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新特提斯洋俯冲起始的地质记录:土耳其南部蛇绿岩和变质底板*

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Abstract Subduction initiation is an essential process in magmatic and tectonic evolution of the Earth and plays an important role in plate tectonics. During subduction initiation, four main geological units are formed, namely; magmatic episodes with various geochemical characteristics, supra-subduction zone (SSZ) ophiolites, metamorphic soles and boninitic magmatism with associated chromitite deposits. The Tethyan orogenic belt has been attracting a great deal of attention for a long time as it preserves an excellent record of plate tectonic processes. The southern Turkey occupies part of this belt, and preserves well-defined SSZ ophiolites and associated metamorphic soles, which are considered as the remnants of the Neo-Tethyan oceanic plate between the Eurasian and Arabian continental plates. These geological records of subduction initiation in southern Turkey are summarized as following: 1) mantle-derived magmatic rocks are widely developed and show large compositional variations from MORB-like, through transitional to boninitic; 2) most ophiolites and their associated metamorphic soles are well preserved and contain complex mafic dykes systems, indicating multiple episodes of magmatic activities; 3) the metamorphic soles commonly underlie the ophiolites and their metamorphic histories are coeval to the formation of the ophiolites; 4) numerous chromitite deposits occur in the mantle and crustal sequences of the ophiolites and span a wide range of compositions from high-Cr, intermediate to high-Al types, most likely in response to various magmatic events. Thus, these well-characterized geological massifs record the entire formation to subduction process of the Neo-Tethyan ocean.

Key words Subduction initiation; Ophiolite; Metamorphic sole; Chromite deposit; Neo-Tethyan ocean

摘 要 在现行板块构造理论的框架下,板块的初始俯冲是岩浆活动和构造运动发生转变的重要过程,亦是理解板块运动的关键节点。在俯冲起始过程中,主要存在四个方面的地质记录,分别为一系列地球化学成分多样的岩浆活动、SSZ 型蛇绿岩、变质底板和玻安岩及其对应的铬铁矿床。特提斯造山带作为公认的研究板块构造理论尤其是初始俯冲的关键场所,一直备受地学界的重视。而土耳其南部构造带作为特提斯造山带的重要组成部分,亦是确定亚欧板块和阿拉伯板块之间缝合线存在的重要标志。该南部构造带是研究新特提斯洋俯冲起始的理想场所,上述关于俯冲初始的四个地质记录均保存良好,且

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有如下方面的重要特点：1) 不同地区的镁铁质岩石甚至同一地区的镁铁质岩石具有不同的地球化学特征，从似洋中脊玄武岩，到过渡型岩石类型和玻安质岩石均有发育；2) 大部分蛇绿岩具有完整的序列，各单元及变质底板岩石中普遍发育侵入的基性岩脉，产状多变，是多期岩浆事件的产物；3) 蛇绿岩下部通常发育一套角闪岩相变质底板，且其年龄与蛇绿岩的形成年龄基本一致；4) 蛇绿岩中普遍发育铬铁矿床，以高 Cr 型为主，部分蛇绿岩中还赋存高 Al-高 Cr 的过渡型铬铁矿，均被认为是幔源岩浆与地幔橄榄岩反应的产物。因而，这些地质体完整记录了新特提斯洋形成-俯冲-消减的演化过程。

关键词 初始俯冲；蛇绿岩；变质底板；铬铁矿床；新特提斯洋

中图法分类号 P542

自板块构造理论提出以来，板块俯冲起始的动力学机制一直是科学界研究的热点，且通常认为板块俯冲开始于洋内俯冲（Stern，2004；Stern *et al.*，2012）。到目前为止，初始俯冲的原因和机制仍然没有很好的解释；同时由于现今构造格局中典型洋内俯冲环境的产出并不广泛，使得洋内俯冲起始和演化过程的研究也存有较大争议。代表古大洋残片的蛇绿岩是板块间缝合线存在、恢复洋陆格局及构造演化的重要岩石学标志，记录了大洋岩石圈的形成演化信息，其属性、就位过程及构造内涵对研究洋内俯冲的起始和演化及相应的资源效应都具有重要意义（Gass，1968；Coleman and Keith，1971；Dewey and Bird，1971；Coleman，1977；吴福元等，2014）。因此，蛇绿岩也被认为是研究俯冲初始过程最好的地质材料（van Hinsbergen *et al.*，2015）。特提斯构造带（图1）是现今最大的碰撞造山带，保存了古老和现今大洋俯冲、陆-陆碰撞造山等威尔逊旋回的完整地质记录，是公认的研究板块构造理论（如板块俯冲起始过程）最为理想的天然实验室。而其中广泛出露的蛇绿岩岩石组合和构造特征，更是记录了新特提斯洋的演化信息，是研究新特提斯洋俯冲起始过程的关键。

1 初始俯冲的理论模型及演化阶段

目前，关于初始俯冲的形成机制存在多种假说，主要包括：1) 由大洋板块或者被动边缘的裂隙转变而来（McKenzie，1977；Dickinson and Seely，1979；Mitchell，1984；Mueller and Phillips，1991）；2) 已经存在的俯冲发生极性倒转（Mitchell，1984）；3) 转换断层到海沟的转变（Uyeda and Ben-Avraham，1972；Hilde *et al.*，1977；Karson and Dewey，1978；Casey and Dewey，1984）；4) 大陆或者岛弧边缘顶部沉积加载所致（Dewey，1969；Fyfe and Leonardos，1977；Cloetingh *et al.*，1982；Karig，1982；Erickson，1993；Toth and Gurnis，1998；Pascal and Cloetingh，2009）；5) 板块作用力使得断层汇聚于大洋板块边缘的断裂处（Mueller and Phillips，1991；Toth and Gurnis，1998；Doin and Henry，2001；Hall *et al.*，2003）；6) 板块年龄差使得大洋板块断裂区域存在横向的热浮力差而触发俯冲（Gerya *et al.*，2008；Nikolaeva *et al.*，2008；Zhu *et al.*，2009）；7) 断裂作用使得岩石圈中存在拉张解耦（Kemp and Stevenson，1996）；8) 岩石圈横向组分浮力差导致 Rayleigh-Taylor 不稳定性（Niu *et al.*，2003）；9) 岩石圈中存在较多被释放的游离水（Regenauer-Lieb *et al.*，2001；Van Der Lee *et al.*，2008）；10) 上浮大陆或岛弧地壳对大洋板块形成自发的逆冲作用（Mart *et al.*，2005；Goren *et al.*，2008；Nikolaeva *et al.*，2010）；11) 岩石圈地幔中存在小尺度对流（Solomatov，2004）；12) 热化学地幔柱和岩石圈之间的相互作用（Ueda *et al.*，2008）；13) 陨石撞击使得地幔的热流值重

