Tibetan uplift prior to the Eocene-Oligocene climate transition: Evidence from pollen analysis of the Xining Basin

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ABSTRACT

Uplift of the Tibetan Plateau and the Himalayas since the onset of the Indo-Asia collision is held responsible for Asian aridification and monsoon intensification, but may also have gradually cooled global climate, leading to the 34 Ma Eocene-Oligocene transition. To unravel the interplay between Tibetan uplift and global climate, proxy records of Asian paleoenvironments constrained by accurate age models are needed for the Paleogene Period. Here we report the 38 Ma appearance of high-altitude vegetation recovered from palynological assemblages in precisely dated lacustrine sediments from the Xining Basin of the northeastern Tibetan Plateau region. This result confirms previous evidence for important regional uplift in the central and northern Tibetan Plateau regions during the early stage of the Indo-Asia collision. This is consistent with the idea that the associated increase in rock weathering and erosion contributed to lowering of atmospheric CO_2, leading to the Eocene-Oligocene transition.

INTRODUCTION

According to prevailing hypotheses supported by various tectonic and climate models, the impact of the Indo-Asia collision on climate is twofold. (1) Globally, orogenesis increases rock weathering and organic carbon burial, which enhances consumption of atmospheric CO_2, leading to global cooling (Raymo et al., 1988; Zachos and Kump, 2005). This mechanism, rather than the opening of a sea passage around Antarctica, is now believed to have led to the 34 Ma Eocene-Oligocene transition, an abrupt cooling event associated with the onset of Antarctic ice sheet formation (DeConto and Pollard, 2003). (2) Regionally, uplift of the Tibetan Plateau and the retreat of an epicontinental sea formerly extending over Eurasia has triggered dramatic aridification and cooling of continental Asia and the onset of the Asian monsoons (Harris, 2006; Zhang et al., 2007).

Despite the profound implications of these hypotheses, well-dated Asian geologic records of climate change and mountain uplift required to test them are still scarce for the Paleogene Period (ca. 64–24 Ma), when these events took place, following the onset of the Indo-Asia collision. There is, however, some emerging evidence for Paleogene tectonism, uplift, and associated high paleoelevations (Rowley and Currie, 2006; DeCelles et al., 2007; Wang et al., 2008). Existing Paleogene paleoenvironmental records suggest monsoon intensification (Garzione et al., 2005), cooling, aridification (Graham et al., 2005), major faunal turnovers (Meng and McKenna, 1998), and, of particular interest here, drastic floral changes (Sun and Wang, 2005), but they lack the precise age control required to associate them with tectonism or global climate variations.

Palynological analysis of fossil pollen assemblages preserved in sediments is a well-established method for reconstructing the composition of past vegetation and thus paleoenvironmental conditions (e.g., temperature, precipitation, elevation, latitude). In China, a large database of modern vegetation and pollen occurrences is available (Hou, 1983; Ni et al., 2000; Yu et al., 2001, 2004; Lu et al., 2007; Fig. 1). These data sets provide an excellent reference for paleoenvironmental reconstructions based on the existing palynological database (see Sun and Wang, 2005, and references therein). In the Paleogene records, the most striking first-order paleoenvironmental change is the combined regional appearance of conifers (and in particular the taxon *Picea*), along with a marked change in the geographic distribution of arid versus tropical and subtropical taxa. These regional features are widely recognized as diagnostic for Tibetan uplift with aridification north of the plateau and monsoonal intensification to the south and east (Harris, 2006). However, the timing of these changes, roughly constrained to Paleogene time, does not exclude their relation to global climate events such as cooling and aridification at the Eocene-Oligocene transition (Dupont-Nivet et al., 2007). At best, epoch ages assigned to the pollen-bearing sediments are based on stratigraphic correlations to distant and inadequately dated type sections. We present here well-dated pollen assemblages that record these Paleogene environmental changes, thus providing new insight into the temporal relationship between global climate and regional uplift.

