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Pollen stratigraphy, vegetation and environment of the last glacial and Holocene—A record from Toushe Basin, central Taiwan

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Abstract

The pollen record from the Toushe Basin (23°49′N; 120°53′E; 650 m above sea level), a peat bog of central Taiwan, displays a continuous vegetation history of the past 96,000 yr BP of monsoon Asia. Instead of today's closed subtropical evergreen broadleaved forest dominated by *Machilus–Castanopsis* surrounding the basin, temperate deciduous forest predominated during most of the last glacial. In early MIS 4, *Alnus* reaches the highest value of the whole sequence (60–70%) representing temperate deciduous forest and relatively cold and arid conditions. Following this stadial, *Alnus* and herbs (mainly Cyperaceae) dominated alternately, with a minor increase of *Castanopsis.* Peaks of monolete spores between cal. 42.2 and 37.0 kyr BP (kyr BP represent calibrated years) indicate episodic wet conditions. The later glacial, especially between 23.2 and 18.7 kyr BP, shows a high percentage of Gramineae, indicating dry and possibly sometimes cold conditions. The late glacial shows a remarkable increase of warm-temperate to temperate forest elements, such as *Ilex*, *Cyclobalanopsis* and *Symplocos.* At about 15.1 kyr BP a peak of monolete spores indicates wet–warm conditions. A subsequent sharp increase of *Salix* and then Gramineae between 13.0 and 11.6 kyr BP corresponds to the Younger Dryas. A warming event at 11.5 kyr BP is also evident. The Holocene is characterized by warm–wet conditions of the overwhelmingly abundant monolete spores since 10.7 kyr BP and the prominent increase of *Castanopsis*.

1. Introduction

Toushe Basin (23°49′N; 120°53′E; 650 m above sea level), a 1.75 km^2 desiccated peat bog in the low hills of central Taiwan, is one of a series of north–south trending middle Pleistocene tectonic basins along the island's backbone (Fig. 1). To the north lies Sun-Moon Lake (or Jih-Yueh Tan, 750 m above sea level) where a pollen sequence covering time since the last glacial has been reported by Tsukada (1967). Mountains surrounding these basins range in altitude from 700 m to higher than 1000 m eastward. The fluvial and lake deposits in Toushe Basin are about 80 m thick. The bog became desiccated at about 1.8 kyr BP.

In the context of global climate, changes in low-latitude areas have the same importance as those at high latitudes. Marine records of the last glacial from offshore Taiwan show that low-latitude sea-surface temperature is not as warm (Huang et al., 1997) as previously estimated by CLIMAP (1981). This is also shown for other low-latitude terrestrial areas (Flenley, 1979; Hooghiemstra, 1989; Farrera et al., 1999). On the other hand, a chronological discrepancy of climatic events between the two poles is recognized (Sowers and Bender, 1995). Thus, the latitudinal variations of regional climates should be better understood before attempting to interpret the global features of climate change, even though the climate conditions of higher latitude since the last glacial have been well documented. The tropical–subtropical record is crucial in understanding the driving force of climate change from a global point of view (Stock, 1999). Recent studies from the stalagmites of Hulu Cave (China) show that the timing of changes in the monsoon generally agrees with the timing of temperature changes from the Greenland ice core GISP2 (Wang et al., 2001). This indicates that the East Asian monsoon is integral to millennial-scale changes in atmosphere/oceanic circulation patterns and is affected by orbitally induced insolation variations. Remarkable

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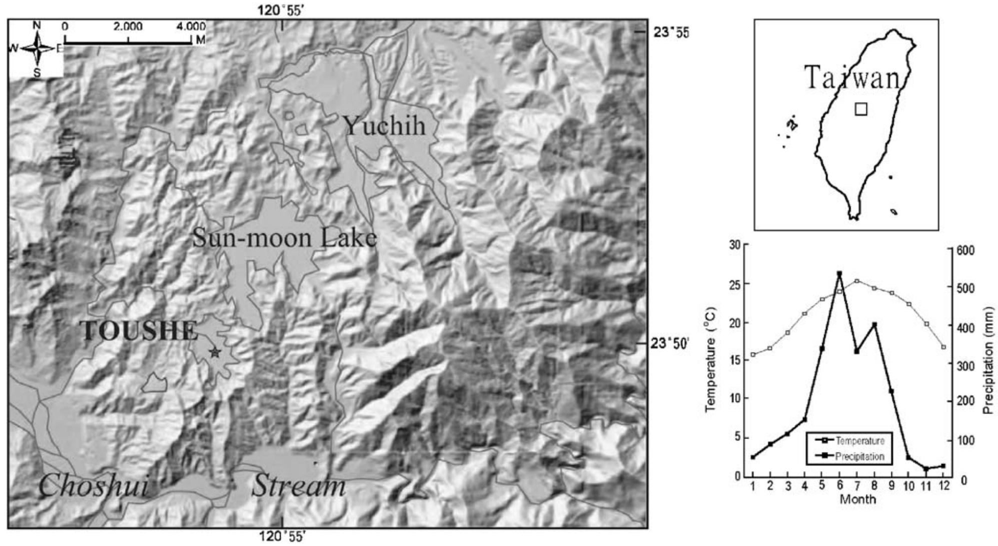


Fig. 1. Location map of the studied site with the climate conditions of Sun-Moon Lake.

vegetation and climate changes during glacial time in the subtropical island of Taiwan were found in a previous study of Sun-Moon Lake (Tsukada, 1967). According to his study, by excluding *Alnus* pollen, an early stadial at some time subsequent to 60,000–50,000 BP contains predominantly boreal conifers and pine and a low percentage of temperate elements, indicating a temperature decrease of 8–11 °C; the period from about 50,000 to 10,000 BP is dominated by cool-temperate species. However, there are only four radiocarbon dates in the core and a detailed record of climate change is not available. It is important to obtain a high-resolution pollen record with good age control from the last glacial in Taiwan so as to reveal the synchronism (or not) of global climate events. Thus, the Toushe Basin was chosen for a study of its palynostratigraphy. We use biomization of fossil pollen assemblages as proposed by Prentice et al. (1992, 1996) and used for the reconstruction of vegetation in Europe, Africa and Asia to discuss the climatic conditions of the stadials and interstadials of the last glacial and Holocene based on the record of surface pollen assemblages of the natural forests nearby in the Salixian area (Jolly et al., 1998; Tarasov et al., 1998; Yu et al., 1998; Allen et al., 2000; Takahara et al., 2000; Gotanda et al., 2002). We aim to describe the vegetational changes quantitatively so as to interpret the magnitude of possible environmental changes. The simplified pollen diagram of the upper 17 m of this site has been published previously (Liew et al., 1998; Kuo and Liew, 2000), but data to 39.5 m depth will be described here.

2. Modern vegetation and climate of the study area

Taiwan is a subtropical mountain island whose climate is dominated by the East Asian monsoon. Warm–wet summers and cool-relatively dry winters prevail and the whole island is generally humid. According to the meteorological data near the study site (Fig. 1), the Sun-Moon Lake Station (altitude 1014 m) immediately north of the Toushe peat bog, mean annual rainfall is 2341 mm, annual evaporation is 1098 mm and mean annual temperature is 19.2 °C. The coldest month has an average temperature of 13.9 °C, whereas the warmest month is 23.6 °C, with an average of 155.6 rainy days. The estimated mean annual temperature of Toushe is 21.2 °C, the lapse rate being 0.54 °C/100 m. The present vegetation surrounding the study area belongs to the subtropical evergreen Lauro-Fagaceae forest. This forest consists mainly of *Machilus kasanoi*, *M. zuihoensis*, *Beilschmiedia erythrofolia*, *Phoebe formosana*, *Sapium discolor*, *Michelia formosana*, *Cyclobalanopsis flauca*, *Pasania uraiana*, *P. konishii*, *P. ternaticupula*, *P. brebicaudata*, *Ardisia sieboldii*, *Zelkova fomosana*, *Engelhardtia roxburghiana*, *Glochidion hongkongensis*, *Trema orientalis*, *Liquidambar formosana*, *Rhus succedanea*, *Schefflera octophylla*, *Castanopsis hystrix*, *Quercus variabilis*, *Fraxinus formosana*, *Lagerstroemia subcostata*, *Symplocos theophrastaefolia* and *Sapindus mukorosii* among others (Lin et al., 1968).

Tsukada (1967) described the vegetation of mountain forests above the nearby subtropical forest as follows:

- *Warm-temperate forest (ca. 500–1800 m)*: Dominated by *Castanopsis*, *Lithocarpus*, *Cyclobalanopsis* and *Cinnamomum* with other broadleaved species and with conifers such as *Keteleeria* and *Podocarpus* species. The undergrowth is crowded with ferns and mosses.
- *Cool-temperate forest (ca. 1800–2400 m)*: Composed of deciduous hardwood species of *Cyclobalanopsis*, *Ulmus*, *Zelkova*, *Juglans*, *Carpinus* and others, mixed with conifers including *Chamaecyparis*. *Cyclobalanopsis* and the *Chamaecyparis* species form two separate associations but both groups occupy the misty climate belt.

- *Subalpine coniferous (or boreal) forest (ca. 2400–3500 m)*: Composed of *Tsuga chinensis*, *Abies kawakami* and *Picea morrisonicola* mixed with *Pinus armandii*. Above about 3300 m, alpine shrubs and herbs occur.

Su (1984) studied the vegetation in the mountains of central Taiwan and identified the following altitudinal zones (Fig. 2) with annual temperature range:

(1) *Ficus–Machilus* Zone (below altitude 500 m; 23–26 °C; tropical): Lowland evergreen broadleaved forest including species of *Ficus* and *Machilus*.
(2) *Machilus–Castanopsis* Zone (500–1500 m; 17–23 °C; subtropical), submontane evergreen broadleaved forest with two major types: 1. *Castanopsis* type: mainly composed of *Castanopsis hystrix*, *C. Kawakamii*, *Schima superiba*, *Engelhardtia*, *Lithocarpus* and 2. *Machilus* type: mainly *Machilus japonica*, *M. kusanoi*, *Ficus*, *Lagerstroemia* and tree fern species.
(3) Lower *Quercus* Zone (1500–2000 m; 14–17 °C; warm temperate), with major components *Cyclobalanopsis longinus*, *C. gilva, Lithocarpus* and *Litsea* species.
(4) Upper *Quercus* Zone (2000–2500 m; 11–14 °C; temperate), with major components *Cyclobalanopsis morii*, *C. stenophylloides*, *Trochodendron* and *Castanopsis carlesii.*
The Upper *Quercus* Zone is often mixed with montane mixed coniferous forest including *Chamaecyparis*, Pinaceae and Taxodiaceae, although they may separate into associations. When local conditions are less humid, montane deciduous broadleaved forest appears in *Quercus* Zone including species of *Acer, Juglans*, *Ulmus*, *Carpinus*, *Platycarya* and *Quercus*. When aridity increases *Alnus formosana* prevails in this zone although this tree may appear at altitudes between 900 and 2600 m. However, *Alnus* with *Salix*, *Carpinus* and *Acer* frequently appear near 2000 m, whereas *Alnus* associated with Urticaceae usually occurs below this altitude. In addition, *Pinus* exists in the still drier conditions of this zone.
(5) *Tsuga–Picea* Zone (2500–3100 m; 8–11 °C; cool temperate), with major components *Tsuga chinensis*, *Picea morrisonicola* and *Pinus armandii mastersiana*.
(6) *Abies* Zone (3100–3600 m; 5–8 °C; cold temperate), mainly *Abies kawakami.* Beyond 3300 m, alpine shrubs and herbs are scattered.
(7) Alpine vegetation (>3600 m; <5 °C; cold), mainly Gramineae with some *Juniperus*.

