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西准噶尔蛇绿岩:古大洋俯冲增生过程的记录

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内容提要：蛇绿岩记录了大洋岩石圈形成、演化、消亡的全过程，是刻画区域板块构造和洋-陆格局演化的关键证据。本文通过系统梳理前人相关研究，总结西准噶尔蛇绿岩最新研究成果，探讨大陆地壳增生方式、恢复古大洋演化历史，从而对西准噶尔构造体制转化提供新制约。西准噶尔地区发育多条震旦纪—石炭纪被构造肢解的蛇绿岩带，具有典型的岩块-基质结构，绝大多数蛇绿岩包括正常洋壳组分和海山/大洋高原残片，其中基性岩具有 MORB 和 OIB 的地球化学特征。基于前人研究，本文认为在西准噶尔古大洋发育过程中，发育不同时代与地幔柱有关的海山/大洋高原，同时存在增生型和侵蚀型两类汇聚板块边界。另外，大洋高原增生不仅是大陆地壳增生的有效途径之一，还可能诱发俯冲极性反转和传递。而在大洋高原形成初期，还可能存在地幔柱诱发俯冲起始机制。

关键词：大地构造；蛇绿岩；海山；俯冲起始；西准噶尔

蛇绿岩是保存在造山带中的古大洋岩石圈残片，其形成时代和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（Coleman，1977；史仁灯，2005；张进等，2012；吴福元等，2014；王国灿等，2019；张继恩等，2021；敖松坚等，2022）。目前，国内外学者对蛇绿岩的分类方案众多（Pearce et al.，1984；肖序常，1995；Dilek et al.，2011），但被学界普遍接受的是将其分为洋中脊型（MOR）和俯冲带之上型（SSZ）。而 Dilek et al.（2011）以蛇绿岩的形成环境为依据，将蛇绿岩分为与俯冲作用无关型和与俯冲作用相关型两大类，强调蛇绿岩是一套时间和成因上相互联系的超基性岩、基性岩、长英质岩石的组合。近年来，随着对早期地球的形成和演化、超大陆的裂解与聚合、深部高压矿物的厘定和板块构造的起源等研究（Zhai Mingguo et al.，2020；Yang Jingsui et al.，2021；Yao Jinlong et al.，2021；Zhu Rixiang et al.，2021；董云鹏等，2022；李三忠等，2022；张招崇等，2022；赵国春等，2022；Wang Tao et al.，2023a），进一步拓展了蛇绿岩的研究领域。

中亚造山带是世界上最大的增生型造山带之一（图 1a；Sengör et al.，1993；Windley et al.，2007；Xiao Wenjiao et al.，2015），也是全球显生宙大陆地壳生长最显著的地区（Jahn et al.，2000；Huang He et al.，2020；Wang Tao et al.，2023b），主要由一系列微陆块、岛弧、海山、增生杂岩及蛇绿岩构成（Yang Gaoxue et al.，2015；Xiao Wenjiao et al.，2020；Ao Songjian et al.，2021；Zhou Hai et al.，2022），其形成记录了新元古代—早中生代古亚洲洋演化历程（Wilhem et al.，2012）。中亚造山带发育新元古代晚期至三叠纪数条蛇绿岩带（Furnes et al.，2019），而地处中亚造山带西南缘的西准噶尔地区蛇绿岩发育尤为突出（图 1b；Zhang Chi et al.，1993；何国琦等，2007；Zhao Lei et al.，2013；Yang Gaoxue et al.，2015；高俊等，2022；Zhang

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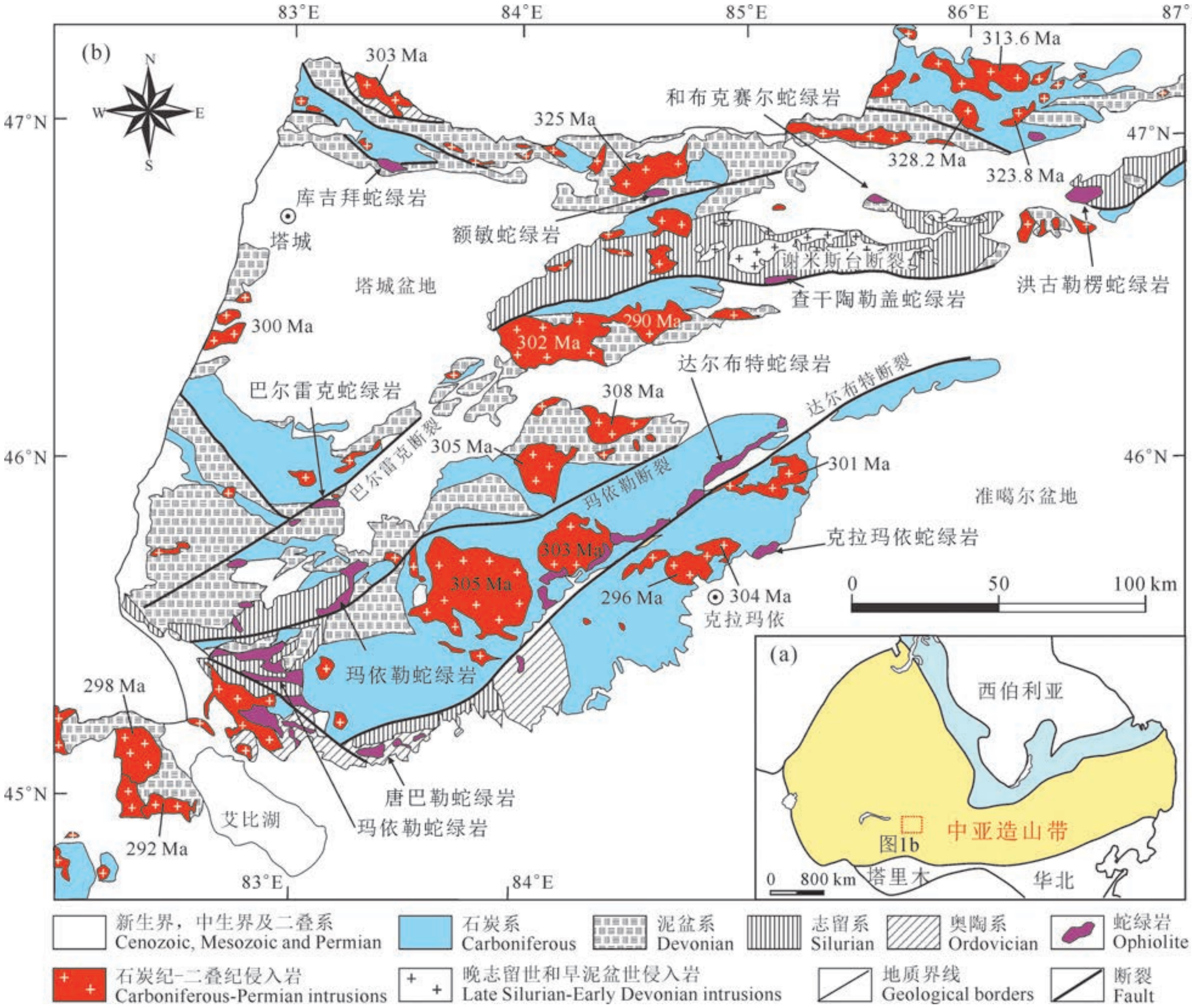

