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ORIGINAL PAPER

# Paleoenvironmental inferences from diatom assemblages of the middle Miocene Shanwang Formation, Shandong, China

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**Abstract** Diatoms were analyzed in a laminated sediment sequence from the middle Miocene, lacustrine Shanwang Formation, Shandong Province, eastern China, to reconstruct past conditions in the lake and evaluate relationships between inferred changes in the aquatic and terrestrial environments. Changes in the diatom assemblages over the 22.9-m-long sediment sequence were used to assign 19 lithologic layers to five zones. In Zone 1, *Aulacoseira* cf. *distans* and *Melosira youngi* were dominant in diatomaceous laminations. In Zone 2, only a few *Aulacoseira* spp. and *Cymbella* spp. were found in the yellow-green mudstone samples. In Zone 3, benthic pennate taxa, such as *Fragilaria*, *Pinnularia*, and *Cymbella* dominated in parts of the laminites. In Zone 4, *Aulacoseira* taxa regained dominance, and in Zone 5, benthic diatoms were found in only one sample. Shifts in the diatom assemblages and other sedimentological evidence indicate a change in the water level from a relatively deep system (>8–12 m) to a mudflat, then fluctuating water levels (8–12 m), shallower conditions (4–8 m), and finally a terrestrial environment. Abundant *Aulacoseira* indicate not only cold water, but also wind-induced turbulence. Water depth fluctuations coincided with the aridity index, reflected by terrestrial plant fossils in the sediments. Water pH, total phosphorus (TP), and total organic carbon (TOC) reconstructions were undertaken using the European Diatom Database (EDDI), and results showed a correlation between fluctuating water levels and volcanic activity in Zone 3.

**Keywords** Paleolimnology · Shanwang · Miocene · Aquatic environment · Diatoms

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## Introduction

Global climate change has aroused increasing concern in the international scientific community and among non-scientists, as well. Paleoclimate research will help us elucidate global climate change trends and enable us to make reasonable forecasts of future climate changes. The Miocene Epoch witnessed a series of geological and climate events, including the uplift of the Himalayas and Tibetan plateau, intensified Asian monsoons, and enhanced aridity in central Asia, all of which led to conspicuous climate changes in eastern Asia. As such, the Miocene Epoch represents a key interval in the global climatic evolution of the Cenozoic Era (Flower and Kennett 1993; An et al. 2001; Jiang and Ding 2008; Royden et al. 2008). After a warm period in the late middle Miocene, a global cooling trend set in, involving an approximately 3.1–4.3°C drop in marine water temperatures at the base of the photic zone between the early and late Miocene, as inferred from the isotope record (Schoell et al. 1994). During the Miocene Epoch, climatic regions in eastern Asia changed from being influenced primarily by prevailing westerly winds, to being dominated by a monsoon climatic regime, similar to the present (Wright et al. 1992; Liu et al. 1998; Zachos et al. 2001).

The fossil biota of the Shanwang Formation was deposited during this transitional period in the Miocene, and has already provided substantial information about paleovegetation and paleoclimate (Liu and Leopold 1992; Yang and Yang 1994; Sun et al. 2002; Liang et al. 2003; Yang et al. 2007). The diatomaceous sediments, with their well-preserved fossils, should not only contain information on variations in water depth and temperature (Brugam et al. 1998; Sarmaja-Korjonen and Alhonen 1999; Moos et al. 2005; von Gunten et al. 2007; Heinsalu et al. 2008), but should also provide valuable data on other environmental and climatic changes, as well (Pilskaln and Johnson 1991; Stoermer and Smol 1999; Mitbavkar and Anil 2006).

Research into the diatoms of the Shanwang Formation began in the 1930s. Skvortzov (1937) conducted pioneering research and recorded 24 taxa, including five new taxa, such as *Melosira youngi* Skvortzov and *Pinnularia major* (Kutz.) Cleve var. *shantungensis* Skvortzov. Nine of 18 living species belong to forms reported from lakes of alpine and northern districts, such as *Melosira distans* (Her.) Kutz. (*Aulacoseira distans* (Ehrenb.) Simonsen), *Fragilaria pinnata* Ehr. (*Staurosirella pinnata* (Ehrenb.) D.M. Williams & Round), and *Eunotia clevei* Grun. (*Amphorotia clevei* (Grunow in Cleve) D.M. Williams & G. Reid). Further detailed analysis of diatom assemblages was carried out by Li (1982), and 95 species and varieties were recorded, the main species being *Melosira* spp., *Fragilaria construens* (Ehr.) Grun., *F. lapponica* Grun., and *F. pinnata*. These mixtures of planktonic, benthic, and epiphytic diatoms, and of northern cold-water and southern warm-water species, indicate a shallow, freshwater lake with a large surface area and stable water column, situated at the boundary between the temperate and subtropical zones (Li 1982). This conclusion was based on data from different sediment sequences, but detailed development of this ancient lake was not considered by Li (1982).

In the present study, 19 stratigraphic layers were grouped into five zones based on changes in the sediment diatom assemblages, and the water level and temperature changes of this ancient Miocene lake were estimated. The relationship between diatom assemblages and wind, air temperature, and precipitation are also discussed.

## Study site

The Shanwang Basin (36°32′53″ N, 118°43′32″ E) is located 20 km east of Linqu County in the middle of Shandong Province, eastern China, adjacent to the Tan-Lu fault zone (Zhang et al. 2003). About 240 $km^2$ of basaltic lava and minor tephra, caused by fissure eruptions, form the basement layer of the Shanwang Formation (Li 1991; Guo et al. 2007) (Fig. 1). The Shanwang Formation was divided into six units (Li 1991), with unit II, the main diatomaceous layer that contains abundant well-preserved fossils, further divided into 19 layers (Li et al. 2000) (Figs. 2, 3a). Our study was based on this 19-layer division. Previous research indicated that the mean annual temperature at Shanwang was similar to that of today, but the annual range of temperatures was smaller than present, with greater, but more evenly distributed annual precipitation (Liu and Leopold 1992; Yang et al. 2007). At present, the Shanwang area is characterized by a north-temperate monsoonal climate, with a mean annual temperature of 12.4°C, mean precipitation of 709 mm, and an elevation of 250 m.

