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Reconstructing Neogene vegetation and climates to infer tectonic uplift in western Yunnan, China

Bai-Nian Sun [a,b,*], Jing-Yu Wu [a,b,*], Yu-Sheng (Christopher) Liu [c,*], Su-Ting Ding [a], Xiang-Chuan Li [a], San-Ping Xie [a], De-Fei Yan [a], Zhi-Cheng Lin [a]

[a] Key Laboratory of Western China's Environmental Systems of the Ministry of Education, College of Earth and Environmental Science, Lanzhou University, Lanzhou 730000, China
[b] State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Paleontology, Nanjing 210008, China
[c] Department of Biological Sciences, East Tennessee State University, PO Box 70703, Johnson City, TN 37614-1710, USA

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ABSTRACT

Neogene climates and vegetation history of western Yunnan are reconstructed on the basis of known fossil plants using the Coexistence Approach (CA) and Leaf Margin Analysis (LMA). Four Neogene leaf floras from Tengchong, Jianchuan and Eryuan in southwestern China are analyzed by the CA, and the paleoclimatic data of one Miocene carpoflora from Longling and three Pliocene palynofloras from Longling, Yangyi and Eryuan are used for comparison. The Miocene vegetation of the whole of West Yunnan is subtropical evergreen broad-leaved forest, and a similar mean annual precipitation is inferred for Tengchong, Longling and Jianchuan. However, by the Late Pliocene a large difference in vegetation occurred between the two slopes of Gaoligong Mountain, western Yunnan. The region of Tengchong retained a subtropical evergreen broad-leaved forest vegetation, whereas in Yangyi and Eryuan a vertical vegetation zonation had developed, which consists, in ascending order, of humid evergreen broad-leaved, needle and broad-leaved mixed evergreen, and coniferous forests. Distinctively, the Late Pliocene vegetational patterns of West Yunnan were already very similar to those of the present, and the Pliocene mean annual precipitation in Tengchong was markedly higher than that of Yangyi and Eryuan. Considering that the overall vegetation of West Yunnan and the precipitation at Yangyi and Eryuan have undergone no distinct change since the Late Pliocene, we conclude that the Hengduan Mountains on the northern boundary of West Yunnan must have arisen after the Miocene and approached their highest elevation before the Late Pliocene. Furthermore, the fact of the eastern portion of the Tibetan Plateau underwent a slight uplift after the Late Pliocene is also supported.

1. Introduction

Western Yunnan is situated to the south of the Hengduan Mountains and along the southeastern edge of the Qinghai–Tibetan Plateau. Within the Neogene this area has been intensively affected by Himalayan tectonic movement, leading to the formation of a complicated physiognomy, peculiar vegetation, and a tri-dimensional climate (Tang and Shen, 1996). The various vegetation conditions, abundant modern plant resources, and plentiful Cenozoic plant remains in western Yunnan provide us with a unique opportunity to understand the evolution of plant diversity and climates in this geologically and biologically dynamic region. Plotting vegetation evolution allows us to further understand the relation of uplift and paleoclimatic change in the eastern portion of the Tibetan Plateau.

Several studies on Neogene climates of western Yunnan from a paleobotanic point of view have been published and interesting conclusions have been drawn (Xu, 2002; Zhao et al., 2004; Kou et al., 2006; Xie, 2007). For example, by applying the Coexistence Approach (CA) (Mosbrugger and Utescher, 1997) on palynofloras, Kou et al. (2006) deduced that the uplift of the eastern Tibetan Plateau, represented by Gaoligong Mountain in western Yunnan, must have occurred during or after the Late Pliocene. This conclusion, however, appears to contradict the opinion of geologists, who have usually supported an Early Miocene uplift of the Plateau (Quade et al., 1989; Harrison et al., 1992; Quade and Cerling, 1995). The basic physiognomy of western Yunnan formed at least in the Late Miocene and intense uplift of this region took place from Late Miocene to Early Pliocene (Ming, 2007). Magnetostratigraphic studies further indicate that the rapid uplift of the eastern Tibetan Plateau, now represented by the Hengduan Mountains, occurred before the Middle Pliocene (ca. 3.4 Ma) (Chen, 1992, 1996). In the present study, we make use of

* Corresponding authors. Sun and Wu are to be contacted at Key Laboratory of Western China's Environmental Systems of the Ministry of Education, College of Earth and Environmental Science, Lanzhou University, Lanzhou 730000, China. Tel.: +86 931 8915280; fax: +86 931 8915280.
E-mail addresses: bnsun@lzu.edu.cn (B.-N. Sun), jywu@lzu.edu.cn (J.-Y. Wu), liuc@etsu.edu (Y.-S.(C.) Liu).

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fossil plants uncovered from western Yunnan to revisit the debate on when the eastern Tibetan Plateau arose.

Two of the fossil sites, from Tengchong and Longling, are situated on the southwestern slope of Gaoligong Mountain (western part of Hengduan Mountains) in western Yunnan (Fig. 1), viz., on the windward side of the Tibetan Plateau, which largely receives the moist air-stream from the Indian monsoon and thus now experiences a humid climate. The third fossil site, from Yangyi, lies on the eastern slope of Gaoligong Mountain, viz., on the leeward side of the Tibetan Plateau, and is therefore under a humid subtropical climate but much drier than that of Tengchong and Longling. The last two fossil sites from Jianchuan and Eryuan, located on the western slope of the northeast Hengduan Mountains, now have similar climates to that of Yangyi.

In the present study, four previously reported Neogene macrofloras from Tengchong, Jianchuan and Eryuan, western Yunnan, were chosen for quantitative climatic reconstructions using CA, and four climatic parameters have been estimated. For comparison, the quantitative climates from the Leaf Margin Analysis (LMA) and the Climate Leaf Analysis Multivariate Program (CLAMP) are compared with those from CA, and the data of four other floras, viz., a Miocene carpoflora from Longling and three Pliocene palynofloras from Longling, Yangyi and Eryuan are also reviewed (Xu, 2002; Xu et al., 2003, 2004; Zhao et al., 2004; Kou et al., 2006). Moreover, the paleovegetations and paleoclimates of the eight floras are compared with recent data to interpret further the paleoclimatic and paleoelevation evolution of western Yunnan during the Neogene.

2. Material and methods

2.1. Study sites and materials

According to the K–Ar method, the basaltic rocks of the middle part of Mangbang Formation date to 3.297 ± 0.040 Ma (Li et al., 2000), and the andesitic rocks of overlying Mingguang Formation to 2.322 ± 0.036 Ma (Li et al., 2000). In combination with the local stratigraphic correlations (BGMRYP, 1990) and biostratigraphic comparison (Tao and Du, 1982; Ge and Li, 1999), the fossil-bearing deposits of the upper part of Mangbang Formation are confined to the Late Pliocene. Based on a detailed comparison of leaf architectural and cuticular characters, Wu (2009) reported 37 species of leaf fossils from the upper part of Mangbang Formation belonging to 28 genera within 20 families. The underlying Nanlin Formation is considered to be of Early to Middle Miocene age based on lithostratigraphic and biostratigraphic research (He et al., 1996; Ge and Li, 1999), and yielded a total of 17 species (Tao and Du, 1982; Ge and Li, 1999).

