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Pollen record from red clay sequence in the central Loess Plateau between 8.10 and 2.60 Ma

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Abstract **The Late Miocene and Pliocene are the key periods for understanding the origin and development of the present Asian monsoon circulations and ecologic environments. Here we present a pollen record from Chaona Red Clay section located in the central Loess Plateau in attempt to establish the histories of vegetation and associated climate changes between 8.10 and 2.60 Ma. Our results show that Gramineae-dominated woodland-grasslands developed in this region with *Cedrus*- and *Pinus*-characterized montane coniferous forests distributing in higher elevations from 8.10 to 6.73 Ma, probably suggesting a semi-humid climate in a warm-temperate zone. A subsequent expansion of *Ulmus*-dominated deciduous forests and a synchronous increase of Gramineae-dominated grassland reflect a warmer and more humid climate between 6.73 and 5.67 Ma. The vegetation changed to an *Artemisia*- and Gramineae-characterized steppe in lower elevations and to a coniferous forest in higher elevations from 5.67 to 3.71 Ma, implying probably a warm and semiarid climate in lowland and hill, and a colder and moister climate in mountain. During this period, a considerable warmer and more humid climate occurred between 4.61 and 4.07 Ma as indicated by pollen assemblages. The period between 3.71 and 2.58 Ma was characterized by the disappearance of *Cedrus* and *Tsuga* and also by an abrupt expansion of Cupressaceae, reflecting a drastic enhancement of monsoon-related climatic seasonality.**

Keywords: Loess Plateau, red clay, pollen record, vegetation evolution, winter and summer monsoon.

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The origin and development of Asian monsoon circulation, the desertification and aridification of Asian inland in relation to vegetation evolution and the soil erosion in northwest China have been more and more drawing intensive scientific and society attention. Recently the studies of monsoon evolution from some Tertiary Red Clay sections located at the central Loess Plateau in the eastern Liupan Mountains, based on chronology, dust flux, grains size, magnetic susceptibility, and rates of deposition and Rb/Sr, indicate that the Asian monsoon climate has existed in the interior of Asia since the Late Miocene (7—8 Ma), and was remarkably enhanced between 3.6 and 2.6 Ma due to the uplift of the Tibetan Plateau[1—5]. However the changes of lithology, iron, and value of total iron of eolian dust accumulation show that Asia summer monsoon increased dramatically in 4.8—4.0 Ma, then markedly decreased[6,7], with an expansion of C_4 steppe vegetation at 4 Ma[8]. Moreover, studies on mineral assemblage, grain shape and size, and susceptibility of Tertiary Red Clay on the Loess Plateau have further demonstrated that the source areas of aeolian dust and the winter monsoon carrying dusts must have existed in the inland of Asia during the Early Miocene (22 Ma), suggesting an earliest phase of desertification[9]. Vegetation provides direct evidence and is sensitive to environmental changes. Here we present a detailed pollen record from the Chaona Red Clay Section, which is the longest sequence on the central Loess Plateau and has been precisely dated. The results provide strong scientific evidence for the scientific topics above.

1 Section and physiographic setting

The studied area is located at the Longdong basin in the central Loess Plateau (Fig. 1). The present climate is semi-humid in warm temperate zone where the mean annual temperature is 8—9℃, mean warmest month temperature is 22—24℃, and mean annual precipitation is 350—500 mm. The modern natural vegetation is warm-temperate forest-grassland in which the constructive species are *Stipa bungeana*, *Artemisia giraldii* and *Bothriochloa ischaemum*. In the river and valley lower than 1000 m warm grasslands constitute ecological landscape, which mainly consists of *Arundinella hirta*, *Spodiopogon sibiricus* and *Themeda triandran*; on the hill the shrubs such as *Lespedeza dahurica*, *Zizyphus jujub*, *Sophora viciifolia*, *Ostryopsis davidiana* present and forests consisting of *Quercus liaotungensis*, *Pinus tabulaeformis*, *Platycladus orientalis*, *Juniperus chinensis*, *Pinus armandi*, *Populus davidiana* and *Betula platyphylla* cover mountains[10,11].

The studied section is situated at Chaona Town of Lingtai County in Gansu Province (107°21′E, 35°7′N), and has an altitude of 1464 m at top. The Cenozoic Red Clay is 126 m thick and consists of five lithologic units from the top to the bottom. The first unit (0—21 m) is red brown in color due to well developed paleosols with many Fe-Mn coatings. The second unit (21—45 m) shows light red brown in color and has five interbedded nodule horizons with each being 50—80 cm thick. The third unit

