Shallow Stratigraphy of Lake Okeechobee, Florida: A Preliminary Reconnaissance

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ABSTRACT
The shallow stratigraphy of Lake Okeechobee in south-central Florida has been studied on a preliminary basis using a high resolution seismic profiling technique combined with vibracoring. The main purpose was to investigate the unconsolidated sediment infill, but incidental information on the first few meters of the underlying rockhead has been obtained. The deepest reflector is from a surface exhibiting basins separated by “reefs” or ridges and cut by V-shaped channels. The basins are filled by thin calcareous and similarly channelled horizons, probably the Caloosahatchee-Fort Thompson Formation. The overlying sediments form an incomplete cover and are developed in different areas, having limited overlap. There are three contrasted deposits. Rooted peats occur extensively in the shallow margins at the northeastern and southern ends of the lake. In the northwest a fan of quartz sand reaches its maximum thickness off the Kissimmee River, from which it apparently was derived. It extends over the peats in the northeast quadrant.

The topmost deposit occupies about a third of the lake bed and involves about 0.2 km³ of organic-rich black mud. The mud lies mainly in the northern half of the lake and has an eccentric location with greatest depths to the northeast of the central axis of the lake and an inclined surface sloping down to the southwest. The mud thickness is frequently less than 30 cm, but reaches 80 cm in one area. The older, deeper part of the mud succession is differentiated into various colored clays interbedded with sand and shells, whereas younger mud is undifferentiated and spreads over the peats of the shallow periphery. The lower sections of clays show submillimeter lamination, which is evidence that neither storms nor bioturbation have reworked these deposits. Density and shear strength profiles confirm that only the thin surficial flocculent layer evident in some places is liable to periodic reworking by wave-induced currents.

INTRODUCTION
Lake Okeechobee is the largest lake entirely within the borders of the United States (Figure 1). It is roughly circular, 48 km wide but very shallow, a maximum of 4.5 m deep. The lake provides water supply, drainage and flood relief for a large area of south-central Florida and is used extensively for recreation. The water quality of the lake has deteriorated over thirty years or more, as evidenced by its chemical properties (Dickinson et al., 1992). South Florida Water Management District, West Palm Beach, has sought to establish the reasons underlying this deterioration with a view to halting and reversing the trend. As a result a multi-disciplinary and coordinated research program was undertaken to explain the deterioration and provide data upon which a rational management policy to improve the water quality could be based. The study reported here is one component of this wider initiative. It comprises a preliminary reconnaissance aimed at mapping and characterizing the bed sediments. Arising from the purpose of the study, interest has been focused on the organic-rich surficial muds. Incidental information on the underlying deposits has also been obtained.

GEOLOGICAL HISTORY
The Okeechobee basin has been a site of subsidence since at least the early Tertiary, and a thick sequence of Miocene clay in its axis has resulted in slow differential compaction to perpetuate the feature. Pettijohn (1987) studied the Tertiary history of the lower third of the Florida peninsula and recognized a ring of Pliocene coral reefs surrounding the palaeobasin, at the northern apex of which lies the lake and the Okeecho-
the present lacustrine plain of the Florida peninsula represents in unmodified form the seabed surface at the time of its latest emergence (Heap, 1887; Brooks, 1984). The other controlling influence on the geological history has been the

Figure 1. Lake Okeechobee in south-central Florida. Depths are relative to a datum which is 3.81 m above NGVD.
pattern of deposition of clastic sediments during Plio-Pleistocene periods of high sea level (Brooks, 1984) (Figure 2).

The Plio-Pleistocene Tamiami limestones and marls were eroded to form a shallow basin which has been progressively infilled by a complex sequence of at least five calcareous deposits. Brooks (1984) reported that this Caloosahatchee-Fort Thompson Formation outcrops on the bottom of Lake Okeechobee, forms the double row of "reefs" across its southern portion and underlies the peats, marls and surficial sands surrounding the lake. Brooks (1984) also recognized a bed of Rangia cuneata reaching 1 m in thickness overlying the Fort Thompson deposits in South Bay and extending out into the lake. The Rangia beds were identified as estuarine deposits and dated at more than 25,000 yr BP. They were not sampled in the present study.

