

福建仙云洞石笋记录的 Heinrich 1 事件突变特征

崔梦月¹, 肖海燕¹, 孙晓双¹, 洪晖¹, 姜修洋^{1,2*}, 蔡炳贵^{1,2*}

1. 福建师范大学地理科学学院, 湿润亚热带生态地理过程教育部重点实验室, 福州 350007;

2. 福建师范大学地理研究所, 福州 350007

* 联系人, E-mail: xyjiang@fjnu.edu.cn; bingguicai@qq.com

2017-03-13 收稿, 2017-05-05 修回, 2017-05-08 接受, 2017-06-26 网络版发表

国家自然科学基金(41672170, U1405231)、福建省自然科学基金(2017J01654)和福建省高校杰出青年科研人才培育计划资助

摘要 Heinrich 1 事件(H1事件)是末次冰期一系列冰漂碎屑事件中最为突出的寒冷事件. 本文基于闽西连城县仙云洞石笋(编号: XYIV-3)8个²³⁰Th年龄和256个氧同位素结果, 获得了16.8~15.2 ka BP期间平均分辨率达7 a的东亚夏季风演变序列. 该石笋氧同位素记录最为显著的特征是在16.3~16.1 ka BP时段出现两个阶段的偏正过程, 振幅达1.8‰, 指示了一次显著的弱季风事件突变过程, 对应于北大西洋显著的H1事件. 与具有年层时标的南京葫芦洞和神农架青天洞石笋记录对比发现, 尽管在定年误差范围内3个洞穴的石笋记录都捕捉到了H1事件的这次突变过程, 但我国东南仙云洞记录的H1突变过程的时间(~260 a)明显比长江中下游的青天洞(18 a)和葫芦洞(19 a)长得多, 表现出显著的差异响应. 分析表明, 在北半球突变事件诱发后, 热带西太平洋的海气过程有可能是造成这种差异响应的原因.

关键词 H1 事件, 石笋, 东亚季风, 仙云洞

北大西洋冰漂碎屑事件(Heinrich事件, H事件)是发生在末次冰期的一系列千年尺度气候突变事件^[1], 事件导致全球海-气系统快速重组, 对全球气候影响深远^[2]. H1事件是末次冰期6个典型冰漂碎屑事件中最为突出的寒冷事件, 当时极地的海表冷水团可抵达现今亚热带海洋, 其影响范围甚至波及到40°S海域^[3,4]. H1时, 北半球冰盖融化使大量淡水汇入大西洋, 导致北大西洋径向环流(AMOC)减弱^[5], 赤道辐合带(ITCZ)南移^[6], 热带大西洋变干^[7,8], 中低纬非洲季风减弱^[9], 阿拉伯半岛变干^[10], 东亚夏季风减弱^[11], 与之相反, 南美季风则增强^[12], 南极温度升高^[13], 南北半球呈现“跷跷板”变化模式.

我国泥炭^[14]、黄土-古土壤^[15]、盆地沉积^[16]等地质载体都记录了H1事件. H1事件发生时, 东亚夏季风减弱, 温度和降水甚至低于末次盛冰期^[15]. 但由

于各载体所用指标不同, 定年精度和分辨率也不同, 很难将各记录进行细节对比. 高分辨率的南京葫芦洞^[17]、贵州衙门洞^[18]、神农架青天洞^[19]和豫西东石崖洞^[20]等石笋 $\delta^{18}\text{O}$ 记录更为详细地记录了H1事件发生时东亚夏季风的变化过程, 但不同记录所揭示的突变过程, 在发生时间、持续时间和振荡幅度等特征上均存在一定的差异, 需要定年可靠、高分辨率的记录进一步确定不同区域H1突变事件的响应模式(突变或缓变), 为研究此类事件的动力学机制提供参考.

目前, 对东亚季风区石笋 $\delta^{18}\text{O}$ 所指示的气候意义存在争议. 其中, Pausata等人^[21]通过数值模拟结果, 提出H1事件发生时东亚季风区的降水氧同位素变化受控于印度季风降水的变化, 进而提出中国季风区石笋氧同位素记录的是印度季风降水变化. 然而这一观点假设一直存在争议. 例如, Tan^[22]就通过

引用格式: 崔梦月, 肖海燕, 孙晓双, 等. 福建仙云洞石笋记录的 Heinrich 1 事件突变特征. 科学通报, 2017, 62: 3078–3088

Cui M Y, Xiao H Y, Sun X S, et al. Characteristics of the Heinrich 1 abrupt climate event inferred from a speleothem record from Xianyun Cave, Fujian Province (in Chinese). Chin Sci Bull, 2017, 62: 3078–3088, doi: 10.1360/N972017-00091

对比中国中部和印度地区的近百年石笋氧同位素记录,从年代际尺度上对这一观点提出了质疑.当前,我国对H1事件的石笋记录研究主要集中在受印度夏季风和东亚夏季风双重影响的西南地区 and 受东亚夏季风影响的长江中下游地区,缺乏对我国东南部受典型东亚夏季风影响区域的研究.因此,来自福建的石笋氧同位素序列,其记录的H1气候突变特征,能够为验证这一假设的正确与否提供直接的证据.

本文根据福建仙云洞石笋8个高精度的 ^{230}Th 年龄及256个稳定氧同位素数据获得了16.8~15.2 ka BP平均分辨率达7 a的 $\delta^{18}\text{O}$ 变化序列,揭示出我国东南部典型东亚季风区H1事件的变化特征.通过与已有高分辨率石笋记录和高低纬古气候记录对比,探讨其内部特征及可能的影响机制.

1 材料与方法

仙云洞(116°59'E, 25°33'N; 海拔970 m)位于福建省连城县赖源乡(图1),为3层阶状廊道式溶洞,该洞长约1200 m,上覆30~50 m二叠纪石灰岩.洞穴封闭性较好,尤其是第2层和第3层通风不畅,相对湿度接近100%(2016年5~8月测).洞内滴水点众多,次生碳酸盐沉积物发育良好.仙云洞位于典型的东亚季风区,全年气候温和,无霜期长,雨量充沛,年平均气温为19~21℃,降水量为1600~1800 mm,主要集中于4~10月.洞内实测温度为17.5℃,与洞外年均温较为接近.

