



# 超深渊生境特征及生物地球化学过程研究进展

李 栋<sup>1,2</sup>, 赵 军<sup>1,2\*</sup>, 刘诚刚<sup>1,2</sup>, 孙承君<sup>3</sup>, 陈建芳<sup>1,2</sup>, 潘建明<sup>1,2</sup>,  
杨 志<sup>1,2</sup>, 王 奎<sup>1,2</sup>, 韩正兵<sup>1,2</sup>, 于培松<sup>1,2</sup>

1. 国家海洋局第二海洋研究所海洋生态与环境实验室, 浙江杭州 310012
2. 国家海洋局海洋生态系统与生物地球化学重点实验室, 浙江杭州 310012
3. 国家海洋局第一海洋研究所海洋生态中心, 山东青岛 266237

**摘要:** 海沟等超深渊环境具备独特的“V”形地质构造、水动力环境及物质循环和能量流动体系, 具有相比其他大洋环境更高的有机碳等生源要素的沉降通量和储碳效率, 是海洋初级生产的巨大“捕获器”和有机碳的沉积汇, 并作为连接深部生物圈与海洋的窗口和通道, 在海洋和全球碳循环中扮演重要角色。对超深渊带的形成、分布、生境特征、内部碳循环、在全球碳循环中的潜在重要性及其对全球气候变化的可能响应进行了描述, 重点从“物理水文—化学沉积环境—生物活动”耦合的角度, 探讨独特生境特征影响下超深渊带中生源要素的生物地球化学过程, 并对今后的发展趋势进行展望。

**关键词:** 超深渊带; 生境特征; 生物地球化学过程; 有机碳; 碳循环; 构造。

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## Advances of Living Environment Characteristics and Biogeochemical Processes in the Hadal Zone

Li Dong<sup>1,2</sup>, Zhao Jun<sup>1,2\*</sup>, Liu Chenggang<sup>1,2</sup>, Sun Chengjun<sup>3</sup>, Chen Jianfang<sup>1,2</sup>, Pan Jianming<sup>1,2</sup>,  
Yang Zhi<sup>1,2</sup>, Wang Kui<sup>1,2</sup>, Han Zhengbing<sup>1,2</sup>, Yu Peisong<sup>1,2</sup>

1. Laboratory of Marine Ecology and Environment, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China
2. Key laboratory of Marine Ecosystem and Biogeochemistry, State Oceanic Administration, Hangzhou 310012, China
3. Marine Ecology Center, First Institute of Oceanography, State Oceanic Administration, Qingdao 266237, China

**Abstract:** The hadal zone (e.g. trench) is characterized by its unique V-shaped geological structure, hydrodynamic environment and material and energy circulation system, has relatively higher deposition flux and burial efficiency of biogenic elements (e.g. carbon) compared with other ocean environments. As the window and channel connecting the deep biosphere and the ocean, this unique area is the tremendous trapper of marine primary production and the sink of sedimentary organic carbon, and plays a very important role in the ocean and global carbon cycling. In this paper, the advances of the formation, distribution, living environment characteristics, internal carbon cycling, potential importance in the global carbon cycling and possible responses to the global climate change of the hadal zone are reviewed, and the biogeochemical processes of biogenic nutrients influenced by the living environment in the hadal zone are mainly discussed, from the point of coupling of “physical hydrology-chemical sedimentary environment-biological activity”. And the outlook of the developing tendency in the hadal zone is summarized.

**Key words:** hadal zone; living environment characteristics; biogeochemical process; organic carbon; carbon cycling; tectonics.

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**作者简介:** 李栋 (1986 —), 男, 助理研究员, 主要从事海洋环境中化学生物标志物的分析测定及其在碳循环中应用等方面研究工作。  
ORCID:0000-0002-5470-4594.E-mail:lidong@sio.org.cn

\* **通讯作者:** 赵军, ORCID:0000-0001-6592-3365.E-mail:jzhao@sio.org.cn

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# 0 引言

人类对水深超过 6 000 m 的大洋超深渊带的探索始于 18 世纪末至 19 世纪初期, 主要利用回声探测技术对大洋不同海域进行深度测定 (Agassiz and Mayer, 1902), 未能真正实地勘察超深渊现场环境或取得可靠的超深渊底栖生物和沉积物样品. 直到 20 世纪 60 年代, 人们还普遍认为极端高压、完全黑暗和低温的超深渊环境是“生命禁区”. 随着近 50 年研究人员先后在波多黎各海沟、日本海沟、马里亚纳海沟和汤加海沟等超深渊开展的一系列水文、地质和生物调查 (Jamieson and Fujii, 2011), 人们才开始发现, 超深渊带环境并非生命罕至的“一潭死水”, 而是参与深层气旋环流 (Johnson, 1998) 和大洋深海环流 (Jamieson *et al.*, 2010) 等物理过程, 具有较为可观的物质输入 (Danovaro *et al.*, 2003), 丰富的生物多样性 (Todo *et al.*, 2005; Itoh *et al.*, 2011; Fujii *et al.*, 2013) 和活跃的底栖生物生命活动 (Epping, 2013; Glud *et al.*, 2013).

超深渊带不是大陆坡或海底平原的延续, 与河口、陆架、陆坡和海底平原等海洋环境相比, 具有高压、低温、地形隔绝、高地震活动和高度本土化的物种特异性等生境特征 (Canganella and Kato, 2002; Blankenship-Williams and Levin, 2009; Jamieson *et al.*, 2009, 2010; Jamieson and Fujii, 2011; Gallo *et al.*,

2015), 同时, 这些特点在超深渊内部也存在巨大的空间差异性 (图1). 超深渊带中独特的生境特征可能是决定海沟特异性存在的重要驱动力 (Jamieson and Fujii, 2011), 对该环境中物质循环和能量流动的研究具有重要意义. 为了更好地认识超深渊带生境特征的独特性及其对该环境中生物地球化学过程的影响, 本文在基于国内外研究基础上开展工作, 重点从“物理水文—化学沉积环境—生物活动”耦合的角度, 对超深渊带生物的营养来源、地形特征和水动力环境等生境特征及其影响下的碳等生源要素的生物地球化学过程进行了分析和总结, 并论述了超深渊带在全球碳循环中的潜在重要性以及超深渊生态系统对气候变化的可能响应.

# 1 超深渊的形成和分布

全球海洋超深渊带主要包括 26 处海沟和 13 处海槽, 平均深度 8 076 m, 最深点为 10 982 m 的马里亚纳海沟, 面积最大的海沟为伊豆—小笠原海沟 (约 99 801 km<sup>2</sup>), 全球海沟面积约占海洋总面积的 2% 左右 (Schrope, 2014). 如图1所示, 海沟是由于大陆板块和海洋板块 (亦或是两个海洋板块) 相向聚合运动形成的狭长区域, 其形成可分为“板块俯冲前的边缘变形旋转”、“板块边缘新岩石圈的形成”和“板块俯冲与原始海沟形成”