The Shuanghe Formation at Jianchuan was assigned to the Miocene based on radiometric dating of volcanic rocks (22.0 Ma) (Sha and Ao, 2001) and biostratigraphic comparison (WGCPC, 1978; Ge and Li, 1999; Sha and Ao, 2001). Lithostratigraphic and biostratigraphic studies indicate that the Sanying Formation at Eryuan is of Late Pliocene age (Tao and Kong, 1973). A total of 21 species were recorded from the Shuanghe Formation (WGCPC, 1978; Ge and Li, 1999) and 14 species from the Sanying Formation (Tao and Kong, 1973; WGCPC, 1978). The Cenozoic stratigraphic subdivision of West Yunnan is shown in Fig. 2. All the fossil taxa and their nearest living relatives (NLRs) are listed in Appendix 1.

2.2. Methods

For this study we selected four macrofossil floras from the eastern edges of the Tibetan Plateau to reconstruct their paleoclimates by the CA, and two further floras were studied using LMA.

2.2.1. Coexistence Approach (CA)

The CA is used for determination of climate estimates. The principles of CA were described in detail by Mosbrugger and Utescher (1997) and have been applied repeatedly for Cenozoic paleoclimatic

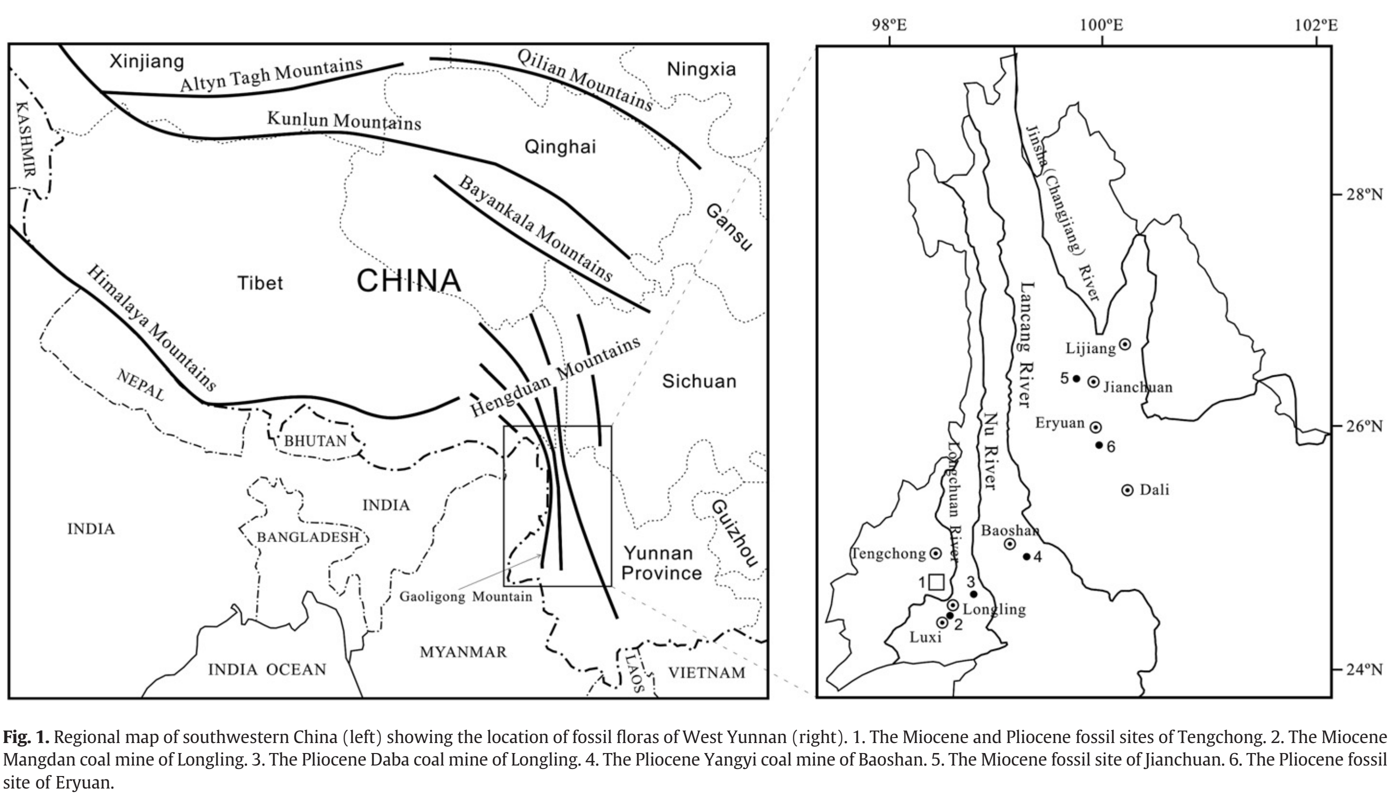

Fig. 1. Regional map of southwestern China (left) showing the location of fossil floras of West Yunnan (right). 1. The Miocene and Pliocene fossil sites of Tengchong. 2. The Miocene Mangdan coal mine of Longling. 3. The Pliocene Daba coal mine of Longling. 4. The Pliocene Yangyi coal mine of Baoshan. 5. The Miocene fossil site of Jianchuan. 6. The Pliocene fossil site of Eryuan.