Brooks (1984) sampled a calcitic freshwater mud in the southeastern portion of the lake. This mud overlies, in part, the Rangia beds as well as the cap rock of the Caloosahatchee-Fort Thompson Formation and is probably the same as the black mud sampled in this study.

Brooks (1984) believes that a water body on the present site of Lake Okeechobee dates back to at least 12,000 years BP, but the oldest radiocarbon date on fresh water calcitic lake mud is 6,300 years BP. Gleason and Stone (1975) and Gleason et al. (1984) have provided age dates on peats from the southern end of the lake, ranging from 5,490 ± 90 yr BP to 2,670 ± 80 yr BP, whereas at Belle Glade, landward of the lake shore, peat deposits with an oldest age of 4,400 years BP were analyzed by McDowell et al. (1969). It seems clear from these dates that around 6,300 years ago the lake was small in size and organic-rich mud was being deposited in what is now the deepest, central part of the lake. Penecontemporaneously, vegetation was growing directly on the Caloosahatchee-Fort Thompson carbonates exposed around the margin. The vegetation is preserved as the extensive peats now widely developed along the southern and northeastern margins of the lake.

From this proto-lake the extensive modern water body began to develop just over 4,000 years ago (Brooks, 1984). Its extension can only be attributed to steady organic deposition along its southern rim over this period. The northern and eastern margins of the lake are enclosed by a series of beach ridges, which are best developed between Taylor Creek and Chancey Bay. The lowest part of the oldest ridge has been radiocarbon dated using an unidentified species of fresh water clam at 1,685 ± 75 yr BP (Brooks, 1984).

Based on the age and height of the earliest beach ridges, Brooks (1984) concludes a historic maximum lake level shortly after 265 AD. The most recent beach ridges were emplaced probably in the period 900–1200 AD, a warm, hurricane-prone climatic interval. An organic sill rising at the southern end of the lake reached a maximum of 6.1 m above present sea level. During periods when the lake reached the 6.2 m stage according to the lake datum, as in 1886, and again in 1878 (7.1 m), water overflowed the whole southern rim, resulting in high velocities in the rivers to the south and possibly at the southern end of the lake.

The geophysical and sampling data obtained during this program provides additional detail on the history and nature of the sediments in the lake.

METHODS

A continuous seismic profiling survey was undertaken to map the three dimensional structure and distribution of the bed deposits. This was followed by a vibracoring survey to characterize the various acoustic horizons recognized in the geophysical survey. Undisturbed samples were re-
turned to the laboratory for sedimentological and geophysical testing.

Field Techniques

The extremely shallow nature of the lake, together with the suspected presence of gas in the muddy sediments, imposed stringent requirements on the seismic devices used. An EG&G (Model SMS-960) side-scan sonar was used to map surface topography and acoustic character of the lake bed. This device digitally rectifies to produce slant range and along-track undistorted images. A Datasonics (Model SBT-5000) frequency selectable pinger and 200 kHz echo-sounder were operated in parallel.

Sampling was carried out using a small, purpose-built vibracorer from the University of Florida’s research vessel. The core tube was fitted with flexible transparent core liners to enable the undisturbed samples to be removed and returned to the laboratory for analysis. It proved difficult to anchor over or sample the rock bed in the south. Mud and peat were readily sampled, the sand less so, and in many cases short sections of white “beach rock” of various lithologies were obtained at the base of core samples. Care was taken not to bury the core barrel too deeply in stiff deposits because of the limited break-free and lifting capability of the vessel. In circumstances where the upper surface of the mud deposits was very loosely consolidated a Paar (Model DMA 35) densimeter was used in the field to measure the density of these lowly consolidated materials. This densimeter operates on the principle of a vibrating glass U-tube. Slurries sucked into the tube change the vibration frequency which is converted to density and displayed digitally.

Laboratory Techniques

In the laboratory core samples were first bi­sected lengthwise, opened, described and photographed. No further studies were made on quartz sand, peat or beach rock, but attention was concentrated on the upper muddy zone, where present. Before the freshly opened sample could dry out, vertical profiles of density and shear strength were made in one half-core. Density profiles were measured gravimetrically and shear strength measured with a calibrated, Wykeham Farrance (Model 100) vane.

A thin axial slice was cut from the undisturbed half and X-rayed. The X-radiographs showed the primary and secondary fabric with a very high (submillimeter) resolution.

