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亚洲古季风变率和机制的洞穴石笋档案

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摘要 洞穴石笋气候档案具有深海沉积等长尺度记录和树轮日历年两种不同气候载体的特征, 开启了研究轨道尺度、千年尺度和年际气候变化三者联系的新窗口. 本文主要回顾了近20年来亚洲季风区石笋的高精度定年和气候代用指标等研究进展. 精确定年的石笋气候序列为米兰科维奇"轨道假说"解释低纬气候变化奠定了基础, 并有可能深入了解突变气候事件的驱动机制. 在此基础上, 讨论了目前学术界普遍关心的"中国石笋δ^{18}O信号解释"问题, 认为在千年尺度以上, 石笋同位素序列反映了季风气候控制下的干/湿变化过程. 跨越中布容事件的石笋记录有可能联系低纬岁差尺度水文循环与高纬冰盖过程, 将冰盖、季风、温室气体和生物地球化学过程置于高精度年代框架下, 研究其驱动与响应关系. 最后指出, 精确定年的石笋气候序列有可能成为大陆同位素气候层型, 并在解决当代全球变暖机制问题上发挥重要作用.

关键词 石笋档案, 季风气候, 岁差旋回, 高低纬气候联系, 晚第四纪

深海沉积、极地冰芯和黄土地层是古气候和古环境重建的三大支撑载体, 成为研究全球古气候变化过程和动力学机制的里程碑. 始于1964年的"深海钻探计划"(DSDP), 1982年开展的国际性大洋钻探计划(ODP), 使得深海沉积记录开启了解地球气候演化历史的大门. 先后诞生了经典的大陆冰量假说[1], 挑战传统4次冰期理论的深海同位素气候序列[2]和支持米兰科维奇气候旋回轨道驱动假说的证据[3]. 格陵兰冰芯提供了100 ka BP来气候突变事件过程和频率证据, 如Dansgaard/Oeschger旋回[4], 一直是古气候研究领域的热点, 并产生一系列气候突变的理论和假说. 南极冰芯是探索气候变化和温室气体相位联系的最好载体, 如覆盖过去4个冰期旋回的Vostok冰芯记录[5]. 中国黄土高原地层展示了第四纪气候变化的最直观的大陆记录[6], 并从中产生古季风理论[7]和发现亚洲腹地风尘堆积最早开始于20 Ma BP[8].

三大支撑载体奠定了当今全球变暖的长期气候演化背景. 与这些长尺度研究不同, 近来, 国际组织, 如政府间气候变化专门委员会(IPCC)越来越关注近千年气候变化. PAGES和CLIVAR等国际计划也将获取过去2 ka 来连续、高分辨自然记录作为工作重点之一. 目前, 能达到日历年要求的载体有珊瑚礁、树木年轮以及冰芯、湖泊、历史文献等. 在重建近千年来北半球温度序列中, 树轮资料占据相当大的比重[9,10]. 三大支撑载体中的冰芯由于分布于两极和高寒地区, 仅26个地区获得的32支冰芯可用于气候重建[10], 我国仅在青藏高原可获得屈指可数的冰芯记录[11]. 将近千年气候序列置于长期气候演化背景上考察, 有望在当今全球变暖机制上取得突破性进展. 然而, 在地质档案中寻找过去千年气候变化的"历史相似形"却非常困难, 原因是具有"自然时钟"特性的信息载体(如珊瑚礁层理、树木年轮、冰芯年层和

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湖泊纹泥等)在更久远的冰期-间冰期难以保存完好.

岩溶洞穴内发育的次生碳酸盐可保存丰富的气候环境信息, 其中, 石笋气候信号通过岩溶动力系统, 联系了四大圈层, 对当前的国际前沿科学, 如岩溶作用与大气CO_2的关系、全球碳循环过程的认识有重要作用. 从生长动力过程看, 石笋记录直接联系了大气降水和相关气候要素的变化, 故被称为雨水的"化石". 洞穴碳酸盐研究始于60年前[12], 但石笋古气候记录在2001年后才大量涌现, 并引起国际学术界高度关注[13]. 高精度定年的石笋记录不仅在三大支撑载体理论框架范围内有新的突破, 而其研究尺度已从千年精细到年际, 甚至季节变化, 在评估当今全球变暖的千年序列重建中有巨大发展潜力. 本文重点回顾近20年来亚洲洞穴石笋古气候研究进展, 讨论了石笋定年和气候代用指标的优势和问题, 分析了极地冰芯、深海沉积统一于石笋高精度时标上的可能性及其意义, 最后对未来石笋古气候研究方向提出了肤浅认识.

