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

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Received 14 January 2016; received in revised form 18 September 2016; accepted 19 October 2016

Available online 28 October 2016

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 claystone, marl, 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 Gongjue Formation, and their implications regarding the geological age and paleoclimate are discussed. The results reveal that the assemblages are dominated mainly by angiosperm pollen (tricolpates and tricolporate), including *Nitrariadites* (*Pokrovskaja*), *Quercoidites*, and *Labitricolpites*, followed by gymnosperm pollen taxa, such as *Ephedripites* and *Taxodiaceapollenites*, 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 *Nitrariadites*, 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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Keywords: Palynology; Tibetan Plateau; Stratigraphy; Late Eocene; Paleoclimate

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

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et al., 2012). 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, marlite, 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 the 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; Miao 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-Minhe-Lanzhou Basin (Dupont-Nivet et al., 2008; Miao, 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 (Zheng 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 dur-

ing 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 Gongjue Formation (Wei, 1985; Wang et al., 2001; Zhou et al., 2002). The Gongjue Formation is divided into three Members: 1) the Ri'Anongguo 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 Gongjue 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- μ m nylon mesh. Subsequently, the residue was density separated using ZnCl_2 (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.

Fig. 1. Regional map of the study area. (A) Map of the Tibetan Plateau showing the location of the Nangqian Basin; the data were obtained from <http://www.ngdc.noaa.gov/mgg/global/global.html>. (B) Map of the Nangqian Basin; the location of the Yang Ala section is indicated with a star (data obtained from Google Earth).

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.

Sequence	Lithology	Depth to the top (m)	Bed thickness (m)	Sample numbers
D	Gypsum bed	0–0.80	0.80	No sampling
	d: Red-orange mudstone alternating with green-white marly gypsum beds	0.80–5.20	4.40	22–29
C	Gypsum bed	5.20–7.70	2.50	20–21
	c: Red-orange mudstone, greyish-green mudstone, marly limestone and gypsum	7.70–11.30	3.60	16–19
B	Gypsum bed	11.30–13.30	2.00	No sampling
	b: Gypsum beds with green-white mudstone, 2015–1330 cm thick	13.30–20.15	6.85	8–15
A	Gypsum bed	20.15–22.11	2.36	6–7
	a: Red-orange mudstone intercalated with green-white mudstone	22.11–25.52	3.01	1–5

ples to one palynological assemblage on the basis of the relative abundance of the different pollen groups (Figs. 3 and 4).

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 *Taxodiaceapollenites*, 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 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 *Ephedripites*, *Nitrariadites* (*PokrovskajalMeliaceoidites*), and *Chenopodipollis* (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 Suiweiyi Formation in the Kuche Basin (Wang et al., 1986), those of the Huoshaogou 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. 4. Diagram showing the variations of palynology ecological groups and the ratio of *Nitraria/Ephedra* (N/E). The dashed red line indicates the transition point between the typical desert ecosystem (numbers below 1) and stepped desert (numbers above 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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. *Taxodiaceapollenites* 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

Fig. 5. Representative photographs of palynological grains from the Yang Ala section of Nangqian Basin. (A, B) *Taxodiacaepollenites hiatus* Kremp. (C) *Ephedripites yilipingenensis* Zhu et Wu. (D) *Ephedripites yueyashanensis* Zhu et Wu. (E, F) *Nitrariadites communis* Zhu. (G) *Qinghaipollis paradoxus* Zhu. (H) *Qinghaipollis subrotundus* Zhu. (I, J) *Nitrariadites subrotundus* Zhu. (K) *Gemmatricolporites subrotundus* Song et Zhu. (L) *Rutaceipollis lentiporus* Ke et Shi. (M, N) *Euphorbiacites granostratus* Song et Zhu. (O, P) *Labitricolporites stenosis* Ke et Shi. (Q, R) *Quercoidites henrici* Thomson et Thiergart. (S, T) *Fupingopollenites minutus* Liu. (U, V) *Tricolporopollenites eschweileri* Pflug et Thomason. (W, X) *Cruciferaepites elegans* Zheng. All scale bars are 20 μ m.

