

<https://doi.org/10.3799/dqkx.2025.291>



海洋甲烷运移扩散机制及环境影响研究进展与展望

倪鑫^{1,2,3}, 梁前勇^{1,2*}, 刘修国³, 董一飞^{1,2}, 郭斌斌^{1,2}, 吴杨^{1,2}, 吴学敏^{1,2},
苏丹仪^{1,2}, 许安迪^{1,2}, 杨林^{1,2}, 肖曦^{1,2}, 王智刚^{1,2}, 吴晓钰^{1,2}, 窦晓峰^{1,2},
李嘉成^{1,2}, 蒋钟叶^{1,2}

1. 中国地质调查局广州海洋地质调查局, 广东广州 511458

2. 天然气水合物勘查开发国家工程研究中心, 广东广州 511458

3. 中国地质大学(武汉)地理与信息工程学院, 湖北武汉 430078

摘要: 甲烷作为强效温室气体, 其单分子温室效应在百年尺度上是二氧化碳的 30 倍, 而海洋甲烷储量占全球总储量的 95%, 甲烷源汇过程直接影响全球气候变化。本文通过文献调研和数据分析方法, 系统梳理了全球海洋甲烷渗漏的空间分布格局与运移扩散机理, 并结合南海、墨西哥湾等典型案例区实测数据定量评估环境效应。结果显示全球甲烷渗漏呈显著空间差异, 环太平洋海域渗漏最为活跃, 北极与大西洋沿岸次之, 环南极洲海域最低。这种分布格局主要由板块构造活动、水合物稳定带条件以及沉积有机质供给共同控制。北极等高纬度地区的实际渗漏活跃度可能被低估, 这些地方是海洋甲烷进入大气的主要来源。从全球来看约 70%~90% 的海底渗漏甲烷被微生物氧化消耗, 但仍有 1.5%~4.0% 直接进入大气, 年贡献量 6~12 Tg。海底甲烷渗漏通过水体运移扩散、生态重构和温室气体排放对全球环境产生显著影响。应加强动态监测及甲烷负排放技术研发, 服务“双碳”目标与全球气候治理。

关键词: 甲烷渗漏; 空间分布; 多维运移扩散; 全球海洋; 环境效应; 环境地质。

中图分类号: P731

文章编号: 1000-2383(2026)06-2295-28

收稿日期: 2025-09-23

Progress and Prospect of Marine Methane Leakage, Migration and Diffusion Mechanism and Ecological Environment Impact

Ni Xin^{1,2,3}, Liang Qianrong^{1,2*}, Liu Xiuguo³, Dong Yifei^{1,2}, Guo Binbin^{1,2}, Wu Yang^{1,2}, Wu Xuemin^{1,2},
Su Danyi^{1,2}, Xu Andi^{1,2}, Yang Lin^{1,2}, Xiao Xi^{1,2}, Wang Zhigang^{1,2}, Wu Xiaoyu^{1,2}, Dou Xiaofeng^{1,2}, Li Jiacheng^{1,2},
Jiang Zhongye^{1,2}

1. Guangzhou Marine Geological Survey, China Geological Survey, Guangzhou 511458, China

2. National Engineering Research Center for Natural Gas Hydrate Exploration and Development, Guangzhou 511458, China

3. School of Geography and Information Engineering, China University of Geosciences (Wuhan), Wuhan 430078, China

基金项目: 国家自然科学基金项目(Nos. 42276087, U2544219); 中国地质调查局项目(Nos. DD20221706, DD20230065); 广东省基础与应用基础研究重大项目(No. 2023B0303000021)。

作者简介: 倪鑫(2001—), 男, 硕士研究生, 研究方向为海洋环境。ORCID: 0009-0004-6477-212X。E-mail: nixin.prc@cug.edu.cn

*** 通讯作者:** 梁前勇, 教授级高级工程师, 研究方向为海洋地球化学。ORCID: 0000-0002-9172-1828。E-mail: tomlqy@163.com

引用格式: 倪鑫, 梁前勇, 刘修国, 董一飞, 郭斌斌, 吴杨, 吴学敏, 苏丹仪, 许安迪, 杨林, 肖曦, 王智刚, 吴晓钰, 窦晓峰, 李嘉成, 蒋钟叶, 2026. 海洋甲烷运移扩散机制及环境影响研究进展与展望. 地球科学, 51(6): 2295-2322.

Citation: Ni Xin, Liang Qianrong, Liu Xiuguo, Dong Yifei, Guo Binbin, Wu Yang, Wu Xuemin, Su Danyi, Xu Andi, Yang Lin, Xiao Xi, Wang Zhigang, Wu Xiaoyu, Dou Xiaofeng, Li Jiacheng, Jiang Zhongye, 2026. Progress and Prospect of Marine Methane Leakage, Migration and Diffusion Mechanism and Ecological Environment Impact. *Earth Science*, 51(6): 2295-2322.

Abstract: Over a 100-year period, methane has a global warming potential 30 times that of carbon dioxide on a per-molecule basis. As a potent greenhouse gas, methane stored in the ocean accounts for 95% of the global total reserves, and the processes of methane sources and sinks directly influence global climate change. In this paper, the spatial distribution pattern and transport and diffusion mechanism of global marine methane leakage are systematically investigated through literature research and data analysis, and the environmental effects are quantitatively assessed by combining the measured data of typical case areas such as the South China Sea and the Gulf of Mexico. The global methane seepage shows significant spatial differences, with the most active seepage in the Pacific Rim, followed by the Arctic and Atlantic coasts, and the lowest in the Antarctic Rim. This distribution pattern is primarily controlled by tectonic activity, conditions within the hydrate stability zone, and the supply of sedimentary organic matter. The actual seepage activity in high-latitude regions such as the Arctic may be underestimated, representing a major source of oceanic methane in the atmosphere. Approximately 70%–90% of seafloor methane seepage is oxidized and consumed by microorganisms, but 1.5%–4% enters the atmosphere directly, contributing 6–12 Tg per year. Seafloor methane seepage has significant impacts on the global environment through ocean acidification, ecological restructuring, and greenhouse gas emissions. Dynamic monitoring and research and development of methane negative emission technologies should be strengthened to serve the dual carbon goals and global climate governance.

Key words: methane leakage; spatial distribution; multidimensional transport and dispersion; global ocean; environmental effect; environmental geology.

0 引言

甲烷作为一种强效温室气体,在全球气候变化中扮演着关键角色.根据联合国政府间气候变化专门委员会(IPCC)第五次和第六次评估报告,甲烷的全球增温潜势在 20 年尺度内约为二氧化碳的 83 倍,在 100 年尺度内约为 30 倍(Adopted, 2014).甲烷辐射强度为 0.61 W/m^2 ,约为二氧化碳的三分之一,是仅次于一氧化碳的第二大羟基自由基吸收汇,在全球对流层的氧化能力方面起着重要作用(Etminan *et al.*, 2016).近年来,大气中的甲烷年排放量达到 1983 年开始系统监测以来的最高水平,对全球温室效应的贡献率超过三分之一(Feng *et al.*, 2022).甲烷主要排放源包括湿地、农业、人为活动(如化石燃料的生产和消费)、生物质燃烧,以及地质渗流、白蚁、内陆水域和海洋等(Saunio *et al.*, 2020).甲烷在大气中的寿命约为 9 年,主要通过羟基自由基的反应、土壤微生物代谢以及与氯原子的反应等途径被清除(Thanwerdas *et al.*, 2019),相关全球甲烷释放途径及储量如图 1 所示.

海洋作为地球最大的甲烷储库,甲烷源汇作用不容忽视.据估计海洋每年产生的甲烷量约占全球甲烷产生总量的 30%,对大气甲烷的贡献可达 1.5%–4% (Cicerone *et al.*, 1988; Judd *et al.*, 2002; Reeburgh, 2007).冷泉系统是海洋重要的甲烷来源之一,常见于世界各地的大陆边缘,富含碳氢化合物的流体以每年几厘米到几米的速度从海底渗出,其中主要成分为硫化氢和甲烷(Luff and Wallmann,

2003; Brown *et al.*, 2005).在冷泉区,以天然气水合物甲烷为能量源的缺氧沉积层孕育了海洋中最庞大的微生物生态系统之一,其细胞数达到 $10^7 \sim 10^9$ 个/ cm^3 (Michaelis *et al.*, 2002; Treude *et al.*, 2007).在这些环境中,甲烷厌氧氧化(anaerobic oxidation of methane, AOM)和硫酸盐还原(sulfate reduction, SR)耦合是主要的能量生成过程,由甲烷厌氧氧化古菌(anaerobic methanotroph, ANME)和硫酸盐还原细菌(sulfate-reducing bacteria, SRB)共同介导(Niemann *et al.*, 2006; Schreiber *et al.*, 2010).因此, AOM 过程是海洋最重要的甲烷汇,估计每年可消耗海底约 300 Tg 甲烷.海底沉积物和深部储层释放的甲烷超过 80% 在逸出前被氧化,不仅有效减缓了温室气体甲烷的排放,又孕育了繁盛的微生物和底栖动物(Reeburgh, 2007).

海底甲烷从深层水合物区向大气的垂直迁移是一个复杂的生物地球化学过程.大陆架沉积物中的甲烷,主要来自深层水合物分解,全球海洋大陆架边缘沉积物的甲烷释放量约为 $0.01 \sim 0.05 \text{ Gt C a}^{-1}$,占全球大气甲烷含量的 1%–5% (Cicerone *et al.*, 1988; Dickens, 2003).在海底沉积物中,产甲烷古菌通过多种代谢途径生成甲烷,主要包括:乙酸裂解途径,将乙酸分解为甲烷和二氧化碳;氢营养二氧化碳还原途径,利用氢气还原二氧化碳生成甲烷;甲基营养途径,通过甲基化底物歧化或还原生成甲烷(陈焘等, 2022; 王旭东等, 2024).冷泉系统中甲烷的主要消耗机制为硫酸盐耦合的 AOM 过

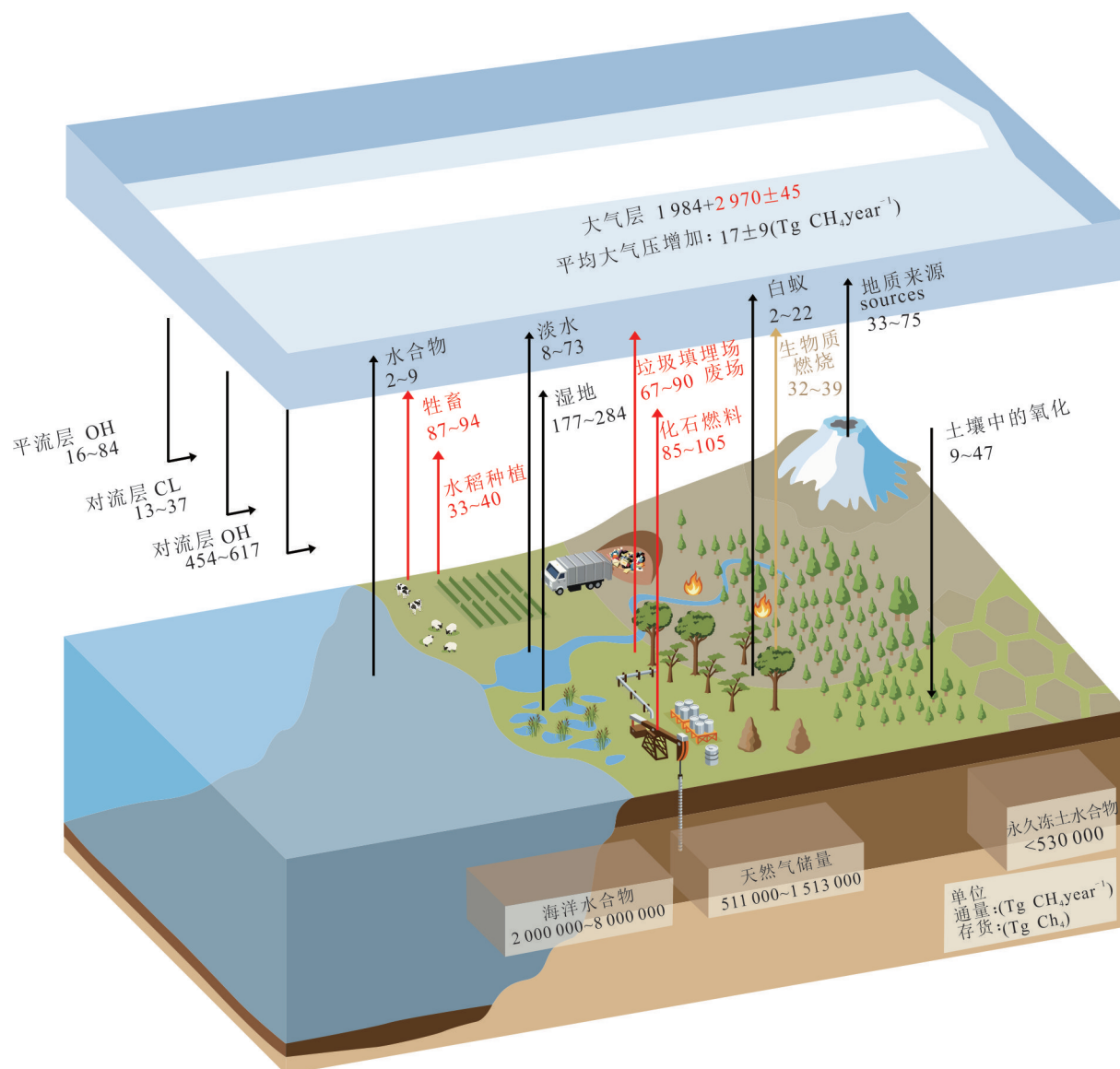


图1 全球甲烷储量和通量

Fig.1 Global methane reserves and fluxes

数字代表 2000—2009 年估计的第四季度 (Tg CH_4) 年度通量和第四季度 (Tg CH_4) CH_4 储量. 黑色箭头表示“自然”通量, 即自 1750 年以来不是由人类活动直接引起的通量, 红色箭头表示人为因素造成的通量, 浅棕色箭头表示自然和人为因素共同造成的通量, 引自 Ciais *et al.* (2014); Reay *et al.* (2018)

程, 由 ANME 与 SRB 在硫酸盐—甲烷转换带 (sulfate methane transition zone, SMTZ) 中协同完成 (Boetius *et al.*, 2000; Knittel and Boetius, 2009; Chen *et al.*, 2023a). 大部分甲烷在沉积物中经 AOM 作用被厌氧氧化, 少量进入上覆水体后再被有氧氧化, 构成甲烷向大气释放的关键屏障 (Valentine *et al.*, 2001; Knittel and Boetius, 2009). 尽管存在这些消耗机制, 部分水体仍出现甲烷过饱和现象, 来源包括深部冷泉渗漏和水体甲基化化合物的细菌裂解等 (Damm *et al.*, 2010; 张亭亭等, 2020;

Wang *et al.*, 2021; Li *et al.*, 2024).

在全球变暖和人类活动加剧背景下, 深海甲烷渗漏规模和频率呈上升趋势, 对海洋生态系统产生潜在影响 (Joung *et al.*, 2022; Nisbet, 2022). 深海甲烷渗漏增加可能带来海水酸化、局部缺氧区扩大、化能合成生态系统扰动等海洋环境问题, 并可能通过甲烷释放加速气候变暖, 形成正反馈循环. 尽管海洋甲烷对大气的直接贡献相对较小, 但潜在气候影响不容忽视. 地质历史上的古新世—始新世极热事件 (paleocene-eocene thermal maximum, PETM)

表明,甲烷氧化放大了甲烷的排放量,大规模甲烷释放可引发全球剧烈气候变化和生态系统重大变迁(Li *et al.*, 2022a; Kim *et al.*, 2025). 在全球变暖和人类活动加剧的背景下,海洋甲烷系统面临多重扰动:(1)极地和高纬度海域水合物稳定带上移,可能触发大规模甲烷释放(Shakhova *et al.*, 2010);(2)深海资源开发可能破坏水合物稳定性,虽然目前中纬度海洋分解水合物产生的大气释放可以忽略不计(Joung *et al.*, 2022);(3)海洋酸化和缺氧可能削弱微生物氧化屏障(Gelesh *et al.*, 2016). 虽然地质历史上的PETM等大规模甲烷爆发情景与当前情况存在显著差异,但这些事件揭示了甲烷—气候系统潜在的非线性响应和临界点风险(Ruppel and Kessler, 2017).

本文通过系统的文献调研和多源数据综合,分析了全球海洋甲烷渗漏空间分布. 结合南海、墨西哥湾等典型案例,梳理了海底甲烷从深部储层到大气释放的过程,评估了不同环境条件下的运移扩散规律和环境效应. 本研究拓展了海洋甲烷渗漏空间分布与运移扩散机制的理论认知,深化对环境和生态效应的理解,为海洋生态环境保护和甲烷泄漏监测提供科学支撑.

1 全球海洋甲烷渗漏空间分布特征

1.1 全局空间分布特征

全球海洋甲烷渗漏呈现显著的空间异质性,受到季节性变化(Mogollón *et al.*, 2011)、气候变化(Sultan *et al.*, 2020; Serov *et al.*, 2023)和地质活动(Hiruta and Matsumoto, 2023)等多种因素影响. Gelesh *et al.* (2016)在美国富营养化的切萨皮克湾观察到,季节性缺氧与较高的甲烷通量之间存在直接联系. Sultan *et al.* (2020)在北极西斯瓦尔巴群岛进行的水声实验和沉积物孔隙测样证实,潮汐显著影响甲烷气体排放的强度和周期. Ferré *et al.* (2020)在北冰洋的研究发现,海底天然气水合物活动比温暖条件下明显减少了甲烷排放. 从空间分布来看,环太平洋地区因活跃的板块俯冲带和转换断层系统发育,形成了深部甲烷运移的优势通道,成为全球甲烷渗漏最活跃的海域之一. 北大西洋沿岸因第四纪冰川活动和海底滑坡广泛发育,形成了大量甲烷渗漏点. 近年来针对北极地区特别是东西伯利亚海等浅水大陆架的观测表明,该区域的甲烷渗漏实际上非常活跃,是全球大气甲烷的重要来源区之一

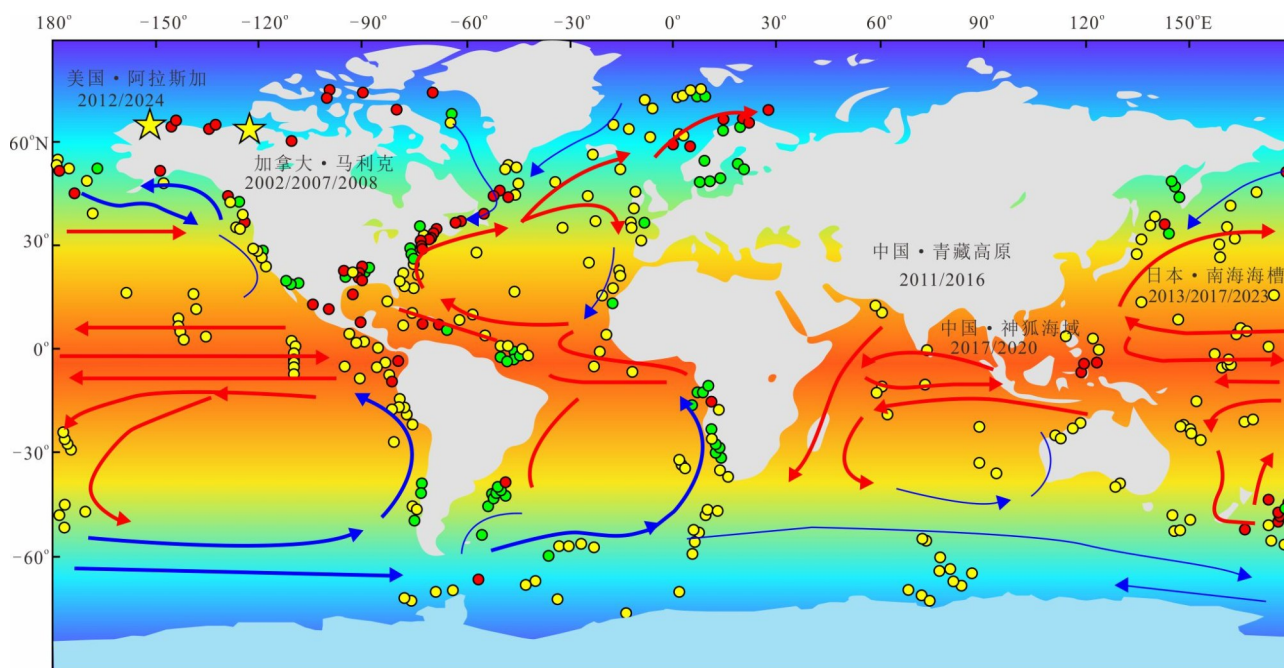
(Shakhova *et al.*, 2010, 2015; Serov *et al.*, 2023). 相比之下,环南极洲地区因深水环境、低沉积速率和较低的有机质供给,渗漏活动相对较弱.

