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Plio–Quaternary stepwise drying of Asia: Evidence from a 3-Ma pollen record from the Chinese Loess Plateau

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Abstract

A 3-Ma pollen record was obtained from a continuous red clay–loess–paleosol sequence at Chaona in the central Chinese Loess Plateau (CLP). The record shows a permanent change of a domination of typical Cupressaceae forest vegetation representative of an ecological environment with a relative warm and humid climate during 3.0–2.6 Ma to largely steppe vegetation under dry climate conditions after 2.6 Ma. The later is further manifested itself as steppe to forest or forest–steppe (spruce forest — mostly mesophilous herbs) between 2.6 Ma and 1.5 Ma, forest–steppe (pine–grass) between 1.5 Ma and 0.95 Ma, open forest–steppe (mesophilous and xeromorphic herbs–pine) between 0.95 Ma and 0.5 Ma, and steppe (xeromorphic herbs) after 0.5 Ma, suggesting a process of stepwise aridification in Central Asia at the late Pliocene and the Quaternary.

Keywords: Chinese Loess Plateau; pollen; red clay–loess–paleosol sequence; aridification; vegetation change

1. Introduction

Drying of central Asia and north China is of great interest and significance to global change since it has been thought to be the result of growth of the Tibetan Plateau [1–3], to have strong feedbacks with global cooling [4,5], to couple with Asian monsoon [3], and to have considerable contribution to iron-rich dust input into the North Pacific Ocean that is the major source of nutrition for metabolism of microorganisms related to global CO_2 drop [6,7]. It has been confirmed that the eolian deposition of the red clay–loess sequences in the CLP mainly originated from the deserts in northern and northwestern China through the transportation of northwesterly Asian winter monsoon and thus records the history of drying of Asia [3,8,9]. The wide accumulation of the eolian deposition has extended back the aridification history of central Asia and north China to 7–8 Ma [10,11], or even 22 Ma [12]. However,

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the evolution of the aridification and its mechanism are still unclear and remain in debate. One of the main reasons for this controversy is that such studies are mainly from inorganic climatic proxies, and rarely from organic ones.

Vegetation change is a direct and sensitive response to environmental changes. The study of vegetation history on the CLP is very limited [8,13–15]. The reported vegetation records are rarely continuous and largely focus on late Pleistocene and Holocene and most of them have poor age constrains and show extremely low pollen content in red clay–loess–paleosol sequences [16], which diminishes the information and conclusions drawn from the records. Here we present the first detailed continuous pollen record of the last 3.0 Ma from the Chaona section on the central CLP, to understand how vegetation change responds to climate change and the aridification process in central Asia and north China.

2. Regional physiographic setting

The study area is located near the town of Chaona (107°12′ E, 35°7′ N) in the central CLP. The present summer climate of the study area is warm and humid and winter climate is cold and dry. The average annual temperature and precipitation are 8–9 °C and 350–550 mm, respectively, with the highest temperature of 22–24 °C in July (Fig. 1). The present vegetation of the area is warm–temperate forest steppe, which is characterized by *Stipa bungeana*, *Artemisia giraldii*, *Bothriochloa ischaemum* [17]. However, large elevation differences between valleys and surrounding mountains cause large vertical vegetation changes. In the valleys under 1000 m elevation on the CLP, the vegetation is dominated by warm to temperate grasses, including *Arundinella hirta*, *Spodiopogon sibiricus* and *Themeda triandran*. Above 1000 m elevation *Lespedeza dahuric*, *Zizyphus jujub*, *Sophora viciifolia*, *Ostryopsis davidiana* shrubs densely cover the slopes, and *Quercus liaotungensis*, *Pinus tabulaeformis*, *Platycladus orientalis*, *Juniperus chinensis*, *Pinus armandi*, *Populus davidiana* forest and *Betula platyphylla* forest are present on the upper slopes, especially on slopes exposed to higher rainfall [17,18] (Fig. 1).

Recently, a 300 m thick outcrop section of red clay–loess–paleosol sequence was studied at Chaona. The loess deposit of the sequence is 175 m thick, and contains 33 paleosols [11]. Field observations, and magnetic susceptibility and median grain-size records show that Chaona loess–paleosol sequence is well correlated with the standard sections of the CLP [11,19]. The basal age of this loess–paleosol sequence is 2.6 Ma based on detailed paleomagnetic studies [11] (c.f. Fig. 2). The paleosols within the loess are of brownish or reddish color with substantial clay skins developed. Carbonate nodules are scattered commonly below the soils. The nodule horizons of most of the paleosols in the lower part of the loess sequence are 20–80 cm thick. Underlying the loess–paleosol, the red clay is 125 m thick with an accumulation age between 8.1 Ma and 2.6 Ma [11]. Our pollen record is from the loess–paleosol sequence and the uppermost part of the red clay with a paleomagnetic age of ~3.0 Ma.

