



# Late Cenozoic continuous aridification in the western Qaidam Basin: evidence from sporopollen records

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**Abstract.** Cenozoic climate changes in inner Asia provide a basis for understanding linkages between global cooling, the Tibetan Plateau uplift, and possibly the development of the East Asian monsoon. Based on a compilation of palynological results from the western Qaidam Basin, this study reconstructed a 15-million-year (Ma) record of changing vegetation and paleoclimates spanning the middle Miocene to present (comprising two series:  $\sim 18$ –5 Ma and  $\sim 3.1$ –0 Ma, respectively). The thermophilic percentages were highest between 18 and 14 Ma, and decreased after 14 Ma, closely corresponding to the Middle Miocene Climatic Optimum (MMCO) between 18 and 14 Ma and the following global climatic cooling between 14 and 5 Ma. At the same time, decreases in the xerophytic and coniferous taxa percentages, and the increasing logarithmic ratio of non-arboreal pollen to arboreal pollen ( $\ln(\text{NAP}/\text{AP})$ ), reveal the continuous aridification across both the basin and surrounding mountains. Between  $\sim 3.1$  and 0 Ma, the percentages of the thermophilic, xerophytic and coniferous pollen as well as the  $\ln(\text{NAP}/\text{AP})$  imply further cooling and drying in this region since 3.1 Ma. We argue that these vegetation and climate patterns during the late Cenozoic western Qaidam Basin are primarily a result of the global cooling, with the Tibetan Plateau uplift and East Asian summer monsoon having contributions of lesser importance.

## 1 Introduction

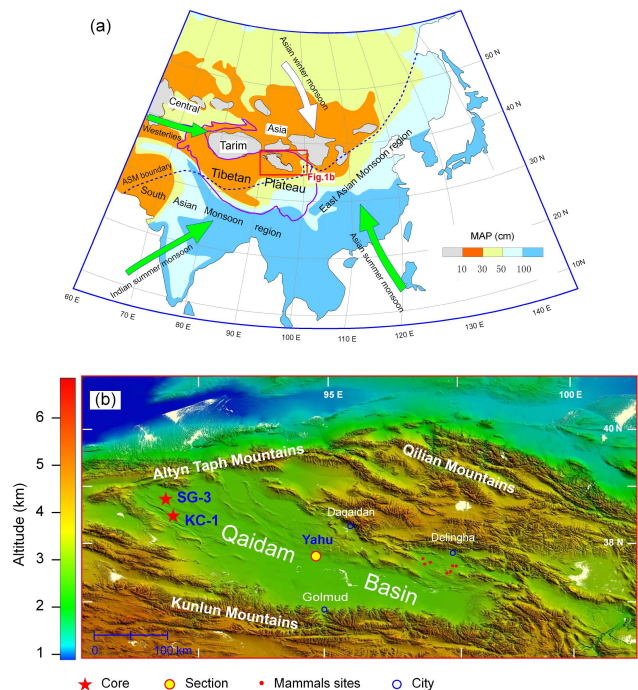
Central Asia experienced generally dry conditions during the late Oligocene–early Miocene period, in contrast to East Asia where humid conditions are thought to indicate the key period in the development of the modern-like arid and Asian monsoon climates (e.g., Wang, 1984; Liu et al., 1998; Sun and Wang, 2005; Zhang and Guo, 2005; Guo et al., 2008). Since the mid-Cenozoic, the evolution of climate near the boundary of Central Asia and East Asia has influenced the wind-blown sediment characteristics and the vegetation history. Hence, studies of both the wind-blown silt sediments (loess and red clay) deposited in Central Asia (e.g., Liu, 1985; Ding et al., 1992; Sun et al., 1998; An et al., 2001; Guo et al., 2002; Qiang et al., 2011) and the vegetation history (e.g., Jiang and Ding, 2008; Sun and Zhang, 2008; Hui et al., 2011; Miao et al., 2011; Tang et al., 2011; Zhang and Sun, 2011) can provide information about the environmental changes and driving forces influencing the landscape and climate. However, reconstructions of some dramatic events and even of the longer term climatic trends can vary between different climate proxies (e.g., Ma et al., 1998, 2005; Sun and Zhang, 2008; Kent-Corson et al., 2009; Tang et al., 2011; Zhuang et al., 2011). For example, eolian sediments suggest enhanced aridity at 5.3 Ma in the Tarim Basin (Sun and Liu, 2006), whereas pollen records show a humid phase during the same period in the neighboring Tian Shan Mountains (Sun et al., 2007). Accordingly, two basic theories have

been proposed with regard to climatic influences: (i) that climate responded primarily to a stepwise uplift of the Tibetan Plateau following the India–Asia collision and associated tectonic events, which altered the atmospheric circulation (e.g., Manabe and Terpstra, 1974; Kutzbach et al., 1989; Ruddiman and Kutzbach, 1989; Manabe and Broccoli, 1990; Raymo and Ruddiman, 1992; An et al., 2001; Liu et al., 2003) and initiated rapid silicate weathering (e.g., Edmond and Huh, 1997; Wan et al., 2012), while the global cooling only played a secondary role; and (ii) global cooling reduced the amount of the precipitation and the effective moisture, and the Tibetan Plateau uplift was less important (e.g., Lu et al., 2010; Miao et al., 2011, 2012; Tang et al., 2011). Although the retreat of the shallow Paratethys Sea has also been identified as an important factor in the decreasing precipitation in Central Asia (Ramstein et al., 1997; Zhang et al., 2007), this seems to have occurred before the late Cenozoic (Bosboom, et al., 2011).

The first key step in addressing these uncertainties is to determine better the characteristics of the climatic trends by obtaining high-quality climate records. The Qaidam Basin in central Inner Asia (north of the Tibetan Plateau) provides a key location to explore climate changes, where the effects of the global temperature, Tibetan Plateau uplift and development of the Asian monsoon are preserved due to the basin's ideal location and super-thick Cenozoic sediments (e.g., Rieser et al., 2005; Fang et al., 2007; Wang et al., 2007; Lu and Xiong, 2009; Miao et al., 2011, 2012; Wu et al., 2011; Cai et al., 2012; Chang et al., 2012) (Fig. 1a). This study compiles pollen results from the western Qaidam Basin to reveal the aridification patterns and trends, and then discusses the associated mechanisms.

## 2 Geological setting

The Qaidam Basin, with an average elevation of  $\sim 2900$  m and area of  $\sim 120\,000$  km<sup>2</sup>, is the largest intermontane basin at the northeastern edge of the Tibetan Plateau. The basin is surrounded by the Altyn Tagh Mountains to the northwest, the Qilian Mountains to the northeast, and the Kunlun Mountains to the south (Fig. 1b). In modern times, the climate in the Qaidam Basin has been mainly controlled by westerlies, while the Asian summer monsoon usually extends only to the southeastern part of the basin. The basin's mean annual temperature (MAT) lies between 2 °C and 4 °C, and the mean annual precipitation (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 Asian summer monsoon during summer (Du and Sun, 1990). The mean annual evaporation exceeds the MAP by more than 20 times, leading to a temperate, arid-type climate (Zhou et al., 1990). Deserts (including the Gobi) and salt lakes are the main features of the basin today.