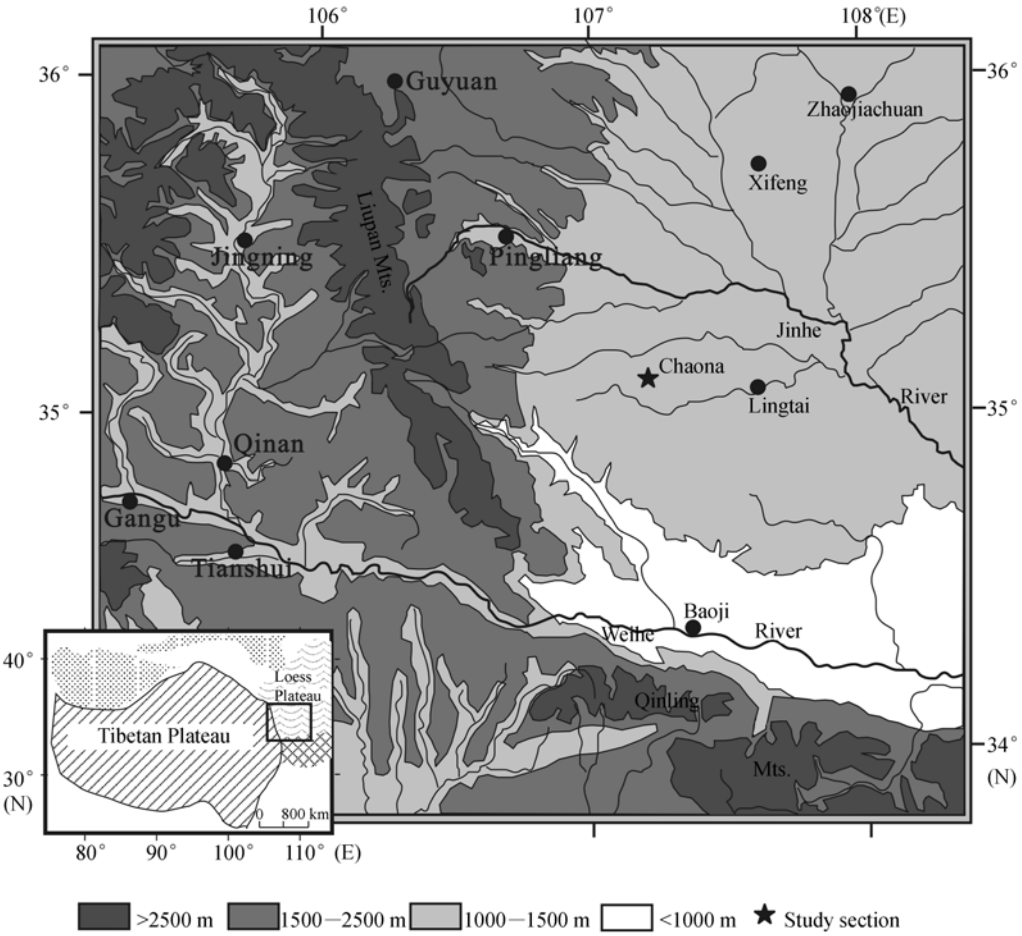

Fig. 1. The location of studied section.

(45—68 m) exhibits deep red brown in color, the reddest layer in the entire Red Clay section, and contains abundant Fe-Mn coatings and carbonate nodules. The fourth unit (68—98 m) shows yellow brown and has a small quantity of nodules. The fifth unit (98—126 m) presents light yellow brown and paleosols are very weak and lack nodules. The Red Clay is in unconformity contact with the underlying Late Cretaceous sandstone and siltstone (Fig. 2). Paleomagnetic dating shows that the age of the Red Clay section was formed between about 8.1 and 2.58 Ma (Fig. 2)[12].

2 Pollen record

One hundred and thirty samples at 1 m interval were taken from the Red Clay of the Chaona section. The samples were pretreated as follows: 150—200 g samples were reacted respectively with 36% HCl and 73% hydrofluoric acid (HF), then remains were sieved through a 10 μm mesh in an ultrasonic bath, finally the pollen-spores were collected from the mesh and stored in glycerol ready for identification under high resolution optical bio-microscope at × 400.

Pollen grains are obtained from 130 samples and most (90%) treated samples contain over 100 pollen grains adequate for a minimal statistic requirement of pollen-spore analysis. 28 families and 33 genus of fossil pollen were observed. Those pollen include some arboreal components consisting mainly of Cupressaceae, *Juniperus*, *Pinus*, *Picea*, *Cedrus*, *Tsuga*, *Abies*, *Ulmus*, *Betula*, *Quercus*, *Salix* and *Juglans*, and some scrubby and herbaceous components composed mainly of Gramineae, *Artermisia*, *Aster*, *Anthemis* and Chenopodiaceae (Fig. 3). Based on change of the percentages of important pollen types, in combination with the proportions of coniferous, temperate and warm-temperate deciduous trees, and herbaceous plants and pollen concentrations, four pollen assemblage zones were distinguished and are numbered from 4 (bottom) to 1 (top) as shown in Fig. 4.

Zone 4 (126—97 m, ca.8.10—6.73 Ma): Gramineae-*Cedrus*-*Pinus*. This zone is characterized by a low pollen concentration. The dominant components are coniferous trees pollen (25.00%—73.47%), including mainly *Pinus* (7.50%—44.90%) and *Cedrus* (2.50%—21.74%) along with Cupressaceae (0%—20.34%), *Picea* (0%—

