评述

俯冲带橄榄岩及其记录的壳幔相互作用

郑建平*, 熊庆, 赵伊, 李文博

中国地质大学(武汉)地球科学学院, 地质过程与矿产资源国家重点实验室, 武汉 430074

* E-mail: jpzhang@cug.edu.cn

收稿日期: 2018-10-06; 收修改稿日期: 2019-02-18; 接受日期: 2019-03-13; 网络版发表日期: 2019-04-09

国家自然科学基金项目(批准号: 41520104003、41873032)和中央高校基本科研业务费专项资金项目(编号: CUG180604)资助

摘要 俯冲过程是板块构造运动的核心过程, 而地幔楔作为俯冲系统中连接俯冲盘和仰冲盘的关键构造单元, 在地球层圈之间物质循环和能量交换等方面发挥了重要作用. 本研究汇总了全球代表性俯冲带橄榄岩(包括俯冲带型蛇绿岩和地幔楔型造山带橄榄岩)的研究现状, 并展望未来需要解决的关键科学问题. 俯冲带型蛇绿岩地幔单元和地幔楔型造山带橄榄岩分别代表着大洋和大陆俯冲带侵位的地幔岩石, 是研究俯冲带壳幔相互作用的关键对象. 该相互作用的本质是俯冲板片和地幔楔之间在物理过程主控下发生复杂的化学交换作用. 俯冲带型蛇绿岩能够记录从大洋岩石圈产生到俯冲启动直至成熟到消亡等不同阶段复杂的熔-岩和水-岩相互作用、变形变质过程、金属成矿元素富集以及壳幔物质交换等. 地幔楔型造山带橄榄岩则反映洋-陆和陆-陆俯冲/碰撞、折返等阶段强烈的变形变质历史, 多种性质的熔/流体交代作用(硅酸盐熔体、碳酸盐熔体、含硅酸盐组分的C-H-O流体/超临界流体), 以及复杂的壳幔物质循环过程等. 利用俯冲带橄榄岩进一步探索壳幔相互作用, 需要采用高空间分辨率、高精度的测试方法从微观尺度上约束复杂的化学交代过程和变质变形历史, 并与宏观构造的时、空演化相联系.

关键词 俯冲带, 蛇绿岩, 造山带橄榄岩, 地幔楔, 交代作用, 壳幔相互作用

1 引言

俯冲过程是板块构造运动的核心过程, 驱动了地球的进一步分异演化, 并实现了圈层间的物质循环和能量交换(Stern, 2002; Bebout, 2007; Zheng和Chen, 2016). 自从30亿年前(Shirey和Richardson, 2011)、甚至冥古宙时期(Wilde等, 2001)地球可能开始出现板块俯冲运动, 其内部的动力学体制便可能发生从“垂向地幔柱过程主控”到“横向板块俯冲过程主控”的转变, 并逐步导致水圈、大气圈、生物圈的协同演化. 同时, 板

块俯冲过程随时间的演变也诱发了弧岩浆和对流地幔不均一体的产生以及大陆地壳的形成和成熟(Ringwood, 1974; Hofmann, 1997; Kelemen等, 2014).

地幔楔是俯冲带系统(俯冲工厂)的重要组成部分, 位于俯冲板片之上、上覆板块地壳之下的“楔形”地幔区(图1), 在地球内部物质循环、壳幔相互作用过程中起着承上启下的关键作用(Stern, 2002; Tatsumi和Kogiso, 2003; Zheng和Chen, 2016). 地幔楔在空间上可划分为岩石圈地幔楔和软流圈地幔楔(即对流地幔楔). 根据俯冲带构造属性的不同又可划分为洋-洋、洋-陆和

中文引用格式: 郑建平, 熊庆, 赵伊, 李文博. 2019. 俯冲带橄榄岩及其记录的壳幔相互作用. 中国科学: 地球科学, 49: 1037–1058, doi: 10.1360/N072018-00272
英文引用格式: Zheng J, Xiong Q, Zhao Y, Li W. 2019. Subduction-zone peridotites and their records of crust-mantle interaction. Science China Earth Sciences, 62: 1033–1052, <https://doi.org/10.1007/s11430-018-9346-6>

图1 三种不同俯冲带类型及其地幔楔几何结构示意图

(a) 大洋-大洋俯冲, 例如现今的西太平洋Izu-Bonin-Mariana俯冲带;
(b) 大洋-大陆俯冲, 例如现今美洲西海岸大陆弧;(c) 大陆-大陆俯冲, 例如现今的喜马拉雅造山带和大别-苏鲁造山带

陆-陆俯冲带之上的不同地幔楔(图1)。这些俯冲带系统在几何结构、温度场和流动场上的差异, 同样会造成地幔楔物理结构和化学属性的不同。例如, 俯冲角度的平与陡、上覆板片的厚与薄、上覆板片流变学强度的大与小, 都会导致地幔楔几何结构的不同, 从而产生不同类型与程度的板块脱水和熔融过程、壳幔相互作用、弧岩浆体系的空间位置以及地幔楔运动过程等(Stern, 2002; Schmidt和Poli, 2014; Zheng和Chen, 2016)。岩石圈地幔楔兼具岩石圈地幔的熔融残余体属性以及汇聚板块边缘高度富集交代特征; 而对流地幔楔则主体具有软流圈地幔的饱满高温特征并叠加熔/流体交代作用影响。对地幔橄榄岩而言, 其发生部分熔融程度的高与低, 通常依据其相对原岩地幔的易熔主量元素的低与高, 划分为“难熔”与“饱满”两类; 而根据

熔体活动性不相容微量元素含量及其放射性同位素特征又可划分为“亏损”与“富集”两类, 前者指示仅经历部分熔融过程, 后者则暗示在部分熔融基础上叠加较强的熔/流体交代作用(Zheng等, 2007)。

在俯冲带“壳幔界面”处(即俯冲隧道内), 俯冲板片与地幔楔之间发生强烈且复杂的物理混杂作用、壳幔物质交换和流/熔体活动, 诱发汇聚板块边缘大规模的构造、岩浆、变质和成矿作用(Zheng, 2012; Richards, 2013; Bebout, 2014; Hermann和Rubatto, 2014; Kelemen等, 2014; Schmidt和Poli, 2014)。“俯冲隧道”(Subduction channel)是俯冲带板片界面之间发生壳幔相互作用最为强烈的位置, 由来自俯冲板片和地幔楔的物质经构造混杂而成(Bebout, 2007; Guillot等, 2009; Spandler和Pirard, 2013; 郑永飞等, 2013)。俯冲隧道内壳幔相互作用分为两种极端类型: 一类是大洋板片与地幔楔相互作用(图2a); 另一类是大陆板片与地幔楔相互作用(图2b)。

俯冲隧道模型是在大洋俯冲带研究基础上发展而来(Shreve和Cloos, 1986), 通过地质学、地球化学、地球物理学、数值模拟和高温高压实验的研究已经形成相对系统和清晰的认识(图2a)。大洋板片(通常包括沉积物、蚀变洋壳和部分蛇纹石化的岩石圈地幔)随着俯冲深度的增加和温度的升高发生一系列脱挥发分过程, 具体包括从脱孔隙水到矿物进变质脱挥发分, 再到高压/超高压条件下释放超临界流体或高温下发生熔融; 随后, 这些经脱挥发分过程所形成的流/熔体在俯冲隧道内以弥散流和通道流的方式运移, 并与俯冲隧道内地壳和/或地幔的组分发生复杂相互作用(Gerya等, 2002; Stern, 2002; Manning, 2004; Bebout, 2007, 2014; Gao等, 2007; Konrad-Schmolke等, 2011; John等, 2012; Spandler和Pirard, 2013; Schmidt和Poli, 2014; 郑永飞等, 2016; Li J L等, 2017)。最后, 形成的流体、熔体和低密度混杂体向上迁移, 诱发地幔楔的富化和熔融, 形成弧岩浆, 并最终演化为岛弧和新生陆壳(Ringwood, 1974; Tatsumi, 1989; Stern, 2002; Lee等, 2006; Bebout, 2007; Behn等, 2011; Marschall和Schumacher, 2012; Spandler和Pirard, 2013; Kelemen等, 2014; Xiong等, 2014)。经历富化作用后的地幔和俯冲残余的板片, 被卷入对流地幔后, 成为板内岩浆的重要源区(Hofmann, 1997; 郑永飞等, 2018)。

近几年, 俯冲隧道的概念被拓展到大陆俯冲带

图 2 两种极端情形下俯冲带壳-幔相互作用示意图

(a) 大洋俯冲(修改自Konrad-Schmolke等, 2011); (b) 大陆俯冲(修改自郑永飞等, 2013)

(图2b). 与大洋俯冲带相比, 大陆俯冲带具有相对较低的温度, 并且俯冲陆壳具有相对较少的易挥发组分, 使得在大陆俯冲过程中相对缺乏流体和岩浆活动(Chopin, 2003; Ernst和Liou, 2008; Zheng, 2012; Hermann和Rubatto, 2014). 然而, 大量的岩石学、地球化学研究和实验模拟表明, 在深俯冲的大陆地壳内(包括基性和中酸性岩石)发育着规模较小、但类型丰富的熔/流体活动及伴随的熔/流体-岩石相互作用(Philippot和Selverstone, 1991; Shen和Keppler, 1997; Fu等, 2001; Hwang等, 2001; Scambelluri和Philippot, 2001; Xiao等, 2002; Ferrando等, 2005; Hermann和Spandler, 2008; Zhang Z M等, 2008; Wu等, 2009; Zeng等, 2009; Zheng等, 2011; Gao等, 2012; Hermann等, 2013; Wang等, 2014; Zheng和Hermann, 2014; Frezzotti和Ferrando, 2015; Yu等, 2015; 肖益林等, 2015; Guo等, 2017). 同时, 大陆俯冲隧道内不同深度来源的地幔楔岩石也记录着复杂的熔/流体活动和壳幔相互作用, 例如对中国苏鲁带(杨建军等, 1994; Yang, 2003; Zheng等, 2005, 2006a; Malaspina等, 2006, 2009a, 2009b; Liou等, 2007; Zhang等, 2007; Ye等, 2009; Zhang等, 2011; Su等, 2016, 2017; Li等, 2018a)、大别带(Xiao等, 2001; Malaspina等, 2009b, 2015, 2017; Chen等, 2013a, 2013b; 陈

意等, 2015; Campione等, 2017)、柴北缘带(Song等, 2005a, 2007; Xiong等, 2011, 2014, 2015; Chen R X等, 2017), 以及意大利Ulten带(Rampone和Morten, 2001; Scambelluri等, 2006)、挪威西片麻岩省(van Roermund等, 2002; Scambelluri等, 2008; Malaspina等, 2010; Rielli等, 2017)等造山带中地幔楔型橄榄岩的研究, 都取得了丰富的成果.

大陆边缘的橄榄岩是记录俯冲带壳幔相互作用最直接的对象. 它们多以汇聚板块边缘地质体橄榄岩形式产出, 主要分为两大类: 一类是反映大洋俯冲过程的“俯冲带型蛇绿岩”, 另一类是记录大陆俯冲的“地幔楔型造山带橄榄岩”. 俯冲带型蛇绿岩的主要特点是在岩石学上显示玄武岩-辉长岩-方辉橄榄岩-二辉橄榄岩这样一个典型的地幔熔融层序, 但是在微量元素地球化学上洋壳层岩石显示岛弧属性(看上去像岛弧玄武岩、玻安岩等), 以及地幔橄榄岩显示高 $\text{Cr}^\#$ [$\text{Cr}^{3+}/(\text{Cr}^{3+} + \text{Al}^{3+})$]的难熔属性和明显的熔/流体交代特征(Bodinier和Godard, 2014; Zheng和Chen, 2016), 正是这些地球化学变化记录大洋俯冲带壳幔相互作用(图2a). 全球典型的俯冲带型蛇绿岩(图3)包括塞浦路斯的Troodos (Batanova和Sobolev, 2000; Woelki等, 2018)、新喀里多尼亚(Marchesi等, 2009; Ulrich等, 2010; Pirard等,

图3 文中涉及的代表性俯冲带型蛇绿岩与造山带橄榄岩出露位置

修改自Liou等(2009); 岩体缩写代号: TR, Troodos; NC, New Caledonia; TM, Thetford Mines; LBS, Luobusa; ZD, Zedang; BL, Beila; YSG, Yushigou; SSG, Songshugou; SV, Svartberget; YI, Yinggelisayi; BXL, Bixiling; OF, Otrøy-Fjortoft; UL, Ulten; SLK, Shenglikou; MW, Maowu; RC, Rongcheng; YK, Yangkou; XG/ZMF, Xugou/Zhimafang

2013)、加拿大的Thetford Mines(Pagé等, 2008)、中国雅江带的罗布莎(Zhou等, 1996, 2005; Yang等, 2014)、泽当(Xiong等, 2016, 2017a, 2017b)、班怒带的北拉(Tang等, 2018)、北祁连带的玉石沟(Song等, 2009)、北秦岭带的松树沟(Cao等, 2016, 2017; Yu等, 2017)等. 造山带橄榄岩分为地幔楔来源的M型和俯冲大陆岩石圈来源的C型(Zhang等, 2000; Bodinier和Godard, 2014), 分别记录了大陆板片与地幔楔相互作用的过程(图2b). 本文将分别对俯冲带型蛇绿岩内地幔岩石和M型造山带橄榄岩的研究现状进行综述, 汇总二者反映的两类俯冲带壳幔相互作用特点, 进而提出未来急需解决的重要科学问题.

