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Paleolimnological environment indicated by the diatom and pollen assemblages in an alpine lake in Taiwan*

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Abstract

Yuanyang Lake (24°35'N, 121°24'E), located at an altitude of 1,670 m within a nature preserve in northern Taiwan, is an acidic lake. Remains of diatoms and pollen from a 3.72-m sediment core were used to elucidate the relationships between the vegetation of the watershed and the paleolimnological environment. Past pH, saprobity level, and total P of the lake were inferred from the diatom assemblages and were analyzed with respect to changes in the terrestrial vegetation. The inferred pH values fluctuated only slightly, whereas the inferred saprobity level increased markedly towards the sediment surface. In the topmost sediment, a slight drop in the inferred pH was associated with a lowering in the saprobity index. This was interpreted as a possible result of recent anthropogenic acidification and changes in productivity related to changes in acidity. Based on pollen analyses, we conclude that *Chamaecyparis* persisted over at least the last four thousand years in the watershed. The vegetation in the watershed changed little during this period of time, which is consistent with the constancy of inferred pH values. A positive correlation between the inferred pH and $\delta^{13}C$ values of the sediments was found.

Introduction

Lake sediments provide an informative historical record of changes in lake ecosystems and their surrounding drainage basins. Reconstruction of a paleoenvironment is usually based on microfossils or chemical information from sediments. Diatoms and scaled chrysophytes are generally used to infer environmental changes because their siliceous cell wall components are well preserved in the sediments. Paleoecological events such as changes in trophic state (Agbeti & Dickman, 1989), acidity (Battarbee et al., 1986), climate (Halfman et al., 1992), lake development (Whitehead et al., 1989), phosphorus concentrations (Hall & Smol, 1992) and anthropogenic effects (Schmidt & Simola, 1991) have been inferred using siliceous algae.

Yuanyang Lake, a subtropical alpine lake situated at 24°35'N, 121°24'E at an altitude of 1,670 m, is located within a nature preserve in northern Taiwan (Figure 1). It has a maximum depth of ca. 4 m, an area of about 3.6 ha, and a volume of ca. 5.4 x 10^4 m^3. The watershed area of ca. 370 ha is forested by cypress (a mixture of *Chamaecyparis formosensis* Matsum and *C. obtusa* var. *formosana* (Hay.) Rehder), with an understory of primarily *Rhododendron formosanum* Heiml, and a rich array of epiphytes, mainly mosses (Liu & Hsu, 1973). The climate conditions are moist, with temperature ranging between 5 and 20°C, annual precipitation between 250–450 cm, and relative humidity always greater than 80%. Because this area has remained virtually undisturbed by human activities, it provides an unique site for paleoecological study. It is an area where very little paleoenvironmental data are available.

The Yuanyang Lake is an oligotrophic, brown-water lake colored by fulvic acids. A summary of water

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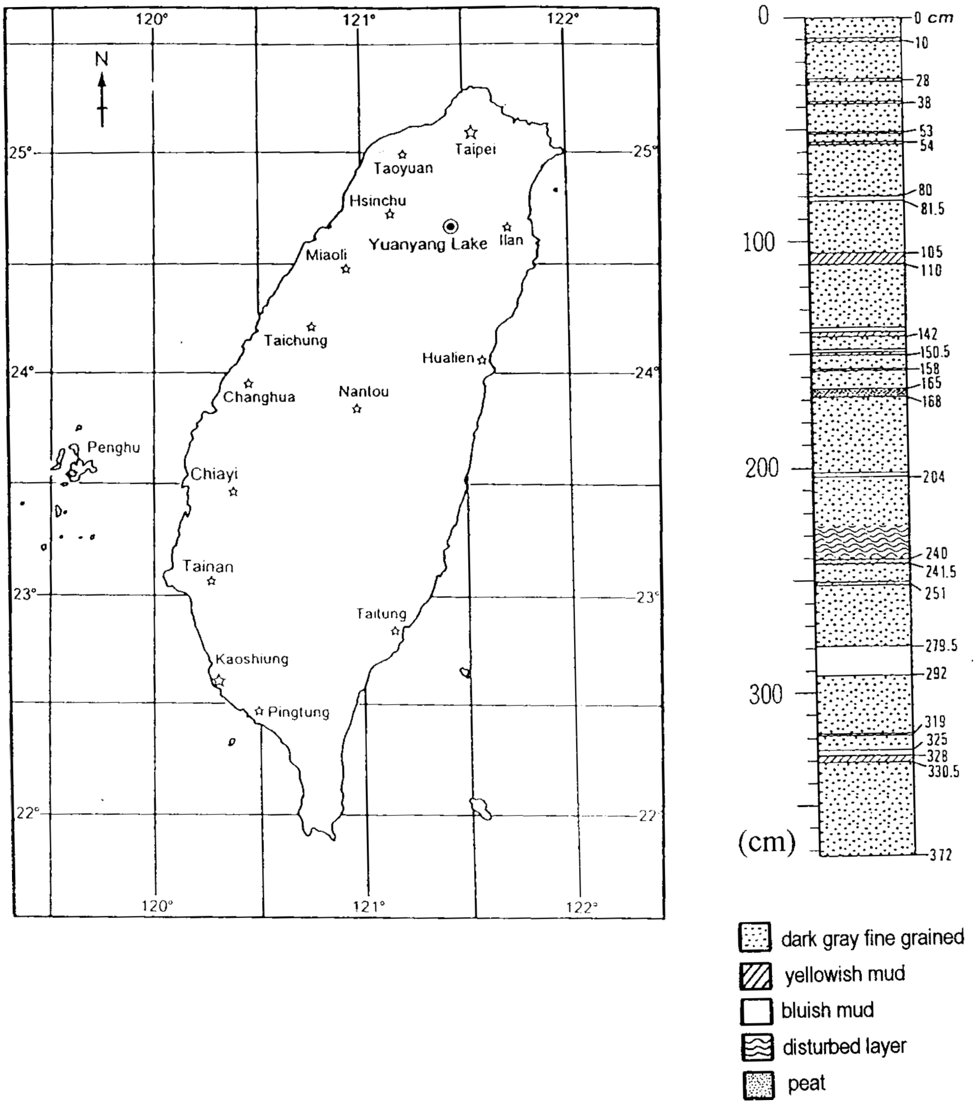