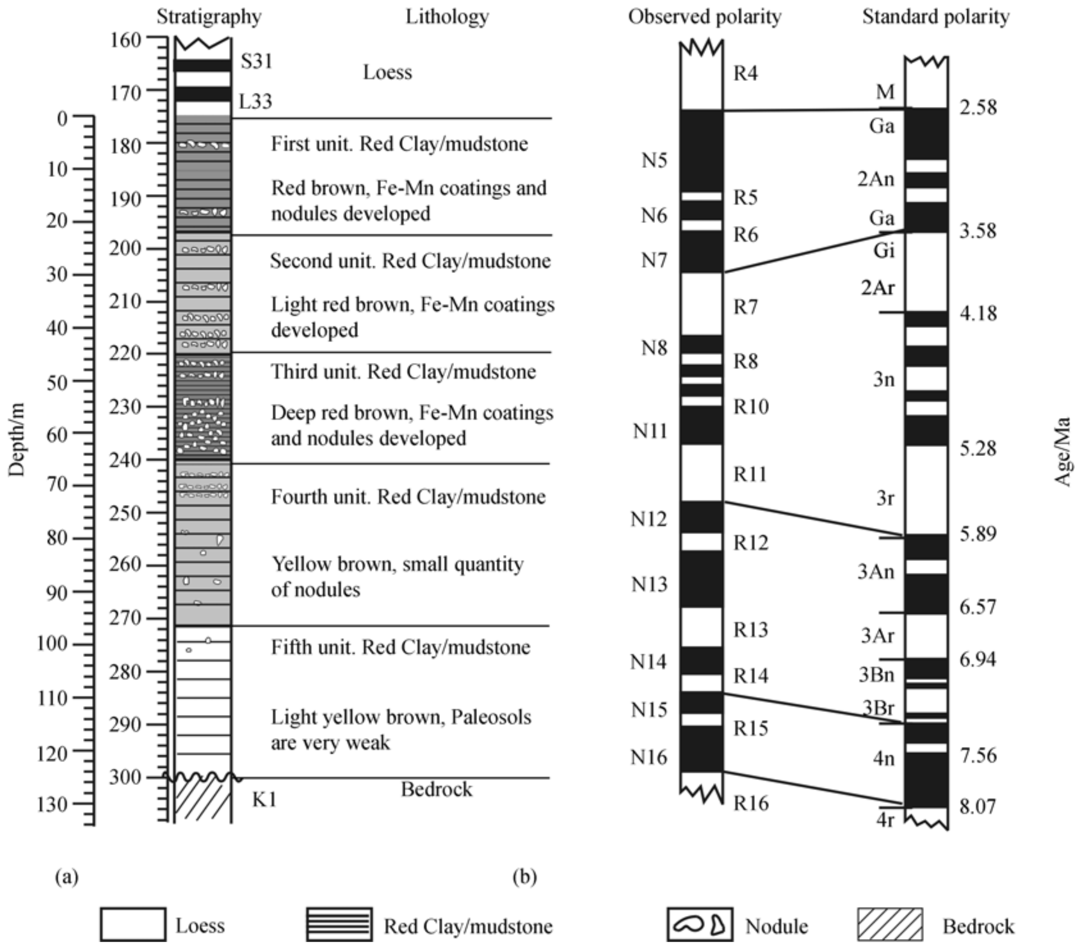

Fig. 2. (a) Stratigraphy, paleomagnetic and chronology of Chaona section in Longdong Basin characterization of stratigraphy; (b) stratigraphy and paleomagnetic[12].

20.00%), *Tsuga* (0%—5.00%) and *Juniperus* (0%—3.77%). The second dominant components are herbaceous plants (20.34%—65.00%), consisting of *Artemisia* (2.17%—35.16%) and Gramineae (4.47%—25.00%), Chenopodiaceae (2.56%—22.73%), *Aster* (0%—7.50%) and *Anthemis* (0.00%—7.23%). The less components are temperate and warm-temperate deciduous pollen (6.15%—23.86%), comprising *Ulmus* (2.53%—12.00%), *Quercus* (0.00%—17.39%), *Salix* (0.00%—8.19%), *Betula* (0.00%—6.67%) and *Juglans* (Fig. 4).

This zone can be divided into two subzones. The observable feature is that the percentages of *Cedrus* (2.50%—7.89%) and Gramineae (4.47%—21.62%) are lower and *Pinus* (15.00%—44.90%) is higher in subzone 4-2 (129—120 m, ca. 8.10—7.76 Ma), while the percentages of *Cedrus* (6.33%—21.74%) and Gramineae (5.70%—25.00%) are higher and *Pinus* (7.50%—29.73%) is lower in subzone 4-2 (120—97 m, ca. 7.76—6.73 Ma) (Fig. 4).

Zone 3 (97—67 m, ca. 6.73—5.67 Ma) : Gramineae-*Ulmus-Pinus*. The concentration is lower. This zone is marked by increasing of deciduous arbor pollens (9.46%—35.56%) which are at their highest for the entire section, and also by declining of coniferous pollens (16.67%—46.15%). The percentages of herbaceous (32.79%—59.09%) remain unchanged. That is to say, this zone is characterized by increasing of *Ulmus* (6.32%—35.56%) and *Juglans* (0%—5.70%), decreasing of *Cedrus* (0%—9.6%) and *Quercus* (0%—7.41%), and unchanging of *Pinus* (7.19%—38.89%), Gramineae (6.67%—29.27%), Cupressaceae, *Juniperus*, *Picea*, *Tsuga*, *Betula*, *Salix*, *Artemisia*, *Aster*, *Anthemis* and Chenopodiaceae compared with zone 4 (Fig. 4).