2 大洋型俯冲带橄榄岩

蛇绿岩的概念最早是在1813年法国矿物学家Alexandre Brongniart研究阿尔卑斯-亚平宁造山带中的基性-超基性岩石组合时提出(Brongniart, 1813), 随后Gustav Steinmann提出经典的蛇绿岩三位一体模式(Steinmann, 1927). 直至20世纪60~70年代, 随着板块构造学说的诞生, 蛇绿岩被广泛认为是代表产生于离散板块边缘的古老洋壳和上部地幔的残片(Gass, 1968; Bailey等, 1970; Anonymous, 1972; Moores和Jackson, 1974). 随着对现今西太平洋和南大西洋弧-盆体系开展大洋钻探, 蛇绿岩中的俯冲带地球化学信息被识别出来(Pearce等, 1984). 近20多年来, 大量的岩石地球化学、同位素组成和岩石物性研究表明, 全球多数蛇绿岩具有或叠加有岛弧地球化学信息, 形成于初始弧或弧前背景, 而其岩石学层序则可以是弧后裂谷或者洋中脊背景下的海底扩张过程产生. 因此, 蛇绿岩内部结构和组成反映了不同背景下海底扩张和大洋岩石圈俯冲引起交代作用的多期次地质事件(Bodinier和Godard, 2014; Zheng和Chen, 2016). 特别是在微量元素组成上, 许多蛇绿岩含有俯冲带岩石地球化学信息, 有的蛇绿岩甚至含有与洋岛玄武岩相似的地球化学信息, 由此前人将这些成分差别与形成构造背景挂起钩来, 导致对蛇绿岩划分出现种种混淆(Dilek和Furnes, 2011). 对于侵位于弧前环境的俯冲带型蛇绿岩, 其地幔单元代表了大洋俯冲带之上的地幔楔残片, 能够记录大洋板片与地幔楔之间的复杂壳幔相互作用过程(Dilek, 2003; Marchesi等, 2009; Song等, 2009; Cao

等, 2016; Xiong等, 2017a, 2017b). 这里强调的地幔楔并非单指处于异常低温状态的弧前地幔楔(Hyndman和Peacock, 2003; Zheng和Chen, 2016), 也包括处于局部伸展环境的弧前或弧后的对流地幔楔/岩石圈地幔楔.

2.1 国外经典的俯冲带型蛇绿岩

本文重点介绍三个国外经典的俯冲带型蛇绿岩(图3), 包括: 特提斯带西段塞浦路斯的Troodos蛇绿岩(Batanova和Sobolev, 2000; Woelki等, 2018)、西太平洋南段新喀里多尼亚蛇绿岩(Marchesi等, 2009; Ulrich等, 2010; Pirard等, 2013)以及加拿大东部阿巴拉契亚造山带的Thetford Mines蛇绿岩(Pagé等, 2008).

Troodos蛇绿岩地处地中海东段的塞浦路斯岛, 出露面积达3000km², 由典型的蛇绿岩层序构成, 从下至上包括: 二辉橄榄岩/富含单斜辉石方辉橄榄岩、方辉橄榄岩、超镁铁质堆晶岩、层状/均质辉长岩、席状岩墙群、枕状火山岩等(Gass, 1968; Batanova和Sobolev, 2000; Dilek和Furnes, 2009). 蛇绿岩壳层岩石的岩浆结晶年龄为92~90Ma(Woelki等, 2018). Miyashiro(1973)发现, 在Troodos壳层底部约三分之一的岩浆岩具有钙碱性演化特征. Robinson等(1983)对壳层火山岩中的原生玻璃进行研究, 发现熔体具有从下部的玄武质-安山质到上部的玻安质的变化特点. Pearce和Robinson(2010)对这些原生玻璃重新分析后, 发现Troodos蛇绿岩可能形成于俯冲启动时期的弧前扩张中心. 由于Troodos蛇绿岩壳层岩石内缺失弧前玄武岩, 与典型的Izu-Bonin-Mariana弧前岩石圈岩石组合不同, Woelki等(2018)则认为Troodos蛇绿岩并非形成俯冲启动的弧前环境. 尽管学术观点上存在争议, 但Troodos蛇绿岩的壳层岩石显示从拉斑质到玻安质岩浆演化的趋势, 是大家普遍认识到的事实. 这种岩浆属性的演变, 在该蛇绿岩地幔单元岩石上也有一定反映, 例如Batanova和Sobolev(2000)发现, Troodos蛇绿岩存在两个属性截然不同并经后期构造置位于一起的地幔单元: 东部是相对饱满的二辉橄榄岩/富含单斜辉石方辉橄榄岩, 可能形成于洋中脊环境并与拉斑质岩浆的产生有关, 后期又与俯冲带玻安质熔体反应形成纯橄岩脉体(例如图4a); 西部是紧接壳层堆晶岩的方辉橄榄岩和纯橄岩透镜体, 形成于俯冲带地幔楔与玻安质岩浆的强烈相互作用(Kelemen和Dick, 1995). 磁性岩石

图4 代表性俯冲带型蛇绿岩中反映熔/水-岩反应的野外照片

(a) 雅江带罗布莎蛇绿岩东段方辉橄榄岩内纯橄榄岩透镜体; (b) 雅江带罗布莎蛇绿岩内豆状铬铁矿岩与纯橄榄岩; (c) 阿尔巴尼亚Mirdita蛇绿岩方辉橄榄岩先后被纯橄榄岩和辉石岩穿切; (d) 雅江带日喀则蛇绿岩内异剥钙榴岩脉体

学和构造地质学的研究发现, Troodos蛇绿岩初始形成于慢速扩张洋中脊(呈现变质核杂岩构造特征; [Abelson等, 2001](#); [Nuriel等, 2009](#))或大洋转换断层([Morris和Maffione, 2016](#)), 但是在地球化学上体现出俯冲带型性质, 这种两面性在全球多数蛇绿岩中均有体现, 被[Moores等\(2000\)](#)称为“ophiolite conundrum”. 为了解释蛇绿岩在岩石学和地球化学上所具有的两面性, [Zheng和Chen\(2016\)](#)提出洋脊-海沟转换模型, 认为这可以解释所有在蛇绿岩中发现的地质地球化学特征.

新喀里多尼亚蛇绿岩在白垩纪-新生代时期西太平洋西向俯冲的大背景下, 经历从弧后Loyalty海盆扩张过渡到Loyalty洋中脊转变为汇聚板块边缘并发生俯冲启动的过程, 是世界上最典型的记录俯冲带初始启动的蛇绿岩之一([Cluzel等, 2016](#)). 新喀里多尼亚蛇绿岩呈北西-南东向展布、以多个推覆岩片形式仰冲于高压/低温变质岩带以及大陆边缘基底之上([Cluzel等, 2001, 2016](#); [Marchesi等, 2009](#); [Ulrich等, 2010](#); [Pirard等, 2013](#); [Soret等, 2016](#); [Secchiari等, 2016, 2018](#)). 这些蛇绿岩主要由岩石圈地幔单元(主体方辉橄榄岩和纯橄榄岩、少量二辉橄榄岩)和少量镁铁质-超镁铁质

堆晶岩构成, 缺失上覆壳层单元; 其中地幔单元内含纯橄榄岩-铬铁矿岩透镜体、辉石岩脉体, 并先后被具有玻安性质质的长英质/中性岩脉体(约55~50Ma)和具有岛弧拉斑性质质的辉绿岩脉体(约50~47Ma)穿切([Cluzel等, 2016](#); [Secchiari等, 2018](#)). 新喀里多尼亚蛇绿岩北段的Poum二辉橄榄岩属尖晶石相和长石相, 记录了较低程度的熔体抽取以及MORB熔体轻度再富集特征, 可能代表俯冲启动之前形成于洋中脊的岩石圈地幔([Secchiari等, 2016](#)). 而最南端的Massif du Sud橄榄岩是最具代表性的弧前岩石圈地幔橄榄岩, 其主体的方辉橄榄岩具有极度难熔特征(部分熔融程度超过25%), 经历了无水部分熔融和加水部分熔融两次地幔熔体抽取事件, 并叠加多次熔/流体交代事件: 如包括极度亏损且硅不饱和硅酸盐熔体交代(形成纯橄榄岩、少量铬铁矿以及玻安质-辉绿岩脉体; [Marchesi等, 2009](#); [Ulrich等, 2010](#); [Pirard等, 2013](#))、富硅熔体交代(形成辉石岩和长英质脉体; [Cluzel等, 2001, 2016](#))以及俯冲带高温-低温流体交代(形成橄榄岩岩片底部的含水基性-超基性脉体; [Soret等, 2016](#))等复杂过程. 这些复杂的熔/流体交代事件发生在白垩纪-新生代早期的西太平

洋俯冲和South Loyalty洋盆俯冲启动(即初生岛弧时期)两大阶段。从橄榄岩与熔体的交代反应、基性-长英质脉体的产生、堆晶岩体系的演化以及蛇绿岩底部含水脉体的发育等地质现象,可以刻画出伴随大洋板片俯冲的熔/流体与地幔楔相互作用的完整时空演化过程(Cluzel等, 2016; Soret等, 2016; Secchiari等, 2018)。

加拿大东部阿巴拉契亚造山带的Thetford Mines蛇绿岩是来自早古生代时Iapetus大洋边缘的弧前岩石圈残片,并伴随Taconian造山过程增生于劳亚大陆边缘(Pagé等, 2008, 2009)。Thetford Mines蛇绿岩由较为完整的蛇绿岩序列构成,由下至上包括:含角闪岩的变质底板(变质时代在~477Ma; Whitehead等, 1995)、~5km厚的难熔地幔橄榄岩(主体方辉橄榄岩,内含纯橄岩-铬铁矿透镜体以及斜方辉石岩脉体)、约1~5km厚度不等的玻安质壳层(包括下部的镁铁质-超镁铁质堆晶岩和上部的席状岩脉和火山岩,其中辉长岩和火山岩的锆石U-Pb年龄为480~478Ma)(Pagé等, 2008, 2009)。该蛇绿岩地幔单元中的纯橄岩和铬铁矿岩,形成于来自难熔地幔楔加水熔融后抽取的玻安质熔体与方辉橄榄岩之间的熔-岩反应以及在纯橄岩通道内的熔体-熔体混合过程(Pagé和Barnes, 2009);斜方辉石岩脉体同样结晶于玻安质熔体。此外,主体的方辉橄榄岩具有LREE富集的熔/流体交代特征,指示含水熔/流体的隐性交代作用(Pagé等, 2008)。变质底板中的角闪岩变质年龄与蛇绿岩内玻安质熔体活动时间一致,均为约480~477Ma,暗示大洋板片俯冲(变质底板形成)与弧前扩张以及玻安质熔体演化同时发生,均指示在趋向成熟过程的俯冲带中发生弧前岩石圈增生以及熔/流体与地幔楔之间的相互作用过程。

2.2 国内典型的俯冲带型蛇绿岩

本文涉及的国内典型俯冲带型蛇绿岩(图3)主要包括:西藏南部雅鲁藏布江缝合带的罗布莎(Zhou等, 1996, 2005; Yang等, 2014)和泽当蛇绿岩(Xiong等, 2016, 2017a, 2017b)、西藏中部地区班公湖-怒江缝合带的北拉蛇绿岩(Tang等, 2018)、北祁连造山带的玉石沟蛇绿岩(Song等, 2009; Cao等, 2015)以及北秦岭造山带的松树沟蛇绿岩(Cao等, 2016, 2017; Nie等, 2017; Yu等, 2017)。

罗布莎和泽当蛇绿岩均位于雅江缝合带东段,形成于侏罗纪-白垩纪早期新特提斯北缘的扩张脊(Zhou

等, 1996, 2005; Yang等, 2014; Chan等, 2015; Zhang等, 2016; Xiong等, 2016)。目前关于二者的构造成因演化的关键争议点在于:是形成于“单一阶段”还是“多阶段增生叠加而成”,是形成于“洋中脊环境”还是“俯冲带的弧前或弧后扩张脊”,是由“浅部对流地幔上涌而成”还是“深部转换带或对流地幔来源”(Xiong等, 2016及其中参考文献)。尽管这些争论仍需进一步工作来解决,但一个基本事实是罗布莎和泽当蛇绿岩的地幔单元均记录着明确的多期熔/流体交代、熔体-橄榄岩反应等过程,并且这些复杂的再富集过程与新特提斯洋俯冲板片上部熔/流体与地幔楔橄榄岩之间的相互作用有关(Zhou等, 1996, 2005; Hébert等, 2012; Su等, 2015; Xiong等, 2016, 2017a, 2017b)。具体存在下列过程: (1) 在板片后撤或俯冲启动的地幔流动背景下,对流地幔楔来源的含水玻安质熔体以及弧前拉斑玄武质熔体,在俯冲过程的不同阶段与上覆岩石圈地幔反应,形成Cr[#]高低不同的纯橄岩透镜体(图4a),这一作用的实质是硅不饱和硅酸盐熔体与方辉橄榄岩内辉石反应、消耗辉石生成橄榄石,并逐步形成方辉橄榄岩内纯橄岩熔体通道(Kelemen和Dick, 1995); (2) 在纯橄岩熔体通道内,硅不饱和熔体与方辉橄榄岩内辉石反应后产生富硅熔体,该熔体与新加入的贫硅熔体混合、诱发铬铁矿的晶出,并在纯橄岩通道内逐步聚集成不同产状的铬铁矿岩(图4b; González-Jiménez等, 2014);同时,新产生的富Cr熔体能够迁移进入周围方辉橄榄岩内形成弥散状铬铁矿脉(Xiong等, 2017b); (3) 上述熔-岩反应后产生的富硅熔体能够进一步向上迁移,形成辉石岩脉、穿切早期的纯橄岩熔体通道和方辉橄榄岩(图4c);同时,熔/流体还能够与方辉橄榄岩发生交代作用,使得橄榄岩内多数不相容微量元素得以再富集(Xiong等, 2016, 2017a); (4) 在微观上,含水玻安质熔体或拉斑玄武质熔体与方辉橄榄岩反应,能够产生各种富含挥发分的矿物组合(图5a和5b),并被保存在较为稳定的铬铁矿内部(图5c和5d)。