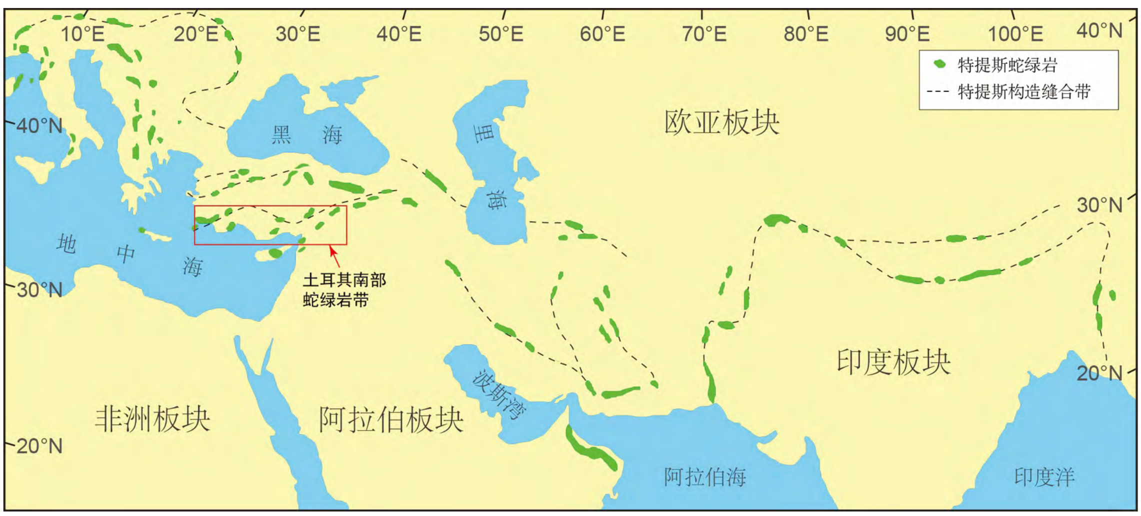

图1 特提斯蛇绿岩分布图（据 Dilek and Furnes，2009 修改）

Fig. 1 Distribution of Tethyan ophiolites (modified after Dilek and Furnes, 2009)

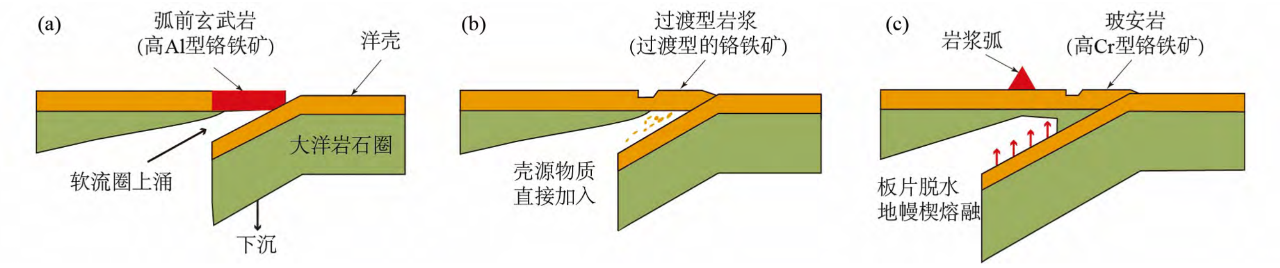

图2 洋内初始俯冲作用形成演化模式图(据 Stern，2004；Metcalf and Shervais，2008；Stern *et al.*，2012 改编)

Fig.2 Formation and evolution model of the intra-oceanic initial subduction (modified after Stern，2004；Metcalf and Shervais，2008；Stern *et al.*，2012)

置(O'Neill *et al.*，2017)。根据驱动力来源的不同，上述假说可分为诱发和自发两类(Gurnis *et al.*，2004；Stern，2004)。诱发模型的特点是俯冲板块的初始化无法通过板块自身的性质差异产生，而由外界应力诱发；更多的可能是一种基于上升的地幔柱与岩石圈发生相互作用而引起的地球动力学过程，典型实例如 Mussau 海沟。而自发模型的触发机制则存在两种观点：1)板块相互运动及其间的相互作用力所致；2)年龄差诱发而成，典型实例如 Izu-Bonin-Mariana 和 Tonga-Kermadec 的汇聚边界(彭鸿和冷伟，2017)。大部分 SSZ 型蛇绿岩的岩石序列与 Izu-Bonin-Mariana 洋内弧俯冲系统具有良好的对应关系(Pearce and Robinson，2010；Whattam and Stern，2011；Zhang *et al.*，2016)，所以自发俯冲模型可能更符合洋内初始俯冲机制。不论哪种假说，初始俯冲过程中均会留有某些地质印迹。因此，寻找更多的地质观测记录，并对其开展系统的研究工作将有助于进一步理解和制约初始俯冲的机制和时限。对于自发产生的板块俯冲初始化过程，从洋内洋底扩张的证据，到初始俯冲的大面积岛弧活动和玻安岩的出露以及地壳的快速生长(Stern and Bloomer，1992)均存在于 Izu-Bonin-Mariana 洋内弧俯冲系统，使其吸引了众多学者的目光，并开展了广泛的研究和讨论。根据 Metcalf and Shervais (2008)和 Stern (2004)等的认识，可将洋内初始俯冲系统的形成过程主要分为以下3个阶段(图2)：

1)软流圈上涌阶段：两个具有不同年龄、厚度、密度和温度的大洋板块之间存在一个薄弱带(转换断层或构造带)。大洋板块沿转换断层或构造带发生断裂错位之后，年龄相对较老的低温高密度大洋板块因重力失稳而下沉，板块破裂沉降为软流圈上涌提供了空间(图2a)。而上涌的软流圈发生减压熔融作用触发了具有似洋中脊玄武岩的最早期岩浆活动(Reagan *et al.*，2010；肖庆辉等，2016；彭鸿和冷伟，2017)。

2)壳源物质直接加入阶段：随着板块的下沉，其上覆的壳源物质(海洋沉积物、蚀变洋壳等)不同程度地直接加入到地幔源区，与软流圈地幔橄榄岩相互混合，有些可能来不及熔融就直接被裹入到上涌的软流圈岩浆中，产生具有似洋中脊玄武岩-岛弧拉斑玄武岩的过渡型成分变化的岩浆作用(图2b)。

