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RESEARCHARTICLE

Quantitative reconstruction of the palaeoclimate of the Shahejie Formation in the Chezhen Depression, Bohai Bay Basin, eastern China

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Abstract This paper uses pollen climate analysis and coexistence analysis to systematically analyze the climatic evolution of the Shahejie Formation in the Chezhen Depression, Bohai Bay Basin, eastern China and discusses the relationship between palaeoclimatic evolution and lake level rise. The results show that the sedimentary period of the Shahejie Formation in the Chezhen Depression had an overall temperature change trend from hot to cold and simultaneously experienced a dry and wet balance–wet–dry and wet balance–wet transition process. The climatic parameters of the Shahejie Formation in the Chezhen Depression include a mean annual temperature of 8.1°C – 15.1°C, a mean coldest monthly temperature of – 0.1°C – 2°C, a mean warmest monthly temperature of 18.6°C – 28°C, a mean annual precipitation of 389 – 1164 mm, a wettest monthly precipitation amount of 215 – 262 mm, and a driest monthly precipitation amount of 8 – 48 mm. Climate change is believed to affect the rise and fall of lake levels to some extent. The quantitative reconstruction of these climatic parameters allows researchers to more intuitively understand the geological background of the Chezhen Depression and guide the exploration and development of oil and gas resources.

Keywords Shahejie Formation, Chezhen Depression, pollen, coexistence analysis, palaeoclimate reconstruction

1 Introduction

Over the years, progress in oil and gas exploration has enabled the exploration of the shallow and middle layers of the Chezhen Depression to enter a stage of medium to high maturity, and the Shahejie Formation, as the main oil-bearing rock layer and reservoir in this region, has gradually become an important site for increasing reserves and production, with great exploration potential (Zhang et al., 2005a; Wang, 2007; Han et al., 2009). Despite the continuous advancements in the understanding of exploration areas and developmental blocks in the Chezhen Depression, existing knowledge no longer meets the needs for the exploration and development of subtle oil and gas reservoirs in this area. Therefore, there is an urgent need to reanalyse the sediments in this area to gain a deeper understanding of the geological background of the region. These efforts represent the further exploration and development of oil and gas.

The palaeoclimate is the main sedimentary driving force for the formation of strata in land-phase basin sequences, as the palaeoclimate controls the high-frequency lake level changes, and influences the degree of weathering of rocks in the stripped area as well as the supply of material resources in the sedimentary area of the lake basin, thus controlling the filling pattern and sedimentary type of the lake basin to a certain extent (Abbott et al., 2000; Zhang et al., 2005b; Liu and Li, 2007; Yan et al., 2009; Wu et al., 2012). The palaeoclimate has always been the focus of palaeo-sedimentary environmental analyses, and the application of many research methods, such as petrology, geochemistry, and microscopic palaeontological methods, has led to the rapid development of palaeoclimate-related research (Alexandrine et al., 2019; Han et al., 2020; Huth et al., 2020; Tan et al., 2020).

Pollen is the sexual reproductive cell of seed plants. Palaeoclimatic variations directly control the growth and development of plant communities, and different vegetation types develop under specific natural conditions,

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producing abundant and easily preserved pollen. As a result, pollen assemblages and their abundances are good indicators of changes in temperature and humidity. Fossil records of pollen in lake sediments are widely used to reconstruct regional vegetation and climate changes (Qin et al., 2015; Wei and Zhao, 2016; Han et al., 2020). In particular, the advent of modern calibration systems has led to increasing interest in quantitative pollen-based palaeoclimate reconstructions and improved our understanding of past climatic environmental changes and their driving mechanisms (Chen et al., 2017). Qin and Zhao (2013) and Zheng et al. (2016) summarized and reviewed the quantitative pollen-based palaeoclimate reconstructions obtained in China in recent years.

Of course, pollen climate analysis has drawbacks, because pollen types vary greatly and the responsive climate band is wide; as a result, this approach is being effective only in limited stratigraphic analyses (Wu et al., 2012). Under this premise, this paper improves an evaluation model used in pollen climate analyses. According to the evaluation criteria used to quantify climatic parameters based on the nearest living relatives of temperature- and humidity-sensitive fossil pollen, we take advantage of the benefits of pollen climate analyses while effectively avoiding their drawbacks, combine them with coexistence analysis to quantitatively reconstruct the palaeoclimatic parameters of the Shahejie Formation in the Chezhen Depression, and discuss the controlling role of palaeoclimate evolution on lake level changes.

The coexistence approach has been widely used for palaeoclimate reconstructions based on Eurasian plant fossil assemblages. Studies based on the coexistence approach have had a marked impact in the literature, generating over 10000 citations thus far (Grimm and Potts, 2016; Grimm et al., 2016). However, due to its violation of certain basic assumptions, the coexistence analysis method is considered by some researchers to be seriously flawed (Grimm and Denk, 2012; Grimm and Potts, 2016; Grimm et al., 2016; Zhang et al., 2015, 2019b). Aside from these disputes, our research is considered reliable due to the following two points: (i) The coexistence analysis method has a good effect on the reconstruction of the Oligocene and younger floras (Grimm and Denk, 2012; Zhang et al., 2015). The Shahejie Formation belongs to the Eocene, its sedimentary age is relatively young, and its reconstruction is thus more reliable. (ii) The pollen climate analysis method and the coexistence analysis method are used in this paper to verify each other, further supporting the reliability of the research conclusions. This study perfected the pollen climate analysis method and combined it with the coexistence analysis method to reconstruct the palaeoclimate of the Shahejie Formation in the Chezhen Depression, thereby addressing the lack of palaeoclimatic research in this area and providing a certain theory for the guidance of further oil and gas exploration.

2 Geological setting

The Bohai Bay Basin is a Mesozoic-Cenozoic superimposed basin in a Paleozoic craton that is distributed in the northcentral part of northern China, the Bohai Sea and the Xialiaohe region and covers an area of 201000 km^2 (Fig. 1(a)) (Lao et al., 2019). The Chezhen Depression is located in Dongying City, Shandong Province, China. It is a secondary depression in the northern part of the Jiyang Subbasin in the Bohai Bay Basin and is a typical E-W-trending S-shaped rift depression basin (Su et al., 2011; Lao et al., 2019). The depression is approximately 81 km in length from east to west and 23 km in width from north to south, covering an area of approximately 2390 km^2. The northern, western, and southern ends of the Chezhen Depression are surrounded by the Chengning Rise and the Yihezhuang Rift, and the eastern part of the depression is adjacent to the Zhanhua Depression (Fig. 1(b)). In the structure, the Chezhen Depression is a typical Tertiary compound torsional fracture depression. The Chezhen Depression is a normal fault-controlled half-graben that is bounded by the Chengnan Fault (Fig. 1(b)) (Lao et al., 2019). The Chengnan Fault is connected with the Chengning Rise with a crystalline Precambrian basement, and the tertiary strata of the Chezhen Depression overlay the Yihezhuang Rift in the south, thus creating a tectonic pattern of northern faulting and southern overlapping (Lao et al., 2019). The Chezhen Depression can be subdivided into three secondary structural zones: northern abrupt slopes, southern gentle slopes and central sags (Su et al., 2011). The internal fault development of the depression and structural unit segmentation are strong, and the depression is divided into three narrow and deeply depressed sags, Chexi, Dawangbei, and Guojuzi, by four secondary faults, the DA90 Fault, the DA1 Fault, the DA14 Fault, and the CJZ Fault (Fig. 1(b)).

