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海洋镉生物地球化学循环研究进展*

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摘 要 镉是一种重要的有毒重金属元素，对生态系统和人体健康造成严重威胁. 目前已有学者对土壤、大气、植物等介质中镉的环境行为进行了综述，而对海洋镉循环的系统梳理较少. 本文综述了海洋中镉的来源、浓度分布与影响因素、镉生物地球化学循环过程及镉同位素在海洋中的示踪应用，并对海洋镉循环未来研究方向进行了展望. 在现有研究的基础上，未来应在镉全球海洋大尺度循环、迁移转化及微观动力学机制方面开展更深入研究. 海洋镉及其同位素生物地球化学循环的研究可为深入理解镉的环境行为与风险和发展有效的镉污染风险防控技术提供科学依据和数据支撑.

关键词 镉，海洋，生物地球化学循环，同位素分馏.

Research progress on the biogeochemical cycling of cadmium in the ocean

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Abstract Cadmium (Cd) is an important toxic metal that poses a serious threat to ecosystem and human health. Researchers have already comprehensively reviewed the environmental behavior of Cd in soil, atmosphere, plants; however, there is still lack of a systematic review of Cd cycling in marine environments. This paper reviewed the source, distribution and influencing factors of Cd, the biogeochemical cycling of Cd and its isotopes, and the application of Cd isotopes in the ocean. Future perspectives of this research area were also discussed. Based on the current studies, future studies should focus on the large-scale cycling of Cd in global ocean, transport and transformation processes of Cd and their microcosmic mechanisms. The study on the biogeochemical cycling of marine Cd and its isotopes can provide scientific basis and data support for deep understanding of the environmental behavior and risk of Cd and the development of effective prevention and control techniques for Cd pollution.

Keywords cadmium，ocean，biogeochemical cycling，isotopic fractionation.

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镉, 位于元素周期表第五周期ⅡB 族, 在自然界中主要以+2 价存在, 是毒性较强的重金属, 在美国有毒物质和疾病登记署(ATSDR)公布的危害人体健康的有毒物质中位居第 7 位[1]. 镉在环境中具有不易降解、存留时间长、溶解度高等特点, 可沿食物链、食物网进行迁移传递[2]. 2015 年全球镉储量约 500000 t, 主要分布在中国和墨西哥[3], 镉广泛存在于电池、颜料、涂料、电镀、金属(锌、铅和铜等)冶炼副产品、塑料稳定剂、化妆品、烟草肥料、杀虫剂及其他产品中[4－7], 这些消费品的使用过程增加了人体镉暴露的风险.

环境中的镉有两种主要来源: 自然来源和人为来源. 自然来源包括岩石风化、火山喷发、森林和丛林火灾燃烧、海底热液喷发等[8－9]. 镉主要的人为来源包括工业生产、种植业、养殖业、城市垃圾与污水污泥、有色金属冶炼与精炼、化石燃料燃烧、磷酸盐肥料生产、金属与电子废物回收和城市垃圾燃烧等[4, 10－11], 这些人类活动每年向环境中释放了大量含镉的污染物, 加剧了环境中镉的污染, 并威胁到人类健康[1, 12－15]. 日本“痛痛病”事件即是由于锌冶炼厂产生的含镉废水排入神通川河中, 导致附近居民饮用或食用镉污染的水、稻米、鱼后出现身体疼痛的症状[16]. 2017 年江西九江“镉大米”事件再次引起公众对镉污染问题的重视[17].

海洋是地球水圈的主要组成部分. 海洋环境作为镉重要的“汇”在全球镉循环中起着重要作用. 重金属可通过陆源输入、大气沉降、海底热液释放等方式进入海洋, 之后可由生物吸收、结合到悬浮颗粒物与铁锰结核/结壳上、形成硫化镉沉淀等过程从海水中去除, 重金属通过沉积物再悬浮和扩散、悬浮颗粒物解吸、有机质再矿化等过程可以再次释放到水体, 造成二次污染(图 1). 全球每年消耗大量海产品, 海产品人均年消费量在 1960 年为 10 kg, 这一数字在 2014 年上升到 20 kg[18], 海洋软体动物和甲壳类动物等海产品中具有较高含量的镉[9], 海洋镉污染问题密切关系到消费者的饮食健康[19－20].