3. Materials and methods

We collected 222 samples for pollen analysis with an interval of ~1 m from the Chaona section. 50–300 g sediment was treated with 5%–10% HCl and 73% hydrofluoric acid. For high organic content samples, 10% caustic soda was added and they were boiled in a waterbath after the acid pretreatment. We then concentrated pollen by sieving the material remaining from the acid and/or alkaline digestion through a 10 μm mesh in an ultrasonic bath and disposed of the fine fraction [20]. The prepared specimens were mounted in glycerol for identification. All samples have been studied at Tongji University and Lanzhou University by comparing with officially published pollen plates and modern pollen slides preserved in the Geography Department of Lanzhou University. Some of the samples were double checked at the Institute of Botany, the Chinese Academy of Sciences.

4. Pollen record

More than 100 pollen grains were obtained from 90% of the samples. Approximately 200 pollen grains were collected from 85% of the samples. The collected pollen was grouped into 31 families and 41 genera, which include arboreal taxa, e.g. *Pinus*, *Picea*, *Abies*, *Betula*, *Juglans*, *Quercus*, *Ulmus*, etc., and scrubby and herbaceous taxa, e.g. Chenopodiaceae, *Artemisia*, Compositae (excluding *Artemisia*), Gramineae, *Rosa*, *Ranunculu*s, *Elaeagnu*s, Cruciferae, *Polygonum*, Solanaceae, Leguminosae, Caryophyllaceae. In addition, we found a few algae spores, i.e. Concentricystis, Hystrichospphaera, Zygnema, aside some fern spores, i.e. Polypodiaceae, and *Selaginella*. We selected arboreal pollen of four families, ten genera and the ln (NAP/AP) (the natural logarithm of Non Arboreal Pollen/Arboreal Pollen ratio, which is a proxy for the degree of aridification [21]) to construct the pollen diagram (Fig. 2).