XINING BASIN ENVIRONMENT AND SAMPLING

At the northeastern margin of the Tibetan Plateau, Eocene to mid-Miocene deposition in the Xining Basin is characterized by slow accumulation of lacustrine saline playa to distal alluvial fan deposits, suggesting little local tectonism (Dai et al., 2006). High-resolution dating and lithofacies analysis of the Eocene-to-Oligocene stratigraphy has shown that the regional upsection disappearance of gypsiferous playa lake deposits, indicative of aridification, is precisely correlated to the Eocene-Oligocene transition (Dupont-Nivet et al., 2007). Previous palynological work from the basin (Wang et al., 1990; GSA Data Repository Fig. DR1[1]) is consistent with cooling and aridification north of the uplifting Tibetan Plateau; however, despite the new magnetostratigraphic age constraints, the low stratigraphic resolution precludes determining whether these changes can instead be associated with global

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[1] GSA Data Repository item 2008245, methods of pollen extraction and details of palynologic analysis, previously published palynology results from the Xining Basin (Fig. DR1), observed fossil pollen and spore taxa (Table DR1 and Fig. DR2), and abundances of vegetation types (Table DR2 and Fig. DR3) and groups (Table DR3), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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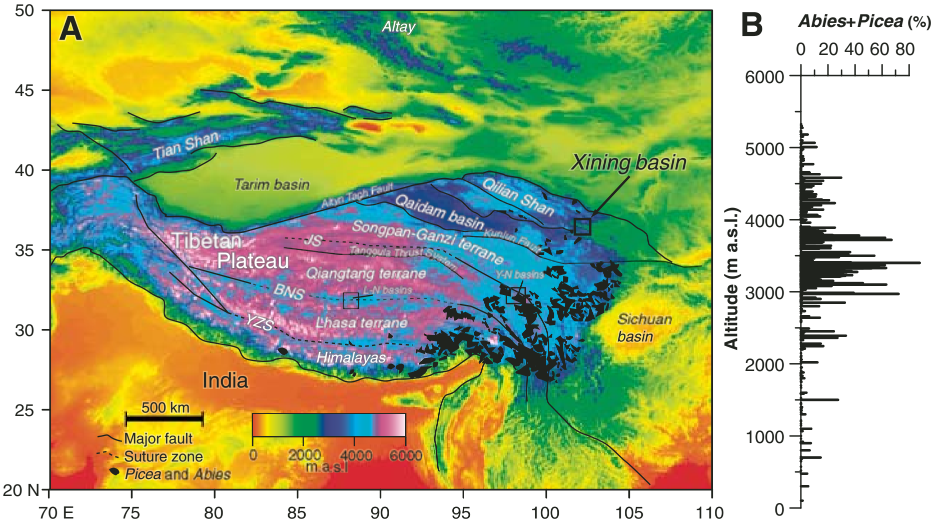

Figure 1. A. Topographic map of Tibetan Plateau region with major tectonic features (YZS—Yarlung Zangpo suture; BNS—Bangong-Nujiang suture; JS—Jinsha suture; L-N—Lunpola and Nima basins; Y-N—Yushu-Nangqiang basins). Black areas indicate modern distribution of spruce (*Picea*) and fir (*Abies*) for Tibetan Plateau region. Box indicates location of study area in Xining Basin. B: *Abies* and *Picea* pollen abundances (%) versus altitude in meters above sea level (m.a.s.l.) for Tibetan Plateau region (modified from Lu et al., 2007).

climate at the Eocene-Oligocene transition. To better constrain the existing record in time and provide a new detailed palynological analysis, sampling for pollen was performed at higher resolution on the interval, including the Eocene-Oligocene transition, at two recently dated parallel sections separated by ~15 km (Fig. 2; for precise location, see Dupont-Nivet et al., 2007). The studied stratigraphy consists of regular alternations of laterally continuous gypsum layers and red mudstone intervals. Gypsiferous intervals are decimeter- to meter-thick tabular, nodular, or laminar beds. As oxidation in red layers typically obliterates pollen material, samples were collected from gypsum layers that occasionally preserve greenish-gray lacustrine mud. In the upper part of the stratigraphy, above the Eocene-Oligocene transition, fully developed gypsum layers disappear, so samples were collected from rare layers of thin greenish mudstones.

PALYNOLOGIC ANALYSIS

A specific method was devised to extract pollen from gypsiferous beds (Methods section; see the Data Repository).