As a secondary structural unit of the Jiyang Depression, the Chezhen Depression is also a product of the disintegration of the North China Platform, which has experienced three developmental stages of faulting, fault depression and depression. The Palaeogene units of the Chezhen Depression formed in the synrift stage and developed the Kongdian (E*k*), Shahejie (E*s*) and Dongying (E*d*) Formations (Fig. 2) (Zhang et al., 2005a; Su et al., 2011; Ma et al., 2014). The synrift Kongdian Formation overlies the Mesozoic basement (Zhang et al., 2019a). The Shahejie Formation is composed of the Es_1, Es_2, Es_3, and Es_4 members.

3 Methods

3.1 Materials

Samples were taken from the Che 6 well of the Chezhen

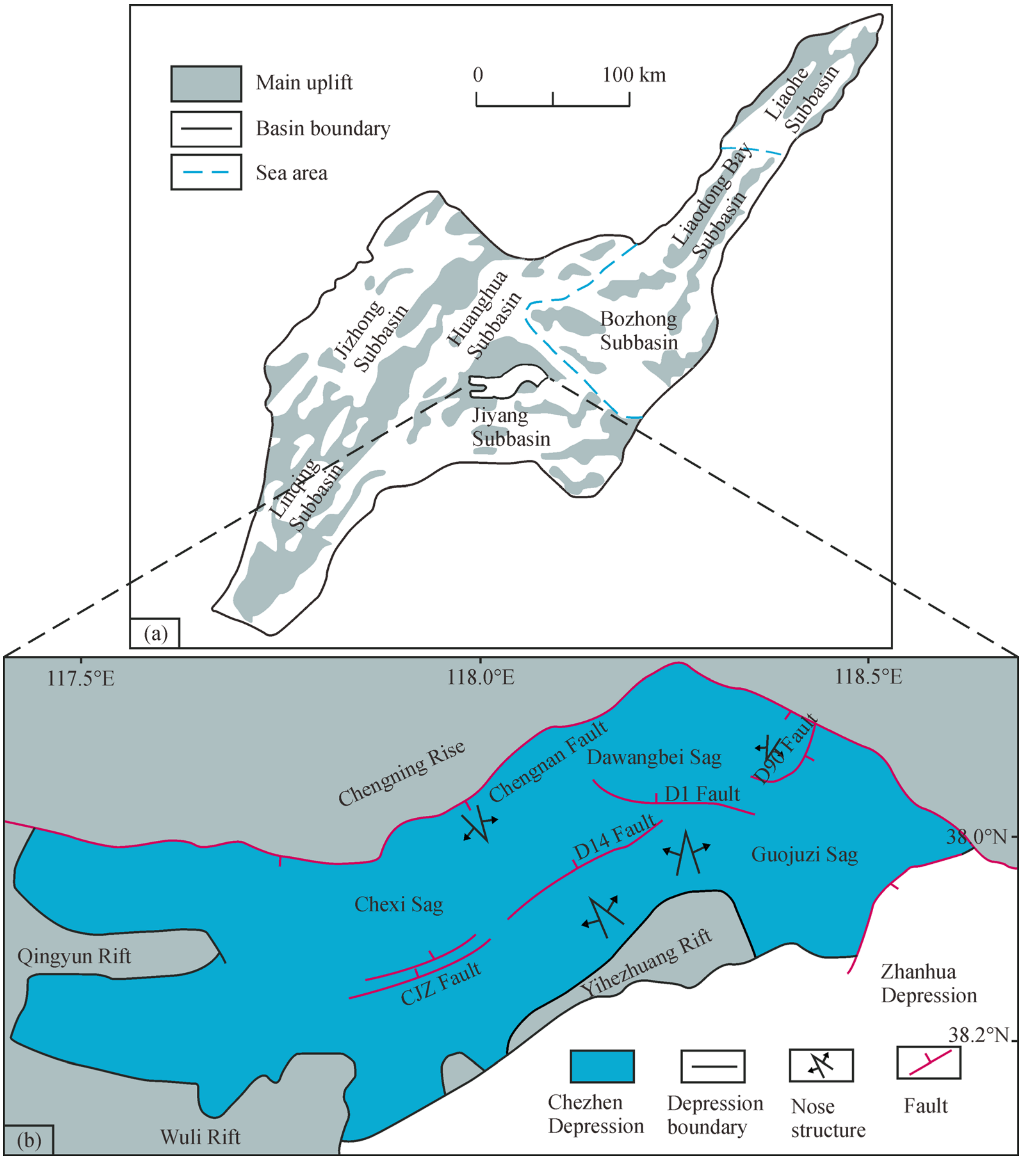

Fig. 1 (a) Location of the Chezhen Depression; (b) structure of the Chezhen Depression.

Depression. Cores of the Shahejie Formation were selected from a depth range of 1485 – 2552 m for pollen testing and identification, the sampling interval ranged from 10 – 60 m, and 40 samples were taken in total.

Pollen identification was carried out in the Stratigraphy Room of the Geology Institute at the Shengli Oilfield Exploration and Development Research Institute. First, approximately 5 g of dried sample was weighed and then broken up and oxidized by adding a mixed liquor of potassium chlorate and nitric acid to remove humic acid. The sample was washed to neutral pH, sodium carbonate was added at a 1% concentration, and the sample was heated to boiling (approximately 1 h). After washing to neutral, the spore powder was enriched using a sieve with a pore size of 10 μm, and glycerine was added to obtain thin sections for identification under an optical microscope. The pollen in the samples was identified using a binocular biomicroscope.

3.2 Research methods

The reproductive pollen of plants is light in weight and large in quantity and can be easily and widely preserved, so the combination of pollen types and their abundances in a certain area can roughly reflect the vegetation type combinations in the corresponding geological period in that area (Lei et al., 2018). At the same time, the growth and development of plant communities are directly controlled by the climatic environment, and different vegetation types develop in specific natural conditions and geographical zones and are sensitive to temperature and humidity conditions. Thus, pollen type composition and

