A late Eocene palynological record from the Nangqian Basin, Tibetan Plateau: Implications for stratigraphy and paleoclimate

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Abstract

With the uplifting, large-scale thrusting and striking of the Tibetan Plateau, several Paleogene intracontinental basins formed within the northern Tibetan Plateau (TP). Stratigraphical and paleoenvironmental studies of the sedimentary successions within these basins are critical for understanding Paleogene climatological changes in Eurasia. The Nangqian Basin, one of such basins, formed in the Yushu area of the northeastern Tibetan Plateau. A set of lacustrine sediments, dominated by red clasolite, marlite, and gypsum, developed in the Yang Ala section in this basin. Paleontological records from the Nangqian Basin remain poorly known. Here, we investigate the palynological assemblages of one sedimentary succession at the Yang Ala section that belongs to the Gongjie Formation, and their implications regarding the geological age and paleoclimate are discussed. The results reveal that the assemblages are dominated mainly by angiosperm pollen (tricolpate and tricolpate), including Nitriaridites (Pokrovskaja), Quercoidites, and Labitricolpites, followed by gymnosperm pollen taxa, such as Ephedripites and Taxodiaceae pollenites, and sparse pteridophyte spores produced by ferns. A late Eocene age is inferred based on palynostratigraphy and comparison with other pollen assemblages in the TP. A relatively dry climate with brief humid periods is indicated by the high abundance of xerophytic pollen taxa, such as Ephedripites and Nitriaridites, which are associated with broadleaved deciduous and evergreen plants. The characteristics of the pollen assemblages from the studied Yang Ala section are consistent with other Cenozoic palynofloras from the Mahalagou Formation in the Xining Basin and with those of the Yaxicuo Group in the Hoh Xil Basin. These results provide an improved stratigraphical scheme for parts of the Cenozoic and enrich the current knowledge of the vegetation history of the northeastern Tibetan Plateau.

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1. Introduction

The Cenozoic climate and ecosystems of Asia are commonly thought to have been governed mainly by the formation of the Tibetan Plateau (TP) (Bosboom et al., 2011) and were key drivers of Asian and even whole planetary paleoenvironmental changes. These changes marked a significant time interval in Earth’s history, with the beginning of the critical transition period from the early Eocene thermal maximum to the early Oligocene ice age (Westerhold and Röhl, 2013). We selected the Yang Ala section for palynological analysis to gain new knowledge on the biostratigraphy and ecosystems during the Eocene in this area.

The TP is the highest elevation plateau in the world and was formed as a result of the collision between the Indian and Asian continents, which was initiated during the early Cenozoic (Molnar and Tapponnier, 1975; Aitchison and Davis, 2001; Wang et al., 2008; Xia et al., 2010; Aitchison et al., 2011; Zhang...
Infilling with non-marine sedimentary deposits of numerous Cenozoic tectonic basins of various sizes took place on the Tibetan Plateau. These deposits have been used as a record of environmental changes that occurred throughout the Cenozoic Era. The goal of this study is to estimate the age of the sedimentary successions of the Nangqian Basin, which are exposed along the Yang Ala section, based on palynology. A further goal is to obtain detailed insight into the paleoenvironment and paleoclimate based on the vegetation patterns that developed over particular time intervals to better understand the major climate changes that occurred in the region.

2. Geological setting

The Nangqian Basin is located at the border between the Qinghai Province and Tibet Autonomous Region (Fig. 1) at an elevation of approximately 4500–5000 m. It is a typical small fluvial-lacustrine Paleogene basin (approximately 55 km long and 18 km broad) located along the Jinsha River-Red River belt at the northeastern margin of the Tibetan Plateau, with a NNW trend (Shi et al., 1999; Mo et al., 2003; Zhang et al., 2007; Pan and Fang, 2010).

