Middle Eocene Paleoenvironmental Reconstruction in the Gonjo Basin, Eastern Tibetan Plateau: Evidence From Palynological and Evaporite Records

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The early uplift of the Tibetan Plateau (TP) had a profound influence on the paleoenvironment and paleoclimate. However, we still have little information about the link between the paleoclimatic changes and flora ecosystem caused by the uplift. The Eocene fluvial-lacustrine sequences in the Gonjo Basin, eastern TP, provide excellent archives of the paleoecological and paleoclimatic responses to the surface uplift of the TP. In this study, we investigated a section of the middle Eocene Ranmugou Formation (47.8–44 Ma) and used the sporomorphs assemblages, sedimentology, and geochemistry of the evaporites to reconstruct the paleoclimate and paleovegetation. The palynological assemblages and coexistence analysis reveal that the middle Eocene ecosystem in the Gonjo Basin was dominated by warm and humid temperate deciduous broad-leaved forests. The $^{87}$Sr/$^{86}$Sr ratios (0.709942–0.710062) of all of the gypsum samples are higher than those of contemporaneous seawater, while the $\delta^{34}$S values (10.3–11.0%) are much lower, indicating a lacustrine environment. Combined with published palynological and paleoelevation data for eastern Tibetan lacustrine basins, we infer that the paleoenvironment changed from warm and humid deciduous broad-leaved forests during 47.8–44 Ma, to cool and arid temperate forest during 44–40 Ma in the Gonjo Basin, and to arid and cool steppe-desert vegetation in the late Eocene Nangqian Basin. The changes in the paleoclimate and vegetation were primarily driven by the surface uplift of the Central Watershed Mountain, the high topography of which blocked the moisture from the Asian Eocene monsoon.

Keywords: palynology, vegetation, paleoclimate, paleoenvironment, Gonjo Basin, Tibetan plateau

INTRODUCTION

The Eocene was a key period for Asian paleoenvironmental changes (Hoorn et al., 2012) and was characterized by a warmer climate than any other interval in the Cenozoic (Zachos et al., 2001). The highest temperatures were recorded during the Paleocene-Eocene transition (Paleocene-Eocene Thermal Maximum, PETM) (Zachos et al., 2008; Cramwinckel et al., 2018). During the Eocene-
Oligocene transition, the expansion of the polar ice sheets marked a sharp global cooling event in the long-term gradual cooling period after PETM and the climate transformed from a greenhouse to an icehouse (Bohaty and Zachos, 2003; Eldrett et al., 2009). The Middle Eocene Climatic Optimum (MECO) was a very short interval (between ~40.5 Ma and ~40 Ma) of warming during this long-term descent witnessing the Asian tectonic development and monsoon intensification (Fang et al., 2021). The proto-Tibetan Plateau (TP) (Lhasa and Qiangtang terranes) reached an elevation of ~4,000 m (Wang et al., 2008). The Central Watershed Mountain attained a near-present altitude (Xiong et al., 2020). In the middle Eocene, the high topography, retreat of the proto-Paratethys Sea, and global cooling intensified the Asian monsoon (Fang et al., 2021). Nevertheless, how the terrestrial ecosystem and climate changed in response to these Eocene events is still not well constrained. The main obstacle to revealing these responses is the absence of an altitude history with a well-constrained chronology. Moreover, previous studies based on palynological and isotopic proxies are regionally limited and were conducted in separate continental basins (e.g., the Xining Basin and the Nangqian Basin, Hoorn et al., 2012; Yuan et al., 2020). Therefore, paleoenvironmental reconstruction, including climate and vegetation, under well-constrained paleoaltimetry in basins on the regional scale is crucial to understanding how the ecosystem responded to the uplift of the TP and global cooling.

The Gonjo Basin, located on the eastern part of the Central Watershed Mountain, hosts a thick, successive Paleocene-Eocene sedimentary record (Studnicki-Gizbert et al., 2008). The accurate age constraints based on magnetostratigraphy and radioactive isotopes (Li et al., 2020; Xiao et al., 2021) of uplift history (Xiong et al., 2020) make the ~2,000 m sedimentary sequences in the Gonjo Basin perfect for conducting Eocene paleoclimatic and paleovegetation reconstruction, although the age of the Ranmugou Formation is still controversial. Palynological studies are a useful tool for constraining the age and reconstructing the vegetation, paleoclimate, and paleoecological evolution of a region (Hoorn et al., 2012; Miao et al., 2016; Tang et al., 2020). The use of sedimentology and isotopic geochemistry to study paleoenvironmental changes is also well-established. In this study, we used palynological, sedimentary, and geochemical records of the middle Eocene Ranmugou Formation to discuss the age of the Ranmugou Formation and reconstruct the paleoenvironmental changes in the Gonjo Basin. Then, we compared the climate and vegetation with other continental basins in the northeastern TP and determined the driving forces of the paleoenvironmental changes.