**Fig. 1.** (a) Physical geography and distribution of mean annual precipitation (MAP) in Asia and main precipitation sources influencing the Qaidam Basin (ASM: modern Asian summer monsoon, after Gao, 1962), and (b) digital elevation map of the Qaidam Basin, showing the locations of the KC-1 (Miao et al., 2011) and SG-3 (Cai et al., 2012) pollen cores; Yahu pollen section (Wu et al., 2011); and mammal sites used for isotopic studies in the eastern Qaidam Basin (C. F. Zhang et al., 2012).

Work by petroleum geologists over the last 50 yr has established a basin-wide lithostratigraphic framework for the Qaidam Basin. Throughout the basin, seven formations (Fm) have been defined (from the lowest, upward): the Lulehe Fm, the Xia Ganchaigou Fm, the Shang Ganchaigou (SGCG) Fm, the Xia Youshashan (XYSS) Fm, the Shang Youshashan (SYSS) Fm, the Shizigou (SZG) Fm, and the Qigequan (QGQ) Fm. Seismic profiles show good lithostratigraphic correlations and comparability of the different horizons throughout the entire basin (e.g., Gu et al., 1990; Huang et al., 1996; Xia et al., 2001; Rieser et al., 2005, 2006; Zhou et al., 2006). Several geologists have identified and studied numerous animal fossils (e.g., Wang et al., 2007; Chang et al., 2008; C. F. Zhang et al., 2012) or have provided paleomagnetic dating (e.g., Sun et al., 2005; Fang et al., 2007; Lu and Xiong, 2009; Chang et al., 2012; W. L. Zhang et al., 2012, 2013) in this basin.

This paper reports the analysis of two cores: KC-1 and SG-3. The depth of the KC-1 core reaches 3435 m, passing through the bottom of the SZG Fm, the entire SYSS Fm, and ending just into the upper part of the XYSS Fm (Fig. 2). The ages of the KC-1 core cover  $\sim 18$  Ma to 5 Ma (see details in Miao et al., 2011). A paleomagnetic study of the SG-3 boring

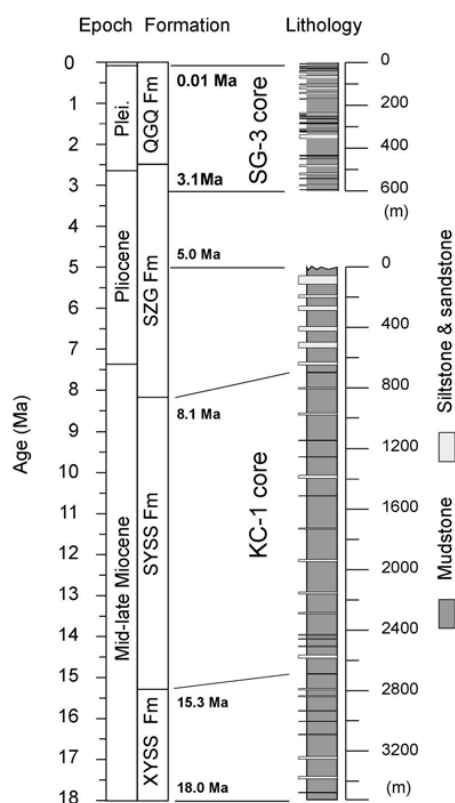


Fig. 2. Late Cenozoic stratigraphic distribution in the KC-1 (Miao et al., 2011) and SG-3 (Cai et al., 2012) cores.

(drilled to a depth of 600 m) indicates that it covers the age range between 3.1 and 0 Ma (for details, see Cai et al., 2012). In total, the ages of these two cores cover from ~18 Ma to 0 Ma, with a gap of 1.9 million years between 5 and 3.1 Ma.

### 3 Data and methods

A total of 58 and 103 samples were taken from the KC-1 and SG-3 sites, respectively, for palynological analysis. In both cores, more than 300 pollen grains per sample were identified in order to obtain the detailed palynomorph content of each sample. In the KC-1 core, the coniferous pollen taxa dominated most of the samples; *Picea*, *Pinus*, Podocarpaceae, *Tsuga*, *Cedrus* and Taxodiaceae/Cupressaceae/Taxaceae (TCT) were identified in all pollen slides. The other most common pollen taxa came from terrestrial shrubs and herbs (TSH), such as Chenopodiaceae, Ephedraceae, Asteraceae, *Artemisia*, *Nitraria*, Poaceae, etc. In comparison, the diversity and abundances of broad-leaved pollen taxa like *Quercus*, Juglandaceae, Ulmaceae and Betulaceae were much lower. Only a few types of algae and fungal spores were found in some samples (Miao et al., 2011). Meanwhile, in the SG-3 core, the sporopollen taxa primarily comprised TSH: *Artemisia*, Chenopodiaceae, Poaceae,

Asteraceae, Ephedraceae and *Nitraria* (the average of the sum of all these herbs and shrubs was 94.0%); the trees *Picea*, *Abies*, *Pinus*, Betulaceae, Ulmaceae, *Quercus* and Juglandaceae were of secondary importance with low percentages (average 6.0%). A few pteridophyte and algal spores were also found (Cai et al., 2012).

Although distinct pollen zones in the cores have been identified and discussed, as of yet there has been no detailed comparison, proper statistical analysis or combination between cores. In this study, we used the Tilia software (E. Grimm of Illinois State Museum, Springfield, Illinois, USA) to plot pollen diagrams. Next, we used detrended correspondence analysis (DCA) and principle component analysis (PCA) to identify the pollen ecologic similarities, and finally we discuss the long-term vegetation history and its driving forces.

### 4 Results and analysis

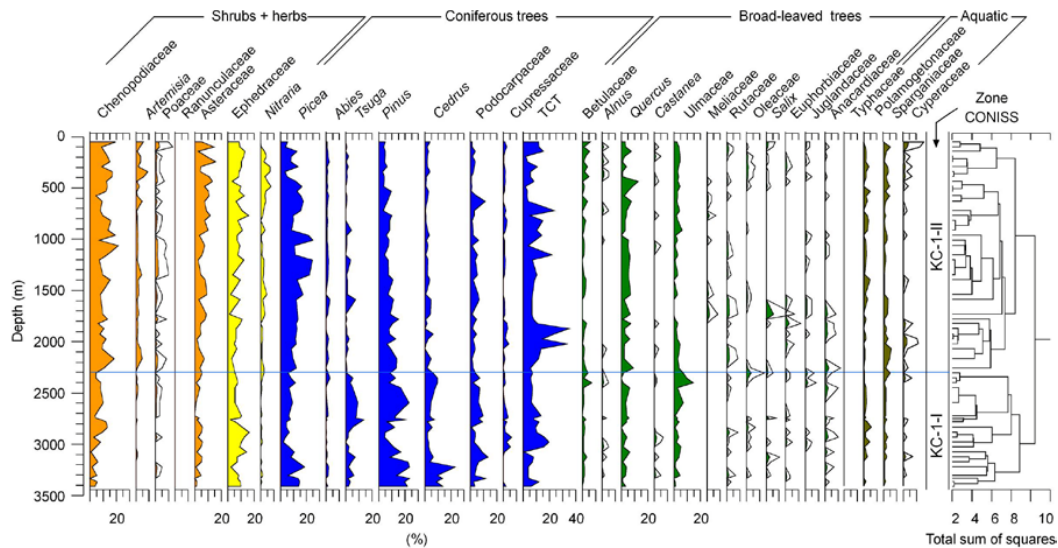
In both cores we reconstructed the pollen diagram in the same taxa order using any taxa that occurred in at least two samples with a relative abundance of > 1% in either core. This allowed easy comparison of percentage changes (Figs. 3 and 4). Stratigraphically constrained cluster analysis (CONISS) yielded two distinct zones (periods) in the KC-1 core, as follows.

