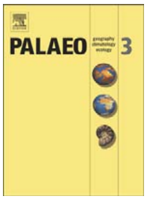
Palaeogeography, Palaeoclimatology, Palaeoecology 279 (2009) 201–206

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo



Significant mid-latitude aridity in the middle Miocene of East Asia

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ARTICLE INFO

Article history:
Received 20 October 2008
Received in revised form 14 May 2009
Accepted 16 May 2009

Keywords:
Herbivorous mammals
Hypsodonty
Paleoprecipitation
Middle Miocene
East Asia

ABSTRACT

The East Asian climate history during the Neogene is a complicated and contentious issue, in particular because of its bearing on the development of the East Asian monsoon and Tibetan uplift chronology. Here we present a paleoprecipitation analysis based on mean molar tooth height (hypsodonty) of large herbivorous mammals to investigate the spatial pattern of climate zonation in East Asia during the middle Miocene. We show a generally humid and uniform situation before the late middle Miocene, replaced by a mid-latitude arid belt from the late middle Miocene, into the earlier part of the late Miocene. These findings are concordant with the global phenomena of the middle Miocene climate optimum and the subsequent cooling, and suggest that the predominant climate in East Asia for most of the Miocene was planetary rather than monsoonal. Our results support a late initiation of the East Asian summer monsoon, coincidentally with the beginning of eolian red clay deposition in the later late Miocene at 7–8 Ma.

1. Introduction

The Neogene climate system represents the transition from the green house climate of the Paleogene to the icehouse climate of the Quaternary (Zachos et al., 2001; Retallack 2001; Willis and McElwain 2002; Bruch et al., 2007). Within the Neogene the middle Miocene is considered the most critical interval, known as "The Middle Miocene Transition" (Flower and Kennett, 1994; Zachos et al., 2001). As a result, the latitudinal gradient increased through time and arid belts appeared in the middle latitudes (Flower and Kennett, 1994).

While the occurrence of continental mid-latitude drying in the later Neogene is well documented from Europe, America, East Africa, Australia and Siwaliks (Flower and Kennett, 1994; Fortelius et al., 2002; Barry et al., 2002; Ivanov et al., 2002; Böhme, 2003; Jiménez-Moreno and Suc, 2007), its occurrence in East Asia remains unclear. In particular, the contentious question of when the Asian monsoon became established complicates the issue. One view holds that the Asian monsoon began in the later late Miocene, ca 7–8 Ma (Sun et al., 1998; Ding et al., 1999, 2001; An et al., 2001), another view has it beginning much earlier, in the early Miocene (Guo et al., 2002; Sun and Wang, 2005). The monsoon shifted the control of East Asian climate from a planetary (north–south gradient) to a monsoonal (west–east gradient) system. Since a dry band at the mid-latitudes represents the north–south gradient such a pattern is unexpected after the shift. In this paper, we present a paleoprecipitation analysis to investigate the spatial pattern of humidity zonation in East Asia during middle Miocene. The investigation makes use of mean hypsodonty, a mammalian proxy for paleoprecipitation (Fortelius et al., 2002). Our data provide independent proof that significant mid-latitude aridity existed in East Asia during the middle Miocene.

2. Analytical methods

We use a method developed by Fortelius et al. (2002) to map the rough rainfall estimation based on large mammal hypsodonty (molar tooth crown height). The higher the crown part of a tooth, the more hypsodont is the animal. For example modern horses of the genus *Equus* are very hypsodont, with high tooth crowns, while *Alces alces* (moose) is brachydont, with low tooth crowns. Increased tooth height or hypsodonty is fundamentally an adaptive response to increasing demands for wear tolerance and functional durability brought about by the development of more fibrous or abrasive plants in a progressively more open and arid-adapted vegetation (Van Valen, 1960; Fortelius, 1985; Janis and Fortelius, 1988; Solounias et al., 1994; Fortelius and Solounias, 2000). The factors favoring hypsodonty are many, but virtually all increase in effect with increasing aridity and openness of the landscape (increased fibrousness, increased abrasiveness due to intracellular silica or extraneous dust, and decreased nutritive value) (Fortelius, 1985; Janis, 1988; Janis and Fortelius, 1988). It should be explained here that once a species has evolved hypsodont teeth, they appear not to revert to a more brachydont state even if the diet becomes less demanding (Fortelius, 1985). However, the main proximate mechanism determining mean hypsodonty is not evolutionary change but geographic sorting of species. A lowering of mean hypsodonty is easily accomplished by immigration of species with low-crowned teeth, even in the unlikely case of all hypsodont species remaining unaffected