Results

The most conspicuous palynological event within the analyzed sequence is the sudden appearance of the Pinaceae family, and in particular that of taxon *Picea* (*Piceapollenites*). This event is recorded in both sections and bracketed between 38.3 and 37.3 Ma (between samples P384 of the Xiejia section and P376 of the Shuiwan section; see Fig. 2). It is interesting that some other pollen assemblages seem affected by this change. The pre-conifer pollen assemblage is characterized by *Eleagnacidites*, *Retitrescolpites*, and *Catinipollis*, and a variety of taxa from the *Retitricolpites* group is abundant. At the conifer appearance, the latter dwindles while the others disappear.

Most of the palynological assemblage throughout both sections is composed of the xerophytic shrubland element *Ephedra* (*Ephedripites*), a taxon that currently grows on arid mountain slopes. Other than *Ephedra*, there are essentially no arid indicative taxa in the assemblages. Elements typical of the Neogene and present Asian steppe, such as herbs of the Chenopodiaceae, Amaranthaceae, Caryophyllaceae (CAC group, see Figs. DR2, DR3), Poaceae, and Compositae, are nearly absent in the lower part of the record, but emerge (<5%) ca. 38 Ma and increase (>5%) toward the Eocene-Oligocene transition (and above; see Fig. DR1; Wang et al., 1990). The xerophytic shrubland thus most probably constituted a large part of the local landscape but differed from present as it lacked the now common *Artemisia* and the Poaceae.

Another common group is the Meliaceae-Anacardiaceae (*Meliaceoidites-Rhoipites*) assemblage, which, like *Ephedra*, occurs abundantly throughout the sequence. At present Meliaceae (e.g., *Aglaia*, *Aphanamixis*, *Azadirachta*, *Chukrasia*, *Cipadessa*, *Dysoxylon*, *Toona*, *Trichilia*) and Anacardiaceae (e.g., *Buchanania*, *Holigarna*, *Lannea*, *Mangifera*, *Nothopegia*, *Rhus*, *Semecarpus*) are very common throughout all Indian forests and part of the undergrowth. Nevertheless, they cannot easily be linked to one particular forest type, as they are common in both subtropical and deciduous forest types (D. de Franchesi, 2008, personal commun.).

Fagaceae also are common throughout the studied interval, but with higher abundances in the basal part of the section. This group, composed of *Quercus* (*Quercoidites*), *Cupuliferoipollenites*, *Lithocarpus*, and *Castanopsis*, resembles taxa from the present Asian broad-leaved tropical and temperate forests.

Interpretations

The abundance of steppe elements and the presence of tropical forest taxa throughout the record are indicative of a warm, humid climate in the vicinity of the arid Xining Basin. Their continuous presence through the entire studied interval and regionally up to the Quaternary when this group disappears (Wang et al., 1999; Sun and Wang, 2005; Sun et al., 2007) suggests that climate was warmer and more humid than in the Quaternary.

Smaller increasing amounts of CAC group representatives in the upper part of the record suggest a gradual shift toward less humid conditions that is substantiated by the aridification expressed in the lithofacies variations at 34 Ma (Dupont-Nivet et al., 2007) and the reported increasing occurrence of this group stratigraphically higher in the Xining record as well as regionally (Fig. DR1; Wang et al., 1990; Sun and Wang, 2005).

The appearance of conifers (and in particular *Picea*), and the drop or even disappearance of elements typical of the pre-conifer assemblage, is a distinctive event that was recognized in the existing regional biostratigraphic charts of the Xining Basin, but also as far as the eastern Tarim Basin (Wang et al., 1990), and deserves further explanation. *Picea* occurrences, albeit scarce and intermittent, are reported in the Mesozoic Asian records, indicating that the taxon migration into Asia is older and unrelated to the Eocene expansion. The taxon is virtually absent from early Paleogene continental Chinese basins, with some exceptions (e.g., Van Itterbeeck et al., 2007). After this, large occurrences are reported from various parts of China and interpreted to result from Tibetan uplift (Wang et al., 1990; Sun and Wang, 2005). In the Xining Basin, precise ages of the studied sections now enable us to appreciate the significance of this event. After their appearance at 38 Ma, conifers constitute a major component of the palynological record. Their presence is indicative of a shift to a cold-temperate climate (but still warmer and more humid than in the Quaternary, as indicated by the continuous occurrence of steppe to tropical taxa). The abundance of conifer forest taxa following a zone of abundant broad-leaved forest taxa and the wide palynological spectrum of genera typical of different vegetation belts on mountain slopes suggest the establishment of a temperate forest zonation

