

# 西准噶尔玛依勒蛇绿混杂岩锆石 U-Pb 年代学、地球化学及源区特征\*

杨高学<sup>1</sup> 李永军<sup>1</sup> 杨宝凯<sup>1,2</sup> 刘振伟<sup>1</sup> 佟丽莉<sup>1</sup> 张洪伟<sup>3</sup>

YANG GaoXue<sup>1</sup>, LI YongJun<sup>1</sup>, YANG BaoKai<sup>1,2</sup>, LIU ZhenWei<sup>1</sup>, TONG LiLi<sup>1</sup> and ZHANG HongWei<sup>3</sup>

1. 长安大学地球科学与资源学院, 西部矿产资源与地质工程教育部重点实验室, 西安 710054

2. 青岛地质工程勘察院, 青岛 266071

3. 新疆维吾尔自治区地质矿产勘查开发局第七地质大队, 乌苏 833000

1. *Earth Science & Resources College of Chang'an University, Key Laboratory of Western China's Mineral Resources and Geological Engineering, Ministry of Education, Xi'an 710054, China*

2. *The Qingdao Geological Engineering Investigation Institute, Qingdao 266071, China*

3. *No. 7 Geological Survey Team, Xinjiang Bureau of Geology and Mineral Resource Exploration, Wusu 833000, China*

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**Abstract** Precise zircon U-Pb dating and geochemical composition analysis on the ophiolitic mélange belts in West Junggar. It is a clue for forming and evolution of the pale-ocean, rebuilding palaeotectonics and tracing the source of magma source. LA-ICP-MS zircon U-Pb weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of the gabbros from the Mayile ophiolitic mélange in the West Junggar is  $572.2 \pm 9.2\text{Ma}$ , belong to Early Sinian, this is oldest age from ophiolitic mélange in the Junggar as well as North Xinjiang. The alkalic pillow basalts from Mayile ophiolitic mélange are similar with the ocean island basalt (OIB), characteristics by high Ti ( $\text{TiO}_2 = 1.65\% \sim 3.13\%$ ), Fe ( $\text{FeO}^T = 8.93\% \sim 18.11\%$ ), Mg ( $\text{MgO} = 3.95\% \sim 5.27\%$ ) and P ( $\text{P}_2\text{O}_5 = 0.17\% \sim 0.51\%$ ), and high Th/Ta ratios (1.1 ~ 1.9), and clear differentiation between LREE and HREE ( $(\text{La}/\text{Yb})_N = 2.5 \sim 7.4$ ). It is assumed that the magma extruded into ocean island or seamount of the ocean floor. However, the geochemical characteristics of the gabbros different from basalts, may be form subduction-related setting. The geochemical features of the basalts show they have ocean island basalts, derived from EMI type enriched-mantle. Petrogenesis is closely related to asthenosphere mantle, asthenospheric mantle upwelling led to a large proportion of spinel lherzolite mantle partial melting to forming the basalt magam. It is a product of asthenosphere interacted with lithosphere.

**Key words** Mayile ophiolitic mélange; Zircon U-Pb geochronology; Geochemistry; Ocean island basalt (OIB); West Junggar

**摘要** 西准噶尔地区出露多条蛇绿混杂岩带, 对其进行精确的锆石 U-Pb 年代学及岩石地球化学研究可以为揭示西准噶尔地区古大洋形成与演化过程、恢复古构造格局及追溯岩浆源区物质来源提供线索。本文对玛依勒蛇绿混杂岩中的辉长岩及玄武岩进行了 LA-ICP-MS 锆石 U-Pb 年代学及全岩地球化学研究, 获得辉长岩中锆石的加权平均  $^{206}\text{Pb}/^{238}\text{U}$  年龄为  $572.2 \pm 9.2\text{Ma}$ , 属于早震旦纪, 该年龄是准噶尔乃至北疆地区报道的最古老的蛇绿混杂岩年龄。玛依勒蛇绿混杂岩中的枕状玄武岩为碱性玄武岩, 岩石具有高 Ti ( $\text{TiO}_2 = 1.65\% \sim 3.13\%$ )、高 Fe ( $\text{FeO}^T = 8.93\% \sim 18.11\%$ )、高 Mg ( $\text{MgO} = 3.95\% \sim 5.27\%$ ) 及高 P ( $\text{P}_2\text{O}_5 = 0.17\% \sim 0.51\%$ )、Th/Ta 比值相对较高 ( $= 1.1 \sim 1.9$ )、LREE 和 HREE 分异较为明显 ( $(\text{La}/\text{Yb})_N = 2.5 \sim 7.4$ ) 等特征, 这些特征与洋岛玄武岩类似, 可能形成于大洋板内的洋岛或海山环境。其中的辉长岩地球化学特征不同于玄武岩, 可能形成与俯冲有关的环境。玛依勒蛇绿混杂岩中玄武岩与 EMI 型洋岛玄武岩具有相似的地球化学特征, 表明其岩浆源区可能为 EMI 型富集地幔。岩石成因与软流圈地幔关系密切, 软流圈的上涌导致尖晶石相二辉橄辉岩地幔源区大比例部分熔融,

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第一作者简介: 杨高学, 男, 1980 年生, 博士, 讲师, 主要从事蛇绿岩及火山岩研究, E-mail: mlylgx@126.com

是岩石圈-软流圈地幔相互作用的产物。

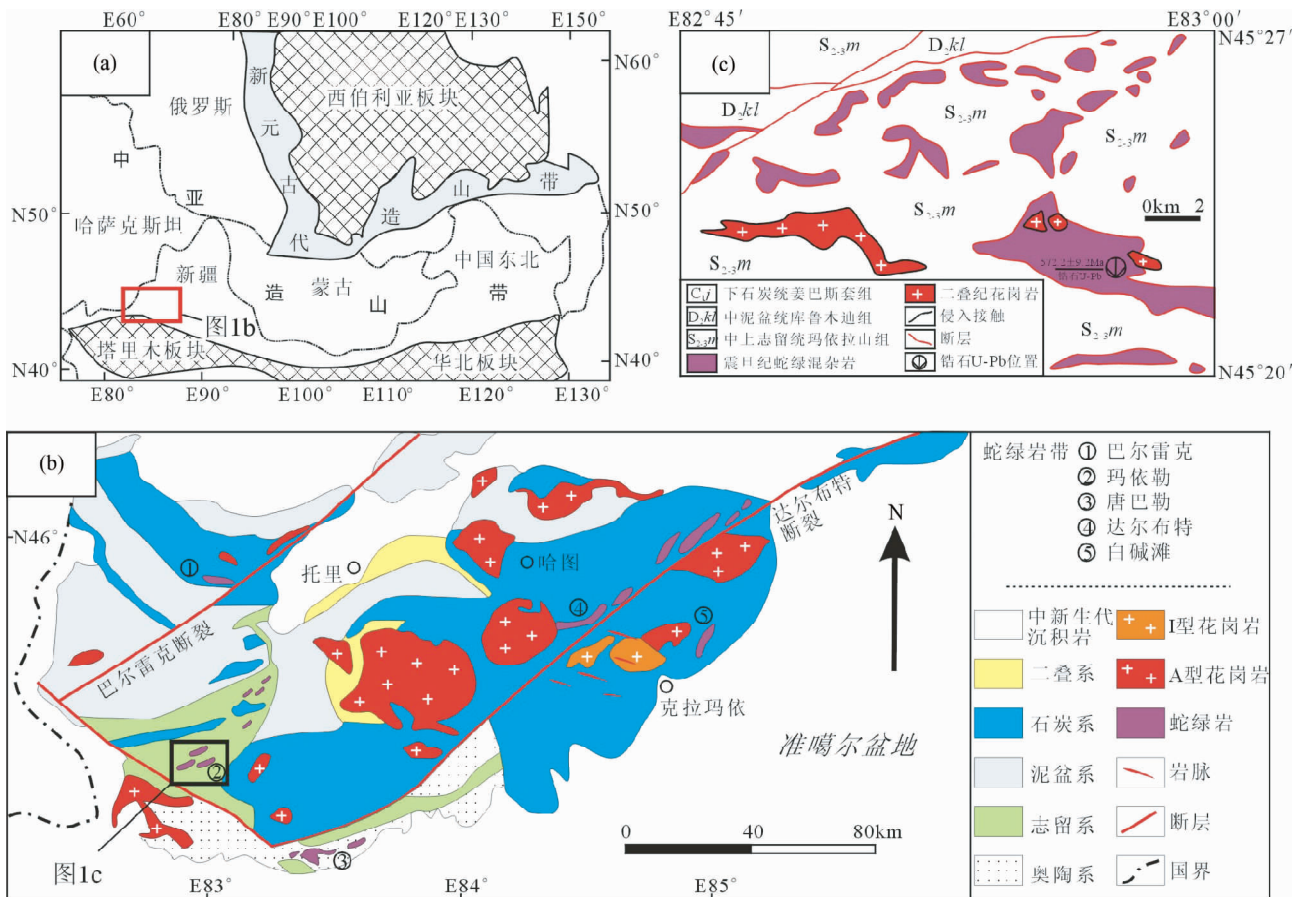
**关键词** 玛依勒蛇绿混杂岩; 锆石 U-Pb 年代学; 地球化学; 洋岛玄武岩; 西准噶尔

