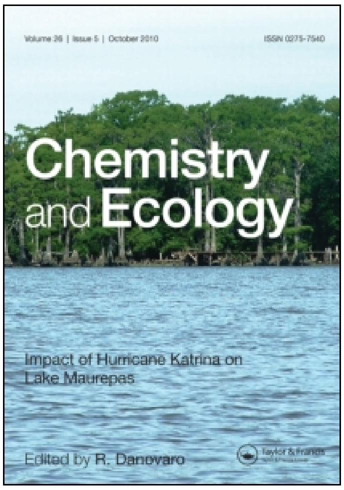

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# THE USE OF SELECTED SEDIMENT ANALYSES TO ANSWER LAKE MANAGEMENT QUESTIONS: A CASE STUDY FOR LAKE PANASOFFKEE, FLORIDA

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Selected analyses were performed on Lake Panasoffkee sediment to answer critical cause/effect lake management questions, and the collected data indicate their usefulness for similar assessments. Sediment depths in Lake Panasoffkee are very deep ($>6.1$ m) in most places, but Pb-210 dating indicates sedimentation rates have historically been low (0.04 – 0.6 g-dry wt/cm$^2$-yr). Increasing lake shallowness is more likely related to a gradual lake level decrease than to high rates of sedimentation, as was previously thought. Since approximately 70% of the water inputs to the lake are from artesian groundwater seepage, the decreasing lake level is believed to be related to long term lowering of the groundwater level in the area, which has recently (1988–1993) been accelerated by a deficit of rainfall. Palaeo-analysis of sediments, based on diatom and trophic state index (TSI) reconstructions, indicates that the lake has undergone very few changes in the last 150 years, and that it has been eutrophic over this time span. Although the lake has always been a macrophyte dominated system, there is some indication from palaeo-analysis that plankton production is of more importance now than in the past. The sediments of Lake Panasoffkee are sized primarily in the silt/clay fraction and contain much more inorganic carbonate matter (mean = 72.3%) than organic matter (mean = 17.4%). The high carbonate content of the sediments is due primarily to precipitation by aquatic macrophytes during photosynthesis and there is no relationship between water temperature and calcite saturation in this water body. Although low, the principal organic matter source, based on organic matter biomarker studies, was found to be primarily dead and decaying macrophytes.

KEY WORDS: Sedimentation, calcite saturation, biomarker, Pb-210 dating, palaeolimnology.

## INTRODUCTION

It has long been recognized that a water body's sediment provides valuable information regarding the processes which occur in the entire water body. Sediments are often depositional sites for mineral and organic matter that is both transported to the water body from its drainage basin, and formed within the water body and subsequently deposited (Bowser and Jones, 1978). In view of this, our study focused on the analysis of sediments in Lake Panasoffkee in order to answer several important questions concerning the lake and its management. For example, there has been considerable concern and controversy over the increasing shallowness of the lake and it has been suggested that sediment accumulation is the principal cause (Greiner Engineering Sciences Inc., 1978). The Southwest Florida Water Management District (SWFWMD 1989), however, stated that the bulk of sediments in Lake Panasoffkee are naturally occurring marl ($CaCO_3$) provided by groundwater inflow. Our study focused on the causes of the increasing lake shallowness, the sources of sediment to the lake bottom and the extent of man-made versus natural lake degradation. In an attempt to resolve these issues, the sediments of Lake Panasoffkee were analyzed and mapped in terms of depth to hardpan and their physical/chemical characteristics. Additionally, Pb-210 sedimentation rate, organic matter "biomarker" and palaeolimnology investigations were undertaken. This project serves as an example of how sediment chemical and physical data can be used to answer similar management questions in other lakes.

## MATERIALS AND METHODS

### *Site Description*

The location of Lake Panasoffkee within the Southwest Florida Water Management District is shown in Figure 1. Lake Panasoffkee is approximately 9.7 km long and 2.4 km wide and is the largest lake in Sumter County (1821 hectares). Although the maximum depth is 3.1 m, this depth is found only near the outlet of the lake (Taylor, 1977) . The greater part of the lake is very shallow (0.9–1.8 m). The lake's catchment is small compared to the complete topographic basin (109,000 ha) because only 15,500 ha, primarily on the east side, actually drains to the lake (Taylor, 1977). The major source of inflow to the lake is groundwater seepage from the Floridan aquifer, estimated at 70% (Greiner Engineering Sciences Inc., 1978). The present water quality of the lake is considered fairly good (mesotrophic), due to the nature of the groundwater source and short residence time of water in the lake (SWFWMD, 1989) .

### *Depth to Hardpan*

In Lake Panasoffkee, 127 depth-to-hardpan measurements were made at sites established by the Long Range Area Navigation System (LORAN). The LORAN system uses three point radio wave signal information, with a typical accuracy of 15 m after local ground calibration. Measurements were made with calibrated aluminium electrical conduit and were limited to a depth of 6.1 m due to field problems (e.g. bending) with greater lengths of conduit.

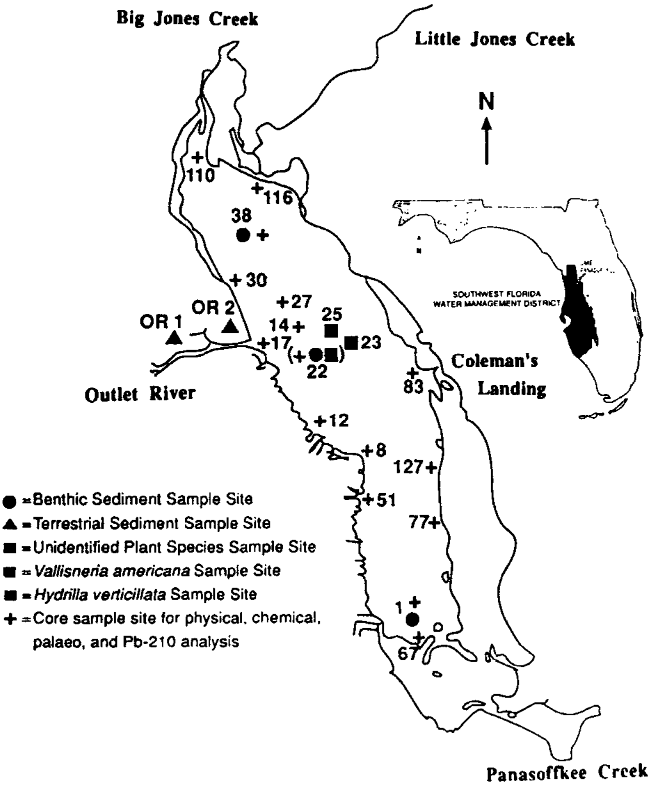


**Figure 1** Location of core (physical, chemical, palaeo- and Pb-210 analysis) and organic matter bio-marker sampling sites in Lake Panasoffkee.

### *Sediment Organic Matter, Carbonate Matter and Particle Size*

Vertical sediment cores were obtained from 16 sites (12.6% of the sediment depth measurement sites) in Lake Panasoffkee (Fig. 1). At these sites, 15 cm vertical intervals of 45 to 60 cm cores were extruded and analyzed for particle size, organic matter (loss on ignition at 550°C) and loss on ignition (LOI) at 550–1000°C. Samples were split and replicate analyses were run on all samples. Duplicates were run on 10% of the samples. Organic matter content (LOI at 550°C) was evaluated by combusting a weighed amout of dry sediment for two hours at 550°C in a muffle furnace and weighing the remaining ash. LOI at 1000°C was determined by igniting the same sample at 1000°C for 1.5 hours and weighing again to determine the LOI. Multiplying the LOI 550–1000°C percentage by the ratio of $CaCO_3$:$CO_2$, or 2.27, yields an estimate of the carbonate content (Dean, 1974). Particle (grain) size analyses were also made on mixed 15 cm vertical intervals of cores using standard sieving techniques (US Standard Sieve Series) according to the methods outlined in Hakanson and Jansson (1983) and Folk (1965).

### *Sediment Mapping*

Sediment mapping (organic matter (%), carbonate matter (%), silt/clay (%), and depth to hardpan (m) was produced for the 0–15 cm layer using the Geographic Information System (GIS) and PC ARC/Info software.

### *Palaeolimnology*

Two types of coring devices were used for the palaeo-ecology and Pb-210 dating studies. A piston corer (ID = 10.2 cm), as modified by Davis and Doyle (1969), was used for the principal (central) core (site 22), and a smaller KB gravity corer (ID = 7.6 cm), designed by Glew (1991), was used for other sites. Sectioning was done in the field with sediments placed in Whirl-Pak bags and kept in coolers until placed in an environmental chamber (4°C) at Indiana University. Other details on core sectioning can be found in Charles and Whitehead (1986*b*). All cores were obtained in clear Lucite tubes and the integrity of the upper sediment was undisturbed. Site locations are shown in Figure 1. Quality control sampling and analysis procedures for palaeo work followed those developed by Charles and Whitehead (1986*a*, *b*), which have become the standard in the paleolimnology field.

One high quality Davis-Doyle piston core (approx. 50–75 cm in length) was taken from the central area of Lake Panasoffkee (site 22). This was sectioned in the field at 0.5 cm intervals through the first 30 cm and at 1.0 cm intervals thereafter. The core was dated using Pb-210 analysis. Diatom analyses were made on numerous intervals, and historical pH, acid neutralizing capacity (ANC), dissolved organic carbon (DOC) and trophic state were inferred. Concentrations of lead, zinc and copper were analyzed from several intervals.