3)地幔楔熔融阶段：随着板块俯冲的进行，俯冲倾角开始发生变化，并伴随着俯冲板块的脱水作用。地幔楔橄榄岩在软流圈上涌和俯冲板片脱水产生流体的共同作用下再次发生部分熔融，形成高镁安山岩、玻安岩等火山岩(图2c)。此外，冷板块的俯冲可使上部板块温度降低，同时使得上部板块底部的橄榄岩发生变质交代作用，而俯冲物质熔融产生的熔体也可进一步交代其上覆岩石。

因此，在大洋板块初始俯冲过程中，从软流圈的上涌到俯冲板块洋壳脱水与熔融析出的流体组分作用于上部地幔楔(Reagan *et al.*，2010；肖庆辉等，2016)，地幔橄榄岩不断发生部分熔融的同时，上部的镁铁质岩石序列也从类似洋中脊型的弧前玄武岩到过渡类型玄武岩系列以及玻安质系列，分别对应于洋内初始俯冲的不同阶段。弧前玄武岩与玻安岩均是在俯冲初始阶段的伸展环境下形成的，但相对而言，与玻安质相关的岩浆事件要晚于弧前玄武岩，玻安岩也因而被认为是弧前环境的重要岩石学标志。上述一系列岩浆活动的过程也正是俯冲型(SSZ)蛇绿岩的形成过程。蛇绿岩就位过程中热的超镁铁质岩与下伏岩石接触，使得下伏岩石发生高温变质，形成变质底板(Spray and Williams，1980；Dilek，2003；Wakabayashi and Dilek，2003)。通常认为，变质底板形成于新生俯冲带的开启阶段，稍晚于蛇绿岩的就位启动时间(<2Myr)(Wakabayashi and Dilek，2003)，因此变质底板的变质年龄可精确限定蛇绿岩就位的启动时间。综上所述，地球化学成分多样的镁铁质岩石、玻安岩、SSZ 型蛇绿岩以及变质底板分别从不同方面记录了洋内初始俯冲过程。

2 初始俯冲的地质记录

2.1 镁铁质岩石地球化学成分的多样性

通过对 Izu-Bonin-Mariana 洋内弧中镁铁质岩石地球化学变化特征的总结归纳，发现镁铁质岩石存在由底部拉斑质向上部钙碱性过渡的趋势，且早期弧前玄武岩显示似洋中脊玄武岩的特征，而后期的钙碱性岩石显示俯冲物质的加入，分别对应于早期拉张背景和后期俯冲作用的改造(Ishizuka *et al.*，2011）。由于后期俯冲作用可以交代改造早期形成的镁铁质岩石，导致岛弧体系内原生镁铁质岩石的成分发生不同程度的改变（Pearce，2014），若初始俯冲不同阶段形成的镁铁质岩石以岩脉的形式侵入到蛇绿岩中，则保存相对完好。因此，蛇绿岩中的基性岩脉可用于限定其形成的构造环境和源区特征（Dilek and Furnes，2014；Pearce，2014）。通过对不同期次基性岩脉的研究，可以了解不同阶段所处的构造背景，进而反演大洋形成-俯冲的演化过程。已有的研究表明，蛇绿岩及其变质底板基性岩石的原岩成分差异显著，可隶属于不同构造环境的碱性或拉斑玄武质岩浆，如洋中脊玄武岩、岛弧拉斑玄武岩和洋岛玄武岩（Parlak *et al.*，1995；Çelik *et al.*，2006；Parlak，2006；Lian *et al.*，2017）。同时，一个引人注意的现象是，世界很多地方的蛇绿岩各单元以及变质底板中普遍发育侵入的基性岩脉（主要为辉绿岩或辉长岩），且地球化学成分变化明显（Juteau *et al.*，1977；Dilek *et al.*，1999；Çelik and Chiaradia，2008；Elitok and Drüppel，2008；Dilek and Thy，2009；Lian *et al.*，2017）。不论这些基性岩浆事件与其所侵入的蛇绿岩和变质底板在成因上是否存在联系，它们都可能记录了大洋初始俯冲阶段构造环境的演变。因此，对蛇绿岩中镁铁质岩石开展系统工作，可以查明蛇绿岩形成时的构造背景和岩浆活动，为进一步研究初始俯冲提供关键信息。但是，目前的研究仅集中于这些基性岩脉的地球化学特征，而忽略了对应的野外产状和年代学分析，严重制约了人们对俯冲事件起始及后续地质过程的认识和理解。

2.2 SSZ 型蛇绿岩

蛇绿岩的就位过程与板块运动密切相关，标志着区域尺度甚至全球尺度下的地球动力学体系调整（Robertson，2002；Dilek and Furnes，2011）。蛇绿岩最初被认为是形成于大洋中脊（MOR）扩张中心的典型洋壳，后来新增加的大量蛇绿岩和洋盆研究数据表明板片俯冲才是蛇绿岩形成过程的重要阶段，并将这种由板片俯冲而形成的蛇绿岩命名为俯冲带（SSZ）型蛇绿岩（Pearce *et al.*，1984；Stern，2004）。根据对全球范围内蛇绿岩的现有研究，学术界普遍认为，洋中脊形成的蛇绿岩（MOR-型）极少存在（$<0.001\%$）（Coleman，1977；Pearce，2003），而绝大部分都是与俯冲作用密切相关的 SSZ 型蛇绿岩（Pearce，2003），并且只有 10% 的蛇绿岩具有完整的岩石组合序列（van Hinsbergen *et al.*，2015）。大洋岩石圈通常由于板块汇聚作用而残留于缝合带内，当板块发生仰冲时，在缝合带中残留的大洋岩石圈即为 MOR-型蛇绿岩，其年龄代表着主洋盆内一次裂解事件的发生时间；当板块发生向下俯冲时，俯冲岩石圈（包括洋中脊玄武岩和亏损的地幔橄榄岩）和地幔楔发生部分熔融形成岩浆弧（史仁灯，2005），对应于 SSZ 型蛇绿岩，其年龄代表的是主洋盆开始俯冲消减并在俯冲带上产生新洋壳的时间。通常认为，洋内俯冲作用是形成 SSZ 型蛇绿岩的主要机制（史仁灯，2005），最典型例子如 Izu-Bonin-Mariana 弧前，巴布亚新几内亚的 Cape Vogel 以及 Tonga 弧前。研究表明，Bonin 和 Mariana 弧前地区的初始弧火成岩组合剖面基本一致，底部均为似洋中脊型玄武岩，基底则是 SSZ 型蛇绿岩，自下而上依次为地幔橄榄岩、辉长岩、席状岩墙（Reagan *et al.*，2010；Ishizuka *et al.*，2011）。这一对应关系进一步表明 SSZ 型蛇绿岩形成于初始俯冲阶段的弧前背景（Stern，2004；Reagan *et al.*，2010；Ishizuka *et al.*，2011；Whattam and Stern，2011；Stern *et al.*，2012）。因此，明确蛇绿岩的属性、就位过程及其构造内涵对初始俯冲的研究显得至关重要。目前学者对于蛇绿岩的研究仅集中于序列中的某一层位，而忽略了对整体框架的考虑，导致不同学者对同一蛇绿岩的构造背景存在不同的观点。其次，前人对蛇绿岩的研究主要关注于蛇绿岩的岩石地球化学特征及构造背景的鉴别，尚未对蛇绿岩的就位机制及时限开展全面研究和讨论。毫无疑问，上述不足均严重制约了人们对蛇绿岩属性的明确以及俯冲起始过程的认识。

