科学通报 2016 年 第 61 卷 第 36 期：3940 ~ 3945
快 讯 www.scichina.com csb.scichina.com

晚冰期大兴安岭植被气候变化的气孔器记录

伍婧*, 刘强, 储国强, 旺罗, 刘嘉麒

中国科学院地质与地球物理研究所, 中国科学院新生代地质与环境重点实验室, 北京 100029
* 联系人, E-mail: wujing@mail.iggcas.ac.cn

2016-10-22 收稿, 2016-11-21 修回, 2016-11-22 接受, 2016-12-05 网络版发表
国家自然科学基金(41572353, 41202259, 41272392, 41320104006)资助

摘要 月亮湖末次盛冰期到早全新世湖泊沉积物气孔器分析的结果, 揭示了大兴安岭地区以落叶松为主的针叶树演化历史: 15.0 cal ka BP 之前研究地点周围没有针叶树生长; 15.0~12.8 cal ka BP 开始到达研究区, 在植被中所占比例逐渐升高; 12.8~11.8 cal ka BP 所占比例达到峰值, 11.8~10.8 cal ka BP 针叶树成分退缩. 大兴安岭地区晚冰期的森林群落演化与东亚季风区不同纬度区域的植被演替具有可比性. 气孔器和花粉记录揭示的植被演化阶段在时间上与欧洲地区 Meiendorf 间冰段、Oldest Dryas 冷事件、Bølling-Allerød 暖期、Younger Dryas 冷期以及早全新世温暖湿润期较为一致, 温度变化是控制植被变化的主要因素. 研究区的植被演替响应了全球冰量控制的北半球温度变化, 揭示了东亚中纬度地区与北大西洋地区晚冰期快速气候变化的同步性.

关键词 晚冰期, 月亮湖, 气孔器, 千年/百年尺度, 大兴安岭地区

落叶松属(*Larix*)植物是北半球中高纬度地区分布的泰加林、寒温带针叶林以及寒温带针阔混交林的重要成分[1]. 前人研究显示末次盛冰期落叶松的避难所位于亚洲北部大陆和岛屿, 15~14 ka分布区到达欧洲中部和南部, 13~11 ka在欧亚大陆迅速扩张, 进入全新世之后在植被中所占的比例下降[2~6]. 落叶松属植物区域演化历史和分布范围的变化很可能与气候变化有关, 其15~14 ka分布区的扩张很可能指示了晚冰期的气候好转. 但是由于落叶松花粉产量低, 传播距离短, 母体植物盖度较低时在花粉谱中含量极低, 甚至不出现[7,8], 以花粉为指标研究落叶松林的演化历史时, 常常难以确定植物到达研究区的准确时间. 因此, 研究落叶松属植物区域演化历史, 进而反映晚冰期的快速气候变化需要新的生物学指标. 气孔器在植物表皮层中广泛存在, 是气孔与两个保卫细胞的合称. 其中针叶树有木质化的气孔器, 常常随叶、花、果实等植物器官或残片沉积在湖泊中, 其他部分被腐蚀分解后, 气孔器以单体或者表皮小碎片的形式保存下来[9,10]. 根据气孔器形态特征的差异可以将其鉴定到属一级水平, 水体表层沉积物和表土样品中气孔器的出现和母体植物在当地的存在有很好的对应关系[9~13]. 因此, 针叶树气孔器的出现可以指示某个地质历史时期母体植物的存在, 具有保存好、当地沉积、在沉积物中分布连续和鉴定精确等优点, 有重要的古生态意义[9,10]. 对于花粉呈低代表性的针叶树, 如北美[14,15]和西伯利亚地区[13]常见的落叶松属、金钟柏属(*Thuja*)和刺柏属(*Juniperus*)植物, 都可以气孔器为代用指标成功地进行古植被重建. 大兴安岭地区的北坡分布着以兴安落叶松(*L. gmelinii*)和桦木(*Betula* spp.)建群的寒温带针阔混交林, 东南部分布着以桦木、椴(*Tilia* spp.)和栎属(*Quercus* spp.)植物建群的温带落叶阔叶林, 植被分布的地带性特征由南北温度梯度决定, 植被演化对温度变化响应敏感, 是研究落叶松演化历史与气候变化关系的理想场所. 但是已有的孢粉工作由于落叶松属花粉在孢粉谱中含量低[16], 或研究的时间尺度短[17], 无法精确重建落叶松属植物在该地区的演化历史. 因此, 在大兴安岭地区获取长时间尺度高分辨率的连续湖相沉积进行气孔器指标分析, 可以确定落叶松到达研究区的准确时间, 重建末次盛冰期到早全新世区域植被的演化历史, 进而揭示研究区气候变化特征和