西藏班怒带的北拉蛇绿岩、北祁连的玉石沟蛇绿岩以及北秦岭的松树沟蛇绿岩,均记录着伴随大洋板片俯冲的壳源熔/流体与岩石圈地幔楔之间的相互作用过程。北拉蛇绿岩形成于侏罗纪的新特提斯班怒洋俯冲阶段(Tang等, 2018),玉石沟蛇绿岩产生于早古生代原特提斯洋的俯冲过程(Song等, 2009),而松树沟蛇绿岩至少形成于早古生代甚至新元古代的大洋俯冲环

图5 代表性俯冲带型蛇绿岩中熔/流体交代作用显微((a), (b))或背散射((c), (d))照片

(a) 北祁连玉沟蛇绿岩纯橄岩透视镜体内发育的单斜辉石-角闪石脉体; (b) 北秦岭松树沟蛇绿岩的纯橄岩发育自形角闪石(引自Cao等, 2016); (c), (d) 雅江带泽当蛇绿岩铬铁矿内含水矿物包裹体(引自Xiong等, 2017b)。矿物代号: Cpx, 单斜辉石; Opx, 斜方辉石; Ol, 橄榄石; Ch, 铬铁矿; Amp, 角闪石; Phl, 金云母; Serp, 蛇纹石

境、并随后卷入早古生代的碰撞造山过程(Cao等, 2016)。这三个不同时代的蛇绿岩均记录了丰富的熔/流体与地幔楔橄榄岩反应等复杂过程, 具体包括: (1) 对流地幔楔来源的玻安质/玄武质熔体与岩石圈地幔楔反应, 生成纯橄岩和铬铁矿岩(图4a-d); (2) 俯冲板片来源的富硅熔/流体沿着地幔楔内纯橄岩通道迁移, 形成含角闪石的辉石岩脉(图5a; 作者未发表数据); (3) 俯冲板片来源高密度富硅流体交代岩石圈地幔楔, 生成角闪石(图5b; Cao等, 2016)和金云母(图5c), 并保留不同氧化-还原性质的流体包裹体(Song等, 2009); (4) 俯冲板片来源的低密度、低温流体交代岩石圈地幔楔, 形成蛇纹石和绿泥石等(图5d), 并交代岩石圈地幔楔内辉长岩脉体形成异剥钙榴岩(图4d; Tang等, 2018); (5) 俯冲板片来源的高密度含水流体交代地幔楔橄榄岩, 能够使得橄榄岩强烈富集流体活动性元素(例如Li)、并适当富集高场强元素(例如Zr; 图6), 而硅酸盐熔体交代无法分馏Li和Yb(二者具有类似的不相容性)、却能明显分馏Zr和Yb(Zr的不相容性远高于Yb)。

2.3 小结

俯冲带型蛇绿岩中的原始超基性岩来自大洋扩张中心(包括洋中脊)岩石圈, 记录了伴随大洋俯冲带启动(例如新喀里多尼亚蛇绿岩)、演化(例如Troodos、

图6 代表性俯冲带型蛇绿岩中橄榄岩全岩和单斜辉石的 $(Zr/Yb)_N$ 和 $(Li/Yb)_N$ 变化图

松树沟橄榄岩数据来自Cao等(2016)和Yu等(2017), 泽当方辉橄榄岩、二辉橄榄岩的全岩和单斜辉石数据来自Xiong等(2017a); N代表原始地幔(McDonough和Sun, 1995)标准化元素比值

泽当、罗布莎蛇绿岩)和趋向成熟(例如Thetford Mines蛇绿岩)不同阶段、不同空间位置的熔/流体-地幔楔相互作用。熔体可来自俯冲板片, 也可来自对流地幔楔, 可以是富硅熔体, 也可以是贫硅熔体, 但碳酸盐熔体却相对罕见; 流体则来自不同深度的俯冲板片, 可来自俯冲壳层, 也可来自俯冲的蛇纹石化地幔, 可以是富水流体, 也可以是含碳酸盐流体。来自俯冲板片的熔/流体会在大洋俯冲隧道内沿着因机械混杂而成的裂隙向上以不同形式迁移, 并与地幔楔橄榄岩发生化学反应, 形成一系列独特的交代岩石、矿物甚至化学特征显示(图2a)。来自俯冲带上覆地幔楔的熔体会伴随地幔角流和弧前岩石圈扩张, 向上迁移并与岩石圈地幔楔发生复杂的熔-岩相互作用。可见, 如何识别熔/流体的起源和性质及其与地幔楔橄榄岩相互作用的方式和时代, 如何识别洋中脊橄榄岩与板块边缘地壳之间的相互作用, 是研究俯冲带型蛇绿岩的难点, 也是理解大洋型俯冲带壳幔相互作用的关键。

3 大陆型俯冲带橄榄岩

造山带橄榄岩与蛇绿岩不同, 其原始超基性岩来自岩石圈地幔, 主要经历与大陆边缘有关的汇聚或裂解等动力学过程及其相关的岩石物理和化学性质演变, 但少量蛇绿岩经历俯冲带过程叠加也可形成造山

带橄榄岩(Bodinier和Godard, 2014). 按照变质相和压力条件的不同, 可将造山带橄榄岩划分为三类: (1) 高压/超高压型, 例如挪威西片麻岩带和大别-苏鲁带中的石榴子石相橄榄岩地质体; (2) 中压型, 主体尖晶石相, 例如摩洛哥的Beni Bousera和西班牙的Ronda; (3) 低压型, 浅部伸展体制下的尖晶石相和斜长石相橄榄岩地质体, 例如意大利阿尔卑斯的Lanzo和External Ligurides. 同时, 这三类造山带橄榄岩可形成于板块汇聚造山过程(例如高压/超高压型), 或产生于大陆边缘裂解抬升过程(例如中-低压型)(Bodinier和Godard, 2014).

形成于大陆碰撞过程的石榴子石相橄榄岩地质体, 由于其原岩属性的差异(Carswell, 1983; Zhang等, 2000), 又分为M型(或Mg-Cr型)和C型(或Fe-Ti型). 世界上代表性的地幔楔型造山带橄榄岩(图3), 包括: 挪威西片麻岩省的Otrøy-Fjortoft橄榄岩(van Roermund等, 2002; Spengler等, 2006; Scambelluri等, 2008)、意大利东阿尔卑斯的Ulten橄榄岩(Rampone和Morten, 2001; Scambelluri等, 2006), 以及中国柴北缘带的胜利口橄榄岩(Song等, 2004, 2005a, 2005b, 2007; Xiong等, 2011, 2014, 2015; Chen R X等, 2017)、大别造山带的毛屋超镁铁质岩(Malaspina等, 2009b, 2015, 2017; Chen等, 2013a, 2013b; Campione等, 2017)、苏鲁造山带的荣成、仰口、许沟、东海-芝麻坊等地造山带橄榄岩(杨建军等, 1994; Zhang等, 1995, 2000, 2004, 2007, 2009, 2010; Yang, 2003; Zheng等, 2005, 2006b, 2014; Malaspina等, 2006, 2009a; Liou等, 2007; Ye等, 2009; Zhang等, 2011; Su等, 2016, 2017; Li等, 2018a). 代表性的壳源型造山带橄榄岩(图3), 包括: 挪威西片麻岩省的Svartberget橄榄岩(Vrijmoed等, 2013), 以及中国西部阿尔金造山带的英格礼萨伊橄榄岩(刘良等, 2002; Wang等, 2011)、大别造山带的碧溪岭橄榄岩(Zheng等, 2008)等, 它们均是早先侵入到大陆深部地壳的超基性-基性堆晶岩体, 后伴随大陆俯冲-折返而形成的石榴子石相造山带橄榄岩. 本文将重点介绍上述地幔楔型造山带橄榄岩的研究现状, 关于壳源型造山带橄榄岩的研究进展可见其他文章(Zhang等, 2000; Zheng等, 2008; Liou等, 2009).

3.1 国外经典的地幔楔型造山带橄榄岩

挪威西片麻岩省的Otrøy-Fjortoft橄榄岩是世界上已知出露规模最大、最具代表性的造山带超硅石榴石

橄榄岩, 来自早古生代Baltica俯冲大陆上盘的Laurentia大陆岩石圈地幔楔(van Roermund和Drury, 1998; Spengler等, 2006; van Roermund, 2009a, 2009b), 该橄榄岩最近一次完全再平衡的深度在~200km(~6GPa)的地幔深度. Otrøy-Fjortoft石榴石橄榄岩和其中辉石岩发育至少七期变质组合(van Roermund, 2009b), 其中形成超硅石榴石的阶段就有三期(M1~M3), 分别对应于太古宙超高温下减压熔融、中元古代等压冷却和早古生代大陆深俯冲三大阶段, M4~M7期所形成的矿物组合分别对应伴随俯冲陆壳折返的不同退变质阶段, 其中最能反映大陆俯冲隧道壳幔相互作用的是M3~M7阶段所形成的岩石类型和矿物组合(Spengler等, 2006; Scambelluri等, 2008; van Roermund, 2009a, 2009b). 前人对这些橄榄岩内部小规模出现的辉石岩透镜体和辉石岩脉体(图7a、7b、8a)开展了一系列研究, 结果显示与M3期超硅石榴石平衡共生的矿物有单斜辉石、斜方辉石(图8b)、金云母、白云石、菱镁矿和硫化物等, 并且在超硅石榴石内部发育类型复杂的多相包裹体(包括尖晶石、辉石、金云母、钾霞石、角闪石、碳酸盐矿物、Fe-Ni硫化物、重晶石、磷灰石、金红石、锆石、榍石和金刚石/石墨等); 这些复杂矿物组合被解释为高密度富含硅酸盐组分的C-H-O流体/超临界流体, 在约180~200km深度的地幔楔内交代橄榄岩后结晶而成, 这些流体被认为可能起源于俯冲的Baltica大陆地壳(van Roermund和Drury, 2000; van Roermund等, 2002; Brueckner等, 2002; Carswell和van Roermund, 2005; Scambelluri等, 2008, 2010; Malaspina等, 2010; Rielli等, 2017). 此外, 地球化学证据显示, M3期超硅石榴石及其平衡共生的含水矿物(例如金云母)具有明显的陆壳来源流体交代特征(Scambelluri等, 2008, 2010). M4~M7期矿物组合, 包括石榴石次变边、尖晶石-辉石-角闪石的环状边以及退变质阶段生成的低温角闪石、绿泥石、滑石和蛇纹石等含水矿物. 这些矿物的存在暗示, 在俯冲隧道内的折返陆壳中依然发生着复杂且强烈的流体与地幔楔岩石的交代作用(van Roermund, 2009a, 2009b).

意大利东阿尔卑斯造山带的Ulten石榴石橄榄岩是华力西期造山作用的产物, 橄榄岩峰期变质时代与其内部交代岩石以及地壳围岩一致, 均为约335~330Ma, 暗示石炭纪大陆俯冲隧道的壳幔相互作用(Tumiati等, 2003). Ulten石榴石橄榄岩最早来自高

图 7 代表性地幔楔型造山带橄榄岩中熔/流体交代现象野外和手标本照片

(a), (b) 挪威Otøy-Fjortoft纯橄岩内石榴石辉石岩脉体, 分别暗示硅酸盐熔体交代和含硅酸盐组分的碳酸盐熔体交代; (c) 意大利东阿尔卑斯造山带的Ulten石榴石-角闪石橄榄岩内含石榴石辉石岩脉体, 暗示含水流体交代和含水硅酸盐熔体交代(引自Braga和Bargossi, 2014); (d) 柴北缘带胜利口橄榄岩内石榴石方辉橄榄岩与石榴石二辉橄榄岩互层(引自Xiong等, 2015)

温的尖晶石相(约50km)岩石圈地幔楔, 随后卷入大陆俯冲隧道并被携带至约100km的地幔深度(石榴石相)发生峰期变质平衡, 并伴随陆壳折返抬升至造山带浅部(Scambelluri等, 2006, 2010; Braga和Bargossi, 2014). 该地质体主体为饱满的含有角闪石和金云母的二辉橄榄岩, 橄榄岩内含辉石岩脉体(图7c); 矿物组合的演变关系主要为: 尖晶石外生长石榴石环, 并且从无水尖晶石相二辉橄榄岩转变为含水石榴石相二辉橄榄岩(Nimis和Morten, 2000; Scambelluri等, 2006, 2010; Braga和Bargossi, 2014). 在石榴石相矿物组合内, 还发育多种显性交代矿物, 如角闪石、金云母、磷灰石、褐帘石、白云石、绿泥石、蛇纹石等(Tumiati等, 2003; Marocchi等, 2007, 2010; Sapienza等, 2009). 同时, 在地球化学上, Ulten橄榄岩显示多种隐性交代过程: 包括硅酸盐熔体交代(Scambelluri等, 2006)、碳酸盐熔/流体交代(Sapienza等, 2009)、壳源C-H-O氧化流体交代等(Rampone和Morten, 2001; Marocchi等, 2007, 2010; Malaspina等, 2009b; Ionov等, 2017; Rielli等, 2017). 这些显性和隐性化学交代作用的发生, 同时伴

随俯冲隧道内/俯冲带壳幔界面处的机械变形过程, 例如Marocchi等(2007, 2010)展示过橄榄岩内交代岩石多分布在陆壳围岩附近以及内部剪切带的证据.

