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VERTICAL MIGRATION OF FORESTS DURING THE LAST GLACIAL PERIOD IN SUBTROPICAL TAIWAN

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ABSTRACT

Vertical migration of forests during the early stadial of the last glacial is studied. A 8-10°C lowering of temperature and 1500-1600 m of vertical migration of forests are suggested during the early stadial according to the pollen data of peat bog deposits at Toushe, central Taiwan. This interpretation is based on: 1. a shift of the lower boundary of coniferous forest indicated by pollen record; 2. comparison of assemblages of fossil records with modern surface pollen assemblages at varying altitudes.

The surface pollen assemblages of natural forests along Salisien-chi in central Taiwan as well as two pollen diagrams of neighboring sites, Toushe peat bog (650 m-high) and JihTan (750 m-high), are main references in this study. According to the latter two pollen records, during the early stadial of the last glacial (stage 4), the coniferous elements dominated in the higher lake (Tsukada, 1967) while the deciduous broad-leaved forest element *Alnus* **dominated in the lower peat bog. This indicates the lower limit of the coniferous zone was probably at an altitude of about 700 m at that time, rather than today's 2300-2500 m. The annual temperature difference today between these two altitudes reaches 9-10°C, which agrees with a lowering of 8~11°C between the early stadial and the present, as reported by Tsukada (1967).**

During the so-called last glacial maximum (OIS 2), a remarkably high value of herbs (Poaceae) indicates a dry environment. However, the associated arboreal elements are *Cyclobalanopsis*. **This suggests that during most part of OIS 2 was drier but possibly less cold than OIS 4, different from the records of temperate areas, which show OIS 2 as the coldest. This phenomenon is probably due in part to the low latitude of the area.**

Key words: last glacial, forest migration, subtropical, Taiwan, surface pollen

INTRODUCTION

The last glacial has been well documented in recent decades, especially after the emergence of high-resolution data of the polar ice core. In the context of a global view, phenomena of low latitude have the same importance as that of high latitude. Recent findings about the last glacial shows that the SST of low latitudes is not as warm (Huang *et al*., 1997) as estimated by CLIMAP (1981), with terrestrial data of low latitudes also showing the same trend (Flenley, 1979; Hooghiemstra, 1989). On the other hand, leads and lags of phase of climatic events are recognized between two poles (Sowers and Bender, 1995). Thus the latitudinal variations need to be well understood before interpreting a global features.

We try to discuss the cold and dry intensity of the stadials of the last glacial based on pollen data from the Toushe peat bog (altitude 650 m) and Jih Tan (altitude 750 m), both located in central Taiwan. The amount of temperature drop is tentatively estimated with reference to the recent surface pollen study of the natural forests in central Taiwan.

VEGETATION OF THE STUDIED AREA

Taiwan is an island sitting on the subtropical belt lower than 25.5°N of Southeast Asia but still possesses tropical to cold climatic vegetation due to its high elevations up to almost 4000 m. Vegetation in the mountain areas of central Taiwan has been divided into the following altitudinal zones by Su (1984)

1) *Ficus-Machilus* Zone (below 500 m; 23-26°C): this is the lowland evergreen broad-leaved forest including *Ficus*, *Machilus*, etc.

2) *Machilus-Castanopsis* Zone (500-1500 m; 17-23°C), submontane evergreen broadleaved forest with two major types. 1. *Castanopsis* type: mainly composed of *Castanopsis hystrix, C. Kawakamii, Schima superiba, Engelhardtia* and *Lithocarpus*, and 2. *Machilus* type: main components include *Machilus japonica, M. kusanoi, Ficus, Lagerstroemia* and tree fern. Pollen assemblages of this zone are characterized by *Castanopsis* associated with other warm temperate elements such as *Elaeocarpus* etc; The equivalent climate is Subtropical.

3) Lower *Quercus* Zone (1500-2000 m; 14-17°C), with major components as *Cyclobalanopsis longinus, C. gilva, Lithocarpus* and *Litsea*. The equivalent climate is Warm-temperate.

4) Upper *Quercus* Zone (2000-2500 m; 11-14°C), with major components as *Cyclobalanopsis morii, C.stenophylloides, Trochodendron* and *Castanopsis carlesii*. Components of this zone are usually simpler than the Lower Quercus Zone. The equivalent climate is Temperate.