Figure 1. Map of Taiwan, showing the location of Yuanyang Lake, and the stratigraphy of the sediment core used in this study.

quality has been given in a previous paper (Wu & Chang, 1996). It is an acidic lake. The acidity of contemporary lake water exhibits spatial and temporal variations, with pH ranging between 3.9 and 6.7 (average 5.2, measured over the last four years) (Wu & Chang, 1996; Wu et al., 1998). It is more acidic during the dry season (spring) and at the localities near the input of runoff from the watershed. The low pH values were closely correlated with the runoff from the terrestrial vegetation. The acidification of this lake, therefore, was believed to be primarily a natural one. However, acidic precipitation is quite common in Taiwan, having been well documented over a large part of the island by the Environmental Protection Administration of Taiwan, and has presented a serious environmental problem. In other studies (Wu et al., 1998), acid rainwater caused an increase in the acidity of runoff from the epiphytes of the terrestrial vegetation surrounding Yuanyang Lake. In this regard, the study of acidification in Yuanyang Lake was potentially of great value, particularly for studying the additional effect of acid rain on lake acidification.

A previous study based on isotopic composition of organic carbon showed fluctuations in the ratio of $^{13}C/^{12}C$ (i.e. $\delta^{13}C$) throughout a core taken from Yuanyang Lake (Yeh et al., 1995). Such a change was thought to be a regional phenomenon and a result of climatic change. A change in the composition of the vegetation would likely be associated with a change in climatic conditions. In the present study, both the diatoms and pollen preserved in the sediments were analyzed to reconstruct the paleoenvironment of this lake.

Materials and methods

A 3.72-m sediment core was taken from the deepest part (4 m depth) of the lake. The stratigraphy of the core has been described by Lin (1994). The sediments were sub-sampled in the laboratory, and about 1 cm^3 of each sample was used for preparation of diatom as well as pollen analysis. For diatom analysis, samples were treated with hydrogen peroxide and hydrochloric acid and washed in distilled water, after the procedures given by Steinberg et al. (1988). Subsequently, they were filtered under reduced pressure onto a cellulose nitrate filter (pore size 0.45 µm, Sartorious AG, Göttingen, Germany), and mounted in immersion oil on a cover slip for study and identification under a light microscope. Four hundred diatoms were counted in each sample. The identification of taxa was based on descriptions in the literature including Hustedt (1927–1966), Huber-Pestalozzi (1942), Cleve-Euler (1951–1955), Gerloff & Cholnoky (1970), Rabenhorst (1971), Krammer & Lange-Bertalot (1986-91), and Simonsen (1987).