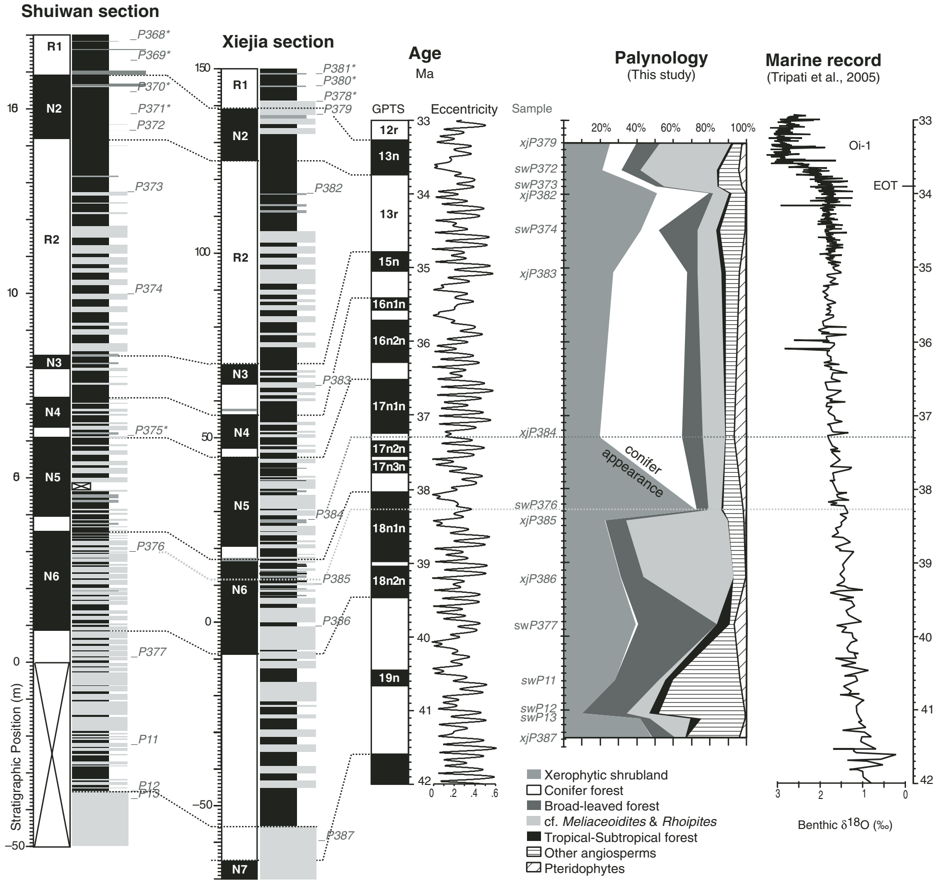

Figure 2. Palynologic records at the two sampled sections (Xiejia and Shuiwan) compared to stable isotope marine records (Tripati et al., 2005). Age model was previously published (Dai et al., 2006; Dupont-Nivet et al., 2007), and is based on magnetostratigraphic correlation to geomagnetic polarity time scale (Ogg and Smith, 2005) and eccentricity solution (Laskar et al., 2004).