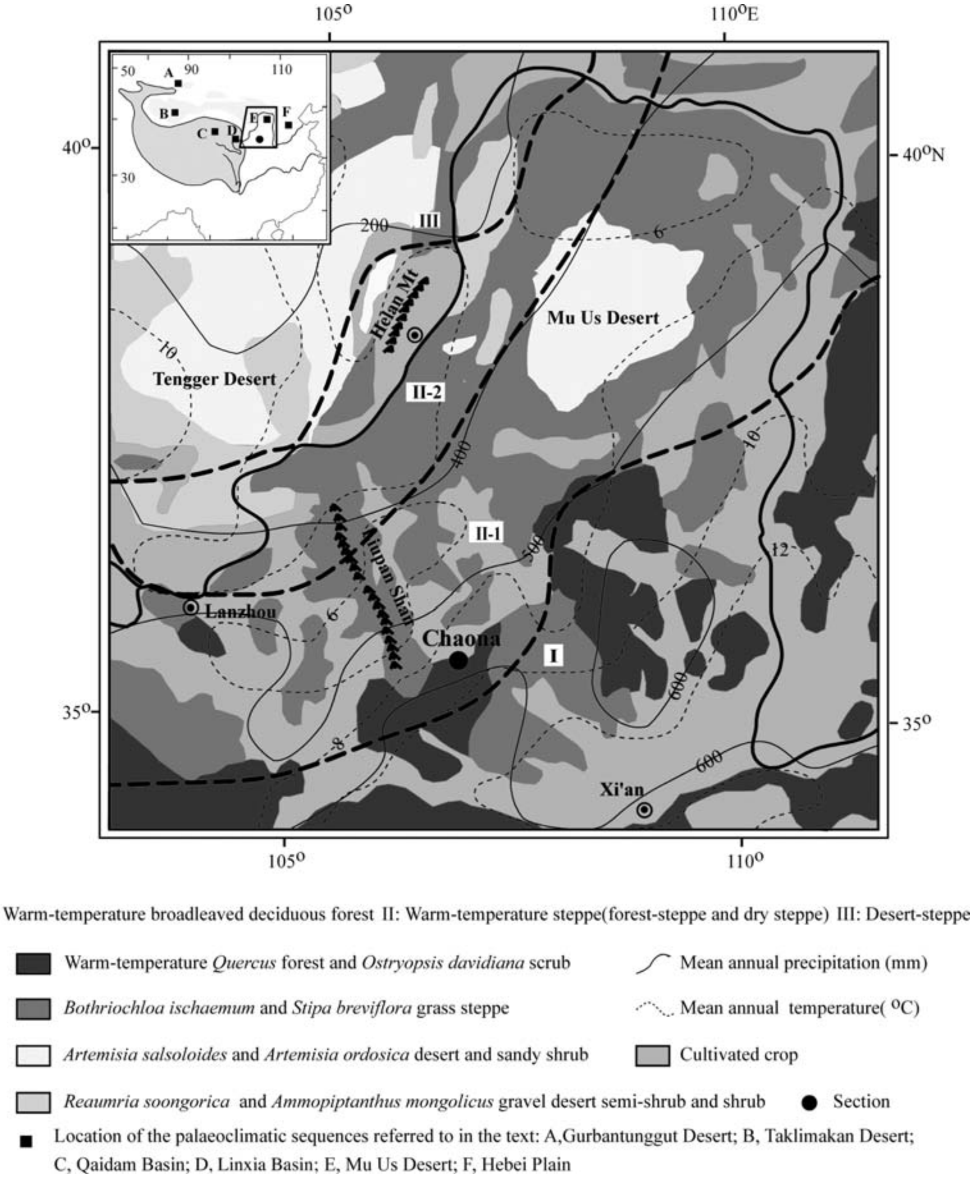

Fig. 1. Location of the study area, and its geomorphology and vegetation distribution map.

Based on the relative abundance and pollen assemblage, six major zones, are identified in our record.

4.1. Zone I (190–175 m, 3.0–2.6 Ma)

The zone is characterized by a high abundance of arboreal plants with a maximum of 99.4%. The arboreal plants mainly include Cupressaceae type (48.1%–85.87%) and *Juniperus* (5.43%–18.84%), along with *Ulmus* (2.94%–17.04%) and *Pinus* (1.18%–12.63%). If we rule out the possibility of the influence of Cupressaceae type on percentage, then this zone is marked by a high abundance of *Ulmus* (13.79%–53.08%) and *Pinus* (2.52%–38.3%), and small amounts of *Picea* (1.67%–10%), Gramineae (1.2%–6.82%), *Artemisia* (0–15.15%),*Aster* type, *Anthemis* type and *Salix*. The ln (NAP/AP) ratios are very low (1.27–3.52 with an average of 2.02).

4.2. Zone II (175–132 m, 2.6–1.85 Ma)

Pollen types are relatively rare in this zone. The percentage of arboreal pollen, especially deciduous trees declines abruptly in conjunction a drastic increase of