(1) Zone KC-1-I: between 3435 and 2360 m (corresponding to approx. 18–14 Ma), showing a high abundance of alpine *Cedrus*, *Tsuga*, Podocarpaceae and *Pinus*, but low *Picea*, while TSH taxa such as *Nitraria* and *Artemisia* exhibited low abundances and Ephedraceae was relatively high. (2) Zone KC-1-II: between 2300 and 50 m (approx. 14–5 Ma), all TSH showed increasing percentages, while the conifers decreased except for *Picea*, which steadily increased until ~9 Ma and then slightly decreased (Fig. 3).

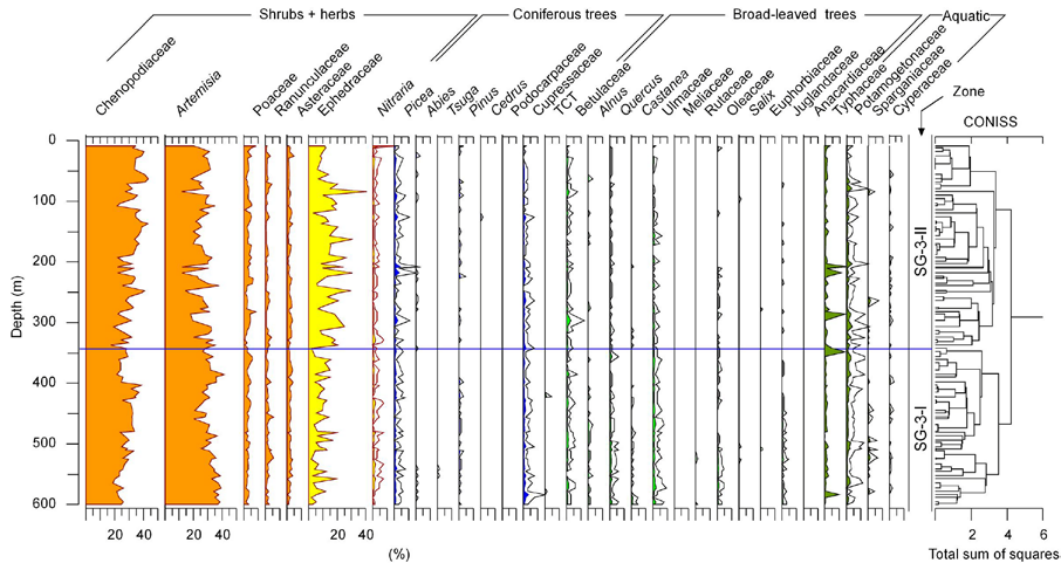
In the SG-3 cores, again two periods could be identified based on the CONISS. In Zone SG-3-I (between 600 and 346 m, 3.1–1.2 Ma), the TSH were dominant and characterized by high percentages of Chenopodiaceae (average (av.) ~30%), *Artemisia* (av. ~33%) and Ephedraceae (av. ~10%), while tree percentages were low. In Zone SG-3-II (between 346 and 0 m, 1.2–0 Ma), TSH percentages continuously increased and were characterized by higher Chenopodiaceae (av. ~34%), *Artemisia* (av. ~30%) and Ephedraceae (av. ~14%), while trees continued to decline (Fig. 4). At the northwestern margin of the Qaidam Basin, pollen retrieved from Sugan Lake indicates sustained dry and cold conditions in the late Holocene (2.7 ka to today), following the end of the Pleistocene (K. Zhang et al., 2012).

In previous studies of the KC-1 core, we divided the pollen diagram into five parts based on traditional analysis (variations in the abundance of the dominant taxa); however, in Fig. 3 the pollen diagram is clearly divided into two parts such that the former boundaries identified at ca. 17.0, 15.5, 14 and 8 Ma by Miao et al. (2011) are now the





**Fig. 3.** KC-1 core pollen diagram in the western Qaidam Basin adapted from Miao et al. (2011) (TCT: Taxodiaceae/Cupressaceae/Taxaceae).

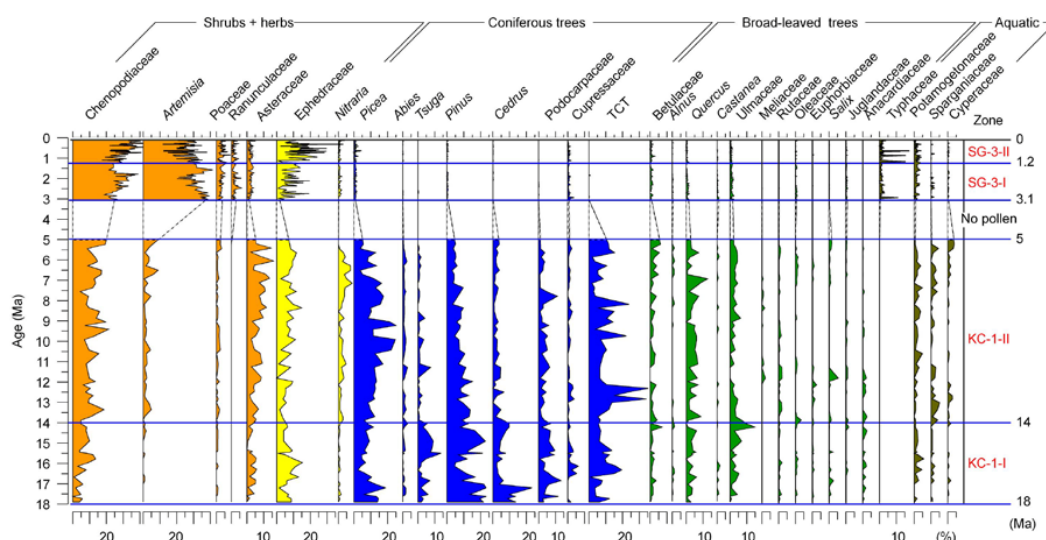


**Fig. 4.** SG-3 core pollen diagram in the western Qaidam Basin adapted from Cai et al. (2012) (TCT: Taxodiaceae/Cupressaceae/Taxaceae).

sub-boundaries at best. This means that only the boundary at 14 Ma is significant relative to the others. Similar results for the SG-3 core yielded a boundary at 1.2 Ma, which is better defined than the others at 2.6, 1.8, 0.9 and 0.6 Ma (Cai et al., 2012).

