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摘 要 Heinrich 1(H1)事件是末次冰期向全新世转变过程中,北高纬大冰盖快速崩塌的冰盖不稳定事件,其气候环境影响深远。东亚地区石笋$\delta^{18}O$记录在H1事件时,普遍正偏至冰期的较大值,此正偏值通常指示东亚季风整体减弱。然而,在长江中游地区反映局地水文变化的石笋微量元素和碳同位素记录,显示在H1事件时梅雨量增加。梅雨与东亚季风强度的反相关关系是否存在,这有待更多记录的验证与支持。基于长江下游梅雨区南京葫芦洞石笋铀元素的水文变化特征,发现在H1事件时,梅雨整体增多。在H1事件内部结构特征上,高分辨率石笋$\delta^{18}O$记录显示,以~16.1 ka B.P.为界,东亚季风强度存在两个不同状态,类似的转变过程在铀元素记录中有所体现,表现为梅雨量由低到高的转变特征。石笋$\delta^{18}O$记录的这一季风强度变化过程在20年内完成,铀元素记录尽管分辨率不高,但也表现为快速转变的特征。这种对应的快速转变过程,表明石笋铀元素对东亚季风大气环流变化的积极响应;另一方面,也证实了铀元素对气候环境变化的有效记录。南京葫芦洞石笋铀元素记录了梅雨在长江下游地区H1事件期间增强的特征,进一步支持了梅雨与季风强度变化的反相关关系,提供了中国季风区降水空间差异的东部记录。

关键词 Heinrich 1事件;梅雨;$\delta^{234}U_{Initial}$值;^{238}U浓度;季风强度

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0 引言

1988年Heinrich发现北大西洋深海沉积物中有数层陆源碎屑层[1]。四年后,Bond *et al*.[2]进一步证实了这些碎屑层的存在,并命名Heinrich事件(简称H事件)。整个末次冰期和末次冰消期共发生了6次H事件,按照发生的顺序编号为H6~H1,他们发生的时间依次为63.2 ka B.P.、50 ka B.P.、40.2 ka B.P.、32.7 ka B.P.、26.5 ka B.P.、18 ka B.P.[3-4]。

东亚季风与北大西洋的气候遥相关早已在石笋和黄土等地质记录中得到证实[5-7]。东亚石笋$\delta^{18}O$记录显示H事件时亚洲季风强度显著减弱。然而,Zhang *et al*.[8]指出H1事件期间长江中游地区呈现异常湿润的水文气候,认为大西洋经向翻转环流(Atlantic Meridional Overturning Circulation,简称AMOC)减弱导致北高纬温度下降,极地—赤道温度梯度增加,西风带北移时间推迟,梅雨期延长,降水量增加。此石笋微量元素与$\delta^{18}O$记录的显著不同,反映了梅雨与东亚季风强度的差异。在年—年代际尺度上,东亚季风区降水量在空间分布上具有经向三极子模式[9-11],即季风增强时,中国南北部多雨,长江中下游降水减少,反之亦然。此外,Ge *et al*.[12]借助清朝史料和器测降水数据,重建了清朝后期长江流域梅雨量变化序列,指出与季风强度存在反相关关系,即季风强度减弱或增强时,梅雨期延长或缩短,降水量增加或减少。

梅雨量与季风强度的反相关关系在千年尺度上是否仍然存在有待进一步验证。本文选取梅雨带的南京葫芦洞H82石笋,通过铀同位素数据来研究长江下游地区的水文变化特征,揭示梅雨带与东亚季

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风强度在H1事件期间的协同性和差异性，对梅雨与东亚季风强度的反相关关系是否成立来做进一步验证。

1　研究区域与材料

南京市位于长江下游，地貌特征属宁镇扬丘陵地区，以低山缓岗为主，具有典型的北亚热带湿润气候特征，四季分明，年温差较大。年均温为15.4 °C，年均降水量1 275 mm，其中6—7月份降水量将近30%。葫芦洞（119°2′ E，32°3′ N；海拔90 m），位于南京东部汤山镇西，发育在下奥陶统红花园组白云质灰岩和灰岩中，洞穴上覆植被以C3植物为主，洞顶土壤厚度30~40 cm[13]。本文进一步分析了葫芦洞H82的$\delta^{18}O$和铀元素数据。数据来自网络（https://www.ncdc.noaa.gov/）。样品细节及测试结果见相关文献描述[14]。