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## 1 引言

蛇绿岩是仰冲到大陆地壳之上的古大洋岩石圈残片,其形成时代和形成环境的确定对于恢复古大洋形成演化史和重建古板块构造格局等具有重要的大地构造意义。西准噶尔是巨型中亚造山带的一部分,也是中亚-兴蒙巨型构造带的重要组成部分(肖序常等,1992;李锦轶,2004;Zhu *et al.*,2005;Xiao *et al.*,2008)(图1a)。该地区蛇绿岩分布广泛,保存比较完整,主要包括唐巴勒、玛依勒、达尔布特、白碱滩、巴尔雷克等多条蛇绿岩带(图1b),中外学者都有过较多研究(Kwon *et al.*,1989;张弛和黄萱,1992;张立飞,1997;徐

新等,2006;何国琦等,2007;朱永峰和徐新,2007;雷敏等,2008;朱永峰等,2008;辜平阳等,2009;刘希军等,2009;陈博和朱永峰,2010;陈石和郭召杰,2010;Yang *et al.*,2011;Xu *et al.*,2012),其中玛依勒蛇绿岩带是西准噶尔地区比较重要的蛇绿岩带之一,由其代表的洋(盆)的演化历史对恢复和重建西准噶尔古生代以来的地质演化过程具有重要意义。但是,对其形成时代仍然存在争议:新疆第一区调大队在玛依勒蛇绿混杂岩建造上部的细碎屑岩中获得中晚志留世的笔石、珊瑚等,其上依次发育大量的晚志留世化石和早泥盆世沉积,因此确定其形成时代为中志留世(新疆维吾尔自治区地质矿产局,1993);朱宝清等(1987a)对玛依勒蛇绿混杂岩中火山岩进行全岩 Rb-Sr 等时线测年获得年龄 421Ma;最近,



魏荣珠等(2010)用同样的方法在玄武岩中获得年龄  $435.3 \pm 6.5$  Ma 和  $432.5 \pm 7.4$  Ma。

目前,不仅对玛依勒蛇绿混杂岩的侵位时限存在不同的认识,而且对其构造背景的认识也存在争议,主要包括:岛弧环境(何国琦和李茂松,2001;Wang *et al.*,2003),弧后盆地环境(肖序常等,1991),弧前盆地环境(Peng,1996),大洋中脊(MOR,张弛和黄莹,1992;韩松等,2004),大陆-大洋的过渡区(朱宝清等,1987b)。这对约东准噶尔古生代板块构造演化造成很大困难。本文在对玛依勒蛇绿混杂岩中辉长岩进行精确的 LA-ICP-MS 锆石 U-Pb 定年,限定其准确的侵位时限的同时,对辉长岩和玄武岩进行了详细的岩石地球化学研究,依据区域地质资料和前人研究成果,对其构造背景及源区特征进行深入探讨。

## 2 区域地质

西准噶尔主要由一系列的增生杂岩带、古生代岩浆弧构成(Windley *et al.*,2007;Xiao *et al.*,2009;Han *et al.*,2010),其主要构造特征为 NE-SW 向断裂非常发育,由北向南依次为巴尔雷克和达尔布特断裂,它们控制着花岗岩和蛇绿岩的分布(图 1b)。该地区出露大量晚古生代中酸性侵入体,根据产状可以分为两类:一类呈大岩基状产出(如:庙尔沟、阿克巴斯套、克拉玛依、红山及哈图岩体等)的晚石炭世-中二叠世后碰撞花岗岩类(Chen and Jahn,2004;韩宝福等,2006,2010;苏玉平等,2006;范裕等,2007;Zhou *et al.*,2008;Chen *et al.*,2010;陈家富等,2010),但也有学者认为其就位于洋脊俯冲有关的构造背景(高山林等,2006;张连昌等,2006;Xiao *et al.*,2008;Geng *et al.*,2009;Tang *et al.*,2010;Yin *et al.*,2010);另一类是以小岩株或岩脉形式出露(如:包古图 V 岩体)的石英闪长斑岩、闪长玢岩和花岗闪长斑岩等,主要分布在包古图地区(沈远超等,1993)。另外,在西准噶尔地区一个显著的特点是有较多的蛇绿混杂岩发育,如达尔布特、白碱滩、唐巴勒、玛依勒及巴尔雷克等蛇绿混杂岩或蛇绿岩带(图 1b)(Feng *et al.*,1989;Zhang *et al.*,1993;Jian *et al.*,2005;徐新等,2006,2010;辜平等,2009;张元元和郭召杰,2010;Yang *et al.*,2011)。这些蛇绿岩形态复杂,变形强烈,多沿走滑断裂分布,时代跨度大,从震旦纪到石炭纪均有出现。研究区出露的地层主体为奥陶系至石炭系火山-沉积地层,各地层单位多为断层接触(新疆维吾尔自治区地质矿产局,1993)。

## 3 蛇绿混杂岩地质特征及样品描述

### 3.1 岩体特征

玛依勒蛇绿混杂岩总体走向 EW 向,不连续延伸超过 30km,由西向东渐宽呈三角状展布,由 20 余个大小不一的岩体构成,其多呈透镜状、串珠状和小岩株分布于中上志留统

玛依拉山组和中泥盆统库鲁木迪组中(图 1c)。混杂岩带内各岩块均为构造接触界面,岩块原生构造被后期构造改造或置换,发育透入性构造面理,产状近于直立,成为堆叠在一起的构造杂岩体,但蛇绿岩的各组成单元出露仍较为齐全,主要包括超镁铁质岩石(蛇纹石岩和蛇纹石化纯橄岩等),辉长岩和辉长闪长岩脉以及枕状玄武岩,另外,伴生有放射虫硅质岩、硅质泥岩和凝灰岩等,其中辉长岩和辉长闪长岩脉主要呈岩脉穿插于蛇纹岩和蛇纹石化纯橄岩中,大量的溢流相枕状及块状玄武岩组成上部基性熔岩单元,玄武岩中枕状构造较为发育,也存在冷凝边、扭动构造和流动构造。