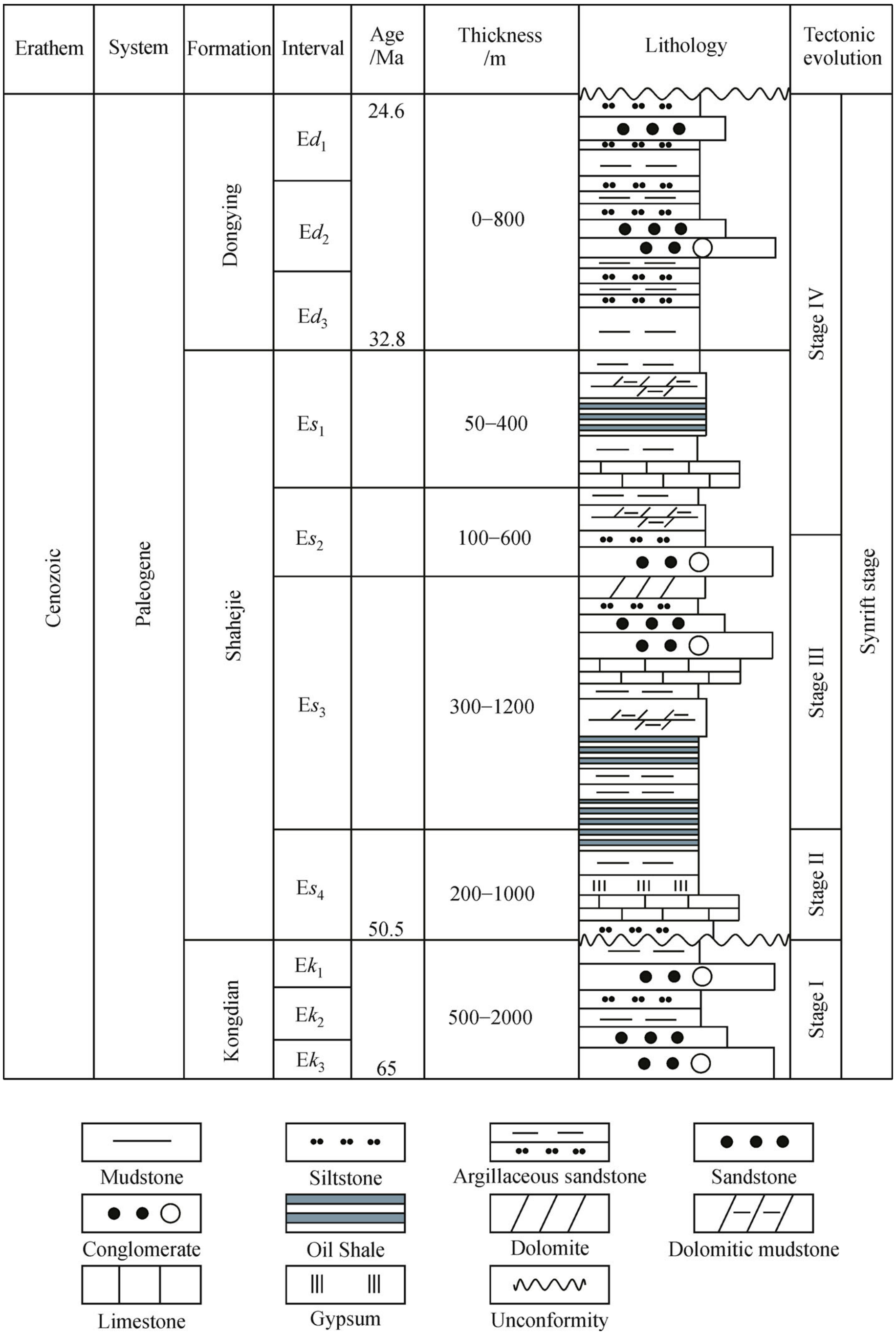

Fig. 2 Stratigraphy and lithological development of the Paleogene in the Chezhen Depression.

abundance are important and effective indicators of the palaeoclimate.

A total of 2922 pollen grains were identified in the 40 samples, including 24 angiosperm taxa and 12 gymnosperm taxa, for a total of 36 taxa of pollen (Fig. 3). After excluding taxa with low frequencies or quantities, a total of 16 plant pollen taxa with a statistical value were selected for detailed research and analysis: 9 angiosperm taxa, including *Liquidambarpollenites*, *Lamiaceae*, *Meliaceae*, *Ulmipollenites*, *Quercoidites*, *Corylus*, *Juglanspollenites*, *Rhoipite*, *Alnipollenites*, and 7 gymnosperm taxa, including *Taxodiaceae*, *Ephedripites*, *Pinuspollenites*, *Abietineaepollenites*, *Piceapollis*, *Podocarpidites*, *Betulaceoipollenites*. The contents of the pollen taxa in the samples selected for this study are shown in Fig. 3.

The principle of the nearest living relatives must be used in the taxonomic method; this principle is based on the assumption that the climatic conditions necessary for the survival of fossil taxa are the same or similar to those of their nearest living relatives. By calibrating the climatic