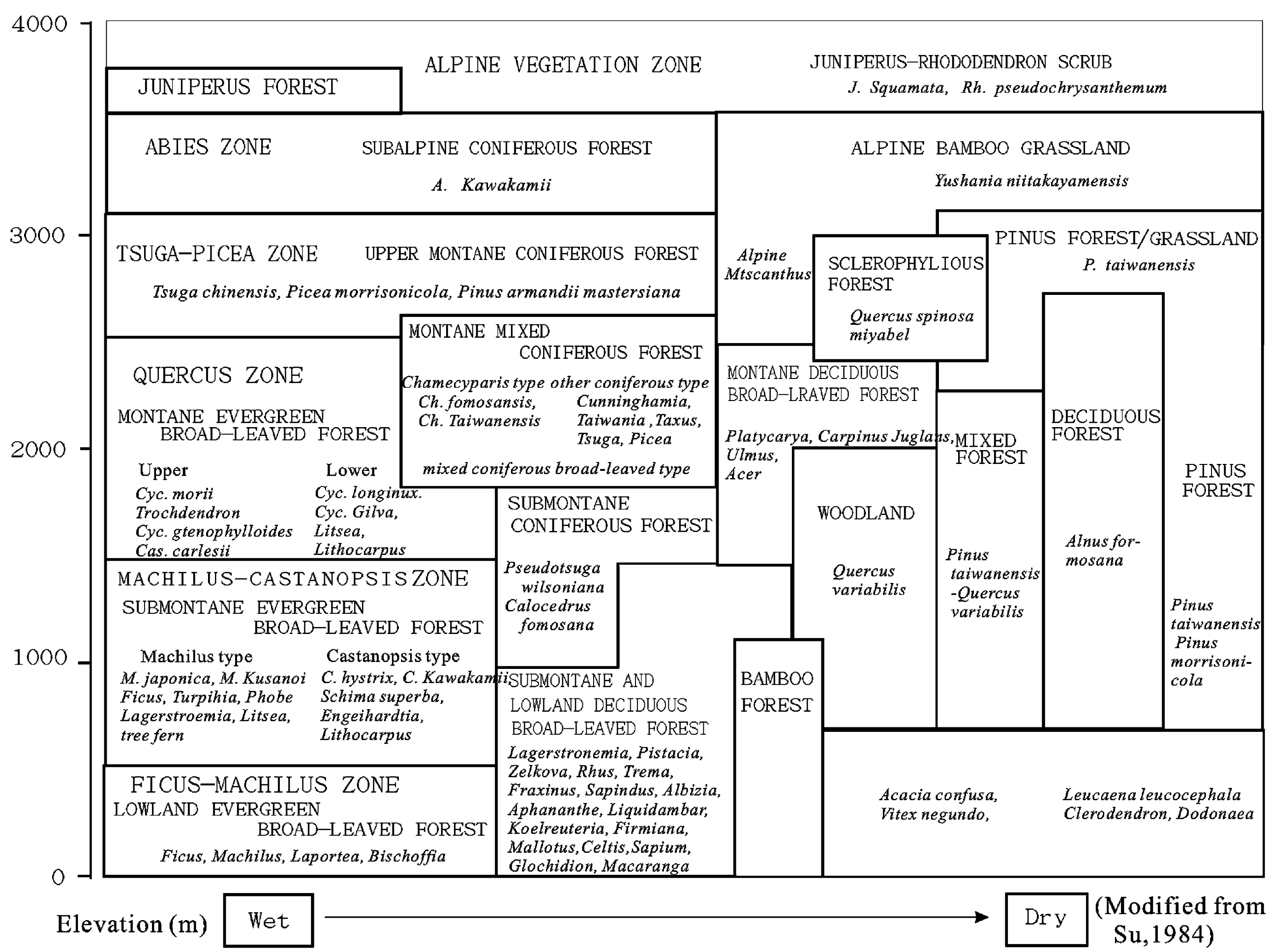


Fig. 2. Present vegetational zone in mountain area, central Taiwan (after Su, 1984).

In an effort to elucidate the fossil sequence of Toushe, a preliminary study was made of the surface pollen assemblages of the natural forest in Salixian (23°28′–23°33′N; 120°53′–120°59′E), 30 km southeast of the Toushe site (Liew and Chung, 2001). This area includes the *Machilus–Castanopsis* Zone, Lower and Upper *Quercus* Zones and *Picea–Tsuga* Zone (Fig. 2) of Su (1984) between altitudes 700 and 2800 m (Chung, 1994). Pollen assemblages above 2500 m, the *Picea–Tsuga* Zone, are dominated by *Pinus*, *Tsuga* and *Picea*. Below 2500 m, in the Upper and Lower *Quercus* Zones, pollen assemblages are more complex. Between 2500 and 2250 m, an *Alnus*-dominant pollen assemblage appears while below 2250 m *Castanopsis*-dominant pollen assemblages are common. *Cyclobalanopsis* pollen is expected to prevail in the *Quercus* Zone if sampling in different parts of this zone is wide enough to cover more associations of this zone. Nevertheless, the Upper *Quercus* Zone may sometimes also be represented by a *Castanopsis*-dominant pollen assemblage associated with *Cyclobalanopsis* and *Alnus*, even though *Cyclobalanopsis* is common in this zone. This is possibly because some of the prevailing genera in the zone belong to the *Castanopsis* pollen types, such as *Castanopsis carlesii.* *Castanopsis*-type pollen includes *Castanopsis*, *Lithocarpus* and *Pasania*, totaling 26 species. However, *Castanopsis-dominant* pollen assemblages in the *Quercus* Zone (above 1500 m) can still be differentiated from those of the *Castanopsis–Machilus* Zone (below 1500 m) if there exist significant associated elements in the pollen assemblages. The latter are characterized by *Castanopsis* associated with subtropical to warm-temperate elements such as *Elaeocarpus, Diospyros* and Euphorbiaceae, and abundant spores, which are different from those of the *Castanopsis*-dominant assemblages at higher altitudes.

3. Methods

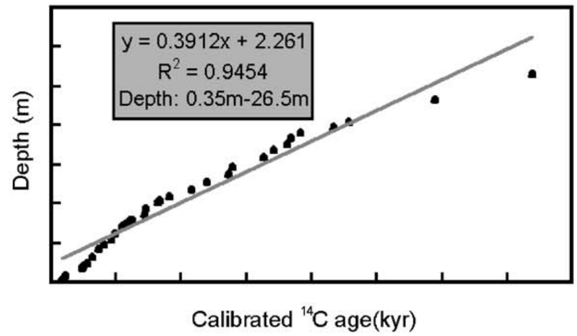
3.1. Chronology

The 39.5-m-long core was taken in the center of this small, rectangular basin. The sediment from 39.5 to 32.8 m depth is clay. The upper 32.8 m is mainly peaty sediments intercalated with thin layers of clay or gyttja except for backfill in the top 0.3 m. Each sample for analysis was about 1 cm^3, with an average sampling interval of 9 cm. The total number of samples is 395, yielding 114 pollen taxa. Thirty-one radiometric analyses were performed, including three AMS and 28 radiometric ^{14}C dates. Each sample for conventional ^{14}C dating was 6–10 cm in length. The sedimentation rate is relatively constant, as shown in Fig. 3. Ages of sediments beyond the limit of ^{14}C radiometric dating are extrapolated by tentatively correlating the *Alnus*-dominant interval with MIS 4 (MIS 3/4, 23.3 m and MIS 4/5a, 26.5 m) (Martinson et al., 1987). This high *Alnu*s-interval, representing cold/dry conditions, is most likely to correspond to MIS 4. It contrasts with the layer beneath where less cold and less dry elements, i.e. *Castanopsis* or Cyperaceae, are still significant. The bottom of this core at 39.5 m is estimated as 95.2 kyr BP by the least-squares equation shown in the figure, and the ages of depths between 39.5 and 26.5 m are then extrapolated.

3.2. Vegetation reconstruction

Yu et al. (2002) transferred the surface pollen assemblages of Salixian (Liew and Chung, 2001) into modern vegetational types by the biomization technique (Prentice et al., 1996) by which vegetation can be described by biomes and major vegetation categories defined on the basis of their dominant plant functional types (PFTs). However, the ecological reference is not as complete at that time as it is at present and the results show overlaps between the upper boundary of subtropical/warm temperate and also between warm-temperate/temperate vegetation types. In this study, we slightly modified (Tables 2 and 3) the previous work of Yu et al. (2002) with reference to the altitudinal vegetational zones of Su (1984) (Fig. 2) and also to newly available ecological data (Editorial Committee of the Flora of Taiwan, 1993, 1994, 1996, 1998, 2000). For example, PFT sut are those broadleaved evergreen plants that appear in subtropical evergreen forest (*Machilus–Castanopsis* Zone of Su; 500–1500 m in altitude central Taiwan). We attempted to name biomes by following the aforementioned altitudinal zones proposed by Su (1984). Thus, the tropical evergreen forest corresponds to the *Ficus–Machilus* Zone (<500 m; >23 °C) and subtropical evergreen forest to the *Machilus–Castanopsis* Zone (500–1500 m; 17–23 °C); warm-temperate evergreen forest to the Lower *Quercus* Zone (1500–2000 m; 14–17 °C) and temperate broadleaved and conifer mixed forests (comprised of the montane evergreen forest, montane mixed coniferous forest; montane deciduous forest) to the Upper *Quercus* Zone (2000–2500 m; 11–14 °C); cool-temperate coniferous forest to the *Tsuga–Picea* Zone (2500–3100 m; 8–11 °C). We also included in the biome list the tropical rain forest occurring in southern but not in central Taiwan, and for the biomes absent in Taiwan we followed Yu et al. (2002), and Editorial Committee of the Vegetation of China (1980) as a reference to forest steppe.