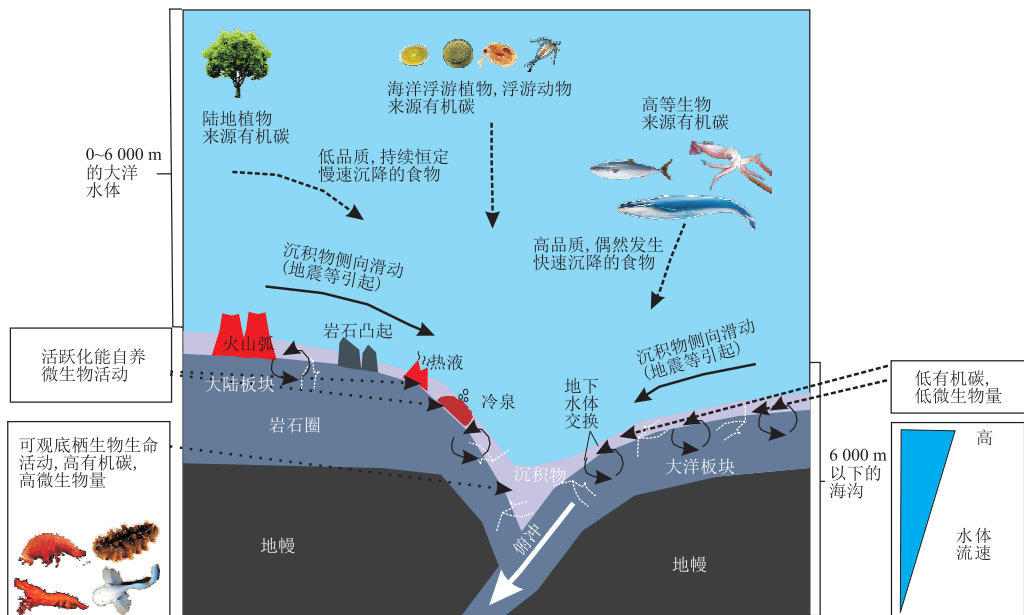


图 1 海沟地形及生境特征概念示意

Fig.1 Conceptual model of trench geography and habitat features

图据 Fujiwara *et al.*(2000), Jamieson and Fujii(2011), Ichino *et al.*(2015), Jamieson(2015) 修改

3 个过程 (Kobayashi, 2004; Castillo *et al.*, 2009; Jamieson and Fujii, 2011). 其中, 当陆地和海洋板块发生碰撞, 陆地板块因密度较低, 会抬升形成岛弧或海岸山脉, 而海洋板块边界则俯冲形成海沟 (例如安第斯山脉和秘鲁—智利海沟、日本群岛和其周围的日本海沟). 同样, 当两个海洋板块发生碰撞时, 抬升的板块形成火山岛弧或海山, 俯冲进入地幔的板块边缘形成海沟, 例如世界最深的马里亚纳海沟及其西部的火山岛弧即是太平洋板块与菲律宾板块相互碰撞作用的结果 (Jamieson and Fujii, 2011). 对于海槽, 则形成于板块张裂 (如冲绳海槽)(国坤等, 2016), 其形状更为宽广, 更像是深海平原中多个海盆的聚集体 (如位于北太平洋中部的奇努克海槽 (8 053 m)、皇帝海槽 (8 526 m), 位于赤道太平洋区的诺瓦—坎顿海槽 (8 465 m) 以及位于南太平洋的亨利海槽 (6 819 m)). 本文中超深渊带主要指海沟, 其在全球海洋中的分布如图2所示.

## 2 超深渊带生境特征及其对生物群落和生源要素循环的影响

### 2.1 超深渊带生物的营养来源

真光层中浮游植物和浮游动物的残骸、粪便以及微生物等小体积颗粒物和絮状物 (“海洋雪花”) 输入稳定、沉降速率较低, 在长时间的沉降过程中经历了异养细菌和浮游动物的高效降解和利用 (易降解部分的选择性移除过程). 虽然浮游植物和浮游动物碎屑对海沟底栖生物而言属于低品质食物来源, 但由于其输送通量巨大, 依然是全球海沟生物群落的主要食物来源 (Gage, 2003)(图1和3). 特别是在地震频发以及有较高初级生产力水平的区域 (如日本海沟), 海沟通过 “侧向输运” 汇聚周围海底平原初级生产来源的有机质更为显著 (Itou *et al.*, 2000; Oguri *et al.*, 2013). 在日本海沟、波多黎各海沟

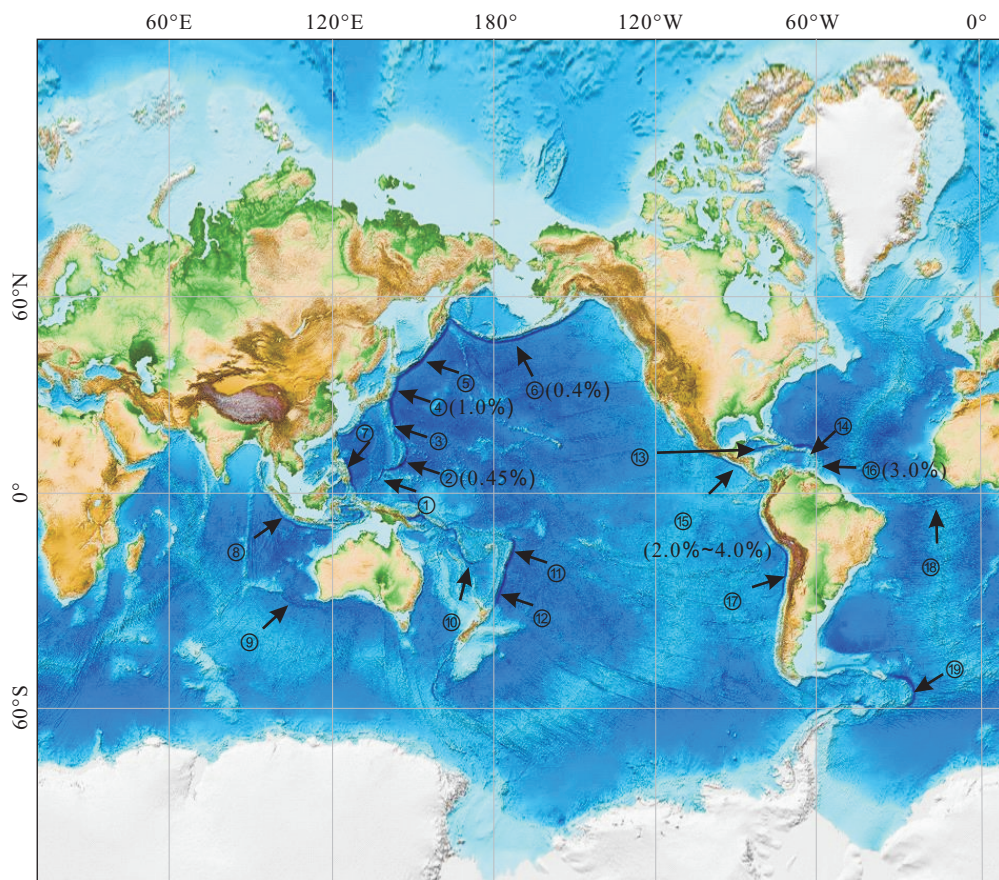


图 2 世界主要海沟分布

Fig.2 Locations of world famous trenches

图中括号内数字代表对应海沟沉积物中有机碳含量: ①雅浦海沟; ②马里亚纳海沟 (Glud *et al.*, 2013); ③伊豆—小笠原海沟; ④日本海沟 (Brassell *et al.*, 1980); ⑤千岛海沟; ⑥阿留申海沟; ⑦菲律宾海沟; ⑧爪哇海沟; ⑨蒂阿曼蒂蒂海沟; ⑩新赫布里底海沟; ⑪汤加海沟; ⑫克马德克海沟; ⑬波多黎各海沟; ⑭开曼海沟; ⑮中美洲海沟 (Pecher *et al.*, 2001); ⑯卡里阿利科海沟 (Wakeham and Ertel, 1988); ⑰秘鲁—智利海沟; ⑱罗曼什海沟; ⑲南桑德韦奇海沟

