.79	1.88	1.72
δEu	0.99	0.80	0.98	1.00	0.98	0.98	0.96
$(La/Yb)_N$	0.95	1.10	1.02	1.07	1.06	1.06	0.88
$(La/Sm)_N$	0.77	0.92	0.81	0.82	0.81	0.95	0.86
$(Gd/Yb)_N$	1.25	1.16	1.29	1.30	1.29	1.07	0.97
V	373.26	363.51	374.17	378.38	367.85	313.00	323.00
Cr	211.38	197.93	198.17	197.87	263.13	166.00	164.00
Co	47.58	52.37	46.12	47.23	47.88	50.80	47.60
Ni	106.75	91.93	100.33	101.50	96.89	90.20	97.80
Rb	19.43	13.72	6.30	5.86	7.94	13.70	6.50
Sr	192.84	213.65	218.43	213.00	228.93	159.00	155.00
Y	19.42	27.59	19.02	19.11	18.12	22.80	22.90
Zr	53.70	54.17	54.55	53.39	56.19	56.60	53.70
Nb	2.48	2.82	2.50	2.51	2.68	2.83	2.53
Cs	0.92	2.09	0.67	0.64	0.25	2.88	0.93
Ba	51.52	33.70	41.35	56.75	237.76	33.60	40.10
Hf	1.46	1.50	1.53	1.46	1.56	1.86	1.78
Ta	0.16	0.19	0.16	0.16	0.18	0.19	0.17
Pb	4.85	3.12	1.22	1.39	4.32	3.07	1.36
Th	0.31	1.18	0.30	0.40	0.29	0.41	0.34
U	0.17	0.13	0.16	0.13	0.15	0.12	0.16
Nb/U	14.64	21.89	15.17	19.53	17.53	23.58	15.81
Nb/Ta	15.18	15.08	15.31	15.49	15.25	14.89	14.88
Nb/La	0.87	0.59	0.85	0.79	0.86	0.76	0.78
Ti/Y	339.55	234.66	337.28	335.62	360.63	289.23	285.35
Nb/Yb	1.22	0.96	1.28	1.26	1.34	1.19	1.02
Ta/Yb	0.08	0.06	0.08	0.08	0.09	0.08	0.07
Zr/Y	2.76	1.96	2.87	2.79	3.10	2.48	2.34

注:$Mg^{\#}=Mg/(Fe+Mg)$.

样两大步骤:①计算烧失量:将坩锅在烘箱内 150 ℃干燥 3 h 后,称其重量 W_1,加入约 1 g 样品,称样品重量 W_2;然后放入 900 ℃的马弗炉中 8 h,降温后放入干燥器静置 20 min,随后称重得 W_3.通过公式 $(LOI)=(W_1+W_2-W_3)/W_2$ 计算出样品的烧失量(LOI);②玻璃熔融法制样:主量元素测定时首先称取样品 0.50 g,以无水四硼酸锂和硝酸铵为氧化剂,倒入铂金坩锅中,再加入适量溴化锂,在 1 200 ℃左右振荡熔融制成玻璃薄片,使用 X 射线荧光光谱仪测定.全岩稀土和微量元素分析在长安大学西部矿产资源与地质工程教育部重点实验室完成,采用 Thermo-X7 电感耦合等离子体质谱仪,分析精度和准确度优于 10%.将 200 目以下样品(500 mg)置于 PTFE 坩锅,加入添加剂(1.0 mL 高纯 HF 和 1.5 mL高纯 HNO_3),按照标准测试程序,反复添加、加热、冷却后,最后在离心管中稀释到 50 mL;将所得溶液在电感耦合等离子体质谱仪(ICP-MS)上完成测定.分析测试结果见表 1.