A test of modern forest reconstruction is carried out by using the same set of surface pollen assemblages in Salixian that was used by Yu et al. (2000). We apply two strategies when assigning *Castanopsis*-type pollen in PFTs: (1) include *Castanopsis* in PFTs sut and wte2, i.e. in subtropical and warm-temperate forests since *Castanopsis* is the main forest element of subtropical and warm-temperate forests; (2) include *Castanopsis* in PFTs sub, wte2 and wte1, i.e. in subtropical, warm temperate and also temperate broadleaved and conifer mixed forests, since four of 26 species of *Castanopsis*-type pollen grow in temperate broadleaved and conifer mixed forests. Among the 16 sites between altitudes 700 and 2800 m in the Salixian area, the result of strategy (1) shows two sites incorrectly assigned (altitudes 2000 and 2150 m: temperate



Depth (cm)	^{14}C age (yr B.P.)	Calibrated ^{14}C age (yr)	Lab no or ^{18}O age equivalent
30-40	1840±50	1711-1857	NTU-1883
80-90	2230±50	2156-2326	NTU-1862
172-182	4230±50	4650-4851	NTU-1873
190-210	4410±40	4873-5042	NTU-2061
235-245	4800±50	5473-5594	NTU-2062
310-320	5640±60	6314-6487	NTU-1856
420-430	6480±60	7319-7430	NTU-1865
473-483	7370±60	8041-8289	NTU-1928
535-545	8270±70	9131-9417	NTU-1934
610-620	8780±60	9633-10105	NTU-1847
705-707	9600±130	10750-11157	NZ-4089
700-710	9720±60	10892-11201	NTU-1852
733-734	10059±87	11263-11885	NZA-6258
780-781	10309±89	11768-12582	NZA-6259
787-796	10450±70	12158-12786	NTU-1944
861-870	12100±90	14380-14942	NTU-1988
930-941	12350±90	14116-15053	NTU-1996
1008-1019	13700±100	16188-16701	NTU-3006
1035-1045	13900±100	16416-16933	NTU-2077
1084-1095	15200±110	17872-18469	NTU-2068
1177-1187	18150±120	21205-21925	NTU-2039
1275-1285	20500±100	23944	NTU-2766
1370-1380	23400±190	27331	NTU-2763
1460-1467	23900±150	27915	NTU-2765
1587-1592	28000±250	32704	NTU-3017
1680-1686	29300±300	34222	NTU-3022
1758-1764	31100±400	36325	NTU-2182
1840-1846	31600±350	36909	NTU-2233
1900-1906	32800±500	38310	NTU-2236
1973-1979	37200±600	43450	NTU-3135
2036-2042	39200±600	45786	NTU-2166
2330		58960	Stage3/4
2650		73910	Stage4/5a

Equation incorporates ^{18}O ages for the pollen equivalents stages 3/4 and stages 4/5a boundaries.

Fig. 3. Ages and information used to establish age–depth relations at Toushe bog. Radiocarbon yr were converted to calendar yr (kyr) by use of refs Bard et al. (1998) and Stuiver and Reimer (1993).

broadleaved and conifer mixed forests are incorrectly assigned to warm temperate evergreen forest). The result of strategy (2) shows three sites incorrectly assigned (altitudes 1500 m: warm-temperate forest incorrectly assigned to temperate broadleaved and conifer mixed forest; 1780 m: warm-temperate forest incorrectly assigned to subtropical forest; 2150 m: temperate broadleaved and conifer mixed forests incorrectly assigned to subtropical forest). In Japan, Gotanda et al. (2002), following Takahara et al. (2000), studied the reconstruction of forests by surface pollen samples. They improved the reconstruction of present forests by assigning *Fagus* to temperate deciduous forest instead of several forest types and excluding Gramineae. For the biomization of the Toushe fossil pollen sequence, we use strategy (1) based on the better results of the modern forest reconstruction in Salixian, by assigning *Castanopsis* in subtropical and warm-temperate forests (Tables 2 and 3).

4. Palynostratigraphy of the Toushe bog

4.1. Palynological zones

The pollen zones are described as follows and also in Table 1. The percentage of each pollen genus is based on the total pollen sum, whereas that of spores is based on the sum of pollen and spores (Figs. 4.1 and 4.2). In the following discussion, years (e.g. 2.9 kyr BP) represent calibrated years, and ^{14}C years are expressed as 2900 yr BP.

Zone 20 (39.5–39.0 m, tentatively estimated as 95.2–94.4 kyr BP): arboreal pollen (AP) is about 70% in which *Castanopsis* is dominant (>60%). Other associated elements are *Cyclobalanopsis*, *Quercus* and *Symplocos*.

Zone 19 (39.0–37.2 m, tentatively estimated as 94.4–91.4 kyr BP): AP still prevails but Cyperaceae and Gramineae continuously increase. Among the AP, *Castanopsis* and *Salix* are the most important. Associated elements are *Quercus* and *Cyclobalanopsis*. Compared with the previous zone, *Salix* increases to more than 20% at the expense of *Castanopsis*. *Liquidambar* and *Ilex* values also increase.

Zone 18 (37.2–35.6 m, tentatively estimated as 91.4–88.8 kyr BP): is characterized by an abrupt increase of Pteridophytes (>60%). AP is dominant, *Symplocos* (>50%) and *Myrica* (25%) being the most common ones.

Zone 17 (35.6–30.5 m, tentatively estimated as 88.8–80.5 kyr BP): AP reaches 60%, slightly less than in the previous zones in which the major element *Castanopsis* (20–40%) again reaches its dominant situation. *Myrica* reaches 15% in the lower part. Cyperaceae increase upward to 30%.

Zone 16 (30.5–29 m, tentatively estimated as 80.5–78.0 kyr BP): is characterized by a sharp decrease of *Castanopsis*, from 40% to <15%, and herbs outnumber arboreal pollen for the first time. Cyperaceae increase to 40% or more, whereas *Salix* increases remarkably in the upper part at the expense of Cyperaceae.

Zone 15 (29–28.2 m, tentatively estimated as 78.0–76.7 kyr BP): exhibits remarkable changes in both AP and NAP (non-arboreal pollen). AP dominates in this zone (80%) but instead of *Castanopsis*, the major tree pollen are *Ilex* (40%) and *Alnus* (up to 70%). *Alnus* reaches its climax for the first time in this sequence. *Castanopsis* is at about 5%, even less than in Zone 16, and is lower than *Cyclobalanopsis*. Cyperaceae decrease sharply, while the *Artemisia* content rises slightly.

Zone 14 (28.2–26.5 m, tentatively estimated as 76.7–73.9 kyr BP): Cyperaceae dominate in the lower part. *Alnus* sharply decreases while *Cyclobalanopsis* increases. In the upper part *Alnus* reaches 40%. *Cyclobalanopsis* (about 15%) is higher than *Castanopsis* and maintains this trend during the glacial. *Artemisia* is relatively higher in Zones 14 and 15.

Zone 13 (26.5–23.3 m, tentatively assigned as 73.9–59.0 kyr BP): AP dominates (>80%) with *Alnu*s as the major component (generally 60% or more). *Salix* increases while *Cyclobalanopsi*s decreases in comparison with the previous zone. Cyperaceae decrease as well. *Pinus* decreases from Zone 15 upward.

Zone 12 (23.3–23 m), tentatively estimated as 59.0–57.6 kyr BP: is characterized by a decrease of *Alnus* (20%) and *Salix* and the increase of *Ilex* (from <5% to >25%).

Zone 11 (23.0–22.4 m, tentatively estimated as 57.6–54.0 kyr BP): *Alnus* predominates again (60%). Compared with Zone 13, *Castanopsis* and *Symplocos* increase at the expense of *Salix*. *Symplocos* occasionally increases in Zones 11 and 12.

Zone 10 (22.4–21.0 m, tentatively estimated as 54.0–48.5 kyr BP): *Alnus* decreases remarkably to about 40% or even less, although it is still the main component of AP. *Cyclobalanopsis* and *Castanopsis* are relatively significant, similar to the last two zones 12 and 11. *Ilex* and *Symplocos* decrease. Cyperaceae dramatically increase again. *Castanopsis* is relatively higher from Zones 12 to 10, after its decrease to a very low value in Zone 13.

Zone 9 (21.0–18.4 m, tentatively estimated as 48.5–36.9 kyr BP): *Alnus* has the same amount as in Zone 10 but peaks at the middle. Cyperaceae frequently fluctuate at the expense of *Alnus*. The most notable feature is the increase of Pteridophytes, especially monolete spores. *Salix* increases episodically in this zone. *Castanopsis* decreases slightly and maintains the trend from this zone upward until the beginning of the Holocene. *Ilex* is common from Zone 12 upward.

Zone 8 (18.4–16 m, cal. 36.9–31.2 kyr BP; ^{14}C years, 41,100–31,600 yr BP): Pteridophytes and Cyperaceae decrease sharply. Compared with the previous zone *Alnus* and *Ilex* increase while *Cyclobalanopsis* decreases. Gramineae increase slightly.

Zone 7 (16–14.6 m, 31.2–27.9 kyr BP; 31,600–23,900 yr BP): *Cyclobalanopsis* slightly increases. *Alnus* is still dominant with a level similar to the previous zone. *Ilex* and *Symplocos* decrease. *Castanopsis* increases slightly. *Alnus* is relatively low but with remarkable fluctuations from Zones 10 to 7.

Zone 6 (14.6–13.8 m, 27.9–27.4 kyr BP; 23,900–23,400 yr BP): compared with Zone 7, *Alnus* increases clearly. *Cyclobalanopsis*, *Castanopsis*, *Quercus*, *Ligustrum* and *Salix* decrease. *Artemisia* decreases slightly. Zones 6–12 are assumed to belong to MIS 3.