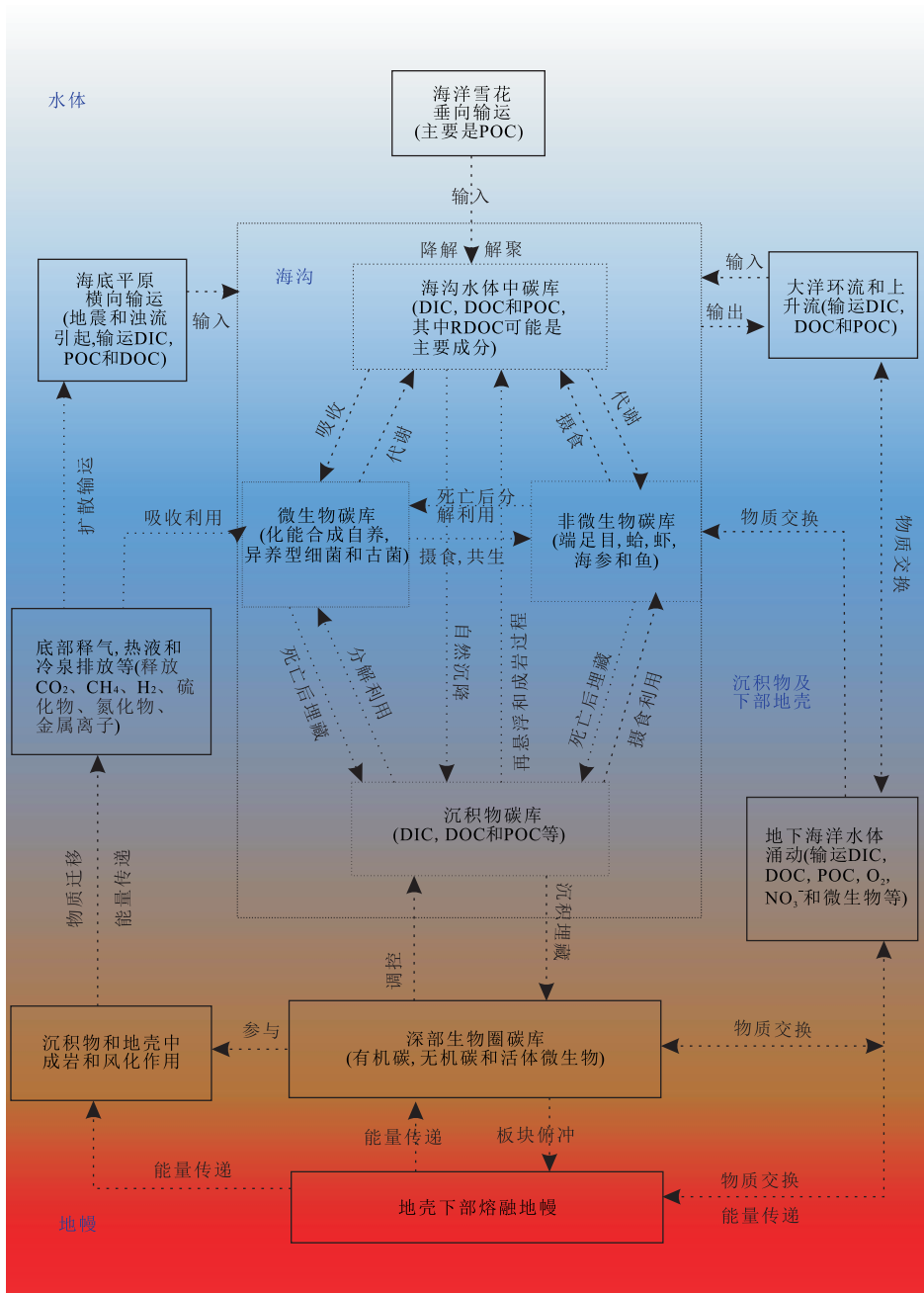


图3 海沟与上覆水体、下部深部生物圈间碳循环的概念模型示意

Fig.3 Conceptual model of carbon cycling between trench and overlying water and underlying deep biosphere

DIC:溶解无机碳;DOC:溶解有机碳;RDOC:惰性溶解有机碳;POC:颗粒有机碳(包括生物残骸、粪便和活体微生物等);图据 Fujiwara *et al.*(2001);D'Hondt(2003);党宏月等(2005);Blankenship-Williams and Levin(2009);Jiao *et al.*(2010);方家松和张利(2011);Jamieson and Fujii(2011);焦念志等(2011);焦念志(2012);汪品先(2013);谢树成等(2012);Ichino *et al.*(2015);Jamieson(2015);谢树成等(2017)

甚至马里亚纳海沟中均发现了新鲜浮游藻碎屑以及浮游藻色素(Danovaro *et al.*, 2003; Glud *et al.*, 2013; Oguri *et al.*, 2013). 对马里亚纳海沟沉积有机碳的元素组成和碳稳定同位素分析同样表明海洋浮游藻对该区域沉积有机碳贡献较大(Luo *et al.*, 2017). 全球海沟中颗粒有机碳(particulate organic carbon, POC)的日沉降通量依然可达到较为可观的 $1.3 \text{ mg}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$

(Lutz *et al.*, 2007; Longhurst *et al.*, 2009; Jamieson, 2015). 其中, 在日本海沟(8 789 m处)、千岛—勘察加海沟以及秘鲁—智利海沟中的POC的沉降通量高达 $5.0\sim 8.6 \text{ mg}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (Nakatsuka *et al.*, 1997; Lutz *et al.*, 2007; Longhurst *et al.*, 2009), 是西印度群岛东北部马尾藻海、东北太平洋海域、大西洋亚热带海域和热带海域等海底平原(约5 000 m)处POC通

量的 3~70 倍 (Deuser and Ross, 1980; Honjo, 1980; Martin *et al.*, 1987; Usbeck, 1999). 此外, 由于上层水体初级生产力水平和水体环流等因素的差异, 最终进入每个海沟中的初级生产来源颗粒有机质通量具有较大差异 (Lutz *et al.*, 2007; Longhurst *et al.*, 2009)(表1), 进而影响了海沟小型底栖动物和细菌等微生物的丰度和生物量 (Graf, 1989; Danovaro *et al.*, 1995, 1999; Itoh *et al.*, 2011). 例如克马德克海沟上层水初级生产力相较马里亚纳海沟更高, 因而食物来源更充足, 其物种多样性和生物量相较马里亚纳海沟也更高 (Schrope, 2014).

高等生物 (例如鱼类和鲸类) 残骸, 作为一种快速沉降的富含多种优质脂肪酸和蛋白质的高品质食物 (Litzow *et al.*, 2006), 在超深渊有机碳的垂直输送中扮演重要角色 (Higgs *et al.*, 2014). 其作为富营养的硬质基质, 可在短时间内提升局部区域的生物多样性, 对底栖生物群落的发育具有重要影响 (Wakeham *et al.*, 1997; Danovaro *et al.*, 2002a, 2002b, 2003; Wigham *et al.*, 2003; Drazen *et al.*, 2012). 由于动物残骸沉降速率为浮游植物碎屑的  $10^4 \sim 10^6$  倍, 因而其沉降时经历更少的微生物降解等过程, 且其分布受水动力输运过程影响相对更弱. 利用饵陷阱方法模拟的海沟底栖生物对生物残骸的摄食过程表明, 由于片脚类大型底栖生物数量众多且移动速度较快, 能够在 24 h 内快速截获并消耗掉大块生物残骸, 成为海沟中对生物残骸类食物来源反应最为迅速的食腐者 (Blankenship-Williams and Levin, 2009; Jamieson *et al.*, 2011). 这些处于海沟食物链底端的片脚类的空间和密度变化会引起虾和鱼等大型高级捕食者的再分布. 在大型捕食者较少的 8 000 m 以下深区域中, 片脚类死亡后也会造成沉积有机碳的重新分布 (Jamieson, 2015).