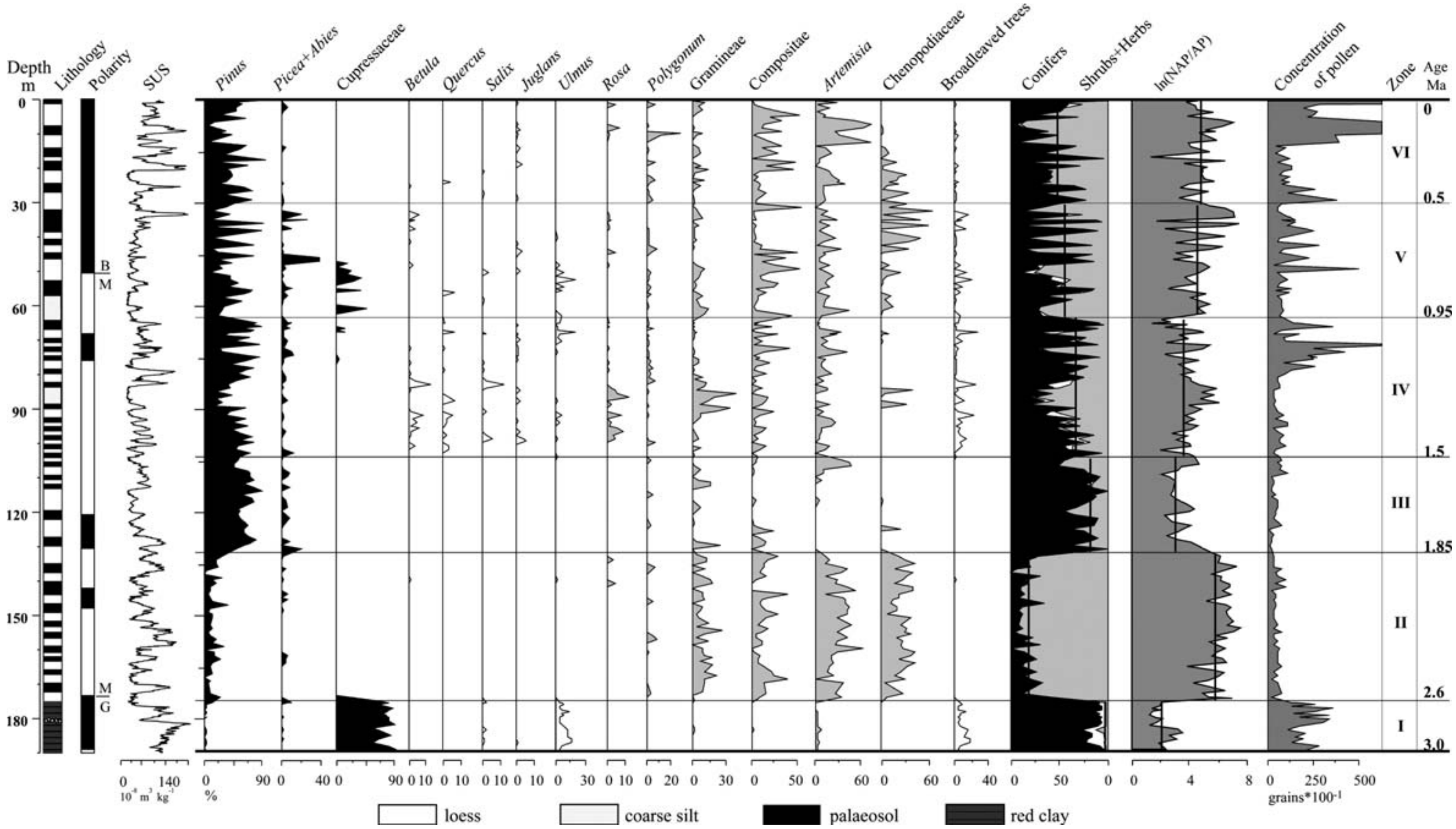

Fig. 2. Pollen diagram of Chaona section at the central CLP. Detailed Loess–paleosol stratigraphy, magnetic susceptibility and interpreted observed paleomagnetic [11,19] zones are plotted as well for comparison. (Vertical heavy solid lines in the percentage columns of conifers and herbs+shrubs and ln (NAP/AP) represent the average percentage of herbs+shrubs and ln (NAP/AP), respectively).

herbaceous plants (64.28%–95.1% with average of 83.27%), which mainly consist of arid types, *Artemisia* (0–46.2%), Chenopodiaceae (0–44.4%) and mesophilous Gramineae (0–33.3%). There are only small amounts of coniferous, and temperate deciduous taxa, which include *Pinus* (0–35.7%), *Picea* and *Abies* (0–6.5%). Cupressaceae type has an extremely low abundance in the zone. The ln (NAP/AP) ratios (3.22–7.58 with an average of 5.85) are high because of high percentage of herbaceous plant pollen in this zone.

4.3. Zone III (132–105 m, 1.85–1.5 Ma)

Pinus is the dominant species of the zone with a percentage of 46.9%–90.9%. Following *Pinus* is *Picea* and *Abies* (0–20%). Warm–temperate deciduous trees remain at the same percentage as in Zone II. Arid plants are still rare in spite of a slight increase in the percentage of some samples, which include Compositae (25%), *Artemisiae* (47%), and Chenopodiaceae (25%). Mesophilous plants dominate the zone despite a slight decrease in percentage, such as Gramineae (0–15.8%) and *Ranunculus* (0–17%). The ln (NAP/AP) ratios decrease to 2.0–4.67 with an average of 3.02.

4.4. Zone IV (105–64 m, 1.5–0.95 Ma)

In this zone, arboreal pollen reaches the highest value (21.7%–95.6%), whereas herbaceous plants have a very low percentage. *Pinus* is still the main arboreal component (20%–89.7% with an average of 59.0%). *Pinus* percentages exceed 60% with the exception of loess-dominated layers, such as L19 (*Pinus*: 51%–52%), L16 (33.3%–39.6%), L15 (16.8%–43.7%), L13 (32.4%–59.6%), L12 (24.0%–26.3%), L11 (46.6%) and L10 (25%– 36.3%). *Picea* and *Abies* are present in small amounts (0–9.58% with an average of 3.1%), whereas broadleaved trees, mainly *Betula*, *Quercus*, *Juglans*, are more abundant (0–34.4% with an average of 6.3%). Mesophilous herbaceous plants are very common in the zone, primarily Gramineae type (average of 4.94%), *Ranunculus* (average of 3.37%) and *Rosa* (average of 1.09%). The percentage of arid herbaceous pollen such as *Artemisia*, Chenopodiaceae type and Compositae type is relatively low with mean values of 11.2%, 2.49% and 7.45%, respectively. The ln (NAP/AP) ratios increase to 1.96–6.05, with an average of 3.87.