Table 1
Toushe bog pollen zones with inferred paleovegetation and paleoclimate

Zone depth and age	OIS and age	Characteristics	Paleovegetation	Paleoenvironment
1b (1.4–0.3 m) 3.8–1.8 kyr BP	1	Herbaceous pollen rise (70–80%). Increase in *Liquidambar*; decrease in *Cyclobalanopsis*, *Ilex*. Cyperaceae and Gramineae frequent. Increase in pteridophytes	Grassland	Subtropical to warm temperate, wet
1a (2.5–1.4 m) 5.7–3.8 kyr BP	0–12.1k yr	Herbaceous pollen increase. Increase in *Salix*, *Symplocos*, *Ilex*; decrease in *Mallotus*. Increase in Cyperaceae	Subtropical forest but fluctuated	Fluctuated subtropical to temperate
2c (3.1–2.5 m) 6.3–5.7 kyr BP		Increase in *Ilex*, *Ligustrum*; decrease in *Pinus.* Decrease in Cyperaceae and pteridophytes	Subtropical to tropical forest	Subtropical, less wet
2b (3.9–3.1 m) 7.0–6.3 kyr BP		Increase in Gramineae and Cyperaceae, *Salix* peaks at first and then decrease. Increase in *Pinus*. Increase in pteridophytes (to 50%)	Subtropical forest mainly	Subtropical, wet
2a (4.7–3.9 m) 8.0–7.0 kyr BP		Woody taxa sum increase slightly. Increase in *Ilex* and *Mallotus*, *Salix* peak at early part. Sharp decrease in pteridophytes and Cyperaceae	Subtropical forest but fluctuated	Fluctuated subtropical to temperate less wet
3 (7.10–4.7 m) 11.0–8.0 kyr BP		Woody taxa sum decreases (to 40%). Increase in *Castanopsis*, *Trema*, *Pinus*; decrease in *Cyclobalanopsis* and *Symplocos. Salix* varies; peak of *Ilex* at middle. Increase in Cyperaceae and Gramineae, sharp increase in pteridophytes	Subtropical to warm-temperate forest	Subtropical to warm temperate, wet
4d (7.6–7.10 m) 11.9–11.0 kyr BP		Increase in *Cyclobalanopsis*, *Symplocos* and *Salix*; increase in Gramineae (to 40%)	Temperate to subtropical forest	Temperate, less dry
4c (9.2–7.6 m) 14.5–11.9 kyr BP		Woody taxa ≒85%. Increase in *Salix*, *Symplocos*. Decrease in Cyperaceae and *Artemisia*. Gramineae is low but peak at end. Decrease in pteridophytes	Temperate forest	Temperate, less dry
4b (9.8–9.2 m) 15.7–14.5 kyr BP	2	Woody taxa sum varies, increase in *Alnus*. Increase in Cyperaceae. Sharp increase in pteridophytes	Warm-temperate forest	Warm temperate, moist to wet
4a (10.3–9.8 m) 16.7–15.7 kyr BP	12.1–24.1 kyr	Woody taxa rise (to 70%), decrease in *Alnus*; increase in *Ilex*, *Symplocos*, *Cyclobalanopsis*. Decrease in Cyperaceae and Gramineae	Temperate forest	Temperate less dry
5 (13.8–10.3 m) 27.4–16.7 kyr BP		Decrease of woody taxa percentages, herbs rise (to 75%) of pollen sum, Gramineae rise (to 50%). Decrease in *Alnus* (to 20%); increase in *Cyclobalanopsis*, *Ilex, Symplocos*. Increase in *Artemisia* (to 10%), Cyperaceae	Temperate forest to forest steppe	Temperate, dry
6 (14.6–13.8 m) 27.9–27.4 kyr BP		Woody taxa ≒80%; increase in *Alnus*; decrease in *Cyclobalanopsis*, *Castanopsis*, *Quercus*, *Ligustrum* and *Salix*. Decrease in Cyperaceae and *Artemisia*	Temperate deciduous forest	Temperate
7 (16–14.6 m) 31.2–27.9 kyr BP		Woody taxa sum varies 60–90%, *Alnus* fluctuated at the compense of Cyperaceae. Increase in *Cyclobalanopsis* and *Castanopsis*. Increase in *Salix* at the early part; decrease in *Ilex* and *Symplocos*, peak in Gramineae at end	Temperate deciduous forest	Temperate
8 (18.1–16 m) 36.9–31.2 kyr BP	3	Woody taxa sum increase ≒80%, *Alnus* varies and peak at middle; increase in Ilex; *Cyclobalanopsis* slightly decrease; decrease in Cyperaceae and increase in Gramineae. pteridophytes decrease sharply	Temperate deciduous forest	Temperate, getting drier
9 (21.0–18.4 m) 48.5–36.9 kyr BP	27.6–58.9 kyr	Woody taxa sum fluctuates 40–85%, decrease in *Castanopsis*. Fluctuation of *Alnus* at the compense of Cyperaceae. Increase in *Symplocos*; two peaks of *Salix* at middle and so does *Ilex*; increase in pteridophytes (to 60%)	Temperate deciduous forest	Temperate, moist to wet
10 (22.4–21.0 m) 54.0–48.5 kyr BP		Woody taxa sum decreases and then increases. Increase in *Cyclobalanopsis* and *Castanopsis*. Decrease in *Alnus* (to 40%), *Ilex*, *Symplocos*; Increase in Cyperaceae	Temperate deciduous forest	Temperate, less dry
11 (23.0–22.4 m) 57.6–54.0 kyr BP		Woody taxa ≒80%, increase in *Alnus* (to 60%); *Castanopsis* the same as the previous zone. Decrease in *Ilex* and *Salix*. Increase in Gramineae	Temperate deciduous forest	Temperate, dry

12 (23.4–23.0 m) 59.0–57.6 kyr BP	4	Increase in *Ilex* (to 25%), *Castanopsis*, *Symplocos*. Decrease in *Alnus* (to 20%) and *Salix*	Temperate deciduous forest	Temperate
13 (26.6–23.4 m) assigned as 73.9–59.0 kyr BP	58.9–73.9 kyr	Woody taxa ≒80%, mainly *Alnus* (to 60%), increase in *Salix*; 1 peak in *Symplocos*; decrease in *Cyclobalanopsis*. Decrease in Cyperaceae	Temperate deciduous forest	Temperate, dry
14 (28.2–26.6 m) 76.7–73.9 kyr BP		Woody taxa sum varies 30–70%, *Alnus* decline but rises at in the later part (to 40%), *Cyclobalanopsis* (15%) higher than *Castanopsis*; decrease in *Salix*, increase in Cyperaceae (to 50%), *Artemisia* similar to the previous zone	Temperate deciduous forest	Temperate, less dry
15 (29–28.2 m) 78.0–76.7 kyr BP	5a?	Woody taxa ≒80%; decline in *Castanopsis* (to 5%) and *Salix*. Increase in *Ilex* (40%) and then *Alnus* (70%), decrease in *Pinus*, increase in *Artemisia*, decrease in Cyperaceae	Temperate deciduous forest	Temperate, getting dry
16 (30.5–29 m) 80.5–78.0 kyr BP	73.9–85.1 kyr	Woody taxa sum varies ≒40%, decline in *Castanopsis* (15%). Increase in *Salix* (to 40%). Increase in Cyperaceae (to 40%) and Gramineae	Temperate deciduous forest	Temperate, moist
17 (35.6–30.5 m) 88.8–80.5 kyr BP		Woody taxa ≒60% but up to 80% at lower, *Castanopsis* varies (20–40%). *Myrica* decreases upward. Increase in Cyperaceae (to 30%), decrease in pteridophytes (10%)	Subtropical to warm-temperate forest, less closed	Subtropical to warm temperate, less wet
18 (37.2–35.6 m) 91.4–88.8 kyr BP	5b?	Woody taxa sum varies 50–90%, decline in *Castanopsis* (<15%), increase in *Symplocos* (to 50%) and *Myrica* (25%). Increase in *Polygonum* and pteridophytes (to 80%)	Tropical to subtropical forest	Subtropical, wet
19 (39.0–37.2 m) 94.4–91.4 kyr BP	85.1–93.6 kyr	Woody taxa sum 60–85%, decrease in *Castanopsis*, increase in *Salix* (to 20%) and also *Ilex*, *Liquidambar* and *Ligustrum*. Increase in Gramineae and Cyperaceae	Temperate forest	Temperate, moist
20 (39.0–39.5 m) 95.2–94.4 kyr BP	5c? >93.8 kyr	Woody taxa ≒70%; dominant taxa is *Castanopsis* (to 60%). *Cyclobalanopsis*, *Quercus*, *Symplocos* and *Pinus* also significant; Cyperaceae about 20%, pteridophytes are low	Warm-temperate forest	Warm-temperate, moist

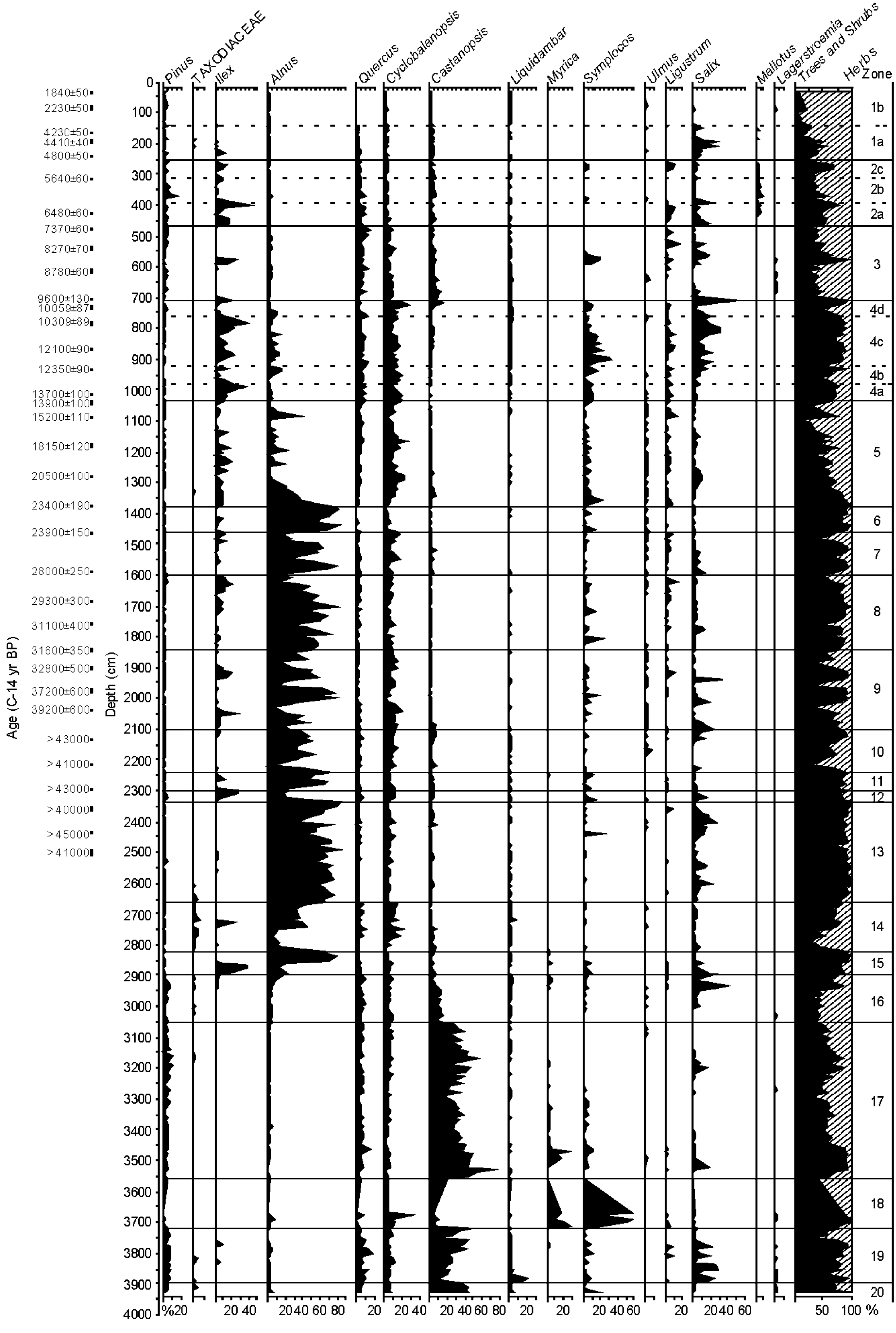


Fig. 4.1. Pollen diagram for the Toushe Basin. Percentage of each pollen genus is based on total pollen sum.