1 精确"时钟"

石笋精确"时钟"来源于Henderson[14]在*Science*上发表的一篇评论文章"Caving in to new chronologies." 该文评价了南京葫芦洞和贵州董哥洞石笋两个冰期旋回的千年尺度气候事件的U/Th定年研究成果, 认为高精度定年的石笋记录有可能弥补极地冰芯突变气候事件研究的不足. 正因为石笋的精确"时钟"作用, 在重建格陵兰冰芯400 ka BP来气候事件工作中, 可将相应事件年龄调谐到中国三宝洞石笋记录上[15].

铀系定年的重要里程碑是美国加州理工学院地球化学家Wasserburg等人[16]开创的同位素质谱技术. 其后, 测定海水和珊瑚U/Th同位素技术上的改进, 减小了样品量并将定年精度提高一个数量级[17,18]. U/Th半衰期测定精度也在不断提高[19,20], 特别是近期U/Th半衰期的精确标定, 使得湖北三宝洞石笋记录在500~600 ka BP时段与太阳辐射完美匹配[21]. 突破500~600 ka BP左右U/Th定年瓶颈的石笋记录, 不仅有可能审视中布容事件和同位素11阶段问题, 而且对长期争议的冰期终止点问题有新认识[22]. 需要关注的是, 冰期终止点2的三宝洞石笋记录呈现了复杂的多阶段演化特征[22], 其中包括海洋同位素的停止事件(Termination Ⅱ pause), 是联系海陆气候的重要标志. 该多阶段演化特征也反映了冰期终止点2存在不同驱动力, 需诊断其相对贡献.

建立于精确时钟的石笋记录在重建大气^{14}C浓度历史方面得到较好的应用. 树轮计年恢复的大气^{14}C浓度仅覆盖距今14 ka左右. 海相盆地纹层计数和珊瑚U/Th 定年以及湖泊纹泥将大气^{14}C记录有效延伸至50 ka BP[23~26]. 同时测定石笋U/Th和^{14}C年龄对这一时段大气^{14}C校准发挥了重要作用[27~31]. 然而, 上述重建数据随年龄增大而离散, 影响因素之一是石笋中死碳的校准问题. Southon等人[32]研究了南京葫芦洞石笋样品, 发现10~27 ka BP时段死碳的贡献相当稳定. 因此, 结合葫芦洞石笋高分辨率气候曲线, 有可能在重建14~50 ka BP时段的大气^{14}C历史中发挥更大作用.

U/Th定年的石笋记录很难达到日历年要求. 1960年, 石笋微层理的"年旋回性"得到^{14}C测年结果支持[33]. 与树轮生长机理相似, 在气候环境季节性变化显著区域, 洞穴石笋因季节沉积差异可形成微生长层[34~36]. 目前, 已经发现的纹层类型有荧光年层、可见年层、方解石/文石层耦、微量元素年层等[35~37]. 在地表环境下, 限制性环境因子相同, 不同树木形成的树轮宽度一致. 然而, 在同一个洞穴, 不同微环境会导致形成的石笋微层厚度不一致. 一般来说, 年层厚度作为气候信号输出端需要沉积校正[38].

刘东生等人[39]发现石花洞年层与北京地区旱涝指数相关, 证实洞穴碳酸盐微层可作为高分辨率古气候研究载体. 美国西南约4 ka洞穴石笋微层序列揭示的有效湿度变化与历史记录一致[40], 3~0.8 ka BP气候湿润、凉爽. 随后, 气候类型与现代类似, 仅在0.44~0.29 ka BP稍微湿润. 但Betancourt等人[41]发现该记录指示的雨量变化与当地树轮重建结果差异显著, 从而质疑石笋纹层的"年沉积性质", 由此引发了一场争议[42~44]. 然而, 在采集时, 美国瓜达卢佩山的石笋样品已停止发育, 且存在生长间断, 其年龄模式与树轮之间可能不完全吻合. 另外, 石笋微层记录的气候信号可能与以地表过程为主的树轮信号有本质区别.

验证石笋微层理的"年沉积性"一般手段有: 与放射性测年结果进行对比、在已知年龄的同位素事件层之间计层、洞穴监测或与模拟的累积速率对比[35,36]. 对于正在发育的石笋而言, 适合的测年方法有U/Th, ^{137}Cs, ^{210}Pb和^{14}C等. 研究表明, 对于近0.1 ka

以来的石笋材料, ^{210}Pb法[45,46]和^{137}Cs法[47,48]具有独特的优势, 同时, 高精度U/Th测年技术也可判辨年旋回微层理[49]. ^{14}C测年法在石笋中运用受到"死碳"干扰, 若在发育时段"死碳"贡献保持不变[50], 则^{14}C方法同样适于年轻石笋年代测定[51]. 影响石笋年层统计的一个重要方面是"缺年"和"伪年层", 由于各种测年方法存在误差, 很难通过放射性测年法解决. 在冰芯、湖泊纹泥及珊瑚研究中, 多参数对比方法对石笋年层研究具有启发意义. 因为石笋蕴含各种微量元素, 同样具有多参数分析潜力[52]. 石笋微层的氧、碳同位素[53,54]、微量元素[55~58]均可反映洞穴温度、水文条件季节性变化.