The *Quercus* Zone is often mixed with montane mixed coniferous forest including *Chamaecyparis* type, Taxodiaceae and Pinaceae.

5) *Tsuga-Picea* Zone (2500-3100 m; 8-11°C) with major components, *Tsuga chinensis, Picea morrisonicola* and *Pinus armandii mastersiana*. The equivalent climate is Cool-temperate.

6) *Abies* Zone (3100-3600 m), mainly *Abies kawakami*. Above 3300 m, alpine shrubs and herbs are scattered. The equivalent climate is Cold-temperate.

7) Alpine vegetation (>3600 m, <5°C), mainly *Juniperus* and grassland. The equivalent climate is Subarctic.

Tsukada (1967) described the forests of central Taiwan between altitudes of 500 and 2400 m near the studied area as follows: warm-temperate forest (ca. 500-1800 m) dominated by *Castanopsis* and cool-temperate forest (ca. 1800-2400 m) composed of conifers like *Chamaecyparis* mixing with deciduous hardwood species *Cyclobalanopsis*, *Ulmus*, *Zelkova*, *Juglans*, *Carpinus* etc..

Pollen records discussed in this study are from the Toushe peat bog and its neighboring Jih-Yueh Tan (23°49'N; 120°53'E), which originated from middle Pleistocene pull-apart basins. Toushe was a lake during the early late Pleistocene. It became a peat bog during the last glacial and then desiccated about two thousand years ago. The neighboring lake Jih-Yueh Tan (Sun-moon Lake) is a composite lake originally consisting of two separate lakes, i.e. Jih Tan (sun lake) in the east and Yueh Tan (moon lake) in the west. There are three cores where pollen diagrams are available in this composite lake; one is from Jih Tan (Tsukada, 1967) and two from Yueh Tan (Huang and Huang, 1977; Lu, 1996). The annual rainfall is 2341 mm, annual evaporation is 1098 mm with an average of 155.6 rainy days. The mean annual temperature is 19.2°C with the coldest month having an average temperature of 13.9oC and the warmest month 23.6°C. The vegetation currently surrounding the studied area belongs to the subtropical evergreen broad-leaved forest-the *Machilus-Castanopsis* Zone. The forest consists mainly of *Machilus kasanoi*, *M. zuihoensis*, *Beilschmiedia erythrofolia*, *Phoebe formosana*, *Sapium discolor*, *Alnus* formosana, *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 theophrastaefoli* and *Sapindus mukorosii* etc (Lin *et al.*, 1968).

SURFACE POLLEN ASSEMBLAGES OF NATURAL FORESTS NEAR THE STUDIED LAKES

Surface pollen assemblages of natural forests are taken from the natural preserved Salisien-chi area (23°28'-23°33'N; 120°53'-120°59'E, at altitudes between 1400m and 3400m). It belongs to the territory of Yushan National Park and is located about 35 km to the south of the Toushe peat bog. This high-gradient area distributes today's forests into *Quercus* Zone, *Tsuga-Picea* Zone and alpine vegetation (Chung, 1994). Samples were taken from the surface soils of forests in sites where canopies are relatively less closed. Samples between 1400 and 1500 m are from Tuli Shan, located at eastern side of the Salisien River whereas samples between 1530 and 3300 m are from the western side of the river in places near Tai-18 highway (Tab.1).

Quercus Zone of the forests, distributed between 1500-2500 m, consists of many forest types (Chung, 1994), such as *Chamaecyparis formosensis* type (2500-2200 m); *Salix fulvopubescens* type (2350-2250 m), *Alnus formosana-Aralia bipinnata* type (2260-2430 m), *Castanopsis carlesii-Machilus Japonica* type (1970-2200 m), *Carpinus kawakamii* type (1250-2000 m), *Pasania brevicaudata* type (1830 m), *Litsea acuminata* type (1800 m), *Cyclobalanopsis stenophylla* var. *stennophylloides-Machilus zuihoensis* type (1350-1600 m) and *Pseudotsuga wilsoniana-Cyclobalanopsis globosa* type (1750 m) c. *Tsuga-Picea* Zone, which lies between 2500 and 3100 m, consists of *Tsuga chinensis var. formosana* type (2500-3200 m), *Pinus taiwanensis* type (2600 m), *Alnus formosana-Rhododendron oldhamii* type (2600 m), *Yushania niitakayamensis-Rhododendron rubropilosum* scrub type (2600-2800 m) and *Picea morrisonicola* type (2500-3000 m). When it is less humid, deciduous forests of *Alnus formosana* appear at altitudes between 900 m and 2600 m, and are associated altitudinally with different elements. For example, *Alnus* associated with *Carpinus* or *Acer* frequently appear at near 2000 m, *Alnus* associated with *Pinus* at between 2200 and 2400 m, and *Alnus* associated with Urticaceae usually at below altitudes of 2000 m. *Pinus* forests occur in between 2400 m and 3000 m, whereas grasslands grow above 3000 m (Chung, 1994). The surface pollen assemblages are taken from various types of each vegetation zone (Tab. 1, Fig. 1.). In the riverine area of Salisien-chi, the low altitude forest–*Castanopsis-Machilus* Zone, which is distributed below 1500 m, is not well represented. Thus, samples of altitude 700 m come from Lien-hua Pond, about 5 km NW of Jih-Yueh Tan. Samples of 1330 m and 1550 m are from Chi-Tou, the Experimental Forest of National Taiwan University.