在波多黎各海沟、克马德克海沟、帕劳海沟以及马里亚纳海沟等超深渊中, 发现了数量可观的海草碎屑、甘蔗、椰壳和竹子等陆源和沿海湿地植物碎屑, 以及专门摄食陆源木质碎屑的可螺科腹足类和片脚类等动物. 这表明在距离陆地较近的海沟中, 陆源有机质的输入作为一种特殊食物来源, 促进了海沟中高效专性分解陆地高等植物来源有机质生物的发育 (Lemche *et al.*, 1976; George and Higgins, 1979; Baird and White, 1985; Smith and Demopoulos, 2003; Kobayashi *et al.*, 2012; Luo *et al.*, 2017). 整体

而言, 尽管自上而下的颗粒有机质的质量和品质均有所下降, 但其中所含的浮游植物色素、蛋白质和关键脂肪酸依然是超深渊异养生物群落的重要营养来源 (Danovaro *et al.*, 2002a; Wigham *et al.*, 2003; Danovaro *et al.*, 2003). 此外, 海沟底部活跃的板块运动导致的蛇纹石化和底部释气, 以及沉积有机质在早期成岩过程中产生的铁 (II) 和锰 (II) 等金属离子和硫化氢、甲烷等气体, 作为一种特殊食物来源, 极大地促进了周围化能合成自养微生物和内共生生物的发育 (王家生等, 2007; Moore and Braucher, 2008; Blankenship-Williams and Levin, 2009; Hulme *et al.*, 2010; Homoky *et al.*, 2013; Yoshinaga *et al.*, 2014). 特别是强烈的可穿透几百米厚沉积物层的海水循环以及流速达到  $30 \text{ ma}^{-1}$  的海底地下水 (地下海洋), 可能也会通过板块俯冲的海沟 (特别是陆地板块一侧火山地壳) 这一连通地球内部和表层的“窗口和通道”, 使得大洋底层水体与地下海洋之间利用洋壳及其上覆沉积物内部的断层、裂隙或其他可渗透性的通道, 进行流体、热量、溶解质和颗粒质的交换 (图3)(汪品先, 2007; 方家松和张利, 2011; 谢树成等, 2017). 例如广泛分布于太平洋边缘海的冷泉生物群落在板块运动活跃的海沟中普遍存在, 并可能孕育出新的冷泉菌种 (Fujiwara *et al.*, 2001; Blankenship-Williams and Levin, 2009). 在阿留申海沟 (Rathburn *et al.*, 2009) 和日本海沟 (Fujikura *et al.*, 1999; Fujiwara *et al.*, 2001) 中均发现了密度非常高的与化能合成细菌共生生活的巨型双壳蛤类. 从另一角度来看, 海沟中普遍存在的化能自养和异养细菌等各种微生物, 通过“无光固碳”过程 ( $\text{CO}_2$ 、 $\text{CH}_4$  转化为 POC, 溶解有机碳 (dissolved organic carbon, DOC) 转化为 POC 和惰性溶解有机碳 (refractory dissolved organic carbon, RDOC))(党宏月等, 2005; Jiao *et al.*, 2010; Jiao, 2012; Glud *et al.*, 2013; 谢树成等, 2017), 又为其他以底栖有机碎屑和微生物为食的海参等棘皮类底栖生物提供了充足食物来源 (Fang *et al.*, 2000; 王家生等, 2007; 方家松和张利, 2011). 例如嗜压和嗜寒细菌即被认为是马里亚纳海沟 11 000 m 沉积物中多不饱和脂肪酸的主要来源, 对维持该处高等底栖生物生命活动具有重要意义 (Fang *et al.*, 2000). 因此, 化能合成初级生产和异养细菌等微生物对超深渊生态系统食物供给的贡献可能十分可观, 并有待深入研究 (Jamieson, 2015).

## 2.2 超深渊带独特地形特征的影响

板块挤压运动使得海沟中的地形复杂多变, 大洋板块一侧较为平坦, 陆地板块一侧有较多岛弧火山和岩石突起分布 (Belyaev and Brueggeman, 1989; Oji *et al.*, 2009), 且两侧坡度随深度增加愈加陡峭 (图1). 在地震活动引起的岩石崩落和浊流影响下, 底质类型既有细粒级的粉砂, 又有松散的砾石和大卵石分布 (Otosaka and Noriki, 2000; Rathburn *et al.*, 2009). 沉积物成分既含碳酸盐质的白垩岩, 又有火山岩和其他高度蚀变的岩石, 以及硅质的软泥 (Smith and Demopoulos, 2003; 王汾连等, 2016), 特别是在初级生产力水平较高的区域, 由于海沟深度已极大超出碳酸钙补偿深度, 沉积物多以富含硅藻和放射虫碎屑的硅质软泥为主 (Smith and Demopoulos, 2003). 同时, 大部分海沟均位于陆地板块边缘, 因而在距离陆地较近的海沟中, 在火山喷发、大气输运、海底地震活动、海沟陡峭的侧坡以及裸露的基岩影响下, 来自于陆地的风尘、矿物和高等植物来源颗粒物也会在海沟中得以沉积 (Berger, 1974; Angel, 1982; 王汾连等, 2016) (图1). 此外, 由于地貌、距离陆地远近和地震活动等因素的差异, 不同海沟间甚至海沟内部不同区域在沉积物类型上具有较大差异 (Jamieson, 2015).

超深渊地形特征会显著影响沉积有机质的分布, 进而引起生物群落组成的变化. 一方面, 相较海底平原、海山和海底峡谷等地形, 海沟的“V”形构造 (越靠近底部越陡峭) 会促进上部颗粒物沿海沟侧坡向下输送 (Richardson *et al.*, 1995; Glud *et al.*, 2013), 进而导致海沟底部区域具有较海沟侧坡更高的有机碳沉积 (Smith and Demopoulos, 2003; Glud *et al.*, 2013; Leduc *et al.*, 2016), 并由于“食物可利用性”差异导致海沟底部沉积物中具有较海沟边缘更高的鱼类活动 (Jamieson *et al.*, 2009)、棘皮类移动速度 (Jamieson *et al.*, 2011) 和底栖生物生物量 (如细菌等微生物和线虫等小型底栖生物) (Glud *et al.*, 2013; Leduc *et al.*, 2016) (图1). 同时, “漏斗效应”导致的海沟侧坡食物匮乏区 (即“相对封闭性”), 既会限制海底平原生物向海沟下潜, 又会导致该区域较低的生物量 (Jamieson, 2015). 另一方面, 由于地质构造原因, 大陆板块侧坡常分布有较多的甲烷冷泉区和富含硫化物的热液口, 更有利于化能合成自养微生物的发育 (图1) (Jamieson and Fujii, 2011; 杨克红等, 2016). 在这里, 海沟底部沉积物质地松软且食物丰富, 大型底栖生物的掘穴觅

食以及异养微生物的新陈代谢活动较海沟侧坡更为活跃, 而在硬质沉积基质中多有表面栖息型生物发育 (Thistle, 2003; Glud *et al.*, 2013; Leduc *et al.*, 2016). 此外, 通过对比不同海沟中同一类生物 (海参和片脚类等) 的进化关系, 科学家发现相邻近的海沟, 同种类生物也具有非常独特的特征, 表明不同海域海沟生物群落在地理空间上的特异性 (Jamieson and Fujii, 2011).

## 2.3 水动力环境的影响

海洋环境中深海水体流速主要受控于大洋温盐环流和海水潮汐涨落 (Tyler, 1995), 海沟中水体多源自于极地下沉冷水 (Mountfort *et al.*, 1998; Maruyama *et al.*, 2000; Nogi *et al.*, 2002). 整体而言, 海沟中水体流速较为稳定, 一般为  $\text{cm}\cdot\text{s}^{-1}$  量级, 并随深度增加而降低 (特别是在沉积物—水界面流速可能会降低至  $0\text{ cm}\cdot\text{s}^{-1}$ ; 图1和表1) (Hallock and Teague, 1996; Shinzou *et al.*, 2000; Thistle, 2003; Taira *et al.*, 2004), 且大陆板块沉积物上方水体流速往往较大洋板块更低 (Turnewitsch *et al.*, 2014; Jamieson, 2015), 仅在因地震活动、地形抬升或涡流形成的较强浊流和上升流区域具有较高的流速 (例如新不列颠海沟中由地震引发的浊流流速高达  $110\text{ cm}\cdot\text{s}^{-1}$ ) (Krause *et al.*, 1970; Hollister and McCave, 1984), 而水体流速越低的区域 (如海沟底部) 往往具有更弱的沉积物冲刷和更好的保存情况, 且沉降颗粒物一旦进入海沟沉积物中便很难再被搬离, 因而利于海参、片脚类和微生物等底栖生物的稳定发育 (Thistle, 2003).