Because available inference models for pH and total P are lacking in Taiwan or its nearby regions, the inferences of these variables were done by adopting models from other regions. Inference of pH were based on using the pH optimum of each indicator species in the diatom assemblages, employing the methods of Charles (1985) and Davis & Anderson (1985). The pH categories of Hustedt (1937–1939) were followed. Because Yuanyang Lake is an oligotrophic lake and a number of its diatom taxa were similar to those listed by Hall & Smol (1992), their method for inferring the concentration of total P was employed. For evaluation of change in the saprobity level, the method of Zelinka & Marvan (1961), and the indicator species listed by Sládeček (1973) were adopted. The contents of total organic N and total P in the sediment were determined according to APHA (1992).

The methods given by Beug (1957) were followed to extract the fossil pollen. Samples were first boiled in 10% KOH for 5 min, and then sieved through a mesh screen with an aperture of 200 µm to remove larger plant parts. Subsequently, the samples were treated with acetolysis (Erdtman, 1952). Pollen and spore counts were conducted under a light microscope. For each sample, the frequency of arboreal pollen (AP) was calculated by counting five hundred pollen grains. The relative abundance of non-arboreal pollen (NAP) was calculated as the difference between total pollen and AP.

The dating of ^{14}C for sediment samples was conducted by the Institute of Geological & Nuclear Science, Lower Hutt, New Zealand as well as by the Institute of Geology, National Taiwan University, Taipei, Taiwan.

Results

Characteristics of lake sediments

Based on the results of the ^{14}C-dating and the sediment characteristics, Yuanyang Lake was probably formed about four thousand years ago. A sedimentation rate of about 1 mm per yr was calculated on the basis of ^{14}C-dating.

Diatom assemblages in the sediments

A total of 79 diatom taxa, from 20 genera, were identified from the sediment core (Table 1). The diatom assemblages were dominated by a variety of *Eunotia* species in association with *Frustulia rhomboides, Pinnularia interupta* f. *minutissima, P. microstauron, Caloneis bacillum, Cymbella amphicephala, Tabellaria fenestrata* and *T. flocculosa.* The relative abundance of these taxa fluctuated significantly throughout the entire core, showing the succession of these taxa (Figure 2). There were marked increases in the abundances of *Caloneis baccilum, Eunotia praerupta, P. interrupta, P. microstauron,* and *T. flocculosa* toward the topmost portion of the sediments.

Inference of paleo-environment by diatom assemblages

The majority of diatoms occurring in the sediment were either acidophilous or circumneutral (= indifferent) species, whereas alkaliphilous taxa were present in only trace amounts (Figure 2). Acidophilous and circumneutral taxa persistently dominated throughout the entire core. A slight increase in the abundance of alkaliphilous species was observed at depths between 130 and 190 cm, however they declined toward the surface of the sediments.

The pH values inferred on the basis of indicator taxa in the diatom assemblages fluctuated between 6.2 and

Table 1. Diatom taxa observed in the sediment samples of Yuanyang Lake, their averages of pH and total phosphorus, pH occurrence categories, and saprobity index

Diatom species	pH ave.[1]	total P[2] (μg/L)	pH category[3]	saprobity index[4]
Achnanthes exilis Kütz.				
Achnanthes impexiformis Lange-Bertalot				
Achnanthes lanceolata (Bréb.) Grun.				0.75
Achnanthes lanceolata ssp. *miota* (Carter) Lange-Bertalot				
Achnanthes microcephala (Kütz.) Cl.		8.8	cir	
Achnanthes minutissima v. *minutissima* Kütz.	7.2	9.0	cir	1.45
Achnanthes montana v. *montana* Krasske				
Amphora ovalis (Kütz.) Kütz.			alp	1.65
Anomoeneis brachysira v. *brachysira* (Bréb.) Grun.				
Aulacoseira granulata (Ehr.) Simonsen				1.8
Aulacoseira italica (Ehr.) Simonsen				1.6
Aulacoseira valida (Grun.) Krammer				
Caloneis bacillum (Grun.) Cleve				0.4
Caloneis silicula (Ehr.) Cl.				1.5
Cocconeis placentula v. *placentula* Ehr.		12.9	cir	1.35
Cyclotella bodanica Eulenst.		11.7		1.0
Cyclotella radiosa (Grun.) Lemm.		11.3		
Cyclotella stelligera v. *stelligera* (Cl. & Grun.) Van Heurck	6.8	9.7	cir	
Cymbella amphicephala Näg.	6.5	6.4		
Cymbella borealis Cl.				
Cymbella gracilis (Rabh.) Cl.				0.2
Cymbella hebridica (Grun.) Cl.	5.1	3.6	acp	
Cymbella similis Krasske				
Cymbella sinuata Greg.				
Cymbella subcuspidata Krammer				
Cymbella turgidula Grun.				
Diploneis parma Cleve				
Eunotia bilunaris v. *bilunaris* (Her.) Mills				0.55
Eunotia bilunaris v. *mucophila* Lange-Bertalot & Norpel				
Eunotia fallax v. *fallax* Cl.-Euler				
Eunotia formica Ehr.			acp-cir	
Eunotia monodon v. *monodon* Ehr.			acp	
Eunotia muscicola v. *perminuta* (Grun.) Norpel & Lange-Bertalot				
Eunotia praerupta (Ehr.) Grun.			acp	
Eunotia serra v. *serra* Ehr.	4.9	5.8	acp	
Eunotia soleirolii (Kütz.) Rabenh.				
Eunotia zygodon v. *elongata* Hust.				
Fragilaria capucina v. *capucina* Desma.				1.6
Fragilaria fasciculata (Ag.) Lange-Bertalot				
Fragilaria pinnata v. *pinnata* Ehr.	7.3	15.0	alp	
Fragilaria rumpens v. *fragilarioides* Grun.				
Frustulia rhomboides (Ehr.) De Toni	5.5	5.6	acp	0.6
Gomphonema acuminatum Ehr.			alp	1.7
Gomphonema affine Kütz				
Gomphonema angustatum (Kütz.) Rabh.	6.6	11.1		1.15
Gomphonema angustum Ag.		8.6		
Gomphonema bohemicum Reichelt & Fricke				
Gomphonema clavatum Ehr.				
Gomphonema gracile Ehr.			alp-cir	
Gomphomena minutum (C. Ag.) C. Ag.				
Gomphonema parvulum Kütz.		10.2	acp-cir	1.95
Navicula cari Ehr.		12.8		
Navicula cryptonella Lange-Bertalot				
Navicula elginensis (Greg.) Ralfs				
Navicula heimansii Van Dam et Kooyman				
Navicula heimansioides Lange-Bertalot				