尽管石笋日历年表有待进一步完善, 近2 ka石笋气候序列重建将弥补树轮和冰芯材料空间覆盖度不足和代用指标的局限性, 有助于深入理解气候系统年际-年代际尺度的自然变率, 包括高铀石笋的^{230}Th定年[59,60]、连续年层计数[40,53,61~64]和季节性碳旋回确定的石笋年表[65]. 进一步发展"石笋微层年代学和气候学"理论和方法, 通过"历史相似形"的研究, 有可能区分当今全球变暖的自然和人为贡献.

2 气候信息的提取

石笋δ^{18}O是运用极为广泛的古气候指标之一, 蕴含着温度和降水变化信息. 依据现代降水量与同位素组成之间关系, Bar-Matthews等人[66]曾假定其在间冰期不变, 藉此推算当时古降水量水平, 但该假设前提尚需要进一步论证. Hu等人[67]运用贵州董哥洞[68]与湖北和尚洞石笋δ^{18}O记录残差定量评估全新世中国西南大气降水变化, 发现全新世适宜期大气降水比现代高8%. 影响该评估结果的一个重要因素是, 两记录时标精度差异可能导致对应的数据并非同一次降水结果. 而且, 现代观测发现, 降水量并不是大气降水同位素组成的主控因素[69,70]. δ^{18}O测温法一直处于发展中, 其中包裹体研究占有重要地位. 直接测试液相包裹体δ^{18}O发现[71], 13.5 ka BP以来秘鲁气温变化很小, 全新世期间对流降雨增加15%~30%. 然而, 自圈闭后, 固-液之间一直存在δ^{18}O交换, 使得初始降水同位素信号难以保存. 因石笋方解石中不含氢, 后续研究测试岩溶水中δD, 进而评估古温度变化[72]. 但包裹体不易保存、萃取难、分析误差大(详见文献[73]综述), 制约其在古温度重建中运用. 新近发展的"同位素团测温法"[74,75]通过测试含重同位素(^{13}C^{18}O^{16}O)CO_2分子丰度变化直接获取温度变化信息(简称为Δ47法). 相对于早期的碳酸盐古温度法, Δ47指标只与温度有关, 不需要了解古岩溶水δ^{18}O信息.

石笋δ^{13}C影响因素复杂, 在古气候、古环境研究中运用远不如δ^{18}O广泛. 一般认为, 千年尺度石笋δ^{13}C变化受控于当地植被类型、覆盖度、生物活动等区域环境变化[76~78], 间接反映气候信号. 在轨道尺度上, 南美石笋δ^{1}(~40 ka周期)变化呈现出与δ^{18}O(~20 ka万年周期)信号完全不同的周期特征[79], 说明以土壤过程为主的区域环境变化与大气水汽循环的驱动力不同. 在年际尺度上, 印度石笋研究发现, δ^{18}O和δ^{13}C及年层厚度同步正相关变化[53], 甚至可以反映ENSO活动[47]. 正是由于δ^{13}C对洞穴内部CO_2浓度等区域环境变化较敏感, 在某些年层不发育的石笋中, δ^{13}C季节旋回被用于精细时标研建[65,80].

年层厚度和灰度是石笋生长动力学和岩溶通道渗滤状况指标, 进而指示洞穴外部气候及当地环境变化. 在石笋发育过程中, 可溶性和非可溶性杂质随着石笋母液一起沉积, 这些物质在荧光激发下可发光[37,81]. 在欧洲, 这些暗色层耦形成被认为与冬季降水有关[82]. 北京石花洞石笋微层显微结构及年际变化分析显示, 地表气温(特别是夏季温)是影响灰度变化的重要因素[83,84], 其年际变化序列可作为近千年气温重建指标. 同时, 灰度的物质来源与洞穴上覆土壤带有机质产率有关[85], 从而可提取温度和降水变化等气候信息. 年层厚度的控制因子包含气候和非气候因素. Tan等人[61]发现, 北京石花洞石笋年层序列主控因素是暖季温度(5~8月), 经土壤-有机质-洞穴CO_2系统进一步放大, 据此重建2650年来北京暖季地面温变化. 欧洲洞穴现代观测显示, 年均温与生长速率之间的相关性可达0.63, 与滴水方解石浓度达0.61[34]. 在水量充足的年份, 多沉积暗色致密方解石[85]. 在器测期, 苏格兰西北洞穴石笋年层与NAO相关的冬季降水变化高度相关, 反映当地降水量对年层厚度变化主控作用[62], 进一步研究发现, 多个方解石层耦含有亚层, 这些亚层可能是携带有机质的春季融雪水造成[86]. 西班牙洞穴石笋岩相及同位素季节性变化显著, 浅色柱状方解石的δ^{13}C值较低, 发育于冬季; 而暗色微晶方解石的δ^{13}C值较高, 发育于夏季, 这些变化与洞穴CO_2分压的季节变化有关[58]. 母液是石笋发育的基础, 与大气降水量直接

相关，通过年层厚度序列研建可反演极端降水事件[87]及与降水有关的ENSO活动[88].