引用格式: 伍婧, 刘强, 储国强, 等. 晚冰期大兴安岭植被气候变化的气孔器记录. 科学通报, 2016, 61: 3940–3945
Wu J, Liu Q, Chu G Q, et al. Vegetation history and climate change recorded by stomata evidence during the late glacial in the Great Khingan Mountain Region, Northeastern China (in Chinese). Chin Sci Bull, 2016, 61: 3940–3945, doi: 10.1360/N972016-01181

驱动机制.

月亮湖(47°30′25″N, 120°52′05″E, 海拔1190 m)是阿尔山-柴河火山区内的一个小型火山口湖, 位于大兴安岭中部内蒙古自治区扎兰屯市柴河镇. 湖泊水域面积0.03 km², 最大水深为6.5 m. 离该湖最近的阿尔山市气象站的年均温为–4~0℃, 年降水量为300~600 mm. 该湖靠近落叶松林自然分布范围的南界[18], 周围的现生植被为兴安落叶松、白桦和黑桦为建群种的寒温带夏绿针阔混交林(图1). 利用活塞钻于2007年3月在月亮湖获取了长886 cm的沉积岩芯, 其中21个植物残体和全岩样品被送往波兹南放射性碳同位素实验室进行AMS ^{14}C测年, 钻孔的岩性特征和年代学结果已发表[19]. 本研究使用的年代框架是由原有的年代数据用贝叶斯软件Bacon V2.2 model[20]重新校正得到, 钻孔底部年代为20.3 cal ka BP.

气孔器样品的前处理过程和花粉分析相似, 经酸碱处理后过筛. 气孔器和花粉都在400倍的显微镜下进行鉴定和颗粒数统计. 气孔器的鉴定参数包括上木质片长度(*L*a)和宽度(*W*a)、茎的长度(*L*b)和宽度(*W*b)、中间木质片的宽度(*W*c)以及上木质片和茎的夹角(Angle)(图2(a)), 鉴定标准参照已发表的文献[10,21~23]以及本研究采集的东北地区现生针叶树的气孔器(图2(b)~(g)). 兴安落叶松的上木质片轮廓为长方形, 上木质片的侧边呈直线, 上木质片和茎的夹角在25°~35°之间, 茎、中间木质片和气孔的宽度都比较窄(图2(a)和(b)). 其形态特征与落叶松

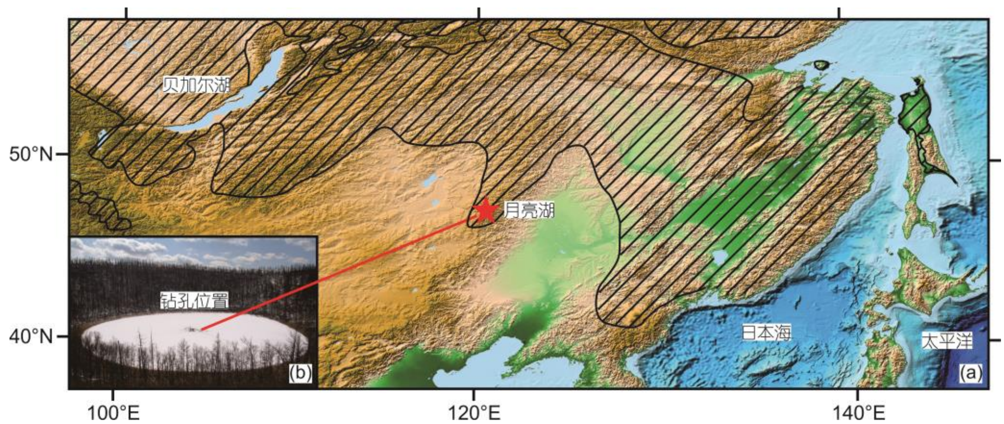

图 1 月亮湖位置及落叶松林在东亚的分布(黑色阴影)(a)以及月亮湖钻孔位置(b)