2　结果与讨论

在千年尺度上，H事件在南北半球记录中均有体现：格陵兰冰芯记录[15]（图1a）和欧洲大陆及附近海域沉积物记录[16-19]反映温度和降水量下降；而在南半球，陆地冰川快速退缩[20-21]、南大洋生物生产量增加[22]、南极冰芯记录的温度[23]（图1f）和大气CO_2浓度升高[24-28]。南北半球H事件时的温度变化显示了晚更新世以来两极气候间存在的跷跷板模式[23]。H事件期间，北大西洋岩心$^{231}Pa/^{230}Th$记录[29-30]（图1b）显示AMOC强度减弱，卡里亚科岩心[31]（图1d）和环赤道大西洋孢粉[32]记录显示ITCZ显著南移。印尼石笋[33-34]（图1c）与巴西石笋$\delta^{18}O$记录[35]（图1e）表明，H事件期间ITCZ以南和以北的低纬地区气候状况相反。以北地区的非洲[36-38]、北印度洋[39-40]、中美洲[41]区域降水量大幅下降，亚非季风减弱[42-44]；而以南地区湿度增加[45]，南美季风[46-49]、澳洲季风[50-52]强盛，导致热带湿

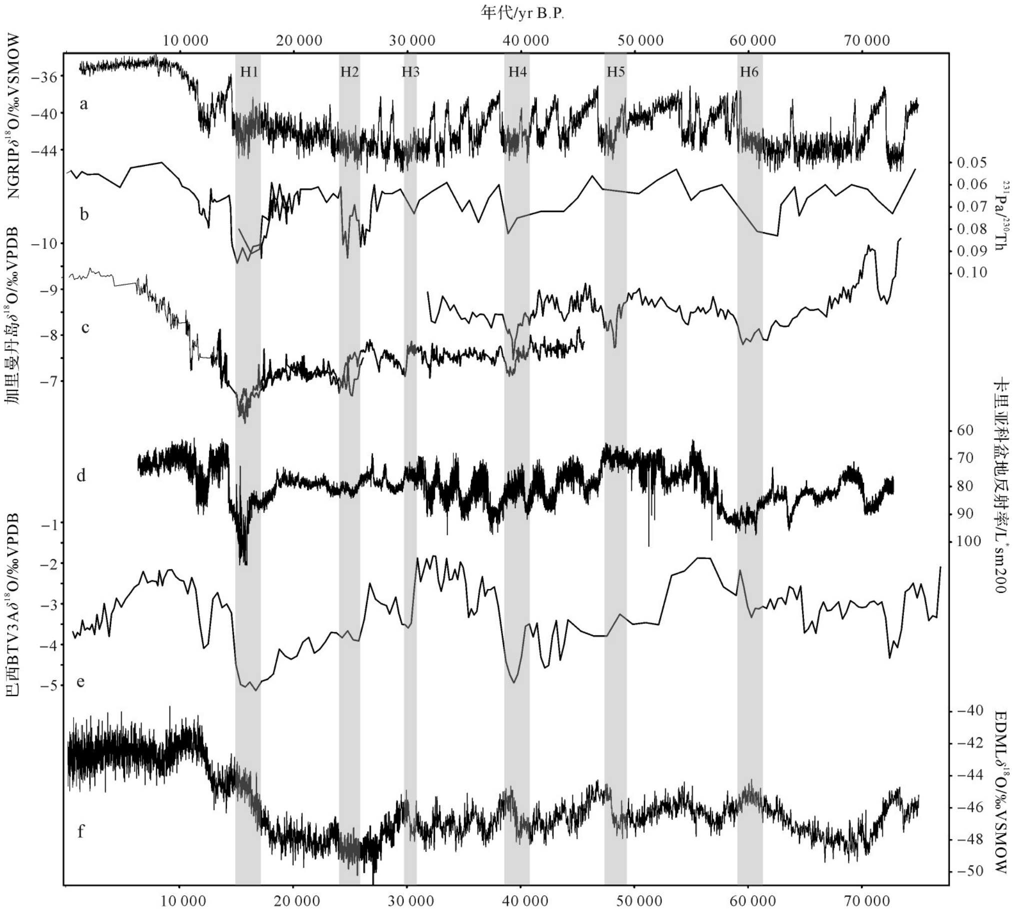

图1　Heinrich事件全球记录

(a)格陵兰NGRIP$\delta^{18}O$记录[15]；(b)北大西洋GGC5[29]、ODP1063[30]岩心$^{231}Pa/^{230}Th$记录；(c)加里曼丹岛石笋$\delta^{18}O$记录[33-34]；(d)卡里亚科盆地反射率记录[31]；(e)巴西BTV3A洞石笋$\delta^{18}O$记录[35]；(f)南极冰芯EDML$\delta^{18}O$记录[23]，冰芯记录都基于AICC2012时标[56]

Fig.1　Global records of the Heinrich events from various archives

地甲烷释放量增加[53]。

南北半球高低纬地区对H事件的快速响应，表明了全球气候系统之间密切联系。在H事件机制上，主流观点认为与AMOC的强度有关[29,54-55]。当北半球升温时，冰盖崩塌并进入北大西洋，抑制了深层水的形成，导致AMOC输送到北高纬的热量减少，造成北半球气候冷干，西风带和ITCZ南移，南半球气候变得暖湿。

