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# 珊瑚礁区海底地下水排泄的环境效应 及其珊瑚记录研究进展

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**摘要:** 海底地下水排泄 (SGD) 是近岸海洋化学和生态系统演化的重要驱动因素, 其携带的大量物质对珊瑚礁发育和退化具有非常重要的影响。本文综述了珊瑚礁区的 SGD 特征及其对珊瑚礁发育和退化的潜在生态环境效应, SGD 的珊瑚替代指标以及全球各海域 SGD 的高分辨率珊瑚记录研究进展, 并以南海北部为例探讨珊瑚礁退化的主导因素及 SGD 的潜在影响。研究发现, 目前珊瑚礁区, 尤其是岸礁区长时间序列的 SGD 动态变化记录的研究极为薄弱; 利用珊瑚骨骼的地球化学指标来重建局部海域的 SGD 通量的动态历史变化具有较强的可操作性; 虽然 SGD 极有可能是以南海北部为代表的珊瑚礁区珊瑚礁退化的重要因素, 但目前无论是政府机构还是公众对 SGD 的关注和重视相当有限。未来的研究应该聚焦于珊瑚礁区 SGD 及其携带物质通量的高分辨率珊瑚记录, 进而探讨 SGD 对珊瑚礁发育和退化影响的关键过程与机制, 并提出科学合理的应对建议。

**关键词:** 珊瑚礁; 地球化学; 海底地下水排泄; 南海

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## 1 引言

作为海洋中生物多样性最高和资源最为丰富的生态系统, 珊瑚礁承担着极其重要的资源与生态功能<sup>[1]</sup>, 为全球数亿人提供食物供给、休闲旅游、海岸保护等服务<sup>[2–3]</sup>。同时, 作为对全球变化与人类活动最为敏感的生态系统之一<sup>[4]</sup>, 珊瑚礁面临着包括气候恶化、水体污染和过度捕捞在内的前所未有的多重压力<sup>[5–6]</sup>, 在全球范围内发生了严重退化。因此, 珊瑚礁退化的驱动因素及机制一直是国际上研究的热点问题<sup>[7–8]</sup>。珊瑚礁退化被认为是由一系列独立和相互作用的局部及全球因素所共同驱动的<sup>[9]</sup>。虽然气候异常导致的

珊瑚热白化被公认为全球范围内珊瑚礁退化的主要因素<sup>[10]</sup>, 但像纬度相对较高的南海北部海域, 珊瑚礁退化往往是由局部的驱动因素主导的<sup>[1, 11]</sup>。

作为海岸带陆海相互作用的关键过程, 海底地下水排泄 (Submarine Groundwater Discharge, SGD) 是海岸带生物地球化学循环的一个重要源过程<sup>[12]</sup>。SGD 的研究虽然早在 19 世纪就已经开始, 但由于其受限于不易现场调查观测, 而且对 SGD 的研究还需要海洋科学、地下水科学以及地球化学等多个领域学者的共同合作, 因此, 直到 20 世纪末, 人们才逐渐认识到 SGD 对沿海海域物质来源的巨大贡献<sup>[13]</sup>。在一些海岸或海湾, SGD 甚至已经成为营养物质和重金属

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元素等陆源物质向海洋输送的最重要通道<sup>[14]</sup>。

近年来,珊瑚礁海域的 SGD 对珊瑚礁生态系统具有极为显著的潜在负面影响<sup>[15-16]</sup>,因此得到了越来越多的关注<sup>[16-23]</sup>。以“submarine groundwater discharge”和“coral reef”作为共同关键词在 Web of Science 上共检索到 110 篇文献。最早的文献出现在 1997 年,自 2012 年之后,尤其是 2017 年以来珊瑚礁区 SGD 的研究论文数量迅速增长(图 1)。但从全球范围内来看,珊瑚礁区 SGD 的相关研究较为有限。其中,准确描