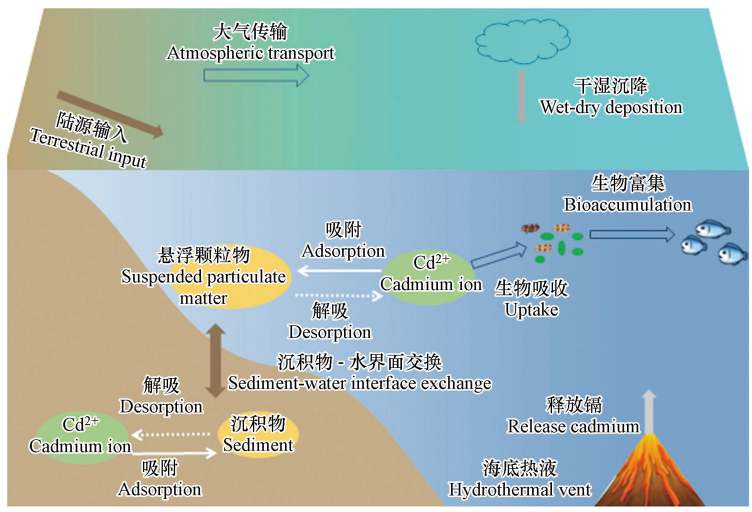

图 1　海洋镉生物地球化学循环图

Fig.1　A schematic figure showing the cycling of cadmium in the ocean

已有学者对土壤[8]、大气[21]、植物[22－23] 等介质中镉的环境行为进行了系统综述, 而目前缺乏对于海洋镉循环的系统梳理总结. 本文综述了海洋中镉的来源、浓度分布与影响因素、镉的生物地球化学循环过程及镉同位素在海洋中的示踪应用, 并对海洋镉循环的未来研究方向进行了展望.

1　海洋中镉的来源、分布与影响因素(Sources, distribution and influencing factors of cadmium in the ocean)

释放到环境中的镉可由多种方式进入海洋. 例如, 大气中的镉可通过干湿沉降的方式进入海洋, 湿沉降的贡献可占全球海洋镉大气沉降通量的 80%—90%; 河流输入也是海洋镉的重要来源, 每年约 3000 t 溶解态镉和 23000 t 颗粒态镉输入到海洋[24]. 中国近海镉河流输送量在 2016 年为 83 t, 2017 达到 105 t[20]. 此外, 海底热液[25－26] 和沉积物释放[27] 也会影响到海水中镉的分布. 不同海域大气沉降和河流输入的相对贡献不同. 例如, 波罗的海每年镉的大气输入量为 33 t, 河流输入量为 24 t[28]. 东海受径流输入影响显著的海域中仅有 7.8% 的镉来源于大气沉降, 其余受陆源排放的影响[29].

海水中镉的平均浓度约为 100 ng·L^{-1} 或更低，海洋沉积物中浓度为 30—1000 μg·kg^{-1}[19]. 海水中镉的存在形式可分为溶解态和颗粒态. 大洋表层海水中镉的平均浓度在 1—100 ng·L^{-1} 左右[30]，大洋中颗粒态镉浓度为 0.00448—0.448 ng·kg^{-1}[24]. 受人类活动影响显著的近海、河口、海湾等水域，海水中镉浓度通常更高. 例如，斐济苏瓦沿海地区[31]、恩诺尔河口[32] 和孟加拉湾拆船厂附近[33] 的海水中镉浓度值远高于海水中镉的平均浓度[19].

