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Late Cenozoic central Asian drying inferred from a palynological record from the northern Tian Shan

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ABSTRACT

Sediments contained in basins adjacent to great mountains provide opportunities to reconstruct the aridification history of central Asia. Here we use a palynological record from the fluviolucustrine Jingou River section collected from the northern Tian Shan, NW China, to reconstruct aridification in central Asia during the late Cenozoic. Biogeomagnetic results show that the section was continuously deposited through the interval 28–4.2 Ma. The palynological record, with the auxiliary of the principal component analysis and the diversity index, indicates that a late Oligocene wet condition existed in central Asia and shifted to dry conditions at 23.8–23.3 Ma. The dry condition remained until 17.3 Ma and subsequently ameliorated to a relatively wet stage to 16.2 Ma, but then began to increase once again and reached a peak at 13.5 Ma that last throughout the late Miocene and the early Pliocene. Comparing the aridification process to the global temperature trend and history of tectonics, we suggest that the long-term drying trend in central Asia is dominated by late Cenozoic cooling, while the dry events that occurred at 23.8–23.3 Ma and 16.2–13.5 Ma are more likely associated with regional mountain building. The land–sea redistribution further complicated the drying processes.

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1. Introduction

Central Asia is the world's largest mid-latitude, inland arid region. Development of arid Asia is generally regarded as a product of interactions between the lithosphere, hydrosphere and atmosphere, and in turn exerts a significant impact on Earth's climate system by influencing the radiative balance and the biogeochemical cycles via dust emission. Although numerous studies on the central Asian environmental history have been published in past decades, little consensus exists between them. Eolian deposits in north China and the North Pacific have been used to trace the aridification history of central Asia back to 2.6 Ma (Ding et al., 1997; Liu, 1985), and then to 7–8 Ma (Ding et al., 1998; Rea et al., 1998), or even to 22–24 Ma (Guo et al., 2002; Rea, 1994; Sun et al., 2010). In contrast to these indirect records, evidence from the continental interior of Asia shows aridity initiation is generally younger than the late Miocene. The Kazakhstan Plain, with an annual precipitation of more than 1000 mm in the Early Miocene (Bruch and Zhilin, 2007), gradually dried after 15 Ma (Akhmetyev et al., 2005; Velichko, 2005). In westernmost China, desert conditions were initiated ca. 7 Ma ago in the Tarim Basin (Sun et al., 2009), slightly older than dry events in the Junggar Basin where xerophilous *Artemisia* and Chenopodiaceae expanded after 6 Ma (Sun and Zhang, 2008). A wide chronological gap in time of arid Asia exists between records from surrounding areas and from the interior, and the history of the aridification is still open to debate.

To better constrain the evolution of drying in central Asia, a promising approach is to reconstruct a long-term, well-dated environmental history for the interior. The Tian Shan separates the Tarim basin to the south from the Junggar basin to the north. Cenozoic uplift of the Tian Shan resulted in the continuous deposition of Tertiary and Quaternary sediments on its flanks (Allen et al., 1991; Yin et al., 1998). These thick fluvial-lacustrine deposits provide a well-dated archive, with a well-preserved pollen record, for reconstructing a long term environmental history. We present here a detailed palynological record of the Jingou River section from a northern foreland basin of the Tian Shan to decipher the inland vegetation and climate evolution.

2. Geological setting

The Tian Shan, a 2500 km long range, has an average elevation of 2500 m above sea level (a.s.l.) with peaks higher than 7000 m a.s.l.

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The range may be traced back to a Paleozoic fold belt (Allen et al., 1993; Tapponnier and Molnar, 1979). It is higher than the surroundings throughout the Mesozoic and Cenozoic and continuously filled the adjacent basins, Junggar Basin to the north and Tarim Basin to the south, with clastic sediments eroded from the range (Hendrix et al., 1992). In response to the Indo–Asian collision, reactivation of the Tian Shan during the late Cenozoic deformed the Cenozoic sediments into three successive fold–thrust belts on the north pediment, which are made up of linear anticlines (Fig. 1). These fold belts are well exposed along north-flowing rivers that incised the piedmont most likely during the late Quaternary (Lu et al., 2009). The section presented here is from the Huoerguosi Anticline in the central fold–thrust belt.

The Jingou River section (44°10.4′N, 85°27.4′E) is exposed along a valley formed by the perpendicular incision of the Jingou River through the center of the Huoerguosi Anticline. In the southern limb of the anticline, from the core to the south, the Jingou River section consists of the Anjihaihe, Shawan, Taxihe, Dushanzi and Xiyu Formations (Li, 1984). The dominant lithology changes from distal fine-grained lacustrine mudstone upward to proximal coarse conglomerates. Specifically, the Anjihaihe Formation is made up of grayish green mudstone with interbedded thin marlstones, sandstones, shales and layers of gypsum. These fine-grained sediments commonly display parallel laminations and are interpreted to represent lake facies. The overlying Shanwan Formation is about 520 m thick and lithologically divided into three units. The lower unit is ~100 m thick and is dominated by dark brown massive mudstones and represents a lacustrine prodelta facies. The middle unit contains ≥18 couplets of red-brown silty mudstone and conglomerates within a thickness of ~250 m, likely deposited in a distal fan-delta environment. The upper unit consists of brown and minor grayish green silty mudstones and mudstones with cross-bedding and parallel-ripple lamination and is interpreted to represent a delta front facies. The Taxihe Formation consists of grayish green mudstone in its lower part and brown silty mudstones with interbeded thin sandstones and conglomerates in the upper part, indicating a lacustrine and a fluvial delta plain facies, respectively. The Dushanzi Formation consists mainly of brown pebbly sandstones, conglomerates and interbeded silty mudstones, representing a braided river and alluvial fan facies. The Dushanzi Formation grades into the overlying Xiyu Formation within about 200 m of strata dominated by conglomerates and subordinate fine-grained sandstones. The Xiyu Formation is characterized by dark grey massive conglomerates with rare siltstones and sandstones in the lower part. These strata do not contain any significant unconformities, while they are unconformably overlain by the Pleistocene Wusu Group.