4.5. Zone V (64–32 m, 0.95–0.5 Ma)

Arboreal plants decrease to 6.2%–94.8%, with an average of 46% in this zone. The percentage of *Pinus* decreases to 4.4%–93.5% with an average of 41.9%. Although the percentage of *Picea* and *Abies* increases slightly to 0–37.9% with an average of 5.8%, broadleaf trees decrease to 0–14.7% with an average of 4.1% (Fig. 2). Herbs and shrubs rise from 34.1% in Zone IV to 46.5% in this zone, whereas Compositae type and Chenopodiaceae type increase largely to 0–52.4% and 0–66.0%, and Gramineae type slightly decreases to an average of 3.7%. The ln (NAP/AP) ratios increase to 1.7–7.48 with an average of 4.65.

4.6. Zone VI (32–0 m, 0.5–0 Ma)

Arboreal pollen types decrease again to a mean value of 43.5%. Means of *Pinus* (6.6%–96.6%) and *Picea* and *Abies* (0–6.9%) decrease to 41.3% and 0.6%, respectively. Broadleaf trees also decrease sharply to 0–6.3% with an average of 1.14%. Herbs and shrubs increase to a mean value of 55.8%, whereas *Artemisia* (0–71.8%) and Compositae (0–88%) increase by 19.24% and 18.65%, respectively. Gramineae in this zone continue to decrease with an average of 2.8%. The ln (NAP/AP) ratios increase to 1.2–7.06 with an average of 4.75.

5. Drying of Asia indicated by vegetation

5.1. Reliability of the pollen record

Because pollen cannot be well preserved in the oxidizing environment where loess and red clay are deposited, the long-term pollen record in the loess–red clay sequence has been rarely studied. However, improvements in pollen extraction techniques and lab equipment have made it possible to obtain enough pollen from the loess–paleosol sequence for paleovegetation studies [16,22]. By taking a large bulk sample, more than 100 grains of pollen have been obtained from most samples, which is statistically reliable for reconstructing the ecologic environment.

Some studies show that the *Pinus* taxon living on the CLP in Quaternary times might be *P. tabulaeformis*. *P. tabulaeformis* is a widely-distributed warm–temperate coniferous genus. Its present distribution on the CLP is controlled by temperature and precipitation, especially the latter. Therefore, *P. tabulaeformis* adapts mostly to a humid habitat, and disappears where annual precipitation falls below 400 mm and annual relative humidity is lower than 55 [23]. When annual precipitation and temperature increase, the general order of vegetation succession on the present CLP is showed as Fig. 3 [24]. *P. tabulaeformis* forest is similar to *Q. liaotungensis*

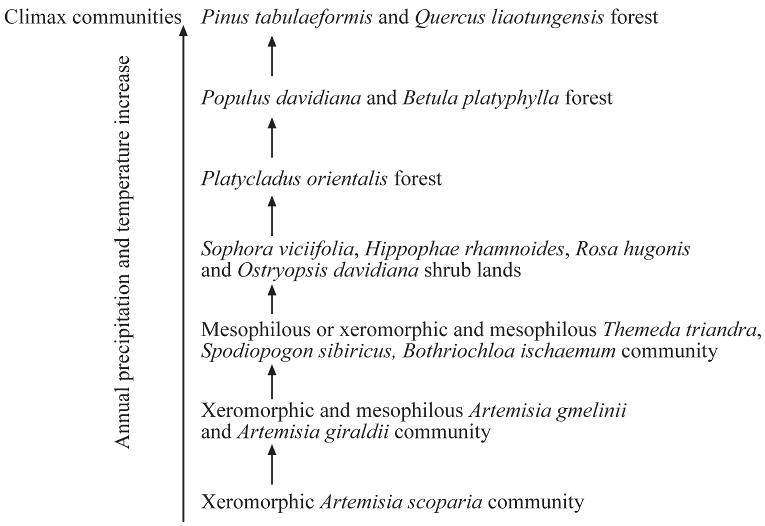

Fig. 3. Schematic diagram of the vegetation succession process on the CLP [24,25].

forest, so they both belong to a terminal community [25]. In addition, the pollen-climatic response surface model implies that the response surface of *Pinus* is a saddle type, which has two peaks in the areas of low temperature–high humidity and high temperature–moderate humidity. Thus, *Pinus* is distributed mainly in more humid and warmer mountainous environments [26]. The distribution condition for pine forest exceeds that of herbs and shrubs on the CLP (Fig. 3).