为全面揭示海洋甲烷渗漏的全球分布格局,研究人员综合了近年来海洋水合物区甲烷渗漏的文献以及大洋钻探计划(ODP/IODP)等数据,获取全球各大洋已探明及潜在甲烷渗漏点位信息(Ni *et al.*, 2025),绘制了全球海域甲烷渗漏空间分布图(图2). 数据显示,全球已识别的天然气水合物赋存区域约占全球海底面积的10%,其中70%以上分布在构造边界区和深海边缘. 全球天然气水合物潜在分布图与甲烷渗漏点分布图高度一致,表明水合物分解释放是现代甲烷通量的重要贡献途径,这一分布规律也为预测未来气候驱动下的潜在渗漏风险区提供了重要依据.

空间分布数据显示,甲烷渗漏点主要集中在大陆架边缘和大洋边缘地带,特别是在北大西洋、地中海、北极地区以及环太平洋沿岸呈现出高密度分布. 其中,渗漏点分布与洋流系统在全球尺度上呈现显著正相关($R^2 = 0.86$, $RMSE = 1.38$)(Ni *et al.*, 2025). 这种现象可能暗示了洋流动力学对天然气水合物稳定性及甲烷释放的影响. 一方面,洋流系统通过暖流(如湾流、黑潮)引起的海底温度变化,可能触发水合物分解和甲烷释放(Mienert *et al.*, 2005). 另一方面,强洋流产生的底层剪切应力和压力扰动可能改变甲烷的运移路径(Plaza-Faverola *et al.*, 2017). 此外,洋流控制的海底沉积物分布格局还可能影响有机质供给和微生物产甲烷活性,从而进一步调节甲烷的生成与释放(Graves *et al.*, 2015). 然而,洋流与甲烷渗漏分布的相关性也可能部分源于观测偏差,主要洋流路径往往是科学考察活动最为密集的区域. 因此,相关机制的验证仍需依赖更多高精度、长时序的原位观测数据(Ruppel and Kessler, 2017). 此外,北极地区甲烷渗漏的高密度分布尤为引人注目,这可能与全球变暖导致的永久冻土融化和海底甲烷水合物失稳有关,并可能进一步形成气候变化的正反馈机制(Serov *et al.*, 2017; Shakirov *et al.*, 2020).

1.2 区域空间分布特征

基于全球分布格局,不同海域的甲烷渗漏在空间密度、释放强度和赋存形态等方面呈现显著的区域差异,这主要受地质构造背景、气候环境条件和沉积过程的耦合作用控制(图3). 以北极东西伯利

图2 全球海域甲烷渗漏空间分布图(引自 Ni *et al.*, 2025)Fig.2 Spatial distribution map of methane leaks in global oceans (Ni *et al.*, 2025)

亚海大陆架为例,该区域大量甲烷渗漏现象与多年冻土解冻、水合物稳定带下限抬升等气候驱动因素高度相关(Stotler *et al.*, 2010).甲烷渗漏形式主要表现为浅水环境中密集气泡排放及甲烷羽状流,羽流高度可达数十米甚至上百米,部分渗漏点将甲烷输送至大气.研究表明,北冰洋海底直径为3~5 mm的甲烷气泡在上升过程中路径稳定、停留时间短,极易越过水体氧化层进入海气界面.这种现象在夏季尤为多发,使得北极浅海区域成为全球少数能够在短期内直接影响大气甲烷浓度的区域之一(Shakhova *et al.*, 2010, 2017; James *et al.*, 2016).

北大西洋沿岸是甲烷渗漏的另一重要区域,其甲烷活动与第四纪以来的沉积物滑坡和冰川地貌改造密切相关.其中挪威海 Storegga 滑坡带是最典型的代表,该滑坡带的残留构造中富集大量甲烷气体,形成了持久的气体羽流输运系统(Bünz *et al.*, 2003; Karstens *et al.*, 2023).类似的甲烷活动也出现在苏格兰西部陆坡和爱尔兰盆地边缘,其甲烷羽流分布主要受控于中新世以来的构造抬升带与断陷盆地边界(Talling *et al.*, 2014).此外,对波罗的海波恩霍姆盆地44个站点的沉积物分析均显示出明显的甲烷富集(Hilligsøe *et al.*, 2018),进一步证实了北欧边缘海普遍存在显著的甲烷活跃特征.

环太平洋地区是全球甲烷渗漏最为活跃的区域之一.墨西哥湾北部陆坡是该区域研究最为深入

的典型代表.2011年和2014年的系统调查发现,该区域既存在“深水地平线”漏油事件引发的人为甲烷释放,也广泛分布着天然气水合物自然分解形成的甲烷渗漏点(Kessler *et al.*, 2011; Skarke *et al.*, 2014).这些深水碳氢化合物渗漏点是大气甲烷的重要来源(Hu *et al.*, 2012).在美国加州外海,E/V 鸚鵡螺号科考同样识别出多处活跃的甲烷渗漏点(Levin *et al.*, 2016).在西太平洋,日本海西北部的水柱、沉积物和浅层水合物层中均发现了明显的甲烷渗漏证据(Vereshchagina *et al.*, 2013; Aoyama and Maeda, 2021),表明环太平洋构造活动带普遍存在活跃的甲烷渗漏过程.

南海是我国海洋甲烷渗漏研究的核心区域,在陆坡断裂构造带、盆地边缘及沉积中心附近普遍发育羽状气泡和声学异常反射.北部陆坡区域的琼东南盆地、珠江口盆地南缘及陆丰凹陷等地广泛分布多点并发型羽状流,其海底局部沉积物温度较正常地热梯度异常升高,主要受深部热流体上涌和水合物分解影响,并伴随高通量甲烷释放(尹希杰等, 2008; 郝海燕等, 2018; 景建恩等, 2018).珠江口盆地东部海域天然气水合物尤为富集(吴能友等, 2009; 尹希杰等, 2010; 沙志彬等, 2015; 杨克红等, 2016),陆坡广泛发育数米至公里尺度麻点构造(Zhu *et al.*, 2025),西部海域的“海马”冷泉展现出更为明显的甲烷渗漏羽流(梁前勇等, 2017; 赵静

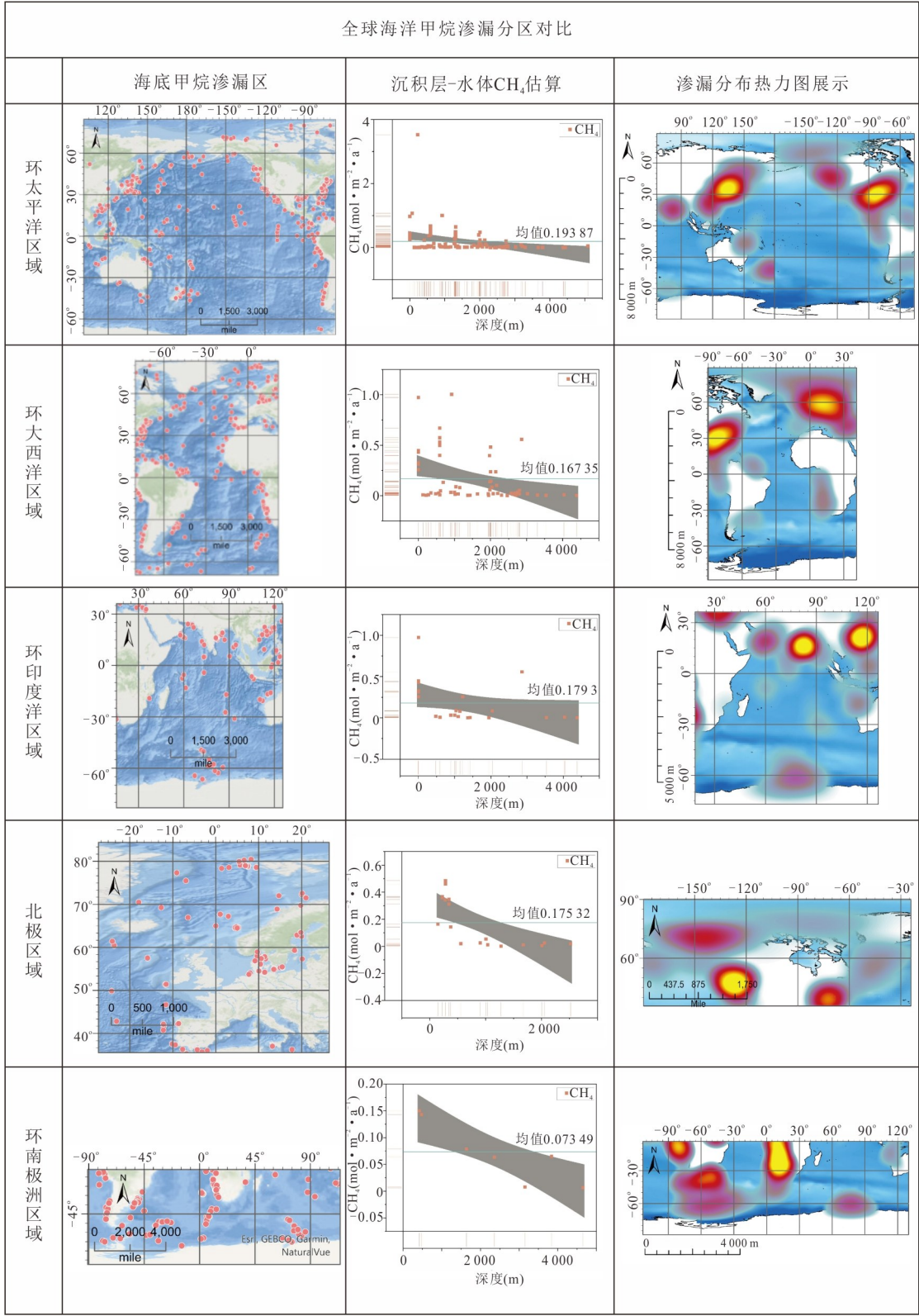


图 3 全球海洋甲烷渗漏分区对比

Fig.3 Comparison of global methane seepage zones

左侧位各区域沉积层和水体中甲烷浓度分布;中间为基于SMT深度估算的甲烷渗漏通量随水深变化(横坐标为水深(m),纵坐标为CH₄通量/mol·m⁻²·a⁻¹);右侧为全球甲烷渗漏空间分布.引自 Ni *et al.* (2025)

等, 2020). 台湾西南海域甲烷渗漏最为显著, 沉积物孔隙水中甲烷浓度达1~10 mM, 底层海水浓度为5~50 nM, 是背景区域的10~100倍. 该区域硫酸盐还原速率显著加快, CH_4 的碳同位素($\delta^{13}\text{C}$)值为 -60‰ ~ -75‰ , 表明存在强烈的生物成因产甲烷过程 (Chuang *et al.*, 2010; Chuang *et al.*, 2013; Hu *et al.*, 2017). 总体而言, 南海地区的研究揭示了边缘海盆地中甲烷渗漏的多样性特征, 为理解西太平洋构造活动区的甲烷循环提供了关键证据.

2 海底甲烷来源与泄漏机制

海底甲烷的来源、赋存形式及其向水体和大气的释放过程, 是理解海洋甲烷循环的核心问题. 海底甲烷主要有生物成因和热成因两种来源 (Lollar *et al.*, 2006; Stolper *et al.*, 2015). 生物成因甲烷在低温、厌氧环境下由微生物分解有机质产生, 主要通过氢营养型、乙酸发酵型和甲基营养型等代谢途径形成, 通常赋存于浅层沉积物中; 热成因甲烷则在高温高压条件下由有机质热解生成, 主要存在于深部地层中 (图4). 这些成因途径受沉积环境和地质构造的综合控制. 沉积环境决定了有机质类型、

丰度及保存条件, 进而影响微生物产甲烷的底物供给和代谢途径选择; 地质构造则控制温度—压力条件和流体运移通道, 深部高温高压环境促进热成因甲烷形成, 浅层低温环境则有利于生物成因甲烷产生. 因此, 深水盆地、活动大陆边缘等不同构造—沉积背景下的甲烷成因机制呈现明显差异 (Whiticar, 1999; Milkov and Etiope, 2018). 甲烷从海底向上运移和释放受到多重机制的调控, 包括水合物分解、地质构造活动、气候变化等. 例如, 在末次冰消期, 高纬度地区如北极的冰盖消退和海平面上升导致水合物稳定带上移, 引发了区域性的甲烷释放增强 (图4a) (Portnov *et al.*, 2013).

生物成因甲烷是浅层海洋沉积物中 CH_4 的主要来源 (Maltby *et al.*, 2016; Wallenius *et al.*, 2021). 北极海底沉积物富含浮游生物残骸, 经微生物分解持续产生生物成因甲烷并占主导地位 (Shakhova *et al.*, 2010). 生物成因甲烷具有显著的同位素特征, 其碳同位素($\delta^{13}\text{C}$)值通常较轻, 一般在 -60‰ ~ -110‰ , 这是因为微生物在代谢过程中优先利用 ^{12}C , 导致生成的甲烷中 ^{13}C 的相对含量较低 (Blair, 1998; Zhang *et al.*, 2002; Wang *et al.*, 2024). 根据母质来源和形成条件, 生物成因甲烷可

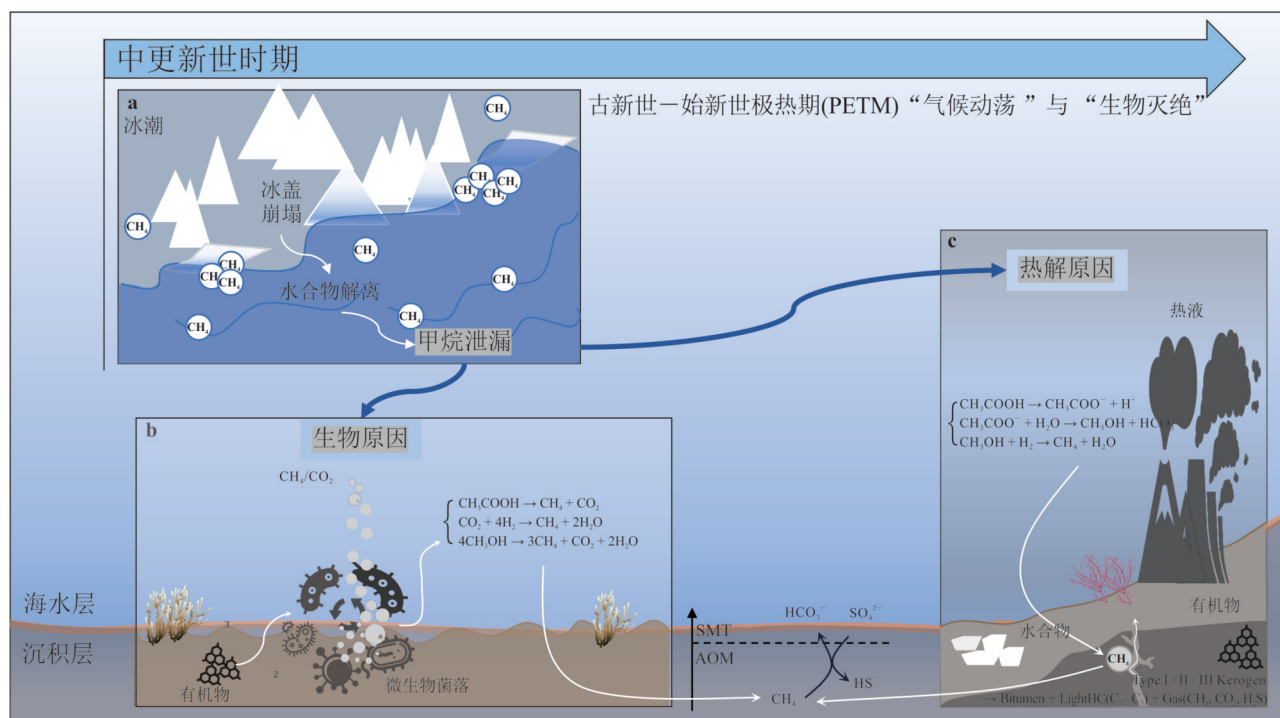


图4 甲烷成因类型与古气候事件示意

Fig.4 Schematic diagram of methane sources and paleoclimatic events

a. 末次冰消期高纬度地区 (如北极) 的甲烷渗漏过程, 蓝色箭头表示时间序列; b. 生物成因甲烷的形成途径; c. 热成因甲烷的形成过程; 据 Sluijs *et al.* (2007); Dickens (2003) 修改绘制

分为原生型和次生型两个亚类.原生型生物成因甲烷的碳源主要是浅部地层中的活性有机质(尚未转化成干酪根)和未成熟干酪根(Rice and Claypool, 1981; Tori *et al.*, 1999).次生型生物成因甲烷的碳源则来源于深部地层中的成熟有机质,包括成熟干酪根、原油和湿气组分(C_{2+} 烃类,如乙烷、丙烷等高碳烃类气体),是深部热成因烃类在运移过程中经微生物降解改造后生成(Lai *et al.*, 2021).

热成因甲烷的生成主要发生在深部高温高压环境中.当有机质埋藏深度达到数千米时,地层温度升高至120~150 °C以上,使得有机质发生热裂解反应,逐步转化为甲烷及其他烃类气体(如图4c所示).与生物成因甲烷不同,热成因甲烷的 $\delta^{13}C$ 值相对较重,且常伴生乙烷、丙烷等重烃组分(Milkov *et al.*, 2005).在板块俯冲带、裂谷带等构造活跃区域,深部地层的温度和压力条件更有利于热成因甲烷形成.构造活动为甲烷向上迁移行为提供有效通道.此外,在适当的温压条件下,深部油气藏可分解释放大量的 CH_4 (Adler *et al.*, 2011; James *et al.*, 2016).