高分辨率石笋$\delta^{18}O$记录的东亚弱季风事件，与南北极冰芯差值所反映的温度梯度下降相对应（图2g，h）。H事件发生时，葫芦洞[5,14]、豪猪子洞[57]、永兴洞[58]、小白龙洞[59]石笋$\delta^{18}O$值偏正反映东亚季风强度减弱（图2b~d），对应于格陵兰岛NGRIP冰芯$\delta^{18}O$值偏负[15]指示的北高纬降温（图2a）和南极TALDICE[27]与EDML[23]冰芯$\delta^{18}O$值偏正（图2e，f）指示的南高纬升温阶段。H事件时南北两极温度梯度减小表明AMOC减弱导致南北两极能量传输减弱，两极能量趋于平衡。

关于石笋$\delta^{18}O$指标，在平衡分馏情况下，其变化主要受洞穴温度和滴水$\delta^{18}O$值影响[60]。经过研究，东亚季风区石笋$\delta^{18}O$值主要继承了降水的$\delta^{18}O$信号，在千年尺度上反映东亚夏季风强度[61]。西南地区石笋$\delta^{18}O$记录[59,62-65]和湖泊记录[66-67]、西北地区石笋灰度记录和黄土剖面记录[68-69]，都支持H1期间季风强度减弱带来降水量减少的理论。然而，有些研究认为东亚大陆石笋$\delta^{18}O$值与降水量之间可能不存在线性关系[70-72]。Pausata *et al*.[73]通过模拟认为在H1事件发生时，东亚季风区的石笋$\delta^{18}O$指示了印度季风强度的变化。此时印度地区降水减少，水汽$\delta^{18}O$值偏正，使得风向下游区中国石笋$\delta^{18}O$值偏正。另一种观点则认为，印度夏季风并不是控制中国石笋$\delta^{18}O$值的唯一因素，H1事件期间中印石笋氧同位素的变化幅度间存在差异，认为中国石笋$\delta^{18}O$值还受到热带太平洋的影响[74]。Cheng *et al*.[75]认为不论水汽是来自印度洋还是太平洋，二者并不矛盾，中国石笋$\delta^{18}O$记录了从水汽源到洞穴地点全程降水的累计结果，从总体