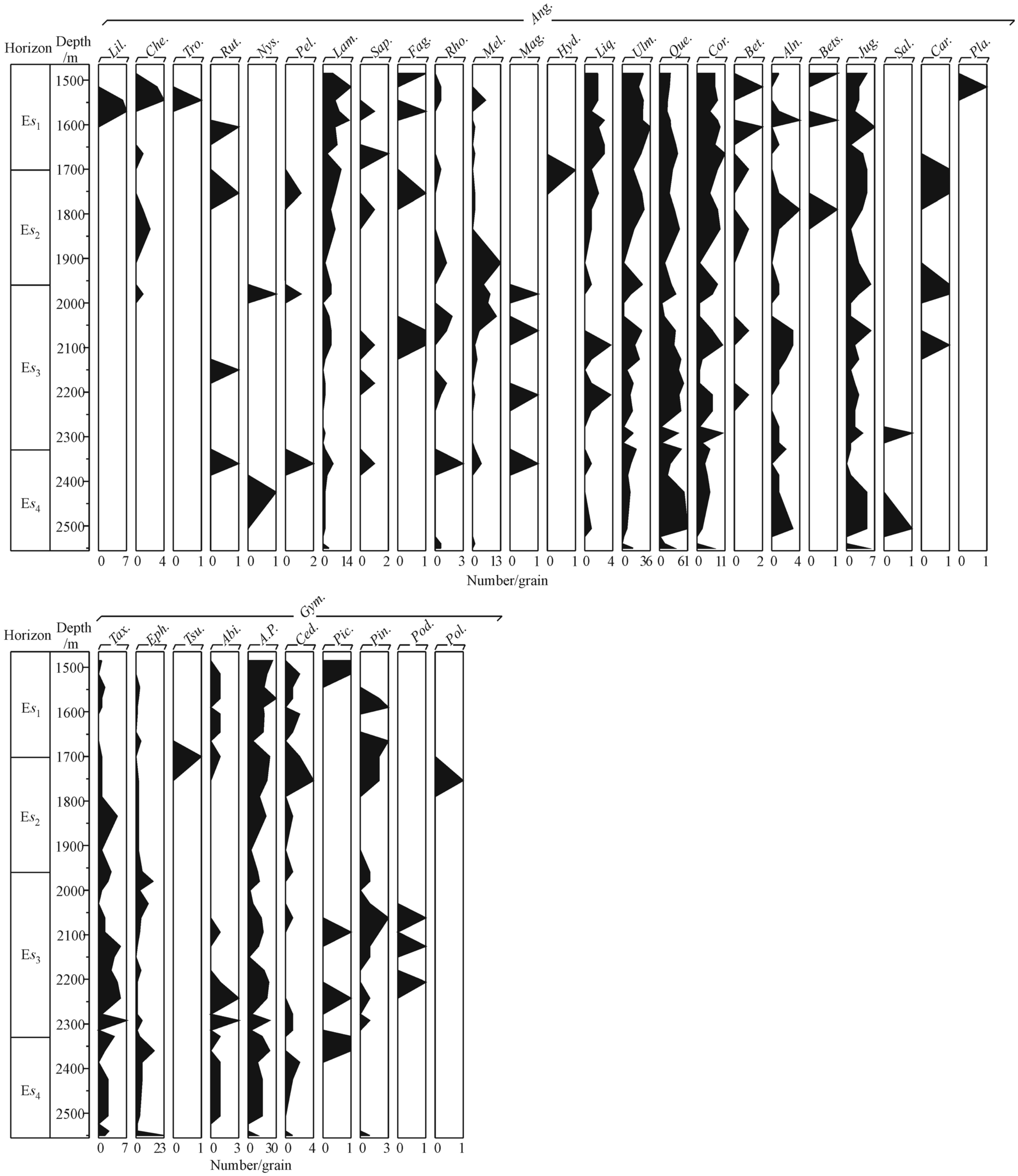

Fig. 3 Pollen panel of the Shahejie Formation in the Chezhen Depression. *Ang. = Angiospermae, Gym. = Gymnospermae, Lil. = Liliacidites, Che. = Chenopodiaceae, Tro. = Trochodendraceae, Rut. = Rutaceae, Nys. = Nyssapollenites, Pel. = Peltandripites, Lam. = Lamiaceae, Sap. = Sapindaceaepiles, Fag. = Faguspollenites, Rho. = Rhoipites, Mel. = Meliaceae, Mag. = Magnolipollis, Hyd. = Hydrocharitaceae, Liq. = Liquidambarpollenites, Ulm. = Ulmipollenites, Que. = Quercoidites, Cor. = Corylus, Bet. = Betulaceae, Aln. = Alnipollenites, Bets. = Betulaepollenites, Jug. = Juglanspollenites, Sal. = Salixipollenites, Car. = Caryapollenites, Pla. = Platycaryapollenites, Tax. = Taxodiaceae, Eph. = Ephedripites, Tsu. = Tsugaepollenites, Abi. = Abies, A.P. = Abietineaepollenites* and *Pinuspollenites, Ced. = Cedripites, Pic. = Picea, Pin. = Pinaceae, Pod. = Podocarpidites, Pol. = Polypodiaceae.*

parameters of regions where the nearest living relatives of fossil pollen live, the range of climatic parameters in which the fossil species were most likely to survive and develop can be obtained (Mosbrugger and Utescher, 1997; Mosbrugger, 1999).

The nearest extant living relatives of the selected fossil pollen taxa were retrieved from the Palaeoflora database, and the climatic parameters of their growth and development were obtained in combination with the Atlas of Woody Plants in China: Distribution and Climate (Fang et al., 2011; Lei et al., 2018). The climatic parameters (see Table 1), including the mean annual temperature (MAT, reflecting the optimum temperature range for the development of vegetation), the mean coldest monthly temperature (CMT, reflecting the lowest temperature limit for the development of vegetation), the mean warmest monthly temperature (WMT, reflecting the highest temperature limit for the development of vegetation), the mean annual precipitation (MAP, reflecting the optimum precipitation range for the development of vegetation), the wettest monthly precipitation (WMP, reflecting the optimum wettest monthly precipitation for the development of vegetation), and the driest monthly precipitation (DMP, reflecting the optimum driest monthly precipitation for the development of vegetation), are based on the climatic parameters that are suitable for the development of the nearest living relatives of the selected fossil pollen taxa.

3.2.1 Pollen climate analysis

According to the selected nearest palynological living relatives of the fossil pollen and their growth and development parameters, five indicators, the MAT, CMT, MAP, WMP, and DMP, were used to determine the palaeoclimate, indicating the significance of palynology. The MAT reflects the optimum growth and development interval for each vegetation type, and the CMT defines the limiting temperature for vegetation development. The combination of these two parameters can reflect the responses of different vegetation types to temperature. The MAP reflects the optimal range of annual precipitation for the development of each vegetation type. The WMP and DMP define the precipitation in the wettest and driest months, which affects the development of vegetation. The MAP, in combination with the WMP and the DMP, can reflect the responses of vegetation types to moisture.

According to the quantitative classification basis described above, the selected fossil pollen taxa were grouped into five categories. According to the temperature indexes of different fossil pollen types, they were divided into three categories: the hot climate group, the warm climate group, and the cold climate group. According to the humidity indexes of different fossil pollen types, they were divided into two categories: the xerophytic group and the wet group. The specific division of the above groups was based on the contents of Table 2. The 5 parameters described in the study, the MAT, the CMT, the MAP, the WMP, and the DMP, have certain intervals, and the median values of these intervals were taken for the calculations to standardize the quantitative treatment.

To make the study of climate evolution more accurate and intuitive, the temperature indicator (T) and the humidity indicator (H) were quantified according to Eqs. (1) and (2):

Table 1 Climatic parameters of the nearest living relatives of the studied pollen

Fossil Spore-pollen	nearest living relative	MAT/°C	CMT/°C	WMT/°C	MAP/mm	WMP/mm	DMP/mm
Liquidambarpollenites	*Liquidambar*	11.5–24.6	− 1–23.8	23–29.3	619–1823	109–340	2–72
Lamiaceae	*Elsholtzia*	2.2–15.1	− 16.1–2.0	18.6–28.0	332–1164	215–488	8–53
Meliaceae	*Melia*	2.9–24.8	− 8.6–20.1	10.6–30.1	465–2993	251–1428	10–547
Ulmipollenites	*Ulmus*	− 5.8–21.6	− 29.8–13.2	8.3–29.4	21–1770	15–959	0–228
Quercoidites	*Quercus*	0–27	− 22.7–25.9	13.7–28.3	201–3905	33–610	5–180
Corylus	*Corylus*	− 4.9–24	− 32.4–16.7	12.9–29.4	389–1682	45–343	3–73
Juglanspollenites	*Juglandaceae*	0–27.5	− 22.7–25	13.7–31.2	210–2617	44–582	1–114
Rhoipites	*Anacardiaceae*	3.4–27.7	− 12.9–27	18.7–28.1	130–3151	17–389	0–165
Alnipollenites	*Alnus*	− 13.3–27.4	− 40.9–25.6	12–38.6	41–2559	8–353	0–135
Taxodiaceae	*Cunninghamia*	2.0–24.7	− 7.2–19.8	9.9–30.1	626–2435	299–1428	15–259
Ephedripites	*Ephedraceae*	8.1–27.6	− 0.1–25	12.5–33.7	30–1741	5–262	1–48
Abietineaepollenites	*Pinus*	− 9.2–25.5	− 36.8–21.4	7.1–32.9	180–1741	28–293	0–94
Pinuspollenites	*Pinus*	− 9.2–25.5	− 36.8–21.4	7.1–32.9	180–1741	28–293	0–94
Piceapollis	*Picea*	− 8.9–21.7	− 28.6–15.6	13.8–31.6	235–1958	36–323	8–83
Podocarpidites	*Podocarpus*	11–27.7	1.7–27	15.1–28.8	652–3151	68–448	16–165
Betulaceoipollenites	*Betula*	− 12.4–25.8	− 26.8–21.1	3.9–28.7	110–2559	23–353	3–135