Figure 1 Location of Lake Moon and distribution of larch forest in the East Asia shown by the black shadow (a) and coring point of Lake Moon (b)

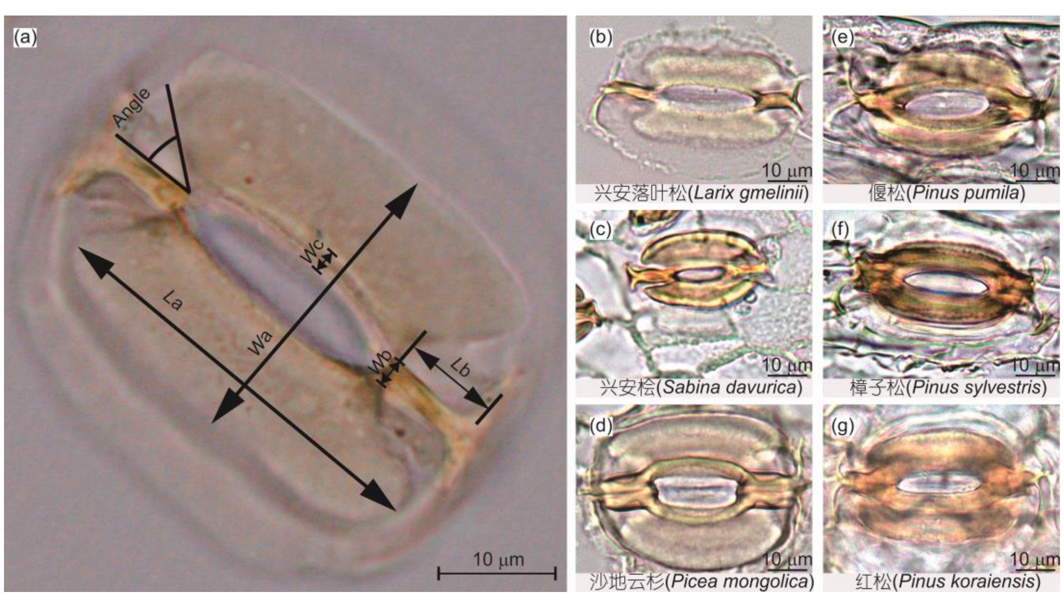

图 2 气孔器的形态参数和照片. (a) 湖泊表层沉积物中落叶松气孔器的形态参数; (b)~(g) 中国东北常见针叶树植物叶片气孔器照片

Figure 2 Morphological indices measured and photoes of stomata. (a) *L.gmelinii* stomata from the lake surface sample with morphological indices measured; (b)–(g) stomata photoes of fresh needles from conifers distributed in Northeast China

属其他种极为相似，易鉴定，研究区其他针叶树气孔器也可以鉴定到属(图2(b)~(g))．月亮湖湖泊沉积物岩芯气孔器分析以2 cm为间隔，自545 cm至沉积序列底部共分析171个样品，每个样品都加入染色的石松孢子以计算气孔器的通量．

月亮湖湖泊沉积物样品中共鉴定出3个类型的针叶树气孔器，绝大部分是落叶松属，圆柏属(*Sabina*)含量低，云杉属(*Picea*)仅零星出现，气孔器的通量约为针叶树花粉的2倍．针叶树气孔器通量和花粉通量如图3所示，其变化揭示了研究区20.3~10.8 cal ka BP的植被演化经历了4个主要阶段．