The sedimentary successions of the Nangqian Basin mainly comprise reddish mudstone, marl, and gypsum. Previous studies of the basin have focused primarily on the sedimentology (Yin and Harrison, 2000; Wang et al., 2002; Zhou et al., 2002), tectonic evolution (Spurlin et al., 2005), tectonic-magmatic activity, and chronology (Yang and Wang, 1988; Deng et al., 2001; Spurlin et al., 2005; Zhu et al., 2006). Though only briefly mentioned regarding the Nangqian Basin, palynology has been extensively applied as a biostratigraphic tool for other petroleum-producing basins (Wang et al., 1990; Zhang and Zhan, 1991; Gao et al., 2000) and to assess changes in Cenozoic climate captured in the geological record of plateau basins of the TP, such as the Qaidam Basin (Xu et al., 1958; Zhu et al., 1985; Wang et al., 1999; Sun et al., 2005; Lu et al., 2010; Ji et al., 2011; Miaow et al., 2011, 2012, 2013a; Cai et al., 2012; Herb et al., 2015; Wei et al., 2015), Jiuquan Basin (Miao et al., 2007; Zhang et al., 2015), Guide Basin (Pares et al., 2003), Lanzhou Basin (Flynn et al., 1999; Miao et al., 2013b), Xining-Minh-Lanzhou Basin (Dupont-Nivet et al., 2008; Miaow, 2010; Hoorn et al., 2012; Miao et al., 2013c; Bosboom et al., 2014), Hoh Xil Basin (Liu et al., 2003; Miao et al., 2016a), Tianshan Mountain (Chen et al., 2002; Sun et al., 2004), Tarim Basin (Sun et al., 1999; Zhu et al., 2005; Bosboom et al., 2011; Wang et al., 2013), Linxia Basin (Li et al., 1997; Fang et al., 2003), Yecheng Basin (Zhang et al., 2000), and Zhaotong Basin (Chang et al., 2015). Although most of these studies are limited to the sedimentary successions within the foreland basins of the northern TP, they serve as an important source for comparisons of taxonomy, composition of palynological assemblages, and comparative paleoenvironmental and climatological signals. This study will contribute to the knowledge concerning dating and the vegetation composition as well as its development within the northeastern Tibetan Plateau during an important time period when the global climate changed from relatively warm to relatively cold.

3. Materials and methods

3.1. Sedimentology

The presently studied red strata within the Nangqian Basin belong to the Gongjie Formation (Wei, 1985; Wang et al., 2001; Zhou et al., 2002). The Gongjie Formation is divided into three Members: 1) the Ri’An’gou conglomerate Member, which reaches a thickness of approximately 1300 m; 2) the Dong Y’ru sandstone with limestone beds, which reaches a thickness of 700–1000 m; and 3) the uppermost Member Gouriwa, comprising mudstones (generally developed as red beds) intercalated with gypsum and reaching 900–1200 m in thickness (Wang et al., 2002). The red beds within the Nangqian Basin are further cross-cut by volcanic intrusions dated to 37–38 Ma (Deng et al., 2001; Spurlin et al., 2005; Zhu et al., 2006). The palynological study here is based on a section at Yang Ala (95°20’55.73”E, 32°14’37.5”N) in the northwestern part of the Nangqian Basin (Fig. 1). The section (Fig. 2), capped by alpine meadow, is subdivided into four sedimentary cycles A–D (Table 1) based on lithology. Each cycle comprises red mudstones and siltstones (a, b, c, d) capped by gypsum beds. Twenty-nine samples were collected, mainly from the red beds (a, b, c, d) at approximately equally-spaced intervals, but also from the gypsum.

An approximately 26 m sedimentary succession is exposed along the Yang Ala section. This succession belongs to the uppermost unit of the Gongjie Formation, also called the Gouriwa Member.

3.2. Laboratory work and pollen analysis

The samples were first treated with 36% HCl and 39% HF to remove carbonates and silica and then sieved through a 10-μm nylon mesh. Subsequently, the residue was density separated using ZnCl₂ (density = 2.1). The organic residue was mounted on microscopic slides in glycerin jelly. All slides were examined under a Leica light microscope, and micrographs were taken of selected specimens. From each of the 22 productive samples > 200 grains were identified and counted wherever possible. The other seven samples (5, 7, 15, 16, 23, 25 and 26) that contained very little pollen and spores were not plotted in the diagram (Fig. 3). The pollen and spore percentages were calculated out of the total sum of spores and pollen grains, and the diagrams were plotted using Tilia 2.0 software (Fig. 3). The samples are currently housed at the Qinghai Institute of Salt Lakes, Chinese Academy of Sciences.