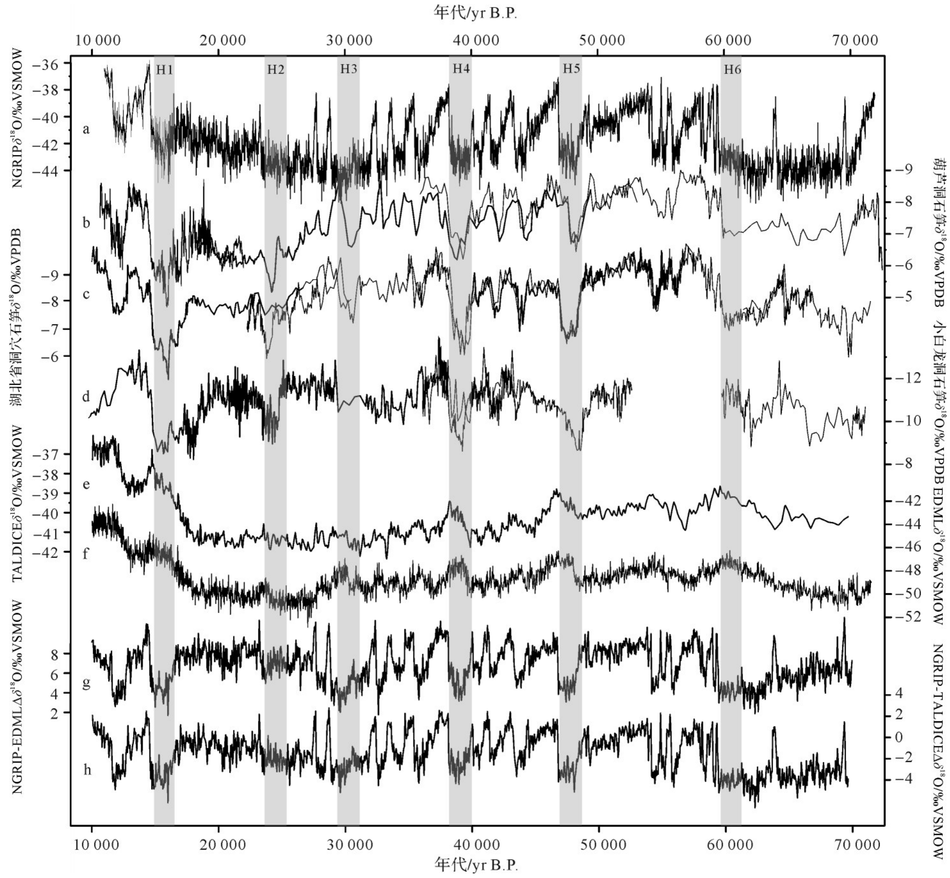

图2 中国石笋和南北两极记录中的Heinrich事件

(a)格陵兰NGRIP$\delta^{18}O$记录[15]；(b)葫芦洞石笋$\delta^{18}O$记录[5,14]；(c)湖北省永兴洞、豪猪子洞石笋$\delta^{18}O$记录[57-58]；(d)云南省小白龙洞$\delta^{18}O$记录[59]；(e)南极冰芯TALDICE$\delta^{18}O$记录[27]；(f)南极冰芯EDML$\delta^{18}O$记录[23]；(g)(h)南北极冰芯$\Delta\delta^{18}O$记录，冰芯记录都基于AICC2012时标[56]

Fig.2 Heinrich events recorded in polar ice cores and Chinese stalagmites

上反映了亚洲季风的强弱。为了进一步认识石笋 $\delta^{18}O$ 在东亚季风区的气候意义，分析同支石笋的微量元素能成为有效补充。

2.1 H1事件期间长江中下游微量元素变化

石笋微量元素是当地水文条件变化的重要指标[76-79]，其变化对理解石笋 $\delta^{18}O$ 指标的气候意义具有重要参考价值。微量元素铀（U），具有放射性，其天然同位素有 ^{238}U、^{235}U 和 ^{234}U。学术界对石笋U元素的研究主要集中于 ^{238}U 浓度、$\delta^{234}U_{Initial}$ 值两方面。在自然界中，U主要以+4和+6两种价态为主，其价态转换主要受氧化还原环境的影响[80-82]。大气降水、洞穴上覆土壤带和石灰质母岩是U主要的来源途径。石笋中U含量受土壤和母岩、岩溶水的渗透路径和滞留时间的长短等因素影响，其变化可能指示土壤湿度和有效降水变化[83-84]。$\delta^{234}U_{Initial}$ 值可通过公式计算得到：$\delta^{234}U_{Initial}=\delta^{234}U_{measured}\times e^{\lambda 234\times t}$。$\delta^{234}U_{Initial}$ 代表了石笋碳酸盐物质沉淀时岩溶水中过剩 ^{234}U（$^{234}U_{exc}$）与 ^{238}U 之间的放射比。Kuang *et al.*[83]分析葫芦洞U来源的比重，认为该指标受土壤有机质作用强烈，受控于地表土壤发育过程，具有反映洞穴上覆土壤成壤作用的环境意义。当水热条件好时，土壤发育，$^{234}U/^{238}U>1$，表土 ^{234}U 富集，富含 U^{+6} 的 ^{234}U 比富含 U^{+4} 的 ^{238}U 更容易形成溶于水的化合物。此外，α衰变形成 ^{234}Th 时的反冲作用导致 ^{234}U 更易迁移到地下水中，使洞穴沉积中 $\delta^{234}U_{Initial}$ 值增大。因此，石笋 $\delta^{234}U_{Initial}$ 值可反映土壤发育程度，间接指示当地降水量变化。