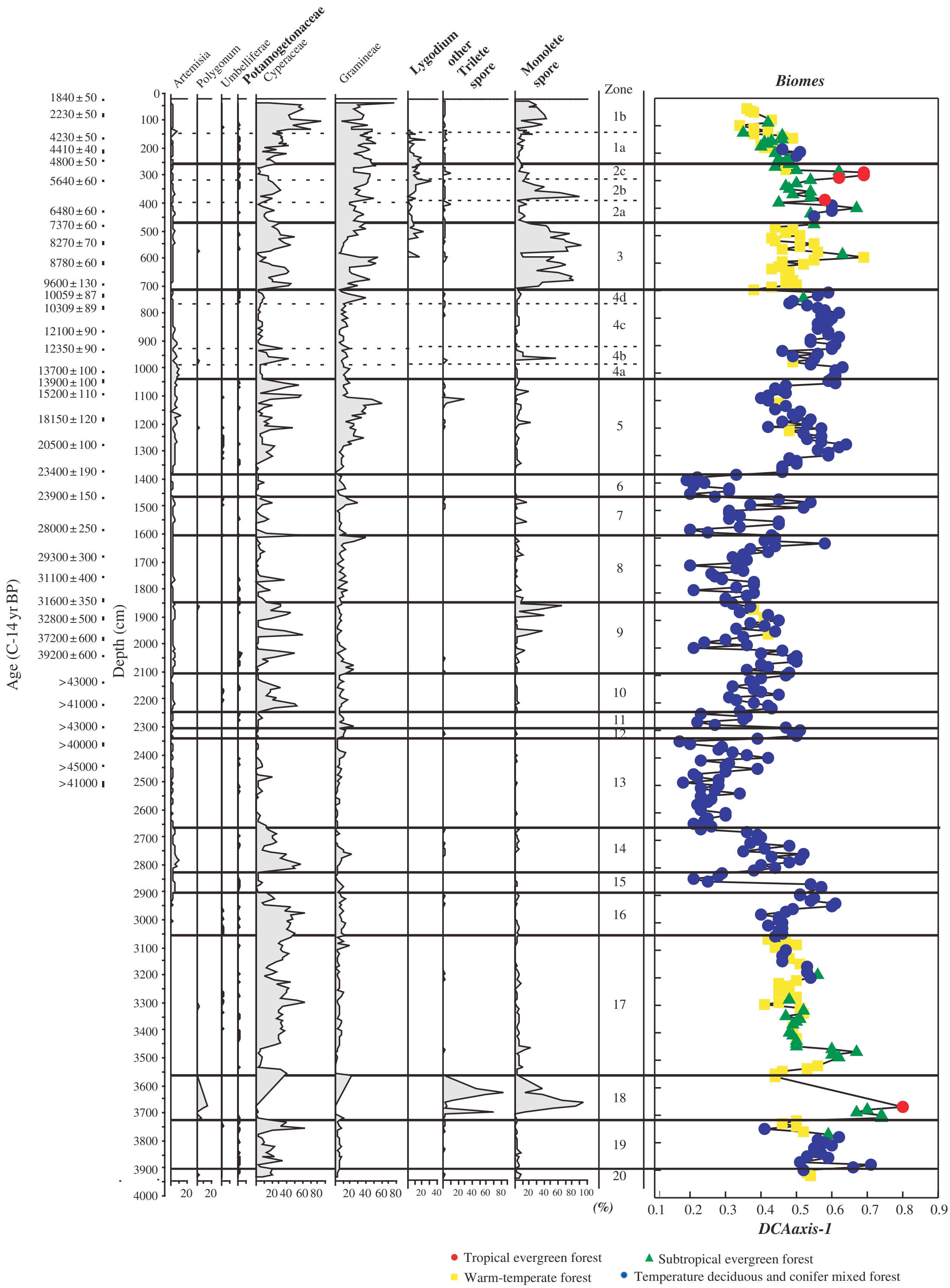


Fig. 4.2. Percentage of each spore genus is based on sum of pollen and spore. Reconstructed biomes plotted stratigraphically in relation to sample scores on the 1st axis of a detrended correspondence analysis of the pollen data.

Zone 5 (13.8–10.3 m, 27.4–16.7 kyr BP; 23,400–13,800 yr BP): NAP prevails in the middle and upper parts of this zone in which Gramineae (up to 40% once in the upper part) as well as *Artemisia* (at about 10%) reach their highest values. *Alnus* decreases remarkably to less than 20% and *Cyclobalanopsis* increases slightly. *Symplocos* is higher than in the previous zone but decreases gradually upward in the upper part of this zone. This zone belongs to MIS 2.

Zone 4 (10.3–7.10 m, 16.7–11.0 kyr BP; 13,800–9700 yr BP): differs from the previous zone remarkably. The forest elements rise again and NAP falls. AP increases to 80% in the upper part. *Cyclobalanopsis* together with *Ilex*, *Symplocos* and *Salix* are the main woody elements. Gramineae decrease. Due to the abrupt change of assemblages, the zone is divided into three subzones. In subzone 4a (10.3–9.8 m) Cyperaceae sharply decrease. *Ilex, Cyclobalanopsis* and *Symplocos* increase. NAP is clearly lower. In subzone 4b (9.8–9.2 m) spores increase abruptly and Cyperaceae also increase. *Alnus* is higher and *Ilex* is lower than in the previous subzone. *Cyclobalanopsis* maintains the same level as previously. In subzone 4c (9.2–7.6 m) spores decrease remarkably. *Symplocos* dramatically increases in the lower part and *Salix* in the upper part. *Ilex* is common. Herbs are relatively low. In subzone 4d (7.6–7.1 m) Gramineae rise to 40%. *Salix* reaches its highest value in the upper part.

Zone 3 (7.10–4.70 m, 11.0–8.0 kyr BP; 9700–7200 yr BP): Pteridophytes are high. *Castanopsis* is dominant among AP. *Trema* increases. *Salix*, *Symplocos* and *Ilex* are reduced. NAP increases again. It is probably hydrophyllus because of the accompanying large amount of fern-spores. AP is higher than NAP.

Zone 2 (4.70–2.50 m, 8.0–5.7 kyr BP; 7200–4900 yr BP): is characterized by the increase of *Ilex* and *Mallotus*. Pteridophytes reach their maximum value in the middle part. Three subzones are distinguished here: In subzone 2a, *Salix, Ligustrum* (12–15%) and *Ilex* (25%) increase again. *Cyclobalanopsis* decreases. Cyperaceae are reduced. Pteridophytes decrease remarkably. *Mallotus* appears from the middle part of this zone upward. In subzone 2b Pteridophytes increase to maximum (average in 50%). *Ilex* decreases while *Pinus* increases. In subzone 2c, *Pinus* is lower while *Symplocos* and *Ilex* rise again. Herbs increase again. *Ligustrum* and *Symplocos* also increase.

Zone 1 (2.50–0.30 m, 5.7–1.8 kyr BP; 4900–1800 yr BP): is characterized by the increase of Cyperaceae. *Salix* increases but *Ilex* decreases. Herbs reach their maximum values. Cyperaceae and monolete spores become important. This zone is further divided into two subzones due to the changing amounts of NAP. In subzone 1a (2.5–1.4 m) *Pinus* is lower while *Symplocos* and *Ilex* rise again. *Salix* increases but monolete spores decrease. Cyperaceae also increase upward. In subzone 1b (1.4 m upward) Cyperaceae reach their maximum. Monolete spores increase as well.

4.2. *Paleovegetation: a quantitative reconstruction*

The characteristics of vegetation of pollen spectra from Toushe Basin appear in Fig. 4.2 according to PFTs and biomes shown in Tables 2 and 3 with the biomes plotted on the 1st axis of detrended correspondence analysis (DCA by Tilia; Grimm, 1997). The results show that subtropical evergreen forest dominated during the Holocene, in contrast to temperate broadleaved and coniferous mixed forests, specifically the temperate deciduous forest within them, during the last glacial.

Vegetation reconstruction shows that the *Castanopsis*-dominant pollen assemblages of the early glacial are mainly subtropical to warm-temperate evergreen forests except Zone 19. The warmest conditions are in Zone 18 (tropical and subtropical forests) and the lower part of Zone 17 (subtropical to warm-temperate forests). Thus, Zone 19, where temperate broadleaved and conifer mixed forests prevailed, might correspond to MIS 5b. From Zones 16 to 4, the temperate broadleaved and conifer mixed forests, especially the deciduous forest, dominated except for some intervals of the last glacial at cal. 41.6, 38.0 and 37.3 kyr BP and at 22.3 and 18.9 kyr BP as well as 15.1 kyr BP where warm-temperate evergreen forest or subtropical forest appeared. It shows a distinct interstadial at about 42–37 kyr BP. The warm conditions occurred at 22.3 and 18.9 kyr BP just before and within the dry phase (Gramineae prevail) of the late stadial. However, due to high amounts of Gramineae in these samples, this result needs to be further discussed. Nevertheless, an abrupt warm phase around 22 ka is reported in the Siple Coast of Antarctica (Taylor et al., 2004) and a warm phase very near Last Glacial Maximum (LGM) is also reported in New Zealand (Hormes et al., 1999). Post-Bølling subtropical conditions are found at 11.5 kyr BP. Thus, the subtropical conditions of 15.1 kyr BP (depth 9.59 m) and 11.5 kyr BP (depth 7.28 m) of this study correspond to the spikes of Atlantic melting events (Bond et al., 1992). After 10.7 kyr BP, subtropical conditions continue. Tropical forest appeared at 6.9 and 6.1–5.9 kyr BP. Temperate broadleaved and conifer mixed forest appeared at about 11.2–11.0, 7.5, 7.2 and 7.1, 5.2, 5.0 and 4.9 kyr BP. The cool interval at 3.7–2.0 kyr BP which was found in alpine lakes of Taiwan (Liew and Huang, 1994) appeared here only as a change from subtropical to warm-temperate forests. It indicates that it is a less prominent cooling than those in the first half of the Holocene. Subtropical and tropical forests are frequent from 8 to 5 kyr BP. Warm-temperate evergreen forest is common in early Holocene before 8 kyr BP.