Table 1. Location and vegetational characteristics of surface soil samples.

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[illegible]	Tai 18 highway	[illegible]	[illegible]	[illegible]
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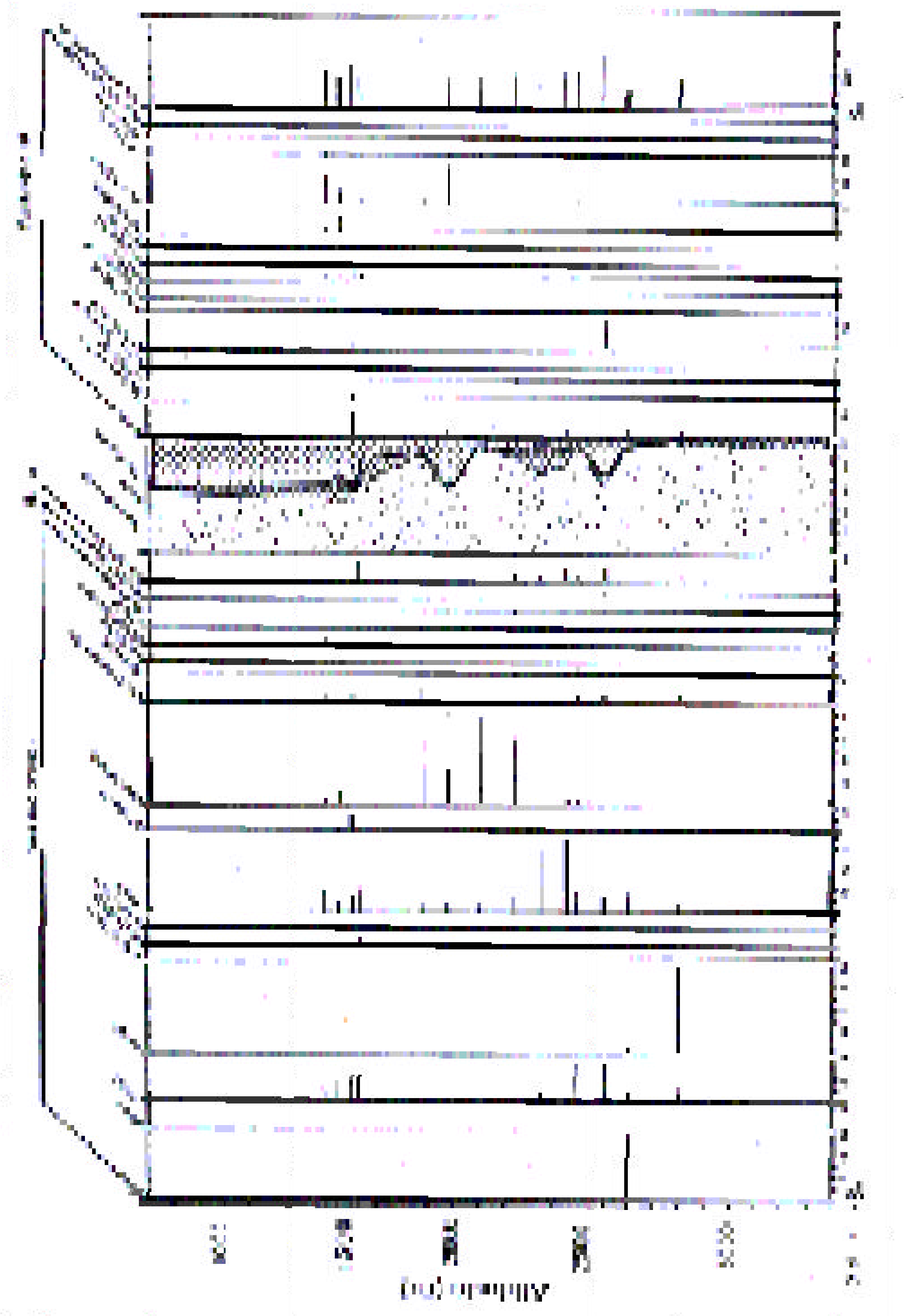