述 SGD 所携带物质排放的时间地点的分布模式和深入了解 SGD 所携带物质的来源和供应,进而对自然或人为活动可能造成的影响进行有效评估成为相关研究的主要方向。因此,对 SGD 通量的长时间序列和高分辨率变化记录的研究显得尤其重要<sup>[23]</sup>。而作为热带海洋中理想的古环境记录载体,珊瑚礁区的大型滨珊瑚骨骼中记录的地球化学信号恰好可以用来反演 SGD 通量的历史变化,并已经广泛应用于全球各个珊瑚礁海域<sup>[24-26]</sup>。

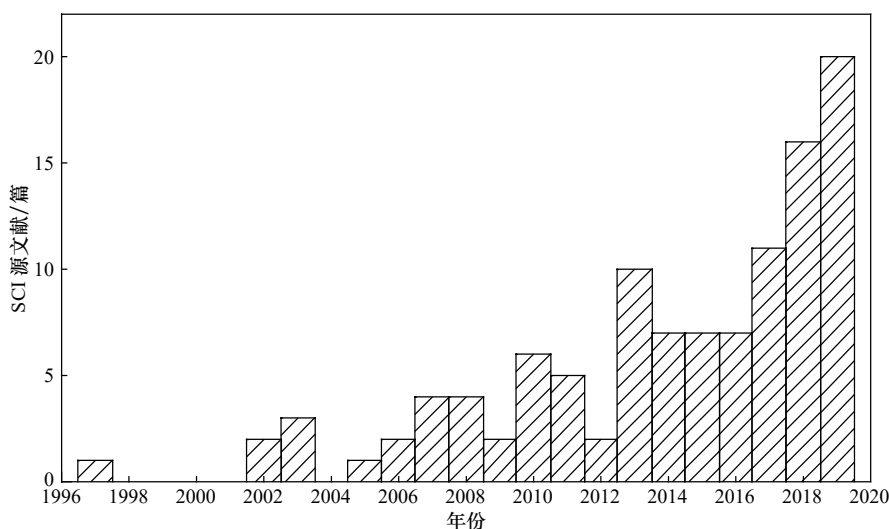


图 1 珊瑚礁区 SGD 研究文献分布 (关键词:“submarine groundwater discharge”和“coral reef”, 统计于 2019 年 10 月 30 日)

Fig. 1 The record of published articles about SGD in coral reefs (key words: “submarine groundwater discharge” and “coral reef”, according to statistics obtained on October 30th, 2019)

为了深入了解珊瑚礁区 SGD 的历史变化记录及其环境意义,本文将结合全球已有的研究并以南海北部主要珊瑚礁区为例,系统介绍珊瑚礁区的 SGD 珊瑚记录的研究案例、替代指标及其局限性,并对 SGD 及其携带物质对珊瑚礁发育和退化的潜在影响进行了总结。

## 2 南海北部珊瑚礁退化驱动因素

在过去的几十年中,全球珊瑚礁发生了严重退化,而气候异常导致的珊瑚热白化已经成为全球范围内珊瑚礁退化的主要因素<sup>[10]</sup>。虽然在南海也出现了珊瑚热白化的历史记录<sup>[27-28]</sup>,但总体而言,南海北部珊瑚礁分布位于世界珊瑚礁分布北缘,离赤道较远,受厄尔尼诺等异常气候的影响相对较小。此外,健康的珊瑚礁应对自然气候变化时具有非常强的弹性和自然恢复能力<sup>[29-30]</sup>。例如,三亚野猪岛珊瑚礁在 2010 年遭遇了升温 and 台风的双重影响,活造礁石珊瑚覆盖率从 80% 降低到 30%,但仅在 1 年之后就发生了自然

恢复<sup>[31]</sup>。值得注意的是,南海北部由于其地处相对高纬度的亚热带海域,在全球变暖的气候背景下甚至可能成为未来的“珊瑚避难所”<sup>[32-34]</sup>。由此可见,引起南海北部珊瑚礁退化的主要驱动因素并不是全球气候变化引发的升温,而是逐渐加剧的人类活动<sup>[1]</sup>。