海底沉积物的甲烷需要通过特定的构造通道才能从源区向海底运移并最终发生渗漏.地质构造活动为深部甲烷提供了向上运移的通道(Ciotoli *et al.*, 2020).在板块俯冲带、扩张脊及转换断层等构造活跃区域,地壳变形和应力变化频繁,产生大量断层和裂隙系统.这些断层系统切穿巨厚沉积层延伸至海底,有效连接了深部油气系统和微生物活跃带,促进了海底甲烷的释放过程.甲烷的运移形式主要有溶解态和气泡态两种:溶解态甲烷通过分子扩散缓慢进入水体;气泡态甲烷以游离气泡形式快速从海底上升(Sloan *et al.*, 2007).固态水合物本身并非主要运移形式,仅在极少数情况下(如大规模海底滑坡)可能发生含水合物沉积物的整体搬运,但水合物在运移过程中通常会因压温条件变化而迅速分解(Sultan *et al.*, 2004).

从全球碳循环角度看,中深部热成因甲烷和中浅部原生/次生微生物成因甲烷,运移至相对浅部的水合物稳定带内形成水合物,成为海洋沉积系统中甲烷最大的汇(图5).

气候变化对海底甲烷泄漏的影响主要体现在温度和压力两个相互作用但效应相反的因素上.一方面,全球变暖导致海水温度上升,打破甲烷水合物的相平衡条件,促使水合物分解为甲烷气体和水

(Kretschmer *et al.*, 2015; Yu *et al.*, 2021).另一方面,气候变暖引起海平面上升,增加了海底的静水压力,理论上有利于甲烷水合物的稳定(Brown *et al.*, 2005; Bohnhoff *et al.*, 2024).然而,定量分析表明,海水温度上升1 °C对水合物稳定性的破坏作用远大于海平面上升数十厘米带来的压力稳定效应(Sultan *et al.*, 2020).北极地区的观测证实,海底温度升高正导致水合物稳定带上移,甲烷释放速率增加(Westbrook *et al.*, 2009).

3 甲烷在水体中的运移扩散过程

3.1 甲烷在沉积层中的迁移机制

在海底沉积物中,甲烷从深层微生物生成区向海底界面运移主要通过三种方式实现(图6):分子扩散、气泡渗流和构造对流输运.分子扩散是甲烷在沉积物中最基本的运移方式,溶解态甲烷沿浓度梯度由深部向浅部缓慢迁移.低渗透细粒沉积物中,甲烷主要依赖分子扩散运移.例如,在北极东西伯利亚陆架和南海深水盆地,沉积物有效扩散系数为 $10^{-9} \sim 10^{-10} \text{ m}^2/\text{s}$.在这种扩散主导的系统中,甲烷从数百米深的产甲烷层运移至海底界面通常需要数千至数万年,渗漏通量较低(Bakunov *et al.*, 2023).当甲烷生成速率超过扩散消耗速率时,甲烷会在SMTZ以下快速积累并形成自由气相,从而转变为更快速的气泡运移模式.

自由气相渗流是甲烷运移的重要机制.当沉积物中甲烷浓度超过溶解度极限或孔隙气体压力超过沉积物的毛细管突破压力时,甲烷开始以游离气泡形式存在(Cahill *et al.*, 2018).这些气泡在浮力、压力梯度和毛细压力的共同驱动下,沿着相互连通的孔隙网络向上运移.气泡的运移路径和效率主要受控于沉积物的孔隙结构、渗透性和含气饱和度.在粗粒沉积物(如砂质层、粉砂层)中,高渗透性使气泡运移更为高效;而在细粒黏土层中,低渗透性显著限制气泡运动,导致甲烷优先沿高渗透层运移,形成渗漏快道.

构造控制的对流输运可优先加快甲烷的迁移速率(Wood and Sanei, 2016).当地层中甲烷生成速率过快或压力积聚到临界值时,甲烷会沿断裂构造形成稳定羽状流.声学剖面 and 地球化学剖面显示,甲烷渗漏在断裂密集区更为活跃,与新生代以来的构造活动密切相关(Daigle and Dugan, 2010).在南海北部陆坡和墨西哥湾盆地,调查发现大量“气烟

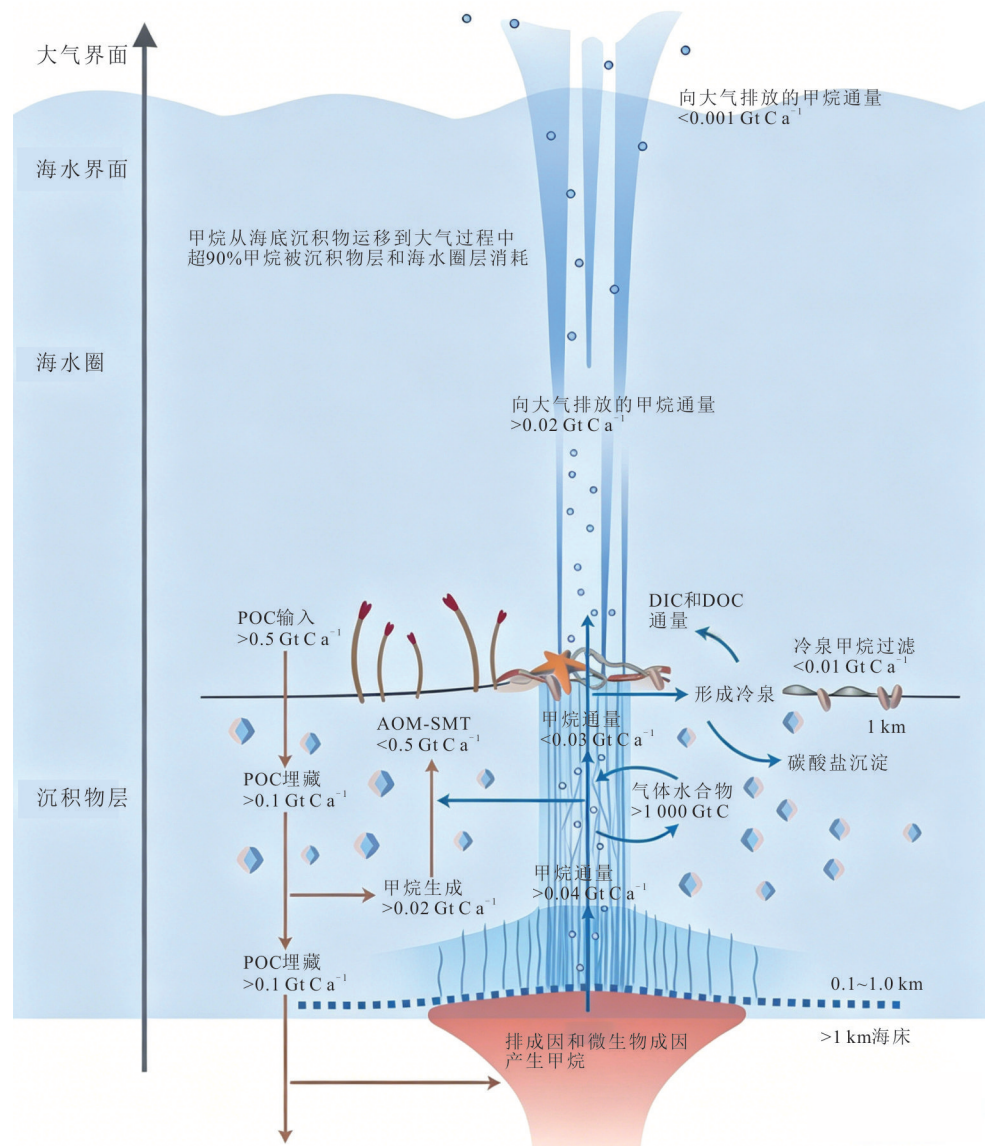


图5 沉积层至海水大气甲烷渗漏碳通量示意

Fig.5 Schematic of carbon flux from sedimentary layers to seawater and atmospheric methane seepage

AOM-SMT表示在硫酸盐-甲烷过渡区的甲烷厌氧氧化,棕色箭头表示扩散驱动系统中通量,蓝色箭头表示对流(冷泉)系统中通量;据 Boetius *et al.*(2013)修改

窗”结构,直径数十米至百米,穿透厚层沉积物向上输送气体,成为沉积柱中的主要逸散路径(Gorchov Negrón *et al.*, 2020;Ye *et al.*, 2019).在东非裂谷延伸至海底的区域,陆坡滑坡体充当气体聚集与运移的通道,重力滑塌产生的剪切带为甲烷渗漏提供优势路径,并诱发羽状流发育(Jia *et al.*, 2023).构造控制的快速输运可使甲烷在短时间内(数年至数十年)从深部储层直接到达海底界面,形成高通量渗漏点.因此,甲烷在沉积物中的运移沿纵向呈现非均质性,同时受控于沉积物渗透性差异和构造通道分布:低渗透性的细粒沉积物限制气泡扩散运移,

而高渗透性的粗粒层和断裂构造带则成为甲烷快速上升的优势通道.

3.2 SMTZ与甲烷运移的关系

SMTZ是海洋沉积物中的一个关键地球化学界面,在甲烷循环和渗漏过程中扮演着重要角色(张劼等, 2018).SMTZ是硫酸盐还原和AOM过程的交汇处.AOM是指在缺氧环境中,将甲烷氧化为二氧化碳和水的过程.SMTZ的深度在不同海洋环境中差异显著,在无深部甲烷来源的背景区域,SMTZ深度主要取决于沉积速率和有机质降解产生的甲烷通量.深海环境中SMTZ通常位于海底以

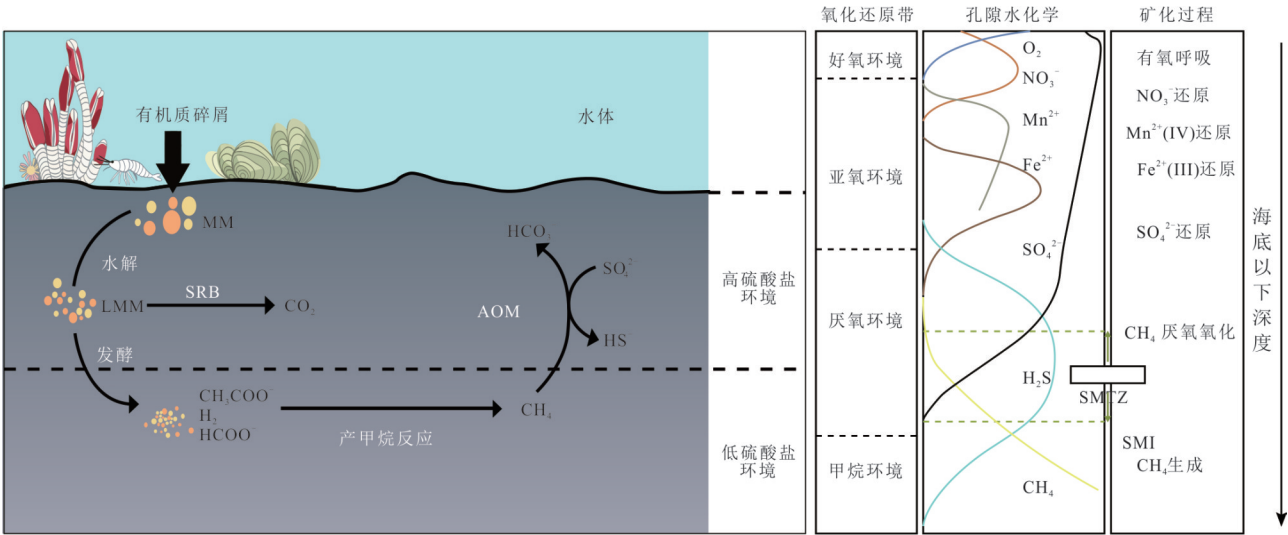


图6 海洋沉积物中甲烷迁移的主要机制示意

Fig.6 Schematic representation of the primary mechanisms of methane migration in marine sediments

据 Madison *et al.* (2013); 牛明杨等 (2018) 修改

下数十米至数百米深度,而在陆架和海岸带区域,由于沉积速率较高和有机质含量丰富,SMTZ深度相对较浅,通常在海底以下数米至数十米范围内.相比之下,在存在深部甲烷渗漏的活跃冷泉区,向上的高甲烷通量会驱动SMTZ显著上移至海底表层,深度可浅至海底以下数十厘米至数米(Chen *et al.*, 2023b).通过分析全球范围内的数据,发现SMTZ深度越浅,通常对应着越高的甲烷渗漏通量.而在深部甲烷通量较高的活跃渗漏区,强烈的甲烷通量驱动SMTZ向海底表层抬升,形成浅层SMTZ,并伴随高强度的AOM作用和硫酸盐消耗(Hu *et al.*, 2023).这种深部甲烷源对维持海底以下硫酸盐收支平衡起着关键作用(Hu *et al.*, 2022).因此,SMTZ深度是指示海底甲烷渗漏强度的有效地球化学指标:SMTZ越浅,指示的甲烷通量越高;SMTZ越深甚至缺失,则表明深部甲烷供给有限或不存在活跃渗漏.

AOM过程的反应速率主要与甲烷和硫酸盐的浓度有关,当甲烷和硫酸盐的浓度越高时,AOM作用越强烈,消耗甲烷、硫酸盐的速率越快(徐思南等, 2024).因此SMTZ不仅是判断甲烷渗漏强度的指标,还是理解海洋甲烷循环过程的关键.然而,SMTZ的厚度和位置并非固定不变,而是受到多种因素的动态影响,包括沉积速率、有机质含量、甲烷通量等.在高甲烷通量区域,SMTZ往往更靠近海底表面,这不仅增加了甲烷渗漏的可能性,还可能导致自生碳酸盐岩的形成,进而影响海底地貌和生

态系统(Boetius *et al.*, 2000; Peckmann and Thiel, 2004; Suess, 2014).

基于全球冷泉和甲烷渗漏区的研究表明,SMTZ深度与甲烷渗漏通量之间存在显著的负相关关系(Egger *et al.*, 2018).在活跃冷泉区,强烈的深部甲烷供给使SMTZ抬升至海底浅层,形成高通量渗漏.而深层SMTZ(埋藏在海底以下数百米至上千米)所代表的甲烷渗漏通量微弱,对海—气界面甲烷通量的贡献可忽略不计.因此,海洋甲烷的有效释放主要集中在大陆架浅水区和活跃冷泉系统,这些区域的浅层SMTZ是控制甲烷向上运移的关键屏障(Weber *et al.*, 2019).

SMTZ的位置主要受控于向上的甲烷通量和向下扩散的硫酸盐通量之间的平衡(Niewöhner *et al.*, 1998).储层中水合物分解产生的甲烷通过3种机制运移:浅层沉积物中的分子扩散、孔隙水溶解运移,以及深部地层中游离态气体的浮力上升(Boetius and Wenzhöfer, 2013).这三种运移方式的甲烷截滤效率和渗漏通量存在显著差异.在分子扩散方式下,甲烷向上运移速率缓慢,大部分在沉积物浅表层即被甲烷厌氧氧化作用消耗(Valentine, 2011).微渗漏在海底分布更加普遍,甲烷渗漏量对环境的影响较大(Etiope, 2012).当甲烷以气体和游离态气泡沿着海底断层和断裂向上运移时,甲烷气泡群在海底形成“甲烷羽状流”(Greinert *et al.*, 2006),这类气泡群可通过多波束声呐系统或海底原位观测装置直接探测.由于此类运移方式的甲烷

渗漏通量较大,通常被称为宏渗漏.综上所述,SMTZ作为沉积物中甲烷运移的关键屏障,其深度和强度直接影响甲烷能否有效穿透沉积层进入上覆水体,进而影响海—气界面的甲烷交换通量.

3.3 水柱中甲烷的运移扩散机制

3.3.1 甲烷在海水中的溶解机制 甲烷在海水中的溶解遵循亨利定律,溶解量与甲烷分压、温度和盐度有关(Zhao *et al.*, 2024).当甲烷从海底泄漏进入水体,首先发生溶解过程,随着与海水的接触时间增加,溶解量逐渐达到平衡.亨利定律指出,在一定温度下,气体在液体中的溶解度与在气相中的分压成正比(适用于温度 0~30 °C、压力 0.1~10.0 MPa、盐度 0~40 PSU 的海水环境).对于甲烷在海水中的溶解,甲烷溶解度表示如下:

$$C = kH \times P, \quad (1)$$

式(1)中, C 为溶解度, P 为甲烷分压度, kH 为亨利常数.

温度对甲烷在海水中的溶解度有着显著影响(Dickens and Quinby-Hunt, 1994).随着温度的升高,甲烷分子的热运动加剧,分子间的相互作用力减弱,会导致甲烷在海水中的溶解度降低.盐度的增加也会降低甲烷在海水中的溶解度(Tishchenko *et al.*, 2005).海水中的盐分主要由各种离子组成,这些离子会与水分子相互作用,改变水分子的结构和性质,使得甲烷分子更难进入水分子的间隙,从而降低了甲烷的溶解度.

除了温度和盐度外,压力对甲烷在海水中的溶解度也有重要影响.在深海环境中,随着海水深度的增加,压力增大,甲烷在海水中的溶解度也会相应增加(Zhao *et al.*, 2022).挪威海域的甲烷及其他水体气体扩散溶解过程,从剖面分析和其他各气体的扩散来看,甲烷的水体扩散溶解随深度增加压力增大而上升(图7).

甲烷在水体中的扩散过程主要包括分子扩散和湍流扩散两种形式,它们在不同的时空尺度和环境条件下对甲烷的分布和运移起着不同程度的作用.分子扩散是由于分子热运动而引起的物质迁移现象,是甲烷在水体中扩散的基本形式之一.根据菲克第一定律:

$$J = -D \frac{dC}{dx}, \quad (2)$$

式(2)中, J 为扩散通量, $\frac{dC}{dx}$ 为浓度梯度, D 为分子扩散系数,反映了分子在介质中扩散的难易程度.

在海洋中,湍流主要由海流、海浪、潮汐等因素引起,通过剧烈混合水体物质,从而加速海水中甲烷扩散过程,湍流扩散公式如下:

$$J_t = -K_d \frac{dC}{dx}, \quad (3)$$

式(3)中, J_t 为湍流扩散通量, K 为湍流扩散系数,其大小取决于湍流的强度和尺度,取值比分子扩散系数 D 大得多, $\frac{dC}{dx}$ 为浓度梯度.

在强海流和大风浪作用下,水体的湍流强度增大,湍流扩散系数也会显著增大.例如在墨西哥湾的甲烷泄漏事件中,强大的海流和海浪引起的湍流扩散导致甲烷在短时间内扩散到了广阔的海域(Hu *et al.*, 2012).