Fig. 6. Representative photographs of palynological grains from the Yang Ala section of Nangqian Basin. (A) *Chenopodipollis maximus* Nagy. (B) *Chenopodipollis multiporatus* Zhou. (C) *Faguspollenites koraiensis* Takahashi. (D) *Maceopolipollenites xiaokuzibaiensis* Sun et Wang. (E) *Dendriopoteriumpollis scabratus* Song et Zhu. (F) *Tubulifloridites macroechinatus* Song et Zhu. (G–I) *Pterisporites undulates* Sung et Zheng. (J–L) *Retitrescolpites pellucidus* Zheng. (M) *Sapindaceidites oblatus* Zhang et Zhan. (N) *Sapindaceidites projectus* Wang et Zhao. (O) *Retitricolporites firmianoides* Ke et Shi. (P) *Psilatricolporites fusuporus* Song et Liu. (Q) *Betulaceipollenites bituitus* Potonic. (R, S) *Rhoipites reticulatus* Zheng. (T, U) untitled. (V) *Tiliaepollenites paradoxus* Sun. All scale bars are 20 μm .

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 (*Taxodiaceapollenites*) 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 xerophytic elements, such as *Ephedripites* and *Nitrariadites*, with intervals when cypresses thrived. Ferns of *Taxodiaceapollenites* 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.

Acknowledgments

We thank Prof. Qing-Hai Xu and Dr. Sheng-Rui Zhang for assistance in the laboratory and Prof. Jin-Geng Sha for helpful comments and suggestions to improve the manuscript. We also thank the editor and referees (Prof. Jian-Guo Li and Prof. Carina Hoorn) for helpful comments. This work was financially supported by grants from the National Natural Science Foundation of China (Grant No. 41302024) and The Youth Guiding Fund of Qinghai Institute of Salt Lakes, CAS (Grant No. Y360391053).