在洞穴次生碳酸盐发育过程中，地表或岩溶带微量元素Mg, Sr和Ba等以离子形式进入碳酸盐晶格，取代Ca^{2+}离子，其分配系数取决于温度、水文等变化[89]. 因此，这些元素浓度变化在某种程度上与气候、环境变化之间存在量化关系. 已有工作显示，在古环境研究中石笋微量元素在轨道尺度[90]、百年尺度[91]、甚至在季节变化[55~58]等方面显示出巨大潜力. Fairchild和Treble[52]总结了石笋微量元素研究进展，指出激光熔融ICP-MS和离子探针法对提高元素分析分辨率具有重要意义. 另外，高分子化石标志物[92,93]、酸溶有机质[94]等指标逐步应用于洞穴古环境重建.

3 石笋记录中季风气候变率和机制

自从Hays等人[3]验证了冰量变化周期与天文轨道参数基本吻合以来，米兰科维奇“轨道假说”成为解释古气候演化的流行学说. 太平洋-印度洋深海沉积和中国黄土地层等地质记录揭示了北半球高纬冰量变化对亚洲季风气候的主导控制作用. 理论上太阳辐射的岁差周期对低纬季风气候有显著影响，但其作用的过程和机理并不完全清楚，精确定年的石笋记录为解答这一问题提供了新的途径.

中国湖北神农架三宝洞石笋的高精度铀钍年代测定和高分辨率氧同位素分析结果，重建了最后2个冰期/间冰期旋回亚洲夏季风强度变化序列[95]. 精确定年的石笋记录发现季风与北半球7月太阳辐射变化基本同步，同时揭示了岁差旋回的季风气候与大气$\delta^{18}O_{atm}$(低纬生物生产力)有着成因上的联系. 其后，这一洞穴记录延伸至400 ka BP[22]，完整覆盖了4个冰期过程，具备了必要的重现性检验，揭示了季风演化的显著岁差周期特征，明显不同于海洋和黄土记录的10万年季风旋回. 所以，米兰科维奇单一触发机制并非完全控制低纬气候变化. 云南小白龙洞穴石笋记录覆盖了过去2个冰期旋回，其氧同位素波动可靠地反映了印度季风演化，在岁差时间尺度上与三宝洞石笋记录一致[96]. 来自巴西洞穴一支石笋完整地覆盖了过去120 ka以来气候记录，可靠的定年数据揭示了该地区季风降水与南半球中纬度2月太阳辐射呈同步变化[97]. 独立定年的季风记录有利于澄清目前国际上争议较大的科学问题，即轨道尺度亚洲季风的相位及驱动机制[98,99]. 正因为石笋记录在理解长期气候变化机制上的重要意义，日渐成为冰芯、黄土和深海沉积三大古气候支柱的另一重要支柱.

支持北大西洋冰漂事件与季风突变同步发生的证据来源于南京葫芦洞石笋记录[100]. 基于U/Th独立定年的葫芦洞石笋氧同位素，与格陵兰冰芯记录相互补充，已成为全球冰期古气候参比基准. Shackleton等人[101]依照葫芦洞石笋时标校正了格陵兰冰芯75~40 ka BP年龄，由此获得了SFCP2004时标. 其他若干洞穴记录[78,102]也证实了南京葫芦洞记录的可靠性. 故区域分布广、高精度定年的石笋时标有助于建立全球统一时标，进而理解晚第四纪气候变化动力学机制[14]. 不过，葫芦洞石笋记录年龄有待进一步完善，相关的工作有MIS3[103]和DO2[104]的年龄修正. 尽管高、低纬气候突变事件基本同步，但石笋记录的事件有明显不同特征[54,100,105,106]，其中，亚洲季风区石笋$\delta^{18}O$缓变显著，可能反映低纬季风与高纬温度在突变事件内部的路径和过程差异. 深入研究这一特征有助于回答Broecker[107]提出的冰期气候突变机制科学命题. 石笋记录也为全新世气候不稳定性提供了年龄证据，其中包括北大西洋发现的冰漂事件[108]和太阳黑子的联系问题[68,109]，但年龄的精度制约了这些精细的对比工作. “8.2 ka”事件的高精度年龄标定[110]和年层控制的事件结构研究[111,112]说明了北大西洋气候的重要作用.