3.3.2 气泡态甲烷的运移机制 甲烷主要通过3种方式进入海水:扩散作用、气泡上升和断层裂隙渗漏.这些释放机制受到温度、压力、沉积物特性和微生物活动等多种因素的影响(Wuebbles and Hayhoe, 2002).在气泡上升过程中,其速度受浮力、阻力和表面张力共同作用而逐渐改变(Kulkarni and Joshi, 2005).气泡的实际行为取决于压力效应与溶解效应之间的相对强弱.在深水环境中,溶解效应往往占主导,大部分小气泡(直径<5~10 mm)在上升几十至几百米后完全溶解于水体中(Rehder *et al.*, 1999; Greinert *et al.*, 2010).相比之下大气泡(直径>10 mm)体积大而不易溶解,且上升过程中压力降低引起的膨胀效应显著,更容易到达海面(Leifer and MacDonald, 2003).

海底释放的甲烷在垂直运移过程中呈现出独特的浓度分布特征,Rusakov and Kutas(2018)在黑海研究发现,海底附近释放的甲烷在向上运移过程中浓度逐渐降低.James *et al.*(2016)通过对大西洋多个区域的观测进一步指出,甲烷自海底释放后,同时受到垂直混合与水平输运的影响,但垂直浓度梯度仍然是判断甲烷来源和扩散速率的关键指标).此外,Shakhova *et al.*(2017)在北冰洋陆架区发现,季节性海冰融化会导致大量甲烷从海底释放,并在水柱中形成明显的垂直浓度梯度.

甲烷气泡在海水中的上升过程计算如斯托克斯公式(适用于层流条件下,雷诺数 $Re < 1$ 的小气泡,直径通常<1 mm),在黏性流体中的上升速度 v 可以表示为:

$$v = \frac{2r^2 g (\rho_f - \rho_g)}{9\mu}, \quad (4)$$

式(4)中, r 为气泡半径, g 为重力加速度, ρ_f 和 ρ_g 分别

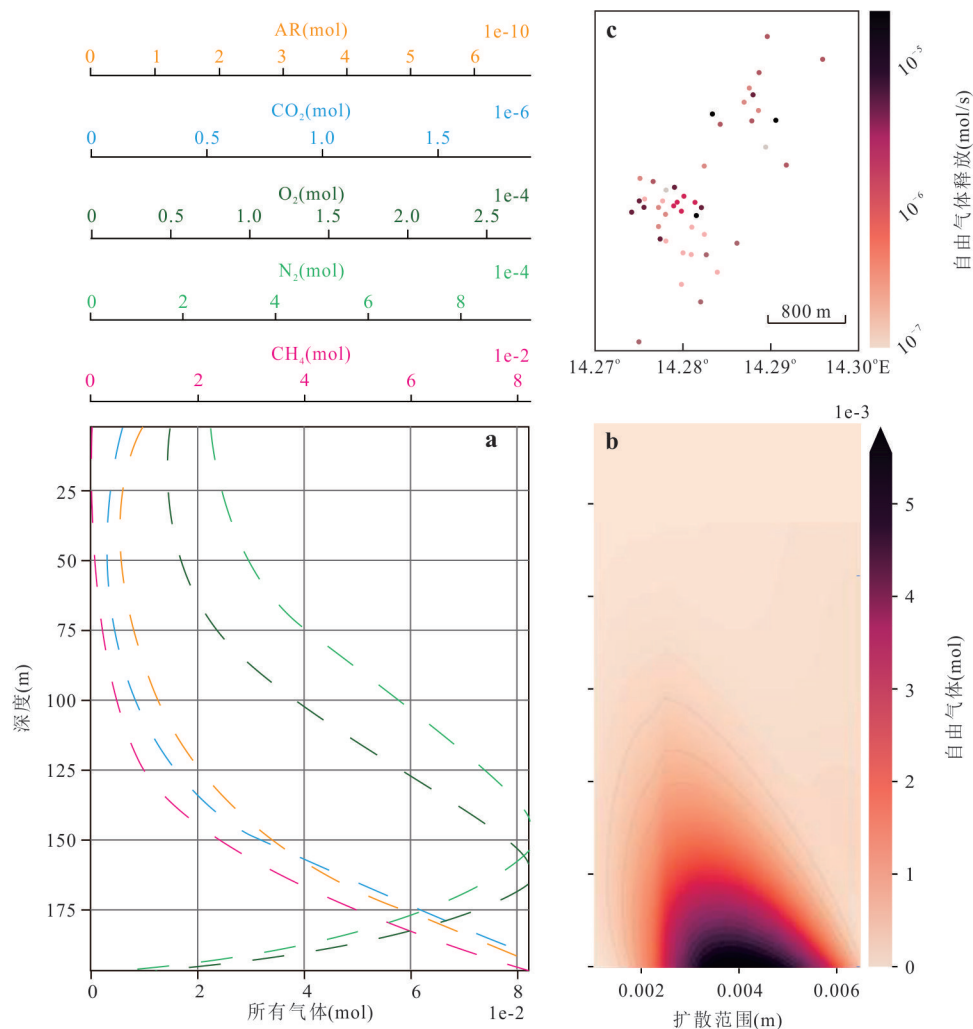


图 7 水柱自由气体分布及通量

Fig.7 Distribution and flux of free gases in the water column

a. 水柱中CH₄、N₂、O₂、CO₂、Ar等5种气体(彩色坐标轴)及总自由气体(黑色,下方x轴)的垂直剖面含量;b. 不同深度下,所有渗漏点及气体综合的气泡大小分布;c. 45个渗漏点处海面自由大气气体通量分布(对数色标);引自Dølven *et al.* (2025)

为流体和气泡的密度, μ 为流体的动力黏度。

在实际海洋环境中,甲烷气泡的上升速度还受到海水温度、盐度、压力以及海流等因素的影响.例如,海水温度的升高会降低其黏度,从而加快气泡的上升速度;而海流则会影响气泡的上升轨迹,使其发生偏移.在墨西哥湾的甲烷泄漏事件中,海流作用就曾使气泡的上升路径呈现明显弯曲,并扩大了甲烷的扩散范围(Solomon *et al.*, 2009a).

甲烷气泡在上升过程中还会发生一系列物理变化,包括气泡的变形、旋转和内部环流等.在此过程中,气泡可能发生破裂和合并现象:破裂通常由压力不均或气体过度膨胀引起,而合并则源于气泡间的吸引和碰撞(Leifer *et al.*, 2002b).这些行为会改变甲烷在水体中的分布和运移路径.部分甲烷会溶解进入海水形成溶解态甲烷,其余则以微小气泡形式继续上升,最终释放至大气.

Schmale *et al.* (2011). 基于在黑海 2 000 m 水深区域的甲烷预算研究(图 8)发现,甲烷气泡在水体中的垂直分布受到溶解度和水合物稳定性的显著影响.该研究进一步指出,黑海水体中甲烷的最终稳定浓度是多次输入事件的累积结果,证实了其垂直分布具有动态演变的运移特性

海底释放的甲烷在水体中的最终归宿,主要受释放水深和微生物代谢活动的控制.在浅海区域(水深<100 m),尤其是高通量渗漏区,甲烷气泡可直接上浮至表层并进入大气(McGinnis *et al.*, 2006).而在深海环境(水深>600 m)中,甲烷运移行为则更为复杂.在甲烷水合物稳定域内,气泡表

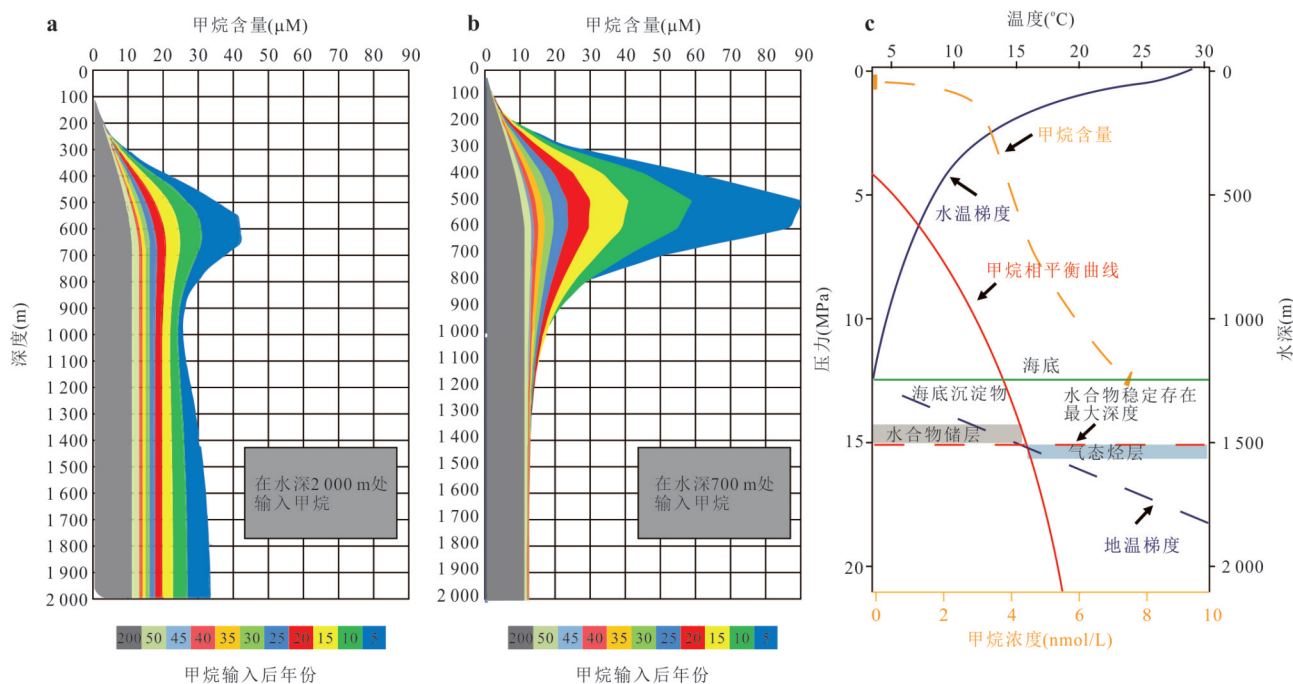


图8 海水甲烷溶解度曲线和平衡相图

Fig.8 Methane solubility curves and equilibrium phase diagrams in seawater

.a, b图显示的是黑海2000 m和700 m水深的甲烷预算, 色标表示甲烷输入事件时间, 灰色区域表示黑海水体中甲烷的最终稳定浓度, 据Schmale *et al.* (2011)修改. c图红色实线表示海水中甲烷水合物的平衡线; 蓝色实线为试采区海水温度曲线; 红色虚线表示生产试验后海水溶解甲烷含量的实测值

面可能形成水合物膜, 暂时抑制其溶解; 随着上升过程中压力降低, 气泡体积膨胀并逐渐破碎、溶解, 其上浮高度与初始渗漏量呈正相关 (Leifer *et al.*, 2006). 深海甲烷气泡的溶解速率与其气泡大小、上升速度及周围水体甲烷浓度密切相关 (Greiner *et al.*, 2010). 值得注意的是, 即使在深海区域, 仍有部分甲烷气泡能穿越数百米水深抵达上层水体 (McGinnis *et al.*, 2006), 这主要受益于气泡表面形成的水合物膜对溶解过程的暂时保护作用 (Sun *et al.*, 2018; Fu *et al.*, 2021).

3.4 海—气界面甲烷交换

海底甲烷经过沉积层和水体的多重过滤后, 最终到达海—气界面. 全球海洋向大气排放的甲烷通量约为2.2~6.3 Tg/a (Weber *et al.*, 2019). 其中, 浅水沿岸海域 (水深<50 m) 虽然仅占海洋面积的约3%, 但贡献了全球海洋甲烷排放总量的约50%, 是海洋甲烷释放的主要贡献区 (Weber *et al.*, 2019). 在背景区域, 甲烷主要通过扩散作用缓慢释放, 而在地质构造活跃的冷泉系统, 甲烷以气泡或溶解态快速涌出, 其释放通量比背景区域高出2~3个数量级 (Regnier *et al.*, 2011). 在水深较浅的渗漏区, 大量甲烷气泡甚至可以穿过海水柱直接进入大气, 甲

烷氧化损失较少 (Solomon *et al.*, 2009b). 因此, 近岸浅水区域被认为是海洋甲烷大气排放的主要场所 (Chen *et al.*, 2024b). 尽管这些高通量点源的空间覆盖范围有限, 但由于其极高的释放速率, 对区域乃至全球的甲烷收支具有不可忽视的影响.

IPCC首次评估报告(1990)给出, 海洋甲烷排放到大气通量范围为0~9 Tg·a⁻¹ (表1); 除第二次评估报告(1996)外, 历次IPCC报告均将此来源纳入大气甲烷清单 (约为5 Tg·a⁻¹), 与Kvenvolden *et al.* (2005)估算的4 Tg·a⁻¹甲烷基本吻合. 这一相对较低的贡献量反映了甲烷运移过程中的多重生物地球化学消耗机制. 水合物储层通常位于深部沉积层, 分解释放的甲烷在向上运移时首先在SMTZ被厌氧氧化作用大量消耗, 进入水体后又经历好氧甲烷氧化和物理溶解过程, 导致最终到达海—气界面的甲烷比例很小. 然而需要注意的是, 在类似PETM等灾难性事件发生时, 水合物分解可能成为大气甲烷的主要短期来源, 引发显著的气候效应 (Archer *et al.*, 2009; Ruppel *et al.*, 2017).

在IPCC的报告中把水合物分解作为大气甲烷的一个可能来源, 首先是考虑到水合物储层中封存的甲烷数量比地球系统其他部分的数量要多. 但

表 1 IPCC 对海洋水合物分解后向大气释放通量的历次估算

Table 1 Historical estimates by the IPCC of fluxes released into the atmosphere following the decomposition of marine hydrates

IPCC 评估年份(a)	海洋地质甲 烷排放对大 气的贡献量 (Tg·a ⁻¹ CH ₄)	主要参考文献
第一次 IPCC 报告(1990)	5	甲烷水合物与全球气候(Kvenvolden, 1988)
第二次 IPCC 报告(1995)	未提及	水合物来源未纳入总清单
第三次 IPCC 报告(2001)	5	全球甲烷循环三维模型综述(Fung <i>et al.</i> , 1991)
第四次 IPCC 报告(2007)	5	政府间气候变化, 2007 年气候变化综合报告(Bernstein <i>et al.</i> , 2008)
第五次 IPCC 报告(2013)	6	利用大型、动态和微生物介导的天然气水合物电容器反思全球碳循环(Dickens, 2003)
第六次 IPCC 报告(2021)	54(33~75)	AR6 增强了对海洋中红树林和深海大洋最小含氧带(OMZ)的 CH ₄ 排放量估算. 当 OMZ 上升并接近透光带时, 近海区低氧或严重缺氧期延长, 都会增强海气 CH ₄ 通量(袁佳双等, 2024)

是, IPCC 的报告并未提到天然气水合物分解产生的甲烷向大气排放的占比. 虽然天然气水合物有分解并释放甲烷到沉积物和海洋中, 但目前仍然没有证据表明这种水合物来源的甲烷大量到达大气层, 或者到达大气层的数量可能到明显影响大气甲烷的总收支(表 1). 在当前气候条件下, 海洋水合物和永久冻土对大气甲烷的直接贡献确实相对有限. 真正令气候科学家担忧的是这些系统的巨大潜在储量及其对气候变化的高度敏感性(Ruppel *et al.*, 2017; Dean *et al.*, 2018). 因此, 不能因为当前通量小就认为水合物和冻土不重要. 恰恰相反, 正是因为这些系统储存了巨大的甲烷储量, 且其稳定性对气候变化高度敏感, 才使其成为气候系统中最危险的定时炸弹之一(Archer *et al.*, 2009).

4 甲烷运移扩散的影响因素

海底甲烷的运移扩散受到物理、化学、生物和地质四大因素的综合控制. 海水温度和盐度变化影响甲烷溶解度, 海流和海浪控制甲烷的水平输运与垂直混合, 溶解氧含量决定微生物氧化消耗速率, 而海底地形则控制甲烷渗漏点分布和气泡上升路径(图 9). 这些因素相互作用, 共同决定了甲烷在海洋环境中的分布特征和运移规律.

4.1 物理因素

海水温度和盐度是影响甲烷溶解度的关键因素. 温度升高显著降低甲烷在海水中的溶解度, 海水温度每升高 1 °C, 甲烷溶解度降低约 3%~4% (Tishchenko *et al.*, 2005). 盐度增加同样导致溶解度下降. 因此, 在低温、低盐度的极地海域, 甲烷溶

解度相对较高; 而在温暖、高盐度的热带海域, 甲烷更易从水体中逸出. 温度升高使甲烷分子热运动加剧, 扩散系数增大, 在热带海域甲烷能够快速扩散到较大范围(Xu *et al.*, 2001). 在南海北部陆坡等甲烷渗漏区域, 夏季高温使更多甲烷以气泡形式上升. 而在河口等淡水注入区域, 温度和盐度的剧烈变化导致甲烷溶解度和扩散系数出现显著的时空差异(Rehder *et al.*, 2001). 对于气泡态甲烷, 海水密度和压力共同控制其上升行为. 根据斯托克斯定律, 海水密度增大时气泡浮力相对减小, 上升速度降低; 压力增大使气泡体积收缩, 同时改变其上升速度和溶解速率. 在深海环境(如大西洋马尾藻海)中, 高密度、高压以及温度分层共同作用, 使得甲烷气泡在上升过程中经历复杂的溶解—收缩动力学过程(Reeburgh, 2007), 部分气泡甚至在到达海表前完全溶解.

海流和海浪是甲烷水平和垂直输运的主要动力. 强海流能够将甲烷进行长距离水平输运, 海浪通过引起湍流混合和垂直混合作用, 加速甲烷的垂直输运过程, 在强风暴期间, 海浪能使甲烷垂直扩散系数增大数倍(Hofmann *et al.*, 2010). 海浪破碎时产生的气泡还能将海水中的甲烷携带到大气中, 增强海—气交换过程, 在海浪频繁破碎的近岸海域, 甲烷的海—气交换通量明显增高.

