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博 士 学 位 论 文

末次冰消期及早全新世台湾南部古环境及东亚夏季季风演化

Paleoenvironment and East Asian summer monsoon rainfall evolution in southern Taiwan during last deglaciation and early Holocene

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摘要

末次冰消期一直以来是古气候研究的热点，这一时期地球气候系统发生了一系列剧烈的快速气候变化事件（H1 冰阶-H1，Bølling-Allerød 暖期-BA 和新仙女木事件-YD），研究这些气候事件有助于我们认识全球气候系统的演变及其驱动机制。东亚季风是全球气候系统的重要一环，在全球和区域水汽循环中都扮演着重要作用。东亚季风的盛衰影响着东亚地区降水分布与生态环境演化，进而影响着季风区社会经济发展和文明演替。因此研究东亚季风的演化还具有重大的现实意义。

台湾位于东亚季风的前缘区，属于典型的季风气候，年均降水量约 2000 毫米，其中 90%的降水主要集中 5 - 9 月份。此外，该地区常常遭遇台风袭击，夏季近一半的降水来自台风。但是该区域目前仍然缺乏末次冰消期定年准确的高分辨率气候记录。本文以台湾南部恒春半岛上的东源湖一根沉积岩芯为研究对象，进行高精度 ^{14}C 年代学分析（全部基于植物残体），高分辨率取样（共 460 个样品），利用地球化学指标（有机质及其堆积速率、碳同位素化学蚀变指数和磁化率等）重建分辨率达 5 - 40 年末次冰消期及早全新世（17 - 9 ka BP）台湾南部气候环境变化以及东亚夏季季风降水的变化历史，并将东源湖沉积记录与其他北半球区域地质记录进行比较，探讨台湾南部东亚夏季季风降水变率的驱动机制。结果发现：

末次冰消期东亚夏季季风降水在千年尺度上（H1、BA、YD）和百年尺度（OD、IACP）的振荡与北高纬气候变化有紧密的联系，表明北高纬冰川融水注入大西洋引起 AMOC 的减弱通过 ITCZ 对东亚夏季季风有重要的调控作用。但是在千年尺度事件内部，东亚夏季季风记录与格陵兰冰芯温度记录的变化有着明显的差异。如在整个 H1 事件当中，格陵兰冰芯温度记录显示北高纬气候寒冷但相对稳定，但是东亚季风记录则在 H1 事件当中分为前后两个阶段，东亚季风降水在 H1 晚期（16-14.7 ka）较早期（17-16 ka）显著减弱，表明 ITCZ 在 16 ka 进一步向南移动。而在 BA 时期，格陵兰冰芯温度记录显示为逐渐变冷，而东亚季风记录则表现为逐渐变强，表明有其他因素如穿赤道气流或太阳辐射驱动东亚季风在 BA 时期逐渐变强。东源湖沉积记录的东亚夏季季风降水在 YD 期间十分干旱，但是发生比格陵兰冰芯晚 500 - 800 年左右。

通过东源湖沉积记录与赤道西太平洋温度记录的对比发现东源湖沉积记录中一系列百年尺度的异常事件（强降雨事件）与赤道西太平洋的温度异常事件有很好对应关系，当赤道西太平洋表层海温升高时，上空大气对流活动加强，往北输送水汽通量增加，表明赤道西太平洋的热力学状态对东亚夏季季风在百年尺度上有着重要调控作用。

通过对比东源湖沉积记录与台湾古山体滑坡记录结果发现，在早全新世东源湖的一些高沉积速率事件（10.5 和 9.4 ka）伴随着高有机质含量及木屑等植物残体，这些事件与台湾冲积阶地上的最大的古山体滑坡记录发生时间十分吻合，表明这些时期，台湾南部遭受到更多台风的侵袭，可能是由于早全新世西太平洋温度较高引起台风频次增加。

