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利用石笋 δ13C 重建岩溶石漠化研究进展

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摘 要: 岩溶石漠化的形成演化机制是被关注的科学问题, 对脆弱的岩溶区生态环境恢复具有重要的现实意义。洞穴石笋 δ13C 受到多种因素影响, 能敏感响应地表生态环境以及岩溶水文条件的变化。因此, 利用石笋 δ13C 研究岩溶地区生态环境演变历史成为一个重要方向。本文从地表环境和洞穴沉积两个方面梳理了影响石笋 δ13C 的主要因素。结合现代洞穴监测及模型模拟研究, 分析整理了影响洞穴滴水和沉积物中 δ13C 的主要因素和机理。在多重因素的影响下, 石笋 δ13C 的环境意义具有多解性, 文章从时间尺度、空间分布、沉积环境三方面归纳了石笋 δ13C 的指示意义。为了准确解释石笋 δ13C 环境意义, 提出了综合分析、现代监测以及模型模拟的解决方案。通过对岩溶石漠化概念、成因、发展过程、以及环境效应的讨论, 分析了地表石漠化与石笋 δ13C 记录的密切联系。总结了已经发表的利用石笋 δ13C 重建区域石漠化的研究成果, 讨论了目前研究中面临的主要问题: (1) 如何正确解译石笋 δ13C 的指示意义？这是石笋 δ13C 能够用于重建区域石漠化历史的前提; (2) 在空间上, 石笋 δ13C 记录反映上覆地表的面积是有限的, 需考虑石笋能否代表目标研究区域的环境变迁; (3) 石漠化可在年—十年际时间尺度上快速发展, 而石笋测年存在一定的年龄误差, 石笋 δ13C 是否能够敏感记录地表的石漠化过程？为了准确重建区域岩溶环境以及石漠化演变历史, 提出以下主要建议: (1) 为了避免石笋 δ13C 重建古环境的不确定性, 可加强石笋 δ13C 与 δ18O、微量元素、矿物结构等指标的综合对比分析, 与现代监测以及模型模拟的解决方案综合集成, 能更加准确重建研究区岩溶水文变化过程, 判定石漠化的演化历史; (2) 通过区域和同一洞穴的多根石笋记录对比, 减少单一石笋记录的区域代表性问题; (3) 高精度年代控制的高分辨率多指标石笋记录, 有助于捕捉快速发生的石漠化过程。

关键词: 岩溶石漠化; 洞穴石笋; 石笋 δ13C; 古环境重建
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0 引 言

石漠化是指在湿润半湿润的岩溶地区, 由于自然因素和人类活动的干扰, 地表植被遭到破坏, 土壤受侵蚀、水土流失加剧, 土壤生产力降低甚至退化, 最终导致基岩大面积裸露成为荒漠的过程[1-2]。中国

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岩溶地貌分布广泛，2016 年我国岩溶地区第三次石漠化监测结果显示，我国石漠化土地总面积达 1 007 万 hm², 占岩溶总面积的 22.3%[3]。石漠化已成为岩溶地区的首要生态问题，严重制约着区域社会经济发展和生态安全[4]。过去二十年来，石漠化研究主要集中在现代过程，如石漠化的成因、工程和生态治理、动态监测等方面[5]。自然因素和人类活动被认为是决定岩溶石漠化发生的最重要因素[6]，历史上岩溶地区的石漠化过程对于研究石漠化发展规律具有重要借鉴意义；而当前关于石漠化演变历史的研究相对不足。

石笋由于具有分布广泛、生长连续、定年准确、代用指标多等特征，成为古气候研究的重要载体[7–9]。石笋 $\delta^{13}C$ 由于受到多种因素影响，限制了 $\delta^{13}C$ 在古气候重建中的应用。随着洞穴监测以及模型模拟等研究的深入开展，关于 $\delta^{13}C$ 对环境的响应机制取得了一些新的认识。石笋 $\delta^{13}C$ 与区域环境联系紧密，能敏感地响应局地气候环境波动[10–12]，可以记录区域地表生物活动、岩溶水文条件变化等[13–15]。人类活动对岩溶生态环境和地表植被的影响也能在洞穴滴水溶解无机碳的 $\delta^{13}C$ 中快速体现出来[11, 16]。以石笋 $\delta^{13}C$ 为主要替代指标，多指标综合集成研究区域岩溶石漠化演变历史，成为石笋古气候古环境研究中新的重要方向之一。本文将在梳理岩溶地区碳元素主要影响因素及运移过程的基础上，回顾石笋 $\delta^{13}C$ 在岩溶石漠化研究中的进展；针对现存的问题，提出一些建议，为下一步工作中围绕石笋 $\delta^{13}C$ 重建岩溶地区生态环境演变过程提供参考。