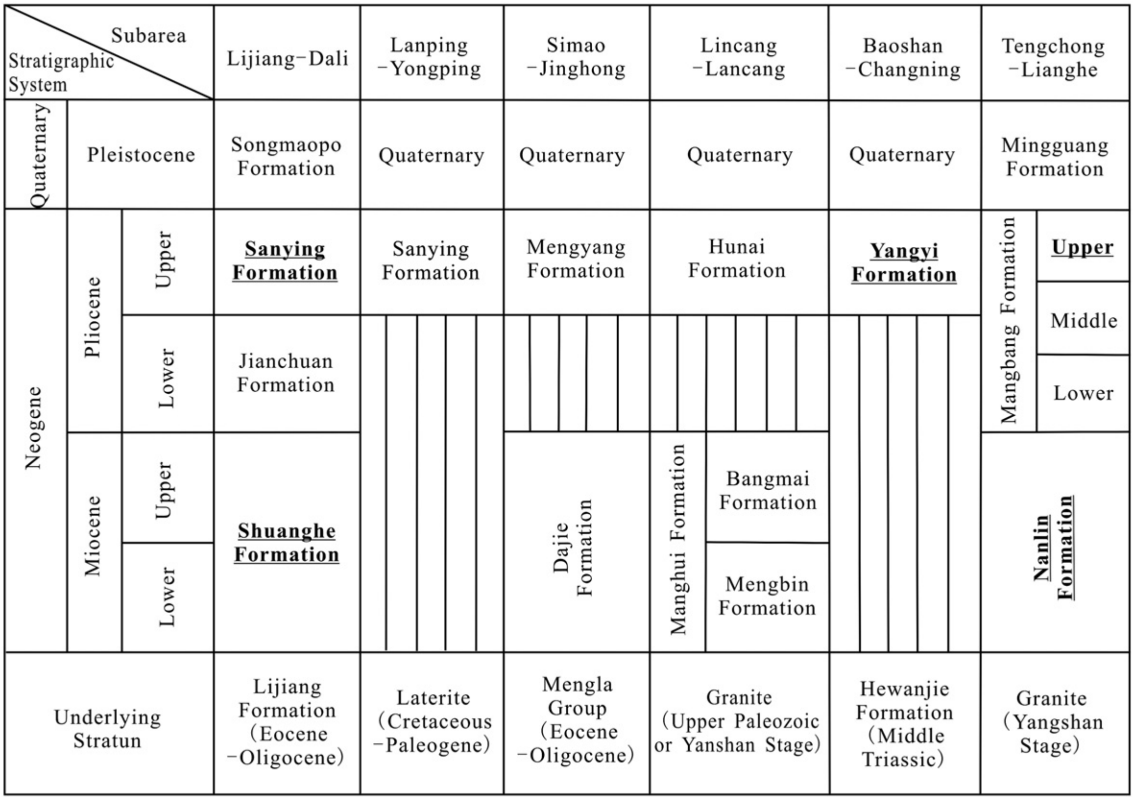

Fig. 2. Cenozoic stratigraphic sequence of Western Yunnan, China.
From Ge and Li (1999).

reconstructions (e.g., Utescher et al., 2000; Sun et al., 2002; Liang et al., 2003; Uhl et al., 2003; Kou et al., 2006; Böhme et al., 2007; Syabryaj et al., 2007; Yang et al., 2007; Xia et al., 2009). The climatic parameters of the NRLs were derived from both the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/shuju/index3.jsp?tpcat=SURF&dsid=SURF_CLI_CHN_MUL_MMON_19712000&pageid=3) and the World Weather Information Service (http://www.worldweather.org/). All the climatic parameters of the NLRs have also been reviewed with the PALAEOFLORA Database, which was developed by Utescher and Mosbrugger (http://www.geologie.uni-bonn.de/Palaeoflora/Palaeoflora_home.htm). Certain climatic parameters, e.g., mean annual temperature (MAT), temperature of the coldest month (CMT), temperature of the warmest month (WMT), and mean annual precipitation (MAP), have been estimated.

2.2.2. Leaf Margin Analysis (LMA)

LMA was first introduced by Bailey and Sinnott (1915, 1916) and revisited more recently by Wolfe (1979), Wing and Greenwood (1993), Wilf (1997) and Greenwood (2005, 2007). LMA relies on the established correlation between the percentage of entire-margined leaves of any woody dicot in a given patch of stable (nonpioneer) vegetation and the mean annual temperature. The following regression equation, mainly based on the mesic vegetation of East Asia (Wolfe, 1979), was used to calculate the MAT of the West Yunnan megafloras:

$$MAT = 1.141 + 0.306 \times P \qquad (1)$$

where P is the percentage of entire-margined species.

The MAT error was calculated using the equation of Wilf (1997):

$$\delta MAT = c\sqrt{P(1-P)/r} \qquad (2)$$

where $c = 30.6$ and is the slope of the equation of the MAT regression, where P is defined as above, and r is the number of total woody dicots studied in a fossil flora.

3. Results

The climatic parameters of the four selected Neogene macrofloras of western Yunnan were reconstructed using the CA; the four climatic parameters of all the NLRs are listed in Appendix 1.

The climatic parameters of Miocene Tengchong and Jianchuan floras are also gained by using the LMA. The percentage of entire-margined species is 62.5% of 16 woody species in the Miocene Tengchong flora and 55.6% of 18 species in the Miocene Jianchuan flora. Therefore, the reconstructed MATs using the LMA of the Miocene Tengchong and Jianchuan floras were 20.3 ± 3.7 °C and 18.2 ± 3.6 °C, respectively. The LMA technique requires a diverse sample with at least 20 taxa of leaves of woody dicotyledonous plants (Wolfe, 1993). In order to compensate for the taphonomic effect, a high number of collected specimens is required as well (Uhl et al., 2003). However, the reported 16 fossil species of woody dicot from the Miocene in Tengchong and 18 species in Jianchuan are less than 20 taxa and may possibly lead to unreliable results. Therefore, the MATs obtained from the LMA in the present study are only used for comparison with the climatic data of CA.

For a further comparison, the climatic parameters of the Pliocene Tengchong flora gained by using the Climate Leaf Analysis Multivariate Program (CLAMP) were reviewed. Xie (2007) divided 531 specimens of fossil woody leaves into 52 morphotypes for the CLAMP study. In addition, three Late Pliocene palynofloras from Eryuan, Yangyi and Longling (Xu, 2002; Kou et al., 2006) and one Miocene carpoflora from the Mangdan coal mine of Longling (Zhao et

Table 1
The climatic parameters of eight Neogene floras of West Yunnan.

Location	Age	MAT (°C)	WMT (°C)	CMT (°C)	MAP (mm)	Reference and method
Tengchong	Late Pliocene	16.3–20.8	21.3–27.1	10.8–16.9	1225.7–1695.4	Present paper; CA of leaf flora
		17.7	25.0	10.8	1834.3[a]	Xie (2007); CLAMP
Tengchong	Miocene	15.6–22.5	20.8–26.1	10.8–19.5	858.9–1546.4	Present paper; CA of leaf flora
		20.3 ± 3.7				Present paper; LMA
Longling	Late Pliocene	18.6–22.1	22.8–27.5	9.7–15.1	815.8–1254.7	Xu (2002); CA of palynoflora
Longling	Miocene	18.8–20.5	27.6–28.0	7.9–11.3	1170–1300	Zhao et al. (2004); CA of carpoflora
Yangyi	Late Pliocene	13.3–20.9	22.5–27.5	1.9–12.6	797.5–1254.7	Xu (2002); CA of palynoflora
Eryuan	Late Pliocene	12.7–18.0	17.3–25.4	2.9–11.8	621.5–1546.4	Present paper; CA of leaf flora
Eryuan	Late Pliocene	13.3–18.6	24.6–27.5	1.9–12.1	619.9–1483.3	Kou et al. (2006); CA of palynoflora
Jianchuan	Miocene	13.8–21.7	18.6–27.3	7.7–18.9	987.2–1546.4	Present paper; CA of leaf flora
		18.2 ± 3.6				Present paper; LMA

[a] Growing season precipitation (GSP).

al., 2004) using the CA are also referred to in this paper. All the paleovegetation and paleoclimate data of the eight Neogene floras and their modern equivalents from the four sites of western Yunnan are listed in Tables 1–3.