木质素主要来自陆生维管束植物组织，具有较高的化学稳定性和抗降解能力，可以作为一种良好的地球化学示踪剂，其含量、单体组成及比值在古环境研究中可以反映植被变化，有机质降解程度等，继而可以反映气候环境信息。我们分析了东源湖沉积岩心中的木质素含量与组成，结果发现在 12.2 ka 以前东源湖流域植被主要由裸子植物和被子植物混合组成，而 12.2 ka 之后则转变为被子植物主导。木质素降解参数显示沉积物中木质素已经历了中等程度的氧化降解，去甲基/去甲氧基是最主要的木质素降解过程。结合其他地球化学参数发现东源湖流域在 YD 期间是整个冰消期最干旱时期。有机质保存显著降低，碳同位素变重，木质素降解参数显著升高，一方面由于气候干旱，有机质在陆地上停留时间较长，降解程度较高，另一方面，极端干旱的气候导致地下水水流路径变深，使得深层土壤中降解程度更高，年龄较老的有机碳进入到湖泊沉积物中被埋藏下来。东源湖沉积物的环境参数在 YD 期间较格陵兰冰芯和中国石笋记录的变化时间大概晚 500 到 800 年左右。通过与其他区域地质记录对比发现，低纬地区的水文环境变化在 YD 开始和结束的发生时间相同，但是相对于北高纬地区要缓慢的多，平均慢 300 至 500 年左右。东源湖沉积物中环境参数发生变化的时间正好在 Cariaco 盆地沉积物反射率和石笋氧同位素发生变化的最低点，恢复的时间则在 Cariaco 盆地沉积物反射率和石笋氧同位素值恢复到 YD 发生前的水平，这可能由于区域气候变化达到一定临界值，从而引起当地环境发生突变。此外碳同位素、木质素及其降解参数等都与植被演替和土壤微生物活动息息相关，而这些过程对快速气

候变化的响应可能有一定的延迟现象。

在本论文中我们分析了东源湖沉积物岩芯末次冰消期及早全新世期间硫元素的地球化学特征。结果发现东源湖沉积物在 10.5 ka 时硫含量异常高（4.8%）并伴随有硫铁矿形成，这在淡水湖泊中非常少见。东源湖沉积物中硫同位素变化范围为+9.5‰到+17.1‰，在 10.5 ka 和 9.4 ka 有两次显著的正偏事件。我们讨论了引起硫同位素变化的来源及其相关过程包括硫酸盐还原作用、火山释放、流域内矿物化学风化以及海岩输入的影响。碳-铁-硫化学计量关系表明硫酸盐还原作用发生在沉积物中，但该湖泊为封闭系统，不会影响同位素的变化。此外，火山释放、流域内矿物化学风化都不能解释东源湖沉积物硫同位素的变化。只有海洋源硫酸盐的输入是最为合理的解释。东源湖两次硫同位素正偏事件与台湾冲积阶地股山体滑坡记录最大的山体滑坡事件发生时间十分吻合，结合东源湖沉积记录在 10.5 ka 和 9.4 ka 有大量的有机质及木屑等植物残体的存在，以及较高的沉积速率，表明在 10.5 ka 和 9.4 ka 很有可能有频繁的高强度的台风侵袭台湾，引起山体滑坡，而强台风也携带大量的海洋源硫酸盐（同位素值为+20.3‰）到陆地上，因此导致沉积物中硫同位素正偏。

关键词：末次冰消期；东亚夏季季风；台湾东源湖；木质素；硫同位素

Abstract

The climate variability during the last deglaciation is one of the most intriguing areas of paleoclimate research due to a serial abrupt climatic oscillation (Heinrich stadial 1-H1, Bølling-Allerød-BA, and Younger Dryas event-YD). A better understanding of these events may advance our understanding of global climate system and its forcing. The East Asian summer monsoon (EASM) is an important component of the global climate system and plays a significant role in global hydrologic and energy cycles. The strength of the EASM is a important factor that has influenced the past environment changes and culture evolution in East Asia and the prosperity of livelihood of over a billion people who live in monsoonal regions in East Asia.