4 讨论

4.1 中国石笋$\delta^{18}O$的气候意义

对于石笋氧同位素信号本质的认识和解释，最早开始于20世纪70年代. 在同位素平衡分馏情况下，石笋$\delta^{18}O$主要受控于洞穴滴水$\delta^{18}O$和洞穴温度的变化[113]. 由于洞穴温度控制的水-岩反应同位素分馏系数较小(−0.24‰/℃)，石笋$\delta^{18}O$主要受控于大气降水$\delta^{18}O$. 目前，仅在温度变化敏感区域，如欧洲石笋$\delta^{18}O$被认为是温度的代用指标[114]. 在热带地区或典型的印度季风控制区，石笋$\delta^{18}O$与雨量关系密切，主要反映了季风降水的变化[115].

南京葫芦洞研究表明，石笋$\delta^{18}O$主要受冬/夏季降水比率的影响，进而可以用来指代夏季风强弱[100]. 冰期时段，贵州董哥洞与南京葫芦洞石笋$\delta^{18}O$数值和相对振幅基本一致[116]，由此认为在冰期-间冰期尺

度上, $\delta^{18}O$的变化是水汽从源区向沉降地点传输在不同时期(间冰期、末次冰期和现代)的水汽剩余比不同所造成的. 最近2 ka以来, 万象洞石笋$\delta^{18}O$记录与历史文献资料重建的旱涝指数也具有良好的相关性, 说明在十年-年际尺度上夏季风强弱带来的降水量变化是影响东亚季风区石笋同位素组成的主要因素[59]. 根据贵州董哥洞、南京葫芦洞和神农架三宝洞石笋记录的重现性, Cheng等人[22]指出, 在轨道和千年尺度上石笋$\delta^{18}O$主要受控于夏季风降水量或者夏季风强度的影响, 具有广泛的区域意义和全球对比性. 从全球季风视角上认识, 千年和轨道尺度上中国石笋$\delta^{18}O$变化较可靠地反映了季风的基本特征[117].

然而对于中国石笋氧同位素信号也有不同的认识. Maher[118]发现中国南方与印度季风区石笋记录具有很好的一致性, 却与中国其他区域降水记录不一致. 由此认为中国南方石笋记录的并不是季风降水量的变化, 而是反映了水汽源的变化. 印度洋和印度季风区降水变化决定了东亚季风降水同位素组成, 石笋同位素可能记录了雨水同位素信号变化, 而与当地雨量无关, 该观点也得到中国内陆湖泊记录支持[119]. Clemens等人[120,121]认为中国石笋$\delta^{18}O$信号复杂, 可能受不同轨道相位的3种水汽来源影响, 而最终的石笋同位素记录是上述3种水汽混合结果. Dayem等人[122]根据大气环流模型(GCM)的模拟结果, 对中国石笋$\delta^{18}O$在轨道和千年尺度上反映夏季风强度及与之相关的降水量变化这一解释提出了质疑, 认为包括水汽源、水汽输送路径、水汽的凝结蒸发过程及不同的降雨类型诸多因素叠加或某个因素主控才是石笋$\delta^{18}O$变化的合理解释. H1事件的模式诊断认为南京葫芦洞降水$\delta^{18}O$主要反映了印度洋水汽源的控制作用[123]. Caley等人[124]应用全球气候模型分析了150 ka BP来亚洲季风降水同位素变化, 认为仅在轨道尺度上, 中国石笋$\delta^{18}O$可作为夏季风降水的有效代用指标. 然而, 另一数值模拟方法揭示了中国石笋$\delta^{18}O$可反映亚洲季风强度的变化[125].

完整理解季风区石笋氧同位素的气候意义有待今后深入研究, 但作为"雨水化石"的石笋氧同位素应能代表区域尺度降水演化过程. 在轨道尺度上, 中国季风石笋$\delta^{18}O$与冰芯气体$\delta^{18}O$两者存在高度一致性和内在机制联系[95], 并被证明时间上同步变化[126], 在理论上支持石笋氧同位素的季风气候解释. 基于印度洋季风降水量与$\delta^{18}O$高度耦合的观测事实, 云南小白龙洞穴与三宝洞石笋$\delta^{18}O$记录一致性证据[96]说明了东亚季风与印度洋季风降水具有相似的演化规律, 但东亚大陆石笋$\delta^{18}O$与降水量之间可能并不存在线性关系. 在千年尺度变率上, 已发表的冰期中国石笋$\delta^{18}O$在空间上基本一致[54,100,103,105], 显著的$\delta^{18}O$正漂移事件在年龄上对应北大西洋冰漂事件. 黄土高原地层研究表明[127]: 当北大西洋冰漂事件发生, 中国大陆显著干旱, 故夏季降水显著减少是石笋$\delta^{18}O$正漂移事件的最合理解释. 在全新世4.2 ka BP左右, 亚洲大陆的普遍干旱化已得到考古学和古气候学研究的证实[128], 无疑, 持续百年的"4.2 ka事件"的中国石笋$\delta^{18}O$记录[68]反映了区域尺度降水显著减少的季风气候特征.

