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Paleogene temperature gradient, seasonal variation and climate evolution of northeast China

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ABSTRACT

Continental Paleogene climates have been well studied in Europe and North America, but very little is known from Asia because paleoclimatic results have only been reported from particular geological intervals. Here, based on 29 plant assemblages from 8 well age-controlled fossiliferous sites, we quantitatively reconstruct the climates through most of the Paleogene of northeast China and discuss related seasonal variations. Our results demonstrate that the mean annual temperature (MAT) gradient was fairly shallow (0.27 °C/1° latitude) during the Paleocene throughout this region. In the Eocene, seasonality was high in the region, indicated by marked differences in both temperature and precipitation between winters and summers of the sites. The paleo-East Asian monsoon must have had intensified at least in the late mid Eocene, shown by apparent differences in annual precipitation distribution at all the sites. Regarding the Paleogene climatic evolution of northeast China, our quantitative results suggest that MAT overall declined from warm in the Paleocene and Eocene to moderate in the Oligocene, generally consistent with the trend of marine records but with some distinctions. Two significant cooling events are recognized in the early and mid Eocene with MAT 3.4 °C and 3.8 °C lower, and winter temperature 5.8 °C and 4.7 °C lower, respectively, in similar magnitudes to corresponding variations in Europe and North America. Furthermore, the present results show that MAT rebounded in the late mid Eocene and then decreased until the Oligocene, a similar pattern demonstrated in Europe during the mid Eocene to Oligocene interval.

1. Introduction

Paleogene climates are characterized as being in a generally warm and equable "greenhouse" state across the world, punctuated by brief hyperthermals, and a transition to an "icehouse" state by the late Eocene to early Oligocene (Zachos et al., 2008; Eldrett et al., 2009). The climatic evolution during this period provides unique perspectives for the modern global changes that help probe into the integrated response of the Earth system to various driving forces (Zachos et al., 2008; Utescher et al., 2009). Case studies of geological records offer direct evidence to explain the paleoclimatic changes, while model simulations of quantitative paleoclimatic results are of considerable potential for climate prediction, especially for events such as hyperthermals in the latest Paleocene to earliest Eocene interval, the long- and short-lived optima during the Eocene, and the "icehouse" both in the Eocene–Oligocene transition and the latest Oligocene (Sloan and Barron, 1992; Shellito and Sloan, 2006; Zachos et al., 2008; Bijl et al., 2009; Eldrett et al., 2009; Stap et al., 2010; Huber and Caballero, 2011).

The evolution of Paleogene climates has been well studied on the basis of either fossil plants from Australia, Europe and North America (Greenwood and Wing, 1995; Wilf, 2000; Wing and Harrington, 2001; Jolley and Widdowson, 2005; Mosbrugger et al., 2005; Wing et al., 2005; Utescher et al., 2007; Greenwood et al., 2010; Utescher et al., 2011) or marine proxy data from both hemispheres (Pearson et al., 2007; Zachos et al., 2008; Bijl et al., 2009). However, it is only recently that quantitative climatic reconstructions have been conducted on individual sites of the East Asian Paleogene (e.g., He and Tao, 1997; Quan and Zhang, 2005; Su et al., 2009; Hao et al., 2010; Wang et al., 2010). These studies have largely improved the paleoenvironmental interpretations of this vast region, but an overview of the climate trend in East Asia is still lacking. This is mainly because of the poor stratigraphic resolution and confused sampling horizons of plant fossils, limiting paleoclimate simulation at a global scale. For example, Shellito and Sloan (2006) modeled the dynamic progress of vegetation distribution in the early Eocene to examine the vegetation response to coeval climate changes in which studies the East Asian data had to be inferred from North American analogues. On the other hand, Paleogene climatic data have been

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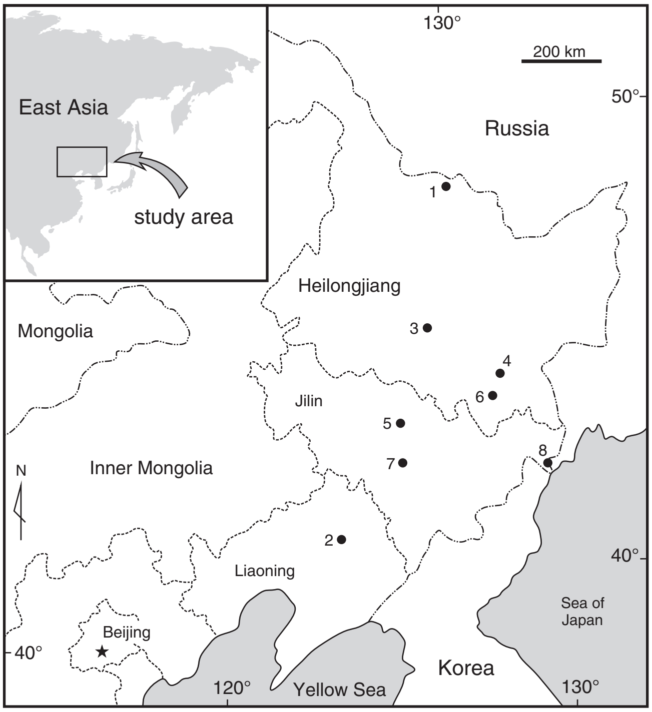

Fig. 1. Location of plant fossil sites. 1. Wuyun; 2. Fushun; 3. Yilan; 4. Hualin; 5. Shulan; 6. Huanghua; 7. Huadian; 8. Hunchun.

accumulated over recent decades based on both continental quantitative estimates and marine proxy results. It is unfortunate that emphases have been usually imposed on mean annual climatic conditions; as a result, only a few studies have reconstructed the seasonal changes of paleoclimates (e.g., Crowley et al., 1986; Greenwood and Wing, 1995; Eldrett et al., 2009). Seasonal variations play one of the key roles in the climate system that are primarily controlled by land–sea distribution, general atmospheric circulation, and ocean currents (Rohli and Vega, 2008). Therefore seasonality, including annual distributions of both temperature and precipitation, is also critical to paleoclimatic studies.