**GEOLOGIC SETTING**

The TP is composed of the Qiangtang, Lhasa, and Tethyan Himalaya terranes and several sutures between these continental terranes, including the Jinsinjiajiang suture, Longmuco-Shuanghu suture, Bangong-Nujiang suture, and Yarlung-Zangbo suture (Yin and Harrison, 2000; Metcalfe, 2013) (Figure 1). The Qiangtang terrane is further subdivided into the southern and northern Qiangtang terranes (SQT and NQT) by the Longmuco-Shuanghu suture, which is believed to be related to the closure of the Paleo-Tethyan Ocean in the Late Triassic (Zhai et al., 2011; Metcalfe, 2013). A series of Cenozoic strike-slip pull-apart basins were developed in the southeastern margin of the TP, including the Nangqian, Shanglaxiu, Gonjo, Markham, Jianchuan, Lanping, and Simao basins. These basins were commonly infilled by alluvial fan and fluvial coarse clastic rocks interbedded with lacustrine mudstone and marls, and these deposits are thousands of meters thick along the faults and suture zone (Zhang et al., 2007).

The Gonjo Basin is located in the northeastern part of the NQT and is bounded by the Jinsinjiajiang suture to the east and the Bangong-Nujiang suture to the west. The Gonjo Basin is a syn-contraction basin (Studnicki-Gizbert et al., 2008) and is composed of an asymmetric syncline controlled by a thrust system (Li et al., 2020; Xiong et al., 2020). The Cenozoic red beds in the Gonjo Basin are divided into the Gonjo and Ranmugou formations. The Gonjo Formation is conformably overlain by the Ranmugou Formation and is unconformably underlain by Lower and Middle Triassic limestone and volcanic rocks (Tong et al., 2017). The Gonjo Formation consists of eolian sandstones in the lower part and fluvial sandstones and siltstones in the upper part (Xiong et al., 2020). The Ranmugou Formation can stratigraphically be divided into three parts. The lower part is mainly composed of massive gray-purple conglomerates interlayered with sandstones (BGMRT, 1993), indicating a distal alluvial fan or fluvial facies (Xiong et al., 2020). The middle part is mainly reddish-brown sandstones, which have been hypothesized to be deltaic deposits (Tang et al., 2017). The upper part consists of green lacustrine carbonaceous shales, carbonates, red mudstone, and evaporites (Studnicki-Gizbert et al., 2008).

Although several geochronological studies have been recently conducted, the ages of these beds remain controversial (Figure 2). The previous geochronological studies of the Gonjo red beds were based on palynology and palm fossils. The palm fossil *Sabalites* sp. was initially assigned an Eocene age (He et al., 1983). A Tibetan regional study suggested a Paleocene to Eocene age based on fossil sporomorphs (BGMRT, 1993). Studnicki-Gizbert et al. (2008) identified limited palynomorphs of *Momipites* sp., *Retitricolporites* sp., *Taxodiaceae*, and/or *Cupressaceae* sp., *Inaperturites* sp., *Striatricolpites* sp., *Caryaepollenites* sp., *Psilamonocolpites* sp., *Psilatricolpites* sp., *Tricolpites* sp., and *Schizosporis* sp. and concluded these to be Late Eocene and Oligocene deposits. However, the volcanic rocks in the upper Ranmugou Formation yielded an age of ~43 Ma based on *Ar*-*Ar* and U-Pb zircon dating methods (Studnicki-Gizbert et al., 2008; Tang et al., 2017). Recently, Xiong et al. (2020) reported several ages for the volcanic rocks in the upper Ranmugou Formation, ranging from 50 Ma to 40 Ma in northern and southern parts of basin. A magnetostratigraphic study in the central part of the basin revealed that the ages of the continuous sequences of the Gonjo and Ranmugou formations ranged from ~69 Ma to 41.5 Ma, of which the Ranmugou Formation is ~65.2 Ma to 41.5 Ma (Li et al., 2020) (Figure 2). Xiao et al. (2021) indicated that the Gonjo and Ranmugou formations are 69 to
50 Ma in the central Gonjo Basin, and the Ranmugou Formation was assigned an age ranging between 63.5 Ma and 50 Ma. They believed that the magnetostratigraphic results of Li et al. (2020) were inaccurate due to their isotopic age deriving from other sections. Therefore, the age constraint of the upper Ranmugou Formation lacustrine sequences is still controversial (Figure 2). The biostratigraphy based on palynology will be used to limit the age in this study.

