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中亚造山带西准噶尔地区达尔布特蛇绿岩研究进展与展望

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摘 要：蛇绿岩是研究古大洋的主要载体和划分古板块边界的重要证据，记录了从大洋岩石圈的最初形成到最后洋盆闭合的诸多信息，是研究洋–陆转换过程的关键地质体。西准噶尔达尔布特蛇绿岩是北疆地区发育规模最大、最为典型的蛇绿岩带之一，相关研究近年来取得了系列成果。①在萨尔托海铬铁矿中发现金刚石等深部矿物群，从而对此前铬铁矿的浅部成矿理论提出了质疑。②在蛇绿岩中识别出前弧玄武岩，它是俯冲起始的地质记录之一。③蛇绿岩中存在古海山物质组分，其中玄武岩具有OIB特征。④萨尔托海铬铁矿是深部地幔预富集和浅部再富集的结果。⑤达尔布特蛇绿岩形成于俯冲有关的构造环境，并有地幔柱的参与。在取得进展的同时，也出现了一些新的科学问题和研究方向，主要包括深部物质循环过程、俯冲起始机制、陆壳增生机制和俯冲带型蛇绿岩成因等。

关键词：大地构造；蛇绿岩；海山；达尔布特；西准噶尔

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Progress and Prospect of the Darbut Ophiolite in West Junggar, Central Asian Orogenic Belt

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Abstract：Ophiolite is a major material for studying of ancient oceans and important lithological evidence for delineating ancient plate boundaries. It records valuable information from the initial formation of the oceanic lithosphere to the final closure of the ocean basin, and is also a key geological target for studying the ocean–con-

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tinent transition process. The Darbut ophiolite in West Junggar is one of the largest and most typical ophiolites exposed in northern Xinjiang. A series of new advances have been achieved in recent years: ① Diamonds and other exotic minerals have been recovered from chromitites of the Sartohay ophiolites, thus challenging the previous theory of shallow chromitite genesis. ② Fore–arc basalts have been identified in the ophiolite, which is one of the geological records of subduction initiation. ③ Ancient seamount material components have been recognized in the ophiolite, in which the basalt show OIB characteristics. ④ Sartohay chromitite is the result of deep mantle pre–enrichment and shallow re–enrichment. ⑤ A formation environment mainly associated with a subduction–related tectonic setting, with the involvement of the mantle plume, has been suggested. Despite progresses mentioned above, some new scientific issues and research directions have emerged, mainly concerning deep mantle mass recycling processes, subduction initiation mechanisms, crustal growth processes, and subduction zone ophiolite genesis.

Keywords：tectonics；ophiolite；seamount；Dartbut；West Junggar

蛇绿岩是构造侵位大陆边缘的古大洋岩石圈残片，主要组成包括上部的玄武质洋壳和下部的地幔岩，通常被作为恢复古大洋、识别古板块边界的最直接证据（Coleman, 1977; 马中平等, 2004; 史仁灯, 2005; 张进等, 2012; 臧遇时等, 2013; 吴福元等, 2014; 王国灿等, 2019; 翟庆国等, 2019; 张继恩等, 2021; Yao et al., 2021; 敖松坚等, 2022）。自 1813 年，法国矿物学家 Alexandre Brongniart 提出蛇绿岩概念以来，关于蛇绿岩分类有很多种，聚焦其不同的方面的性质，比如依据地壳岩石地球化学（Pearce et al., 1984）、地幔岩石成分（Nicolas et al., 2003）、洋中脊扩张速率（肖序常, 1995）、蛇绿岩出露特征（Wakabayashi et al., 2003）及形成构造环境（Dilek et al., 2014）对蛇绿岩进行分类的方案。最新研究认为，在威尔逊旋回的各个阶段都会形成性质不同的蛇绿岩，并根据其形成环境不同，将蛇绿岩分为与俯冲作用无关和与俯冲作用相关两大类（Dilek et al., 2011）。