References

- Abels, H.A., Dupont-Nivet, G., Xiao, G.Q., Bosboom, R., Krijgsman, W., 2011. Step-wise change of Asian interior climate preceding the Eocene–Oligocene Transition (EOT). *Palaeogeography, Palaeoclimatology, Palaeoecology* 299, 399–412.
- Aitchison, J.C., Davis, A.M., 2001. When did the India–Asia collision really happen? *Gondwana Research* 4, 560–561.
- Aitchison, J.C., Xia, X.P., Baxter, A.T., Ali, J.R., 2011. Detrital zircon U–Pb ages along the Yarlung–Tsangpo suture zone, Tibet: implications for oblique convergence and collision between India and Asia. *Gondwana Research* 20, 691–709.
- Bosboom, R.E., Dupont-Nivet, G., Houben, A.J.P., Brinkhuis, H., Villa, G., Mandic, O., Stoica, M., Zachariasse, W.J., Guo, Z.J., Li, C.X., Krijgsman, W., 2011. Late Eocene sea retreat from the Tarim Basin (west China) and concomitant Asian paleoenvironmental change. *Paleogeography, Paleoclimatology, Paleocology* 299, 385–398.
- Bosboom, R.E., Abels, H.A., Hoorn, G., Van den berg, B.C.J., Guo, Z.J., Dupont-Nivet, G., 2014. Aridification in continental Asia after the Middle Eocene Climatic Optimum (MECO). *Earth and Planetary Science Letters* 389, 34–42.
- Cai, M.T., Fang, X.M., Wu, F.L., Miao, Y.F., Appel, E., 2012. Pliocene–Pleistocene stepwise drying of Central Asia: evidence from paleomagnetism and sporopollen record of the deep borehole SG-3 in the western Qaidam Basin, NE Tibetan Plateau. *Global and Planetary Change* 94–95, 72–81.
- Chang, L., Guo, Z.T., Deng, C.L., Wu, H.B., Jin, X.P., Zhao, Y., Zhang, C.X., Ge, J.Y., Wu, B.L., Sun, L., Zhu, R.X., 2015. Pollen evidence of the palaeoenvironments of *Lufengpithecus lufengensis* in the Zhaotong Basin southeastern margin of the Tibetan Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology* 435, 95–104.
- Chen, J., Burbank, D.W., Scharer, K.M., Sobel, E., Yin, J.H., Rubin, C., Zhao, R.B., 2002. Magnetostratigraphy of the Upper Cenozoic strata in the Southwestern Chinese Tian Shan: rates of Pleistocene folding and thrusting. *Earth and Planetary Science Letters* 195, 113–130.
- Cour, P., Zheng, Z., Duzer, D., Calleja, M., Yao, Z., 1999. Vegetational and climatic significance of modern pollen rain in northwestern Tibet. *Review of Paleobotany and Palynology* 104, 183–204.
- Dai, S., Fang, X.M., Dupont-Nivet, G., Song, C.H., Gao, J.P., Krijgsman, W., Langereis, C., Zhang, W.L., 2006. Magnetostratigraphy of Cenozoic sediments from the Xining Basin: tectonic implications for the northeastern Tibetan Plateau. *Journal of Geophysical Research* 111, 1–19.
- Deng, W.M., Sun, H.J., Zhang, Y.Q., 2001. Petrogenesis of Cenozoic potassic volcanic rocks in Nangqian Basin. *Chinese Journal of Geology* 36, 304–318 (in Chinese, with English abstract).