**MATERIALS AND METHODS**

**Measured Section and Sedimentology**

A 90 m thick section of the upper Ranmugou Formation is exposed in Youzha, Gonjo Basin (30.719468°N, 98.420275°E) (Figure 3A). This section is near the core of the Youzha syncline and consists of thin-bedded limestones and marls, siltstones, mudstones, shales, and evaporites (Figure 3B). The lower part of the section is characterized by limestones and marls interbedded with thin-bedded gypsum rocks. The middle part of the section is composed of purple siltstones interbedded with shales and mudstones. Ripple marks, parallel bedding, and horizontal bedding are common (Figure 4). The lithology of the upper part is mainly dark grey limestones and marls interbedded with thin gypsum rocks and conglomerates. Secondary gypsum usually cuts through the bedding and occurs in veins (Figure 4). Based on a previously recovered drill core, the evaporites are composed of gypsum, anhydrite, and rock salts (Chen, 1990). The thickness of the rock salt is up to 356.8 m. It mainly consists of clay gravel and halite, and it exhibits tectonic reworking, salt solution, and leaching. The rock salts that outcrop at the surface are usually conglomerates composed of clay gravels. Due to the Quaternary cover, the thick halite sequences in the core of the syncline are not exposed.

**Samples and Analytical Methods**

Four gypsum samples were collected for trace element and rare Earth element (REE) analyses and S and Sr isotopic analyses. The trace element and REE contents were obtained via inductively coupled plasma mass spectrometry (ICP-MS) after being treated with 5 M HCl and filtered through a cellulose acetate membrane filter at the Beijing Research Institute of Uranium Geology. For the S isotope analysis, the samples were purified as BaSO₄ after combustion with an Eschka reagent, and then, they were treated with V₂O₅ to produce SO₂. The resulting SO₂ was measured using the MAT 251 EM mass spectrometer at the MNR Key Laboratory of Metallogeny and Mineral Assessment, Beijing. The δ³⁴S values are reported vs. the Canyon Diablo troilite (CDT), and the estimated error is about ±0.2‰. The Sr isotope analyses were performed at the Beijing Research Institute of Uranium Geology. About 10 mg of sample (200 mesh) were dissolved using 4 M HNO₃ after being washed with milli-Q water and dried. The Sr was extracted from the Sr-resin and was analyzed using a Neptune Plus multicollector ICP-MS. The Sr isotopes are reported as ⁸⁷Sr/⁸⁶Sr. ⁸⁷Sr/⁸⁶Sr values of 0.71022–0.71030 were obtained for standard NBS987. The reported uncertainties of the ⁸⁷Sr/⁸⁶Sr ratios are 1σ.

A total of 16 limestone and marl samples from the Youzha section were analyzed for the palynological investigations. The sample processing employed a standard technique and was
conducted at the Institute of Geology, Chinese Academy of Geological Sciences. About 50 g of crushed sample (100 mesh) was treated with 15% HCl for 24 h and then washed 3 to 5 times to a neutral pH. Then, the samples were treated with 39% HF for 72 h and were washed to a neutral pH. The residue was sieved through a 10 μm nylon mesh and collected in a 10 ml centrifuge tube (2,500 rpm). The final organic residue was placed in a 1.5 ml centrifuge tube in glycerin jelly and was mounted on microscope slides. The palynomorph identification and photography were performed using a LEICA DM4500P microscope. At least 200 grains from each sample were identified and counted. The coexistence approach (CA) was widely used to quantitatively reconstruct paleoclimate in recent decades (e.g., Quan et al., 2012; Xie et al., 2019), although the CA remains uncertainties (Mosbrugger and Utescher, 1997). The CA is based on assumption that climatic tolerances of a fossil plant are similar to its nearest living relative (NLRs) when its modern affinity is determinable (Quan et al., 2012). We determine NLRs from a Palaeoflora Database (Utescher and Mosbrugger, 1997) and data from Quan et al. (2012) (Table 2). We only reconstruct two climatic parameters, i.e., mean annual temperature (MAT) and mean annual precipitation (MAP). It should be noted that the CA was challenged and referred to as “useless” by Grimm and Denk (2012). However, ongoing updates of the database, new successful

![Figure 2](https://example.com/figure2.png)

**FIGURE 2** | The stratigraphic and geochronological division of the Gonjo Basin.
tests with modern florals, and probability considerations for a high number of taxa overlapping make the method of paleoclimate reconstructions reliable (Hoorn et al., 2012; Quan et al., 2012; Utescher et al., 2014).