### 3.2 样品描述

由于超镁铁质岩石发生了强烈的蛇纹石化、滑石化和碳酸盐化,本次仅对弱蚀变的辉长岩和玄武岩进行取样分析。野外采集辉长岩和玄武岩样品共 30 余件,首先研碎手工挑选出杏仁体,再经过镜下仔细鉴定排除杏仁体含量高的玄武岩和后期剥离钙榴岩化的产物,最终挑选出用于岩石全分析的 12 件样品,包括 7 件玄武岩和 5 件辉长岩。这些样品均采自基岩露头,样品新鲜,采集位置避开了研究区内的接触带、蚀变带和断裂破碎带等。用于 LA-ICP-MS 锆石 U-Pb 定年的样品采自辉长岩(编号:08TW-XII-1),采样位置为  $N45^{\circ}22'30''$ ,  $E82^{\circ}57'25''$ 。

辉长岩表面风化色为灰绿色(局部为黑色),新鲜面为深绿色,辉长辉绿结构,局部具有堆晶结构,块状构造。岩石主要由基性斜长石(50%~60%)、普通辉石(20%~30%)和角闪石(5%~10%)组成。辉石、斜长石局部绢云母化、绿泥石化和绿帘石化(图 2a)。

玄武岩枕多为椭球体,表面光滑,大小为  $5 \times 8$  cm ~  $40 \times 60$  cm,枕体边部分布有压扁或同向的杏仁体或气孔,向中心逐渐减少,外壳具有 1~5 cm 的冷凝边,表面可见放射状裂纹或凹凸不平的球颗。岩石主要组成为斜长石(55%~65%)、辉石(5%~15%)、纤闪石(5%~10%)、玄武玻璃(5%~10%)及钛铁矿(<1%)等,偶见斜长石斑晶(图 2b)。

## 4 分析方法

微量元素在宜昌地质矿产研究所用 X 射线荧光光谱(XRF)方法分析完成,XRF 溶片法按照国家标准 GB/T 14506.28—1993 执行。元素分析误差小于 2.5%,氧化物总量介于 99.75%~100.25%。FeO 用湿化学分析法单独测定完成,烧失量(LOI)在烘箱中经 1000℃ 高温烘烤 90min 后称重获得。微量元素在长安大学西部矿产资源与地质工程教育部重点实验室采用 Thermo-X7 电感耦合等离子体质谱仪进行样品测定,仪器工作参数:Power:1200w, Nebulizer gas:0.64 L/min, Auxiliary gas:0.80 L/min, Plasma gas:13 L/min。

激光剥蚀电感耦合等离子体质谱(LA-ICP-MS)原位 U-Pb 定年在西北大学大陆动力学国家重点实验室完成。首先



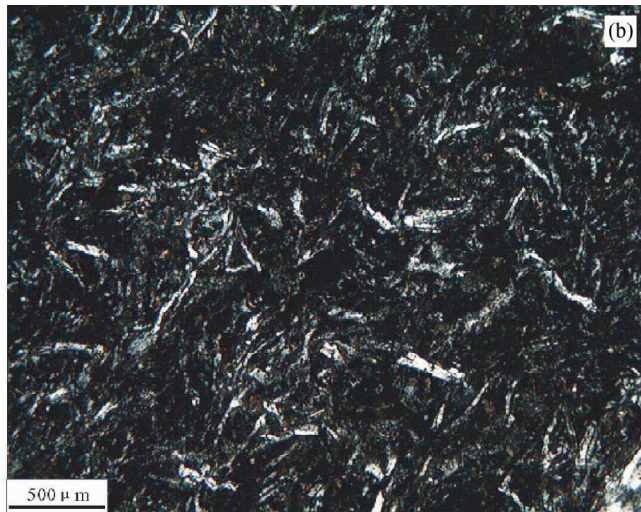
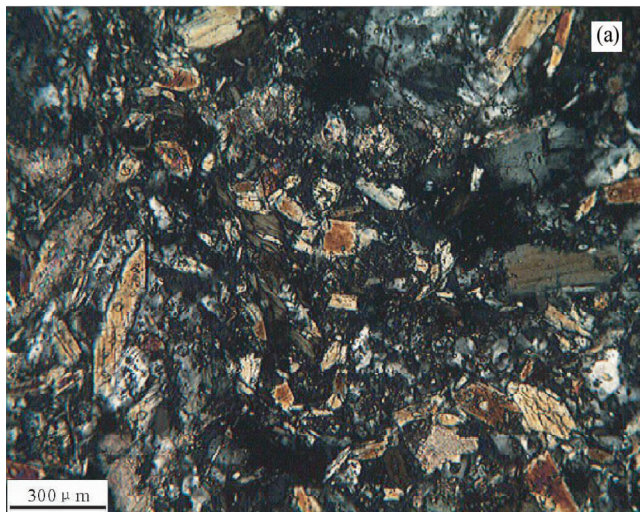


图2 辉长岩(a)和玄武岩(b)正交偏光显微照片

Fig. 2 Crossed polarized light micrographs of gabbros (a) and basalts (b)

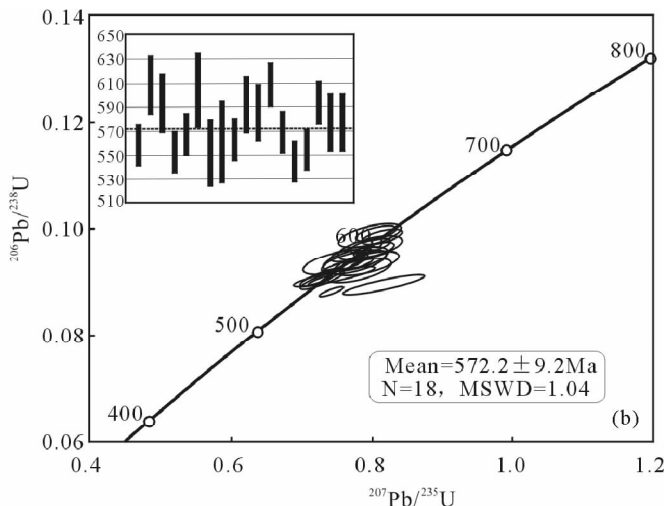
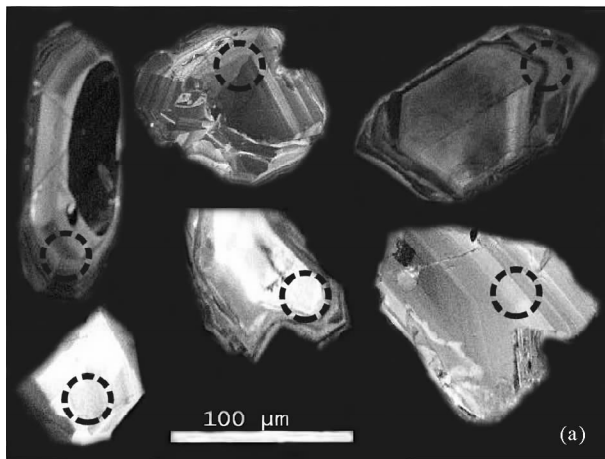