这些人类活动主要包括:(1)过度捕捞导致的珊瑚礁生态系统内的草食性生物量大幅度减少,进而致使珊瑚礁生态系统的严重失衡<sup>[11, 35-36]</sup>;(2)采挖珊瑚等活动,直接减少了珊瑚礁资源量,间接地破坏了礁盘<sup>[11, 35-36]</sup>;(3)海湾的养殖鱼排、近岸的养殖池塘和深水网箱养殖等造成的水质污染和生物资源浪费<sup>[37]</sup>;(4)未经处理的生活和农业污水的排放也影响着近岸区域的水质环境<sup>[11, 36]</sup>,特别是营养盐太多会引起生态系统失衡以及生物侵蚀,阻碍珊瑚的自然恢复<sup>[37-40]</sup>;(5)海洋工程(挖泥和抛泥)和土壤侵蚀等造成的水质退化等<sup>[35-36]</sup>。

20 世纪 90 年代以后,随着珊瑚礁自然保护区(如三亚、徐闻珊瑚礁自然保护区等)的建立和珊瑚礁立

法保护的出現, 以過度捕撈、采挖珊瑚和海洋工程為代表的人類活動對珊瑚礁的影響得到較為有效的遏制<sup>[1]</sup>, 但南海北部近岸主要珊瑚礁區活珊瑚覆蓋度仍然處於快速下降趨勢<sup>[1, 35]</sup>。根據國家海洋局南海分局發布的《2016年南海區海洋環境狀況公報》<sup>[41]</sup>, 南海近岸局部海域污染嚴重, 部分水體呈富營養化狀態, 所監測的近岸海域典型生態系統中, 半數處於亞健康狀況。因此, 南海北部珊瑚礁所面臨的形勢依然十分嚴峻。在當前珊瑚礁所面臨的各類威脅中, 通過地表和地下徑流輸入到近海海域的陸源物質, 尤其是與流域施肥和污水排放相關的過量營養物質, 被認為對珊瑚礁的退化起着不容忽視的作用<sup>[6, 42-46]</sup>, 也極有可能是南海北部珊瑚礁快速退化的主要驅動因素<sup>[17-18]</sup>。

### 3 珊瑚礁區 SGD 特征及環境效應

作為全球水循環的重要組成部分, SGD 是海洋中水及營養物質的重要來源之一(圖 2), 同時也是各類污染物質從陸地向海洋輸送的一個重要而隱蔽的通道<sup>[13]</sup>。除了輸入豐富的營養物質以外, SGD 還可以改變近海海洋環境中的總鹼、可溶無機碳含量以及海水 pH 等<sup>[17, 47-48]</sup>。由於 SGD 在許多近岸海域具有比地表徑流更高的營養物質、碳及金屬元素含量<sup>[48-53]</sup>, 更高的氮/磷比例<sup>[53-57]</sup> 以及與地表徑流相當的通量<sup>[14, 53, 58-60]</sup>, 因而其對珊瑚礁生態系統的多樣性具有十分顯著的影響<sup>[15-16]</sup>。儘管 SGD 本身就具有非常豐富的營養物質, 人類活動還可以進一步提高 SGD 的營養物質水平<sup>[53, 61]</sup>。此外, 與受到降水驅動的河流<sup>[62]</sup> 不同的是, SGD 受地下河口與近海之間的水文梯度驅動, 也就是受到潮汐的調節<sup>[17, 48, 63]</sup>。由於潮汐的驅動, 受到 SGD 影響的近海海洋系統在 1 天或者半天的時間尺度上經常可以觀測到富含營養物質的 SGD 的脈沖信號, 進而導致短期的營養物質水平變率提高<sup>[64]</sup>。