RESULTS

Geochemistry

The most concentrated trace element was strontium (Sr), with concentrations of 96–111 ppm. The V, Co, and Ni contents were much higher (V: 7.9–35.3 ppm; Co: 10.1–10.9 ppm; and Ni: 15.6–18.1 ppm) (Table 1), similar to those in the mid-Cretaceous anhydrite in the Mengyejing Formation in the Simao Basin (Xia and Li, 1983). This probably indicates contribution from a deep fluid. The concentrations of other metals such as Sc, Cr, Cu, and Zn range from 0.9 to 7.4 ppm. The REE concentrations are all low and are much lower than the heavy REE (HREE) concentrations. The δ³⁴S VCDT values vary in a very narrow range from 10.3% to 11.0%, which is much lower than those of the contemporaneous seawater (Claypool et al., 1980). The Rb contents are much lower than the Sr contents, with Rb/Sr ratios of <0.1 (average of 0.014), indicating that the values do not need to be corrected for the decay of Rb to Sr. The ⁸⁷Sr/⁸⁶Sr ratios of the gypsum samples range from 0.709942 to 0.710062, which are higher than modern seawater (0.70920) and Eocene seawater (0.70755) (McArthur et al., 2012).

Palynological Records and CA Results

Of the 16 samples analyzed, palynomorphs were identified in 10 samples, and the recovery was poor in all of the samples. There are rare palynomorphs in the upper part of the Youzha section, which is likely related to the aridity inferred from the presence of gypsum and halite. Vegetation is usually sparse and their palynomorphs are easily destroyed in arid environments (Yuan et al., 2020). We identified 56 palynomorphs, including 13 spores and 43 pollen taxa (4 gymnosperm and 39 angiosperm morphospecies) (Figure 5). The palynoflora are predominantly angiosperm pollen (20.5–95.3%), which are dominant by Celtispollenites and Caryapollenites, as well as Tricolpites, Tricolporopollenites, and Lonicerapollis (Figure 6). Pollen of Liquidambarpollenites, Ulmipollenites, Ulmoideipites, Juglanspollenites, Multiporopollenites, and Subtriporopollenites occur frequently. There are minor amounts of Ptericaryapollenites, Fagaspollenites, Quercoideites, Retitricolpites, Averipollenites,
Ranunculacidites, and Sapotaceoidaepollenites. The gymnosperm pollen (2.2–9.5%) are mainly from Ephedripites and Taxodiaceaepollenites with minor Cycadopites and Cedripites. The ferns include 13 sporomorphs; and the dominant taxa are Lycopodiumsporites and Osmundacidites; while Triporoletes, Toroisporites, Pterisporites, and Zlivisporis sporadically appear.

Middle Eocene fossil sporomorphs from the Gonjo Basin were used to reconstruct the MAT and MAP using CA. The estimated paleoclimatic parameters are shown in Figure 7. The CA quantitative estimates show a warm and humid climate with a MAT ranging from 13 to 15°C and a MAP of ~1,400 mm.

DISCUSSION

Age Constraints
As was previously stated, the ages of the lacustrine marlstone, mudstone, and evaporite of the upper Ranmugou Formation in

![Field photos of the upper part of the Ranmugou Formation, Gonjo Basin. (A) The contact between the marls and siltstones in the lower part of section. (B) Outcropped photos show the thin-bedded siltstones and marls interbedded with gypsum rocks. (C,D) Ripple marks. (E) Marls interbedded with gypsum rocks in the upper part of section. (F) Conglomerates that are composed of clay gravels show the rock salt solution. Noted that the secondary gypsum veins cut into the conglomerates.](figure4.png)
assemblages in the Youzha section discussed below give an age of middle Eocene, which is congruent with the isotopic ages in the Qudeng section (Xiong et al., 2020).