海水环境中毒性较大的自由离子态镉通常只占很少一部分，无机镉主要以氯化物形式存在[19, 30]. 此外，镉也可以与海洋中的有机质相互作用，如与乙二胺四乙酸（EDTA）、氨基酸、乙酸、柠檬酸、邻苯二甲酸等小分子物质或胡敏酸、富里酸、脂质等复杂有机质进行络合或螯合[34]. 研究表明黄、渤海海水中溶解有机态镉占总溶解态镉的比例为 20%—92%，大洋表层水中这一比例为 70%—99%[35].

一般近岸海水中镉的浓度较高[36－41]，不同海域浓度值有明显差异（表 1）. 波斯湾[42]、加贝斯湾[43] 以及凯佩兹港口[44] 海水由于人为源输入较大导致镉浓度较高. 除了人为输入，海水中镉浓度还受其它因素影响. 例如，河口区 Cd^{2+}可以与 Cl^-、SO_4^{2-}等无机离子络合，从而由沉积物转移至水相[45]；Ca^{2+}、Mg^{2+}可与 Cd^{2+}竞争悬浮颗粒上的吸附位点[46－48]，导致颗粒中镉的释放. 这些过程也会影响海水中镉的浓度. 镉在海水中的垂直分布特征多为类营养盐型[49－54]，表层浓度通常最低. 南大洋南极半岛附近和威德尔海表层海水中镉浓度较低，在 200—400 m 达到最大值，1000 m 以下海水中浓度几乎不变[55]. 南大西洋西部海水中溶解镉浓度在<100 m 内开始增加，750 m 处达到最大值，2000 m 处浓度最低，反映了营养盐耗尽的北大西洋深层水（NADW）的输入，而受南极底层水（AABW）影响的 3000 m 以下海水镉浓度基本保持一致[56]. 东北太平洋 SAFe 站（30°N, 140°W）表层海水中溶解态镉浓度较低，随着深度增加浓度迅速增加，在 1000 m 处浓度最高，1000 m 以下浓度又略微降低[53].

表 1 海水中镉的浓度分布及主要来源

Table 1 Concentrations and distribution of cadmium in seawater and its major sources

研究区域 Study area	浓度/(μg·L^{-1}) Concentration	主要来源 Main source	参考文献 Reference
山东半岛南部近海	春季: 0.15 夏季: 0.3 秋季: 0.28 冬季: 0.22	陆源输入	[36]
莱州湾	0.28	河流输入	[57]
罗源湾	0.14	径流输入、沿岸排污	[38]
丁字湾	湾内: 0.43 湾外: 0.31	—	[39]
黄、渤海	渤海: 0.644 北黄海: 0.470 南黄海: 0.274	径流输入、大气沉降、人类活动	[35]
厦门九龙江河口	0.34	径流输入、沉积物再悬浮	[45]
印度东南沿岸	0.11	—	[58]
波斯湾	30	人类活动	[42]
凯佩兹港口	73800	多瑙河排放、污水排放、压舱水工业废料、船舶事业及港口设施	[44]
加贝斯湾	48.1	工业活动	[43]
斐济苏瓦沿海地区	130	人类活动	[31]
德雷克海峡与南极半岛	0.067	—	[59]
孟加拉湾拆船区附近	4	人类活动	[33]
印度恩诺尔河口	5.6	人类活动	[32]
175°E, 赤道太平洋（0—40 m）	2001年: 0.003 2002年: 0.002	—	[60]
印度洋	表层: 0.015 底层: 0.064	—	[61]
北冰洋楚科奇海	巴罗海谷: 0.23 波因特莱: 0.1	—	[62]
南大西洋	表层: 0.07	—	[63]

受人类活动和自然因素的影响, 不同海域沉积物含量表现出显著差异(表 2), 近岸沉积物中镉浓度通常更高[64－69]. 渤海锦州湾的表层沉积物由于采矿厂含镉污水的排放导致浓度较高[65]. 尼日利亚翁多沿岸[70] 和孟加拉湾科罗曼德海岸[71] 沉积物中镉浓度最高值分别达到 31.60 μg·g^{-1} 和 19.8 μg·g^{-1}, 远高于北冰洋喀拉海(0.09 μg·g^{-1})[72]、西北太平洋雅浦海沟(0.22 μg·g^{-1})等大洋沉积物[73]. 河口作为地表径流与海水的汇合处, 是污染物沉降的主要区域[74－75], 沉积物中镉浓度通常也较高[74, 76].