4 地球化学特征

4.1 主量元素

清泉沟玄武岩 SiO_2 含量介于 48.60%~49.28%,平均值为 48.97%,MgO 含量介于 7.72%~8.00%,平均值为 7.77%.Na_2O 含量介于 2.05%~2.56%,K_2O 含量介于 0.12%~0.26%.TiO_2 含量介于 1.07%~1.10%,平均值为 1.09%,与西太平洋 Izu-Bonin-Mariana 弧前玄武岩值相近,明显低于洋岛玄武岩(>2.0%)和洋中玄武岩(1.5%),而高于岛弧岩浆岩 TiO_2 值(0.83%)(Pearce and Norry,1979).$Mg^{\#}$ 介于 47.21~51.91,平均值为 49.67,明显低于原生岩浆范围($Mg^{\#}$ = 68~75),表明岩浆经历了结晶分异作用.在 Nb/Y−Zr/TiO_2×0.000 1 岩石分类图解(Winchester and Floyd,1977)(图 4a)上,样品全部落入玄武岩区域.在 $SiO_2-Fe_2O_3^T$/MgO 图解上(Jensen, 1976),样品落入亚碱性拉斑玄武岩系列(图 4b).

4.2 稀土元素

清泉沟玄武岩 LREE 含量介于 22.64×10^{-6}~33.31×10^{-6},HREE 含量介于 13.13×10^{-6}~18.37×10^{-6},∑REE 介于 35.77×10^{-6}~51.68×10^{-6},LREE/HREE 介于 1.70~1.88(表 1).δEu 介于0.80~1.00,平均值为 0.96,没有明显的 Eu 异常,表明没有发生斜长石的结晶分异作用.清泉沟玄武岩$(La/Sm)_N$ 介于 0.77~0.95,$(La/Yb)_N$ 介于 0.88~1.10,$(Gd/Yb)_N$ 介于 0.97~1.30.球粒陨石标准化稀土元素配分图呈现轻稀土元素弱亏损−弱富集的特征(图 5),与正常大洋中脊玄武岩(NMORB)和西太平洋 IBM 弧前玄武岩(FAB)配分特征相似(Falloon *et al.*, 2014),而与轻稀土富集的 E-MORB 和 OIB 特征截然不同.

4.3 微量元素

微量元素 NMORB 标准化蛛网图解(图 6)显示,清水泉玄武岩微量元素含量整体较低,蛛网图曲线总体呈"水平状"且贴近于 NMORB 参考线.此外,相对于 NMORB 而言,清泉沟玄武岩总体富集大离子亲石元素(Rb、Ba、Th、U 等),Nb 和 Ta 呈弱亏损特征,可能为俯冲带流体改造的结果.玄武岩 Nb/Ta 介于 14.88~15.49,平均值为 15.16,与 NMORB 值相当(17.65).Nb/La 介于 0.59~0.87(平均值为 0.78),略低于 NMORB 相应比值(0.93, Sun and McDonough,1989).Nb/U 介于 14.64~