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doi:10.1016/j.palaeo.2009.05.014

by the change. Even today, after millions of years of increasing tooth height in many lineages, there is a strong relationship between local mean hypsodonty and local mean annual precipitation in modern mammal communities (Damuth and Fortelius, 2001). In our view, hypsodonty implies a condition of the vegetation that might be termed 'generalized water stress', either in overall conditions, or perhaps more commonly, as a regularly occurring extreme period, such as a dry season. The higher the mean hypsodonty, the more arid the environment, while low hypsodonty value indicates more humid conditions. Further description of the method can be found in Fortelius et al. (2002, 2006) and Eronen (2006).

Our analysis is based on a dataset derived from the Neogene Old World Database (NOW) (Fortelius, 2008). The dataset was downloaded on 6th April 2008. We constrained our investigation to Chinese localities, and we selected only large mammals classified as plant-eaters or plant-dominated omnivores for our analysis. Thus, all pigs were included but no carnivoran omnivores. Localities with only one large herbivore species were omitted from the analysis to minimize random noise, indeterminate species were also omitted if the same genus species was already present in the locality. The three hypsodonty classes were assigned scores of 1 (brachydont), 2 (mesodont) and 3 (hypsodont). The mean hypsodonty value in

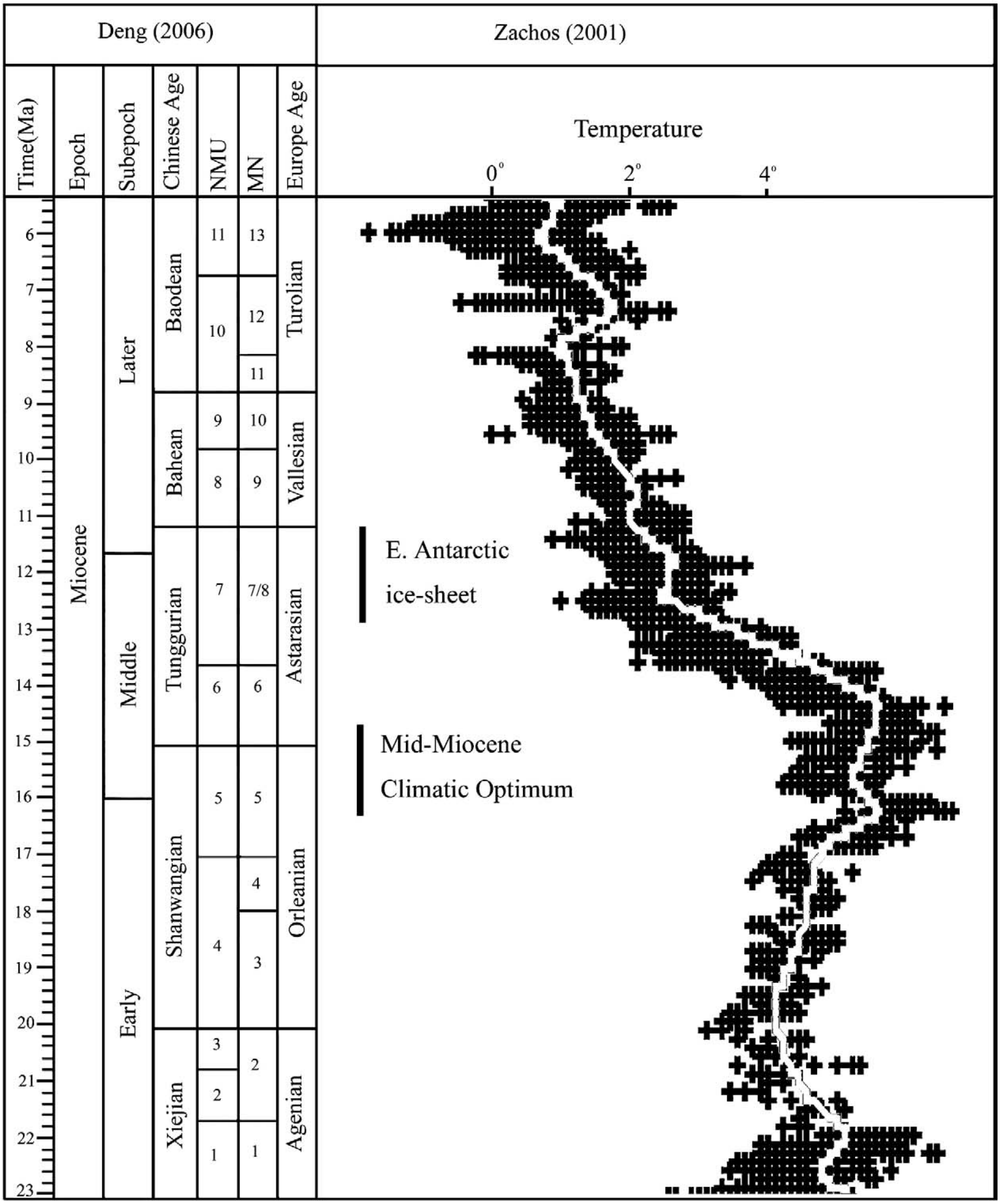

Fig. 1. Correlation of Chinese (NMU) and European (MN) mammal zones according to Deng (2006), with Cenozoic temperature history and events from Zachos (2001).

every locality was calculated by averaging its herbivore scores. The possible range of mean hypsodonty is thereby constrained to values between 1 and 3. The mean hypsodonty values were plotted on maps using interpolated contours.

As in previous analyses (Fortelius et al., 2002, 2003, 2006), we used modern maps as a background for these patterns. All GIS maps were made in MapInfo Professional 8.0 using the inverse distance weighted (IDW) algorithm and the following settings: cell size 50 km, search radius 500 km, grid border 500 km, number of inflections 10, and values rounded to 1 decimal. After this, they were imported to Vertical Mapper 8.0 and contoured to 4 classes.