2.3 变质底板

变质底板通常被认为是与蛇绿岩构造侵位有关的热动力学变质作用产物。蛇绿岩在就位过程中，位于上盘的仍处于高温状态的超镁铁质岩体沿断层逆冲至下伏岩石之上，这一过程可以导致断层之下的镁铁质岩石及沉积岩发生高温变质作用，从而形成上部斜长角闪岩、麻粒岩及下部绿片岩的倒转变质梯度（Spray and Williams，1980；Dilek，2003；Wakabayashi and Dilek，2003），这一变质岩席即被称为变质底板。变质底板的厚度可达 500m，主要位于蛇绿岩地幔部分的底部，也可包裹于地幔橄榄岩内（如 Dewey and Casey，2013；van Hinsbergen *et al.*，2015）。变质底板不仅是蛇绿岩构造就位过程的热效应产物，同时也是形成新洋壳的一种机制，与蛇绿岩的演化有着密切关系。通常认为变质底板形成于俯冲初始的早期阶段（Hacker，1990），并且已有的年代学研究显示地球上大多数变质底板岩石的冷却年龄与相关蛇绿岩的地壳岩石的结晶年龄接近（Guilmette *et al.*，2008，2009，2012；Plunder *et al.*，2016），表明这些蛇绿岩在形成后不久便发生了构造就位。因此，变质底板的出现是蛇绿岩形成并就位于初始俯冲阶段的关键证据，也被认为是 SSZ 型蛇绿岩的重要标志（Coleman，1977；Wakabayashi and Dilek，2000，2003；Bortolotti *et al.*，2013）。但到目前为止，关于变质底板形成的根本机制仍存在疑问，针对其温压条件和构造特征的工作也相对匮乏（Spray，1984；Wakabayashi and Dilek，2003；Dewey and Casey，2013）；变质底板的岩石组合在蛇绿岩中的构造属性亦尚不明确，例如：变质底板与蛇绿岩相接合并折返到地表的方式和过程仍不明确，变质底板的温压条件和蛇绿岩的厚度不相匹配等问题。

2.4 玻安岩与铬铁矿成矿作用

根据对横穿现代岛弧剖面的地球化学变化特征的研究

和总结,通常认为从岛弧向海沟方向,由于熔体产生的深度逐渐变浅使得地幔橄榄岩变得更加难熔,从而造成靠近海沟的弧岩浆比远离海沟的弧岩浆更加亏损。其中横剖面上的火山岩成分存在由底部拉斑质弧前玄武岩向上部玻安质岩石过渡的趋势(Ishizuka *et al.*, 2011)。由于上述两组岩石之间并无显著的不整合现象,因而是目前提出的蛇绿岩形成于俯冲初始阶段和弧前环境的重要证据(Stern *et al.*, 2012),玻安岩也因此被认为是在俯冲初始阶段具有异常高热流值的地幔楔部分熔融的产物(Stern *et al.*, 2012),是弧前盆地形成环境的重要岩石学标志(Crawford *et al.*, 1989)。同时,玻安岩与拉斑玄武岩存在成因上的继承和渐变关系,故而蛇绿岩中岩性变化特征也可被用来判断大洋的俯冲方向。

玻安岩不仅具有构造环境的指示意义,还与蛇绿岩中豆荚状铬铁矿的成矿作用密切相关。很多研究学者认为在俯冲背景下地幔楔的方辉橄榄岩与富 H_2O 的玻安质熔体在浅部地幔发生橄榄岩-熔体反应从而形成豆荚状铬铁矿(Roberts, 1988; Zhou *et al.*, 1996, 2005; Melcher *et al.*, 1997; Rollinson, 2005; Uysal *et al.*, 2007; 熊发挥等, 2014; 章奇志等, 2017; 刘霞等, 2018)。根据现有研究,铬铁矿可被划分为高 Cr 型($Cr^{\#} = 100 \times Cr/(Cr + Al) > 70$)、高 Al 型($Cr^{\#} < 50$)和高 Cr-高 Al 过渡型($50 < Cr^{\#} < 70$)(Dick and Bullen, 1984; 鲍佩声等, 1999; 兰朝利等, 2006; Zhou *et al.*, 2014; Uysal *et al.*, 2018)。已有的对比结果表明,蛇绿岩中高 Cr 和高 Al 型铬铁矿在成分上分别与玻安岩和洋中脊玄武岩中的铬铁矿具有可比性,进而推断高 Cr 型铬铁矿与玻安质熔体有关(图 2c),高 Al 型铬铁矿则与洋中脊玄武质熔体有关(图 2a)(如 Arai, 1992; Arai and Yurimoto, 1994; Zhou *et al.*, 1994, 1996, 1998; Arai and Miura, 2016)。然而,豆荚状铬铁矿的成因一直颇有争议。东太平洋扩张洋脊中高 Cr 铬铁矿的发现(Allan and Dick, 1996; Arai and Matsukage, 1996; Dick and Natland, 1996)表明高 Cr 铬铁矿不一定来自俯冲带环境。另外,由于铬铁矿中超高压异常矿物的发现(Yang *et al.*, 2007, 2014; 杨经绥等, 2008; Trumbull *et al.*, 2009; Yamamoto *et al.*, 2009; Robinson *et al.*, 2015; Xu *et al.*, 2015),学者们进一步提出铬铁矿的形成环境可能位于地幔过渡带(410 ~ 660km)(杨经绥等, 2007, 2008)。事实上前人的工作主要通过铬铁矿的主微量元素和铂族元素及铬铁矿中的矿物包裹体来研究铬铁矿的成矿作用,对其母岩浆的制约也主要是建立在铬铁矿成分对比之上,而忽略了同样重要的主要矿物—橄榄石的成分对比(Xiao *et al.*, 2016; 苏本勋等, 2018)。