The absence of the diagnostic Cretaceous taxa *Cicatricosisporites*, *Schizaeoisporites*, and *ClassoLLpolis* (Li et al., 2019a), the predominance of the Paleogene pollen taxa, and the presence of Cretaceous relic taxa *Acquitriradites* (Tripathi, 2008) indicate that the samples from the Youzha section could be early Paleogene in age. The amount of Pinaceae pollen suddenly increased at ~36 Ma in the Xining Basin (Hoorn et al., 2012; Page et al., 2019), which was common during the E/O transition, which predominantly occurred in the Oligocene (Zhang, 1995; Page et al., 2019), indicating that the Youzha section cannot be younger than the latest Eocene. In northwestern China, the Paleocene taxa *Normapolles* and *Proteacidites* are dominant (Song, 1999), but these taxa are absent in our samples, indicating that the sedimentary age of the Youzha section is likely younger than the Paleocene. The assemblage of *Ephedrites*, *Nitriadites/Nitriripollis*, and *Chenopodipollis* are dominant in the late Eocene Tibetan basins, such as Xining Basin (Hoorn et al., 2012), Juquan Basin (Miao et al., 2008), Hoh Xil Basin (Miao et al., 2016), and Nangqian Basin (Yuan et al., 2017; Yuan et al., 2020). Zhang (1995) comprehensively reviewed the Paleogene palynological flora in China and concluded that the xerophytic pollen of *Zygophyllaceae* flourished in the late Eocene. Tong et al. (2001) reported that the average percentage of *Ephedrites* is 30, 20, and 15% in the halite, glauberite, and purple mudstones, respectively, of the middle and late Eocene evaporites in the Jianghan Basin. Therefore, the lower abundances of *Ephedrites* and *Nitriadites/Nitriripollis* and the absence of *Zygoxyphylaceae* and *Chenopodiaceae* (Dupont-Nivet et al., 2008) preclude a late Eocene age for the Youzha section. Ulmaceae, Betulaceae, and Juglandaceae pollen are significant in the early Eocene strata in southern China (Zhang, 1995). This assemblage is similar to those in the Linzhou Basin, central Tibet (Li et al., 2019a), but it differs from the Eocene Hengyang Basin, where a high percentage of *Ephedrites*
was recovered (Xie et al., 2020). The middle Eocene was characterized by dominant tricolporate pollen of Fagaceae and a remarkable decline in tricolporate to multiporate pollen of the early Eocene taxa (Song and Liu, 1982; Zhang, 1995), although Ulmipollenites still account for a large proportion in southern China (Xie et al., 2019). Therefore, the fossil pollen assemblage of Celtispollenites-Caryapollenites-Tricolpites-Tricolporopollenites in our samples is similar to the middle Eocene palynoflora records in China. Xiong et al. (2020) gave the age range between 44 Ma and 40 Ma of the lacustrine carbonates from the Rannmugou Formation in the Qudeng section with a thickness of more than 400 m, which is close to the Youzha section. Due to the Quaternary cover, absence of thick salt-solution conglomerates of the upper part of the studied section, and the warm temperate pollen (discussed below) which is inconsistent with the significant cooling since 44 Ma (Xiong et al., 2020), we thus speculate that the age of the section is from 47.8 Ma to >44 Ma.

**Paleoenvironmental Reconstruction in the Gonjo Basin**

The $\delta^{34}$S values in our gypsum samples are lower than those of the contemporaneous seawater, which is probably the result of either the reservoir effect (Holser and Kaplan, 1966) or dissolved sulfates with lower $\delta^{34}$S values in continental water. However, the reservoir effect would not cause lower values in gypsum due to the negligible depletion of $^{34}$S in sulfate during gypsum precipitation (Shen et al., 2021). The high $^{87}$Sr/$^{86}$Sr values were likely caused by radiogenic $^{87}$Sr based on the high Rb/Sr ratios and/or continental
water. Based on the low Rb/Sr ratios, we speculate that continental water was the only reason for the observed high $^{87}$Sr/$^{86}$Sr ratios of the gypsum samples. Therefore, we argue that the gypsum was precipitated from a continental water body, not from marine water. The $\delta^{13}$C and $\delta^{18}$O values of the marls in the upper part of the Ranmugou Formation have been reported to range from $-5.9\%$ to $-7.2\%$ and from $-16.6\%$ to $-13.8\%$, respectively (Xiong et al., 2020). These values coincide with typical lacustrine carbonates (Talbot, 1990). Thus, during the middle Eocene, the Gonjo Basin was a typical lacustrine environment with input from a continental water body and deep fluids.