Table 1. Continued

Diatom species	pH ave.[1]	total P[2] (µg/L)	pH category[3]	saprobity index[4]
Navicula laevissima Kütz.	6.6	10.2		
Navicula modica Hust.				
Navicula pupula v. *pupula* Kütz.	6.9	12.1	alp	2.2
Navicula radiosafallax Lange-Bertalot				
Navicula tridentula Krasske				
Neidium affine (Ehr.) Pfitzer	5.1	4.5	acp	
Neidium ampliatum (Ehr.) Krammer		8.0		
Neidium iridis (Ehr.) Cl.			cir	
Neidium sp.				
Nitzschia fonticola Grun.	6.9	11.5	alp	1.4
Nitzschia perminuta (Grun.) Peragallo				
Pinnularia divergentissima (Grun.) Cl.			cir	
Pinnularia interrupta f. *minutissima* Hust.				
Pinnularia maior (Kütz.) Rabh.				
Pinnularia microstauron (Ehr.) Cl.	5.2	4.9	acp	0.8
Pinnularia viridis (Nitz.) Ehr.			acp	
Stauroneis javanica (Grun.) Cl.				
Stauroneis pygmaea Krieger				
Surirella biseriata Bréb.			acp	2.0
Surirella linearis v. *helvetica* (Brun) Meister				
Surirella tenera Greg.			acp	2.1
Surirella tenuissima Hust.				
Tabellaria fenestrata (Lyng.) Kütz.		9.5	acp	1.4
Tabellaria flocculosa (Roth) Kütz.			acp	0.6

[1]Weighted average of pH based on Charles (1985); [2]Total P: according to Hall & Smol (1992) and Charles (1985); [3]pH category: Hustedt (1937-39); cir – circuumneutral; alp – alkaliphilous; acp – acidophilous; [4]Saprobity index based on Sládeček (1973).

6.8 throughout the entire core, indicating only a small change in the acidity over the period of the last four thousand years (Figure 3-A). There was a slight, although likely insignificant, lowering in the inferred pH values toward the sediment surface.

The inferred pH values were unrelated to the concentrations of total organic N, total P, or their ratios in the sediments (Figure 3-C–E). However, there was a positive correlation between the inferred pH and $\delta^{13}C_{PDB}$ values measured by Yeh et al. (1995) (cf. Figures 3-B & 4-A). A comparison of $\delta^{13}C_{PDB}$ values from various plants in the watershed with that of the sediments was showed in Table 2.

The diatom inferred limnetic total P concentrations ranged between 6 and 11 µg/L throughout the entire core (Figure 5-A). It did not change prominently over the time period represented by the core. The change in the saprobity index inferred by diatom assemblages, however, was pronounced (cf. Figure 5-B). The saprobity index gradually increased from ca. 0.5 at 3840 yr BP (oligosaprobic level) to ca. 1.6 at ca. 1400 yr BP (β-mesosaprobic level). The degree of fluctuation in index values diminished between 1400 yr BP and ca. 200 yr BP, and decreased toward the surface sediment.