图3 玛依勒蛇绿混杂岩中辉长岩锆石 CL 图像(a)及谐和曲线图(b)

Fig. 3 CL images and U-Pb concordia plots of zircons for gabbros from the Mayile ophiolitic mélange

使用常规的重液浮选和电磁分离方法挑选出锆石,然后在双目镜下根据锆石颜色、自形程度、形态和透明度等特征初步分类,挑选出具有代表性的锆石,用环氧树脂固定,待其充分固化后抛光至锆石露出核部,进行锆石 CL 显微图像分析。锆石 U-Pb 同位素测定在西北大学大陆动力学国家重点实验室用德国 MicroLas 公司生产的 GeoLas 200M 激光剥蚀系统与 Elan 6100DRC ICP-MS 联机上进行分析,分析采用的激光斑束直径为  $30\mu\text{m}$ ,激光脉冲为 10Hz,能量为  $32\sim 36\text{mJ}$ ,激光剥蚀样品的深度为  $20\sim 40\mu\text{m}$ 。锆石年龄测定采用国际标准锆石 91500 作为外部标准物质。详细分析步骤和数据处理方法参见相关文献 (Horn *et al.*, 2000; Ballard *et al.*, 2001; Košler *et al.*, 2002; 袁洪林等, 2003)。采用 Glitter (ver 4.0, Macquarie University) 序对锆石的同位素比值及元素含量进

行计算。并按照 Andersen Tom 的方法 (Andersen, 2002)。用 LAM-ICPMS Common Lead Correction (ver 3.15) 进行普通铅校正。年龄计算及谐和图采用 Isoplot (ver 3.0) 完成 (Ludwig, 1991, 1999)。

## 5 分析结果

### 5.1 锆石 U-Pb 年代学

蛇绿混杂岩中辉长岩样品 (08TW-XII-1) 的锆石颗粒形状比较规则,粒径在  $100\sim 150\mu\text{m}$  之间,锆石的 CL 图像显示大多数锆石具有较好的晶型,并显示明显的岩浆结晶环带,没有被后期改造的痕迹,个别的锆石晶体内部环带不发育,仅见稀疏的直线条带 (图 3a)。锆石的 Th/U 比值范围为 0.3



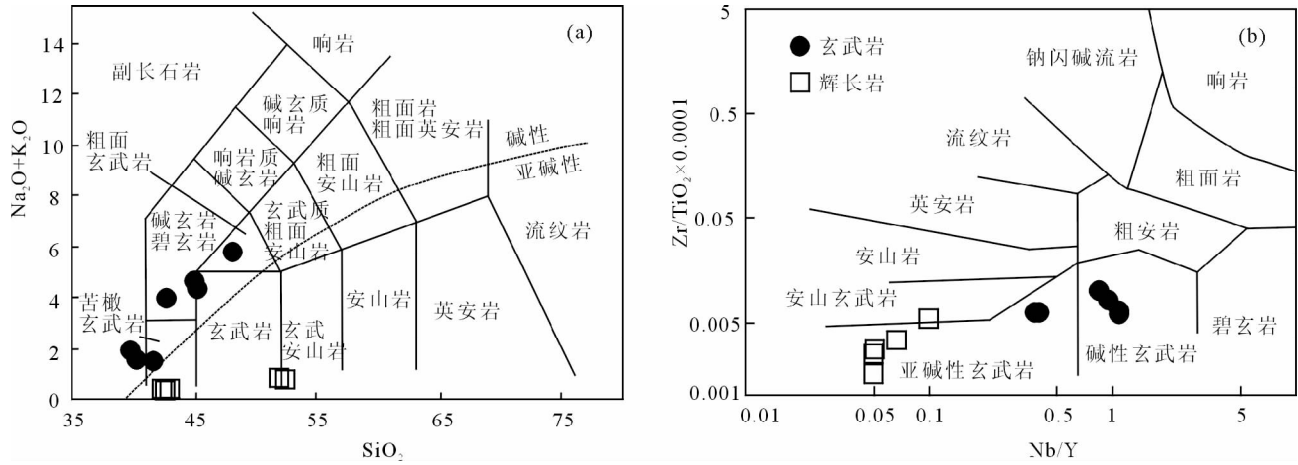


图4 玛依勒蛇绿混杂岩中玄武岩和辉长岩 TAS 图 (a, 据 Le Bas *et al.*, 1986) 和 Nb/Y-Zr/TiO<sub>2</sub> 图 (b, 据 Winchester and Floyd, 1977)

Fig. 4 TAS (a, after Le Bas *et al.*, 1986) and Nb/Y-Zr/TiO<sub>2</sub> (b, Winchester and Floyd, 1977) for gabbros and basalts from the Mayile ophiolitic mélange in the West Junggar

~1.0, 均大于 0.1 (表 1), 且 Th、U 之间具有良好的正相关关系, 表明其为岩浆成因锆石 (Claesson *et al.*, 2000; Fernando *et al.*, 2003)。

由于<sup>235</sup>U 的衰变比<sup>238</sup>U 快 6.3 倍, 放射成因的<sup>207</sup>Pb 在地球早期历史中更为丰富, 而显生宙以来<sup>207</sup>Pb 生成率很低, 这种变化是显生宙锆石的<sup>207</sup>Pb 计数速率低, 而造成<sup>207</sup>Pb 测定的误差较大, 使得<sup>207</sup>Pb/<sup>206</sup>Pb 和<sup>207</sup>Pb/<sup>235</sup>U 比值可信度降低。因此, 对于显生宙锆石, 一般采用<sup>206</sup>Pb/<sup>238</sup>U 年龄 (Compston *et al.*, 1992)。辉长岩锆石微区有效数据分析点共 18 个, <sup>206</sup>Pb/<sup>238</sup>U 年龄范围在 545 ~ 608Ma, 最大的年龄误差 12Ma, 所有 18 个数据点集中分布在谐和曲线附近, 其<sup>206</sup>Pb/<sup>238</sup>U 年龄的加权平均值为 572.2 ± 9.2Ma, MSWD = 1.04 (95% 置信度) (图 3b)。

## 5.2 主量元素

蛇绿混杂岩中辉长岩和玄武岩岩石化学分析结果及有关参数列于表 2。从表 2 可以看出, 玄武岩 SiO<sub>2</sub> 含量 36.13% ~ 45.98%, 接近于 MORB 中 SiO<sub>2</sub> 含量 (49.80%) 和达尔布特蛇绿岩中玄武岩 (43.46%; 刘希军等, 2009), 但低于 Upper Troodos 枕状熔岩 (53.27%; Pearce, 1975) 和 Semail 玄武岩 (53.21%; Alabaster *et al.*, 1982), Al<sub>2</sub>O<sub>3</sub> 含量 12.21% ~ 14.03%, MgO 为 3.95% ~ 5.27%, Mg<sup>#</sup> 为 32 ~ 68, 略低于原生岩浆 (Mg<sup>#</sup> = 68 ~ 75; Wilson, 1989), 反映岩浆经历了一定程度的结晶分异作用。TiO<sub>2</sub> 含量为 1.65% ~ 3.13%, 明显高于 IAB (0.58% ~ 0.85%) 及 MORB (1% ~ 1.5%), 而与加拿大 Flin Flon 带的 Long Bay 的 OIB (1.35% ~ 2.29%; Stern *et al.*, 1995) 及克拉玛依 OIB 型枕状玄武岩 (1.29% ~ 2.48%; 朱永峰等, 2007) 相近。Na<sub>2</sub>O 含量 1.12% ~ 5.27%, 平均为 3.0%, 略低于碱性玄武岩的平均值 (3.2%), K<sub>2</sub>O 为

