DOI: 10.16262/j.cnki.1005-0841.2009.02.002

A New Approach to Reconstruct Paleogene Atmospheric Hydrology at High Latitudes

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Reconstruction of ancient atmospheric conditions through the analysis of precipitation patterns is a novel endeavor in the study of paleoclimate. A new approach is now available for a quantitative reconstruction of Paleogene atmospheric hydrological conditions in High Arctic. It is based on 1) the discovery of exceptionally-preserved Paleogene plant fossils from the Canadian Arctic which yielded in situ labile biomolecules; 2) the development of compound-specific hydrogen isotope analysis which can be applied to small amount of plant material; and 3) taxon-specific apparent hydrogen isotope fractionation factors obtained from empirical measurement. A new moisture recycling model is established to explain the reconstructed paleohydrologic pattern in the High Arctic during Paleogene.

Key words Paleogene hydrology, Arctic air-mass, compound-specific hydrogen isotope analysis, exceptionally-preserved plant fossils, taxon-specific hydrogen fractionation factors

A better understanding of the important role that Polar air-mass played in the past Earth dynamics is critical for the evaluation of the current global climate system and for a more accurate prediction of the impact of future climate changes. Among climate parameters, atmospheric conditions are a key to interpret past climate conditions, while they are also the most difficult to be reconstructed. Cenozoic climate change history, especially during the early Paleogene warming period, is often used as the data resource for the analysis of current climate change. The early Paleogene warmth is composed of a series of hyperthermals among which the Paleocene-Eocene Thermal Maximum (PETM, ~55 Ma) elevated global mean annual temperature (MAT) by ~5℃ in less than 10 000 years with more than 2 000 Gt carbon injected into the atmosphere and ocean. As its rate and magnitude of both temperature increase and greenhouse gas emission are believed to be comparable to those predicted to occur over the coming centuries, PETM as well as the background early Paleogene warmth are considered as one of the geological analogues for modern climate change. Due to the fact that no ice core record can be extended to early Paleogene and ocean sediments from high latitudes are not readily available from polar area, quantitative assessment of precipitation at high latitudes during Paleogene, which largely reflected the then air-mass conditions, has been limited. However, four areas of recent progresses have changed the situation. First, Paleogene fossils unearthed from the Arctic area, particularly those exceptionally-preserved fossil leaves found in Axel Heiberg and Ellesmere Islands in the Canadian Arctic as far north as 80°N, have provided suitable material for taxon-specific molecular level analysis. Second, the improvement of compound-specific hydrogen isotope analysis allowed precisely quantitative assessment of hydrogen isotope values of ancient precipitation which was largely controlled by atmospheric conditions. Third, recent experimental studies have pioneered the evaluation of empirical apparent hydrogen fractionation factors which in turn have increased the accuracy of ancient precipitation reconstruction. Finally, a better modeling of modern air-mass movement aided the effort for a better understanding of ancient

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atmospheric conditions.

Here we summarize these recent theoretical developments and technological breakthroughs based on which we discuss a new approach to infer paleohydrology of the Arctic region through quantitatively reconstructing ancient precipitation using genus-specific stable hydrogen isotopic analysis of *in situ* biomolecules from exceptionally-preserved fossil plants.

An extensive deciduous conifer vegetation of the Paleogene age was discovered in the High Arctic area during the late 19th and early 20th Centuries by pioneer geologists through polar explorations. But no one expected that some of these floras would yield exceptionally-preserved plant fossils (Fossil *Lagerstätten*) from which intact biomolecules can be isolated, characterized, and subjected to the latest isotope measurement[1]. Abundant and exceptionally-preserved fossil leaves that are dominated by three deciduous genera, *Metasequoia* Miki, *Larix* Miller, and *Glyptostrobus* Endlicher, in Axel Heiberg and Ellesmere Islands in the Canadian Arctic as far north as 80°N have illustrated a general picture of the paleoecosystem of lush deciduous conifers (Figure 1, cover picture). Molecular characterizations of these fossils revealed the preservation of a suite of liable biomolecules that were usually only found in a few thousand years old material[2]. These readily identifiable fossils with well-preserved biomolecules provided scientists with opportunities to apply the latest isotope technologies for accurately inferring climate parameters, especially paleo-precipitation that can reveal ancient air-mass conditions.