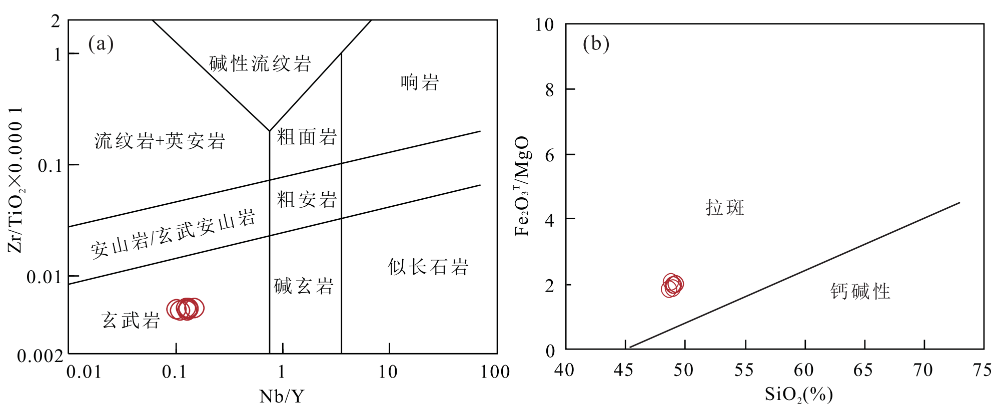

图 4 清泉沟玄武岩岩石类型判别图解

Fig.4 Discrimination diagrams of rock types of Qingquangou basalts

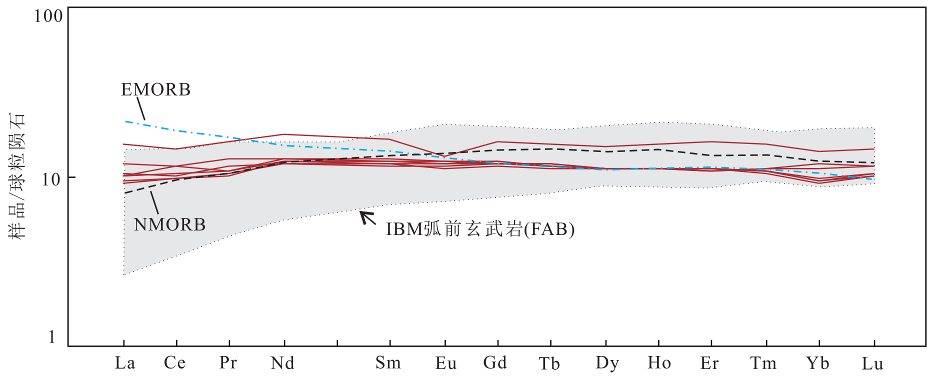

图 5　清泉沟玄武岩稀土元素球粒陨石标准化配分图解

Fig.5　Chondrite-normalized REE patterns of Qingquangou basalts

球粒陨石数据据 Boynton(1984)；IBM 弧前玄武岩数据据 Falloon *et al*.(2014)

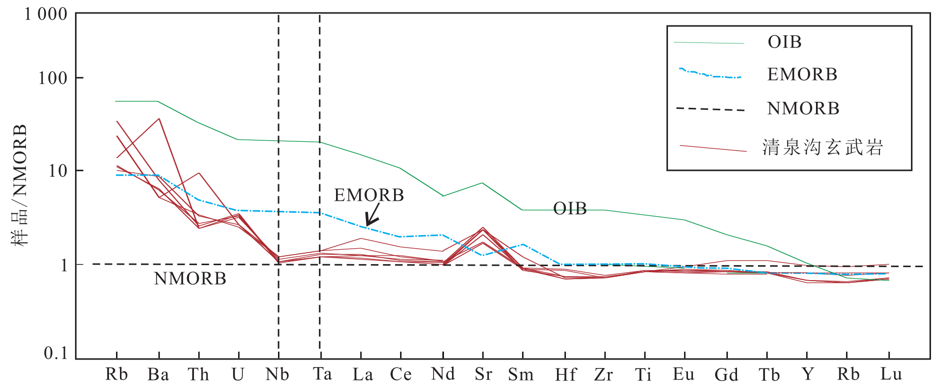

图 6　清泉沟玄武岩微量元素 NMORB 标准化蛛网图解

Fig.6　NMORB-normalized spidergram of Qingquangou basalts

原始地幔标准化数据据 Sun and McDonough(1989)

23.58(平均值为 18.31)，低于洋中脊玄武岩相应值(49.57)(Sun and McDonough，1989)和印度洋 Central Indian 与 Carlsburg Ridge 的 NMORB 相应值(44.0～50.0)(Rehkamper and Hofmann，1997).

5　讨论

5.1　形成时代

东昆中蛇绿构造混杂岩带作为中央造山系中西段重要的板块缝合带，其形成时代一直是学者研究的重点.早期学者通过对东昆中蛇绿岩及周缘地区进行了系统的填图研究，根据东昆中蛇绿岩的围岩时代、围岩变形变质特征，将出露在东昆中断裂带的清水泉蛇绿岩、乌妥蛇绿岩、塔妥蛇绿岩分别厘定为中元古代、早古生代和晚古生代，并分别与 3 个不同阶段的洋陆构造旋回相联系(王国灿等，1999；朱云海等，1999)，然而该结论尚缺乏高精度同位素年龄支撑.也有学者通过蛇绿岩中的橄辉岩全岩 Sm-Nd 年龄限定其形成时代为 1 297～1 372 Ma(殷鸿福和张克信，1997).