The sedimentary sequences in the Youzha section represent a typical lacustrine environment and are characterized by a cycle from saline water to freshwater to hypersaline water (Figure 3B). During the saline water stage, lacustrine carbonates and gypsum rocks were deposited, indicating a sulfate deposition stage. In the freshwater stage, fine-grained clastic rocks such as siltstones, mudstones and shales were deposited, indicating that the lake was dilute by influent water. During the hypersaline stage, large amounts of gypsum and halite were deposited when the saline water evaporated and minerals precipitated under hyper-arid conditions. However, due to the unexposed thick halite
sequences (Figure 3B), the hypersalinity in the studied section was not reached.

Our palynological results show that the flora consisted of arbors *Celtispollenites*, *Carya*, *Betulaceae*, *Pterocarya*, and *Liquidambar*, and the herbs *Caprifoliaceae*, *Ranunculaceae*, *Asteraceae*, accompanied by the ferns *Lycopodiatae* and *Osmunda*, which indicates that the vegetation was a temperate deciduous broad-leaved forest. The abundance of *Celtispollenites* and *Caryapollenites* together with *Ulmus*, *Taxodiaceaepollenites*, and *Juglans* suggest a humid and warm climate (e.g., Sun and Wang, 2005; Lu et al., 2020), which is consistent with the CA results. It should be noted that some freshwater algae such as *Pediastrum*, *Leiosphaeridia*, and *Psiloschizosporites* occurred in large amounts in the lower part of the Youzha section, indicating that the depositional environment was near a water body, which is supported by our sedimentary results.

In the Youzha section, the xerophytic taxa *Ephedripites* is only found in the lower part (samples GJ-52 and GJ-53) and top part (sample GJ-64) of the section in low abundance. In addition, *Nitrariadites* is absent throughout the section. The xerophytic shrub *Ephedra* (*Ephedripites*) usually grows in arid environments (Dupont-Nivet et al., 2008). The modern equivalent of *Nitrariadites* is *Nitraria*, which is a steppe-desert taxon (Sun and Wang, 2005). The xerophytic taxa *Ephedripites*, *Nitrariadites*, and *Chenopodiaceae* are typical in alluvial gravelly plains and treeless alpine desert landscapes with an annual rainfall of <100 mm (Herzschuh et al., 2003; Sun and Wang, 2005). Thus, the paleoenvironment recorded by the pollen assemblages in the Youzha section (47.8–44 Ma) was a warm and humid temperate deciduous broad-leaved forest (Figure 8).

The carbonate clumped isotope thermometry indicates a warm climate, with a temperature of about 24°C, during the early Eocene (54–50 Ma) and a dramatic decrease in temperature to about 7°C during 44–40 Ma (Xiong et al., 2020). Thus, based on our sedimentary and pollen evidence and the isotope-based temperature, we conclude that the paleoenvironment in the Gonjo Basin changed from the warm and humid deciduous broad-leaved forest in the early middle Eocene (47.8–44 Ma), to the cool and arid temperate forest during 44–40 Ma.

**Comparison With Other Middle Eocene Paleovegetation in Western China**

Our palynological assemblages are comparable with those in the Kuqa and Yarkand basins (Wang et al., 1986). Our findings indicate a paleoenvironmental change from warm and humid to cool and arid at ~44–40 Ma, which is quite consistent with the change in the Qaidam Basin. The palynological assemblage of the Luluhe Formation (50–43 Ma) in the Qaidam Basin is predominantly *Betulaceaepollenites-Taxodiaceaepollenites-Potamogetonaceites-Tsugaepollenites*, indicating a deciduous broad-leaved forest and a warm and humid climate (Lu et al., 2020). During 43–41 Ma, a certain amount of the coniferous taxa *Piceaepollenites*, *Pinuspollenites*, and *Abiespollenites* began to appear, suggesting that the climate changed to arid and cool (Lu et al., 2020). These environmental and ecosystem variations are supported by a recent paleoclimate estimate. A quantitative reconstruction suggests that the MAP in the Qaidam Basin was ~800–1,400 mm during ~49–43 Ma, and the MAP and mean temperature of the coldest month (MTCO) declined after ~43 Ma, indicating a climatic change from warm and humid
to cool and arid at ~43 Ma (Jia et al., 2021). The paleoenvironmental variation in the middle Eocene is also regionally corroborated by the records in the Xining Basin. The palynological composition in the Xining Basin changed from abundant *Ulmipollenites* to 80% desert-steppe vegetation at ~40 Ma, indicating significant aridification (Bosboom et al., 2014). The palynofloras are different from those in the Lunpola Basin which is dominated by *Quercoidites-Ulmipollenites-Taxodium* assemblage (Li et al., 2019a). The middle Eocene vegetation in southern China was a mixture of evergreen and deciduous broad-leaved forests, indicating a warm and humid subtropical climate under the influence of the East Asian Monsoon (Xie et al., 2019), which changed from the early Eocene arid desert (Xie et al., 2020).