Zone 2 (67—30 m, ca. 5.67—3.71 Ma): *Artemisia* -*Pinus-Picea*. Pollen concentration is higher. The percentages of deciduous arboreal pollens (3.60%—23.33%) decrease as coniferous pollens (12.95%—75.39%) increasing, and the percentages of herbaceous (18.29%—

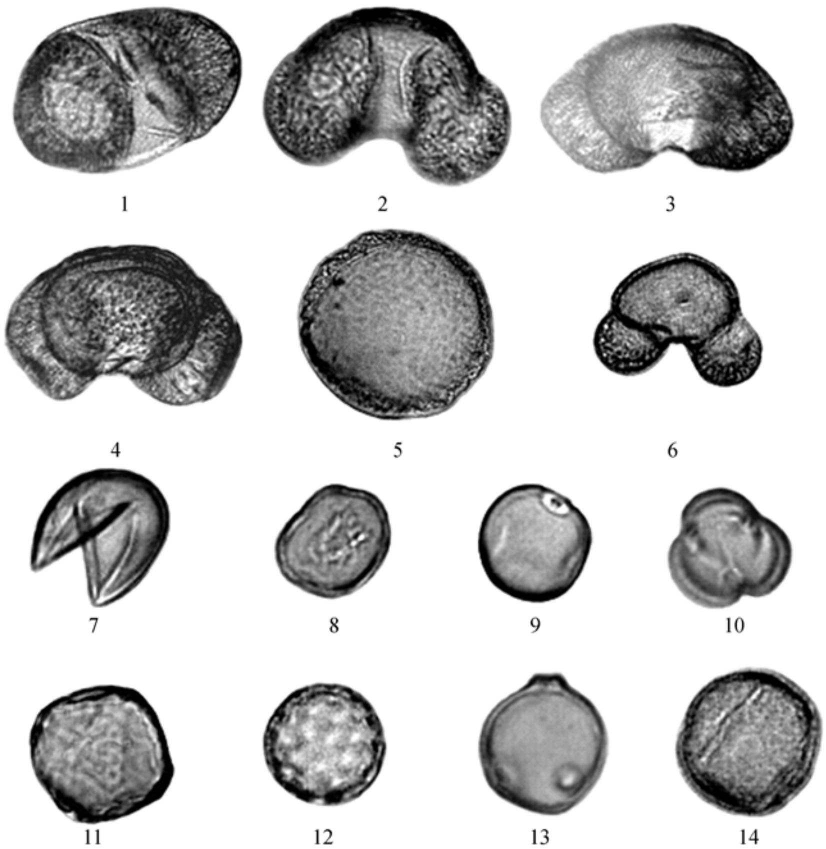

Fig. 3. The shape of important pollen types in the studied section. 1. *Picea*; 2. *Abies*; 3, 4. *Cedrus*; 5. *Tusga*; 6. *Pinus*; 7. *Junierpus*; 8. Cupressaceae; 9. Gramineae; 10. *Artemisia*; 11. *Ulmus*; 12. Chenopodiaceae; 13. *Betula*; 14. *Quercus*.

65.49%) remain unchanged. The one above all the obvious features is that the fluctuating increases of *Pinus* (7.06%—59.62%), *Picea* (4.35%—36.96%) and *Artemisia* (6.52%—46.60%) occurred at the expense of *Ulmus* (1.92%—12.21%) and Gramineae (4.42%—22.95%). Apart from this, the percentages of *Quercus* (0.71%—13.33%), *Salix* (1.22%—10.71%) and *Betula* (1.19%—2.43%) are relatively low, and *Juglans* is also present but in merely detectable amount. This zone can be divided into three subzones (Fig. 4).

Zone 2-3 (67—49 m, ca. 5.67—4.61 Ma): *Pinus*-*Artemisia*-*Picea*. This subzone has three observable characteristics. Firstly the outstanding feature is the striking increase of *Pinus* (7.06%—59.62%) and *Artemisia* (6.98%—46.60%), which reaches their greatest abundances in the entire section. Secondly alternative occurrence of four cycles of vegetation was noticed with respect to coniferous component (44.29%—79.81%) consisting mainly of *Pinus* and *Picea* (4.35%—36.59%) and herbaceous plants (51.43%—61.90%) composed mainly of *Artemisia* and Gramineae (4.88%—17.30%). Thirdly the percentages of deciduous arbors (4.29%—21.18%) are drastically lower than zone 3, which is marked by a rapid reduce of *Ulmus* (0%—9.30%) and *Juglans* (0%—1.22%) (Fig. 4).

Zone 2-2 (49—37 m, ca. 4.61—4.01 Ma): *Pinus*-Gramineae-*Ulmus*. The zone is characterized by a persistent high percentage of coniferous trees pollen (20.34%—64.05%), a slight decrease of herbaceous (23.04%—59.32%) and an increase of deciduous plants (7.69%—23.335%). In particular the marked features are although *Pinus* (9.52%—43.98%) and *Picea* (8.10%—22.39%) are dominant, *Cedrus* (1.31%—12.77%) and *Tsuga* (1.92%—6.38%) continually present in coniferous component, and although *Artemisia* (4.92%—35.71%) are relatively high, Gramineae (6.48%—22.98%), *Aster* type (2.09%—10.17%) and *Anthemis* type increased and turned into the important elements in herbaceous component. In addition the contents of *Quercus* (2.13%—13.11%), *Salix* (0.65%—10.73%) and *Ulmus* (0.79%—13.56%) are higher than subzone 2-1 (Fig. 4).