Figure 1. Pollen diagram of surface soil samples from Salisien-chi forest, central Taiwan (pollen and spore as the sum).

The most representative surface pollen assemblage in the *Castanopsis-Machilus* Zone (below 1500 m-high) is the one from the natural forest of Lien-hua Pond (700 m) which shows *Castanopsis* dominant. Three other samples from Tuli Shan are locally influenced by the Pinus forest distributed further up. Although *Castanopsis* type pollen is dominant in the *Machilus-Castanopsis* Zone, the *Castanopsis* dominant assemblage (also including pollen of *Castanopsis carlesii* and *Pasania brevicaudata*) may rise to 2100 m, reaching the lower *Quercus* Zone. This is due to the fact that some species of *Castanopsis* also distribute in the *Quercus* Zone, such as *Castanopsis carlesii* and *Pasania brevicaudata*. However, pollen assemblages of *Castanopsis* dominant ones below 1500 m (*Machilus-Castanopsis* Zone) can still be distinguished from that of the *Quercus* zone (above 1500 m) by their associated subtropical elements such as *Elaeocarpus*, etc. Monolete spores are found frequently at altitudes below 1850 m whereas *Cyclobalanopsis* is higher in the *Quercus* Zone. Samples between 2150-2400 m belong to the upper *Quercus* Zone, with pollen assemblages showing that *Alnus*, *Quercus*, *Pinus*, *Osmanthus* and Gramineae increase. *Alnus* dominant (60%) pollen assemblage is found at around altitude 2250 m. Above 2400 m, *Pinus* prevails occasionally with high *Lycopodium* peak. Above 2600 m, *Picea* and *Tsuga* prevail.

POLLEN RECORDS OF THE STADIALS OF THE LAST GLACIAL FROM TOUSHE PEAT BOG AND JIH TAN

Toushe peat bog

The 39.8 m-thick core was taken near the middle part of this small sized (1.75 km^2), rectangular basin-Toushe. Mountains to the south and east reach heights of more than 2000 m. Peat deposit intercalated with thin layers of clay or gyttia spreads the upper 32.8 m. There are twenty-nine sets of conventional ^{14}C dating data with 10 cm-thick samples of each needed, which spreads a duration of either 130 yrs (interglacial) or 320 yrs (glacial). This sequence shows a rather constant sedimentation rate. Depths below 30.5 m are assigned to OIS 5 based on both extrapolation of available dating data and changes of pollen assemblages. The fine, thick sediments down to 39.8 m probably extend to cal. 96,000 kyr (probably stage 5c). Below this depth are coarse-grained fluvial to fan deposits.

Pollen records of this peat bog show that *Alnus* was the dominant genera during the last glacial (Liew, 1998). Today this genus is common in the upper part of *Quercus* zone of forests in central Taiwan where conditions are less humid and soils does not develope well. The cold-warm conditions can be indicated by the amounts of warm elements: *Castanopsis*, *Mallotus*, or cold elements: *Alnus* and *Salix*. Dry conditions are usually represented by Gramineae (without accompanied by large amounts of monolete spore), Cyperaceae, *Alnus* and *Salix*, whereas wet conditions are indicated by large amounts of spores and hydrophytes. Higher amounts of monolete spores in the diagram is looked as a proxy of higher precipitation. Precipitation is usually an index of intensification of summer monsoons owing to an increase of tropical cyclone frequency. Spore dominant intervals are during the Holocene as well as certain intervals of OIS 3 and 5, but they were generally few such periods during the stadials of glacial.