Table 2 Quantitative classification of the climate indicator significance of pollen. The subscript med represents the median of the interval

Climate Indicator Type	Division Basis	Description	Fossil Pollen
Hot Climate Group	$MAT_{med} > 15°C$, $CMT_{med} > 5°C$	Pollen parent plants are mainly distributed in tropical and subtropical regions, and a few can reach warm temperate zones.	*Liquidambarpollenites*, *Ephedripites*, *Podocarpidites*, *Rhoipites*
Warm Climate Group	$10°C < MAT_{med} < 15°C$, $0°C < CMT_{med} < 5°C$	Pollen parent plants are mainly distributed in warm temperatures, and a few can reach cold temperate or subtropical zones.	*Quercoidites*, *Ulmipollenites*, *Juglanspollenites*
Cold Climate Group	$MAT_{med} < 10°C$, $CMT_{med} < 0°C$	Pollen parent plants are widely distributed in the cold temperate zone, warm temperate zone, subtropical and even tropical zone. Compared with the heat-loving group and the temperature-loving group, its cold tolerance is generally stronger and can be adapted to harsh environments.	*Corylus*, *Alnipollenites*, *Piceapollis*, *Pinuspollenites*, *Abietineaepollenites*, *Betulaceoipollenites*
Xerophytic Group	$MAP_{med} < 1200$ mm, $DMP_{med} < 100$ mm	Pollen parent plants are adapted to arid and water-deficient terrestrial environments, such as deserts or dry grasslands with sparse rainfall, with strong drought tolerance, well-developed root systems, and small and thick leaves.	*Piceapollis*, *Alnipollenites*, *Pinuspollenites*, *Abietineaepollenites*, *Ephedripites*
Wet Group	$MAP_{med} > 1200$ mm, $WMP_{med} > 200$ mm	Pollen parent plants are wet, marsh, or aquatic plants.	*Liquidambarpollenites*, *Quercoidites*, *Juglanspollenites*, *Rhoipites*, *Podocarpidites*

$$T = \frac{\text{Cold Climate Group}}{\text{Hot Climate Group} + \text{Warm Climate Group} + \text{Cold Climate Group}}, \tag{1}$$

$$H = \frac{\text{Wet Group}}{\text{Xerophytic Group} + \text{Wet Group}}. \tag{2}$$

According to the above quantitative classification method, a pollen climate analysis chart (Fig. 4) was drawn. In the figure, Fig. 4(a) and Fig. 4(b) represent the temperature group percentages and the humidity group percentages, respectively, and T and H correspond to the evolution of the temperature and humidity, respectively.

3.2.2 Coexistence analysis

Mosbrugger and Utescher (1997) proposed a taxonomic-based coexistence analysis method that is based on the nearest-living-relative taxonomic method; in this method, the climate parameters of each vegetation type are calibrated according to the nearest-living-relative taxon method and are superimposed to produce a coexistence interval. The results represent the palaeoclimatic conditions on which the fossil flora depended. Coexistence analysis refers to the palaeoclimate reconstruction of plant and animal macrofossils and spore fossils and characterizes a widely used and effective method for the quantitative reconstruction of terrestrial paleoclimates (Utescher et al., 2014; van Dam and Utescher, 2016). Utescher and Mosbrugger (2014) established a palaeoflora database that contains climate data for all known nearest living relatives of fossil flora assemblages; this database has greatly advanced coexistence analysis.

In this study, coexistence analysis was taken as the basic principle and applied to the fossil pollen of the Shahejie Formation in the Chezhen Depression to quantitatively recover the palaeoclimatic parameters of the corresponding geological period. We divided the research area into zones based on pollen identification. Each zone has unique pollen assemblage characteristics, and the climatic parameters of the fossil pollen in each zone are superimposed on each other to produce a coexistence interval. This coexistence interval represents the palaeoclimatic parameters of the stratum defined by the pollen zone in the historical geological period.

A fossil flora assemblage is assumed to have three taxa, A, B, and C, with a, b, and c being their nearest extant related genera, respectively. The average annual temperature of the environment suitable for the growth of “a” is $4°C - 12°C$, the average annual temperature of the environment suitable for the growth of “b” is $8°C - 6°C$, and the average annual temperature of the environment suitable for the growth of “c” is $6°C - 20°C$. Thus, these three kinds of extant plant species, a, b, and c, can coexist in an environment with an annual mean temperature of $8°C - 12°C$. According to this coexistence interval, we can assume that the three kinds of plant species represented by the fossil pollen, A, B, and C, coexisted in such an annual mean temperature range; then, this annual mean temperature interval reflects three kinds of plant species, A, B, and C, living in the geological history of the annual mean temperature climatic parameters. The other climate parameters were estimated quantitatively in the same way.