由地震活动、上升流或涡流形成的具有较高颗粒物浓度的海底浊流层 (雾状层) 可以厚达  $50\sim 3\ 000\text{ m}$ . 在海沟斜坡地形的影响下, 浊流层顺坡而下, 对海沟中总悬浮颗粒物以及颗粒物沉降通量贡献显著, 且其贡献随水深的增加而增大 (Nakatsuka *et al.*, 1997; Itou *et al.*, 2000; Jamieson *et al.*, 2010; Oguri *et al.*, 2013). 首先, 浊流可以裹挟高含量的再悬浮沉积物进入海沟, 带来较平时更高的物质输送, 形成高通量沉积事件, 导致底栖生物残骸等有机碎屑的快速埋藏 (Nozaki and Ohta, 1993), 并在沉积物中形成亚表层的富含有机质和丰富微生物活动的热点区域 (Glud *et al.*, 2013; Oguri *et al.*, 2013). 其次, 由于海沟底部水体流速较低, 浊流层可以在海沟底部持续存在数月, 会导致海参等底栖生物丰度降低 (在海沟底部更显著) (Oguri *et al.*, 2013). 再次, 海底

表 1 海沟中水体流速、温度、溶解氧含量、所属海域初级生产力、内部年平均颗粒有机碳 (POC) 沉降通量以及沉降总量  
Table 1 Major trenches around the world with the current rate, temperature, dissolved oxygen content, primary production rate, mean POC flux per unit area and total POC flux

海沟	水体流速 (cm·s <sup>-1</sup> )	水体温度 (°C)	溶解氧 (mol·L <sup>-1</sup> )	对应海域初级生产力 (mg·m <sup>-2</sup> ·d <sup>-1</sup> )	平均 POC 通量 (mg·m <sup>-2</sup> ·d <sup>-1</sup> )	总 POC 通量 (g·a <sup>-1</sup> )	参考文献
班达海沟	-	-	91~94	899	4.4	161	Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)
爪哇海沟	-	-	178~209	899	2.9	253	Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)
秘鲁—智利海沟	-	1.98(6 173 m)~2.25(8 074 m)	-	737	8.7	997	Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Lacey <i>et al.</i> (2016)
千岛—勘察加海沟	-	1.65(6 000 m)~2.15(9 000 m)	106~194	723	6.2	3 119	Belyaev and Brueggeman (1989); Johnson (1998); Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)
阿留申海沟	2~3(垂向剖面平均)	-	134~175	636	4.8	1 827	Johnson (1998); Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)
菲律宾海沟	11.8(9 605 m)~31.7(9 806 m)	1.85(6 000 m)~2.56(9 864 m)	100~159	529	1.9	395	Belyaev and Brueggeman (1989); Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)
琉球海沟	-	-	-	529	2.5	145	Longhurst <i>et al.</i> (2009); Jamieson (2015)
日本海沟	5.2(6 400 m)	-	约 156	529	8.4	910	Johnson (1998); Longhurst <i>et al.</i> (2009); Jamieson (2015)
卡曼海沟	-	4.46(6 200 m)~4.49(6 900 m)	219~309	520	2.1	41	Longhurst <i>et al.</i> (2009); Jamieson (2015)
南桑德韦奇海沟	5~10	-0.27(6 047 m)~0.09(7 390 m)	219~309	452	1.8	385	Vanhove <i>et al.</i> (2004); Longhurst <i>et al.</i> (2009); Jamieson (2015)
伊豆—小笠原海沟	西侧 4.6(6 000 m)~2.4(9 000 m) 东侧 12.8(6 000 m)~3.0(9 000 m)	-	约 169	301	4.6	1 595	Nozaki and Ohtai (1993); Johnson (1998); Shinzou <i>et al.</i> (2000); Longhurst <i>et al.</i> (2009); Jamieson (2015)
波多黎各海沟	1~5(8 350 m)	1.41~1.43	219~309	290	2.3	505	Belyaev and Brueggeman (1989); Longhurst <i>et al.</i> (2009); Jamieson (2015); Hare (2015)
新不列颠海沟	-	-	-	274	2.9	110	Longhurst <i>et al.</i> (2009); Jamieson (2015)
圣克立托巴海沟	-	-	-	274	2.2	37	Longhurst <i>et al.</i> (2009); Jamieson (2015)
新赫布里底海沟	-	2.09(6 000 m)~2.23(6 948 m)	-	274	2.4	18	Longhurst <i>et al.</i> (2009); Jamieson (2015); Lacey <i>et al.</i> (2016)
汤加海沟	-	1.18(6 252 m)~1.91(1 0787 m)	178~209	238	2.7	711	Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2011); Jamieson (2015)
克马德克海沟	4.1(6 116 m)~0.4(9 281 m)	1.17(6 000 m)~1.80(9 856 m)	178~209	238	4.5	1 270	Johnson (1998); Longhurst <i>et al.</i> (2009); Lutz <i>et al.</i> (2007); Jamieson <i>et al.</i> (2011); Jamieson (2015); Lacey <i>et al.</i> (2016)
雅浦海沟	约 4(未发表数据)	约 1.5(未发表数据)	约 159(未发表数据)	225	1.5	68	Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)
帕劳海沟	约 4(未发表数据)	-	162~166	225	1.7	12	Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)
马里亚纳海沟	1.3(6 960 m)~0.1(10 286 m)	1.57(6 000 m)~2.4(10 910 m)	138~197	162	1.5	607	Belyaev and Brueggeman (1989); Johnson (1998); Lutz <i>et al.</i> (2007); Longhurst <i>et al.</i> (2009); Jamieson (2015)

地下水的涌动(流速较低,约为 $9.5 \times 10^{-5} \text{ cm} \cdot \text{s}^{-1}$ )可能也会通过沉积物内部的断层、裂隙或其他可渗透性的通道,与海沟沉积物和上覆水体进行流体、热量、溶解质和颗粒质的交换(图3),影响海沟内生物生命活动(汪品先, 2007; 方家松和张利, 2011; 谢树成等, 2017). 另外, 海沟中大洋内波(如内潮等)变化也会导致生物泵过程运输而来的有机碳通量的变化(Turnewitsch *et al.*, 2014; Gallo *et al.*, 2015; Ichino *et al.*, 2015; Leduc *et al.*, 2016). 海沟内强烈的内波交错现象导致的小范围切变力剧增,在一定程度上促进了水体中悬浮颗粒物的解聚,进而导致颗粒物沉积速率的降低(Turnewitsch *et al.*, 2014)以及沉降颗粒物上有机碳组成特征的改变(Wakeham and Beier, 1991). 受控于水动力条件的沉积物粒度组成同样会对海沟底栖生物多样性产生一定影响(Leduc *et al.*, 2012; Kitahashi *et al.*, 2013).

#### 2.4 温度、压力和溶解氧等因素的可能影响

海沟中不足 $4^\circ\text{C}$ 的低温(表1)通过降低生物体内酶活性、代谢速率和压力耐受能力而对其空间分布和生物地球化学过程产生影响. 海水中温度每降低 $10^\circ\text{C}$ ,就会引起生物体内化学反应速率降低 $2\sim 3$ 倍(Carney, 2005). 随着海沟深度的增加,其生物体内酶浓度和酶活性越高(Samerotte *et al.*, 2007),从而可以更好的摄取和分解利用各种营养物质. 当海沟中由于静水压力作用引起的绝热增温效应开始显现时,水体温度会以 $0.16^\circ\text{C} \cdot \text{km}^{-1}$ 的速率随深度增加而上升(Jamieson, 2015),因此海沟中水体温度会略高于海底平原上覆水温度. 这可能是海沟底部具有较上部更高微生物活动和沉积有机质再矿化速率的原因(Glud *et al.*, 2013),同时也会极大的促进生物体对外界巨大静水压力的耐受性,从而提升海沟生物在极端高压环境中的适应性(Brown and Thatje, 2011). 然而也有研究认为,由于海沟内温度较为稳定,单独温度这一环境因子的影响可能较弱(Jamieson, 2015).