中亚造山带是属于巨大的增生型造山带，也是全球显生宙以来增生最强烈的地区之一（Sengör et al., 1993; Jahn et al., 2000; Windley et al., 2007; Xiao et al., 2015, 2018, 2020; Huang et al., 2020; Wang et al., 2022, 2023a, 2023b; Liu et al., 2023）。西准噶尔地区位于增生型中亚造山带西南缘，也是中亚–兴蒙构造成矿域的主要组成部分（Shen et al., 2017; Zhu et al., 2019）。西准噶尔主要由一系列的增生杂岩带、古生代岩浆弧和蛇绿岩构成（Zhang et al., 1993, 2022b; Buckman et al., 2004; Choulet et al., 2012; Yang et al., 2015a; 高俊等, 2022），发育 NE–SW 向断裂构造，由北向南依次主要包括为巴尔雷克、玛依勒、达尔布特断裂和乌尔禾逆冲断层，这些断裂构造控制着西准噶尔地区花岗岩类和蛇绿岩的分布（图 1）。在西准噶尔地区最为显著的特征是发育数条不同时代的蛇绿岩带，如唐巴勒、玛依勒、巴尔雷克、达尔布特、白碱滩等蛇绿带（张向飞等, 2023）（图 1）。这些蛇绿岩主要沿断裂带分布，变形强烈，形态复杂，时代跨度较大，自震旦纪到石炭纪均有发育（Feng et al., 1989; Zhang et al., 1993; Yang et al., 2012a, 2012b, 2013, 2019, 2020a; Du et al., 2019）。近年来，对达尔布特蛇绿岩的研究取得了系列进展，但缺少系统总结。为此，笔者在前人基础上将取得的成果和存在问题进行梳理和总结，以期对达尔布特蛇绿岩成因及其构造环境提供新的制约。

1 达尔布特蛇绿岩地质特征

达尔布特蛇绿岩是新疆境内出露的规模最大、最为典型的蛇绿岩带之一，近年来备受国内外学者关注（雷敏等, 2008; 辜平阳等, 2009; 刘希军等, 2009; Yang et al., 2012b; Chen et al., 2014; Zhang et al., 2018; 田亚洲等, 2019; 李海等, 2021; Zhu et al., 2022）。达尔布特蛇绿岩分布于克拉玛依市以北的扎依尔山一带，东起木哈塔依，向南西经萨尔托海、也格孜卡拉、达尔布特、科果拉，在坎土拜克越向达尔布特河谷南侧，再经库朗库朵克转向西至苏鲁乔克后被阿克巴斯套花岗岩体所侵入截断（图 2）。实际上，向西在阿克巴斯套和阿音那巴斯套，再向北的包古图河上游地区，也有蛇绿岩断续出露，只是展布方向由 EW 向转为近 SN 向，全长达 100 km，大部分蛇绿岩带与达尔布特断

