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

Y. F. Miao[1], X. M. Fang[2], F. L. Wu[2], M. T. Cai[2], C. H. Song[3], Q. Q. Meng[3], and L. Xu[4]

[1]Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences, Lanzhou, 730000, China
[2]Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, 100085, China
[3]School of Earth Science, Lanzhou University, Lanzhou, 730000, China
[4]Qinghai Petroleum Sub-corporation of Petro China Company Limited, Dunhuang, 736202, China

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Correspondence to: X. M. Fang (fangxm@itpcas.ac.cn)

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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 the compiled palynological results from the western Qaidam Basin, this study reconstructed an 18 Ma record of changing vegetation and paleoclimates since the middle Miocene. Thermophilic taxa percentages were highest between 18 and 14 Ma and decreased after 14 Ma, corresponding closely with the Middle Miocene Climatic Optimum (MMCO) between 18 and 14 Ma and the following global climatic cooling. After 3.6 Ma, the thermophilic taxa percentages further decreased, showing the inevitable relations with the ice-sheets enlargement in the North Hemisphere. During the same period of time, the increase in xerophytic taxa percentages and decrease in conifers percentages imply aridification in both the basin and surrounding mountains since 18 Ma. These results indicate that global cooling mainly controlled the climate change from a relative warm-wet stage to a cold-dry stage during the late Cenozoic at the western Qaidam Basin, and that the Tibetan Plateau uplift also contributed in contrast to the East Asian summer monsoon.

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 of the modern-like arid and Asian monsoon building climate (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 sediments and the vegetation history. Hence, the studies of both the wind-blown silt sediments (loess and red clay) deposited in Central Asia (e.g. Liu, 1985; Ding et al., 1998; 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., 2011a; Tang et al., 2011; Zhang and Sun, 2011) can provide information about the environmental changes and driving forces behind the landscape and climate. However, for an understanding of the driving mechanisms, two basic theories have been raised: (i) that a stepwise uplift of the Tibetan Plateau (mostly) following the India–Asia collision changed 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 triggered by the Indo-Asia collision and associated tectonic events (e.g. Edmond and Huh, 1997; Wan et al., 2012); and (ii) global cooling reduced the amount of the precipitation and the effective moisture (e.g. Lu et al., 2010; Miao et al., 2011a, 2012; Tang et al., 2011). Although the retreat of the shallow Paratethys Sea has also been identified as an important factor in the decrease of precipitation in Central Asia (Ramstein et al., 1997; Zhang et al., 2007), but this seems to have occurred before the late Cenozoic (Bosboom et al., 2011).

Nevertheless, we must first better determine the characteristics of the climatic trends by obtaining continuous climate records. The Qaidam Basin in central Inner Asia (north of the Tibetan Plateau) provides a key location to explore climate changes, the effects of the global climate change, the Tibetan Plateau uplift, development of the Asian monsoon. This study compiles sporopollen results from the western Qaidam Basin that indicate the drying patterns and trends, and then discusses possible mechanisms.

2 Geological setting

The Qaidam Basin, with an average elevation of ~2900 m, holds the largest intermontane basin at the northeastern edge of the Tibetan Plateau (covering an area of ~120 000 km^2). The Altyn Tagh Mountains surround the basin to the northwest, the Qilian Mountains to the northeast, and the Kunlun Mountains to the south (Fig. 1). In modern times, the East Asian summer monsoon usually extends to the southeastern part of the Qaidam Basin. The Basin's mean annual temperature lies between 2 and 4 °C and the mean annual precipitation (MAP) falls below 100 mm in most parts of the basin (less than 25 mm in the western part), whereas the MAP reaches 150–200 mm at the southeastern margin of the basin because of the long-range influence of the East Asian summer monsoon during summer (Du and Sun, 1990). The mean annual evaporation exceeds the MAP by more than 20 times, causing a temperate arid type climate to evolve (Zhou et al., 1990). Deserts (including the Gobi) and salt lakes provide the main features of the basin today. 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 a 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). A number of geologists have identified and studied numerous animal fossils (e.g. Wang et al., 2007; Chang et al., 2008) or provided palaeomagnetic dating (e.g. Sun et al., 2005; Fang et al., 2007a; Lu and Xiong, 2009; Zhang et al., 2012a) from this basin.