由于超深渊带极深的深度,静水压力会从垂向压力变化速率、潮流和潮汐引起的压力自然循环和对水体性质间接影响等方面(Jamieson *et al.*, 2011; Jamieson, 2015),对超深渊带中生物群落及其中生物地球化学过程产生影响. 由于海沟侧坡坡度随深度增加而显著增大(图1),生物每迁徙相等距离所经受的静水压力变化成倍增加,造成了海沟中显著的生物成带现象(Jamieson and Fujii, 2011; Kobayashi *et al.*,

2012; Gallo *et al.*, 2015). 生活于海沟中的物种,高达39%的生存深度变化范围在100 m以内,66%的小于500 m,仅有10%的在2 000 m以上(Jamieson, 2015). 压力效应亦会造成海沟内沿不同深度分布的物种高度特异性和同一深度上分类水平较高相似性(特别是鱼类)(Pradillon and Gaill, 2007; Jamieson and Fujii, 2011). 同时,静水压力影响下的碳酸钙溶解度变化,提升了硬壳生物在海沟的生存难度,并促进了硬壳骨化生物向软体动物群落结构(例如海参、海胆、海百合和狮子鱼等)的演变(Jamieson, 2015). 例如在马里亚纳海沟中即存在一种具有较高丰度的特有软壳类有孔虫,证明了超高静水压力影响下的物种演化和特有现象(ToDo *et al.*, 2005).

通过对比马里亚纳海沟、小笠原海沟与日本临近陆架边缘的海底微生物群落间的异同,发现小笠原海沟底栖微生物群落与陆地边缘浅海沉积物中微生物群落组成相似,而马里亚纳海沟底栖微生物群落与它们截然不同,表明距离陆地环境的远近同样是决定海沟底栖微生物群落的一个重要因素(Jamieson and Fujii, 2011). 此外,海沟水体通过等密度混合过程与周围海底平原水体等有一定程度的流通,因而溶解氧含量不足 $9 \mu\text{mol} \cdot \text{L}^{-1}$ 的低氧区还未在全球的海沟中发现(Mantyla and Reid, 1983; Belyaev and Brueggeman, 1989; Jamieson, 2015). 虽然海沟水体中溶解氧浓度在不同季节、深度和位置上都会出现波动(Belyaev and Brueggeman, 1989),但基本维持在 $91 \mu\text{mol} \cdot \text{L}^{-1}$ 以上(表1). 即使在帕劳海沟和班达海沟中偶尔检测到了低氧区域( $41\sim 59 \mu\text{mol} \cdot \text{L}^{-1}$ ),但是依然发现了丰富多样的底栖动物群落,表明海沟中溶解氧浓度波动对周围底栖生物影响力较弱(Lemche *et al.*, 1976; Belyaev and Brueggeman, 1989). 海沟中盐度较为恒定(为 $34.7\text{‰}\sim 35.0\text{‰}$ ,变化率不足 $0.42\text{‰}$ ),且与外界环境压力和深度无关,因而对海沟中生态效应的影响可能较为有限(Belyaev and Brueggeman, 1989; Tyler, 1995).

### 3 超深渊带碳循环及其在全球碳循环中的潜在重要性

超深渊环境中的关键生源要素可能主要是为底栖生物生命活动提供能量的碳(有机碳和无机碳)以及合成生命体蛋白质所必须的氮(有机氮和无机氮),但在局部小生境区域(例如热液喷口化能自养微生



物主导的群落), 还原态硫可能也是一种重要的能量供给 (Jamieson *et al.*, 2010; Jamieson and Fujii, 2011; Glud *et al.*, 2013; Jamieson, 2015; Luo *et al.*, 2017; 张新旭等, 2014). 由于目前对超深渊环境中氮和硫等生源要素循环的研究资料十分稀少, 本文主要以碳为例探讨海沟与上覆水体、下部深部生物圈间的碳循环过程.

作为连通地球内部和表层的“窗口和通道”, 海沟等超深渊带水体碳库、微生物碳库、非微生物(多细胞生物)碳库以及沉积物碳库既受到下部深部生物圈和地下海洋的物质输送和能量传递的调控, 又接收了上部生物泵和溶解度泵经大洋环流、海底浊流以及颗粒物自然沉降等过程输运来的各种营养物质, 同时海沟内部各碳库之间也通过一系列诸如高等生物摄食、微生物化能合成和异养分解、自然沉降和再悬浮等过程进行物质和能量的流通传递(图3)(Fujiwara *et al.*, 2001; D'Hondt, 2003; 党宏月等, 2005; Blankenship-Williams and Levin, 2009; 方家松和张利, 2011; Jamieson and Fujii, 2011; 焦念志等, 2011; 焦念志, 2012; 汪品先, 2013; Jamieson, 2015; Ichino *et al.*, 2015). 其中, 微生物参与了上覆水体、海沟沉积物及其下部深部生物圈中溶解态、颗粒态和固结岩石中碳等生源要素的生物地球化学循环过程 (Jiao *et al.*, 2010; 方家松和张利, 2011; 汪品先, 2013), 微生物介导的诸如热液/冷泉区化能合成作用、水体 DOC 向 POC 和/或 RDOC 的转化、与蛤等更高等生物共生、碎屑 POC 的降解等物质和能量流通过程可能是海沟等黑暗生物圈中生源要素循环的主要途径 (Blankenship-Williams and Levin, 2009; Jamieson and Fujii, 2011; Glud *et al.*, 2013; 张新旭等, 2014; Jamieson, 2015; Luo *et al.*, 2017). 如图3所示, 海沟及深部生物圈中碳循环与水循环密切联系, 受到诸如大洋热盐环流、地震引发的海底浊流、上升流以及潮汐驱动的地下海洋等环流或水团的显著影响 (Krause *et al.*, 1970; Rathburn *et al.*, 2009). 一方面, 这些流体可以直接更新海沟中 DOC、溶解无机碳 (dissolved inorganic carbon, DIC) 和 POC; 另一方面, 又可以通过物理搬运过程将海沟周围火山喷发、热液和冷泉排放产生的 CO<sub>2</sub>、CH<sub>4</sub>、H<sub>2</sub>、硫化物、氮化物和金属离子等输入海沟水体和沉积物中, 对其中的化能合成自养微生物的生命活动产生重要影响. 此外, 地下海洋可以通过水体涌动将流经下覆玄武岩

壳的富含 O<sub>2</sub> 和 NO<sub>3</sub><sup>-</sup> 等物质的水体带入上部沉积物和上覆水体中 (D'Hondt, 2003; 方家松和张利, 2011; 汪品先, 2013), 从而对其中微生物的群落结构以及有机质的降解途径产生影响, 进而对海沟及深部生物圈中碳循环产生影响. 整体而言, 由于有机质惰性高和生物新陈代谢速率慢的特征, 海沟等超深渊带中“POC-DOC-DIC”间的循环转化较为缓慢.

虽然海沟仅占海底总面积的 2%, 但其所处深度范围覆盖了海洋总深度范围的 45%, 在物理、化学、地质和生物等多方面具有显著的特异性, 并在全球碳循环中扮演重要角色 (Canganella and Kato, 2002; Jamieson *et al.*, 2011; Jamieson and Fujii, 2011; Glud *et al.*, 2013; Gallo *et al.*, 2015; Leduc *et al.*, 2016; Luo *et al.*, 2017). 由于受海沟的“V”形构造和所导致的“漏斗效应”影响, 海沟底部更易于收集由频发地震活动引起的海沟侧坡侧向滑动输运而来的沉积物(图1). 沉积物中往往具有较高有机碳含量(图2), 且发生于海沟中的 POC 年均沉降总量可以占到整个海洋中输送到海底总量的 6.2%, 成为深层大洋有机碳的“捕获器”(Jumars and Hessler, 1976; Belyaev and Brueggeman, 1989; Danovaro *et al.*, 2003; Smith and Demopoulos, 2003; Lutz *et al.*, 2007; Longhurst *et al.*, 2009; Glud *et al.*, 2013; Oguri *et al.*, 2013; Jamieson, 2015). 同时, 全球尺度上海底沉积有机碳的矿化速率约为 192 mg·m<sup>-2</sup>·d<sup>-1</sup>(朱茂旭等, 2011), 而诸如马里亚纳海沟底部沉积有机碳的氧化分解速率约为 1.8 mg·m<sup>-2</sup>·d<sup>-1</sup>(假设海沟中以有氧呼吸矿化路径为主要沉积有机碳矿化途径, 且沉积物间隙水中氧气的消耗和有机碳的氧化分解摩尔比为 1:1)(Glud *et al.*, 2013), 可以看出海沟中沉积有机碳的矿化分解速率仅为全球海底沉积有机碳平均矿化速率的 1% 左右, 海沟中得以再循环的沉积有机碳总量更是不足全球再循环总量的 0.02%. 因此, 海沟中往往具有较高的储碳效率.