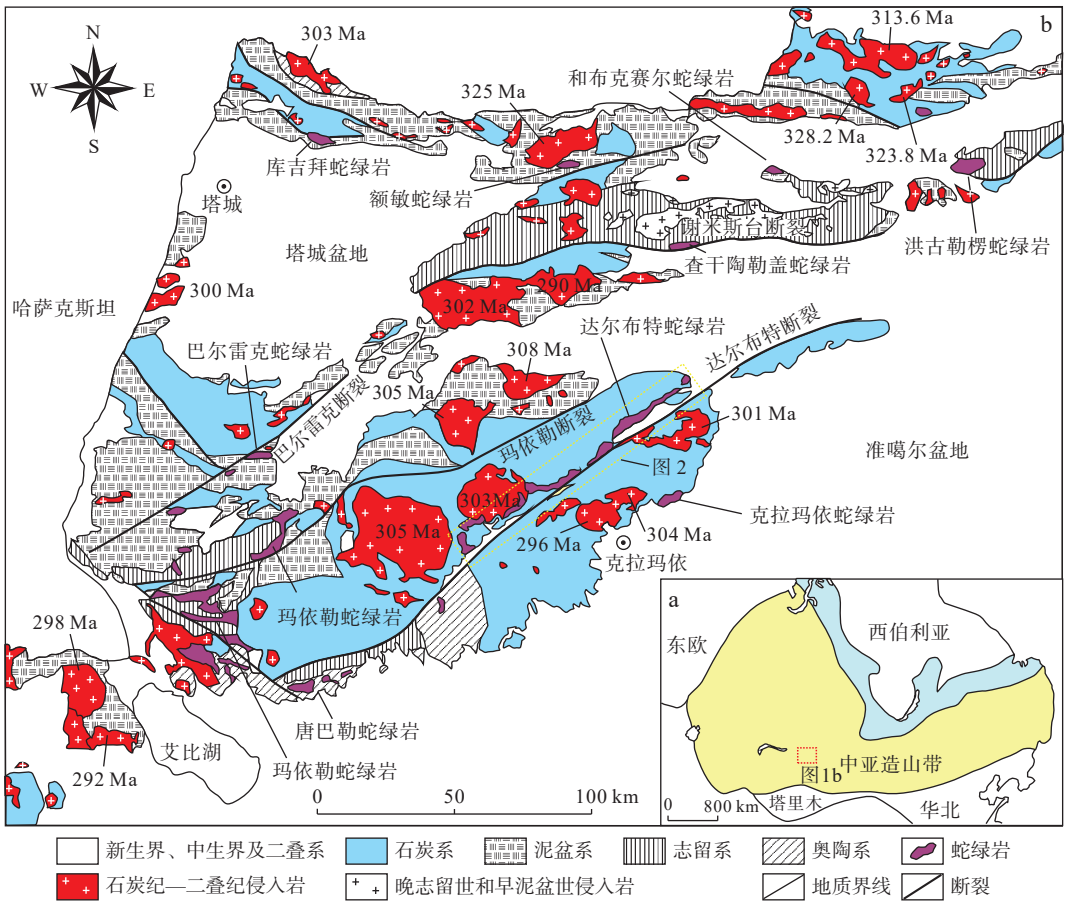

图1　中亚造山带构造格架图(a)(据 Jahn et al.，2000)及西准噶尔地质简图(b)(据 Yang et al.，2013)

Fig. 1　(a) Simplified tectonic sketch of the Central Asian Orogenic Belt and (b) regional geological map of the West Junggar

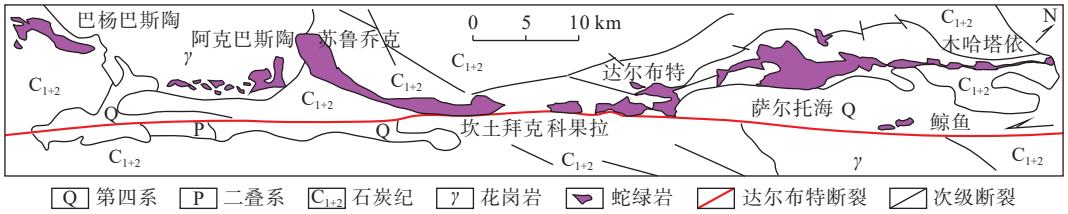

图2　西准噶尔达尔布特蛇绿岩带简图(据李行等，1987)

Fig. 2　Spatial distribution map for the Darbut ophiolite from West Junggar

裂带平行, 甚至沿断裂分布, 宽多为 2～9 km, 出露面积约为 50 km^2, 在苏鲁乔克及萨尔托海一带出露面积最广, 而窄处只有数十米, 甚至缺失。蛇绿岩原有层序被构造强烈改造, 原始的属于下部层位的铁镁质(超铁镁质)岩石逆冲到复理石沉积地层之上, 深海硅质岩和枕状玄武岩与地幔橄榄岩断层接触(Yang et al., 2012b; Chen et al., 2014)。