Transfer functions were constructed between environmental variables and diatom assemblages by relating current conditions to those diatoms found in the surficial sediments of a set of lakes from Florida known as the 'calibration' or 'training' set. pH is the most common and usually the most statistically viable water chemistry measurement reconstruction using diatoms, and ecological studies worldwide often find that pH is a dominant variable in explaining the variance in diatom populations. Transfer functions for DOC, ANC, trophic state, and aluminium concentrations have all been calculated successfully. A full review of the history and techniques of these methods can be found in Dixit *et al.* (1992) and Charles *et al.* (1989).

Two methods of calculating transfer functions were used in this study. One is the multiple regression of preference categories. In this method, diatom species are classified according to their distribution along an environmental gradient. For example, a diatom taxon found only in waters with a pH > 6.5 might be considered alkalibiontic, or one occurring primarily in waters with a TSI between 40–50 would be classed as mesotrophic. The relative abundances of the diatoms belonging to the preference categories in the surface sediments of the calibration lakes are then regressed against the measured variable for the same set of lakes. A regression equation is then calculated. Applying that equation to diatoms identified in a dated sediment core allows reconstruction of the environmental variable. The chief weaknesses usually cited for this method are the lack of ecological reality and the subjective assignment of diatoms to categories. The strength of this method *is* subjectivity: the researcher may use his/her experience with diatoms and the voluminous published literature to assign diatoms to the categories, and is not restricted to the information in the calibration set.

The second method, swiftly becoming standard, uses the weighted averaging calibration method developed by Line and Birks (1990) known as WACALIB. In this method, each diatom is assigned a single number (its abundance weighted mean for the variable being studied) based on its distribution in the calibration set. Each taxon becomes a term in the resulting transfer function. This method's greatest strength may be its ecological simplicity and the more refined and appropriate statistical evaluations available. Its weakness is that the ecological knowledge that can be employed in the analysis is limited to the data from the calibration set. Even if the ecology of a diatom found in the core is well known, if it is not in the calibration set, it can provide no information. All WACALIB equations presented are based on the Sweets calibration lakes (Sweets *et al.*, 1990). The main deficiency of the WACALIB equations used in this study are that they utilize a relatively small percentage of the actual diatom information available. For that reason, the older multiple regression equations were also calculated.

To infer pH, three different transfer equations were used: 1) the Whitmore pH multiple regression (MR) equation (Whitmore, 1989) with an $R^2 = 0.65$ and a standard error (se) = 0.70 pH units, 2) the Sweets pH MR equation (Sweets *et al.*, 1990) with a $R^2 = 0.89$ and a SE = 0.34 pH units, 3) the WACALIB pH equation ($R^2 = 0.89$; SE = 0.24 pH units). For ANC reconstructions only the WACALIB ANC equation is used ($R^2 = 0.76$; SE = 31.2 $\text{meql}^{-1}$). Two methods to estimate the trophic state index (TSI) were used. The Whitmore (1989) equation uses the multiple regression approach and the TSI regressed is an average of TSI values calculated from Huber (1982) and based on the limiting nutrient, chlorophyll a, and Secchi depth ($R^2 = 0.83$; SE = 9.29). However, to provide an alternative independent measurement, the popular TSI of Carlson (1977) based on Secchi depth was used ($R^2 = 0.75$; SE = 1.9).

### *Pb-210 Analysis*

Volumetric subsamples were removed from selected intervals of the Davis-Doyle core (site 22, Fig. 1). Samples were dried for 24 hours at 95°C to determine percent water and sediment density. The dried material was ground and divided into three subsamples for a) sediment metals analysis, b) Pb-210 dating, and c) organic component determinations. Any remaining dried material was archived. Samples were weighed on a Shimadzu Libror AEu-1210 electronic analytical balance (0.1 mg sensitivity) and ashed in a Thermolyne 48000 muffle furnace. Other details of sediment handling are described in Charles and Whitehead (1986b). The procedure of Eakins and Morrison (1977), as modified by Cornett, Chant, and Link (1984), was used to analyze the samples.

### *Organic Matter Biomarker Studies*

Our aim was to determine the principal source(s) of organic matter to Lake Panasoffkee sediments. One or more "biomarkers" are needed to differentiate between terrestrial and aquatic sources of organic matter. A biomarker can be a compound or discrete set of compounds, whose structure or composition can be interpreted in terms of its terrestrial or aquatic biological origin. We chose to use as a biomarker one class of natural organic matter – n-alkanes. There is extensive literature on distributions of n-alkanes in nature (Clark, 1966; Eglinton, 1969; Hatcher, 1981; Nissenbaum and Kaplan, 1972; Sohn, 1979). Source (biomarker) samples were collected at selected sites in the lake with an Ekman dredge and placed in acid-washed 1 litre plastic bottles. In addition, soil samples were obtained from the drainage area for comparison. Autochthonous (aquatic plant) input was characterized by analyzing the two or three dominant aquatic plant species in the lake. The location of each sample site is shown in Figure 1.

The first approach used was to determine the carbon number distribution of n-alkanes in the soils and sediments, which is highly indicative of their biological source material (Eglinton, 1969). For example, n-alkane distributions with carbon number maxima in the 17–21 range ($C_{17}$–$C_{21}$) are typical of aquatic algae, while terrestrial plant sources typically produce alkanes with $C_{23}$–$C_{33}$ maxima. Thus, by determining the carbon number distribution of the alkane fraction of the sedimentary organic matter collected, we were able to pinpoint the source as either terrestrial, aquatic, or a combination of the two.

The n-alkane extraction and measurement details are quite complex (Belanger *et al.*, 1993). The diluted extract was analyzed on a Finnigan ITS-40 Gas Chromatograph/Mass Spectrophotometer using the hot needle injection technique. Calibration curves for each of the n-alkanes analyzed were generated over a concentration range of 0.1–1.0 mg ml$^{-1}$. Four replicates of each sample were analyzed and the m/z 71 ion peak area was used to determine sample concentrations by comparison to the appropriate calibration curve. A procedural blank was substracted from all samples, and this corrected concentration was divided by the extracted mass to determine the sediment concentrations which were then used to calculate the Odd-to-Even Preference (OEP). Higher molecular weight n-alkanes, derived from terrestrial sources, tend to have a predominance of an odd number of carbons relative to even number carbon backbones due to their predominance in higher plant cuticular waxes. In contrast, aquatic plants and algae produce almost equivalent amounts of odd and even numbered homologues (see Scalan and Smith, 1970). The basic OEP equation has been used in the form of a plot of carbon chain length to characterize the series of n-alkanes found. If $C_i$ is the relative weight (%) of a n-alkane containing $i$ carbons per molecule, then

$$\mathrm{OEP} = \left[\frac{C_i + 6C_{i+2} + C_{i+4}}{4C_{i+1} + 4C_{i+3}}\right]^{(-1)^{i+1}}.$$

The ratio incorporates the weight percentages of five consecutive alkanes centered about the alkane containing $i+2$ carbon atoms (Scalan and Smith, 1970).

### *Calcite Saturation*

The solubility of calcium carbonate can be determined indirectly by the modified Langelier saturation index. An extensive evaluation of various saturation indices by

Rossum and Merrill (1983) showed that this yielded good results over a wide range of pH values. Figure 2 shows the water sampling sites in Lake Panasoffkee used to obtain data for modified Langelier saturation index calculations.

## RESULTS

### *Calcite Saturation*

Table I shows the modified Langelier saturation index (Langelier, 1936) values (SIN) for Lake Panasoffkee sampling sites as shown in Figure 2. These values are calculated from data obtained from both the literature and from three field sampling trips in the winter and summer of 1992. The lake is seen to be over-saturated in January, both over-and under-saturated in June, depending on sample site, and over-saturated in July. Calcium in Lake Panasoffkee derives mainly from groundwater inputs. The removal of $CO_2$ due to intense macrophyte growth and photosynthesis drives the equilibrium of $Ca(HCO_3)_2$ and $CO_2$, as shown in equation 1, to be disrupted, and the reversible reaction will be forced to the right, culminating in the