对于更短尺度的石笋$\delta^{18}O$波动, 控制因素更为复杂. 理解和认识石笋$\delta^{18}O$机制成因必须追溯洞穴外部信号输入——大气降水$\delta^{18}O$变化. 早在1964年, Dansgaard[129]据瑞利分馏方程提出了大气降水氧同位素季节和地理分布模型, 认为高纬度地区影响降水稳定同位素组分变化的主控因子是温度, 在低纬度热带地区则是降水量, 中纬度地区受到温度和降水量双重影响. 全球现代降水同位素体系时空变化研究表明, 降水$\delta^{18}O$受到各种"量效应"的影响, 例如纬度、海拔、降雨量等因素. 大气降水$\delta^{18}O$在蒸发和冷凝时也存在温度效应($\delta^{18}O/\Delta T$), 在欧洲为0.59‰/℃, 在亚洲季风区为0.23‰/℃[130]. 尽管现代年度及季节雨量仅在500 km范围内变化一致[122], 但雨水同位素组成可在更大空间尺度上保持一致[131]. 现代热带太平洋和印度洋(亚洲季风降水源区)的海水同位素组成较为一致[132], 各沉降地点雨水同位素组成差异多归因于气候、传输路径等时空变化[133]. 近年来, 众多研究则关注大气降水$\delta^{18}O$信号与其气候模态背景联系(大气环流和气候型). 如厄尔尼诺时期太平洋中部对流雨的增加, 降水$\delta^{18}O$值较低[70,134,135], 经向环流增强与南极洲较高的大气降水$\delta^{18}O$值相对应[136~138]. 其他地区降水$\delta^{18}O$与大气环流的关系也有深入研究, 包括北极涛动和北大西洋涛动(AO/NAO)[139~143]、北美PNA指数[144]等.

现代洞穴过程监测有助于深入理解短尺度石笋$\delta^{18}O$波动意义. 目前有关洞穴现代观测工作报道主要有: 爱尔兰Crag洞3年观测[145]、澳大利亚Kooringa洞2.5年观测[146]、比利时Pere Noel洞6年观测[147]、法国Villas洞13年观测[148]、美国达拉斯地区洞穴3年观

测[149]和直布罗陀地区4年观测[58]等. 这些观测工作分别从不同角度较为详细地研究了洞穴滴水氧同位素和溶解无机碳(DIC)的碳同位素变化特征及其与洞穴温度、降水等因素的可能关系, 并通过对洞穴的水化学特征分析, 探讨了基岩溶解、方解石前期沉积效应、饱和度指数以及洞穴空气的季节性流动等因素对新生成碳酸盐沉积量以及氧、碳同位素的影响. 国内监测最早见于我国广西桂林洞穴滴水和降水观测[150]. 此后, 对贵州七星洞等多个洞穴[151]、北京石花洞[152]、重庆芙蓉洞[153]、云南仙人洞[154]和湖北和尚洞[57]进行了系统监测研究. 这些观测工作从不同角度研究了洞穴滴水氧同位素与洞穴温度、降水等因素的可能关系. 谭明[155]分析了中国季风区多个石笋记录, 认为年代际至百年尺度季风区石笋δ^{18}O反映了印度洋/太平洋海区的环流变化. 当印度洋海水和中东太平洋海水温度偏高时, 西太平洋副热带高压偏南西伸增强, 近源水汽(西太平洋水汽)比例增大, 降水δ^{18}O系统偏正, 石笋δ^{18}O记录也相应记录了这一信息. 作者进一步综合若干洞穴监测数据和近百年石笋记录, 指出中国季风区石笋氧同位素可能反映了ENSO模态的特征[156].

4.2 低纬岁差与高纬冰盖信号的联系

低纬岁差信号广泛见于深海记录中, 如印度洋MD900963深海钻孔岩芯260 ka BP以来深海沉积物颗石藻中*F. profunda*百分比[157]、地中海530 ka BP以来腐泥质地层标志和δ^{18}O记录[158]、赤道大西洋深海沉积物500 ka BP以来动物化石组合记录[159]和南非比勒陀尼亚闭合盆地200 ka BP以来沉积物<20 μm组分百分比记录[160]等. 不可否认, 持有低纬驱动假说的学者[161,162]有其重要的地质证据和理论依据. 但关于低纬岁差和高纬冰盖信号的相位联系摆脱不了海洋沉积SPECMAP年龄模式. 在SPECMAP年龄模式制约下, 印度洋和东亚季风岁差周期滞后于7月北半球太阳辐射[163~168].