表 2　沉积物中镉的浓度分布及主要来源

Table 2　Concentrations and distribution of cadmium in sediment and its major sources

研究区域 Study area	浓度/(μg·g^{-1}) Concentration	主要来源 Main source	参考文献 Reference
长江口及其邻近海域	0.136	陆源输入、工业污染、生物活动	[64]
东海沿岸	0.096	陆源输入	[69]
马来西亚吉兰丹沿岸河口区	3.69	人类活动	[80]
渤海	0.27	河流输入、大气沉降、直接排放、生物过程	[65]
莱州湾	0.33	河流输入	[57]
渤海	1980s: 0.26 近15年: 0.31	径流输入、大气沉降、人类活动	[81]
亚马逊瓜亚加拉河口	雨季: 491 干季: 536	—	[82]
胶州湾	0.11	—	[20]
内伊兹米特湾	0.37	地表径流、河流输入和废水排放	[83]
长江口及毗邻东海海域	0.19	地表径流输入的农药和化肥	[66]
埃德雷米特湾	0.14	自然过程、人为输入	[84]
突尼斯湾沿岸	0.3	城镇污水、工业废弃物、河流、泻湖输入	[85]
孟加拉湾拆船区附近	4.81	人类活动	[33]
加贝斯湾	198.7	工业活动	[43]
北冰洋边缘海-东西伯利亚海	0.21	—	[46]
北冰洋	0.29	—	[72]

沉积物中镉的分布、流动性和生物可利用性不仅取决于总浓度, 还与赋存形态有关[77]. 人为成因的金属主要存在于非残渣态中, 残渣态金属来自于成岩矿物[78－79]. 采用改进的 BCR 顺序提取法研究北冰洋表层沉积物中镉赋存形态, 结果显示镉主要存在于可交换和碳酸盐结合态中(平均 43.4%), 非残渣态占比在 66.7%—100%, 且 39.4% 的站位表现出非常高的环境风险(风险评估指数(RAC)>50%)[72]. Tessier 修正法提取结果表明, 渤海中部表层沉积物中镉在各相中的分布顺序为: 残渣态>碳酸盐结合态>可交换态>可氧化态>可还原态, 可交换态和碳酸盐结合态之和平均值为 47.4%, 略高于残渣态平均值(46.3%)[77]. 改进的 BCR 顺序提取法对巴西萨尔河口沉积物中镉赋存形态的研究结果表明, 沉积物中镉可氧化态(37%)>残渣态(32%)>可交换和碳酸盐结合态(15%)>可还原态(14%), 非残渣态占比高于残渣态, 对水环境潜在的不利影响较大[78].

综上所述, 海洋环境中镉的分布和行为受多种因素共同控制, 污水直排、采矿、航运、径流输入、大气沉降、浮游植物吸收、沉积物再悬浮、颗粒物吸附、沉降、降雨、河流输入、海水输入、洋流等都会对海洋中镉的含量和分布产生影响[35, 65, 82, 86]. 镉的毒性和环境行为与其形态密切相关, 目前研究工作多集中于对于沉积物和水体镉总量的测定, 对于镉赋存形态的了解相对较少.

2　镉在海洋中的生物地球化学循环过程(Biogeochemical cycling of cadmium in the ocean)

海洋是水圈的主体部分, 镉进入水体之后会经历一系列生物地球化学过程, 例如上升流、水团混合等水动力过程、悬浮颗粒物吸附解吸、沉积物吸附解吸、再悬浮过程、浮游植物吸收、再矿化等[34, 87－91].