Zone 2-1 (37—30 m, ca. 4.01—3.71 Ma): *Artimisia*-*Picea*-Chenopodiaceae. Drastic increases of herbaceous

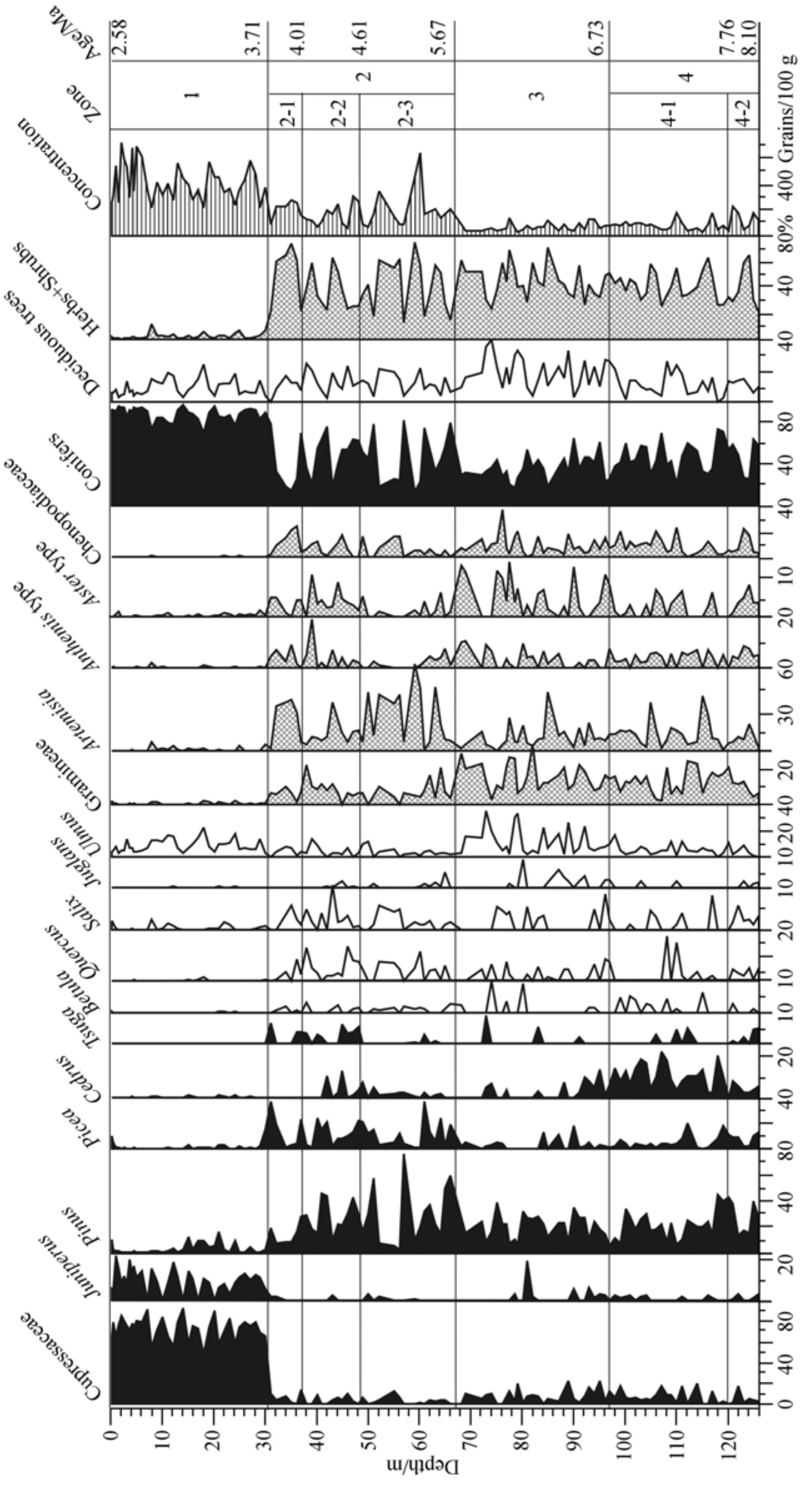

Fig. 4. Pollen percentage diagram of the Chaona section.

plants (59.65%—73.53%) occurred primarily at the expense of coniferous (13.97%—25.98%) and deciduous trees (8.33%—16.81%). The zone is marked by high percentages of *Artemisia* (28.35%—36.76%), Chenopodiaceae (2.17%—24.41%), Gramineae (4.42%—10.62%), *Picea* (1.77%—19.30%), *Pinus* (7.02%—16.54%), *Ulmus* (3.90%—7.96%) and *Salix* (0.82%—5.88%), minor amounts of *Aster* type, *Arthemis* type, *Tsuga*, *Quercus* and *Betula*, and disappearance of *Cedrus* and *Juglans* (Fig. 4).

Zone 1 (30—0 m, ca. 3.71—2.58 Ma): Cupressaceae-*Ulmus*. Pollen concentrations are highest. Coniferous (73.27%—96.15%) trees composed of Cupressaceae (48.10%—85.87%) and *Juniperus* (5.43%—18.84%) abruptly increase against a drastic reduction of herbaceous (0.56%—6.19%) plants consisting mainly of *Artemisia* (0.00%—4.89%), Gramineae and *Aster* type (0.00%—2.56%). The deciduous trees (4.02%—24.29%) composed mainly of *Ulmus* (2.94%—22.86%) and *Salix* (0.00%—2.30%) decrease slightly.