Taiwan is located along the front edge of the EASM range and its climate is mainly influenced by EASM. The annual precipitation in Taiwan is more than 2000 mm, approximately 90% of which occurs during the summer seasons. In addition, Taiwan' climate was significantly influenced by typhoon and almost half of the rainfall of Taiwan during summer comes from episodic typhoons. However, well-dated and high-resolution climatic records during the last deglaciation are rarely been reported in Taiwan. In this study, a well-dated and high-resolution lacustrine record from Dongyuan Lake at southern Taiwan was used to reconstruct local environmental variation and multi-timescale oscillations of EASM during last deglaciation and early Holocene (17 – 9 ka BP). Based on a comprehensive analysis of the proxy data from Dongyuan Lake and comparison with other climatic records, we got the following conclusions:

The oscillation of the EASM intensity during last deglaciation registered in our record generally coincided with the variation of North Atlantic climate at millennial and centennial time scales suggesting the strength of EASM is modulated by climate anomalies in the North Atlantic region through changes in the intensity of the Atlantic Meridional Overturning Circulation (AMOC) and migration of the annual mean position of the Intertropical Convergence Zone (ITCZ). However, some significant

discrepancies between our records and Greenland ice core record within these events are observed. Our records shows a clear two phase characteristic during H1 with a significant decrease in EASM rainfall during the later H1 suggesting further southward shift of the ITCZ while no obvious change was observed in Greenland ice core record. During the BA, Greenland ice core temperature record shows a clear decreasing trend; however, the EASM rainfall in our records shows an opposite trend suggesting other climate forcing beyond North Atlantic climate jointly modulated the EASM rainfall variation. The EASM rainfall significantly decreased during the YD with a time lag of 500 – 800 yr when compared to Greenland ice core record at both the onset and termination of the YD event.

We found a series of centennial-scale distinct wet events were in concert with Sea surface temperature (SST) anomaly events in the western tropical Pacific, which indicates an inherent connection between the western tropical Pacific SST and the variations of EASM rainfall in Sothern Taiwan. Increased SST in the western tropical Pacific likely enhanced the meridional heat transport from tropical ocean to high latitudes, which futher increase the monsoon convection.

Two pronounced high sedimentation events at 10.5 and 9.4 ka BP accompanied by an amount of wood fragment burial are observed in the lake sediments during the Early Holocene. These events were synchronous with the largest landslides events in past 16 ka recorded in alluvial terraces over Taiwan Island. Such coherence possibly resulted from significantly increased both intensity and frequency of typhoon activities during these period.

Lignin, an abundant biopolymer found almost exclusively in terrestrial vascular plants, has been regarded as resistant to microbial degradation in comparison to other plant components. Thus, lignin in lake sediments and peat deposits offers considerable information in paleoclimate research, as compositions of lignin oxidation products can reveal information about vegetation source, terrestrial organic matter degradation processes, and thus climate. We analyzed the lignin oxidation products of the core sediments from Dongyuan Lake. The lignin phenol ratios show a clear shift from gymnosperm-dominant to angiosperm-dominant vegetation type in the lake catchment

at 12.2 ka BP, which probably suggesting a warm climate that resulted from persistent increase in solar insolation and SST in tropical Pacific. Significantly decreased lignin concentrations and apparently elevated lignin degradation parameters in combination with other geochemical proxies during 12.2 – 10.7 ka BP suggest a catastrophic drought had occurred in southern Taiwan during this specific period. We propose that deepened groundwater flow routes, caused by significantly decreased precipitation during the warm and dry summers, may leach the older carbon with higher degradation state and lignin depleted in the catchment. Moreover, lignin is subject to increased degradation before it is transported and buried in sediments because of a longer residence time in soil during dry periods. The climate changes registered in our records lagged the temperature records in North Atlantic region with 500 – 800 years. Generally, the tropical hydroclimate records required 300 – 500 years to reach and recover from the full YD conditions. We note that the drastic changes in proxies from Dongyuan Lake occurred at the time of the maximum oxygen isotope values of stalagmites during the YD, and the termination of catostropic dry event in our record occurred at the time of stalagmite oxygen isotope values recovered to its pre-YD condition. This might imply the climate change reached to a threshold which lead a significant environmental change in southern Taiwan. The time lag between our record and the climate change in North Atlantic region might suggest a delayed response of vegetation and soil processes to rapid climate changes.