4.2 化学因素

溶解氧含量和氧化还原电位控制着甲烷的氧化速率. 在有氧条件下, 好氧甲烷氧化菌(aerobic methane-oxidizing bacteria, MOB)催化甲烷氧化为二氧化碳, 这一过程是水体甲烷浓度降低的主要机制(Kotelnikova, 2002). 氧化还原电位较低的环境

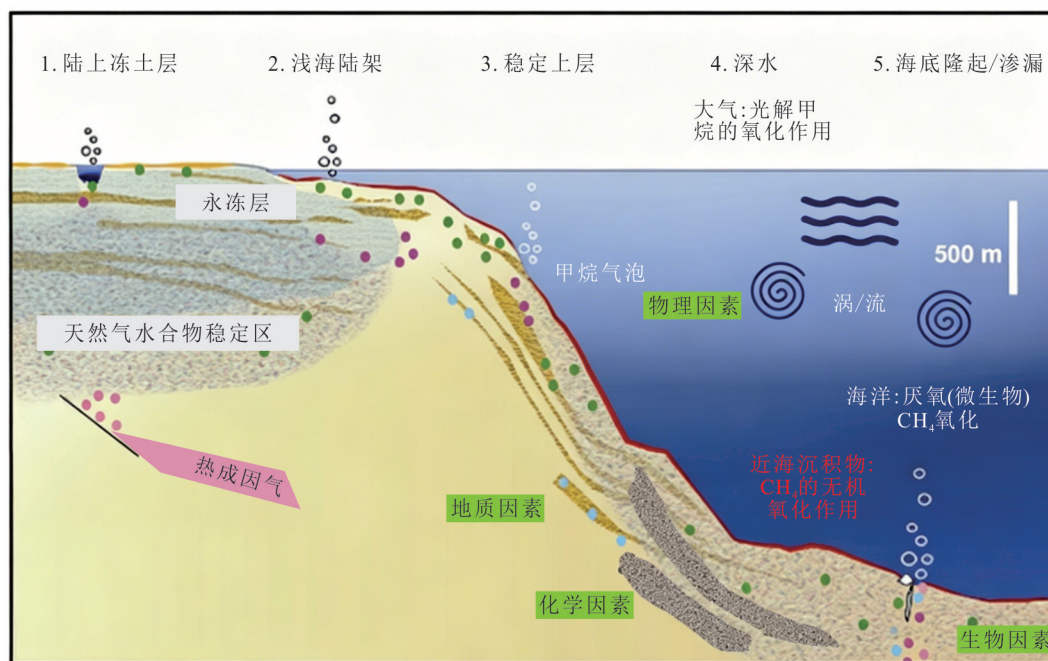


图9 海底甲烷运移扩散影响因素图(据 Ruppel, 2011 修改)

Fig.9 Map of factors affecting the transport and diffusion of seabed methane (modified from Ruppel, 2011)

有利于甲烷的保存和运移,而高氧化还原电位区域甲烷氧化速率加快.海水中的化学成分(如硫酸根离子、金属离子等)与甲烷发生化学反应,影响甲烷运移扩散.例如,硫酸根离子参与甲烷厌氧氧化过程,消耗甲烷并产生硫化氢(Timmers *et al.*, 2016).

氧化还原电位(oxidation-reduction potential, ORP)作为衡量水体氧化还原状态的重要指标,与甲烷的氧化和运移密切相关.较高的氧化还原电位通常意味着水体具有较强的氧化性,有利于甲烷的氧化反应进行.在这种环境下,甲烷能够更容易地被氧化为二氧化碳和水,从而减少了甲烷在水体中的含量和运移距离.在一些富氧的河口区域,由于水体中含有大量的溶解氧和氧化性物质,氧化还原电位较高,甲烷在这些区域的氧化速率明显加快,运移范围也受到了较大的限制(Li *et al.*, 2022b).在低氧化还原电位的缺氧或厌氧水体中,甲烷氧化效率大幅降低,甲烷因而在水体中保持较高稳定性,更易通过扩散和对流方式向上运移.

4.3 生物因素

微生物在甲烷的氧化、消耗及运移过程中起关键作用.甲烷氧化菌可利用甲烷作为碳源和能源,将甲烷氧化为二氧化碳(Caldwell *et al.*, 2008).微生物的代谢活动还会改变周围环境的化学性质,影响甲烷的溶解度和扩散系数.甲烷氧化菌是甲烷氧

化的关键参与者,通过甲烷单加氧酶(methane monooxygenase, MMO)的催化作用,将甲烷逐步氧化为甲醇、甲醛、甲酸,最终转化为二氧化碳(Lawton *et al.*, 2016).在浅海区域,水体与大气的交换频繁,溶解氧含量较高,好氧甲烷氧化菌的活性较强,能够有效地氧化甲烷(Liebner *et al.*, 2011).在黑海的深层水体中,由于缺氧,厌氧甲烷氧化菌通过与硫酸盐还原菌的共生作用,将甲烷氧化,同时消耗水体中的硫酸盐(Cheng *et al.*, 2022).微生物在代谢过程中会产生多糖等物质,这些物质能够吸附甲烷,降低甲烷的扩散系数,从而减缓甲烷在水体中的扩散速度(Alperin *et al.*, 2010; Ruff *et al.*, 2013).

生物扰动是影响甲烷运移扩散的重要方式之一,大型生物(如鱼类、底栖生物)的行为活动对甲烷运移扩散产生间接影响.鱼类的游动引起水体扰动,促进甲烷的扩散.底栖生物如贝类、虾类和蟹类等,在海底沉积物中挖掘洞穴、摄食和移动的行为会改变沉积物结构和孔隙度,进而影响甲烷在沉积物中的释放和运移(Miller *et al.*, 2002).在一些潮间带区域,大量的贝类和虾类活动频繁,使得该区域的甲烷从沉积物向水体的释放速率明显高于其他区域(Bonaglia *et al.*, 2017).

4.4 地质因素

海底地形地貌是影响甲烷泄漏点分布和运移

路径的重要因素.在海沟、峡谷等地形区域,甲烷容易聚集并沿地形通道运移,海底山脊和凸起则可能阻碍甲烷的扩散(Tryon *et al.*, 2002).复杂的地形地貌导致甲烷在水体中的运移呈现非均匀性.然而,一旦海沟附近发生地质构造活动,如板块俯冲、地震等,可能导致甲烷水合物分解,从而引发甲烷泄漏.海山的形成过程可能导致地层中形成裂缝和通道,为甲烷的运移提供了条件.相关研究表明海山顶部和山坡的甲烷浓度明显高于周围海域,表明这些区域存在甲烷泄漏点,且甲烷通过海山的裂缝和孔隙向上运移(Iyer *et al.*, 2012; Polonik *et al.*, 2024).

海底地形的坡度和起伏也会对甲烷的运移产生影响.在坡度较大的海底区域,甲烷气泡在上升过程中受到的重力分力较大,导致气泡的上升路径发生偏移.当海底坡度达到一定程度时,甲烷气泡的上升路径会向坡度较低的方向弯曲,使得甲烷在海水中的扩散范围发生改变(Leifer *et al.*, 2002a, 2002b; Liu *et al.*, 2022).海底的起伏还会影响海水的流动,进而影响甲烷的运移.在海底起伏较大的区域,海水会形成复杂的环流和涡流,这些水流会携带甲烷气泡,使甲烷运移路径变得更加复杂.由于海底地形起伏较大,海水形成了多个局部环流,甲烷在这些环流的作用下,运移路径呈现出不规则的形态,扩散范围也受到了显著影响(Liang *et al.*, 2012).沉积物的粒度、孔隙度等特性对甲烷吸附和运移也有重要影响.细粒沉积物孔隙度小,甲烷扩散速度慢;粗粒沉积物孔隙度大,有利于甲烷的运移(Duan *et al.*, 2023).

5 海洋甲烷泄漏的监测技术

5.1 现有监测技术的优势与局限性

海底原位观测技术是直接在海底甲烷泄漏现场进行观测和数据采集的关键手段,原理基于多种物理、化学和生物传感器,能够实时获取甲烷泄漏区域的各种参数信息.在南海北部陆坡的甲烷泄漏观测中,声学多普勒流速剖面仪(acoustic doppler current profiler, ADCP)被用于监测海流的变化,发现海流的流速和流向对甲烷的扩散范围和路径有着显著影响(Chen *et al.*, 2024a).溶解氧传感器则基于电化学原理,通过测量海水中溶解氧的浓度变化,进而了解甲烷在水体中的氧化速率和运移过程.在墨西哥湾的甲烷泄漏区域,溶解氧传感器的观测

数据表明,随着甲烷浓度的升高,溶解氧浓度显著降低,揭示了甲烷氧化对水体溶解氧的影响(Ayasse *et al.*, 2022; Irakulis-Loitxate *et al.*, 2022).

利用自主式水下航行器(autonomous underwater vehicle, AUV)和遥控水下机器人(remote operated vehicle, ROV)搭载各种传感器,能够对甲烷泄漏区域进行高精度的原位观测.AUV具有自主航行能力,可按照预设航线对大面积海域进行巡查,获取甲烷浓度、海水温度和盐度等参数的空间分布数据(Aguzzi *et al.*, 2019; Radziejewska *et al.*, 2024; Wohleber *et al.*, 2025).在挪威海域的甲烷泄漏研究中,AUV多次对泄漏区域进行探测,绘制出了详细的甲烷浓度分布图,为研究甲烷的扩散规律提供了重要数据(Fallati *et al.*, 2023).ROV则可在操作人员的远程控制下,对特定的甲烷泄漏点进行近距离观测和采样,获取更准确的甲烷泄漏源信息.

近年来,我国在海洋甲烷渗漏监测技术方面取得了重要进展.中国广州海洋地质调查局等机构针对海洋甲烷渗漏循环过程,系统开展了从海底沉积物到海水的甲烷溶解—扩散—运移规律研究,建立了覆盖海底—水体—大气三层两界面的甲烷调查监测技术体系(图10).该体系包括:(1)深海沉积物孔隙水长期原位采集技术,可实现海底以下8 m剖面的连续观测;(2)海底甲烷渗漏气泡通量声—光联合测量技术,结合多波束声呐和光学成像实现高精度通量估算;(3)水体甲烷锚系潜标监测技术,通过感应耦合传输实现1 500 m级深海长期观测;(4)海—气界面甲烷交换通量的连续监测采用涡度相关法自动测量技术.这些技术的应用为天然气水合物试采等重大工程提供了监测保障,推动了我国海洋甲烷监测能力的提升(Di *et al.*, 2023; Liang *et al.*, 2025).

然而,现有监测技术也存在明显的局限性.在测量技术方面,甲烷浓度的精确测量仍面临挑战,特别是在低浓度环境下,传感器的稳定性和漂移问题影响长期观测精度.溶解态甲烷和气泡态甲烷的区分测量技术尚不完善,难以准确评估不同形态甲烷的贡献比例(Erland *et al.*, 2022; Lin *et al.*, 2023).深海环境的高压、低温、黑暗以及复杂的地形条件,对观测设备的性能和稳定性提出了极高要求,增加了设备研发和维护的难度.观测设备的能源供应和数据传输也存在一定限制,难以实现长时间、大范围的连续观测,导致时空观测密度不足.

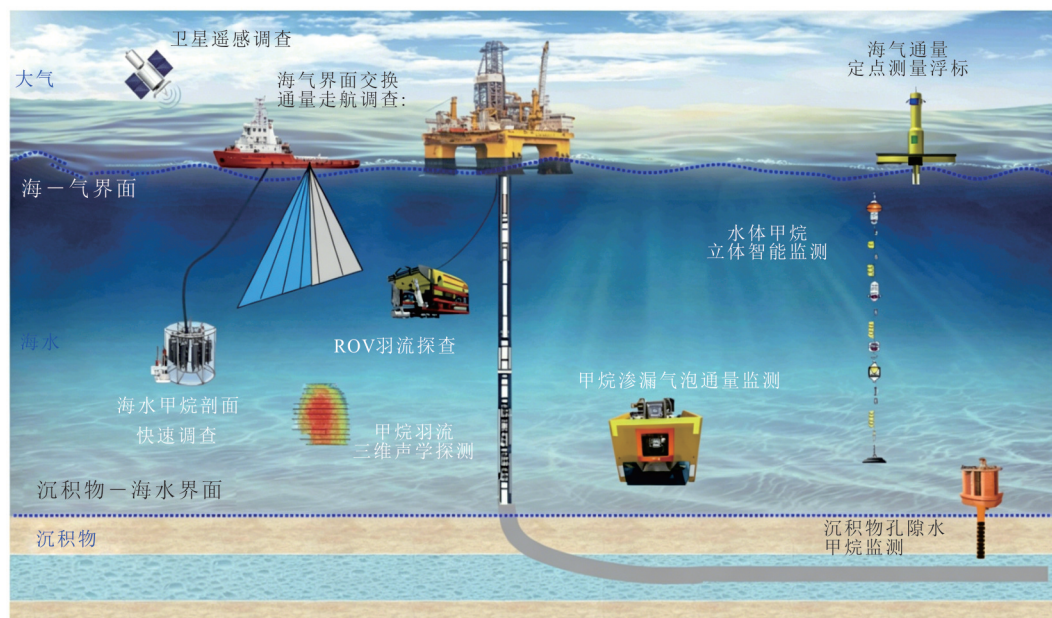


图10 海底—水体—大气“三层两界面”的甲烷调查监测技术装备体系

Fig.10 The methane survey and monitoring system for the “three layers and two interfaces” of seabed, water column, and atmosphere

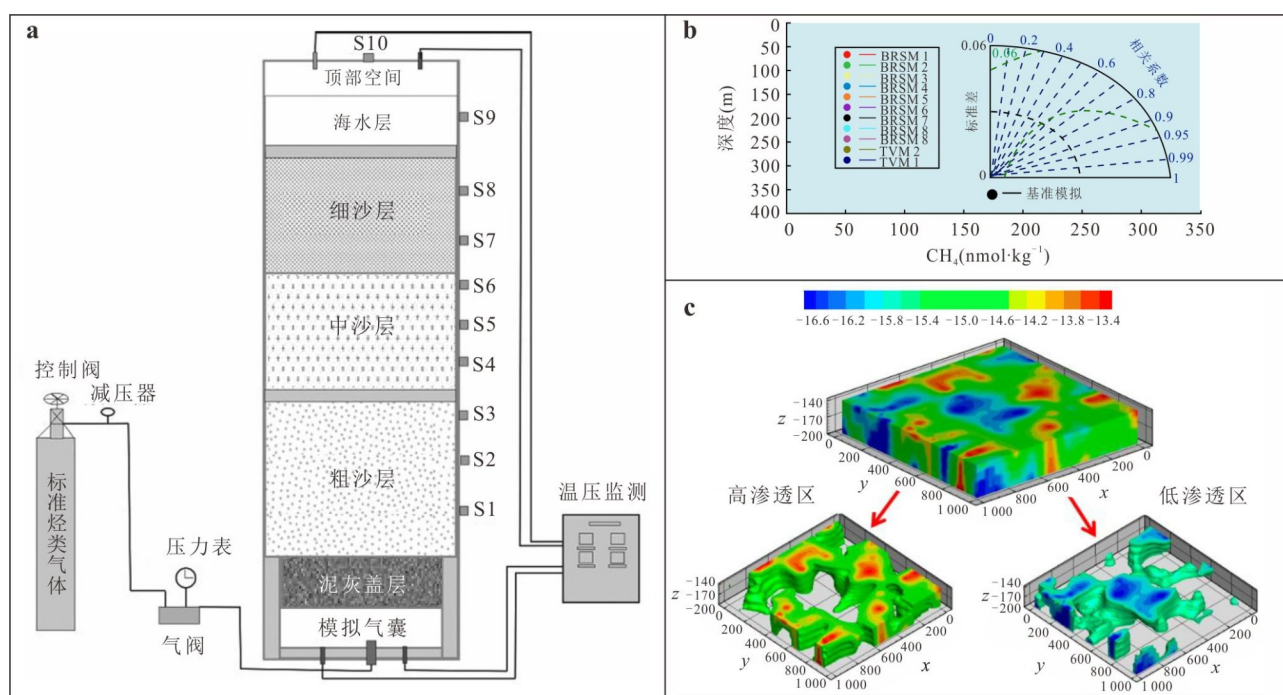


图11 实验室模拟及甲烷渗漏数值模拟

Fig.11 Laboratory simulations and numerical modeling of methane leaks

a图为海底烃类气体渗漏实验模拟装置(李双林等, 2020);b图为北冰洋水柱中溶解的 CH_4 浓度曲线模拟(Jansson *et al.*, 2019);c图为具有空间异质性的水合物储层的渗透率分布(Bei *et al.*, 2019)

5.2 实验模拟与数值模拟技术

根据海洋的点位监测,可以通过实验模拟的手段,将海洋点数据模拟成为面上数据.从局部的静

态观测,到全球的面上动态模拟,实验模拟与数值模拟技术为监测提供了有效扩充.为深入探究海底甲烷泄漏后在水体中的运移扩散机理,研究人员搭

建了一套高精度的室内模拟实验装置(Xie *et al.*, 2022). 此类装置主要由高压反应釜、温度控制系统、压力控制系统、气体注入系统、数据采集系统等部分组成. 高压反应釜是实验的核心部分, 采用高强度不锈钢材质制成, 能够承受高达 100 MPa 的压力, 有效模拟深海高压环境.

在实验设计方面, 采用控制变量法, 系统研究各因素对甲烷运移扩散的影响. 设置了多组实验, 每组实验控制一个变量, 如温度、压力、盐度、海流速度等, 其他变量保持不变. 基于实验结果, 建立了综合考虑多维运移过程的数值模拟模型(Gamwo *et al.*, 2010; Xu *et al.*, 2022). 利用现场观测数据对模型进行验证, 收集北冰洋实际海底甲烷泄漏区域的观测数据, 包括甲烷浓度、海流速度、温度、盐度等参数. 数值模拟技术将监测体系的各个点位数据或者站点数据进行拟合, 实现由点到面的全局空间分布分析(图 11).

模型验证通过后, 将其应用于不同泄漏情景下甲烷运移扩散的模拟分析, 为监测技术优化和防控对策制定提供科学依据. 数值模拟可综合考虑泄漏源强度、持续时间、海底地形和海洋环境等多种参数, 预测甲烷在水体中的三维运移扩散过程及浓度时空分布, 为监测站布局 and 预警系统设计提供理论支撑.

6 结论与展望

海洋甲烷渗漏作为全球碳循环的重要环节, 运移扩散机制及生态环境影响对深入理解海洋碳汇功能和气候变化具有重要意义. 综述整合了多源数据与多尺度研究方法, 概述海底到大气的甲烷渗漏空间分布、来源机制、运移扩散及环境效应. 主要结论与展望如下.

(1) 海底甲烷渗漏的全球分布格局受构造活动主导, 呈现活跃构造带高渗漏, 向稳定边缘递减的空间梯度. 环太平洋构造带因板块俯冲使 SMTZ 浅化, 为全球渗漏最活跃区域之一. 大西洋中脊、地中海弧后盆地等构造活跃区同样表现出高渗漏特征. 相比之下, 受控于较低的热流和有限的断裂系统, 被动大陆边缘如美国东海岸、西非边缘等区域渗漏强度显著降低.

(2) 沉积层甲烷渗漏强度与分布模式由地球动力学与生物地球化学过程综合控制, 主要受 4 类因素控制: 地质构造断裂系统提供甲烷向上运移的优势通道; SMTZ 深度(受热流与沉积速率调控)决定

厌氧氧化带的消耗能力; 有机质丰度影响甲烷生成潜力; 水合物稳定带边界的位置控制深部甲烷储库的封存与释放.

(3) 甲烷垂直剖面的水体分层输运过程受多重物理化学机制控制. 气泡上升过程遵循浮力-溶解耦合机制, 溶解度随水深减小而降低, 但海水密度分层、气泡尺寸演化(受表面张力与压力变化影响)及湍流混合显著改变气泡滞留时间. 垂向传输效率取决于渗漏通量、水深、微生物群落活性及物理混合强度的综合作用.

(4) 海洋作为全球甲烷的源汇双重角色, 在空间上呈现显著差异. 北极浅海陆架及构造活跃带的高通量渗漏区是甲烷向大气输送的源区. 相比之下, 深海和低渗漏通量的被动边缘区域则构成强效的甲烷汇. 海洋微生物构成的多层次生物过滤器显著削减甲烷大气排放, 沉积层 SMTZ 内 AOM 消耗为 70%~90% 的向上扩散甲烷, 剩余进入水体后大部分被好氧化, 最终逸出大气的甲烷约 1.5%~4.0%.