The Jingou River section has an elevation of ca. 900 m a.s.l. and has a typical continental climate regime with a mean annual temperature of 6.9 °C and a mean annual precipitation of 183 mm. Because of orogenic precipitation, the Tian Shan supports various vegetation types and has five altitudinal vegetation belts on the north slope (Fig. 2): desert steppe occurs below 1200 m a.s.l., dry steppe occurs at elevations of 1200–1800 m a.s.l., montane conifer forest dominated by *Picea* occurs at 1800–2800 m a.s.l., montane meadows occur at

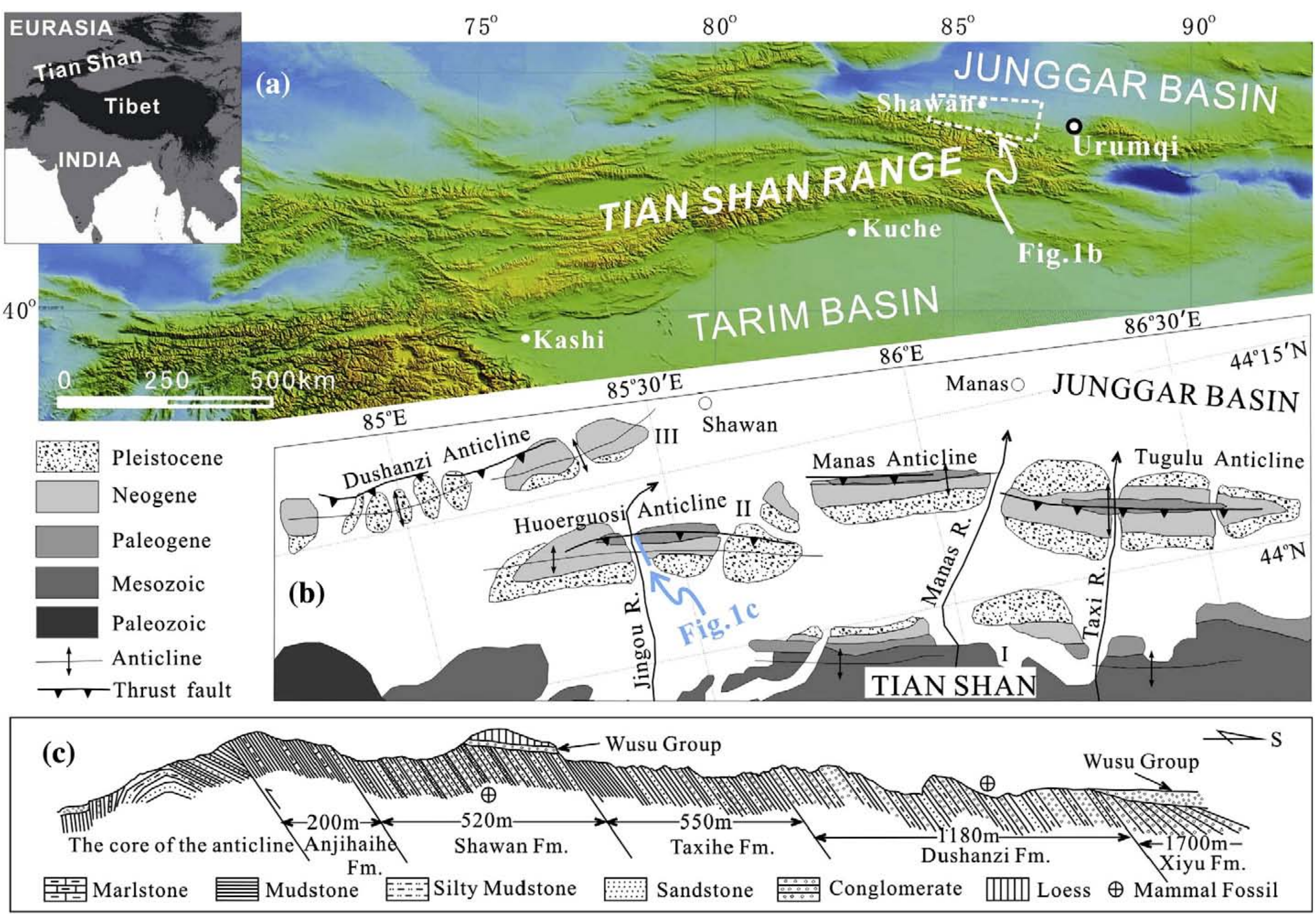

Fig. 1. (a) Topographic map of the central Asia; (b) Simplified geological map of the northern Tian Shan area showing the three fold-thrust zone (I, II, and III) and the location of the Jingou River section; (c) Strata exposed at the Jingou River section.

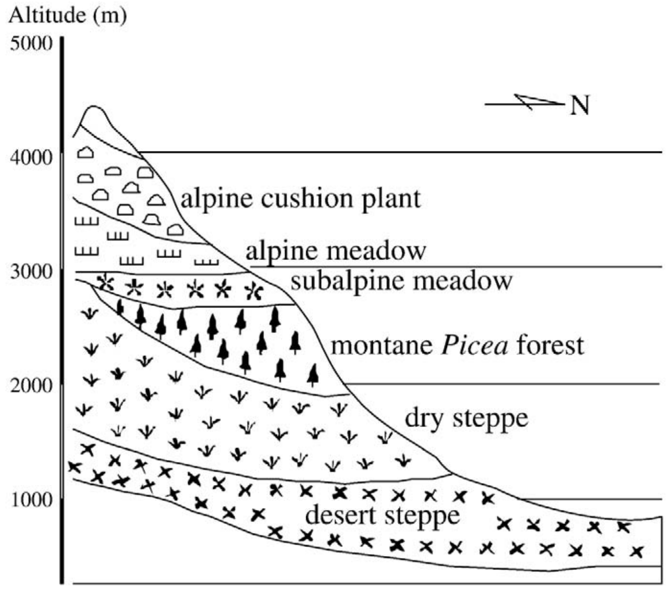

Fig. 2. Present altitudinal distribution of the major vegetation belts on the northern slope of the Tian Shan.