## Materials and methods

### Dating and sampling

An absolute date for the laminated sediments is not available, but K–Ar dates for the underlying basalt of the Niushan Formation, immediately below the

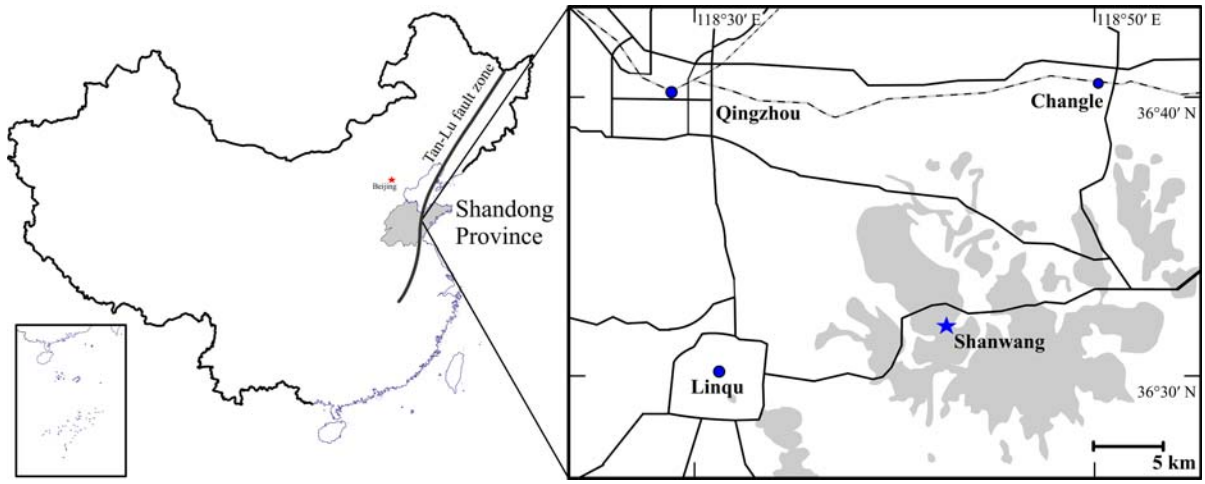


**Fig. 1** Map showing the location of the Shanwang Basin. Star indicates the study site, dots indicate the major cities, and shaded areas indicate volcanics belonging to the Niushan Formation underlying the Shanwang Formation (modified from Guo et al. 2007)

Shanwang Formation, range from 18 to 16 Ma, while the upper basalt in the Yaoshan Formation, which overlies the Shanwang Formation, dates to 10–9 Ma (Chen and Peng 1985; Zhu et al. 1985; Wang and Jin 1986). Mammalian faunas from the Shanwang Formation have been assigned to MN5, which equates to 17–15.2 Ma (Qiu 1990; Steininger et al. 1996). These results indicate that the Shanwang Formation is most likely of early middle Miocene age (Gradstein and Ogg 2004), and spanned about two million years.

One hundred and thirty-three sediment samples were collected from the 22.85-m fossiliferous profile for palynological analysis (Liang et al. 2003; Liang 2004). In the present study, diatom analysis was carried out on 97 of these 133 sediment samples.

## Laboratory and statistical analyses

Each sample consisted of 0.5 g of dry sediment, which was cleaned by $H_2O_2$ and HCl digestion according to Renberg (1990). Equal amounts of evaporated suspensions were mounted using Plastic optical mount (RI = 1.52) and prepared for scanning electron microscopy. Diatom identifications were made using an FEI QUANTA 200F scanning electron microscope (SEM), and were based mainly on standard references (Hustedt and Jensen 1985; Qi 1995; Huang et al. 1998; Zhu and Chen 2000; Qi and Li 2004; Shi 2004). Diatom nomenclature follows the Interagency Taxonomic Information System ITIS (http://www.itis.gov). Diatoms were counted under a LEICA DM 2500 microscope at 400×, with phase contrast. A minimum of 300 individual valves was generally counted on each slide, except for a few samples in which diatoms were scarce. Each central area of a pennate diatom, or more than half a valve, was counted as a single remain. In some samples, frustules were so poorly preserved that they could only be identified to genus level. Chrysophycean stomatocysts and phytoliths were counted along with diatoms.

Biostratigraphic diagrams were made using the program C2 (Juggins 2003). Major diatom zones were subdivided according to diatom assemblages, using constrained cluster analysis (CONISS). Squared-chord distance was used to estimate dissimilarity, and was performed with TILIA v. 2.0.b.4 (Grimm 1991, 1993).

To estimate climate change trends, the aridity index (AI) was calculated by using the mean annual temperature (MAT) and mean annual precipitation (MAP) inferred for Layers 4, 5, 7, 13, 14 and 15. These MATs and MAPs were reconstructed using the Coexistence Approach (CA) and Overlapping Distribution Analysis (ODA), employing the taxa of fossil plants in these layers (Liang et al. 2003; Yang et al. 2007). We utilized the formula described by de Martonne (1926):

$$I_{dm} = P/(T + 10) \quad (1)$$

in which, $I_{dm}$ is the de Martonne aridity index, P is the mean annual precipitation, and T is the mean annual temperature, with higher $I_{dm}$ values indicating more humid climates.