(5) 尽管海洋甲烷渗漏对全球大气甲烷浓度的直接贡献相对有限, 但海底储存的数千 Gt 甲烷水合物在气候变暖情景下具备巨大释放潜势, 构成长期气候威胁. 仍需建立长期监测体系, 特别针对热点区域的高频动态监测网络. 推进基于甲烷氧化微生物的负排放工程化应用, 构建全球甲烷渗漏数据库, 为海洋碳汇评估、气候模型搭建等提供支撑, 服务双碳目标与全球气候治理.

致谢: 感谢编辑及两位审稿人的细心审阅和专业意见.

References

- Adler, M., Eckert, W., Sivan, O., 2011. Quantifying Rates of Methanogenesis and Methanotrophy in Lake Kinneret Sediments (Israel) Using Pore-Water Profiles. *Limnology and Oceanography*, 56(4): 1525–1535. <https://doi.org/10.4319/lo.2011.56.4.1525>
- Adopted, I., 2014. Climate Change 2014 Synthesis Report. IPCC. Geneva, Switzerland, 1059, 1072.
- Aguzzi, J., Chatzievangelou, D., Marini, S., et al., 2019. New High-Tech Flexible Networks for the Monitoring of Deep-Sea Ecosystems. *Environmental Science & Technology*, 53(12): 6616–6631. <https://doi.org/10.1021/acs.est.9b00409>
- Alperin, M., Hoehler, T., 2010. The Ongoing Mystery of Sea-Floor Methane. *Science*, 329(5989): 288–289.

- <https://doi.org/10.1126/science.1189966>
- Aoyama, C., Maeda, N., 2021. Proposed Methodology to Quantify the Amount of Methane Seepage by Understanding the Correlation between Methane Plumes and Originating Seeps. *Frontiers in Earth Science*, 9: 589399. <https://doi.org/10.3389/feart.2021.589399>
- Archer, D., Buffett, B., Brovkin, V., 2009. Ocean Methane Hydrates as a Slow Tipping Point in the Global Carbon Cycle. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49): 20596—20601. <https://doi.org/10.1073/pnas.0800885105>
- Ayasse, A. K., Thorpe, A. K., Cusworth, D. H., et al., 2022. Methane Remote Sensing and Emission Quantification of Offshore Shallow Water Oil and Gas Platforms in the Gulf of Mexico. *Environmental Research Letters*, 17(8): 084039. <https://doi.org/10.1088/1748-9326/ac8566>
- Bakunov, N. A., Bolshiyarov, D. Y., Aksenov, A. O., et al., 2023. On Global ^{13}C s Diffusion in Bottom Sediments of Northern Seas. *Radiochemistry*, 65(4): 485—492. <https://doi.org/10.1134/s1066362223040100>
- Bei, K., Xu, T., Shang, S., et al., 2019. Numerical Modeling of Gas Migration and Hydrate Formation in Heterogeneous Marine Sediments. *Journal of Marine Science and Engineering*, 7(10): 348. <https://doi.org/10.3390/jmse7100348>
- Bernstein, L., P. Bosch, O. Canziani., et al., 2008. IPCC, 2007: Climate Change 2007: Synthesis Report. IPCC, Geneva, Switzerland.
- Blair, N., 1998. The $\delta^{13}\text{C}$ of Biogenic Methane in Marine Sediments: The Influence of C_{org} Deposition Rate. *Chemical Geology*, 152(1—2): 139—150. [https://doi.org/10.1016/S0009-2541\(98\)00102-8](https://doi.org/10.1016/S0009-2541(98)00102-8)
- Boetius, A., Ravensschlag, K., Schubert, C. J., et al., 2000. A Marine Microbial Consortium Apparently Mediating Anaerobic Oxidation of Methane. *Nature*, 407: 623—626. <https://doi.org/10.1038/35036572>
- Boetius, A., Wenzhöfer, F., 2013. Seafloor Oxygen Consumption Fuelled by Methane from Cold Seeps. *Nature Geoscience*, 6(9): 725—734. <https://doi.org/10.1038/geo1926>
- Bohnhoff, M., Martínez-Garzón, P., Ben-Zion, Y., 2024. Global Warming will Increase Earthquake Hazards through Rising Sea Levels and Cascading Effects. *Seismological Research Letters*, 95(5): 2571—2576. <https://doi.org/10.1785/0220240100>
- Bonaglia, S., Brüchert, V., Callac, N., et al., 2017. Methane Fluxes from Coastal Sediments are Enhanced by Macrofauna. *Scientific Reports*, 7: 13145. <https://doi.org/10.1038/s41598-017-13263-w>
- Brown, K., Tryon, M., Deshon, H., et al., 2005. Correlated Transient Fluid Pulsing and Seismic Tremor in the Costa Rica Subduction Zone. *Earth and Planetary Science Letters*, 238(1—2): 189—203. <https://doi.org/10.1016/j.epsl.2005.06.055>
- Bünz, S., Mienert, J., Berndt, C., 2003. Geological Controls on the Storegga Gas-Hydrate System of the Mid-Norwegian Continental Margin. *Earth and Planetary Science Letters*, 209(3—4): 291—307. [https://doi.org/10.1016/S0012-821X\(03\)00097-9](https://doi.org/10.1016/S0012-821X(03)00097-9)
- Cahill, A. G., Parker, B. L., Mayer, B., et al., 2018. High Resolution Spatial and Temporal Evolution of Dissolved Gases in Groundwater during a Controlled Natural Gas Release Experiment. *Science of the Total Environment*, 622: 1178—1192. <https://doi.org/10.1016/j.scitotenv.2017.12.049>
- Caldwell, S. L., Laidler, J. R., Brewer, E. A., et al., 2008. Anaerobic Oxidation of Methane: Mechanisms, Bioenergetics, and the Ecology of Associated Microorganisms. *Environmental Science & Technology*, 42(18): 6791—6799. <https://doi.org/10.1021/es800120b>
- Chen, J. W., Li, Y. D., Zhong, C., et al., 2023a. Genomic Insights into Niche Partitioning across Sediment Depth among Anaerobic Methane-Oxidizing Archaea in Global Methane Seeps. *mSystems*, 8(2): e01179—e01122. <https://doi.org/10.1128/msystems.01179-22>
- Chen, Q. W., Hu, Y., Peckmann, J., et al., 2023b. The Formation of Authigenic Phosphorus Minerals in Cold-Seep Sediments from the South China Sea: Implications for Carbon Cycling below the Sulfate-Methane Transition. *Marine and Petroleum Geology*, 155: 106425. <https://doi.org/10.1016/j.marpetgeo.2023.106425>
- Chen, K. T., Hsu, S. K., Lin, A. T., et al., 2024a. Changes in Marine Sedimentation Patterns in the Northeastern South China Sea in the Past 35, 000 Years. *Communications Earth & Environment*, 5: 420. <https://doi.org/10.1038/s43247-024-01593-3>
- Chen, Z. H., Jia, Z. C., Gong, S. G., et al., 2024b. Behaviors of Trace Elements under Varying Methane Seepage Intensity: Insight from Tubular Seep Carbonates in the South China Sea. *Marine and Petroleum Geology*, 163: 106816. <https://doi.org/10.1016/j.marpetgeo.2024.106816>. [LinkOut]
- Chen, Y., Sun, Z. L., Wu, N. Y., et al., 2022. Advances in the Study of Methane-Metabolizing Microbial Communities in Marine Sediments. *Marine Geology & Qua-*

- ternary Geology*, 42(6): 82–92 (in Chinese with English abstract).
- Cheng, C., He, Q., Zhang, J., et al., 2022. Is the Role of Aerobic Methanotrophs Underestimated in Methane Oxidation under Hypoxic Conditions? *Science of the Total Environment*, 833: 155244. <https://doi.org/10.1016/j.scitotenv.2022.155244>
- Chuang, P. C., Dale, A. W., Wallmann, K., et al., 2013. Relating Sulfate and Methane Dynamics to Geology: Accretionary Prism Offshore SW Taiwan. *Geochemistry, Geophysics, Geosystems*, 14(7): 2523–2545. <https://doi.org/10.1002/ggge.20168>
- Chuang, P. C., Yang, T. F., Hong, W. L., et al., 2010. Estimation of Methane Flux Offshore SW Taiwan and the Influence of Tectonics on Gas Hydrate Accumulation. *Geofluids*, 10(4): 497–510. <https://doi.org/10.1111/j.1468-8123.2010.00313.x>
- Ciais, P., C. Sabine, G. Bala., et al., 2014. Carbon and Other Biogeochemical Cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, the United Kingdom, 465–570.
- Cicerone, R. J., Oremland, R. S., 1988. Biogeochemical Aspects of Atmospheric Methane. *Global Biogeochemical Cycles*, 2(4): 299–327. <https://doi.org/10.1029/gb002i004p00299>
- Ciotoli, G., Procesi, M., Etiope, G., et al., 2020. Influence of Tectonics on Global Scale Distribution of Geological Methane Emissions. *Nature Communications*, 11: 2305. <https://doi.org/10.1038/s41467-020-16229-1>
- Daigle, H., Dugan, B., 2010. Origin and Evolution of Fracture-Hosted Methane Hydrate Deposits. *Journal of Geophysical Research: Solid Earth*, 115(B11): 2010JB007492. <https://doi.org/10.1029/2010jb007492>
- Damm, E., Helmke, E., Thoms, S., et al., 2010. Methane Production in Aerobic Oligotrophic Surface Water in the Central Arctic Ocean. *Biogeosciences*, 7(3): 1099–1108. <https://doi.org/10.5194/bg-7-1099-2010>
- Dean, J. F., Middelburg, J. J., Röckmann, T., et al., 2018. Methane Feedbacks to the Global Climate System in a Warmer World. *Reviews of Geophysics*, 56(1): 207–250. <https://doi.org/10.1002/2017rg000559>
- Di, P. F., Li, N., Chen, L. Y., et al., 2023. Elevated Nutrients and Surface Chlorophyll- α Associated with Natural Methane Seeps in the Haima Cold Seep Area of the Qiongdongnan Basin, Northern South China Sea. *Marine Pollution Bulletin*, 191: 114873. <https://doi.org/10.1016/j.marpolbul.2023.114873>
- Dickens, G. R., 2003. Rethinking the Global Carbon Cycle with a Large, Dynamic and Microbially Mediated Gas Hydrate Capacitor. *Earth and Planetary Science Letters*, 213(3/4): 169–183. [https://doi.org/10.1016/S0012-821X\(03\)00325-X](https://doi.org/10.1016/S0012-821X(03)00325-X)
- Dickens, G. R., Quinby-Hunt, M. S., 1994. Methane Hydrate Stability in Seawater. *Geophysical Research Letters*, 21(19): 2115–2118. <https://doi.org/10.1029/94gl01858>
- Dølven, K. O., Espenes, H., Hanssen, A., et al., 2025. Modeling Water Column Gas Transformation, Migration and Atmospheric Flux from Seafloor Seepage. *Ocean Science*, 21(6): 3031–3054. <https://doi.org/10.5194/os-21-3031-2025>
- Duan, X. Y., Yin, P., Tsona, N., et al., 2023. Biogenic Methane in Coastal Unconsolidated Sediment Systems: A Review. *Environmental Research*, 227: 115803. <https://doi.org/10.1016/j.envres.2023.115803>
- Egger, M., Riedinger, N., Mogollón, J. M., et al., 2018. Global Diffusive Fluxes of Methane in Marine Sediments. *Nature Geoscience*, 11(6): 421–425. <https://doi.org/10.1038/s41561-018-0122-8>
- Erland, B. M., Thorpe, A. K., Gamon, J. A., 2022. Recent Advances toward Transparent Methane Emissions Monitoring: A Review. *Environmental Science & Technology*, 56(23): 16567–16581. <https://doi.org/10.1021/acs.est.2c02136>
- Etiope, G., 2012. Methane Uncovered. *Nature Geoscience*, 5(6): 373–374. <https://doi.org/10.1038/ngeo1483>
- Etminan, M., Myhre, G., Highwood, E. J., et al., 2016. Radiative Forcing of Carbon Dioxide, Methane, and Nitrous Oxide: A Significant Revision of the Methane Radiative Forcing. *Geophysical Research Letters*, 43(24). <https://doi.org/10.1002/2016gl071930>
- Fallati, L., Panieri, G., Argentino, C., et al., 2023. Characterizing Håkon Mosby Mud Volcano (Barents Sea) Cold Seep Systems by Combining ROV-Based Acoustic Data and Underwater Photogrammetry. *Frontiers in Marine Science*, 10: 1269197. <https://doi.org/10.3389/fmars.2023.1269197>
- Feng, J. C., Yan, J. Y., Wang, Y., et al., 2022. Methane Mitigation: Learning from the Natural Marine Environment. *The Innovation*, 3(5): 100297. <https://doi.org/10.1016/j.xinn.2022.100297>
- Ferré, B., Jansson, P. G., Moser, M., et al., 2020. Reduced Methane Seepage from Arctic Sediments during Cold Bottom-Water Conditions. *Nature Geoscience*, 13

- (2): 144–148. <https://doi.org/10.1038/s41561-019-0515-3>
- Fu, X., Waite, W. F., Ruppel, C. D., 2021. Hydrate Formation on Marine Seep Bubbles and the Implications for Water Column Methane Dissolution. *Journal of Geophysical Research: Oceans*, 126(9): e2021JC017363. <https://doi.org/10.1029/2021jc017363>
- Fung, I., John, J., Lerner, J., et al., 1991. Three-Dimensional Model Synthesis of the Global Methane Cycle. *Journal of Geophysical Research: Atmospheres*, 96(D7): 13033–13065. <https://doi.org/10.1029/91jd01247>
- Gamwo, I. K., Liu, Y., 2010. Mathematical Modeling and Numerical Simulation of Methane Production in a Hydrate Reservoir. *Industrial & Engineering Chemistry Research*, 49(11): 5231–5245. <https://doi.org/10.1021/ie901452v>
- Gelesh, L., Marshall, K., Boicourt, W., et al., 2016. Methane Concentrations Increase in Bottom Waters during Summertime Anoxia in the Highly Eutrophic Estuary, Chesapeake Bay, U.S.A.. *Limnology and Oceanography*, 61(S1): S253–S266. <https://doi.org/10.1002/lno.10272>
- Gorchov Negron, A. M., Kort, E. A., Conley, S. A., et al., 2020. Airborne Assessment of Methane Emissions from Offshore Platforms in the U.S. Gulf of Mexico. *Environmental Science & Technology*, 54(8): 5112–5120. <https://doi.org/10.1021/acs.est.0c00179>
- Graves, C. A., Steinle, L., Rehder, G., et al., 2015. Fluxes and Fate of Dissolved Methane Released at the Seafloor at the Landward Limit of the Gas Hydrate Stability Zone Offshore Western Svalbard. *Journal of Geophysical Research: Oceans*, 120(9): 6185–6201. <https://doi.org/10.1002/2015jc011084>
- Greinert, J., Artemov, Y., Egorov, V., et al., 2006. 1 300 m-High Rising Bubbles from Mud Volcanoes at 2 080 m in the Black Sea: Hydroacoustic Characteristics and Temporal Variability. *Earth and Planetary Science Letters*, 244(1–2): 1–15. <https://doi.org/10.1016/j.epsl.2006.02.011>
- Greinert, J., McGinnis, D. F., Naudts, L., et al., 2010. Atmospheric Methane Flux from Bubbling Seeps: Spatially Extrapolated Quantification from a Black Sea Shelf Area. *Journal of Geophysical Research: Oceans*, 115(C1): 2009JC005381. <https://doi.org/10.1029/2009jc005381>
- Hao, H. Y., Zhao, J., Liu, H. S., et al., 2018. Prediction of Oil and Gas Reservoir Traps by Aromatic Hydrocarbons from Seabed Sediments in Chaoshan Depression, South China Sea. *Acta Petrolei Sinica*, 39(5): 528–540 (in Chinese with English abstract).
- Hilligsoe, K. M., Jensen, J. B., Ferdelman, T. G., et al., 2018. Methane Fluxes in Marine Sediments Quantified through Core Analyses and Seismo-Acoustic Mapping (Bornholm Basin, Baltic Sea). *Geochimica et Cosmochimica Acta*, 239: 255–274. <https://doi.org/10.1016/j.gca.2018.07.040>
- Hiruta, A., Matsumoto, R., 2023. Seafloor Activity and Deep-Subsurface Geology of Gas Hydrate Areas Revealed from $\delta^{13}\text{C}$ of Methane-Derived Authigenic Carbonates along the Eastern Margin of the Sea of Japan. *Marine Geology*, 464: 107124. <https://doi.org/10.1016/j.margeo.2023.107124>
- Hofmann, H., Federwisch, L., Peeters, F., 2010. Wave-Induced Release of Methane: Littoral Zones as Source of Methane in Lakes. *Limnology and Oceanography*, 55(5): 1990–2000. <https://doi.org/10.4319/lo.2010.55.5.1990>
- Hu, C. Y., Frank Yang, T., Burr, G. S., et al., 2017. Biogeochemical Cycles at the Sulfate-Methane Transition Zone (SMTZ) and Geochemical Characteristics of the Pore Fluids Offshore Southwestern Taiwan. *Journal of Asian Earth Sciences*, 149: 172–183. <https://doi.org/10.1016/j.jseas.2017.07.002>
- Hu, L., Yvon-Lewis, S. A., Kessler, J. D., et al., 2012. Methane Fluxes to the Atmosphere from Deepwater Hydrocarbon Seeps in the Northern Gulf of Mexico. *Journal of Geophysical Research: Oceans*, 117(C1): 2011JC007208. <https://doi.org/10.1029/2011jc007208>
- Hu, Y., Feng, D., Peckmann, J., et al., 2023. The Crucial Role of Deep-Sourced Methane in Maintaining the Sub-seafloor Sulfate Budget. *Geoscience Frontiers*, 14(3): 101530. <https://doi.org/10.1016/j.gsf.2022.101530>
- Hu, Y., Zhang, X. X., Feng, D., et al., 2022. Enhanced Sulfate Consumption Fueled by Deep-Sourced Methane in a Hydrate-Bearing Area. *Science Bulletin*, 67(2): 122–124. <https://doi.org/10.1016/j.scib.2021.09.006>
- Irakulis-Loitxate, I., Gorroño, J., Zavala-Araiza, D., et al., 2022. Satellites Detect a Methane Ultra-Emission Event from an Offshore Platform in the Gulf of Mexico. *Environmental Science & Technology Letters*, 9(6): 520–525. <https://doi.org/10.1021/acs.estlett.2c00225>
- Iyer, S. D., Mehta, C. M., Das, P., et al., 2012. Seamounts-Characteristics, Formation, Mineral Deposits and Biodiversity. *Geologica Acta*, 10(3): 295–308. <https://doi.org/10.1344/105.000001758>
- James, R. H., Bousquet, P., Bussmann, I., et al., 2016. Ef-