3 新特提斯洋俯冲起始在土耳其南部的地质记录

3.1 土耳其南部蛇绿岩和变质底板分布

东地中海广泛出露蛇绿岩,从塞尔维亚经阿尔巴尼亚、希腊再到土耳其、叙利亚(图 1)。这些蛇绿岩通常被认为是来自欧亚大陆和冈瓦纳大陆之间的洋盆,属于新特提斯洋岩石圈的残余(Şengör and Yılmaz, 1981; Robertson and Dixon, 1984; Dilek and Moores, 1990),其中多数已成为研究新特提斯洋演化的绝佳对象和经典实例。同时,这些蛇绿岩下部普遍发育一套角闪岩相变质岩石组合,如前南斯拉夫的 Dinaride 蛇绿岩(Lanphere *et al.*, 1975)、阿尔巴尼亚蛇绿岩(Beccaluva *et al.*, 1994; Vergely *et al.*, 1998; Dimo-Lahitte *et al.*, 2001)、土耳其境内的 İzmir-Ankara-Erzincan(Önen and Hall, 2000; Önen, 2003)和 Tauride 带(Lytwyn and Casey, 1995; Dilek and Whitney, 1997; Çelik *et al.*, 2006; Parlak, 2006)、叙利亚的 Baër-Bassit 蛇绿岩(Al-Riyami *et al.*, 2002)以及阿曼的 Semail 蛇绿岩(Searle and Malpas, 1980, 1982; Hacker, 1990; Searle and Cox, 1999)。

土耳其作为特提斯造山带的重要组成部分,其境内分布有大量的侏罗纪和白垩纪的蛇绿岩或蛇绿混杂岩(图 3)(Dilek and Moores, 1990; Dilek *et al.*, 1999; Karaoğlan *et al.*, 2013a),自北向南分可划分为两个蛇绿岩带:北部带和南部带,其中北部蛇绿岩带被认为是新特提斯洋分支 Pontide 洋的残余,而南部带则属于新特提斯主大洋的岩石圈残片(Dilek and Moores, 1990)。南部带上产出的大部分蛇绿岩均保存有较为完整的蛇绿岩单元序列,自下而上依次包括底部地幔方辉橄榄岩和镁铁-超镁铁质堆晶岩以及上部席状岩墙群、枕状熔岩和玻安岩(Parlak and Delaloye, 1999; Robertson, 2002; Dilek and Furnes, 2009; Chen *et al.*, 2015, 2018; Lian *et al.*, 2017)。这些蛇绿岩蚀变较弱,并赋存有丰富的铬铁矿床。同时,土耳其南部带中的蛇绿岩种类繁多,包括 MOR 型、SSZ 型和 MOR-SSZ 过渡型(Bağcı and Parlak, 2009; Dilek and Thy, 2009; Lian *et al.*, 2017; Sayit *et al.*, 2017; Su *et al.*, 2018),指示了构造环境的多样性,从而为特提斯洋从扩张到俯冲的完整演化过程的细致研究提供了理想场所。另外,土耳其南部蛇绿岩带在保存有完整的蛇绿岩序列的同时,还伴随着变质底板的出露(Juteau, 1980; Dilek and Moores, 1990)。蛇绿岩及变质底板下伏蛇绿混杂岩主要由蛇绿岩相关组分、斜长角闪岩块体、火山岩、硅质岩和灰岩组成,年龄分布于二叠纪到晚白垩世。

3.2 蛇绿岩中的基性岩脉

土耳其南部蛇绿岩带内各岩石单元及变质底板中普遍发育基性侵入岩脉(Dilek and Thy, 2009; Lian *et al.*, 2017),并具有一系列显著特征:1)从岩性来看,这些基性岩脉以辉绿岩-辉长岩为主;2)基性岩脉大量侵入到橄榄岩当中,部分情况下甚至侵入于玄武岩中;3)侵入同一蛇绿岩中的基性岩脉并不一定是同期形成的。如 Pozantı-Karsantı 蛇绿岩的地幔方辉橄榄岩中侵入的基性岩脉产状多变,根据野外观察可初步将基性岩脉分为三期:一期颗粒较粗(>0.5mm),脉体宽度较小(<0.5m);另外两期脉体,岩石粒度细,且侵入方

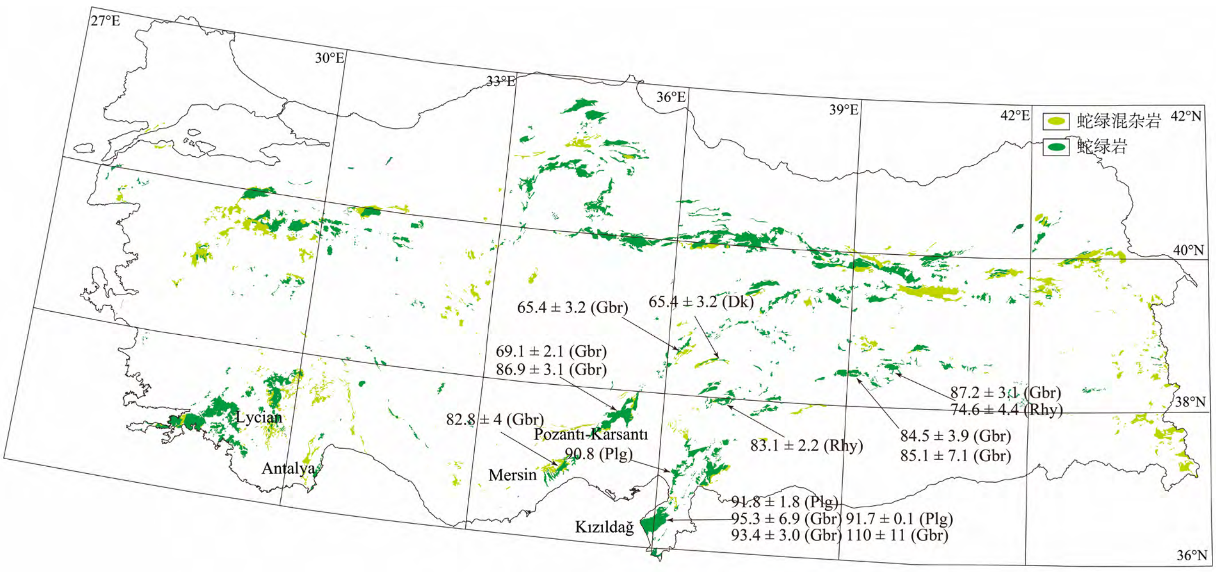

图 3　土耳其南部蛇绿岩中的基性岩的年龄(据土耳其矿物研究与勘探总局，2002[①]改编)