近些年，随着单颗粒锆石 U-Pb 测年方法的大量应用，在东昆中蛇绿岩及其周边地区陆续获得了一批高精度锆石 U-Pb 年龄.Yang *et al*.(1996)获得东昆中清水泉蛇绿岩中辉长岩锆石 U-Pb 年龄为 518±3 Ma；Li *et al*.(2013a)获得东昆中断裂带南侧可可科特地区镁铁－超镁铁质岩锆石 U-Pb 年龄为 509～502 Ma.刘战庆等(2011a，2011b)测得东昆仑南缘布青山地区得力斯坦蛇绿岩锆石 U-Pb 年龄为 516.4±6.3 Ma.最近，Li *et al*.(2017)获得东昆中阿此特蛇绿岩中玻安质辉长岩锆石 U-Pb 年龄为 510.0±5.2 Ma 和 512.4±4.2 Ma.综上，本文认为东昆中蛇绿岩形成时代为寒武纪，且与区域上秦岭造山带的商丹洋(Dong *et al*.，2011，2016；Dong and Santosh，2016)、北祁连洋(许志琴等，1994；宋述光，1997；宋述光等，2011；夏林圻等，2016)形成时

限大致相同.

5.2 岩石类型

弧前玄武岩(FAB)一般出露于洋壳俯冲带上盘靠近海沟坡折处,通常在洋壳初始俯冲阶段形成的一套以玄武岩和玄武安山岩为主的洋壳岩石组合.西太平洋 Izu-Bonin-Mariana 岛和西南太平洋 Tonga-Kermadec 岛是现代弧前玄武岩研究的热点地区之一(Reagan, 2010).地球化学特征方面,弧前玄武岩具有低的 TiO_2 含量(1.0%)和 Ti/V 比值(<20),且具有与 NMORB 相似的轻稀土亏损的配分特征,稀土元素总量(略)低于 NMORB.然而弧前玄武岩微量元素中大离子亲石元素富集和弱的 Nb、Ta 亏损特征(图 6),指示其源区为抽取过 NMORB 玄武岩的亏损地幔源区(Dilek and Thy, 2009; Reagan, 2010).清泉沟玄武岩 TiO_2 含量介于 1.07%~1.10%,平均值为 1.09%,与西太平洋 Izu-Bonin-Mariana 弧前玄武岩值相近,低于洋中玄武岩(MORB=1.5%),而略高于活动陆缘和岛弧拉斑玄武岩 TiO_2 值(0.83%)(Pearce and Norry, 1979).样品稀土元素总量略低于 NMORB,微量元素蛛网图显示明显的 Cs、Rb、Ba、U 富集和 Nb、Ta 弱亏损特征.此外,板内玄武岩相对俯冲带玄武岩具有较高的 Ti/Y 比值和 Ti/V 比值(Rollinson, 1993).样品具有低的 Ti/Y 比值(平均值为 312)和 Ti/V(<20)比值,在 Ti/Y-Zr/Y 判别图解(图 7a)中,样品落入板块边缘玄武岩区域,在 V-Ti/1 000 图解中(图 7b),样品全部落入弧前玄武岩区域而远离太平洋洋中脊玄武岩和菲律宾海玄武岩区域.综上,清泉沟玄武岩具有弧前玄武岩地球化学特征.

5.3 岩石源区

Nb/Y、Zr/Y、Nb/Yb 和 Ta/Yb 比值对于分离结晶作用和部分熔融作用过程不敏感,其比值可以确定地幔源区性质(Pearce, 2008).通常认为,抽取完 NMORB 熔体的亏损地幔(DM)具有较低的不相容元素比值,例如,Nb/Y、Zr/Y、Nb/Yb 和 Ta/Yb,而相对较高的不相容元素比值则代表源区为富集地幔(Condie, 2003).清泉沟玄武岩相对低的 Nb/Yb(0.96~1.34)、Ta/Yb(0.06~0.09)和 Zr/Y 比值(1.96~3.10)表明其源区很可能为亏损地幔(NMORB).在 Nb/Yb-Th/Yb 源区判别图解中(图 8a),样品落入靠近 NMORB 源区上方的 IBM 弧前玄武岩区域,表明其源区性质与 NMORB 型亏损地幔相当,且显示有少量俯冲流体的加入.样品 Nb/La 比值介于 0.59~0.87(平均值为 0.78),低于 NMORB 的 Nb/La 比值(0.93, Sun and McDonough, 1989),表明俯冲带流体参与了楔形地幔的部分熔融作用.重要的是,清泉沟玄武岩富集 Cs、Rb、Ba、U 等大离子亲石元素和亏损 Nb、Ta 等元素的特征(图 6),与西太平洋弧前玄武质玻璃特征非常相似,说明俯冲带板片流体的加入对楔形地幔起到了一定的助熔作用(Reagan, 2010).