- fects of Climate Change on Methane Emissions from Seafloor Sediments in the Arctic Ocean: A Review. *Limnology and Oceanography*, 61(S1). <https://doi.org/10.1002/lno.10307>
- Jansson, P., Ferré, B., Silyakova, A., et al., 2019. A New Numerical Model for Understanding Free and Dissolved Gas Progression toward the Atmosphere in Aquatic Methane Seepage Systems. *Limnology and Oceanography: Methods*, 17(3): 223–239. <https://doi.org/10.1002/lom3.10307>
- Jia, Z. J., Wu, H. J., Peng, J. B., et al., 2023. The Deep Origin of Ground Fissures in the Kenya Rift Valley. *Scientific Reports*, 13: 3672. <https://doi.org/10.1038/s41598-023-30918-z>
- Jing, J. E., Zhao, Q. X., Deng, M., et al., 2018. A Study on Natural Gas Hydrates and Their Forming Model Using Marine Controlled-Source Electromagnetic Survey in the Qiongdongnan Basin. *Chinese Journal of Geophysics*, 61(11): 4677–4689(in Chinese with English abstract).
- Joung, D., Ruppel, C., Southon, J., et al., 2022. Negligible Atmospheric Release of Methane from Decomposing Hydrates in Mid-Latitude Oceans. *Nature Geoscience*, 15(11): 885–891. <https://doi.org/10.1038/s41561-022-01044-8>
- Judd, A. G., Hovland, M., Dimitrov, L. I., et al., 2002. The Geological Methane Budget at Continental Margins and Its Influence on Climate Change. *Geofluids*, 2(2): 109–126. <https://doi.org/10.1046/j.1468-8123.2002.00027.x>
- Karstens, J., Haflidason, H., Berndt, C., et al., 2023. Revised Storegga Slide Reconstruction Reveals Two Major Submarine Landslides 12, 000 Years apart. *Communications Earth & Environment*, 4: 55. <https://doi.org/10.1038/s43247-023-00710-y>
- Kessler, J. D., Valentine, D. L., Redmond, M. C., et al., 2011. A Persistent Oxygen Anomaly Reveals the Fate of Spilled Methane in the Deep Gulf of Mexico. *Science*, 331(6015): 312–315. <https://doi.org/10.1126/science.1199697>
- Kim, B., Zhang, Y. G., Zeebe, R. E., et al., 2025. Arctic CO₂ Emissions Amplified by Aerobic Methane Oxidation during the Palaeocene–Eocene Thermal Maximum. *Nature Geoscience*, 18(10): 975–982. <https://doi.org/10.1038/s41561-025-01784-3>
- Knittel, K., Boetius, A., 2009. Anaerobic Oxidation of Methane: Progress with an Unknown Process. *Annual Review of Microbiology*, 63: 311–334. <https://doi.org/10.1146/annurev.micro.61.080706.093130>
- Kotelnikova, S., 2002. Microbial Production and Oxidation of Methane in Deep Subsurface. *Earth-Science Reviews*, 58(3–4): 367–395. [https://doi.org/10.1016/S0012-8252\(01\)00082-4](https://doi.org/10.1016/S0012-8252(01)00082-4)
- Kretschmer, K., Biastoch, A., Rüpke, L., et al., 2015. Modeling the Fate of Methane Hydrates under Global Warming. *Global Biogeochemical Cycles*, 29(5): 610–625. <https://doi.org/10.1002/2014gb005011>
- Kulkarni, A. A., Joshi, J. B., 2005. Bubble Formation and Bubble Rise Velocity in Gas-Liquid Systems: A Review. *Industrial & Engineering Chemistry Research*, 44(16): 5873–5931. <https://doi.org/10.1021/ie049131p>
- Kvenvolden, K. A., 1988. Methane Hydrates and Global Climate. *Global Biogeochemical Cycles*, 2(3): 221–229. <https://doi.org/10.1029/gb002i003p00221>
- Kvenvolden, K. A., Rogers, B. W., 2005. Gaia's Breath—Global Methane Exhalations. *Marine and Petroleum Geology*, 22(4): 579–590. <https://doi.org/10.1016/j.marpetgeo.2004.08.004>
- Lai, H. F., Fang, Y. X., Kuang, Z. G., et al., 2021. Geochemistry, Origin and Accumulation of Natural Gas Hydrates in the Qiongdongnan Basin, South China Sea: Implications from Site GMGS5-W08. *Marine and Petroleum Geology*, 123: 104774. <https://doi.org/10.1016/j.marpetgeo.2020.104774>
- Lawton, T. J., Rosenzweig, A. C., 2016. Methane-Oxidizing Enzymes: An Upstream Problem in Biological Gas-to-Liquids Conversion. *Journal of the American Chemical Society*, 138(30): 9327–9340. <https://doi.org/10.1021/jacs.6b04568>
- Leifer, I., Judd, A. G., 2002. Oceanic Methane Layers: The Hydrocarbon Seep Bubble Deposition Hypothesis. *Terra Nova*, 14(6): 417–424. <https://doi.org/10.1046/j.1365-3121.2002.00442.x>
- Leifer, I., Luyendyk, B. P., Boles, J., et al., 2006. Natural Marine Seepage Blowout: Contribution to Atmospheric Methane. *Global Biogeochemical Cycles*, 20(3): 2005GB002668. <https://doi.org/10.1029/2005gb002668>
- Leifer, I., MacDonald, I., 2003. Dynamics of the Gas Flux from Shallow Gas Hydrate Deposits: Interaction between Oily Hydrate Bubbles and the Oceanic Environment. *Earth and Planetary Science Letters*, 210(3/4): 411–424. [https://doi.org/10.1016/S0012-821X\(03\)00173-0](https://doi.org/10.1016/S0012-821X(03)00173-0)
- Leifer, I., Patro, R. K., 2002. The Bubble Mechanism for Methane Transport from the Shallow Sea Bed to the Surface: A Review and Sensitivity Study. *Continental*

- Shelf Research*, 22(16): 2409–2428. [https://doi.org/10.1016/S0278-4343\(02\)00065-1](https://doi.org/10.1016/S0278-4343(02)00065-1)
- Levin, L., P. R. Girguis, C. R. German., et al., 2016. Exploration and Discovery of Methane Seeps and Associated Communities in the California Borderland. *Oceanography*, 29:40–43.
- Li, C., Feng, J. C., Chen, X., et al., 2024. Behaviours of Methane Metabolism and Community Dynamics of Methane Anaerobic Oxidation Microbes on Carbonate Rocks with Long-Term Cultivation in Cold Seep Environment. *Applied Energy*, 365: 123296. <https://doi.org/10.1016/j.apenergy.2024.123296>
- Li, M. S., Bralower, T. J., Kump, L. R., et al., 2022a. Astrochronology of the Paleocene-Eocene Thermal Maximum on the Atlantic Coastal Plain. *Nature Communications*, 13: 5618. <https://doi.org/10.1038/s41467-022-33390-x>
- Li, Y., Xie, H., Scarratt, M. G., et al., 2022b. Dissolved Methane in the World's Largest Semi-Enclosed Estuarine System: The Estuary and Gulf of St. Lawrence (Canada). *Journal of Geophysical Research: Oceans*, 127(8): e2022JC018850. <https://doi.org/10.1029/2022jc018850>
- Li, S. L., Dong, H. P., Zhao, Q. F., et al., 2020. Experimental Simulation of Seabed Hydrocarbon Gas Seepage: Variation of Content and Molecular Composition of the Hydrocarbon Gas and Reconstruction of Seepage Process. *Marine Geology Frontiers*, 36(5): 1–13(in Chinese with English abstract).
- Liang, J. H., McWilliams, J. C., Sullivan, P. P., et al., 2012. Large Eddy Simulation of the Bubbly Ocean: New Insights on Subsurface Bubble Distribution and Bubble-Mediated Gas Transfer. *Journal of Geophysical Research: Oceans*, 117(C4): 2011JC007766. <https://doi.org/10.1029/2011jc007766>
- Liang, Q. Y., Wu, X. M., Yu, Z. C., et al., 2025. Submarine Deformation Monitoring during the Second Gas Hydrate Production Test in the South China Sea. *Energy*, 335: 138149. <https://doi.org/10.1016/j.energy.2025.138149>
- Liang, Q. Y., Zhao, J., Xia, Z., et al., 2017. Distribution Characteristics and Influential Factors of Dissolved Methane in Sea Water above Gas Hydrate Area on the Northern Slope of the South China Sea. *Earth Science Frontiers*, 24(4): 89–101 (in Chinese with English abstract).
- Liebner, S., Zeyer, J., Wagner, D., et al., 2011. Methane Oxidation Associated with Submerged Brown Mosses Reduces Methane Emissions from Siberian Polygonal Tundra: Moss-Associated Methane Oxidation. *Journal of Ecology*, 99(4): 914–922. <https://doi.org/10.1111/j.1365-2745.2011.01823.x>
- Lin, J. J. Y., Buehler, C., Datta, A., et al., 2023. Laboratory and Field Evaluation of a Low-Cost Methane Sensor and Key Environmental Factors for Sensor Calibration. *Environmental Science: Atmospheres*, 3(4): 683–694. <https://doi.org/10.1039/d2ea00100d>
- Liu, H. T., Zhan, L. S., Lu, H. L., 2022. Mechanisms for Upward Migration of Methane in Marine Sediments. *Frontiers in Marine Science*, 9: 1031096. <https://doi.org/10.3389/fmars.2022.1031096>
- Lollar, B. S., Lacrampe-Couloume, G., Slater, G. F., et al., 2006. Unravelling Abiogenic and Biogenic Sources of Methane in the Earth's Deep Subsurface. *Chemical Geology*, 226(3–4): 328–339. <https://doi.org/10.1016/j.chemgeo.2005.09.027>
- Luff, R., Wallmann, K., 2003. Fluid Flow, Methane Fluxes, Carbonate Precipitation and Biogeochemical Turnover in Gas Hydrate-Bearing Sediments at Hydrate Ridge, Cascadia Margin: Numerical Modeling and Mass Balances. *Geochimica et Cosmochimica Acta*, 67(18): 3403–3421. [https://doi.org/10.1016/S0016-7037\(03\)00127-3](https://doi.org/10.1016/S0016-7037(03)00127-3)
- Madison, A. S., Tebo, B. M., Mucci, A., et al., 2013. Abundant Porewater Mn(III) is a Major Component of the Sedimentary Redox System. *Science*, 341(6148): 875–878. <https://doi.org/10.1126/science.1241396>
- Maltby, J., Sommer, S., Dale, A. W., et al., 2016. Microbial Methanogenesis in the Sulfate-Reducing Zone of Surface Sediments Traversing the Peruvian Margin. *Biogeosciences*, 13(1): 283–299. <https://doi.org/10.5194/bg-13-283-2016>
- McGinnis, D. F., Greinert, J., Artemov, Y., et al., 2006. Fate of Rising Methane Bubbles in Stratified Waters: How Much Methane Reaches the Atmosphere? *Journal of Geophysical Research: Oceans*, 111(C9): 2005JC003183. <https://doi.org/10.1029/2005jc003183>
- Michaelis, W., Seifert, R., Nauhaus, K., et al., 2002. Microbial Reefs in the Black Sea Fueled by Anaerobic Oxidation of Methane. *Science*, 297(5583): 1013–1015. <https://doi.org/10.1126/science.1072502>
- Mienert, J., Vanneste, M., Bünz, S., et al., 2005. Ocean Warming and Gas Hydrate Stability on the Mid-Norwegian Margin at the Storegga Slide. Ormen Lange—An Integrated Study for Safe Field Development in the Storegga Submarine Area. Elsevier, Amsterdam.

- dam, 233–244. <https://doi.org/10.1016/b978-0-08-044694-3.50024-x>
- Milkov, A. V., 2005. Molecular and Stable Isotope Compositions of Natural Gas Hydrates: A Revised Global Dataset and Basic Interpretations in the Context of Geological Settings. *Organic Geochemistry*, 36(5): 681–702. <https://doi.org/10.1016/j.orggeochem.2005.01.010>
- Milkov, A. V., Etiope, G., 2018. Revised Genetic Diagrams for Natural Gases Based on a Global Dataset of >20 000 Samples. *Organic Geochemistry*, 125: 109–120. <https://doi.org/10.1016/j.orggeochem.2018.09.002>
- Miller, D. C., Muir, C. L., Hauser, O. A., 2002. Detrimental Effects of Sedimentation on Marine Benthos: What can be Learned from Natural Processes and Rates? *Ecological Engineering*, 19(3): 211–232. [https://doi.org/10.1016/S0925-8574\(02\)00081-2](https://doi.org/10.1016/S0925-8574(02)00081-2)
- Mogollón, J. M., Dale, A. W., L'Heureux, I., et al., 2011. Impact of Seasonal Temperature and Pressure Changes on Methane Gas Production, Dissolution, and Transport in Unfractured Sediments. *Journal of Geophysical Research*, 116(G3): G03031. <https://doi.org/10.1029/2010jg001592>
- Ni, X., Liu, X. G., Pang, S. L., et al., 2025. Global Marine Methane Seepage: Spatiotemporal Patterns and Ocean Current Control. *Marine Geology*, 487: 107589. <https://doi.org/10.1016/j.margeo.2025.107589>
- Niemann, H., Duarte, J., Hensen, C., et al., 2006. Microbial Methane Turnover at Mud Volcanoes of the Gulf of Cadiz. *Geochimica et Cosmochimica Acta*, 70(21): 5336–5355. <https://doi.org/10.1016/j.gca.2006.08.010>
- Niewöhner, C., Hensen, C., Kasten, S., et al., 1998. Deep Sulfate Reduction Completely Mediated by Anaerobic Methane Oxidation in Sediments of the Upwelling Area off Namibia. *Geochimica et Cosmochimica Acta*, 62(3): 455–464. [https://doi.org/10.1016/S0016-7037\(98\)00055-6](https://doi.org/10.1016/S0016-7037(98)00055-6)
- Nisbet, E. G., 2022. Methane's Unknowns Better Known. *Nature Geoscience*, 15(11): 861–862. <https://doi.org/10.1038/s41561-022-01049-3>
- Niu, M. Y., Liang, W. Y., Wang, F. P., 2018. Methane Biotransformation in the Ocean and Its Effects on Climate Change: A Review. *Science China Earth Sciences*, 61(12): 1697–1713(in Chinese).
- Peckmann, J., Thiel, V., 2004. Carbon Cycling at Ancient Methane-Seeps. *Chemical Geology*, 205(3–4): 443–467. <https://doi.org/10.1016/j.chemgeo.2003.12.025>
- Plaza-Faverola, A., Vadakkepuliyambatta, S., Hong, W. L., et al., 2017. Bottom-Simulating Reflector Dynamics at Arctic Thermogenic Gas Provinces: An Example from Vestnesa Ridge, Offshore West Svalbard. *Journal of Geophysical Research: Solid Earth*, 122(6): 4089–4105. <https://doi.org/10.1002/2016jb013761>
- Polonik, N. S., Legkodimov, A. A., 2024. Methane Distribution above the Emperor Seamount Chain. *Deep Sea Research Part II: Topical Studies in Oceanography*, 218: 105431. <https://doi.org/10.1016/j.dsr2.2024.105431>
- Portnov, A., Smith, A. J., Mienert, J., et al., 2013. Offshore Permafrost Decay and Massive Seabed Methane Escape in Water Depths >20 m at the South Kara Sea Shelf. *Geophysical Research Letters*, 40(15): 3962–3967. <https://doi.org/10.1002/grl.50735>
- Radziejewska, T., Węśławski, J. M., Tomczak, M., et al., 2024. Deep Sea Research Methods to be Used during the Exploration of the Mid-Atlantic Ridge Polymetallic Sulphide Areas. In: Radziejewska, T., Węśławski, J. M., Tomczak, M., eds., *The Natural Environment of the Mid-Atlantic Ridge: A Case Study of the Potential Mining Site*. Springer Cham: International Publishing, 101–111. https://doi.org/10.1007/978-3-031-51865-2_7
- Reay, D. S., Smith, P., Christensen, T. R., et al., 2018. Methane and Global Environmental Change. *Annual Review of Environment and Resources*, 43: 165–192. <https://doi.org/10.1146/annurev-environ-102017-030154>
- Reeburgh, W. S., 2007. Oceanic Methane Biogeochemistry. *ChemInform*, 38(20): chin.200720267. <https://doi.org/10.1002/chin.200720267>
- Regnier, P., Dale, A. W., Arndt, S., et al., 2011. Quantitative Analysis of Anaerobic Oxidation of Methane (AOM) in Marine Sediments: A Modeling Perspective. *Earth-Science Reviews*, 106(1–2): 105–130. <https://doi.org/10.1016/j.earscirev.2011.01.002>
- Rehder, G., Keir, R. S., Suess, E., et al., 1999. Methane in the Northern Atlantic Controlled by Microbial Oxidation and Atmospheric History. *Geophysical Research Letters*, 26(5): 587–590. <https://doi.org/10.1029/1999gl900049>
- Rehder, G., Suess, E., 2001. Methane and p_{CO_2} in the Kuroshio and the South China Sea during Maximum Summer Surface Temperatures. *Marine Chemistry*, 75(1–2): 89–108. [https://doi.org/10.1016/S0304-4203\(01\)00026-3](https://doi.org/10.1016/S0304-4203(01)00026-3)
- Rice, D. D., Claypool, R. G. E., 1981. Generation, Accumulation, and Resource Potential of Biogenic Gas. *AAPG*