This paper reports on the analysis of three cores: the detailed KC-1 and SG-3 cores, and the less detailed F2 core (Fig. 1). The depth of the KC-1 core reaches 3435 m, through the bottom of the SZG Fm, the entire SYSS Fm, and ending just in the upper part of the XYSS Fm (Fig. 2). The ages of the KC-1 core cover from ∼ 18 to 5 Ma (see details in Miao et al., 2011a). A palaeomagnetic study of the SG-3 boring (drilled to a depth of 600 m) indicates that it covers the age range between 3.1 and 0.01 Ma (for details, see Cai et al., 2012). About 300 m in top part of the F2 core (totally drilled to a depth of 2770 m) is the entire SZG Fm, roughly correspond in age to about 8.0–2.5 Ma (Wang et al., 1999). Totally, the ages of these three cores cover from ∼ 18 to 0.01 Ma.

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3 Materials and methods

Samples from all sites were taken for the same palynological analysis. All samples were treated with 10 % HCl and 40 % HF to remove carbonates and silica. Separation of the palynomorphs from the residue was carried out using a 10-µm nylon sieve. Finally, the palynomorphs were mounted in glycerin jelly for palynomorph determination. From the KC-1, F2, and SG-3 cores, the numbers of palynology samples are 58, ca. 8 (seemingly) and 251 samples, respectively.

4 Results and analysis

In the KC-1 core, coniferous pollen taxa dominate in most of the samples; *Picea, Pinus, Podocarpus, Tsuga* and *Cedrus* have been identified in all pollen slides. The other most common pollen came from shrubs and herbs, such as Chenopodiaceae, *Ephedra*, Asteraceae, *Artemisia*, *Nitraria*, Poaceae, etc. In comparison, the diversity and abundances of broadleaved pollen taxa like *Quercus*, Juglandaceae, Ulmaceae, Betulaceae are much less abundant. Only a few types of algae and fungal spores have been found in some samples (see detailed species in Miao et al., 2011a). No detailed pollen assemblages were described from the F2 core; only *Pinus*, *Picea*, and *Podocarpus* can be directly read from the diagram (Fig. 3) (Wang et al., 1999). Whereas in the SG-3 core, the sporopollen taxa include mainly major herbs and shrubs: *Artemisia*, Chenopodiaceae, Poaceae, Asteraceae, Ephedraceae, and *Nitraria* (the average of the sum of all these herbs and shrubs reaches 94.0 %); and the trees *Picea*, *Abies*, *Pinus*, *Betula*, *Ulmus*, *Quercus*, *Juglans* and *Alnus*, only can be the second dominance with very low percentages (average 6.0 %). A few pteridophyte and algal spores were also found.

Based on the variations in the abundance of the dominant taxa, we delineate five periods: (1) the period between approx. 18–14 Ma, which showed a high abundance of alpine *Cedrus*, *Tsuga*, *Podocarpus*, and *Pinus*, but *Picea* was low, whereas in the steppe taxa, *Nitraria* and *Artemisia* exhibited low abundances, *Ephedra* was relatively

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high; (2) the period between approx. 14–8 Ma, when all steppe taxa increased their percentages, whereas the conifers decreased except for *Picea*, which steadily increased its percentages until ∼ 9 Ma and then maintained a high level; (3) between approx. 8–5 Ma, when steppe taxa continuously increased, while the conifers decreased further; (4) between approx. 5–3 Ma, when *Picea* and *Podocarpus* almost disappeared, while *Pinus* remained stable; and (5) between 3–0.01 Ma, during which the herbs and shrubs taxa continuously increased, characterized with the highest percentages of the Chenopodiaceae (average 30.6 %), *Artemisia* (average 30.4 %) and Ephedraceae (average 12.2 %), whereas trees further disappeared (Fig. 2). At the northwestern margin of the Qaidam Basin, the pollen from Sugan Lake, indicate continued dry and cold conditions in the late Holocene (2.7 ka to today), following the end of the Pleistocene (Zhang et al., 2010).