In summary, when the two cores are analyzed together, we find the following characteristics. During 18–14 Ma, arboreal pollen taxa had the highest percentage (approx. 70 %) and were dominated by conifers (ca. 60 %, including *Tsuga*, Podocarpaceae, *Cedrus* and *Pinus*, etc.), while the TSH taxa (such as Chenopodiaceae, Asteraceae, Ephedraceae and *Nitraria*) were lowest (approx. 12 %). During 14–5 Ma, the vegetation experienced a relatively long-term deterioration,

characterized by increasing TSH and decreasing conifers, although Podocarpaceae, *Cedrus* and *Tsuga* occurred frequently. Meanwhile, broad-leaved arbors (such as *Quercus*, Betulaceae, Ulmaceae, Juglandaceae, etc.) remained at roughly the same low levels (about 10–5 %). The early period of the Pliocene (5–3.1 Ma) remains unknown due to a lack of pollen data, but the vegetation has suffered even harsher conditions since 3.1 Ma, such that almost all conifers have disappeared: especially Pinaceae and Podocarpaceae. In the broad-leaved trees, no subtropical taxa were found and the deciduous arbors have continuously decreased ( $\sim 10$ –1.4 %). Meanwhile, TSH percentages have generally remained high (approx. 90 %) (Fig. 5). Overall, the compiled pollen data

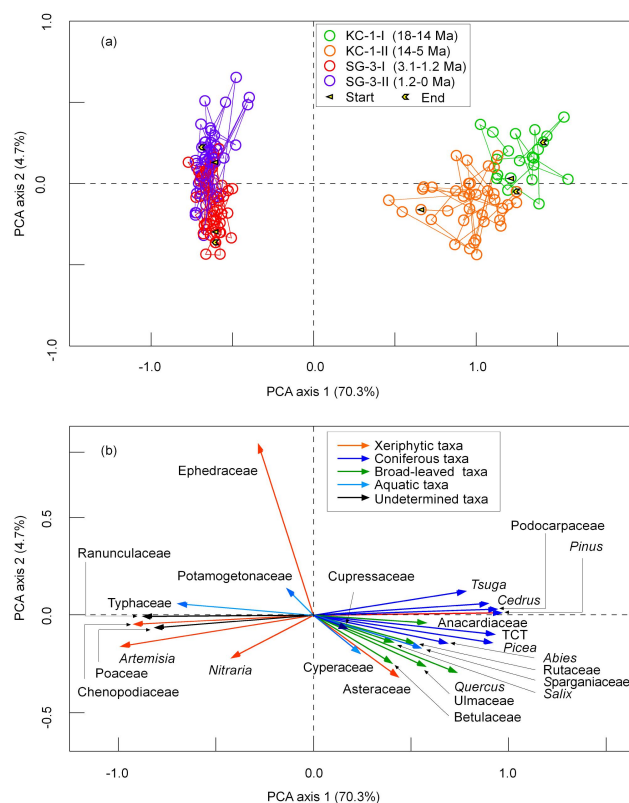


**Fig. 5.** Late Cenozoic pollen diagram with zones of the KC-1 and SG-3 cores (TCT: Taxodiaceae/Cupressaceae/Taxaceae).

show a continued expansion in TSH in contrast to decreasing arbors (including coniferous and broad-leaved trees) (Fig. 5).

In order to assess the pollen ecological similarities, 25 pollen taxa with percentages > 2 % in any one sample were selected for detrended correspondence analysis (DCA) and principle components analysis (PCA) using the program CANOCO (ter Braak, 1988). Firstly, DCA was used to identify the length of the environmental gradient and to determine whether linear- or unimodal-based techniques should be employed in subsequent ordination analyses. The length of the gradient was 2.14 standard deviation units, suggesting linear techniques were most appropriate for our data (Birks, 1998). To summarize the data structure, PCA of the pollen assemblages was performed (Fig. 6).

PCA of the pollen samples (Fig. 6a) and pollen taxa (Fig. 6b) reflects the characteristics of the pollen diagram and summarizes the main vegetation shifts. PCA axis 1 accounts for 70.3 % of variability, and mostly reflects the relative change in TSH (Ephedraceae, Chenopodiaceae, *Artemisia* and others) on the left side and in trees (both the coniferous and broad-leaved taxa) on the right side; PCA axis 2 only accounts for 4.7 %, and no clear significance was identified due to its much lower contribution. The variations in sample scores represent shifts in four pollen zones and vegetation types, characterized by four separated clusters (Fig. 6a). For example, the loosely clustered zone KC-1-I and KC-1-II samples were characterized by high percentages of the conifers (such as *Pinus*, *Tsuga*, *Cedrus*, Podocarpaceae, *Picea*, and TCT), whereas zones SG-3-I and SG-3-II were characterized by high percentages of *Artemisia*, Chenopodiaceae, Poaceae and Ephedraceae (Fig. 6b). PCA axis 1 mostly separates zones of the KC-1 core from those of the SG-3 core.



**Fig. 6.** PCA plot of (a) pollen samples, with pollen zones indicated in the KC-1 and SG-3 cores in the western Qaidam Basin (“Start” and “End” represent the first and last samples, respectively, in each zone), and (b) pollen types (the end of the arrow indicates the score values of PCA axes 1 and 2; TCT: Taxodiaceae/Cupressaceae/Taxaceae).

## 5 Discussion

Today, almost all conifers belong to the alpine elements: for example, Podocarpaceae grows mainly in the subtropical southern Asian mountains under a warm and humid climate at elevations between 800 and 1000 m. In contrast to the Podocarpaceae, *Tsuga* also prefers humid conditions in mountainous regions, but experiences its maximum growth between 2800 and 3200 m and tolerates a cooler climate. *Cedrus* tolerates warm and humid conditions, although it needs less precipitation than Podocarpaceae and *Tsuga*. *Picea* tolerates low temperatures and (depending of the species) less precipitation (Florin, 1963), and thrives at elevations between 2300 and 4200 m. *Pinus*, however, adapts to a wide range of temperature and precipitation conditions in Asia and occurs over a relatively wide elevation range of 1300–4200 m (Florin, 1963; Wu, 1995). Cupressaceae mainly grows on sunny slopes between 1700 and 5300 m. Due to an unclear relationship (or distribution), the preferred environment of TCT is uncertain.

The broad-leaved trees are mainly distributed in the humid to semi-humid East Asia in relatively low-lying areas, since the Rutaceae, Euphorbiaceae, Sapindaceae and Anacardiaceae usually need a warmer (subtropical) environment than the temperate deciduous taxa such as Betulaceae, *Quercus*, *Castanea*, Ulmaceae, Meliaceae, Oleaceae, *Salix* and Juglandaceae (Wu, 1995).

In contrast to the alpine flora and broad-leaved trees, the TSH group, including Ephedraceae, Chenopodiaceae, *Nitraria*, Asteraceae and *Artemisia*, inhabits mainly arid and semi-arid regions of northwestern China, and is defined as “xerophytic flora”. Besides the TSH, other taxa (such as Typhaceae, Potamogetonaceae, Sparganiaceae and Cyperaceae) mainly inhabit water and are defined as “aquatic plants”. PCA shows that the trends in Typhaceae and Potamogetonaceae are opposite to those of the Cyperaceae and Sparganiaceae (Fig. 6b). Highly variable individual percentages yet low averages are possibly the key reason for their opposing PCA directions (Fig. 5). A similar pattern was found for Poaceae and Ranunculaceae, both of which are widely distributed and cannot be regarded as true xerophytic taxa in this study, although their scores are similar to those of typical xerophytic taxa.

Pollen assemblages containing high proportions of xerophytic taxa and humid alpine conifers, as well as low percentages of the broad-leaved and aquatic pollen, indicate an open, dry area (e.g., basins, plains or plateaus) surrounded by an alpine region that is relatively wet due to the topographic influence. In the arid to semiarid regions, broad-leaved trees usually inhabit relatively wet areas and are therefore confined to a narrow range, in contrast to the conifers and xerophytic taxa, but sometimes they can also reach the open areas along the rivers (e.g., Miao et al., 2011; Wu et al., 2011). The aquatic taxa can only depend on the water-covered area.