RESULTS

Geophysics

The quality of geophysical records obtained from the lake previously have been extremely poor (KIRBY et al., 1989). This probably arose from a combination of the unsuitability of the equipment, the extreme shallowness and adverse weather conditions. During the present survey, best results were obtained from the pinger operating at 7 kHz. A total of 177 km of geophysical lines were run. The side-scan records were of indifferent quality showing returns from only a short range, largely due to the shallowness. The sub-bottom profiler performance was strongly influenced by the weather, but records from Lines 2, 3 and especially Line 4 (Figure 3), when the lake waters were calm, were better than any achieved previously. These lines permitted the unconsolidated sediment depths and extent to be determined, together with providing penetration into rock-head along much of their length. An example of the sub-bottom profiles is shown in Figure 4.

The deepest reflectors revealed by the continuous seismic profile records, possibly the top of the Tamiami Limestone, were of well defined, if shallow, bedrock basins. In the north the basins are separated by a N-S orientated narrow ridge, which finds no surface expression today. Further south it appears that the bedrock rises westwards and reaches the lake bed. The extent and number of the basins cannot be established from this brief reconnaissance and with records of such variable quality.

The surface of the deepest reflector, at least in the west of Line 4, where the best quality records are available, was quite irregular and showed a large number of steep, often V-shaped, valleys or channels which criss-cross the margin and bed of the basins (e.g. Figure 4). Record density was insufficient to plot the continuity and extent of these channels and their origin is unknown.

The basins are infilled by a series of extensive, sheet-like, flat-lying sedimentary layers of roughly equal thickness. In the more central areas of the lake up to 3–4 separate layers could be resolved (Figure 4), whereas towards the edge of the lake it is generally the case that only 2 layers were present. The depth of the sequence ranged up to a maximum of 4 m, but was more generally in the range 1.5–2.5 m. The complex history of the de-
Figure 3. Geophysical lines mainly transecting the mud zone in Lake Okeechobee.
posits is illustrated by the fact that deeper layers of this infill are themselves cross-cut by later channels which have subsequently been infilled during deposition of the overlying layer. Apparently a similar environment to that under which the basins and their incised channels were formed existed during the later period when the basins were becoming infilled by the layered deposits.

These layered deposits are in part overlain by modern unconsolidated deposits. The latter are focused at the northern end of the lake and are everywhere very thin (no more than 80 cm). To the south they wedge out, becoming sufficiently thin that it is impossible, from the geophysics records alone, to determine where the edge of these deposits lies. Return signals from the mud were often “acoustically turbid”—possibly indicating the presence of dispersed gas. In a few patches, extending to several tens of meters in width, in addition to this acoustic turbidity the signal from the upper horizon shows strong surface or near surface reflectors and a phase reversal (Kirby et al., 1989). The prospect that such strong reflectors might be due to a shell lag deposit or coral boulders can be discounted from the fact that the pinger records from these zones showed a smooth bed lacking the parabolic reflectors typical of boulders and the side-scan records showed a flat surface with weak reflectance (Kirby et al., 1989). Instead it seems more likely that these signals indicate the presence of gas accumulations.

The lake bed was found to be virtually featureless on the side-scan records. A multitude of small (< 1 m), point-source, strong reflectors were commonly present. These are likely to have been debris or trash from vessels. To investigate the unconsolidated sediments further and to aid geophysical interpretation a small batch of vibracore samples were taken.

Samples
Thirty-one successful cores were taken, and the corer refused on rock exposed at the lake bed at four other sites on the south side of the lake (Figure 5). At a number of other locations it proved impossible to anchor. The basic succession consisted of four horizons. A white, variably cemented “beach rock” of variable lithology forms the bed of the entire lake. This is partly covered at the northern end by a marginal peat, a quartz sand and an extensive mud veneer.

Rock
A cemented, calcareous, white deposit forms the basement of the lake, being exposed at the lake bed for up to 50% of its area. The deposit includes indurated lime mud, nodular limestone, calcareous sand and sandstone with shelly horizons. The shelly fauna consists of gastropod and bivalve species, which were not specifically identified. Gleason and Stone (1975) and Brooks (1984) sampled these beds in onshore irrigation channels and in the southern part of the lake itself. By analogy with the complete succession of five layers recognized at its most complete by these
Figure 5. Distribution and depth of unconsolidated sediment types. Away from the shore sediment mainly occupies the northern two-thirds of the lake bed.
workers, it is suggested that the rock basins in the lake also contain the complete succession of the Caloosahatchee-Fort Thompson Formation (Plio-Pleistocene).