We tested the statistical differences of mean hypsodonty values between timeslices (NMUs) using ANOVA and Kruskal–Wallis tests in JMP 7.01.

3. Study area and age control

Our investigation covers the whole of China. In order to better understand the middle Miocene climate evolution, we recently updated all relevant Chinese localities to correlate with the most detailed dating scheme available (Fig. 1) — the Chinese Neogene Mammal Unit (NMU) zonation described by Qiu et al. (1999). We also reviewed the taxon occurrence data for these localities. In contrast to our previous investigations (Fortelius et al., 2002, 2003; Eronen, 2006), the previously unified middle Miocene localities are here divided between the early middle Miocene (NMU6) and the late middle Miocene (NMU7) time units. In order to show the context of the middle Miocene pattern, the late early Miocene (NMU5) and the early late Miocene (NMU8) are also included in our analysis (Table 1).

In the NOW database, each locality has a maximum and a minimum age estimate, in most cases based on the boundaries of either a magnetochron or NMU. The NMU calibration follows the calibration of MN units, based on Steininger et al. (1996) in the NOW database but on Steininger (1999) in this paper. Localities were grouped into four time intervals as late early Miocene (NMU5), early middle Miocene (NMU6), late middle Miocene (NMU7), and early late Miocene (NMU8). Localities that could not be assigned to a single NMU were excluded from the analysis. We also exclude the recently reviewed Qaidam-tuosu fauna (Wang et al., 2007) because its endemic bovids such as *Olonbulukia*, *Qurliqnoria*, *Tossunnoria*, and *Tsaidamotherium* have no known dentition to be scored in the hyposodonty analysis. Faunas from the Wuzhong-ganhegou and Zhongning-ganhegou localities share *Qurliqnoria cheni*, *Hipparion*, and *Tetralophodon* with Qaidam-tuoso fauna, and are correlated with

Table 1
Localities included in the analyses, with age references and mean hypsodonty values (* signifies magnetostratigraphic age, + signifies radioisotopic age, all other ages are based on by mammal biostratigraphy).