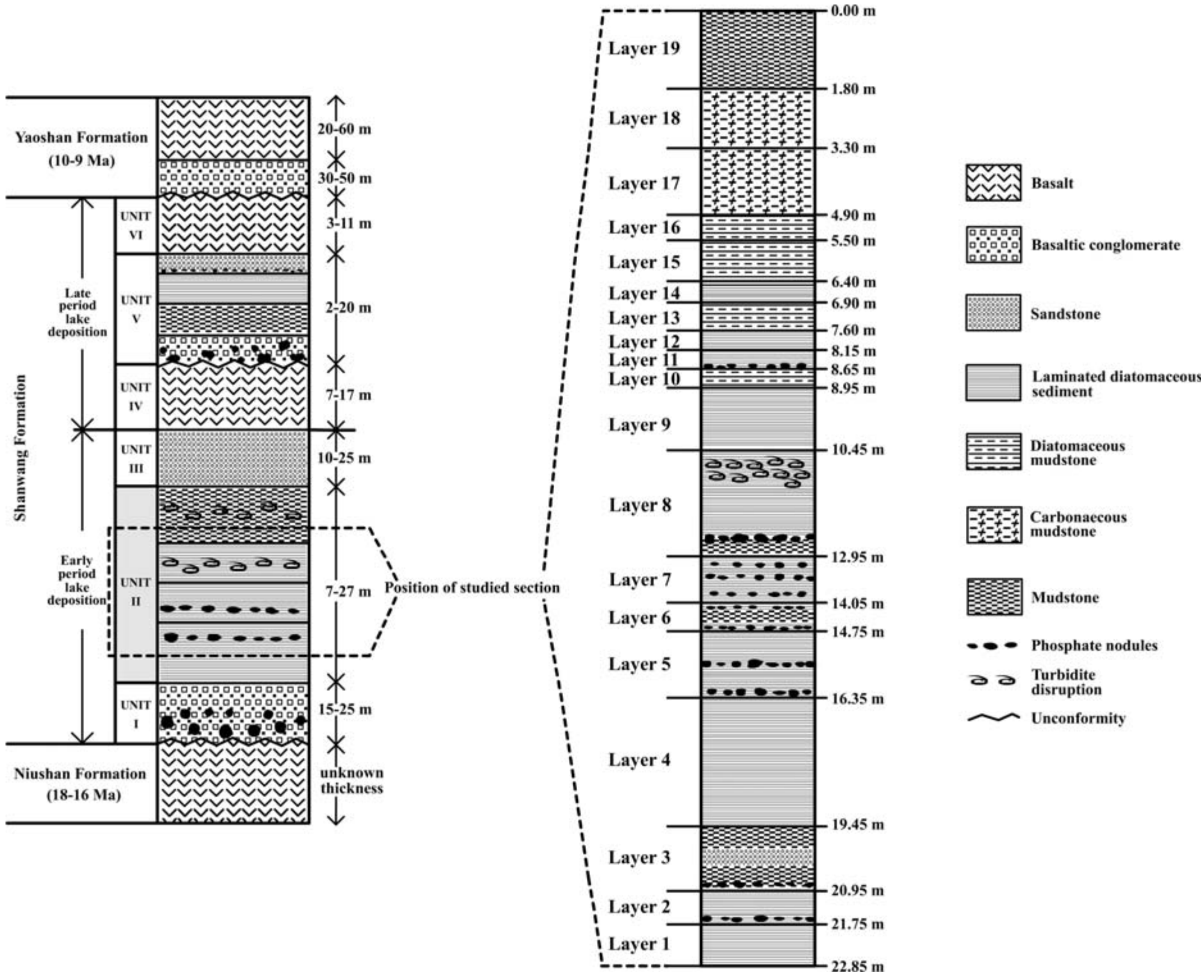


**Fig. 2** Sedimentary succession in Shanwang Basin (*left*) and the sedimentary log through the studied section (*right*) (From Li 1991, Liang et al. 2003)

Quantitative reconstructions of diatom-inferred pH, total phosphorus (TP) and total organic carbon (TOC) for Shanwang Lake were undertaken using a combined pH and TP dataset in the European Diatom Database (EDDI) (http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp) (Juggins 2001). Fossil diatoms were assigned to their nearest living relative (NLR) or genus. The off-line program ERNIE and data format conversion software WinTran are available at http://craticula.ncl.ac.uk/Eddi/jsp/help.jsp.

## Results

The main lithology of this section is diatomaceous sediment with light and dark laminations, diatomaceous mudstone, and mudstone. No detailed lithologic description of the 19-layer sequence is available, but according to Qin et al. (2004) and Zhang and Shan (1994), the light-colored diatomaceous lamination is composed mainly of diatoms (>60%), a few montmorillonite lamellae, plagioclase and quartz detritus, and is about 100 μm thick. The dark-colored diatomaceous lamination is composed mainly of diatoms (20–50%), organic matter, carbonized phytoclasts, a little basalt, plagioclase and quartz detritus, with a thickness of about 100–200 μm. The diatomaceous mudstone is composed mainly of diatoms (~30%), carbonized phytoclasts (8%), and other clastic materials such as quartz, plagioclase, dorgalite and chlorite lumps; the mudstone in Layer 3 is mainly made up of oriented montmorillonite, but also

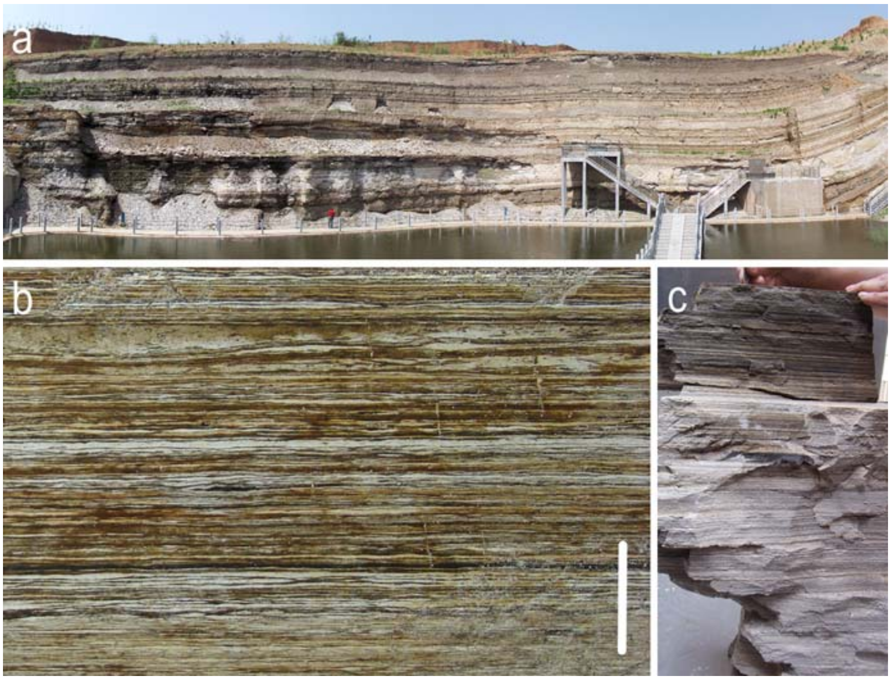


**Fig. 3** Panoramic photo of the modern Shanwang Basin (**a**), and examples of laminated diatomaceous shales from Layer 2 (**b**) and Layer 4 (**c**). Scale bar in 1b = 1 cm

contains minor amounts of quartz, feldspar, biotite, apatite, etc.

Ninety-seven samples were examined within the section. Of these, 17 samples were barren of diatoms. A total of 60 diatom taxa were found in the sediments, belonging to 16 genera, including 14 planktonic and tychoplanktonic taxa, 37 benthic (including epipsammic, epipelic, epilithic and epiphytic) taxa, and nine unidentified taxa. Only 29 taxa displayed relative abundances >3% in at least one sample. Results are presented in the summary diatom diagram (Fig. 4).

In most samples, tychoplanktonic *Aulacoseira* spp. dominated. But in Layers 4 through 10 (19.15–8.65 m), benthic species, mainly pennate diatoms (Fragilariophyceae, Bacillariophyceae), were abundant in the sediments. No diatoms were found between 20.20 and 19.95 m, between 8.55 and 8.45 m, or above 3.0 m.

Five diatom zones were established based on constrained cluster analysis (CONISS). The lithologic features of each layer were described by Li et al. (2000) (Table 1):

(1) Zone 1 (22.85–20.95 m; Layers 1 and 2): shales are grey–white diatomaceous sediments with light and dark laminations, each lamina being <1 mm thick (Fig. 3b). Diatom frustules belonged mainly to *Aulacoseira* cf. *distans* and *Melosira youngi*, accompanied by a few *Cymbella* spp. and *Gomphonema* spp.

(2) Zone 2 (20.95–19.45 m; Layer 3): no diatoms were found, except for two samples at 19.95 and 19.65 m in a yellow–green mudstone and sandstone layer, which contained a few *Aulacoseira* cf. *distans*, *Melosira youngi*, and *Cymbella* spp.