Pollen analysis

Pollen of *Chamaecyparis* (cypress) was dominant throughout the sediment core, ranging in abundance between 38.6 and 72.2%, with an average of 57.3%. Subdominant species of AP included *Quercus, Alnus, Tsuga,* and *Pinus*, with averages of 11.2, 7.5, 6.3, and 5.2 %, respectively (Figure 6). NAP pollen was relatively low (2.2 to 16.8%). Although the abundance of *Chamaecyparis* decreased at times, the vegetation type seemed not to have changed markedly over last four thousand yrs. The only small change in the portion of AP and the relatively low amount of NAP suggests a dominant covering of arboreal plants in the watershed during the deposition of lake sediments. Neither the fluctuation in the abundance of *Chamaecyparis* pollen nor that of NAP showed a close correlation with diatom inferred pH values (cf. Figures 4-B & 4-C).

Discussion

Throughout the entire sediment core, the pollen assemblages were dominated by *Chamaecyparis*, indicating

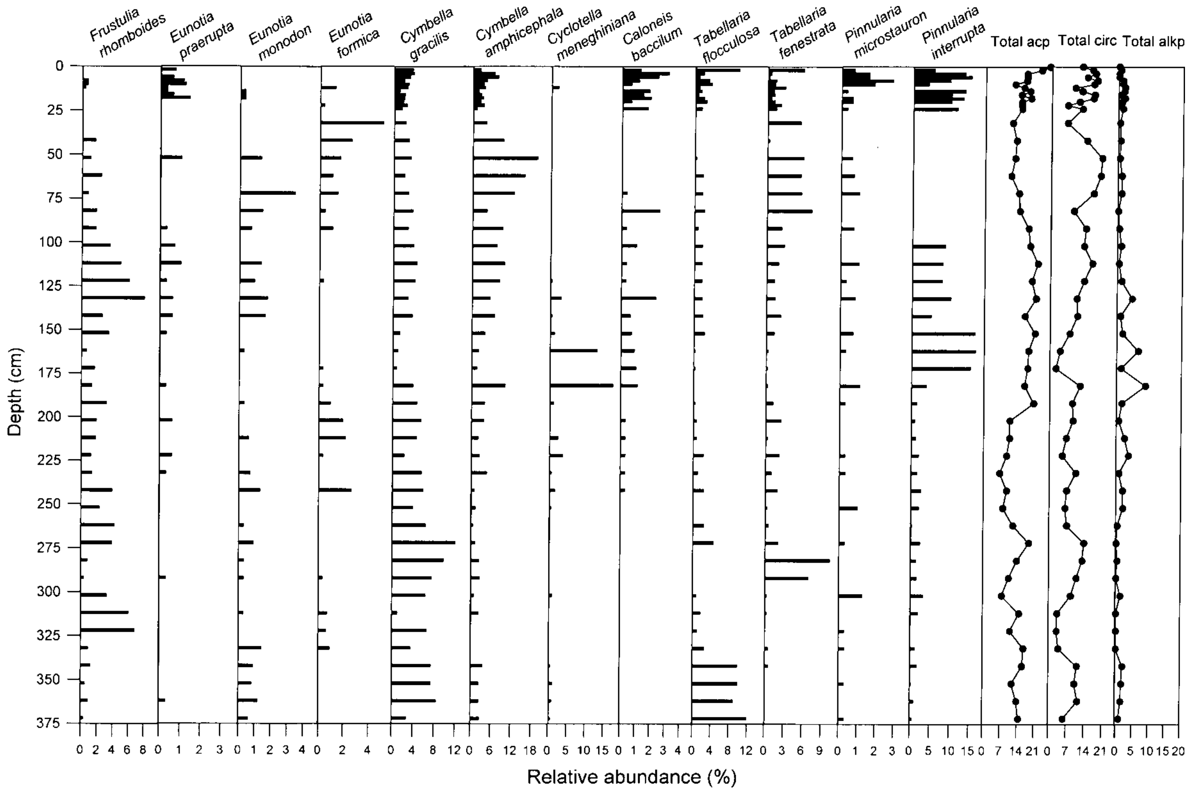

Figure 2. Downcore profile of the common diatom species, total acidophilous (acp), total circuumneutral (circ), and total alkaliphilous (alkp) species in the sediments from Yuanyang Lake.