研究石笋(编号:XYIV-3)采集于仙云洞底层(第3层),样品呈长柱状,总长260 mm,底部直径约80 mm(图2).沿生长轴切开,除顶部0~20 mm存在较多溶孔之外,其余部分岩性较为均一,无明显的生长间

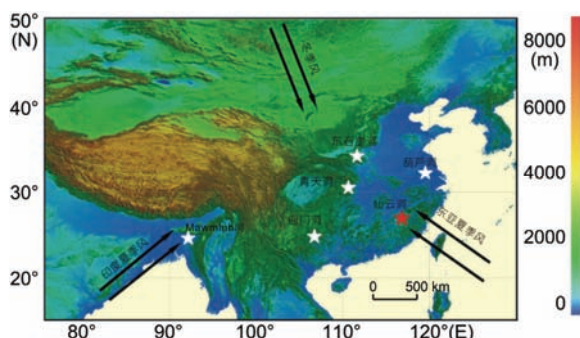


图1 仙云洞地理位置图

Figure 1 Location of the Xianyun Cave (red star)

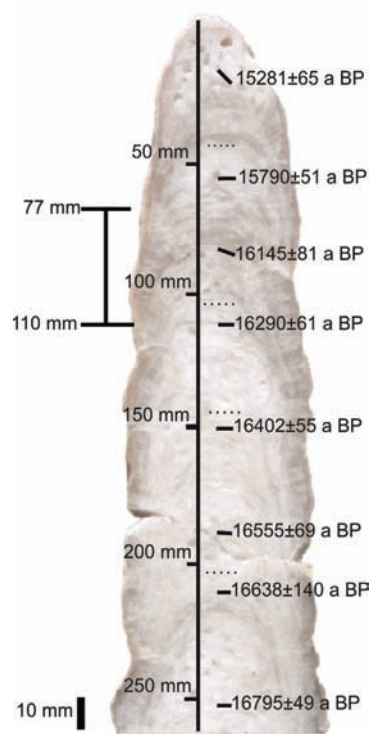


图2 仙云洞XYIV-3 石笋抛光面图. 黑色线为测年点及测年结果;黑点为Hendy-Test采样点;77~110 mm表示H1事件突变过程层段

Figure 2 Photos for the sample XYIV-3 from Xianyun Cave, Southeast China. The black rectangles indicate the positions of dated sub-samples. 77~110 mm represents the layer of the H1 abrupt climate changes

断层(图2).

用直径0.9 mm的钻头在石笋抛光面上共钻取了8个样品用于 ^{230}Th 定年(图2),分析仪器为MC-ICP-MS Neptune,方法参照Shen等人^[23],由台湾大学高精度质谱与环境变迁实验室测试完成.年龄分析误差为 $\pm 2\sigma$,结果见表1.同时,用直径0.5 mm的钻头共采集了256个样品用于氧碳同位素测试,采样间隔为1 mm.采用连续流Gasbench装置与Finnigan MAT-253型质谱仪联机测试,每9个样品加测一个标准样品(NBS-19),结果以 $\delta^{18}\text{O}$ (VPDB标准)表示,计算公式为 $\delta^{18}\text{O} = [({}^{18}\text{O}/{}^{16}\text{O}_{\text{样品}})/({}^{18}\text{O}/{}^{16}\text{O}_{\text{标准}}) - 1] \times 1000$,分析误差($\pm 2\sigma$)优于0.06‰,由福建师范大学同位素实验室测试.

2 结果

2.1 年龄模式

石笋XYIV-3的U, Th同位素组分和 ^{230}Th 年龄测试结果见表1.定年结果显示XYIV-3样品 ^{238}U 含量较

表1 仙云洞石笋XYIV-3的²³⁰Th测年结果^{a)}

Table 1 ²³⁰Th dating results for stalagmites XYIV-3 from Xianyun Cave

样品号 (深度)	²³⁸ U (ppb)	²³² Th (ppt)	²³⁰ Th/ ²³⁸ U (活度比)	δ ²³⁴ U (测量值)	δ ²³⁴ U _{初始值} (校正值)	²³⁰ Th年龄 (a, 未校正值)	²³⁰ Th年龄 (a BP, 校正值)
XYIV-3-15	1437±1	457±10	0.2300±0.0009	736±2	769±2	15350±65	15281±65
XYIV-3-57	1387±1	451±8	0.2321±0.0007	699±2	731±2	15860±51	15790±51
XYIV-3-86	1409±1	2478±15	0.2378±0.0011	703±2	736±2	16237±80	16145±81
XYIV-3-110	1530±1	1319±11	0.2418±0.0008	718±2	752±2	16368±61	16290±61
XYIV-3-151	1366±1	606±9	0.2436±0.0007	721±2	755±2	16474±55	16402±55
XYIV-3-185	2046±2	699±12	0.2422±0.0009	696±2	730±2	16625±69	16555±69
XYIV-3-204	1970±2	914±14	0.2430±0.0019	694±2	728±2	16710±140	16638±140
XYIV-3-251	1361±1	335±11	0.2468±0.0006	706±2	740±2	16864±49	16795±49

a) $\lambda_{230}=9.1577\times10^{-6}\text{ a}^{-1}$; $\lambda_{234}=2.8263\times10^{-6}\text{ a}^{-1}$; $\lambda_{238}=1.55125\times10^{-10}\text{ a}^{-1}$; $\delta^{234}\text{U}=[(^{234}\text{U}/^{238}\text{U})_{\text{活度比}}-1]\times1000$; $\delta^{234}\text{U}_{\text{初始值}}$ 是根据铀钍年龄获得, 即 $\delta^{234}\text{U}_{\text{初始值}}=\delta^{234}\text{U}_{\text{测量值}}\times e^{\lambda_{234}\times T}$; 校正铀钍年龄假设初始的²³⁰Th/²³²Th原子比为 $(4\pm2)\times10^{-6}$. a BP为相对于公元1950年

高(1.4~2.0 ppm), ²³²Th的含量低(0.3~2.5 ppb), ²³⁰Th定年的精度整体较高, 测年误差多在±50~±81 a之间, 仅有一个误差较大(±140 a), 所有年龄符合石笋生长层序. 年代标尺采用线性内插或外推法, 即在15~251 mm层段采用相邻测年点间线性内插法, 在5~15和251~260 mm层段采用外推法, 从而建立了16.8~15.2 ka BP时段的年代标尺. 从石笋年龄-深度曲线图(图3)可以看出, 在251~86 mm层段, 石笋生长速率较快, 约0.26 mm/a; 在86 mm以上层段, 生长速率相对缓慢, 为0.08 mm/a. 根据氧同位素分析的采样间隔, 平均分辨率达7 a.

2.2 同位素平衡分馏沉积检验

在石笋氧同位素古气候重建中, 判断碳酸盐与母液之间是否达到同位素平衡分馏是解释石笋δ¹⁸O气候意义的前提. 根据Hendy-Test检验准则^[24], 选取了4个不同生长层, 每个生长层方向以2 mm间距取5个样品进行同位素分析. 分析结果(图4)显示4个层位的δ¹⁸O值基本一致, 其标准差都落在0.04~0.1范围内. 各层位δ¹⁸O和δ¹³C之间无显著的相关性. 另外, 在整个石笋垂直生长轴上, δ¹⁸O和δ¹³C之间相关系数(r)仅为0.12, 没有明显的相关关系. 上述结果说明石笋XYIV-3受动力分馏作用影响较小, 接近同位素分馏平衡状态.