3.2 国内典型的地幔楔型造山带橄榄岩

中国西部柴北缘带胜利口(或称为绿梁山)造山带橄榄岩是含超硅石榴石的橄榄岩杂岩体, 记录着早古生代(约440~420Ma)大陆深俯冲过程(深度超过200km)以及俯冲隧道壳幔相互作用(Song等, 2004). 尽管前期对该橄榄岩的起源有较大争议, 如认为是阿拉斯加型超镁铁质堆晶杂岩体(Song等, 2007)、早先置位于俯冲陆壳的大洋岩石圈残片(Yang和Powell, 2008)等不同认识, 但最新的研究成果显示, 胜利口造山带橄榄岩, 可能是具有太古宙起源属性的大陆岩石圈地幔楔(Shi等, 2010; Xiong等, 2011, 2014, 2015; Chen R X等, 2017). 胜利口橄榄岩体主体是方辉橄榄岩和纯橄岩, 局部条带状二辉橄榄岩和辉石岩与难熔的方辉橄榄岩或纯橄岩互层(图7d), 橄榄岩主体的变形面理与围岩片麻岩及混合岩的面理一致, 同时在橄榄岩体外

图 8 代表性地幔楔型造山带橄榄岩中熔/流体显性交代作用显微((a), (b), (e)~(h))和背散射((c), (d))照片

(a)和(b)为挪威Otøy-Fjortoft方辉橄榄岩内石榴石辉石岩脉体和石榴石-单斜辉石集合体, 暗示硅酸盐熔体交代作用; (c)和(d)分别为柴北缘胜利口辉石岩内原位锆石(Xiong等, 2014)以及大别毛屋辉石岩内原位锆石, 暗示高密度流体活动; (e)和(f)分别为大别毛屋纯橄岩内碳酸盐矿物巨晶以及苏鲁荣成地区纯橄岩内菱镁矿-方解石集合体(Su等, 2017), 暗示碳酸盐熔体交代作用; (g)和(h)分别为苏鲁东海地区橄榄岩内钛斜硅镁石和金云母, 暗示含硅酸盐组分流体交代作用。矿物代号: Cpx, 单斜辉石; Opx, 斜方辉石; Ol, 橄榄石; Gt, 石榴石; Zir, 锆石; Kely, 次变边; Ru, 金红石; Phl, 金云母; Srp, 蛇纹石; Ti-Chu, 钛斜硅镁石

围出现长英质混合岩与橄榄岩高度混杂的现象, 均指示强烈的壳幔机械混合和塑性变形(Xiong等, 2015)。Re-Os、Lu-Hf、Sm-Nd和U-Pb同位素组成显示, 这些橄榄岩杂岩体可能来自中太古代克拉通型岩石圈地

幔, 经历了伴随Columbia和Rodinia超大陆裂解时期的硅酸盐熔体交代、并在早古生代记录复杂的洋-陆俯冲以及陆-陆俯冲造山过程(Xiong等, 2011, 2014, 2015)。在早古生代大陆深俯冲过程中, 胜利口橄榄岩

处于祁连地块的地幔楔环境, 经历含硅酸盐组分的高密度C-H-O流体/超临界流体交代(Xiong等, 2011, 2015; Chen R X等, 2017)以及低密度含水流体交代作用(Xiong等, 2015). 这些流体交代作用还生成了超硅石榴石内角闪石出溶体(Song等, 2005b)、金云母集合体(Xiong等, 2014)、峰期石榴石和辉石内多种含水矿物包裹体(Yang和Powell, 2008)、锆石(图8c; Song等, 2005a; Xiong等, 2011, 2014; Chen R X等, 2017)等多种交代矿物. 鉴于这些橄榄岩体发育从超硅石榴石相到折返退变质阶段的矿物组合特征, 而且与挪威西片麻岩省的Otrøy-Fjærtøft橄榄岩非常相似, 可以通过分析其不同阶段矿物的物理、化学性质来揭示俯冲隧道内从深到浅的壳幔相互作用过程, 然而目前对该问题的研究仍很缺乏, 急需进一步展开.

大别造山带的毛屋橄榄岩-辉石岩杂岩体产于三叠纪超高压变质陆壳岩石中, 与陆壳岩石呈互层状产出, 主体为石榴石斜方辉石岩, 局部为纯橄岩、方辉橄榄岩、二辉石岩、单斜辉石岩(Jahn等, 2003; Chen等, 2013a, 2013b, 2017). 该杂岩体代表着富硅熔体与难熔的元古宙大陆岩石圈地幔楔发生熔-岩反应的产物(Chen Y等, 2017), 并记录了峰期变质条件下(约4GPa, 750~800℃)复杂的壳源熔/流体交代地幔楔过程(Malaspina等, 2006, 2009b, 2015, 2017; Chen等, 2013a, 2013b; Campione等, 2017). 具体表现为: (1) 石榴石内含水、氧化的单相或多相包裹体组合(如尖晶石、辉

石、角闪石、绿泥石、滑石、云母、钛斜硅镁石等), 代表超高压峰期阶段壳源富硅-富不相容元素的含水熔/流体(或超临界流体)在地幔楔环境下矿物内结晶的产物(Malaspina等, 2006, 2015, 2017; Campione等, 2017); (2) 变质锆石, 多产于辉石岩内金红石和金云母附近(图8d), 代表变质峰期时高密度富硅、富HFSE流体活动的产物; (3) 纯橄岩内菱镁矿、白云石和方解石等原生碳酸盐矿物(图8e), 反映碳酸盐熔/流体交代过程; (4) 矿物微量元素化学特征显示显著的壳源流体交代特征(Malaspina等, 2006; Chen等, 2013b).

苏鲁造山带产出的地幔楔型造山带橄榄岩相对较发育(图3), 按照由北向南划分为5个区域: 荣成、仰口、日照、赣榆和许沟-东海(图9), 其变质峰期温压条件为3~6GPa、700~900℃, 暗示来自大陆俯冲隧道内不同深度位置地幔楔. 前人对苏鲁造山带橄榄岩已经开展了较为系统的工作(例如, Zhang等, 2004; Zheng等, 2006a, 2006b, 2014; 陈意等, 2015), 基本确定了它们具有华北陆下岩石圈地幔楔的起源, 并经历复杂的交代改造事件(Yang等, 1993; Yang和Jahn, 2000; Zhang等, 1995, 2000, 2004, 2007, 2009, 2010; Yang, 2003, 2006; Zheng等, 2005, 2008, 2014; Zheng, 2009; Malaspina等, 2009a, 2012; Liou等, 2007; Yang等, 2007; Ye等, 2009; Zhang等, 2011; Su等, 2016, 2017; Li等, 2018a; 郑建平和戴宏坤, 2018), 具体研究进展不再赘述. 苏鲁造山带地幔楔橄榄岩记录的交代作用非常

图9 苏鲁造山带地幔楔型橄榄岩中单斜辉石的 $Mg^\#$ 和 CaO/Al_2O_3 变化图(a)以及 Ti/Eu 和 $(La/Yb)_N$ 变化图(b)

(a) 虚线来自宗克清和刘勇胜(2018), (b) 源自Coltorti等(1999). 荣成地区数据来自: 叶凯和徐平(1992)、Zhang等(1994)、周秀仲(1996)、Hiramatsu和Hirajima(1995)、任玉峰等(2007)、Zhao等(2007)、Su等(2016); 仰口数据来自: Yoshida等(2004)、Zhang等(2005); 日照地区数据来自: Zhang等(1994)、Hiramatsu等(1995)、Zhao等(2007)、高天山等(2015)、Li等(2018b); 赣榆数据来自: Chen等(2009); 许沟-东海地区数据来自: Zhang等(1994, 2000, 2008, 2010)、Yang和Jahn(2000)、Zheng等(2005, 2006b)、Yuan等(2007)、Yang等(2007)、Malaspina等(2009a)、Ye等(2009)

明显(图9a和9b), 主要表现为: 硅酸盐熔体交代(日照、仰口和荣成橄榄岩)、碳酸盐熔/流体交代(例如图8f; 5个区域的造山带橄榄岩都存在)以及富水流体交代过程(例如图8g和8h; 5个区域都存在); 相应的显性交代矿物也普遍发育, 例如锆石、角闪石、金云母、钛斜硅镁石、帘石、磷灰石、独居石、菱镁矿、白云石、硫化物等(Zhang等, 1995, 2000, 2007, 2009, 2010; Yang和Jahn, 2000; Zheng等, 2006a, 2014; Malaspina等, 2009a, 2012; Ye等, 2009; Zhang等, 2011; Su等, 2016, 2017; 郑建平等, 2018).

3.3 小结

大陆型俯冲带橄榄岩(地幔楔型造山带橄榄岩)主要记录了俯冲大洋和大陆地壳与上覆大陆岩石圈地幔楔之间的相互作用(图2b), 当然它们还记录着大陆岩石圈地幔的早期演化. 大陆俯冲隧道内壳幔相互作用在本质上类似于大洋俯冲隧道, 即均发生不同块体及岩石间的机械混合、变质变形、化学反应和熔/流体活动. 与大洋俯冲隧道相比, 大陆俯冲隧道内发育的流体和熔体活动是否要少得多(Ernst和Liou, 2008; Zheng, 2012; Hermann和Rubatto, 2014), 还是一个尚未解决的问题(郑永飞等, 2016). 无论如何, 这些熔/流体活动对大陆岩石圈地幔楔和大陆俯冲隧道都产生了重要影响, 主控着大陆俯冲带的物质循环. 大陆型俯冲带橄榄岩中所记录的熔/流体活动可以呈弥散状扩散, 可沿物理裂隙迁移, 也可沿着熔/流体通道运输; 熔/流体来自俯冲陆壳, 可以是硅酸盐熔体、富硅高密度/超临界流体, 也可是含硅酸盐组分的C-H-O流体; 熔/流体均具有相对氧化的性质. 对造山带地幔楔型橄榄岩开展进一步研究的难点和热点在于: (1) 如何利用原位地球化学和显微构造学分析手段, 来约束交代事件与变质、变形的关系; (2) 如何限定大陆俯冲隧道内壳幔相互作用的时空演化; (3) 如何将造山带橄榄岩恢复到俯冲前所处的地幔楔空间位置, 并揭示大陆边缘地幔楔的属性及演化; (4) 如何通过热力学计算来揭示流体与地幔楔相互作用的细节.

4 俯冲带橄榄岩记录的壳幔物理和化学作用

4.1 物理相互作用

俯冲隧道内壳幔物理相互作用(Bebout, 2007;

Zheng, 2012; Spandler和Pirard, 2013; 郑永飞等, 2013)主要表现为: (1) 不同岩石通过机械混合形成混杂岩带, 例如阿尔卑斯带中部的Adula-Cima Lunga单元(Scambelluri等, 2015)、新喀里多尼亚的Pouebo单元(Cluzel等, 2001), 它们均以蛇纹岩或泥质岩为基质、内含基性-超基性透镜体, 在几何结构上呈现为塑性变形的构造混杂岩; (2) 地幔楔橄榄岩内各种裂隙和剪切带的发育, 它们是不同的岩性构造混杂的产物, 并构成熔/流体活动的通道(Konrad-Schmolke等, 2011; John等, 2012; Spandler和Pirard, 2013), 例如各种辉石-角闪岩脉体、金云母脉、蛇纹石-滑石脉等; (3) 岩石和矿物的塑性或脆性变形, 岩石在野外上显示出高度塑性揉皱、拉伸甚至局部互层化、片理化, 例如苏鲁仰口橄榄岩(Zhang等, 2005)、大别毛屋辉石岩(Jahn等, 2003); 在显微构造上矿物组合体现出的形变、位错和滑移特征等, 反映了地幔楔的物理化学条件、含水性和构造环境(Cao等, 2015, 2016, 2017); (4) 地幔楔橄榄岩的水化交代过程(如橄榄岩蛇纹石化并析出磁铁矿等)影响了岩石的密度、磁性、波速等物理性质, 并对造山带区域上的地球物理航磁、重力和波速异常现象(Liu等, 2010, 2015; Li Z Y等, 2017).

这些俯冲带壳幔物理作用过程主控着造山带和地幔楔的空间几何结构以及构造组合, 同时也约束了壳幔化学相互作用所发生的物理空间. 宏观和微观的变形作用对俯冲带壳幔界面的变质过程、熔/流体活动以及交代作用, 均起着关键的“催化”作用. 更重要的是, 岩石和矿物的物理性质是进行地质学、地球化学与地球物理学交叉的重要纽带, 需要大力开展对俯冲带地质体橄榄岩, 特别是对不同蚀变程度的橄榄岩进行岩石和矿物物理性质的对比研究.

4.2 化学相互作用

俯冲带内壳幔元素交换和物质循环的主要方式是通过流/熔体与地幔楔岩石发生化学相互作用来实现(Zheng, 2012; Hermann等, 2013; Zheng和Hermann, 2014). 在不同温压条件下的硅酸盐岩石-水体系中, 俯冲带内的流/熔体可划分为富水流体(aqueous fluid)、含水熔体(hydrous melt)和超临界流体(supercritical fluid)(Manning, 2004; Zheng等, 2011; Hermann等, 2013; Ni等, 2017). 此外, 低密度C-H-O流体、碳酸盐流/熔体和硫化物熔体等其他成分的流体或熔体, 也在

俯冲带壳幔物质交换循环中扮演重要角色(Schmidt和Poli, 2014).

对于俯冲的中酸性、基性和超基性岩石体系, 在相对低压(如 $<3\sim4$ GPa)条件下, 富水流体和含水熔体以湿固相线为界, 分别在低温和高温条件下独立为两个液相存在; 而在相对高压(如 $>3\sim4$ GPa, 达到第二临界点)条件下, 这两相混溶为一体, 出现超临界流体(Mibe等, 2011; Zheng等, 2011; Hermann等, 2013; Ni等, 2017). 实验岩石学的研究结果显示, 随着俯冲隧道内温度和压力的升高, H_2O 的溶解能力显著提高, 而且阴离子化学配体(如 Cl^- 等)的络合效应被放大, 使得超临界流体携带和运移溶质的能力比富水流体和其他低密度C-H-O流体高出几个数量级(Manning, 2004; Kessel等, 2005; Zheng和Hermann, 2014; Schmidt和Poli, 2014). 因此, 在深度超过约130 km时, 与大陆俯冲隧道内地幔楔岩石发生相互作用的流体可能主要为超临界流体, 当然不排除熔体和低密度C-H-O流体存在的可能.