达尔布特蛇绿中发育早—中泥盆世和早石炭世放射虫和珊瑚化石, 前人在辉长岩和橄长岩中获得 Sm–Nd 同位素年龄为(395±1.2)Ma(Zhang et al., 1993); 辜平阳等(2009)在辉长岩中获得 LA–ICP–MS 锆石年龄为(391.1±6.8)Ma; 最新在玄武岩及辉长岩中获得锆石 U–Pb 年龄分别为(375±2)Ma 和(368±11)Ma(Yang et al., 2012c), 表明达尔布特蛇绿岩形成时代为中泥盆世—早石炭世。蛇绿岩带上覆上石炭统包古图组和太勒古拉组, 主要为一套火山–沉积岩岩石组合。此外, 位于达尔布特蛇绿岩带北西段的萨尔托海岩体产出典型的蛇绿岩型铬铁矿, 是中国第二大铬铁矿产地, 吸引了众多研究者针对铬铁矿成矿与找矿开展了丰富的研究(鲍佩声等, 1990, 1992; 郝梓国等, 1991; Zhou et al., 2001; 鲍佩声, 2009; 田亚洲等, 2015, 2016, Qiu et al., 2018, 杨经绥等, 2022; Li et al., 2023)。

2 达尔布特蛇绿岩研究进展

2.1 金刚石等矿物的发现

自 1981 年在西藏罗布莎蛇绿岩的地幔橄榄岩中首次发现金刚石以来，在西藏和俄罗斯的极地乌拉尔等地的蛇绿岩铬铁矿中新发现了金刚石等深部矿物群(Bai et al., 1993; 杨经绥等, 2013, 2014, 2021; Yang et al., 2021)，对此前铬铁矿的浅部成因理论提出了质疑(杨经绥等, 2022)。超高压、强还原性和壳源矿物在西藏罗布莎、土耳其 Aladag、内蒙古贺根山和俄罗斯的极地乌拉尔蛇绿岩中也有报道(Bai et al., 1993; Xu et al., 2015; Yang et al., 2015b; Huang et al., 2015; Xiong et al., 2017; Rui et al., 2022)，暗示可能存在深部地幔物质循环过程(图 3)。最近，田亚洲等(2015)在达尔布特蛇绿岩带的萨尔托海高铝型铬铁矿中发现 20 余种矿物，包括金刚石、单质铬、自然铁、单质硅等元素类矿物，除此之外还有铁镍铬合金、碳硅石、方铁矿、方铅矿、顽火辉石等(Tian et al., 2015)，暗示萨尔托海铬铁矿的形成可能经历了深部地幔预富集过程和浅部再富集成矿两个阶段(田亚洲等, 2015)。总体而言，上述这些超高压、强还原性和壳源矿物的发现，为认识板块深俯冲、地幔不均一性和地幔深部动力学等过程提供了窗口(Lian et al., 2019; Yang et al., 2021)。

2.2 前弧玄武岩的识别

前弧玄武岩最初是在 Mariana 岛弧定义的(Reagan et al., 2010, 2013)，在岩石学和地球化学上与洋脊玄武岩和弧后盆地玄武岩类似(Ishizuka et al., 2011; Shervais et al., 2021)，前弧玄武岩低 Ti/V 和 Yb/V 值表明其地幔源区比大洋中脊和弧后盆地玄武岩源区更加亏损(Shervais et al., 2019)。前弧玄武岩是地幔楔熔融的最初产物，形成于俯冲起始之前的扩张中心或俯冲起始之后靠近海沟的位置(Reagan et al., 2010)。因此，前弧玄武岩是研究俯冲起始过程的最好地质记录之一(Ishizuka et al., 2011)。事实上，前弧玄武岩和玻安岩一起经常出现在蛇绿混杂岩中。例如，塞浦路斯 Troodos、西藏雅鲁藏布江和西昆仑库地等蛇绿岩带中均有玻安岩产出(Taylor et al., 1994; Wang et al., 2002; Dilek et al., 2009; Dai et al., 2013; Li et al., 2021; Yang et al., 2022a, 2022b)。Zhu 等(2022)通过岩石地球化学研究发现，萨尔托海蛇绿岩中均质辉长岩具有平坦的 REE 模型、低 Nb/Yb 和高 Ti/V 值的特征，类似于 MORB，而角闪石辉长岩显示较高流体活动元素含量和高 Th/Yb 值特征，类似于前弧玄武岩。据此认为，达尔布特蛇绿岩形成于弧前环境(Zhu et al., 2022)。