2.3 石笋δ¹⁸O序列

仙云洞石笋δ¹⁸O记录随时间变化序列见图5所示. δ¹⁸O时间序列整体可分成3个时期(图5(c)): 16.8~

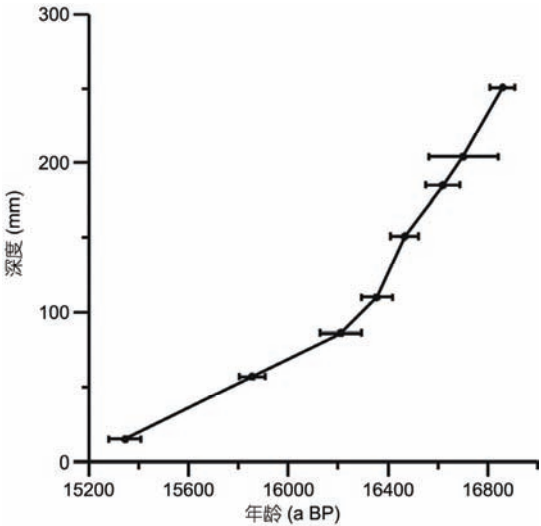


图3 仙云洞石笋XYIV-3年龄-深度曲线. 误差棒表示石笋²³⁰Th测年点及测年误差(±2σ)

Figure 3 XYIV-3 ²³⁰Th dating model from Xianyun Cave. Error bars represent the dating points and dating errors

16.3 ka BP, δ¹⁸O值整体相对偏负, 在-6.38‰~-5.01‰间波动, 平均值为-5.74‰; 16.3~16.1 ka BP期间δ¹⁸O值快速正偏, 变化范围为-6.38‰~-4.62‰, 振幅达1.8‰, 期间呈现出两个阶段的偏正过程, 为H1事件的突变阶段; 16.1~15.2 ka BP时期δ¹⁸O值缓慢负偏, 在-4.77‰~-5.69‰变化, 平均值为-5.30‰.

3 讨论

3.1 仙云洞石笋氧同位素的指示意义

亚洲夏季风存在3个子系统: 印度夏季风(ISM)、

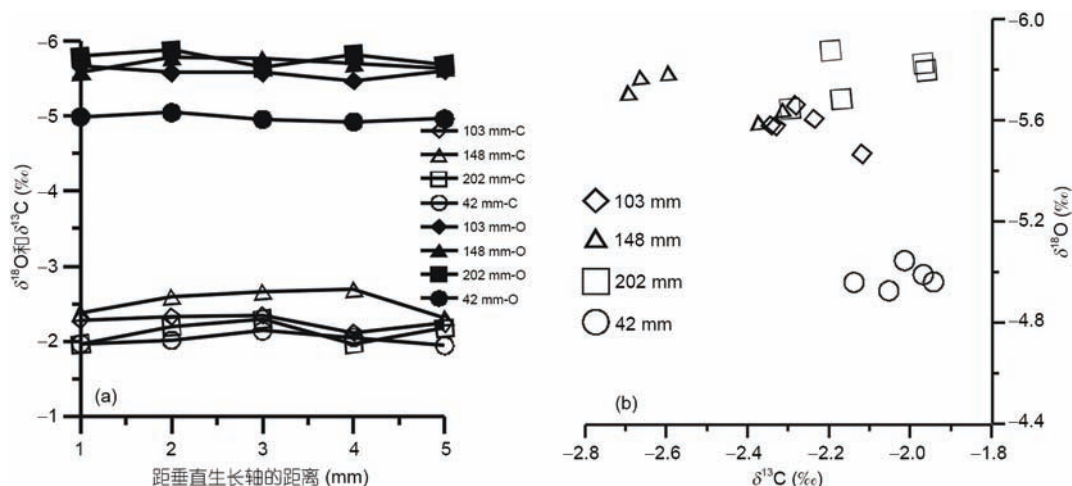


图4 仙云洞石笋XYIV-3 Hندی-text结果. (a) 距顶不同深度各层位的 $\delta^{18}\text{O}$ 和 $\delta^{13}\text{C}$ 值; (b) 各层位 $\delta^{18}\text{O}$ 和 $\delta^{13}\text{C}$ 的关系

Figure 4 Hندی-tests along four growth layers of XYIV-3. (a) The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variability within growth layers varies; (b) plots of $\delta^{18}\text{O}$ versus $\delta^{13}\text{C}$ for coeval subsamples

东亚夏季风(EASM)和西北太平洋夏季风(WNPSM),其中ISM和WNPSM属于热带季风系统,而EASM则处于热带和亚热带季风系统的交汇地带^[27].影响属于热带季风系统的印度夏季风变化的因素较为单一,水汽主要源自于印度洋,该区的石笋 $\delta^{18}\text{O}$ 与降水量关系密切^[28,29].相对而言,EASM地区的降水 $\delta^{18}\text{O}$ 受不同的水汽来源(印度洋和热带西太平洋等)的影响^[30],其变化较为复杂,该区石笋 $\delta^{18}\text{O}$ 的气候意义尚存在较大争议.

南京葫芦洞研究表明,石笋 $\delta^{18}\text{O}$ 主要受冬/夏季降水比率的影响^[11].在冰期-间冰期尺度上,中国南方石笋 $\delta^{18}\text{O}$ 的变化指代水汽团在热带印度洋-太平洋和洞穴地点之间运移过程的水汽剩余比^[31].最近1810年以来的万象洞石笋 $\delta^{18}\text{O}$ 记录与历史文献资料重建的旱涝指数具有良好的相关性,说明在十年-年际尺度上夏季风强弱引起的降水量变化是影响东亚季风西北边缘区石笋 $\delta^{18}\text{O}$ 组成的主要因素^[32].Cheng等人^[33]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,指出中国季风区石笋 $\delta^{18}\text{O}$ 不同于印度季风的降水量效应,在轨道和千年尺度上主要反映了夏季风降水或者夏季风强度.但是,对于东亚季风区石笋 $\delta^{18}\text{O}$ 指示夏季风强度或者夏季风降水这一解释也有不同的认识.Maher^[34]发现中国南方石笋记录与印度季风区石笋记录具有很好的一致性,却与中国季风区降水记录不一致,由此认为中国南方石笋记录并不是反映季风降水量的变化,而是反

映了水汽源的变化.谭明^[35]分析了中国季风区多个石笋记录,并结合气象观测资料,提出了环流效应.而对于H1事件的模拟诊断认为东亚季风区的氧同位素变化受控于印度季风降水量的变化,与水汽来源无关^[21].Dayem等人^[36]根据GCM的模拟结果,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水类型诸多因素叠加或某个因素主控才是石笋 $\delta^{18}\text{O}$ 变化的合理解释.