ca. 38 Ma. High-altitude climatic conditions are further indicated by the specific occurrence of *Picea*, a taxon currently found at high elevation in the Tibetan Plateau region (Lu et al., 2007; Fig. 1B). Present-day analogues to the Eocene *Piceaepollenites* are high-altitude taxa such as *Picea schrenckiana*, a conifer that grows in the Tian Shan Mountains within altitudinal range of 1500–1600 m to 2700–2800 m, or *Picea crassifolia*, dominating coniferous and mixed forests preserved on shady slopes of the nearby Qilian Shan between 2600 and 2900 m (Herzschuh et al., 2006). Given that during recent ice ages the timberline in the Tian Shan is estimated to have declined only ~330 m (Zhang et al., 2006), the appearance of these taxa associated only to changes in humidity and temperature without any elevation gain is unlikely. Furthermore, these elevations should be considered as minima given the higher temperatures and less pronounced seasonality in Eocene time (Tripati et al., 2005), and the site latitude was similar to, if not slightly lower than, today (Huang et al., 2005). In addition, oceanic climate records during this precise time interval (Fig. 2) show no dramatic global shift (such as the Eocene-Oligocene transition) that could have caused drastic atmospheric changes. Thus, the observed temperate forest zonation with conifer forest taxa requires high-altitude climatic conditions at this latitude (Ohsawa, 1990), which implies the emergence of significant relief at that time. The relatively high abundances of conifer pollen reported here suggest that the source plants grew in the vicinity of the study area during the time of deposition. Present pollen dispersal studies (Cour et al., 1999) show that wind-transported exotic bisaccate pollen from as far away as the Himalaya can reach northwestern Tibet, but the resulting percentages are quite low (typically ~1%). For high percentages such as found in our samples (>40% in some cases), regional dispersal studies clearly indicate high spatial correlation between modern bisaccate pollen and source plants for *Pinus* and *Picea* (Yu et al., 2004; Lu et al., 2007). This suggests that the fossil pollen is not far traveled, and therefore the 38 Ma conifer appearance in the study area can reasonably be associated with coeval orographic uplift in the Tibetan Plateau region.

DISCUSSION

Evidence for Paleogene tectonism and uplift exists for the central and northern part of the Tibetan Plateau. In the center of the plateau, estimates of the paleoaltimetry of late Eocene and younger deposits of the Lunpola and Nima basins (spanning the Bangong-Nujiang suture between the Lhasa and Qiangtang terranes; Fig. 1A) indicate an elevation of >4 km (Rowley and Currie, 2006; DeCelles et al., 2007). Farther north, paleoaltimetry combined with thermochronologic and geologic data from the northern-central part of the Qiangtang terrane indicate the emergence of similarly high elevation related to exhumation along the Tanggula thrust system ca. 40 Ma (Wang et al., 2008). In the east-central regions of the Tibetan Plateau, Paleocene–Eocene (older than 37 Ma) shortening is also documented in the Yushu-Nangqiang basins neighboring the Jinsha suture in the eastern part of the Qiangtang terrane (Horton et al., 2002; Spurlin et al., 2005). In the Xining-Lanzhou region, tectonic vertical axis rotations provide evidence for Paleogene deformation (Dupont-Nivet et al., 2004). The sum of the evidence for deformation and uplift provides a potential source for the high-elevation palynologic assemblages recovered from the Xining Basin.

Global climate, as expressed by marine benthic $\delta^{18}O$ values, during the studied interval (Fig. 2) is characterized by a gradual decrease associated with deep-sea temperature cooling, leading to the rapid and large shift at the Eocene-Oligocene transition (Tripati et al., 2005). Although this major shift affected the Tibetan region (as clearly expressed by aridification in the studied section at 34 Ma), the Eocene-Oligocene transition significantly postdates and thus was not the cause for the conifer appearance at 38 Ma. Based on the apparent time frame of the conifer appearance (38.3–37.3 Ma), we propose that threshold conditions for vegetation change were reached after the long-term combined effects of regional uplift and gradual global cooling, rather than several kilometers of uplift within such a short time span. Similarly to the Eocene-Oligocene transition, the time frame of the conifer appearance corresponds to a period with low variations in the Earth's orbital eccentricity, thus characterized by damped seasonality (Fig. 2; Laskar et al., 2004). Low seasonality for sufficient time may have provided the opportunity for the conifers to spread and occupy the niche open by the uplifting mountains.

Significant regional uplift throughout the Tibetan region prior to the Eocene-Oligocene transition is now substantiated by our results dating precisely the appearance of high-elevation taxa. Regional uplift at least 4 m.y. before the Eocene-Oligocene transition is consistent with the idea that the associated increase in rock weathering and erosion contributed to the lowering of atmospheric CO_2, leading to the Eocene-Oligocene transition (Zachos and Kump, 2005). This is in agreement with increasing $^{87}Sr/^{86}Sr$ values starting ca. 40–38 Ma in marine carbonate records interpreted to indicate enhanced silicate weathering associated with uplift (Kump and Arthur, 1997).

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