2.1 悬浮颗粒物对镉环境行为的影响

水环境包含水相和悬浮颗粒物两部分. 悬浮颗粒物由有机和无机组分构成, 其表面丰富的有机基团和无机离子可与重金属作用, 通过吸附、沉降、再悬浮等途径使重金属在水相和沉积物中发生迁移, 是重金属重要的载体[82, 92－93].

在模拟河口条件下的悬浮颗粒物实验中发现, 超过 90% 的镉可在几个小时内被吸附, 且该过程可逆[48]. 悬浮颗粒物吸附镉后可携带其沉降至沉积物中[82, 94], 降低水相中的浓度. pH、离子浓度是影响悬浮颗粒物吸附镉的重要环境因素. 海水中镉-氯络合物的形成以及钙离子和镁离子对颗粒表面吸附位点的竞争[48, 95－96] 可以促进颗粒态镉的解吸, pH 升高[95－97] 则有利于悬浮颗粒物对镉的吸附.

2.2 镉与海洋生物的相互作用

一般认为镉的生物毒性与其自由离子形态含量而不是总量相关[98]. 浮游植物作为海洋生态系统的初级生产者对重金属较敏感, 镉浓度较高时会对浮游植物产生毒性. 镉暴露下, 浮游植物表现出活性氧含量、叶绿素含量、最大光能转化效率、可溶性蛋白含量降低及类胡萝卜素、谷胱甘肽过氧化物酶、超氧化物歧化酶、过氧化氢酶、丙二醛增加的趋势, 说明镉对浮游植物产生了毒性伤害及机体应对镉胁迫做出了自我保护反应[99－106]. 镉也可对海洋动物产生毒性, 并引发生物体内的氧化应激反应[107]. 例如, 暴露镉一段时间后水生动物(虾夷扇贝、近江牡蛎、栉孔扇贝、缢蛏、紫贻贝等)体内镉蓄积量增加[108－112], 超氧化物歧化酶[113]、过氧化氢酶[114]、谷胱甘肽过氧化物酶[115] 等活性增强. 在微生物作用下, 硫酸盐可还原为硫化物, 促使溶解态的镉向不溶性硫化镉转化[82, 116], 从而降低镉的毒性. 此外, 多项研究表明, 锌限制时镉可以替代碳酸酐酶中的锌表现出一定的生物功能, 促进浮游植物生长[117－123]. 例如, 在锌浓度为 3 pmol·L^{-1}、二氧化碳浓度为 350 mg·L^{-1} 条件下, 镉添加浓度由 0 增加到 45 pmol·L^{-1} 时, 威氏海链藻的生长速率增加了 2.375 倍[124].

2.3 海洋沉积物镉行为研究

沉积物是海洋重金属重要的储存场所, 沉积物理化环境发生变化时重金属可以再次释放进入水相中, 成为水体重金属的二次源, 对镉的环境行为产生重要影响.

热力学吸附实验结果表明, 随着镉离子浓度的增加, 沉积物镉吸附量显著增加[125]. 有氧条件有利于沉积物镉的释放, 进而会增加海水中镉的浓度[126]. 在不同盐度的人工海水中, 盐度由 0‰增加到 35‰时, 沉积物中镉的释放量明显增加, 这主要是镉离子与氯离子形成络合物促进了镉从沉积物中的解吸[79, 127]. 随着 pH 的降低, 沉积物中镉总浓度呈现下降趋势, 酸性的增加可能会促进金属由沉积相向水相迁移[128]. 蛋白质中含有疏水组分以及多种络合基团, 外源加入牛血清白蛋白可显著促进沉积物中镉的释放[129]. 此外, 沉积物再悬浮过程也会导致沉积物中镉向水体的释放[130－134].