In summary, the proportions of arboreal pollen decrease continuously from high (approx. 70 %) to low (approx. 4 %) percentages over the time span of the cores, which is caused by the decrease of conifer pollen from about 60 to 6 % (including *Tsuga*, *Podocarpus*, *Cedrus*, *Pinus*, etc.). Meanwhile, broadleaved arboreal taxa (*Quercus*, Betulaceae Ulmaceae, Juglandaceae, etc.) remain at roughly the same low levels (about 10–5 %) before Pleistocene and decrease obviously (about 10–1.4 %) throughout the whole Pleistocene. The sum of the steppe elements increases continuously from low levels (approx. 12 %) to higher levels (approx. 90 %), with increases of Asteraceae, *Artemisia*, *Nitraria*, Ephedraceae, and Chenopodiaceae (Fig. 3).

5 Discussion

Today, the alpine elements, such as *Podocarpus,* grow mainly in the subtropical southern Asian mountains under a warm and humid climate. In contrast to the *Podocarpus* climate, *Tsuga* also prefers humid conditions in mountainous regions for maximum growth, but tolerates a cooler climate. *Cedrus* tolerates warm and humid conditions, although it needs less precipitation. *Picea* tolerates low temperatures and (depending of the species) less precipitation (Florin, 1963). *Pinus*, however, adapts to a wide range of temperature and precipitation in Asia (Florin, 1963; Wu, 1995). Of the steppe elements, *Ephedra*, Chenopodiaceae, and *Nitraria* inhabit mainly arid and semi-arid regions of northwestern China as xerophytic taxa. *Artemisia* can also prefer dry condition, but with relatively wetter environment compared to these previous three xerophytic taxa (e.g. Zheng et al., 2008; Miao et al., 2011b). Pollen assemblages containing high proportions of xerophytic taxa and alpine conifers indicate an open dry area (e.g. basins, plains or plateaus) with a surrounding alpine region with a relatively wet climate due to the topography influence. The broad-leaved taxa percentages are always low because the areas of their preferred conditions tend to be small in the dry region (e.g. Wu et al., 2011; Miao et al., 2012).

5.1 Aridification trend

As a result of these floral associations, the interactions between steppe flora and mountainous flora can be used as proxies for the climate development in the Qaidam Basin. To illustrate this relationship, Fig. 4 plots the degree of aridity in the basin (represented by the xerophytic taxa percentages against, line A) and the humidity of the alpine zone (represented by the relatively humid tolerant conifers, sum of *Pinus*, *Podocarpus*, *Tsuga* and *Cedrus,* line B) in the Qaidam Basin. The increase of the xerophytic taxa from about 10 % to 80 % (Fig. 4a), and the decrease of the total conifers from about 70 % to 2 % (Fig. 4b) between 18 and 0.01 Ma supports continuous aridification in the western Qaidam Basin during that time period. The decrease of the logarithmic ratio of non-arboreal pollen (NAP) to arboreal pollen (AP) (ln(NAP/AP)), ranges between −1.5 and 4.2, varying similarly to the aridification trends (Fig. 4c). In the Yahu section, middle Qaidam Basin (Fig. 1), both the xerophytic plants and NAP/AP ratios also indicate the drying process between 5.3–1.8 Ma (Wu et al., 2011). This drying is also indicated by the extraordinarily thick-boned fish at the same area (Chang et al., 2008).