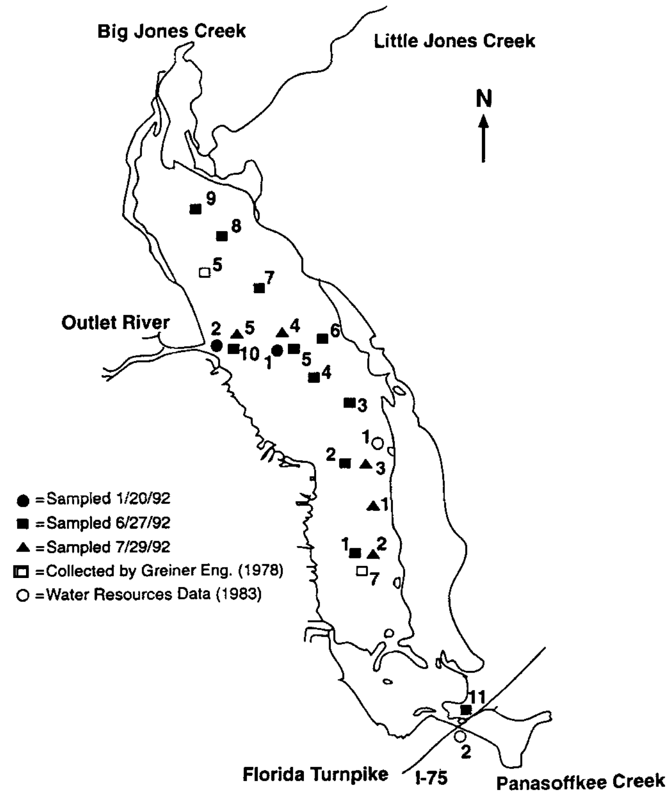


**Figure 2** Lake Panasoffkee sampling sites for modified Langelier saturation index.

**Table I** Saturation index (SIN) data and calculated values for Lake Panasoffkee (Site numbers in Fig. 2).

| SITE/DATE | WATER TEMP (°C) | CONDUCT (μmhos/cm$^{-1}$) | ALKALINITY (mgl$^{-1}$asCaCO$_3$) | pH | [Ca$^{2+}$] (mgl$^{-1}$) | IONIC STRENGTH (M) | SIN |
|---|---|---|---|---|---|---|---|
| 1/20/92 | | | | | | | |
| LP1 | 11.6 | 213 | 59.6 | 8.72 | 25.5 | 0.0034 | 0.313 |
| LP2 | 11.6 | 237 | 72.2 | 8.41 | 32.5 | 0.0038 | 0.194 |
| 6/27/92 | | | | | | | |
| LP1 | 27.9 | 194 | 52.3 | 8.06 | 24.3 | 0.0031 | −0.169 |
| LP2 | 28.1 | 228 | 67.2 | 7.47 | 32.3 | 0.0036 | −0.529 |
| LP3 | 27.9 | 206 | 48.4 | 7.98 | 27.3 | 0.0033 | −0.235 |
| LP4 | 28.2 | 195 | 48.4 | 8.30 | 26.3 | 0.0031 | 0.071 |
| LP5 | 28.0 | 205 | 48.4 | 8.23 | 26.3 | 0.0033 | −0.003 |
| LP6 | 27.6 | 206 | 46.5 | 8.32 | 26.6 | 0.0033 | 0.066 |
| LP7 | 27.7 | 170 | 39.3 | 8.74 | 21.1 | 0.0027 | 0.306 |
| LP8 | 27.3 | 244 | 92.2 | 7.14 | 34.6 | 0.0039 | −0.707 |
| LP9 | 27.0 | 162 | 46.0 | 8.55 | 19.9 | 0.0026 | 0.164 |
| LP10 | 28.2 | 186 | 48.1 | 8.67 | 25.2 | 0.0030 | 0.408 |
| LP11 | 25.2 | 352 | 176.1 | 6.99 | 70.4 | 0.0056 | −0.326 |
| 7/29/92 | | | | | | | |
| LP1 | 32.6 | 168 | 42.0 | 9.66 | 19.3 | 0.0027 | 1.074 |
| LP2 | 32.1 | 182 | 45.0 | 9.22 | 24.0 | 0.0027 | 0.894 |
| LP3 | 31.8 | 186 | 45.6 | 9.23 | 24.0 | 0.0030 | 0.903 |
| LP4 | 32.0 | 191 | 41.1 | 9.45 | 21.3 | 0.0031 | 0.965 |
| LP5 | 32.7 | 182 | 43.5 | 9.41 | 21.3 | 0.0029 | 0.976 |
| | Greiner Engineering Sciences, Inc (1978) | | | | | | |
| North (5) | 18.5 | 225 | 98.0 | 8.40 | 43.0 | 0.0036 | 0.541 |
| South (7) | 19.0 | 220 | 98.0 | 8.40 | 39.0 | 0.0035 | 0.507 |
| Taylor (1977) (Average of numerous sampling sites) | | | | | | | |
| May 1967 (N/A) | 28.9 | 210 | 61.0 | 7.90 | 26.0 | 0.0034 | −0.221 |
| May 1970 (N/A) | 27.0 | 240 | 101.0 | 7.50 | 42.0 | 0.0038 | −0.228 |
| Water Resources (1983) Data at I–75 | | | | | | | |
| LP at I–75 | | | | | | | |
| Jan 1983 (2) | 18.0 | 310 | 143.0 | 7.5 | 58.0 | 0.0050 | −0.086 |
| July 1983 (2) | 26.0 | 280 | 132.0 | 7.2 | 55.0 | 0.0045 | −0.319 |
| Aug 1983 (2) | 27.5 | 330 | 161.0 | 7.2 | 68.0 | 0.0053 | −0.131 |
| Water Resources (1983) Data at Coleman's Landing | | | | | | | |
| Jan 1983 (1) | 17.0 | 335 | 144.0 | 7.4 | 61.0 | 0.0054 | −0.181 |
| July 1983 (1) | 29.5 | 220 | 96.0 | 8.0 | 41.0 | 0.0035 | 0.278 |

precipitation of $CaCO_3$, with a rise in pH. This reaction is revealed by the calcareous encrustation on the plants.

$$Ca(HCO_3)_2 \rightleftharpoons CaCO_3\downarrow + H_2O + CO_2\uparrow$$

Because the exchange of atmospheric $CO_2$ with water is comparatively slow (Verduin, 1975), the $CO_2$ uptake by plants can cause the water to become depleted of $CO_2$ within a short time, resulting in calcite supersaturation and precipitation. Seasonal temperature effects on the solubility of $CO_2$ and calcite were not important in Lake Panasoffkee, as neither the literature nor the field data showed any correlation between water temperature and saturation (Table I). Generally, the lake was over-saturated during both warm and cold periods, as indicated by the Langelier saturation index. However, there was a strong correlation between pH and calcite saturation; for pH values of about 8.3 and above, the lake water was always over-saturated, while for values below 8.3 the water was nearly always under-saturated. The distribution of pH throughout Lake Panasoffkee is determined largely by the patchy plant growth and photosynthesis in the lake. This conclusion was supported by both visual inspection of plant density and by the relatively large pH differences measured between locations in 1992 (Fig. 2; Table I). Highest pH values were always found in areas of dense vegetation.

Lake Panasoffkee contains both submergent aquatic plants, emergent marshes, and floating islands of vegetation. The dominant submergent vegetation is eelgrass (*Vallisneria americana*), with smaller areas of coontail (*Ceratophyllum demersum*), southern naiad (*Naias quadalupenses*), parrot feather (*Myriophyllum aquaticium*), water milfoil (*Myriophyllum brasiliense*), and pondweed (*Potamogeton illinoensis*) interspersed throughout the lake. *Hydrilla verticillata* is present, but is not considered to be widespread in the lake ($CH_2M$ Hill, 1991). Currently, it is estimated that 70% of the lake bottom is covered by vegetation (SWFWMD, 1989).

The leaves of nearly all the plants observed in Lake Panasoffkee have a heavy film of calcium carbonate precipitate on their surfaces. Analyses for total carbonate and organic matter in *Vallisneria*, and the precipitate itself, indicate that the plants (with film) had an average carbonate and organic matter content of 61 and 32%, respectively. The thick film on the plant was approximately 64 and 27% carbonate and organic matter, respectively. The *Vallisneria* plant itself, after the leaves were washed of the carbonate film, had a carbonate content of 17%. Thus, a large fraction (>70%) of the carbonate associated with the *Vallisneria* appears due to biogenic precipitation, undoubtedly the dominant source of calcite to the benthic sediment. This is unusual, as the biogenic control of calcite precipitation is usually more important in marine environments, while inorganic factors usually dominate in lacustrine environments.

Although detailed chemical and crystallography studies were not carried out, we are fairly certain that the carbonate phase precipitated in the lake is calcite, consistent with lake chemistry. Calcite is generally the dominant carbonate precipitate in fresh and brackish water lakes, although other carbonate minerals such as aragonite, dolomite, magnesite, huntite, siderite and others are known. The Mg/Ca ratio in the water appears to control the carbonate phase precipitated. Most freshwater lakes have Mg/Ca molar ratios well below 3 (Müller *et al.*, 1972), as in the case of Lake

Panasoffkee. The water chemistry data for Lake Panasoffkee (Taylor, 1977; Bays and Crisman, 1981; $CH_2M$ Hill, 1991) indicate Mg/Ca ratios range from 0.10–0.33, suggesting calcite is the precipitate.

### *Sediment Physical and Chemical Characteristics*

More than 75% of the lake has a sediment depth greater than 6.1 m (Fig. 3). Table II lists organic matter, carbonate matter and particle size data for all core sections from Lake Panasoffkee sites, as shown in Figure 1. The average organic matter in the lake sediment was 17.4%, and it appears that macrophyte die-off contributes greatly to its organic content. The highest organic matter level, 41.3%, was found in the extreme northern end of the lake at site 110. The lowest, 6.6%, occurred at site 17 at the mouth of the outlet river. The data varied widely throughout the lake between these two extremes.