年龄数据引自 Dilek and Thy，2009；Karaoğlan *et al.*，2012，2013a，b；Parlak *et al.*，2013. Plg-**斜长花岗岩**；Gbr-**辉长岩**；Rhy-**流纹岩**；Dk-**辉绿岩岩脉**

Fig. 3　Ages of mafic rocks in ophiolites，southern Turkey (modified after General Directorate of Mineral Research and Exploration，Turkey，2002)

Age data from Dilek and Thy，2009；Karaoğlan *et al.*，2012，2013a，b；Parlak *et al.*，2013. Plg-plagiogranite；Gbr-gabbro；Rhy-rhyolite；Dk-dolerite dyke

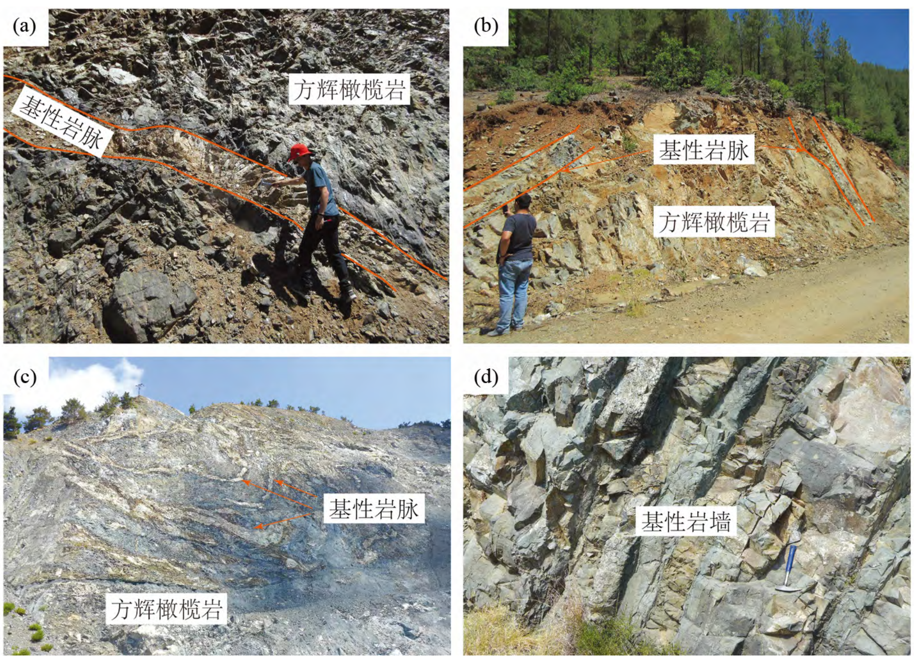

图 4　蛇绿岩中侵入的基性岩脉

(a、b) Pozantı-Karsantı **蛇绿岩的方辉橄榄岩中侵入的基性岩脉**；(c、d) Kızıldağ**蛇绿岩中的基性岩脉和岩墙**

Fig. 4　Mafic rocks in Pozantı-Karsantı (a，b) and Kızıldağ (c，d) ophiolites

① **土耳其矿物研究与勘探总局**. 2002. **地质勘查报告**

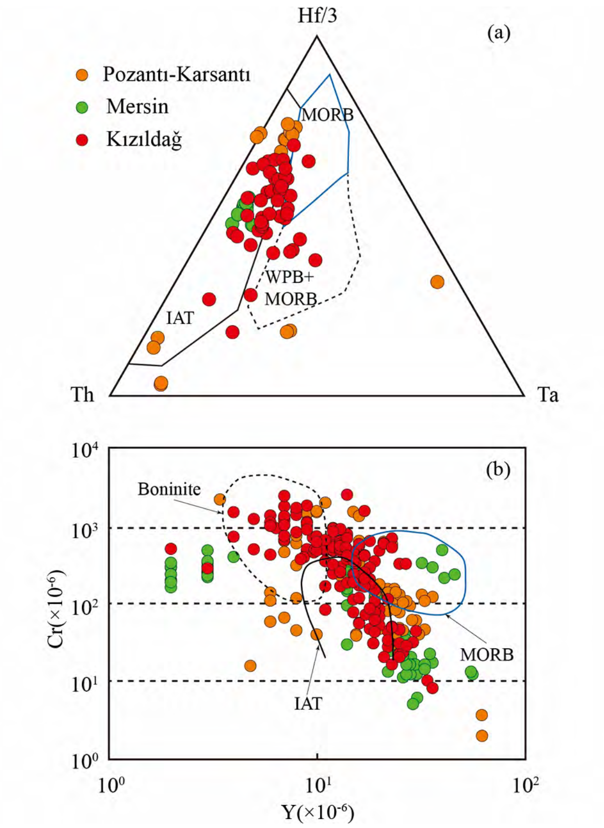

图 5 土耳其南部 Kızıldağ、Mersin 和 Pozantı-Karsantı 蛇绿岩中基性岩脉的全岩成分图解

数据引自 Parlak *et al.*, 1998, 2002; Parlak, 2000; Parlak and Robertson, 2004; Bağcı *et al.*, 2008; Dilek and Thy, 2009; Rizeli *et al.*, 2016; Lian *et al.*, 2017; Sayit *et al.*, 2017. IAT-岛弧拉斑玄武岩; MORB-洋中脊玄武岩; WPB-板内玄武岩; Boninite-玻安岩

Fig. 5 Plots of Ta-Th-Hf/3 (a) and Y vs. Cr (b) for mafic dykes from Kızıldağ, Mersin and Pozantı-Karsantı ophiolites

Data from Parlak *et al.*, 1998, 2002; Parlak, 2000; Parlak and Robertson, 2004; Bağci *et al.*, 2008; Dilek and Thy, 2009; Rizeli *et al.*, 2016; Lian *et al.*, 2017; Sayit *et al.*, 2017. IAT: island-arc tholeiite; MORB: mid-ocean ridge basalt; WPB: within plate basalt