In addition, the general order of vegetation from south to north of the present CLP is showed as Figs. 1 and 4 [17,24,25,27]. Thus, the growth condition for *P. orientalis* forest exceeds that of *Artemisia* and grassland.

According to modern surface pollen studies, we know that the percentage of *Pinus* is usually 30% in non-pine areas, with the highest value up to 55.5% [28], or even 60.9% in non-pine forest areas [29]. The low percentage of *Betula*, usually less than 2%, implies that *Betula* is absent in the surrounding area [30]. On the other hand, a percentage of *Quercus* over 2.5% suggests robur grows there [31]. Shrubs, undershrubs and herbs are usually short, their pollen drops near the surface and can not be transported over long distances due to friction, so they are very representative of local vegetation [32]. However, because of low pollen productivity, even in an area dominated by Gramineae, the average percentage of Gramineae pollen is only ~3.0%–6.0% or a little bit higher [30,33,34]. Small amounts of arid *Artemisia* and Chenopodiaceae are usually regarded to be from exotic sources because of their high productivity. Only when percentages are over 30%, can they be regarded as from local sources [33,34].

Taking into account the representation of the genera above, our observed vegetation changes show an overall

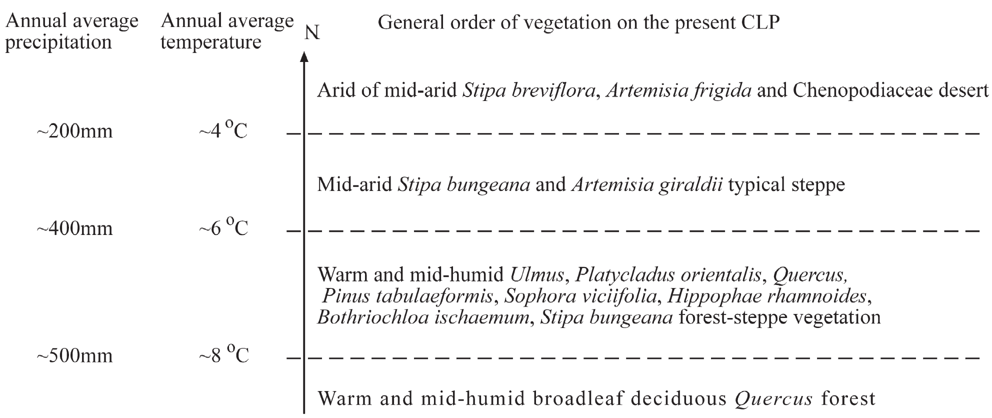

Fig. 4. Schematic diagram of the general vegetation order from south to north of the CLP [17,24,25,27].

pattern that arid herbs (largely *Artemisia* and Chenopodiaceae) and trees (mainly *Pinus*, *Betula* and *Quercus*) dominate loess and paleosols units, respectively, reflecting cycles of cold–dry and warm–humid conditions during glaciation and interglaciation. This alternating variation of vegetation matches the summer monsoon proxy, the magnetic susceptibility of loess and paleosols (Fig. 2), demonstrating the reliability of pollen preservation and statistics.

5.2. Ecologic environmental change and stepwise drying of Asia

Our vegetation record above demonstrates a first order pattern of long-term but stepwise drying of central Asia and north China with transitions occurring at 2.6 Ma, 1.85 Ma, 1.5 Ma, 0.95 Ma and 0.5 Ma (Fig. 2).

Cupressaceae and *Juniperus* dominate the period 3.0–2.6 Ma together with *Ulmus*. The amount of *Pinus* is so low that it would be a long-distance transport component, though the average percentage of redundant trees is up to 97.6%. This pollen assemblage implies a Cupressaceae forest vegetation, mixed with some broadleaf trees, such as *Ulmus*, and sporadical *Quercus*, *Salix*, *Betula*.