当俯冲隧道的温压条件达到俯冲板片岩石内含水矿物的脱挥发分线后, 能够产生不同性质的流体或熔体. 这些流/熔体相对富硅, 在化学上与地幔岩石不平衡, 从而会与俯冲隧道内裹挟的地幔楔碎片, 主要是橄榄岩块, 发生不同方式和程度的相互作用. 研究显示, 在俯冲带环境下流/熔体-橄榄岩相互作用的方式有两类(Zheng, 2012; O'Reilly和Griffin, 2013), 一类是隐性交代作用(流/熔体与橄榄岩发生化学反应但是没有生成新生矿物), 另一类是显性交代作用(熔/流体与橄榄岩反应形成新生矿物), 其中均伴有流/熔体的产生及其对地幔楔橄榄岩的溶解-运移-沉淀作用(例如, Campione等, 2017). 这些相互作用具有如下效应: (1) 造成地幔楔橄榄岩内不相容元素和挥发分的富集(Zheng等, 2005; Zhang等, 2007; Chen等, 2013a); (2) 形成新生的无水/含水硅酸盐矿物、碳酸盐矿物以及伴生硫酸盐矿物/硫化物、单质和氧化物等(Rampone和Morten, 2001; Yang, 2003; Scambelluri等, 2006; 杨经绥等, 2006; Zheng等, 2006a, 2014; Xiong等, 2011; Su等, 2016, 2017; Chen Y等, 2017); (3) 富硅熔体与橄榄岩反应, 诱发贫硅矿物(橄榄石)的溶解和富硅矿物(辉石等)的结晶, 形成橄榄岩内的辉石岩脉体(Tang等, 2013; Xiong等, 2014; 陈意等, 2015); (4) 导致在橄榄岩矿物内保留流/熔体包裹体及其与矿物反应后的产物(Xiao

等, 2001; Malaspina等, 2006, 2009a, 2015, 2017; Song等, 2009; Campione等, 2017).

在大洋型俯冲带橄榄岩中, 来自软流圈对流地幔楔的硅酸盐熔体占据主导, 与岩石圈地幔楔反应形成纯橄岩、铬铁矿岩、辉石岩、辉长-辉绿岩脉等; 而来自俯冲大洋板片的流体以富水流体为主, 主要沿着俯冲隧道内裂隙或剪切带等薄弱带交代上覆岩石圈地幔楔, 形成在俯冲型蛇绿岩底部发育的含水矿物聚集脉体. 在大陆型俯冲带橄榄岩中, 来自俯冲陆壳的硅酸盐熔/流体、碳酸盐熔/流体和富水流体占据主导, 与大陆岩石圈地幔楔反应形成多种交代岩石或交代矿物; 而来自对流地幔楔的贫硅熔体却很罕见. 这些差异的根本原因在于俯冲带的物理几何结构、温度场结构和动力学过程的不同(郑永飞等, 2013, 2016). 例如, 洋-洋俯冲时上盘岩石圈厚度通常较薄, 而洋-陆或陆-陆俯冲时上盘岩石圈较厚, 从而决定了它们俯冲角度的差异以及对地幔楔温度和流动轨迹的影响范围, 最终体现在俯冲带壳幔化学相互作用上的差异. 大洋型和大陆型俯冲带壳幔相互作用的差异, 同样可能部分解释豆荚状铬铁矿体仅在蛇绿岩内发育、而极少存在于大陆岩石圈地幔楔, 原因可能在于前者是软流圈来源的熔体(富Cr)为主控因素, 而后者是俯冲陆壳来源的小比例熔/流体(贫Cr)为主控因素.

5 主要认识与展望

俯冲带型蛇绿岩中地幔单元和地幔楔型造山带橄榄岩, 分别代表了大洋俯冲和大陆俯冲两种情形下的地幔楔岩石, 是记录俯冲带物质循环和能量交换的关键对象, 也是理解地球层圈相互作用的重要途径. 俯冲带壳幔相互作用的本质是两种构造单元(俯冲地壳和地幔楔)在机械作用(物理过程)主导下发生复杂的化学相互作用, 核心过程是俯冲带熔/流体和地幔楔岩石在多种物理化学条件下发生相互作用(包括进入深部地幔的残余俯冲板片与地幔的相互作用等). 俯冲带大洋型橄榄岩记录了从洋-洋俯冲启动、发展、成熟甚至消亡阶段复杂的熔/流体交代、熔-岩和水-岩相互作用、变形变质过程、金属成矿作用(如铬铁矿成因)以及壳幔物质交换动力学过程; 俯冲带大陆型橄榄岩则记录了从洋-陆俯冲到陆-陆俯冲、碰撞、折返阶段的强烈物理变形变质过程、多种性质的熔/流体交代作

用以及高度复杂的壳幔物质循环过程。

未来对俯冲带地质体橄榄岩开展工作的重心应该放在: (1) 利用原位微区地球化学和显微构造学等综合分析手段约束交代过程与变质、变形的时空关系; (2) 精细识别在俯冲带内活动熔/流体的起源与性质, 甚至在微米-纳米尺度对熔/流体活动的产物进行系统研究; (3) 结合热力学模拟计算恢复俯冲带壳幔相互作用的温度、压力、氧逸度、流体组分等物理化学条件; (4) 利用地幔楔岩石属性及演化约束汇聚板块边缘的金属成矿作用; (5) 结合地质学、地球化学、数值模拟、高温高压实验和岩石物性资料, 对特定构造区的岩石圈演化开展跨学科研究。

致谢 感谢郑永飞院士的组织、邀请和建议, 以及三位审稿专家的宝贵修改意见。杨经绥院士和Griffin W L教授给予有益讨论, 曹毅博士提供图5b的原始照片, 周翔博士、吴魏伟博士和梁豪、田廉荣、李一雄、郑鸿达等研究生为本文的完成提供了协助。

参考文献

- 陈意, 苏斌, 郭顺. 2015. 大别-苏鲁造山带橄榄岩: 进展和问题. 中国科学: 地球科学, 45: 1245–1269
- 高天山, 陈江峰, 谢智. 2015. 苏鲁造山带中胡家林超镁铁质岩岩石地球化学特征. 矿物岩石地球化学通报, 34: 601–618
- 刘良, 孙勇, 肖培喜, 车自成, 罗金海, 陈丹玲, 王焰, 张安达, 陈亮, 王永合. 2002. 阿尔金发现超高压(>3.8GPa)石榴二辉橄榄岩. 科学通报, 47: 657–662
- 任玉峰, 杨经绥, 张仲明, 李天福. 2007. 中国大陆科学钻探工程卫星孔CCSD-PP6钻孔橄榄岩岩石学研究. 地质学报, 81: 1004–1016
- 肖益林, 孙贺, 顾海欧, 黄建, 李王晔, 刘磊. 2015. 大陆深俯冲过程中的熔/流体成分与地球化学分异. 中国科学: 地球科学, 45: 1063–1087
- 杨建军, 朱红, 邓晋福, 周天祯, 赖绍聪. 1994. 柴达木北缘石榴石橄榄岩的发现及其意义. 岩石矿物学杂志, 13: 97–105
- 杨经绥, 李天福, 张仲明, 陈松永, 张儒媛. 2006. 苏鲁芝麻坊超镁铁岩的岩石成因: 大陆科学钻探卫星孔(CCSD-PP1)岩心研究. 地球科学-中国地质大学学报, 31: 437–456
- 叶凯, 徐平. 1992. 山东荣成大吨榴辉岩成因岩石学研究. 岩石学报, 8: 27–39
- 郑建平, 赵伊, 熊庆. 2018. 造山带橄榄岩中的锆石及其成因意义. 地球科学, doi:10.3799/dqkx.2018.275
- 郑建平, 戴宏坤. 2018. 西太平洋板片俯冲与后撤引起华北东部地幔置换并导致陆内盆-山耦合. 中国科学: 地球科学, 48: 436–456
- 郑永飞, 赵子福, 陈伊翔. 2013. 大陆俯冲隧道过程: 大陆碰撞过程中的板块界面相互作用. 科学通报, 58: 2233–2239
- 郑永飞, 陈仁旭, 徐峥, 张少兵. 2016. 俯冲带中的水迁移. 中国科学: 地球科学, 46: 253–286
- 郑永飞, 徐峥, 赵子福, 戴立群. 2018. 华北中生代镁铁质岩浆作用与克拉通减薄和破坏. 中国科学: 地球科学, 48: 379–414
- 周秀仲. 1996. 山东大吨榴辉岩和石榴透辉石岩的成因. 岩石矿物学杂志, 15: 110–125
- 宗克清, 刘勇胜. 2018. 华北克拉通东部岩石圈地幔碳酸盐熔体交代作用与克拉通破坏. 中国科学: 地球科学, 48: 732–752
- Abelson M, Baer G, Agnon A. 2001. Evidence from gabbro of the Troodos ophiolite for lateral magma transport along a slow-spreading mid-ocean ridge. *Nature*, 409: 72–75
- Anonymous. 1972. Penrose field conference on ophiolites. *Geotimes*, 17: 24–25
- Bailey E H, Blake M C, Jones D L. 1970. On-land Mesozoic oceanic crust in California Coast Ranges. *Geological Survey Research, U.S. Geol Survey Prof Paper*, 700: 70–81
- Batanova V G, Sobolev A V. 2000. Compositional heterogeneity in subduction-related mantle peridotites, Troodos massif, Cyprus. *Geology*, 28: 55–58
- Bebout G E. 2007. Metamorphic chemical geodynamics of subduction zones. *Earth Planet Sci Lett*, 260: 373–393
- Bebout G E. 2014. Chemical and isotopic cycling in subduction zones. In: Holland H D, Turekian K K, eds. *Treatise on Geochemistry*. 2nd ed. Amsterdam: Elsevier. 703–747
- Behn M D, Kelemen P B, Hirth G, Hacker B R, Massonne H J. 2011. Diapirs as the source of the sediment signature in arc lavas. *Nat Geosci*, 4: 641–646
- Bodinier J L, Godard M. 2014. Orogenic, ophiolitic, and abyssal peridotites. In: Holland H D, Turekian K K, eds. *Treatise on Geochemistry*. 2nd ed. Amsterdam: Elsevier. 103–167
- Braga R, Bargossi G M. 2014. Crust-mantle relationships close at hands. Walking through the Ulten-Nonsberg orogenic lower crust. *Geol Field Trips Società Geol Italiana*, 6: 1–46
- Brongniart A. 1813. Essai de classify cation minéralogique des roches mélanges. *Journal des Mines*, XXXIV: 190–199
- Brueckner H K, Carswell D A, Griffin W L. 2002. Paleozoic diamonds within a Precambrian peridotite lens in UHP gneisses of the Norwegian Caledonides. *Earth Planet Sci Lett*, 203: 805–816
- Campione M, Tumati S, Malaspina N. 2017. Primary spinel+chlorite inclusions in mantle garnet formed at ultrahigh-pressure. *Geochem Persp Lett*, 4: 19–23
- Cao Y, Jung H, Song S, Park M, Jung S, Lee J. 2015. Plastic deformation and seismic properties in fore-arc mantles: A petrofabric analysis of the Yushigou harzburgites, North Qilian