2800–3200 m a.s.l., and alpine cushion plants occur above 3200 m a.s.l. (Wu, 1995).

Biomagnetostratigraphic investigations define the chronology of the Jingou River section. Vertebrate fossils, *Dzungariotherium orgosensis* gen. et sp. from the middle of the Shawan Fm and the bovine *Turcocerus* cf. *grangeri* and *Turcocerus* cf. *noverca* from the middle of the Dushanzi Fm, anchor the temporal framework at the Early and the early Late Miocene, respectively (Fortelius, 2009; Wang et al., 2003). We have re-evaluated the raw data of a previous magnetostratigraphy (Ji et al., 2008), and present a revised geomagnetic polarity sequence for the entire Jingou River section which is correlated with the geomagnetic polarity time scale of Gradstein et al. (2004) (Fig. 3). The revised chronology yields a basal age of 6 Ma for Xiyu Fm and 28 Ma for Anjihaihe Fm, slightly younger than the results of Ji et al. (2008). From the Shawan Formation upwards, Charreau et al. (2009) established the magnetic polarity sequence and obtained a temporal framework for the same section, which is consistent with the chronology presented here.

3. Materials and methods

Palynological sampling was designed to produce a temporal resolution of one sample per 100 ka or less. Most of the pollen samples came from the green lacustrine mud in the Anjihaihe and Taxihe Formations and grayish fine-grained intercalations in the Shawan, Dushanzi, and Xiyu Formations to minimize taphonomic effects on palynomorphs. The conglomerates, sandstones and reddish claystones in the Shawan, Dushanzi, and Xiyu Formations had been tentatively sampled because palynomorphs do not usually preserve under oxidizing conditions. The entire Jingou River section yielded 292 samples.

Pollen extraction followed a modified version of a technique originally proposed by Horowitz (1992). Samples of about 100 g were crushed and bathed in diluted HCl solution (~18%) to remove any carbonate. After excess HCl was washed off, the samples were treated with HF (40%) to digest silica, and then rinsed till a neutral pH was obtained. This was followed by ultrasonic sieving over a 10 µm screen. The residues, if necessary, were floated using $ZnCl_2$ solution (specific gravity = 2.0) to further concentrate palynomorphs. The resulting samples were mounted in glycerol gel.

A transmitting light microscope using 160× and 640× magnifications was used for pollen classification and counting. Pollen identifications

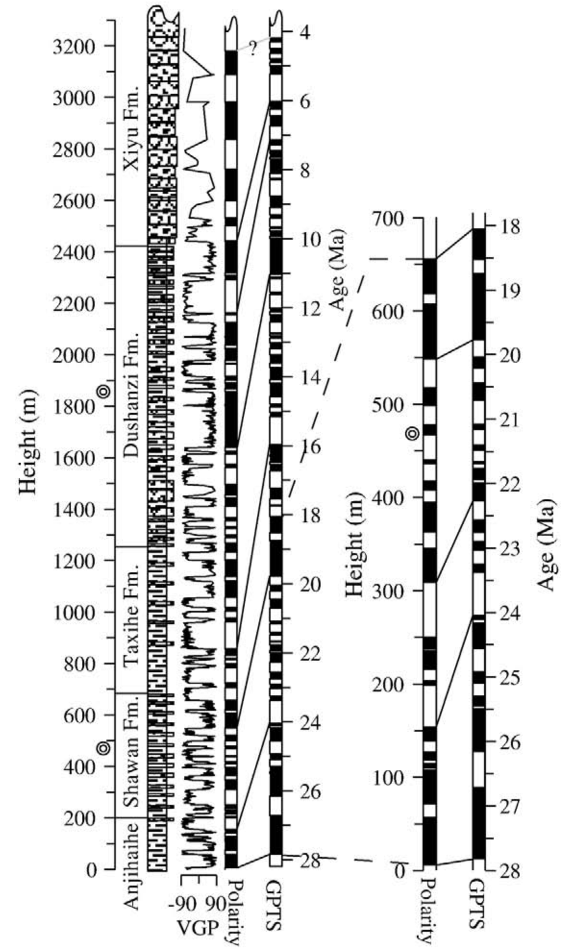

Fig. 3. Lithology and revised biomagnetostratigraphy for the Jingou River section and its correlation with the GPTS (Gradstein et al., 2004) with an expanded view of the lower part. ◎ represent locations of mammal fossils.

were performed referring to *the Late Cretaceous and Tertiary Spores and Pollen* (Song et al., 1999) and *Pollen Flora of China* (Wang et al., 1995). The only exception is *Nitraria* that was identified according to the criteria proposed by Xi and Sun (1987). Palynomorphs were designated to modern taxa at the genus or family level, rather than to the morphotaxa.

To summarize the primary features of variance in the pollen data, we performed a principal component analysis (PCA). Pollen taxa with percentages >2% with respect to the palynomorph sum (including all pollen and spores) were used for PCA after applying a log10-transformation. We also used the Simpson's index to measure pollen diversity, which was estimated from the counting number of the palynomorph grains. The PCA and diversity analyses were conducted using the MVSP program (Kovach, 1999).