Organic matter in the core fractions was relatively constant throughout most core depths. The central deep water cores (sites 14 and 22) showed considerably higher levels in the recent 0–15 cm layer, although still low (13–18%). This was also found at the extreme northern site (110) and stations near southeast (77, 83) and northeast (30) woody marsh areas. This indicates reduction of organic matter by diagenesis and/or possible accelerated organic matter inputs in more recent times. The extreme southern site (67), however, had less organic matter in recent sediments, indicating

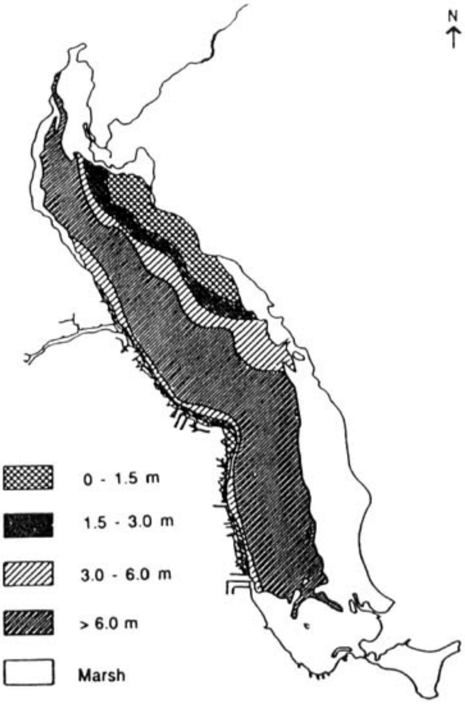


**Figure 3** Sediment depths (m) in Lake Panasoffkee.

**Table II** Organic matter (%), LOI 550–1000°C (%) and particle size data for selected sites in Lake Panasoffkee.

| Station | Core Interval (cm) | %Organic Matter | %LOI 550–1000°C | %Granule or larger | %Sand | %Silt/ Clay |
|---|---|---|---|---|---|---|
| 1 | 0–15 | 16.2 | 21.1 | 3.7 | 8.9 | 87.4 |
| 1 | 15–30 | 14.2 | 35.4 | 9.0 | 10.2 | 80.8 |
| 1 | 30–45 | 13.7 | 20.8 | 2.2 | 14.7 | 83.1 |
| 8 | 0–15 | 10.5 | 37.6 | 68.8 | 26.2 | 5.0 |
| 8 | 15–30 | 11.3 | 36.6 | 37.3 | 13.7 | 49.0 |
| 8 | 30–45 | .. | .. | .. | .. | .. |
| 12 | 0–15 | 9.8 | 37.7 | 41.4 | 23.2 | 35.4 |
| 12 | 15–30 | 10.3 | 21.6 | 19.1 | 15.7 | 65.2 |
| 12 | 30–45 | 8.8 | 22.0 | 17.0 | 13.9 | 69.1 |
| 14 | 0–15 | 18.5 | 33.6 | 1.9 | 11.0 | 87.1 |
| 14 | 15–30 | 7.2 | 36.4 | 12.7 | 9.5 | 77.8 |
| 14 | 30–45 | 9.7 | 37.8 | 14.3 | 11.2 | 74.5 |
| 17 | 0–15 | 6.6 | 39.8 | 30.4 | 10.0 | 59.6 |
| 17 | 15–30 | 8.2 | 37.4 | 37.1 | 18.3 | 44.6 |
| 17 | 30–45 | 5.3 | 38.7 | 80.6 | 19.1 | 0.3 |
| 22 | 0–15 | 13.6 | 36.1 | 1.1 | 9.9 | 81.0 |
| 22 | 15–30 | 6.9 | 39.5 | 39.2 | 10.8 | 50.0 |
| 22 | 30–45 | 8.4 | 38.4 | 40.7 | 13.4 | 45.9 |
| 27 | 0–15 | 9.1 | 38.4 | 19.8 | 7.3 | 72.9 |
| 27 | 15–30 | 9.2 | 38.0 | 13.0 | 9.9 | 77.1 |
| 27 | 30–45 | 9.6 | 37.6 | 12.6 | 9.7 | 77.7 |
| 30 | 0–15 | 33.7 | 23.6 | 5.0 | 9.2 | 85.8 |
| 30 | 15–30 | 13.4 | 35.9 | 22.1 | 16.0 | 61.9 |
| 30 | 30–45 | 7.3 | 38.2 | 27.4 | 15.6 | 57.0 |
| 38 | 0–15 | 7.0 | 36.4 | 10.5 | 17.6 | 71.9 |
| 38 | 15–30 | 7.3 | 39.1 | 28.8 | 27.2 | 44.0 |
| 38 | 30–45 | 4.4 | 40.8 | 16.4 | 18.5 | 65.1 |
| 51 | 0–15 | 22.4 | 19.3 | 15.5 | 19.9 | 64.6 |
| 51 | 15–30 | 21.7 | 3.8 | 1.8 | 3.5 | 95.0 |
| 51 | 30–45 | 19.0 | 26.4 | 4.1 | 8.8 | 87.1 |
| 67 | 0–15 | 10.7 | 37.5 | 14.3 | 18.3 | 67.4 |
| 67 | 15–30 | 11.4 | 37.5 | 3.6 | 10.4 | 86.0 |
| 67 | 30–45 | 17.0 | 34.7 | 12.3 | 9.0 | 78.7 |
| 77 | 0–15 | 23.5 | 31.7 | 3.1 | 8.9 | 88.0 |
| 77 | 15–30 | 16.4 | 35.5 | 8.6 | 10.2 | 81.2 |
| 77 | 30–45 | 13.0 | 37.2 | 25.1 | 9.0 | 65.9 |
| 83 | 0–15 | 25.6 | 31.0 | 13.5 | 17.0 | 69.5 |
| 83 | 15–30 | 18.6 | 19.8 | 33.2 | 20.5 | 46.3 |
| 83 | 30–45 | 7.5 | 39.7 | 56.6 | 23.4 | 20.0 |
| 110 | 0–15 | 41.3 | 14.7 | 2.9 | 26.6 | 70.5 |
| 110 | 15–30 | 30.4 | 25.0 | 10.2 | 24.1 | 65.7 |
| 110 | 30–45 | 21.2 | 30.3 | 12.0 | 24.9 | 63.1 |
| 116 | 0–15 | 13.2 | 35.9 | 58.6 | 19.5 | 21.9 |
| 116 | 15–30 | 14.6 | 36.3 | 25.8 | 21.1 | 53.1 |
| 116 | 30–45 | 14.3 | 36.3 | 9.0 | 16.1 | 74.9 |
| 127 | 0–15 | 17.5 | 34.3 | 0.9 | 12.6 | 86.5 |
| 127 | 15–30 | 14.1 | 36.2 | 17.1 | 3.0 | 80.0 |
| 127 | 30–45 | 17.8 | 34.0 | 0.8 | 6.9 | 92.3 |
| AVERAGE VALUES | | | | | | |
| | 0–15 | 17.4 | 31.8 | 18.2 | 15.4 | 65.9 |
| | 15–30 | 13.4 | 32.8 | 19.9 | 14.0 | 66.1 |
| | 30–45 | 11.8 | 34.2 | 22.1 | 14.2 | 63.6 |
| | ALL | 14.3 | 32.9 | 20.0 | 14.6 | 65.2 |

that organic matter deposition there was higher in the past, or that diagenesis has been greater in recent times.

The collected data indicate that the sediment in Lake Panasoffkee is primarily inorganic (calcium carbonate) in nature in the silt/clay size fraction (Table II). Analysis of sieve data from 15 cm core fractions to a depth of 45 cm in 16 cores distributed throughout the lake indicated that the silt/clay fraction comprised the largest component of the sediment (65.2%), while the granule or larger fraction was next in order (20.0%). Coarse, medium, fine and very fine sand contributed much less. Particle size data (% granule or larger, % sand, % silt/clay) from the various core depths of each core were usually very similar and the overall average of each particle size for each site was usually within two percent of the overall average for each depth (Table II).

Table II also shows loss on ignition (LOI) for the 16 cores. The average carbonate matter (0–15 cm depth) in the lake was 72.2%, and no clear areal trend in carbonate matter was evident. The highest carbonate level in the surface layer, 90.3%, was found at site 17, located at the mouth of the outlet river. The lowest percent carbonate matter, 33.4%, was located at site 110, the northernmost station near the entrance of Big Jones Creek. Carbonate content was generally fairly consistent with depth in the cores (Table II), with some exceptions (sites 1, 12, 51, 112). Comparison of LOI and organic matter in the 0–15 cm core fractions indicated a significant inverse relationship ($R = 0.82$; $p < 0.05$). This supports the work of Suarez (1977) which indicates that organic matter coatings or excretions from micro-organisms block crystal growth sites and calcite precipitaion. Reynolds (1978) and Innskeep and Bloom (1986) have also shown that some organic matter constituents may inhibit calcite precipitation.

### *Biomarker Studies*

N-alkanes in the range $C_{12}H_{26}$–$C_{30}H_{62}$ were found in the sediments of Lake Panasoffkee and in samples from the shore and wooded area near the Outlet River. Three aquatic plants (*Hydrilla verticillata*, *Vallisneria americana*, and an unidentified species) were also found to contain n-alkanes in the same range. The relative distribution of the n-alkanes in these samples are shown in Figures 4–6. The concentrations of n-alkanes in shore and terrestrial samples ranged from 0.40 to 3.05 $\mathrm{mg\,g^{-1}}$ (dry wt.) for the three plant samples. The fraction of higher carbon number n-alkanes ($C_{24}H_{50} - C_{30}H_{62}$) ranged from 42 to 87% of the total in the range of $C_{16}H_{34} - C_{30}H_{62}$ (Table III).