**Paleoenvironmental Evolution and Driving Factors During the Eocene on the Eastern TP**

The Eocene sedimentary records in the Xining, Jiuquan, Qaidam, Hoh Xil, and Nangqian basins, which have accurate age control, and their pollen and other climate proxies can provide good climatic and ecological correlations. Large amounts of xerophytic taxa are a significant feature of the late Eocene sedimentary basins in the northeastern TP, such as the Xining (Dupont-Nivet et al., 2008; Hoorn et al., 2012), Jiuquan (Miao et al., 2008), Qaidam (Lu et al., 2020), Hoh Xil (Miao et al., 2016), and Nangqian basins (Yuan et al., 2020). After the MECO (~40 Ma), the Xining Basin was characterized by halophytic and xerophytic vegetation, including *Ephedrites* and *Nitriastrides/Nitrariopollis* (Hoorn et al., 2012; Bosboom et al., 2014), with a sudden increase in the high-altitude pollen of Pinaceae at ~37 Ma (Abels et al., 2011; Hoorn et al., 2012). During ~40–33 Ma, arid-semiarid shrubs, represented by *Nitriastrides* and *Chenopodiopollis*, prevailed in the Jiuquan Basin (Miao et al., 2008). It should be noted that Pinaceae accounted for 5–25.6% (*Pinuspollenites, Abietineacpollenites, Piceae pollenites, and Abiespollenites*) at ~40 Ma (Miao et al., 2008). This sharp increase in Pinaceae (6.3–32%, *Piceae pollenites, Pinuspollenites, and Abiespollenites*) also began at 43 Ma in the Qaidam Basin (Lu et al., 2020). The pollen in the late Eocene to Oligocene Yaxicuo Group in the Hoh Xil Basin (Jin et al., 2018; Lin et al., 2020) are predominantly from xerophytic *Ephedrites, Nitriastrides*, and *Chenopodiopollis* with a low abundance of *Picea* due to the aridity and low elevation in this area (Miao et al., 2016). Thus, the flora in the late Eocene Hoh Xil Basin reflects a subtropical arid climate and the paleoenvironment changed from warm and humid to arid and cool at ~41 Ma (Li et al., 2019a). This is consistent with the cooling trends inferred from clumped isotopes in the Nangqian Basin (Li et al., 2019b). Therefore, the paleoclimate in the northeastern TP basins became to be arid and relatively cool during ~43–40 Ma. It should be noted that the cooling was a long-term and stepwise trend, and it ultimately lead to significant cooling during the Eocene-Oligocene transition (EOT).

The flora in the Markam Basin were previously thought to be Miocene and are currently dated as latest Eocene to earliest Oligocene, reflecting a change from late Eocene subtropical/warm temperate evergreen and deciduous mixed vegetation (mainly represented by Fagaceae and Betulaceae) to early Oligocene cool temperate vegetation (represented by Eosaceae and Salicaceae) (Su et al., 2019; Chen et al., 2021). In the Jianchuan Basin, southwestern Yunnan, the late Eocene flora in the Shuanghe Formation (Gourbet et al., 2017) are characterized by *Caryapollenites, Cupuliferoipollenites, Abiopollenites, Juglanspollenites, Pterocaryapollenites*, and *Meliaecoidites*, indicating a temperate deciduous broad-leaved forest (Wu et al., 2018).