4. Discussion

4.1. Paleovegetation

Tengchong is located in the West of Yunnan within the Hengduan Mountains (Fig. 1), with a recent vegetation of subtropical monsoon evergreen broad-leaved forest (Wu and Zhu, 1987). A total of 17 species have been reported from the Miocene Nanlin Formation (Tao and Du, 1982; Ge and Li, 1999) with some tropical and subtropical genera, such as *Alangium*, *Calocedrus*, *Chukrasia*, *Lithocarpus*, *Magnolia* and *Phoebe* reported from the Tengchong area (Tao and Du, 1982; Ge and Li, 1999), which suggests that the Miocene vegetation was also subtropical evergreen broad-leaved forest. We have collected more than 800 compression fossils from the Late Pliocene Mangbang Formation at Tuantian in Tengchong, and identified 37 species of seed plants based on detailed comparisons of leaf architectural and cuticular features (Wu, 2009). The Late Pliocene Tuantian flora consists mainly of Lauraceae, Fagaceae, Betulaceae, Hamamelidaceae, Leguminosae, Myricaceae, Ulmaceae and Cupressaceae, of which *Alseodaphne*, *Machilus*, *Ormosia*, *Rhodoleia*, *Exbucklandia*, *Myrica* and *Calocedrus* represent a humid subtropical climate. The fossil record indicates that the Miocene and Pliocene vegetation of the Tengchong region was subtropical evergreen broad-leaved forest. It appears that the Miocene and Pliocene vegetation of Tengchong was similar to that of today.

Longling is adjacent to Tengchong (Fig. 1), and its modern vegetation is also similar to that of the Tengchong region (Wu and Zhu, 1987). The Miocene Mangdan carpoflora from Longling is composed mainly of tropical and subtropical taxa of Lauraceae, with *Lithocarpus*, *Corylopsis*, *Symplocos* and *Zanthoxylum*, which represents a subtropical evergreen broad-leaved forest (Zhao et al., 2004). The Late Pliocene palynoflora from the Longling coal mine consists of 82 palynomorphs belonging to 61 families, and the diversity of the palynoflora would suggest that Longling must have experienced a warm climate during the Late Pliocene (Xu et al., 2004). Xu et al. (2004) also deduced that the vegetation at Longling in the Late Pliocene was Montane Humid Evergreen Broad-leaved Forest because *Cyclobalanopsis*/evergreen *Quercus* is well represented (3.1–39.6%) throughout the sequence. The fossil record indicates that the vegetation at Tengchong and Longling has shown no evidence of change since the Miocene.

The Yangyi coal mine is located to the southeast of Baoshan City and on the eastern slope of Gaoligong Mountain (Fig. 1). The palynoflora from the Late Pliocene Yangyi Formation in the mine consists of 52 palynomorphs that belong to 32 families (Xu, 2002). Most palynomorphs are angiospermous (61.5%), with gymnosperms (9.6%), pteridophytes (25.0%) and algae (3.9%) also represented. The angiosperms consist mainly of *Betula*, *Alnus*, *Carpinus*, *Corylus*, *Cyclobalanopsis*, *Castanea*, *Castanopsis*, *Lithocarpus*, *Polygonum* and Gesneriaceae, whereas most gymnosperms are represented by *Pinus*, *Tsuga*, *Abies*, *Picea*, *Cedrus* and *Podocarpus* (Xu, 2002; Xu et al., 2003). Moreover, two species of *Quercus* sect. *Heterobalanus*, *Quercus pannosa* (Xiao et al., 2006) and *Quercus senescens* (Li et al., 2009), were found in the Yangyi Formation. The modern plants of *Quercus*

Table 2
Paleovegetation and present-day equivalents of five fossil sites in West Yunnan.

Location	Altitude (m a.s.l.)	Time	Vegetation
Tengchong	1350	Modern	Subtropical evergreen broad-leaved forest
Longling	1802	Modern	Subtropical evergreen broad-leaved forest
Yangyi	1521	Modern	Vertical vegetation zone
Eryuan	2279	Modern	Vertical vegetation zone
Jianchuan	2500	Modern	Vertical vegetation zone
Tengchong	–	Pliocene	Subtropical evergreen broad-leaved forest
Longling	–	Pliocene	Subtropical evergreen broad-leaved forest
Yangyi	–	Pliocene	Vertical vegetation zone
Eryuan	–	Pliocene	Vertical vegetation zone
Tengchong	–	Miocene	Subtropical evergreen broad-leaved forest
Longling	–	Miocene	Subtropical evergreen broad-leaved forest
Jianchuan	–	Miocene	Subtropical evergreen broad-leaved forest

Note: the vertical vegetation zonation consists of evergreen broad-leaved, needle and broad-leaved mixed evergreen, and coniferous forest.

Table 3
Paleoclimates and present-day equivalents of five fossil sites of West Yunnan.

Location	Altitude (m a.s.l.)	Time	MAT (mid-value) (°C)	MAP (mid-value) (mm)
Tengchong	1350	Modern	15.1[a]	1527.1[a]
Longling	1802	Modern	14.9[b]	2122.0[b]
Yangyi	1521	Modern	15.5[c]	966.4[c]
Eryuan	2279	Modern	13.9[d]	1078.9[d]
Jianchuan	2500	Modern	12.7[e]	968.0[e]
Tengchong	–	Pliocene	16.3–20.8 (18.6)	1225.7–1695.4 (1460.6)
Longling	–	Pliocene	18.6–22.1 (20.4)	815.8–1254.7 (1035.3)
Yangyi	–	Pliocene	13.3–20.9 (17.1)	797.5–1254.7 (1026.1)
Eryuan	–	Pliocene	13.3–18.0 (15.7)	621.5–1546.4 (1084.0)
Tengchong	–	Miocene	15.6–22.5 (19.1)	858.9–1546.4 (1202.7)
Longling	–	Miocene	18.8–20.5 (19.7)	1170–1300 (1235.0)
Jianchuan	–	Miocene	13.8–21.7 (17.8)	987.2–1546.4 (1266.8)

[a] The record of Tengchong Meteorological Station (No. 56739) (China Meteorological Data Sharing Service System, http://cdc.cma.gov.cn/shuju/index3.jsp?tpcat=SURF&dsid=SURF_CLI_CHN_MUL_MYER_19712000&pageid=3).
[b] The record of Longling Meteorological Station (WGYV, 1987; Kou et al., 2006).
[c] The record of Baoshan Meteorological Station (No. 56748) (Chen, 2001).
[d] The record of Dali Meteorological Station (No. 56751) (Chen, 2001).
[e] The record of Lijiang Meteorological Station (No. 56651) (China Meteorological Data Sharing Service System).