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5.2 Temperature trends

Besides the drying trends, the sporopollen records can reveal information about the temperature trends. The pollen records from these three cores suggest that the temperature decreased gradually since 18 Ma ago. For example, *Podocarpus*, and other thermophilic taxa such as Anacardiaceae, Euphorbiaceae, Rutaceae, Sapindaceae populated the basin mainly in the early period, then decreased slowly since the late Miocene, almost disappearing after late Pliocene. To illustrate the temperature intuitively, Fig. 4d plots an indicator of temperature, represented by the cumulative percentages of the thermophilic taxa discussed above in the KC-1 and F2 cores (Cai et al., 2012, for the former thermophilic taxa in the KC-1 and F2 cores disappearance), and replaced by the cumulative percentages of *Betula*, *Quercus*, *Castanea*, and *Juglans* in the SG-3 core. These data support continuous cooling from a relatively warm stage to a cold stage, beginning 18 Ma ago in the western Qaidam Basin.

5.3 Global cooling and Tibetan Plateau uplift

All records from these three sites show continuous drying and cooling since the middle Miocene. The following important basic scientific question is: what controlled the aridification of the western Qaidam Basin during the late Cenozoic? Does global cooling dominate, or does stepwise uplift of the Tibetan Plateau?

Figure 4 includes the global deep-sea oxygen isotope records in order to show the Earth's late Cenozoic oceanic climate evolution (e.g. Miller et al., 1987; Zachos et al., 2001, 2008). As shown in Fig. 4e, the global climate change (reported by the averaged $\delta^{18}O$ values) shifted from about 2.2 ‰ at 18 Ma, to ~ 1.7 ‰ between 17 Ma, and 14 Ma, but then to ~ 3 ‰ at 3 Ma, and even higher than ~ 4 ‰ by today 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° C cooling in the North Hemisphere (de Boer et al., 2010). The changes of temperature in the western Qaidam Basin indicated by the thermophilic taxa parallel those temperature changes indicated by the 1-D ice-sheet model records (Fig. 4).

In addition to the similar $\delta^{18}O$ trends, three other trends support that the cooling process since 18 Ma ago in the western Qaidam Basin may have been strongly influenced by worldwide Miocene global cooling. First, the thermophilic taxa percentages correlate well with the oxygen isotope curve; for example, between approx. 18–14 Ma, the thermophilic taxa percentages (from 3 to 12 %) show an increase roughly coupled with the Middle Miocene Climate Optimum (Zachos et al., 2008, Fig. 4e). At the same time, the xerophytic taxa fall to their lowest values (between 5 and 33 %). Based on the high-density pollen records, the thermophilic taxa percentages correlate fairly well during the Pleistocene with the glacial-interglacial cycles indicated by oceanic oxygen isotope records (Cai et al., 2012). Second, the thermophilic and xerophytic taxa percentages of the western Qaidam Basin compare better with the compiled temperature and precipitation records from Europe than with the sites near the Tibetan Plateau. This could result from the tectonic uplift at the Tibetan Plateau affecting the climate pattern by topographic changes driven by the tectonics. The source for much of the precipitation than the Qaidam Basin lies in Europe (e.g. Mosbrugger et al., 2005; Utescher et al., 2007; Jiménez-Moreno et al., 2010), and the Westerlies will carry less moisture eastward. Third, many studies have shown the relationships between the temperature and the atmospheric vapor capacity; the capacity to carry vapor in higher temperature air can be several times that in lower temperatures. This relationship explains why Eurasian precipitation generally decreased along with the global cooling (Miao et al., 2012). This also provides an understanding of the relationship between the precipitation and global cooling, including that the strength of the East Asian summer monsoon decreasing gradually with a long-term trend (e.g. Passey et al., 2009).

On the other hand, many models support the assumption that strong Tibetan Plateau uplift caused a 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

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could have effectively disturbed precipitation patterns in mountainous regions of Central Asia (especially the Tibetan Plateau) as it underwent various extensive phases of orogeny.

