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深俯冲地壳物质如何循环至地表?

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作为太阳系唯一有生命的星球,地球宜居环境的演变与地球各圈层(如大气圈、水圈、岩石圈以及地球深部)相互作用、协同变化紧密关联.例如,超大陆聚合与雪球地球事件、超级地幔柱与生物灭绝等事件高度相关(Courtillot and Olson, 2007; Hoffman *et al*., 2017).板块俯冲是地壳物质进入深部地幔的重要机制,深俯冲板片携带大量地壳物质进入地球深处,并在地幔条件下发生一系列物理化学反应,释放出熔/流体(包括水)、挥发分(包括碳、氢、硫等)等物质,改造了地幔的物理化学属性,如电导率、粘滞度、波速、热导率、氧逸度、不均一性等(孙卫东, 2020; 刘佳和夏群科, 2021; 杨晓志等, 2022).在地球深部动力学过程(如地幔上涌、地幔柱等)控制下,引发了地球表层规模宏大、变化万千的地壳运动(如遍布全球的火山作用、巨型山脉和高原形成等),进而影响地球宜居性(纪伟强和吴福元, 2022).

探寻俯冲板片从深部再循环回到地表的过程,目前主要基于地球物理地震波层析成像研究;利用高温高压实验模拟地球深部的岩石和矿物形成条件;通过现代火山岩和洋岛玄武岩寻找来自深部早期俯冲物质的地球化学记录;借助金伯利岩中地幔过渡带甚至下地幔起源的超深金刚石及其包裹体,从中寻找早期深俯冲的壳源物质证据.近些年开展的蛇绿岩地幔橄榄岩和铬铁矿中金刚石等超高压矿物研究,开辟了研究深俯冲物质再循环的一个新窗口(杨经绥等, 2021).

1 科学问题

地球物理研究表明俯冲板片可穿过地幔过渡带到达核幔边界(Grand *et al*., 1997; Rubie and Van der Hilst, 2001; Fukao *et al*., 2009),计算机模拟证实了冷的大洋岩石圈发生深俯冲的可行性(Stern and Gerya, 2018).高压-超高压变质岩(许志琴等, 2005;Liou *et al*., 2014)、金伯利岩型金刚石(Walter *et al*., 2011; Wirth *et al*., 2014)、洋岛和大陆板内玄武岩(Hofmann, 1997; Sobolev *et al*., 2007; Chen *et al*., 2022)从不同角度证明地球内部不同深度储库中存有深俯冲再循环的壳源物质.我们认为应该将"俯冲物质深部循环"作为一个独立科学问题,通过系统研究,调查深俯冲地壳物质在地幔深部的赋存、活化、迁移和演化历史,模拟和重建板块的深俯冲和深部地质作用,探讨俯冲物质到达深部地幔再回到地表的轨迹和产生板块构造的地球深部动力学机制.

2 科学意义

"俯冲物质深部循环"研究的重要科学意义包括:(1)建立深俯冲和地球深部再循环轨迹;(2)探讨板块构造的深部动力学.

蛇绿岩中地幔橄榄岩及其豆荚状铬铁矿记录

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了大洋的扩张、俯冲消减和闭合过程(Dilek and Furnes, 2011),对认识大洋岩石圈属性以及地幔动力学过程具有重要意义(Arai and Miura, 2016).近年来在全球多条不同时代造山带蛇绿岩中发现一系列超高压－强还原矿物组合,包括金刚石、青松矿、假象斯石英、退变高硅石榴子石以及高压尖晶石等,暗示蛇绿岩经历了＞300 km的深地幔环境.蛇绿岩型金刚石中含Mn钙钛矿、H_2O、碳酸盐、含Mn硅酸盐、碳氢化合物、固体CO_2等固体和流体包裹体,以及亏损的C同位素特征表明这些物质可能源于俯冲再循环的洋壳物质(Yang *et al.*, 2007, 2015a, 2015b; Dobrzhinetskaya *et al.*, 2009; Trumbull *et al.*, 2009; Yamamoto *et al.*, 2009; Arai, 2013; Zhou *et al.*, 2014; Howell *et al.*, 2015; McGowan *et al.*, 2015; Robinson *et al.*, 2015; Griffin *et al.*, 2016; Zhang *et al.*, 2016; Butler and Beaumont, 2017; Das *et al.*, 2017; Moe *et al.*, 2018; Wu *et al.*, 2019; Kusky *et al.*, 2022).上述研究对认识地幔组成、壳－幔圈层相互作用以及地球深部动力学过程具有重要意义(Liou *et al.*, 2014; Robinson *et al.*, 2015; Yang *et al.*, 2015a, 2021; Dilek and Yang, 2018; 杨经绥等, 2021, 2022),蛇绿岩可以作为探究深俯冲地壳物质再循环过程的新窗口(图1)(Yang *et al.*, 2021;杨经绥等, 2021).板块构造的深部动力学机制是研究板块构造理论最具挑战性的核心问题,包括板块构造运动最早产生在什么时候?板块运动的动力学机制是什么?这些问题涉及到地球的早期历史,大陆的形成演变及其动力学背景,是当今地学界最为关注的前沿问题之一,并伴随板块构造研究的深入不断发展.