The relative carbon content of various concentration ranges in humic acids from Lake Panasoffkee sediments and from a terrestrial soil humic acid (Aldrich reference soil) was estimated from their C-13 NMR spectra. The fraction of carbon in the 0–50 ppm range in the three Lake Panasoffkee benthic sediment samples (assigned to aliphatic carbons) was 21.6–36.3% of the total in the 0–200 ppm range, and that in the 110–160 ppm range (assigned to aromatic carbons) was 15.4–22.6%.

The two terrestrial sediment samples (OR-1 and OR-2) both possess the features of terrestrial organic matter, but this is less in the shore sample (OR-1). The soil

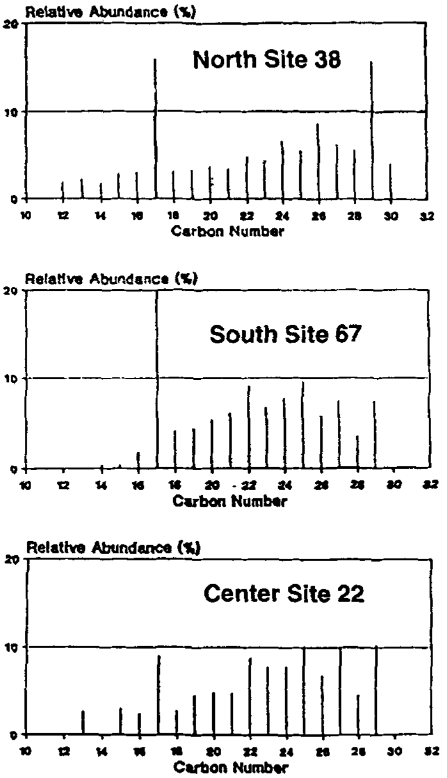
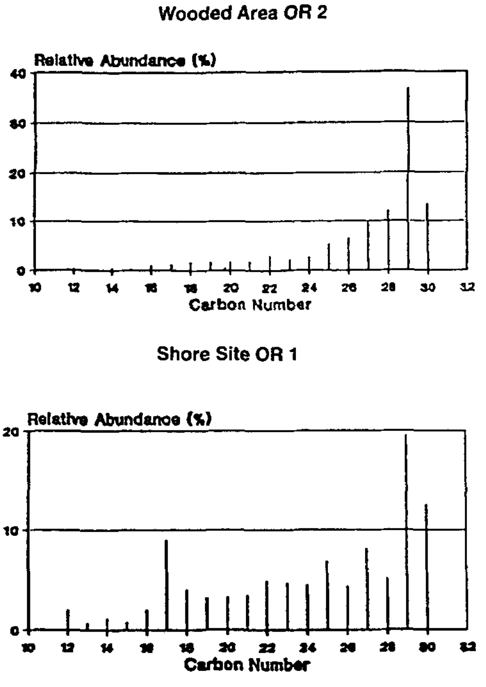


**Figure 4** Relative abundance of n-alkanes in the benthic sediment at sites 38 (north), 67 (south) and 22 (centre).

sample from the wooded are (OR-2) near the Outlet River (Fig. 1) illustrated n-alkane distribution characteristics typical of a terrestrial organic matter source. In this sample, there was a clear predominance of higher carbon number alkanes, 87% to 13% (by mass) for the $C_{24}-C_{30}$ and $C_{16}-C_{23}$ ranges, respectively (Table III), with $C_{29}$ being the most abundant n-alkane. The n-alkane distribution of the shore sample (OR-1; Fig. 5) resembles that of the soil sample, but has evidence of aquatic input. The $C_{29}$ n-alkane is still the most abundant, but the higher carbon number content is lower than that of the wooded area soil sample, 63% for $C_{24}-C_{30}$ to 37% for $C_{16}-C_{23}$ (Table III). There is a significant $C_{17}$ component in this sample, which can be attributed to the contribution of aquatic plants and algae. Two aquatic plant samples analyzed in this study, *Vallisneria americana* and *Hydrilla verticillata*, both contained a significant $C_{17}$ constituent (Fig. 6). The n-alkane distribution from an algae sample (*Lyngbya sp.*). taken in the Crystal River/Kings Bay system (Belanger *et al*., 1993), and in other aquatic plant and algae samples (Simoneit, 1978; Clark and Blumer, 1967), all show significant contributions from the $C_{17}$ n-alkane.

The n-alkane distribution for site 38, the northern lake sample (Fig. 4), is bimodal, with $C_{17}$ and $C_{29}$ being the major contributors, with a slight predominance of higher


Wooded Area OR 2

Shore Site OR 1

**Figure 5** Relative abundance of n-alkanes in the terrestrial sediment at sites ORI and OR2.

carbon number n-alkanes: 56% (by mass) for the $C_{24}$–$C_{30}$ range to 44% (by mass) for the $C_{16}$–$C_{23}$ range, respectively (Table III). These values are not as high as found typically for a terrestrial organic matter source, but are among the highest for samples from the lake. The bimodal n-alkane distribution and fairly strong terrestrial signals for this sample indicate a significant terrestrial contribution to the sedimentary organic matter. Possible sources of these terrestrial components, and ones which will be discussed later, are the two inflow streams at the northern end of the lake.

The n-alkane distribution for site 22 (Fig. 4), is split between the high ($C_{24}$–$C_{30}$) and low ($C_{16}$–$C_{23}$) carbon number n-alkanes, with levels of 53% and 47%, respectively (Table III). This even distribution of high and low carbon number n-alkanes, combined with the absence of a significant maximum in the higher carbon numbers (which would be expected for a terrestrial organic matter, source), indicate a largely aquatic source.

The carbon number distribution for site 67, the southern lake sample (Fig. 4), also showed a slight predominance of lower carbon numbers, as the $C_{16}$–$C_{23}$ range contained 58% of the n-alkane fraction $C_{16}$–$C_{30}$ (Table III). As with the northern sample, the relative abundance of the $C_{17}$ component was high (approximately 20% of the range $C_{12}$–$C_{30}$) and could be attributed to the input from aquatic algae sedimentation and decay and from the other aquatic plants present in the lake.

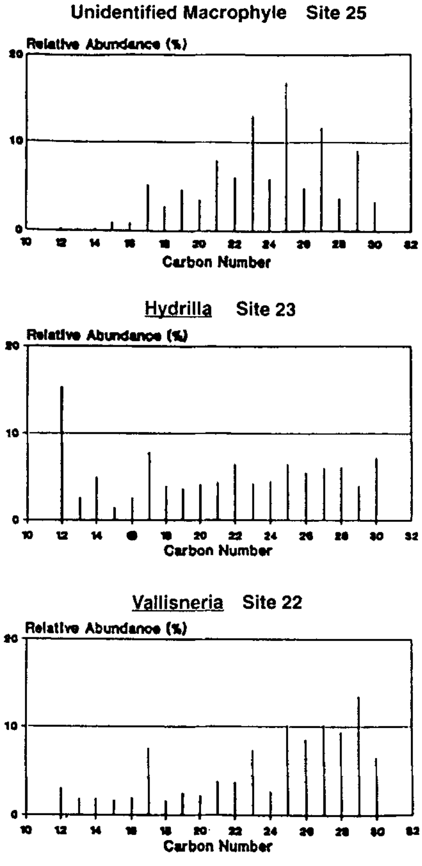


**Figure 6** Relative abundance of n-alkanes in aquatic plants collected at sites 22, 23, and 25 in the centre of the lake.

Analysis of the OEP curves of the three lake sediments and the soil and shore samples (Fig. 7) reveals that there is considerable variation in the lower carbon number region (i.e. $<C_{20}$), but the higher carbon number region is essentially the same for all five samples. The degree to which curves for the shore and lake sediment samples overlap that for the terrestrial soil sample suggests that terrestrial soil is the source of the higher carbon number n-alkanes. The considerable variation in the lower carbon numbers is due to different amounts and types of aquatic algae contributing to the sediments of these sites.

## *Pb-210 Studies*

In the principal core (22), both the density and the organic and water content indicate a normal compaction curve (Fig. 8). Organics (%) in the surface subsample were quite high (40%), probably due to a large component of macrophyte debris. Both water and organics decline precipitously and flatten out by 23 cm. Below this

**Table III** Summary of n-alkane distribution for Lake Panasoffkee.

| Sample | %Fraction Low[a] | %Fraction High[b] | Concentration ($\mu g\,g^{-1}$ dry mass) |
|---|---|---|---|
| Benthic Sediment Site 38 | 44 | 56 | 0.9 |
| Benthic Sediment Site 22 | 47 | 53 | 0.4 |
| Benthic Sediment Site 67 | 58 | 42 | 0.9 |
| Ter. soil OR-2 | 13 | 87 | 4.9 |
| Shore Site OR-1 | 37 | 63 | 3.1 |
| *Vallisneria* Site 22 | 34 | 66 | 1.2 |
| *Hydrilla* Site 22 | 48 | 52 | 10.4 |
| Unid. Plant Site 22 | 44 | 56 | 13.0 |

a. $\%\mathit{Fraction\ Low} = \dfrac{\Sigma[C_{16}H_{34} \ldots C_{23}H_{48}]}{\Sigma[C_{16}H_{34} \ldots C_{30}H_{62}]} * 100$

b. $\%\mathit{Fraction\ High} = \dfrac{\Sigma[C_{23}H_{48} \ldots C_{30}H_{62}]}{\Sigma[C_{16}H_{34} \ldots C_{30}H_{62}]} * 100$

point marl and clay content increased and snail shells became common. The few density measurements taken below 30 cm were somewhat variable, as is the character of the sediment itself.