LM 1带(886~729 cm, 20.3~15.0 cal ka BP)，没有针叶树气孔器出现，花粉通量主要来自草本植物的贡献，阔叶树花粉通量较低，针叶树的花粉通量非常低．LM 2带(729~635 cm, 15.0~12.8 cal ka BP)，以气孔器的出现和阔叶树花粉通量的增加为特征，其中14.3~14.0 cal ka BP气孔器通量和针叶树、阔叶树、草本植物花粉通量的低值将该带分为了3个亚带：LM 2a亚带(15.0~14.3 cal ka BP)以落叶松属气孔器的连续出现、圆柏属气孔器的不连续出现为特征，针叶树、阔叶树的花粉通量较上一带略有升高；LM 2b亚带(14.3~14.0 cal ka BP)气孔器通量和针叶树、阔叶树、草本植物的花粉通量均明显降低；LM 2c亚带(14.0~12.8 cal ka BP)气孔器通量和针叶树、阔叶树、草本植物的花粉通量均有较为明显的增高．LM 3带(635~585 cm, 12.8~11.8 cal ka BP)，该带以针叶树气孔器和针叶树花粉通量达到最高值为特征，阔叶树和草本花粉通量明显降低．LM 4带(585~545 cm, 11.8~10.8 cal ka BP)，该带针叶树气孔器和花粉通量较上一带有所降低，阔叶树和草本花粉通量明显增加．

根据月亮湖沉积记录的气孔器和孢粉分析结果，研究地点的古植被、古气候演化大致经历了以下阶段：20.3~15.0 cal ka BP当地植被以草本植物建群，木本植物不发育，气候寒冷干燥；15.0~12.8 cal ka BP植被由草本植物建群向森林草原转变，以落叶松为代表的针叶树已经到达研究区，针叶树、阔叶树和草本植物的盖度增加，但总盖度仍然比较低，气候条件有所好转，其中14.3~14.0 cal ka BP针叶树、阔叶树、草本植物盖度一致降低，气候变冷；12.8~11.8 cal ka BP森林斑块中阔叶树成分减少，针叶树盖度增高，气候条件恶化；11.8~10.8 cal ka BP森林斑块中针叶树减少，阔叶树成分增加，草本植物盖度也明显增高，气候温暖湿润．

月亮湖晚冰期千年/百年尺度上的植被-气候快速变化表明，15.0 cal ka BP落叶松的出现和格陵兰冰芯记录的北半球温度快速上升的起始时间基本一致，在东亚季风区不同纬度、不同类型沉积序列的高分辨率研究中[24,28]，植被演替反映的这一时间界限也有很好的一致性(图3)．针叶树种与阔叶树种之间此消彼长的现象表明，研究区的植被变化对于气候变化非常敏感．Bølling-Allerød暖期和早全新世喜暖的阔叶树成分增加，而在Younger Dryas冷期阔叶树含量降低，以落叶松和圆柏为主的针叶树成分增加．温度变化可能是影响研究区乔木树种在森林中所占比例变化的主要因素．植被演化阶段明确指示了研究区晚冰期经历的冷暖序列变化与欧洲地区气候变化的