尽管存在上述争议,但东亚季风区内各洞穴石笋 $\delta^{18}\text{O}$ 记录在轨道-千年尺度具有大范围的区域一致性,说明该区石笋 $\delta^{18}\text{O}$ 记录最有可能是反映了夏季风强度,具有全球性意义.最近,Cheng等人^[37]指出EASM地区石笋 $\delta^{18}\text{O}$ 值变化一般指示平均气候状态下的夏季风强度变化,即 $\delta^{18}\text{O}$ 值偏正指示夏季风减弱,反之亦然.此解释也得到模型研究结果的支持^[38].基于年层时间标尺的葫芦洞和青天洞石笋 $\delta^{18}\text{O}$ 记录在百年甚至更短时间尺度上的一致性变化,以及 $\delta^{18}\text{O}$ 和纹层厚度变化的一致性,支持东亚石笋 $\delta^{18}\text{O}$ 能够反映东亚夏季风强度变化的解释^[19].对南京葫芦洞生长于盛冰期的一支石笋多指标($\delta^{18}\text{O}$ 、纹层厚度、灰度和Sr/Ca等)分析,进一步支持东亚季风区石笋 $\delta^{18}\text{O}$ 反映东亚季风强度变化^[39].

与已发表的南京葫芦洞石笋^[17]和神农架青天洞^[19]石笋 $\delta^{18}\text{O}$ 记录对比发现,仙云洞石笋 $\delta^{18}\text{O}$ 记录与上述洞穴石笋 $\delta^{18}\text{O}$ 记录千年尺度气候事件上都表现出整体一致的变化特征:在~16.2 ka BP时 $\delta^{18}\text{O}$ 值

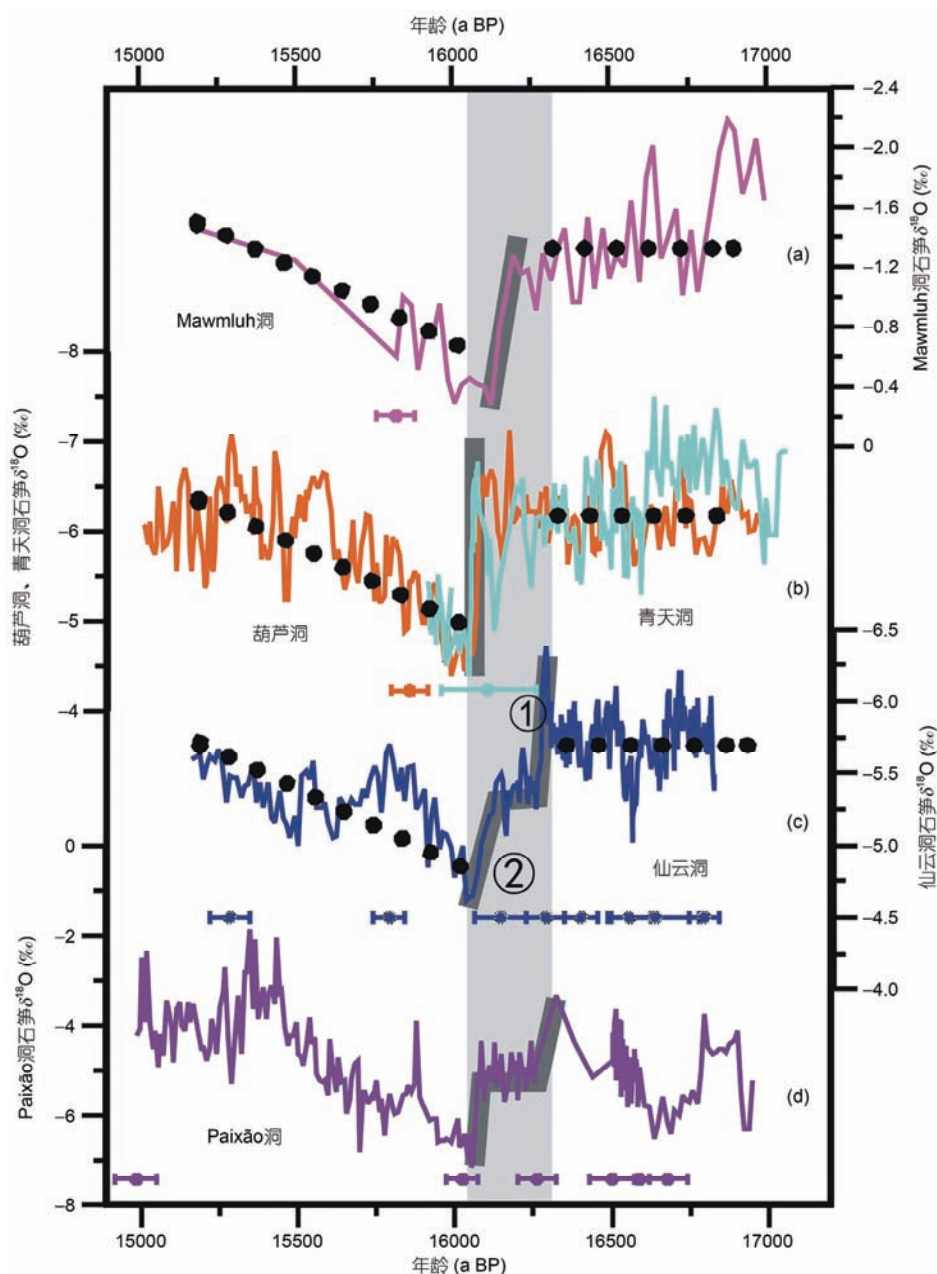


图5 H1突变阶段不同洞穴记录的对比。(a) 印度Mawmluh洞石笋 $\delta^{18}\text{O}$ 记录^[25]；(b) 葫芦洞石笋 $\delta^{18}\text{O}$ 记录(橘黄色)^[17]，青天洞石笋 $\delta^{18}\text{O}$ 记录(天蓝色)^[19]；(c) 仙云洞石笋 $\delta^{18}\text{O}$ 记录；(d) 巴西Paixão洞石笋 $\delta^{18}\text{O}$ 记录^[26]；不同颜色的误差棒为各自石笋记录的测年点及误差($\pm 2\sigma$)；深灰色粗线表示各记录H1时期的突变过程

Figure 5 Comparison of $\delta^{18}\text{O}$ records of different caves in H1. (a) Mawmluh $\delta^{18}\text{O}$ record^[25]; (b) spliced stalagmite $\delta^{18}\text{O}$ record from Hulu Cave^[17] and Qingtian Cave^[19]; (c) Xianyun $\delta^{18}\text{O}$ record (this study); (d) Paixão $\delta^{18}\text{O}$ record^[26]. ²³⁰Th ages and errors are color-coded by cave. The dark gray thick lines indicate the abrupt changes in H1

快速偏正，之前的时期 $\delta^{18}\text{O}$ 值整体相对偏负；而在此突变过程之后的16.1~15.2 ka BP时期 $\delta^{18}\text{O}$ 值呈现出缓慢偏负的趋势(图5)。仙云洞与葫芦洞和青天洞石笋 $\delta^{18}\text{O}$ 记录整体一致性的证据说明，同位于东亚季风区的仙云洞石笋记录在千年尺度气候事件上指

示了季风强度的变化，即季风越强，石笋氧同位素越偏负，反之则偏正。

Pausata等人^[21]通过数值模拟，并基于印度季风区和东亚季风区石笋氧同位素在H1时偏正的事实，提出中国季风区石笋 $\delta^{18}\text{O}$ 记录的是印度季风降水变