- suture zone, NW China. *J Petrol*, 56: 1897–1944
- Cao Y, Song S, Su L, Jung H, Niu Y. 2016. Highly refractory peridotites in Songshugou, Qinling orogen: Insights into partial melting and melt/fluid-rock reactions in forearc mantle. *Lithos*, 252–253: 234–254
- Cao Y, Jung H, Song S. 2017. Olivine fabrics and tectonic evolution of fore-arc mantles: A natural perspective from the Songshugou dunite and harzburgite in the Qinling orogenic belt, central China. *Geochem Geophys Geosyst*, 18: 907–934
- Carswell D A. 1983. The petrogenesis of contrasting Fe-Ti and Mg-Cr garnet-peridotite types in the high grade gneiss complex of western Norway. *Bull Mineral*, 106: 727–750
- Carswell D A, van Roermund H L M. 2005. On multi-phase mineral inclusions associated with microdiamond formation in mantle-derived peridotite lens at Bardane on Fjortoft, west Norway. *Eur J Mineral*, 17: 31–42
- Chan G H N, Aitchison J C, Crowley Q G, Horstwood M S A, Searle M P, Parrish R R, Chan J S L. 2015. U-Pb zircon ages for Yarlung Tsangpo suture zone ophiolites, southwestern Tibet and their tectonic implications. *Gondwana Res*, 27: 719–732
- Chen R X, Li H Y, Zheng Y F, Zhang L, Gong B, Hu Z, Yang Y. 2017. Crust-mantle interaction in a continental subduction channel: Evidence from orogenic peridotites in North Qaidam, Northern Tibet. *J Petrol*, 58: 191–226
- Chen S Z, Yang J S, Li T F. 2009. Petrological investigation of the Ganyu peridotite in the Sulu ultrahigh-pressure terrane, eastern China. *Tectonophysics*, 475: 383–395
- Chen Y, Ye K, Guo S, Wu T F, Liu J B. 2013a. Multistage metamorphism of garnet orthopyroxenites from the Maowu mafic-ultramafic complex, Dabieshan UHP terrane, eastern China. *Int Geol Rev*, 55: 1239–1260
- Chen Y, Ye K, Wu Y W, Guo S, Su B, Liu J B. 2013b. Hydration and dehydration in the lower margin of a cold mantle wedge: Implications for crust-mantle interactions and petrogeneses of arc magmas. *Int Geol Rev*, 55: 1506–1522
- Chen Y, Su B, Chu Z Y. 2017. Modification of an ancient subcontinental lithospheric mantle by continental subduction: Insight from the Maowu garnet peridotites in the Dabie UHP belt, eastern China. *Lithos*, 278–281: 54–71
- Chopin C. 2003. Ultrahigh-pressure metamorphism: Tracing continental crust into the mantle. *Earth Planet Sci Lett*, 212: 1–14
- Cluzel D, Aitchison J C, Picard C. 2001. Tectonic accretion and underplating of mafic terranes in the Late Eocene intraoceanic forearc of New Caledonia (Southwest Pacific): Geodynamic implications. *Tectonophysics*, 340: 23–59
- Cluzel D, Ulrich M, Jourdan F, Meffre S, Paquette J L, Audet M A, Secchiari A, Maurizot P. 2016. Early Eocene clinostatite boninite and boninite-series dikes of the ophiolite of New Caledonia; a witness of slab-derived enrichment of the mantle wedge in a nascent volcanic arc. *Lithos*, 260: 429–442
- Coltorti M, Bonadiman C, Hinton R W, Siena F, Upton B G J. 1999. Carbonatite metasomatism of the oceanic upper mantle: Evidence from clinopyroxenes and glasses in ultramafic xenoliths of grande comore, indian ocean. *Acta Mathematica Hungarica*, 134: 269–285
- Dilek Y. 2003. Ophiolite concept and its evolution. In: Dilek Y, Newcomb S, eds. *Ophiolite Concept and the Evolution of Geological Thought*. Boulder, Colorado, Geol Soc Am, 373: 1–16
- Dilek Y, Furnes H. 2009. Structure and geochemistry of tethyan ophiolites and their petrogenesis in subduction rollback systems. *Lithos*, 113: 1–20
- Dilek Y, Furnes H. 2011. Ophiolite genesis and global tectonics: Geochemical and tectonic fingerprinting of ancient oceanic lithosphere. *Geol Soc Am Bull*, 123: 387–411
- Ernst W G, Liou J G. 2008. High- and ultrahigh-pressure metamorphism: Past results and future prospects. *Am Miner*, 93: 1771–1786
- Ferrando S, Frezzotti M L, Dallai L, Compagnoni R. 2005. Multiphase solid inclusions in UHP rocks (Su-Lu, China): Remnants of supercritical silicate-rich aqueous fluids released during continental subduction. *Chem Geol*, 223: 68–81
- Frezzotti M L, Ferrando S. 2015. The chemical behavior of fluids released during deep subduction based on fluid inclusions. *Am Miner*, 100: 352–377
- Fu B, Touret J L R, Zheng Y F. 2001. Fluid inclusions in coesite-bearing eclogites and jadeite quartzite at Shuanghe, Dabie Shan (China). *J Metamorph Geol*, 19: 531–547
- Gao J, John T, Klemm R, Xiong X. 2007. Mobilization of Ti-Nb-Ta during subduction: Evidence from rutile-bearing dehydration segregations and veins hosted in eclogite, Tianshan, NW China. *Geochim Cosmochim Acta*, 71: 4974–4996
- Gao X Y, Zheng Y F, Chen Y X. 2012. Dehydration melting of ultrahigh-pressure eclogite in the Dabie orogen: Evidence from multiphase solid inclusions in garnet. *J Metamorph Geol*, 30: 193–212
- Gass I G. 1968. Is the Troodos massif of Cyprus a fragment of Mesozoic ocean floor? *Nature*, 220: 39–42
- Gerya T V, Stöckhert B, Perchuk A L. 2002. Exhumation of high-pressure metamorphic rocks in a subduction channel: A numerical simulation. *Tectonics*, 21: 6–1–6–19
- González-Jiménez J M, Griffin W L, Proenza J A, Gervilla F, O'Reilly S Y, Akbulut M, Pearson N J, Arai S. 2014. Chromitites in ophiolites: How, where, when, why? Part II. The crystallization of chromitites. *Lithos*, 189: 140–158

- Guillot S, Hattori K, Agard P, Schwartz S, Vidal O. 2009. Exhumation processes in oceanic and continental subduction contexts: A review. In: Lallemand S, Funiciello F, eds. *Subduction Zone Geodynamics*. Frontiers in Earth Sciences. Berlin, Heidelberg: Springer. 175–205
- Guo S, Tang P, Su B, Chen Y, Ye K, Zhang L G, Gao Y J, Liu J B, Yang Y H. 2017. Unusual replacement of Fe-Ti oxides by rutile during retrogression in amphibolite-hosted veins (Dabie UHP terrane): A mineralogical record of fluid-induced oxidation processes in exhumed UHP slabs. *Am Miner*, 102: 2268–2283
- Hébert R, Bézard R, Guilmette C, Dostal J, Wang C S, Liu Z F. 2012. The Indus-Yarlung Zangbo ophiolites from Nanga Parbat to Namche Barwa syntaxes, southern Tibet: First synthesis of petrology, geochemistry, and geochronology with incidences on geodynamic reconstructions of Neo-Tethys. *Gondwana Res*, 22: 377–397
- Hermann J, Rubatto D. 2014. Subduction of continental crust to mantle depths: Geochemistry of ultrahigh-pressure rocks. In: Holland H D, Turekian K K, eds. *Treatise on Geochemistry*. 2nd ed. Amsterdam: Elsevier. 309–339
- Hermann J, Spandler C J. 2008. Sediment melts at sub-arc depths: An experimental study. *J Petrol*, 49: 717–740
- Hermann J, Zheng Y F, Rubatto D. 2013. Deep fluids in subducted continental crust. *Elements*, 9: 281–287
- Hiramatsum N, Banno S, Hirajima T, Cong B. 1995. Ultrahigh-pressure garnet lherzolite from Chijiadian, Rongcheng County, in the Su-Lu region of eastern China. *Isl Arc*, 4: 324–333
- Hiramatsum N, Hirajima T. 1995. Petrology of the Hujialin garnet clinopyroxenite in the Su-Lu ultrahigh-pressure province, eastern China. *Isl Arc*, 4: 310–323
- Hofmann A W. 1997. Mantle geochemistry: The message from oceanic volcanism. *Nature*, 385: 219–229
- Hwang S L, Shen P, Chu H T, Yui T F, Lin C C. 2001. Genesis of microdiamonds from melt and associated multiphase inclusions in garnet of ultrahigh-pressure gneiss from Erzgebirge, Germany. *Earth Planet Sci Lett*, 188: 9–15
- Hyndman R D, Peacock S M. 2003. Serpentinization of the forearc mantle. *Earth Planet Sci Lett*, 212: 417–432
- Ionov D A, Bigot F, Braga R. 2017. The provenance of the lithospheric mantle in continental collision zones: Petrology and geochemistry of peridotites in the Ulten-Nonsberg Zone (Eastern Alps). *J Petrol*, 58: 1451–1472
- Jahn B, Fan Q, Yang J J, Henin O. 2003. Petrogenesis of the Maowu pyroxenite-eclogite body from the UHP metamorphic terrane of Dabieshan: Chemical and isotopic constraints. *Lithos*, 70: 243–267
- John T, Gussone N, Podladchikov Y Y, Bebout G E, Dohmen R, Halama R, Klemd R, Magna T, Seitz H M. 2012. Volcanic arcs fed by rapid pulsed fluid flow through subducting slabs. *Nat Geosci*, 5: 489–492
- Kessel R, Schmidt M W, Ulmer P, Pettke T. 2005. Trace element signature of subduction-zone fluids, melts and supercritical liquids at 120–180 km depth. *Nature*, 437: 724–727
- Kelemen P B, Dick H J B. 1995. Focused melt flow and localized deformation in the upper mantle: Juxtaposition of replacive dunite and ductile shear zones in the Josephine peridotite, SW Oregon. *J Geophys Res*, 100: 423–438
- Kelemen P B, Hanghoj K, Greene A R. 2014. One view of the geochemistry of subduction-related magmatic arcs, with an emphasis on primitive andesite and lower crust. In: Holland H D, Turekian K K, eds. *Treatise on Geochemistry*. 2nd ed. Amsterdam: Elsevier. 749–805
- Konrad-Schmolke M, O'Brien P J, Zack T. 2011. Fluid migration above a subducted slab—constraints on amount, pathways and major element mobility from partially overprinted eclogite-facies rocks (Sesia Zone, Western Alps). *J Petrol*, 52: 457–486
- Lee C T A, Cheng X, Horodyskyj U. 2006. The development and refinement of continental arcs by primary basaltic magmatism, garnet pyroxenite accumulation, basaltic recharge and delamination: Insights from the Sierra Nevada, California. *Contrib Mineral Petrol*, 151: 222–242
- Li J L, John T, Gao J, Klemd R, Wang X S. 2017. Subduction channel fluid-rock interaction and mass transfer: Constraints from a retrograde vein in blueschist (SW Tianshan, China). *Chem Geol*, 456: 28–42
- Li Z Y, Zheng J P, Moskowicz B M, Liu Q S, Xiong Q, Yang J S, Hu X Y. 2017. Magnetic properties of serpentinized peridotites from the Dongbo ophiolite, SW Tibet: Implications for suture-zone magnetic anomalies. *J Geophys Res-Solid Earth*, 122: 4814–4830
- Li H Y, Chen R X, Zheng Y F, Hu Z, Xu L. 2018a. Crustal metasomatism at the slab-mantle interface in a continental subduction channel: Geochemical evidence from orogenic peridotite in the Sulu orogen. *J Geophys Res-Solid Earth*, 123: 2174–2198
- Li H Y, Chen R X, Zheng Y F, Hu Z. 2018b. Water in garnet pyroxenite from the Sulu orogen: Implications for crust-mantle interaction in continental subduction zone. *Chem Geol*, 478: 18–38
- Liou J G, Ernst W G, Zhang R Y, Tsujimori T, Jahn B M. 2009. Ultrahigh-pressure minerals and metamorphic terranes—The view from China. *J Asian Earth Sci*, 35: 199–231
- Liou J G, Zhang R Y, Ernst W G. 2007. Very high-pressure orogenic garnet peridotites. *Proc Natl Acad Sci USA*, 104: 9116–9121
- Liu Q S, Zeng Q L, Zheng J P, Yang T, Qiu N, Liu Z, Luo Y H, Jin Z M. 2010. Magnetic properties of serpentinized garnet peridotites from the CCSD main hole in the Sulu ultrahigh-pressure metamorphic belt, eastern China. *J Geophys Res*, 115: B06104

- Liu Q S, Qiu N, Zheng J P, Li Z Y, Wang H C. 2015. Crustal large-scale serpentinized mantle peridotite body in the Sulu ultrahigh-pressure metamorphic belt, eastern China: Evidence from gravity and magnetic anomalies. *J Struct Geol*, 70: 190–199
- McDonough W F, Sun S S. 1995. The composition of the Earth. *Chem Geol*, 120: 223–253
- Malaspina N, Hermann J, Scambelluri M, Compagnoni R. 2006. Polyphase inclusions in garnet-orthopyroxenite (Dabie Shan, China) as monitors for metasomatism and fluid-related trace element transfer in subduction zone peridotite. *Earth Planet Sci Lett*, 249: 173–187
- Malaspina N, Hermann J, Scambelluri M. 2009a. Fluid/mineral interaction in UHP garnet peridotite. *Lithos*, 107: 38–52
- Malaspina N, Poli S, Fumagalli P. 2009b. The oxidation state of metasomatized mantle wedge: Insights from C-O-H-bearing garnet peridotite. *J Petrol*, 50: 1533–1552
- Malaspina N, Scambelluri M, Poli S, Van Roermund H L M, Langenhorst F. 2010. The oxidation state of mantle wedge majoritic garnet websterites metasomatised by C-bearing subduction fluids. *Earth Planet Sci Lett*, 298: 417–426
- Malaspina N, Langenhorst F, Fumagalli P, Tumati S, Poli S. 2012. Fe³⁺ distribution between garnet and pyroxenes in mantle wedge carbonate-bearing garnet peridotites (Sulu, China) and implications for their oxidation state. *Lithos*, 146–147: 11–17
- Malaspina N, Alvaro M, Campione M, Wilhelm H, Nestola F. 2015. Dynamics of mineral crystallization from precipitated slab-derived fluid phase: First *in situ* synchrotron X-ray measurements. *Contrib Mineral Petrol*, 169: 26
- Malaspina N, Langenhorst F, Tumati S, Campione M, Frezzotti M L, Poli S. 2017. The redox budget of crust-derived fluid phases at the slab-mantle interface. *Geochim Cosmochim Acta*, 209: 70–84
- Manning C E. 2004. The chemistry of subduction-zone fluids. *Earth Planet Sci Lett*, 223: 1–16
- Marchesi C, Garrido C J, Godard M, Belley F, Ferré E. 2009. Migration and accumulation of ultra-depleted subduction-related melts in the massif du sud ophiolite (New Caledonia). *Chem Geol*, 266: 171–186
- Marocchi M, Hermann J, Morten L. 2007. Evidence for multi-stage metasomatism of chlorite-amphibole peridotites (Ulten Zone, Italy): Constraints from trace element compositions of hydrous phases. *Lithos*, 99: 85–104
- Marocchi M, Hermann J, Tropper P, Bargossi G M, Mair V. 2010. Amphibole and phlogopite in “hybrid” metasomatic bands monitor trace element transfer at the interface between felsic and ultramafic rocks (Eastern Alps, Italy). *Lithos*, 117: 135–148
- Marschall H R, Schumacher J C. 2012. Arc magmas sourced from mélange diapirs in subduction zones. *Nat Geosci*, 5: 862–867
- Mibe K, Kawamoto T, Matsukage K N, Fei Y, Ono S. 2011. Slab melting versus slab dehydration in subduction-zone magmatism. *Proc Nat Acad Sci USA*, 108: 8177–8182
- Miyashiro A. 1973. *Metamorphism and Metamorphic Belts*. London: George Allen Unwin. 492
- Moore E M, Jackson E D. 1974. Ophiolites and oceanic crust. *Nature*, 250: 136–139
- Moore E M, Kellogg L H, Dilek Y. 2000. Tethyan ophiolites, mantle convection and tectonic “historical contingency”: A resolution of the “ophiolite conundrum”. In: Dilek Y, Moore E M, Elthon D, Nicolas A, eds. *Ophiolites and Ocean Crust: New Insights from Field Studies and the Ocean Drilling Program*. Boulder: Geological Society of America Special Paper 349. 3–12
- Morris A, Maffione M. 2016. Is the Troodos ophiolite (Cyprus) a complete, transform fault-bounded Neotethyan ridge segment? *Geology*, 44: 199–202
- Ni H W, Zheng Y F, Mao Z, Wang Q, Chen R X, Zhang L. 2017. Distribution, cycling and impact of water in the Earth’s interior. *Natl Sci Rev*, 4: 879–891
- Nie H, Yang J, Zhou G, Liu C, Zheng J, Zhang W X, Zhao Y J, Wang H, Wu Y B. 2017. Geochemical and Re-Os isotope constraints on the origin and age of the Songshugou peridotite massif in the Qinling orogen, central China. *Lithos*, 292–293: 307–319
- Nimis P, Morten L. 2000. P-T evolution of ‘crustal’ garnet peridotites and included pyroxenites from Nonsberg area (upper Austroalpine), NE Italy: From the wedge to the slab. *J Geodyn*, 30: 93–115
- Nuriel P, Katzir Y, Abelson M, Valley J W, Matthews A, Spicuzza M J, Ayalon A. 2009. Fault-related oceanic serpentinization in the Troodos ophiolite, Cyprus: Implications for a fossil oceanic core complex. *Earth Planet Sci Lett*, 282: 34–46
- O’Reilly S Y, Griffin W L. 2013. Mantle metasomatism. In: Harlov D E, Austrheim H, eds. *Metasomatism and the Chemical Transformation of Rock*, Lecture Notes in Earth System Sciences. Berlin Heidelberg: Springer-Verlag. 471–533
- Pagé P, Bédard J H, Schroetter J M, Tremblay A. 2008. Mantle petrology and mineralogy of the Thetford Mines ophiolite complex. *Lithos*, 100: 255–292
- Pagé P, Bédard J H, Tremblay A. 2009. Geochemical variations in a depleted fore-arc mantle: The Ordovician Thetford Mines ophiolite. *Lithos*, 113: 21–47
- Pagé P, Barnes S J. 2009. Using trace elements in chromites to constrain the origin of podiform chromitites in the Thetford Mines ophiolite, Quebec, Canada. *Econ Geol*, 104: 997–1018
- Pearce J A, Lippard S J, Roberts S. 1984. Characteristics and tectonic significance of supra-subduction zone ophiolites. *Geol Soc Lond Spec Publ*, 16: 77–94