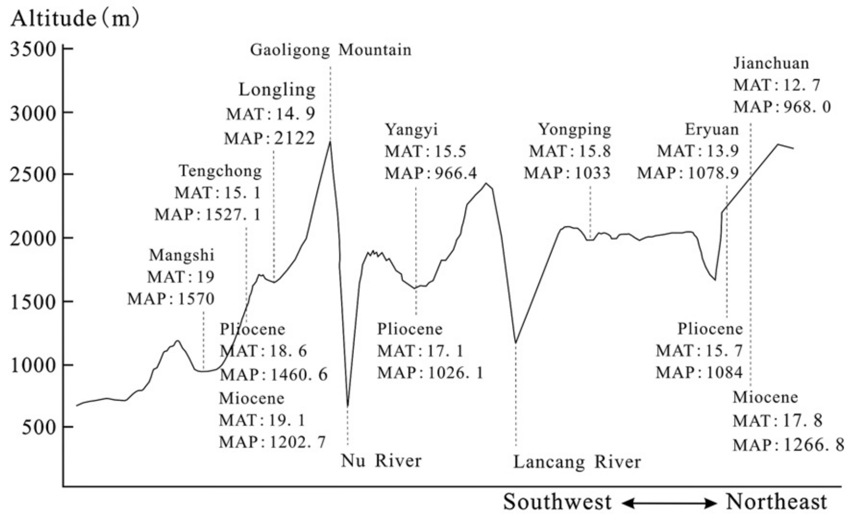

Fig. 3. Modern hypsographic changes and climatic evolution since the Miocene from the southwest to northeast of West Yunnan, China. Note: MAT (°C), MAP (mm). Modified from Kou et al. (2006).

sect. *Heterobalanus* are distributed at an elevation above 2000 m, which indicates that the hinterland for the Yangyi flora had achieved this height in the Late Pliocene. However, the current elevation of Yangyi fossil site is 1521 m and the highest mountain surrounding the Yangyi flora is below the elevation of 2500 m (Fig. 3) and so it appears that the mountains of the Yangyi region had no visible uplift since the Late Pliocene. The palynological assemblage of the Late Pliocene Yangyi flora indicates a vertical vegetation zone that includes humid evergreen broad-leaved forest, needle and broad-leaved mixed evergreen forest, and coniferous forest (Xu et al., 2003). Evidently, the Late Pliocene vegetation of Yangyi was very similar to that of today.

Both Jianchun and Eryuan lie to the east of the Gaoligong Mountains (Fig. 1). The Miocene Jianchuan flora consists mainly of subtropical genera such as evergreen *Quercus*, *Sassafras*, *Cinnamomum*, *Paliurus*, *Phoebe*, and *Cupressus*, which indicate that the vegetation in the Miocene can be attributed to subtropical evergreen broad-leaved forest (WGCPC, 1978; Ge and Li, 1999). The Late Pliocene palynoflora from Eryuan consists of 58 palynomorphs belonging to 49 families represented by conifers (*Pinus*, *Tsuga*, *Picea*, and *Abies*), angiospermous trees (*Quercus* and *Alnus*), and herbs (*Artemisia* and Chenopodiaceae) (Kou et al., 2006). Quite a few tropical or subtropical plants such as *Liquidambar*, Euphorbiaceae, Sapindaceae, and Palmae were also frequent (Kou et al., 2006). This palynological assemblage suggests that the Late Pliocene Eryuan vegetation is similar to that of Yangyi, which displays a distinct vertical distribution.

Table 2 shows the vegetation evolution of West Yunnan since the Miocene. Notably, the Miocene vegetation from Jianchuan is similar to those of Tengchong and Longling that were represented by subtropical evergreen broad-leaved forest. However, the vegetational evolution of West Yunnan exhibits a major change in the Late Pliocene. In the western edges of the Hengduan Mountains, the areas of Tengchong and Longling inherited the Miocene to Late Pliocene vegetation type of subtropical evergreen broad-leaved forest, which is also consistent with the modern vegetation. However, the Late Pliocene vegetation of Yangyi (eastern slope of Gaoligong Mountain) and Eryuan (northeast of Hengduan Mountains) are different from those of Tengchong and Longling, as there was formed a vertical montane vegetation zone that consisted of evergreen broad-leaved forest, needle and broad-leaved mixed evergreen forest, and coniferous forest. Therefore, we can infer that the vegetation types of West Yunnan underwent a major transition after the Miocene and before the Late Pliocene.

4.2. Paleoclimates

The paleoclimatic results derived from the eight Neogene floras from Tengchong, Longling, Jianchuan, Eryuan and Yangyi are listed in Table 1. In the present paper four leaf floras have been reconstructed using the CA and LMA. For comparison, paleoclimatic data using CLAMP analysis from the Pliocene Tengchong flora, the CA from one Miocene carpoflora of Longling and three palynofloras of the Late Pliocene of Longling, Yangyi and Eryuan, as well as the modern climatic parameters of these localities in West Yunnan are also considered.

Our investigations (Tables 1 and 3) indicate that the data from the CA of the Pliocene and Miocene floras of Tengchong are in accord with the CLAMP and LMA (Table 1), and the climates of Tengchong in both the Miocene and Pliocene were of warm subtropical type, which is supported by results from other studies (Sun et al., 2003a,b; Xie, 2007; Wu et al., 2008, 2009). The results show that the MAT in Tengchong is basically unaltered from the Miocene to the Pliocene whereas the MAP increased from 858.9–1546.4 (1202.7) mm in the Miocene to 1225.7–1695.4 (1460.6) mm in the Late Pliocene.

Based on the climatic preferences of the NLRs, Zhao et al. (2004) reconstructed the Miocene climate of Mangdan as a warm and humid subtropical climate with a MAT of 18.8–20.5 °C and a MAP of 1170–1300 mm (Tables 1 and 3). Accordingly, the present climates of the Mangdan (of Longling) region belong to the subtropical monsoon climate zone with a MAT of 19–21 °C and a MAP of 1300–1400 mm (Wu and Zhu, 1987), which indicates that the Miocene climates were similar to today's climates in this region, possibly with slightly less rainfall (Zhao et al., 2004). The climatic parameters obtained from the Late Pliocene palynoflora of Longling coal mine were also estimated using the CA (Xu, 2002; Xu et al., 2003). The MAT was 18.6–22.1 °C and MAP 815.8–1254.7 mm, which displays a marked difference from the Late Pliocene to the Holocene of today, with the MAT dropping to 14.9 °C but the MAP doubling to 2122 mm (Kou et al., 2006).

According to Xu (2002), the Late Pliocene climates of Yangyi were estimated to have a MAT of 13.3–20.9 °C and a MAP of 797.5–1254.7 mm. Evidently, the Late Pliocene MAT of Yangyi was similar to that of Tengchong (16.4–19.8 °C), but the MAP was much lower than that of Tengchong (1225.7–1695.4 mm).