1　石笋碳同位素基本原理

1.1　石笋碳同位素来源及影响因素

洞穴石笋碳元素的主要来源有：大气 CO_2、上覆土壤 CO_2, 碳酸盐岩 (基岩)[17–19]。大气 CO_2 对石笋 $\delta^{13}C$ 的影响主要通过大气二氧化碳浓度 (pCO_2)、大气 CO_2 同位素组成，以及与土壤 CO_2 的浓度比值实现。大气 CO_2 的碳同位素组成显著偏重于土壤生物成因的 CO_2 碳同位素组成。当大气 CO_2 的碳同位素组成不变时，大气 pCO_2 与石笋 $\delta^{13}C$ 值成正比[20]。在过去的 80 万年里，大气 CO_2 浓度在 180×10^{-6}~280×10^{-6} 之间变化[21]，大气 $\delta^{13}C$ 值在 −6 ‰~−7‰变化[22–23] (本文所涉及的 $\delta^{13}C$ 值均为 V-PDB 标准，以下同)。工业革命之后，全球大气 CO_2 浓度逐年升高，至 2021 年已达 414.2×10^{-6}, 大气 CO_2 的 $\delta^{13}C$ 值也降至 −8.5 ‰(http://www.gosat.nies.go.jp/en/recent-global-co2.html)。虽然大气 CO_2 浓度及 $\delta^{13}C$ 值的变化会引起土壤 CO_2 浓度及其 $\delta^{13}C$ 值的改变[24]，但土壤 CO_2 浓度可达 10^4 ppm[25]，远高于大气 CO_2 浓度。与土壤相比，大气 CO_2 对石笋 $\delta^{13}C$ 的影响较小，因此，石笋最终记录的 $\delta^{13}C$ 信号仍主要来源于土壤。

土壤 CO_2 直接影响着表层岩溶作用过程[26]，是岩溶作用向地下发展的关键纽带，也是洞穴 CO_2 的重要来源[27–30]。土壤物理状况 (如温度、湿度)、生物作用 (如呼吸，有机质分解) 等都会影响土壤 CO_2 浓度[31]。地表植被密切反映区域水热条件，土壤 CO_2 也主要与生物作用有关[32–33]。温度上升，降水增加，土壤温湿度适宜，则生物活性增加，土壤 CO_2 产率增加，$\delta^{13}C$ 值降低[34–36]；若降水不足，高温可能引发干旱，抑制土壤生物活性，土壤 CO_2 产率降低[37]。而在岩溶地区，石漠化导致地表水土流失，土层变薄；土壤有机碳含量、生物碳含量等也随着石漠化程度的加重而减少；同时限制了土壤中生物成因的 CO_2 产率，最终导致土壤 CO_2 的 $\delta^{13}C$ 值偏重[38]。

此外，C3/C4 植物的比例也是影响土壤 CO_2 $\delta^{13}C$ 值的重要因素[39]。植物依据光合作用方式不同可以分为 C3 和 C4 植物类型；自然环境下 CAM 植物生活在干旱地区，在这里不作讨论。C3 植物喜湿冷，C4 植物喜干热气候，因此 C3/C4 植物的比例可以反映气候条件。C3 植物的 $\delta^{13}C$ 值为−20‰~−35‰, 平均为−27‰; C4 植物的 $\delta^{13}C$ 值为−9‰~−19‰, 平均为−13‰[14]。C3 和 C4 植被的 $\delta^{13}C$ 平均值相差 14‰, 对土壤 CO_2 的 $\delta^{13}C$ 值有重要影响。气候条件不同，上覆地表植被类型不同，最终会被洞穴石笋 $\delta^{13}C$ 记录[40]。单一植被类型下，C3 和 C4 植被对应的石笋 $\delta^{13}C$ 值分别为−14‰~−6‰和−6‰~2‰[41]。

土壤 CO_2 溶于土壤水形成碳酸，溶解碳酸盐岩也是石笋 $\delta^{13}C$ 的来源之一。由于碳酸盐岩的 $\delta^{13}C$ 一般在 0‰左右，显著偏重于土壤 CO_2 中的 $\delta^{13}C$; 因此碳酸盐岩贡献的碳元素对石笋 $\delta^{13}C$ 有一定影响。岩溶水中碳酸的溶解能力与土壤 pCO_2 成正比；土壤 CO_2 浓度增加，岩溶水对碳酸盐岩溶解能力越强[42]。另一方面，土壤 CO_2 对基岩的溶解也受控于水文条件。当地表降水减少时，表层岩溶带中水岩相互作

用时间延长，来自基岩贡献的碳比例增加，最终导致石笋 $\delta^{13}C$ 偏重。干旱时期，岩溶水在岩层停留时间长，水岩作用充分，为蒸发或先期沉积（PCP, prior calcite precipitation）创造条件，也会导致洞穴滴水 $\delta^{13}C$ 偏重[20]。

而在降水充足、岩溶水文条件适宜、岩溶裂隙管道畅通的情况下，开放的岩溶系统导致土壤 CO_2 不断补充到岩溶水中，这种情况下碳酸盐溶解对石笋 $\delta^{13}C$ 的影响很小[43]。在开放系统中，洞穴滴水 $\delta^{13}C$ 的变化主要继承土壤 CO_2 变化的结果[44–45]。而在封闭系统中，则同时受控于土壤和基岩的 $\delta^{13}C$ 值[41]。但也有学者认为从长时间尺度上看，上覆碳酸盐岩的厚度或渗流通道不太可能发生重大的改变，基岩对滴水 $\delta^{13}C$ 值的影响可以视为一个常量[46]。综上所述，石笋 $\delta^{13}C$ 主要受土壤 CO_2 产率以及岩溶水文条件的影响。