(3) Zone 3 (19.45–8.65 m; Layers 4–10): sediments in these layers are mainly grey-white diatomaceous sediments with light and dark laminations. In Layer 4, *A.* cf. *distans* and *Melosira youngi* (including *M. youngi* var. *tenuissima*) are still abundant. But beginning in Layer 5, benthic pennate species such as *Cymbella cymbiformis*, *Staurosirella pinnata*, *Fragilaria capucina* and *Pinnularia major* var. *shantungensis* become dominant. In Layers 8–10, abundance of pennate diatoms decreases, but there are still large numbers of *S. pinnata* and *Staurosira construens* var. *venter* in some samples. The total abundance of diatoms and their preservation fluctuated considerably during this period, indicating variable water conditions. There are also abundant phosphate nodules, which were composed mainly of segelerite, anapaite, and whitlockite. A small amount of phosphorite occurred in

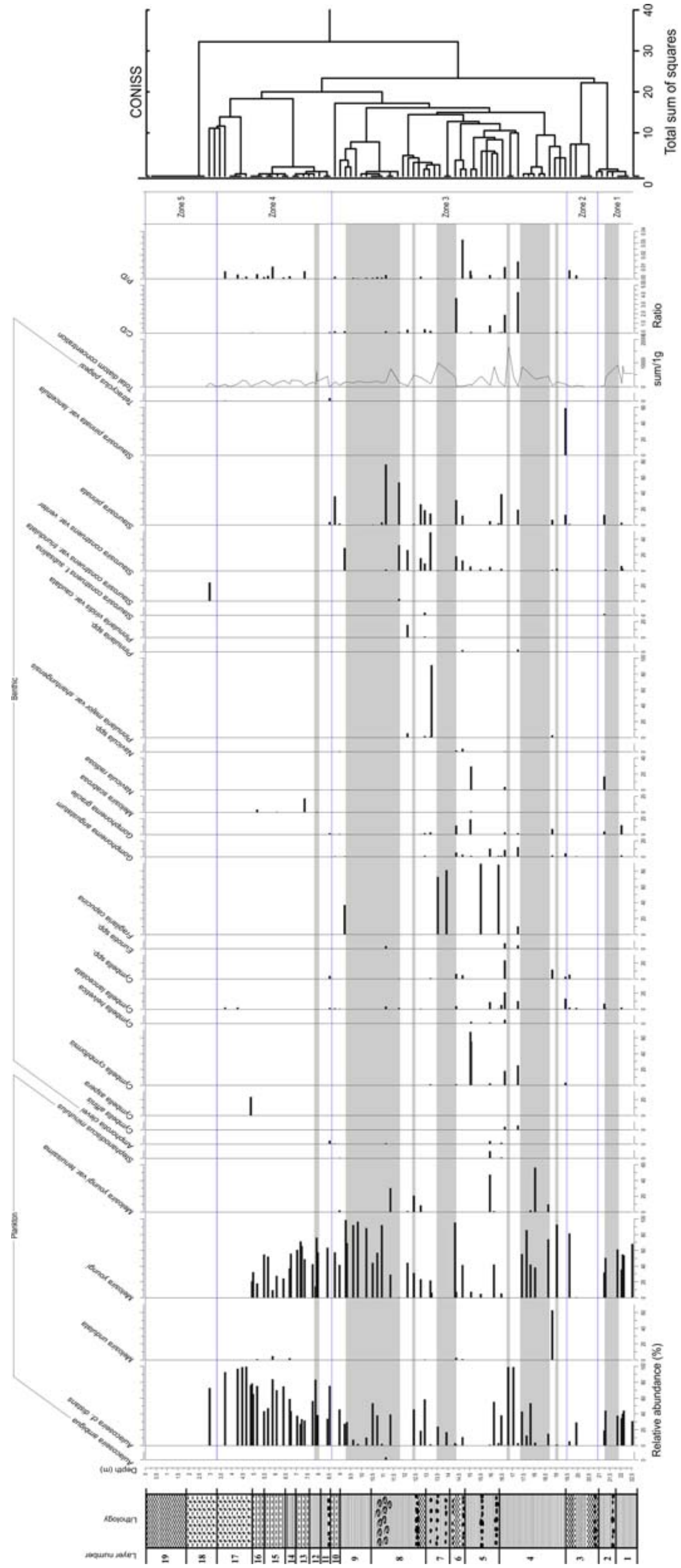


**Fig. 4** Summary diatom diagram (taxa > 5% abundance) through the middle Miocene Shanwang profile. Total diatom concentrations, calculated as diatoms per gram oven-dried mass (DW), C/D ratio between chrysophycean cysts and diatom frustules, P/D ratio between phytoliths and diatom frustules. Five zones were established by CONISS. Shaded areas indicate samples from well-preserved laminated shales

**Table 1** Lithological features of the studied section (see also Fig. 2) (according to Li et al. 2000 and Zhang and Shan 1994)

| Layer | Thickness (m) | Lithology and fossils | Number of samples |
|---|---|---|---|
| *Overburden of Quaternary sediments* | | | |
| 19 | 1.8 | Dark grey–green and grey–white mudstone with intercalated grey–yellow mudstone | 5 |
| 18 | 1.5 | Grey–black carbonaceous mudstone (seeds, fruits) | 8 |
| 17 | 1.6 | Black carbonaceous mudstone (seeds, fruits, leaves) | 6 |
| 16 | 0.6 | Grey–black diatomaceous mudstone (seeds, fruits, leaves) | 4 |
| 15 | 0.9 | Grey diatomaceous mudstone (leaves, fish) | 4 |
| 14 | 0.5 | Grey–black diatomaceous shale with light and dark thin laminations (leaves, fish) | 2 |
| 13 | 0.7 | Grey diatomaceous mudstone (leaves, fish) | 4 |
| 12 | 0.55 | Grey–black diatomaceous shale with light and dark thin laminations (leaves, fish) | 4 |
| 11 | 0.5 | Grey diatomaceous shale with grey and black thin laminations. Yellow–green mudstone 3-cm thick at the top, black diatomaceous shale 10-cm thick with nodules at the bottom (leaves, fish) | 3 |
| 10 | 0.3 | Grey–black diatomaceous mudstone | 1 |
| 9 | 1.5 | Grey–black diatomaceous shale with well-developed light and dark laminations (leaves, fish, insects, mammals) | 7 |
| 8 | 2.5 | Thickly-stratified grey muddy diatomaceous shale with light and dark laminations. Black diatomaceous shale with black nodules at 30 cm from the base, yellow–green mudstone 20-cm thick at the bottom (leaves, fish, insects, mammals) | 10 |
| 7 | 1.1 | Grey–black muddy diatomaceous shale with well-developed light and dark laminations. Nodule layers of 5-10-cm thick at the top, middle and bottom of the bed (leaves, fish, insects, mammals) | 4 |
| 6 | 0.7 | Dark, grey–black diatomaceous shale with abundant nodules, yellow–green mudstone 5-cm thick in the middle part (leaves, fish, insects, frogs) | 3 |
| 5 | 1.6 | Grey–white muddy diatomaceous shale with light and dark laminations. Grey–black Fe/P nodule layer 20-cm thick in the middle and lower parts (leaves, fish, insects) | 6 |
| 4 | 3.1 | Grey–white muddy diatomaceous shale with well-developed light and dark laminations. Grey–black muddy diatomaceous shale at 70 cm, close to the base and on the bottom (leaves, fish, insects, mammals) | 13 |
| 3 | 1.5 | Yellow–green mudstone. Structureless, sand-conglomerate 40–60-cm thick in the middle part, with grain sizes of 0.10–1.25 mm; black diatomaceous shale 10-cm thick in the lower part; nodules 5–10 cm in diameter at the bottom | 5 |
| 2 | 0.8 | Grey–white diatomaceous shale with well-developed light and dark laminations. Black diatomaceous shale with nodules 10-cm thick at the bottom (leaves, fish) | 3 |
| 1 | 1.1 | Grey–white diatomaceous shale with light and dark laminations. Diatomaceous shale 30-cm thick with black and white thin laminations at the top (leaves) | 5 |
| | | Underlying bed a nodule layer (unseen) | |

Layers 5–8, which indicates hypoxia in bottom waters (Zhang and Shan 1994).