葫芦洞石笋 $\delta^{234}U_{Initial}$ 值和 ^{238}U 浓度记录在H事件存在对应关系（图3）。$\delta^{234}U_{Initial}$ 值和 ^{238}U 浓度的高低对应气候的湿干状况，反映降水量的变化。

葫芦洞石笋 $\delta^{234}U_{Initial}$ 在H4和H5事件期间处于高值，指示湿润气候状况。不远的鄱阳湖土壤剖面未产生H5事件的风沙沉积层，暗示此时并不是极端干旱期[85]。因此，$\delta^{234}U_{Initial}$ 值在H4、H5事件的表现可能与此时湿润水文气候有关；H2和H3时 $\delta^{234}U_{Initial}$ 值变化不明显或处于低值，却没有像H1、H4和H5事件那样升高，这表明所有H事件在长江下游地区的水文影响并不相同。$\delta^{234}U_{Initial}$ 值在H2和H3事件的表现可能反映东亚季风强度减弱并未造成该地区降水增加，使得土壤有机质含量降低，土壤发育程度变弱，$\delta^{234}U_{Initial}$ 值不高。

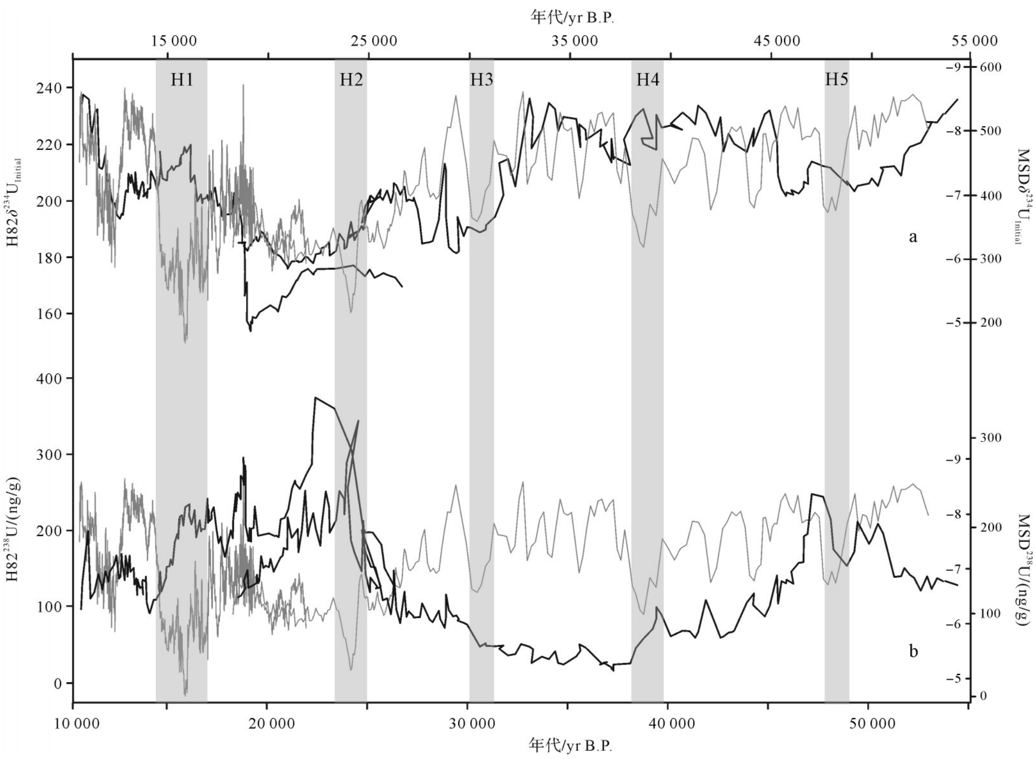

图3 葫芦洞石笋铀元素记录

（a）H82、MSD石笋 $\delta^{18}O$（灰色）[5,14]和 $\delta^{234}U_{Initial}$ 记录（黑色）；（b）H82、MSD石笋 $\delta^{18}O$（灰色）和 ^{238}U 浓度记录（黑色）