2.3 古海山的厘定

海山(大洋高原)是在板块内部由地幔柱热点作用形成的(图 3)，通常认为板块是运动的，地幔柱是固定的，当板块在地幔柱上方移动时，就形成了系列海山组合即为火山岛链(Morgan, 1971)。在现代大洋中发育规模不等、源自地幔柱的火山岛链，如太平洋的 Hawaiian-Emperor 海岭(Duncan et al., 2004)，大西洋的 Walvis 及 Rio Grande 脊(O'Connor et al., 1990)，印度洋的 Deccan 高原(O'Neill et al., 2003)及中国南海中的玳瑁海山(Yan et al., 2015)。实际上在古大洋中也有海山发育，如特提斯洋及古亚洲洋中均有与地幔柱相关的 OIB 发育(朱弟成等, 2008; Yang et al., 2012a, 2020b; Safonova et al., 2014)。中亚造山带西段蛇绿岩的物质组成复杂，各个蛇绿混杂岩中除了正常洋壳的主要组成之外，还发育枕状玄武岩、火山角砾岩、礁灰岩、滑塌堆积岩、陆源碎屑岩等(Safonova et al., 2014; Yang et al., 2015a, 2019)，这是典型的海山岩石组合特征(Buchs et al., 2011)。在西准噶尔达尔布特蛇绿岩中也有类似组分发育，其中的玄武岩均为碱性系列，具有较高的 TiO_2 含量(大多>2.5%)，无明显 Nb、Ta 负异常，强烈富集轻稀土元素，轻稀土元素含量总体与典型 OIB 及夏威夷洋岛型玄武岩一致(Hofmann et al., 1996)，认为其来源于地幔柱有关的海山或大洋高原(Yang et al., 2013, 2015a)。

2.4 豆荚状铬铁矿的成因

豆荚状铬铁矿是蛇绿岩中特有的矿产，主要赋存于蛇绿岩莫霍面过渡带或地幔上部的超基性岩中(Zhou et al., 2014; Arai et al., 2016)。尽管豆荚状铬铁矿的研究已经近 100 年的历史，但是其成矿机制一直是争论的焦点(Yang et al., 2021)，其成矿模型主要包括以下 5 种：①镁铁质–超镁铁质岩浆分异(Dickey, 1975)。②地幔橄榄岩部分熔融(鲍佩声, 2009)。③地幔橄榄岩与熔体反应(Zhou et al., 1996)。④熔体与古大陆岩石圈地幔反应(Shi et al., 2012)。⑤深部地幔柱成因模式(Yang et al., 2015b, 2021)。萨尔托海岩体产出典型的蛇绿岩型铬铁矿，是中国第二大铬铁矿产地。矿石类型主要为致密块状，次为浸染状和条带状等，矿体大小悬殊、形态各异，单个矿体多呈豆荚状、透镜状、囊状和脉状等(李海等, 2021)。在铬铁矿成

