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Late Cenozoic genus *Fupingopollenites* development and its implications for the Asian summer monsoon evolution

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A B S T R A C T

An extinct palynomorph, *Fupingopollenites*, was used as the basis for a discussion of the late Cenozoic Asian summer monsoon (ASM) evolution and its possible driving forces. Based on the spatial and temporal variations in its percentages across Inner and East Asia, we found that *Fupingopollenites* mainly occurred in East Asia, with boundaries to the NE of ca. 42°N, 135°E and NW of ca. 36°N, 103°E during the Early Miocene (ca. 23–17 Ma). This region enlarged westwards, reaching the eastern Qaidam Basin (ca. 36°N, 97.5°E) during the Middle Miocene (ca. 17–11 Ma), before noticeably retreating to a region bounded to the NW at ca. 33°N, 105°E during ca. 11–5.3 Ma. The region then shrank further in the Pliocene, with the NE boundary shrinking southwards to about 35°N, 120°E; the area then almost disappeared during the Pleistocene (2.6–0 Ma). The flourishing and subsequent extinction of *Fupingopollenites* is indicative of a narrow ecological amplitude with a critical dependence on habitat humidity and temperature (most likely mean annual precipitation (MAP) > 1000 mm and mean annual temperature (MAT) > 10 °C). Therefore, the *Fupingopollenites* geographic distribution can indicate the humid ASM evolution during the late Cenozoic, revealing that the strongest ASM period occurred during the Middle Miocene Climate Optimum (MMCO, ~17–14 Ma), after which the ASM weakened coincident with global cooling. We argue that the global cooling played a critical role in the ASM evolution, while the Tibetan Plateau uplifts made a relatively small contribution.

1. Introduction

The humid monsoonal East Asia and contrasting dry Inner Asia (monsoon–arid system) are the basic environmental characteristics of Asia. Many studies have focused on the region's climatic patterns, including their origin, development and driving forces. Previous studies have shown that the middle Cenozoic was the key period in the origin of the monsoon: for example, based on the compiled results from different climatic proxies (including pollen, mammals, megafloras, lithology, halite, gypsum etc.), the East Asian summer monsoon was initiated during the late Oligocene–early Miocene (e.g., Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008), when the arid zone became restricted to Northwest China. The paleoclimate parameters of the Lanzhou Basin, retrieved from pollen records, even indicate an embryonic monsoon as early as ca. 30 Ma (Miao et al., 2013a). However, in terms of its development, opinions are widely debated, briefly including phase strengthening (e.g., Kutzbach et al., 1993; Li and Fang, 1999; Ding and Yang, 2000; An et al., 2001, 2005; Molnar, 2005; Sun et al., 2010; Li et al., 2014) in contrast to continuous weakening (e.g., Passey et al., 2009; Lu et al., 2010; Miao et al., 2012, 2013b) or no obvious changes during the whole Miocene (e.g., Liu et al., 2011). There are two contradictory opinions regarding the monsoon driving forces: one is that the uplift of the Tibetan Plateau was a significant forcing factor for the ASM intensity through its physical (Kutzbach et al., 1989; An et al., 2001; Molnar et al., 2010) and chemical effects (Raymo and Ruddiman, 1992; France and Derry, 1997; Gaillardet et al., 1999; Clift, 2006). The other opinion is that global temperature controlled the ASM via changes in the amount of water vapor held in the atmosphere, based on recent evidence (e.g., Lu et al., 2010; Miao et al., 2011; Tang et al., 2011; Miao et al., 2012, 2013b; Zhang et al., 2013).

To inform such debates on the monsoonal-arid climate system evolution and driving forces, it is still important to acquire high-quality climate records, including single-site and the synthesized multi-site records, because the quality of the records can directly influence our understanding of the relationships among them. In this study, firstly we introduce the genus *Fupingopollenites* found in the eastern Qaidam Basin, northern Tibetan Plateau; we then compile a data set of the spatial and temporal variability in its percentages across Asia; next we analyze the climate information contained in these records; and lastly we discuss the implications for ASM evolution and driving forces.