一般地,软流圈地幔在大洋中脊处减压熔融抽取完玄武质岩浆之后会变得更加亏损和难熔,只有在具备异常高的温度或有流体加入的条件下,该难熔地幔才可能再次发生熔融.Dilek and Thy(2009)和 Ishizuka *et al*.(2014)通过研究西太平洋弧前火山岩和特提斯蛇绿岩后,提出大洋洋壳初始俯冲带上盘的楔形地幔源区是形成弧前玄武岩的理想场

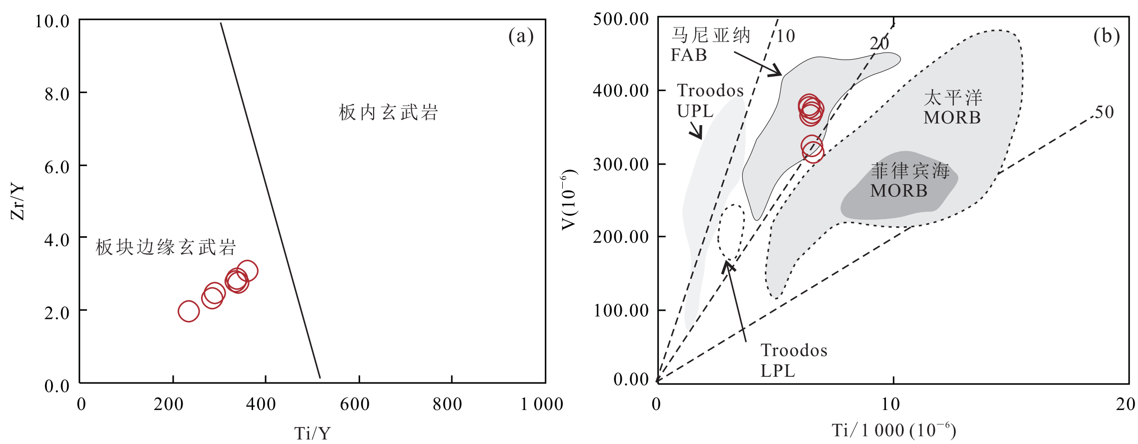

图 7 清泉沟玄武岩 Ti/Y-Zr/Y 图解(a)和 Ti-V 图解(b)

Fig.7 Ti/Y-Zr/Y (a) and Ti-V (b) diagrams of Qingquangou basalts

a.据 Meschede(1986); b.据 Shervais(1982)