化的观点. 假如这一解释正确的话, 印度季风区和东亚季风区的石笋 $\delta^{18}\text{O}$ 在H1事件时的突变模式应当一致. 但仙云洞石笋 $\delta^{18}\text{O}$ 记录与南京葫芦洞和青天洞石笋 $\delta^{18}\text{O}$ 记录以及印度Mawmluh洞^[25] $\delta^{18}\text{O}$ 记录对比结果显示, 尽管在千年尺度事件的整体变化特征上具有一致性, 但在H1的突变模式上差异明显. 葫芦洞和Mawmluh洞为一个阶段的突变过程, 持续时间仅为20~60 a (图5(a)和(b)), 而仙云洞石笋氧同位素由于在突变过程的中间部分存在一个达120 a的 $\delta^{18}\text{O}$ 相对稳定变化的平台, 因而呈现出明显的两个阶段的变化过程(图5(c)). 仙云洞石笋XYIV-3两个阶段的变化过程对应于石笋77~110 mm层段, 生长速率较快, 根据线性内插的年代标尺得到此过程持续时间达~260 a. 即使按照整根石笋最快的生长速率0.37 mm/a计算此过程持续时间也达90 a, 远比葫芦洞和青天洞年纹层计数所得到的~20 a长得多. 另外, Pausata等人^[21]的模拟结果显示, H1事件中国受印度季风影响的区域 $\delta^{18}\text{O}$ 变化范围为0.9‰~1.1‰, 而在东南部似乎不能够引起降水 $\delta^{18}\text{O}$ 的变化, 或在这些区域变化幅度很小. 如果H1在福建只考虑一个阶段(即阶段2)的话, 其0.6‰左右的 $\delta^{18}\text{O}$ 变化幅度与模拟结果比较接近, 似乎支持这一模拟结果, 但H1事件在仙云洞石笋记录显示了两个阶段的变化过程, $\delta^{18}\text{O}$ 变化幅度达到1.8‰, 说明模拟结果存在较大偏差. 基于以上两点证据, 本文研究结果不支持Pausata等人^[21]模型模拟的研究结果. 另外, Tan^[22]通过对比中国中部和印度地区的近百年石笋氧同位素记录, 结合最近几十年来的气象资料, 认为水汽源的变化是引起东亚季风区石笋 $\delta^{18}\text{O}$ 变化的主要因素, 而不是降水量, 对Pausata等人^[21]的模拟结果从年代际尺度上也提出了质疑.

3.2 ~16.2 ka BP左右的季风突变过程

高精度定年的仙云洞石笋 $\delta^{18}\text{O}$ 记录清晰地捕捉了H1事件的突变特征. 在16.3~16.1 ka BP左右, $\delta^{18}\text{O}$ 记录偏正, 总体振幅约为1.8‰, 在~260 a的时间内呈现出两个阶段的偏正过程. 葫芦洞、青天洞和印度Mawmluh洞石笋 $\delta^{18}\text{O}$ 值在~16.1 ka BP时快速偏正, 振幅分别为2‰, 2‰和1‰. 葫芦洞和青天洞在²³⁰Th定年的基础上建立了年层时标, 其所测的²³⁰Th年龄误差分别为 $\pm 59 \sim \pm 164$ 和 $\pm 74 \sim \pm 174$ a. 基于²³⁰Th年龄线性内插时标的印度Mawmluh洞石笋记录在此突变

阶段没有定年点, 最近的一个²³⁰Th年龄 15811 ± 60 a. 因此在定年误差范围内, 4个洞穴的石笋氧同位素记录的H1突变事件在发生时间上具有一致性(图5), 但在H1突变的模式和持续时间上却差异明显: 基于年层时标的青天洞和葫芦洞石笋 $\delta^{18}\text{O}$ 值完成2.0‰的突变过程仅需18和19 a^[19]; ²³⁰Th定年的印度Mawmluh洞石笋 $\delta^{18}\text{O}$ 则经历了70 a^[25], 但该记录在17.0~15.0 ka BP仅有1个定年点; 仙云洞石笋 $\delta^{18}\text{O}$ 则在~260 a的时间内呈现出两个阶段的偏正过程. 仙云洞两个阶段的变化特征同样体现在反映南美季风系统(SAMS)的高分辨率巴西Paixão洞穴石笋记录上^[26](图5(d)). 但由于Paixão洞穴石笋记录在第一阶段上 $\delta^{18}\text{O}$ 数据点较少, 此处有可能存在间断, 其两个阶段的变化过程仍有待进一步研究.

北大西洋气候在千年尺度气候突变事件上对东亚季风气候具有调控作用^[11,40~43]. H1冰漂碎屑事件发生时^[44], 北大西洋深海沉积物中Pa/Th比值记录表明AMOC减弱(图6(a)), AMOC的减弱使得北大西洋温度降低, 海冰范围增加, 大范围的海冰不仅降低了北大西洋及格陵兰地区的温度, 同时将ITCZ向南推移^[45]. 仙云洞、葫芦洞和青天洞石笋 $\delta^{18}\text{O}$ 记录在~16.2 ka BP时的偏正过程, 在定年误差范围内与Cariaco盆地反照率记录(图6(b))的ITCZ南移时间一致, 进一步支持AMOC通过改变ITCZ位置来调节亚洲季风^[19].

虽然, 东亚季风各洞穴石笋记录都捕捉到了这次H1事件, 但是各记录对于H1突变阶段的持续时间上却差异明显, 仙云洞石笋记录的突变时间(~260 a)比青天洞和葫芦洞记录(18 a和19 a)长得多, 这说明另有北高纬驱动外的因子影响着我国东南仙云洞石笋氧同位素的变化. 类似的差异响应在其他千年尺度事件中也同样可见. Partin等人^[46]基于菲律宾巴拉望洞穴和东亚季风区洞穴石笋记录及与格陵兰冰芯记录的对比, 发现越靠近热带西太平洋地区新仙女木事件开始的突变过程也越长. 进一步通过模型模拟说明, 受热带西太平洋水文气候影响的低纬度地区与受海冰影响的高纬区域相比对气候突变的响应需要更长时间^[46]. H1时, 阿拉伯海钻孔记录^[10]和印度洞穴石笋记录^[25]均表明, 印度夏季风快速响应北大西洋变冷, 表现为印度夏季风减弱, 降水减少. 然而, 热带西太平洋海洋钻孔记录表明, H1期间热带西太平洋海表温呈现缓慢升温的过程且季节性差异增