向截然不同(图 4a, b),其中一期被颗粒较大的基性岩脉穿插,另一期则未见此现象。Kızıldağ蛇绿岩的方辉橄榄岩中零星分布有基性侵入岩脉,相应产状也明显不同:淡色基性岩脉发生扭折变形,其侵入时间可能早于蛇绿岩的构造就位(图 4c);而暗色基性岩墙则较为平直,无明显扭折变形,可能与蛇绿岩同期形成(图 4d),并且部分基性岩脉中还可见橄榄岩捕掳体;4)通过收集土耳其南部蛇绿岩中基性岩脉的地球化学特征资料,发现其地球化学成分变化很大,从似洋中脊玄武岩、岛弧拉斑玄武质到玻安质的成分均有所体现(图 5a, b);5)已有的报道显示这些基性岩脉的形成时代跨度较大,年龄范围为 62~121Ma(图 3)。综上所述,土耳其南部蛇绿岩带中发育的基性岩脉应为多期次岩浆事件的产物,既可能源自大洋扩张阶段地幔熔融产生的熔体在上升过程中与橄榄岩反应,也有可能是蛇绿岩侵位到地壳浅部层位后,其下部地幔发生部分熔融而新形成的侵入体(吴福元等, 2014)。其中,后者的地幔熔融既可能代表另外一次洋壳扩张事件(Girardeau *et al.*, 2002),也可能是与蛇绿岩无关的一次地幔岩浆事件的产物(Juteau *et al.*, 1977)。不论这些基性岩浆事件与它所侵入的蛇绿岩及变质底板在是否存在成因联系,该基性岩脉均可能记录了土耳其南部蛇绿岩"形成-演化-侵位-侵位后"过程中岩浆活动和构造环境的变化。

3.3 不同构造背景下的蛇绿岩

土耳其南部蛇绿岩带广泛发育 SSZ 型和 MORB-SSZ 过渡型蛇绿岩,可能记录了大洋岩石圈的岩浆、构造演化过程,并提供古洋盆形成、发展和消亡等方面的重要信息(Parlak and Delaloye, 1996; Robertson, 2002; Dilek and Furnes, 2009; Chen *et al.*, 2015; Lian *et al.*, 2017)。在地中海地区,塞浦路斯 Troodos 蛇绿岩和阿曼 Semail 蛇绿岩是在初始俯冲阶段弧构造背景下形成的典型蛇绿岩(Stern, 2004; Reagan *et al.*, 2010; Ishizuka *et al.*, 2011; Whattam and Stern, 2011; Stern *et al.*, 2012)。Kızıldağ蛇绿岩与 Troodos 和 Semail 蛇绿岩位于同一构造带内,且具有与 Izu-Bonin-Mariana 系统相似的特征,可能形成于俯冲早期阶段(Dilek and Thy, 2009; Chen *et al.*, 2019)。另外,岩石和矿物的主微量及同位素研究表明,Pozantı-Karsantı 蛇绿岩主要来源于亏损地幔,只有少量俯冲组分的加入,是在俯冲早期弧前构造背景下形成的(Lian *et al.*, 2017; Su *et al.*, 2018; 刘霞等, 2018)。Mersin 蛇绿岩虽与 Pozantı-Karsantı 蛇绿岩处于同一构造带之内,构造环境却有所不同,被认为形成于弧后盆地拉张的构造环境(Sayit *et al.*, 2017)。Antalya 蛇绿岩经历的演化过程和构造背景则更为复杂,可能形成于弧前构造背景,后又经历了板片断裂或洋脊俯冲的改造(Bağcı and Parlak, 2009)。综上所述,土耳其南部蛇绿岩的构造背景和形成过程虽不尽相同,但均经历过俯冲改造,应为板块俯冲作用不同阶段的产物。

3.4 土耳其南部蛇绿岩带中的变质底板

针对土耳其南部蛇绿岩带中广泛出露的变质底板,现有的研究和认识包括:1)含斜长角闪岩的变质底板总是作为蛇绿混杂岩和蛇绿岩之间的构造岩出现;2)角闪岩显示强烈的同变质构造(矿物片理与拉伸线理),与蛇绿岩的就位变形具有良好的一致性;3)与角闪岩互层的变沉积岩(大理岩、云母片岩或石英岩)显示出与角闪岩相一致的变形组构和变质级别;4)通过变质底板的结构(如矿物片理、相关的拉伸线理、与褶皱轴平行的矿物线理、不对称组构)及其与上覆蛇绿岩之间的构造关系研究,证实蛇绿岩中的变形作用与逆冲断层相关,而非走滑断层或拆离断层所致;5)有时可见变质底板和上覆蛇绿岩被一个与蛇绿岩无成因联系的岛弧拉斑质的基性岩横切,暗示了下伏于蛇绿混杂岩的基性岩被卷入俯冲

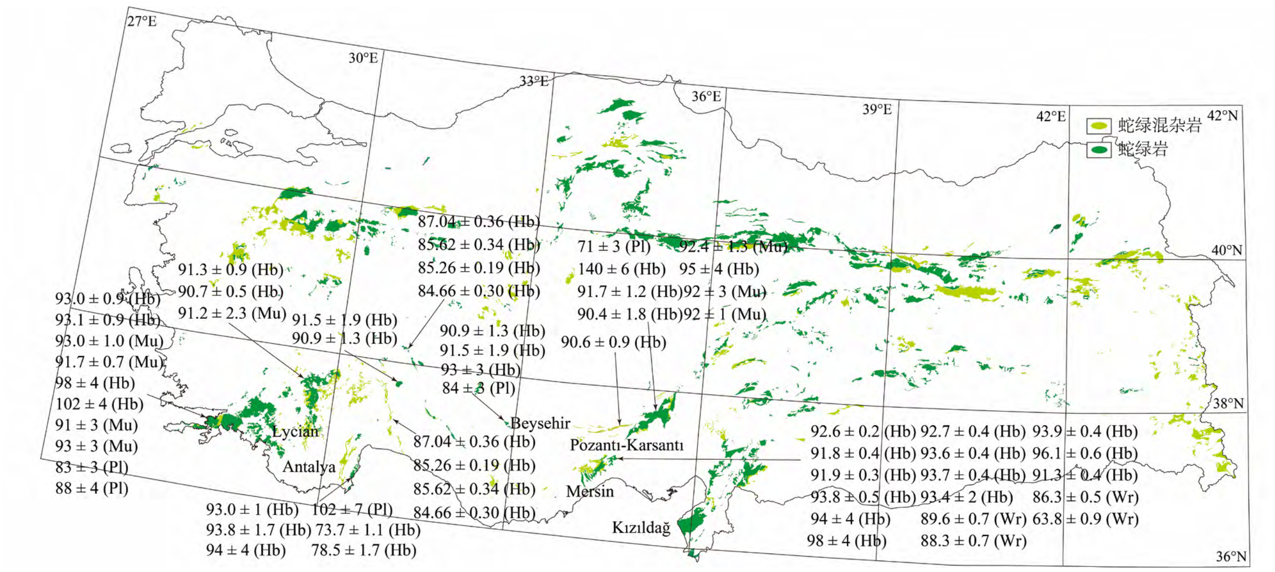

图6　土耳其南部与蛇绿岩共生的变质底板分布与年龄(据土耳其矿物研究与勘探总局，2002 改编)