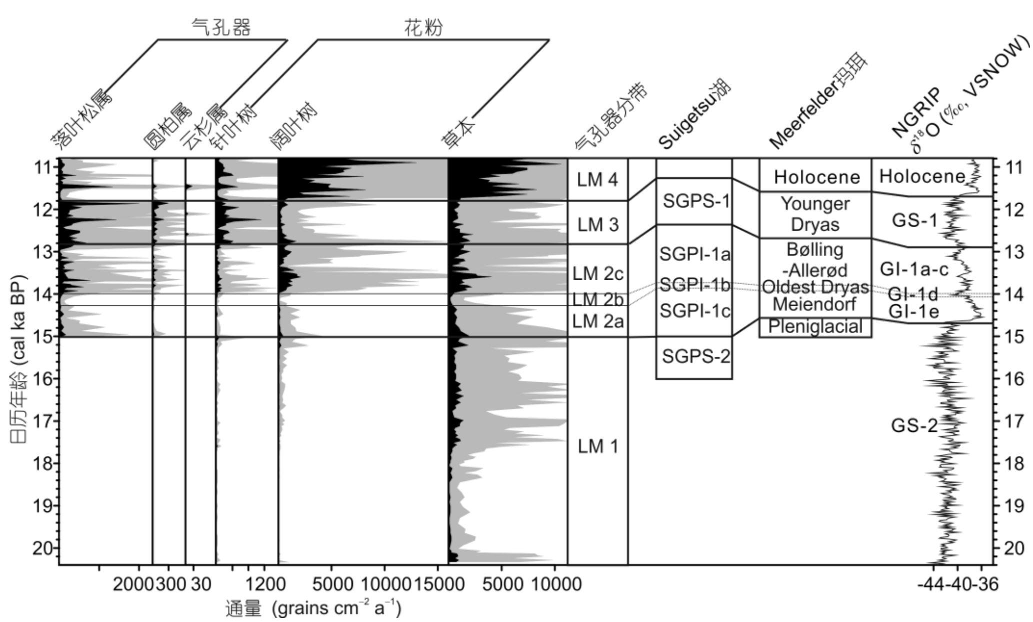

图 3 月亮湖气孔器和花粉通量图[16]与日本Suigetsu湖[24]、德国西北部Meerfelder玛珥[25]沉积地层以及格陵兰冰芯δ^{18}O记录[26,27]的比较

Figure 3 Influx diagram of conifer stomata and pollen[16] from Lake Moon, and comparison with the stratigraphy from Lake Suigetsu in Japan[24] and Meerfelder Maar in NW-Germany[25], δ^{18}O record from Greenland[26,27]

序列相同[25], 如Meiendorf间冰段(15.0~14.3 cal ka BP), Oldest Dryas冷事件(14.3~14.0 cal ka BP), Bølling-Allerød (14.0~12.8 cal ka BP)暖期以及Younger Dryas(12.8~11.8 cal ka BP)冷期等, 在时间上与北大西洋地区气候快速变化基本相同, 与东亚季风区其他记录的对比表明该地区与北大西洋地区晚冰期的气候变化基本同步[24,28,29].

综上所述, 气孔器为大兴安岭地区针叶树演化历史研究提供了新的可靠代用指标. 气孔器和花粉分析的结果表明15.0 cal ka BP之前研究区的植被以草本植物建群, 气候寒冷干燥; 15.0~12.8 cal ka BP植被逐渐向森林草原转变, 温度逐步升高; 12.8~11.8 cal ka BP针叶树扩张, 阔叶树和草本植物减少, 气候变冷; 11.8~10.8 cal ka BP针叶树退缩, 阔叶树和草本植物扩张, 气候温暖湿润. 植被演化阶段指示的研究地点晚冰期千年/百年尺度上的快速气候变化与东亚地区其他记录之间有很好的一致性, 与北大西洋和格陵兰地区的气候变化基本同步.

致谢 感谢中国科学院地质与地球物理研究所吕厚远研究员对文章写作的指导和帮助.

参考文献

1 Prentice I C, Cramer W, Harrison S P, et al. A global biome model based on plant physiology and dominance, soil properties and climate. J Biogeogr, 1992, 19: 117–134

2 Binney H A, Willis K J, Edwards M E, et al. The distribution of late-Quaternary woody taxa in northern Eurasia: Evidence from a new macrofossil database. Quat Sci Rev, 2009, 28: 2445–2464

3 Brubaker L B, Anderson P M, Edwards M E, et al. Beringia as a glacial refugium for boreal trees and shrubs: New perspectives from mapped pollen data. J Biogeogr, 2005, 32: 833–848

4 Feurdean A, Bennike O. Late Quaternary palaeoecological and palaeoclimatological reconstruction in the Gutaiului Mountains, northwest Romania. J Quat Sci, 2004, 19: 809–827

5 Igarashi Y, Murayama M, Igarashi T, et al. History of *Larix* forest in Hokkaido and Sakhalin, northeast Asia since the last glacial. Acta Palaeontol Sin, 2002, 41: 524–533

6 Müller S, Tarasov P E, Andreev A A, et al. Late Quaternary vegetation and environments in the Verkhoyansk Mountains region (NE Asia) reconstructed from a 50-kyr fossil pollen record from Lake Billyakh. Quat Sci Rev, 2010, 29: 2071–2086

7 Xu Q H, Li Y C, Zhou L P, et al. Pollen flux and vertical dispersion in coniferous and deciduous broadleaved mixed forest in the Changbai Mountains. Chin Sci Bull, 2007, 52: 1540–1544 [许清海, 李月丛, 周力平, 等. 长白山针阔混交林带花粉通量及垂直散布特征初步研究. 科学通报, 2007, 52: 568–571]