1.2 洞内过程对石笋碳同位素的影响

洞穴滴水在进入洞穴之后受到的脱气作用显著影响着石笋 $\delta^{13}C$ 值。渗流水流经土壤，溶解土壤 CO_2，导致渗流水中 pCO_2 高于洞穴空气中的 pCO_2，渗流流出洞穴顶板即为滴水。滴水通过脱气与洞穴大气平衡，$CaCO_3$ 沉淀[47]。降水减少 (干旱) 可能导致岩溶裂隙和管道缺水，增强岩溶系统的通风效应，也会导致洞内空气 pCO_2 减小[48]，增强滴水脱气作用，动力分馏效应引起碳酸钙沉积物中 $\delta^{13}C$ 偏重[49]。滴率对石笋同位素分馏影响较大，滴率慢，动力分馏强，石笋同位素偏重[50–52]。此外，PCP 也是岩溶过程中的重要现象，模型以及实验室研究表明 PCP 程度与岩溶水在基岩中的运移时间、水-洞内二氧化碳分压（pCO_2），以及滴水与洞穴空气接触时间有关[53]。干旱条件下，岩溶带表层或洞顶蒸发、水岩相互作用时间延长有助于 PCP 作用发生，导致石笋 $\delta^{13}C$ 偏重[54–55]。滴率、PCP、以及洞穴通风等均受到地表水文状况的影响[56–57]；因此，这些因素引起的石笋 $\delta^{13}C$ 变化，在一定程度上反映了岩溶水文状态的变化。

石笋根据矿物组成可分为纯文石型、纯方解石型、文石-方解石型[58]。同一母液，沉积的文石 $\delta^{13}C$ 比方解石偏重[59–60]。文石疏松多孔，被淋溶容易转变为方解石[61–63]。在这个转变过程中方解石 $\delta^{13}C$ 值比原生文石偏轻[64–65]，但也有研究显示方解石 $\delta^{13}C$ 几乎没有发生变化[66]。因此，石笋矿物类型以及矿物转变对石笋 $\delta^{13}C$ 值产生的影响仍存在不确定性。

2 石笋碳同位素解译

2.1 不同时间尺度石笋碳同位素记录解译

石笋 $\delta^{13}C$ 受地表气候环境、生物过程，岩溶水文条件以及洞穴沉积过程等多个因素综合影响[67]，关于石笋 $\delta^{13}C$ 的环境意义仍需要更加深入的研究。有研究认为石笋 $\delta^{13}C$ 主要记录了洞穴上覆植被的变化，可以利用石笋 $\delta^{13}C$ 重建区域生态环境的变化过程[68]。在轨道时间尺度上，石笋 $\delta^{13}C$ 记录同太阳辐射曲线变化一致 [69–70]，主要反映了气候变化控制的植被演变，也就响应了气候的变化。在百年—千年时间尺度上，可以重建区域温度、降水等变化引起的地表植被密度、类型以及土壤 CO_2 产率等变化[20, 71]。如欧洲伊比利亚半岛的三根石笋 $\delta^{13}C$ 对地表温度变化十分敏感，记录了该区域过去 4 000 年的冷暖交替[72]。自然条件下，区域植被演替的时间在数十年至数百年不等[73]。因此，在无重大自然灾害的前提下，年—十年际的短时间内植被类型一般不会发生重大改变；而地表水文状况、洞穴内部过程等对石笋 $\delta^{13}C$ 值的影响显得更加重要[74–75]。中美洲伯利兹的石笋 $\delta^{13}C$ 与南方涛动指数 (Southern Oscillation Index; SOI) 之间具有强相关性，石笋 $\delta^{13}C$ 记录了在短时间尺度上热带雨林生态系统的碳循环[76]。客观而言，轨道时间尺度的气候变化周期中包含了多个百年—千年时间尺度的气候环境变化[77]。如在距今 11.5 万~1.4 万年的格陵兰冰芯记录发现了 24 次气候突变事件，即 Dansgaard-Oeschger(D-O) 事件[78]。南京葫芦洞石笋记录了末次冰期-间冰期过渡时期植被对剧烈气候变化的响应，而在千年尺度上，偏轻的石笋 $\delta^{13}C$ 反映了 D-O 暖事件中降水量的增加[79]。而百年—千年时间尺度的气候变化下又包含了十年尺度的气候波动[80–82]。利用贵州石将军洞高分辨率石笋分析小冰期内部结构时，发现在过去的 1 300 年里，共有 6 次弱亚洲夏季风事件[83]。这些不同时间尺度的气候环境变化，有可能通过影响地表植被丰度、土壤生物过程、表层岩溶带水文条件等，进而影响到石笋 $\delta^{13}C$ 值[15]。当气候处于寒冷或偏干时，石笋 $\delta^{13}C$ 偏重[30]。

2.2　不同区域石笋碳同位素的指示意义

石笋 $\delta^{13}C$ 记录了局地环境信息，例如洞穴所在区域温度、降水、以及海拔差异，会使得石笋 $\delta^{13}C$ 呈现出不同的变化特征[84]，表现为同一时间段的不同石笋 $\delta^{13}C$ 记录存在区域差异。

大多数研究认为石笋 $\delta^{13}C$ 主要受地表植被的影响，$\delta^{13}C$ 越偏重，指示上覆植被覆盖度越低[85]。但四川东北部的多根石笋 $\delta^{13}C$ 记录，在气候显著干旱的(Heinrich) 事件发生时，并没有反映出植被可能存在的变化[86]。Fohlmeister 等人在总结全球石笋 $\delta^{13}C$ 记录时发现，有一些洞穴如欧洲直布罗陀的 St. Michaels 洞、美国得克萨斯州的 Natural Bridge 洞群，这些地区温度高、植被稀疏。根据当地碳通量监测数据，表层土壤 CO_2 并不是洞穴石笋碳元素的主要来源，在土壤下层存在贫 ^{13}C 的碳源，使得在植被覆盖度低的情况下，洞穴石笋 $\delta^{13}C$ 仍然偏轻[84, 87–88]。同属于欧洲末次间冰期的两根石笋 $\delta^{13}C$ 记录在同一时期变化趋势相反，也可能表明了湿度差异对两个地点土壤生物活动以及岩溶系统中同位素分馏程度的不同影响[89–90]。