数据引自 Thuizat *et al.*，1981；Dilek *et al.*，1999；Parlak and Delaloye，1999；Robertson，2002；Roepke *et al.*，2002；Önen，2003；Çelik *et al.*，2006；Chan *et al.*，2007；Karaoğlan *et al.*，2013b；Daşçı *et al.*，2015；Parlak，2016；Lian *et al.*，2017. Mu-**白云母**；Hb-**角闪石**；Pl-**斜长石**；Wr-**全岩**

Fig. 6　Distribution and ages of metamorphic soles associated with ophiolites in southern Turkey (modified after General Directorate of Mineral Research and Exploration，Turkey，2002)

Age data from Thuizat *et al.*，1981；Dilek *et al.*，1999；Parlak and Delaloye，1999；Robertson，2002；Roepke *et al.*，2002；Önen，2003；Çelik *et al.*，2006；Chan *et al.*，2007；Karaoğlan *et al.*，2013b；Daşçı *et al.*，2015；Parlak，2016；Lian *et al.*，2017. Mu-muscovite；Hb-hornblende；Pl-plagioclase；Wr-whole rock

带，裹挟至包含变质底板的上部板块，并且早于蛇绿岩就位进入游离的大洋岩石圈。因而该现象更能表明变质底板中角闪岩的变质作用最有可能发生在新特提斯洋俯冲带的初始俯冲过程；6) 变质底板的年龄分布范围广，在 64～110Ma **时间段均有分布(图6)**(Dilek and Thy，1992；Dilek and Whitney，1997；Robertson，2002；Karaoğlan *et al.*，2013b；Daşçı *et al.*，2015；Parlak，2016；Lian *et al.*，2017)。**除此之外，对变质底板的研究还揭示了部分岩石经历过高压变质作用的改造**(Guilmette *et al.*，2009；Plunder *et al.*，2016)，**表明其后期可能经历过俯冲作用并沿俯冲通道构造折返(吴福元等，2014)。同时，经历了高温变质作用的变质底板既可能与洋壳形成时的高温变质作用有关，也可能与后来的构造侵位过程相联系**(Dewey and Casey，2013)。

3.5　不同类型的铬铁矿床

蛇绿岩与豆荚状铬铁矿间具有明显的成矿专属性，故铬铁矿床的形成过程与蛇绿岩的环境、所处的构造位置间存在密切联系。通常情况下，铬铁矿体赋存于蛇绿岩的两个层位中，地壳堆晶岩中或莫霍面以下的地幔橄榄岩中。前者通常形成似层状铬铁矿床，而后者大多形成了极具工业价值的豆荚状铬铁矿床。土耳其南部蛇绿岩均赋含不同规模的铬铁矿床：既有位于地幔方辉橄榄岩中的豆荚状铬铁矿，也有地壳堆晶岩中的(似)层状铬铁矿(Uysal *et al.*，2007，2009；Saka *et al.*，2014；Chen *et al.*，2015，2019；Avcı *et al.*，

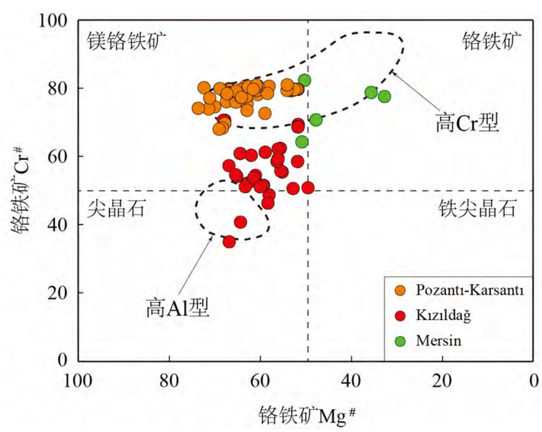

图7　土耳其南部 Kızıldağ、Mersin **和** Pozantı-Karsantı **蛇绿岩中铬铁岩的铬铁矿的成分相关性图解**

数据引自 Parlak and Delaloye，1996；Parlak *et al.*，2002；Bağcı *et al.*，2008；Chen *et al.*，2015；Rizeli *et al.*，2016；Avcı *et al.*，2017

Fig. 7　Plot of $Mg^{\#}$ vs. $Cr^{\#}$ for chromite in the chromitite from Kızıldağ，Mersin and Pozantı-Karsantı ophiolites

Data from Parlak and Delaloye，1996；Parlak *et al.*，2002；Bağcı *et al.*，2008；Chen *et al.*，2015；Rizeli *et al.*，2016；Avcı *et al.*，2017

2017；**刘霞等，2018)，其中尤以豆荚状铬铁矿最为发育。整个南部蛇绿岩带上，豆荚状铬铁矿床主要为高** Cr **型，而** Kızıldağ**蛇绿岩中铬铁矿床则呈现出高** Cr-**高** Al **过渡型的特**

征(图7)(Chen *et al.*, 2015)。高 Cr 型铬铁矿主要被解释为玻安质岩浆与地幔橄榄岩的作用,而过渡型铬铁矿则是过渡型岩浆与地幔橄榄岩反应的结果(Uysal *et al.*, 2007, 2009; Avcı *et al.*, 2017; 刘霞等, 2018; Chen *et al.*, 2019)。更为关键的是土耳其南部带内发育铬铁矿床的蛇绿岩,并非全都伴随有玻安岩的出露(Dilek *et al.*, 1999)。这可能暗示了玻安质岩浆没有到达地壳深度,而是在上升过程中与地幔橄榄岩反应形成高 Cr 型铬铁矿床,亦或是高 Cr 型铬铁矿的形成与玻安岩之间并无必然联系。因此,土耳其南部蛇绿岩带内的铬铁矿床是蛇绿岩形成侵位、大洋俯冲起始和玻安质岩浆活动之间的关系纽带。

4 结论

初始俯冲是地球构造演化过程中的一个重要环节,尤其是在现行板块构造理论的框架下,其对地球科学的重要性不言而喻。同时,初始俯冲过程的研究对全球海陆构造演化以及地幔深部过程也有着重要的科学价值。蛇绿岩和变质底板是初始俯冲过程的重要印迹。从早期的三位一体同源结晶分异,到板块构造理论所主张的同源残留体-熔体成因假说,蛇绿岩的概念和内涵均经历了很大的变化。虽然蛇绿岩的产出遍布全球,但强烈的构造作用使得大部分地区并非蛇绿岩研究的理想落脚点。相反,土耳其南部蛇绿岩剖面连续完整,各类岩石蚀变轻微,并发育有与蛇绿岩密切伴生的变质底板,完整记录了新特提斯洋形成-俯冲-消减的演化过程。

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