研究證實, 許多近海海域的富營養化和藻類暴發性繁殖, 均與當地 SGD 輸送的營養物質具有非常密

切的关系<sup>[65-70]</sup>。而過量的營養物質輸入正是珊瑚礁退化的最主要驅動因素之一<sup>[15, 40]</sup>。一方面, 營養鹽過量會刺激藻類大量繁殖而導致富營養化, 使得珊瑚失去與大型藻類的競爭優勢, 嚴重阻礙珊瑚礁的自然恢復<sup>[39-40]</sup>; 另一方面, 大型藻類的大量繁殖也會促進侵蝕性無脊椎動物和內岩生微生物的生長, 進而導致珊瑚生物侵蝕加劇<sup>[15, 38, 40, 64, 71-72]</sup>。此外, SGD 與近岸海洋酸化<sup>[17, 73]</sup> 也具有密切的聯繫, 而這些也會嚴重制約珊瑚礁的生長<sup>[64, 74]</sup>。一般來說, 珊瑚礁區的  $p\text{CO}_2$  的變異性會由於 SGD 所攜帶的營養物質對光合作用/呼吸作用的刺激而增強<sup>[46]</sup>。儘管 SGD 養分輸入也會驅動生物初級生產力增強<sup>[75]</sup>, 進而可以影響海水的化學組成, 但在 SGD 營養物質非常豐富或 SGD 通量很高的系統中, 地下水化學組成可以壓倒生物過程而在改變海水化學組成過程中佔據主導地位<sup>[47]</sup>。實際上, 營養元素和 pH 的相互作用對珊瑚礁關鍵生態功能的影響還需要根據不同珊瑚礁海域的特點進行評估<sup>[76]</sup>。總之, 由於珊瑚礁主要位於寡營養鹽區域, 過量營養物質成分的輸入會導致珊瑚礁碳酸鈣骨架逐漸被藻類所取代<sup>[74, 77]</sup>, 進而導致珊瑚礁的退化<sup>[47, 78]</sup>。此外, 最近的一項研究指出 SGD 還可以通過控制營養鹽水平, 鹽度以及潛在的病原體來源等因素顯著降低珊瑚的健康水平和恢復能力, 甚至導致珊瑚疾病的爆發<sup>[79]</sup>。

珊瑚礁區 SGD 在全球各個海域都得到了廣泛的關注, 如太平洋<sup>[17, 21, 23, 48, 64, 79-82]</sup>、澳大利亞<sup>[73, 83-84]</sup>、中北美洲及加勒比海海域<sup>[85-87]</sup> 等。但在南海北部海域, 除了少數研究以外<sup>[17-18]</sup>, 大部分研究並非專門針對珊瑚礁區 SGD 對珊瑚礁生態系統的潛在影響, 而是其研究區域恰好處於珊瑚礁區。由於受限於不易現場觀測和歷史數據極度缺乏, 目前珊瑚礁區 SGD 的相關研究主要聚焦於特定時間內珊瑚礁區 SGD 所攜帶的豐富營養物質和  $p\text{CO}_2$  等<sup>[17-18, 20, 84]</sup> 對海水化學的影響, 而關注到 SGD 長時間序列動態變化<sup>[88]</sup> 的研究則十分缺乏<sup>[26]</sup>。

### 4 珊瑚礁區 SGD 的代用指標研究進展

作為 SGD 的主要特征元素, 鉍<sup>[24, 89-92]</sup> 和稀土元素<sup>[25, 93-98]</sup> 的相關研究已經較為成熟。幸運的是, 珊瑚礁海域的表層海水鉍和稀土元素的時間序列變化已經被證實可以從各個海域的珊瑚文石骨骼中得到, 諸如, 北太平洋海域<sup>[25, 99]</sup>、東大西洋海域<sup>[24, 100]</sup>、南海<sup>[101-104]</sup>、南太平洋海域<sup>[105]</sup>、大堡礁海域<sup>[106]</sup> 和西印度洋海域<sup>[107]</sup>。比較特殊的是, 在沒有較大入海河流而只有 SGD 的海域, 珊瑚記錄的表層海水鉍和稀土元素