- Bulletin*, 65:5—25. <https://doi.org/10.1306/2f919765-16ce-11d7-8645000102c1865d>
- Ruff, S. E., Arnds, J., Knittel, K., et al., 2013. Microbial Communities of Deep-Sea Methane Seeps at Hikurangi Continental Margin (New Zealand). *PLoS One*, 8(9): e72627. <https://doi.org/10.1371/journal.pone.0072627>
- Ruppel, C. D., 2011. Methane Hydrates and Contemporary Climate Change. *Nature Education Knowledge*, 3(10):29.
- Ruppel, C. D., Kessler, J. D., 2017. The Interaction of Climate Change and Methane Hydrates. *Reviews of Geophysics*, 55(1): 126—168. <https://doi.org/10.1002/2016rg000534>
- Rusakov, O., Kutas, R., 2018. Mantle Origin of Methane in the Black Sea. *Geofizicheskiy Zhurnal*, 40(5): 191—207. <https://doi.org/10.24028/gzh.0203-3100.v40i5.2018.147482>
- Saunio, M., Staver, A. R., Poulter, B., et al., 2020. The Global Methane Budget 2000—2017. *Earth System Science Data*, 12(3): 1561—1623. <https://doi.org/10.5194/essd-12-1561-2020>
- Schmale, O., Haeckel, M., McGinnis, D. F., 2011. Response of the Black Sea Methane Budget to Massive Short-Term Submarine Inputs of Methane. *Biogeosciences*, 8(4): 911—918. <https://doi.org/10.5194/bg-8-911-2011>
- Schreiber, L., Holler, T., Knittel, K., et al., 2010. Identification of the Dominant Sulfate-Reducing Bacterial Partner of Anaerobic Methanotrophs of the ANME-2 Clade. *Environmental Microbiology*, 12(8): 2327—2340. <https://doi.org/10.1111/j.1462-2920.2010.02275.x>
- Serov, P., Mattingdal, R., Winsborrow, M., et al., 2023. Widespread Natural Methane and Oil Leakage from Submarine Arctic Reservoirs. *Nature Communications*, 14: 1782. <https://doi.org/10.1038/s41467-023-37514-9>
- Serov, P., Vadakkepuliambatta, S., Mienert, J., et al., 2017. Postglacial Response of Arctic Ocean Gas Hydrates to Climatic Amelioration. *Proceedings of the National Academy of Sciences of the United States of America*, 114(24): 6215—6220. <https://doi.org/10.1073/pnas.1619288114>
- Sha, Z. B., Liang, J. Q., Su, P. B., et al., 2015. Natural Gas Hydrate Accumulation Elements and Drilling Results Analysis in the Eastern Part of the Pearl River Mouth Basin. *Earth Science Frontiers*, 22(6): 125—135 (in Chinese with English abstract).
- Shakhova, N., Semiletov, I., Gustafsson, O., et al., 2017. Current Rates and Mechanisms of Subsea Permafrost Degradation in the East Siberian Arctic Shelf. *Nature Communications*, 8: 15872. <https://doi.org/10.1038/ncomms15872>
- Shakhova, N., Semiletov, I., Salyuk, A., et al., 2010. Extensive Methane Venting to the Atmosphere from Sediments of the East Siberian Arctic Shelf. *Science*, 327(5970): 1246—1250. <https://doi.org/10.1126/science.1182221>
- Shakhova, N., Semiletov, I., Sergienko, V., et al., 2015. The East Siberian Arctic Shelf: Towards Further Assessment of Permafrost-Related Methane Fluxes and Role of Sea Ice. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 373(2052): 20140451. <https://doi.org/10.1098/rsta.2014.0451>
- Shakirov, R. B., Mau, S., Mishukova, G. I., et al., 2020. The Features of Methane Fluxes in the Western and Eastern Arctic: A Review. Part I. *Geosystems of Transition Zones*, 4(1): 4—25. <https://doi.org/10.30730/2541-8912.2020.4.1.004-025>
- Skarke, A., Ruppel, C., Kodis, M., et al., 2014. Widespread Methane Leakage from the Sea Floor on the Northern US Atlantic Margin. *Nature Geoscience*, 7(9): 657—661. <https://doi.org/10.1038/ngeo2232>
- Sloan, E. D. Jr, Koh, C. A., Koh, C. A., 2007. Clathrate Hydrates of Natural Gases. Boca Raton: CRC Press, <https://doi.org/10.1201/9781420008494>
- Sluijs, A., Brinkhuis, H., Schouten, S., et al., 2007. Environmental Precursors to Rapid Light Carbon Injection at the Palaeocene/Eocene Boundary. *Nature*, 450(7173): 1218—1221. <https://doi.org/10.1038/nature06400>
- Solomon, E. A., Kastner, M., MacDonald, I. R., et al., 2009a. Considerable Methane Fluxes to the Atmosphere from Hydrocarbon Seeps in the Gulf of Mexico. *Nature Geoscience*, 2(8): 561—565. <https://doi.org/10.1038/ngeo574>
- Solomon, S., Plattner, G. K., Knutti, R., et al., 2009b. Irreversible Climate Change Due to Carbon Dioxide Emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 106(6): 1704—1709. <https://doi.org/10.1073/pnas.0812721106>
- Stolper, D. A., Martini, A. M., Clog, M., et al., 2015. Distinguishing and Understanding Thermogenic and Biogenic Sources of Methane Using Multiply Substituted Isotopologues. *Geochimica et Cosmochimica Acta*, 161: 219—247. <https://doi.org/10.1016/j.gca.2015.04.015>
- Stotler, R. L., Frape, S. K., Ahonen, L., et al., 2010. Origin and Stability of a Permafrost Methane Hydrate Occurrence in the Canadian Shield. *Earth and Planetary*

- Science Letters*, 296(3–4): 384–394. <https://doi.org/10.1016/j.epsl.2010.05.024>
- Suess, E., 2014. Marine Cold Seeps and Their Manifestations: Geological Control, Biogeochemical Criteria and Environmental Conditions. *International Journal of Earth Sciences*, 103(7): 1889–1916. <https://doi.org/10.1007/s00531-014-1010-0>
- Sultan, N., Cochonat, P., Foucher, J. P., et al., 2004. Effect of Gas Hydrates Melting on Seafloor Slope Instability. *Marine Geology*, 213(1–4): 379–401. <https://doi.org/10.1016/j.margeo.2004.10.015>
- Sultan, N., Plaza-Faverola, A., Vadakkepuliambatta, S., et al., 2020. Impact of Tides and Sea-Level on Deep-Sea Arctic Methane Emissions. *Nature Communications*, 11: 5087. <https://doi.org/10.1038/s41467-020-18899-3>
- Sun, X. H., Wang, Z. Y., Sun, B. J., et al., 2018. Modeling of Dynamic Hydrate Shell Growth on Bubble Surface Considering Multiple Factor Interactions. *Chemical Engineering Journal*, 331: 221–233. <https://doi.org/10.1016/j.cej.2017.08.105>
- Talling, P., Clare, M., Urlaub, M., et al., 2014. Large Submarine Landslides on Continental Slopes: Geohazards, Methane Release, and Climate Change. *Oceanography*, 27(2): 32–45. <https://doi.org/10.5670/oceanog.2014.38>
- Thanwerdas, J., M. Saunio, A. Berchet., et al., 2019. Impact of Atomic Chlorine on the Modelling of Total Methane and Its ^{13}C : ^{12}C Isotopic Ratio at Global Scale. *Atmospheric Chemistry and Physics Discussions*. <https://doi.org/10.5194/acp-2019-925>
- Timmers, P. H. A., Suarez-Zuluaga, D. A., van Rossem, M., et al., 2016. Anaerobic Oxidation of Methane Associated with Sulfate Reduction in a Natural Freshwater Gas Source. *The ISME Journal*, 10(6): 1400–1412. <https://doi.org/10.1038/ismej.2015.213>
- Tishchenko, P., Hensen, C., Wallmann, K., et al., 2005. Calculation of the Stability and Solubility of Methane Hydrate in Seawater. *Chemical Geology*, 219(1–4): 37–52. <https://doi.org/10.1016/j.chemgeo.2005.02.008>
- Tori, M., Albert, D. B., Alperin, M. J., et al., 1999. Acetogenesis from CO_2 in an Anoxic Marine Sediment. *Limnology and Oceanography*, 44(3): 662–667. <https://doi.org/10.4319/lo.1999.44.3.0662>
- Treude, T., Orphan, V., Knittel, K., et al., 2007. Consumption of Methane and CO_2 by Methanotrophic Microbial Mats from Gas Seeps of the Anoxic Black Sea. *Applied and Environmental Microbiology*, 73(11): 3770. <https://doi.org/10.1128/aem.00806-07>
- Tryon, M. D., Brown, K. M., Torres, M. E., 2002. Fluid and Chemical Flux in and out of Sediments Hosting Methane Hydrate Deposits on Hydrate Ridge, OR, II: Hydrological Processes. *Earth and Planetary Science Letters*, 201(3–4): 541–557. [https://doi.org/10.1016/S0012-821X\(02\)00732-X](https://doi.org/10.1016/S0012-821X(02)00732-X)
- Valentine, D. L., 2011. Emerging Topics in Marine Methane Biogeochemistry. *Annual Review of Marine Science*, 3: 147–171. <https://doi.org/10.1146/annurev-marine-120709-142734>
- Valentine, D. L., Blanton, D. C., Reeburgh, W. S., et al., 2001. Water Column Methane Oxidation Adjacent to an Area of Active Hydrate Dissociation, Eel River Basin. *Geochimica et Cosmochimica Acta*, 65(16): 2633–2640. [https://doi.org/10.1016/S0016-7037\(01\)00625-1](https://doi.org/10.1016/S0016-7037(01)00625-1)
- Vereshchagina, O. F., Korovitskaya, E. V., Mishukova, G. I., 2013. Methane in Water Columns and Sediments of the North Western Sea of Japan. *Deep Sea Research Part II: Topical Studies in Oceanography*, 86/87: 25–33. <https://doi.org/10.1016/j.dsr2.2012.08.017>
- Wallenius, A. J., Dalcin Martins, P., Slomp, C. P., et al., 2021. Anthropogenic and Environmental Constraints on the Microbial Methane Cycle in Coastal Sediments. *Frontiers in Microbiology*, 12: 631621. <https://doi.org/10.3389/fmicb.2021.631621>
- Wang, Q., Alowafeer, A., Kerner, P., et al., 2021. Aerobic Bacterial Methane Synthesis. *Proceedings of the National Academy of Sciences of the United States of America*, 118(27): e2019229118. <https://doi.org/10.1073/pnas.2019229118>
- Wang, X. C., Chen, B. Y., Chen, L. Y., et al., 2024. Biogenic Methane Clumped Isotope Signatures: Insights from Microbially Enhanced Coal Bed Methane. *Fuel*, 365: 131307. <https://doi.org/10.1016/j.fuel.2024.131307>
- Wang, X. D., Zhuang, G. C., Feng, D., 2024. Advances in Studying the Biogeochemistry of Methane in Marine Depositional Systems through Trace Element Geochemistry. *Marine Geology & Quaternary Geology*, 44(6): 82–95(in Chinese with English abstract).
- Weber, T., Wiseman, N. A., Kock, A., 2019. Global Ocean Methane Emissions Dominated by Shallow Coastal Waters. *Nature Communications*, 10: 4584. <https://doi.org/10.1038/s41467-019-12541-7>
- Westbrook, G. K., Thatcher, K. E., Rohling, E. J., et al., 2009. Escape of Methane Gas from the Seabed along the

- West Spitsbergen Continental Margin. *Geophysical Research Letters*, 36(15). <https://doi.org/10.1029/2009gl039191>
- Whiticar, M. J., 1999. Carbon and Hydrogen Isotope Systematics of Bacterial Formation and Oxidation of Methane. *Chemical Geology*, 161(1–3): 291–314. [https://doi.org/10.1016/S0009-2541\(99\)00092-3](https://doi.org/10.1016/S0009-2541(99)00092-3)
- Wohleber, A., Blouzon, C., Witwicky, J., et al., 2025. A Membrane Inlet Laser Spectrometer for In Situ Measurement of Triple Water Isotopologues. *Limnology and Oceanography: Methods*, 23(1): 26–38. <https://doi.org/10.1002/lom3.10660>
- Wood, J. M., Sanei, H., 2016. Secondary Migration and Leakage of Methane from a Major Tight-Gas System. *Nature Communications*, 7: 13614. <https://doi.org/10.1038/ncomms13614>
- Wu, N. Y., Yang, S. X., Wang, H. B., et al., 2009. Gas-Bearing Fluid Influx Sub-System for Gas Hydrate Geological System in Shenhu Area, Northern South China Sea. *Chinese Journal of Geophysics*, 52(6): 1641–1650 (in Chinese with English abstract).
- Wuebbles, D. J., Hayhoe, K., 2002. Atmospheric Methane and Global Change. *Earth-Science Reviews*, 57(3–4): 177–210. [https://doi.org/10.1016/S0012-8252\(01\)00062-9](https://doi.org/10.1016/S0012-8252(01)00062-9)
- Xie, Y., Feng, J. C., Hu, W. Q., et al., 2022. Deep-Sea Sediment and Water Simulator for Investigation of Methane Seeping and Hydrate Formation. *Journal of Marine Science and Engineering*, 10(4): 514. <https://doi.org/10.3390/jmse10040514>
- Xu, S. N., Wu, Z. J., Zhang, X. L., et al., 2024. Advances in Numerical Modelling of Carbon Cycling Processes in Marine Sediments. *Earth Science*, 49(4): 1431–1447 (in Chinese with English abstract).
- Xu, S. N., Sun, Z. L., Geng, W., et al., 2022. Advance in Numerical Simulation Research of Marine Methane Processes. *Frontiers in Earth Science*, 10: 891393. <https://doi.org/10.3389/feart.2022.891393>
- Xu, W. Y., Lowell, R. P., Peltzer, E. T., 2001. Effect of Seafloor Temperature and Pressure Variations on Methane Flux from a Gas Hydrate Layer: Comparison between Current and Late Paleocene Climate Conditions. *Journal of Geophysical Research: Solid Earth*, 106 (B11): 26413–26423. <https://doi.org/10.1029/2001jb000420>
- Yang, K. H., Yu, X. G., Chu, F. Y., et al., 2016. Environmental Changes in Methane Seeps Recorded by Carbon and Oxygen Isotopes in the Northern South China Sea. *Earth Science*, 41(7): 1206–1215 (in Chinese with English abstract).
- Ye, J. L., Wei, J. G., Liang, J. Q., et al., 2019. Complex Gas Hydrate System in a Gas Chimney, South China Sea. *Marine and Petroleum Geology*, 104: 29–39. <https://doi.org/10.1016/j.marpetgeo.2019.03.023>
- Yin, X. J., Zhou, H. Y., Yang, Q. H., et al., 2008. The Evidence for the Existence of Methane Seepages in the Northern South China Sea: Abnormal High Methane Concentration in Bottom Waters. *Acta Oceanologica Sinica*, 30(6): 69–75 (in Chinese with English abstract).
- Yu, Y. S., Zhang, X. W., Liu, J. W., et al., 2021. Natural Gas Hydrate Resources and Hydrate Technologies: A Review and Analysis of the Associated Energy and Global Warming Challenges. *Energy & Environmental Science*, 14(11): 5611–5668. <https://doi.org/10.1039/d1ee02093e>
- Yuan, J. S., Qiu, S., 2024. A Review Analysis of Methane Research Progress Related to IPCC AR6 and Its Implications for China. *Climate Change Research*, 20(3): 327–336 (in Chinese with English abstract).
- Zhang, C. L., Li, Y. L., Wall, J. D., et al., 2002. Lipid and Carbon Isotopic Evidence of Methane-Oxidizing and Sulfate-Reducing Bacteria in Association with Gas Hydrates from the Gulf of Mexico. *Geology*, 30(3): 239. [https://doi.org/10.1130/0091-7613\(2002\)0300239:laci-eo>2.0.co;2](https://doi.org/10.1130/0091-7613(2002)0300239:laci-eo>2.0.co;2)
- Zhang, J., Lei, H. Y., Yang, M., et al., 2018. The Interactions of P-S-Fe in Sediment from the Continental Slope of Northern South China Sea and Their Implication for the Sulfate-Methane Transition Zone. *Earth Science Frontiers*, 25(3): 285–293 (in Chinese with English abstract).
- Zhang, T. T., Liang, Q. Y., Zhao, J., et al., 2020. Discussion on the Sources and Mechanism of Supersaturated Methane in Euphotic Seawater. *Marine Geology & Quaternary Geology*, 40(1): 50–59 (in Chinese with English abstract).
- Zhao, G. J., Gong, G. J., Sun, H. R., et al., 2022. Effect of Methane Solubility on Hydrate Formation and Dissociation: Review and Perspectives. *Energy & Fuels*, 36 (14): 7269–7283. <https://doi.org/10.1021/acs.energyfuels.2c01017>
- Zhao, J., Liang, Q. Y., Yu, J. G., et al., 2020. Seafloor Geology and Geochemistry Characteristic of Methane Seepage of the “Haima” Cold Seep, Northwestern Slope of the South China Sea. *Geochimica*, 49(1): 108–118 (in Chinese with English abstract).

- Zhao, Y., Yu, J. H., Shi, H. L., et al., 2024. Study of Methane Solubility Calculation Based on Modified Henry's Law and BP Neural Network. *Processes*, 12(6): 1091. <https://doi.org/10.3390/pr12061091>
- Zhu, J. J., Ding, X., Liu, Z. Y., et al., 2025. Geomorphological Characteristics and Formation Mechanisms of Large Pockmarks in the Baiyun Submarine Channel System, Northern South China Sea. *Journal of Earth Science*. <https://doi.org/10.1007/s12583-025-0346-7>

中文参考文献

- 陈烨, 孙治雷, 吴能友, 等, 2022. 海洋沉积物中甲烷代谢微生物的研究进展. *海洋地质与第四纪地质*, 42(6): 82—92.
- 郝海燕, 赵静, 刘海生, 等, 2018. 海洋沉积物中芳香烃预测中国南海潮汕坳陷油气圈闭方法. *石油学报*, 39(5): 528—540.
- 景建恩, 赵庆献, 邓明, 等, 2018. 琼东南盆地天然气水合物及其成藏模式的海洋可控源电磁研究. *地球物理学报*, 61(11): 4677—4689.
- 李双林, 董贺平, 赵青芳, 等, 2020. 海底烃类气体渗漏实验模拟: 烃类气体含量及分子组成变化与渗漏过程重建. *海洋地质前沿*, 36(5): 1—13.
- 梁前勇, 赵静, 夏真, 等, 2017. 南海北部陆坡天然气水合物区海水甲烷浓度分布特征及其影响因素探讨. *地学前缘*, 24(4): 89—101.
- 牛明杨, 梁文悦, 王风平, 2018. 海洋环境中甲烷的生物转化及其对气候变化的影响. *中国科学: 地球科学*, 48(12): 1568—1588.
- 沙志彬, 梁金强, 苏丕波, 等, 2015. 珠江口盆地东部海域天然气水合物钻探结果及其成藏要素研究. *地学前缘*, 22(6): 125—135.
- 王旭东, 庄光超, 冯东, 2024. 海洋沉积体系甲烷生物地球化学循环的微量元素地球化学示踪研究进展. *海洋地质与第四纪地质*, 44(6): 82—95.
- 吴能友, 杨胜雄, 王宏斌, 等, 2009. 南海北部陆坡神狐海域天然气水合物成藏的流体运移体系. *地球物理学报*, 52(6): 1641—1650.
- 徐思南, 吴自军, 张喜林, 等, 2024. 海洋沉积物碳循环过程数值模型的研究进展. *地球科学*, 49(4): 1431—1447.
- 杨克红, 于晓果, 初凤友, 等, 2016. 南海北部甲烷渗漏系统环境变化的碳、氧同位素记录. *地球科学*, 41(7): 1206—1215.
- 尹希杰, 周怀阳, 杨群慧, 等, 2008. 南海北部甲烷渗漏活动存在的证据: 近底层海水甲烷高浓度异常. *海洋学报*, 30(6): 69—75.
- 尹希杰, 周怀阳, 杨群慧, 等, 2010. 珠江口淇澳岛海岸带沉积物中硫酸盐还原和不同形态硫的分布. *海洋学报*, 32(3): 31—39.
- 袁佳双, 邱爽, 2024. IPCC AR6 相关甲烷研究进展分析及其对中国的启示. *气候变化研究进展*, 20(3): 327—336.
- 张劼, 雷怀彦, 杨鸣, 等, 2018. 南海北部陆坡沉积物中 P-S-Fe 的相互作用及其对划分硫酸盐—甲烷转换带的指示意义. *地学前缘*, 25(3): 285—293.
- 张亭亭, 梁前勇, 赵静, 等, 2020. 真光层海水过饱和甲烷的来源及机制探讨. *海洋地质与第四纪地质*, 40(1): 50—59.
- 赵静, 梁前勇, 尉建功, 等, 2020. 南海北部陆坡西部海域“海马”冷泉甲烷渗漏及其海底表征. *地球化学*, 49(1): 108—118.