(4) Zone 4 (8.65–3.30 m; Layers 11–17): sediments in these layers are mainly diatomaceous mudstone. *Aulacoseira* cf. *distans* and *Melosira youngi* regained dominance. As the abundance of *A.* cf. *distans* increased, however, *Melosira youngi* became less frequent. A few *Amphorotia clevei* (also described as *Eunotia clevei*) and *Melosira undulata* were found.

(5) Zone 5 (3.30–0.00 m; Layers 18–19): no diatoms were found except in a single sample at 3.00 m, which contains numerous epipelic *Staurosira construens* var. *triundulata* in the carbonaceous mudstone facies.

Chrysophycean stomatocysts and opal phytoliths were present in most samples. The ratio of the cysts to diatom frustules is included in Fig. 4. The chrysophyte cyst to diatom ratio (C/D) was higher in Zone 3, especially in Layers 4–6, at depths of 17.25 m, 16.65 m, and 14.40 m (C/D > 1.0). Because most of the stomatocysts have not yet been linked to the taxa that produced them (Zeeb and Smol

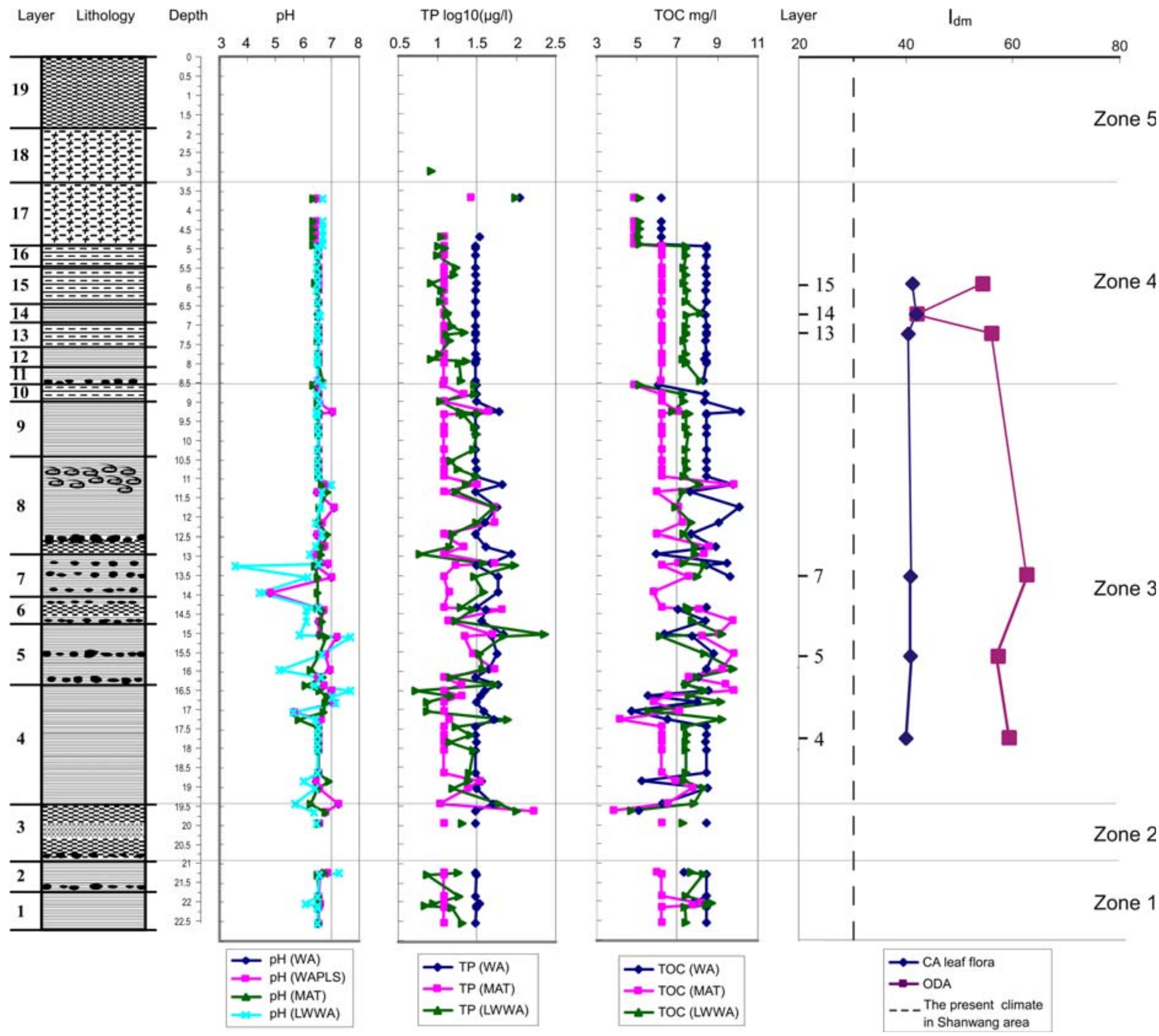


**Fig. 5** The diatom-inferred pH, TP, and TOC based on the EDDI datasets, and the $I_{dm}$ values obtained from CA and ODA (data cited from Yang et al. 2007)

2002), and there is a lack of pertinent literature, we only report the relative abundance of cysts to the diatom frustules. Dumbbell-shaped opal phytoliths, produced mainly by C4 grasses, including Paniceae (Stromberg et al. 2007), were found in several samples. The phytolith to diatom ratio (P/D) was higher in the middle of Zone 3 and in Zone 4.

Values for the de Martonne aridity index $I_{dm}$, obtained from the CA and ODA, were all >30, which indicates forest vegetation in a humid climate regime, without periods of desiccation (Fig. 5). The $I_{dm}$ values from CA were similar throughout these layers, but much higher in Layer 7 and much lower in Layer 14 than values from ODA (Liang et al. 2003; Yang et al. 2007).

Because China lacks a diatom-based pH dataset, transfer functions for pH reconstruction were developed using the EDDI combined pH and TP datasets, using weighted averaging (WA), weighted averaging partial least squares (WAPLS; ter Braak and Juggins 1993), modern analog techniques (MAT; Flower et al. 1997), and locally-weighted weighted averaging (LWWA) regressions (Fig. 5). The resulting curves from the different methods show similar trends, especially among the pH curves. For TP and TOC curves, however, the values obtained from LWWA were higher than MAT and lower than WA. According to Juggins (2001), LWWA is a new method, which generates a "local" training set for each fossil sample based on the 50 closest (minimum squared chi-squared distance) modern samples. Comparisons suggest that this method is more effective when applied to the large merged data sets than simply fitting a single global transfer function. In general, the lake water was slightly acidic, and the pH reconstructions, using four different methods, were $6.6 \pm 0.3$, $6.6 \pm 0.3$, $6.5 \pm 0.2$, and $6.4 \pm 0.5$ (mean $\pm$ standard deviation) respectively, but fluctuated widely in Zone 3. The TP and TOC curves were similar to those for pH, fluctuating widely in Zone 3 (Fig. 5).