Figure 4f shows one of best researched opinions of the Tibetan Plateau elevation history during the late Cenozoic (An et al., 2006). Our results seem to support those findings. Continuous cooling also can be linked with the continuous uplift of the Tibetan Plateau, explained by resulting changes in atmospheric circulation (e.g. Ruddiman and Kutzbach, 1989; Manabe and Broccoli, 1990; Liu et al., 2003) and rapid silicate weathering (e.g. Edmond and Huh, 1997; Wan et al., 2012). However, no consensus yet exists regarding the timing of uplift of the Tibetan Plateau. In addition to the late Cenozoic uplift, some infer from the isotope evidence that the Tibetan Plateau reached its modern height during the Oligocene or Eocene (Rowley, 2007; Garzione, 2008; Quade et al., 2011). Wu (2008) even concluded that the entire uplift of the Tibetan Plateau to today's elevation most likely occurred between 30 and 20 Ma. If this later is true, the aridification of the western Qaidam Basin could be more closely linked with the global cooling, rather than with the Tibetan Plateau uplift itself.

In the western part of the Qaidam Basin, both lithofacies and pollen counts form the KC-1 core show no direct tectonics occurring between 18–5 Ma. However, the eastern part of the Qaidam Basin does show some evidence of tectonic activity during that time frame (e.g. Fang et al., 2007a; Lu and Xiong, 2009), both near or at some distance from the surrounding mountains (e.g. George et al., 2001; Kirby et al., 2002; Wang et al., 2003; Zheng et al., 2003; Sun and Wang, 2005; Fang et al., 2007b; Ritts et al., 2008; Bovet et al., 2009). In the SG-3 core, the pollen assemblage shifts at approx. 2.6, 1.2, 0.9, and 0.6 Ma appear to have been responses to both long-term global cooling and Tibetan Plateau uplift (Cai et al., 2012). Similar explanations have been proposed for the changes at 3.6 and 2.6 Ma in the Yahu section (e.g. Wu et al., 2011). The series of events represented in the SG-3 and Yahu records seem to be influenced less by tectonics than by the global cooling, in that such shifts occur over very short time-scales ($10^{3–5}$ yr), in contrast to more common tectonic time-scales ($10^{5–7}$ yr). Furthermore,

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these five periods coincide with important shifts in the oxygen isotope records (e.g. Zachos et al., 2001).

Besides of the global cooling and the Tibetan Plateau uplift, consideration also include the possible influence of the retreat of the shallow Paratethys (Ramstein et al., 1997; Zhang et al., 2007), however which is thought to have retreated from the Tarim Basin mainly before the Miocene (e.g. Bosboom et al., 2011), and no direct relations with our discussing late Cenozoic period of time.

5.4 Asian monsoon

In Asia, the compilation of paleobotanical and lithologic 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 retreats or expansions of the Asian monsoon; the nearer the area to the boundary, the stronger effect it has. However it is very difficult to separate effects of the Asian monsoon from the global cooling, especially as evidence has now shown that the Asian monsoon also decreased along with the global cooling (e.g. Miao et al., 2011a, 2012; Jiang and Ding, 2008; Tang et al., 2011; Lu et al., 2010; Passey et al., 2009); although some alternative conclusions have also been presented. For example, the alternative interpretations (Zhang et al., 2012b) arise from the late Cenozoic carbon and oxygen isotope records of the mammals in the eastern Qaidam Basin indicating a warmer and wetter environment during the late Miocene and early Pliocene, and increased aridification lasting until the early Pliocene. This interpretation differs from our compiled climate results. Because the sites of Zhang et al. (2012b) lie nearer the monsoon boundary than ours, they may be more closely linked with the monsoon system; so different climatic trends in the western Qaidam may not be as closely linked with the monsoon system. Moreover, the wetness of the eastern Qaidam Basin may result from the more effective barrier preventing moisture from the Indian Ocean or Bay of Bengal from reaching the basin (Zhang et al., 2012b). The western part of the basin should also be influenced

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by the same barrier, if it had been similarly influenced by the East Asian summer monsoon.

Hence, we conclude that the 18 Ma long-term aridification trend documented by the three sites of the western Qaidam Basin to have been mainly driven by global cooling and the Westerlies. No relationship with the East Asian summer monsoon seems necessary as far as the long aridification trend is concerned. However, we emphasize that the lack of linkage between the surrounding mountain humidity of the western Qaidam Basin and East Asian summer monsoon has not been confirmed, and we will continue to investigate this issue further.