As such, based on the flora and climatic records in the TP, it is clear that a warm and humid temperate broad-leaved forest dominated in the northeastern (NE) TP during the middle Eocene (e.g., Gonjo Basin). During ~44–40 Ma, region-wide aridification and cooling prevailed, with significant amounts of conifers and xerophytic shrubs, indicating a cool and arid steppe-desert environment (e.g., Nangqian Basin). During the EOT, which is represented by the flora in the Markam Basin, vegetation indicative of a cool temperate environment dominated. We infer that the paleoenvironmental changes in the Gonjo, Nangqian, and Markam Basins during the middle to late Eocene were forced by the uplift of the Central Watershed Mountain, although several drivers such as global cooling, the retreat of the Paratethys Sea, and the uplift of the TP have been proposed to explain the aridification and cooling on the NE TP (Dupont-Nivet et al., 2008; Bosboom et al., 2014; Zhang et al., 2018; Yuan et al., 2020). The uplift of the Tanggula Shan, Nangqian, Gonjo, and Markam Basins in the Central Watershed Mountain during the middle to late Eocene attained near present elevations. The Tanggula Shan was elevated to about 4,000 m at ~40 Ma based on thermochronologic and structural evidence (Wang et al., 2008). The paleoelevation recovered from n-alkane δ^13^H data for the Yaxicuo Group indicate that the source of the Tanggula Shan was located at about 4,000 m in the late Eocene (Lin et al., 2020). Carbonate stable and clumped isotopic evidence suggests an altitude of ~3,000 m in the Nangqian Basin and its surrounding mountains during the late Eocene (Li et al., 2019b). Also, the Gonjo Basin reached its elevation of 3,800 m in the 44–40 Ma based on carbonate clumped isotopes (Xiong et al., 2020), while the Markam Basin reached an elevation of about 3,000 m in the latest Eocene (~34 Ma) (Su et al., 2019), indicating the southward expansion of the Central Watershed Mountains. Collectively, the high topography of the Central Watershed Mountain leads to the development and intensification of the Asian monsoon during the middle Eocene (~44–40 Ma) (Xiong et al., 2020; Fang et al., 2021) by blocking the southerly source of moisture and altering the atmospheric circulation (Raymo and Ruddiman, 1992), which is similar to the scenario in the Gangdese Mountains (Ding et al., 2014). The development of the Eocene Asian monsoon was controlled by the paleogeography resulting from the uplift of the TP rather than by the CO_2_ concentration (Farnsworth et al., 2019). Recent climate model simulations also suggest that the northward migration of the high-elevation proto-TP intensified the aridity and affected the precipitation (Zhu et al., 2019). As such, we infer that the climate and ecosystem transition since the middle Eocene in the regional-wide Central Watershed Mountain.
were largely controlled by the tectonic uplift of the TP rather than by global cooling and the retreat of the Paratethys Sea.

However, for the interior basins in the northern TP, we conclude that global cooling, the uplift of the northern TP, and the retreat of the Paratethys Sea were the combined driving force. First, the rapid decreases in temperature and precipitation in the Qaidam Basin at ~43 Ma were inferred to be caused by global cooling alone (Jia et al., 2021). Similarly, the appearance of high-elevation conifers predated the significant cooling in the EOT in the Xining Basin (Dupont-Nivet et al., 2008), which supports the hypothesis that the stepwise global cooling could not sufficiently drive the paleoenvironmental changes. Second, the increased amount of coniferous taxa reflect the uplift of the surrounding mountains with plant zonation, but the fossils and isotope-based paleoaltimetry indicate relatively low elevations for the interior basins during the middle Eocene (Miao et al., 2008, 2016; Lin et al., 2020). Although model simulations have shown the important role of the uplift of the central TP in the long-term trend of aridity (Li et al., 2018), the short-term fluctuations between dry and wet (Fang et al., 2015; Meijer et al., 2019) cannot be explained by the slow tectonic uplift. Third, the major retreat of the Paratethys Sea from the Tarim Basin at ~41 Ma (Bosboom et al., 2013) was broadly coeval with the stepwise aridification and cooling in the Xining, Jiuquan, Qaidam, and Hoh Xil basins. Moreover, owing to the sustained blocking of the southerly source moisture by the Central Watershed Mountain, the moisture carried by the westerlies was significant to the climate change in these basins. Thus, the retreat was an important driving factor.

CONCLUSION

In this study, we analyzed the palynological assemblages, sedimentary records, and geochemistry of evaporites from the Youzha section in the Gonjo Basin. The conclusions that follow were drawn.

1. The outcropped section in the Youzha is middle Eocene in age, with an upper age limit of 44 Ma.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

LW: investigation, writing, review, and revision. QY: writing, review, revision. LS: investigation and review. LD: conceptualization, supervision, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research was financially supported by the STEP (Grant nos. QZKK20190803, QZKK20190708), and Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA 20070301).

ACKNOWLEDGMENTS

We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.
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