图 1　中亚造山带构造格架图(a,修改自 Jahn et al.,2000)及西准噶尔地质简图(b,修改自 Yang Gaoxue et al.,2013)

Fig. 1　Simplified tectonic sketch of the Central Asian Orogenic Belt (a, after Jahn et al.,2000) and regional geological map of the West Junggar (b, after Yang Gaoxue et al.,2013)

Jien et al.,2022)。

西准噶尔蛇绿岩的研究从 20 世纪 50 年代开始,主要针对基性、超基性岩和铬铁矿进行零散的地质普查勘探和科学研究工作。张弛(1981)认为新疆蛇绿岩(包括西准噶尔)大多形成于华里西期,并且与世界典型蛇绿岩岩石组合具有相似性。1981～1985 年,随着中国地质科学院西安地质矿产研究所承担的“新疆西准噶尔地区基性超基性岩生成地质背景及区域成矿(铬)特征”项目的实施,正式拉开了西准噶尔蛇绿岩研究的序幕,项目主要从蛇绿岩特征及意义、形成地质背景、区域岩石矿物学、工业铬铁矿及预测、矿物包裹体及成岩成矿物理化学条件以及数学地质等 6 个方面进行系统研究。1987 年,西安地质矿产研究所所刊第 17 号以“西准噶尔超基性岩、蛇绿岩及铬铁矿”为标题进行专刊报道,对上述项目重要成果进行了系统总结,最为重要的认识有:① 西准噶尔地区发育中奥陶世、中志留世和中泥盆世三期蛇绿岩,呈叠瓦状岩片产出,均为断裂构造侵位;② 三期蛇绿岩从南向北,时代由老渐新,具有多期次活动特征;③ 依据超基性岩中 Al_2O_3 和 CaO 含量,将其分为低铝型(唐巴勒和玛依勒蛇绿岩)和高铝型(萨尔托海蛇绿岩);④ 在超基性岩中发现了幔源尖晶石二辉橄榄岩及其部分熔融残余体岩石或矿物,提出了深熔分异成岩(矿)模式;⑤ 成矿铬元素主要来源于地幔熔融辉石,特别是单斜辉石,时间上分为早、晚两个阶段,对应两种成因类型,即浅部豆荚状(富)矿床和深部似层状(贫)矿床。1989 年,Feng Yiming et al.(1989)对西准噶尔唐巴勒和达尔布特蛇绿岩进行了年代学、地球化学和构造环境研究,认为它们形成于岛弧有关的环境。实

际上，同年在《Tectonics》还有两篇有关西准噶尔构造演化和陆壳增生的文章(Coleman, 1989; Kwon et al., 1989)，一起将西准噶尔蛇绿岩研究推向了国际视野。随后国内外诸多单位和学者相继做过系列研究工作，发表了上百篇的研究论文和专著，对其岩石组合、地质时代、地球化学特征、形成环境、构造变形、大地构造属性及铬铁矿等都有论述(Zhang Chi et al., 1993; 张立飞, 1997; Zhou Meifu et al., 2001; Zhu Yongfeng et al., 2016)。

近几十年来，经过地质学家坚持不懈的研究，已取得系列新进展，特别是在西准噶尔蛇绿岩中识别出不同时代的海山/大洋高原残片(Yang Gaoxue et al., 2012b, 2012c, 2013, 2019; Yang Yaqi et al., 2020; Zhang Jien et al., 2018; Du Houyuan et al., 2019)，同时开展了蛇绿岩相关的俯冲起始时限和机制研究，并积累了大量的资料(Yang Gaoxue et al., 2020, 2022)。但依然存在一些争论，亟需针对西准噶尔蛇绿岩研究现状和新进展进行系统总结，为此，本文对西准噶尔蛇绿岩相关研究进行系统分析，探讨西准噶尔蛇绿岩成因及其地质意义，为西准噶尔乃至中亚造山带西南缘发展和演化研究提供制约。