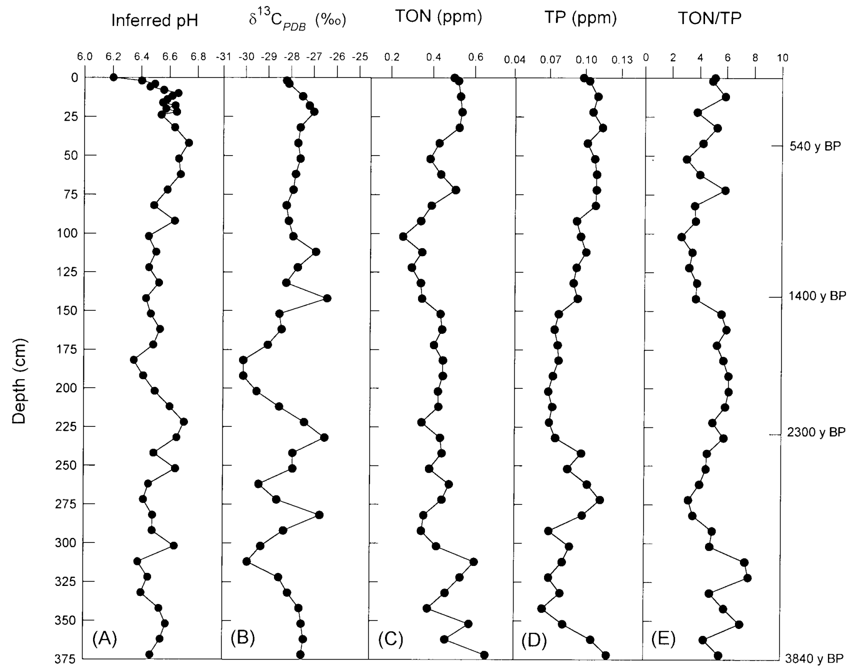

Figure 3. Downcore profile of (A) the diatom inferred pH, (B) $\delta^{13}C_{PDB}$ values, (C) the contents in total organic nitrogen (TON), (D) total phosphorus (TP), and (E) the ratios of TON/TP in the sediments from Yuanyang Lake.

Table 2. Comparison of $\delta^{13}C_{PDB}$ values of some plants from the Yuanyang Lake nature preserve with the lake sediments

Plants	$\delta^{13}C_{PDB}$(‰)	Remarks
Rhododendron formosanum	–30.4	shrub community
Chamaecyparis formosensis	–29.5	dominate vegetation
Neolitsea accuminatissima	–31.3	shrub community
Skimmia reevesiana	–31.9	slope community
Damnacanthus angustifolius	–32.9	marsh shrub and slope community
Dendropanax dentiger	–31.2	marsh shrub and slope community
Scheffera taiwanensis	–33.5	slope community
Shortia exappendiculata	–31.7	marsh shrub
Plagiigyria glanca	–31.7	marsh shrub
Sparganium fallax	–30.7	hydrophyte
Sphagnum palustre	–31.1	moss
Araiostegia parvipinnula	–27.9	fern
Bazzania fauviana	–27.4	moss
moss (unidentified species)	–27.3	moss
Spirogyra sp.	–44.9	algae
lake sediments	–26.5 to –30.1 average –27.9	sediment core

Note: data are adopted from Yeh et al. (1995).

a relatively stable vegetation community in the watershed over the last four thousand years. Previous studies showed that acidic runoff (with pH ranging between 3.8–4.8) from the watershed was the main contributor of acidity to Yuanyang Lake (Wu et al., 1998). The acidity of the runoff from the watershed was found to be related to organic acids eluted largely from epiphytes growing on the arboreal plants. Hence, as long as the vegetation type has not significantly changed, the sources contributing to the acidity of the lake should be principally the same, and so not surprisingly lake-water pH has not changed markedly.

The values of $\delta^{13}C$ in the sediments provided a unique method for determining the sources of carbon. Yeh et al. (1995) found that $\delta^{13}C$ values of plants varied from species to species. Moreover, they found that $\delta^{13}C$ values fluctuated significantly throughout the sediment core of Yuanyang Lake, suggesting a possible shift in C-sources during the deposition of the sediments. Noteworthy is that the $\delta^{13}C$ values in the sediments are closer to those of epiphytes, such as mosses and ferns,