Early stadial (depths 26.6-23.4 m; 58.9-73.9 kyr, calibrated years):

The interstadial within OIS 5, is characterized by *Castanopsis* prevailing assemblage and is found in the lower part of the pollen diagram from 39.8 m to 30.5 m. Then a sharp decrease of *Castanopsis* (from 40% to 10-15%) and the succeeding increase of *Salix* (from 5% to 40%) mark the transition from warm to cold conditions. This abrupt cold phase is then followed by a warm pulse indicated by an increase of *Ilex*. Again, it is soon replaced by a pulse of high *Alnus* (75%). Then Cyperaceae continued to maintain their important role before the early stadial. In depths 26.6-23.4 m, a high percentage of *Alnus* (40-75%) and a low frequency of *Castanopsis* (about 5%) witnessed the coming of early stadial. *Salix* (up to 20%) is the second most common element next to *Alnus*. The percentage of arboreal pollen is high (> 80%), in which the major component is *Alnus* (generally 60% or more). This easily recognized, high-*Alnus* percentage interval is tentatively assigned to be corresponded to OIS 4. This, in turn helps make the age model of the core beyond ^{14}C dating limit. In the study of surface pollen assemblage of the Salisien-chi natural forests, *Alnus* dominant (60% or more) assemblages were found at about 2250 m and above. Comparing this with 650 m altitude of the Toushe site, it can be seen that at least 1500 m vertical migration of forests occurred during the early stadial.

Between depths 23.4 and 13.8 m, *Alnus* fluctuates at the expense of herbs (Gramineae and Cyperaceae). Amelioration of the climate is indicated by the relatively higher percentage of *Castanopsis* between 19.9 and 24 m. Spores increasing dramatically between 18.5 to 19.5 m indicates wet conditions. The decrease of *Alnus* and the increase of *Cyclobalanopsis* and *Ilex* are a witness to the less cold-dry conditions. This interval corresponded to OIS 3.

Late stadial (depths 13.8 - 10.4 m; 12.1~24.1 kyr)

Between depths 13.8 and 10.4 m, herbs increased remarkably (20-70%), including Gramineae (20-55%), Cyperaceae (10-60%) and *Artemisia* (3-12%), indicating very dry conditions. This indicates it should be a forest-steppe vegetation (Kuo and Liew, 2000). However, the associated woody elements are *Cyclobalanopsis*, *Ilex* and *Symplocos*, of which *Cyclobalanopsis* is relatively common. This indicates that most time of late stadial (OIS 2) was not as cold as the early stadial (OIS 4) if judged from the associated woody elements.

The late stadial ended when high percentage of the arboreal element (80%, mainly *Ilex*, *Symplocos* and *Cyclobalanopsis*) of late glacial appeared. In this paper, % is based on total pollen.

Jih Tan

To the northeast of the Toushe peat bog basin is Jih-Yueh Tan, which means sun-moon lake in Chinese. Pollen diagram of Jih Tan (Tsukada, 1967) showed the following results:

Early stadial

The pollen records of Jih Tan (eastern part) shows that the early stadial (T-2) is characterized by Pinaceae and that it is the coldest interval of the last glacial (Tsukada, 1967).

Late stadial

The late stadial (within T-3) is not well represented in the same pollen diagram of Tsukada (1967), probably due to the sampling spacing. The small Gramineae peak in the upper part of the T-3 Zone may correspond to the late stadial.

COMPARISON AND DISCUSSION

Early stadial

The contrast of pollen assemblage of the early stadial between a Pinaceae dominant assemblage in Jih Tan and the *Alnus* dominant assemblage in Toushe is remarkable. It indicates that the lower limit of the coniferous forest was at an altitude between these two sites, i.e., about 700 m. One point which needs to be clarified is that in his pollen diagram, Tsukada (1967) disregarded *Alnus* due to its high pollen production. Does this preclusion result in a Pinaceae dominant assemblage of the early stadial in Jih Tan result? In the records of Toushe (the lower site), the importance of Pinaceae in the early stadial is not recognized at all even excluding *Alnus*, and it seems impossible to obtain a Pinaceae dominant assemblage through such exclusion. Thus, the authors believe that a Pinaceae dominant assemblage in Jih Tan would still appear even if Tsukada included *Alnus* pollen. This indicates that Jih Tan is possibly just on or above the lower limit of the coniferous zone and that Toushe should be below the zone. That is to say, coniferous forest was possibly distributed down to this altitude (the higher site).