## Discussion

### *Aulacoseira* and its paleoenvironmental significance

*Aulacoseira distans* reportedly displays 18 varieties and eight forms, and has typically been recognized by its low mantle height/valve diameter ratio (Edgar 2003). Scanning electron microscope studies have raised many of these varieties to species rank (Florin 1981; Krammer 1991). On the other hand, many varieties have not yet been examined for micromorphological characters (Edgar and Theriot 2004). The most abundant *A.* cf. *distans* in the Shanwang deposits is similar to the type species of *Aulacoseira distans* (Ehrenb.) Simonsen, but differs with respect to a few morphological characteristics, including shorter linking spines and larger areolae. It probably represents a variety of *A. distans*. Moos et al. (2005) suggested that *A. distans* should be classified as tychoplanktonic, which has a preference for shallower depths, but nevertheless exists over a range of depths. Brugam et al. (1998) also found *A. distans* in water <4 m deep, and classified it as a benthic form. The optimum temperatures of most varieties of *A. distans*, such as *A. distans* var. *nivalis*, *A. distans* var. *nivaloides*, and *A. distans* var. *tenella*, lie between 10.89 and 12.15°C (Weckstrom et al. 1997). Leira (2005) considered *Aulacoseira* species such as *A. distans*, *A. lirata* and *A. alpigena*, the latter two previously considered to be varieties of *A. distans*, to be associated with slightly acidic, oligotrophic conditions, and suggestive of relatively cold climate conditions. We assume that *A.* cf. *distans* is characteristic of such water conditions.

*Melosira youngi* Skvortzov and its variety *M. youngi* var. *tenuissima* Skvortzov were found in the Shanwang Formation by Skvortzov (1937), but have not been further studied due to a lack of type material (Haworth and Sabater 1993). This species is similar to *Aulacoseira islandica* (O. Müll.) Simonsen, but has denser areolae, and also resembles both *Aulacoseira granulata* (Ehrenb.) Simonsen and *Aulacoseira baikalensis* (K. Meyer) Simonsen (Skvortzov 1937). Li (1982) recognized parts of *M. youngi* as *A. islandica* or *A. granulata*. Here we follow Skvortzov's (1937) identification and suggest that *M. youngi* and its variety be formally transferred to the genus *Aulacoseira*, as suggested by Haworth and Sabater (1993).

Most *Aulacoseira* spp. are heavily silicified and need wind-induced turbulence or mixing of the water column to prevent cells from sinking (Dean et al. 1984; Pilskaln and Johnson 1991; Ruhland et al. 2003). Håkanson and Jansson (1983) suggest that a minimum wind speed of about 40 km/h (10 m/s) is necessary to suspend unconsolidated sediments in a 4–6-m-deep lake that is 1,000 m wide. Given the present wind speed in eastern China (average annual wind speed is 2.7 m/s in Linqu County at $\sim$100 m altitude) and the paleolatitude of the Shanwang Basin (32.4°N) (Liu and Shi 1989), the occurrence in great abundance of *Aulacoseira* such as *A.* cf. *distans* may imply low water temperature and wind-induced water turbulence, and indicate that the ancient lake was in an exposed area or at high elevation. Using the ODA approach, Yang et al. (2007) suggested that the altitude may have been between 1,000 and 1,200 m.

### Water temperature and depth variations

There are thick sections of well-preserved laminated rocks in the Shanwang Formation, which were generally deposited in the relatively deep (>7–20 m), well-stratified water column of a small lake (O'Sullivan 1983). Chen et al. (2000) investigated fish taphonomy in Shanwang Formation and recognized two facies: (1) finely laminated diatomaceous sediments, mainly in the lower part of the section, such as Layers 2, 4 and 8, in which fish skeletons are intact, without signs of scavenging, which suggests that the fish were buried immediately after death, without decay, at the bottom of a lake that was >8–12 m deep and had a temperature <15°C in the hypolimnion, and (2) diatomaceous mudstone, mainly in the upper part of the section, such as Layers 13, 15 and 16, in which bones were scattered, indicating that the fish decayed in a hypolimnion warmer than 15°C and at depths <8-12 m.

In Zone 1 (22.85–20.95 m, Layers 1–2), the grey–white diatomaceous shale with light and dark laminations and the presence of fossil fish, *Aulacoseira* cf. *distans* and *Melosira youngi* indicated that the water depth was >8–12 m and the surface water temperature was 12–15°C (Fig. 6a).

In Zone 2 (20.95–19.45 m, Layer 3), the absence of diatoms in the yellow-green mudstone and sandstone layer probably indicates that the sediments were deposited in a mudflat environment, possibly during a temporary period of desiccation (Fig. 6b).

In Zone 3 (19.45–8.65 m, Layers 4–10), the depositional environment was complex. *Aulacoseira* cf. *distans* and *Melosira youngi* were dominant in most of the finely laminated diatomaceous sediments, which indicate a greater water depth. Benthic or tychoplanktonic *Fragilaria-Staurosira-Staurosirella* taxa, which are indicative of shallow-water conditions (Brugam et al. 1998), were well represented in most of the samples where the laminations were not well developed. Freshwater diatoms, however, do not indicate changes in water depth under certain circumstances, especially when light penetration is reduced by phytoplankton blooms caused by a change in trophic status (Wolin and Duthie 1999; Heinsalu et al. 2008). Freshwater, epiphytic *Cymbella cymbiformis* is common in the temperate zone and tychoplanktonic *Staurosirella pinnata* and *Staurosira construens* var. *venter* are common in cold (5–7°C), shallow lakes and marshes. Both indicate eutrophic conditions (Vos and de Wolf 1993; Brugam et al. 1998; Finkelstein and Gajewski 2008). Some aquatic plants such as *Ceratophyllum miodemersum* and *Potamogeton* sp., which are common in eutrophic waters, were found in Layers 7 and 9 (Sun 2000; Keskinkan et al. 2004). Thus, abundance of benthic diatoms in the laminae may reflect an algal bloom triggered by changing trophic state conditions, specifically by species adapted to growing on aquatic macrophytes near the lake margin. Alternatively, algal mats may have formed in shallow water, broken off, and floated into deeper water. The diatom assemblages are characterized by forms that are common in cold water (~5–12°C), suggesting the water temperature was still cold during this period. But abundant *Fragilaria capucina* occurred in the samples from 16.35, 15.55, 13.95, and 13.55 m, indicating a longer growing season and/or higher summer temperatures (Schmidt et al. 2004). The water depth may have fluctuated, but tended to be deep (~8-12 m) throughout the whole deposition period. Most insect and mammal fossils in this zone probably washed into the lake after death (Fig. 6c).