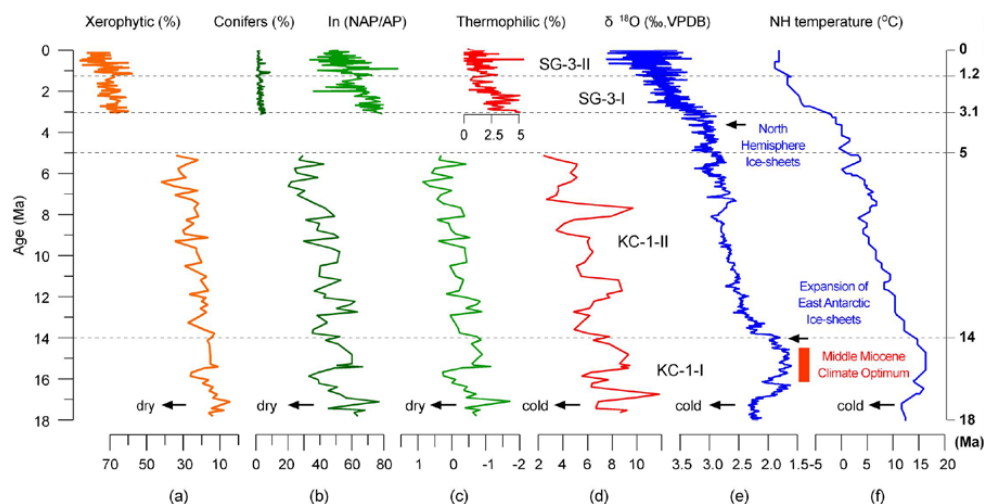
In summary, the pollen and PCA results from the western Qaidam Basin reveal four major changes in vegetation over the last 18 million years. From 18 to 14 Ma, the coniferous flora grew in the alpine zone and the relatively sparse xerophytic flora were found in the basin. During 14–5 Ma, the coniferous flora retreated and xerophytic flora expanded continuously (Figs. 3 and 5). However, during 3.1–1.2 Ma, the steppe flora expanded greatly and coniferous forest almost disappeared. In the following period (1.2–0 Ma), the steppe flora spread further (Figs. 4 and 5).

### 5.1 Aridification and temperature trends

As a result of these floral associations, the interactions between xerophytic flora and alpine flora can be used as ideal proxies for the paleoclimate development in the Qaidam Basin. To illustrate this relationship, Fig. 7 plots the degree of aridity in the basin (represented by the xerophytic taxa, defined as the sum of Chenopodiaceae, Ephedraceae, *Nitraria*, *Artemisia* and Asteraceae, Fig. 7a) and the humidity of the alpine zone (represented by all conifers, Fig. 7b) in the Qaidam Basin. The increase of the xerophytic percentages from about ~12 % to ~80 % (Fig. 7a), and the decrease of the total conifers from about ~70 % to ~2 % (Fig. 7b) between ~18 and 5 Ma and between 3.1 and 0 Ma support continuous aridification in the western Qaidam Basin during that time period. The decreasing logarithmic ratio of non-arboreal pollen to arboreal pollen ( $\ln(\text{NAP/AP})$ ), which ranged between −1.5 and 4.2, followed a similar pattern to the aridification trends (Fig. 7c).

Overall, time series of the xerophytic, alpine and coniferous percentages, and  $\ln(\text{NAP/AP})$  indicate a continuous drying process in both the basins and surrounding alpine regions.

At the same time, the PCA results did not yield any temperature information. Here we select Podocarpaceae, Anacardiaceae, Euphorbiaceae, Rutaceae, Meliaceae and Sapindaceae in the KC-1 core as the thermophilic taxa, mainly owing to their modern relationships with the subtropical region (Wu, 1995). The total percentage of this group reveals the continuous cooling trend during 18–5 Ma (Fig. 7d). During 3.1–0 Ma, when the thermophilic taxa in the KC-1 core had disappeared, Cai et al. (2012) replaced the thermophilic taxa by the cumulative percentages of *Betula*, *Quercus*, *Castanea* and *Juglans* in the SG-3 core due to their relatively warmer habitat preference than the widely eurythermal but dry-tolerant shrubs and herbs; these data support further cooling (Fig. 7d). All correlations between thermophilic (%) and xerophytic (%), conifers (%), and  $\ln(\text{NAP/AP})$  are strong (Fig. 8a, b and c).



**Fig. 7.** Comparison of (a) xerophytic percentages, (b) conifer percentages, (c)  $\ln(\text{NAP}/\text{AP})$  (NAP: non-arboreal pollen; AP: arboreal pollen) and (d) thermophilic element percentages, with (e) the global deep-sea oxygen isotope ( $\delta^{18}\text{O}$  ‰) records (20-point running average) (Zachos et al., 2008) and (f) temperature simulations using a 1-D ice-sheet model (de Boer et al., 2010).

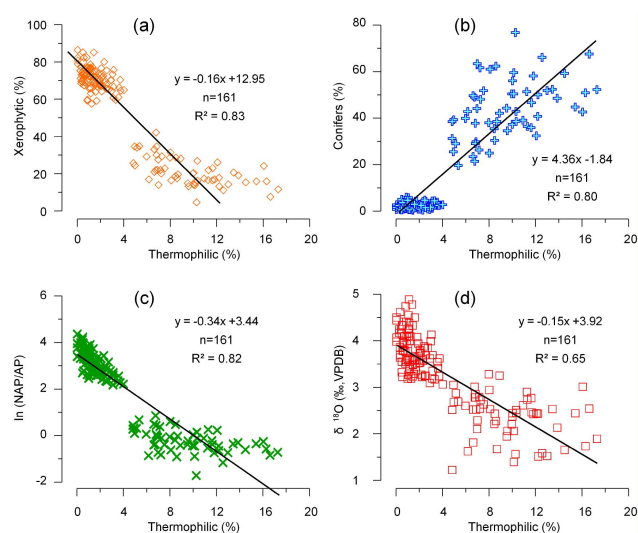
## 5.2 Global cooling and Tibetan Plateau uplift

All records from the two sites show continuous drying and cooling since the middle Miocene. The following important basic scientific question is the following: what controlled the aridification of the western Qaidam Basin during the late Cenozoic – was it dominated by global cooling or by an uplift of the Tibetan Plateau?

Figure 7 includes the global deep-sea oxygen isotope records (e.g., Miller et al., 1987; Zachos et al., 2001, 2008) and temperature simulations with a 1-D ice-sheet model (de Boer et al., 2010) to show the Earth's late Cenozoic global temperature evolution. As shown in Fig. 7e, the global climate (reported by the averaged  $\delta^{18}\text{O}$  values) shifted from about 2.2 ‰ at 18 Ma, to  $\sim 1.7$  ‰ between 17 Ma and 14 Ma, but then to  $\sim 3$  ‰ at 3 Ma. Values have now increased to over  $\sim 4$  ‰, indicating an overall cooling trend since the Middle Miocene Climatic Optimum (Zachos et al., 2008). Temperature simulations with a 1-D ice-sheet model show as much as a  $15^\circ\text{C}$  cooling in the Northern Hemisphere (de Boer et al., 2010) (Fig. 7f). Temperature changes in the western Qaidam Basin indicated by the thermophilic percentages clearly parallel those temperature changes indicated by both the  $\delta^{18}\text{O}$  and 1-D ice-sheet model. Correlation between the thermophilic (%) and  $\delta^{18}\text{O}$  values is still strong (Fig. 8d).