Among available proxy based techniques used to track long-term hydrospheric changes, stable hydrogen isotopic analysis is a new and powerful tool in diagnosing large-scale ancient hydrological processes by tracing the direct flow of environmental hydrogen. Compared with carbon isotope analysis of bulk material, compound-specific hydrogen isotope analysis yields more precise results by detecting hydrological signals from plant molecules with known origins. In addition, if the taxon-specific hydrogen isotopic analysis using a model plant species, e. g. , a well studied species with morphological stasis, with long history, and with well documented fossil records, is applied, more accurate reconstruction of environmental water hydrogen isotope based upon molecules from that plant taxon can be achieved. *Metasequoia* (also known as Dawn Redwood) is one of these model species with well characterized patterns of biomolecules, carbon and hydrogen isotope signals, as well as apparent hydrogen isotope fractionations under different environmental conditions[3].

One of the roadblocks for accurate reconstruction of hydrogen isotope values of ancient precipitation has been the obtaining of a precise apparent hydrogen isotope fractionation factor between source water and leaf lipid ($\varepsilon_{lipid\text{-}water}$) from plants grown under high latitudinal conditions. The high-latitudes were illuminated by ~4 months of continuous, low angle, and low-intensity light irradiation in the summer and were under darkness of almost equal amount of time duration during the winter time. Such light conditions should have impact on the registration of both environmental carbon and hydrogen isotope signals into leaves of deciduous conifers by impacting their photosynthesis. Previous studies have used average apparent hydrogen fractionation factors regardless of their taxonomy and original latitudes. Such a practice obviously introduced errors. Clearly, a better reconstruction of the difference between precipitation hydrogen isotope values and plant leaf hydrogen isotope signals requires a correction that was affected by the unique light condition at high latitudes, and such a correction can only be precisely made through laboratory (greenhouse) experiments imitating climate conditions of Paleogene Arctic.

The two year experiment was set up at the University of Maine (USA, ~45°N Lat) and led to the determination of the first genus-specific apparent hydrogen isotope fractionation factors between environmental water and leaf lipid of *Metasequoia glyptostroboides* Hu et Cheng (the family Cupressaceae) and *Larix laricina* (Du Roi) K. Koch (the family Pinaceae) in greenhouse with controlled light, water, and CO_2 conditions that best simulated the High Arctic environmental conditions. Genetically identical seedlings were separated into two blocks: One was under diurnal light (DL) and the other was under continuous light (CL) condition that was exposed to 4 months (May-August) artificial Arctic light[4]. Water with known hydrogen isotope compositions was identical for watering plants in the two blocks. When we measured carbon and hydrogen isotopic compositions ($\delta^{13}C$ and δD) from leaf lipids after two years of growth, we detected noticeable difference in isotope fractionations under different light conditions[5]. Applying the obtained empirical data of molecular hydrogen isotope composition, we calculated the apparent hydrogen isotope fractionation factors between leaf wax lipids and source water which were subsequently applied to fossil leaf material to evaluate the hydrological characteristics of Paleogene precipitation in High Arctic[5].

In contrast to previous studies, we reconstructed ancient Arctic hydrological conditions using readily identifiable three-dimensionally-preserved fossil leaves of *Metasequoia* and *Larix* from Canadian Arctic Archipelago (paleolatitude ~80°N) with their hydrogen fractionation factors between leaf molecules and environmental water experimentally determined under simulated Arctic conditions. Given that deciduous conifers in the Paleogene Arctic produced most of their organic matters during the summer growing season under continuous light conditions, hydrogen isotopic ratios of these leaves should reflect summer precipitation δD. To our surprise, our newly reconstructed precipitation δD for growing seasons during early Late Paleocene to Middle Eocene were similar or only slightly more D-depleted to δD values of present-day summer precipitation in the High Arctic[5]. We believe that such hydrogen isotope signals reflect a unique atmospheric condition that existed at the High Arctic during the early Paleogene warming period.