In Zone 4 (8.65–3.30 m, Layers 11–17), coarse grey diatomaceous mudstone and poorly preserved fish fossils indicate that the water became shallower (~4–8 m) and warmer (>12–15°C), while the reemerging dominance of *Aulacoseira* taxa suggests a trend to slightly acidic and oligotrophic conditions. Other common taxa such as the epiphytic *Amphorotia clevei* are common in Mongolia and the Baikal area (Edlund et al. 2000; Williams and Reid 2006). Planktonic *Melosira undulata* is common in maar lakes and indicates clear, oligotrophic, fresh water or weakly alkaline water (Carter et al. 2006). This species has also been found as a fossil in the upper Miocene deposits of central Washington (Sovereign 1958) (Fig. 6d).

In Zone 5 (3.30 m–0.00 m, Layers 18–19), only a few benthic taxa occur, in one sample from the lower part of Layer 18. They are entirely absent in Layer 19. The carbonaceous mudstone also indicates that the ancient lake became shallower and finally desiccated (Fig. 6e).

Based on the changes in the diatom assemblages, sedimentology, and other evidence in the five zones, Shanwang Lake would appear to have changed from being relatively deep (>8–12 m), to a mudflat, to fluctuating (8–12 m), to shallower (4–8 m), and finally to a terrestrial environment. The presence of *Aulacoseira* and other cold-water diatoms indicates cold conditions throughout the depositional period.

Smol (1985) suggested that the ratio of total cysts to diatoms provides a quick and easy measure of the relative importance of these two algal groups in paleolimnological studies. In some temperate lakes, a lower percentage of chrysophyte cysts often indicates

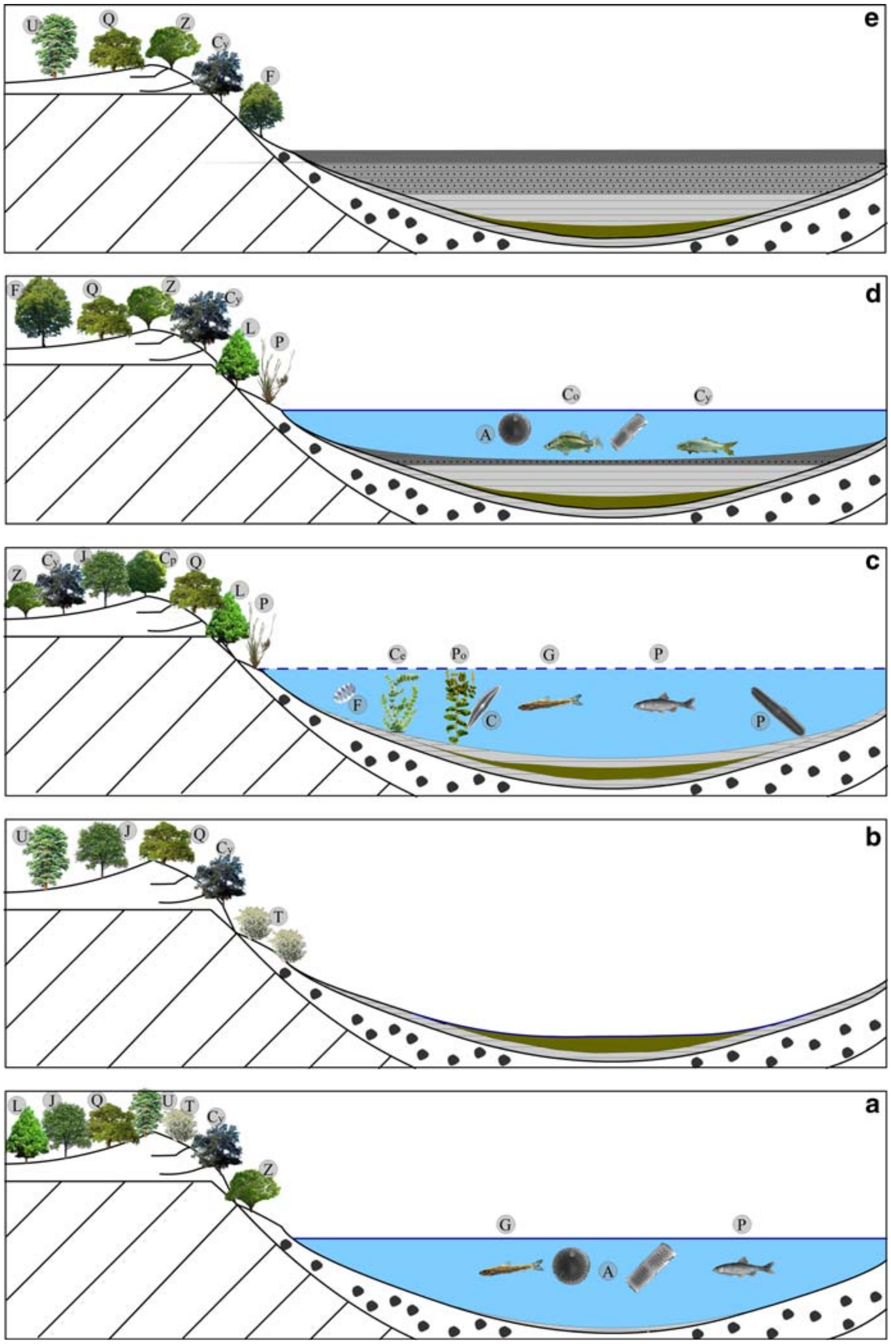


**Fig. 6** The main environmental phases in the lake evolution history. (Some data from Chen et al. 2000; Liang 2004; Sun 2000) For trees and aquatic plants: Ce, *Ceratophyllum miodemersum*; Cp, *Carpinus*; Cy, *Carya*; F, *Fagus*; J, *Juglans*; L, *Liquidambar*; P, PACCAD group; Q, *Quercus*; Po, *Potamogeton* sp.; T, *Tricolporopollenites wackersdorfensis*; U, *Ulmus*; Z, *Zelkova*; For fishes: Co, *Coreoperca*; Cy, *Cyprininae* (*Lucyprinus* and *Qicyprinus*); G, *Gnathopogon*; P, *Plesioleuciscus*; For diatoms: A, *Aulacoseira*; C, *Cymbella*; F, *Fragilaria—Staurosira—Staurosirella* taxa; P, *Pinnularia*

more eutrophic conditions, as these algae are often competitive in cooler, oligotrophic waters (Smol 1985; Wilkinson et al. 1997). Douglas and Smol (1995) observed that the highest percentage of cysts was found in semi-aquatic mosses of high arctic ponds. Thus, a high C/D ratio indicates that the lake water was oligotrophic, cold and shallow.

## Linkages between climate and water fluctuations

Variations in air temperature and precipitation must have influenced the water conditions in Shanwang Lake. We might therefore expect to see coincident trends between changes in the terrestrial environment as recorded by pollen and macrofossils, and shifts in aquatic conditions, reflected in the diatom assemblages.