综上所述, 镉在海洋中的循环与生物吸收、悬浮颗粒物吸附/解吸以及沉积物-水界面交换过程等密切相关, 而目前对于全球海洋尺度镉的收支及镉关键迁移转化过程微观动力学机制尚不清楚.

3 海洋镉的生物地球化学及镉同位素应用(Biogeochemistry of marine cadmium and application of cadmium isotopes)

镉有 8 种稳定同位素, 包括 ^{106}Cd(1.25%)、^{108}Cd(0.89%)、^{110}Cd(12.49%)、^{111}Cd(12.80%)、^{112}Cd(24.13%)、^{113}Cd(12.22%)、^{114}Cd(28.73%)以及^{116}Cd(7.49%)[135]. 目前, 研究中多采用^{114}Cd 和^{110}Cd 的比值来表征镉同位素组成[136－137], 具体计算过程见式(1—2)[50, 55]. 镉同位素数据可用于解释控制水柱中镉分布的因素或过程[25, 55, 87, 122].

$$\delta^{114/110}\mathrm{Cd}=\left[\frac{(^{114}\mathrm{Cd}/^{110}\mathrm{Cd})_{\mathrm{sample}}}{(^{114}\mathrm{Cd}/^{110}\mathrm{Cd})_{\mathrm{NISTSRM3108}}}-1\right]\times 1000(‰) \tag{1}$$

$$\varepsilon^{114/110}\mathrm{Cd}=\left[\frac{(^{114}\mathrm{Cd}/^{110}\mathrm{Cd})_{\mathrm{sample}}}{(^{114}\mathrm{Cd}/^{110}\mathrm{Cd})_{\mathrm{NISTSRM3108}}}-1\right]\times 10000(‱) \tag{2}$$

式中, $\delta^{114/110}$Cd 和 $\varepsilon^{114/110}$Cd 分别代表样品^{114}Cd/^{110}Cd 值相对于标准物质^{114}Cd/^{110}Cd 值的千分偏差(δ)和万分偏差(ε); $(^{114}\mathrm{Cd}/^{110}\mathrm{Cd})_{\mathrm{sample}}$ 和 $(^{114}\mathrm{Cd}/^{110}\mathrm{Cd})_{\mathrm{NIST\ SRM\ 3108}}$ 分别代表样品和标准物质 NIST SRM 3108 中

^{114}Cd 和^{110}Cd 的比值[136].

同位素比值的变化可用来反应浮游植物的吸收和再矿化过程[53, 138 − 139]. 研究者发现热带南太平洋东部海水 $\delta^{114/110}$Cd 值由深层水向表层水呈增加趋势, 说明表层浮游植物优先吸收更轻的同位素[140]. 在秘鲁上升流区, 表层海水中由于浮游植物的吸收表现为低镉浓度和高 $\delta^{114/110}$Cd 值, 而深层水中由于有机质再矿化表现为相反趋势[141]. 此外, 在大西洋、南大洋、太平洋及北冰洋≤50 m 的透光层中也发现了更低的镉浓度和高的 $\varepsilon^{114/110}$Cd 值[138]. 南大洋威德尔环流 $\varepsilon^{114/110}$Cd 最低值与镉浓度最高值存在的深度大致相同, 可能是有机质再矿化的结果[55].

镉同位素分馏情况还可用来指示水团混合过程[25, 138 − 139, 141 − 143]. 热带大西洋中层和深层水的 $\delta^{114/110}$Cd 值与南极中层水(AAIW)/南极底层水(AABW)和北大西洋深层水(NADW)的混合结果一致, 表明镉同位素分布受水团混合的控制[144]. 在北冰洋西部海水中镉同位素的剖面图中发现, 300 m 以上海水中镉浓度及 $\delta^{114/110}$Cd 值均处在北大西洋和北太平洋浓度值之间, 反映了大西洋和太平洋水的混合; 300 m 以下北极水中镉浓度和 $\delta^{114/110}$Cd 值和北大西洋类似, 这一现象与北冰洋深处大部分水是从大西洋经弗拉姆海峡流入的事实相符[50]. 北大西洋海水中 $\delta^{114/110}$Cd 值存在垂直梯度, >3000 m 的深水区 $\delta^{114/110}$Cd 值最低(0.24‰±0.06‰), 1000 m 处约为 0.4‰, 表层混合层表现出了最大同位素比值(5‰), 这种变化可能是由于南极水团和北大西洋水团的混合, 以及表层海水中生物对轻同位素的优先吸收[25].