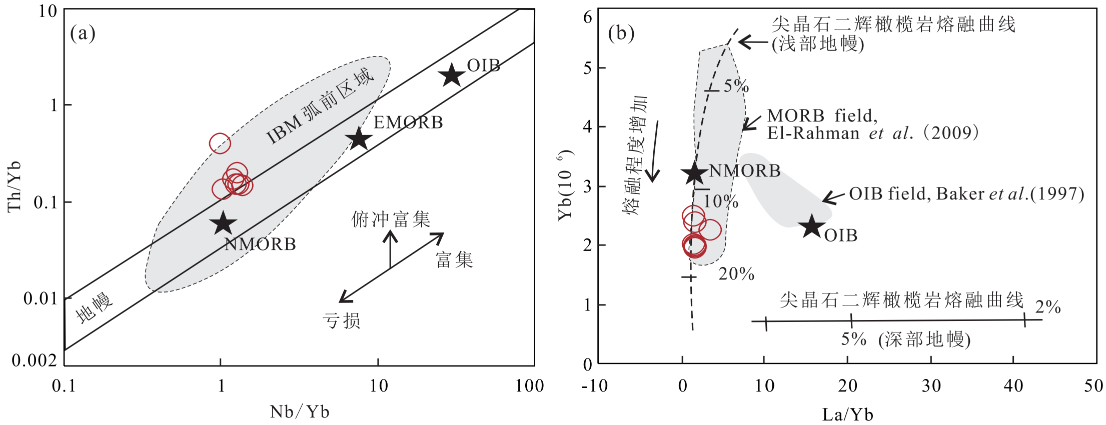

图 8　清泉沟玄武岩 Nb/Yb—Th/Yb 图解(a)和 La/Yb—Yb 图解(b)

Fig.8　Nb/Yb—Th/Yb (a) and La/Yb—Yb (b) diagrams of Qingquangou basalts

MORB，OIB 数据据 Baker *et al*.(1997)；Pearce(2008)；El-Rahman *et al*.(2009)

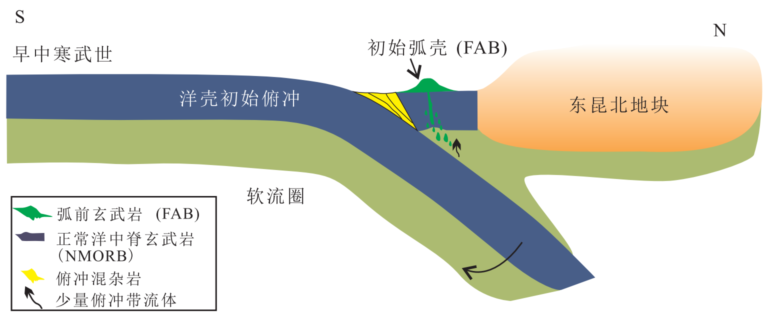

图 9　清泉沟弧前玄武岩形成模式

Fig.9　Formation mechanism of Qingquangou forearc basalts (FABs)

所，并认为洋壳俯冲初始阶段由于深部热的软流圈地幔大量涌入俯冲带上方(角流，corner flow)和少量流体加入，导致弧前难熔地幔再次发生熔融，从而导致其源区熔融程度增高且变得更加亏损.在 La/Yb—Yb 图解中，样品主体落入尖晶石二辉橄榄岩曲线附近，且位于 NMORB 源区下方，表明其熔融程度比 NMORB 源区熔融程度较高，并估算其源区尖晶石二辉橄榄岩部分熔融比例可达 15%～18%(图 8b，图 9).综上，本文认为清泉沟弧前玄武岩的源区是初始俯冲带上盘靠近海沟的熔融程度更高且更加亏损的地幔，且该地幔经历了更高的熔融程度.

5.4　地质意义

前人对东昆中蛇绿岩形成环境及俯冲起始时限争议较大，形成环境主要有岛弧环境(姜春发等，2000)与弧后盆地及陆间裂谷(殷鸿福和张克信，1997；王国灿等，1999；朱云海等，1999)等不同认识.在 Y—Cr 构造环境判别图中，样品落入岛弧与 MORB 过渡区域(图略)，指示其形成于弧前或弧后盆地构造环境.前已述及，清泉沟玄武岩具有较低的 TiO_2 含量，其稀土、微量元素特征与西太平洋 IBM 弧前玄武岩相当，而 IBM 弧前玄武岩则被认为形成于洋壳俯冲的初始阶段.也就是说，东昆中清泉沟玄武岩属于俯冲带弧前型蛇绿岩(SSZ 类型，Dilek and Furnes，2011)，应形成于与洋壳俯冲相关的构造环境(图 9).此外，区域上东昆中蛇绿岩带具弧前属性的阿此特玻安质辉长岩的年龄为 510 Ma(Li *et al*.，2017)，而弧前玄武岩形成时代一般略早于玻安质岩石(Reagan，2010)，藉此推测清泉沟弧前玄武岩形成时代早于 510 Ma.因此，结合区域地质资料认为东昆中古洋盆至少于中寒武世(510 Ma)之前已经开始向北俯冲，并在俯冲初期形成了清泉沟弧前玄武岩及阿此特玻安质辉长岩(Li *et al*.，2017)，二者共同构成了俯冲带初始弧壳或不成熟洋内岛弧(图 9).区域上，Meng *et al*.(2013a)在东昆仑西段祁漫塔格地区识别出一套早古生代初始岛弧型镁铁—超镁铁质岩，进一步研究认为其代表了与原特提斯洋俯冲相关的洋内弧壳碎片.