Peat

One of the noteworthy observations of the sampling campaign was the depth and geographical extent of peat deposits at the northern end of the lake. The peat deposits are believed to lie in place. In a number of cases the rock on which they rest is penetrated by rootlet beds from the vegetation which originally invaded the bare rock surface. The fact that the peat is in place is layered and shows a variety of textural features may also support the view that it is in situ. The relatively thick, (0.50 m), and layered peats hint at a quite prolonged period of subaerial exposure during which a variety of environmental changes occurred. The brief nature of this reconnaissance and the fact that interest was focused on the muddy deposits prevented any further study of the peats. The previous recognition of peats in several locations in the southern shallows and this extensive bed in the northeastern quadrant suggests that in earlier times the water area may have been confined to the deeper central zone. Radiocarbon dates and interpretation by GLEASON and STONE (1975) and BROOKS (1984) may be taken to imply that lake level began to rise, possibly about 2,500 yr BP.

Sand

In those few cores where the succession was complete, the peat was found to be overlain by a greyish quartz sand. The sand occupies a broader zone than the peat at the northern end of the lake, although it is generally thin (< 10 cm). Only around the entrance to the Kissimmee River does its thickness increase (40–50 cm). Here a series of sand layers with differing grain-size and shell content overlap each other. In the west the sand layers are exposed at the lake bed and not entirely covered by the more recent black mud.

The northern distribution of the sand patch and the fact that it is thickest in the proximity of the Kissimmee River, combined with the fact that it overlies the paludal peat, are all indicative of a fluvialite sand supplied by the Kissimmee drainage basin. The Kissimmee River constitutes more than 50% of the Okeechobee drainage basin and the presumed Plio-Pleistocene source deposits in the region become more sandy in the north.

Mud

Black, organic-rich mud forms an extensive veneer in the northeastern quadrant of the lake, possibly covering a third of the entire bed. A map (Figure 6) showing the thickness and extent of the mud patch has been compiled by combining the interpretation of the pinger records and coring attempts at 31 vibracorer stations from this study and 131 core samples taken without mechanical aids by University of Florida's Soil Science Department (Kirby et al., 1989). The mud layer is generally less than 30 cm thick, although in two areas it exceeds 30 cm and in one reaches 80 cm. The maximum thickness is almost coincident with the area of deepest water, possibly indicating a link. The volume of mud is approximately 193 × 10^6 m³. Maps showing both bathymetric contours and the margin and isopachytes of the mud patch reveal that it is offset to the northeast and has a surface inclined to the southwest.

The cut cores contain only very occasional living organisms; these being confined to a small, highly ribbed, fresh water bivalve. There were also only a few bivalve shells in the cores. As a consequence the internal fabric of the cores was almost entirely a primary and depositional one, with very little secondary biogenic disturbance. Nine vibracore samples, from the deepest mud area, showed zones of different colored clay or thin beds of shell or sand. BROOKS (1984) dated shells from these lower muds at as early as 6,300 yr BP. These variable layers appear to reflect climatic perturbations in the lake or hinterland, such as hurricanes (shell and sand layers), forest fires or other short term events (clay layers).

The upper part of the mud zone is invariably developed as a more homogeneous and extensive black silty clay. It appears that following the deposition of varied lithologies and beds in what are now the deeper areas, a period of more uniform and widespread deposition commenced. These apparently homogeneous beds were examined using X-radiography.

X-radiography

The apparent homogeneity of the mud deposits hides much of the evidence for how the mud was deposited and its subsequent history. In this case the apparent homogeneity could have been real and arisen from intense bioturbation, core disturbance or disruption due to gas generation and release. Alternatively, it could have been an artefact of the small size of the sediment grains and
Mud thickness contour map derived from the University of Florida's geophysical and coring surveys (after Kirby et al., 1989).

Figure 6. Mud thickness contour map derived from the University of Florida's geophysical and coring surveys (after Kirby et al., 1989).
uniformity of the sediment supply over a prolonged period.