3 Vegetation and climatic interpretation

The studies of modern surface pollen show: 1) A very low percentage of Gramineae pollen (3.0%—6.0%) probably indicates the existence of grassland/steppe vegetation in which Gramineae is constructed and dominant species because Gramineae is usually underrepresented[13—18]. 2) *Artemisia* and Chenopodiaceae are generally super-representative of pollen in surface soils so that minor amounts of *Artemisia* and Chenopodiaceae pollen presented in pollen assemblages may be indicative of their extraneous origin, while their higher percentages (over 30% respectively) suggest the in situ existence of *Artemisia* and Chenopodiaceae[13—15,18—21]. 3) A very high percentage of *Pinus* pollen (25.0%—30.0%) seems to be associated with wind and water transportation because *Pinus* is greatly over-represented[13—15,17,22,23]. 4) A very high percentage of *Picea* pollen (20%—80%) suggests the existence of spruce forest or approach to a spruce forest, a very low percentage of *Picea* pollen (2%—3%) is in desert and desert steppe zone, a rather low percentage of *Picea* pollen (10%—5%) appears to be compatible with long-distance air transportation[14,15,23—25], and a relatively low percentage of *Picea* pollen (30%—10%) seems to be associated with water transportation (alluvial deposits)[26]. 5) Generally, when the percentages of *Betula* and *Quercus* are higher than 3.0%—5.0%, it is likely to grow *Betula* and *Quercus* forest nearby, while *Salix* pollen has low production and dispersibility near their plants[14,15,27,28]. 6) Different opinions are given for *Ulmus* pollen, some studies show that *Ulmus* is underrepresented[22,27,28] while some others indicate that *Ulmus* belongs to the represented type[29]. For example, the percentage of *Ulmus* from the surface pollen in the Loess plateau, even from the deciduous forest that contains elm tree is less than 1% at any time, that shows that the production of *Ulmus* pollen is possibly very low in the Loess Plateau, but the percentage of *Ulmus* from the surface pollen of the deciduous forest that contains elm tree in Zhongtiao mountains at an altitude of 1700 m can reach to 34%[30]. According to these data, several major changes in vegetation can be reconstructed based on the pollen diagram from Chaona section between 8.10 and 2.61 Ma.

During the period of 8.10—6.73 Ma the pollen assemblage is characterized by the higher percentages of Gramineae (4.47%—25.00%) and *Ulmus* (2.53%—12.00%), lower percentages of Chenopodiaceae (under 30%), *Artemisia* (under 30%), *Pinus* (7.50%—44.90%) and *Picea* (0.00%—20.00%). As Gramineae is considerably under-represented by its pollen rain, and the relatively high percentage of Gramineae pollen at this time indicates that the taxon was a constructed and dominant species in the vegetation. The percentages of Chenopodiaceae, *Artemisia*, *Pinus* and *Picea*, which are generally super-representative, probably imply that these taxa were regionally unimportant or absent in the landscape. Although the representation of *Ulmus* is not very clear, the value of *Ulmus* suggests elm present in local area. Thus the pollen assemblages probably suggest that the zonal vegetation probably was the grassland dominated by Gramineae with scattered broadleaved hardwood trees often consisting of *Ulmus* along with *Quercus*, *Salix*, *Juglans*, *Betula*, *Acer*, *Tilia* and *Fraxinus*, meanwhile the mountains were covered with *Cedrus*, *Pinus*, *Picea*, Cupressaceae, *Juniperus* and *Tsuga* between 8.10 and 6.73 Ma.

Significantly, the percentages of *Cedrus* were higher (2.50%—21.74%) in the pollen assemblages during this period. As ancient plants, *Cedrus* whose pollen often occurred in the sediments of Cretaceous to early Tertiary in the Northern Hemisphere has presented in Miocene, and it also was an important component in vegetation during the Neogene in the Pamir and Tibetan Plateau areas. Today the natural *Cedrus* always accompanied by *Pinus excelsa*, *Abies webbiana*, *Picea marimda* mainly grows on the mountains of southern and eastern Mediterranean Sea, and also distributes over on the southern slopes of the western Himalayas between 1200 and 3000m where the precipitation is abundant and falls throughout the years[31,32]. Accordingly, the high value of *Cedrus* pollen not only indicates the warmer and humid climate, but also reflects that summer and winter monsoon remained at moderate levels, precipitation falls throughout the years and temperature annual range was limited. Thus, the higher percentage of *Cedrus* together with *Tsuga* and *Juglans*, the grassland dominated by Gramineae and scattered deciduous trees maybe suggest semi-moist climate in the warm temperate zone. There is no indication that the winter and summer monsoons regime during 8.10—6.73 were as strong as today.

From 6.73 to 5.67 Ma Gramineae (6.67%—29.27%) and *Ulmus* (6.23%—35.56%) probably were constructed species but *Pinus*, *Picea*, Chenopodiaceae and *Artemisia* were likely absent in the vegetation. During this period the vegetation type possibly was a forest-grass steppe composed of grass steppe communities dominated by Gramineae and broadleaved hardwood forest communities dominated by *Ulmus* with *Quercus*, *Salix*, *Juglans*, *Betula*, *Acer*, *Tilia* and *Fraxinus*, and in mountains the plant communities are coniferous forest consisting of *Pinus*, *Picea*, *Cedrus*, Cupressaceae, *Juniperus* and *Tsuga*.