However, the result of biomization shows that samples with equal score of warm-temperate evergreen forest and subtropical evergreen forest are common although they should be assigned as warm-temperate forest according to the rule of less number of PFTs in biomization (among the samples assigned as warm-temperate forest are almost with the same score as subtropical forest except at depths 31.1,

Table 2
Assignment of pollen taxa to plant functional types (PFT)

PFT code	Pollen taxa
te	Ficus, Lithocarpus, Bischoffia, Homalanthus, Palmae, Piperaceae, Trema, Albizzia, Acacia, Celtis, Schefflera, Ardisia, Myrica, Elaeocarpus, Sloanea, Mallotus, Omalanthus, Macaranga, Melanolepis, Glochidian, Daphniphyllum, Citrus, Zanthoxylum, Chloranthus, Sapium, Michelia, Melia, Algaia, Syzygium, Helicia, Meliosma, Styrax, Wendlandia, Myrsine, Viburnum, Symplocos, Ligustrum, Saurauia, Ilex, Kandelia, Rhizophora, Lumnitzera, Dysoxyllum, Aralia, Fraxinus, Osmanthus, Callicarpa, Cycas, Lagerstroemia, Maesa, Diospyros, Rutaceae, Combretaceae, Moraceae, Leguminosae, Proteaceae, Melastomaceae, Ulmaceae
tr	Diospyros, Dysoxylum, Aglaia, Albizzia, Terminalia, Ficus, Syzygium, Bombacaceae, Bombax, Combretaceae, Euphorbiaceae, Leguminosae, Melanolepis, Microtropis, Myrsinaceae, Proteaceae, Sapotaceae, Ulmaceae, Ulmus, Wendlandia
sut	Cyclobalanopsis, Castanopsis, Lithocarpus, Pasania, Cryptocarya, Schefflera, Ardisia, Myrica, Elaeocarpus, Sloanea, Platycarya, Mallotus, Daphniphyllum, Michelia, Meliosma, Ilex, Diospyros, Engelhardtia, Myrsine, Schima, Maesa, Fraxinus, Ligustrum, Osmanthus, Prunus, Callicarpa, Actinidia, Saurauia, Capaparis, Anacardiaceae, Araliaceae, Citrus, Zelkova, Chloranthus, Camellia, Helicia, Symplocos, Syzygium, Celtis, Zanthoxylum, Sapium, Viburnum, Cycas, Moraceae, Rhamnaceae, Rubiaceae, Rutaceae, Ebenaceae, Meliaceae, Apocynaceae, Euphorbiaceae, Lagerstroemia
wte2	Cyclobalanopsis, Castanopsis, Lithocarpus, Quercus, Viburnum, Daphniphyllum, Schima, Aralia, Myrsine, Ligustrum, Osmanthus, Elaeocarpus, Trochodendron, Actinidia, Cleyera, Eurya, Gordonia, Platycarya, Dendropanax, Illicium, Ilex, Meliosma, schfflera Magnoliaceae, Aaliaceae, Hydrangeaceae, Symplocos
wte1	Ilex, Ligustrum, Cyclobalanopsis, Quercus, Shortia, Viburnum, Trochodendron, Symplocos, Prunus, Actinidia
ts1	Alnus, Ribes, Ulmaceae, Salix
ts2	Carya, Alnus, Elaeognus, Fagus, Juglans, Liquidambar, Pterocarya, Quercus, Salix, Castanea, Carpinus, Zelkova, Ulmus, Helwingia, Ulmaceae
ts3	Rhus, Zelkova, Lagerstroemia, Sapindus, Platycarya, Sapium, Taxillus, Celtis, Ulmus, Liquidambar, Trema, Koelreuteria, Terminalia, Albizia, Helwingia, Ebenaceae. Diospyros, Fraxinus
ts	Acanthopanax, Acer, Viburnum, Alnus, Ulmus Rutaceae, Rosaceae, Rhamnaceae
ec	Pinus, Juniperus
wtc	Keteleeria, Podocarpus, Calocedrus, Cephalotaxis
tc	Chamacyparis, Cryptomeria, Cunninghamia, Taiwania, Pinus, Taxodiaceae
ctc	Picea, Tsuga
bec	Abies
tef	
	Impatiens, Microlepia, Cuscuta, Zanthoxylum, Rumax, Chenopodium, Amaranthus, Clematis, Ranunculus, Cocculus, Nymphaea, Hydrangia, Chloranthus, Hypericum, Drosera, Arabis, Kalanchoe, Sedum, Deutzia, Pittosporum, Rosa, Rubus, Sanguisorba, Rhamnus, Cissus, Elaeognus, Begonia, Actinostemma, Melastoma, Bredia, Epilobium, Ludwigia, Trapa, Myriophyllum, Helwingia, Schefflera, Tetrapanax, Shortia, Maesa, Ardisia, Myrsine, Lysimachia, Styrax, Symplocos, Gentiana, Galium, Callicarpa, Callitriche, Solanum, Justicia, Strobilanthus, Plantago, Viburnum, Sagittaria, Potamogeton, Musa, Bryophyllum, Typha, Stautonia, Piper, Actinidia, Loranthus, Microtropis, Wirkstroemia, Acanthaceae, Gesneriaceae. Gramineae
tf	Actinostema, Gentiana, Cuscuta, Galium, Polygonum, Stautonia, Hypericum, Arabis, Sedum, Deutzia, Hydrangia, Pittosporum, Rosa, Rubus, Impatiens, Euonymus, Rhamnus, Elaeognus, Epilobium, Shortia, Lysimachia, Primula, Symplocos, Swertia, Plantago, Lonicera, Clematis, Loranthus, Microtropis, Cucubitaceae, Gramineae, Labiatae, Ranunculaceae, Rutaceae Scrophulariaceae, Solanaceae, Umbeliferae
af	Polygonum, Rhododendron, Thalictrum, Salix, Actinidia, Juniperus, Chenopodium, Clematis, Ranunculus, Damnacanthus, Eurya, Galium, Rosa, Lonicera, Sedum, Cruciferae, Ericaceae, Compositae. Berberis, Ribes
sf	Artemisia, Justicia, Rubus
g	Gramineae, Compositae
h	Ericaceae
s	Cyperaceae
wod	Symplocos, Quercus, Ilex, Cyclobalanopsis
Ferns (x)	Psilotum, Lycopodium, Selaginella, Equisetum, Ophioglossum, Angiopteris, Archangiopteris, Marattia, Osmunda, Lygodium, Schizaea, Dicranopteris, Hemenophyllum, Cibotium, Cyathea, Dennstaedtia, Microlepia, Pteridium, Davallia, Vittaria, Woodwardia, Dryopteris, Dipteris, Polypodium, Azolla, Ctenitis, Diplaziun, Plagiogyria, Microsorium, Selaginella
trx	Cyatheaceae

Key to PFT code: te, tropical evergreen; tr, tropical raingreen; sut, subtropical evergreen; wte2, warm-temperate evergreen; wte1, temperate evergreen; ts1, cool-temperate summergreen; ts2, intermediate-temperate summergreen; ts3, southern warm-temperate summergreen; ts, temperate summergreen; ec, eurythermic conifer; wtc, south warm-temperate conifer; tc, temperate conifer; ctc, cool-temperate evergreen conifer; bec, boreal evergreen conifer; tef, tropical and subtropical evergreen forbs/shrubs; tf, temperate forbs/shrubs; af, arctic-alpine forbs/shrubs; sf, steppe forb/shrub; g, grass; h, Ericaceae; s, sedge; wod, woodland; x, ferns; trx, Cyatheaceae.

Table 3
Assignments of plant functional types to biomes

Biome	PFTs
Tropical evergreen forest	te, tef, trx, x
Tropical rainforest	tr, tef, trx, x, ts3
Subtropical evergreen forest	sut, tef, ts3, wtc, trx, x
Warm-temperate evergreen forest	wte2, tf, ts3, x
Temperate broadleaved and conifer mixed forest	wte1, ec, tc, ts1, ts2, ts, tf
Cool-temperate conifer forest	ctc, ec, g, h
Cold-temperate conifer forest	bec, ec, g, h
Alpine conifer forest	ec, af, g
Forest steppe	wod, g, sf
Alpine shrub land	af, sf, g

35.4, 39.1 and 39.2 m where warm-temperate forest has the higher score). It possibly indicates that further discrimination of the altitudinal zones within the Lauro-Fagaceae forest using genus level data is not very easy. This is partly due to the fact that the main pollen types of forests lower than the *Tsuga–Picea* Zone are the Fagaceae—*Castanopsis* and *Cyclobalanopsis*—whose altitudinal spread of species is wide.

The other problem in biomization here is the difficulty when Gramineae-dominant assemblages are encountered, such as during LGM, due to the wide occurrence of Gramineae in these tropical–subtropical areas. Consequently, even though the Gramineae-dominated assemblages of LGM possibly represent forest steppe or steppe conditions, the biome of temperate broadleaved and conifer mixed forests occurred. We hope more work in the future will further refine the rule set of the biomes.

5. Interpretation of vegetational history and climatic conditions

In the pollen diagram, warm elements, such as *Castanopsis* and *Mallotus*, alternated with cold elements, such as *Alnus* and *Salix*. Higher spore values in the diagram are regarded as a proxy of higher precipitation conditions or water-transport processes. Precipitation is usually an index of an intensifying summer monsoon, which in turn represents more frequent tropical cyclones. Relatively dry conditions are represented by high values of Gramineae (i.e. Gramineae without accompanying large amounts of monolete spores), *Alnus* and *Salix*. According to modern vegetation assemblages (Fig. 2) *Alnus* and *Salix* grow in less humid parts of the *Quercus* Zone even though they are well known as temperate, boreal or arctic-alpine trees and shrubs indicating wet conditions in other places (Tarasov et al., 1998).