- Duan, Q.F., Zhang, K.X., Wang, J.X., Yao, H.Z., Bu, J.J., 2007. Sporopollen assemblage from the Totohe Formation and its stratigraphic significance in the Tanggula Mountains, Northern Tibet. *Earth Science – Journal of China University of Geosciences* 32, 629–637 (in Chinese, with English abstract).
- Dupont-Nivet, G., Hoorn, C., Konert, M., 2008. Tibetan uplift prior to the Eocene–Oligocene climate transition: evidence from pollen analysis of the Xining Basin. *Geology* 36, 987–990.
- Fang, X.M., Garzone, C., Voo, R.V., Li, J.J., Fan, M.J., 2003. A flexural subsidence by 29 Ma on the NE edge of Tibet from the magnetostratigraphy of Linxia Basin, China. *Earth and Planetary Science Letters* 210, 545–560.
- Flynn, L.J., Downs, W., Opdyke, N., Kainian, H., Lindsay, E., Ye, J., Xie, G.P., Wang, X.M., 1999. Recent advances in the small mammal biostratigraphy and magnetostratigraphy of Lanzhou Basin. *Chinese Science Bulletin* 44, 105–118.
- Gao, R.Q., Zhu, Z.H., Zheng, G.G., Zhao, C.B., 2000. *Palynology of Petroleum Basins in China*. Petroleum Industry Press, Beijing, 250 pp. (in Chinese).
- Guo, Z.T., Sun, B., Zhang, Z.S., Peng, S.Z., Xiao, G.Q., Ge, J.Y., Hao, Q.Z., Qiao, Y.S., Liang, M.Y., Liu, J.F., Yin, Q.Z., Wei, J.J., 2008. A major reorganization of Asian climate by the early Miocene. *Climate of the Past* 4, 153–174.
- He, Y.M., Sun, X., 1977a. Palynological investigation of Palaeogene in the Qingjiang Basin, Kiangsi Province, I. *Acta Botanica Sinica* 19, 72–82 (in Chinese, with English title).
- He, Y.M., Sun, X., 1977b. Palynological investigation of Palaeogene in the Qingjiang Basin, Kiangsi Province, II. *Acta Botanica Sinica* 19, 237–243 (in Chinese, with English abstract).
- Herb, C., Koutsodendris, A., Zhang, W.L., Appel, E., Fang, X.M., Voigt, S., Pross, J., 2015. Late Pliocene–Pleistocene humidity fluctuations in the western Qaidam Basin (NE Tibetan Plateau) revealed by an integrated magnetic–palynological record from lacustrine sediments. *Quaternary Research* 84, 457–466.
- Hoorn, C., Straathof, J., Abels, H.A., Xu, Y.D., Utescher, T., Dupont-Nivet, G., 2012. A late Eocene palynological record of climate change and the Tibetan Plateau uplift (Xining Basin, China). *Palaeogeography, Palaeoclimatology, Palaeoecology* 344, 16–38.
- Ji, L.M., Meng, F.W., Yan, K., Song, Z.G., 2011. The dinoflagellate cyst *Subtilisphaera* from the Eocene of the Qaidam Basin, northwest China, and its implications for hydrocarbon exploration. *Review of Paleobotany and Palynology* 167, 40–50.
- Jiang, H.C., Ding, Z.L., 2008. A 20 Ma pollen record of East-Asian summer monsoon evolution from Guyuan Ningxia, China. *Paleogeography, Paleoclimatology, Paleocology* 265, 30–38.
- Li, J.J., Fang, X.M., Van der Voo, R., Zhu, J.J., Mac Niocaill, C., Cao, J.X., Zhong, W., Chen, H.L., Wang, J.L., Wang, J.M., Zhang, Y.C., 1997. Late Cenozoic magnetostratigraphy (11–0 Ma) of the Dongshanding and Wangjiashan sections in the Longzhong Basin, western China. *Geologie en Mijnbouw* 76, 121–134.