4. Palynology results

Over 70 taxa of pollen and spores were identified from the sampled sediments, of which 57 taxa are presented in the pollen diagram shown in Fig. 3. Wherever possible, the botanical affinity of the pollen and spores was applied, while form taxa were only applied to taxa with unknown affinities.
The palynological assemblages from the Yang Ala section are entirely non-marine and dominated by a mix of angiosperm and gymnosperm pollen taxa, while spores are rare. The predominant elements observed in most of the samples include the angiosperm pollen Nitrariadites and the gymnosperm pollen taxa Ephedripites and Taxodiaceae pollenites. Pollen produced by deciduous broadleaved and evergreen broadleaved trees, such as Quercoidites and Rhoipites, is less common. There is no major change through the succession, and therefore, we assign all sam-
Fig. 2. The sedimentary successions exposed at the Yang Ala section, Nangqian Basin. Four sedimentary cycles A–D are identified (Table 1) based on lithology, with each capped by a thicker gypsum bed that is grey in color.

Table 1
Lithological scheme of the Yang Ala section, with information on the bed thickness and sampling intervals.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Lithology</th>
<th>Depth to the top (m)</th>
<th>Bed thickness (m)</th>
<th>Sample numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Gypsum bed</td>
<td>0–0.80</td>
<td>0.80</td>
<td>No sampling</td>
</tr>
<tr>
<td></td>
<td>d: Red-orange mudstone alternating with green-white marly gypsum beds</td>
<td>0.80–5.20</td>
<td>4.40</td>
<td>22–29</td>
</tr>
<tr>
<td>C</td>
<td>Gypsum bed</td>
<td>5.20–7.70</td>
<td>2.50</td>
<td>20–21</td>
</tr>
<tr>
<td></td>
<td>c: Red-orange mudstone, greyish-green mudstone, marly limestone and gypsum</td>
<td>7.70–11.30</td>
<td>3.60</td>
<td>16–19</td>
</tr>
<tr>
<td>B</td>
<td>Gypsum bed</td>
<td>11.30–13.30</td>
<td>2.00</td>
<td>No sampling</td>
</tr>
<tr>
<td>A</td>
<td>Gypsum bed</td>
<td>20.15–22.11</td>
<td>2.36</td>
<td>6–7</td>
</tr>
<tr>
<td></td>
<td>a: Red-orange mudstone intercalated with green-white mudstone</td>
<td>22.11–25.52</td>
<td>3.01</td>
<td>1–5</td>
</tr>
</tbody>
</table>

This assemblage is dominated by Ephedripites, Nitrariadites, and Quercoidites (Figs. 3 and 4). The xerophytic taxa together contribute nearly 45%, as represented by Ephedripites (30%) and Nitrariadites (13%), together with more rare xerophytic taxa, such as Chenopodiaceae (1%) and Elaeagnacites (1%). The pollen produced from gymnospermous trees, such as Taxodiaceae pollenites, appears sporadically and reaches as high as 36% in abundance at some levels, but the average is 9%. The pollen produced by broadleaved tree taxa, representing a temperate and warm climate, reached 42% (average 24%) in this assemblage and is represented primarily by Quercoidites (average 11%) and Rhoipites (average 3%). The herbs, reaching as high as 28% (average 11%), are represented by pollen, such as Qinghaipollis (average 2.5%). Pteridophyte spores are represented primarily by ferns and only reached 18%, with an average of 8.5% for this assemblage (Figs. 3 and 4).