In addition to the similar  $\delta^{18}\text{O}$  trends, four other aspects support the suggestion that the cooling since 18 Ma in the western Qaidam Basin may have been controlled by world-wide global cooling.

First, the thermophilic percentages correlate well with the oxygen isotope curve; for example, between approx. 18 and 14 Ma, the thermophilic percentages (from  $\sim 3$  % to  $\sim 12$  %) show an increase roughly coincident with the



**Fig. 8.** Correlation between (a) xerophytic percentages and thermophilic percentages, (b) coniferous percentages and thermophilic percentages, (c)  $\ln(\text{NAP}/\text{AP})$  and thermophilic percentages, and (d)  $\delta^{18}\text{O}$  ‰ (data from Zachos et al., 2008) and thermophilic percentages.

Middle Miocene Climatic Optimum (MMCO; Zachos et al., 2008). At the same time, the xerophytic percentages fall to their lowest values (between  $\sim 5$  % and  $\sim 15$  %, average 12 %). From 14 Ma until 5 Ma, the thermophilic percentages continuously decreased (from  $\sim 8$  % to  $\sim 2$  %) coincident with the global cooling, while the xerophytic percentages increased from  $\sim 15$  % to  $\sim 30$  %. Based on the pollen records for 3.1–0 Ma, the thermophilic percentages compare fairly well with both the cooling trend and the glacial–interglacial

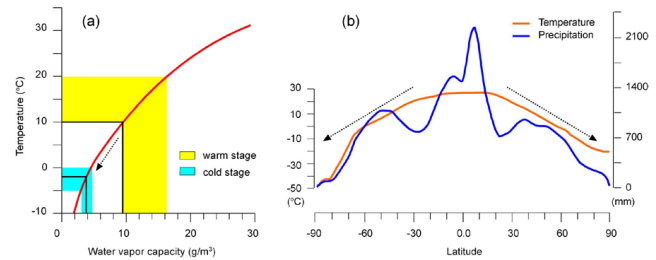


cycles indicated by oceanic  $\delta^{18}\text{O}$  data. The strong correlation between the thermophilic (%) and  $\delta^{18}\text{O}$  values supports such relationships (Fig. 8d).

Second, the precipitation (moisture) reaching inner Asia firstly has to cross Europe, high-latitude Asia, the East Asian monsoon region, or the South Asian monsoon region, which means that the precipitation in the Qaidam Basin should follow a similar trend to that in one or all four of these regions (e.g., Miao et al., 2012). Notably, most records from these four regions have shown drying and cooling trends during the Miocene (e.g., Europe: Mosbrugger et al., 2005; Utescher et al., 2007; Jiménez-Moreno et al., 2010; high-latitudes: White et al., 1997; East Asia and South Asia: Quade et al., 1989, 1995; Wang et al., 2001; Clift, 2006; Clift et al., 2008; Passey et al., 2009; Wan et al., 2010). In the western Qaidam Basin, the long-term trends of xerophytic percentages, coniferous percentages and  $\ln(\text{NAP/AP})$  covering 18–5 Ma and 3.1–0 Ma further support this model.

Third, many studies have found relationships between temperature and the atmospheric vapor capacity. For example, Oard (1990) established a relationship between the water vapor capacity and temperature. Normally, high precipitation requires relatively rapid evaporation of sea water, which only occurs from warm water because water evaporation increases exponentially with temperature (Oard, 1990) (Fig. 9a). This can explain well the general precipitation trend as a function of latitude for the present day: specifically, the reduction in precipitation as temperature decreases (except in the subtropical high belt between 20° and 40° latitude) (Fig. 9b). So, the western Qaidam Basin aridification and cooling trends can be explained by Oard's (1990) model and the global precipitation pattern: during the warm Miocene (18–14 Ma), increased precipitation could fall in the Qaidam Basin due to the higher water vapor capacity (Fig. 9a), similarly to the abundant precipitation in low latitudes (Fig. 9b). Consequently, precipitation has decreased as a result of global cooling during 14–5 and 3.1–0 Ma and the corresponding reduction in water vapor capacity (Fig. 9a), similarly to the lower precipitation in the high latitudes (Fig. 9b). Such clear relationships can also explain the climatic trends in Eurasia (e.g., Lu et al., 2010; Tang et al., 2011; Miao et al., 2011) and the Asian monsoonal region (e.g., Quade et al., 1989, 1995; Passey et al., 2009).

Fourth, the global cooling would have lowered the upper timberline. For example, on the Tibetan Plateau, *Picea* can reach 2300 to 4200 m above sea level; however, in the Tian Shan Mountains, it can only grow below 2800 m due to falling temperatures. All other arbors have also experienced a similar upper timberline retreat with temperature, which means that in the western Qaidam Basin, all arboreal percentages should decline as the climate cools and their suitable habitat shrinks. The related pollen percentages will continuously decrease until their eventual disappearance, whereas the xerophytic taxa percentages have increased (Fig. 7a and b, also shown as Fig. 10a and c).



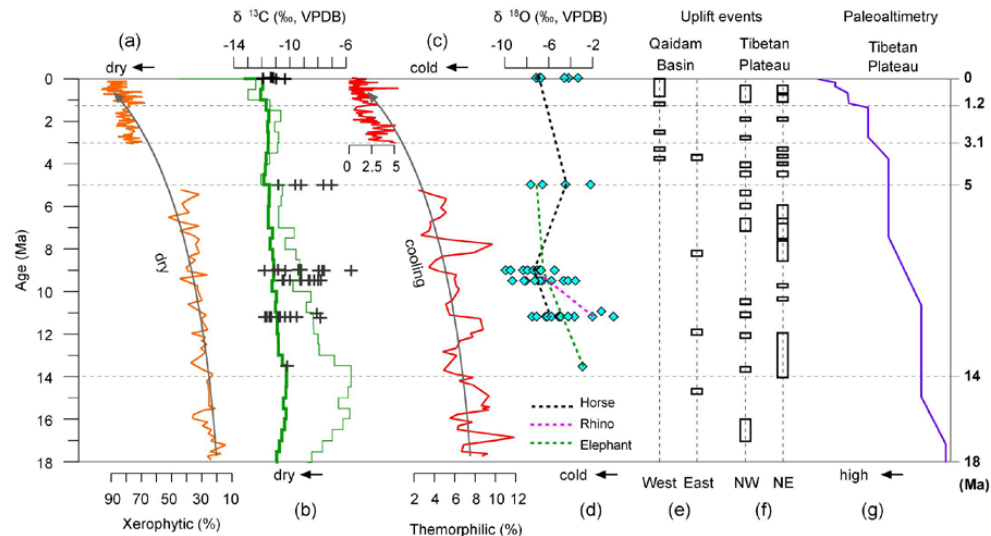
**Fig. 9.** Plots showing (a) water vapor capacity at saturation (11 % relative humidity) versus temperature (Oard, 1990) (note the 60 % drop in capacity as temperature decreases from 10 to  $-2^{\circ}\text{C}$  (black line); highlighted areas show the vapor capacity in the warm Miocene (yellow) and cold Pleistocene (blue) according to de Boer et al. (2010) (arrow showing the exponential relationship between cooling and water vapor capacity reduction), and (b) variations in MAT and MAP as a function of latitude for the present day (Haywood et al., 2000) (arrow indicating the general relationship between cooling and precipitation reduction).