This vegetation is probably similar to the modern vegetation composed of grassland communities dominated by *Stipa bungeana*, *Bothriochloa ischaemum* and *Artemisia sacrorum* covering the top of hills, and forest communities dominated by *Ulmuns glaucescens*, *U. macrocarpa*, *Prunus armeniaca*, *Pyrus betulaefolia*, *Pinus tabulaeformis* and *Platycladus orientalis* growing in the relatively humid gully in the Loess Plateau between 1000 and 1400m, where the climate is semi-arid in warm temperate zone, the mean annual temperature is 7.5—9.8℃ and the mean annual precipitation is 400—500 mm[33]. Lacking *Artemisia*, present warm-temperate taxa such as *Tsuga*, *Quercus* and *Juglans*, abundance of mesophytic Gramineae and higher percentage of *Cedrus* (reached to 9.6%) in this pollen assemblages probably reflect a warmer and more humid climate than today. Thus, the pollen evidence points out the climate between 6.73 and 5.67 Ma was likely both warmer and moister than present.

During the period from 5.67 Ma to 3.71Ma, *Ulmus* and Gramineae although present in the vegetation, the percentage of *Artemisia* (6.52%—46.60%) that indicates the in situ existence of *Artemisia*, and *Pinus* (7.06%—59.62%) and *Picea* (4.35%—36.96%) that maybe suggest the existence of or near pine and spruce forest implies the vegetation type probably was forest-steppe or woodland-steppe in the region. The ecological landscape probably was that the grass steppe composed of *Artemisia*, Compositae and Gramineae grew in open forest, hillside, hill and lowland, meanwhile the broadleaved hardwood open forest consisting of *Quercus*, *Salix*, *Ulmus* and *Betula* occurred in hillside and gully area; the coniferous forest made up of *Pinus*, *Picea*, Cupressaceae, *Juniperus*, *Cedrus* and *Tsuga* covered the mountains. This landscape indicates that the vertical vegetation zonation was obvious, the climate was cool and humid in mountains area, warm and semi-arid in hilly and lowland. In addition, during the period of 4.61—4.07 Ma, the increase of *Quercus*, *Salix*, *Ulmus*, *Cedrus*, *Tsuga*, *Aster* Type and *Anthemis* Type probably reflects that the climate was quite warmer and moister at that time.

The vegetation shows significant abrupt changes at about 3.71 Ma when Cupressaceae and *Juniperus* drasticcally increased at the expense of herbaceous plant. During the period of 3.71—2.58 Ma, the vegetation probably was predominated by Cupressaceae and *Juniperus* along with *Ulmus* and scattered individual *Quercus*, *Salix* and *Betula*.

This vegetation reflected by pollen assemblages can be correlated with the Arborvitae woodlands that mainly distributed in warm temperate forest-grasslands subzone in eastern Gansu and northern Shanxi. The Arborvitae woodlands with *Ulmus macrocarpa*, *Quercus liaotungensis*, *Celtis bungeana* generally occur on mountain sun-slopes, while *Quercus liaotungensis*, *Populus davidiana*, *Betula platyphylla* and *Pinus tabulaeformis* grow on shade-slopes in these areas of the Loess Plateau, where the elevation is between 1200 and 1700 m, the annual precipitation is 500—550 mm, and the mean annual temperature is 10℃[34]. Today *Platycladus orientalis*, a warm-adapted xerophilous or mesophytic plant, generally appears in humid and subhumid areas in warm temperate zone having a hot-moist summer and a cold-dry winter (strong seasonality in both temperature and precipitation). Present *Platycladus orientalis* in the Loess Plateau is mainly controlled by temperature and occupies the region where the mean annual temperature is 9℃ (not less than 8℃) and the mean annual precipitation is more than 450 mm with annual relative moisture higher than 55%. This ecological distribution indicates that Arborvitae can tolerate dry and warm environment and occupies areas where other arboreal species are restricted[35,36]. Therefore the predominance of Cupressaceae and *Juniperus* with lower *Ulmus* during 3.71—2.58 Ma suggests that the environment markedly changed, and the climate was temperate and semi-humid exhibited as hot and rainy in summer and colder and dry in winter, implying the climatic seasonality obviously enhanced as both winter monsoon and summer monsoon system obviously strengthened simultaneously and the East Asian monsoon prevailed in the region. Besides this, the disappearance of *Cedrus* and *Tsuga* at this time lends further support to the inferred increased seasonality above. However, more lines of evidence will be needed in future to confirm this, as the ecologic amplitude of Cupressaceae is broader.

4 Discussion and conclusions

Four characteristics of vegetation evolution and climatic change are inferred by the pollen record from the Chaona section above.

(1) During the period of 8.10—6.73 Ma the zonal vegetation probably was the woodland-grassland dominated by Gramineae, and the conifers such as *Pinus* and *Cerdus* grew in montane areas. These maybe reflect that climate was warmer and subhumid and the vertical vegetation zonation had existed, the summer and winter monsoons remained at a moderate level, precipitation fell

throughout the year and temperature annual range was limited. In addition, the landscape of woodland steppe corresponded with the lithologic and pedogenic evidence for this time period, where pedogenesis was not prominent, nodule was absent, and evolutional degree of paleosol was the lowest in the whole section (unit 5, Fig. 2).

(2) Between 6.73 and 5.76 Ma broadleaved hardwood forest dominated by *Ulmus* with *Quercus*, *Salix*, *Juglans* and *Betula*, and Grass steppe dominated by Gramineae prevailed, which may indicate that the climate was warm and moister. Furthermore, the environmental inference conforms with lithologic features, for example, the pedogenic degree in funit 4 is stronger than that in unit 5 (Fig. 2).