We investigated the sulfur geochemistry including isotopic composition of the same core from Dongyuan Lake. The variation of sulfur isotope during last deglaciation and early Holocene ranged from + 9.5 to + 17.1‰. Two significant positive shifts in $\delta^{34}S$ were observed at 10.5 and 9.4 ka BP with an extraordinary sulfur peak (up to 4.8%) accompanying pyrite presence at 10.5 ka BP. Carbon–sulfur–iron relationships suggested that the bacterial sulfate reduction had occurred in sediments instead of water column, and the Dongyuan Lake sediment is a closed system to efficiently trap H_2S generated via sedimentary sulfate reduction. The sources sulfur input to the lake sediments and potential processes involving the sulfur isotope variation are discussed (e.g. bacterial sulfate reduction, volcanic emissions,

sulfide oxidation from catchment and marine aerosols). All processes except marine aerosol input cannot explain the peaks of sulfur content and $\delta^{34}S$. The positive $\delta^{34}S$ shifts appeared concurrently with the recorded maximum mass-wasting events over Taiwan which resulted from enhanced typhoon activities. The synchronicity among records suggests the positive shift in $\delta^{34}S$ was likely caused by greatly increased influx of marine sourced sulfate with more positive $\delta^{34}S$ (+20.3‰) due to enhanced typhoon activities in the early Holocene. Our sulfur geochemistry data provides new insights of the sea spray history or marine influence onto the terrestrial environment at coastal regions.

Key words: Last deglaciation; East Asian summer monsoon; Dongyuan Lake; Lignin, Sulfur Isotope

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第 1 章 绪 论

气候与环境变化是地球上的生物演化和人类社会文明盛衰的重要控制因素。然而，自工业革命以来，随着科技进步，人类社会大规模工业化过程中的经济活动却迅速地改变着地球环境，甚至引起全球气候变暖，冰川融化、海平面上升、极端事件频发，海洋酸化等，而这些变化反过来又冲击着人类社会。因此预测未来的气候变化趋势以规避其对人类社会的负面影响就变得尤为重要。知古鉴今，古为今用。要预测未来环境变化，则需要了解过去地球气候环境变化的历史及其演变规律。建立于 1986 年的国际地圈生物圈计划（International Geosphere-Biosphere Program，IGBP）也于 1991 年将过去全球变化研究计划（Past Global Changes, PAGES）列为其核心研究计划之一。该计划拟通过对历史文献资料和自然环境档案如冰芯、海洋沉积物、石笋、黄土、珊瑚、树轮、湖泊和泥炭沉积物等记录的环境信息进行研究，重建过去过去全球与区域气候与环境在不同时间尺度的演化，并整合不同地质档案资料，交互检验，校正能够预测未来全球气候与环境变化的模型。

我们现在生活的全新世（11.5 ka BP 至今）为间冰期，气候环境相对稳定，适宜人类生活。然而在此之前的末次冰期与此截然不同。高纬度冰芯记录揭示在全新世以前地球气候有着剧烈振荡（图 1.1）。末次冰消期的一个显著的气候特征就是具有一系列千年尺度气候快速气候变化事件。在末次冰期存在 24 次 Dansgaard/Oeschger 事件（DO 事件，Dansgaard et al., 1993）。DO 事件表现为冰阶（stadials）与间冰阶（interstadials）的交替。在这些事件中，格陵兰地区地表温度往往在数十年内突变 15-20℃（Jouzel et al., 1997）。在冰阶中，最冷且持续时间较长事件对应着北大西洋深海沉积记录中大小不同的冰筏碎屑（ice-rafted debris，IRD）事件被称为 Heinrich 事件（H 事件，Bond et al., 1993）。后来研究发现，在全球范围内均有类似千年尺度气候突变事件（Leuschner and Sirocko, 2000; Seager and Battisti, 2007）。这些地质记录表明其他区域可能对北大西洋气候变化产生响应或存在共同的驱动机制。对于千年尺度气候突变机制，目前较为广泛认可的是北大西洋深层水的生成和关闭及北大西洋径向翻转流（Atlantic meridional ocean ciruclation，AMOC）的强弱影响着千年尺度的气候变化（Broecker