1 区域地质背景

西准噶尔是中亚造山带的重要组成部分(图1b)，位于哈萨克斯坦山弯构造的北翼，主要由一系列的增生杂岩带、古生代岩浆弧构成(Buckman et al., 2004; Choulet et al., 2012)，发育一系列 NE—SW 向断裂，由北向南依次为巴尔雷克、玛依勒和达尔布特断裂，这些断裂及所夹的构造地块，构成了西准噶尔“多”字型构造体系(陈宣华等, 2011)，它们控制着地层、花岗岩类和蛇绿岩的分布。西准噶尔地区出露的地层主体为奥陶系至石炭系火山-沉积地层，分布最为广泛的当属石炭系，主要组成为巨厚的火山-碎屑沉积建造。该地区出露大量晚古生代中酸性侵入体及岩脉，具有高正的 $\varepsilon_{Nd}(t)$ 值(Chen Bin et al., 2004; Geng Hongyan et al., 2009; Yin Jiyuan et al., 2010; Zheng Bo et al., 2020)。此外，发育多条形态复杂，变形强烈及时代跨度大的蛇绿岩带(Feng Yimin et al., 1989; Zhang Chi et al., 1993)，主要包括达尔布特、白碱滩、唐巴勒、玛依勒及巴尔雷克等蛇绿岩带(图 1b)。最新研究发现在这些蛇绿岩带中均发育洋岛玄武岩，可能形成于大洋板内的海山环境(Yang Gaoxue et al., 2013, 2015; Zhao Lei et al., 2014; Yang Yaqi et al., 2019b; 杨高学等, 2023)。西准噶尔成矿作用丰富多样，形成多种类型的金属矿床，如斑岩型铜金矿床、斑岩-石英脉-云英岩型钨钼矿床及豆荚状铬铁矿等(Shen Ping et al., 2017; Zhu Yongfeng et al., 2016; Zhu Qingmin et al., 2019; Zhang Huichao et al., 2022)。

2 蛇绿岩分布及年龄特征

西准噶尔发育多条蛇绿岩带，从北向南依次为库吉拜、额敏、和布克赛尔、洪古勒楞、查干托勒盖、巴尔雷克、达尔布特、玛依勒、唐巴勒和克拉玛依蛇绿岩带。位于西准噶尔北部的蛇绿岩，受近东西向断裂控制，从东向西依次为库吉拜、额敏、和布克赛尔、查干托勒盖和洪古勒楞蛇绿岩，形成时代主要集中在早奥陶世(表 1)，与东准噶尔北部的扎河坝和阿尔曼太蛇绿岩时代一致，并且它们大部分构造侵位于泥盆纪—石炭纪火山-沉积地层中，它们应该是同一条蛇绿岩带(张元元等, 2010)。向西进入哈萨克斯坦与 Char 蛇绿岩带相连(Buslov et al., 2004)。西准噶尔南部蛇绿岩主要受北东向断裂控制，向北东延伸进入准噶尔盆地，很可能与东准噶尔卡拉麦里蛇绿岩相接(何国琦等, 2001)，向西进入哈萨克斯坦境内，可以和北巴尔喀什蛇绿岩对比连接(Degtyarev et al., 2021)。最为典型的是达尔布特蛇绿岩沿北东向达尔布特断裂呈串珠状出露长达 70 km，其中萨尔托海和苏鲁乔克出露规模最大，研究最为深入。达尔布特蛇绿岩主要岩石有纯橄岩、二辉橄榄岩、辉石岩、铬铁矿、辉长岩、辉绿岩、闪长岩、斜长花岗岩、安山质玄武岩及上覆的硅质岩、灰岩和碎屑岩(Zhang Pan et al., 2018)。唐巴勒和玛依勒蛇绿岩位于西准噶尔的南部边缘，前者主体位于拉巴断裂以南，而后者发育在拉巴断裂和玛依勒断裂加持的三角区域，岩石组成基本与达尔布特蛇绿岩一致(图 2; Ren Rong et al., 2014)，均被强烈构造肢解。其他蛇绿岩出露面积较小，特别是库吉拜、额敏和查干托勒盖蛇绿岩沿断裂零星分布。

西准噶尔蛇绿岩形成时代跨度大，从震旦纪到石炭纪均有出现(表 1)。Yang Gaoxue et al. (2012b)在玛依勒蛇绿岩中的辉长岩中获得锆石 U-Pb 年龄为 572.2±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岩年龄。与之相当年龄的是唐巴勒蛇绿岩，年龄主要集中在 531～508 Ma，其中高压变质蓝片岩的 ^{39}Ar-^{40}Ar 年龄为 458±2.3 Ma 和 470±2.5 Ma(张立飞, 1997)。发育在西准噶尔中部的查干托勒盖、

表 1　西准噶尔蛇绿岩年龄、岩石组合、地球化学和构造环境综合对比表

Table 1　Summary of the age, lithology, geochemistry and tectonic setting of the ophiolites in West Junggar