热带地区，植被演替过程缓慢，赤道辐合带(Intertropical Convergence Zone, ITCZ) 的南北移动促使区域降水量改变，因此石笋 $\delta^{13}C$ 变化反映了区域降水的季节变化和年际变化[74]。而在温带地区的澳大利亚塔斯马尼亚岛，石笋 $\delta^{13}C$ 受温度控制，温度越高，基岩溶解对碳同位素的贡献增加，会导致石笋 $\delta^{13}C$ 偏重[91]。在对阿尔卑斯山南坡不同海拔高度的洞穴研究中也发现，随着海拔的增加，植被覆盖度和土层厚度降低，位于高海拔地区的洞穴石笋 $\delta^{13}C$ 更加偏重[92]。因此，不同气候带或者不同海拔高度的地区，通过影响温度和降水，影响地表植被和土壤生物活动强度、土壤厚度与 CO_2 产率、基岩溶解等过程，最终影响石笋 $\delta^{13}C$ 值。

除了区域自然条件外，历史事件或特殊的人类活动也会在石笋 $\delta^{13}C$ 记录中留下痕迹。例如北京石花洞石笋 $\delta^{13}C$ 记录了在 360 a BP 以来，虽然气候条件有所改善，但是该区域的植被条件一直没有恢复到之前的平均水平。反映了元大都建立之后到明代晚期，城市扩张之下对建筑用材、薪柴需求量增加，人类大量砍伐北京西山森林导致了对地表植被和环境的改造[93]。

2.3　洞内过程造成的石笋 $\delta^{13}C$ 差异

洞内过程会使得石笋 $\delta^{13}C$ 发生偏移；即使是同一洞穴内同一时期的石笋 $\delta^{13}C$ 记录，也可能存在差异。洞穴上覆地表环境、洞穴系统开闭条件等是相对一致的，这种差异可能来自于每个滴水点的滴水

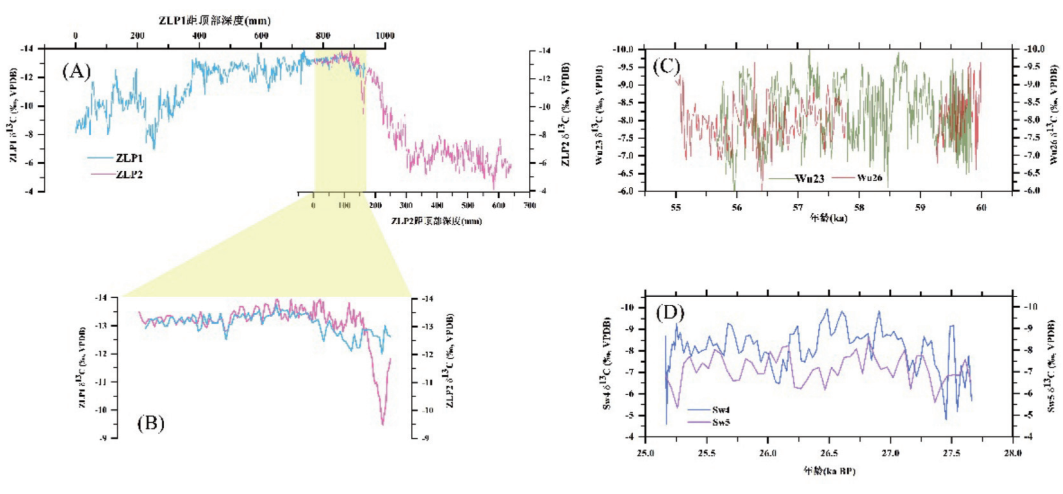

图 1　洞内过程对石笋 $\delta^{13}C$ 的影响

注: (A), (B) 贵州省竹蹓坪洞石笋 ZLP1(蓝色曲线)、ZLP2(粉色曲线)$\delta^{13}C$ 对比，黄色条带表示同一沉积时间段；(C) 贵州省雾露洞石笋 Wu23(绿色曲线)、Wu26(红色曲线) $\delta^{13}C$ 对比；(D) 河北省天鹅洞 Sw4(深蓝色曲线)、Sw5(紫色曲线) $\delta^{13}C$ 对比；(A), (B) 引自参考文献 [94]；(C)、(D) 分别修改自参考文献 [12]、[95]

Fig. 1　Influence of cave process on $\delta^{13}C$ value of stalagmite

(A), (B) Comparison of ZLP1(blue curve) and ZLP2(pink curve) $\delta^{13}C$ of Zhuliuping cave, Yellow bands indicate the same deposition period; (C) Comparison of Wu23(green curve) and Wu26(red curve) $\delta^{13}C$ in the Stalagmite of Wulu cave; (D) Sw4(dark blue curve) and Sw5(purple curve) $\delta^{13}C$ of Tian’e cave; (A), (B) cited from references [94]; (C) and (D) are revised from references [12] and [95]