Fig.3 Uranium element records of stalagmites H82 and MSD in Hulu Cave

^{238}U浓度变化对H事件也有明显响应。湿润的H事件发生时^{238}U浓度升高或者处于升高时期(图3)。这表明湿润的水文气候有利于^{238}U的富集。在三宝洞石笋^{238}U记录分析中,董进国等[86]认为在降水高的情况下石笋^{238}U含量会有所增加。H事件期间南京地区降水量增加,土壤pH值下降,溶解基岩能力增强,易溶的UO_2OH^+增加[87],导致石笋^{238}U浓度增加。总之,在湿润的H事件中,土壤微生物活动增强,导致表层土壤进一步风化和溶解基岩能力增强,促使石笋^{238}U浓度和$\delta^{234}U_{Initial}$值增加。

此外,不同于H2事件期间$\delta^{234}U_{Initial}$值的变化,^{238}U浓度的明显增加可能与U的另一个环境意义有关:在气候干旱期,土壤水分含量降低构成氧化环境,U氧化形成易溶于水的$[UO_2]^{2+}$,并加入石笋沉积过程,使U含量增加[88];另一方面,岩溶水的滞留时间延长,也有利于从母岩含铀矿物中淋滤出更多的U。

H1事件期间H82石笋$\delta^{234}U_{Initial}$值和^{238}U浓度记录也存在对应关系。$\delta^{234}U_{Initial}$值在204.93~226.57区间内波动,平均值约为214.88(图4a)。$\delta^{234}U_{Initial}$值的整体趋势表现为自末次盛冰期后大幅增加,随后其值在210上下波动,在~16.1 ka B.P.快速达到峰值,对应于H82石笋$\delta^{18}O$记录的最大值,此后以波动减小的形式进入博林间冰阶。在整个H1事件期间,$\delta^{234}U_{Initial}$值变化总体呈倒"V"型;^{238}U浓度在114.28~234.49 ng/g区间内波动,平均值约为190.1 ng/g(图4b)。值得注意的是,石笋$\delta^{18}O$记录在~16.1 ka B.P.时于20年内突增2‰,指示东亚夏季风快速从强变弱[5,89]。这一突变事件得到$\delta^{234}U_{Initial}$值和^{238}U浓度记录的支持(图4)。此外,~16.1 ka B.P.的气候转型在石笋铀元素记录中的对应关系也证实了$\delta^{234}U_{Initial}$值和^{238}U浓度对大尺度气