3　展望

近些年开展的蛇绿岩地幔中金刚石等超高压矿物的研究,开辟了探索深俯冲物质再循环过程的一个新窗口.不同于洋岛玄武岩(大洋板内)、金伯利岩型金刚石(大陆克拉通)构造环境,本研究以大洋地幔(大洋扩张中心)为突破口,结合地球物理、高温高压实验以及计算机模拟等手段,通过系统研究,重建深俯冲地壳物质再循环至地球浅部的精细过程.

地球板块构造运动最早产生的时间、表现形式以及动力学机制等问题一直是地学界最为关注的前沿问题,且依旧众说纷纭(Moresi and Solomatov, 1998; O'Neill *et al.*, 2007; O'Neill and Debaille, 2014; Wu *et al.*, 2021).作为古板块构造的主要识别标志,对地球早期(如太古代)形成的蛇绿岩进行系统研究,有助于探讨板块构造起始以及板块构造运动的深时动力学,更有利于揭示地球不同圈层物质能量交换对地球宜居环境的形成、演变的影响范围和深度.

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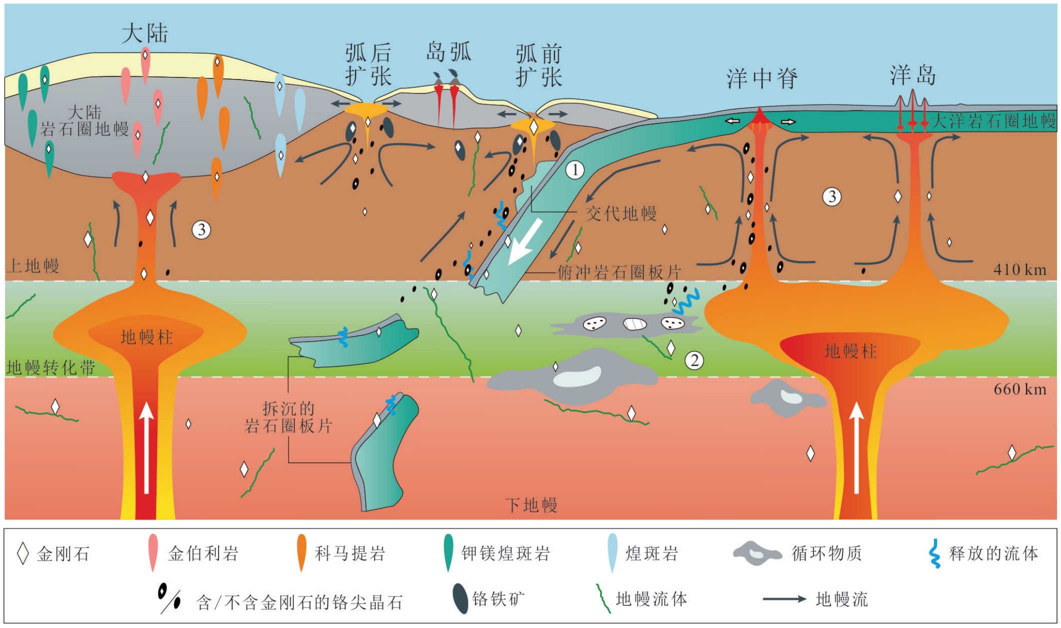

图 1　地球地幔中金刚石和铬铁矿的形成和深部物质循环模式(Yang *et al.*, 2021)

壳源物质(洋壳和陆壳)与大洋岩石圈随板片俯冲进入地幔,可达地幔过渡带甚至下地幔深度.阶段 1:古俯冲事件使得再循环岩石圈物质进入地幔深部,不仅造就了地幔内部不同尺度的不均一性,且使地幔中普遍存在由俯冲物质脱水/熔融形成的熔/流体.阶段 2:金刚石可在~150 km 或更深的深部地幔中从含碳流体中结晶形成.蛇绿岩型金刚石来源于俯冲下去的有机碳,其形成后被高压铬尖晶石捕获.阶段 3:含金刚石的铬尖晶石可由地幔上涌携带至浅部,并与其他铬尖晶石(未含金刚石)一起构成豆荚状铬铁矿,并最终出现在洋脊或俯冲带构造环境.部分金刚石亦可被与地幔柱活动相关的金伯利岩、钾镁煌斑岩和科马提岩等岩浆携带就位于大陆中

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