5. Discussion

5.1. Stratigraphy and climate

The palynological assemblages in the sediment samples from the Yang Ala section are similar, indicating the stability of vegetation types during the deposition of the studied interval. All productive samples are dominated by the Ephedripites–Nitrariadites–Quercoidites complex (Figs. 3 and 4). Interestingly, out of the four gypsum samples, three are productive and show a similar abundance pattern as the palynological residue from the mudstone samples. Xerophytic, halophytic shrubs represented by the angiosperm pollen Nitrariadites and gymnosperm pollen Ephedripites are predominant throughout the section. Ephedripites is a gymnosperm genus that had probably already originated during the Triassic (Yang, 2002; Sun and Wang, 2005) and is currently distributed primarily throughout the arid and semi-arid regions of the world.
The fossil representative, *Ephedrites*, is easily recognized and has been widely detected in Cenozoic evaporites, indicating the xerophytic character of this genus. Relatively high percentages of the taxa have been reported from the thick Paleocene halite deposit of Jiangxi (He and Sun, 1977a, 1977b). Tong et al. (2001) reported that *Ephedrites* in the middle and late Eocene evaporites from the Jianghan Basin, with an average percentage of 30% in halite, 20% in glauberite and 15% in purple mudstones. However, during the late Oligocene, *Ephedrites* decreased in abundance, while a large number of various saccate pollen taxa, such as *Pinus*-type (22%) and *Picea*-type (10%), appeared, and minor relative abundances of *Abies*, *Cedrus* and *Podocarpus* were also observed (Wang, P., 1990; Wang, W.M., 1990; Zhang and Zhan, 1991; Sun et al., 2005).

The angiosperm *Nitrariadites* (synonym to *Pokrovskaja*) occurs in Paleogene successions of China, but only in trace amounts. Examples from the Xining-Minhe Basin, however, show that the abundance increased during the middle and late Eocene, with levels up to 14% and reaching 27.5% during the early-middle Oligocene (Sun et al., 1984; Wang, P., 1990; Wang, W.M., 1990; Ma et al., 1998). The herb producing the pollen *Fupinggopollenites* was first found in Guangxi and is no older than the late Eocene (Liu, 1985). It was widely distributed from the middle Eocene to the Neogene in Asia and Europe, with its affinities uncertain (Liu et al., 2001; Wang and Harley, 2004; Shatilova and Mchedlishvili, 2009; Miao et al., 2016b). In addition, deciduous broadleaved and evergreen broadleaved trees, such as *Quercoidites*, developed in the middle Eocene and spread during the late Eocene (Zhang, 1995). *Rhoipites* is common in sediments within the Funing Formation (Eocene) and the Dainan Formation (Oligocene) in Jiangsu (Zhang and Qian, 1992). *Cupuliferoipollenites* is common in the Eocene of South China. *Euphorbiacites* is relatively abundant in upper Eocene to lower Oligocene successions in the Jianghan Basin (Zhang, 1995).

The palynological assemblages of the studied Yang Ala section are comparable with those of the Yaxicuo Group at the TTH-C section (Miao et al., 2016a) and with those of a lower member of the Mahalagou Formation. Those successions are also dominated by xerophytic pollen types, such as *Ephedrites*, *Nitrariadites* (*Pokrovskaja*/*Meliaceoidites*), and *Chenopodipolpis* (Hoorn et al., 2012) and have been dated by high-resolution magnetostratigraphic dating techniques (Dai et al., 2006; Zhang, 2006; Dupont-Nivet et al., 2008; Abels et al., 2011). The age of the Yaxicuo Group at the TTH-C section and that of the lower member of the Mahalagou Formation were dated to the late Eocene (∼40–37 Ma, Bartonian Stage). The palynological assemblage is also similar to those of the Suweiyi Formation in the Kuche Basin (Wang et al., 1986), those of the Huoshagou Formation along the Hexi Corridor in Gansu (Miao et al., 2007), and those of the Totohe Formation in the Tanggula mountains of Northern Tibet (Duan et al., 2007). Also, the red beds within the Nangqian Basin are further crosscut by volcanic intrusions dated to 37–38 Ma (Deng et al., 2001; Spurlin et al., 2005; Zhu et al., 2006). We therefore conclude that the age of the strata at the Yang Ala section is late Eocene. This is in agreement with the lithological evidence that the red beds of the Nangqian Basin are part of the lower Gongjue Formation.