As an alternative to global cooling, many models support the assumption that rapid Tibetan Plateau uplift has caused the strong drying of Inner Asia (e.g., Manabe and Terpstra, 1974; Kutzbach et al., 1989; Ruddiman and Kutzbach, 1989; Manabe and Broccoli, 1990; Raymo and Ruddiman, 1992; Liu et al., 2003; Zhang et al., 2007). This would mean that orogenesis could have effectively disturbed precipitation patterns in the mountainous regions of Central Asia (especially the Tibetan Plateau) as it underwent various extensive phases of orogeny.

In the western Qaidam Basin, rich *Picea* and other species in Pinaceae, as well as Podocarpaceae and TCT together, form the vertical vegetational bands in the mountains, in contrast to the dry basin occupied by the xerophytic taxa. So, we believe the vertical topography should have existed during the Miocene. However, it is very difficult to directly separate the paleoaltimetry information, and even uplift events, from the pollen results. For example, in the SG-3 core, the pollen assemblage shifts at approx. 2.6 Ma, 1.2 Ma, 0.9 Ma, and 0.6 Ma can be explained by Tibetan Plateau uplift as well as global cooling (Cai et al., 2012) but without any direct evidence. In the eastern Qaidam Basin, based on the enamel  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  records (Fig. 10b and d), C. F. Zhang et al. (2012) noted that the obvious aridification since the early Pliocene was likely due to the combined effects of regional tectonism and global cooling, but lacked tectonism records. So, we only can infer results for the tectonics based on records from the basin and surrounding area.

Firstly, tectonic evidence reveals some tectonic events at 3.6 Ma (W. L. Zhang et al., 2013), 3.2 Ma (Chang et al., 2012), 2.6–2.2 Ma, 1.1 Ma (W. L. Zhang et al., 2013) and < 0.8 Ma (W. L. Zhang et al., 2012) in this region (Fig. 10e). The eastern part of the Qaidam Basin shows some evidence of tectonic activity at about  $\sim 14.7$  Ma (Fang et al., 2007),





**Fig. 10.** Compiled aridification records in the (a) western (this study) and (b) eastern Qaidam Basin (black cross:  $\delta^{13}\text{C}$  records of bulk enamel samples by C. F. Zhang et al. (2012); coarse green line: averaged  $\delta^{13}\text{C}$  records of model-predicted values for animals with pure C3 diets by Passey et al. (2009); thin green line at five times the coarse green line), temperature in the (c) western (this study) and (d) eastern Qaidam Basin (blue diamonds:  $\delta^{18}\text{O}$  records from bulk enamel samples after C. F. Zhang et al., 2012), tectonic uplift events in (e) the Qaidam Basin (rectangle showing the tectonic events; the western basin after Chang et al., 2012, and W. L. Zhang et al., 2012, 2013; the eastern basin after Fang et al., 2007, and Lu and Xiong, 2009) and (f) the northern Tibetan Plateau (rectangles showing the tectonic events; the NW part after Zheng et al., 2000; Chen et al., 2002; Wang et al., 2003; Sun et al., 2004, 2005, 2007, 2008, 2009; Charreau et al., 2005, 2006; Huang et al., 2006; Heermance et al., 2007, 2008; Sun and Zhang, 2008; Tang et al., 2011, and Zhang and Sun, 2011; the NE part after Li et al., 1997; C. H. Song et al., 2001; Y. G. Song et al., 2001; Zhao et al., 2001; Fang et al., 2003, 2005a, b; Pares et al., 2003; Zheng et al., 2006; Lin et al., 2010; Wang et al., 2010; and W. T. Wang et al., 2011; X. X. Wang et al., 2011), and (g) the presumed paleoaltimetry history after An et al. (2006).

~12 Ma (Lu and Xiong, 2009), ~8.1 Ma and ~3.6 Ma (Fang et al., 2007) (Fig. 10e). Looking more widely, we have summarized the timing and signature of tectonic uplifts near, at some distance or far from the surrounding mountains (e.g., Li et al., 1997; Zheng et al., 2000, 2006; C. H. Song et al., 2001; Y. G. Song et al., 2001; Chen et al., 2002; Fang et al., 2003, 2005a, b; Pares et al., 2003; Wang et al., 2003; Sun et al., 2004, 2005, 2007, 2008, 2009; Charreau et al., 2005, 2006; Huang et al., 2006; Heermance et al., 2007, 2008; Sun and Zhang, 2008; Lin et al., 2010; Wang et al., 2010; W. T. Wang et al., 2011; X. X. Wang et al., 2011; Tang et al., 2011; Zhang and Sun, 2011; Nie et al., 2013) (Fig. 10f). Figure 10g also shows an interpretation of the Tibetan Plateau elevation history during the late Cenozoic based on compiled multiple geological records (An et al., 2006).

The above studies suggest that uplift events have become more frequent with time. If this is indeed true, our results of aridification and temperature trends should have been influenced by the tectonic uplifts, especially in the latest period, because the tectonic events can influence climate and vegetation patterns by altering the precipitation (e.g., Miao et al., 2012; Z. G. Zhang et al., 2013). For example, in the SG-3 core, the pollen assemblage shifts at approx. 2.6 Ma, 1.2 Ma, 0.9 Ma and 0.6 Ma appear to have been responses to the Tibetan Plateau uplift in addition to the global cooling (Cai et

al., 2012). In the eastern Qaidam Basin, the timing of aridification mainly after the early Pliocene has also been linked to tectonic events.

In addition to tectonics, paleoaltimetry caused by the tectonics is another important aspect influencing the aridity. However, much evidence shows that the Tibetan Plateau reached its modern height during the Oligocene or Eocene (Rowley, 2007; Garzione, 2008; Quade et al., 2011) or most likely between 30 and 20 Ma (Wu et al., 2008). In this case, the Qaidam Basin probably remained stable during the late Cenozoic; thus the aridification of the Qaidam Basin would have been less closely linked with the Tibetan Plateau uplift according to the models (e.g., Manabe and Terpstra, 1974; Kutzbach et al., 1989; Manabe and Broccoli, 1990; Raymo and Ruddiman, 1992; Liu et al., 2003). However, considering the several tectonic events and stratigraphic deformation history (Liu et al., 2009; Wang et al., 2012) within the basin, and the series of tectonic events on the northern Tibetan Plateau, we argue that the Qaidam Basin might have experienced upwards growth during the late Cenozoic even though an exact paleoaltimetry history cannot be established, which would have intensified aridification.

Additional considerations include the influence of the retreat of the shallow Paratethys (Ramstein et al., 1997; Zhang et al., 2007) or topographic teleconnections (e.g., C. F. Zhang

et al., 2012; Bosboom et al., 2011). However, the Paratethys is thought to have mostly retreated from the Tarim Basin before the Miocene (e.g., Bosboom et al., 2011), suggesting no direct relationship with the late Cenozoic period currently under discussion. For the topographic teleconnections, the aridification of the eastern Qaidam Basin since the early Pliocene is successfully explained by the result of the more effective barrier preventing moisture from the Indian Ocean or Bay of Bengal from reaching the basin; if such a barrier did exist, it should also have influenced the western Qaidam Basin to some extent.