5.1. Zones 20–17, tentatively estimated as 95.2–80.5 kyr BP, probably MIS 5c–a

The early glacial (Zones 20–17) is characterized by assemblages with a high value of *Castanopsis*-type pollen (20–40%) except Zone 18. *Castanopsis*-dominant pollen assemblages usually represent assemblages of subtropical to warm-temperate forest—*Machilus–Castanopsis* Zone (500–1500 m) in present Taiwan, as shown in pollen records studied earlier (Liew, 1977). However, *Castanopsis*-dominant assemblages of the early glacial have much lower spore and much higher Cyperaceae content if compared with the present *Machilus–Castanopsis* Zone. They may indicate a climatic condition less humid than that of today's *Machilus–Castanopsis* forest. Alternatively, if those *Castanopsis*-type pollen during early glacial are the few species growing higher than 2000 m, they may represent a forest within today's Upper *Quercus* Zone. The increase of *Salix* in Zone 19 indicates a relatively cold trend although still within the temperate broadleaved and conifer mixed forests (the Upper *Quercus* Zone), which is tentatively assigned to MIS 5b. After this, a remarkable fluctuation from dry to wet is shown in Zone 18 in which *Symplocos* and *Myrica* replace the important role of *Castanopsis* then followed by high peaks of monolete spores and *Polygonum* (91.4–88.8 kyr BP estimated by the age model here). *Myrica* presently grows in the low altitude (below 1500 m) area of Taiwan. Whether this wet/warm phase corresponds to the wet event at 88 ka in the loess record of China (Rousseau et al., 2000) needs further study. *Castanopsis* returns to its dominant role after this warm–wet phase. Another small wet/dry fluctuation in the lower part of Zone 17 is indicated by various amounts of Cyperaceae. Higher Cyperaceae contents might indicate lower lake levels (Maley and Brenac, 1998). The drought trend in the upper part of Zone 17 is also witnessed by changes of lithological facies from lake clay to peat. Zones 18 and 17 are assumed to be within MIS 5a. The following zones 16–14 represent the transition from warm to cold conditions.

5.2. Zones 16–14, tentatively estimated as 80.5–73.9 kyr BP

The interval begins with the remarkable decrease of *Castanopsis* and increase of *Salix*, indicating less humid and less warm conditions than before. Fluctuations of cold/dry to warm/wet conditions from Zones 15 to 14 are shown by the successive dominance of *Ilex*, *Alnus*, the low value of Cyperaceae in Zone 15 and the increase of *Cyclobalanopsis* and Cyperaceae in Zone 14, although still within the temperate broadleaved and conifer mixed forest.

5.3. Zone 13, tentatively assigned as 73.9–59.0 kyr BP, possibly corresponds to or within MIS 4

Alnus rises to more than 60% and Cyperaceae decrease sharply suggesting spread of *Alnus* in the area. A pollen assemblage with such high value of *Alnus* is similar to surface pollen assemblages between altitudes 2250 and 2500 m of the present natural forest, central Taiwan. Sharp decrease of Cyperaceae indicates still drier conditions than those of the previous zone. This assemblage represents the temperate deciduous forest within the present Upper *Quercus* Zone (or temperate broadleaved and conifer mixed forests). Most of this zone is probably colder than the late stadial (Zone 5), considering the associated woody taxa of Zone 5.

5.4. Zones 12–6 (59.0–27.9 kyr BP): represent interstadial conditions of MIS 3

Alnus and Cyperaceae alternately dominated, within the temperate deciduous forest; Cyperaceae indicate increasing humidity. *Ilex* and *Cyclobalanopsis* increase. *Castanopsis* increases from Zones 12 to 10, indicating a warmer trend between the early and late stadials. There is a remarkable wet episode from cal. 42.2 to 37.0 kyr BP (estimated 36,100–32,500 yr BP) represented by spore-dominant assemblages (Zone 9). Warm-temperate forest conditions at 41.6, 38.0 and 37.3 kyr BP appeared based on forest reconstruction also. A prominent wet episode (35–25 kyr BP) during MIS 3 has been documented by An (2000). Compared with this study, its age appeared to be younger.

The upper part of this interstadial (from Zone 9 upward) appeared relatively drier than the lower part as revealed by the amounts of Gramineae. *Castanopsis* has its lowest value between Zones 9 and 6 although showing a slight increase in Zone 7.

5.5. Zone 5, 27.4–16.7 kyr BP, late stadial, belongs to MIS 2

Vegetation in Zone 5, especially the upper part, is characterized by dominance in NAP, representing a temperate forest or possibly forest steppe. Between 23.2 and 18.7 kyr BP Gramineae and *Artemisia* reach their highest values, indicating relatively dry and sometimes cold conditions. Cyperaceae replace Gramineae at about 18.6 kyr BP and warm elements including *Symplocos*, *Ilex* and *Cyclobalanopsis* increase at about 16.7 kyr BP. However, among the woody elements, *Cyclobalanopsis* rather than *Alnus* or Pinaceae appear. This is the interval corresponding to the LGM. According to the surface pollen study of lowland northeast China, 40% NAP marks the existence of forest-steppe zone, and this boundary almost overlapped the 700 mm/yr annual precipitation (Ren, 1998). Thus, Zone 5 represents relatively dry conditions but probably not as cold as those of Zone 13 (MIS 4). The less cold late stadial is shown in the result of biomization and also indicated by the study of Tsukada (1967) at Sun-Moon Lake. In comparison to present-day temperatures, the estimated temperature was 4–5 °C lower than today during the late stadial and 8–10 °C lower in the early stadial. This study confirms this estimation. Warm-temperate to subtropical conditions appeared at 22.3 and 18.9 kyr BP before or within the Gramineae-prevailing drier phase as mentioned previously.

5.6. Zone 4, 27.4–11.0 kyr BP, the late glacial

The late glacial is characterized by a rise of AP. Among the woody taxa, *Cyclobalanopsis*, *Ilex*, *Symplocos* and *Salix* are of changing importance, mainly representing temperate broadleaved and conifer mixed forests. The climatic conditions are drier and cooler than today, but warmer and wetter than before. A strong peak of monolete spores and warm-temperate forest at 15.1 kyr BP (12,800 yr BP) indicates the warm–wet Bølling interval. At about 13.0–12.5 kyr BP (10,900–10,450 yr BP) the increase of *Salix* marked the beginning of cold conditions. Then *Ilex* peaked at 12.1 kyr BP and Gramineae (>35%) at 11.8–11.6 kyr BP (10,200–10,100 yr BP). They indicate a trend from cold to less cold and then dry-cold conditions of Younger Dryas time similar to the main trend found in the arid–semiarid transition zone of northern China (Zhou et al., 2001). According to a detailed study in the Netherlands (Hoek, 1997), the late Pleniglacial ended about radiocarbon age 12,900 yr BP (uncalibrated). From 12,900 to 12,450 yr BP is the Oldest Dryas, 12,450 to 12,100 yr BP is Bølling, 12,100 to 11,900 yr BP is Older Dryas, 11,900 to 10,950 yr BP is Allerød, 10,950 to 10,150 yr BP is Younger Dryas. In the Toushe record, the warm interval with a peak of monolete spores at 15.1 kyr BP marked the warm–wet episode corresponding to Bølling, while peaks of *Salix* and Gramineae may correspond to Younger Dryas (13.0–11.6 kyr BP or 10,900–10,100 yr BP). Warm-temperate to subtropical elements increase at 11.5 kyr BP, but soon return to temperate conditions at 11.2–11.0 kyr BP (7.18 m). After 11.0 kyr BP warm-temperate to subtropical forests appeared almost continuously.

5.7. Zones 3–1 (11.0–1.8 kyr BP)

A *Salix* peak appeared at 11.0 kyr BP (7.07 m) which just preceded the wet phase indicated by the increase of monolete spores at 10.7 kyr BP (6.97 m). Climatic conditions become subtropical/warm–wet again as indicated by large amounts of monolete spores, hydrophyllus herbs and an increase of *Castanopsis* at the expense of *Ilex*, *Ligustrum*, *Symplocos* and *Salix*. But the rise of *Salix*, *Ilex* and *Symplocos* again at about 9.6–9.4 kyr BP (8600–8400 yr BP) indicates a cold episode. The subtropical-warm elements increased in the middle Holocene, i.e. *Mallotus* began to increase between 7.3 and 6.8 kyr BP (6500 and 6000 yr BP) and *Glochidion* increased at 6.2–5.8 kyr BP (5450–090 yr BP). The higher value of *Pinus*—which grows far from the study site—runs parallel to the trend of the warm element *Castanopsis*, which might indicate an intensified monsoon at about 6.9–6.8 kyr BP (6150–6050 yr BP). *Salix* peaks indicated the prevailing deciduous forest and less warm conditions at about 11.0, 9.6–9.4, 9, 7.9, 7.5, 7.2 and 7.1, 5.2 and 5.0, 4.0 and 3.7 kyr BP.

The most remarkable feature in the Holocene record is a conspicuous dominance of monolete spores which indicate wet conditions. An et al. (2000) mentioned that the Holocene optimum may be represented by a wet interval which is asynchronous in East Asia. There are several intervals during the Holocene with such features especially

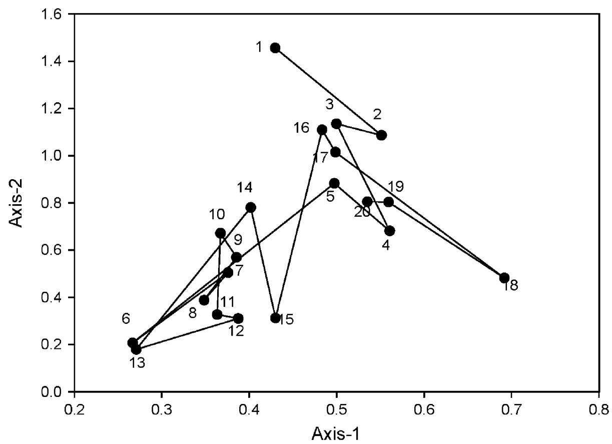


Fig. 5. Detrended correspondence analysis. Mean scores for the samples of each zone (from 20 to 1) plotted for the first two DCA axes.

before 6.8 kyr BP in present study, including 10.6–10.3, 10.0–9.7, 9.5–8.5, 6.9–6.8 and 2.9–1.8 kyr BP (9300–9100, 8900–8600, 8500–7700, 6000–6100 and the last 3000 yr BP). However, the record of the last 5000 yr in the alpine lakes at almost the same latitude has been discussed by the authors elsewhere (Liew and Huang, 1994). The higher value of NAP in the early Holocene is considered to be a result of the enlargement of flooding areas due to early Holocene wet conditions (Bush, 2002), while that of the recent several millennia is attributed to human disturbance.