尽管中国石笋氧同位素信号有不同的解释, 但在更广泛意义上可理解为低纬岁差水文循环信号, 在相位上服从7月65°N太阳辐射[95]. 因为7月才是冰雪覆盖面积最少, 最有利地表吸收太阳辐射的时期. 现代观测资料也表明7月为陆地最热期[169], 因此两者之间的零相位关系有其合理性. 米兰科维奇理论来源于19世纪James Croll (1821~1890)提出的冰期天文轨道假说. Croll强调岁差的重要性, 认为南北半球气候在岁差尺度上呈现反相位关系, 中国石笋记录和南半球巴西洞穴记录[97]的反相位关系在一定程度上验证了Croll假说. 若SPECMAP年龄模式可靠, 则中国石笋记录是对低纬驱动假说的有力支持.

依据葫芦洞得到的北大西洋冰漂事件与季风突变同步发生证据[100], Cheng等人[22]利用三宝洞石笋记录与ODP980孔冰漂事件[170]的联系, 重建了最近4个冰消过程, 比SPECMAP年龄老3 ka左右[22]. 无独有偶, Grant等人[171]重新测定了已发表的东地中海Soreq洞穴石笋[66]年龄, 基于海-陆氧同位素耦合机制, 对代表冰量变化的红海LC21孔浮游有孔虫δ^{18}O[172]进行年龄调谐, 发现过去150 ka来冰量变化高度耦合于南极气温变化, 也比SPECMAP年龄老3 ka左右. 上述工作说明高纬冰盖与7月65°N太阳辐射同步, 动摇了SPECMAP关于驱动与响应的理论基础[173].

改进的高纬冰盖消长过程年代模式说明, 大气CO_2浓度的升高通过气候系统的强反馈机制直接驱动冰消过程. 但由此带来的科学问题是为什么大气CO_2是冰盖消融的关键因素, 而其本身又同时受到冰盖消融的驱动[174]? 从海洋See-saw理论模式分析, 在冰消初期, 北大西洋径向环流总是经历重大调整(如距今17 ka左右的“神秘期”). 由此, 在最近800 ka来每个Termination南极温度记录中出现高于现今温度、持续达1~2 ka温暖期(WPTs)[175]. WPTs与大气CO_2同步发生, 比冰盖消融过程早1~2 ka. 从这点意义讲, 较早的冰盖消融过程是有疑问的, 或许是因为ODP980孔冰漂事件的分辨率不够.

南极Vostok冰芯$\delta^{18}O_{atm}$的变化是一个纯粹的岁差信号, 十分类似于65°N夏季太阳辐射曲线[5], 其变率反映了海洋和陆地的生产力相对贡献[176]. 由于$\delta^{18}O_{atm}$主要来源于海洋生物对海水δ^{18}O的光合和呼吸作用, 不仅反映了生物地球化学循环过程, 而且与全球冰量有关. Bender等人[177]发现末次冰消期南极Dome C冰芯气泡$\delta^{18}O_{atm}$与海水$\delta^{18}O_{sw}$有一致的变化特征. 因此认为, 尽管有各种复杂的分馏过程影响大气$\delta^{18}O_{atm}$, 但是其主要还是受北半球冰盖变化控制, 这也使得使用$\delta^{18}O_{atm}$联系冰芯与海洋时标成为可能. Shackleton[178]将$\delta^{18}O_{atm}$信号滞后冰量1 ka, 推导出大气CO_2与全球冰量的相位关系, 并认为底栖有孔虫δ^{18}O包含很强的深海温度信号, 修正了1967年他本

人提出的观点. 这一工作的问题之一是$\delta^{18}O_{atm}$的年龄不确定, 现有CH_4和N_2两种不同年龄模式, 相位差2~3 ka[179]. Severinghaus等人[126]发现南极冰芯高分辨$\delta^{18}O_{atm}$记录与中国石笋记录在冰期事件尺度甚至在“8.2 ka”事件上存在一一对应关系, 由此说明生物地球化学过程与低纬水文循环之间因果联系. 现有中国石笋$\delta^{18}O$记录连续覆盖了过去640 ka(未发表), 与$\delta^{18}O_{atm}$记录高度一致. 应用南极冰芯$\delta^{18}O_{atm}$和高分辨率δD记录中的千年尺度事件, 将有可能联系高纬冰盖、季风、生物圈和大气CO_2等不同的气候变化和驱动要素, 并在精确年龄框架下讨论太阳辐射如何诱发地球气候变化和一系列正负反馈机制, 其中包括长期困惑学术界的氧同位素11阶段和中布容事件的难题.