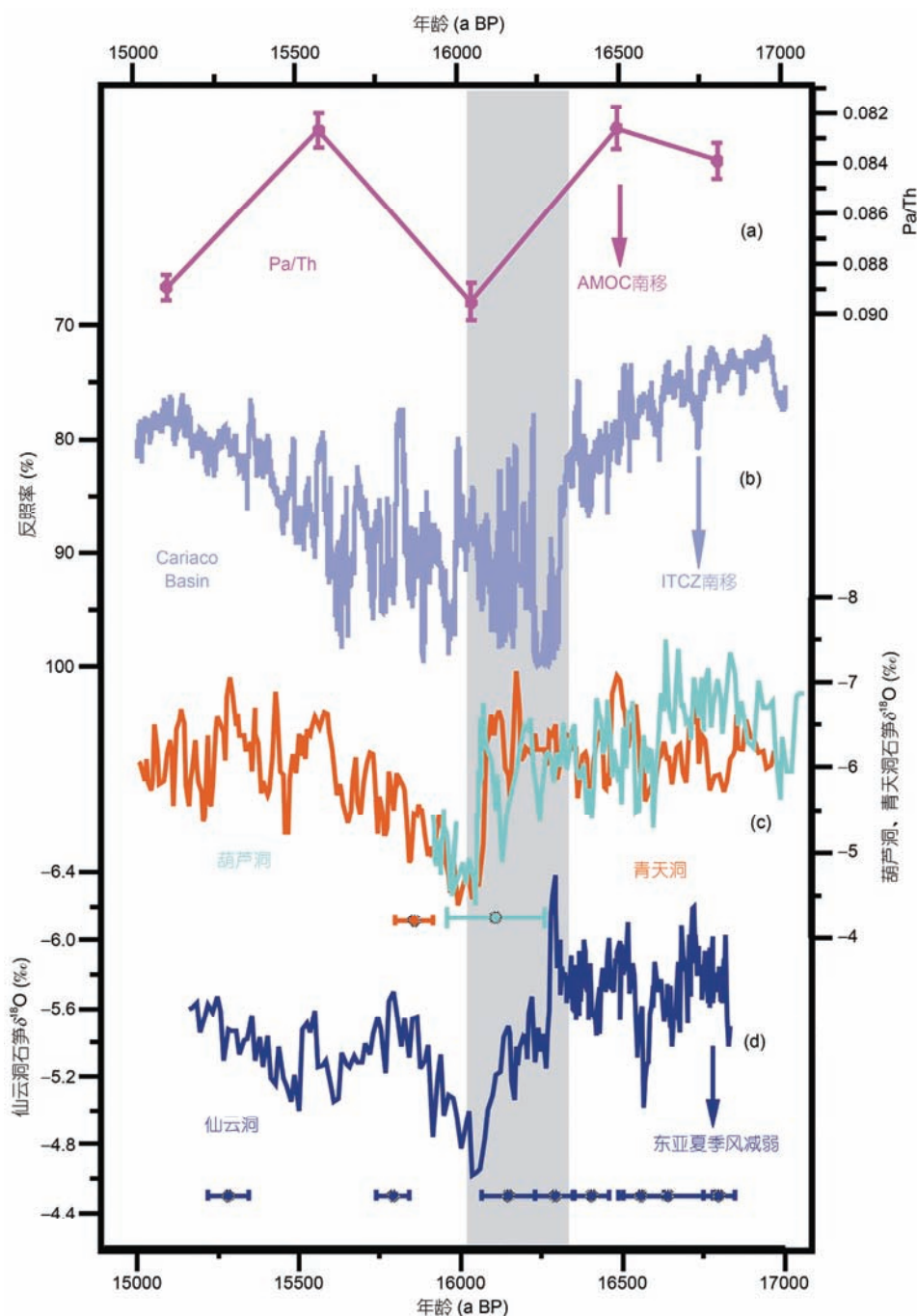


图6 仙云洞石笋 $\delta^{18}\text{O}$ 与高低纬古气候记录对比。(a) 北大西洋沉积物Pa/Th记录^[5]；(b) Cariaco盆地反照率记录^[7]；(c) 葫芦洞石笋 $\delta^{18}\text{O}$ 记录(橘黄色)^[17]，青天洞石笋 $\delta^{18}\text{O}$ 记录(天蓝色)^[19]；(d) 仙云洞石笋 $\delta^{18}\text{O}$ 记录；不同颜色的误差棒为各自石笋记录的测年点及误差($\pm 2\sigma$)

Figure 6 Comparison of $\delta^{18}\text{O}$ records between Xianyun Cave and high-low latitude climate records. (a) Pa/Th, a proxy for Atlantic Meridional Overturning Circulation (AMOC); (b) sediment reflectance record from the Cariaco Basin; (c) spliced stalagmite $\delta^{18}\text{O}$ record from Hulu Cave and Qingtian Cave; (d) Xianyun Cave $\delta^{18}\text{O}$ record (this study); ^{230}Th ages and errors are color-coded by cave

大^[47]。现代气象观测资料表明，热带西太平洋海表温的升高会引起西太平洋副热带高压位置更向西南偏伸，来自西太平洋的水汽增多^[48]。西太平洋暖池

的海气耦合会通过ENSO影响东亚夏季风降水^[49]。因此，我们推断仙云洞较长的(~ 260 a)的H1突变过程在一定程度上还受热带西太平洋海气耦合过程的影响。

Chiang等人^[50]研究发现,在冰期的冰阶时期,北半球西风急流的位置南移,阻止夏季风水汽渗透到东亚内陆地区.受此影响,比我国东南沿海福建仙云洞更靠内陆的长江中下游区域的青天洞和葫芦洞记录的H1突变过程有可能更大程度上响应北高纬的气候,表现为~20 a的突变.上述结果说明热带西太平洋暖池海气耦合过程在气候突变事件中也起着重要的作用.

4 结论

根据福建仙云洞石笋8个高精度²³⁰Th年龄和256个氧同位素分析,获得了16.8~15.2 ka BP时段平均分

辨率7 a的东亚夏季风强度的变化信息.在16.3~16.1 ka BP左右, $\delta^{18}\text{O}$ 记录偏正,总体振幅约为1.8‰,在~260 a的时间内呈现出两个阶段的偏正过程.与基于年层时标的南京葫芦洞和神农架青天洞石笋记录对比发现,尽管在定年误差范围内3个洞穴的石笋记录都捕捉到了H1事件,但我国东南仙云洞记录的H1突变过程的时间(~260 a)明显比长江中下游的青天洞(18 a)和葫芦洞(19 a)长得多.在北半球突变事件诱发后,ITCZ快速南移,但在热带西太平洋暖池海温变化和ENSO影响下,我国东南沿海福建仙云洞石笋 $\delta^{18}\text{O}$ 对H1气候突变的响应需要更长的时间.

致谢 感谢台湾大学沈川洲教授在²³⁰Th定年中给与的帮助.