4. Results

Only 154 out of 292 samples contain enough palynomorphs to provide reliable data while others had less than 100 grains identified. Palynomorph analysis identified 66 taxa and the palynomorph concentration fluctuated between 5 and 5990 grains g^{-1}. Palynomorph abundance is in agreement with lithological changes with maximum values corresponding to fine-grained lacustrine units, and minima to coarse-grained fluvial units. Identified palynomorphs include arboreal taxa (such as *Pinus*, *Quercus*, *Ulmus*/*Zelkova*, *Juglans*, *Betula*, *Tilia*, *Alnus*, Rutaceae, Sapindaceae, Oleaceae and *Pterocarya*), shrubs (such as *Ephedra*, *Nitraria* and *Lonicera*), and herbs (Labiatae, *Artemisia*, Chenopodiaceae, Poaceae, Compositae, *Polygonum*, *Humulus* and

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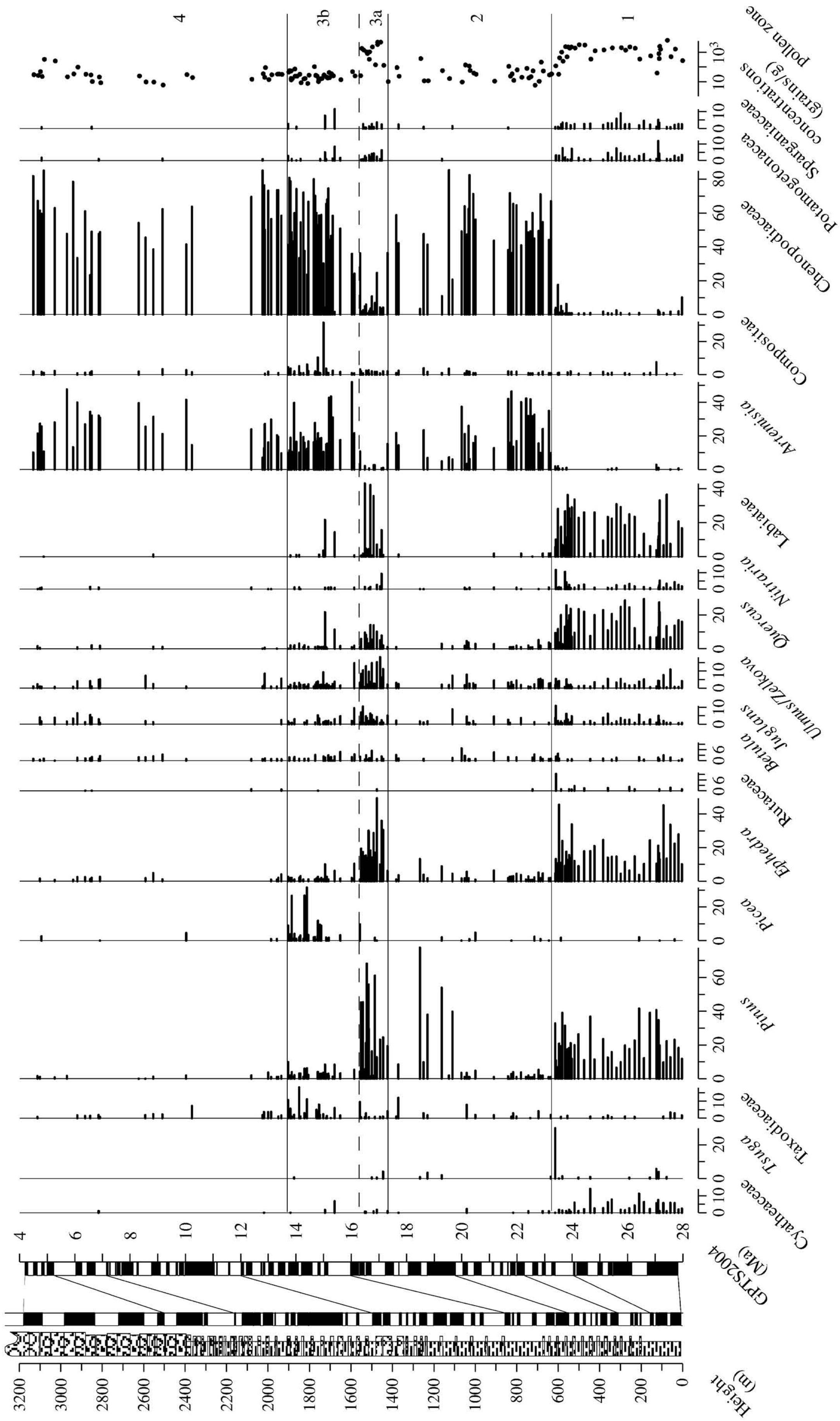

Fig. 4. Palynological percentage diagram and the palynomorph concentrations of the Jingou River section.

Ranunculus). A general trend in the palynological record is a progressive increase of *Artemisia* and Chenopodiaceae. They become the dominant components in the pollen spectra in the Dushanzi and Xiyu formations.

Based on the stratigraphically constrained cluster analysis, pollen percentage and concentration diagrams were divided into four pollen assemblage zones with subzones shown where informative (Fig. 4).

Zone PZ1 (28–23.3 Ma; 0–200 m): This zone is dominated by *Quercus*, Labiatae, and *Pinus*, accompanied by the appearance of *Ulmus*/*Zelkova*, *Betula*, *Juglans*, *Nitraria* and hydrophilous Potamogetonaceae and Sparganiaceae. This zone has the highest pollen concentrations in the entire section, with pollen concentration and arboreal taxa gradually decreasing in the upper part since 23.8 Ma.

Zone PZ2 (23.3–17.3 Ma; 200–735 m): This zone shows abrupt expansions of *Artemisia* and Chenopodiaceae, accompanied by rare arboreal taxa and the absence of hydrophytes. Correspondingly the pollen concentration remains at a relatively low level. After ~19.7 Ma, the percentage of *Pinus* increases in contrast to the almost absent temperate arboreal taxa.

Zone PZ3 (17.3–13.5 Ma; 735–1250 m): Pollen concentration, arboreal taxa and hydrophytes display a slight recovery in this zone, while still less than those in the PZ1. Mostly based on relative changes in pollen concentration and changes in dominant species, two subzones were separated at 16.2 Ma (820 m).