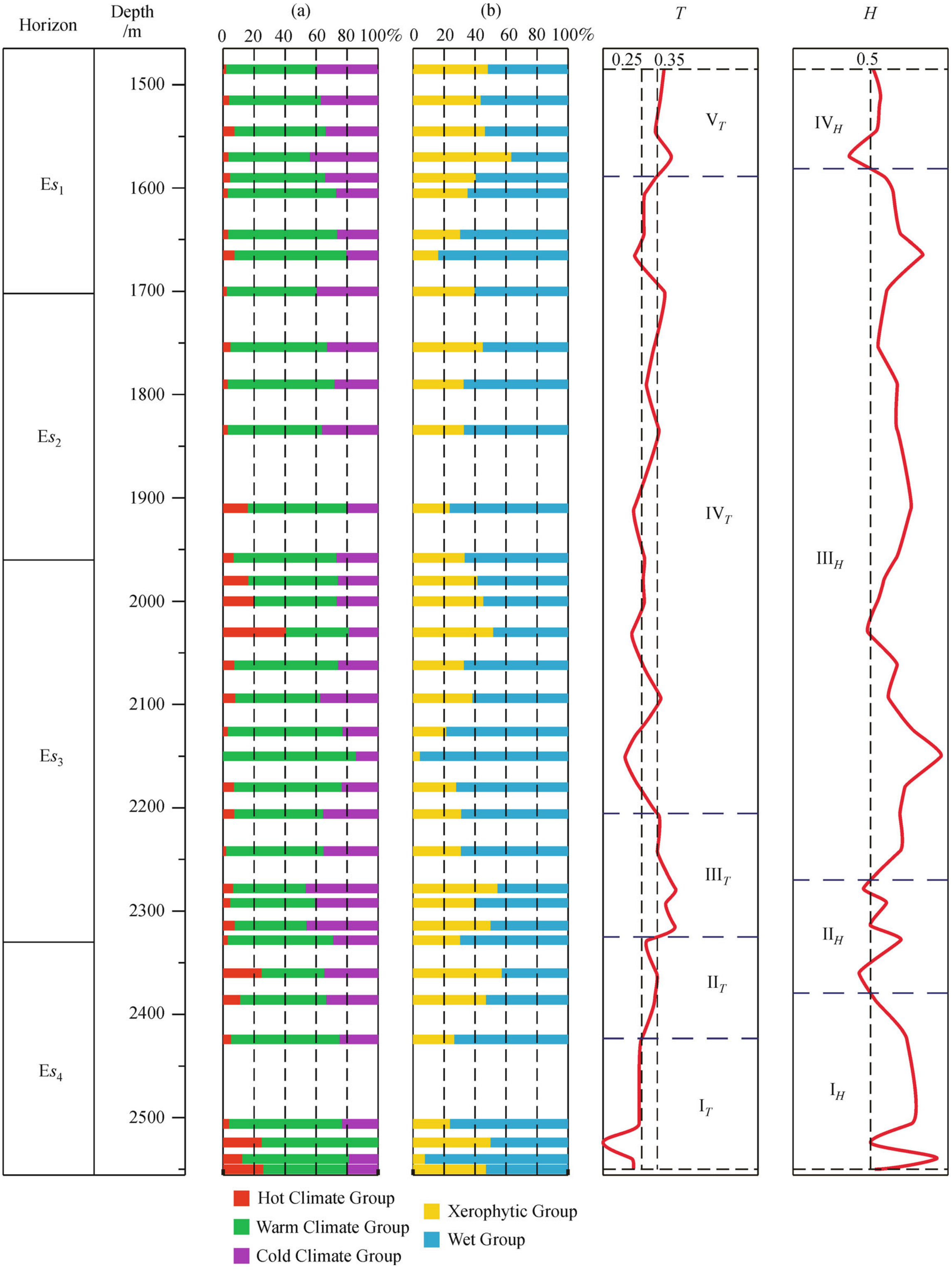

Fig. 4 (a) Percentage of each group of temperature indicators; (b) percentage of each group of humidity indicators; *T*: evolution of the temperature of the Shahejie Formation in the Chezhen Depression; *H*: evolution of the humidity of the Shahejie Formation in the Chezhen Depression.

Among all the pollen types, we selected 12 pollen taxa, namely, *Liquidambarpollenites*, *Lamiaceae*, *Meliaceae*, *Ulmipollenites*, *Quercoidites*, *Corylus*, *Juglanspollenites*, *Alnipollenites*, *Taxodiaceae*, *Ephedripites*, *Abietineaepollenites* and *Pinuspollenites*, that were abundant and varied significantly. According to the characteristics of the pollen assemblages and the variations in the taxa, we divided the Shahejie Formation into 10 pollen assemblage zones from top to bottom (Fig. 5).

R1 Zone: *Liquidambarpollenites*-*Lamiaceae*-*Ulmipollenites*-*Quercoidites*-*Corylus*-*Juglanspollenites*-*Abietineaepollenites*-*Pinuspollenites* combination.

R2 Zone: *Lamiaceae*-*Ulmipollenites*-*Quercoidites*-*Corylus*-*Juglanspollenites*-*Alnipollenites*-*Abietineaepollenites*-*Pinuspollenites* combination.

R3 Zone: *Lamiaceae*-*Meliaceae*-*Ulmipollenites*-*Quercoidites*-*Taxodiaceae*-*Corylus* combination.

R4 Zone: *Meliaceae*-*Ulmipollenites*-*Quercoidites*-*Corylus*-*Juglanspollenites* combination.

R5 Zone: *Meliaceae*-*Ulmipollenites*-*Quercoidites*-*Corylus*-*Juglanspollenites*-*Ephedripites* combination.

R6 Zone: *Liquidambarpollenites*-*Lamiaceae*-*Meliaceae*-*Ulmipollenites*-*Quercoidites*-*Corylus*-*Juglanspollenites*-*Alnipollenites*-*Abietineaepollenites*-*Pinuspollenites* combination.

R7 Zone: *Ulmipollenites*-*Quercoidites*-*Alnipollenites*-*Taxodiaceae* combination.

R8 Zone: *Ulmipollenites*-*Quercoidites*-*Corylus*-*Taxodiaceae*-*Abietineaepollenites*-*Pinuspollenites* combination.

R9 Zone: *Lamiaceae*-*Meliaceae*-*Ulmipollenites*-*Quercoidites*-*Corylus*-*Ephedripites*-*Abietineaepollenites*-*Pinuspollenites* combination.

R10 Zone: *Ulmipollenites*-*Quercoidites*-*Corylus*-*Juglanspollenites*-*Alnipollenites*-*Abietineaepollenites*-*Pinuspollenites* combination.

We reconstructed seven palaeoclimate parameters, including the MAT, CMT, WMT, MAP, WMP, and DMP, using the fossil pollen of the Shahejie Formation in the Chezhen Depression as the material. By applying a coexistence analysis, we quantitatively reconstructed the palaeoclimate parameters of each pollen zone. Taking the R1 zone as an example (Fig. 6), the R1-zone MAT is 11.5°C – 15.1°C, the CMT is – 1°C – 2°C, the WMT is 23°C – 28°C, the MAP is 619 – 1164 mm, the WMP is 215 – 293 mm, and the DMP is 8 – 53 mm. In the same way, the palaeoclimate parameters of R2–R10 were obtained in turn, and the palaeoclimatic characteristics of the strata defined by the 10 pollen zones in their geological history were determined (Table 3).