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2. Field site, materials, and methods

2.1. Geological and climatic setting

The Qaidam Basin, with an average elevation of ~2900 m and area of ~120 000 km^2, is the largest intermontane basin in the northern Tibetan Plateau (Fig. 1a). The basin is surrounded by the Altyn Tagh Shan (shan means mountain) to the northwest, the Qilian Shan to the northeast, and the Kunlun Shan to the south (Fig. 1b). A basin-wide Cenozoic lithostratigraphic framework for the Qaidam Basin has been established, and the stratigraphy has been divided into seven formations (from the lowest upwards): Lulehe, Xia Ganchaigou, Shang Ganchaigou Fm, Xia Youshashan Fm, Shang Youshashan, Shizigou and Qigequan respectively (e.g., Gu et al., 1990; Huang et al., 1996; Xia et al., 2001).

In modern times, the climate in the Qaidam Basin is mainly controlled by the westerlies, while the Asian summer monsoon usually extends only to the southeastern part of the basin. The basin's MAT lies between 2 °C and 4 °C, and the MAP is below 100 mm in most parts of the basin (less than 25 mm in the western part), but reaches 150–200 mm at the southeastern margin of the basin because of the long-range influence of the ASM (Du and Sun, 1990). The mean annual evaporation exceeds the MAP by more than 20 times, leading to a temperate, arid climate (Zhou et al., 1990). Deserts (including the Gobi) and salt lakes are the main features of the basin today.

2.2. Material and methods

The Naoge section is located approximately 43 km south of Delingha City, and has a total thickness of 3075 m comprising the middle to upper Miocene Xia Youshashan, Shang Youshashan and Shizigou formations (Fig. 2). Lithologically, it comprises largely brownish red siltstones, silty mudstones, mudstones and grayish fine sandstones, containing pebbly sandstones, conglomerates and marls. The upper part comprises grayish conglomerates, plus thin beds or lenses of fine sediments. A high-resolution magnetic section, coupled with mammalian faunal assemblages (Wang et al., 2007), has yielded a detailed chronology of 18.4–7.1 Ma (see details in Yang, 2009). The lithology and ages of this section compare well with the Huaitoutala section, located about 80 km to the northwest, due to their similar tectonic and sedimentary environments (Fang et al., 2007) (locations see Fig. 1b).

To extract pollen samples, approximately 30–50 g of sediments were treated with 10% HCl and 39% HF to remove carbonates and silica. Separation of the palynomorphs from the residue was carried out using a 10-μm nylon sieve. Finally, the palynomorphs were mounted in glycerin jelly. Palynomorph determination followed the methods of Song et al. (1999) and others. All samples were studied under microscopes at the Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences and Lanzhou University, China. In the Naoge section, about 16 out of the total of 244 samples contained sufficient pollen grains; these included the *Fupingopollenites* layer at ca. 585–590 m (ca. 15.2 Ma) (for its palynomorphs, see Fig. 3). In the upmost 1300 m (between 1700 and 3075 m), insufficient pollen grains were identified due to the coarse sediment grain sizes (Fig. 2). In the KC-1 core, 58 samples were collected, almost no (rare from very few samples) *Fupingopollenites* grains were found (Miao et al., 2011).