The interpretation of Arctic climate system during Paleogene requires a model that accommodates a much higher global temperature, a low air temperature gradient, an extremely wet Arctic condition, and an ice free polar land that was covered by extensive deciduous plants[6]. A progressive rainout process modeled according to modern atmospheric system may satisfy the low hydrogen isotope values but can not explain the independently documented wet Arctic condition as the low latitude moisture would be lost along the long distance transportation, nor can it accommodate the low temperature gradient that wouldn't facilitate any long trajectory of air-mass transportation[7]. In order to reconcile the reconstructed D-depleted ancient precipitation and high humidity in the Paleogene Arctic, we embarked a new model which proposed an additional source of D-depleted moisture through continental convection of vapor, from both ocean source and evapo-transpiration of land plants in the ancient Arctic[5]. We believe that the local sourced water can significantly influence isotopic signature in precipitation as documented in the tropical and temperate regions[8]. This new model takes the extensive *Metasequoia* dominated forests in the Paleogene Arctic area into full consideration, and it nicely meets paleoenvironmental conditions that were independently reported using conventional paleontological and geological approaches. Furthermore, this new model accounts for the unique polar terrestrial vegetation-climate dynamics under the condition of 24-h continuous light illumination. We further argued that the relationship between the climate and the local vegetation might have played a much more important role in the Paleogene Arctic ecosystems than previously believed.

In conclusion, the Arctic climate during the early Paleogene warmth provides a useful analogue to examine Arctic climate changes under the current global warming context. The challenge of more accurate reconstruction of paleohyrology for Paleogene Arctic is met by analyzing ancient precipitation patterns that were registered as hydrogen isotope signals in plant fossil leaves. Our recent research has shown that insightful information regarding ancient air-mass dynamics in the High Arctic can be inferred by studying compound-specific hydrogen isotope ratios in ancient biomolecules isolated from exceptionally-preserved conifer fossils. Such studies were improved by applying experimentally determined apparent hydrogen isotope fractionation factors from living representatives of these conifers under simulated Arctic light conditions.

This work was funded in part by the CAS/SAFEA International Partnership Program for Creative Research Teams, the Pilot Project of Knowledge Innovation, CAS (KZCX2-YW-105), the Major Basic Research Projects (2006CB806400), the National Science Foundation of China (40402002), the American Chemical Society Petroleum Research Funds, and a NASA RI Space Grant. We thank Yuyang Zhuge for preparation of Cover Figure. This paper is the contribution 201002 for the Laboratory of Terrestrial Environment of Bryant University.

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Thirdly, global change has become a hot issue in basic research. In 2006, the result of a study on the accumulation of organic carbon in mature forest soil was listed as one of the top ten events, and a research on carbon sink was selected in 2007. An oxygen isotope based study on the changes of East Asian monsoon entered the 2008 list of top ten events. In 2009, the result of another research on the carbon balance in China's terrestrial ecosystem was selected, exhibiting the whole society's attention to global change. The continuous investigation into global change not only prepared China for coping with global change, but laid a theoretical foundation for solving those environmental issues that constrained China's economic and social development

Fourthly, state key laboratories functioned as more and more important platforms. For five of the top ten events in 2009, the projects were completed and the main results were obtained by state key laboratories, indicating that with strengthened efforts in the construction of state key laboratories and the convergence of a number of excellent research teams, those laboratories further enhanced their comprehensive capacities and played a more and more important role in the national innovation system.

Fifthly, basic research played a more significant role in supporting the national economic and social development. Food security guarantees the economic and social development in China. Major breakthroughs in hybrid rice research in China has basically solved the food supply for its people and attracted worldwide attention. On this basis, a major breakthrough was achieved again in 2009 on the research of functional genomics of super hybrid rice, shedding light on revealing the genetic basis and molecular mechanism of heterosis, and laying the scientific foundation for improving China's food security capacity.

Lastly, China's traditional preponderant disciplines kept steady development. China enjoys unique academic resources and geographical advantages in paleontology research and has formed a relatively complete research system, displaying international standards in many respects. The animal fossils that were discovered in Chengjiang and Wong'an, Yunnan Province, by Chinese scientists have aroused quite a stir in the international paleontology field. In 2009, China again made a major breakthrough in the origin of birds and found a number of key evidences for solving issues related to the evolution of fingers during the evolution of dinosaurs to birds, resulting in significant international impacts.