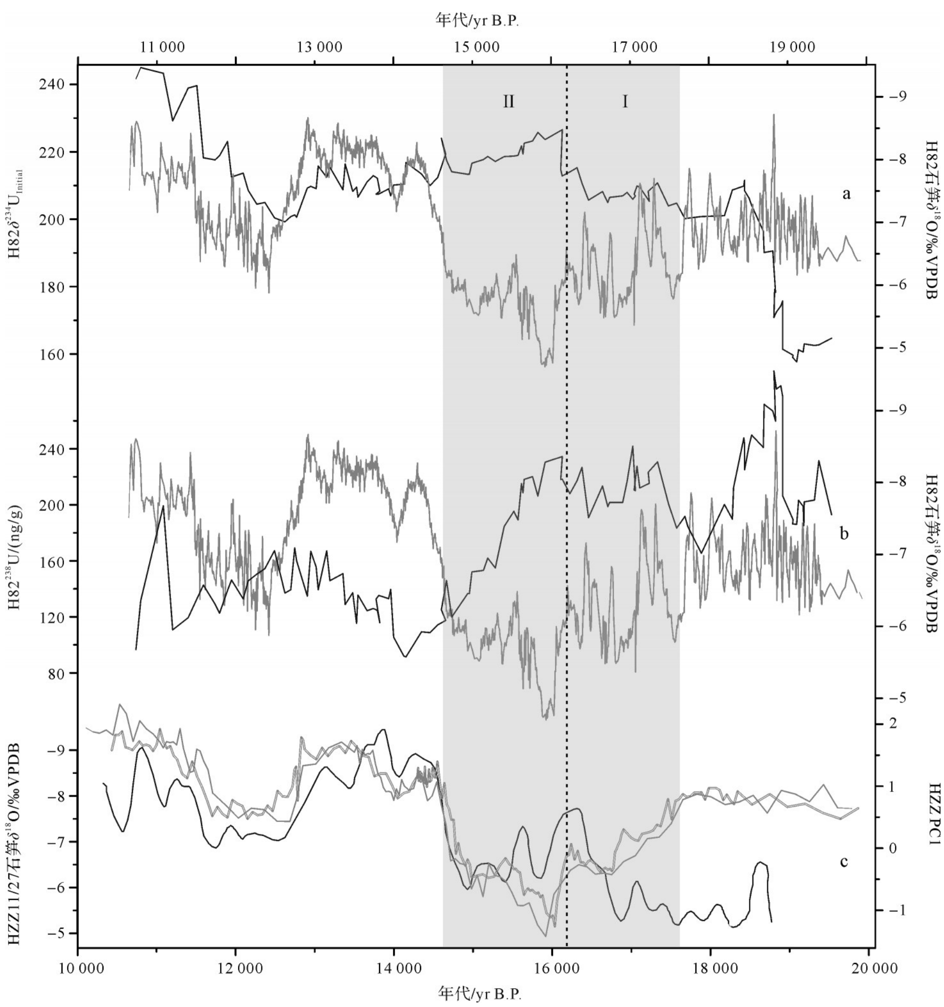

图4 长江中下游地区石笋$\delta^{18}O$和微量元素记录

(a)H82石笋$\delta^{18}O$记录(灰色)[5,14],H82石笋$\delta^{234}U_{Initial}$记录(黑色);(b)H82石笋$\delta^{18}O$(灰色)和$\delta^{238}U$记录(黑色);(c)HZZ11/27石笋$\delta^{18}O$记录(灰色)[57]、HZZ11、27石笋微量元素比值主成分1记录(黑色)[8]

Fig.4 Stalagmite $\delta^{18}O$ and trace element records in the middle and lower reaches of the Yangtze River

候环境变化的敏感性。不同的是，H82石笋$\delta^{18}O$均值从阶段Ⅰ的−6.26‰偏正到阶段Ⅱ的−5.8‰（偏正幅度0.46‰），指示季风强度的逐渐减弱；而$\delta^{234}U_{Initial}$均值则由阶段Ⅰ的209.210 8增至阶段Ⅱ的218.835（增幅约9.62个单位）；而^{238}U浓度均值由阶段Ⅰ的212.7降至阶段Ⅱ的169.3 ng/g（减幅约43.4 ng/g）。$\delta^{234}U_{Initial}$值和^{238}U浓度虽然在变化幅度上不同，但总体上仍都反应降水量的增加，这表明二者与$\delta^{18}O$记录反映的水文气候变化存在指向差异，影响机制也不尽相同。

2.2　H1期间长江中下游降水量变化

豪猪子洞石笋微量元素记录[8]与$\delta^{18}O$记录出现反相关关系（图4c）。石笋微量元素变化指示了H1期间该地区变得湿润，归因为北半球变冷引起半球间温度梯度减小、西风带北移时间偏晚，东亚夏季风减弱，导致梅雨带在长江中游地区停留时间长，促使降水增多。

H82石笋$\delta^{234}U_{Initial}$值和^{238}U浓度在H1期间增高，表明该时期降水量增加。可能的原因为梅雨带在长江下游地区停留时间长、降水增多，提高了南京地区土壤发育程度，导致$\delta^{234}U_{Initial}$值升高；同时，土壤腐殖质中富里酸所结合的铀以UO_2OH^+−腐殖酸络合物的形式存在并迁移，导致^{238}U浓度增大。H82石笋$\delta^{234}U_{Initial}$值和^{238}U浓度的变化特征进一步支持了梅雨与季风强度变化间的反相关关系。