0.03% ~ 0.68%, Na<sub>2</sub>O > K<sub>2</sub>O, Na<sub>2</sub>O + K<sub>2</sub>O 为 1.16% ~ 5.8%, 与克拉玛依 OIB 型枕状玄武岩 (4.33% ~ 9.38%; 朱永峰等, 2007) 及阿尼玛卿蛇绿岩中 OIB (2.2% ~ 4.73%; 郭安林等, 2006) 相近。P<sub>2</sub>O<sub>5</sub> 含量为 0.17% ~ 0.51%, 平均为 0.29%, 与克拉玛依 OIB 型枕状玄武岩 (平均为 0.24%; 朱永峰等, 2007) 相一致。辉长岩相对于玄武岩, TiO<sub>2</sub> (0.06% ~ 1.14%), P<sub>2</sub>O<sub>5</sub> (0.01% ~ 0.03%) 及 Na<sub>2</sub>O + K<sub>2</sub>O (0.2% ~ 0.6%) 偏低, 而 MgO (5.33% ~ 17.12%) 及 Mg<sup>#</sup> (62 ~ 74) 偏高。在 TAS 图 (图 4a) 中, 几乎所有的样品均落在玄武岩区, 个别的落在安山岩及玄武质安山岩区, 另外, 枕状熔岩均属于碱性系列, 而侵入产出的岩脉为亚碱性, 这与在抗蚀变元素图解 Nb/Y-Zr/TiO<sub>2</sub> 中投图结果一致 (图 4b)。所有的样品投点落在克拉玛依 OIB 型枕状玄武岩区或者附近 (图 4a, b)。

## 5.3 微量元素

蛇绿混杂岩中玄武岩稀土元素总量较高 (ΣREE = 65.8 × 10<sup>-6</sup> ~ 149.5 × 10<sup>-6</sup>), 高于 MORB (39.1 × 10<sup>-6</sup>), 无明显 Eu 异常 (Eu/Eu\* = 0.9 ~ 1), 表明没有发生斜长石的分离结晶作用。在球粒陨石标准化曲线图 (图 5a) 上, 轻稀土 (LREE) 略富集, 重稀土 (HREE) 相对略亏损且平坦, 轻重稀土分馏较为明显 ((La/Yb)<sub>N</sub> = 2.5 ~ 7.4)。各个样品 REE 配分模式相互平行, 只有位置的高低, 显示稀土分异程度相当, 具有同源岩浆演化特征。总体上配分曲线高于 E-MORB, 而接近于 OIB, 与夏威夷 (Xia *et al.*, 2008) 和日喀则 (Hofmann and Jochum, 1996) 海山玄武岩相似。辉长岩与玄武岩具有相似的 REE 配分模式, 但前者 REE 总量相对较低 (ΣREE = 3.9 × 10<sup>-6</sup> ~ 60 × 10<sup>-6</sup>), 并呈平坦型 ((La/Yb)<sub>N</sub> = 0.5 ~ 2.3) 伴有弱正 Eu 异常 (Eu/Eu\* = 0.8 ~ 1.5), 可能和斜长石

表 2 西准噶尔玛依勒蛇绿混杂岩中玄武岩和辉长岩主量元素 (wt%)、微量元素 ( $\times 10^{-6}$ ) 分析结果及主要参数Table 2 The concentration of major (wt%), trace elements ( $\times 10^{-6}$ ) and their parameters for the gabbros and basalts of the Mayile ophiolitic mélange in the West Junggar, Xinjiang

岩性 样品号	玄武岩							辉长岩			
	XW-1	XW-2	XW-3	XW-4	XW-5	XW-6	XW-7	HC-1	HC-2	HC-3	HC-4
SiO <sub>2</sub>	38.25	36.13	36.63	40	42.86	42.61	45.98	51.56	52	41.6	40.92
TiO <sub>2</sub>	2.01	2.55	2.32	2.94	1.65	3.13	1.54	0.09	0.06	0.09	0.14
Al <sub>2</sub> O <sub>3</sub>	13.06	12.2	12.41	13.31	13.2	14.03	12.84	2.93	2.47	19.16	15.6
Fe <sub>2</sub> O <sub>3</sub>	8.31	10.69	11.08	11.97	9.07	11.15	9.04	6.99	6.48	3.54	6.28
FeO	1.45	7.47	7.37	7.34	6.24	7.01	6.08	4.87	4.57	2.47	4.37
MnO	0.18	0.14	0.17	0.14	0.12	0.14	0.14	0.19	0.19	0.08	0.12
MgO	3.95	4.95	4.49	4.81	5.27	4.86	5.2	17.12	17.07	5.33	9.26
CaO	27.23	23.3	22.3	12.62	13.69	10.03	11.3	14.54	15.99	24.5	21.89
Na <sub>2</sub> O	1.12	1.48	1.16	3.71	4.11	4.24	5.12	0.56	0.52	0.26	0.24
K <sub>2</sub> O	0.04	0.03	0.04	0.59	0.5	0.64	0.68	0.04	0.04	0.02	0.01
P <sub>2</sub> O <sub>5</sub>	0.24	0.24	0.24	0.45	0.19	0.51	0.17	0.03	0.02	0.01	0.01
LOI	4.12	0.53	1.72	2.15	3.18	1.57	1.71	1.87	2.12	2.81	1.58
Total	99.96	99.71	99.93	100.03	100.07	99.9	99.8	100.79	101.51	99.87	100.42
Mg <sup>#</sup>	68	34	32	34	39	35	40	73	74	62	62
Na <sub>2</sub> O + K <sub>2</sub> O	1.16	1.51	1.2	4.3	4.6	4.88	5.8	0.6	0.54	0.28	0.25
Ba	444	189	111	62.3	135	110	157	124	14.8	15.9	8.35
Rb	1.56	0.87	1.37	1.78	10.5	7.86	9.98	10.7	1.24	1.03	1.2
Sr	142	86.2	192	199	268	234	241	213	31.2	29.4	143
Y	22.71	25.54	26.57	26.76	31.14	24.06	31.83	22.78	6.35	4.76	2.12
Zr	181.9	177.3	191.9	212.6	177.4	98.05	180.5	90.16	4.76	2.04	2.36
Nb	19.97	0.65	26.01	23.61	35.37	10.02	35.95	8.82	0.65	0.33	0.11
Th	2.31	2.31	3.03	2.7	2.68	0.72	2.72	0.66	0.08	0.03	0.06
Ga	12.98	11.04	8.71	12.72	19.36	15.08	20.31	13.85	3.74	3.32	7.14
Ni	74.91	28.54	69.32	63.95	39.55	84.39	38.84	75.97	362.1	386.1	35.63
Cr	153.5	98.12	143.4	127.9	35.43	358.3	34.22	346.1	1187	1420	45.47
Hf	4.32	4.06	4.55	4.98	4.11	2.53	4.11	2.35	0.13	0.06	0.08
Sc	27.82	27.25	29.14	27.78	34.68	38.61	35.07	38.61	16.69	16.33	29.28
Ta	1.27	0.07	1.64	1.45	2.12	0.64	2.18	0.56	0.07	0.05	0.01
Co	45.02	10.16	55.35	50.33	51.9	57.49	49.96	49.13	65.5	69.33	28.02
U	0.61	0.03	0.56	0.55	1.24	0.86	1.26	0.3	0.06	0.05	0.01
V	185.5	9.21	211.8	192.5	354.8	292.7	364.6	277.3	76.61	61.24	77.18
Bi	0.69	0.63	0.66	0.62	0.6	0.56	0.58	0.54	0.49	0.5	0.01
Pb	4.6	2.38	5.56	4.27	6.75	3.42	5.31	4.36	2.39	3.24	0.38
Cd	6.44	5.81	5.97	5.72	5.56	5.34	5.28	5.07	4.63	4.75	0.08
Cs	0.68	0.49	1.35	1.9	1.07	0.33	0.8	0.36	0.27	0.28	0.08
La	15.65	18.58	20.66	19.63	25.51	8.82	26.83	7.6	1.69	0.94	0.47
Ce	33.36	33.11	43.74	39.06	53.13	19.5	54.91	17.53	2.72	1.96	0.98
Pr	4.17	4.22	5.49	4.88	6.43	2.68	6.68	2.42	0.52	0.43	0.15
Nd	19.26	19.4	25.04	22.36	27.88	13.26	29	12.09	2.89	2.28	0.81
Sm	4.71	4.75	6.07	5.47	6.26	3.51	6.41	3.26	0.79	0.58	0.28
Eu	1.61	1.57	1.93	1.77	2.1	1.23	2.15	1.2	0.22	0.29	0.16
Gd	5.27	5.3	6.65	5.94	6.78	4.51	6.96	4.23	0.96	0.61	0.37
Tb	0.77	0.78	0.98	0.89	1.03	0.73	1.06	0.69	0.16	0.1	0.06
Dy	4.39	4.43	5.56	5.09	6.19	4.63	6.43	4.46	1.03	0.67	0.41
Ho	0.82	0.83	1.02	0.95	1.23	0.94	1.28	0.91	0.21	0.14	0.09
Er	2.17	2.23	2.74	2.55	3.54	2.73	3.66	2.6	0.61	0.41	0.25
Tm	0.28	0.28	0.35	0.33	0.47	0.38	0.49	0.35	0.09	0.06	0.04
Yb	1.71	1.79	2.2	2.1	3.09	2.49	3.17	2.35	0.6	0.44	0.23
Lu	0.25	0.26	0.33	0.3	0.47	0.37	0.48	0.35	0.1	0.07	0.03
Σ REE	94.42	97.53	122.8	111.3	144.1	65.78	149.5	60.04	12.59	8.98	4.33
(La/Yb) <sub>N</sub>	6.6	7.4	6.7	6.7	5.9	2.5	6.1	2.3	2.0	1.5	1.5
Eu/Eu*	1.0	1.0	0.9	0.9	1.0	0.9	1.0	1.0	0.8	1.5	1.5