The concentration of Pb-210 in site 22 sediments (Fig. 9) indicates a relatively good fit to models of Pb-210 in lake sediments (Appleby and Oldfield, 1978). Similarly, the concentration of the largely anthropogenic sediment metals lead, zinc, and copper (Fig. 10) follow expected depositional patterns; they are non-detectable or at very small background amounts deeper in the core, but rise steadily in the upper sections. Lead and zinc are atmospheric pollutants produced by human activities (e.g. combustion of fossil fuels) and copper based herbicides are often used for macrophyte control, as in the case of Lake Panasoffkee. Lead concentrations declined slightly in the 1980's, but the overall quantities are quite small. Also, increased use of unleaded fuels in the early 1980's may account for some decline. These tracers of atmospheric pollutants are negligible before 1940, however, and in general agreement with results from the PIRLA study of six Florida acidic lakes (Sweets *et al.*, 1990). For these reasons, the Pb-210 dating of site 22 in Lake Panasoffkee can be applied to the stratigraphy with confidence.

Calculated accumulation rates (g dry wt) for Lake Panasoffkee (Fig. 11) are low (between 0.04 and 0.06 $\mathrm{gDW\,cm^{-2}\,yr^{-1}}$. Organic sedimentation is high and

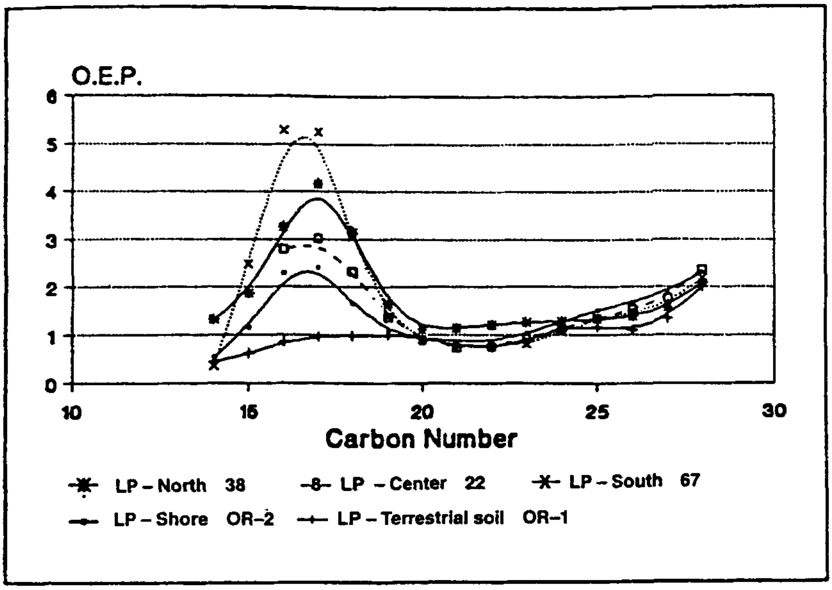


Figure 7 Odd-to-even preference (OEP) carbon curves for benthic and terrestrial sediment samples.

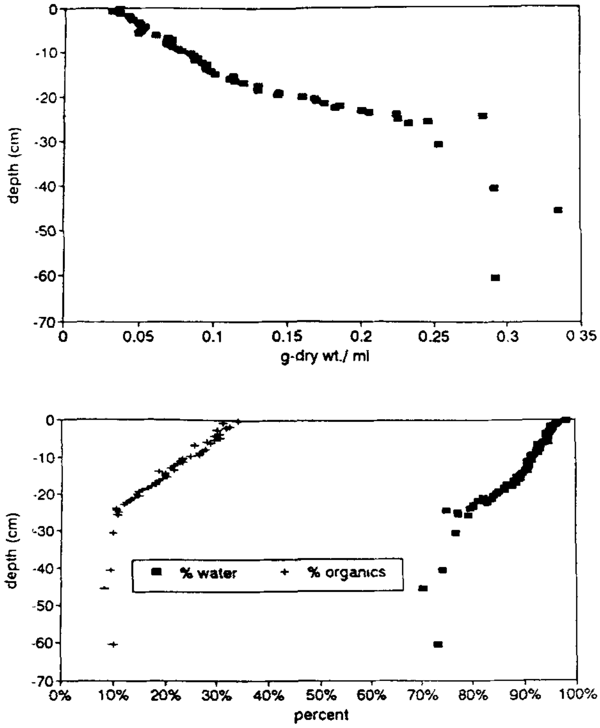


Figure 8 Sediment density (top) (g dry wt ml$^{-1}$), organic matter (%) and water content (bottom) (%) as a function of depth at site 22.

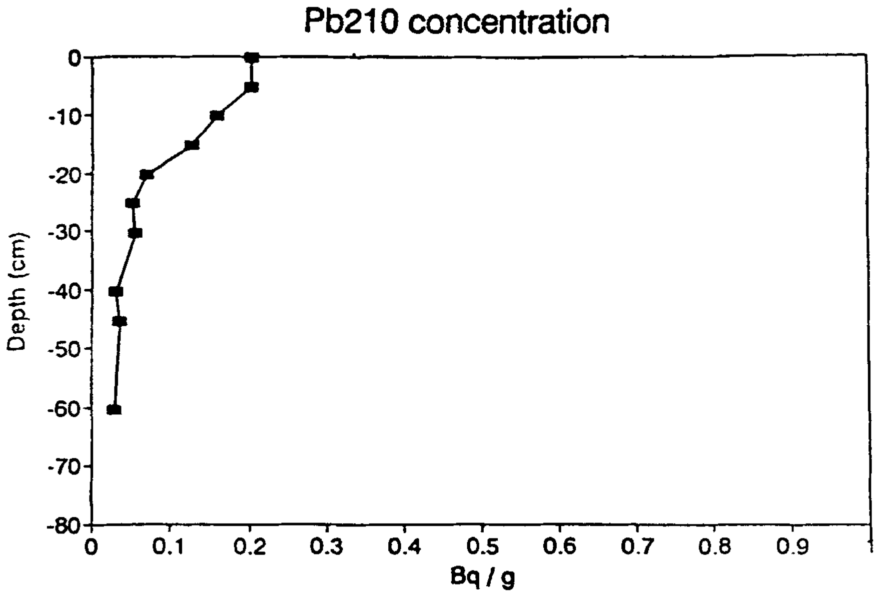


**Figure 9** Pb-210 concentration (Bq $g^{-1}$) as a function of depth at site 22.

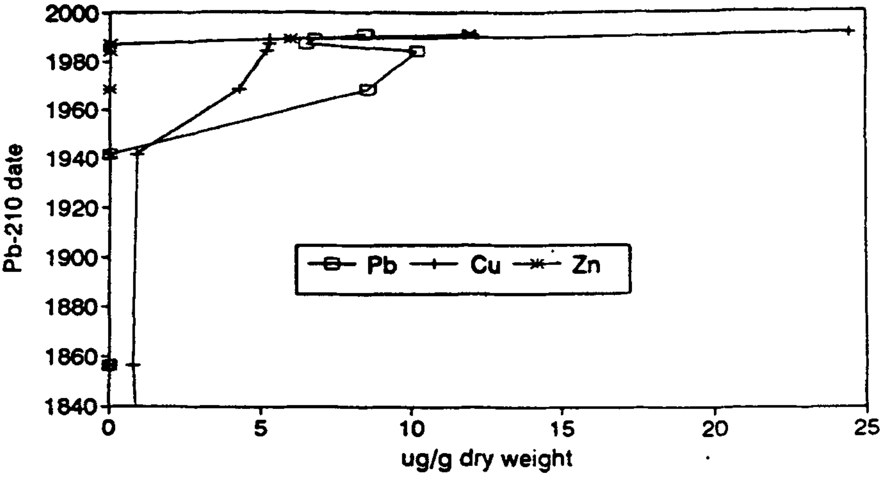


**Figure 10** Lead, copper and zinc concentrations as a function of Pb-210 date at site 22.

accumulation rates in terms of mm $yr^{-1}$ are twice that of oligotrophic, acidic lakes from north Florida. There are high dry weight accumulation rates at 25 cm (approx. 1960) and 35 cm (approx. 1940), although the presence of large Apple Snail shells (*Pomacea calignosa*) in the sediments may account for these two readings by altering sediment density.

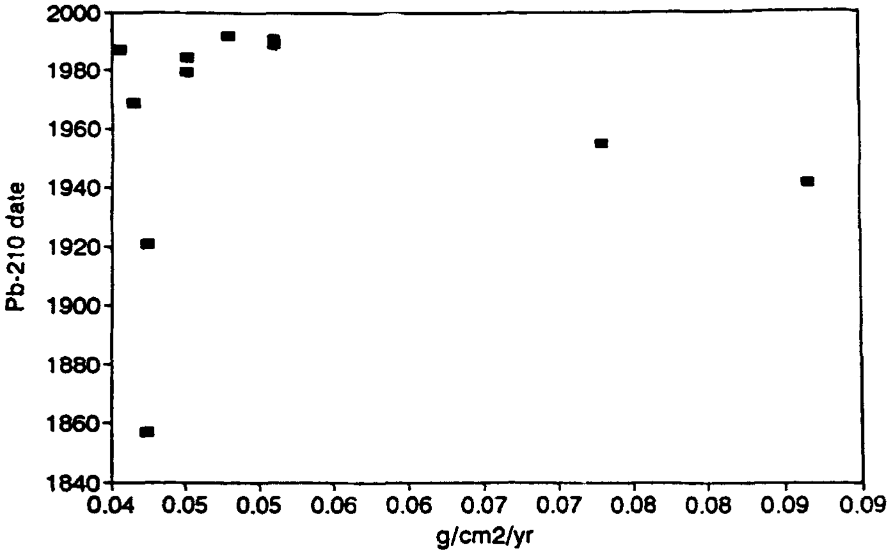


Figure 11 Calculated accumulated rates g $cm^{-2}y^{-1}$ for site 22.