中寒武世以来，东昆中古洋盆持续向北俯冲，岛

弧成熟度逐渐增加，在东昆中断裂北侧仍出露有岛弧型岩浆岩.例如，桑继镇等(2016)在清水泉北侧发现一套岛弧型基性杂岩体，其 LA-ICP-MS 锆石 U-Pb 年龄为 452.1±5 Ma.裴磊等(未刊)报道曲什昂岛弧型中基性杂岩体锆石 U-Pb 年龄为455.6±1.2 Ma，被认为东昆中古洋盆于晚奥陶世仍处于向北俯冲的构造阶段.近些年东昆南构造带亦有早古生代早期弧花岗岩发现(陈加杰等，2016；Zhou *et al.*，2016)，被认为是昆中洋双向俯冲的结果.区域上，早古生代中晚期弧岩浆作用亦较为强烈(Li *et al.*，2016).刘彬等(2012)报道了胡晓钦岩体锆石 U-Pb 年龄为 438 Ma，代表了大洋俯冲向陆陆碰撞造山的转换阶段.早志留世，东昆中洋壳俯冲消减完毕，东昆南地块与东昆北地块发生碰撞拼合，一方面促使东昆中弧前洋壳构造就位并伴随地壳浅表层次的逆冲褶皱变形(陈能松等，2002)，另一方面由于陆陆碰撞造山导致地壳加厚而形成了埃达克质花岗岩(Zhou *et al.*，2016)以及高－超高压变质作用(Meng *et al.*，2013a，2013b，2015；Zhang *et al.*，2015；祁晓鹏等，2016).随后，东昆仑造山带转入后碰撞伸展构造阶段，形成了中晚志留世具后碰撞属性的花岗岩(郝杰等，2003；Li *et al.*，2013b；施彬等，2016).Li *et al.*(2013b)获得东昆仑东段和勒岗那仁 A 型花岗岩锆石 U-Pb 年龄为 425 Ma，郝杰等(2003)报道东昆仑造山带西段具后造山属性的阿牙克岩体 $^{40}Ar/^{39}Ar$ 坪年龄为 420 Ma，Zhou *et al.*(2016)获得智玉闪长岩锆石 U-Pb 年龄为 408 Ma.早中泥盆世以来，东昆仑造山带由与原特提斯洋相关的洋陆演化转入与古特提斯洋相关的构造演化阶段(潘裕生等，1996；Xiong *et al.*，2014)，沉积了以泥盆纪牦牛山组为代表的裂陷伸展型磨拉石组合(陈守建等，2007)，同时代表了晚古生代裂陷伸展盆地演化的启动.也就是说，东昆中构造混杂带是一个以新元古代晚期－寒武纪蛇绿岩为主的构造带，东昆仑造山带与原特提斯洋相关的洋陆演化于早古生代末期已经彻底终结.

6　结论

(1)清泉沟玄武岩主量元素特征表明其属于亚碱性拉斑玄武岩系列，稀土元素和微量元素特征与正常大洋中脊玄武岩(NMORB)和西太平洋 IBM 弧前玄武岩(FAB)特征相似.

(2)清泉沟玄武岩具有弧前玄武岩(FAB)特征，地球化学属性表明其源区具亏损地幔特征，源区熔融程度比 NMORB 源区熔融程度略高，并估算其源区尖晶石二辉橄榄岩部分熔融比例为 15%～18%.

(3)清泉沟玄武岩形成于大洋初始俯冲阶段的弧前环境.综合区域地质资料，认为东昆中古洋盆至少于中寒武世(510 Ma)之前已经开始向北俯冲，在俯冲初期形成了清泉沟弧前玄武岩，构成了俯冲带初始弧壳或不成熟洋内岛弧.

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