表3 准噶尔一带蛇绿混杂岩带年龄数据

Table 3 The ages of the ophiolitic mélangé in the Junggar, Xinjiang

地区	蛇绿岩带	岩性	测年方法	年龄 (Ma)	资料来源
西准噶尔	克拉玛依	辉长岩	锆石 SHRIMP	414.4 ± 8.6	徐新等, 2006
				332 ± 14	
	达尔布特	辉长岩	全岩 Sm-Nd	395 ± 12	张弛和黄萱, 1992
		辉长岩	锆石 LA-ICP-MS	391.1 ± 6.8	辜平阳等, 2009
	唐巴勒	辉长岩	斜长石 Pb-Pb	523.2 ± 7.2	Kwon <i>et al.</i> , 1989
		斜长花岗岩	楣石 Pb-Pb	508 ± 20	肖序常等, 1992
		玄武岩	全岩 Sm-Nd	447 ± 56	张弛和黄萱, 1992
		辉长岩等	全岩 Sm-Nd	489 ± 53	张弛和黄萱, 1992
	玛依勒	辉长岩	锆石 SHRIMP	531 ± 15	Jian <i>et al.</i> , 2005
				> 415	Jian <i>et al.</i> , 2005
		玄武岩	全岩 Rb-Sr	435.3 ± 6.5 432.5 ± 7.4	魏荣珠等, 2010
		火山熔岩	全岩 Rb-Sr	421	朱宝清等, 1987a
		硅质岩	放射虫	中志留世	李红生, 1994
		辉长岩	锆石 LA-ICP-MS	572.2 ± 9.2	本文
	洪古勒楞	橄长岩等	全岩 Sm-Nd	625 ± 25	黄建华等, 1999
		堆晶岩	全岩 Sm-Nd	444 ± 27	张弛和黄萱, 1992
		辉长岩	锆石 SHRIMP	273.3 ± 2.6	张传林等, 2010
		钙长石岩	锆石 SHRIMP	475	Jian <i>et al.</i> , 2005
		辉长岩	锆石 SHRIMP	409 ± 23	Jian <i>et al.</i> , 2005
		辉长岩	锆石 SHRIMP	472 ± 8.4	张元元和郭召杰, 2010
库吉拜	辉长岩	锆石 SHRIMP	478.3 ± 3.3	朱永峰和徐新, 2006	
巴尔雷克	硅质岩等	放射虫	D2	冯益民, 1987	
东准噶尔	卡拉麦里	斜长花岗岩	锆石 SHRIMP	373 ± 10	唐红峰等, 2007
		辉长岩	长石 <sup>40</sup> Ar- <sup>39</sup> Ar	737 ± 1	何国琦等, 2001
		斜长花岗岩	锆石 SHRIMP	497 ± 12	Jian <i>et al.</i> , 2005
		辉长岩	锆石 LA-ICP-MS	329.9 ± 1.6	汪帮耀等, 2009
		硅质岩	放射虫	D <sub>3</sub> -C <sub>1</sub>	舒良树和王玉净, 2003
	阿尔曼太	硅质岩	放射虫	O	李锦轶, 1991
		辉长岩等	全岩 Sm-Nd	525 ± 26	刘伟和张湘烟, 1993
		玄武岩	锆石 SHRIMP	503 ± 7	肖文交等, 2006
	扎河坝	辉长岩	锆石 SHRIMP	489 ± 4	简平等, 2003
		斜长花岗岩	锆石 SHRIMP	495.9 ± 5.5	张元元和郭召杰, 2010
		变质橄欖岩	全岩 Sm-Nd	479 ± 27	刘伟和张湘烟, 1993
	库尔提	斜长花岗岩	锆石 SHRIMP	372 ± 19	张海祥等, 2003

的堆晶作用有关。

在微量元素蛛网图(图 5b)中,玄武岩的大离子亲石元素(LILE)Rb、Ba、Th 相对富集, K 相对亏损,高场强元素(HFSE)Zr、Hf、Nb 相对亏损,在辉长岩中更为显著,表明辉长岩可能形成于不同的构造环境。Sr 在玄武岩中呈现负异常,而在辉长岩中呈现明显的正异常。玄武岩中高场强元素(HFSE)Nb/Ta 比值为 15.7 ~ 16.7, 平均为 16.1, 略低于 OIB (17.8, Sun and McDonough, 1989), 而接近于原始地幔值 (17.5 ± 2.0), Zr/Hf 比值为 38.4 ~ 43.2, 平均为 41.6, 略高于 OIB 和原始地幔(分别为 35.9, 36.3), 但远高于大陆地壳值(Nb/Ta = 12 ~ 13, Zr/Hf = 11)。总体上,玄武岩样品的曲线与 OIB 形态基本一致。