5 结语

极地冰芯、深海沉积氧同位素在过去全球变化研究中占据先导地位, 其本质原因是极地冰芯、深海沉积氧同位素记录在区域甚至全球范围具有高度一致性. 已发表的亚洲季风区石笋数据为研究大陆沉积载体中氧同位素古气候意义提供了良好的契机. 亚洲大尺度季风环流和输送过程特征决定了水汽氧同位素的源/汇关系, 这从阿曼-贵州董歌洞-湖北石笋全新世氧同位素记录得到验证[180]. 季风气候及其降水同位素的较大季节性反差($\delta^{18}O$值波幅在4‰以上)决定了亚洲大陆大部分区域石笋氧同位素对气候响应的继承性和敏感性, 完全有可能建立大陆沉积载体高分辨率氧同位素气候层型曲线.

全球气候变暖是当前国内外科学研究的热点问题. 过去2 ka气候序列重建是诊断全球气候变暖的基本途径, 尽管“石笋微层年代学和气候学”处于萌芽期, 但石笋与树轮等其他材料相比具有一些潜在优势: (1) 石笋微层单序列长度通常达数千年, 如北京石花洞[61]、美国瓜达洛浦洞[40]; (2) 石笋年层序列适于保存低频气候信号[9,181,182], 避免了树轮低频信号提取的幅度偏差问题和生命效应问题; (3) 连续数千年长度的石笋微层不仅见于盛冰期[104], 也发现于200 ka BP的间冰期[183]. 这就有能研究与过去2 ka气候的历史相似形, 从而辨识当前全球增暖的自然和人为驱动贡献, 为气候模拟和未来预测提供科学依据.

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Speleothem records of Asian paleomonsoon variability and mechanisms

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In the last 20 years, speleothems have been increasingly applied in paleoclimate studies, and become one of the most important geologic records like oceanic sediments, loess deposits, and ice cores. Critically, the stalagmite archives from Asian monsoon (AM) area provide an insight into the mechanisms behind low-latitude precessional hydroclimate and abrupt AM changes in line with millennial-scale Greenland temperature variability. These climate records from the Asian continent interiors, well-duplicated over broad regions, extend back to 600 ka BP, and have been widely accepted as a North Hemisphere template for synchronizing global climate records. Here we review these independently- and precisely-dated stalagmite records from those climatically- and environmentally-sensitive locations and discuss various climate factors that control AM variability from annual to orbital time scales. As the speleothems are often annually laminated that extend back into a long growth history, it is possible to understand mechanisms of millennial- to annual-scale climate changes under different Earth's climatic boundaries. By nature, these calcite records are instrumental in resolving the climate background for natural variability of current climate, abrupt climate changes in the distant time, and even a prediction for future climate.

As an important sub-system of global climate, the AM climate characterizes distinct seasonal cycle of wind directions, temperature, and precipitation. It can link tropical ocean processes and even the Southern Ocean via southerly air masses, and high northern latitudes through northerly air parcels. Hence, the AM record is ideal for evaluating the forcing-response correlation between hemispheric climates. On the basis of reviewing various stalagmite proxies (i.e., δ^{18}O, δ^{13}C, trace element, annual layer, fluid inclusions, etc.) for parameters of AM climate, we discuss a potential to understand sources and trajectories of AM circulations by use of the speleothem oxygen isotope over broad regions. However, the interpretation of stable oxygen isotopes, especially a rainfall amount effect, frequently used in Chinese speleothem records remains a topic of intense debate. Considering the sources and sinks of atmospheric hydrological circulations, this review addresses the progress of stalagmite-based Asian paleomonsoon studies and the implication of Chinese speleothem δ^{18}O signal. As a proxy to track atmospheric moisture isotopic compositions, millennial to centennial changes of the speleothem δ^{18}O is supported by the atmospheric δ^{18}O record trapped in ice-cores. Thus, it is likely that at orbital to millennial scales, the stalagmite isotopic sequences from the Asian monsoon area can represent the alternation of aridity/ moisture associated with Asian monsoon changes.

Constrained by high-precision U/Th dates, the speleothem records, covering the Mid-Brunhes Event, provide a chronological benchmark to link low-latitude hydrological circulations and high-latitude ice-sheet processes, and hence can synchronize oceanic, atmospheric, and ice-sheet changes. Once applied a unified time scale, those speleothem records can further evaluate the relationship between changes in continental ice sheets, low-latitude monsoon climates, greenhouse gasses, and biogeochemical processes. In previous literatures, the timing and frequency of these calcite δ^{18}O records have been widely consolidated by other archives within and outside the AM area. This implicates that the climate signals contained in Chinese speleothems can sensitively capture North Hemisphere climate changes via reorganization of atmospheric circulations. Hence, it is possible that stalagmite isotopic sequences can be used to reconstruct a stratotype for terrestrial isotopic climates, and help resolve the mechanism of current global warming.

stalagmite records, Asian monsoon climates, precessional cycle, high- and low-latitude climate teleconnection, late Quaternary

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