- Li, Y., Wang, N.A., Morrill, C., Cheng, H.Y., Long, H., Zhao, Q., 2009. Environmental change implied by the relationship between pollen assemblages and grain-size in N.W. Chinese lake sediments since the Late Glacial. *Review of Paleobotany and Palynology* 154, 54–64.
- Li, Y.C., Xu, Q.H., Zhao, Y.K., Yang, X.L., Xiao, J.L., Chen, H., Lü, X.M., 2005. Pollen indication to source plants in the eastern desert of China. *Chinese Science Bulletin* 50, 1632–1641.
- Liu, G.W., 1985. *Fupingopollenites* gen. nov. and its distribution. *Acta Palaeontologica Sinica* 24, 64–74 (in Chinese, with English abstract).
- Liu, D.S., Zheng, M.P., Guo, Z.T., 1998. Initiation and evolution of the Asian monsoon system timely coupled with the ice-sheet growth and the tectonic movements in Asia. *Quaternary Science* 3, 194–204 (in Chinese, with English abstract).
- Liu, Y.S., Zatter, R., Mohr, B.A.R., Ferguson, D.K., 2001. The lowers of an extinct legume from the Miocene of Southern Germany. *Palaeontographica Abteilung B* 256, 159–174.
- Liu, Z., Zhao, X., Wang, C.S., Liu, H.Y., 2003. Magnetostratigraphy of Tertiary sediments from the Hoh Xil Basin: implications for the Cenozoic tectonic history of the Tibetan Plateau. *Journal of Asian Earth Sciences* 154, 233–252.
- Lu, J.F., Song, B.W., Chen, R.M., Zhang, J.Y., Ye, H., 2010. Palynological assemblage of Eocene–Oligocene pollen and their biostratigraphic correlation in Dahonggou, Daqaidam Regions, Qaidam Basin. *Earth Science – Journal of China University of Geosciences* 35, 839–848 (in Chinese, with English abstract).
- Ma, Y.Z., Li, J.J., Fan, X.M., 1998. Pollen-based vegetational and climatic records during 30.6 to 5.0 Ma from Linxia area, Gansu. *Chinese Science Bulletin* 43, 301–304 (in Chinese).
- Miao, Y.F., 2010. Cenozoic Pollen Records in the Xining Basin and Its Significance for the Palaeoclimate Change. Postdoctoral Report. Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, 95 pp. (in Chinese, with English abstract).
- Miao, Y.F., Fang, X.M., Song, Z.C., Wu, F.L., Han, W.X., 2007. Pollen records of the Huoshaogou Formation of the Jiuquan Basin and rediscussion on the late Eocene palynofloras in northwest China. *Science in China Series D: Earth Sciences* 38, 187–196 (in Chinese, with English abstract).
- Miao, Y.F., Fang, X.M., Herrmann, M., Wu, F.L., Zhang, Y.Z., Liu, D.L., 2011. Miocene pollen record of KC-1 core in the Qaidam Basin, NE Tibetan Plateau and implications for evolution of the East Asian monsoon. *Palaeogeography, Palaeoclimatology, Palaeoecology* 299, 30–38.
- Miao, Y.F., Herrmann, M., Wu, F.L., Yan, X.L., Yang, S.L., 2012. What controlled Mid-Late Miocene long-term aridification in Central Asia? Global cooling or Tibetan Plateau uplift: a review. *Earth-Science Reviews* 112, 155–172.
- Miao, Y.F., Fang, X.M., Wu, F.L., Cai, M.T., 2013a. Late Cenozoic continuous aridification in the western Qaidam Basin: evidence from sporopollen records. *Climate of the Past* 9, 1863–1877.
- Miao, Y.F., Wu, F.L., Herrmann, M., Yan, X.L., Meng, Q.Q., 2013b. Late early Oligocene East Asian summer monsoon in the NE Tibetan Plateau: evidence from a palynological record from the Lanzhou Basin, China. *Journal of Asian Earth Sciences* 75, 46–57.
- Miao, Y.F., Fang, X.M., Song, C.H., Yan, X.L., Xu, L., Chen, C.F., 2013c. Pollen and fossil wood's linkage with Mi-1 Glaciation in northeastern Tibetan Plateau, China. *Palaeoworld* 22, 101–108.
- Miao, Y.F., Wu, F.L., Chang, H., Fang, X.M., Deng, T., Sun, X.M., Jin, C.S., 2016a. A Late-Eocene palynological record from the Hoh Xil Basin, Northern Tibetan Plateau, and its implications for stratigraphic age, paleoclimate and paleoelevation. *Gondwana Research* 31, 241–252.
- Miao, Y.F., Song, C.H., Fang, X.M., Meng, Q.Q., Zhang, P., Wu, F.L., Yan, X.L., 2016b. Late Cenozoic genus *Fupingopollenites* development and its implications for the Asian summer monsoon evolution. *Gondwana Research* 29, 320–333.
- Mo, X.X., Zhao, Z.D., Deng, J.F., Dong, G.C., Zhou, S., Guo, T.Y., Zhang, S.Q., Wang, L.L., 2003. Response of volcanism to the India–Asia collision. *Earth Science Frontiers* 10, 135–148 (in Chinese, with English abstract).
- Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. *Science* 189, 419–426.