序号	蛇绿岩名称	地质年代(Ma)(岩石,方法)	岩石组合	变质类型	基性岩地球化学特征	构造环境	资料来源
1	玛依勒	572±9（辉长岩，LA-ICP-MS），516±5.3（辉长岩，SIMS），435.3±6.5（玄武岩，Rb-Sr），415（辉石岩，SHRIMP）	方辉橄榄岩，二辉橄榄岩，纯橄岩，铬铁矿，辉绿岩，辉长岩，枕状和块状熔岩，深海放射状硅质岩和碎屑岩	绿片岩	MORB，OIB	俯冲带，地幔柱	Jian Ping et al.，2005；Yang Gaoxue et al.，2012b；Ren Rong et al.，2014
2	唐巴勒	531±15（辉长岩，SHRIMP），523.2±7.2（辉长岩，Pb-Pb），508±20（斜长花岗岩，Pb-Pb）	蛇纹石化方辉橄榄岩，二辉橄榄岩，纯橄岩，铬铁矿，辉石岩，辉长岩和斜长花岗岩	蓝片岩，角闪岩	MORB，OIB	俯冲带，地幔柱	Feng Yimin et al.，1989；Zhang Chi et al.，1993；Buckman et al.，2004；Jian Ping et al.，2005
3	查干托勒盖	519±3（辉长岩，LA-ICP-MS），517±3（辉长岩，LA-ICP-MS），515±4（斜长花岗岩，LA-ICP-MS），513±6（斜长花岗岩，LA-ICP-MS），早—中奥陶世	辉石岩，堆晶辉长岩，块状辉长岩，玄武岩，细碧岩和硅质岩	绿片岩?	MORB，OIB	洋中脊，地幔柱	Zhao Lei et al.，2014；Yang Yaqi et al.，2019a；Chen Jiafu et al.，2021
4	巴尔雷克	512.3±7.2（辉长岩，LA-ICP-MS），500±1.6（斜长花岗岩，LA-ICP-MS）	异剥橄榄岩，辉石岩，堆晶岩，辉长岩，玄武岩，硅质岩，蓝片岩和角闪岩	蓝片岩，角闪岩	MORB，OIB	俯冲带，地幔柱	杨高学等，2012a；赵文平等，2012；Liu Bo et al.，2016
5	和布克赛尔	512±9（辉长岩，LA-ICP-MS），505±5（辉长岩，LA-ICP-MS），502±5（斜长花岗岩，LA-ICP-MS），484±3（辉长岩，LA-ICP-MS），475±4（玄武岩，LA-ICP-MS）	橄榄岩，辉石岩，辉长岩，辉绿岩脉，斜长花岗岩，玄武岩，灰岩，硅质泥岩和硅质岩	低级变质岩	N-MORB，OIB	俯冲带，地幔柱	Du Houyuan et al.，2019；Yang Yaqi et al.，2019a，2020
6	库吉拜	478.3±3.3（辉长岩，SHRIMP）	辉长岩，蛇纹岩和硅质岩	低级变质岩	MORB	洋中脊(?)	朱永峰等，2006
7	额敏	476.0±2.4（辉长岩，SHRIMP）	蛇纹岩，橄榄岩，辉长岩，枕状玄武岩和硅质岩	热液蚀变岩	似 MORB	俯冲带	Zheng Rongguo et al.，2019
8	洪古勒楞	472±8.4（辉长岩，SHRIMP），475（辉长岩，SHRIMP）	方辉橄榄岩，蛇纹岩和辉长岩	低级变质岩	N-MORB（?）	俯冲带	Jian Ping et al.，2005；张元元等，2010
9	克拉玛依	414.4±8.6（辉长岩，SHRIMP），395±3（玄武岩，LA-ICP-MS），387±8（辉长岩，LA-ICP-MS），332±14（辉长岩，SHRIMP）	含尖晶石蛇纹岩，蛇纹石化二辉橄榄岩，变玄武岩，枕状熔岩，辉长岩，放射虫硅质岩，硅质泥岩和白云石大理岩，蓝片岩和角闪岩	蓝片岩，角闪岩	N-MORB，OIB	弧后盆地，地幔柱	徐新等，2006；Yang Gaoxue et al.，2013，2015；Zhang Pan et al.，2018
10	达尔布特	391±6（辉长岩，LA-ICP-MS），368±11（辉长岩，LA-ICP-MS），375±2（玄武岩，LA-ICP-MS）	蛇纹石化方辉橄榄岩，辉石岩，纯橄岩，堆晶岩，玄武岩，枕状熔岩，远洋硅质岩，灰岩和豆荚状铬铁矿	绿片岩	N-MORB，OIB	弧后盆地，地幔柱	Yang Gaoxue et al.，2012b，2012c；Zhang Pan et al.，2018