## *Palaeolimnology*

The diatom stratigraphy (Fig. 12) of the principal core (core 22) consists primarily of epiphytic diatoms, particularly the taxonomically troublesome trio of smaller *Fragilaria* species: *F. brevistriata*, *F. construens*, and *F. pinnata*. The only real change in the core is the gradual rise, mostly in the last decade, of *Epithemia argus* var. *alpestris*, *Mastogloia smithii* var. *lacustris*, and several *Melosira* species. The stratigraphy in general suggests that the lake is not different fundamentally now than it was in 1855. Lake Panasoffkee has always been macrophyte dominated, but may have had more production from the planktonic component in the last decade than at any time in the last century.

The pH reconstructions (Fig. 13), based on the Sweets calibration sets, indicate that pH may have decreased since 1950 by an insignificantly small amount (0.4 pH units), but the Whitmore diatom inferred pH (DI-pH) scheme does not indicate any pH change; it also predicts a current pH of about 8, while the two Sweets equations predict a current pH near 7. We found the average pH of the lake to be 8.50, ranging from 6.99–9.66, based on numerous daily measurements made over several seasons during this study (Table I).

All other reconstructions reflect the general diatom flora changes that start around 1960, with decreases in ANC (Fig. 13), DOC (Fig. 14), and diatom inferred trophic state (DI-TSI), as calculated by both Whitmore's and Sweets' equations (Fig. 15). The DI-TSI reconstruction in particular is interesting, indicating a naturally eutrophic system that has become more mesotrophic since the 1970's. The principal Panasoffkee core (22) is the best candidate to represent whole lake conditions, as sediments from around the lake will focus at the deepest, central point. In a large shallow lake like Panasoffkee, no single core could contain a satisfactory integration

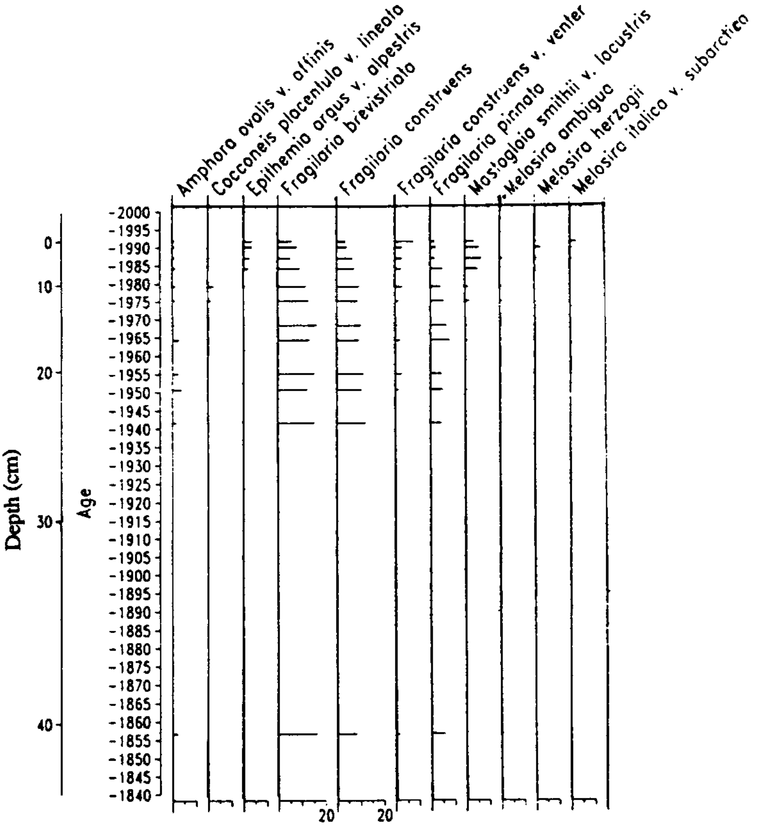


**Figure 12** Diatom stratigraphy of core site 22.

of the variety of zones within the lake. Because of the wide range of chemical and biological conditions in the lake, ancillary cores were collected to see if other areas would show a different palaeo-ecological interpretation. However, cores from very shallow areas, especially zones of macrophyte and shell growth, must be considered with caution, as rooted systems will mix the sediments, and the sediment surfaces will be dominated by the living assemblage. Therefore, these data are not discussed here in detail. Major pH change is not inferred for any of these ancillary cores except for core 30 (northwest shore), where a steady 0.5 rise in pH is indicated by all three equations. The DI-TSI (Carlson), as reconstructed by WACALIB (Fig. 15), indicates a slight decline in core 12 (south-central), but a slight rise in core 30.

## DISCUSSION

Results of our sediment analyses show that the sediments of Lake Panasoffkee are primarily endogenic in nature, containing much more inorganic carbonate (72%)

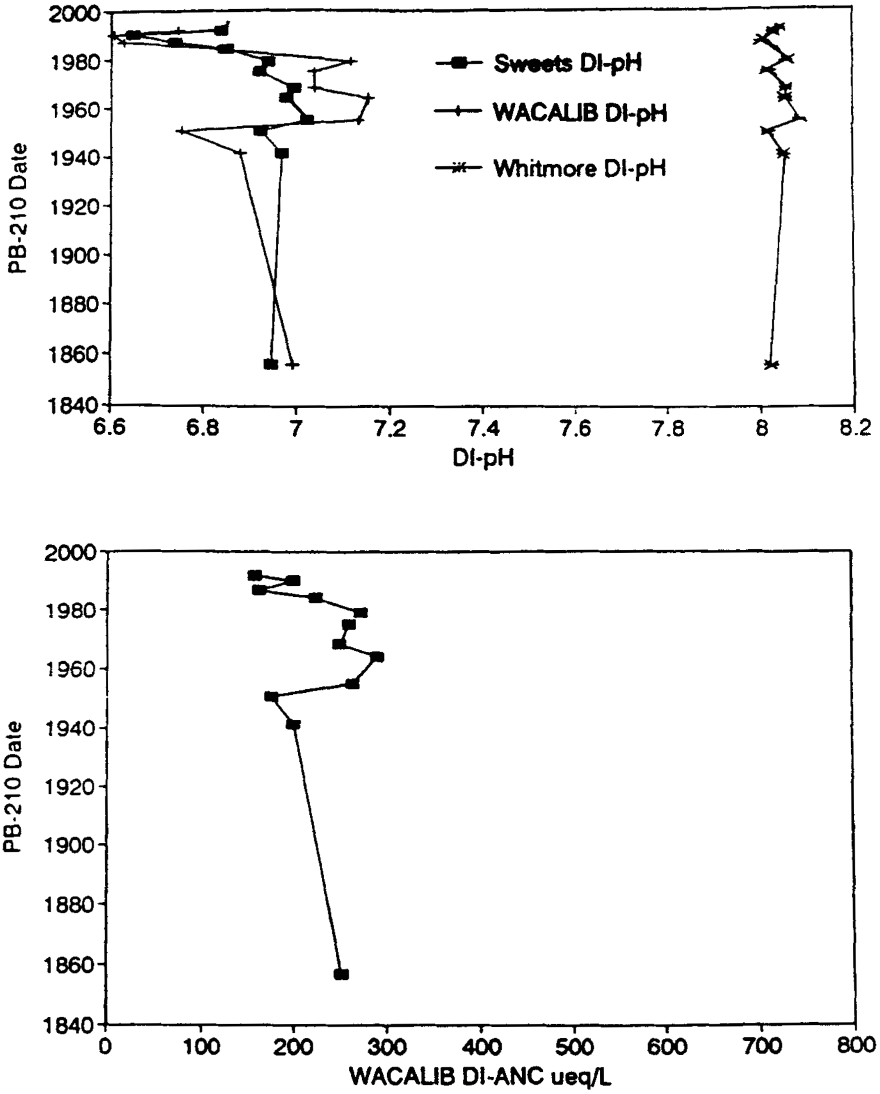


**Figure 13** Diatom inferred pH (top) and ANC (bottom) at site 22.

than organic matter (17.3%). The precipitated carbonate matter was found to be primarily biogenically generated by aquatic macrophytes during photosynthesis. Although sediment depths were generally very deep (>6 m), Pb-210 dating data indicate that macrophyte die-off and carbonate sedimentation do not occur at unusually high rates. The principal source of the organic matter to the sediments, however, was shown to be derived from the macrophytes, with terrestrial components present in varying amounts and reflecting the proximity of the sampling sites to inflow streams.