## 6 讨论

### 6.1 形成时代

根据前人研究成果,本文对东、西准噶尔广泛分布的蛇绿混杂岩时、空分布做了简要总结(表 3)。从表 3 可以看出,这些蛇绿混杂岩时代跨度较大,从震旦纪晚期至早二叠世均有发育,主要集中在奥陶世、志留世及泥盆世,唐巴勒和达尔布特蛇绿混杂岩的同位素年龄数据可信度较高,其代表的洋盆可能分别打开于震旦纪晚期-寒武纪初期和中泥盆世。前人采用不同的测试方法对玛依勒蛇绿混杂岩中的辉石岩、玄武岩等分别进行锆石 SHRIMP 和全岩 Rb-Sr 等时线测年(朱宝清等, 1987a; Jian *et al.*, 2005; 魏荣珠等, 2010), 认



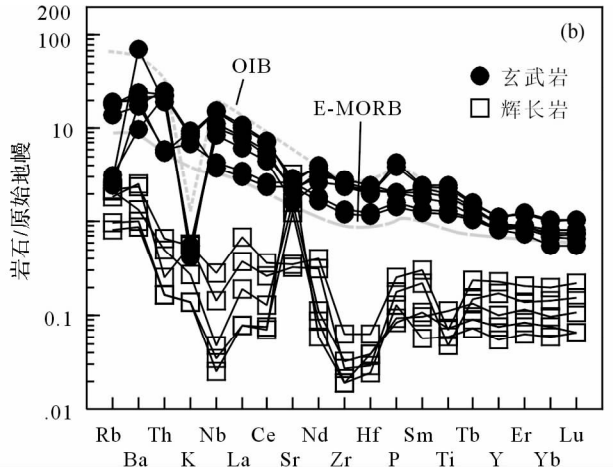
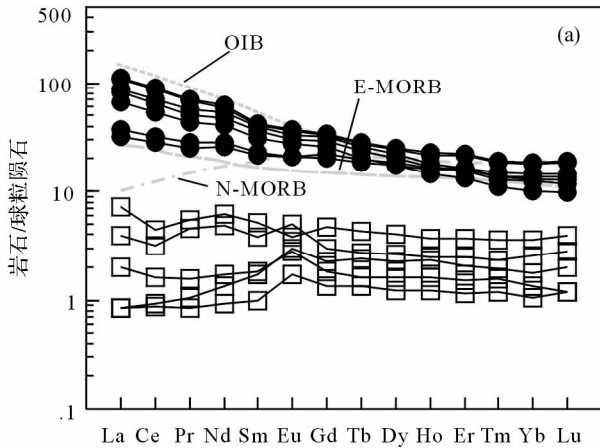


图5 球粒陨石标准化的稀土元素配分模式(a)和原始地幔标准化的多元蛛网图(球粒陨石和原始地幔标准值据 Sun and McDonough, 1989)

Fig.5 Chondrite-normalized REE distribution patterns (a) and primitive mantle-normalized multi-elements spider diagram (b) (chondrite data and primitive mantle data after Sun and McDonough, 1989)

为其形成于中或晚志留世。另外,李红生(1994)还从玛依勒地区玛依勒组地层中发现中志留世放射虫。笔者等对其中的辉长岩进行锆石 LA-ICP-MS 测年获得年龄  $572.2 \pm 9.2\text{Ma}$ ,属于早震旦纪,这些表明在玛依勒山一带可能至少存在两期洋壳,本文获得玛依勒蛇绿混杂岩年龄所代表的洋盆很可能在空间上和震旦纪在唐巴勒地区的洋盆 ( $523.2 \pm 7.2\text{Ma}$ , Kwon *et al.*, 1989) 是并存的。当然,也有可能  $572.2 \pm 9.2\text{Ma}$  的辉长岩代表着俯冲带环境下形成蛇绿岩组分,而  $\sim 430\text{Ma}$  的板内玄武岩为后期保留在增生楔中的组分。另外,本文获得的年龄是早于唐巴勒蛇绿混杂岩及整个准噶尔地区蛇绿岩形成的年龄(表3),是截至目前为止,在准噶尔乃至北疆地区报道的最古老的蛇绿混杂岩年龄。

### 6.2 构造环境

已有研究表明,蛇绿岩可以形成于洋中脊、岛弧、弧前和弧后盆地,且大多数形成于消减带之上(Pearce *et al.*, 1984; Stern *et al.*, 1989)。一般而言,玄武岩地球化学特征是讨论蛇绿混杂岩形成环境的最佳依据。玛依勒蛇绿混杂岩中的枕状玄武岩为碱性玄武岩(图4a,b),岩石具有高 Ti ( $\text{TiO}_2 = 1.65\% \sim 3.13\%$ )、高 Fe ( $\text{FeO}^T = 8.93\% \sim 18.11\%$ )、高 Mg ( $\text{MgO} = 3.95\% \sim 5.27\%$ ) 及高 P ( $\text{P}_2\text{O}_5 = 0.17\% \sim 0.51\%$ )、Th/Ta 比值相对较高 ( $= 1.1 \sim 1.9$ )、LREE 和 HREE 分异较为明显 ( $(\text{La}/\text{Yb})_N = 2.5 \sim 7.4$ ) 等特征,这些特征与 OIB 类似(张旗和周国庆,2001),这与 REE 球粒陨石模式图(图5a)和多元蛛网图(图5b)显示相吻合,同时,也和克拉玛依 OIB 型枕状玄武岩(朱永峰等,2007)及阿尼玛卿蛇绿岩中 OIB(郭安林等,2006)相近。

由于玄武岩样品遭受后期弱的碳酸盐化等蚀变,故选用抗蚀变元素如 Zr、Y、Ti、Hf 等进行构造环境判别。在 Ti/100-

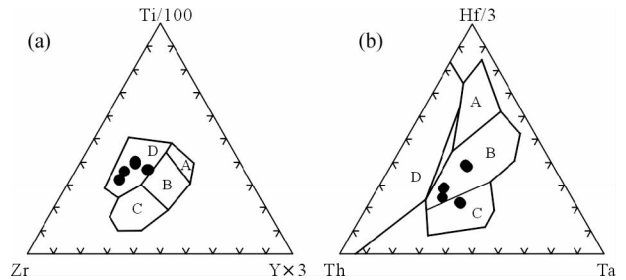


图6 玛依勒蛇绿混杂岩中玄武岩构造环境判别图

(a)-Ti/100-Zr-3 × Y 图解(据 Pearce and Cann, 1973), A-岛弧拉斑玄武岩, B-MORB、岛弧拉斑玄武岩和钙碱性玄武岩, C-钙碱性玄武岩, D-板内玄武岩; (b)-Hf/3-Th-Ta 图解(据 Wood, 1980), A-N-MORB, B-E-MORB 和板内拉斑玄武岩, C-碱性板内玄武岩, D-火山弧玄武岩

Fig.6 Tectonic setting discrimination diagram for the basalts in the Mayile ophiolitic mélangé

(a)-Ti/100-Zr-3 × Y (after Pearce and Cann, 1973), A-island arc tholeiite basalt; B-MORB, island arc tholeiite and calc alkalic basalt; C-calc-alkalic basalt; D-with in plate basalt; (b)-Hf/3-Th-Ta (after Wood, 1980), A-N-MORB; B-E-MORB and within plate tholeiite basalt; C-alkalic within plate basalt; D-volcanic arc basalt

Zr-3Y 判别图(图6a)中,所有样品落入板内玄武岩区域,在 Hf/3-Th-Ta 判别图(图6b)中,样品表现出 E-MORB 及板内碱性玄武岩特征,这与  $\text{TiO}_2-10 \times \text{MnO}-10 \times \text{P}_2\text{O}_5$  (图略) 投图结果相一致。由此可见,玛依勒蛇绿混杂岩中的枕状玄武岩可能形成于大洋板内的洋岛或海山环境。