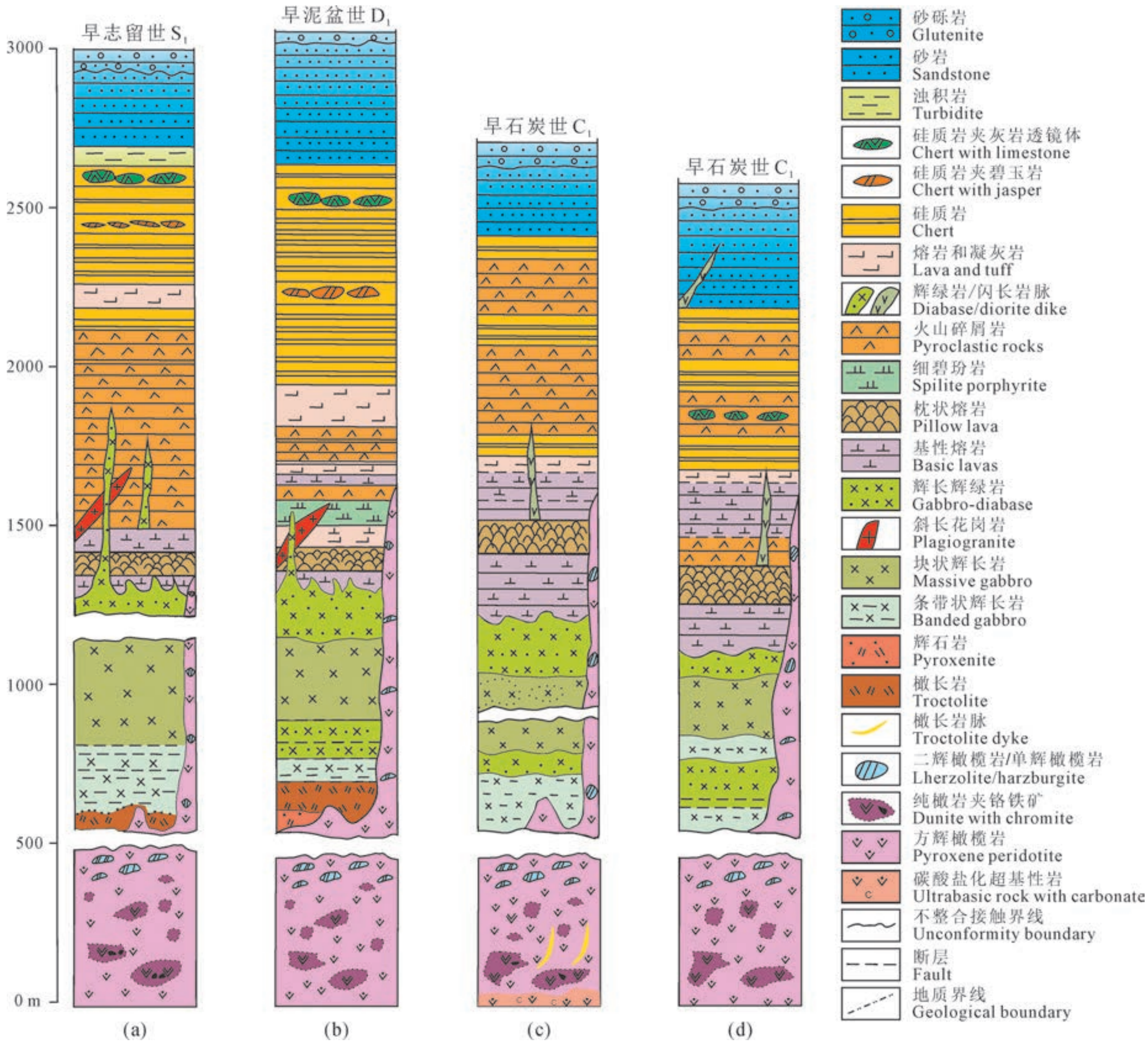

图 2 唐巴勒(a)、玛依勒(b)、达尔布特(c)和克拉玛依(d)蛇绿岩建造图(修改自 Yang Gaoxue et al.,2015)

Fig. 2 Simplified reconstruction of the Tangbale (a), Mayile (b), Darbut (c) and Karamay (d) ophiolites (modified from Yang Gaoxue et al.,2015)

巴尔雷克和和布克赛尔蛇绿岩年龄基本相当,时代为中寒武世(表 1),而发育在最北部且基本受同一条断裂控制的库吉拜、额敏和洪古勒楞蛇绿岩地质时代为 478～472 Ma,暗示它们很可能就是同一条蛇绿岩带。在西准噶尔最为年轻的蛇绿岩为克拉玛依蛇绿岩,在辉石岩中获得锆石 U-Pb 年龄分别为 414.4±8.6 Ma 和 332±14 Ma(徐新等, 2006)。就目前的年龄数据看,西准噶尔中部蛇绿岩年龄最为年轻,两侧年龄较老,且南部老于北部。总体而言,这些蛇绿岩具有形态复杂,组成相似,变形强烈,多沿走滑断裂分布,时代跨度大的特征。

3 海山/大洋高原的识别

在地球化学方面,西准噶尔蛇绿岩中的镁铁质岩可明显分为两组,一类为 MORB 型,属于拉斑系列,富集大离子亲石元素而亏损高场强元素,显示明显的 Nb、Ta 负异常,具有俯冲带相关信息,可能形成于俯冲有关环境(Zhang Chi et al.,1993, Zhang Pan et al.,2018; Zheng Rongguo et al.,2019)。但是目前也存在争议,比如前人对达尔布特蛇绿岩的形成环境就有不同认识。Zhu Qingmin et al. (2022)发现达尔布特蛇绿岩中均质辉长岩具有类似于前弧玄武岩的地球化学特征,认为其形成于弧前环境。Yang Gaoxue et al. (2012c)通过对达尔布特蛇绿岩中基性岩岩石地球化学分析,认为其形成于弧后盆地。而此前 Zhang Jien et al. (2011)通过对达尔布特及邻区大比例填图、构造解析并结合地球化学手段,研究认为达尔布特蛇绿岩形成于较宽阔

的洋盆。另一类为 OIB 型,属于碱性玄武岩系列,轻稀土元素强烈富集,无明显 Nb、Ta 负异常,并与典型的 OIB 玄武岩类似,可能形成于海山或大洋岛屿环境(Yang Gaoxue et al.,2015, 2019; 杨高学, 2016)。而这些与西准噶尔蛇绿岩中普遍发育枕状玄武岩、火山角砾岩、礁灰岩、滑塌堆积岩、陆源碎屑岩的地质事实相匹配,因为这些是典型的海山岩石组合特征(Isozaki et al.,1990; Buchs et al.,2011)。

西准噶尔蛇绿岩中海山或大洋高原残片的存在,说明在准噶尔古大洋发育过程中,普遍发育海山或大洋高原,而这些形成于大洋板内的单个海山或火山岛链随着板块运动被带至俯冲带并与之发生碰撞、刮削和增生,最终保存在造山带中。但事实上,更大部分海山/大洋高原很可能被带进了俯冲带。最新研究认为位于西准噶尔北部的塔城盆地是寒武纪—奥陶纪大洋高原的一部分(Zhang Jien et al.,2018)。但是据仅存地质事实,目前对其规模不能作更好的制约。