The Miocene climates of Jianchuan were similar to those of Tengchong, but warmer and more humid relative to its present climate, which had a MAT of 13.8–21.7 °C and a MAP of 987.2–1546.4 mm (Table 3). However, the MAT of the Late Pliocene of Eryuan (near Jianchuan) (13.3–18.0 °C) was much lower than the Miocene MAT of Jianchuan. The MAP had dropped from 987.2–1546.4 mm of Jianchuan to 621.5–1546.4 mm of Eryuan (Table 3).

4.3. Geological significance

Much research has been done on the uplift of the Tibetan Plateau. Based on radiometric $^{40}Ar/^{39}Ar$ dating, geologists considered that the uplift of the plateau should have begun before 14 Mya at least in some parts (Turner et al., 1993; Coleman and Hodges, 1995; Searle, 1995; Coleman and Hodges, 2002). Other geologists also have concluded that the Tibetan Plateau attained its high mean elevation before the Late Miocene (at 8 Mya) (Quade et al., 1989; Molnar and England, 1990; Harrison et al., 1992; Cerling et al., 1993; Harrison et al., 1995; Quade and Cerling, 1995; Sun and Zheng, 2003). Ming (2007) analyzed the uplift phases of West Yunnan, viz. eastern Tibetan Plateau, in the neotectonics stage and concluded that the intense uplift phase had occurred in the Late Miocene and Early Pliocene. Magnetostratigraphic studies also supported the hypothesis that rapid uplift of the Hengduan Mountains (eastern part of the Tibetan Plateau) occurred before the Middle Pliocene (Chen 1996).

Fossil plants have been widely used for estimation of the uplift of the Tibetan Plateau. Using a numerical general circulation model to estimate moist static energy at a location of more than 400 leaf fossils, Spicer et al. (2003) reconstructed the elevation of the Namling Basin of the Plateau and concluded that the southern Plateau has remained unchanged for 15 Myr. Based on research of *Quercus* sect. *Heterobalanus* from the Miocene Namling and the Pliocene Xixabangma, Zhou et al. (2007) indicated that the Tibetan Plateau had undergone an intense uplift since the Miocene. Kou et al. (2006) reviewed the fluctuation of precipitation in West Yunnan since the Pliocene and indicated that uplift both of Gaoligong Mountain and the eastern portion of the Tibetan Plateau must have occurred during or after the late Pliocene.

The previous hypotheses mentioned above explain some aspects of the uplift of the Tibetan Plateau from either a geologic or paleobotanic point of view. However, the combination of paleovegetation and paleoclimate would also allow us to understand the rate and timing of uplift of the Plateau at least in a general sense.

In the Miocene, the region of Jianchuan in West Yunnan had a similar vegetation, as well as both MAT and MAP, to those of Tengchong, which indicates that mountainous terrain was not there at this time. However, in the period from the Miocene to Late Pliocene, the vegetation of Eryuan and Yangyi underwent a large change from subtropical evergreen broad-leaved forest to the altitudinal vegetation of today. At the same time, as shown in Table 3, the MAP has markedly increased on the western slope of Gaoligong Mountain (Tengchong and Longling) and reduced in the northeastern Hengduan Mountains (Jianchuan and Eryuan). The modern hypsographic and climatic gradient from Mangshi through Longling, Yangyi (Baoshan), Yongping to Eryuan (see Kou et al., 2006) (Fig. 3) demonstrates that the northerly moist air-stream (Indian monsoon) might have been obstructed by Gaoligong Mountain (Hengduan Mountains). Evidently, the regions of Yangyi and Eryuan have lower precipitation than that of Tengchong. Moreover, the local precipitation might also have caused a major alteration of the water cycle since the Early Pleistocene when the eastern portion of the Tibetan Plateau was at the plateau split-longitudinal ridge/valley development stage (Ming, 2007). The MAP of Longling doubled to 2122 mm and that at Tengchong increased slightly from the Late Pliocene to the present, but the precipitation at Yangyi and Eryuan shows no distinct change (Table 3).

Table 3 also shows that the MATs seemingly display a declining trend with increased latitude in the same epoch. Moreover, the temperatures of five sites drop from the Miocene through the Pliocene to the present, which felicitously demonstrates the global cooling trend since the Middle Miocene (Zachos et al., 2001). However, the MAP changes would mainly have been affected by orographic uplift rather than the global cooling. For example, relief rains would have significantly increased on the southwestern slope of Gaoligong Mountain whereas the moist air-stream might have been obstructed on the other slope. Combining the above discussion of vegetation evolution (see 4.1), we can see that a fairly large transition took place before the Late Pliocene, and from then on the modern vegetation and climates developed gradually.

In addition, the Miocene vegetation and climates show no distinct difference on either slope of the Gaoligong Mountain (see 4.1 and 4.2), which would suggest that there was no mountain there at this time. Therefore, we can conclude that the Hengduan Mountains (eastern portion of the Tibetan Plateau) must have risen after the Miocene and approached to its highest elevation before the Late Pliocene. Furthermore, the increase of MAPs in Tengchong and Longling gives support to the hypothesis that the eastern portion of the Tibetan Plateau had a slight uplift after the Late Pliocene.

5. Conclusions

Through comparison of paleovegetation and paleoclimatic data, our investigation provides the following outcomes. (1) In the Miocene, both slopes of Gaoligong Mountain possess similar vegetation of subtropical evergreen broad-leaved forest, and the MAT and MAP of Jianchuan were also similar to those of Tengchong and Longling. It would appear that there was no mountain here at this time. (2) In the Late Pliocene, vegetation diversification occurred between the southwestern and northeastern slopes of Gaoligong Mountain: Tengchong and Longling inherited the subtropical evergreen broad-leaved forest, but the paleofloras of Yangyi and Eryuan evolved into an altitudinal gradient, which consists of humid evergreen broad-leaved forest, needle and broad-leaved mixed evergreen forest, and coniferous forest in ascending order. The MATs and MAPs in the Late Pliocene of the southwestern slope (Tengchong and Longling) were close to those in the Miocene. However, the MATs and MAPs of the northeastern slope dropped markedly from the Miocene of Jianchuan to the Late Pliocene of Eryuan. The vegetation changes show that an intense uplift happened after the Miocene and that the mountains of West Yunnan had been formed roughly before the Late Pliocene. (3) The Late Pliocene vegetation of Tengchong, Longling, Yangyi and Eryuan was already similar to those of today. The MATs of the four sites have dropped 1–5 °C since the Late Pliocene, and the MAPs remained basically unchanged (except the MAP of Longling nearly doubled). The temperature drop might demonstrate global cooling and the doubling of MAP at Longling tends to indicate that Gaoligong Mountain may be continued to uplift slightly after the Late Pliocene.