路径、脱气过程、滴水速率等因素的影响。贵州竹蹓坪洞中的两根石笋 (ZLP1 和 ZLP2) 在相同沉积时间内，石笋 δ^{13}C 值有差异 (图 1(B)) [94]，可能是由于两根石笋在滴水速率和生长速率有差异，引起沉积过程中动力分馏程度不同所导致。雾露洞的两根石笋 Wu23 与 Wu26 的 δ^{13}C 在 59.3~57.7 ka BP 变化趋势一致; 57.7 ka BP 之后，Wu23 的 δ^{13}C 振幅大于 Wu26 (图 1(C))，两者生长速率相差不大，可能是脱气速率不同所导致[12]。天鹅洞的 Sw4 与 Sw5 石笋生长位置相近，在 25~28 ka BP 间，两者的 δ^{13}C 变化趋势相反 (图 1(D))[95]。虽然作者在文中并有对该现象进行详细讨论，但在相似的地表水文条件下，产生这种差异的原因更可能来自于洞内过程。

3 石笋 δ ^{13}C 在石漠化研究中的应用

3.1 石漠化信号传输与石笋 δ ^{13}C

当岩溶地区出现干旱时，植被覆盖度减少，诱发石漠化。一方面，土壤活性受到抑制，土壤 CO_2 浓度降低[6]。另一方面，随着水土流失加剧，土层变薄，雨水快速通过土壤，没有与土壤 CO_2 达到同位素平衡，此时溶液主要继承大气 CO_2 的 δ^{13}C 值[53, 79]。渗流减少，水-岩相互作用时间增长，碳酸盐岩对滴水中的 ^{13}C 贡献增加。在石漠化严重阶段，基岩裸露，降水溶解碳酸盐岩将会成为洞穴石笋 δ^{13}C 的主要来源[96−97]。洞穴滴水减少，滴率减慢，脱气作用增强[52, 98]。最终石笋 δ^{13}C 值偏重 (图 2)。人类活动可直接改变地表植被密度和类型，影响土壤 CO_2 产率，最终导致石笋 δ^{13}C 偏重[11, 99]。例如马达加斯加 Anjohibe 洞穴石笋 δ^{13}C 记录表明，该地区在一个世纪内完成 C3 植物向 C4 植物的快速转变。而石笋 δ^{18}O 代表的降水量在 δ^{13}C 波动过程中并没有显著变化，表明该时期的植被变化与降水变化无关，而是由于饲料作物的种植导致植被类型变化[59, 100]。若地表植被恢复、石漠化状况改善，石笋 δ^{13}C 值会偏轻。现代洞穴监测的结果也有力地证明了这点。例如桂林茅茅头大岩监测表明: 自 20 世纪 90 年代以来，由于造林政策和措施，石漠化面积一直在减少，上覆土壤 pCO_2 和溶解无机碳 (DIC) 浓度同步升高，石笋 δ^{13}C 呈下降趋势，反映了桂林石漠化地区植被恢复的历史[101]。

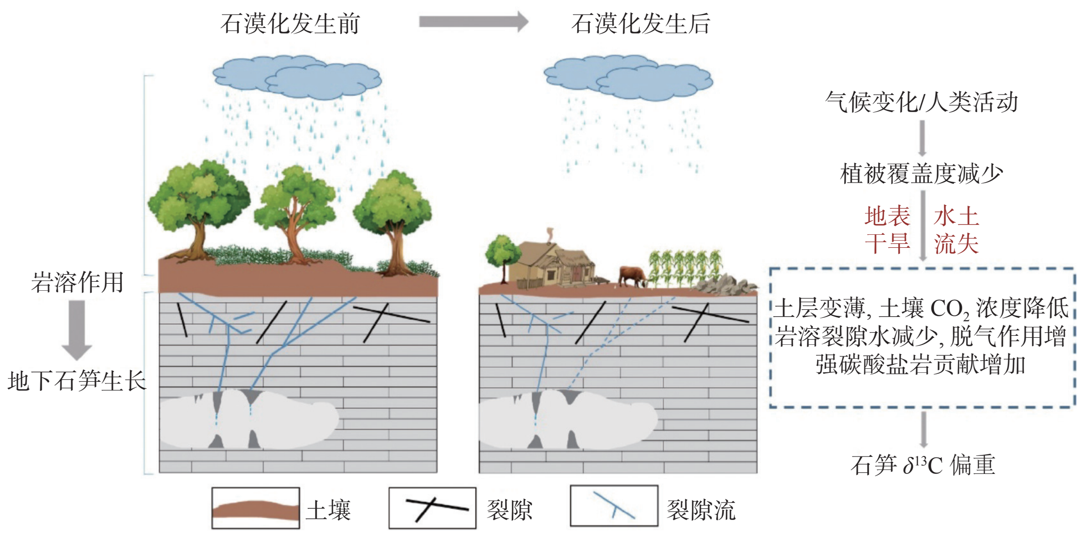

图 2 岩溶石漠化与石笋 δ^{13}C 关系概念图。

Fig. 2 Concept sketch for the relationship between rocky desertification and stalagmite δ^{13}C

由于气候和人类活动导致的植被变化或者石漠化过程需要一定的时间[102]，因此洞穴石笋记录的信息可能会滞后于地表情况的变化[79]。对于上覆基岩较薄以及岩溶管道相对顺畅的洞穴，其石笋 δ^{13}C 对地表环境变化的响应则相对快速[74]。

3.2 利用洞穴石笋 δ ^{13}C 研究石漠化的实例

与利用石笋 δ^{18}O 重建古气候研究相比，当前利用石笋 δ^{13}C 重建岩溶石漠化的研究相对较少 (表 1)。石漠化引起植被和岩溶过程的显著变化，石笋 δ^{13}C 可以灵敏响应于这些变化[12]。已有研究大多将石笋