4　陆壳增生和俯冲侵蚀过程

前文已述及,西准噶尔北部的塔城盆地基底是形成于寒武纪—奥陶纪的大洋高原,这类似于分布在环太平洋大陆边缘地带中的诸多大洋高原碎片,例如在白垩纪末分别增生到美洲中部和亚洲大陆东缘的加勒比海大洋高原(Kerr et al.,2005)和鄂霍次克洋底高原(Zhang Kaijun et al.,2019)。另外,大洋高原可能是构成大陆克拉通基底的重要组成部分,如最新研究认为位于华北克拉通西部的鄂尔多斯盆地基底是前寒武纪形成的大洋高原(Kusky et al.,2015)。事实上,由于大洋高原自身浮力及正地形的影响,随俯冲板片到达汇聚边缘后,可能阻塞俯冲通道,抵制俯冲作用持续进行,从而拼贴至大陆边缘,促使大陆地壳增生(图 3a)。西准噶尔及上述其他实例表明大洋高原增生是大陆地壳增生的有效途径之一。

大洋高原在碰撞增生的同时,海山因其规模较小,可能发生俯冲,更容易导致俯冲上盘发生俯冲侵蚀作用(图 3b)。例如在南美和中美洲西部、西南日本-琉球岛弧及伊豆-小笠原-马里亚纳岛弧等出露有海山的区域,大多形成了侵蚀型边界(von Huene et al.,1991)。通过俯冲侵蚀的上盘物质和海山一并被带到地幔深部,可能改变弧岩浆岩的地幔源区组成(Ulrich et al.,2012; Wang Liangliang et al.,2022)。一个典型的例子就是哥斯达黎加埃达克岩岩浆源区很可能有来自被俯冲侵蚀下来的弧前物质的参与(Goss et al.,2006)。西准噶尔泥盆纪—石炭纪火山岩具有较高的 $^{206}Pb/^{204}Pb$ 值(18.3～19.5)和 Nd/Sm 值(4.5～5.6),这与受到海山俯冲影响的岩浆中比值一致(雷敏等, 2008; Staudigel et al.,2010),表明在西准噶尔地区晚古生代岛弧岩浆过程中有来自俯冲侵蚀物质包括海山的参与。

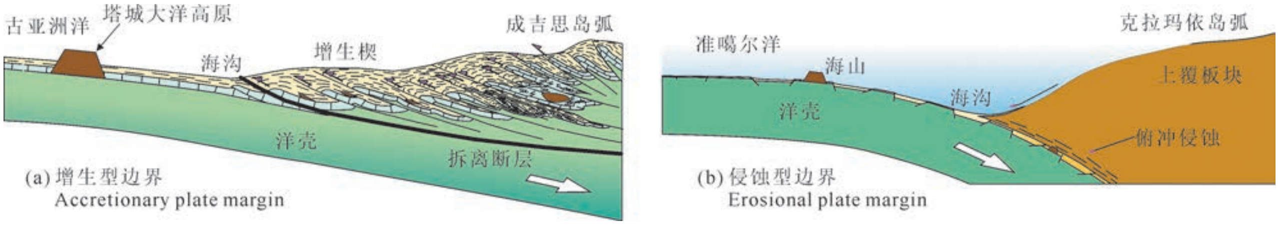

图 3　板块俯冲过程中的两种典型边界类型(修改自 Frisch et al.,2011)

Fig. 3　Two types of convergent plate boundaries in subduction process (modified from Frisch et al.,2011)

5　板块构造体制转化

随着研究的不断深入,在西准噶尔地区识别出不同时代的海山/大洋高原,研究认为它们很可能是不同时期地幔柱活动的产物(Yang Gaoxue et al.,2015; Zhang Jien et al.,2018)。最新通过蛇绿岩、岛弧岩浆岩和相关变质岩综合研究,Yang Gaoxue et al. (2020)在西准噶尔地区提出地幔柱诱发俯冲起始的概念模型,即地幔柱头与大洋岩石圈相互作用,不断热侵蚀大洋岩石圈底部,最终使得其由于重力失衡而诱发俯冲起始(Gerya et al.,2015)。类似的俯冲起始机制在中美地区的加勒比海(Whattam et al.,2015)和卡斯卡迪亚俯冲带(Stern et al.,2019)也有报道。

西准噶尔经历了古生代复杂的俯冲、碰撞、增生造山等构造演化阶段,并伴有洋脊俯冲、板片后撤、海山/大洋高原俯冲增生过程(Zhang Jien et al.,2011, 2022; Xiao Wenjiao et al.,2015, 2018;

Windley et al.,2018; Wang Qiang et al., 2020),产生了不同类型构造背景下的构造-岩浆活动和地质效应。例如西准噶尔地区在石炭纪—二叠纪形成了组分复杂的花岗岩类,包括 A 型花岗岩、I 型花岗岩、紫苏花岗岩等(Geng Hongyan et al.,2009; Yin Jiyuan et al.,2017; Duan Fenghao et al.,2022),同位素特征和地震 V_s 速度显示有巨量的新生物质的加入(图 4;Han Baofu et al.,1997; Zheng Bo et al.,2020)。另外,在达尔布特、唐巴勒和洪古勒楞蛇绿岩中识别出玻安岩和弧前玄武岩组分(Guo Boran et al.,2020; Yang Yaqi et al.,2022; Zhu Qingmin et al.,2022),同时在玛依勒地区识别出震旦纪—寒武纪花岗岩类(Ren Rong et al.,2014; Liao Wen et al.,2021; Zhang Yunying et al.,2022),认为它们是俯冲起始过程的物质记录(Yang Gaoxue et al.,2022; Zhong Xinyi et al.,2022; 杨高学等,2023)。