Epoch	Mammal Age	Mammal Zone	Locality	Age Reference	Mean hypsodonty (number of taxa)
Late Miocene	Bahean	NMU8= MN9	Amuwusu	Qiu, 2006	1(3)
			Wuzhong-ganhegou	this paper	1.67(3)
			Zhongning-ganhegou	this paper	2.33(3)
			Dongxiang-wangji	Deng et al., 2004	3(2)
		11.1Ma	Guonigou*	Deng et al., 2004	2.5(6)
Middle Miocene	Tungurian	NMU7=MN7+8	Xiaolongtan	Qiu et Qiu, 1995	1(7)
			Tunggur-moergen*	Qiu, 2006	1.37(19)
			Lantian-gaopo-64008	Qiu et Qiu, 1995	1.5(4)
			Lantian-gaopo-64004	Qiu et Qiu, 1995	1.67(3)
			Minghe-lierbao	Li et al., 1981	1.5(4)
			Minghe-nanhawangou	Li et al., 1981	1.5(4)
			Xin'an	this paper	1.5(4)
			Lanzhou-quantougou	Qiu, 2006	1(2)
			Siziwangqi-damiao	Zhang and Harrison, 2007	1(2)
			Junggar-duolebulejin	Wu et al., 1998	1.75(8)
			Lengshuigou	Qiu et Qiu, 1995	1.73(11)
		13.5Ma	Fangxian	Qiu et Qiu, 1995	1.8(5)
		NMU6=MN6	Junggar-botamoyin	Wu et al., 1998	1(8)
			Junggar-botamoyindong	Wu et al., 1998	1(2)
			Junggar-chibaerwoyi	Wu et al., 1998	1(4)
			Junggar-ganqikairixi	Wu et al., 1998	1(2)
			Junggar-tieersihabahe	Wu et al., 1998	1(6)
			Lantian-koujiacun	Qiu and Qiu, 1995	1(2)
			Tairum-Nor*	Qiu, 2006	1.4(5)
			Tongxin-gujiazhuang	Qiu et Qiu, 1995	1(3)
			Tongxin-jinzuizigou	Qiu et Qiu, 1995	1(2)
			Tongxin-maerzuizigou	Qiuet Qiu, 1995	1(4)
			Tongxin-shataigou	Qiu et Qiu, 1995	1(3)
			Tongxin-yehuliquezi	Qiu et Qiu, 1995	1(2)
			Tongxin-dingjiaergou	Qiu et Qiu, 1995	1.29(7)
			Tongxin	Qiu et Qiu, 1995	1.33(6)
			Liuhe-lingyanshan+	Shao et al., 1989	1(3)
			Hezheng-laogou	Deng, 2006	1.36(11)
			Qaidam-olongbuluk*	Wang et al., 2007	1.4(5)
		15.0Ma	Jiulongkou	Qiu et Qiu, 1995	1.22(9)
Early Miocene	Shanwangian	NMU5= MN5	Zhongxiang-xiaodian	Qiu et al., 1986	1(2)
			Shanwang	Qiu and Qui, 1995	1(15)
			Guanghe-wangshijie	Deng, 2006	1.4(5)
			Guanghe-dalanggou	Deng, 2006	1(3)

Mammal zones are correlated according to Steininger (1999), with MN-NMU-correlation from Deng (2006). Data from Wu et al., 1998, Shao et al., 1989, Qiu et al., 1986, Qiu and Qiu, 1995, Qiu, 2006, Li et al., 1981, Deng et al., 2004, and Deng, 2006.