This vegetation assemblage is comparable to a *P. orientalis* forest distributed in the south of Gansu Province and the north of Shaanxi Province (Fig. 1). It grows on the rainy side of the valley, and mixes with *Ulmus*, *Q. liaotungensis* and *Celtis bungeana*, with an altitude, average annual temperature and precipitation of 800–1300 m, 10 °C and 500–550 mm, respectively [17]. Therefore, in our estimation the climate during 3.0–2.6 Ma is warm and humid.

Since 2.6 Ma, the pollen types of herbaceous plants become the dominant ones. The pollen assemblage consists of drought-enduring *Artemisia* and Chenopodiaceae (mostly exceeding 30%) and mesophilous Gramineae (0–33.3%). The percentage of coniferous (especially Cupressaceae), temperate and warm–temperate deciduous components decreases with a minimum close to zero at some levels in this interval, indicating that the climate is much drier and colder than before. The drier and colder climate last until 1.85 Ma with pine and spruce forest appearing on the hills far away from the section, and *Artemisia* and Chenopodiaceae plants spreading around the slopes, and grass growing in the valleys.

From 1.85 Ma to 1.5 Ma, *Pinus* dominates the vegetation with pollen percentage of 46.9–90.9%. Mesophilous herbaceous plants also have relatively high percentages. The percentage of *Picea* and *Abies* exceeds 5% at most times suggesting the existence of local spruce forest or a proximal spruce forest. The low percentage of the pollen of *Artemisia* (0–25%) and Chenopodiaceae (0–47%) indicates that they are components of long-distance transport. Therefore, a forest or forest–steppe vegetation dominates Chaona region during this time interval, with spruce forest growing in the mountain areas, and mesophilous herbs in the valleys and glades. The climate is relatively humid and has relatively low temperature.

From 1.5 Ma to 0.95 Ma, *Pinus* and Gramineae dominate the vegetation with a certain amount of broadleaf components such as *Betula*, *Quercus* and *Juglans*. The percentage of the pollen of arid herbaceous plants, mainly Chenopodiaceae and *Artemisia*, are very low with a few exceptions over 30% suggesting that they would be only transported from long distances. This pollen assemblage indicates a forest–steppe vegetation with a warm–temperate and humid climate. It is estimated that the rainy side of mountains and valleys are covered with pine forest and some broadleaf trees, such as *Quercus*, *Betula*, and *Juglans*, whereas the lee sides of mountains are only covered by grass.

From 0.95 Ma to 0.5 Ma, although *Pinus* shows a strong decrease and Gramineae decreases slightly, they are still the dominant taxa. Compositae plants usually are short, and their pollen could only be deposited nearby, thus they are used as the indicator of local vegetation [32]. However, another study suggests this indicator can only be used at low levels [35]. In our record, the percentages of Compositae and Chenopodiaceae are high (Fig. 2), indicating that they may exist locally at that time. The pollen assemblage indicates an open forest–steppe vegetation, namely, grass, Compositae and Chenopodiaceae plants growing on the slopes, mountain areas, valleys and glades, and pine forest growing in mountainous regions and valleys with scattered *Quercus*, *Juglans*, *Ulmus* and *Betula*. The vegetation therefore suggests that the climate is drier than before.

Since 0.5 Ma, the percentage of arboreal pollen decreases strongly with *Pinus*, *Picea* and *Abies* in small amounts. *Betula* and *Quercus* also decrease, whereas herbaceous plants, such as Compositae and *Artemisia* increase dramatically (Fig. 2), indicating that the vegetation is steppe in this period. The dominant plant community is composed first of Compositae, *Artemisia* and Gramineae, and later of *Artemisia* only, with pine forest growing in adjacent mountainous regions. The vegetation therefore indicates an intensified aridification of the climate.

The long-term stepwise aridification above is further demonstrated by the natural logarithm of NAP/AP ratio

(Fig. 2). The ln (NAP/AP) ratio is usually used to indicate the relative area which is covered by shade-indicated taxa versus forest covered area [21]. The change of ln (NAP/AP) in our record reflects three aridification shifts in the Chaona region during the last 3.0 Ma (Fig. 2).