$\delta^{13}C$ 作为区域植被变化的代用指标，在百年—千年尺度上重建石漠化过程。

在贵州和广西的研究发现，石笋 $\delta^{13}C$ 可以记录岩溶作用以及地表植被变化。在暖湿气候下以 C3 植被为主导，C3 植被增加，C4 植被减少，石笋 $\delta^{13}C$ 变轻，石漠化减弱；冷干气候下，C3 植被减少，C4 植被增加，石笋 $\delta^{13}C$ 偏重，石漠化增强[85, 103]。然而薛治国等人基于石笋、孢粉分析和气候记录，分析了古气候变化对石漠化的影响：干旱期生态退化，进入湿润期后，降水量增多也可能导致水土流失加剧，出现石漠化的趋势，干湿振幅的不断增大会触发石漠化的发展[104]。因此，石笋 $\delta^{13}C$ 与其他地质记录的多指标综合分析有助于重建石漠化历史。

在亚洲季风区，石笋 $\delta^{18}O$ 整体偏轻且相对稳定时，指示较为适宜的气候条件；如果对应于石笋 $\delta^{13}C$ 的突然偏重，则可能指示了石漠化的发生[105]。通过对比人口数据，在气候较稳定的背景下，人口增加，人类活动强度增大，有可能导致了贵州地区石漠化的形成[106−107]。此外，单一洞穴石笋记录的代表性有限，多个洞穴石笋记录的综合对比有助于区域石漠化重建的准确性[108]。

表 1　中国利用石笋 δ13C 重建区域石漠化历史研究实例

Table 1　Case studies on the reconstruction of regional rocky desertification in China, based on stalagmite $\delta^{13}C$

洞穴名称	省区	经纬度	海拔/m	时间跨度	指示意义	其他指标	参考文献
丰鱼洞	广西	24°30′N,110°20′E	380	1 500 年以来	C3/C4	石笋$\delta^{18}O$	Zhu等, 2006[85]
响水洞	广西	25°15′N, 110°55′E	400	1 500 年以来	C3/C4	石笋$\delta^{18}O$	Zhu等, 2006[85]
石将军洞	贵州	26°12′N, 105°30′E	1 300	2 000 年以来	植被状况/水文状况	大气CO_2浓度，历史文献	陈朝军等, 2021[108]
董哥洞	贵州	25°17′N, 108°5′E	680	1 500 年以来	C3/C4	石笋$\delta^{18}O$	Zhu等, 2006[85]
织金洞	贵州	26°46′27.31″N, 105°5′13.90″E	1 330	100 年以来	植被状况	石笋$\delta^{18}O$，器测数据，历史文献	刘子琦, 2013[106]
				1 500 年以来	水文状况	石笋$\delta^{18}O$，鹅管$\delta^{18}O$、$\delta^{13}C$，器测数据，历史文献	刘子琦, 2014[105]
				1 100 年以来	植被状况	石笋$\delta^{18}O$，历史文献	Kuo等, 2011[107]
董家洞	云南	24°7′52″N, 104°6′11′E	1476	1 200 年以来	植被状况	石笋$\delta^{18}O$、微量元素，器测数据，历史文献	李媛媛, 2017[103]

3.3　存在的问题及解决方法

明确石笋 $\delta^{13}C$ 的指示意义是利用石笋碳同位素重建区域石漠化历史面临的首要问题。一些研究认为石笋 $\delta^{13}C$ 可以直接反映降水量的变化[74, 109−110]，而另一些研究者认为亚洲季风区的石笋 $\delta^{13}C$ 反映区域水文环境的变化[79, 95, 111]。石笋 $\delta^{18}O$ 可以反映大区域的气候变化共性和大气环流变化[9, 110, 112−115]。因此，石笋 $\delta^{13}C$ 能否代表大区域环境意义需要结合石笋 $\delta^{18}O$。目前研究中，中国石笋 $\delta^{13}C$ 与 $\delta^{18}O$ 的变化模态组合在不同地区以及时段上呈现出差异性[79, 86]。例如，中晚全新世的莲花洞石笋中 $\delta^{13}C$ 记录可以划分出三个阶段，分别是暖湿期 (6.6ka~3.8 ka BP)、过渡期 (3.8ka~1.6 ka BP)、冷干期 (1.6 ka BP 至今)；与 $\delta^{18}O$ 记录相比，尽管二者之间的变化幅度有所差异，在这些时间段内两者的变化趋势是一致的 (图 3A)[20]。同属亚洲季风区，珍珠洞石笋氧碳同位素在千年—轨道尺度上同相协变，但是在百年时间尺度上，两者的变化幅度和趋势存在差异 (图 3B)[110]。因此，虽然石笋 $\delta^{13}C$ 可以反映上覆地表水文环境的变化，但能否作为降水量指标以及大区域环境重建指标，仍然需要进一步的研究。

微量元素等代用指标受温度、降水等条件的控制，与石笋 $\delta^{13}C$ 相互配合，能够更加准确地重建局地环境变化[11, 97, 116−119]。例如巴哈马石笋 Mg/Ca 比值与 $\delta^{13}C$ 变化一致；在 H 事件时，干旱使得水岩作用时间延长，石笋 $\delta^{13}C$ 偏重[120]。此外，贵州石将军洞的多指标记录表明，当夏季风减弱时，降水减少，CO_2 脱气作用增强，石笋的 Mg/Ca 和 Sr/Ca 比值会随着 PCP 的增强而升高，同时导致石笋 $\delta^{13}C$ 值偏重[121]。此外，石笋 $\delta^{13}C$ 的变化慢于 $\delta^{18}O$，这表明气候突变导致的区域生态退化和恢复是一个缓慢的过程。