硫化镉沉淀的形成也会产生镉同位素分馏, 通常硫化镉与海水相比表现出更轻的同位素组成[122, 141, 145 − 147]. 铁锰结核/结壳可以对水柱中的镉进行清除, 其 $\varepsilon^{114/110}$Cd 值与海水的同位素组成接近, 可以反映海水镉同位素组成[122 − 123, 148]. 锰氧化物对镉吸附引起的同位素分馏程度可能与离子强度有关, 在低的离子强度下同位素分馏程度更大, 铁锰结核/结壳与海水的镉同位素组成接近可能是由于海水的离子强度高(~ 0.7 mol·L^{-1})[149].

此外, 镉同位素组成还可以用来示踪污染物来源[135, 150 − 152]. 营养盐极度匮乏的西南太平洋亚热带环流海水 $\delta^{114/110}$Cd 值从混合层底部到顶部呈降低趋势, 除了受到海洋内部上升流的影响外也可能与强降雨事件输送大气 Cd 同位素组成相对较轻有关[87]. 西伯利亚河流与北冰洋混合区大部分海水样品的 Cd 同位素组成符合北极海水-河水准二元混合结果, 5 个镉浓度异常高的样品表明混合过程存在河流悬浮颗粒物镉的释放, 解吸部分 $\delta^{114/110}$Cd 值约为 3, 符合自然来源的特征(河水 $\delta^{114/110}$Cd 值约为 2±1)[153]. 海底烟囱中黑烟硫化物样品的镉同位素数据可反映原始热液的同位素组成, 样品的 $\delta^{114/110}$Cd 值低于大洋深层水的平均值, 而与地球全硅酸盐的值相似, 该现象表明原始热液的镉同位素特征可能主要源自于玄武质洋壳中溶出的镉[123]. 此外, 工业生产及其它人类活动中可产生镉同位素分馏的现象[135, 154], 可根据生物及环境样品同位素组成推测镉污染物可能的来源. 英吉利海峡双壳类动物中, 塞纳河口紫贻贝(*Mytilus edulis*)的镉浓度最高、同位素组成最轻, 推测污染来源于工业废弃物的排放; 地中海沿岸德巴格斯与普雷沃斯特的紫贻贝(*Mytilus galloprovincialis*)相比, 镉浓度更高、同位素组成相对更轻, 推测与附近纳博讷市颜料厂的镉排放有关[154]. 美国切萨皮克湾博德金角比查普唐克河牡蛎(*Crassostrea virginica*)中镉的浓度更高、同位素组成更轻, 受巴尔的摩港人为排放污染影响显著; 查尔斯顿港牡蛎(*Crassostrea virginica*)有较轻的镉同位素组成, 表明镉主要来自具有轻同位素组成的排放源(例如, 锌冶炼、精炼)[155].

4　展望(Prospect)

海洋是陆源镉污染物重要的“汇”. 目前关于海洋镉循环已有较多研究, 但仍有许多问题亟待解决, 例如全球气候变化和海洋酸化等对镉循环的影响、镉对海洋生态系统的长期影响和风险、海洋镉污染物的来源解析等. 为回答这些问题, 需要对镉全球海洋大尺度循环、迁移转化及微观动力学机制等进行更深入的了解, 这依赖于镉同位素示踪/分馏、分子生物学和生物地球化学模式等多学科手段的开发应用.

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