在西准噶尔地区,洋内俯冲作用最早发生在寒武纪以前(Ren Rong et al.,2014; Yang Gaoxue et al.,2020, 2022)。但在早古生代期间,即哈萨克斯坦山弯构造形成之前,西准噶尔和伊犁地块可能为带状展布(Xiao Wenjiao et al.,2015; Li Pengfei et al.,2018)。研究发现北天山温泉地区存在中—晚奥陶世大陆弧岩浆作用(Wang Bo et al.,2012),同时在果子沟地区晚奥陶世硅质页岩中识别出凝灰岩夹层(曹胜楠等,2021),表明西准噶尔地区所代表的古亚洲洋分支应该在中—晚奥陶世开始向伊犁地块俯冲,形成了伊犁北部的活动陆缘(Wang Bo et al.,2012; 王博等,2022)。

虽然在西准噶尔地区不断有俯冲起始的地质记录被识别出来,但前人没有对俯冲起始机制进行详细探讨,当然这个也是目前整个地球科学中尚未解决的难点之一(Stern et al.,2018; Gurnis,2023)。除了上述地幔柱诱发俯冲起始机制之外,Yang Gaoxue et al.(2022)结合西准噶尔古生代多阶段演化模式认为存在俯冲极性反转和传递机制(图 5),俯冲极性反转通常发生在洋内环境,而俯冲传递既可以发生在洋内,也可以在活动大陆边缘,无论是极性反转和俯冲传递,它们均发生在碰撞后 10 Ma(Yang Gaoxue,2022)。西准噶尔地区发育不同时代的海山、大洋高原和洋内弧,这些不同性质的地体在碰撞拼贴过程中,会诱发俯冲极性反转和传递。这类似于西南太平洋的翁通爪哇大洋高原南向俯冲引起俯冲极性反转,形成向北俯冲的新几内亚俯冲带(Mann et al.,2004; Wang Liangliang et al.,2022)。而西准噶尔这些不同时代、不同性质的蛇绿岩恰恰是构造体制转化的岩石记录(图 5)。

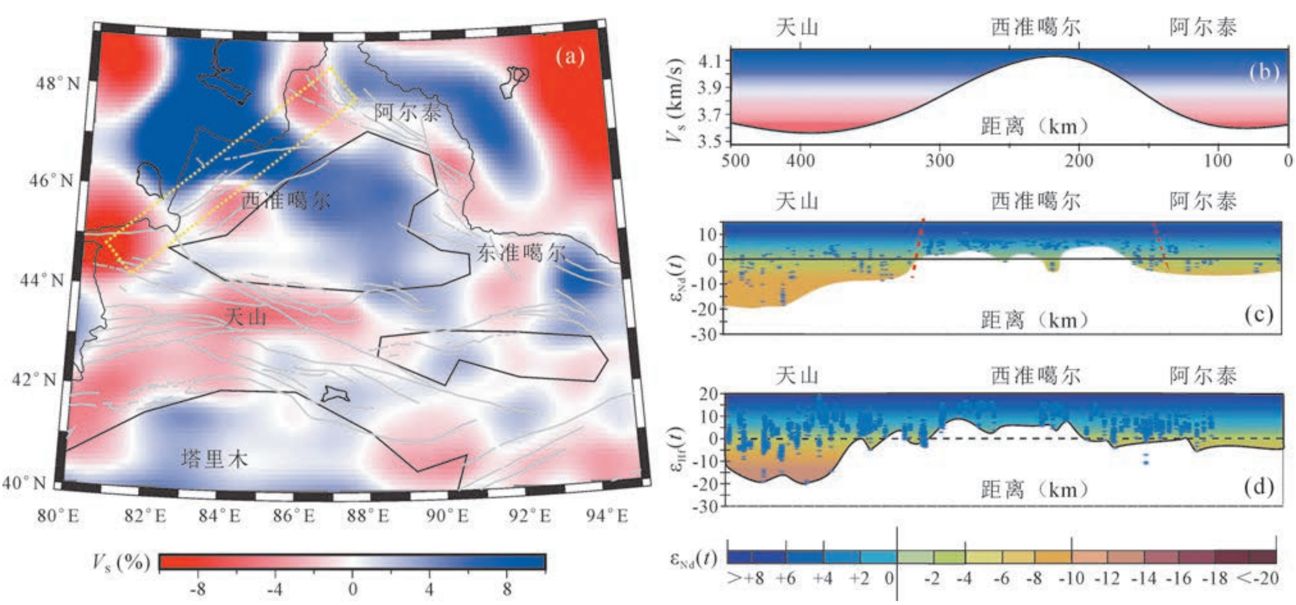

图 4 西准噶尔及邻区火山岩 $\varepsilon_{Nd}(t)$ 和锆石 $\varepsilon_{Hf}(t)$ 值廊带剖面及地震 V_s 速度模型
(修改自 Wang Tao et al.,2023b)

Fig. 4 Sections of $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values of igneous rocks and the V_s velocity profile across the Altai-West Junggar-Tianshan orogens (modified from Wang Tao et al.,2023b)