6 Conclusions

The Qaidam Basin forms the largest basin on the northern margin of the Tibetan Plateau and has experienced an arid climate during the period covered by our investigation. Our study compiled pollen results from three cores in order to decipher the aridification process, spanning the period bewteen 18 and 0.01 Ma.

During this period, the xerophytic taxa percentages increase and conifers decrease, suggesting a general drying process in the Qaidam area, including the basin and surrounding mountains. The thermophilic taxa percentages correspond with the oxygen isotope results linking local conditions with the global climatic cooling. The Tibetan Plateau uplift provides a secondary influence, whereas the East Asian monsoon may not significantly influence this region.

Figure 5 illustrates the relationships between the vegetation, climate, and topography history, as a cartoon picture. During the Miocene, relatively less steppe taxa grew at the possibly low basin, due to the dry conditions. In general, the alpine trees including *Tsuga*, *Picea*, *Podocarpus* and *Pinus* etc. grew on the surrounding mountain utilizing the rich precipitation brought by the Westerlies during a global warming stage (possibly from the East Asian summer monsoon) (Fig. 5a). During the Pliocene, the area of xerophytic taxa increased, and the alpine trees almost disappeared due to less rain

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reaching the basin, due to either global cooling or mountain uplift (Fig. 5b). During Pleistocene, xerophytic taxa almost completely replaced the conifers, due to the further global cooling. During this time, the basin probably reached at the modern elevation (Fig. 5c).

Further pollen work should be done at this basin, especially at those diet mammals' sites of the east part, to better understand the differences between the western and eastern parts of the basin, and the dominating mechanisms.

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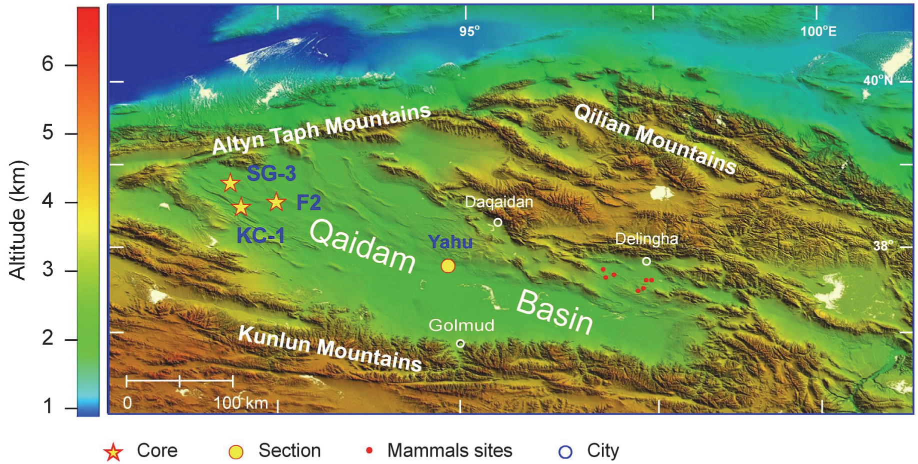

Fig. 1. Digitial elevation map of the Qaidam Basin, showing the locations of: the KC-1 (Miao et al., 2011a), the SG-3 (Cai et al., 2012), and the F2 (Wang et al., 1999) pollen cores; the section at Yahu (Wu et al., 2011); and the mammals sites used for isotopic study (see details in Zhang et al., 2012b).