Subzone PZ3a (17.3–16.2 Ma; 735–820 m): This subzone shows relatively high pollen concentration comparable to Zone PZ1. Arboreal taxa and hydrophytes dominate as in zone PZ1, with a greater abundance of *Juglans*, *Ulmus*/*Zelkova*, *Ephedra* and *Pinus*, and less *Quercus* and Labiatae. Herbaceous *Artemisia* and Chenopodiaceae show low and fluctuant abundances, and Compositae and Poaceae values increase in the assemblages.

Subzone PZ3b (16.2–13.5 Ma; 820–1250 m): Pollen concentration decrease to the level in Zone PZ2, and herbs such as *Artemisia*, Chenopodiaceae, Compositae and Poaceae dominate the subzone. Labiatae and arboreal taxa make up a low percentage with low but greatly fluctuating values for hydrophytes.

Zone PZ4 (13.5–4.2 Ma; above 1250 m): Pollen assemblages are characterized by consistently high Chenopodiaceae and *Artemisia* with the minimum value of pollen concentration observed. The proportion of samples with pollen insufficient to yield reliable data is also greatest in this section. Except sporadic *Ulmus*/*Zelkova*, *Betula* and *Juglans*, other arboreal taxa are rare. Notably, the pollen concentration began to increase at around 7 Ma without significant changes in the pollen assemblages.

5. Central Asian drying indicated by the palynological record

5.1. Reliability of the palynological spectrum

A marked feature of the palynological record in the Jingou River section is coeval changes in palynological spectrum and lithology, i.e. the greenish fine-grained lacustrine beds have dense palynomorph concentrations with relatively high arboreal pollen percentages and reddish coarse-grained fluvial beds have sparse palynomorphs concentrations with high herb pollen percentages. This coincidence raises two serious questions with regard to the reliability of the palynological spectrum: Does the taphonomic bias obscure the vegetation change? And, does the differential pollen preservation alter the vegetation interpretation?

As an environmental proxy, pollen in lake sediments is usually an ideal archive of regional long-term vegetation with high fidelity. In contrast, palaeoclimatic significance of pollen in alluvial sediments needs further clarification. Although alluvially transported pollen cannot be regarded as an immediate reflection of contemporaneous vegetation, its gross trends can, however, provide a record of upstream vegetation history (Brown et al., 2007; Moore et al., 1999; Xu et al., 1996). Specifically, alluvial pollen in the Shawan, Dushanzi and Xiyu Formations, and lacustrine pollen in the Anjihaihe and Taxihe Formations in the Jingou River section share the same source, mainly upstream on the northern Tian Shan range. In addition, the palynological samples mostly from fine-grained beds/intercalation with an average temporal resolution of ~0.1 Ma minimize the taphonomic overprint.

According to the indicators proposed by Hall (1981), palynomorphs from the Jingou River section may have deteriorated, especially those in the reddish fluvial Shawan, Dushanzi and Xiyu Formations. Red beds are characterized by oxidizing conditions (Van Houten, 1961) that are unfavorable for pollen preservation (Moore et al., 1999). In the Jingou River section, the pollen in reddish beds tends to be more deteriorated than those of greenish beds. However, from the greenish Anjihaihe Fm to the reddish Shawan Fm and from the Taxihe Fm to the Dushanzi Fm, percentages of the corrosion-sensitive Chenopodiaceae and *Artemisia* pollen increase and *Pinus* decreases; this most likely results from changes in regional vegetation, rather than differential preservation of pollen under different conditions. Thus, the paleoecological information inferred from the palynological record is reliable.

5.2. Vegetation history and the drying of central Asia

PCA was used to summarize the pollen percentage results (Fig. 5). Because the first principal component (PC1) accounts for 56.3% of the total variance and the variances for the remaining components are similar, we focus on PC1 for further analysis. This component is driven primarily by the taxa *Quercus*, Labiatae and hydrophytes which have the highest scores, and by the herbaceous *Artemisia* and Chenopodiaceae, which have the lowest scores. *Artemisia* and Chenopodiaceae are characteristic components in arid Northern Hemisphere regions (El-Moslimany, 1990), while *Quercus*, Labiatae and hydrophytes are indicators of moisture in central Asia. We hence interpret higher PC1 scores indicating wetter conditions. Pollen proportional data are less efficient in reflecting absolute vegetation abundance, so we calculated the pollen influx data of the Jingou River section (Fig. 6).

Our palynological record demonstrates a long-term and stepwise drying in central Asia with major transitions at 23.3 Ma, 17.3 Ma, 16.2 Ma and 13.5 Ma (Figs. 4 and 6).

The first drying event occurred during the latest Oligocene. Gradual declines in pollen influx, the PC1 scores, and broadleaf arboreal pollen abundance began at ~23.8 Ma. The previously sporadic Chenopodiaceae and *Artemisia* became the dominant taxa and replaced *Quercus*, *Pinus*, Labiatae and hydrophytes at ca. 23.3 Ma. As palaeobotanic studies have revealed, Chenopodiaceae originated from continental Eurasia in the late Cretaceous (Muller, 1981; Zhu, 1995), and *Artemisia* from the arid area of temperate Asia in the mid-Cenozoic (Song, 1965; Wang, 2004; Yunfa et al., 2010). They both are characteristic of continental climates (El-Moslimany, 1990; Yu et al., 1998). Hence, their expansion after 23.3 Ma marked a distinct drying in central Asia. Consequently, the pollen concentration and influx decreased by 1–2 orders of magnitude with a remarkable reduction in the PC1 score.