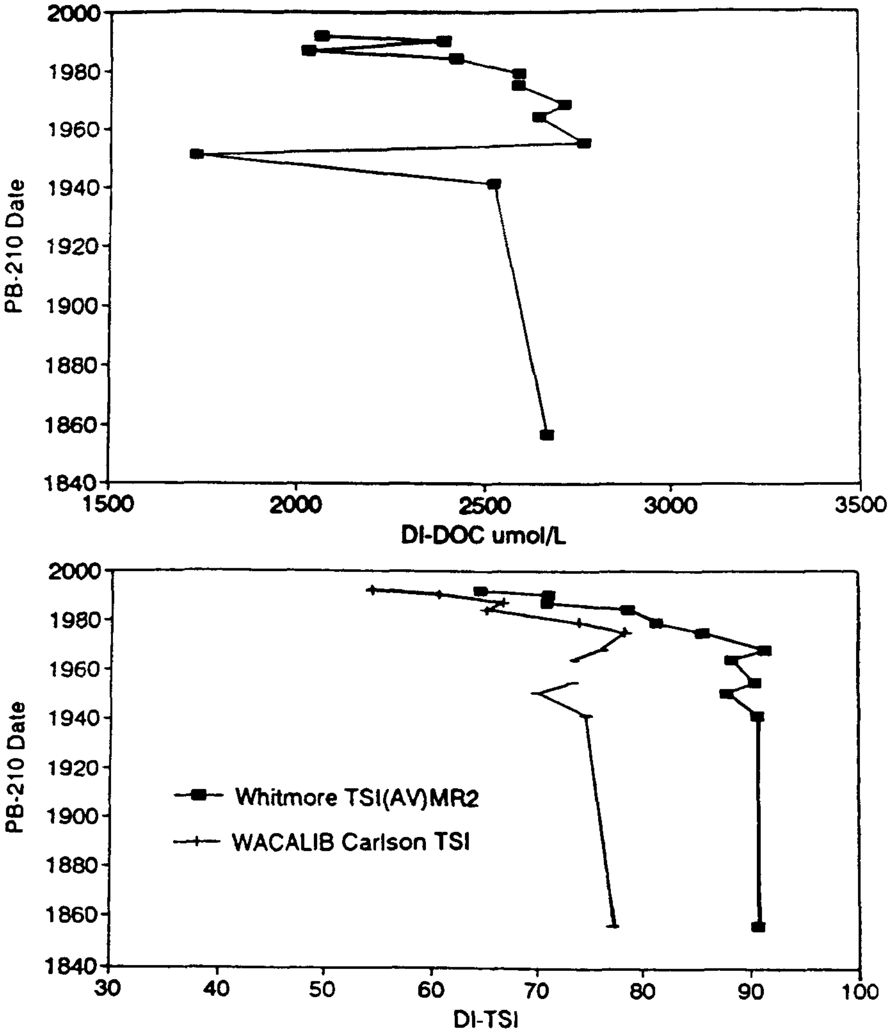


**Figure 14** Diatom inferred DOC (top) and TSI (bottom) at site 22.

Increasing lake shallowness appears to be more related to the documented long term decrease in lake level with increasing aquatic plant coverage than to high rates of sedimentation. The lake level decline appears to be related to the long term lowering of Floridan aquifer levels in the area, reducing seepage to the lake. Figure 16 shows that surface water level changes in Lake Panasoffkee vary directly with groundwater level changes in the Floridan aquifer, indicating that the lake is hydraulically connected to the aquifer. The higher water levels in the aquifer than in the lake also indicate the great potential for groundwater flow into the lake, estimated to be approximately 70% of all water inputs to the lake (Greiner Eng. Sciences Inc., 1978). The lake/groundwater system in the area is governed primarily

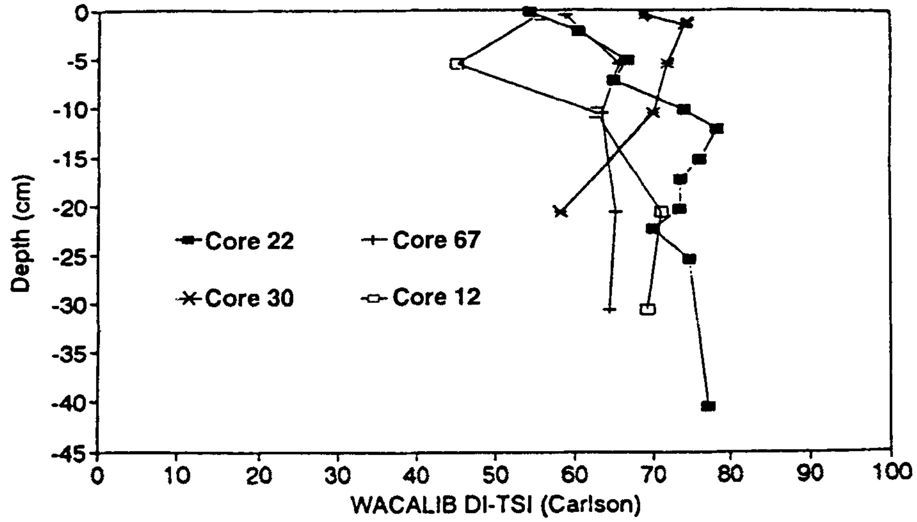


**Figure 15** Diatom inferred TSI (Carlson) at four core sites.

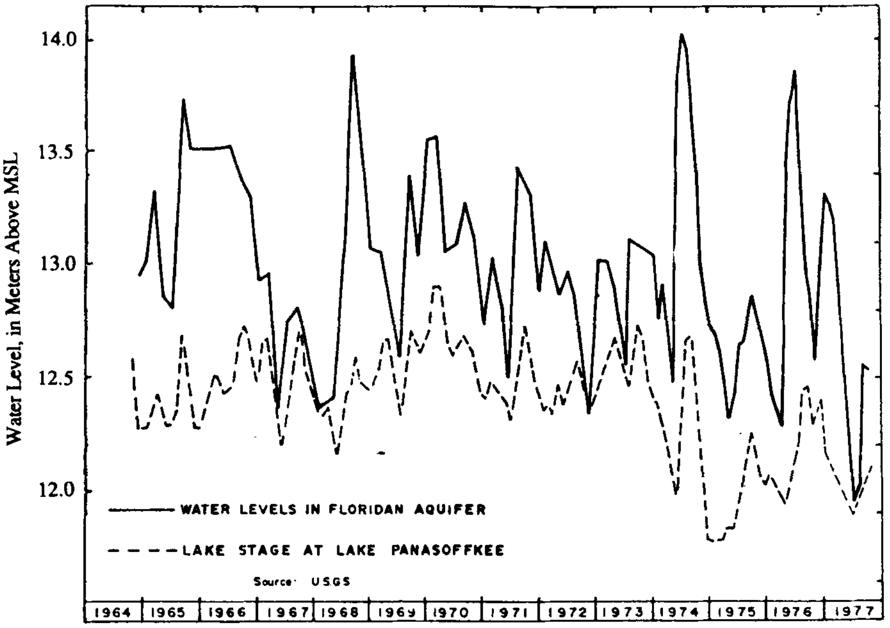


**Figure 16** Water level changes in Lake Panasoffkee and the Floridan aquifer from 1964 through 1977.

by rainfall. However, rainfall at Lake Panasoffkee has been well below normal since 1988, when the Wysong Dam was removed. This deficit of rainfall has thus impacted the lake/groundwater system, causing a significant lake level decline in recent years which has been of concern to lake users. The Pb-210 sedimentation rate data, historical topographic contour data and groundwater level data support these conclusions.

Topographic contours along the north, east and south shores clearly define an early lake shoreline of 15.2 m MSL and an even more recent shoreline at 13.7 m MSL within the last few hundred years (Greiner Engineering Sciences Inc., 1978).

In general, the palaeo-analysis indicates that Lake Panasoffkee does not appear to have changed in the last 150 years. Most of the diatoms found now were abundant in 1850, presumably before human activity had a serious impact. Small changes in the upper part of the sediment cores suggest that planktonic productivity may be more important now than at any other time, but the lake has always been a macrophyte dominated system. The palaeo reconstructions suggest that the TSI may have decreased slightly along with pH during the last 20 years. Changes in the four diatom analyzed cores probably reflect changing zones of macrophyte dominance, perhaps associated with small changes in lake level, water flow, and water clarity. It appears that the lake has a patchy macrophyte distribution, resulting in considerable pH variations. The patchy submerged aquatic vegetation creates micro-environments where $CO_2$ removal often leads to pH levels greater than 9.0. (Table I; Fig. 2)

Basically, all palaeo reconstructions indicate that the diatom flora changed around 1960 with decrease in ANC, DOC and DI-TSI. The DI-TSI reconstruction indicates a naturally eutrophic system that has moved toward a more mesotrophic state since about 1970. The more stable lake level (1965–1988) following upstream dam construction on the Withlacoochee River, the increased rooted aquatic vegetation coverage throughout the lake, and the increased littoral shrub vegetation may have contributed to a recent gradual shift toward less eutrophic diatom species, still found in the central deep water core (site 22) in the upper intervals.

## CONCLUSIONS

This study indicates how selected chemical, physical and biological sediment analyses can provide valuable historical lake information for lake management. The information is critical for the establishment of future lake management decisions, decisions not based on speculation but rather on conclusive scientific data.

In this study, the sediment analyses showed Lake Panasoffkee to be a naturally eutrophic lake, recently moving toward a mesotrophic state. Sediment accumulation occurs at low rate and is not a major problem. The increasing lake shallowness is related more to the lowering of Floridan aquifer levels in the area, resulting in lower inputs of groundwater. Although sedimentation rates are low, the major source of organic matter to the sediment in the lake was shown to be aquatic, rather from runoff or erosion, as previously suspected.

### *Acknowledgement*

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