与周围海底平原相比, 海沟底部较低的水体流速(如马里亚纳海沟底部流速仅为 6 000 m 水深处的十分之一)和较高的沉积有机碳含量(如日本海沟约 1.0%, 是周边太平洋沉积物中有机碳含量的 2 倍左右)为底栖微生物提供了理想的栖息环境和丰富的食物, 为其生命活动提供了有利保证(图1)(Brassell *et al.*, 1980, 1981; 张海生等, 2008; Glud *et al.*, 2013; Nunoura *et al.*, 2015). 受海沟两侧大陆板块和大洋板

块相向聚合运动和俯冲构造侵蚀影响, 密度更高的大洋板块会携带上覆沉积物一起俯冲进入熔融地幔, 从而完成将地表有机碳输送进入地球深处的过程, 因而海沟在地质时间尺度上成为地球岩石圈的沉积碳汇. 新近研究表明, 海草作为一类沿海海域的高效固碳海洋植物 (效率是热带雨林的 50 倍), 其面积虽仅占大洋总面积的 0.1%, 但却固定了全球海洋总固碳量的 10%~18%(Duarte *et al.*, 2005; Kennedy *et al.*, 2010). 在帕劳海沟、新赫布里底海沟等超深渊环境中发现了大量的海草碎屑 (Lemche *et al.*, 1976), 一定程度上提高了海沟这一沉积碳汇的储碳潜力 (Jamieson, 2015). 虽然陆地或大洋构造板块的移动速度很慢 (比如日本海沟两侧板块以  $12.5 \text{ cm}\cdot\text{a}^{-1}$  的俯冲速度), 但经过百万年甚至更长时间的积累, 依然影响巨大 (Belyaev and Brueggeman, 1989; Heki and Kataoka, 2008). 具有现代结构特征的海沟相较其他海底或海床要年轻很多, 这在一定程度上表明其活动更为活跃, 将岩石圈表层的“新近”沉积有机碳 (地质时间尺度) 重新输送进地球内部的效率也更高. 此外, 全球环境变化会造成陆地和大洋板块运动加剧, 导致海底地震活动的增加 (McGuire, 2010), 从而进一步加速海沟中沉积有机碳随板块的俯冲而被“裹挟”进入地球内部这一过程. 因此, 海沟既是海洋初级生产的巨大“捕获器”, 又是有机碳的沉积汇, 与下部深部生物圈一起通过调节海洋沉积物的成岩作用、大洋玄武岩的风化以及向熔融地幔的碳输送等过程对全球碳、能量、气候和营养盐循环等产生巨大影响 (D'Hondt, 2003; 方家松和张利, 2011; 汪品先, 2013).

与边缘海、普通深海环境相比, 由于超深渊带在所处水文条件、地质构造、初级生产力和生物群落结构 (包括微生物和高等生物) 等方面的差异, 使得超深渊环境中碳的生物地球化学过程与另外两者较为不同. 整体而言, 由于边缘海环境受季节性变化的陆地径流、大洋水团入侵和上升流影响较大, 水体中诸如营养盐含量、微量元素、温度、二氧化碳分压、溶解氧水平和初级生产力等变化剧烈 (郭志刚等, 2002; 谭燕等, 2004; 黄邦钦和柳欣, 2015), 发生于其中的碳的生物地球化学过程也会随之变化, 而普通深海和超深渊带中水文环境及其中碳的生物地球化学过程在该时间尺度上相对来说更为稳定 (Lemche *et al.*, 1976; Belyaev and Brueggeman, 1989;

Tyler, 1995; Turnewitsch *et al.*, 2014; Jamieson, 2015). 在有机碳库的组成上, 超深渊等深海环境中含有更高比例的 RDOC、高度降解的海源 POC 以及化能合成微生物来源有机碳比重 (Jiao *et al.*, 2010; 焦念志等, 2011; 焦念志, 2012), 而边缘海环境中由于高浮游植物初级生产力和陆地有机质的输入, 因而具有更高比例的活性溶解有机碳 (labile dissolved organic carbon, LDOC)、半活性溶解有机碳 (semi-labile dissolved organic carbon, SLDOC)、陆源有机碳、新鲜的海源有机碳和异养微生物来源有机碳贡献 (Jiao *et al.*, 2010; 焦念志等, 2011; 焦念志, 2012). 在碳的转化路径上, 边缘海环境碳循环中从最低等的微生物、浮游植物到浮游动物等次级消费者再到鱼类等高等动物, 食物链的每个角色均在碳循环中通过诸如光合作用、呼吸作用、打包效应和激发效应等过程发挥了举足轻重的作用 (Bianchi, 2011; 焦念志, 2012; 姚鹏等, 2013; 黄邦钦和柳欣, 2015). 而超深渊环境中除了浮游藻通过生物泵以“海洋雪花”形式以及大洋环流、地下海洋等水团物理输运过程向海沟输入有机质外 (Gage, 2003), 影响海沟等超深渊带中碳循环的主要是自养和异养微生物介导的一系列无光固碳 ( $\text{CO}_2$ 、 $\text{CH}_4$  转化为 POC, DOC 转化为 POC 和 RDOC) 和成岩降解过程 (POC 转化为 DOC 和 DIC)(党宏月等, 2005; 焦念志, 2012; Glud *et al.*, 2013; 谢树成等, 2017), 诸如端足目、虾和鱼类的生命活动对超深渊带中碳循环的影响可能较为有限. 在储碳效率上, 边缘海固碳能力虽强, 但由于边缘海水深最浅且沉积物再悬浮严重, 生物新陈代谢活动更活跃, 与大气间碳交换能力最强, 储碳效率较低, 可能是大气  $\text{CO}_2$  的源 (比如我国南海)(焦念志等, 2011; 焦念志, 2012), 相比之下, 由于超深渊带向上层海洋的碳输出能力较弱, 且储碳效率更高, 在地质时间尺度上是沉积碳汇 (Danovaro *et al.*, 2003; 党宏月等, 2005; Glud *et al.*, 2013; Jamieson, 2015; Nunoura *et al.*, 2015). 由于普通深海和超深渊带均位于大洋几千米深处的无光环境中, 超深渊带与普通深海环境中碳循环过程间的差异较边缘海更小, 但超深渊带更高的静水压力和显著的生物成带现象, 因而更易于演化出新奇的微生物功能类群, 同时由于海沟中更易于收集周围海底平原的沉积物, 因而可能有更多的生物活动热点区域的存在 (Glud *et al.*, 2013; Jamieson, 2015).

## 4 超深渊带生态系统对全球气候变化的可能响应

在大气二氧化碳浓度急速上升和全球变暖的背景下,诸如超深渊带等深海环境及其生态系统可能正发生急剧变化(Danovaro *et al.*, 2001, 2004). 以前的研究认为,由于深海环境中水体滞留时间约有几十年,深海生物对气候变化的响应存在几十年的滞后性,但新的模型研究表明深海生物响应迅速(Spoel, 1994; Danovaro *et al.*, 2001).