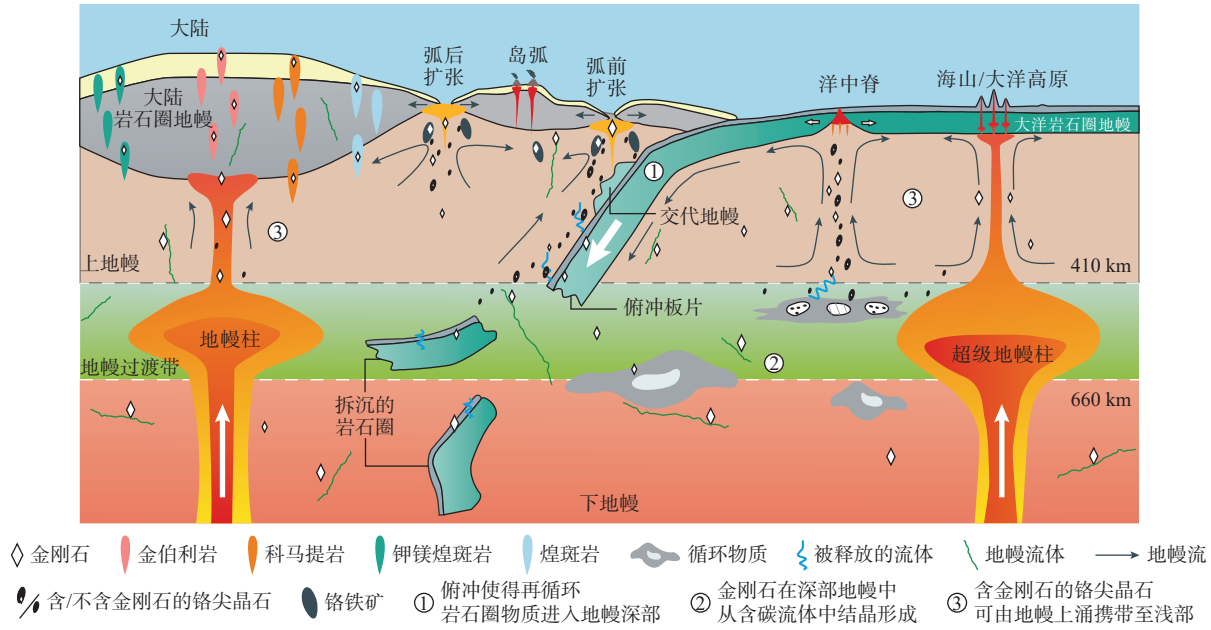

图3　地球地幔中金刚石和铬铁矿的形成和深部物质循环模式(据 Yang et al., 2021)

Fig. 3　The formation of diamond and chromitite in Earth's mantle and recycle of deep subducted crust

矿理论方面,有研究者认为铬铁矿是地幔部分熔融残余形成的(鲍佩声, 2009),也有学者认为其为地幔橄榄岩与熔体反应的结果(Zhou et al., 1996)。最新研究发现,在达尔布特蛇绿岩中发育深部地幔矿物以及浅部壳源矿物(Tian et al., 2015),从而认为达尔布特蛇绿岩中萨尔托海铬铁矿的形成可能经历了深部地幔预富集和浅部再富集成矿两个阶段(田亚洲等, 2015)。该模型认为俯冲板片会抵达地幔过渡带甚至更深,由于温度和流体的作用,俯冲板片发生熔融。这些熔融物质随地幔柱上涌,在地幔过渡带结晶出铬铁矿,伴随携带金刚石等超高压矿物继续向上运移至浅部,从而形成含金刚石等矿物的铬铁矿(图 3)(Yang et al., 2021)。

