Variation of terrestrial ecosystem recorded by stable carbon isotopes of fossils in northern China during the Quaternary

DENG Tao[1, 2], DONG Junshe[1] & WANG Yang[3]

1. Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China;
2. Laboratory of Palaeobiology and Stratigraphy, Chinese Academy of Sciences, Nanjing 210008, China;
3. Department of Geological Sciences, Florida State University, Tallahassee, FL32310, USA

Abstract **Stable carbon isotopes of C_3 and C_4 plants have completely distinct $\delta^{13}C$ values respectively. Carbonate in tooth enamel of herbivorous mammals is significantly and regularly enriched in ^{13}C compared to source carbon. As a result, we can reconstruct distributions of C_3 and C_4 plants in geological history based on carbon isotopes of mammalian tooth enamel. Carbon isotopes of 70 mammalian tooth enamel samples from 11 Quaternary localities in northern China are analyzed. This analysis indicates that C_3 plants were dominant in the terrestrial ecosystem of northern China during the Quaternary, which is completely different from Pakistan with relatively close latitudes where C_4 plants were absolutely dominant. The great difference was caused by the uplift of the Tibetan Plateau. A simulation implied that a marked temperature decrease would happen in the north side of the Tibetan Plateau, but a temperature increase in the south side. The warming condition caused the transition from C_3 to C_4 plants in Pakistan situated in the south side of this plateau. In the north side, on the contrary, the cooling condition restrained the distribution of C_4 plants. As a result, C_3 plants have been dominant in northern China until now.**

Keywords: enamel carbon isotope, northern China, terrestrial ecosystem, Quaternary.

Since the Late Miocene, the global vegetation has shifted from C_3 to C_4 plants. But the expansion of C_4 plants was not simultaneous in the world. Some authors considered even that C_4 plants appeared in 15.3 Ma in East Africa[1]. Expansion of C_4 plants was characteristic of being earlier in low latitudes but later in high latitudes[2]. The stable carbon isotopic analyses to the enamel of mammalian fossils at the beginning of the Quaternary as well as the paleosol carbonate of the red clay-loess sequence during the Late Cenozoic in northwestern China indicated that the vegetable distribution in this region had a feature different from in other regions[3—5]. The present study completely analyzes the enamel isotopes of mammalian teeth in northern China during the Quaternary further, more accurately illustrates the characteristics of the terrestrial ecosystem in this region, and deeply discusses the reasons of its appearance and evolution.

The evidence of C_4 plant advent in the Late Miocene was discovered firstly from the Kranz anatomy on a fossil grass[6]. Many researchers proved that C_4 plants expanded widely in the world after 7 Ma from the evidence of carbon isotopes of fossil soil and mammalian tooth enamel[2,7—13]. C_3 plants have $\delta^{13}C$ values ranging from about −23‰ to −34‰ with an average of −27‰ while C_4 plants from −9‰ to −17‰ with an average of −13‰[14—18]. Soil carbonate and carbonate in tooth enamel of herbivorous mammals is significantly enriched in ^{13}C compared to source carbon. The enriched extent of the enamel carbonate is about 12‰—15‰. The tooth enamel from an animal with pure C_3 diet has a $\delta^{13}C$ value from −15‰ to −12‰ with an average of about −13‰ while that derived from pure C_4 diet has a value from −1‰ to +2‰ with an average of about +1‰[7, 10, 19]. Therefore, we can reconstruct distributions of C_3 and C_4 plants in geological history based on carbon isotopes of fossil soil and mammalian tooth enamel. C_3 plants include trees, most shrubs and many cool-season grasses, while C_4 plants include mostly warm-season grasses. C_3 grasses currently are restricted to cooler high latitude and altitude environments, and can also grow in the understory of forests. On the other hand, C_4 grasses are distributed mainly in tropical and subtropical regions. Because all samples in the enamel isotopic analysis come from herbivorous mammals, C_3 and C_4 plants in this note indicate grasses mainly.

1 Samples and analysis

70 samples of mammalian tooth enamel collected from northern China are analyzed in this paper (fig. 1). All samples come from cheek tooth enamel of herbivorous mammals in the Equidae, Rhinocerotidae, Bovidae, Cervidae, and Proboscidea. The analytic method can be read in ref. [3]. The fossil localities include Xiaochangliang (age: 1.67 Ma, samples: rhinocerotids), Xiashagou (age: 1.5 Ma, samples: equids), Donggutuo (age: 1 Ma, samples: equids and rhinocerotids), and Shenquansi (age: 35ka, samples: equids) in Yangyuan, Hebei; Xinyaozi (age: 2.15 Ma, samples: equids) in Tianzhen, Kehe (age: 1 Ma, samples: rhinocerotids and proboscideans) in Ruicheng, Xujiayao (age: 0.13 Ma, samples: equids and rhinocerotids) in Yanggao, and Tashuihe (age: 26 ka, samples: bovids) in Lingchuan, Shanxi; Bajiazui (age: 2.5 Ma, samples: equids, cervids and bovids) in Qingyang, and Loufangzi (age: 0.12 Ma, samples: equids) in Huanxian, Shaanxi; and Zhoukoudian (age: 0.57—0.3 Ma, samples: equids, rhinocerotids and cervids) in Fangshan, Beijing (fig. 2).