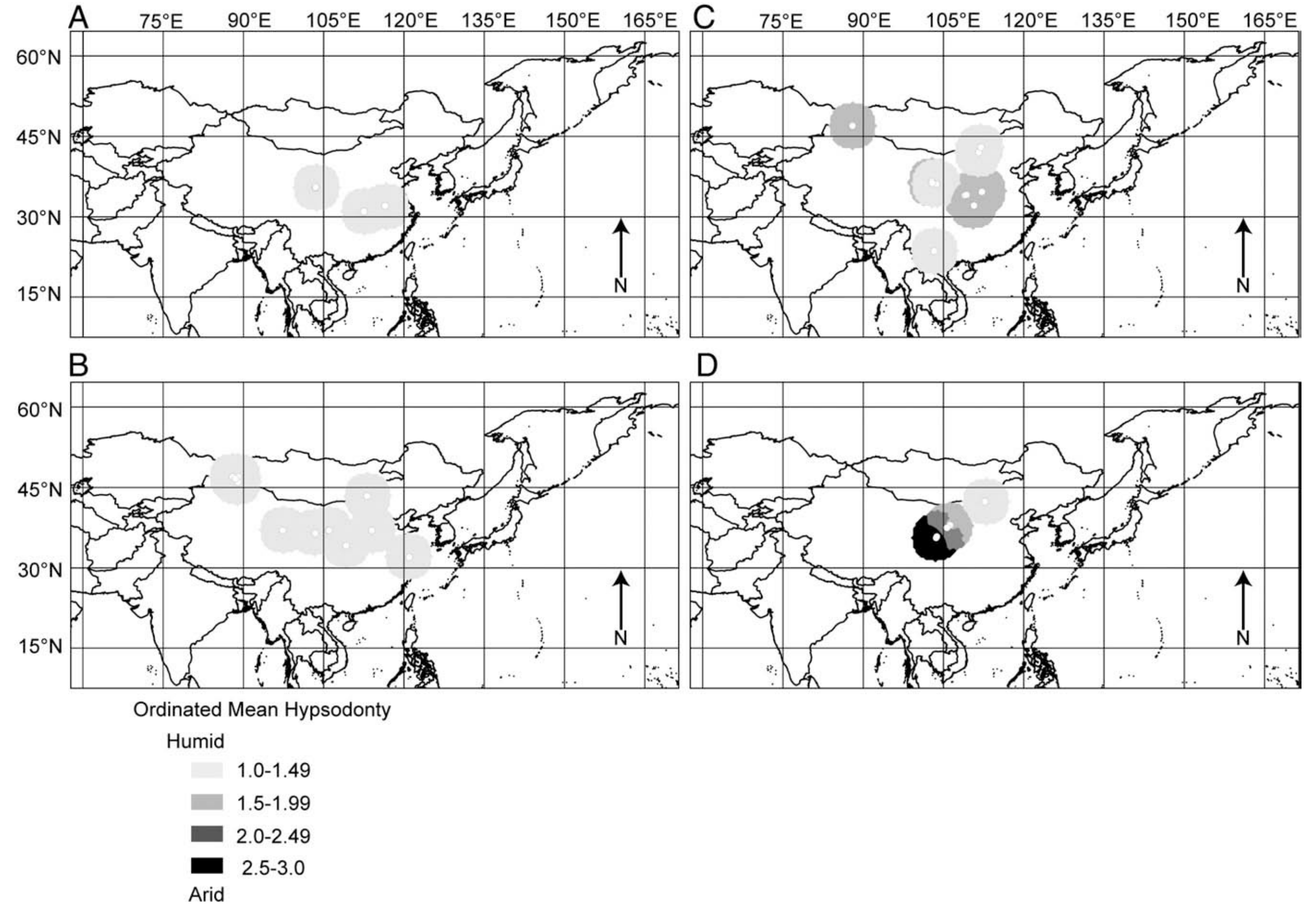

Fig. 2. Mammal hypsodonty maps for Chinese Miocene localities. A, NMU5 (17–15 Ma); B, NMU6 (15–13.5 Ma); C, NMU7 (13.5–11.1 Ma); D, NMU8 (11.1–9.7 Ma).

NMU8 according to recent work in Qaidam (Wang et al., 2007). Locality Xin'an is considered NMU7, because the more advanced suid *Miochoerus* replaces *Kubanochoerus* (Chen, 1997).

4. Results and discussion

In the late early Miocene and early middle Miocene (NMU5-6, 17–13.5 Ma) the whole study area was relatively humid (showing low hypsodonty values; Fig. 2A,B; Table 1). The far west of China shows a similar range of values as seen in the east, and there is no clear evidence of a latitudinal gradient.

A change is seen between NMU6 and NMU7. As indicated by Fig. 2C, although there is some variability among mid-latitude localities, multiple localities indicate more arid conditions in the mid-latitudes during late middle Miocene (NMU7, 13.5–11.1 Ma), while more humid conditions prevailed in the northern and southern areas. There are only two localities in the north showing more humid conditions (Fig. 2C, see also Appendix), but both can be considered relatively solid. The classic locality of Tunggur-moergen has 19 species and very low mean tooth crown height value, while Siziwanqi-damiao includes the primate genus *Pliopithecus*, indicating relatively closed conditions. All other occurrences of *Pliopithecus* in our dataset are in NMU6 localities with mean hypsodonty <1.4: Hezheng-laogou, Junggar-Tieersihabahe, Tongxin-maerzuizigou, and Tongxin (general locality). Taken together this evidence robustly supports the interpretation that relatively humid conditions persisted and most likely dominated, in northern China during NMU7. The observed mid-latitude drying was further strengthened in the early late Miocene, although southern China is unsampled in this interval (NMU8, 11.1–9.7 Ma; Fig. 2D). Statistically, the patterns of NMU5 and NMU6 do not differ from each other (Kruskall–Wallis test, $P=0.92$) and the difference between NMU7 and NMU8 is at most marginally significant ($P=0.09$). However, the difference between NMU6 and NMU7, corresponding to the postulated appearance of a relatively dry belt in the mid-latitudes, is significant ($P<0.002$), while the, difference between the early middle Miocene (NMU5 + NMU6) and the late Middle Miocene (NMU7 + NMU8) is highly significant ($P<0.0001$).