2.5　蛇绿岩的形成环境

目前,国内外学者对蛇绿岩的成因分类方案众多(Pearce et al., 1984; 肖序常, 1995),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)。Dilek 等(2011)以蛇绿岩的形成环境为依据,将蛇绿岩可分为与俯冲过程无关的和与俯冲过程相关的两类,其中与俯冲过程无关的蛇绿岩包括陆缘型、洋中脊型和地幔柱型,而与俯冲作用相关的蛇绿岩包括俯冲带上盘型和火山弧型。可见蛇绿岩可以形成于威尔逊旋回的各个阶段。对于达尔布特蛇绿岩,前人主要通过岩石地球化学方法对其形成环境进行制约,主要有以下观点:大洋中脊环境(Zhang et al., 1993)和岛弧环境(Yang et al., 2012b; Zhang et al., 2018)。如前文述及,在达尔布特蛇绿岩发育弧前玄武岩(Zhu et al., 2022),这充分说明达尔布特蛇绿岩中有形成于俯冲带的物质组分。更为重要的是在蛇绿岩识别出古海山残片,并发现金刚石等深部矿物群(Tian et al., 2015; 杨经绥等, 2021),这表明特蛇绿岩中还保存有来自深部地幔的物质(图 3),即为地幔柱型蛇绿岩(Dilek et al., 2011)。可见,达尔布特蛇绿岩形成于俯冲有关的构造环境,并有地幔柱的参与。

3　未来研究展望

3.1　深部物质循环

达尔布特蛇绿岩的萨尔托海岩体中发育豆荚状铬铁矿,更为重要的是,除了在豆荚状铬铁矿中发现壳源矿物如金红石、锆石等矿物外,识别出金刚石、碳硅石等深部地幔矿物。此外,达尔布特蛇绿岩中还存在碱性洋岛玄武岩(OIB),这些壳源矿物、超高压矿物和洋岛玄武岩的存在,为认识俯冲物质深地幔循环提供了新思路(图 3)。

3.2　俯冲起始机制

板块俯冲起始是岩浆活动和构造运动发生转变的重要过程,其中会形成相应的地质记录,主要包括俯冲带(SSZ)型蛇绿岩、前弧玄武岩、玻安岩和变质底板。目前,在达尔布特蛇绿岩中发育前弧玄武岩,

同时蛇绿岩也具有俯冲带的信息，这将为西准噶尔俯冲起始的时限和机制提供物质基础。

3.3 陆壳增生机制

达尔布特蛇绿岩中存在古海山残片，是海山在俯冲过程中被刮削、增生在增生楔中保存在造山带中。实际上，在西准噶尔也有大洋高原和洋内弧的多阶段增生过程。那么，陆壳增生具体是如何实现的？此外，在地壳增生的同时，是否有俯冲带上盘的物质通过俯冲侵蚀进入地幔深部？需要深入研究。

3.4 俯冲带型蛇绿岩成因

目前，普遍认为达尔布特蛇绿岩与西准噶尔其他蛇绿岩类似，是形成于俯冲带之上的 SSZ 型蛇绿岩。但实际上，其中的俯冲印记可以来源于俯冲板片，也可以来源于超慢速洋脊。换句话说，具有俯冲印记的蛇绿岩也可能是形成于超慢速大洋中脊的大洋核杂岩。实际上，造山带中的蛇绿岩有相当一部分是大洋核杂岩，是洋底拆离断层作用形成的。因此，需要对达尔布特乃至中亚造山带中的蛇绿开展综合对比研究，对蛇绿岩的成因具有普适意义。

4 结论

（1）达尔布特蛇绿岩是新疆境内出露的规模最大蛇绿岩带之一，其形成时代主体为早—中泥盆世。

（2）近年来，对达尔布特蛇绿岩的研究取得以下进展：金刚石等矿物的发现、前弧玄武岩的识别、古海山的厘定、豆荚状铬铁矿地幔柱成因和蛇绿岩构造背景的再厘定。

（3）在取得进展的同时，出现了一些的新的科学问题和方向，即深部物质循环过程、俯冲起始机制、陆壳增生机制和俯冲带型蛇绿岩成因等。

（4）总体而言，在后续的工作中，需要对特定区域的蛇绿岩进行细致解剖，同时开展大时空尺度蛇绿岩的综合对比研究，揭示大洋壳–幔系统演变过程，从而完善大洋岩石圈形成演化和板块构造理论。

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