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Appendix 1

The lists of plant fossils from the Cenozoic floras of West Yunnan, China, including fossil taxa, nearest living relatives (NLR) used for the Coexistence Approach (CA) analysis, and the climate requirements of the NLRs. MAT = mean annual temperature, CMT = coldest month temperature, WMT = warmest month temperature, and MAP = mean annual precipitation.

A: The fossil species and NLRs from the Late Pliocene Tuantian flora of Tengchong (Wu, 2009).

Family	Fossil taxon	NLR	MAT (°C)	CMT (°C)	WMT (°C)	MAP (mm)
Cupressaceae	*Calocedrus lantenoisii*	*Calocedrus*	15.6–25.8	10.8–22.1	19.6–28.6	858.9–2784.7
Aquifoliaceae	*Ilex* sp.	*Ilex*	5.6–27.7	(−2.6)–22.7	11.0–28.5	621.5–2442.7
Berberidaceae	*Mahonia* cf. *fortunei*	*Mahonia*	11.6–25.8	9.2–22.1	18.6–28.0	617.9–2540.0
Betulaceae	*Betula mioluiminfera*	*Betula*	3.2–22.1	(−3.2)–18.8	11.0–27.1	321.6–1695.4
Betulaceae	*Carpinus subcordata*	*Carpinus*	(−4.4)–25.8	(−12.4)–22.1	3.5–28.6	42.1–2439.2
Cornaceae	*Cornus megaphylla*	*Cornus*	(−4.2)–25.8	(−11.3)–22.1	4.3–28.6	16.0–2442.7
Dioscoreaceae	*Dioscorea* sp.	*Dioscorea*	5.3–25.8	(−1.2)–22.1	11.4–28.6	42.1–2442.1
Euphorbiaceae	*Mallotus* cf. *philippensis*	*Mallotus*	12.8–25.8	9.7–22.1	17.6–28.6	862.7–2150.3
Euphorbiaceae	*Mallotus longifolius*	*Mallotus*				
Fagaceae	*Castanopsis* cf. *sclerophylla*	*Castanopsis*	8.6–27.5	2.4–21.5	17.6–28.0	786.4–2150.3
Fagaceae	*Castanopsis* sp.	*Castanopsis*				
Fagaceae	*Cyclobalanopsis* cf. *multiervis*	*Cyclobalanopsis*	8.9–25.8	(−3.0)–21.5	15.6–29.3	621.5–2784.7
Fagaceae	*Cyclobalanopsis chevalieri*	*Cyclobalanopsis*				
Fagaceae	*Castanea miomollissima*	*Castanea*	(−2.5)–27.5	(−9.5)–19.6	3.5–27.5	106.0–2225.7
Guttiferae	*Garcinia* cf. *multiflora*	*Garcinia*	15.3–22.5	10.8–16.9	19.8–27.5	1070.5–2442.7
Hamamelidaceae	*Exbucklandia tengchongensis*	*Exbucklandia*	13.1–27.7	10.3–23.5	17.6–29.3	862.7–3054.4
Hamamelidaceae	*Rhodoleia tengchongensis*	*Rhodoleia*	15.3–27.7	10.8–23.5	20.1–29.3	1005.3–3054.4
Juglandaceae	*Juglans tengchongensis*	*Juglans*	0–27.5	(−3.2)–22.7	10.1–28.8	66.7–2150.3
Juglandaceae	*Juglans* sp.	*Juglans*				
Lauraceae	*Alseodaphne hainanensis*	*Alseodaphne*	16.3–25.8	8.6–21.6	21.3–29.0	858.9–2439.2
Lauraceae	*Machilus leptophylla*	*Machilus*	11.5–23.9	6.6–16.9	21.3–29.4	950.0–1917.0
Lauraceae	*Machilus* cf. *longipedicellata*	*Machilus*				
Lauraceae	*Machilus thunbergii*	*Machilus*				
Lauraceae	*Cinnamomum* cf. *subavenium*	*Cinnamomum*	13.5–27.2	2.5–26.1	18.6–28.8	828.0–3293.0
Lauraceae	*Cinnamomum tuantianensis*	*Cinnamomum*				
Lauraceae	*Lindera* cf. *angustifolia*	*Lindera*	3.2–24.1	2.0–21.5	11.0–28.0	510.7–2784.7
Leguminosae	*Robinia* sp.	*Robinia*	3.4–20.8	(−11.3)–22.7	17.6–28.6	106.0–3054.4
Leguminosae	*Ormosia* cf. *emarginata*	*Ormosia*	12.7–25.0	9.7–21.6	17.6–28.6	621.5–2784.7
Menispermaceae	*Cyclea* sp.	*Cyclea*	12.7–25.8	9.7–21.5	17.6–28.6	621.5–3054.4
Myricaceae	*Myrica* cf. *esculenta*	*Myrica*	12.8–28.1	9.7–23.5	17.6–29.3	621.5–2784.7
Myrtaceae	*Syzygium* cf. *buxifolium*	*Syzygium*	12.7–25.0	7.7–20.6	19.1–28.9	841.8–3081.3
Oleaceae	*Fraxinus* cf.*floribunda*	*Fraxinus*	12.7–23.6	7.7–16.9	19.3–29.0	858.9–2784.7
Rhamnaceae	*Berchemia miofloribunda*	*Berchemia*	3.2–24.1	(−3.2)–22.1	11.0–28.6	471.9–2784.7
Rhamnaceae	*Berchemia* cf. *yunnanensis*	*Berchemia*				
Rutaceae	*Evodia miosinica*	*Evodia*	3.2–25.0	2.0–22.1	11.0–29.0	659.7–2784.7
Smilaceae	*Heterosmilax* cf. *yunnanensis*	*Heterosmilax*	11.6–25.8	9.2–21.5	19.3–28.6	1225.6–3054.4
Ulmaceae	*Ulmus harutoriensis*	*Ulmus*	(−4.4)–27.7	(−12.4)–22.1	3.5–29.3	42.1–2784.7

B: The fossil species and NLRs from the Miocene Nanlin Formation of Tengchong (Tao and Du, 1982; Ge and Li, 1999).