(3) During 5.67—3.71 Ma, Grass steppe composed of *Artemisia* and Gramineae and conifers made up of *Pinus* and *Picea* developed, revealing that the climate was cool and moister in montane region, but warmer and semi-arid in hilly and lowland, which concurred with the strong uplift of Liupan Mountain at 5.2 Ma[11]. Besides, the climate was once warm and moister from 4.61 to 4.07 Ma. But the environment reflected by the vegetation was not consistent with that suggested by lithology, thus more research work should be done in future.

(4) From 3.71 to 2.58 Ma, the woodland predominated by Cupressaceae and *Juniperus* along with *Ulmus* dominated in the area, while the *Cedrus* existed before disappearing, revealing that the environment had a marked change characterized by a hot and rainy summer and a colder and dry winter. This suggests the winter and summer monsoon had a simultaneous intensification which caused the great intensification of the climatic seasonality. But this interpretation should be confirmed by other proxies in future studies as the ecologic amplitude of Cupressaceae is broader. In this period the lithologic zone (unit 1) shows that paleosols developed well with clear horizonation, eluvial structure and carbonate nodules[9], implying that the climate was warmer in summer but the precipitation exhibited more seasonally than the earlier one, i.e., the climatic seasonality was strengthened.

In the south of the studied areas the pollen assemblage from the Late Miocene to Early-Mid Pliocene in the Weihe basin is characterized by small quantity of *Cerdus* pollen, higher content of *Pinus*, *Ephedra*, *Ulmus* and *Carya*, and some sub-tropical taxa such as *Liquidambar, Ruta, Keteleria, Podocarpus* and *Magnolia*[37]. This feature agrees well with the pollen assemblage observed in the Chaona section above. Also in the east of the studied areas the pollen assemblages of lacustrine sediment (5.1—3.8 Ma) from the Yushe basin were dominated by temperate and sub-tropical broadleaf trees including *Ulmus*, *Betula*, *Quercus*, *Liquidambar* and *Carya* along with some subtropical evergreen trees (*Podocarpus* and *Magnolia*), a relatively high content of *Picea* and a small quantity of *Abies* and *Larix*[38], which suggests the climate is warmer and more humid than our studied region.

The environment changes revealed by pollen assem blage from the Chaona section can be also seen in other regions. In the Linxia basin, the vegetation changed from a steppe between 8.5 and 6.0 Ma, via a forest steppe between 6.0 and 5.0 Ma[39], to a dry steppe from 5.0 to 4.4 Ma associated with an intense aridification. In the Jiuxi basin, the vegetation experienced a steppe in 8.6—6.6 Ma, a woodland steppe between 6.64 and 5.67 Ma, and a desert steppe from 5.67 to 5.42 Ma companied by a strengthening of aridification, then at about 3.6Ma the broadleaved trees disappearing is attributed to the great aridification, and finally during the period of 3.30—2.56 Ma the climate turned to an alternation of a spruce forest under a cool and moist climatic condition and a desert-steppe under an arid climatic condition, implying a strong climatic fluctuation[40].

Our vegetation reconstruction is also supported by other proxies in the Loess Plateau. The data of carbon isotope from soil carbonates at Laogaochuan, Fugu County of Shanxi Province, show that a mixing vegetation composed by C_3 and C_4 plant prevailed in 7.3—5.3 Ma, and the biomass of C_4 plant reached 40%, then up to 70% at 5.3—4.4 Ma[41]; the evolution of the *Hipparion* fauna shows that a prevalence of steppe and woodland steppe from 8 to 7 Ma was replaced by a development of a forest between 7 and 5.2 Ma[42], and finally by a cold climate at about 5.3 Ma which may have caused the extinction of the forest fauna dominated by deer[43]; the studies of the chronology, dust flux, grains size, magnetic susceptibility, rates of deposition and Rb/Sr from some Cenozoic Red Clay sections located in the Loess Plateau indicate that the Asia monsoon climate characterized by winter and summer monsoon winds was remarkably enhanced between 3.6 and 2.6 Ma[1−6], which is also explained as being closely related to the uplift of the Tibetan Plateau[44−46].

The phenomenon also took place at other sites in the world. In the south of Pakistan the vegetation shifted from C_3 to C_4 on the floodplain at 8Ma, and then a pure or nearly pure C_4 biomass dominated floodplains at 5.3—3.0 Ma owing to the intensification of aridification[47]. The dust deposit flux of the Southern and Northern Pacific Ocean, which could reflect the development of aridification in Asia and South America, increased at 8—7.7 Ma, and abruptly increased at 3.6 Ma probably in connection with the rapid uplift of the Qinghai-Tibet Plateau at that time[48].

The ratio of free iron to total iron suggests that the East Asian summer monsoon prevailed most strongly in 4.8—4.0 Ma, and then weakened distinctly[7]. The $\delta^{13}C$ value from calcium nodules in soils also indicates that the C_4 grass plants expanded quickly[8], which was also recorded by pollen sequence from Chaona section (3-2 sub-zone, 4.61—4.70 Ma).

The important environment changes at about 6.73, 5.67, 4.61 and 3.71 Ma as revealed by the pollen records above were in broadly consistent with those given by some other proxies, and recorded the sequence and details of environmental change with more comprehensive and higher resolution, especially in details of ecologic and climatic environments.

Nevertheless, it should be kept in mind that the difficulty in the extraction of pollen grains from red clay led 90% of the studied samples only have extracted 100 to 300 grains of pollens, lower than the international convention of over 300 grains in the Quaternary pollen analysis, thus, some information should be confirmed by further studies.

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