In most cases X-radiographs, especially towards the base of the mud layer, revealed a distinctive submillimeter, alternating sequence of dark and light bands (Figure 7). Layers only a few microns thick (approx. 10 μm) could be resolved. The very delicate, small-scale layering is important at two levels. First, it confirms the samples were largely undisturbed. Second, the layering embraces the preserved history of sedimentary events in the lake waters stretching back in this case over several thousand years. This rhythmic interbedding was not investigated in microscope section but is likely to reflect the results of algal blooms known to occur annually in the lake.

In the few X-radiographs available for examination, the submillimeter laminations became less well defined towards the top of the cores. This could be due to core disturbance, lack of consolidation to form distinctive layers or the generation and expulsion of gas. In respect of potential nutrient cycling, any repeated resuspension and re-deposition, on whatever time-scale, can only affect the upper succession where the submillimeter alternations could not be detected. Consequently, resuspension must only affect the upper few centimeters or tens of centimeters at most. Numerical simulation of sediment resuspension events in the lake corroborates this observation (HWANG, 1989).

One X-radiograph, OK1 VC, showed a series of circular or elliptical voids (Figure 8). These are likely to have been due to gas bubbles. As no strong smell of hydrogen sulfide was detected at any stage during sampling or core preparation, it is likely that the gas was methane.

Density and Shear Strength Profiles

Many cores had a very loosely consolidated upper zone of fluid mud in which in situ density measurements were made during collection. These upper zones ranged from a few to eight centimeters in depth and had densities ranging between 1,010 kg m⁻³ and 1,030 kg m⁻³. In the firmer, underlying mud both density and shear strength measurements are available (HWANG, 1989). Density and shear strength measurements were generally closely related. In unlayered deposits the density and shear strength showed a steady increase with depth, consistent with a normally consolidated and undifferentiated substrate. Other samples had a more complex stratigraphy of weak and strong clays or of clays, sands and shelly clays. These showed a gross increase in density and strength with depth but with detailed sharp density and strength variations and reversals (Figure 9). Mud densities ranged up to a maximum of 1,300 kg m⁻³. Sand densities
CONCLUSIONS

Geophysical and vibrocore surveys, in part coupled with results of a separate and wider mud coring survey, have permitted the shallow stratigraphy of Lake Okeechobee sediments to be examined on a preliminary basis. Where the succession is most complete a variable thickness of black mud overlies a thin veneer of fluviatile sand. In the northeastern region of the lake bed the sand lies on an in situ peat deposit, which is rooted into the white, calcareous beach rock forming the foundation of the lake.

The unconsolidated deposits occur mostly at the northern end of the lake suggesting a close affinity with Kissimmee River. The black mud

reacted 1,800 kg m$^{-3}$. Shear strengths reached almost 6 kPa. Even close to the lake bed these shear strengths are generally up to three times greater than the critical shear stress for erosion (Hwang, 1989). A plot of shear strength versus density shows the expected scatter (Figure 10). A best fit curve for the data intercepts the density axis at 1,065 kg m$^{-3}$, implying that samples of lower density had no strength and the material behaved essentially as a fluid.

The evidence of shear strength measurements consequently supports to some extent the X-radiographic evidence and indicates that the thin upper fluid mud layers are likely to be resuspended during windy weather, while the underlying, more consolidated mud is resistant to erosion.

Figure 9. Plot showing mud density and vane shear strength variations with depth at locality OK15 VC.

Figure 10. A composite plot of vane shear strength versus density of mud derived from cores (OK) 6, 9, 12, 13, 14, 15, 17, 22, 23, 28 and 29 (VC). (After Hwang, 1989).
occupies a volume of $193 \times 10^6$ m$^3$ (0.2 km$^3$). It is evident that the earliest mud deposits infill the deeper central portion of the lake. Brooks (1984) showed that these lower mud horizons date from at least 6,300 years BP, implying a very low sedimentation rate. At this early date the lake was apparently much smaller than today. Modern mud deposits are spreading wider. The deposits form an inclined patch extending into shallower water on the northeastern margin of the lake. This eccentric distribution and sloped surface must be controlled by the lake hydrodynamics.

The shear strength profiles indicate that only the upper, low-strength fluid mud zone is susceptible to resuspension, whereas the deeper sections, which exhibit submillimeter lamination, do not participate in sediment reworking.

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**LITERATURE CITED**