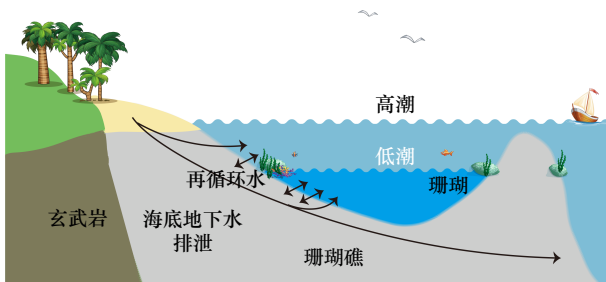


圖 2 珊瑚礁區 SGD 示意圖(以火山島嶼為例)

Fig. 2 Schematic diagram of SGD in coral reefs (a case of volcanic island)

含量变化与当地 SGD 通量具有十分显著的相关性(图 3)<sup>[24-26]</sup>,并被应用于 SGD 通量年际变化历史的重建(图 4a)。因此,根据珊瑚地球化学指标来重建局部海域的 SGD 具有较强的可操作性。值得注意的是,海水中的溶解物质除了与新鲜的 SGD 有关<sup>[108]</sup>,还与海水在沉积物中的再循环有关。

实际上,在 SGD 的常用研究方法中,镭<sup>[59]</sup>和氡<sup>[109]</sup>同位素示踪法应用最为广泛,同时也是大尺度评估海底地下水排泄最为有效的方法<sup>[13]</sup>。珊瑚礁海域具有较低的放射性水平<sup>[110-111]</sup>,因此,极少有人关注珊瑚骨骼的放射性水平。但是,近年来已有研究精确地测量了珊瑚文石骨骼中的镭等放射性核素含量<sup>[112-113]</sup>,这使得利用珊瑚文石骨骼中的镭等放射性核素含量来反演表层海水中的含量在时间序列上的变化,进而来重建局部海域 SGD 通量的变化历史成为可能。

近年来,由于 SGD 输入的氮元素在珊瑚礁生态系统中的重要地位,珊瑚骨骼有机质中的  $\delta^{15}\text{N}$ (CS- $\delta^{15}\text{N}$ )被成功用于重建珊瑚礁海域氮元素来源和供应

的长时间序列的动态变化记录<sup>[88, 114-116]</sup>。原始珊瑚礁通过洋流、河流和地下水输入以及大气沉降从周围地区收集包括氮在内的外部营养物质<sup>[117]</sup>。由于 SGD 携带的氮( $\delta^{15}\text{N}$  富集)<sup>[118]</sup>,生物固定的氮( $\delta^{15}\text{N}$  亏损)<sup>[119]</sup>,以及深海来源的氮( $\delta^{15}\text{N}$  具有定值,如南大洋约为 7‰)<sup>[120]</sup>均具有鲜明的特征,该方法可以有效地对不同来源的氮进行区别。Erlar 等<sup>[88]</sup>成功地将该方法应用于南太平洋热带岛屿,利用长时间序列的 CS- $\delta^{15}\text{N}$  重建了过去 1 个世纪左右与农业有关的 SGD 氮输入变化历史(图 4b)。此外,CS- $\delta^{15}\text{N}$  还被成功用于追踪珊瑚礁生态系统中 SGD 的空间分布<sup>[121-124]</sup>。

## 5 存在问题

首先,以南海北部为代表的近岸珊瑚礁 SGD 得到的关注极为有限。在全球范围内,SGD 约占淡水入海总量的 6%~10%,其中,仅 1/3 的 SGD 来自于热带的大型岛屿<sup>[52]</sup>。但是,前人的研究却主要聚焦于热带岛屿<sup>[21, 23, 54, 61, 63, 75, 84, 88, 125]</sup>,而对人为活动更为频繁,同