辉长岩的中原生角闪石出现而玄武岩中未见(图2a, b);与玄武岩的富  $\text{TiO}_2$  ( $1.54\% \sim 2.94\%$ ) 和  $\text{P}_2\text{O}_5$  ( $0.17\% \sim 0.45\%$ ) 不同的是,辉长岩极度贫  $\text{TiO}_2$  ( $0.06\% \sim 0.14\%$ ) 和  $\text{P}_2\text{O}_5$  ( $0.01\% \sim 0.03\%$ );辉长岩表现为平坦的稀土元素分配

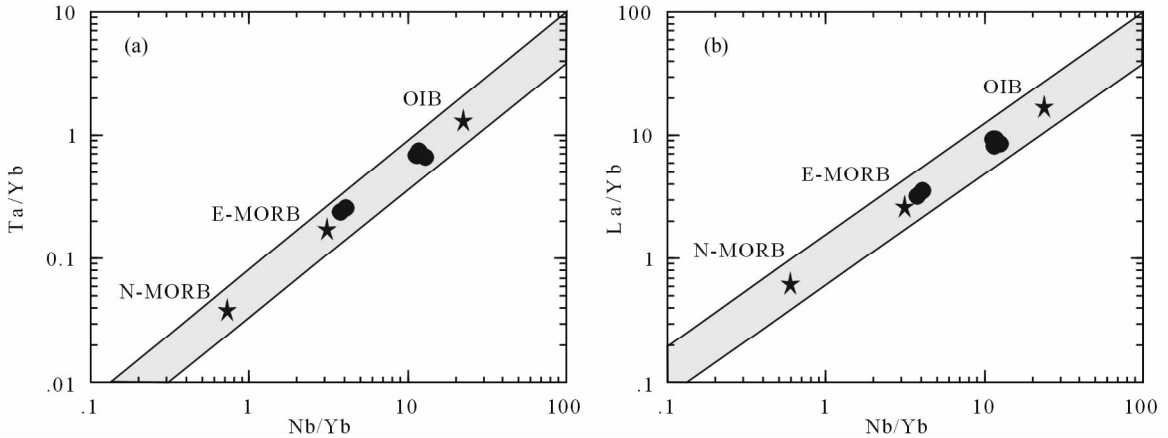


图7 Ta/Yb-Nb/Yb(a)和La/Yb-Nb/Yb(b)图解(据朱永峰等,2007)

阴影区域表示不同类型大洋玄武岩(N-MORB,E-MORB,OIB)相应元素变化范围(据Sun and McDonough,1989)

Fig.7 Plots of Ta/Yb-Nb/Yb (a) and La/Yb-Nb/Yb (b) for basalts (after Zhu *et al.*, 2007)

Shaded areas indicate the range of oceanic basalts (N-MORB, E-MORB and OIB) (normalizing values after Sun and McDonough, 1989)

特征和Nb、Ta、Zr、Hf等高场强元素的明显负异常,与玄武岩的地球化学特征明显不同(图5a,b);另外,辉长岩中的Nb/La比值为0.23~0.38(除HC-1中的1.16外),而玄武岩中为1.14~1.39(除XW-2中的0.03外),前者明显低于后者。表明辉长岩在地球化学上具有明显不同于玄武岩,显示俯冲带信息。这一认识与Xu *et al.* (2012)最新通过矿物学和地球化学研究表明玛依勒蛇绿岩带显示俯冲相关的SSZ型的结论相吻合,另外,晚寒武-早志留世的岛弧侵入岩更是早古生代该地区处于俯冲环境的直接证据。

### 6.3 源区特征

微量元素比值可以有效区分原始岩浆演化过程受流体或地壳混染的程度,其地球化学特征指示源区性质。在Ta/Yb-Nb/Yb(图7a)和La/Yb-Nb/Yb图(图7b)中,玛依勒蛇绿混杂岩中玄武岩落在地幔序列中的E-MORB和OIB之间,表明这些元素主要受岩浆源区控制,后期过程(如流体或地壳混染)对其影响较弱,这与较低的Nb/La比值(1.14~1.39)相一致(夏林圻等,2007)。另外,样品的Zr/Nb=5.02~10.22,Th/La=0.08~0.15,Th/Nb=0.07~0.12,与EMI型洋岛玄武岩(OIB)具有地球化学特征(Weaver,1991),表明其岩浆源区可能为EMI型富集地幔。

玛依勒蛇绿混杂岩中的玄武岩具有较低的 $(La/Yb)_N$ 、 $(Gd/Yb)_N$ 、 $(Dy/Yb)_N$ 、Sm/Yb比值(分别为2.5~7.4,1.5~2.6,1.2~1.7,1.4~2.8)及相对较高的HREE含量(其HREE含量大于10倍球粒陨石),表明其原始岩浆应起源于岩石圈地幔尖晶石二辉橄榄岩的局部熔融(Chung,1999)。另外,在Ti/100-Zr-3×Y图(图6a)中样品几乎无一例外的落在的板内玄武岩区,显示板内富集趋势(Pearce and Norry,1979)。因此我们推测这些玄武岩岩石成因与软流圈地幔关系密切,软流圈的上涌导致尖晶石相二辉橄榄岩地幔源区大

比例部分熔融,是岩石圈-软流圈地幔相互作用的产物。

## 7 结论

通过对玛依勒蛇绿混杂岩中辉长岩和玄武岩开展LA-ICP-MS锆石U-Pb年代学、岩石学及地球化学研究,本为获得以下主要认识:

(1)玛依勒蛇绿混杂岩的各组成单元出露仍较为齐全,主要包括超镁铁质岩石(蛇纹石岩和蛇纹石化纯橄岩等),辉长岩和辉长闪长岩脉以及枕状玄武岩,伴有放射虫硅质岩、硅质泥岩等。

(2)辉长岩的LA-ICP-MS锆石年龄为 $572.2 \pm 9.2$ Ma,属于早震旦纪,该年龄是准噶尔乃至北疆地区报道的最古老的蛇绿混杂岩年龄。

(3)玛依勒蛇绿混杂岩中的枕状玄武岩为碱性玄武岩,岩石具有高Ti( $TiO_2 = 1.65\% \sim 3.13\%$ )、Fe( $FeO^T = 8.93\% \sim 18.11\%$ )、Mg( $MgO = 3.95\% \sim 5.27\%$ )及P( $P_2O_5 = 0.17\% \sim 0.51\%$ )的特征,LREE和HREE分异较明显,其与洋岛玄武岩类似,可能形成于大洋板内的洋岛或海山环境。

(4)辉长岩相对于玄武岩, $TiO_2$ (0.06%~1.14%), $P_2O_5$ (0.01%~0.03%)及 $Na_2O + K_2O$ (0.2%~0.6%)偏低,而MgO(5.33%~17.12%)及 $Mg^\#$ (62~74)偏高,属于亚碱性系列。可能形成于俯冲带环境。

(5)玛依勒蛇绿混杂岩中玄武岩与EMI型洋岛玄武岩具有相似的地球化学特征,表明其岩浆源区可能为EMI型富集地幔。岩石成因与软流圈地幔关系密切,软流圈的上涌导致尖晶石相二辉橄榄岩地幔源区大比例部分熔融,是岩石圈-软流圈地幔相互作用的产物。

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