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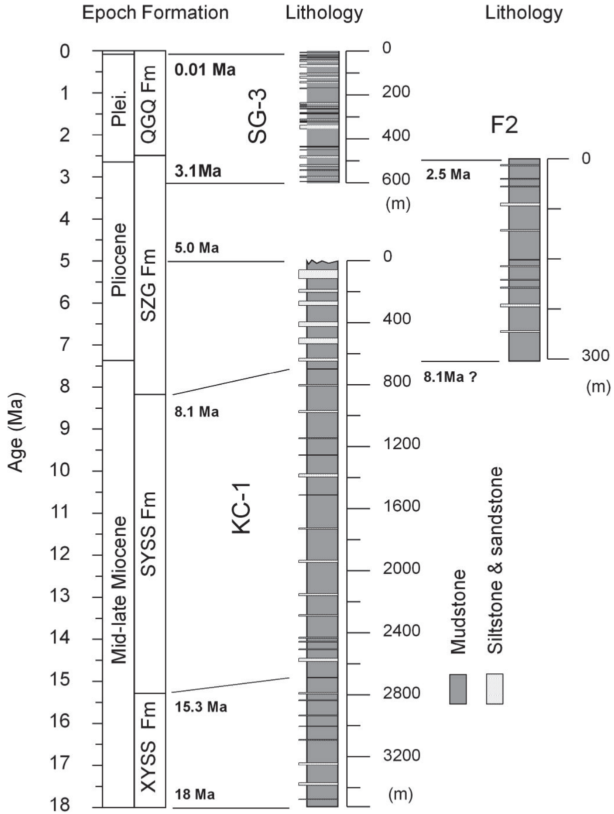

Fig. 2. Late Cenozoic stratigraphic correlation between the three cores (for correlation details see Miao et al., 2011a; Wang et al., 1999 and Cai et al., 2012, respectively).

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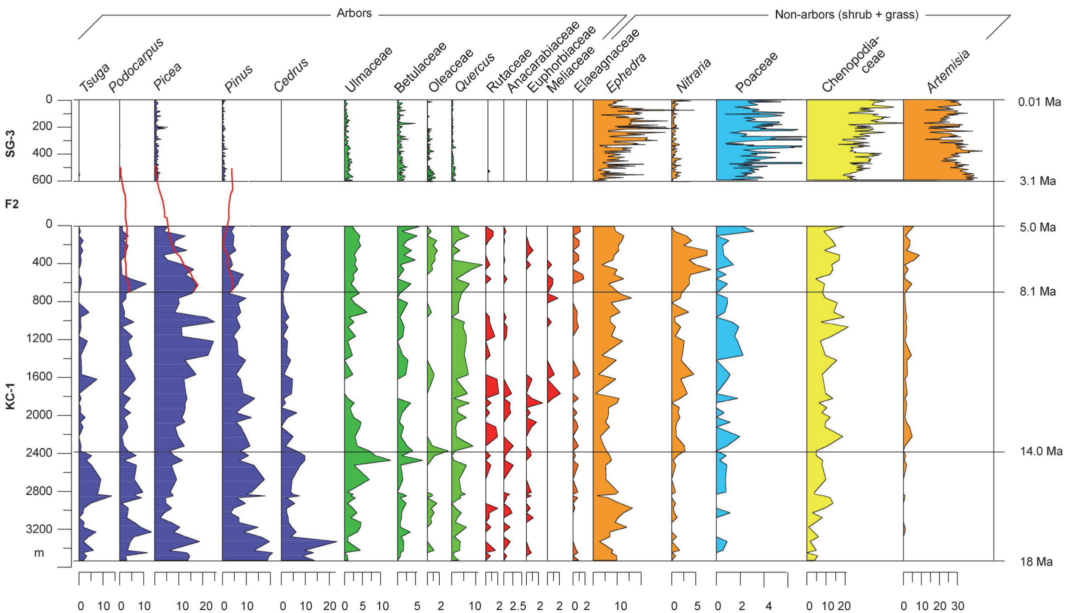

Fig. 3. Late Cenozoic pollen diagram, complied from previous studies: KC-1 from Miao et al. (2011a); F2 (only three arbors taxa shown in red) after Wang et al. (1999); and SG-3 from Cai et al. (2012).