Although the $\delta^{13}C$ values of mammalian tooth enamel fluctuated in northern China during the Quaternary, the carbon isotopic analysis of 70 samples shows that the average of $\delta^{13}C$ values is −8.9‰, which clearly indicates a feature of dominant C_3 plants (about 70%). At the beginning of the Quaternary at 2.5 Ma, the $\delta^{13}C$ value had an average of −10‰, which implied that the C_3 plants were dominant (about 80%)[3]. From 2.15 Ma to 1.5 Ma, $\delta^{13}C$ values fluctuated between −11.28‰ and −0.13‰ with an average of −7.6‰. A $\delta^{13}C$ value of −0.13‰

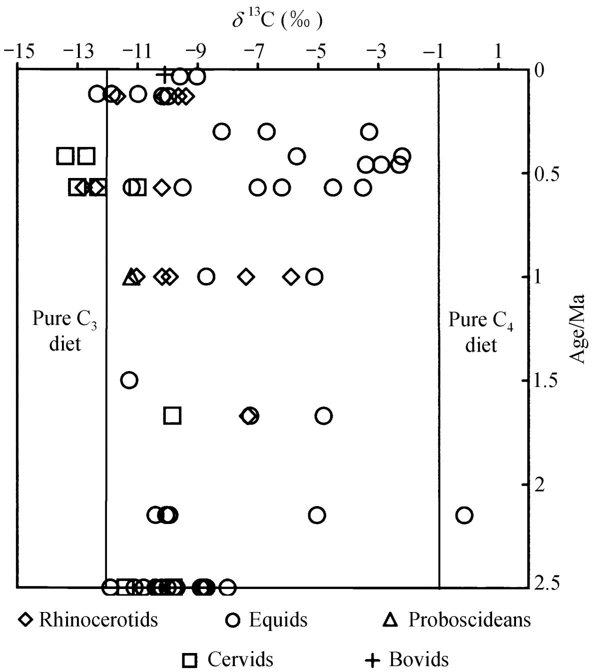

Fig. 1. δ^{13}C values of mammalian tooth enamel from northern China during the Quaternary.

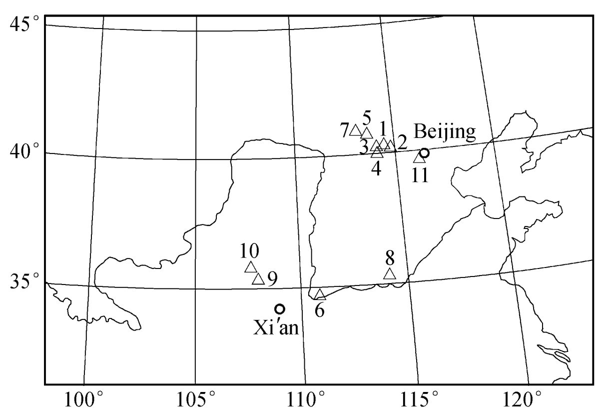

Fig. 2. Geographical locations of the sample localities. 1, Xiaochangliang; 2, Xiashagou; 3, Donggutuo; 4, Shenquansi; 5, Xinyaozi; 6, Kehe; 7, Xujiayao; 8, Tashuihe; 9, Bajiazu; 10, Loufangzi; 11, Zhoukoudian.

showed a nearly pure C_4 diet, but the average of −7.6‰ implied that C_3 plants still were dominant (about 60%) during the Early Pleistocene in northern China. At 1 Ma, the δ^{13}C values ranged from −11.21‰ to −5.12‰ with an average of −8.7‰, as a result, the dominant position of C_3 plants increased further (about 70%). From 0.57 Ma to 0.3 Ma, the δ^{13}C values also fluctuated obviously between −13.4‰ and -2.2‰, but the average of −7.9‰ indicated that C_3 plants still kept the dominant position (about 65%) in the Middle Pleistocene. In the Late Pleistocene from 130 ka to 15 ka, the δ^{13}C values ranged from −11.86‰ to −9.02‰ with an average −10.4‰, so C_3 plants were completely dominant and relatively stable (about 80%).