- Pearce J A, Robinson P T. 2010. The Troodos ophiolitic complex probably formed in a subduction initiation, slab edge setting. *Gondwana Res*, 18: 60–81
- Philippot P, Selverstone J. 1991. Trace-element-rich brines in eclogitic veins: Implications for fluid composition and transport during subduction. *Contrib Mineral Petrol*, 106: 417–430
- Pirard C, Hermann J, O'Neill H S C. 2013. Petrology and geochemistry of the crust-mantle boundary in a nascent arc, Massif du Sud ophiolite, New Caledonia, SW Pacific. *J Petrol*, 54: 1759–1792
- Rampone E, Morten L. 2001. Records of crustal metasomatism in the garnet peridotites of the Ulten Zone (Upper Austroalpine, Eastern Alps). *J Petrol*, 42: 207–219
- Richards J P. 2013. Giant ore deposits formed by optimal alignments and combinations of geological processes. *Nat Geosci*, 6: 911–916
- Rielli A, Tomkins A G, Nebel O, Brugger J, Etschmann B, Zhong R, Yaxley G M, Paterson D. 2017. Evidence of sub-arc mantle oxidation by sulphur and carbon. *Geochem Persp Lett*, 3: 124–132
- Ringwood A E. 1974. The petrological evolution of island arc systems. *J Geol Soc*, 130: 183–204
- Robinson P T, Melson W G, O'Hearn T, Schmincke H U. 1983. Volcanic glass compositions of the Troodos ophiolite, Cyprus. *Geology*, 11: 400–404
- Sapienza G T, Scambelluri M, Braga R. 2009. Dolomite-bearing orogenic garnet peridotites witness fluid-mediated carbon recycling in a mantle wedge (Ulten Zone, Eastern Alps, Italy). *Contrib Mineral Petrol*, 158: 401–420
- Scambelluri M, Philippot P. 2001. Deep fluids in subduction zones. *Lithos*, 55: 213–227
- Scambelluri M, Hermann J, Morten L, Rampone E. 2006. Melt-versus fluid-induced metasomatism in spinel to garnet wedge peridotites (Ulten Zone, Eastern Italian Alps): Clues from trace element and Li abundances. *Contrib Mineral Petrol*, 151: 372–394
- Scambelluri M, Pettke T, van Roermund H L M. 2008. Majoritic garnets monitor deep subduction fluid flow and mantle dynamics. *Geology*, 36: 59–62
- Scambelluri M, van Roermund H L M, Pettke T. 2010. Mantle wedge peridotites: Fossil reservoirs of deep subduction zone processes. *Lithos*, 120: 186–201
- Scambelluri M, Pettke T, Cannao E. 2015. Fluid-related inclusions in Alpine high-pressure peridotite reveal trace element recycling during subduction-zone dehydration of serpentinized mantle (Cima di Gagnone, Swiss Alps). *Earth Planet Sci Lett*, 429: 45–59
- Schmidt M W, Poli S. 2014. Devolatilization during subduction. In: Holland H D, Turekian K K, eds. *Treatise on Geochemistry*. 2nd ed. Amsterdam: Elsevier. 669–701
- Secchiari A, Montanini A, Bosch D, Macera P, Cluzel D. 2016. Melt extraction and enrichment processes in the New Caledonia lherzolites: Evidence from geochemical and Sr-Nd isotope data. *Lithos*, 260: 28–43
- Secchiari A, Montanini A, Bosch D, Macera P, Cluzel D. 2018. The contrasting geochemical message from the New Caledonia gabbro-norites: Insights on depletion and contamination processes of the sub-arc mantle in a nascent arc setting. *Contrib Mineral Petrol*, 173: 66
- Shen A H, Keppler H. 1997. Direct observation of complete miscibility in the albite-H₂O system. *Nature*, 385: 710–712
- Shi R D, Griffin W L, O'Reilly S Y, Zhao G C, Huang Q S, Li J, Xu J F. 2010. Evolution of the Lüliangshan garnet peridotites in the North Qaidam UHP belt, Northern Tibetan Plateau: Constraints from Re-Os isotopes. *Lithos*, 117: 307–321
- Shirey S B, Richardson S H. 2011. Start of the Wilson cycle at 3 Ga shown by diamonds from subcontinental mantle. *Science*, 333: 434–436
- Shreve R L, Cloos M. 1986. Dynamics of sediment subduction, melange formation, and prism accretion. *J Geophys Res*, 91: 10229–10245
- Song S G, Zhang L F, Niu Y L. 2004. Ultra-deep origin of garnet peridotite from the North Qaidam ultrahigh-pressure belt, Northern Tibetan Plateau, NW China. *Am Miner*, 89: 1330–1336
- Song S G, Zhang L F, Niu Y L, Su L, Jian P, Liu D Y. 2005a. Geochronology of diamond-bearing zircons from garnet peridotite in the North Qaidam UHPM belt, Northern Tibetan Plateau: A record of complex histories from oceanic lithosphere subduction to continental collision. *Earth Planet Sci Lett*, 234: 99–118
- Song S G, Zhang L F, Chen J, Liou J G, Niu Y L. 2005b. Sodic amphibole exsolutions in garnet from garnet-peridotite, North Qaidam UHPM belt, NW China: Implications for ultradeep-origin and hydroxyl defects in mantle garnets. *Am Miner*, 90: 814–820
- Song S G, Su L, Niu Y L, Zhang L F, Zhang G B. 2007. Petrological and geochemical constraints on the origin of garnet peridotite in the North Qaidam ultrahigh-pressure metamorphic belt, northwestern China. *Lithos*, 96: 243–265
- Song S G, Su L, Niu Y L, Lai Y, Zhang L F. 2009. CH₄ inclusions in orogenic harzburgite: Evidence for reduced slab fluids and implication for redox melting in mantle wedge. *Geochim Cosmochim Acta*, 73: 1737–1754
- Soret M, Agard P, Dubacq B, Vitale-Brovarone A, Monié P, Chauvet A, Whitechurch H, Villemant B. 2016. Strain localization and fluid infiltration in the mantle wedge during subduction initiation: Evidence from the base of the New Caledonia ophiolite. *Lithos*, 244: 1–19
- Spandler C, Pirard C. 2013. Element recycling from subducting slabs to

- arc crust: A review. *Lithos*, 170-171: 208–223
- Steinmann G. 1927. Der ophiolitischen Zonen in der Mediterranean Kettengebirgen. Madrid: 14th International Geological Congress. 2: 638–667
- Stern R J. 2002. Subduction zones. *Rev Geophys*, 40: 1–38
- Spengler D, van Roermund H L M, Drury M R, Ottolini L, Mason P R D, Davies G R. 2006. Deep origin and hot melting of an Archaean orogenic peridotite massif in Norway. *Nature*, 440: 913–917
- Su B, Chen Y, Guo S, Chu Z Y, Liu J B, Gao Y J. 2016. Carbonatitic metasomatism in orogenic dunites from Lijiatun in the Sulu UHP terrane, eastern China. *Lithos*, 262: 266–284
- Su B, Chen Y, Guo S, Liu J B. 2017. Dolomite dissociation indicates ultra-deep (>150 km) subduction of a garnet-bearing dunite block (the Sulu UHP terrane). *Am Miner*, 102: 2295–2306
- Su B X, Teng F Z, Hu Y, Shi R D, Zhou M F, Zhu B, Liu F, Gong X H, Huang Q S, Xiao Y, Chen C, He Y S. 2015. Iron and magnesium isotope fractionation in oceanic lithosphere and sub-arc mantle: Perspectives from ophiolites. *Earth Planet Sci Lett*, 430: 523–532
- Tang Y J, Zhang H F, Ying J F, Su B X. 2013. Widespread refertilization of cratonic and circum-cratonic lithospheric mantle. *Earth Sci Rev*, 118: 45–68
- Tang Y, Zhai Q G, Hu P Y, Wang J, Xiao X C, Wang H T, Tang S H, Lei M. 2018. Rodingite from the Beila ophiolite in the Bangong-Nujiang suture zone, northern Tibet: New insights into the formation of ophiolite-related rodingite. *Lithos*, 316-317: 33–47
- Tatsumi Y. 1989. Migration of fluid phases and genesis of basalt magmas in subduction zones. *J Geophys Res*, 94: 4697–4707
- Tatsumi Y, Kogiso T. 2003. The subduction factory: Its role in the evolution of the Earth's crust and mantle. *Geol Soc Lond Spec Publ*, 219: 55–80
- Tumati S, Thöni M, Nimis P, Martin S, Mair V. 2003. Mantle-crust interactions during Variscan subduction in the Eastern Alps (Nonsberg-Ulten zone): Geochronology and new petrological constraints. *Earth Planet Sci Lett*, 210: 509–526
- Ulrich M, Picard C, Guillot S, Chauvel C, Cluzel D, Meffre S. 2010. Multiple melting stages and refertilization as indicators for ridge to subduction formation: The New Caledonia ophiolite. *Lithos*, 115: 223–236
- van Roermund H. 2009a. Recent progress in Scandian ultrahigh-pressure metamorphism in the northernmost domain of the Western Gneiss Complex, SW Norway: Continental subduction down to 180–200 km depth. *J Geol Soc*, 166: 739–751
- van Roermund H. 2009b. Mantle-wedge garnet peridotites from the northernmost ultra-high pressure domain of the Western Gneiss Region, SW Norway. *Eur J Mineral*, 21: 1085–1096
- van Roermund H L M, Drury M R. 1998. Ultra-high pressure ($P > 6$ GPa) garnet peridotites in Western Norway: Exhumation of mantle rocks from >185 km depth. *Terra Nova*, 10: 295–301
- van Roermund H L M, Ronde D. 2000. Super-silicic garnet microstructures from an orogenic garnet peridotite, evidence for an ultra-deep (>6 GPa) origin. *J Metamorph Geol*, 18: 135–147
- van Roermund H L M, Carswell D A, Drury M R, Heijboer T. C. 2002. Microdiamonds in a megacrystic garnet websterite pod from Bardane on the island of Fjortoft, western Norway: Evidence for diamond formation in mantle rocks during deep continental subduction. *Geology*, 30: 959–962
- Vrijmoed J C, Austrheim H, John T, Hin R C, Corfu F, Davies G R. 2013. Metasomatism in the ultrahigh-pressure Scartberget garnet-peridotite (Western Gneiss Region, Norway): Implications for the transport of crust-derived fluids within the mantle. *J Petrol*, 54: 1815–1848
- Wang C, Liu L, Chen D L, Cao Y T. 2011. Petrology, geochemistry, geochronology, and metamorphic evolution of garnet peridotites from South Altyn Tagh UHP Terrane, Northwestern China. In: Coleman R G, Wang X, eds. *Ultrahigh Pressure Metamorphism*, Cambridge: Cambridge University Press. 541–577
- Wang L, Kusky T M, Polat A, Wang S J, Jiang X F, Zong K Q, Wang J P, Deng H, Fu J M. 2014. Partial melting of deeply subducted eclogite from the Sulu orogen in China. *Nat Commun*, 5: 5604
- Whitehead J, Reynolds P H, Spray J G, Gates A E, Gundersen L C S. 1995. The sub-ophiolitic metamorphic rocks of the quebec appalachians. *J Geodyn*, 19: 325–350
- Wilde S A, Valley J W, Peck W H, Graham C M. 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature*, 409: 175–178
- Woelki D, Regelous M, Haase K M, Romer R H W, Beier C. 2018. Petrogenesis of boninitic lavas from the Troodos Ophiolite, and comparison with Izu-Bonin-Mariana fore-arc crust. *Earth Planet Sci Lett*, 498: 203–214
- Wu Y B, Gao S, Zhang H F, Yang S H, Liu X C, Jiao W F, Liu Y S, Yuan H L, Gong H J, He M C. 2009. U-Pb age, trace-element, and Hf-isotope compositions of zircon in a quartz vein from eclogite in the western Dabie Mountains: Constraints on fluid flow during early exhumation of ultrahigh-pressure rocks. *Am Miner*, 94: 303–312
- Xiao Y L, Hoefs J, Van Den Kerkhof A M, Li S G. 2001. Geochemical constraints of the eclogite and granulite facies metamorphism as recognized in the Raobazhai complex from North Dabie Shan, China. *J Metamorph Geol*, 19: 3–19
- Xiao Y L, Hoefs J, van K A M, Simon K, Fiebig J, Zheng Y F. 2002. Fluid evolution during HP and UHP metamorphism in Dabie Shan, China: Constraints from mineral chemistry, fluid inclusions and stable isotopes. *J Petrol*, 43: 1505–1527