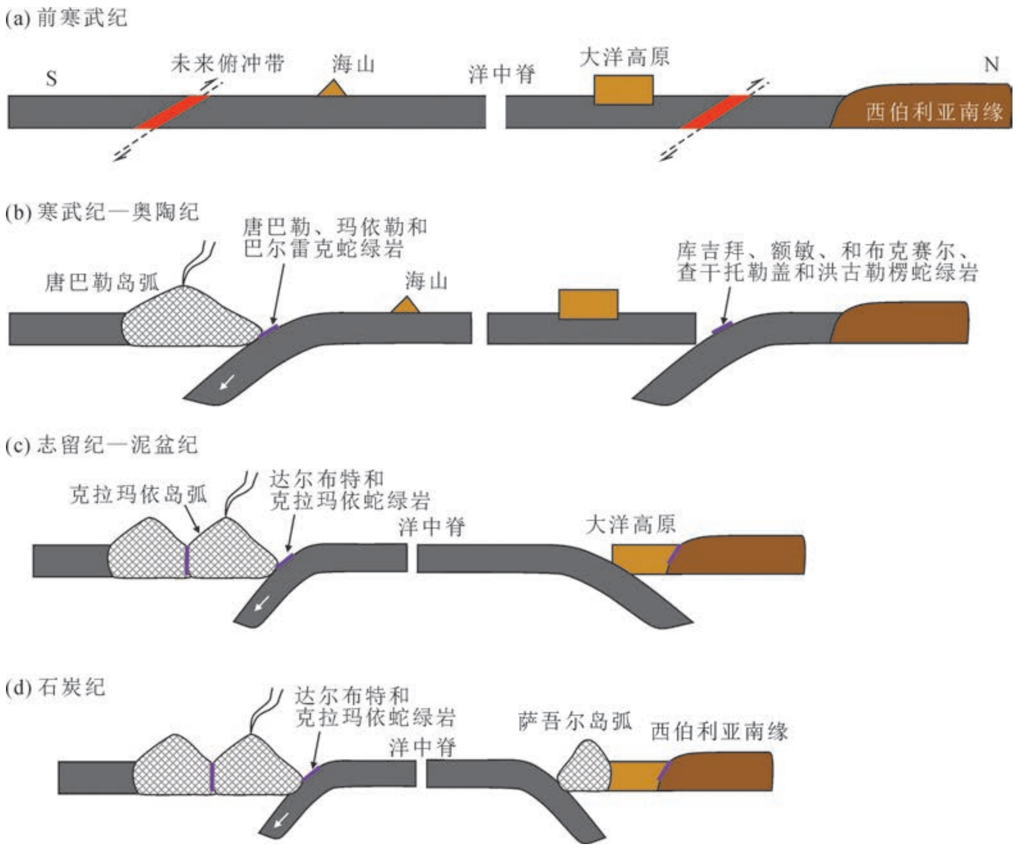

图 5　西准噶尔蛇绿岩形成过程及俯冲极性反转和俯冲传递模型图(据 Yang Gaoxue et al. ，2015 修改)

Fig. 5　Ophiolite formation of West Junggar and geodynamic models of subduction polarity reversal and subduction transference (modified after Yang Gaoxue et al. ，2015)

6　结语

西准噶尔地区发育多条蛇绿岩带，从北向南依次为库吉拜、额敏、和布克赛尔、洪古勒楞、查干托勒盖、巴尔雷克、达尔布特、玛依勒、唐巴勒和克拉玛依蛇绿岩带。这些蛇绿岩多沿近东西向和北东向走滑断裂分布，均被构造强烈改造肢解，普遍发育岩块-基质结构。蛇绿岩时代跨度大，从震旦纪到石炭纪均有发育。蛇绿混杂岩物质基本类似，普遍包括正常洋壳组分和海山/大洋高原残片，蛇绿岩中基性岩可明显分为 MORB 型和 OIB 型。大洋高原碰撞、增生不仅是大陆地壳增生的有效途径之一，而且可能诱发板块构造体制转化，即发生俯冲极性反转和传递。在大洋高原形成初期，还可能存在地幔柱诱发俯冲起始机制。此外，在西准噶尔地区，除了大洋俯冲过程中形成的增生型边界，还可能发育汇聚板块边界形成另外一种类型，即侵蚀型边界。尽管取得系列进展，但也存在很多问题，诸如海山/大洋高原的规模和分布如何，其俯冲增生的地质效应缺少详细刻画，西准噶尔乃至整个中亚造山带中俯冲起始时限和过程，还知之甚少。要解决上述系列问题，在后续的工作中，需要详细解剖和深入研究蛇绿岩及其他相关地质记录。

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Ophiolite in West Junggar: Records of the subduction-accretion process in ancient ocean

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Abstract

Ophiolite records the whole process of formation, evolution and extinction of the oceanic lithosphere, and is a key evidence for studying the regional plate tectonics and ocean-continent frame. This study summarizes the latest research on ophiolite in West Junggar, with the aim of discussing continental crust growth style and recovering the ancient oceanic evolution history, and provideing new constraints on the tectonic regime transition of the West Junggar. A number of tectonically dismembered ophiolite belts with a typical block-matrix structure are developed in the West Junggar region. The ophiolites mainly include oceanic crust components and seamount/oceanic plateau fragments; the mafic rocks in the ophiolites are characterized by MORB and OIB geochemistry. Based on previous research, this study suggests that the seamounts/oceanic plateaus with different ages are related to the mantle plume and developed in different evolution stages of the West Junggar Ocean. At the same time, there are two types of convergent plate boundaries, including accretionary and erosional plate margins. In addition, oceanic plateau accretion is not only one of the effective ways of continental crust growth, but may also induce subduction polarity reversal and subduction transference. Furthermore, there may also be mantle plume induced subduction initiation mechanism at the early stage of oceanic plateau formation in West Junggar.

Key words: tectonics; ophiolite; seamount; subduction initiation; West Junggar