2 Discussion

A study to the paleosol carbon isotopes of Siwalik in Pakistan indicated that a marked transition from C_3 to C_4 plants took place between 7.4 and 7.0 Ma. This event was considered to be probably relevant to the occurrence and strengthening of the regional Asian monsoon system[9]. Because a similar event was found in non-monsoon North America, it suggested that atmospheric CO_2 concentrations could have fallen below a threshold critical to C_3 photosynthesis[2, 8]. On the other hand, some authors concluded that there was not a global expansion of C_4 plants in the Late Miocene, and that there was no link between changes in C_3/C_4 plants and atmospheric chemistry[1, 20, 21].

The analysis of this study indicates that C_3 plants were dominant in the vegetation of northern China during the Quaternary, and this result is much different from that in Pakistan. The δ^{13}C values of equids and proboscideans from Pakistan during the Quaternary had an average of about 0‰, which indicated a typical C_4 vegetation (about 90%), i.e. C3 plants made up only about 10%. The latitudes of these two regions are very close: the sample localities of Pakistan are situated near 33°N, and all samples studied here come from the localities between the latitudes of 35—40°N in northern China. However, the vegetation of northern China is similar to that of Western Europe in the latitudes between 40°and 50°N[2]. The difference between northern China and Pakistan proves that regional conditions have an important influence to the distribution of C_3/C_4 plants, and the uplift of the Tibetan Plateau is a very important factor. The carbon isotopes of paleosol carbonate in the Late Cenozoic red clay and loess sequence at Lingtai in the east of Gansu Province also indicated that the fluctuation of δ ^{13}C values have strengthened, and C_3 plants have been dominant since 2.0 Ma, making up 80%—60%[4, 5]. This result is identical with the conclusion from tooth enamel in this present note.

The boundary of modern distribution of C_3 and C_4 plants is situated between about 30° and 45° latitude[2]. C_4 plants dominate the region to the south of 50°N in North America[10]. In southern China, C_4 plants make up 70% in the open district near 23°N[22], but C_4 plants decrease to 40% while C_3 plants make up 60% in the steppe of northeastern China between 40° and 50°N[23]. Evidently, the boundary of distributions of C_4 and C_3 plants in China is at least 10° lower than that in North America, which is corresponding to the distribution of C_3/C_4 plants in northern China during the Quaternary. In the region near 35°N in the Mediterranean area on the west end of Eurasia, C_4 plants are much fewer than those in the monsoon area in the same latitude. This regional difference is caused by the typical climate of winter rain in the Mediterranean area where temperature is relatively low in growing season of plants. It indicates that temperature is an important condition to influence distribution of C_3/C_4 plants. In modern China, C_4 plants decrease progressively from southeast to northwest, and the climate becomes cold and dry from warm and wet along this direction. Therefore, temperature and humidity are significant conditions influencing the distribution of C_3/C_4 in China[24].

The great difference in the distribution of C_3/C_4 plants in the Quaternary between Pakistan in the southwest side of the Tibetan Plateau and northern China in the northeast was caused by the uplift of the Tibetan Plateau. Based on a simulation, there was a marked temperature decrease in the north side of the Tibetan Plateau but an increase in the south[25]. The Tibetan Plateau uplifted to reach an influential height in the Late Miocene, meanwhile the Indian monsoon occurred in the south side of this plateau. The condition of temperature increase in the south side of the Tibetan Plateau made C_4 plants replace C_3 plants and dominate Pakistan[9]. In the north side, on the contrary, the temperature decrease caused by the uplift of the Tibetan Plateau restrained expansion of C_4 plants in northern China so that C_3 plants still were dominant in the terrestrial ecosystem of this region during the Quaternary, although the East Asian monsoon had begun its arrival stage since 7.2 Ma.

The strengthening of sea-land thermal contrast as well as longitudinal vapor and heat transportation promotes the development of the East Asian summer monsoon[26]. The temperature decrease in the north side of the Tibetan Plateau made this strengthening of the East Asian monsoon in northern China much weaker than that of the Indian monsoon in the south side of the Tibetan Plateau. At the beginning of the Quaternary at 2.5 Ma, the occurrence of the Great Ice Age made C_3 plants dominant in northern China[3]. But Pakistan, situated in the southwest side of the Tibetan Plateau, was not influenced by the Great Ice Age because of temperature increase caused by the plateau uplift, so C_4 plants held a dominant position in this region. The replacement between glacial and interglacial ages in the Pleistocene caused the variation of the distribution of C_3 and C_4 plants in northern China. Because of temperature decrease in the north side of the Tibetan Plateau caused by the plateau uplift, C_3 plants still dominated northern China in spite of the large fluctuation. Until the present, C_4 plants in the terrestrial ecosystem of northern China have not reached 50%, although the Holocene is in the environment of the Postglacial Age. This is the dramatic effect caused by the uplift of the Tibetan Plateau in the Late Cenozoic for the climate and environment in East Asia.

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