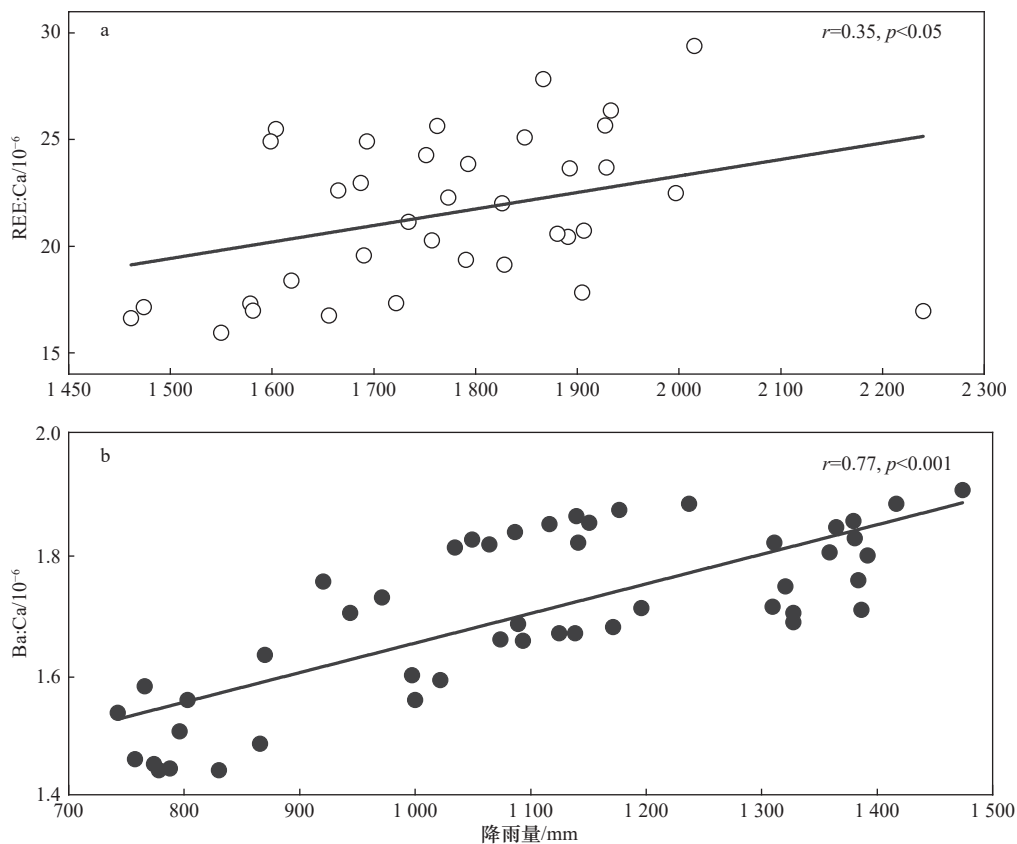


图 3 南海北部三亚海域珊瑚稀土元素(REE)与钙(Ca)比值和控制 SGD 的降雨量相关关系(a, 数据(3 年滑动平均)来源于文献 [26]); 加勒比海尤卡坦半岛海域珊瑚钡(Ba)与 Ca 比值和控制 SGD 的降雨量相关关系(b, 数据来源于文献 [24])  
Fig. 3 The correlation between coral REE/Ca and SGD-associated precipitation near Sanya in the northern South China Sea (a, data (3-year running average) from reference [26]); the correlation between coral Ba/Ca and SGD-associated precipitation near Yucatan Peninsula in the Caribbean (b, data from reference [24])