全球气候变化背景下上层水体颗粒有机质的输送变化对海沟生态系统具有重要影响. 全球 26 个海沟有 20 个分布在太平洋,而太平洋海域海表温度和环流系统变化极大地受控于低纬 ENSO 事件及其引起的高纬度环流变化(McGowan *et al.*, 1998). ENSO 事件在过去 100 年里不断增强并更加持久,其对全球变暖趋势具有强化作用,且在未来会愈加明显(Hoegh-Guldberg, 1999). 热带太平洋地区在过去的 100 年里已升温  $1\sim 2\text{ }^{\circ}\text{C}$ (Hoegh-Guldberg, 1999). 通过影响上升流强弱、透光层初级生产力、浮游动物次级生产力、鱼类迁徙和繁殖等过程(McGowan *et al.*, 1998; Walther *et al.*, 2002; Jones *et al.*, 2014)对太平洋海底广泛分布的海沟生态系统食物来源产生重要影响. 全球持续升温,水体层化加强,上升流减弱,营养盐输送供给不足,会造成海洋上层水体来源食物短缺(Walther *et al.*, 2002). 在海表初级生产和垂向输运两方面减弱对海底的食物供给,从而导致超深渊带中以沉降颗粒有机质为食物的异养微生物、小型底栖动物以及后生动物等更高级捕食者的生物丰度和生物量的降低(Danovaro *et al.*, 1999, 2004),而该过程对基于化能合成自养微生物及其共生生物生命活动和生物量的影响可能较为有限. 此外,有研究表明,全球气候变化下,诸如风暴、沙尘暴等极端天气事件的发生愈加严重和频繁(Wolff, 2014),且会促进对深层营养盐的向上裹挟(陈斌等, 2016),导致寡营养大洋水初级生产力的增加以及 POC 垂向输送通量近 50% 的增幅(Chen *et al.*, 2013). 但由于极端天气事件的偶发性以及有限的区域影响力,因而其对海沟中食物输入的影响可能依然较为有限.

气候变化影响下诸如温度和溶解氧浓度等水体性质的直接变化也会影响海沟等深海生态系统和生物地球化学过程. 自 1971 年以来,地球气候系统增加

的净能量中,93% 被海洋吸收,其中约 33% 的热量储存在中层和深层海洋,且在 1998 年后有更多热量进入深海,使得全球大洋不同深度水体温度均呈现出逐渐升高的趋势(Levitus *et al.*, 2000; Hoegh-Guldberg and Bruno, 2010; Purkey and Johnson, 2010),即使是 3 500~6 000 m 深的深渊环境中,不同海域水体温度也呈现出  $0.1\times 10^{-3}\sim 0.8\times 10^{-3}\text{ }^{\circ}\text{C}\cdot\text{a}^{-1}$  的升高趋势(Purkey and Johnson, 2010). 深海细菌往往是温性的,温度变化会对细菌的生长速率和代谢速率产生影响(Danovaro *et al.*, 2001). 例如,即使温度变化仅  $0.05\sim 0.10\text{ }^{\circ}\text{C}$ ,即会引起海底线虫类生物丰度的极大变化,当温度下降  $0.4\text{ }^{\circ}\text{C}$  时,诸如底栖线虫类等较小型底栖生物生物量(降低 65% 以上)、功能多样性和种类均匀性等均显著降低(Danovaro *et al.*, 2001, 2004). 海洋水体层化加强、大洋环流的减缓以及深层水体温度的升高,均会在一定程度上减弱深海环境中溶解氧的交换和补给,而深海环境溶解氧水平的降低,会导致海底细菌密度和活跃程度的显著降低,从而导致海底沉积有机质再矿化分解过程的减弱以及有机质的累计程度增加(Danovaro *et al.*, 1998, 2001). 在远洋深海这种低初级生产力和沉积速率海域,溶解氧在沉积物中的扩散速率远大于其消耗速率,并是深海沉积物有机质矿化唯一的重要路径(Reeburgh, 1983; 朱茂旭等, 2011). 马里亚纳海沟 10 817 m 深处水体中较高的溶解氧含量(约  $181\text{ }\mu\text{mol}\cdot\text{L}^{-1}$ )、扩散深度(16 cm 时溶解氧含量依然高达  $50\text{ }\mu\text{mol}\cdot\text{L}^{-1}$ )以及沉积物中氧消耗速率(约  $153\text{ }\mu\cdot\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ )均证明了这一点(Glud *et al.*, 2013). 如果超深渊中溶解氧的交换和补给减弱,势必会影响有氧呼吸等不同路径对沉积物中有机质矿化的相对贡献. 一方面这会打破原有碳、氮循环过程,另一方面海沟在海洋碳循环中“沉积碳汇”的作用也会加强. 此外,虽然全球变暖背景下极地海域海水温度升高较低纬赤道海域更显著(例如南大洋深层水升温速度高达  $3\times 10^{-3}\text{ }^{\circ}\text{C}\cdot\text{a}^{-1}$ ,赤道海域深层水升温速度不足  $0.1\times 10^{-3}\text{ }^{\circ}\text{C}\cdot\text{a}^{-1}$ )(Purkey and Johnson, 2010),但南极冷水随大洋环流输送到赤道和北太平洋海域海沟中需要经历千年之久,因此短时间内难以评估极地水温升高和溶解氧降低对海沟生态环境的影响.

## 5 结论与展望

大洋 6 000 m 水深以下的海沟等超深渊环境具有极端高压、低温、地形隔绝且复杂多变、高地震活

动和食物来源多样的生境特征。这些特征对该环境中碳等生源要素分布和生物群落组成具有重要的控制作用,并促进了超深渊环境中独特的物质循环和能量流动体系的形成。作为连通地球内部和表层的“窗口和通道”,海沟等超深渊带中碳库既受到下部深部生物圈和地下海洋的物质和能量传递的调控,又接收了上部生物泵和溶解度泵等过程输运来的各种营养物质。其中,微生物介导的物质和能量流过程可能是超深渊带黑暗生物圈中生源要素循环的主要途径。超深渊带特殊的“V”形地质构造、板块俯冲、较弱的水动力环境和微生物活性,导致超深渊带具有相对其他大洋环境更高的有机碳等生源要素的沉降通量和保存效率,成为海洋初级生产的巨大“捕获器”和有机碳的“沉积碳汇”。

整体而言,由于极端高压环境中采样技术的限制,对超深渊生态系统中碳等生源要素的循环过程以及生物形态结构和生理功能的深入研究工作依然匮乏。目前对超深渊生态系统的研究依然处于对该环境中特有物种的探索与发现阶段,在整个生态系统的群落结构组成及其对极端条件的适应机制、碳等生源要素的生物地球化学过程(如沉积有机碳的矿化速率和埋藏通量)、全球气候变化与独特超深渊带生态系统相互作用和反馈以及超深渊带特殊生物功能基因和化合物的探究等方面的研究依然不足。而这些对全面了解超深渊带生态系统的物质循环和能量流动体系具有重要意义。

在全球气候变化背景下,对海洋以及全球碳的源—汇过程机制的研究愈加重要。但目前为止,超深渊带中系统性的生态调查未见报道,同时,由于超深渊带中沉积物的“侧向输运”以及位于碳酸盐补偿深度以下的深度,使得基于放射性同位素定年技术的沉积物年代测定在该环境中较为困难。因而利用超深渊带沉积柱状样中生物标志物化合物等指标进行生态环境的重建研究具有较大难度,仅凭目前在全球不同海沟已开展的空间上零散、时间上不连续以及相对片面的生态调查取样,为正确和深入认识超深渊带生态系统对全球气候变化的响应引入较高不确定度和提出极大挑战。因此,基于目前在海沟水体和沉积物中已开展的生物群落结构组成和碳等生源要素循环等前期调查研究,在全球不同区域海沟安放长时间序列沉积物捕获器以及进行长期海底生态系统原位观测,对研究气候变化背景下海沟生态系统

的响应具有重要意义,可进一步拓展和完善我们对海洋环境是如何应对不断变化的外部世界的认识。

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