After the onset at the latest Oligocene, this arid condition prevailed in the Asian interior until a relatively wet phase developed in the interior at ~17.3 Ma. The wet phase, spanning the interval 17.3–16.2 Ma, is marked by a decrease in *Artemisia*–Chenopodiaceae abundances, recoveries of the hydrophytes, Labiatae and arboreal taxa (e.g. *Quercus*, *Ulmus*/*Zelkova*, *Juglans* and *Pinus*), and increases in the PC1 scores, pollen concentrations and diversity index. This period had a similar pollen percentage spectrum with the late Oligocene, but was clearly differentiated by the pollen influx diagram (Fig. 6): the influx of *Artemisia* and Chenopodiaceae show an increase but less so than trees and hydrophytes. This suggests that central Asia was largely dominated by arid conditions with recovery of trees limited to wet areas, and the overall regional moisture conditions improved during this interval.

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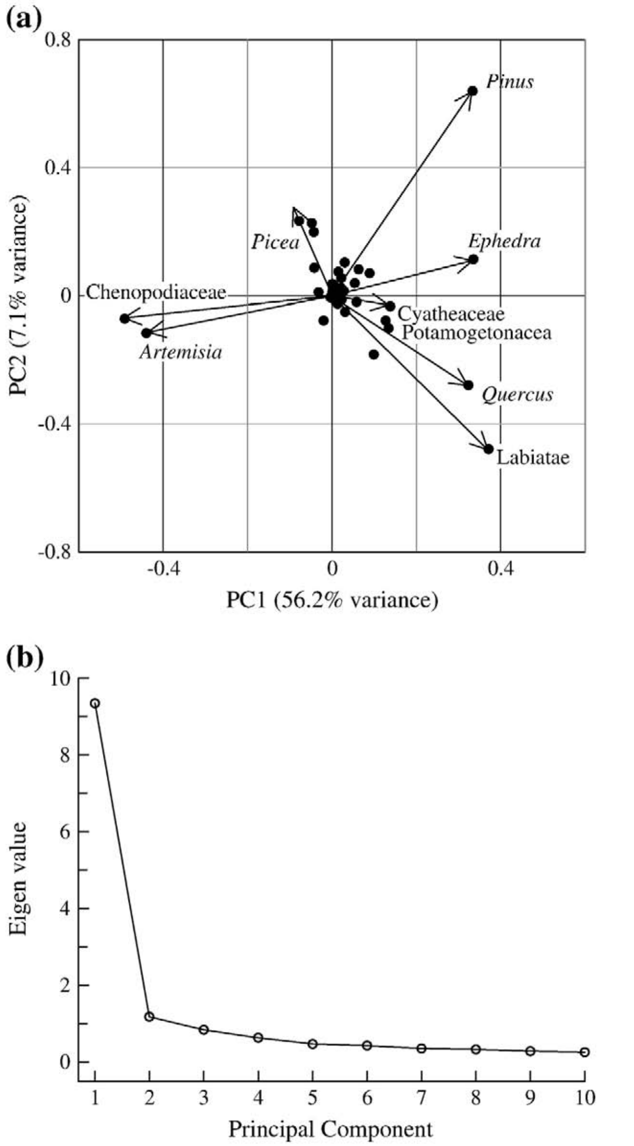

Fig. 5. Principal component analysis (PCA) of the palynological data from the Jingou River section. (a) PC1 (the first principal component) versus PC2 biplot; (b) Scree plot, showing the sorted eigenvalues from large to small as a function of the principal component. Note the elbow in the curve at PC2; hence, PC1 is the most important and is used for interpretation.

Subsequently, the palynological data reveal a gradual drying during the interval 16.2–13.5 Ma as expressed by increased *Artemisia*–Chenopodiaceae percentages, and decreased temperate arboreal taxa (*Ulmus*/*Zelkova*, *Quercus*, *Juglans*, *Betula* and *Pinus*) and Labiatae. Pollen influx also declined. Then, *Artemisia*–Chenopodiaceae percentages continued to increase and remain the dominant taxa in the pollen assemblages, indicating a persistent drier condition in central Asia through the late Miocene and the early Pliocene. The PC1 scores and the pollen influx values are at their minimum for the entire section.

It is noticeable that pollen concentrations significantly increased after 7 Ma without any marked changes in pollen assemblages, suggesting mechanisms other than climate amelioration were responsible. This was probably associated more with the Xiyu Formation, because of its higher sedimentation rates. The Xiyu Formation buried the deposited pollen grains in a very short time and isolated them from oxidizing conditions and hence relatively higher concentrations are observed.

The Simpson's index further supports the interpreted long-term drying trend. In semi-arid or arid areas water is the primary limiting factor for plant growth (Li et al., 2009; Lite et al., 2005), and low available soil water restricts species richness (Ali et al., 2000; Aronson and Shmida, 1992). The diversity index is hence referred to here as a moisture proxy with a higher Simpson's Index corresponding to wetter condition.

The Simpson's Index in our record revealed two drying transitions in the central Asia during the Oligo-Miocene. The first transition occurs at 23.8–23.3 Ma with the decrease of the average value of the Simpson's index from 0.82 to 0.59. Arboreal and hydrophytic components decreased and xerophilous herbs gain dominance after the transition, suggesting the development of an arid climate. Although the area experienced a ~1.1 Ma interval (17.3–16.2 Ma) of slightly humid conditions, the overall regional vegetation gradually shifted from forest to steppe at 16.2–13.5 Ma with a fluctuating Simpson's Index values, and finally to xerophyte-dominated steppe at 13.5 Ma. The Simpson's Index had an average value 0.76 in the earlier Mid-Miocene, then fell to 0.60, and to 0.54 after 13.5 Ma. Both the vegetation type the and palynological diversity index indicate a stepwise aridification of central Asia.

Our records show higher concentrations of *Ephedra* during wet periods, in contrast to its present habitat. It is generally regarded as an arid-adapted group of plants. However, previous studies have shown that *Ephedra* was widely distributed over Asia during the early Cenozoic, and was usually accompanied by many conifers and amentaceous plants (Akhmetyev et al., 2005; Sun and Wang, 2005; Zyryanov, 1992 and references therein). This is consistent with our data. A possible reason is that *Ephedra* has a rather wide ecological amplitude and would be favored in relatively humid conditions and filled ecological niches before the expansion of the major niche competitors (Compositae (*Artemisia*), Chenopodiaceae and Poaceae) around the middle Cenozoic.