石笋微层是石笋响应气候环境变化产生的沉积

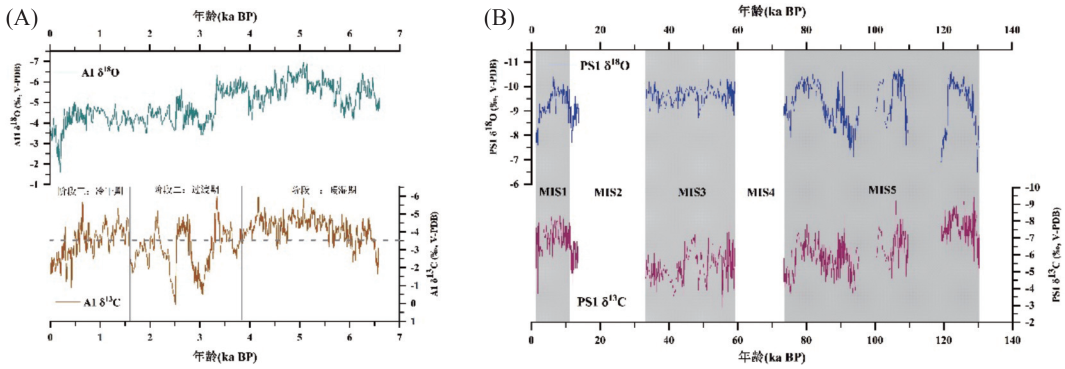

图 3　洞穴石笋氧碳同位素记录在不同时段的模态组合差异

注: (A) 莲花洞 A1 石笋 $\delta^{18}O$ (绿色曲线)、$\delta^{13}C$(黄色曲线) 记录, 灰色虚线表示 $\delta^{13}C$ 平均值;

(B) 珍珠洞 PS1 石笋 1$\delta^{18}O$(蓝色曲线)、$\delta^{13}C$(紫色曲线)。(A)、(B) 分别修改自参考文献 [20]、[110]

Fig. 3　Variation of oxygen and carbon isotope records of stalagmites from different caves

(A) A1 Stalagmite $\delta^{18}O$ (green curve) $\delta^{13}C$ (yellow curve) records of Lianhua cave, the gray dotted line represents the average value of $\delta^{13}C$;

(B) PS1 Stalagmite $\delta^{18}O$ (blue curve) $\delta^{13}C$ (purple curve) of Zhenzhu cave. (A) and (B) revised from references [20] and [110]

形态, 可以提供季节到年际尺度的高分辨水文环境信息[122−126]。欧洲直布罗陀石笋微层与 $\delta^{13}C$ 记录表明, 该地区冬季洞穴 pCO_2 高, 沉积浅色柱状方解石, 石笋 $\delta^{13}C$ 值偏轻; 夏季沉积深色微晶方解石, 石笋 $\delta^{13}C$ 偏重。与地中海气候不同, 在湖北青天洞, 这里雨热同期, 夏季生物量与土壤 CO_2 产率高, 形成的石笋微层 $\delta^{13}C$ 比冬季偏轻[123]。

石笋 $\delta^{18}O$、$\delta^{13}C$、微量元素以及矿物结构等多指标结合的综合分析, 是准确解译石笋 $\delta^{13}C$ 气候环境意义, 并进行岩溶水文过程和岩溶石漠化重建的重要方法和途径[12, 111, 119, 127−128]。除此之外, 现代洞穴监测与模型模拟也有助于了解现代岩溶过程中各地球化学指标 (包括 $\delta^{13}C$) 的变化特征及其与地表环境 (气温、降水等)、土壤过程, 以及表层岩溶带水文条件的关系[14, 129−132]。国内已有多个洞穴开展相关监测工作, 包括芙蓉洞[14, 15, 133−134]、和尚洞[135−137]、珍珠洞[138]、鸡冠洞[139]、茅茅头大岩[140]、石花洞[141]、纳朵洞[142]、九天洞[143]、雪玉洞[129, 144]、凉风洞[145] 等。监测结果表明, 大气降水、温度、CO_2 来源、植被类型等会影响石笋 $\delta^{13}C$ 值[137, 146]。对芙蓉洞和鸡冠洞从植物、土壤、滴水和石笋的碳同位素监测结果表明, 碳同位素在迁移过程中不断富集, 并且敏感地响应当地水文条件变化[14, 139]。实验室模拟可在较短时间内观察碳酸钙沉积过程, 是探索石笋 $\delta^{13}C$ 环境意义的重要途径[147−148]。例如通过在实验室设置不同的溶液流动距离和时间, 模拟石笋生长过程, 发现在动力学过程影响下沉积的 $CaCO_3$ 同位素值有明显差别[149]。Riechelmann 等也通过对比不同滴率下方解石 $\delta^{13}C$ 的值, 认为滴率较低的情况下沉积的方解石 $\delta^{13}C$ 值更加偏重[98]。模拟结果也表明洞穴内部过程有可能引起碳酸钙 $\delta^{13}C$ 的变化, 这些研究成果有助于将气候环境信息从动力过程中剥离出来, 正确解释石笋 $\delta^{13}C$ 指示意义。

其次, 石笋 $\delta^{13}C$ 记录的代表性是石漠化演变历史重建中另一个需要关注的问题。一般认为, 石笋 $\delta^{13}C$ 以及微量元素等指标的变化, 更多指示的是洞穴上覆区域岩溶水文条件以及地表过程变化[11, 14−15, 150]。洞穴上覆区域与人类活动的区域在空间上有可能并不重合; 因此获取多空间分布的石笋记录, 有助于更准确地重建区域岩溶生态环境变化[108]。