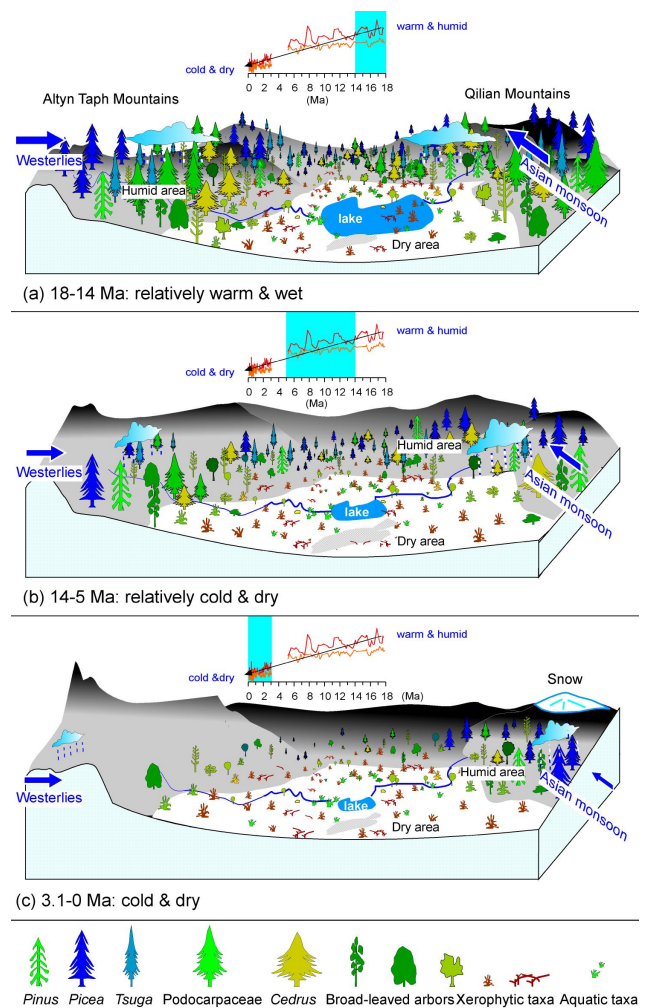
### 5.3 Asian monsoon

In Asia, the compilation of paleobotanical and lithological data from all over China has revealed that the Miocene Asian monsoon boundary was very close to the eastern Qaidam Basin (Liu et al., 1998; Guo et al., 2002, 2008; Sun and Wang, 2005). Theoretically, the climate in the Qaidam Basin could be influenced by the retreat or expansion of the Asian monsoon; the closer the region to the boundary, the stronger effect the monsoon has. However, it is very difficult to separate effects of the Asian monsoon from those of the global cooling, especially as evidence has now shown that the Asian monsoon intensity also decreased during the global cooling (e.g., Jiang and Ding, 2008; Passey et al., 2009; Miao et al., 2012). Some alternative conclusions have also been presented (e.g., Ding et al., 1992; An et al., 2001), and Oard's (1990) model can also explain the relationship between the Asian summer monsoon strength and global cooling (e.g., Clift, 2006; Wan et al., 2007, 2010; Clift et al., 2008; Passey et al., 2009): the Asian monsoon should have expanded in the early Miocene due to higher water vapor contents under higher temperatures. Thus, the western Qaidam Basin may have been influenced by the monsoonal system, as evidenced by the many wet taxa found during that time, including Podocarpaceae and *Tsuga*. With the reducing monsoon strength, the monsoon boundary shifted away from the western basin, but the eastern part might have remained in the monsoon system until the early Pliocene according to records from the eastern Qaidam Basin (C. F. Zhang et al., 2012).

Hence, we consider that the long-term aridification trends during the late Cenozoic (~18–5 Ma, and 3.1–0 Ma) western Qaidam Basin have been mainly driven by global cooling, with a lesser influence from the Tibetan Plateau uplift and Asian monsoon.

### 5.4 Aridification during 5–3.1 Ma

There are no pollen data for reconstructing climate during the period 5–3.1 Ma in the western Qaidam Basin: was there a step change or a continuous decrease? The answer to this question will strongly impact the quality of the correlation between our signals and the global climate. Wu et al. (2011)



**Fig. 11.** Cartoon illustrating the vegetation, paleoclimates, and paleoaltimetry of the Qaidam Basin during (a) 18–14 Ma, (b) 14–5 Ma, and (c) 3.1–0 Ma (blue rectangle showing the corresponding climate background according to the compiled pollen results).

constructed a pollen diagram for the outcropping lacustrine Yahu section in the central Qaidam basin covering 5.3–1.8 Ma. These pollen results revealed much higher percentages of *Picea*, *Pinus*, *Chenopodiaceae* and *Artemisia*, which is obviously different from our compiled results (contemporaneous pollen from the KC-1 core: 5.3–5 Ma, and SG-3 core: 3.1–1.8 Ma), possibly due to more precipitation reaching this region than the western part. However, the pollen data in the Yahu section still show a long-term aridification trend in both the basin and surrounding mountains, with two small drying steps at 3.6 Ma and 2.6 Ma; again, these are explained by both global cooling and uplift of the Tibetan Plateau (Wu et al., 2011). In the Yahu section, the dry conditions are also indicated by the extraordinarily thick-boned fish (Chang et al., 2008). Very close to the KC-1 and SG-3 cores, the F2 core was also used for collecting pollen (Wang et al., 1999), and while there were few pollen samples

and unclear pollen percentages except for *Pinus*, *Picea*, and Podocarpaceae, the aridification trends were similar to our compiled results (Wang et al., 1999), also reflecting a long-term drying trend.

Figure 11 illustrates the relationships between the vegetation, climate and topographic history, as a cartoon picture. During the middle Miocene (18–14 Ma), relatively sparse steppe taxa grew in what was probably a low-lying basin. The alpine trees, including *Tsuga*, *Picea*, Podocarpaceae and *Pinus*, flourished on the surrounding mountains, utilizing the rich precipitation during a global warm stage (possibly from the Asian summer monsoon and westerlies). At this time, the basin and surrounding mountains were relatively low (Fig. 11a). During the late Miocene and early Pliocene (14–5 Ma), the area covered by xerophytic taxa increased, and the alpine trees declined as less rain reached the basin. Then, the basin and mountains were uplifted (Fig. 11b). During the latest Pliocene and Pleistocene (3.1–0 Ma), xerophytic taxa almost completely replaced the conifers, due to the further global cooling, and the basin probably reached its modern elevation (Fig. 11c).

## 6 Conclusions

The Qaidam Basin is the largest basin on the northern margin of the Tibetan Plateau, and has experienced an arid climate during our study period. Our study compiled pollen results from two cores in order to characterize the aridification process, spanning the periods of 18–5 Ma and 3.1–0 Ma with a gap during 5–3.1 Ma. During this extended time period, the xerophytic percentages increased, conifers decreased, and the logarithmic ratio of non-arboreal pollen to arboreal pollen increased. These results suggest a general drying process in the Qaidam region, including both the basin and surrounding mountains. The thermophilic percentages correspond well with the oxygen isotope data, thereby linking local conditions with the global climatic cooling. The Tibetan Plateau uplift and the Asian summer monsoon strength exerted secondary influences.

Further pollen research should address three aims: coring the sediments representing 5–3.1 Ma, identifying more samples in the KC-1 core, and collecting pollen at those fossil mammal sites in the eastern basin, in order to better understand the complete vegetation and climate changes, the differences between the different parts of the basin, and the dominating mechanisms influencing the changes.

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