参考文献

- 1 Heinrich H. Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130000 years. *Quat Res*, 1988, 29: 142–152
- 2 Broecker W S. Massive iceberg discharges as triggers for global climate change. *Nature*, 1994, 372: 421–424
- 3 Chapman M R, Shackleton N J. Millennial fluctuations in North Atlantic heat flux during the last 150000 years. *Earth Planet Sci Lett*, 1998, 159: 57–70
- 4 Bard E, Rostek F, Sonzogni C. Interhemisphere synchronicity of the last deglaciation inferred from Alkenon paleothermometry. *Nature*, 1997, 385: 707–710
- 5 McManus J F. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature*, 2004, 428: 834–837
- 6 Broccoli A J, Dahl K A, Stouffer R J. Response of the ITCZ to Northern Hemisphere cooling. *Geophys Res Lett*, 2006, 33: 1000–1029
- 7 Deplazes G, Lückge A, Peterson L C, et al. Links between tropical rainfall and North Atlantic climate during the last glacial period. *Nat Geosci*, 2013, 6: 213–217
- 8 Gibson K A, Thunell R C, Tappa E J, et al. The influence of rapid, millennial scale climate change on nitrogen isotope dynamics of the Cariaco Basin during marine isotope Stage 3. *Paleoceanography*, 2015, 30: 253–268
- 9 Tierney J E, Russell J M, Huang Y, et al. Northern hemisphere controls on tropical southeast African climate during the past 60000 years. *Science*, 2008, 322: 252–255
- 10 Deplazes G, Lückge A, Stuut J W, et al. Weakening and strengthening of the Indian monsoon during Heinrich events and Dansgaard-Oeschger oscillations. *Paleoceanography*, 2014, 29: 99–114
- 11 Wang Y J, Cheng H, Edwards R L, et al. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. *Science*, 2001, 294: 2345–2348
- 12 Wang X. Hydroclimate changes across the Amazon lowlands over the past 45000 years. *Nature*, 2017, 541: 204–207
- 13 Blunier T, Brook E J. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science*, 2001, 291: 109–112
- 14 Hong Y T, Hong B, Lin Q H, et al. Correlation between India Ocean summer monsoon and North Atlantic climate during the Holocene. *Earth Planet Sci Lett*, 2003, 211: 371–380
- 15 Zhou W J, Wang H, Zhu Y Z, et al. The geological records of ‘Mystery Interval’ in the last 21 ka (in Chinese). *J Earth Environ*, 2012, 1: 685–691 [周卫健, 王浩, 祝一志, 等. 最近 21 ka 以来“神秘时段”的地质记录. *地球环境学报*, 2012, 1: 685–691]
- 16 Zhou X, Sun L, Chu Y, et al. Catastrophic drought in East Asian monsoon region during Heinrich event 1. *Quat Sci Rev*, 2016, 141: 1–8
- 17 Wang Y J, Liu D B, Wu J Q, et al. A quick cooling event of the East Asian monsoon responding to Heinrich 1: Evidence from stalagmite $\delta^{18}\text{O}$ records. *Sci China Ser D-Earth Sci*, 2002, 45: 88–96 [汪永进, 刘殿兵, 吴金全, 等. 石笋记录的东亚季风气候 H1 事件突变性特征. *中国科学 D 辑: 地球科学*, 2002, 32: 53–59]

- 18 Yang Y, Yuan D X, Cheng H, et al. Precise dating of abrupt shifts in the Asian monsoon during the last deglaciation based on stalagmite data from Yamen Cave, Guizhou Province, China. *Sci China Earth Sci*, 2010, 53: 633–641
- 19 Zhang W, Wu J, Wang Y, et al. A detailed East Asian monsoon history surrounding the ‘Mystery Interval’ derived from three Chinese speleothem records. *Quat Res*, 2014, 82: 154–163
- 20 Ren X F. A high-resolution climate changes during H1 event based on multi-proxy stalagmite records and cave monitoring in western Henan, China (in Chinese). Master Dissertation. Chongqing: Southwest University, 2015 [任小凤. 豫西 H1 事件高分辨率气候变化的多指标石笋记录及洞穴监测研究. 硕士学位论文. 重庆: 西南大学, 2015]
- 21 Pausata F S R, Battisti D S, Nisancioglu K H, et al. Chinese stalagmite $\delta^{18}\text{O}$ controlled by changes in the Indian monsoon during a simulated Heinrich event. *Nat Geosci*, 2011, 4: 474–480
- 22 Tan M. Circulation effect: Response of precipitation $\delta^{18}\text{O}$ to the ENSO cycle in monsoon regions of China. *Clim Dyn*, 2015, 42: 1067–1077
- 23 Shen C C, Cheng H, Edwards R L, et al. Measurement of attogram quantities of ^{231}Pa in dissolved and particulate fractions of seawater by isotope dilution thermal ionization mass spectroscopy. *Anal Chem*, 2003, 75: 1075–1079
- 24 Hendy C H. The isotopic geochemistry of speleothems. The calculation of the effects of different modes of formation on the isotopic composition of speleothems and their applicability as palaeoclimatic indicators. *Geochim Cosmochim Acta*, 1971, 35: 801–824
- 25 Som D, Gupta A K, Clemens S C, et al. Abrupt changes in Indian summer monsoon strength during 33800 to 5500 years BP. *Geophys Res Lett*, 2015, 42: 5526–5532
- 26 Stríkis N M, Chiessi C M, Cruz F W, et al. Timing and structure of Mega-SACZ events during Heinrich Stadial 1. *Geophys Res Lett*, 2015, 42: 5477–5484
- 27 Wang B. Rainy season of the Asian-Pacific summer monsoon. *J Clim*, 2002, 15: 386–398
- 28 Sinha A, Cannariato K G, Stott L D, et al. Variability of Southwest Indian summer monsoon precipitation during the Bølling-Allerød. *Geology*, 2005, 33: 813–816
- 29 Shakun J D, Burns S J, Fleitmann D, et al. A high-resolution, absolute-dated deglacial speleothem record of Indian Ocean climate from Socotra Island, Yemen Shanahan. *Earth Planet Sci Lett*, 2007, 259: 442–456
- 30 Wang H, Chen H. Climate control for southeastern China moisture and precipitation: Indian or East Asian monsoon? *J Geophys Res*, 2012, 117: D12109, doi: 10.1029/2012JD017734
- 31 Yuan D X, Cheng H, Edwards R L, et al. Timing, duration, and transitions of the last interglacial Asian monsoon. *Science*, 2004, 304: 575–578
- 32 Zhang P Z, Cheng H, Edwards R L, et al. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science*, 2008, 322: 940–942
- 33 Cheng H, Edwards R L, Sinha A, et al. The Asian monsoon over the past 640000 years and ice age terminations. *Nature*, 2016, 534: 640–646
- 34 Maher B A. Holocene variability of the East Asian summer monsoon from Chinese cave records: A re-assessment. *Holocene*, 2008, 18: 861–866
- 35 Tan M. Circulation effect: Climatic significance of the short term variability of the oxygen isotopes in stalagmites from monsoonal China—Dialogue between paleoclimate records and modern climate research (in Chinese). *Quat Sci*, 2009, 29: 851–862 [谭明. 环流效应: 中国季风区石笋氧同位素短尺度变化的气候意义——古气候记录与现代气候研究的一次对话. 第四纪研究, 2009, 29: 851–862]
- 36 Dayem K E, Molnar P, Battisti D S, et al. Lessons learned from oxygen isotopes in modern precipitation applied to interpretation of speleothem records of paleoclimate from eastern Asia. *Earth Planet Sci Lett*, 2010, 295: 219–230
- 37 Cheng H, Sinha A, Wang X, et al. The global paleomonsoon as seen through speleothem records from Asia and the Americas. *Clim Dyn*, 2012, 39: 1045–1062
- 38 Liu Z, Wen X, Brady E C, et al. Chinese cave records and the East Asia summer monsoon. *Quat Sci Rev*, 2014, 83: 115–128
- 39 Duan F C, Wu J Y, Wang Y J, et al. A 3000-year annually laminated stalagmite record of the Last Glacial Maximum from Hulu Cave, China. *Quat Res*, 2015, 83: 360–369
- 40 Wang Y J, Cheng H, Edwards R L, et al. Millennial- and orbital-scale changes in the East Asian monsoon over the past 224000 years. *Nature*, 2008, 451: 1090–1093
- 41 Cheng H, Edwards R L, Wang Y J, et al. A penultimate glacial monsoon record from the Hulu Cave and two-phase glacial terminations. *Geology*, 2006, 34: 217–220
- 42 Zhou H Y, Zhao J X, Feng Y X, et al. Heinrich event 4 and Dansgaard/Oeschger events 5–10 recorded by high-resolution speleothem oxygen isotope data from central China. *Quat Res*, 2014, 82: 394–404
- 43 Jiang X, Wang X, He Y, et al. Precisely dated multidecadally resolved Asian summer monsoon dynamics 113.5–86.6 thousand years ago. *Quat Sci Rev*, 2016, 143: 1–12