8 Tong G B, Yang X D, Wang S M, et al. Sporo-pollen dissemination and quantitative character of surface sample of Manzhouli-Dayangshu Region (in Chinese). Acta Bot Sin, 1996, 38: 814–821 [童国榜, 羊向东, 王苏民, 等. 满洲里-大杨树一带表土孢粉的散布规律及数量特征. 植物学报, 1996, 38: 814–821]

9 Macdonald G M. Conifer stomata. In: Smol J P, Birks H J B, Last W M, eds. Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators. Dordrecht: Kluwer Academic Publishers, 2001. 33–47

10 Hansen B C S. Conifer stomate analysis as a paleoecological tool: An example from the Hudson Bay Lowlands. Can J Bot, 1995, 73: 244–252

11 Li C, Li Y. Study of modern pollen and stomata from surficial lacustrine sediments from the eastern edge of Tibetan Plateau, China. Rev Palaeobot Palynol, 2015, 221: 184–191

12 Shen H, Li C, Wan H, et al. Relationships between vegetation and stomata, and between vegetation and pollen surface soil in Yunnan, Southwest China. Chin Sci Bull, 2013, 58: 1775–1786

13 Pisaric M F, MacDonald G M, Cwynar L C, et al. Modern pollen and conifer stomates from north-central Siberian lake sediments: Their use in interpreting late quaternary fossil pollen assemblages. Arct Antarct Alp Res, 2001, 33: 19–27

14 Peñalba M C, Payette S. Late-Holocene expansion of Eastern Larch (*Larix laricina* [Du Roi] K. Koch) in Northwestern Québec. Quat Res, 1997, 48: 114–121

15 Yu Z. Late Quaternary paleoecology of *Thuja* and *Juniperus* (Cupressaceae) at Crawford Lake, Ontario, Canada: Pollen, stomata and macrofossils. Rev Palaeobot Palynol, 1997, 96: 241–254

16 Wu J, Liu Q, Wang L, et al. Vegetation and climate change during the last deglaciation in the Great Khingan Mountain, northeastern China. PLoS One, 2016, 11: 1–16

17 Zhao C, Li X, Zhou X, et al. Holocene vegetation succession and response to climate change on the south bank of the Heilongjiang-Amur River, Mohe County, Northeast China. Adv Meteorol, 2016, 2016: 1–11

18 Nadezda M T, Gerald E R, Elena I P. Impacts of climate change on the distribution of *Larix* spp. and *Pinus Sylvestris* and their climatypes

in Siberia. Mitig Adapt Strat Glob Change, 2005, 11: 861–882
19 Liu Q, Li Q, Wang L, et al. Stable carbon isotope record of bulk organic matter from a sediment core at Moon Lake in the middle part of Daxing'an Mountain Range in Northeast China during the last 21 ka (in Chinese). Quat Res, 2010, 30: 1069–1077 [刘强, 李倩, 旺罗, 等. 21 ka BP 以来大兴安岭中段月亮湖沉积物全岩有机碳同位素组成变化及其古气候意义. 第四纪地质, 2010, 30: 1069–1077]
20 Blaauw M, Christen J A. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Anal, 2011, 6: 457–474
21 Hu Y Q, Mingram J, Stebich M, et al. A key for the identification of conifer stomata from N.E. China based on fluorescence microscopy. Rev Palaeobot Palynol, 2016, 233: 12–21
22 Sweeney C A. A key for the identification of stomata of the native conifers of Scandinavia. Rev Palaeobot Palynol, 2004, 128: 281–290
23 Zhang K, Zhao Y, Guo X L. Conifer stomata analysis in paleoecological studies on the Loess Plateau: An example from Tianchi Lake, Liupan Mountains. J Arid Environ, 2011, 75: 1209–1213
24 Nakagawa T, Kitagawa H, Yasuda Y, et al. Asynchronous climate changes in the North Atlantic and Japan during the last termination. Science, 2003, 299: 688–691
25 Litt T, Stebich M. Bio- and chronostratigraphy of the lateglacial in the Eifel region, Germany. Quat Int, 1999, 61: 5–16
26 Rasmussen S O, Andersen K K, Svensson A M, et al. A new Greenland ice core chronology for the last glacial termination. J Geophys Res, 2006, 111: 907–923
27 Rasmussen S O, Seierstad I K, Andersen K K, et al. Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeo-climatic implications. Quat Sci Rev, 2008, 27: 18–28
28 Xu D, Lu H, Wu N, et al. Asynchronous marine-terrestrial signals of the last deglacial warming in East Asia associated with low- and high-latitude climate changes. Proc Natl Acad Sci USA, 2013, 110: 9657–9662
29 Stebich M, Mingram J, Han J, et al. Late Pleistocene spread of (cool-) temperate forests in Northeast China and climate changes synchronous with the North Atlantic region. Glob Planet Change, 2009, 65: 56–70