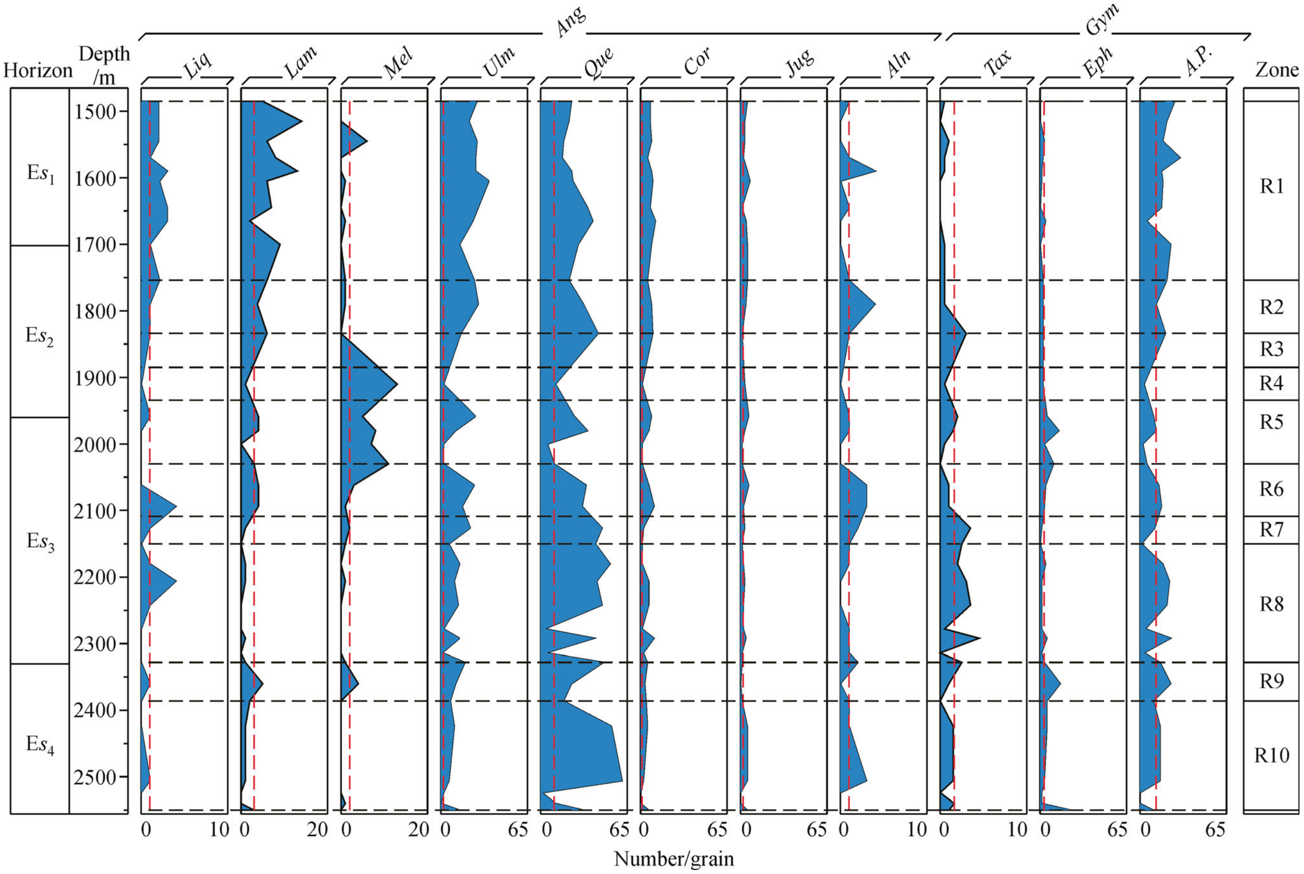

Fig. 5 Ten zones based on 12 pollen taxa in the Shahejie Formation in the Chezhen Depression. *Ang*. = *Angiospermae*, *Gym*. = *Gymnospermae*, *Liq*. = *Liquidambarpollenites*, *Lam*. = *Lamiaceae*, *Mel*. = *Meliaceae*, *Ulm*. = *Ulmipollenites*, *Que*. = *Quercoidites*, *Cor*. = *Corylus*, *Jug*. = *Juglanspollenites*, *Aln*. = *Alnipollenites*, *Tax*. = *Taxodiaceae*, *Eph*. = *Ephedripites*, A.P. = *Abietineaepollenites* and *Pinuspollenites*.

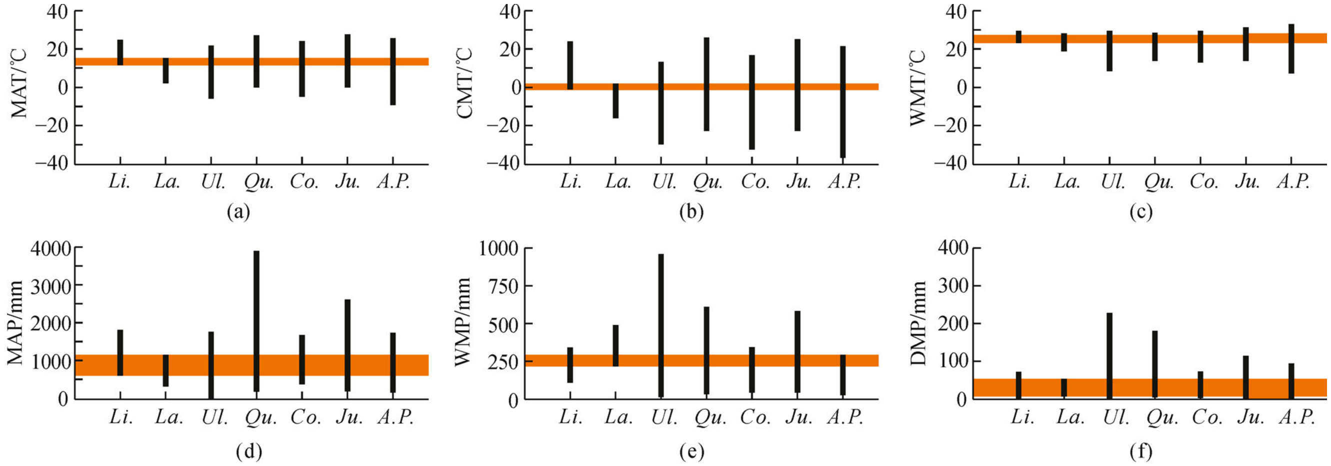

Fig. 6 The principle of climatic parameter restoration in the R1 zone. The orange area is the coexistence interval of the reference pollen climate parameters. (a) Coexistence interval determination of the MAT; (b) coexistence interval determination of the CMT; (c) coexistence interval determination of the WMT; (d) coexistence interval determination of the MAP; (e) coexistence interval determination of the WMP; (f) coexistence interval determination of the DMP. *Li.* = *Liquidambarpollenites*, *La.* = *Lamiaceae*, *Ul.* = *Ulmipollenites*, *Qu.* = *Quercoidites*, *Co.* = *Corylus*, *Ju.* = *Juglanspollenites*, *A.P.* = *Abietineaepollenites and Pinuspollenites*.

Table 3 Climatic parameters for each pollen zone and the entire Shahejie Formation

Zone	MAT/°C	CMT/°C	WMT/°C	MAP/mm	WMP/mm	LMP/mm
R1	11.5–15.1	−1–2	23–28	619–1164	215–293	8–53
R2	2.2–15.1	−16.1–2	18.6–28	389–1164	215–293	8–53
R3	2.9–15.1	−7.2–2	18.6–28	626–1164	251–343	10–53
R4	2.9–21.6	−8.6–13.2	13.7–28.3	465–1682	251–343	10–73
R5	8.1–21.6	−0.1–13.2	13.7–28.3	465–1682	251–262	10–48
R6	11.5–15.1	−1–2	23–28	619–1164	251–293	10–53
R7	2–21.6	−7.2–13.2	13.7–28.3	626–1770	299–353	15–135
R8	2–21.6	−7.2–13.2	13.7–28.3	626–1682	299–343	15–73
R9	2.9–15.1	−0.1–2	18.6–28	465–1164	251–262	10–48
R10	0–21.6	−22.7–13.2	13.7–28.3	389–1682	45–293	5–73
Entirety	8.1–15.1	−0.1–2	18.6–28	389–1164	215–262	8–48

4 Results

From the pollen climate analysis, the data show that in the sedimentary period of the Shahejie Formation, the preference for the warm climate group is dominant, the cold climate group generally has a higher preference than the hot climate group, and these two groups entered into a hostile situation in which the preference for the hot climate group was divided into a lower-higher-lower trend. These results reflect the overall trend of temperature change from hot to cold during the sedimentary period of the Shahejie Formation. The changes in the xerophytic group and the wet group reflect that the evolution of the humidity underwent a transition process of dry and wet balance–wet–dry and wet balance–wet during the sedimentary period of the Shahejie Formation, which is consistent with the lake deposition phases of the Chezhen Depression. At the same time, the evolution of the temperature and humidity was not completely synchronized.