Besides the occurrence of *Fupingopollenites* in the Naoge section, we compiled abundances of *Fupingopollenites* from published data for 65 sites to examine temporal and spatial trends in China and adjacent areas during the late Cenozoic (see Table 1, including the NG section labeled as No. 15). Four categories of *Fupingopollenites* abundances were identified: (1) not present (absent *Fupingopollenites*); (2) occasional (*Fupingopollenites* with average abundances less than 2%); (3) common (*Fupingopollenites* with abundances between 2% and 5%); and (4) abundant (*Fupingopollenites* with abundances greater than 5%). The data sets with reliable dating (e.g., palaeomagnetic, K–Ar, and Ar–Ar etc.) are considered first. Additional data also include the several pollen data sets with other age controls, or those having stratigraphic correlations with adjacent areas. The data were divided into five different time periods and can directly reveal the *Fupingopollenites* evolution during the Early Miocene (ca. 23–17 Ma), Middle Miocene (ca. 17–11 Ma), Late Miocene (ca. 11–5.3 Ma), Pliocene (ca. 5.3–2.6 Ma) and Pleistocene (2.6–0 Ma) (Fig. 4).

3. Results and analysis

3.1. Palynomorph description

Fupingopollenites palynomorphs from the Naoge section are shown in Fig. 3a–e; grains were described by Liu (1985) as follows. Grains are subspherical to spherical in shape and medium to large in size. Polar view triangular, roundly triangular to subcircular; lateral view oblate to circular in outline. Tricolporate, colpi narrow and straight, about 2/3 the length of radiate; inner pores large, oblate and visible only under right polar or equatorial view. Exine columnar, not homogeneous in thickness because of special development of exine columnar structure in certain areas; thickening on both poles approximately "Y" form, which combines with those in mesocolpium areas to form nine concave plate-like thinning areas. Surface sculpture rugureticulate under optical microscope, intertwined reticulate under SEM (Liu, 1985). Here we also show *Fupingopollenites* palynomorphs found in the ZK004 and ZK005

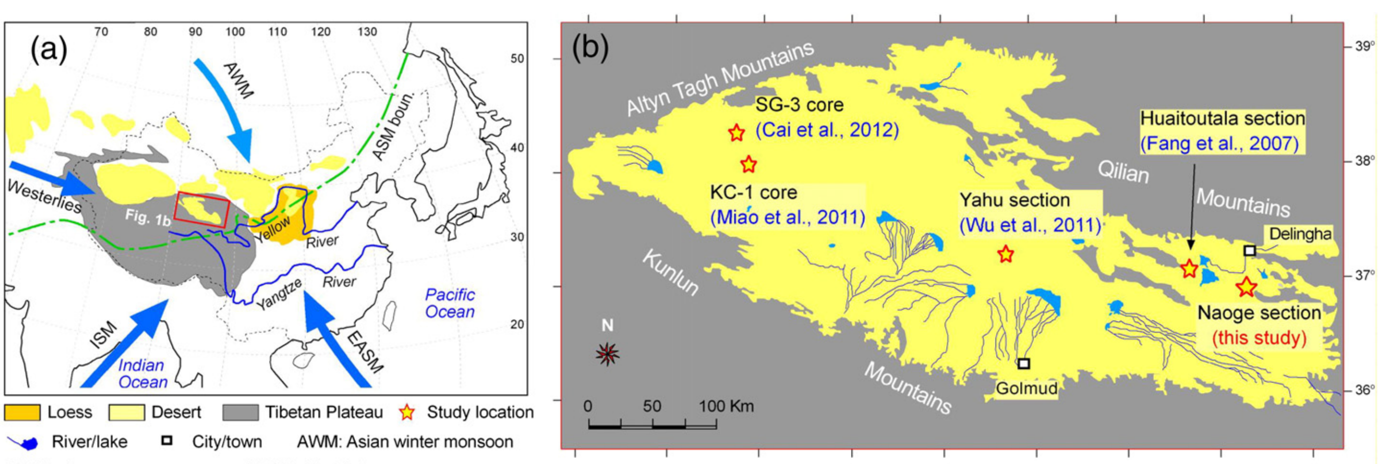

Fig. 1. (a) Physical geography in China and main circulation systems influencing Asia (ASM boun.: modern Asian summer monsoon boundary, after Gao, 1962), and (b) a map of the Qaidam Basin, showing the locations of the KC-1 (Miao et al., 2011) and Naoge sections (this study) used for pollen collection.