- 44 McManus J F, Oppo D W, Cullen J L. A 0.5 million year record of millennial-scale climate variability in the North Atlantic. *Science*, 1999, 283: 971–975
- 45 Chiang J C H, Bitz C M. Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Clim Dyn*, 2005, 25: 477–496
- 46 Partin J W, Quinn T M, Shen C C, et al. Gradual onset and recovery of the Younger Dryas abrupt climate event in the tropics. *Nat Commun*, 2015, 6: 8061, doi: 10.1038/ncomms9061
- 47 Rosenthal Y, Oppo D W, Linsley B K. The amplitude and phasing of climate change during the last deglaciation in the Sulu Sea, western equatorial Pacific. *Geophys Res Lett*, 2003, 30: 1428, doi: 10.1029/2002GL016612
- 48 Lu R. Interannual variability of the summertime North Pacific subtropical high and its relation to atmospheric convection over the warm pool. *J Meteorol Soc Jpn*, 2001, 79: 771–783
- 49 Wang B, Wu R, Fu X. Pacific-East Asian teleconnection: How does ENSO affect East Asian climate? *J Clim*, 2000, 13: 1517–1536
- 50 Chiang J C H, Fung I Y, Wu C H, et al. Role of seasonal transitions and westerly jets in East Asian paleoclimate. *Quat Sci Rev*, 2015, 108: 111–129

Summary for “福建仙云洞石笋记录的 Heinrich 1 事件突变特征”

Characteristics of the Heinrich 1 abrupt climate event inferred from a speleothem record from Xianyun Cave, Fujian Province

CUI MengYue¹, XIAO HaiYan¹, SUN XiaoShuang¹, HONG Hui¹, JIANG XiuYang^{1,2*} & CAI BingGui^{1,2*}

¹Key Laboratory of Humid Subtropical Eco-geographical Processes, Ministry of Education, College of Geography Science, Fujian Normal University, Fuzhou 350007, China;

²Institute of Geography, Fujian Normal University, Fuzhou 350007, China

*Corresponding authors, E-mail: xyjiang@fjnu.edu.cn; bingguicai@qq.com

The climate system of the Earth experienced a series of abrupt changes such as Heinrich events and Dansgaard-Oeschger cycles during the last glaciation. Among them, the Heinrich 1 event (H1 event) is the most prominent cold event. It was recorded in Greenland ice cores, deep sea sediments, loess, stalagmites and lacustrine sediments and was proposed to be a global climate event. During H1 event (~18–15 ka), the ice raft extended southward and large amount of cold and fresh water was integrated into the North Atlantic Ocean. It led to the reduction of the Atlantic Meridional Overturning Circulation (AMOC), cooling of the northern hemisphere, and the weakening of the East Asian summer monsoon (EASM) as the results of the southward shift of the Inter-tropical Convergence Zone (ITCZ).

Pausata et al. (2011) used a numerical climate model with an embedded oxygen-isotope model to assess what caused the shifts in the oxygen-isotope signature of precipitation during a climate perturbation designed to mimic the Heinrich event. The simulations reproduced the enrichment of $\delta^{18}\text{O}$ over Northern India and East Asia evident in speleothem records during Heinrich events. They then concluded that changes in the $\delta^{18}\text{O}$ of Chinese stalagmites associated with Heinrich events reflect changes in the intensity of Indian rather than East Asian monsoon precipitations. The simulation result also shows no significant change in $\delta^{18}\text{O}$ in precipitation over southeastern China, where its climate is influenced by EASM only. However, there is a lack of well-dated stalagmite record covering the H1 event from the southeastern China to test this hypothesis.

Here we present a high resolution stalagmite isotope record (XYIV-3) from Xianyun Cave in western Fujian Province to reveal the detailed precipitation history of the EASM from 16.8 to 15.2 ka BP, based on eight high-precision ²³⁰Th ages and 256 oxygen isotope data, yielding an average resolution of 7 a. This high resolution stalagmite $\delta^{18}\text{O}$ record constrained detailed changes of the EASM during H1 event. It is characterized by a two-step positive shift process beginning at ~16.2 ka BP with the amplitude of 1.8‰, which indicates a significant weakened monsoon period. This result does not support the model simulation which was proposed by Pausata et al. (2011) that the $\delta^{18}\text{O}$ of Chinese stalagmites reflected changes of the Indian Summer Monsoon rainfall. Indeed our record suggests that changes in $\delta^{18}\text{O}$ of Chinese stalagmites reflect changes of EASM, especially during Heinrich events. Comparing with stalagmite records from Hulu Cave and Qingtian Cave, stalagmites records from all 3 caves captured the H1 abrupt climate changes within dating errors. However, changes in Xianyun Cave are more prolonged (~260 a) than the abrupt (18–19 a) changes in Qingtian and Hulu caves. We conclude that the prolonged process of the Xianyun Cave is influenced, to some extent, by ocean-atmosphere coupling processes over the tropical western Pacific Ocean. The hydroclimate of the tropical west Pacific may cause the different responses. Due to the influence of sea-surface temperature changes in the tropical western Pacific warm pool and ENSO, the response of $\delta^{18}\text{O}$ in precipitation in Fujian Province evident by our stalagmites to North Atlantic Ocean change would last longer than other EASM regions.

Heinrich 1 event, stalagmite, East Asian monsoon, Xianyun Cave

doi: 10.1360/N972017-00091