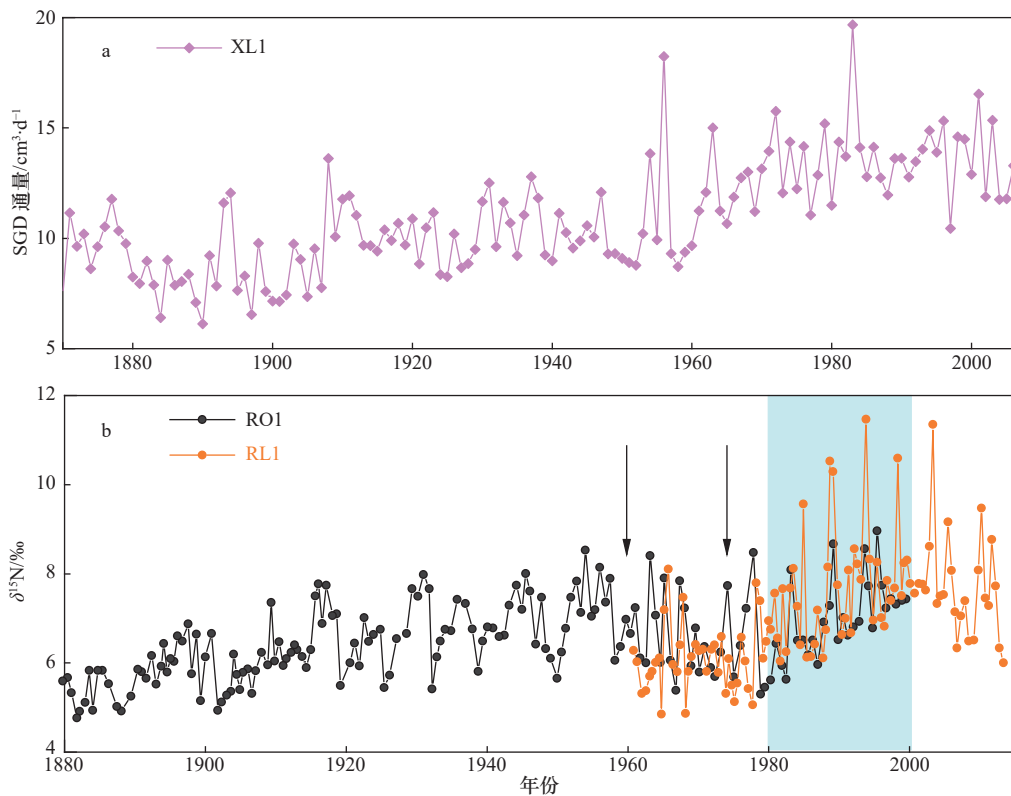


图 4 基于珊瑚稀土元素重建的南海北部海南岛三亚海域 SGD 通量年际变化历史(a, XL1 为珊瑚代号, 数据来源于文献 [26]); 南太平洋拉罗汤加岛珊瑚骨骼有机质中  $\delta^{15}\text{N}$  记录的 SGD 氮输入变化历史(b, RO1 和 RL1 分别为珊瑚代号, 两个黑色箭头分别代表两次农业繁荣时期的开端, 青色背景代表  $\delta^{15}\text{N}$  高值时期, 数据来源于文献 [88])

Fig. 4 The reconstructed annual variations of SGD flux near Sanya of Hainan Island in the northern South China Sea based on coral REE (a, XL1: coral label, data from reference [26]); the input record of N based on  $\delta^{15}\text{N}$  in coral skeleton organic material in the Rarotonga, South Pacific (b, RO1 and RL1: coral label. The black arrows show the start of two agricultural booms. The cyan background represents the elevated period of  $\delta^{15}\text{N}$ , data from reference [88])

时面临的威胁也更大的近岸珊瑚礁的关注很少。例如, 南海北部珊瑚礁分布位于世界珊瑚礁分布的北缘, 受到异常气候的影响不是特别显著, 逐渐加剧的人类活动是南海北部珊瑚礁退化的主要驱动因素<sup>[1]</sup>。目前, 该海域珊瑚礁区的 SGD 研究较为薄弱, 少数已有研究主要聚焦于特定时间内珊瑚礁区 SGD 的通量及其所携带的物质<sup>[17-18]</sup>。