6. Discussion

To date, the eolian dust records from north China and the north Pacific have extended the history of arid central Asia from 2.6 Ma (Ding et al., 1997; Liu, 1985), to 7–8 Ma (Ding et al., 1998, 1999), and then to the early Miocene (Guo et al., 2002, 2008; Rea, 1994). Although these results have greatly improved our understanding of inland aridification, the exact timing of continental drying in Asia cannot be derived from the basal age of the eolian deposits that originated from the central Asia.

In contrast to the inferred foundation provided by the aeolian depositional record our study provides a detailed examination of pollen-based vegetation series from the Asian interior in a dated stratigraphical framework. The palynological results develop a robust sequence spanning the whole aridification process and suggest that the modern-like dry condition was initiated in the latest Oligocene. This bridges a chronological gap and anchors the initiation of aridification to an earlier date.

The aridification of central Asia has been documented in the floral and isotopic records from the neighboring areas around the Junggar Basin. The Kazakhstan Plain, ~1000 km west of the Jingou River section, had a more continental climate with much higher seasonality since the Middle Miocene, and then in the Late Miocene developed a dry steppe and semi-desert landscapes with abundant herbaceous xerophytes (Akhmetyev et al., 2005). To the east, the Jiuxi Basin, which is located at the northern margin of the Tibetan Plateau, was characterized by steppe vegetation at least before 13 Ma (Ma et al., 2005). To the east of the Tibetan Plateau, Linxia basin and Guyuan became more continental around 12 Ma, as recorded by oxygen isotope and palynological records respectively (Dettman et al., 2003; Jiang et al., 2008). In more eastern locations, such as the central Chinese Loess Plateau, the vegetation shift from forest plants to typical grassland and even to desert steppe at about 4.5–3.7 Ma (Wang et al., 2006). These spatial features may reflect a stepwise expansion of aridity in central Asia during the late Cenozoic. Continental aridity

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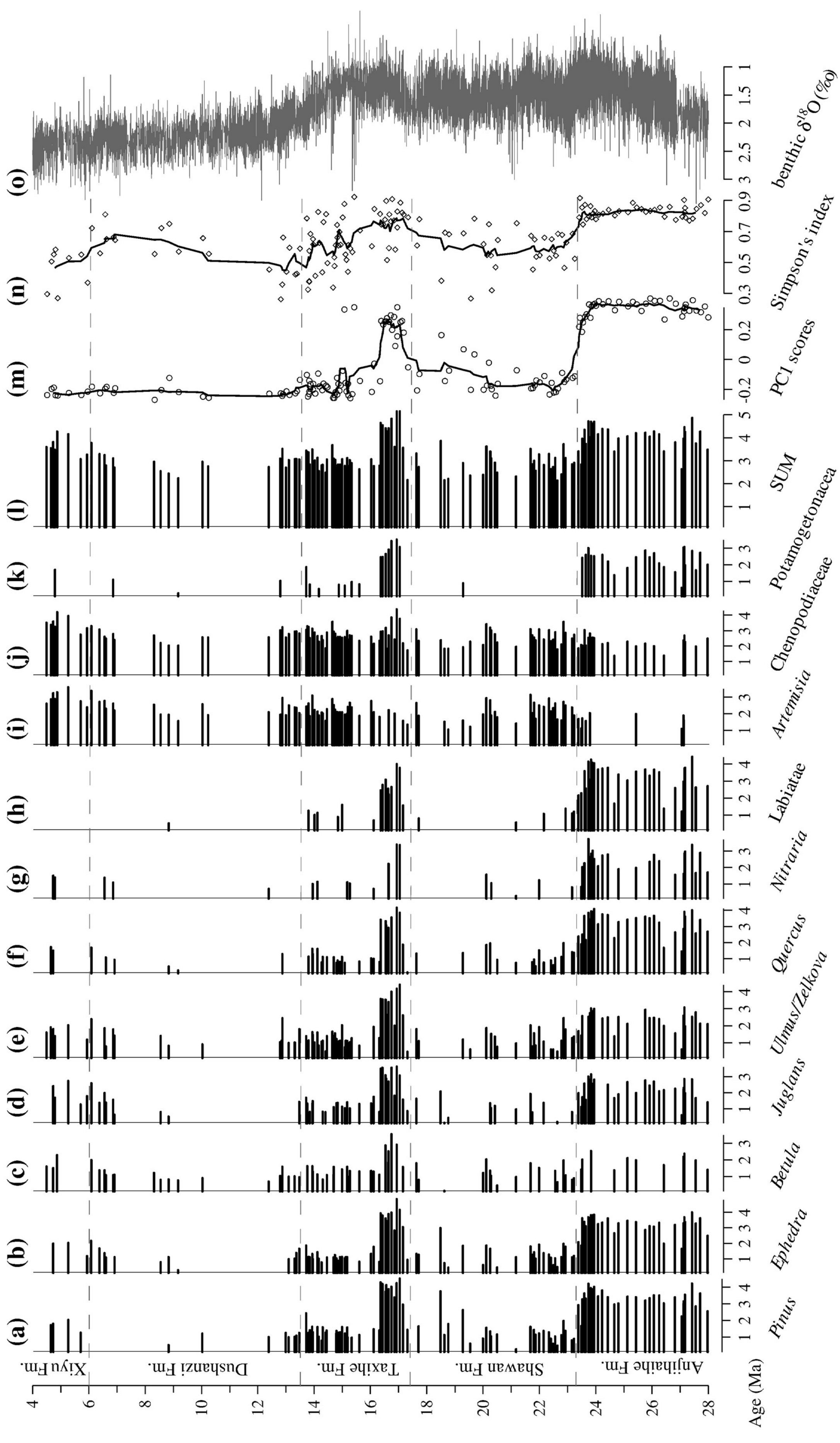

Fig. 6. (a-l) Representative palynomorph flux for log10-transformed data; (m) PC1 scores from the Jingou River section palynomorph percentage; (n) Simpson's diversity index of the palynological record; (o) Compilation of benthic foraminiferal oxygen isotope records (Cramer et al., 2009) with ages relative to GTS2004 (Gradstein et al., 2004).

originated in the Junggar Basin at the latest Oligocene, as our data suggests, and since then has gradually spread outward to adjacent regions.