The generally humid and uniform situation during the late early Miocene and early middle Miocene suggested by the hypsodonty proxy conforms to the global pattern (Flower and Kennett, 1994; Fortelius et al., 2002; Böhme, 2003; Bruch et al., 2004; Kaandorp et al., 2005) associated with the climatic phase known as the "Mid-Miocene Climatic Optimum" (Flower and Kennett, 1994; Zachos et al., 2001). The homogenous environment in Eurasia allowed increased dispersal of species, e.g. *Anchitherium* (originally from North America), *Listriodon* (originally from the Indian Subcontinent), *Platybelodon* and *Gomphotherium* (originally from Africa), which are well documented across the continent. The humid-favoring primate *Pliopithecus* (of African origin) was widely distributed in the study area (Junggar, Hezheng and Tongxin) as well as across Europe (Eronen and Rook, 2004).

In the late middle Miocene (13.5 Ma, ref. Steininger (1999)), the drier areas extended from western China to the eastern coast, while humid areas became restricted to the southern and northern parts. The hypsodont genus *Hispanotherium* ranged east to Fangxian (Hubei), a humid area today. *Pliopithecus* disappeared from mid-latitude areas and pliopithecids were only recorded in the north (Zhang and Harrison, 2008) (there is no good evidence available from the south). During the early late Miocene, mid-latitude aridity intensified. Mid-latitude drying from the late middle Miocene onwards appears concordant with global cooling following the "Middle Miocene Transition" around 15–13 Ma ago (Flower and Kennett, 1994; Zachos et al., 2001; Shevenell et al., 2004). The reasons for middle Miocene cooling are still debated, the most prominent hypotheses being based on changes in atmospheric CO_2 or on continental configurations (e.g. Zachos et al., 2001; DeConto and Pollard, 2003; Barker and Thomas, 2004; Pagani et al., 2005; Kürschner et al., 2008).

The pattern of an arid belt in the middle latitudes discussed above closely resembles what is known from the plant record for the Oligocene according to Sun and Wang (2005), but differs from their Miocene pattern, which shows an arid northwest and a humid northeast. The higher temporal resolution offered by the mammal record reveals that the earlier Miocene environments did not yet have such a "monsoonal" distribution. We have previously shown that the west–east gradient pattern did not develop until the later late Miocene (Fortelius et al., 2002; Eronen, 2006). Our results suggest that the Miocene west–east gradient pattern of the pollen data, reflecting a fully developed monsoonal climate, is strongly driven by localities representing the latest Miocene.

According to our previous hypsodonty analysis (e.g. Fortelius et al., 2002; Eronen, 2006), northern China became more humid from approximately the time of onset of red clay deposition at 7–8 Ma (Sun et al., 1998; Ding et al., 1999; Kaakinen, 2005; Passey et al., 2008). Our interpretation that this change was due to onset or intensification of summer rains is in agreement with multiple lines of evidence, pointing to the start of the proper summer monsoon in East Asia around this time (An et al., 2001; Ding et al., 2001). The present study of the early and middle Miocene adds details to this scenario, suggesting that the predominant wind pattern of the Miocene was the planetary (Oligocene-like) one, with dry summers and a distinctive dry belt in the middle latitudes. The seasonality and regional differentiation were weakened during the warm phase of the climatic optimum, but regained strength with the global cooling in the later middle Miocene and persisted until the beginning of strong summer monsoon in the later late Miocene, when the present monsoonal pattern with a southeast–northwest humidity gradient and humid summers was established. The environmental part of this scenario is robust under multiple climatic interpretations. The particular climatic hypothesis offered here is testable in principle, requiring only that the summer–winter polarity of the wet–dry seasonality can be established from the sedimentary record by independent means.

Acknowledgements

We thank the Academy of Finland for project funding on long-term work in China (to MF). LLP is indebted to the support from the Major Basic Research Projects of MST of China (2006CB806400), the NSFC (40872018, 40672010) and State Key Laboratory of Paleobiology and Stratigraphy (Nanjing Institute of Geology and Paleontology, CAS) (No.083114), JTE and LLP acknowledge funding support from Kone Foundation. We thank Anu Kaakinen, Zhang Zhaoqun and Ben Passey for discussions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.palaeo.2009.05.014.

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