- Pan, Y.S., Fang, A.M., 2010. Formation and evolution of the Tethys in the Tibetan Plateau. *Chinese Journal of Geology* 45, 92–101 (in Chinese, with English abstract).
- Pares, J.M., Van der Voo, R., Downs, W.R., Yan, M.D., Fang, X.M., 2003. Northeastward growth and uplift of the Tibetan Plateau: magnetostratigraphic insights from the Guide Basin. *Journal of Geophysical Research* 108, 113–130.
- Shatilova, I., Mchedlishvili, N., 2009. The pollen of the genus *Fupingopollenites* in the Cenozoic deposits of Georgia. *Bulletin of the Georgian Nation* 3, 153–157.
- Shi, Y.F., Li, J.J., Li, B.Y., Yao, T.D., Wang, S.M., Li, S.J., Gui, Z.J., Wang, F.B., Pan, B.T., Fang, X.M., Zhang, Q.S., 1999. Uplift of the Qinghai-Xizang (Tibetan) Plateau and East Asia environmental change during late Cenozoic. *Acta Geographica Sinica* 54, 10–19 (in Chinese, with English abstract).
- Spurlin, M.S., Yin, A., Horton, B.K., Zhou, J.Y., Wang, J.H., 2005. Structural evolution of the Yushu-Nangqian Region and its relationship to syncolli-sional igneous activity, east-central Tibet. *Geological Society of America Bulletin* 117, 1293–1317.
- Stanley, C., Charlet, D.A., Freitag, H., Maier-Stolte, M., Starratt, A.N., 2001. New observations on the secondary chemistry of world *Ephedra* (Ephedraceae). *American Journal of Botany* 88, 1199–1208.
- Sun, J.M., Zhu, R.X., Bowle, J., 2004. Timing of the Tianshan Mountains uplift constrained by magnetostratigraphic analysis of molasses deposits. *Earth and Planetary Science Letters* 219, 239–253.
- Sun, X.J., Wang, P.X., 2005. How old is the Asian monsoon system? Paleobotanical records from China. *Paleogeography, Paleoclimatology, Paleocology* 222, 181–222.
- Sun, X.Y., Zhao, Y., He, Z., 1984. The Oligocene–Miocene palynological assemblages from the Xining-Minghe Basin, Qinghai Province. *Geology Reviews* 30, 207–216 (in Chinese, with English abstract).
- Sun, Z., Yang, Z.Y., Pei, X.H., Wang, X.S., Yang, T.S., Li, W.M., Yuan, S.H., 2005. Magnetostratigraphy of Paleogene sediments from northern Qaidam Basin, China: implications for tectonic uplift and block rotation in northern Tibetan plateau. *Earth and Planetary Science Letters* 237, 635–646.
- Sun, Z.C., Feng, X.J., Li, D.M., Yang, F., Qu, Y.H., Wang, H.J., 1999. Cenozoic Ostracoda and palaeoenvironments of the northeastern Tarim Basin western China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148, 37–50.
- Tong, G.B., Zheng, M., Yuan, H., Liu, J., Li, Y., Wang, W., 2001. A study of middle and late Eocene palynological assemblages in Jiangnan Basin and their environmental significance. *Acta Geoscientia Sinica* 22, 73–78 (in Chinese, with English abstract).
- Wang, C.S., Zhao, X.X., Liu, Z.Z., Peter, C., Stephan, A.G., Robert, S.C., Zhu, L.D., Liu, S., Li, Y.L., 2008. Constraints on the early uplift history of the Tibetan Plateau. *Proceedings of the National Academy of Sciences of the United States of America* 105, 4987–4992.
- Wang, C.W., Hong, H.L., Li, Z.H., Yin, K., Xie, J., Liang, G.J., Song, B., Song, E., Zhang, K.X., 2013. The Eocene–Oligocene climate transition in the Tarim Basin, Northwest China: evidence from clay mineralogy. *Applied Clay Science* 74, 10–19.
- Wang, D.N., Sun, X.Y., Zhao, Y.N., He, Z., 1986. Palynoflora from late Cretaceous to Tertiary in Qinghai and Xinjiang. *Bulletin of the Institute of Geology Chinese Academy of Geological Sciences* 15, 152–165 (in Chinese, with English abstract).
- Wang, D.N., Sun, X.Y., Zhao, Y.N., He, Z., 1990. The Study on the Micropaleobotany from Cretaceous–Tertiary of the Oil Bearing Basins in Some Regions of Qinghai and Xinjiang. China Environmental Science Press, Beijing, 179 pp. (in Chinese, with English abstract).
- Wang, J., Wang, Y.J., Liu, Z.C., Li, J.Q., Xi, P., 1999. Cenozoic environmental evolution of the Qaidam Basin and its implications for the uplift of the Tibetan Plateau and the drying of central Asia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 152, 37–47.
- Wang, P., 1990. Neogene stratigraphy and paleoenvironments of China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 77, 3125–3334.
- Wang, S.F., Yi, H.S., Wang, C.S., 2001. Sedimentary facies and palaeogeography features of Nangqian Tertiary basin in Yushu district, Qinghai. *Northwestern Geology* 34, 64–67 (in Chinese, with English abstract).