In addition to Toushe and Jih Tan, the two cores of Yueh Tan are worthy to be mentioned. The longer core of Yueh Tan located in the middle part recorded the early stadial as well (Huang and Huang, 1977). Although this core today is also within Jih-Yueh Tan, unlike the records of Jih Tan core, it is characterized by the *Alnus* dominant vegetation, similar to that of the Toushe peat bog. A possible explanation is as follows. As mentioned above, Jih-Yueh Tan is originally two separate lakes, and only in recent years connected by humans. The sedimentation rate of the Yueh Tan core (Huang and Huang, 1977) shows similarity to the Toushe peat bog, with Holocene sediments around 7.5 m-thick, (Kuo and Liew, 2000) whereas that of the eastern Yueh Tan core (Lu, 1996) is similar to Jih Tan, with Holocene sediments approximately 4 m-thick. The different rates of sedimentation within the NW-SE elongated Yueh Tan are probably related to tectonic (probably fault) influences. If so, it is possible that the middle Yueh Tan core (the longer one) might be altitudinally similar to Toushe and surrounded by the *Alnus*-dominant vegetation during the early stadial. Jih Tan (Tsukada, 1967) was possibly higher than Toushe and the middle and western parts of Jueh Tan, and was near the lower limit of the coniferous zone at that time.

Late stadial

Similar to the Toushe peat bog results, the late stadial characterized by herb dominant vegetation is found in both cores of Yueh Tan (Huang and Huang, 1977; Lu, 1996).

REFINEMENT OF COLD CONDITIONS OF THE LAST GLACIAL

As mentioned before, the early stadial of the last glacial of the Toushe core is represented by the highest value of *Alnus* (>60%), whereas the late stadial is represented by the highest value of herbs. Available surface pollen assemblages in the forests near Salisien-chi show that *Alnus* dominant conditions (>60%) occurs as high as 2250 m of today' s forests. Thus, vertical migration of 1500-1600 m occurred between the early stadial of the last glacial and now. On the other hand, the forest boundary of *Alnus*/coniferous is at an altitude of 2300-2500 m nowadays but it appeared down to about an altitude of 750 m during the early stadial, based on the Pinaceae dominant assemblage at this time in Jih Tan (Tsukada, 1967) in contrast to the *Alnus* dominant assemblage at Toushe. This ecotone migration is again estimated about 1600 m, which indicates the temperature difference between OIS 4 and the present may be about 8-10°C.

Although the last glacial maximum (LGM) is not well represented in the Yih Tan core, it is well represented in the Toushe core. The smooth sedimentation rate in the Toushe peat bog excludes problem of diastem during the LGM. During the LGM, the non-tree pollen prevailed with Gramineae reaching more than 40% in the Toushe peat bog, which indicated drought conditions with precipitation at probably half of the present value. However, associated woody elements of that interval are mainly *Cyclobalanopsis* instead of *Alnus*. Considering that altitude of recent distribution of *Cyclobalanopsis* is generally lower than that of *Alnus*, we suggest that less severe cold in most of the late stadial. Thus, OIS 4 was wetter and possibly colder than most part of OIS 2 if excluding the short coldest interval within OIS 2. The cold-dry intensity during stadials of the last glacial here seems different from that of temperate region.

CONCLUSION

Large-scale climatic changes in Asia Monsoon areas like Taiwan may be revealed by vegetational changes. It has been documented that the interglacial climate became more warm-wet compared to glacial due to the intensification of summer monsoons (Huang *et al*., 1997). During the last glacial, the deciduous broad-leaved forests of mainly *Alnus* replaced the recent evergreen broad-leaved *Machilus*-*Castanopsis* forests in low hilly areas as shown by the pollen records of the Toushe peat bog deposits. In the early part of the glacial (OIS 4), *Alnus* percentage was higher than that in the later part (OIS 2). Taking the surface pollen assemblages as comparison, a 8-10°C decrease in temperature during early stadial is suggested, with the vertical migration probably reaching 1500-1600 m. During most part of late stadial, the percentage of *Alnus* was lower, but that of *Cyclobalanopsis* was higher compared with early stadial; this also indicated less cold conditions. However, during late stadial, a forest steppe condition represented by a high NAP indicated a much drier condition than the present.

The wetter and possibly colder early stadial of the last glacial is observed in several terrestrial records of East Asia. This condition is worthy of further study, especially for its relation to global climatic changes during the last glacial.

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