The average score of each zone presented in the first and second axis of DCA (Grimm, 1997) is shown in Fig. 5. Pollen taxa involved in DCA analysis are those with percentage >2%, including *Pinus*, Taxodiaceae, Ericaceae, *Ilex*, *Alnus*, *Quercus*, *Cyclobalanopsis*, *Catanopsis*, *Liquidambar*, *Symplocos*, *Trema*, *Ulmus*, *Ligustrum*, *Salix*, *Glochidion*, *Homalanthus*, *Mallotus*, *Hydrangea*, *Tristellateia*, *Gymnosporia*, Aizoaceae, *Artemisia*, Compositae, *Polygonum*, *Ranunculus*, Umbeliferae, *Typha*, Cyperaceae, Gramineae and Liliaceae. The similarity of Zones 6–13 may indicate cold conditions before the late stadial drought; similarities among Zones 7, 9, 10 and Zones 8, 11, 12 may indicate cyclic changes in humidity during the interstadial. Large shifts occurred between Zones 19 and 18, 18 and 17, 16 and 15, 15 and 14, and 4 and 3 indicating the abrupt change during the early glacial and between the late glacial and Holocene.

6. Discussion

We used a biomization technique to reconstruct past altitudinal vegetation of the Toushe pollen sequence. This allows interpretation of the magnitude of possible environmental changes if the site is sensitive to past ecotone changes. For this site, especially in the Holocene, changes in prevailing biomes appear frequently (Fig. 4.2). Temperate deciduous forest dominated by *Alnus* prevailed during the last glacial. The cold or cold/dry phase in the last glacial is possibly indicated by the times when peaks of Gramineae appeared although they are hardly recognized in the biome reconstruction of this study. *Tsuga–Picea* forest does not appear at this site during the last glacial although it appears during the early stadial in Sun-Moon Lake located 100 m higher. Thus, we believe that the boundary between *Tsuga–Picea* forest and *Alnus* forest was located near the Sun-Moon Lake in the early stadial (Liew and Chung, 2001).

The large altitudinal range of *Castanopsis* pollen type is another concern in the reconstruction of past biomes. In the present study, we include *Castanopsis* in subtropical and warm-temperate forests, which means excluding it from the temperate broadleaved and conifer mixed forest. If we consider the high-growing species and include *Castanopsis*-type pollen in wte1 also, with *Castanopsis* also included in temperate forests, we will find only a small change in Holocene biome reconstruction but a relatively clear change in that of the early glacial (six samples among 83 samples in Holocene, i.e. ages at about 4.8, 4.85, 4.9, 7.6, 7.7 and 7.9 kyr BP will change to temperate broadleaved and conifer mixed forests; while most of Zone 17 will become temperate broadleaved and conifer mixed forests). Thus, the *Castanopsis*-dominant assemblage in early glacial is possibly like that of present subtropical/warm-temperate forests but less humid, or alternatively like parts of temperate broadleaved and conifer mixed forests.

6.1. Maximum cooling of the last glacial

Long-term vegetational records often show the response of local flora to climatic changes. During the last glacial, the winter monsoon intensified (Huang et al., 1997), and the climate was relatively drier and colder than that of today. As mentioned above, the stadials of the last glacial are represented by Zone 13 (possibly MIS 4) and Zone 5 (MIS 2) in which the early stadial (Zone 13) has the highest value of *Alnus* (>60%). Surface pollen assemblages of Salisien area show that *Alnus*-dominant (50%) conditions could be found at about altitude 2250 m of today's forests. Thus, a vertical migration of 1500 m could have occurred between the early stadial of the last glacial and the Holocene. Furthermore, in contrast to the *Alnus*-dominant assemblage of Zone 13 in Toushe, a contemporaneous *Pinus*/*Tsuga*-dominant assemblage is found at the neighboring Sun-Moon Lake (Tsukada, 1967). Thus, the level of Sun-Moon Lake (750 m) should represent the lower boundary of *Alnus*/coniferous forest of the early glacial. Presently the boundary lies at about 2400 m above sea level. Though Taiwan's uplift rate is generally high, this area is fairly stable (Chen, 2003), and vertical displacement due to tectonism is negligible. Thus, the maximum ecotone migration is estimated to be at least >1000 m and possibly about 1500 m; therefore, the temperature difference between MIS 4 and present is 8–10 °C.

The smooth sedimentation rate in this peat bog (Fig. 3) excludes the conspicuous diastem during the LGM. The severity of cold conditions of the early and late stadials of the last glacial here (Zone 5) appeared different from those of many other regions. As described above, Gramineae sometimes reached more than 40% and NAP prevailed during the late stadial, which indicates drought conditions with precipitation less than half the present level probably. However, if we compare the woody elements with the early stadial (Zone 13, MIS 4), the late stadial shows a lower percentage of *Alnus* but higher percentage of *Cyclobalanopsis*. Thus, most of MIS 4 may have been colder than MIS 2. The biomization results show a similar trend. Conditions of relatively higher sea level and lower insolation during MIS 4 than that of MIS 2 may be plausible reasons. The southward shifting ITCZ and trade wind belt as well as the lowering of sea level during the late stadial (MIS 2) possibly resulted in the drought conditions in this area, while the effect of the maximum ice sheet of MIS 2 on subtropical temperature needs to be evaluated.

Many discussions have emphasized the wet interval during the later part (35–25 kyr BP) of MIS 3 and the East Asia monsoon (An, 2000; Shi et al., 2001). In Europe, there is a mild phase during MIS 3 at about 39,000–36,000 yr ago (Andel and Tzedakis, 1996), similar to the warm–wet interval of 37–42 kyr BP characterized by remarkable spore peaks in the present study. If they are related, then the warm phase may have occurred not only in Asia.

6.2. Younger Dryas

The Younger Dryas was indicated by the remarkable increase of *Salix* at about 13.0–12.5 kyr BP which differs from previous *Cyclobalanopsis–Symplocos* prevailing assemblages, and culminated in the later part of this cold event by an increase of Gramineae (>35%) at 11.8–11.6 kyr BP. They indicate a trend from cold to less cold and then dry-cold conditions of Younger Dryas time, similar to the main trend found in the arid–semiarid transition zone of northern China (Zhou et al., 2001). It is almost synchronous with climate records from Europe (Peteet, 1995) and from Africa (Bonnefille et al., 1995). In equatorial and northern Africa, Gasse (2000) also found two drastic arid-humid transitions occurring around 15–14.5 and 11.5–11 ka which correspond to the post-Bølling interstadial and post-Younger Dryas warming event in this study. However, at the present study site, the change of vegetation in 13.0–11.6 kyr BP is still within the range of temperate broadleaved and mixed conifer forest based on biomization. Thus, this cold event is not recognizable from the results of forest change only. Nakagawa et al. (2003) described Younger Dryas in the pollen sequence of Lake Suigetsu, Japan, with about a 400 yr lag compared with the Greenland ice core (Alley, 1993; Mayewski et al., 1993). According to the pollen diagram of Lake Suigetsu, an increase of *Fagus* and a decrease of *Carpinus* occurred about 12,600 yr BP. Thus, the onset of Younger Dryas remains equivocal. One possible explanation of this age discrepancy is the definition of magnitude of coldness for the beginning of the Younger Dryas.

7. Conclusion

The pollen stratigraphy from the low mountain area of central Taiwan shows vegetational change across the last 96,000 yr. During MIS 5 (probably 5c), the *Castanopsis*-dominant assemblage possibly represents a subtropical evergreen broadleaved forest, less humid than at present, assuming that these *Castanopsis* are not high-growing species. A *Salix*-dominant interval follows, which is tentatively correlated with MIS 5b. After that, *Symplocos* and *Myrica* dominate; in conjunction with a high spore level, this indicates a subtropical forest with a wet episode. *Castanopsis* then prevails again. Thus at least one wet interval existed in the early glacial (MIS 5a). The *Alnus*-dominant forest replaced the preceding *Castanopsis* forest during most of the last glacial. In the early stadial (MIS 4), the *Alnus* percentage is higher than that of the late stadial (MIS 2). A 8–10 °C lower annual temperature than at present and an about 1000–1500 m lower boundary of the *Tsuga–Picea* Zone/Upper *Quercus* Zone than at present characterizes the early stadial (MIS 4). However, in MIS 2, the high value of NAP might represent a forest steppe condition; a fall in precipitation to half the present level might be possible. *Alnus* is lower but *Cyclobalanopsis* is higher during the late stadial (MIS 2) than in the early stadial (MIS 4) indicating less cold conditions than in most of the early stadial. The generally drier conditions of the glacial stage are interrupted by an episodic warm/wet interval around 42.2–37.0 kyr BP. Abrupt changes during the late glacial and Holocene are also clear. The peak of monolete spores at 15.1 kyr BP (12,800 yr BP) and a warm-temperate forest mark the warm–wet episode corresponding to the Bølling. At about 13.0–12.5 kyr BP an increase of *Salix* possibly marks the onset of cold conditions. Then after a peak of *Ilex* at 12.1 kyr BP, Gramineae (>35%) rise at 11.8–11.6 kyr BP which may correspond to the cold to less cold and then cold-dry phases of the Younger Dryas. A subtropical warm period also appeared at 11.5 kyr BP as indicated by biomization. Subtropical conditions continue to prevail from 10.7 kyr BP onward. An increase of warm elements, such as *Castanopsis*, appeared around 11.2 kyr BP and wet conditions indicated by spore peaks occurred at about 10.7 kyr BP. Possible abrupt cold episodes are indicated by *Salix* peaks at about 11.0, 9.6–9.4, 7.9, 7.1, 5.2 and 5.0, 4.0 and 3.7 kyr BP. Subtropical to tropical elements such as *Mallotus* increased in the mid-Holocene at about 7.3–6.8 kyr BP (except 7.2 kyr BP), while *Glochidion* was higher between 6.2 and 5.8 kyr BP, probably indicating a warmer interval when the summer monsoon intensified. The warmest climate occurred at 6.9 and 6.1–5.9 kyr BP based on forest reconstruction. High early Holocene spore peaks occurred in the intervals 10.6–10.3, 10.0–9.7, 9.5–8.8, 6.9–6.8 and about 2.9–1.8 kyr BP and are considered as a proxy of higher precipitation induced by an intensifying East Asian monsoon.

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