- Xiong Q, Zheng J P, Griffin W L, O'Reilly S Y, Zhao J H. 2011. Zircon in the Shenglikou ultrahigh-pressure garnet peridotite massif and its country rocks from the North Qaidam terrane (western China): Meso-Neoproterozoic crust-mantle coupling and early Paleozoic convergent plate-margin processes. *Precambrian Res*, 187: 33–57
- Xiong Q, Zheng J P, Griffin W L, O'Reilly S Y, Pearson N J. 2014. Pyroxenite dykes in orogenic peridotite from North Qaidam (NE Tibet, China) track metasomatism and segregation in the mantle wedge. *J Petrol*, 55: 2347–2376
- Xiong Q, Griffin W L, Zheng J P, O'Reilly S Y, Pearson N J. 2015. Episodic refertilization and metasomatism of Archean mantle: Evidence from an orogenic peridotite in North Qaidam (NE Tibet, China). *Contrib Mineral Petrol*, 169: 31
- Xiong Q, Griffin W L, Zheng J P, O'Reilly S Y, Pearson N J, Xu B, Belousova E A. 2016. Southward trench migration at ~130–120 Ma caused accretion of the Neo-Tethyan forearc lithosphere in Tibetan ophiolites. *Earth Planet Sci Lett*, 438: 57–65
- Xiong Q, Griffin W L, Zheng J P, Pearson N J, O'Reilly S Y. 2017a. Two-layered oceanic lithospheric mantle in a Tibetan ophiolite produced by episodic subduction of Tethyan slabs. *Geochem Geophys Geosyst*, 18: 1189–1213
- Xiong Q, Henry H, Griffin W L, Zheng J P, Satsukawa T, Pearson N J, O'Reilly S Y. 2017b. High- and low-Cr chromitite and dunite in a Tibetan ophiolite: Evolution from mature subduction system to incipient forearc in the Neo-Tethyan Ocean. *Contrib Mineral Petrol*, 172: 45
- Yang J J. 2003. Titanian clinohumite-garnet-pyroxene rock from the Su-Lu UHP metamorphic terrane, China: Chemical evolution and tectonic implications. *Lithos*, 70: 359–379
- Yang J J. 2006. Ca-rich garnet-clinopyroxene rocks at Hujialin in the Su-Lu terrane (eastern China): Deeply subducted arc cumulates? *J Petrol*, 47: 965–990
- Yang J J, Godard G, Kienast J R, Lu Y Z, Sun J X. 1993. Ultrahigh-pressure (60 Kbar) magnesite-bearing garnet peridotites from northeastern Jiangsu, China. *J Geol*, 101: 541–554
- Yang J J, Jahn B M. 2000. Deep subduction of mantle-derived garnet peridotites from the Su-Lu UHP metamorphic terrane in China. *J Metamorph Geol*, 18: 167–180
- Yang J J, Powell R. 2008. Ultrahigh-pressure garnet peridotites from the devolatilization of sea-floor hydrated ultramafic rocks. *J Metamorph Geol*, 26: 695–716
- Yang J S, Zhang R Y, Li T F, Zhang Z M, Liou J G. 2007. Petrogenesis of the garnet peridotite and garnet-free peridotite of the Zhimafang ultramafic body in the Sulu ultrahigh-pressure metamorphic belt, eastern China. *J Metamorph Geol*, 25: 187–206
- Yang J S, Robinson P T, Dilek Y. 2014. Diamonds in ophiolites: A little-known diamond occurrence. *Elements*, 10: 123–126
- Ye K, Song Y R, Chen Y, Xu H J, Liu J B, Sun M. 2009. Multistage metamorphism of orogenic garnet-lherzolite from Zhimafang, Sulu UHP terrane, E. China: Implications for mantle wedge convection during progressive oceanic and continental subduction. *Lithos*, 109: 155–175
- Yoshida D, Hirajima T, Ishiwatari A. 2004. Pressure-temperature path recorded in the Yangkou garnet peridotite, in Su-Lu ultrahigh-pressure metamorphic belt, eastern China. *J Petrol*, 45: 1125–1145
- Yu H, Zhang H F, Santosh M. 2017. Mylonitized peridotites of Songshugou in the Qinling orogen, central China: A fragment of fossil oceanic lithosphere mantle. *Gondwana Res*, 52: 1–17
- Yu S Y, Zhang J X, Sun D Y, Li Y S, Gong J H. 2015. Anatexis of ultrahigh-pressure eclogite during exhumation in the North Qaidam ultrahigh-pressure terrane: Constraints from petrology, zircon U-Pb dating, and geochemistry. *Geol Soc Am Bull*, 127: 1290–1312
- Yuan H L, Gao S, Rudnick R L, Jin Z M, Liu Y S, Puchtel I S, Walker R J, Yu R D. 2007. Re-Os evidence for the age and origin of peridotites from the Dabie-Sulu ultrahigh pressure metamorphic belt, China. *Chem Geol*, 236: 323–338
- Zeng L S, Liang F H, Asimow P, Chen F Y, Chen J. 2009. Partial melting of deeply subducted continental crust and the formation of quartzofeldspathic polyphase inclusions in the Sulu UHP eclogites. *Chin Sci Bull*, 54: 2580–2594
- Zhang C, Liu C Z, Wu F Y, Zhang L L, Ji W Q. 2016. Geochemistry and geochronology of mafic rocks from the Luobusa ophiolite, South Tibet. *Lithos*, 245: 93–108
- Zhang R Y, Liou J G, Cong B. 1994. Petrogenesis of garnet-bearing ultramafic rocks and associated eclogites in the Su-Lu ultrahigh-P metamorphic terrane, eastern China. *J Metamorph Geol*, 12: 169–186
- Zhang R Y, Hirajima T, Banno S, Cong B, Liou J G. 1995. Petrology of ultrahigh-pressure rocks from the southern Su-Lu region, eastern China. *J Metamorph Geol*, 13: 659–675
- Zhang R Y, Liou J G, Yang J S, Yui T F. 2000. Petrochemical constraints for dual origin of garnet peridotites from the Dabie-Sulu UHP terrane, eastern-central China. *J Metamorph Geol*, 18: 149–166
- Zhang R Y, Liou J G, Zheng J P. 2004. Ultrahigh-pressure corundum-rich garnetite in garnet peridotite, Sulu terrane, China. *Contrib Mineral Petrol*, 147: 21–31
- Zhang R Y, Liou J G, Zheng J P, Griffin W, Yui T F, O'Reilly S Y. 2005. Petrogenesis of the Yangkou layered garnet-peridotite complex, Sulu UHP terrane, China. *Am Miner*, 90: 801–813
- Zhang R Y, Li T, Rumble D, Yui T F, Li L, Yang J S, Pan Y, Liou J G.

2007. Multiple metasomatism in Sulu ultrahigh-P garnet peridotite constrained by petrological and geochemical investigations. *J Metamorph Geol*, 25: 149–164
- Zhang R Y, Pan Y M, Yang Y H, Li T F, Liou J G, Yang J S. 2008. Chemical composition and ultrahigh-P metamorphism of garnet peridotites from the Sulu UHP terrane, China: Investigation of major, trace elements and Hf isotopes of minerals. *Chem Geol*, 255: 250–264
- Zhang R Y, Liou J G, Ernst W G. 2009. The Dabie-Sulu continental collision zone: A comprehensive review. *Gondwana Res*, 16: 1–26
- Zhang R Y, Jahn B M, Liou J G, Yang J S, Chiu H Y, Chung S L, Li T F, Lo C H. 2010. Origin and tectonic implication of an UHP metamorphic mafic-ultramafic complex from the Sulu UHP terrane, eastern China: Evidence from petrological and geochemical studies of CCSD-Main Hole core samples. *Chem Geol*, 276: 69–87
- Zhang Z M, Shen K, Sun W D, Liu Y S, Liou J G, Shi C, Wang J L. 2008. Fluids in deeply subducted continental crust: Petrology, mineral chemistry and fluid inclusion of UHP metamorphic veins from the Sulu orogen, eastern China. *Geochim Cosmochim Acta*, 72: 3200–3228
- Zhang Z M, Dong X, Liou J G, Liu F, Wang W, Yui F. 2011. Metasomatism of garnet peridotite from Jiangzhuang, southern Sulu UHP belt: Constraints on the interactions between crust and mantle rocks during subduction of continental lithosphere. *J Metamorph Geol*, 29: 917–937
- Zhao R X, Zhang R Y, Liou J G, Booth A L, Pope E C, Chamberlain C P. 2007. Petrochemistry, oxygen isotopes and U-Pb SHRIMP geochronology of mafic?ultramafic bodies from the Sulu UHP terrane, China. *J Metamorph Geol*, 25: 207–224
- Zheng J P. 2009. Comparison of mantle-derived materials from different spatiotemporal settings: Implications for destructive and accretional processes of the North China Craton. *Chin Sci Bull*, 54: 3397–3416
- Zheng J P, Zhang R Y, Griffin W L, Liou J G, O'Reilly S Y. 2005. Heterogeneous and metasomatized mantle recorded by trace elements in minerals of the Donghai garnet peridotites, Sulu UHP terrane, China. *Chem Geol*, 221: 243–259
- Zheng J P, Griffin W L, O'Reilly S Y, Yang J S, Zhang R Y. 2006a. A refractory mantle protolith in younger continental crust, east-central China: Age and composition of zircon in the Sulu ultrahigh-pressure peridotite. *Geology*, 34: 705
- Zheng J P, Griffin W L, O'Reilly S Y, Yang J, Li T, Zhang M, Zhang R Y, Liou J G. 2006b. Mineral chemistry of peridotites from Paleozoic, Mesozoic and Cenozoic lithosphere: Constraints on mantle evolution beneath eastern China. *J Petrol*, 47: 2233–2256
- Zheng J P, Griffin W L, O'Reilly S Y, Yu C M, Zhang H F, Pearson N, Zhang M. 2007. Mechanism and timing of lithospheric modification and replacement beneath the eastern North China Craton: Peridotitic xenoliths from the 100 Ma Fuxin basalts and a regional synthesis. *Geochim Cosmochim Acta*, 71: 5203–5225
- Zheng J P, Sun M, Griffin W L, Zhou M F, Zhao G C, Robinson P, Tang H Y, Zhang Z H. 2008. Age and geochemistry of contrasting peridotite types in the Dabie UHP belt, eastern China: Petrogenetic and geodynamic implications. *Chem Geol*, 247: 282–304
- Zheng J P, Tang H Y, Xiong Q, Griffin W L, O'Reilly S Y, Pearson N, Zhao J H, Wu Y B, Zhang J F, Liu Y S. 2014. Linking continental deep subduction with destruction of a cratonic margin: Strongly reworked North China SCLM intruded in the Triassic Sulu UHP belt. *Contrib Mineral Petrol*, 168: 1–21
- Zheng Y F. 2012. Metamorphic chemical geodynamics in continental subduction zones. *Chem Geol*, 328: 5–48
- Zheng Y F, Xia Q X, Chen R X, Gao X Y. 2011. Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision. *Earth-Sci Rev*, 107: 342–374
- Zheng Y F, Hermann J. 2014. Geochemistry of continental subduction-zone fluids. *Earth Planet Space*, 66: 93
- Zheng Y F, Chen Y X. 2016. Continental versus oceanic subduction zones. *Nat Sci Rev*, 3: 495–519
- Zhou M F, Robinson P T, Malpas J, Li Z. 1996. Podiform chromitites in the Luobusa ophiolite (Southern Tibet): Implications for melt-rock interaction and chromite segregation in the upper mantle. *J Petrol*, 37: 3–21
- Zhou M F, Robinson P T, Malpas J, Edwards S J, Qi L. 2005. REE and PGE geochemical constraints on the formation of dunites in the Luobusa ophiolite, southern Tibet. *J Petrol*, 46: 615–639

(责任编辑: 郑永飞)