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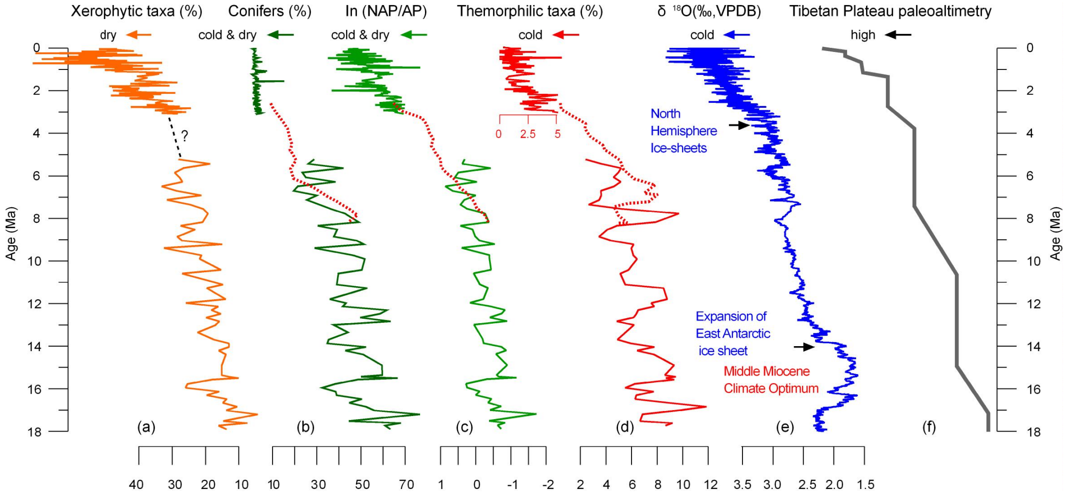

Fig. 4. Compiled pollen records showing: **(a)** xerophytic taxa, **(b)** conifers percentages, **(c)** ln(NAP/AP) (NAP: Non arboreal pollen; AP: Arboreal pollen), and **(d)** thermophilic element percentages (red dashed lines modified from Wang et al., 1999). Trace **(e)** shows the global deep-sea oxygen isotope (δ^{18}O ‰) records (20-point running average) (Zachos et al., 2008); and **(f)** provides a history of the Tibetan Plateau's elevation history (An et al., 2006).

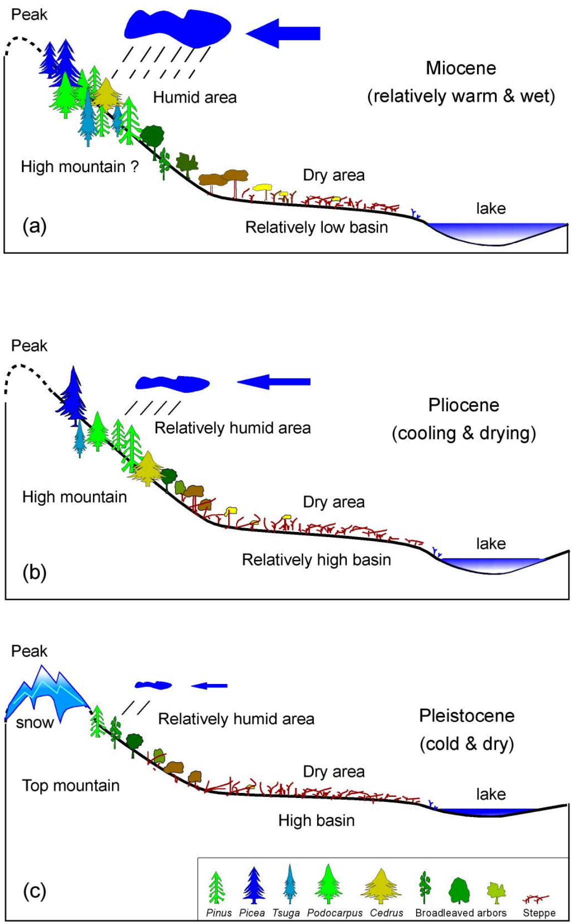

Fig. 5. Cartoon illustrating the vegetation, climate, and paleoaltimetry of the western Qaidam Basin during the **(a)** Miocene, **(b)** Pliocene, and **(c)** Pleistocene.