- Wang, S.F., Yi, H.S., Wang, C.S., 2002. Sediments and structural features of Nangqian Tertiary Basin in eastern of Tibet-Qingzang Plateau. *Acta Scientiarum Naturalium* 38, 109–114 (in Chinese, with English abstract).
- Wang, W.M., 1990. Sporo-pollen assemblages from the Miocene Tonggure Formation of Inner Mongolia and its climate. *Acta Botanica Sinica* 32, 901–904 (in Chinese, with English abstract).
- Wang, W.M., Harley, M.M., 2004. The Miocene genus *Fupingopollenites*, comparisons with ultrastructure and pseudocolpi in modern pollen. *Review of Palaeobotany and Palynology* 131, 117–145.
- Wei, H.C., Fan, Q.S., Zhao, Y., Ma, H.Z., Shan, F.S., An, F.Y., Yuan, Q., 2015. A 94–10 ka pollen record of vegetation change in Qaidam Basin, northeastern Tibetan Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology* 431, 43–52.
- Wei, M., 1985. Eocene ostracods from Nangqian in Qinghai. *Contribution to the Geology of the Qinghai-Xizang (Tibet) Plateau* 17, 313–325 (in Chinese, with English abstract).
- Westerhold, T., Röhl, U., 2013. Orbital pacing of Eocene climate during the Middle Eocene Climate Optimum and the chron C19r event: missing link found in the tropical western Atlantic. *Geochemistry, Geophysics, Geosystems* 14, 4811–4825.
- Xia, L.Q., Li, X.G., Ma, Z.P., Xu, X.Y., Xia, Z.C., 2010. Cenozoic volcanism and tectonic evolution of the Tibetan plateau. *Gondwana Research* 19, 850–866.
- Xu, R., Song, Z.C., Zhou, H.Y., 1958. The palynological assemblages in Tertiary sediments of Qaidam Basin and its significance in geology. *Acta Palaeontologica Sinica* 6, 429–440 (in Chinese).
- Yang, D.X., Wang, P.S., 1988. The determinations of plateau age by ^{40}Ar – ^{39}Ar dating on Cenozoic calc-alkalic trachytes of Nangqen Basin, Northern transverse mountains. *Contribution to the Geology of the Qinghai-Xizang (Tibet) Plateau* 19, 39–44 (in Chinese, with English abstract).
- Yang, Y., 2002. Systematic and Evolution of *Ephedra* L. (Ephedraceae) from China. PhD Thesis. Institute of Botany Chinese Academy of Sciences, Beijing, 231 pp. (in Chinese, with English summary).
- Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan-Tibetan orogen. *Annual Review of Earth and Planetary Sciences* 28, 211–280.
- Zhang, J.J., Santosh, M., Wang, X.X., Guo, L., Yang, X.Y., Zhang, B., 2012. Tectonics of the northern Himalaya since the India–Asia collision. *Gondwana Research* 21, 939–960.
- Zhang, K.X., Wang, G.C., Chen, F.N., Xu, Y.D., Luo, M.S., Xiang, S.Y., Kou, X.H., Zhao, L.S., 2007. Coupling between the uplift of Qinghai–Tibet Plateau and distribution of basins of Paleogene–Neogene. *Earth Science – Journal of China University of Geosciences* 32, 583–597 (in Chinese, with English abstract).
- Zhang, M.Z., Ji, L.M., Du, B.X., Dai, S., Hou, X.W., 2015. Palynology of the Early Cretaceous section in the Jiuquan Basin, Northwest China: the discovery of diverse early angiosperm pollen and paleoclimatic significance. *Palaeogeography, Palaeoclimatology, Palaeoecology* 440, 297–306.
- Zhang, W.L., 2006. The High Precise Cenozoic Magnetostratigraphy of the Qaidam Basin and Uplift of the Northern Tibetan Plateau. PhD Thesis. Lanzhou University, Lanzhou, 109 pp. (in Chinese, with English summary).
- Zhang, Y.Y., 1995. Outline of Palaeogene palynofloras of China. *Acta Palaeontologica Sinica* 34, 213–227 (in Chinese, with English abstract).
- Zhang, Y.Y., Qian, Z.S., 1992. Eocene palynofloras from the Dainan and Sanduo Formation in north Jiangsu with special reference to Eocene climatic changes in southeast China. *Acta Micropalaeontologica Sinica* 9, 1–24 (in Chinese, with English abstract).
- Zhang, Y.Y., Zhan, J., 1991. Late Cretaceous and Early Tertiary Spores and Pollen from the Western Tarim Basin, S. Xinjiang, China. Science Press, Beijing, 319 pp. (in Chinese, with English abstract).
- Zhao, Y., Herzsuh, U., 2009. Modern pollen representation of source vegetation in the Qaidam Basin and surrounding mountains, north-eastern Tibetan Plateau. *Vegetation History and Archaeobotany* 18, 245–260.
- Zheng, H.B., Powell, C.M., An, Z.S., Zhou, J., Dong, G.R., 2000. Pliocene uplift of the northern Tibetan Plateau. *Geology* 28, 715–718.
- Zhou, J.Y., Wang, J.H., Yin, A., Spurlin, M.S., Horton, B.K., 2002. Depositional patterns and tectonic setting of Early Tertiary basins in the NE margin of the Tibetan Plateau: a case study of the Nangqian and Xialaxiu basins. *Acta Sedimentologica Sinica* 20, 85–91 (in Chinese, with English abstract).
- Zhu, H.C., Ouyang, S., Zhan, J.Z., Wang, Z., 2005. Comparison of Permian palynological assemblages from the Junggar and Tarim Basins and their phytoprovincial significance. *Review of Palaeobotany and Palynology* 136, 181–207.
- Zhu, L., Zhang, H.H., Wang, J.H., Zhou, J.Y., Xie, G.H., 2006. $^{40}\text{Ar}/^{39}\text{Ar}$ chronology of high-K magmatic rocks in Nangqian Basins at the northern segment of the Jinsha-Red River Shear Zone (JRRSZ). *Geotectonica et Metallogenia* 30, 241–247 (in Chinese, with English abstract).
- Zhu, Z.H., Wu, L., Xi, P., Song, Z.C., Zhang, Y.Y., 1985. A Research on Tertiary Palynology from the Qaidam Basin, Qinghai Province. Petroleum Industry Press, Beijing, 297 pp. (in Chinese, with English abstract).