最后, 即使在同一洞穴, 不同滴水点对地表环境和岩溶过程的响应也会有差异, 导致信号记录以及分辨率的不同, 对同一个气候环境事件的表达程度不同[30]。石笋记录的分辨率对于解释石笋代用指标的气候环境意义以及重建区域生态环境变化具有重要意义[151]。石漠化的发生和发展可能发生在年—十年际的时间尺度, 高分辨率的石笋记录有助于捕捉快速的环境变化信息。

4　结　论

现代洞穴监测表明洞穴滴水和现代沉积物中 $\delta^{13}C$ 主要受到地表生物过程以及表层岩溶带水文条件变化的影响。气候恶化和不合理的人类活动均可导致地表植被退化、水土流失、生物活动减弱、土壤

CO_2 产率降低、水岩相互作用时间延长等，这些生物和物理化学过程，可导致洞穴滴水中 $\delta^{13}C$ 偏重[57]。岩溶水是连接地表环境与洞穴石笋的纽带；石笋 $\delta^{13}C$ 记录了上覆植被、土壤，水文等生态环境信息，可以利用石笋 $\delta^{13}C$ 重建区域岩溶生态环境演变历史。已有研究证明，石笋 $\delta^{13}C$ 很好地记录了气候变化和人类活动共同触发的石漠化发生和扩展[108]。

今后研究中需要进一步加强现代洞穴监测，有助于准确厘清石笋中各地球化学指标和物理指标对地表环境的响应特征和机理。多个区域的洞穴石笋，以及同一洞穴多根石笋的高分辨率多指标记录和综合对比，有助于解决单一洞穴石笋记录与石漠化在空间上不一致的可能，并更加准确地重建区域生态环境和岩溶水文演变历史。

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Progress in reconstruction of karst rocky desertification by stalagmite $\delta^{13}C$

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Abstract The formation and evolution mechanism of karst rocky desertification is a scientific problem that has been paid increasing attention, and the ecological environment in karst areas is not only fragile, but also unstable. Therefore, the study of karst rocky desertification is of practical significance for the restoration of ecological environment in karst areas. Cave stalagmite $\delta^{13}C$ is affected by many factors and can respond sensitively to the changes of surface ecological environment and karst hydrological conditions. Hence, the use of stalagmites $\delta^{13}C$ on the study of evolution history of ecological environment in karst areas has become an important direction.

In this paper, we discuss the main factors affecting stalagmite $\delta^{13}C$ from two aspects, i.e., the overlying surface environment and cave deposition. Combining the results of modern cave monitoring with model simulation, we analyze the main factors and mechanisms affecting $\delta^{13}C$ in cave drop water and sediment. Under the influence of multiple factors, the environmental significance of stalagmites $\delta^{13}C$ has multiple implications. According to the published research results, in this paper, we summarize the indicative significance of stalagmite $\delta^{13}C$ from three aspects, different time scales, different regional distribution, and different cave sedimentary environments. In order to accurately interpret the environmental significance of stalagmite $\delta^{13}C$, we put forward the solutions-comprehensive analysis, modern monitoring and model simulation. In this paper, we discuss the concept, genesis, development process and environmental effects of karst rocky desertification, and analyze the close relationship between surface rocky desertification and stalagmite $\delta^{13}C$ records in caves. We also summarize published research results about the application of stalagmites $\delta^{13}C$ to the reconstruction of regional rocky desertification. Meanwhile, we discuss main problems faced in the current research, (1) How to interpret the indicative meaning of stalagmite $\delta^{13}C$ correctly? This problem is the premise that stalagmite $\delta^{13}C$ can be used to reconstruct the history of regional rocky desertification. (2) Spatially, the area of the overlying surface reflected by stalagmites $\delta^{13}C$ records is limited, so it is necessary for us to carefully consider whether the selected stalagmite region reflects the same spatial distribution as that of the study area, and whether it represents the environmental changes of the target study area, when using stalagmite $\delta^{13}C$ to reconstruct the evolution history of rocky desertification in a certain region. (3) Karst rocky desertification can develop rapidly on the decadal time scale, while a certain age error may occur in stalagmite dating. Can stalagmite $\delta^{13}C$ record sensitively record the changes of surface environment in such a short period and reconstruct the process of regional rocky desertification?

In order to accurately reconstruct the regional karst environment and the evolution history of rocky desertification, we put forward the following suggestions, (1) In order to avoid the uncertainty of stalagmite $\delta^{13}C$ in paleo-environment reconstruction, the comparative analysis of stalagmite $\delta^{13}C$ and $\delta^{18}O$, trace elements and mineral structure can be integrated with modern monitoring and model simulation to correctly interpret the indicative significance of stalagmite $\delta^{13}C$. On this basis, the karst hydrological process can be reconstructed more accurately and the evolution history of rocky desertification can be determined. (2) By comparing the evolution process of rocky desertification recorded by stalagmites from multiple caves in the study area and multiple stalagmites from the same cave, the regional representativeness of single stalagmite record can be reduced. (3) Multi-index stalagmite records with high resolution and high precision chronological control can accurately record the changes of the land surface environment during the rapid occurrence and development of the rocky desertification process.

Key words karst rocky desertification, cave stalagmites, stalagmites $\delta^{13}C$, paleoenvironmental reconstruction

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