In this paper, we report the quantitative estimates of Paleogene climate changes throughout northeast China on the basis of independently age-constrained plant fossil assemblages. We focus on the evolution of paleoclimate in this region, particularly the geographical distribution and seasonal variations of the paleoclimates (Fig. 1 and Table 1). Our results demonstrate that the Paleogene climates underwent a generally similar pattern to those revealed by marine isotopic proxies and fossil plants from other continents, but show a strong seasonality indicated by high annual thermal and hydrological differentiations.

2. Selection of plant assemblages, stratigraphical background, and age control

Although dozens of the Paleogene sites have been documented from northeast China (Liu et al., 1996; Zhou and Wu, 2002), a total of 29 plant assemblages from 8 sites were selected in the present study because their ages are well constrained (Fig. 1; Table 2). In general, an assemblage was selected when its age is controlled by at least two independent methods (Table 2). An assemblage whose age is only implied by plant fossils is excluded here, regardless of either its biodiversity and abundance, or its potential importance for paleoclimatic reconstruction of some critical intervals. For example, the flora from Sanhe of Jilin Province has been interpreted as Oligocene based on floristic correlations with the adjacent Korean floras (Guo and Zhang, 2002). This is the only known Oligocene site in northeast China with abundant well-preserved macrofossil plants. However, this flora is precluded from the present study because we lack further corroborative evidence for its age-control.

Among these 8 sites, the fossil assemblages used for analysis of the climate evolution are mainly from the following 3 sites, i.e. Fushun, Shulan, and Yilan, because deposits of these 3 sites span the majority of the Paleogene (Fig. 2; Table 2). Stratigraphically, the Paleogene strata of these 3 sites, whose geological features are briefly summarized below, can be well correlated by geochronological results (Zhao et al., 1994; Huang et al., 1998; Yang et al., 2004; Zhang et al., 2007a, 2007b; Shi et al., 2008a) (Fig. 2). The other 5 sites are mainly used to complement the overall climates in the Paleogene.

The Fushun Opencast Coalmine (Site 2 in Fig. 1) is located in a relatively small east–west-trending exposure of Mesozoic and Cenozoic rocks surrounded by Precambrian terrane (Johnson, 1990; Wu et al., 2002). The strata present in the mine are well exposed along the slopes of excavated pits. These continental sequences consist of swampy to fluvio-deltaic and tuffaceous sediments that were deposited in the basin during the early Paleogene (Hong et al., 1980; Johnson, 1990; Yang and Li, 1997; Wu et al., 2002). In ascending order, the sequence is subdivided into Laohutai, Lizigou, Guchengzi, Jijuntun, Xilutian, and Gengjiajie formations (Fig. 2). This sedimentary sequence across the mid Paleocene to late Eocene lacks noticeable unconformities except for the paraconformity between the first two formations, i.e., the Laohutai and Lizigou formations (Hong et al., 1980; Yang and Li, 1997; Fig. 2). In addition to the paleobotanical record, the ages of these formations have been constrained by evidence of either paleomagnetism, isotopes, or animals (Hong et al., 1980; Zhao et al., 1994; Shi, 2010, personal communication) (Table 2; Fig. 2).

In Shulan of Jilin Province (Site 5 in Fig. 1), the Paleogene sediments with fossil plants are subdivided into 3 units. The Bangchuigou and the overlying Jishu formations span the Eocene period, while the Shuiquliu Formation is aged as the Oligocene (Fig. 2). The Bangchuigou Formation is composed of depositional cyclicity incarnating by the lithological transformations among grey sandy stone, yellow-grey siltstone, green mudstone, and clay, mainly deposited in swampy, lacustrine, and deltaic environments (Li, 1997). The Jishu Formation is further subdivided into the coal-bearing member (the lower member) and upper brown sand- and mudstone member (the upper member) (Fig. 2), deposited alternately in lacustrine, swampy, and fluvial environments (Li, 1997). Paleomagnetic dating results indicate that both the Bangchuigou and Jishu formations span the Eocene Epoch (Zhao et al., 1994). On the other hand, the

Table 1
Modern climate of studied sites. Data are available on the website of China Meteorological Data Sharing Service System (open access to registered user, http://cdc.cma.gov.cn/).

Site	MAT (°C)	CMM (°C)	WMM (°C)	MART (°C)	MAP (mm)	HMP (mm)	LMP (mm)	PWM (mm)	MARP (mm)
1. Wuyun	−1.1	−28.5	20.9	49.4	592	146	5	146	141
2. Fushun	8.1	−11.5	24.5	36.0	684	167	7	167	160
3.Yilan	3.4	−19.5	22.4	41.9	513	138	3	128	135
4. Hualin	3.2	−18.8	22.0	40.8	423	122	4	110	118
5. Shulan	5.2	−16.1	22.6	38.7	576	185	3	185	182
6. Huanghua	3.8	−18.0	21.9	39.9	531	120	4	120	116
7. Huadian	6.2	−14.3	23.4	37.7	634	182	5	182	177
8. Hunchun	5.7	−14.0	21.3	35.3	606	134	5	134	129