The results observed above also place constraints on possible driving mechanisms. It is generally believed that in late Cenozoic central Asia experienced profound landscape changes with the uplift of high Asian plateaus and mountains (Tibet–Pamir–Tian Shan), retreat of the Paratethys, and vegetation shifts from forest to steppe and finally to desert. The aridification history inferred from our palynological data results from global climate change and regional mountain-building, as well as land–sea redistribution.

When comparing the palynological record reconstructed for Oligo–Pliocene with global temperature evolution, as benthic $\delta^{18}O$ values indicate (Cramer et al., 2009; Zachos et al., 2001), central Asia shows that the interior wet periods correspond to global warm periods, such as those of the late Oligocene (28–23.3 Ma) and middle Miocene (17.3–13.5 Ma), the latter corresponding to "the Mid-Miocene Climatic Optimum". The drier early Miocene (Shawan Formation, 23.3–17.3 Ma) correlates well with a relative cooling between the warm periods. This is also true for the dry conditions during 13.5–4.2 Ma and the globally cooler climate since the expansion of polar ice-sheets at ca. 14 Ma (e.g. Zachos et al., 2001). The pattern of central Asian aridification coincides with the trends in global temperature, implying the drying of the Asian interior likely resulted from global cooling, which reduced the strength of hydrologic cycle and increased cold air masses from higher latitudes.

However, the dry conditions observed in the Jingou River section were marked by two events at 23.8–23.3 Ma and 16.2–13.5 Ma respectively. These events coincide with changes in lithology, i.e. fluvial deposits with more *Artemisia* and Chenopodiaceae and lower pollen concentration and diversity, while lacustrine deposits with more arboreal taxa had higher concentrations and higher diversities. The duration of these events cannot be sufficiently explained by global climate trends; and other possible causes need to be considered. The impact of uplift in continental Asia on precipitation has been modeled since the 1970s (e.g. An et al., 2001; Kutzbach et al., 1993; Manabe and Terpstra, 1974; Zhang et al., 2007). More recently extensive evidence suggests that by the late Oligocene Tibet was already elevated (DeCelles et al., 2007; Dupont-Nivet et al., 2008; Rowley and Currie, 2006; Wang et al., 2008) while the Tian Shan was reactivated at the Oligocene–Miocene transition (Du and Wang, 2007; Hendrix et al., 1994; Yin et al., 1998) and the middle Miocene (Charreau et al., 2009; Heermance et al., 2007; Huang et al., 2006). The coincidence between the drying events and uplift in Asia suggests a possible causality that has been demonstrated by atmospheric modeling. Geographic barriers, the Tibetan Plateau and Tian Shan block moisture from neighboring oceans and the result is an arid continental interior due to a rain shadow effect (Boos and Kuang, 2010). It also induces stationary wave troughs situated to the east of the Tibetan Plateau, leading to atmospheric subsidence and relatively infrequent storms over central Asia (Broccoli and Manabe, 1992; Manabe and Broccoli, 1990), and hence strengthened central Asian drying.

In addition, the retreat of the Paratethys undoubtedly is another factor intensifying arid conditions in central Asia. The Paratethys gradually but broadly retreat from the Pamir to the Caspian basin during the late Oligocene to the latest Miocene (Popov et al., 2004; Rögl, 1999), increasing the distance of eastward transport of atmospheric water from the Tethys and/or its successors. The presence of an epicontinental sea complicates the interpretation of the aridification process in central Asia. The vastness of the sea is jointly controlled by regional tectonics such as mountain building and/or basin depression, global climate trends and eustatic change, whose contribution and timing are still poorly constrained.

It is believed that multiple factors were responsible for central Asian aridification during the late Cenozoic. From the present study, the gross trend of the palynological and vegetation change in central Asia is correlated with the global climate evolution, and major vegetation changes are concurrent with regional mountain building. The drying of central Asia was dominated by these two processes, but is complicated because the timing of the retreat of the Paratethys is unclear.

7. Conclusions

Cenozoic fluviolacustrine sediments from an interior basin hold great potential for addressing the timing and processes controlling the aridification of central Asia. Palynological analysis of the Jingou River section from the northern Tian Shan, NW China, reveals significant changes in central Asian vegetation and climate over the past 28 Ma. The palynological record shows that during ~28–23.8 Ma a forest-steppe dominated the northern Tian Shan, indicating a wet climate; during 23.8–23.3 Ma xerophilous herbs with Chenopodiaceae–*Artemisia* pollen dominance gradually replaced the forest-steppe and continuously developed until ~17.3 Ma and then began a 6-Ma long relative dry condition. During a global climatic optimum from 17.3 to 16.2 Ma, pollen diversity increased and pollen flux showed that steppe vegetation remained regionally dominant. Later forest taxa decreased and the proportion of xerophilous herbs increased. Around 13.5 Ma, modern-like desert vegetation and dry conditions were established in the northern Tian Shan and thereinafter dominated, as indicated by sustained increase in the percentage of Chenopodiaceae–*Artemisia* in the palynological assemblage.

The long-term trends in the change in vegetation are well correlated with the global temperature record, suggesting the arid trend in central Asia was forced by global cooling during the late Cenozoic. The correlation between the drying events and mountain building implies a link between regional tectonics and drying in central Asia. These two processes were complicated by the retreat of the Paratethys, and its influence deserves of further investigation.

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