In the coexistence analysis, the climate parameter trends of the 10 pollen zones from R10 to R1 basically agreed with the conclusions of the pollen climate parameter analysis. We selected taxa with a total number of more than 100 pollen cells as the dominant taxa to restore the palaeoclimate index of the entire deposition period of the Shahejie Formation. The optimal ranges of the climatic parameters for the dominant taxa were 8.1°C – 15.1°C for the MAT, −0.1°C – 2°C for the CMT, 18.6°C – 28°C for the WMT, 389 – 1164 mm for the MAP, 215 – 262 mm for the WMP, and 8 – 48 mm for the DMP. These quantitative results indicate that the sedimentary period of the Shahejie Formation was a subtropical climate.

5 Discussion

5.1 Stages of climate evolution

In this quantitative study, based on the trend of T (Fig. 4), the strata of the Shahejie Formation were divided into five evolutionary stages: the sustained intense heat period of 2424 – 2552 m (I_T; T values less than 0.25; average of 0.17), the alternating hot and warm period of 2328 – 2424 m (II_T; T values concentrated between 0.25 and 0.35; average of 0.32), the sustained warm period of 2206 – 2328 m (III_T; T values greater than 0.35; average of 0.41), the alternating hot and warm period of 1605 – 2206 m (IV_T; T values frequently and substantially fluctuated, mostly between 0.25 and 0.35; average of 0.27) and the sustained warm period of 1485 – 1605 m (V_T; T values mostly greater than 0.35; average of 0.38).

According to the trend of H (Fig. 4), the strata of the Shahejie Formation were divided into four evolutionary stages: the sustained wet period of 2424 – 2552 m (I_H; H values greater than 0.5; average of 0.69), the alternating wet and dry period of 2278 – 2424 m (II_H; H values frequently and substantially fluctuated near 0.5; average of 0.53), the sustained wet period of 1605 – 2278 m (III_H; H values mostly greater than 0.5; average of 0.68) and the alternating wet and dry period of 1485 – 1605 m (IV_H; H values fluctuated near 0.5; average of 0.52).

The II_H, III_H, and IV_H stages of the humidity evolution correspond to the II_T, III_T, and IV_T stages of the temperature evolution, and the III_H and IV_H stages lagged behind the III_T and IV_T evolutionary stages, respectively. In the Chezhen Depression, the two major factors of climate evolution, temperature and humidity, are not synchronous, which is slightly inconsistent with the good match between temperature and humidity obtained on a global scale (Lei et al., 2018), and the evolution of humidity lags behind that of temperature.

5.2 Palaeoclimate changes and lake-level changes

Changes in lake levels are closely related to the tectonic subsidence of basins and climate change (Wu et al., 2012). Tectonic uplift and tectonic subsidence are the controlling factors that cause large-scale lake level changes, and changes in the elevation of the Earth's crust caused by tectonic activity directly affect the elevation of the bottom of a lake basin, forcing the lake to expand or shrink and the water storage space of the lake to change. Large-scale lake level changes are clearly controlled by tectonic action. However, such changes do not occur instantaneously but rather in a fluctuating manner. These lake level fluctuations have little to do with tectonic activity but are instead closely related to climate change.

Comparing the climate evolution curves of the Shahejie Formation in the Chezhen Depression and the relative lake level change curves studied by previous authors (Wang et al., 2005; Sun et al., 2007), a clear link between the rise and fall in lake levels and the evolution of the climate can be identified. A dry climate and higher temperatures will lead to lower lake levels, while a humid climate and lower temperatures will contribute to higher lake levels. This analysis suggests that the climate affects lake level changes in two main ways: first, a dry climate leads to a decrease in regional precipitation, affecting the water supply and decreasing the overall water intake; second, a hot and dry climate is likely to increase the evaporation of lake basin waters. Based on these two points, when the water intake of a lake basin is less than the evaporation amount, the lake volume and the lake level will decrease under stable tectonic conditions, with only slight changes in the water storage space. In contrast, under humid and cold climatic conditions, when the water intake of a lake is much larger than the evaporation amount, the lake volume and the lake level will increase.

The combination of tectonic activity and climate change leads to the periodic rise and fall of lake levels, with tectonic activity controlling large-scale changes in lake levels, while climatic conditions mainly control high-frequency lake level changes during periods of tectonic stability. Additionally, because lake level changes are the direct cause of the formation of stratigraphic sequences, the climate can indirectly control the development of high-frequency stratigraphic sequences by controlling high-frequency lake level changes.

6 Conclusions

1) This study classifies fossil pollen quantitatively according to climatic parameters, including the MAT, CMT, MAP, WMP, and DMP, and clarifies the significance of the climate indicators of pollen: according to the MAT and the CMT, the fossil pollen was classified into the hot climate group, the warm climate group, and the cold climate group according to their different temperature indicators; according to the MAP, the WMP, and the DMP, the fossil pollen was classified into the xerophytic group and the wet group according to their different humidity indicators.

2) The climate evolution of the Shahejie Formation in the Chezhen Depression was systematically analyzed based on the trends of the temperature indicator T and the humidity indicator H. The temperature evolution of the Shahejie Formation can be divided into five evolutionary stages: the sustained intense heat period of 2424 – 2552 m, the alternating hot and warm period of 2328 – 2424 m, the sustained warm period of 2206 – 2328 m, the alternating hot and warm period of 1605 – 2206 m and the sustained warm period of 1485 – 1605 m. The humidity evolution can be divided into four evolutionary stages: the sustained wet period of 2424 – 2552 m, the alternating wet and dry period of 2278 – 2424 m, the sustained wet period of

1605 – 2278 m and the alternating wet and dry period of 1485 – 1605 m. A lag effect is seen for the evolution of humidity relative to that of temperature.

3) Through a coexistence analysis, the climatic parameters of the 10 pollen zones were obtained and correlated with the evolution of the temperature and humidity, and the climatic parameters of the Shahejie Formation in the Chezhen Depression were as follows: MAT of 8.1°C – 15.1°C, CMT of – 0.1°C – 2°C, WMT of 18.6°C – 28°C, MAP of 389 – 1164 mm, WMP of 215 – 262 mm, and DMP of 8 – 48 mm.

4) Both tectonic activity and climatic conditions can trigger changes in lake levels, and during tectonically stable periods, climatic conditions play an absolute controlling role over high-frequency lake level changes.

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