Shift I appears at 2.6 Ma with the increase of the average value of ln (NAP/AP) from 2.02 to 5.85 (Fig. 2). Coniferous, as well as temperate and warm–temperate deciduous components decrease gradually and drought-enduring plants grow luxuriantly after the shift. Steppe vegetation replaces typical Cupressaceae forest, suggesting the development of an arid climate and the intensification of aridification. Although the climate experienced a short time interval of slightly more humid at 1.85 Ma, the overall regional vegetation changed from forest or forest–steppe (spruce forest–mesophilous herbs) to forest–steppe (pine–grass) at 1.5 Ma, then to open forest–steppe (mesophilous and xeromorphic herbs–pine) at 0.95 Ma, and finally to steppe (xeromorphic herbs) at 0.5 Ma. Their corresponding average values of ln (NAP/AP) show an increase first from 3.87 to 4.65, then to 4.75 (Fig. 2). Thus both vegetation type change and aridification index ln (NAP/AP) indicate a stepwise drying of north China and central Asia since 3.0 Ma with phase turning ages at 2.6 Ma, 1.5 Ma, 0.95 Ma and 0.5 Ma (Fig. 2).

6. Discussion

The aridification event recorded as the expansion of steppe vegetation in our results at 2.6 Ma is consistent with the sedimentary transition from red clay to the loess–paleosol sequence at the CLP [e.g. 8,36]. We know that many environmental events took place at that time around the world, e.g., the expansion of ice sheets in the Northern Hemisphere is recorded by an increase of ice rafted debris and oxygen isotope records in sediments in the Atlantic Ocean [37,38] and by the rapid growth of North America ice cover [39]; the shift toward more arid conditions in Africa recorded by an increase of eolian dust of the Atlantic and Arabian sea sediments [40] and by a strong degradation in tree cover of East Africa [41]; the increase of eolian dust flux in deep sea sediments of the North Pacific Ocean which has been regarded as an indication of a drying Asian interior [5]; and the wide expansion of tundra over northern and central Europe [42,43]. Thus, we think that intense drying of Asia at 2.6 Ma was largely due to the strong global cooling and drying of continents. However, a rapid uplift of the northern Tibetan Plateau has been reported to take place at 2.6 Ma also [2,44]. Thus, the possibility of the partial contribution added by this tectonic event cannot be ruled out.

The relatively humid event at 1.85 Ma is also reported at other places close to the Chaona region. Large amounts of the pollen of spruce and fossil fir trees are preserved in the Linxia Basin west of the study region at that time [2,45] (Fig. 1). Further west in the huge Qaidam Basin on the northern margin of the Tibetan Plateau (Fig. 1), a rapid rise of paleo-lake level is accompanied by a sharp decrease or halt of salt formation at about 1.8 Ma [46]. In the Hebei (or North China) Plain to the north of the study region (Fig. 1), coniferous forest occupied most of the plain indicated by high amounts of *Picea* in the pollen record [47].

Although the stepwise shift at 1.5 Ma has never been recorded by other inorganic climatic proxies, it is certainly noted that the CLP inorganic proxy records after 1.5 Ma are much more coherent with the marine oxygen isotope record than it is prior to 1.5 Ma.

The stepwise shifts at 0.9 Ma and 0.5 Ma are consistent with the great expansions of the Taklimakan Desert and Gurbantunggut Desert at 0.9–0.8 Ma and 0.5 Ma as suggested by grain size and carbonate content records in Xinjiang loess [48,49]. Magnetic susceptibility and grain size studies from the Jingbian loess section also reveal great expansions of the Mu Us Desert at 1.1 Ma and 0.6 Ma, respectively [50] (Fig. 1). A 3-Ma mineralogy record from the Dalangtan Salt Lake core in the Qaidam Basin indicates that the climate in west China is drier in the Quaternary and finally the salt lake is formed in the later stage [51] (Fig. 1). This stepwise aridification of central Asia and north China is also reflected roughly by an obvious increase of grain size and decrease of magnetic susceptibility from many loess sections in the CLP [e.g. 8,9,11,52] and by increases of eolian flux in the North Pacific Ocean [5].

7. Conclusions

During the period of 3.0–2.6 Ma, the ecological environment of Chaona is characterized by Cupressaceae forest vegetation and the climate is humid. Steppe vegetation and cold/dry climate prevail during 2.6–1.85 Ma showing that the ecological environment became more arid than before. Forest or forest–steppe dominates vegetation under relatively humid climate at 1.85 Ma. Then the dominant vegetation changes into forest–steppe at 1.5 Ma, and open forest–steppe at 0.95 Ma, and then steppe at 0.5 Ma showing a strong degradation of tree cover.

The aridification climate trend starts at ~2.6 Ma. Although aridification is relatively weak at 1.85 Ma, the climate in this region became progressively drier with three aridification events occurring at 1.5 Ma, 0.95 Ma and 0.5 Ma.

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