![Fig. 3. Pollen diagram based on the palynological results from samples obtained from the Yang Ala section of Nangqian Basin, Yushu area, SW China (note: the S-1, 2, 3, 4 indicates gypsum beds in the Yang Ala section).](image-url)
5.2. Environmental implications

Pollen and spores are valuable tools for tracing the evolution of vegetation and changes in paleoclimate, as plants rapidly respond to changes in the environment and pollen and spores are durable and generally abundant in sedimentary deposits. For example, *Ephedra* prefers arid environments (semi-desert) and is currently distributed primarily throughout deserts and grasslands globally (Stanley et al., 2001), while *Nitraria* is a relatively more humid steppe/desert taxon (Cour et al., 1999; Sun and Wang, 2005; Jiang and Ding, 2008; Li et al., 2009; Zhao and Herzschuh, 2009). These taxa occur in the most arid regions worldwide, where the annual rainfall is less than 100 mm (Sun and Wang, 2005). According to Li et al. (2005), the *Nitraria/Ephedra* (N/E) ratio (Fig. 5) is less than 1 in typical desert communities and greater than 1 in steppe-desert environments, suggesting that the ratio of these taxa might be used as a proxy for relative humidity in these dry environments. The N/E ratio has been applied to assess the local climatic variability in the Xining Basin for sediments dated 39.9–33.4 Ma (Hoorn et al., 2012). Indeed, the paleoclimate of the Xining Basin during the Bartonian (late Eocene) was extremely dry, consistent with arid vegetation features. The ratio of N/E supports the general palynological signal that the study area was characterized by xerophytic vegetation, indicating a typical arid desert and desert-steppe environment for the late Eocene. It is likely that such aridity was more widespread, spanning the entire north-western China under the control of a subtropical high (Liu et al., 1998; Sun and Wang, 2005; Guo et al., 2008). This vegetation type is in agreement with the depositional environment and is also consistent with current knowledge on the regional Eocene climate of China when a broad belt of aridity stretched longitudinally across China (Sun and Wang, 2005).

When comparing the palynological results to the lithology, it becomes evident that the intervals with red beds probably represent lake deposits in a desert environment, wherein the lake systems dried out episodically, leaving carbonates and, ultimately, evaporates, such as gypsum. The vegetation seems to have persisted through the cycles, as similar flora appear in the subsequent cycles, indicating a stable ecosystem with drought-tolerant vegetation at that time (Fig. 6).

The general climatic trend seems to reflect a typical arid desert and desert-steppe environment. *Taxodiaceae pollenites* appears sporadically, but at some levels reaches as high as 36% abundance, which may reflect a humid or swampy habitat. However, except for dry xerophytic taxa, the relatively low percentage of broadleaved forest taxa (both temperate and warm) is also noticeable, indicating that these broadleaved forest taxa grew
in elevated areas; if so, they are too small or too widely scattered to respond to changes in the environment, and the low but consistent occurrence of pteridophyte spores and pollen produced from swamp cypress (Taxodiaceae pollenites) indicates that these hygrophilous taxa grew along river beds and during periods of increased precipitation.

6. Conclusion

On the basis of palynological assemblages, we conclude that the sediments of the Yang Ala section (Nangqian Basin) are late Eocene, most likely Bartonian in age. Furthermore, the palynological and sedimentological records indicate an overall dry climate, with shorter intervals of slightly more humid conditions intervals. The palynoflora is characterized by high relative abundances of xerophilic elements, such as Ephedripites and Nitrariadietes, with intervals when cypressseeds thrived. Ferns of Taxodiaceae pollenites probably grew along rivers. These results are in agreement with the palynological record from neighboring basins within the northern Tibetan Plateau, such as the Qaidam, Hoh Xil, and Xining basins, and are also consistent with the larger geographical picture of the Eocene climate of China, showing a broad arid belt stretching longitudinally across China.

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