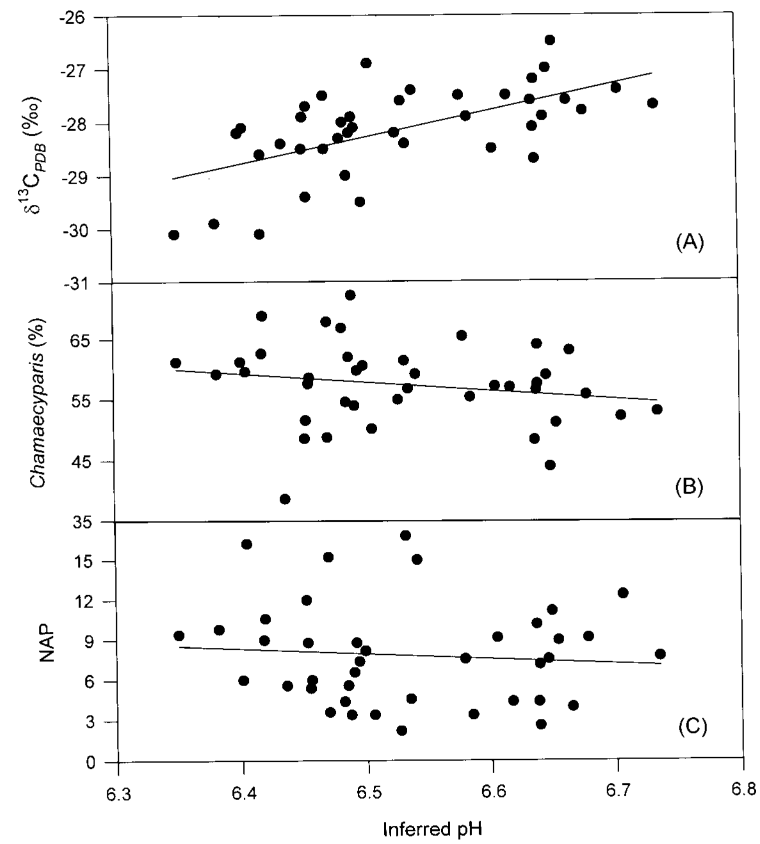

Figure 4. Correlation of the diatom inferred pH with (A) $\delta^{13}C_{PDB}$ values, (B) percentage abundances of *Chamaecyparis* pollen, and (C) non-arboreal pollen (NAP) in the sediments from Yuanyang Lake. (A) is significant at α=0.05, whereas (B) and (C) not.

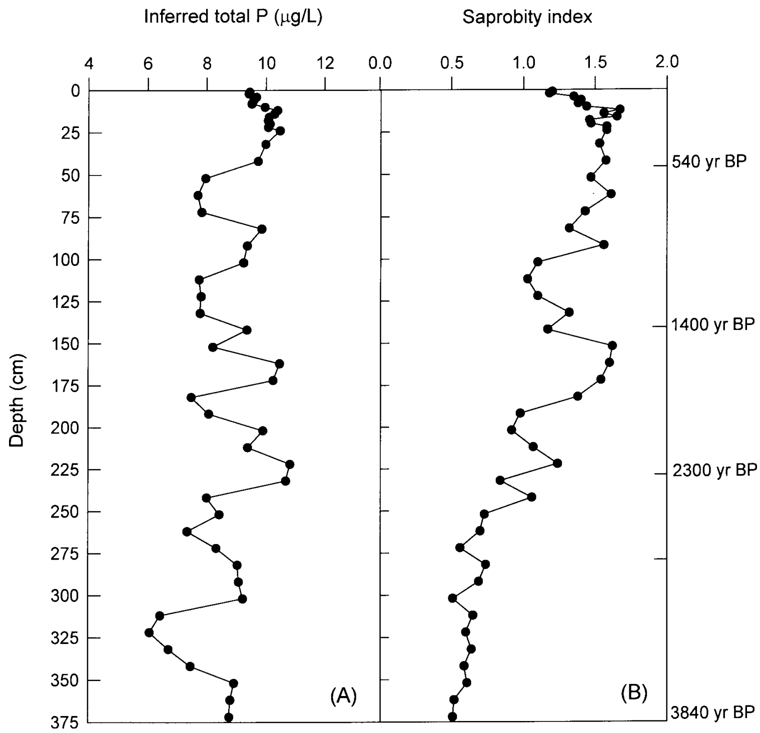

Figure 5. Downcore profile of (A) the diatom inferred total phosphorus and (B) saprobity index in the sediments from Yuanyang Lake.