In Zone 2, for example, there was a decline in the relative abundance of *Liquidambar* and *Pterocarya* pollen, which reflect a warm and humid environment, while *Tricolporopollenites wackersdorfensis*, which is interpreted as an arid element, expanded (Liang 2004; Wang and Harley 2004). This is consistent with intense evaporation of the water, reflected by the absence of a diatom record.

Large numbers of dumbbell-shaped opal phytoliths were found in Zone 3 and Zone 4. The phytoliths came from C4 plants or PACCAD plants, i.e. panicoid, arundinoid, chloridoid, centothecoid, aristidoid and danthonioid grasses, which mainly grow in tropical or subtropical areas. Phytolith assemblages containing abundant grass phytoliths, forest indicator phytoliths from dicotyledonous plants, and infrequent palm phytoliths, were discovered in samples B64 (17.85 m), B54 (15.05 m), A31 (12.95 m), A26 (9.85 m), A16 (6.85 m) and IVPP06-1 (depth unknown) by Stromberg et al. (2007), and suggest a lakeside wooded habitat with abundant helophytic to mesophytic grasses, along with drier areas that supported pooid (and PACCAD) grasses. Cowling (2001) pointed out that the occurrence of C4 plants was related to low atmospheric $CO_2$ and warmer temperatures, coinciding with the warmer and lower $CO_2$ conditions in the middle Miocene Climatic Optimum, during which the sediments that comprise the Shanwang Formation were deposited (Pagani et al. 1999), though $CO_2$ levels during the early and middle Miocene remain controversial (Kurschner et al. 2008). The higher ratio of dumbbell-shaped opal phytoliths to diatoms (P/D) may indicate lower lake levels and reflect relatively warm and dry conditions around the lake (Haberyan and Horn 2005), coinciding with fluctuations in the water level in Zone 3 and the shallowing trend in Zone 4.

Aridity indexes are quantitative indicators of water deficiency at a given location and various indexes have been developed (Oliver 2005). We chose de Martonne's aridity index because it requires minimal data, which can be obtained from CA and ODA reconstructions. The $I_{dm}$ curves present the relationship between temperature and precipitation directly, and coincide with the fossil plant taxa found in these layers. The main fossil plant taxa found in Layer 7 were *Fothergilla viburnifolia*, *Zelkova ungeri*, *Betula mioluminifera* and *Acer subpictum*, which indicate a warm and humid climate, while in Layer 14 *Juglans shanwangensis*, *Platycarya miocenica*, *Tilia miohenryana*, *Ulmus* sp., and others indicate a warm, dry climate (Sun 2000). As variations in air temperature and precipitation on large timescales were the main factors influencing changes in lake water level (Qin and Huang 1998; Li et al. 2007), we assume that the water level declined from Layer 7 to Layer 14. The transition from a wet riparian habitat to a dry upland habitat from Zone 3 to Zone 4, inferred from pollen data, also supports this supposition (Liang 2004). This coincides with the climate-induced water level changes reflected in the diatom assemblage and sedimentology records, and illustrates how closely related the aquatic and terrestrial ecosystems were.

Furthermore, the light and dark couplets in the Shanwang Formation are thought to represent varves (Qin et al. 2004). As a result of differences in their flowering periods, there is more *Quercus* pollen in the dark laminae, while *Ulmus* pollen is more abundant in the light laminae (Wang 1991). The different composition of diatoms in adjacent dark and light laminae, may well indicate that the monsoon climate was already in place in eastern Asia during the middle Miocene epoch. Tanimura et al. (2006) found a similar pattern in diatomaceous laminites.

## Reconstruction of pH, TP and TOC

Most diatom-based water chemistry reconstructions have come from study of late Quaternary to recent lake deposits (Winkler 1988; Prather and Hickman 2000; Zampella et al. 2007). Because pH, TP and TOC reconstructions for this Miocene lake, with several fossil taxa, were based on modern European diatom datasets, the reliability of the results requires independent verification. The NLR approach used here has, however, proved to be reliable in climate reconstructions using Oligocene, Miocene and Pleistocene floras (Mosbrugger 1999). Several studies, based on the nearest living relative techniques (including CA and ODA), yielded what are thought to be relatively reliable reconstructions for the paleoclimate of the Shanwang Formation (Yang et al. 2007). Birks (1998) suggested that a reconstruction employing 10–22% fossil taxa not found in the modern data sets, may be still reliable. Wolfe et al.

(2006) found a middle Eocene diatom species belonging to *Aulacoseira*, with well-preserved ultrastructural and cytoplasmic characters similar to living taxa such as *A. alpigena* and *A. lirata*. It is thus hypothesized that prolonged intervals of evolutionary stasis have characterized the genus *Aulacoseira*. This observation strengthens assumptions concerning taxonomic uniformitarianism, a cornerstone for paleoecological interpretations (Sancetta 1999). We thus assume that the genus *Aulacoseira* has undergone limited evolutionary innovation since the middle Miocene and can be used for quantitative paleoenvironmental reconstruction. Here, we assigned *Aulacoseira* cf. *distans* to *Aulacoseira distans* (agg.) (EDDI taxon code: XXG956), and *Melosira youngi* to *Aulacoseira* sp. (EDDI taxon code: AU9999), in the European Diatom Database. While the absolute values may not be entirely reliable, trends in water chemistry, inferred from the changes in diatom assemblages during the history of Shanwang Lake, are probably meaningful.

Sommaruga-Wograth et al. (1997) studied an alpine lake core and found a strong positive correlation between pH and mean air temperature. Fluctuations in pH and nutrients (including TP and TOC) in ancient Shanwang Lake may have been caused by changes in air temperature and precipitation. Volcanic activity and ash fall can also influence water acidity and nutrient status. Abundant insect and mammal remains found in Zone 3 may be a consequence of the poisonous gases emitted from volcanoes (Pozzo et al. 2002; Guo et al. 2007). Large fluctuations in the pH curve during Zone 3 may indicate it was the period of greatest volcanic activity during the lake's depositional history.

## Conclusions

The Shanwang Basin not only contains a great number of well-preserved fossil plants and animals, but also possesses valuable paleolimnological information in its laminated, diatomaceous sediments. The dominance of *Aulacoseira* taxa in most of the samples probably indicates low water temperatures and wind-induced turbulence. This suggests that Shanwang Lake was located in an open area or at high elevation. Some shallow-water taxa such as *Fragilaria* spp., *Staurosira* spp., and *Staurosirella* spp. were present, but these may have been washed into the center of the lake during periods of heavy precipitation. The changes in diatom assemblages and other sedimentological evidence point to long-term fluctuations in water level, from a relatively deep system (>8–12 m), to a mudflat, to a rapidly fluctuating lake (8–12 m), to a shallower system (4–8 m), and finally to a dry lake bed. This evolution resulted in the deposition of 19 identifiable sediment layers. Variations in water depth, influenced mainly by shifting air temperature and precipitation, were reflected in the diatom assemblages, and coincide with the AI changes seen in the terrestrial plant fossils from the same layers. Reconstruction of the water chemistry, using the European Diatom Database, indicates a widely fluctuating environment in Zone 3. This, and the abundant insect and mammal fossils in Zone 3 suggest it was a period of frequent volcanic activity.

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