Vegetation history and climate change recorded by stomata evidence during the late glacial in the Great Khingan Mountain Region, Northeastern China

WU Jing, LIU Qiang, CHU GuoQiang, WANG Luo & LIU JiaQi

Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

The research on the evolution of larch forest is significant to understand the vegetation and climate change in mid-high latitude region of the Northern Hemisphere. However, the pollen records to reconstruct the larch forest are problematic due to low pollen representation caused by severely poor pollen productivity and dispersal. New proxy of microfossils is needed to solve this problem. Using coniferous stomata as a proxy to reconstruct the evolution of conifers has some advantages, such as well preserved, locally deposited, continuously remained in lake sediments and can be accurately identified to the genus level. Therefore, a high-resolution stomata record covering 20.3–10.8 cal ka BP from Lake Moon was presented, in order to reconstruct larch forest history from the Last Glacial Maximum to early Holocene in the Great Khingan Mountain Region, Northeast China. Reference conifer stomata from fresh leaves of the local coniferous species and lake surface samples were prepared for the identification of the fossil stomata. *Larix*, *Sabina* and *Picea* stomata were identified from the sedimentary sequence of Lake Moon, and the results of stomata influx from this study and pollen influx from the previous study indicate that the vegetation evolution has gone through distinct stages. Before 15.0 cal ka BP, no *Larix* existed in the vicinity of study site. The first arrival of larch is inferred by the continuous presence of stomata at 15.0 cal ka BP, which manifests that the vegetation turned into forest steppe. The coverage of forest increases slightly from 15.0 to 12.8 cal ka BP with an interruption between 14.3 and 14.0 cal ka BP. During 12.8–11.8 cal ka BP, the vegetation were characterized by the expansion of conifers mainly *Larix* and the shrinkage of broadleaves and herbs. From 11.8 to 10.8 cal ka BP, the vegetation type remained as forest steppe with the shrinkage of conifers dominated by *Larix*, in conjunction with the expansion of broadleaves and herbs with high vegetation coverage. The establishment of larch forest inferred by the continuous presence of stomata marks the onset of the late glacial in the Great Khingan Mountain Region at 15.0 cal ka BP. The application of stomata analysis provides detailed scenes of coniferous evolution surrounding the Lake Moon. It is suggested that the analysis of fossil stomata is a valuable tool to demonstrate unambiguous evidence for the local presence of the conifers in study region, even better than pollen records when the component of larch is low in vegetation. The evolution of the forest communities in the late glacial period in the Great Khingan Mountain Region is comparable with the vegetation evolution of other regions at different latitudes in East Asian monsoon region, which indicates that the climate change at millennial/centennial scale in late glacial is roughly synchronous in East Asian monsoon region. The series of climatic periods in this study revealed by the stomata and pollen records is also similar to that of Europe, like Meiendorf interstadial, Oldest Dryas cold event, Bølling-Allerød warm phases, Younger Dryas cold event, warm and humid early Holocene. The temperature change is probably the main factor to impact the vegetation change. The study shows that the vegetation succession in the study area is responsive to the temperature change of the Northern Hemisphere controlled by the global ice volume, and reveals the synchronization of the late glacial climate change in the mid latitude region of East Asia and the North Atlantic region.

late glacial, Lake Moon, stomata, millennial/centennial scale, the Great Khingan Mountain

doi: 10.1360/N972016-01181