总体而言，H82石笋U元素变化在H1期间以~16.1 ka B.P.为界分为两个阶段：在H1事件早期，对应于$\delta^{18}O$记录总体偏正趋势，$\delta^{234}U_{Initial}$值小幅增加，而^{238}U浓度则因土壤酸碱度下降改变了岩溶水中铀的沉淀富集条件而增大。整体反应该时期季风强度呈减弱趋势、降水量呈增加趋势。在~16.1 ka B.P.，$\delta^{18}O$记录指示季风强度快速减弱，而$\delta^{234}U_{Initial}$值和^{238}U浓度快速到达峰值；在H1事件结束期，$\delta^{18}O$记录快速偏负指示季风增强，而$\delta^{234}U_{Initial}$值和^{238}U浓度则相应减少，指示降水量的减少。$\delta^{234}U_{Initial}$值和^{238}U浓度大致经历了先增后减的过程，与$\delta^{18}O$记录呈正相关。

纵上所述，H1事件期间东亚季风区并不表现为一致的气候冷干，经向三极子模式的提出，为解释季风降水的时空差异提供了一种新思路。石笋$\delta^{18}O$指标应用最多，但其水文气候意义备受争议[90]，而石笋微量元素受当地环境影响较大，能够反映当地降水量变化，石笋微量元素的研究有益于石笋$\delta^{18}O$指标的解译。

3　结论

本文对葫芦洞H82石笋$\delta^{234}U_{Initial}$值和^{238}U浓度记录在H1期间的变化进行分析，认为U元素及$\delta^{234}U_{Initial}$值的变化能够指示区域水文变化，并发现H1事件期间研究洞穴所在的长江下游地区降水增多，可能与季风减弱，梅雨带在该区域停留时间较长有关，这支持了H1期间梅雨与季风强度变化间的反相关关系，且有助于完善石笋$\delta^{18}O$指标的水文气候学意义。

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Variations in Monsoonal Precipitation in the Lower Reaches of the Yangtze River During the H1 Indicated by Stalagmite Uranium Element from Hulu Cave, Nanjing, China

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Abstract: The Heinrich 1 (H1) event was an extremely cold period when the northern ice sheet at high latitudes rapidly collapsed during the transition from the last glaciation to the Holocene. This event influenced global climate widely. Stalagmite $\delta^{18}O$ records in the East Asian monsoon domain shifted to a heavier value and indicated weakened East Asian summer monsoonal intensity during the event. Stalagmite trace element and carbon isotope records both reflect hydrological variations at the cave site, and they indicated increased Meiyu rainfall in the middle reaches of the Yangtze River during the H1. This finding indicates an anti-phased relationship between Meiyu rain and East Asian summer monsoonal intensity. This relationship is further supported by a new Hulu record as suggested in this study. The stalagmite uranium element record in Hulu Cave indicated increased Meiyu rain in the lower reaches of the Yangtze River during the H1 event. In terms of the internal structure of the H1 event, previous high-resolution stalagmite $\delta^{18}O$ records have depicted two different phases of the intensity of East Asian summer monsoons at the boundary of ~16.1 ka B.P. within the H1. A similar structure is also recorded in our uranium element data, with the increase in Meiyu rainfall corresponding to weakened East Asian summer monsoonal intensity. Higher-resolution stalagmite $\delta^{18}O$ records suggest that the shift at ~16.1 ka B.P. ceased within 20 years. Although of a lower resolution, the uranium element records also indicate that the corresponding change in the Meiyu rain was rapid. These observations reveal that the uranium element responded positively to the East Asian monsoon circulation, and they support the supposition that uranium element is a valuable indicator of climate change. In sum, the increased Meiyu rain in the lower reaches of the Yangtze River documented by the Hulu uranium element data further supports the inverse relationship between the Meiyu rain and monsoonal intensity during the H1 event. Furthermore, our records point to a spatial discrepancy in monsoonal precipitation in Eastern China.

Key words: Heinrich 1 event; Meiyu; $\delta^{234}U_{initial}$ value; ^{238}U concentration; monsoon intensity