其次, 极其缺乏直接或间接的 SGD 长时间序列动态变化的历史记录。由于具有容易现场监测和相关历史数据丰富的特点, 地表径流所携带物质对珊瑚礁生态系统的影响以及珊瑚对其记录与响应等相关研究较为充分<sup>[15, 42-43, 46, 101, 105-106, 126-129]</sup>。值得注意的是, 我国生态环境部(2018年之后)/国家海洋局(2018年之前)及其下属机构每年发布的海洋环境状况公报都重点关注入海河流污染物排放的监测, 但却从未涉及海底地下水排放<sup>[130-131]</sup>。实际上, 20世纪60年代以来的旅游业和农业的快速发展已经导致近海含水层受到了人为污染的影响<sup>[132-133]</sup>。然而, 由于现有的数据资料

有限, 无法描述 SGD 所携带物质排放的时间地点的分布模式, 进而无法对人为活动造成的影响进行有效评估。总之, 我们对南海北部珊瑚礁 SGD 所携带物质的来源和供应的了解存在严重不足, 尤其是极度缺乏 SGD 长时间序列的动态变化记录。事实上, 全球范围内 SGD 长时间序列的动态变化记录也是极为稀少的。

## 6 结论与展望

珊瑚礁在礁体建造的过程(如珊瑚生长)和分解的过程(如生物侵蚀)之间保持平衡<sup>[38]</sup>。珊瑚的生长和生物侵蚀都对受到 SGD 改造的水体化学变化十分敏感, 如富营养化<sup>[15, 74]</sup>和海水酸化<sup>[74, 134-136]</sup>。虽然评估特定时间内 SGD 对于理解近海生物地球化学过程具有非常重要的意义<sup>[21, 60, 137]</sup>, 但由于缺乏直接或间接的测量数据, 使得评估过去几年到几十年乃至上百年的 SGD 极为困难。显然, 这些不足严重妨碍了我们对 SGD 对珊瑚礁影响机制及其关键过程的深入理解。因此, 开展珊瑚礁区 SGD 在时间序列上的变化

历史及其对珊瑚礁的环境效应方面的研究具有十分重要的科学意义。而珊瑚文石骨骼的地球化学指标则是记录邻近海域 SGD 的天然理想载体。基于此,可以利用珊瑚礁区的大型滨珊瑚骨骼地球化学指标,重建珊瑚礁区 SGD 长时间序列动态变化历史记录。一方面能够填补珊瑚礁海域 SGD 长期动态变化历史

的研究空白,理解 SGD 携带物质对于珊瑚礁生物地球化学过程的影响,并对 SGD 对珊瑚礁的潜在影响以及人类活动在其中所扮演的角色进行有效评估;另一方面,深入了解珊瑚礁的物质来源与动态,可以进一步掌握珊瑚礁在全球变化背景下的适应能力,并为珊瑚礁生态系统的保护和修复提供科学依据。

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## Research progress of environmental influence and coral record of submarine groundwater discharge in coral reefs

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**Abstract:** Submarine groundwater discharge (SGD) is a significant driving factor of marine chemistry and coastal ecosystem evolution, and plays a very important role in the development and degradation of coral reefs due to supplying large loads of chemicals into the coastal ocean. This paper reviews the characteristics of SGD in coral reefs and the potential ecological environment effect. Meanwhile, the northern South China Sea was taken as an example to explore the dominant factors controlling the development and degradation of coral reefs, as well as the potential effects. Results show that the research on the long time serial variations of dynamic changes of SGD in coral reefs, especially in fringing reef areas, is quite weak; it is feasible to reconstruct the historical patterns of the annual fluxes of SGD in local seas by using the geochemical coral skeletons proxies; SGD is likely to be an important factor contributing to the degradation of coral reefs in the northern South China Sea, nevertheless SGD has received limited concerns and attentions from both governmental agencies and the public. The future researches should focus on the high-resolution coral records of SGD and chemicals it carries in coral reefs, explore the key processes and mechanisms of effects from SGD on the development and degradation of coral reefs, and then offer scientific and reasonable advice.

**Key words:** coral reefs; geochemistry; submarine groundwater discharge; South China Sea