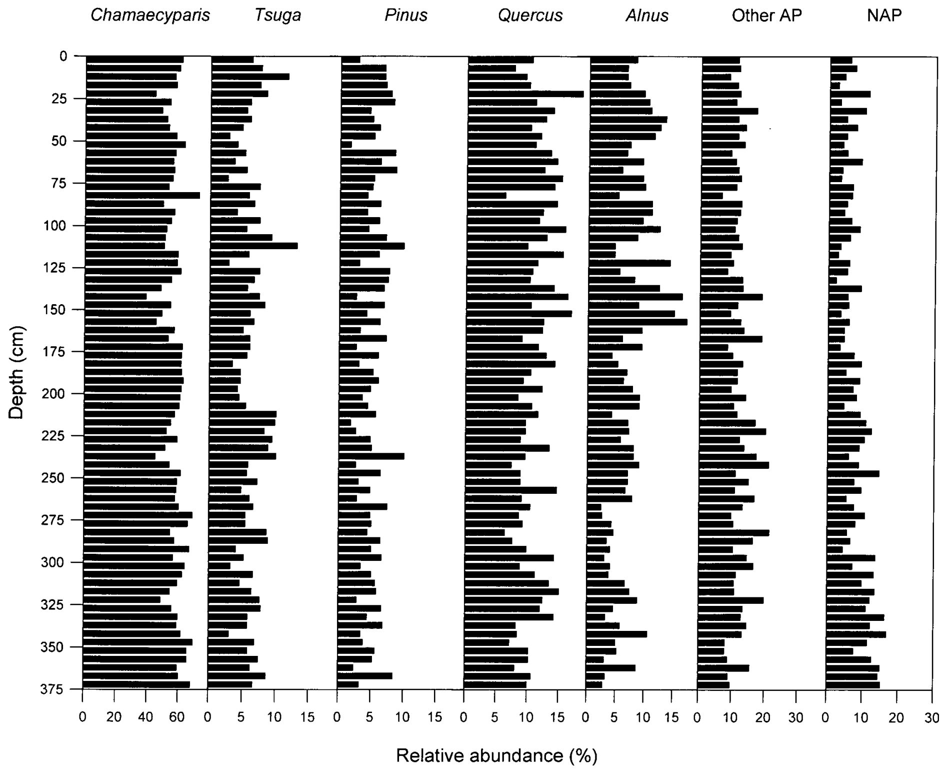

Figure 6. Downcore profile of the fluctuations in the abundance of five dominant and subdominant arboreal pollen (AP), other arboreal pollen and non-arboreal pollen (NAP) in the sediments from Yuanyang Lake.

than to those of higher plants, such as the cypress or shrub vegetation in the associated watershed. These data support the idea that epiphytes were one of the potential C-sources for lake sediments. The variation in $\delta^{13}C$ values in the sediments could be related to the concentration of atmospheric $\delta^{13}C$. Friedli et al. (1986) reported that the fossil fuel combustion and biomass destruction have caused an enhancement in atmospheric CO_2 concentration and a decline in its $\delta^{13}C$ value. Possibly the lowering in $\delta^{13}C$ values near the surface of the sediments was related to such a change.

The diatom inferred pH in the topmost portion of the core was slightly lower than in previous times. This was possibly a sign of recent acid precipitation, as it has been revealed in many other regions (Fritz et al., 1989; Schmidt & Simola, 1991). The measured pH of precipitation in Yuanyang Lake area is usually acidic. In elution experiments of our other study (Wu et al., 1998), acid rainwater was revealed to enhance the acidity of acidic eluents of epiphytes to a certain degree. Thus, acid precipitation has most likely contributed to the acidification of this aquatic ecosystem.

Because available inference models for total P and pH are lacking in Taiwan, in the present study we adopted the existing models from other regions. However, a great number of diatom taxa in Yuanyang Lake are not used as indicator species, because they were not common in the adopted models. The results of the present study are thus inferred on the basis of a few taxa. This does not likely alter our conclusions because the relative abundance of indicator taxa as well non-indicator ones changed little throughout the entire sediment core. Nevertheless, more effort should be expanded, in order to develop a suitable inferring model for Taiwan region.

On the basis of pollen analysis (Liew et al., 1995) and analysis of sediment laminations of some alpine lakes in Taiwan (including Yuanyang Lake) (Chen et al., 1993), several fluctuations in climate have been speculated to have occurred during the last several millennia. The variation in $\delta^{13}C$ values in the sediments of Yuanyang Lake was considered to be the result of climatic fluctuations (Yeh et al., 1995). However, the vegetation in the watershed of Yuanyang Lake seemed to have changed little over last four thousand years. Hence the variation in $\delta^{13}C$ values in the sediments was most likely not attributed to the alteration in the terrestrial vegetation.

In conclusion, the diatom-inferred pH of this lake has changed little over the last four thousand years. This agrees well with the little change in the vegetation of the watershed, indicated by pollen analysis. Nevertheless, a slight drop in pH was observed in the topmost portion of the sediments, possibly indicating a sign of recent acidification due to recent acidic precipitation. Such a change was associated with lowering in saprobic level.

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