Family	Fossil taxon	NLR	MAT (°C)	CMT (°C)	WMT (°C)	MAP (mm)
Anacardiaceae	*Rhus miosuccedanea*	*Rhus*	(−4.2)–25.8	(−11.3)–22.1	3.5–28.8	16.0–2442.7
Alangiaceae	*Alangium aequalifolium*	*Alangium*	8.5–27.7	(−0.2)–27.0	16.4–28.5	338.0–3151.0
Betulaceae	*Betula* sp.	*Betula*	(−4.2)–27.7	(−11.3)–22.4	3.5–29.3	15.6–3054.4
Cupressaceae	*Calocedrus lantenoisii*	*Calocedrus*	15.6–25.8	10.8–22.1	19.6–28.6	858.9–2784.7
Fagaceae	*Quercus* cf. *parachampionii*	*Quercus*	(−4.4)–27.7	(−12.4)–22.4	3.5–29.3	50.0–3054.4
Fagaceae	*Quercus* cf. *lianghensis*	*Quercus*				
Fagaceae	*Quercus* sp.	*Quercus*				
Fagaceae	*Lithocarpus lancifolius*	*Lithocarpus*	5.9–27.0	0.2–19.5	14.5–28.6	553.3–3151.0
Lauraceae	*Nothaphoebe* cf. *precavaleriei*	*Nothaphoebe*	3.0–26.5	(−6.0)–27.0	11.8–26.1	117.5–1546.4
Lauraceae	*Phoebe pseudoelanceolata*	*Phoebe*	6.9–27.0	(−7.3)–24.8	18.3–29.4	376.0–1900.0
Lauraceae	*Phoebe* sp.	*Phoebe*				
Leguminosae	*Gymnocladus* sp.	*Gymnocladus*	3.2–22.5	(−2.6)–19.5	11–28.6	659.7–2442.7
Magnoliaceae	*Magnolia* sp.	*Magnolia*	6.2–27.0	(−10.2)–25.9	19.6–28.6	578–3500
Meliaceae	*Chukrasia* sp.	*Chukrasia*	14.9–22.5	10.3–19.5	20.8–28.6	858.9–2442.7
Smilacaceae	*Smilax* sp.	*Smilax*	(−1.1)–27.7	(−9.7)–27.0	15.1–33.1	37.0–3151.0
Tiliaceae	*Tilia miohenryana*	*Tilia*	(−4.4)–25.8	(−12.4)–22.1	3.5–28.6	50.0–2446.8
Ulmaceae	*Celtis bungeana*	*Celtis*	(−4.2)–27.0	(−11.0)–19.5	3.5–28.6	16.0–3151.0

C: The fossil species and NLRs from the Miocene Shuanghe Formation of Jianchuan (WGCPC, 1978; Ge and Li, 1999).

Family	Fossil taxon	NLR	MAT (°C)	CMT (°C)	WMT (°C)	MAP (mm)
Juglandaceae	*Juglans* sp.	*Juglans*	0–27.5	(−3.2)–22.7	10.1–28.8	66.7–2150.3
Aceraceae	*Acer florinii*	*Acer*	2.7–24.0	(−15.6)–20.6	16.2–28.6	50.0–2446.8
Aceraceae	*Acer* sp.	*Acer*				
Anacardiaceae	*Pistacia miochinensis*	*Pistacia*	(−4.2)–22.5	(−11.3)–19.5	3.5–28.6	16.0–2442.7
Anacardiaceae	*Rhus trifolia*	*Rhus*	(−4.2)–25.8	(−11.3)–22.1	3.5–28.8	16.0–2442.7
Betulaceae	*Alnus* sp.	*Alnus*	(−6.3)–27.7	(−16.5)–19.5	2.0–29.3	371.4–3054
Cupressaceae	*Cupressus* sp.	*Cupressus*	13.8–21.7	7.7–19	16.7–27.3	621.5–1921.2
Fagaceae	*Quercus scottii*	*Quercus*	(−4.4)–27.7	(−12.4)–22.4	3.5–29.3	50.0–3054.4
Fagaceae	*Quercus spathulata*	*Quercus*				
Fagaceae	*Quercus* sp.	*Quercus*				
Fagaceae	*Fagus* sp.	*Fagus*	3.2–23.1	(−2.6)–19.6	11.0–28.8	529.5–2784.7
Lauraceae	*Sassafras paratsumu*	*Sassafras*	12.7–25.8	7.7–22.1	17.6–28.8	987.2–2442.7
Lauraceae	*Cinnamomum* sp.	*Cinnamomum*	13.5–27.2	2.5–26.1	18.6–28.8	828–3293
Lauraceae	*Phoebe pseudolanceolata*	*Phoebe*	6.9–27.0	(−7.3)–24.8	18.3–29.4	376.0–1900.0
Lauraceae	*Phoebe megaphylla*	*Phoebe*				
Lauraceae	*Phoebe* sp.	*Phoebe*				
Pinaceae	*Picea* sp.	*Picea*	(−8.9)–21.7	(−25)–18.9	2.0–28.6	275.5–1546.4
Pinaceae	*Pinus* sp.	*Pinus*	(−4.4)–25.8	(−12.4)–22.1	3.5–28.8	50.0–2446.8
Rhamnaceae	*Paliurus* sp.	*Paliurus*	12.7–25.8	7.7–22.1	17.6–28.8	987.2–2442.7
Ulmaceae	*Zelkova ungeri*	*Zelkova*	(−0.9)–25.8	(−7.2)–22.1	5.7–28.8	113.0–2442.7
Ulmaceae	*Ulmus* sp.	*Ulmus*	(−4.4)–27.7	(−12.4)–22.1	3.5–29.3	42.1–2784.7

D: The fossil species and NLRs from the Pliocene Sanying Formation of Eryuan (Tao and Kong, 1973; Ge and Li, 1999).

Family	Fossil taxon	NLR	MAT (°C)	CMT (°C)	WMT (°C)	MAP (mm)
Aceraceae	*Acer paxii*	*Acer*	2.7–24.0	(−2.6)–20.6	16.2–28.6	115.0–2559.0
Caprifoliaceae	*Viburnum ovalifolium*	*Viburnum*	(−4.4)–27.7	(−12.4)–22.1	3.5–29.3	42.1–2784.7
Fagaceae	*Quercus aquifoliodes*	*Quercus* sect. *Heterobalanus*	(−4.2)–18.0	(−11.3)–11.8	3.5–25.4	321.6–1546.4
Fagaceae	*Quercus senescens*	*Quercus* sect. *Heterobalanus*				
Fagaceae	*Quercus semicarpifolia*	*Quercus* sect. *Heterobalanus*				
Fagaceae	*Quercus pannosa*	*Quercus* sect. *Heterobalanus*				
Fagaceae	*Quercus monimotricha*	*Quercus* sect. *Heterobalanus*				
Fagaceae	*Quercus norini*	*Quercus*	(−4.4)–27.7	(−12.4)–22.4	3.5–29.3	50.0–3054.4
Fagaceae	*Quercus gilliana*	*Quercus*				
Fagaceae	*Quercus spathulata*	*Quercus*				
Pinaceae	*Pinus yunnanensis*	*Pinus*	(−6.7)–27.7	(−25.0)–22.4	8.9–29.3	50.0–3151.0
Salicaceae	*Populus* sp.	*Populus*	(−6.7)–26.0	(−25.0)–22.1	8.9–28.6	50.0–2784.7
Trapaceae	*Trapa* sp.	*Trapa*	(−4.4)–27.7	(−12.4)–22.4	3.5–29.3	50.0–3054.4
Ulmaceae	*Celtis bungeana*	*Celtis*	(−4.2)–27.0	(−11.0)–19.5	3.5–28.6	16.0–3151.0

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